AD-A059 520 ILLINOIS UNIV AT URBANA-CHAMPAIGN COORDINATED SCIENCE LAB F/G 9/3
ANNUAL PROGRESS REPORT FOR JULY 1, 1977 THROUGH JUNE 30, 1978,(U)
AUG 78 R T CHIEN, G G JUDGE, H V KRONE DAAB07-72-C-0259
UNCLASSIFIED NL

1 OF 3
AD
A059 520

AUGUST, 1978

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ANNUAL PROGRESS REPORT 1977-78

UNIVERSITY OF ILLINOIS - URBANA, ILLINOIS

The research reported in this document was made possible through support extended the Coordinated Science Laboratory, University of Illinois, by the Joint Services Electronics Program (U.S. Army Electronics Laboratories and U.S. Army Research Office, Office of Naval Research and the Air Force Office of Scientific Research) under Contract Number DAAB-07-72-C-0259.

Portions of this work were also supported by:

U. S. Air Force -- Office of Scientific Research

Grant AFOSR 73-2570

U. S. Air Force -- Hanscom Air Force Base

Contract AF F19628-78-C-0040

Wright-Patterson Air Force Base

Contract AF F33615-75-C-1291

U. S. Army Research Institute

DAHC-19-78-G-0011

U. S. Army -- Research Office

Contract DAAG-29-76-G-0154

Contract DAAG-29-78-G-0114

U. S. Department of Energy

ERDA EX-76-C-01-2088

U. S. Department of Transportation

DOT-OS-80020

U. S. Navy -- Office of Naval Research

Contract N00014-75-C-0612

Contract N00014-76-C-0806

National Aeronautics and Space Administration

NASA NSG-2119

National Science Foundation

NSF DMR 72-02937	NSF ENG 75-15050	NSF INT 76-84216	NSF ENG 77-15949
NSF DMR 73-02359	NSF ENG 75-20864	NSF DMR 76-20640	NSF DSI 77-26886
NSF MCS 73-03488	NSF ENG 75-22621	NSF DMR 77-08962	NSF DMR 77-22228
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NSF ENG 75-14100	NSF SED 76-18446	NSF ENG 77-20436	

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REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle)

(6) ANNUAL PROGRESS REPORT for July 1, 1977 through June 30, 1978, AD A064341

5. TYPE OF REPORT & PERIOD COVERED

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(S)

(10) R. T. / Chien, G. G. / Judge H. V. / Krone

8. CONTRACT OR GRANT NUMBER(s)

(15) DAAB 07-72-C-0259

9. PERFORMING ORGANIZATION NAME AND ADDRESS

Coordinated Science Laboratory
University of Illinois at Urbana-Champaign
Urbana, Illinois 61801

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS

(12) 274p.

11. CONTROLLING OFFICE NAME AND ADDRESS

Joint Services Electronics Program through U.S. Army Research Research Office, Research Triangle Park, N. C. 27709

12. REPORT DATE

(11) Aug[illegible]978

13. NUMBER OF PAGES

224

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)

15. SECURITY CLASS. (of this report)

UNCLASSIFIED

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release. Distribution unlimited.

DDC RECEIVED SEP 27 1978 F

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

See SUMMARIES, pages xl - xlviii

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

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UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

ANNUAL PROGRESS REPORT 1977-78

August, 1978

Submitted by: R. T. Chien
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COORDINATED SCIENCE LABORATORY
SUMMARY OF
PROGRESS REPORT FOR JULY 1977 THROUGH JUNE 1978

1. New Programs

New programs initiated during the past year in Physical Electronics include semiconductor crystal growth by molecular beam epitaxy (MBE) and by vapor phase epitaxy (VPE). Studies of growth methods and material characterization are the emphasis of these projects. Other new programs include a study of the excitation transfer between excited states in gas discharges, and an exploratory study of the excitation and properties of hot bands and quasi-continuum of gaseous molecules for laser applications.

2. Semiconductor Physics

Ion implanted layers in Si and III-V compounds are studied using electrical and optical measurements. Other studies include secondary ion mass spectroscopy (SIMS) and Auger electron spectroscopy (AES). The recrystallization of amorphous implanted Si is examined, with accompanying impurity activation and migration during annealing. Implantation, encapsulation, and annealing studies in GaAs include development of planar p-n junction devices. Deep-level impurities and defects are studied in Si and III-V compounds.

3. Thin Film Physics

The overall objective of this program is to investigate ion-surface interactions which have a controlling effect on the nucleation and growth kinetics, chemistry, and physical properties of alloy semiconducting films grown by sputtering. Analytical models have been developed to predict enhanced interdiffusion rates at heterojunction interfaces due to ion bombardment of the substrate and growing film during deposition. These calculations were supported by physical measurements using standing wave x-ray diffraction techniques to determine the period and amplitude of the compositional modulation wave in InSb/GaSb superlattice structures deposited under varying degrees of ion bombardment.

Enhanced diffusion coefficients more than five orders of magnitude larger than thermal values were observed. Results showed that using such techniques, interfacial abruptness and coherence could be adjusted on the scale of monolayers to tens of Å even for junctions with large lattice mismatches.

The effect of ion bombardment on elemental sticking probabilities was also investigated and, in III-V compounds, found to have a stabilizing effect on stoichiometric compound formation. It has also been shown to allow the growth of metastable alloys such as In(Sb,Bi) with InBi concentrations more than four times the solid solubility limit. Film growth parameters have been related to the chemistry and physical properties of deposited films as determined by glow discharge optical spectroscopy (GDOS), Auger electron spectroscopy (AES), x-ray photoelectron spectroscopy (XPS), and secondary ion mass spectroscopy (SIMS), in addition to metallurgical and electrical measurements.

4. Microwave Acoustics

The long range objective of this research is to originate and analyze new microacoustic wave principles that will lead to significant device applications. Work has been directed toward the realization of a new class of devices based on the propagation of nondispersive line acoustic waves along the edge of cleaved substrates. Line wave transducers with a resolution requirement four times less than that of surface acoustic wave transducers have been fabricated. The lift off technique has been adapted for edge device fabrication and line acoustic wave devices on GaAs have been demonstrated. The model for surface acoustic wave transducers has been generalized and simplified. As a result, transducers with arbitrary tap weights are now easily and accurately modeled. A technique for analyzing nonperiodic multistrip couplers has been developed. Significant progress has also been made in the study of surface acoustic wave scattering from periodic arrays. A new experimental technique for independently evaluating the scattering parameters has been devised and a theoretical method for determining the dispersion relation of thick metal scattering elements on arbitrary piezoelectric substrates has been developed.

5. Surface Studies

Experiments have been initiated to directly test the surface reactivity of vibrationally excited gas molecules. These measurements, which have concentrated on laser excitation of methane, are still underway. Work has also been started on the thermodynamics of adatom clusters, which are important in thin film phenomena. This effort has resulted in the first quantitative values for the thermodynamics of dimer dissociation.

6. Millimeter Wave Integrated Circuits

New active and passive circuit designs for millimeter waves have been developed using dielectric substrates and complete receiver systems have been successfully developed and tested. Three analytical approaches for predicting the characteristics of planar and tapered dielectric waveguides have been investigated. Extensive numerical results have been derived and good correlation with experimental results have been obtained.

7. Electromagnetic Radiation and Scattering

The Spectral Domain Approach has been employed for the analysis of three important problems in high frequency diffraction with applications to radar, electromagnetic countermeasures and electromagnetic compatibility. Reliable accuracy tests for high frequency asymptotic solutions have been developed and tested. New results have been obtained for the far-fields radiated by sources in the presence of smooth conducting surfaces that are large compared to the wavelength.

8. Plasma Physics

Two interesting studies have been completed in nonlinear beam-plasma interactions. Anomalous harmonic generation by an unstable beam-plasma wave has been observed experimentally, and a model including the effects of nonlinear wave-particle interaction has been proposed to account for the phenomenon. A theory of parametric instability of plasma

waves and ion-acoustic waves in a beam-plasma system has been devised. Experiments on sideband excitation by an unstable beam-plasma wave have been performed, and excellent agreement has been found with the parametric instability theory.

The proposed experiment on wave potential probability density functions in ion-acoustic turbulence has moved out of the planning stage. Diagnostic equipment essential to the experiment has been obtained and set up, and several preliminary tests have been run.

9. Rarefied Gas Dynamics

Under our long range plans to use the kinetic theory treatment to solve gas dynamics problems under non-equilibrium conditions, we have solved the Boltzmann as well as the Krook equations for an evaporation problem as well as a condensation problem. Both problems has a wide range of applications. We have also studied the development of Monte Carlo techniques to study several rarefied gas flow problems including that of the separation process in aerodynamic isotope enrichment devices.

10. Computational Gas Dynamics

Under our long range plans to solve directly the basic gas dynamic equations for complex problems, we have studied the application of finite element, finite difference and hybrid methods to solve selected problems of current interest. Two methods have been developed to generate numerically optimum meshes that can be used to implement both finite element and finite difference methods for problems of complex geometrics. Our major research efforts include the numerical solution of the nonlinear free surface problems and the viscous flow problems of complex boundary conditions and geometries.

11. Fault-Tolerant Systems and Computer Architecture

Research in Fault-Tolerant Distributed Systems covers the development of efficient, functional level testing techniques for memories and microprocessors, the comparison of a new technique of self-diagnosis for distributed systems ("roving diagnosis"), which does not use a global supervisor or dedicated redundancy, with systems using classical redundancy, and the study of the use of semi-Markov processes in the modelling of computer system performance.

Research in Concurrent Self-Diagnosis and Reconfiguration in Large-Scale Systems covers the study of the self-checking capabilities of certain codes with respect to structures of arithmetic circuits and fault models, further applications of alternating self-checking logic, new results on the identification of fault-free rather than faulty units in an interconnected system, new results on the connections and other properties required of a system to permit self-diagnosis by "roving diagnosis", design techniques for reliable interconnection networks, and the specification of a design language for multiprocessor systems that results in deadlock-free control structures.

Research in Computer Architecture covers studies of the performance of functional resources for a multiple-stream pipelined processor and the investigation of analytic models for stochastic scheduling of parallel pipeline processors.

Research in Computer System Organization covers continuing work in the modeling of the performance of multiple-processor virtual memory systems, continuing studies of the performance of interleaved memories in a multiprocessor environment, a report on the experience with the AMP-1 multiple microprocessor system, and a study of levels of program representation vs. computer organization.

Research in Modeling and Evaluation of Large Computer Systems covers the development of a general queueing simulator and the study of the "local balance" property of certain queueing systems.

12. Display, Memory, and Computer Terminal Research

The characteristics of professional teleconferencing are being examined to define those concepts important for efficient remote human graphic communication. A test system has been constructed to simulate low bandwidth interactive facsimile communication.

Low cost video/data disk concepts are being explored. A high speed random access readout servo control system design has been developed. Data encoding techniques for this disk have been examined.

A real time computer controlled AC plasma display panel has been developed. This system displays the wall charge transfer curve of a single plasma cell and allows the engineer to rapidly assess the consequences of design and parameter changes.

13. Applied Computation Theory

Work in the analysis and design of efficient computational techniques has been continued, prevalently in the field of computational geometry. In this area new and significant results have been obtained in the intersection of convex polyhedra and sets of half-spaces, proximity and reachability in the plane, and triangulations. Research has also been conducted in other areas, and interesting results have been reported, specifically in storage management (array-to-tree mapping), parallel computation (matrix inversion), algebraic techniques (boolean matrix multiplication), and combinational design (reduction of depth of switching networks).

14. Advanced Automation

Progress has been made in a number of areas, including natural language understanding, manipulation and assembly, visual information processing and recognition, computer aided decision making, human decision making and human-computer interaction. In natural language understanding improvements have been made in the PLANES natural language question answering system and evaluation of the system has begun, a browsing and alerting system for a large data base has been developed, and

new systems for making spacial inferences about language and for performing automatic planning have been written. A new system which uses visual feedback for manipulation has been developed along with a novel high-level manipulator control system. Visual information processing and recognition work has concentrated on image segmentation, correlation of stereo image pairs, image modeling and reconstruction methods, and networks of automata for low level vision. Computer aided decision making work has progressed toward a system to monitor aircraft systems and help a pilot recover from failures or course deviations. Techniques have been developed for automatic analog test program generation for circuits. In the area of human decision making and human-computer interaction, investigations have been made of human performance in multi-task situations and in computer-aided fault diagnosis. Finally, a system has been developed for the modeling of library networks.

15. Information Retrieval Research

During the 1977-1978 time period the Information Retrieval Research Laboratory (IRRL) conducted a number of research and development projects and directed the operation of the University of Illinois' online search service. Major activities included the following: development of a hybrid approach to fact identification in natural language text using Keyword and AI techniques; analysis of data base data; design of an automatic data base selector; design of an integrated man/machine interface to facilitate network resource utilization; development of a directory on transnational corporations for the United Nations; design of a system for the automatic generation of a state-wide union catalog; computer assistance in development of an index and bibliography of electroorganic synthesis reactions; development of a computer-readable data base directory; and management and direction of the University of Illinois' online search service.

16. Communications Systems and Signal Processing

Progress in communications has been in three major areas. First, new results in weakly- and strongly-universal variable rate data compressions for discrete-time sources have been obtained. Second, optimum data quantizers for signal detection, memoryless detectors for operation in dependent noise, and robust signal detectors for unknown noise environments have been derived. Detection-estimation schemes for estimating signals with Poisson noise input or with Markovian switched noise statistics have been developed. Third, analytical results have been obtained for direct-sequence spread-spectrum multiple-access (SSMA) communications over white noise and fading channels. Sequences with good correlation properties have been designed for such systems.

17. Analog and Digital Circuits

Progress is reported in four different research areas. First, a new project was initiated this past year on the fault analysis of analog circuits. Under the assumption that all the circuit nodes are accessible, two new methods have been found for the location of faults. One method locates a single fault in resistor circuits, and the other method enables one to calculate parameter values from the node voltage measurements. Results are reported for another project on the reduced order modeling of linear systems. An approach is presented for the reduced-order modeling of subnetworks, and the use of topological relationships is being examined for the modeling of the overall system response. A third project involves research for new high performance recursive digital filter structures. Multiple feedback structures are being studied as well as new architectures based on the residue number system. Our study shows that architectures based on the residue number system have advantages in terms of speed and cost. Signals can be processed in parallel using high speed table look-up arithmetic with read-only memories. The fourth research project is concerned with the design of switched-capacitor filters. Present design methods are based on first-order approximations to the analog filter. These techniques require an unusually high sampling rate in order to avoid distortion of the frequency response. Presently we are studying the implementation of some second-order approximations which correct this problem.

18. Decision and Control

Several projects have led to many results involving various aspects of control analysis, synthesis, and optimization. The key directions are control and decision strategies for systems under imperfect information, reduced order modeling by chained aggregation and by singular perturbation, control strategies for large scale systems with multiple decision makers, multimodeling of large scale systems, and structural properties of large scale systems.

19. Population/Food/Weather Studies

The overall objective of the project is to develop and disseminate nationally, to institutions of higher education, multipurpose computer-based instruction models for teaching Population Dynamics and population-related issues, such as population and food, population and economic development. This objective is designed to fill a recognized need for the development of techniques to communicate the structure and dynamics of population by utilizing the latest developments in computer technology. It is a primary objective of the project to design a flexible interactive educational system which can be adapted and implemented on a large number of computer systems [graphics terminals, teletype, slide output, hardcopy output] throughout the nation.

The weather studies are aimed at developing long range forecasting techniques for weather and climate. The forecast range varies from a few months to a few years. In addition to the common meteorological variables, crop data has been found to be a useful indicator of long range weather trends.

1. NEW PROGRAMS*

Faculty and Senior Staff

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1.1 Introduction

The Physical Electronics research program was strengthened considerably in April 1978 by the addition of five new research units. Two of these projects involve the growth and characterization of III-V semiconductors, and three involve basic studies in Quantum Electronics. Since these new programs were begun during the last quarter of the reporting period, only brief summaries of initial work are presented in this section.

1.2 Molecular Beam Epitaxy

Initial work on the MBE project has centered on specification of the growth facility. An appropriate design for a versatile MBE system has been developed and quotations have been obtained from vendors. An order will be placed for a facility having a deposition chamber, a separate analytical chamber, and a sample preparation (load lock) chamber. Appropriate analytical facilities will be included for examination of growth mechanisms and properties of grown crystals.

Work has begun on the theoretical calculation of properties of a single monolayer of AlGaAs imbedded in GaAs. Continuing experimental work includes low temperature photoluminescence and electrical activation studies of MBE GaAs layers.

In October 1978 a new faculty member (Assistant Professor) will be added to this project, with primary responsibility for the MBE crystal growth facility.

*This work was supported by the Joint Services Electronics Program (U.S. Army, U.S. Navy, and U.S. Air Force) under Contract DAAB-07-72-C-0259.

1.3 Vapor Phase Epitaxy

In this research vapor-phase epitaxial growth of high-purity InP is studied using the H_2-HCl-In-PH_3 technique, and residual donor levels are characterized by far-infrared photoconductivity. The goal of this work is to determine the purity at which InP epitaxial layers can be grown using the hydride growth system. There are many parameters that can influence the growth of high purity InP using the hydride growth system. In this work we will study the influence of the controllable parameters such as partial pressure of HCl in the growth zone, HCl flow rates over the In melt, growth rate, substrate orientation, H_2O content in the system, etc., on the purity of InP epitaxial layers. Other less controllable parameters such as the purity of the reactant gases and the purity of the source In will also be evaluated qualitatively.

The influence of these parameters on the toal ionized impurity content of the epitaxial layer grown on insulating substrates will be evaluated initially by Hall effect measurements at room temperature and liquid nitrogen temperature. These measurements are a routine procedure used in our laboratory for the evaluation of semiconductor material. In the second and third year of this research we plan to add a variable temperature Dewar with calibrated thermometer and temperature controller for extending the Hall measurements to cover the 4.2-350K temperature range. Analysis of this data should provide a more accurate estimate of the total ionized impurity content of the epitaxial layers.

In order to more accurately assess the effect of the growth parameters on the purity of the material, measurements will be made to identify the residual acceptors and donors in the grown layers and to study the variation of the relative concentrations of these impurities with varying growth parameters. The different acceptors can be detected using near band edge photoluminescence and near IR photoconductivity techniques with apparatus available in our laboratory. The detection of different donor impurities is much more difficult, however, since all of the shallow donors have very nearly equal ionization energies. However, the technique of far-infrared Fourier transform spectroscopy and the photo-thermal ionization of the shallow donor impurity levels can be combined to detect different donor levels present in high-purity InP.

The Fourier transform measurements will also be supported by NRL for the evaluation of high purity InP and GaAs materials grown in government laboratories and under DOD support.

1.4 Excitation Transfer Between Excited States in Gas Discharges

The general goal of this work unit is to study the excited state chemistry of a gas discharge, with the specific task of investigating those reactions which excite a laser. Our initial efforts have been aimed at the metal-halide salts such as $HgBr_2$, $HgCl_2$, $SnCl_2$, and TlI, etc. The philosophy used in choosing these vapors is that lasing has been achieved [1] in the first two, and Maya [2,3] indicates high quantum efficiencies for photon production in all of the salts.

Although the kinetic processes occurring in an active discharge is our prime interest, a discharge environment is most complicated. Thus our initial effort has involved optical pumping of the salts by the resonance radiation (at 2537 Å and 1849 Å) from a mercury arc lamp. We have measured strong absorption by the above vapors in this wavelength interval, and thus could reasonably expect strong excitation transfer between the excited mercury atoms and the salt vapor.

1.5 Excitation and Study of Highly-Excited States of Molecules

This work is an exploratory study of the excitation and properties of hot bands and quasi-continuum of gaseous molecules for laser applications.

Optical pumping of molecular lasers has, with few exceptions, been done with a single photon pump which accesses only one "rung" of the vibrational ladder of the molecule. This study proposes to use two or more different frequency photons to access more "rungs", combination bands and quasi-continuum of the molecule and evaluate their properties as a quantum electronics system.

The initial work on this problem has involved an extensive literature search, evaluation of excitation schemes, selection and devising of diagnostic methods, and the design of an experiment, since this is a new and not an on-going effort. NH_3, pumped by an N_2O and HF laser, has been selected as the first molecular system for study. This first goal

will be to use the 2.3 μm fluorescence from NH_3 to monitor the highly excited vibrational state.

Ambartsumyan, et al. [4] describe a method of measuring the populations of the vibrational levels by studying the absorption lines in the transitions of molecules from the vibrational states to an excited electronic state. Although they only gave results for $v = 1$, we have been evaluating this method for $v > 1$ on paper and considering the problems of instrumenting this experiment.

1.6 Energy Transfer Processes in Excited Atoms

The development of laser systems like the rare gas halides require a detailed knowledge of the fundamental energy transfer processes into and from excited atoms and molecules. This experimental study is aimed at measurements of electron impact cross sections, spectral broadening, and line shift coefficients and two and three body rate coefficients all associated with excited states.

The approach being adopted entails using a pulsed swarm chamber as a means of exciting the gas, followed by either an electrical or optical interrogation of the subsequently decaying states. From the time evolution, equivalent decay rates and branching ratios may be extracted.

At present the swarm chamber has been constructed and is being used to deduce electron impact excitation and ionization rates from ground state rare gases (Ar, Ne, Kr, and Xe). Briefly, the swarm chamber is basically a gas filled photodiode with a set of guard rings to provide field uniformity [5]. A burst of photoelectrons is generated off the cathode with a pulsed UV source. The resulting electron and ion currents are monitored; the area under each pulse being used to extract the ionization rate [6]. Using these data in a computer program which solves the Boltzmann transport equation, equivalent cross sections for inelastic and ionization processes may be obtained, data which are somewhat lacking for the rare gases [7].

The next stage of the study will be to use the swarm as a means of pulse exciting metastables. Subsequent to their excitation, a second swarm may be used to measure impact excitation from these states or a tunable laser pulse may be used to selectively excite one higher lying

level from which fluorescence may be detected, yielding decay information. Progress along these lines awaits the arrival of a signal averager and a dye laser system and will be reported later.

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2.1 Introduction

Properties of ion-implanted layers in semiconductors are examined in this research, including basic materials properties and device-related effects. Studies of amorphized Si resulting from high-dose implantation include recrystallization effects, migration of impurities, surface contamination, and residual defects after recrystallization. Implantation and annealing studies in GaAs have led to the formation of planar p-n junctions appropriate for GaAs integrated circuit applications. Development of encapsulants for annealing GaAs has led to improved nitride deposition techniques with possible MIS applications. Deep level impurities in the ternary alloys Ga(As,P) and (Al,Ga)As have been examined using photoluminescence, optical absorption, and Raman spectroscopy. A coherent picture of the nitrogen isoelectronic trap in these alloys has emerged from this work.

2.2 Implantation Studies in Si*

2.2.1 Recrystallization of Amorphized Implanted Silicon

A continuous amorphous phase is often formed when Si is heavily implanted. This amorphous region is reordered in the range 550°-600°C by epitaxial recrystallization, as studied recently by backscattering methods [1,2]. In this work we examine the electrical properties of such recrystallized layers [3,4]. Electrical carrier profiles of BF_2 or Si+B implanted layers annealed isothermally at 550°C have been studied by

*This work was supported by the Joint Services Electronics (U.S. Army, U.S. Navy, U.S. Air Force) Program under Contract DAAB-07-72-C-0259 and by the National Science Foundation under Grants DMR73-02359 and DMR77-22228.

differential resistivity and Hall effect measurements. The boron atomic profiles are measured by SIMS. This study shows that boron atoms inside the amorphized Si layers can be fully activated during recrystallization at 550°C, and that the mobility is also recovered (Fig. 2.1). The tail of the B distribution remains inactive, however, if it is located in a damaged region below the original amorphous-crystalline interface. The inactive tail has been observed for all samples implanted with BF_2^+. Only in a thicker amorphous layer, formed for example by Si^+ predamage implants, can the entire B profile be activated.

2.2.2 Fluorine Distribution in BF_2-implanted Layers

The implantation of BF_2 molecular ions into silicon has several practical advantages over B-implantation [3]. However, the outdiffusion and redistribution of fluorine atoms during annealing has not been studied prior to this work. We have performed SIMS measurements on such fluorine distributions as a function of anneal temperature and time [3,5], and find anomalous migration of fluorine in samples which were amorphized during implantation. Outdiffusion of fluorine occurs during recrystallization of the amorphous layer, and fluorine collects in regions of residual damage during annealing (Fig. 2.2). This gettering of fluorine by defects illustrates the residual damage below the amorphized layer apparent in Fig. 2.1. We find this damage to be more severe in samples implanted at room temperature than in samples implanted at lower temperature ($\sim$ -110°C).

2.2.3 Surface Contamination Produced During High-Dose Ion Implantation

We have performed Auger Electron Spectroscopy (AES) measurements to examine surface contamination layers on silicon produced by high-dose ion implantation [6]. Depth profiling studies indicate that when conventional diffusion pump oil is used in the vacuum system of the implanter target chamber, high-dose implantation of Si^+ or BF_2^+ leads to formation of a carbonaceous surface layer $\sim$100 Å thick. Physisorption of hydrocarbons from the implanter residual vacuum followed by radiation-induced polymerization is the most probable cause for the formation of this

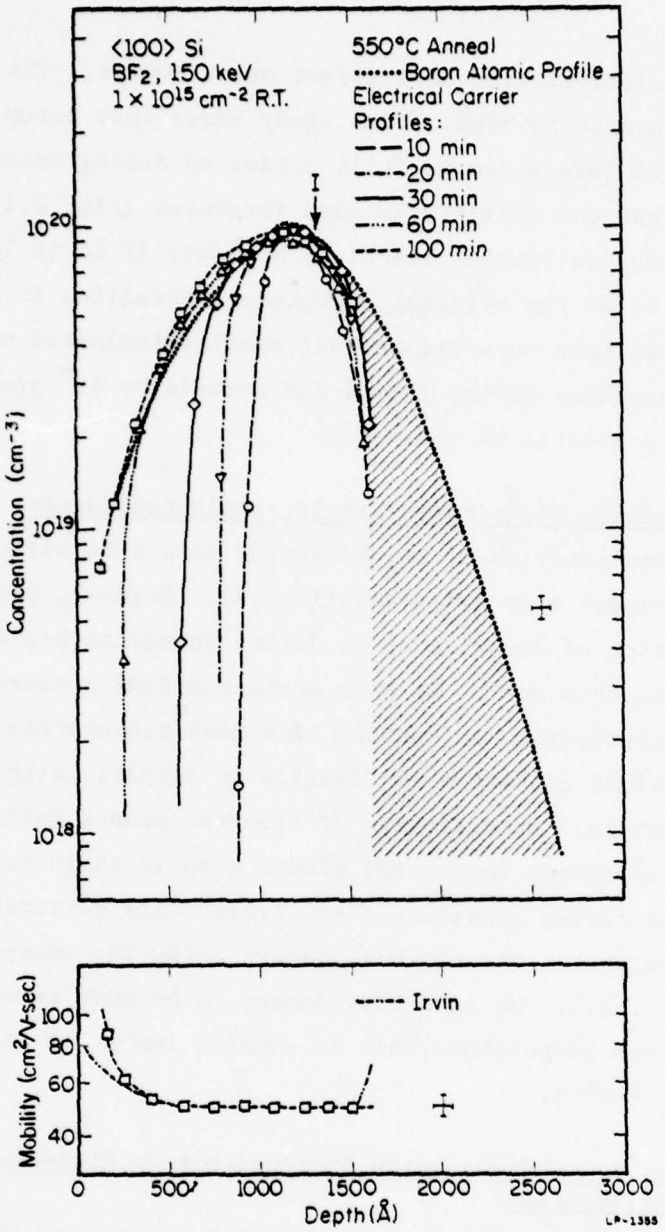

Figure 2.1 Net acceptor concentration and mobility profiles obtained from differential Hall effect measurements after the BF_2^+ implant shown and 550°C isothermal anneals. The dotted curve shows the implanted boron profile from SIMS measurements. The shaded area indicates the electrically inactive tail of the B distribution below the original amorphous-crystalline interface I. Mobility data taken after the 100 min anneal are compared with Irvin's mobility values for bulk Si.

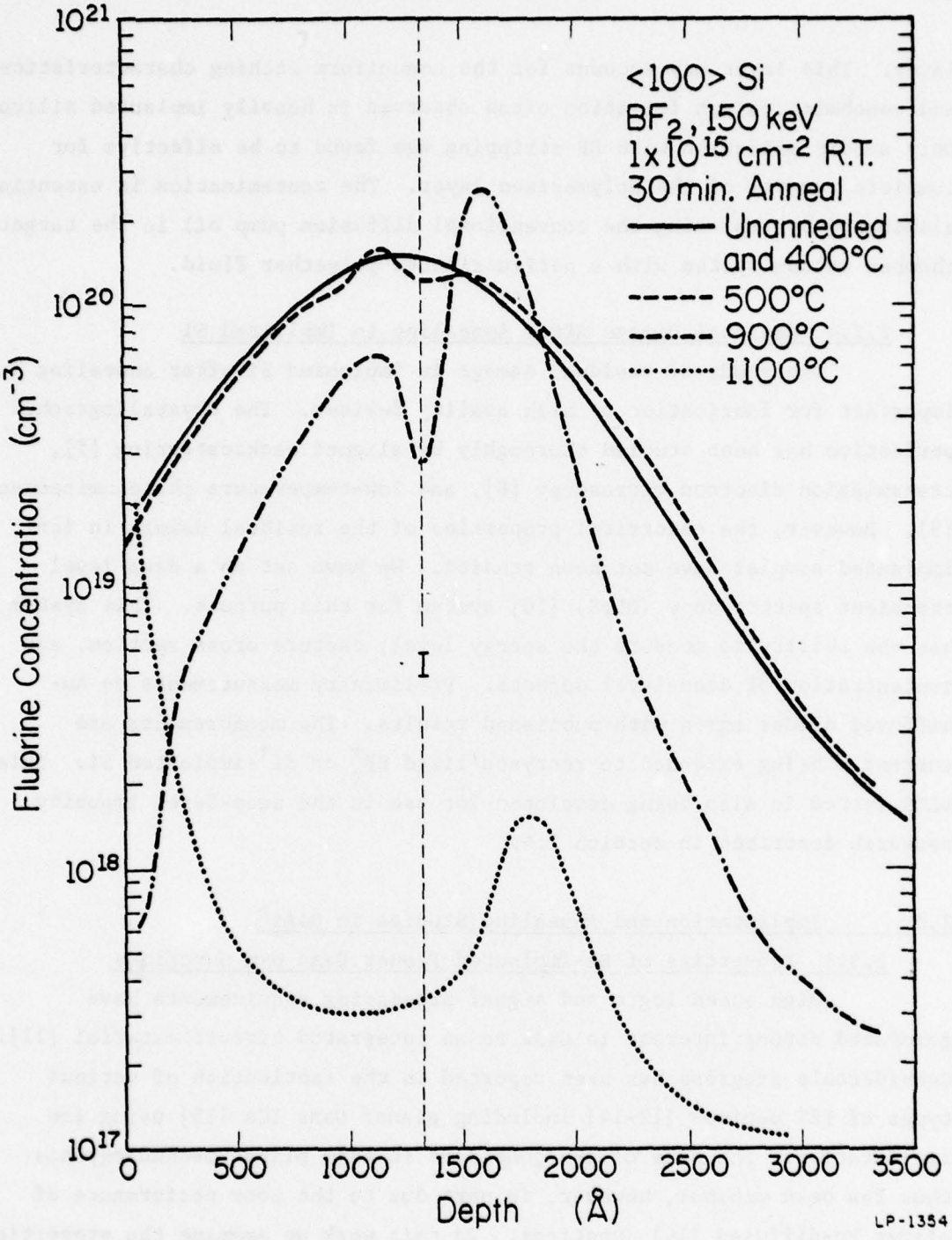

Figure 2.2 Fluorine atomic profiles obtained from SIMS measurements on ⟨100⟩ Si implanted at room temperature with a 1×10^{15} cm^{-2} fluence of BF_2^+ and annealed for 30 min at the temperature shown. A thin dashed line (I) represents the amorphous-crystalline interface after implantation.

layer. This layer may account for the nonuniform etching characteristics and nonohmic contact formation often observed in heavily implanted silicon. Only anodic oxidation with HF stripping was found to be effective for complete removal of the polymerized layer. The contamination is essentially eliminated by replacing the conventional diffusion pump oil in the target chamber vacuum system with a perfluorinated polyether fluid.

2.2.4 Residual Damage After Annealing in Implanted Si

The study of residual damage in implanted Si after annealing is important for fabrication of high quality devices. The crystallographic perfection has been studied thoroughly by aligned backscattering [7], transmission electron microscopy [8], and low-temperature photoluminescence [9]. However, the electrical properties of the residual damage in ion-implanted samples have not been studied. We have set up a deep level transient spectroscopy (DLTS) [10] system for this purpose. This system has the ability to measure the energy level, capture cross section, and concentration of deep-level defects. Preliminary measurements on Au-diffused diodes agree with published results. The measurements are currently being extended to recrystallized BF_2^+ or Si^+-implanted Si. This DLTS system is also being developed for use in the deep-level impurity research described in section 2.4.

2.3 Implantation and Annealing Studies in GaAs*

2.3.1 Properties of Be-implanted Planar GaAs p-n Junctions

High speed logic and signal processing requirements have generated strong interest in GaAs as an integrated circuit material [11]. Considerable progress has been reported in the fabrication of various types of FET devices [12-14] including planar GaAs ICs [15] using ion implantation. The role of p-n junctions in GaAs planar technology has thus far been minimal, however, in part due to the poor performance of planar Zn-diffused [16] junctions. In this work we examine the properties of planar Be-implanted junctions in GaAs and compare the results with

*This work was supported by the Joint Services Electronics Program (U.S. Army, U.S. Navy, and U.S. Air Force) under Contract DAAB-07-72-C-0259, by the Office of Naval Research under Contract N00014-76-C-0806, and by Monsanto Company.

similarly processed Zn-diffused and Zn-implanted devices. We have also examined the influence of the encapsulant used during annealing on the properties of Be-implanted planar junctions.

The diodes were fabricated using standard photolithographic techniques, the details of which have been published elsewhere [17,18]. Oxygen-free Si_3N_4 deposited by an rf plasma deposition technique [19], $Si_xO_yN_z$, and SiO_2 layers deposited by thermal oxidation of silane were used as encapsulants during annealing of the radiation damage which accompanies the implantation process. The measured Be-implanted profiles are ~1.8 μm deep and rather abrupt [20].

Current-voltage characteristics obtained from Be-implanted junctions which were encapsulated during annealing with oxygen-free Si_3N_4 films are exceptionally good. The leakage current is remarkably low, less than 10^{-10} A in 10-mil diodes for reverse bias voltage up to ~80 V. With a background donor concentration of $\sim 5 \times 10^{15}$ cm^{-3}, the breakdown occurs at > 200 V. The forward characteristics can be expressed by the conventional diode equation $I_f = I_0 \exp(qV/nkT)$, where $n \simeq 2$ for $I_f \leq 10^{-9}$A and $n \simeq 1.6$ for $I_f > 10^{-9}$A. The reverse leakage and breakdown properties are unusually good for unguarded planar GaAs diodes. Measurements performed on ~50 such diodes reveal a distribution of breakdown voltages over the range 170-250 V. Diodes fabricated with $Si_xO_yN_z$ encapsulation during annealing had inferior current-voltage characteristics, and SiO_2-encapsulated diodes were much worse. Low temperature photoluminescence (PL) and Auger Electron Spectroscopy (AES) studies show that when GaAs is annealed with SiO_2 or $Si_xO_yN_z$ encapsulation, considerable Ga outdiffusion takes place [21]. Oxygen-free Si_3N_4 prevents such outdiffusion and acts as an excellent encapsulant. The system used to deposit such layers and the film properties are discussed in section 2.3.2. These results clearly show that the presence of Ga outdiffusion during annealing has a dramatic influence on the junction characteristics.

Another important feature of Be-implanted junctions in GaAs is a lack of lateral diffusion during annealing [17]. Using electron-beam lithography facilities at Texas Instruments, we have shown that Be-implanted planar junctions can be maintained to one-micron linewidths. Further studies of this feature, which has important implications for microwave and integrated circuit applications, are underway.

We have examined the photodetection properties of Be-implanted p-n junctions annealed with Si_3N_4 encapsulation. Quantum efficiencies range from ~45% at 8500 Å to ~15% at 6328 Å for devices with junction depths of 1.2 μ and with no antireflection coating. Avalanche gain of $\lesssim$ 10 have been measured on these unguarded planar diodes [22]. More work on the characterization of such photodetectors is presently being carried out in collaboration with Professor G. E. Stillman.

2.3.2 Study of Encapsulants for Annealing GaAs

The process of ion implantation introduces considerable lattice damage which must be annealed out to electrically activate the implanted species. Photoluminescence and electrical measurements indicate that the implanted GaAs samples must be annealed at ~900°C to effectively reduce this damage [20]. The incongruent evaporation of GaAs at these temperatures [23] makes it necessary to either encapsulate the sample with a suitable dielectric [24,25] or to perform the anneal in a carefully controlled ambient [26]. Low temperature photoluminescence (PL) and Auger electron spectroscopy (AES) were used to study the encapsulating properties of chemical vapor deposited SiO_2, rf plasma deposited $Si_xO_yN_z$, and oxygen-free Si_3N_4. The results, discussed in last year's progress report, clearly demonstrate that both SiO_2 and silicon oxynitride allow considerable Ga outdiffusion while oxygen-free silicon nitride layers act as an excellent encapsulant [21]. These conclusions are further substantiated by the results on Be-implanted planar junctions discussed in section 2.3.1.

The rf-plasma nitride deposition system used in this work is shown in Fig. 2.3. A low oxygen content is achieved by pumping the system to a low base pressure before deposition, using a diffusion pump. A nitrogen plasma is then formed before introducing silane separately. We have measured the chemical composition, index of refraction, etch rate, and deposition rate of the films as functions of N_2:SiH_4 ratio, and these results are published elsewhere [19]. Based on Rutherford backscattering (NRL) and Auger electron spectroscopy measurements, the oxygen content of these films is below one atomic percent.

Capacitance-voltage measurements performed on GaAs MIS structures show that our plasma deposited nitride layers result in surface state

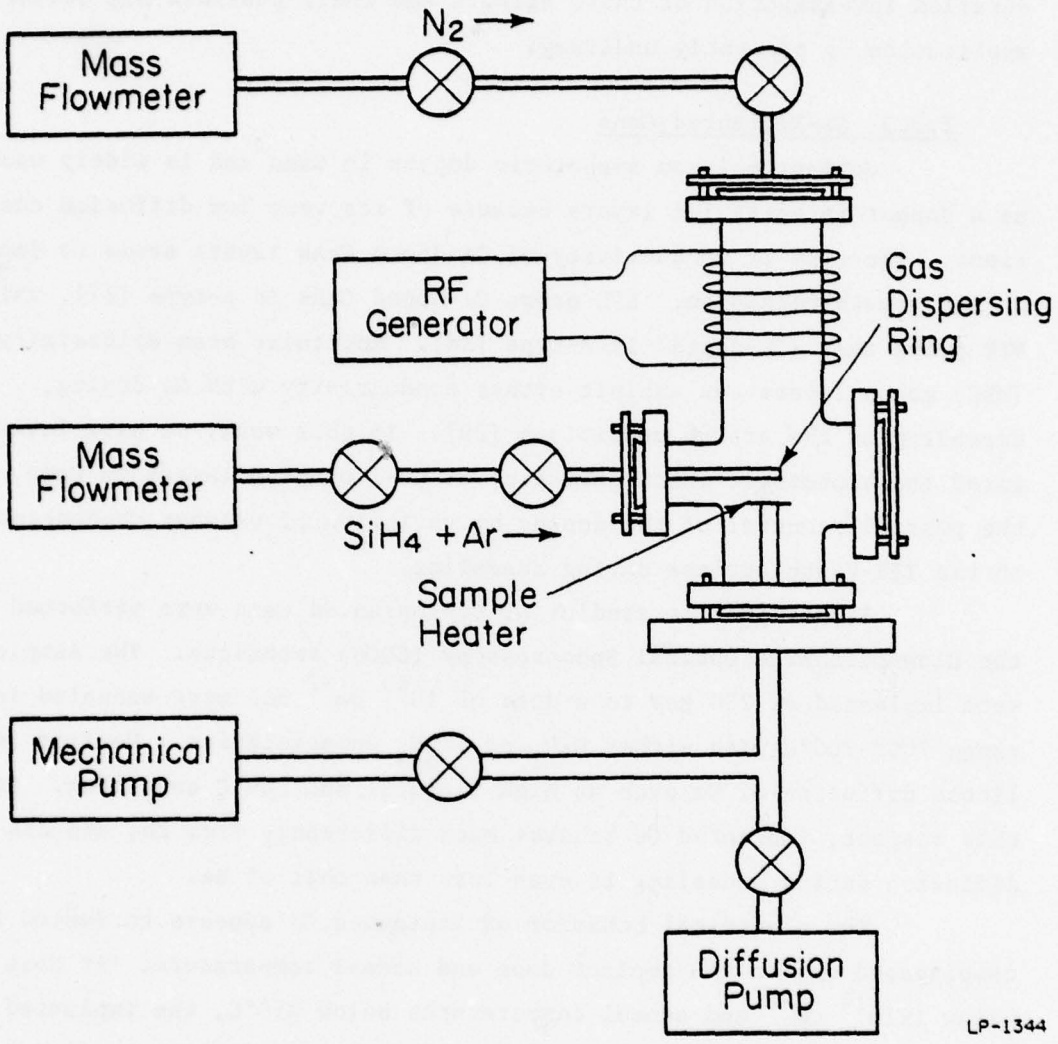

Figure 2.3 Schematic diagram of the rf plasma Si_3N_4 deposition system.

densities of $\sim 10^{12}$ cm^{-2} and appear to have properties considerably better than those obtained using high temperature CVD nitride layers. A more detailed investigation of these effects and their possible MIS device application is presently underway.

2.3.3 Ge-Implanted GaAs

Germanium is an amphoteric dopant in GaAs and is widely used as a dopant in epitaxial layers because of its very low diffusion coefficient. The type of conductivity of Ge-doped GaAs layers seems to depend on the growth mechanism. LPE grown Ge-doped GaAs is p-type [27], while VPE grown GaAs (Ge-doped) is n-type [28]. Molecular beam epitaxially (MBE) grown layers can exhibit either conductivity with Ge doping, depending on the growth conditions [29]. In this work, we have investigated the amphoteric characteristics of Ge-implanted layers in GaAs, and the possible control of the doping by variation of vacancy concentration on the III-V sublattices during annealing.

Atomic profile studies of Ge-implanted GaAs were performed using the Glow Discharge Optical Spectroscopy (GDOS) technique. The samples were implanted at 250 keV to a dose of 10^{15} cm^{-2} and were annealed in the range 700°-900°C with either SiO_2 or Si_3N_4 encapsulation. We find very little diffusion of Ge even at high fluences and 900°C annealing. In this respect, implanted Ge behaves much differently from Zn, and the diffusion during annealing is even less than that of Be.

The electrical behavior of implanted Ge appears to depend in a complicated way on the implant dose and anneal temperature. At doses below 1×10^{14} cm^{-2} and anneal temperatures below 850°C, the implanted layer is p-type with low hole mobility. The electrical activation in this case is $\sim$10%. At anneal temperatures greater than 850°C, the conductivity of the layer changes to n-type and the apparent activation drops down to $\sim$1%. At implant doses of 10^{15} the implanted layer remains n-type with low activation at all anneal temperatures between 700°-900°C. The nature of the encapsulant used (whether SiO_2 or Si_3N_4) does not appear to have a strong influence on the electrical behavior. More detailed studies, including effects of co-implantation (As + Ge, Ga + Ge, P + Ge) and elevated temperature implants are necessary.

2.4 Studies of Deep Levels in Semiconductors*

This work is devoted to understanding the basic physics of various deep-level impurities and defects in semiconductors. In previous reports we have described extensive optical absorption and photoluminescence measurements of the nitrogen trap in the ternary alloy $GaAs_{1-x}P_x$. We have shown that by varying the alloy composition x, many properties of the trap can be varied, including electron binding energy, phonon participation, and effects of lattice relaxation. This variability of basic properties of the trap, coupled with control of impurity concentration by ion implantation, has led to new understanding of this system [30].

Work in the present reporting period has included extensive Raman spectroscopy studies of the N trap [31], and delineation of the two subcomponents of the isolated N trap state (N_X), corresponding to J=1 and J=2 excitons (called A and B in GaP).

The phonon sidebands to the N_X state provide insight into the role of band structure in determining the exciton-phonon coupling strengths. We have analyzed the lineshapes in $GaAs_{1-x}P_x$ employing the linear exciton-phonon coupling theory of Huang and Rhys [32]. We assume for simplicity that the zero-phonon line is inhomogeneously Gaussian broadened and that only three phonons dominate the lineshape: longitudinal optical (LO), longitudinal acoustic (LA), and transverse acoustic (TA). The Huang-Rhys electron-phonon coupling factors S and the zero phonon Gaussian widths extracted from $GaAs_{1-x}P_x$:N luminescence lineshapes are displayed in Fig. 2.4. So long as the electron is localized ($x \gtrsim 0.46$), the alloy broadening follows the expected x(1-x) alloy-disorder dependence. But as the Γ minimum and the N_X line approach one another in $GaAs_{1-x}P_x$, the electron wavefunction becomes increasingly made up of wavevectors near Γ, the exciton becomes increasingly delocalized and insensitive to the local alloy fluctuations, and the exciton-phonon coupling constants drop precipitously.

The role of lattice relaxation in determining the N_X binding energy can be documented by comparing data from $GaAs_{1-x}P_x$ and $Al_xGa_{1-x}As$.

*This work was supported by the Joint Services Electronics Program (U.S. Army, U.S. Navy, and U.S. Air Force) under Contract DAAB-07-72-C-0259 and by Monsanto Company.

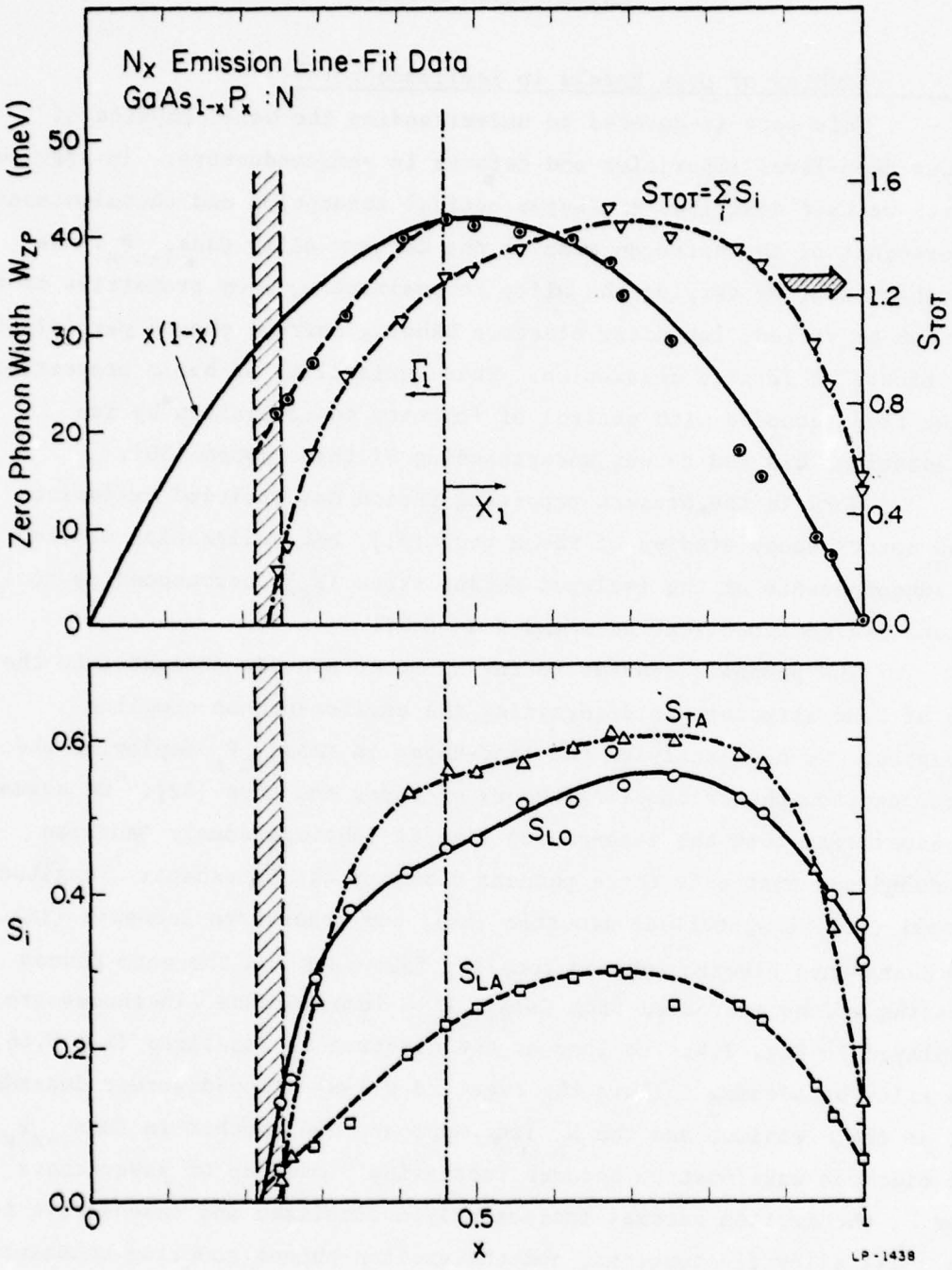

Figure 2.4 Zero-phonon alloy broadening widths and Huang Rhys factors S vs. composition x for $GaAs_{1-x}P_x$:N. At $x \simeq 0.46$ the band structure switches from direct (Γ_1 minimum) to indirect (X_1). Near $x \simeq 0.23$ the N_X state approaches the Γ_1 continuum.

The atomic sizes of Al and Ga are essentially equal, causing the size mismatch and lattice relaxation of nitrogen impurity in $Al_xGa_{1-x}As$ to be constant for all x (in contrast with $GaAs_{1-x}P_x$ where the nitrogen size mismatch is large in GaAs and smaller in GaP). As a result, the N_X state more closely follows the X_1 minimum in $Al_xGa_{1-x}As$.

We are currently examining the oxygen trap in $GaAs_{1-x}P_x$ optically, and in the coming year we will perform time-resolved spectroscopy measurements (in collaboration with IBM) to complete the study of $GaAs_{1-x}P_x$:N. Studies of deep levels will also include DLTS measurements, as mentioned in section 2.2.4.

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3.1 Introduction

The overall objective of this program is to investigate ion-surface interactions which have a controlling effect on the nucleation and growth kinetics, chemistry, and physical properties of alloy semiconducting films grown by sputtering. Analytical models have been developed to predict enhanced interdiffusion rates at heterojunction interfaces due to ion bombardment of the substrate and growing film during deposition. These calculations were supported by physical measurements using standing wave x-ray diffraction techniques to determine the period and amplitude of the compositional modulation wave in InSb/GaSb superlattice structures deposited under varying degrees of ion bombardment. Enhanced diffusion coefficients more than five orders of magnitude larger than thermal values were observed. Results showed that using such techniques, interfacial abruptness and coherence could be adjusted on the scale of monolayers to tens of Å even for junctions with large lattice mismatches.

The effect of ion bombardment on elemental sticking probabilities was also investigated and, in III-V compounds, found to have a stabilizing effect on stoichiometric compound formation. It has also been shown to allow the growth of metastable alloys such as In(Sb,Bi) with InBi concentrations more than four times the solid solubility limit. Film growth parameters have been related to the chemistry and physical properties of deposited films as determined by glow discharge optical spectroscopy (GDOS), Auger electron spectroscopy (AES), x-ray photoelectron spectroscopy (XPS), and secondary ion mass spectroscopy (SIMS), in addition to metallurgical and electrical measurements.

3.2 Ion-Surface Interactions

3.2.1 Ion Bombardment Enhanced Diffusion*

This work represents the first quantitative measurement of low energy (50-5000 eV) ion bombardment enhanced diffusion [1,2]. Such an effect is important not only for controlling the composition distribution in sputtered alloy films and the abruptness of heterojunction interfaces, but also for determining altered layer thicknesses due to preferential sputtering of alloy targets and deconvoluting compositional depth profiles obtained by such techniques as AES and SIMS combined with sputter etching.

Enhanced diffusion was observed experimentally in a series of InSb/GaSb superlattice structures deposited under various conditions of ion bombardment. The films were grown using multitarget sputtering (MTS) techniques developed in this laboratory (see 1976/1977 JSEP Progress Report) and had layer thicknesses between 12 and 30 Å. (Film growth results are summarized in section 3.3.1.) Standing wave x-ray diffraction techniques were used to measure the period and amplitude of the composition modulation wave as a function of the ion bombardment energy which was increased by decreasing the Ar discharge pressure in the range from 15 mTorr to 1 mTorr.

Diffraction theory [3,4] predicts satellite peaks at angles of $\theta_{\pm}$ about the Bragg reflection at θ_B when the diffracting crystal planes are stacked with a small wavelength sinusoidal modulations in atomic scattering factors and/or interplanar spacing. θ_B is the Bragg angle for the average film composition. The angles $\theta_{\pm}$ are related to the x-ray wavelength λ and the modulation period Λ by

$$\sin\theta_{\pm} = \sin\theta_B \pm \lambda/2\Lambda \qquad (1)$$

A nonsinusoidal periodic modulation, such as a square wave, can be represented by a Fourier series of increasing harmonic frequencies resulting in higher-order satellites at increasing separations from θ_B. However, higher-order satellites are generally not observed due to the

*This work was supported by the Joint Services Electronics Program (U.S. Army, U.S. Navy, and U.S. Air Force) under Contract DAAB-07-72-C-0259.

rapid interlayer diffusion of high-frequency components. When the sample contains a modulation in both the scattering power and the interplanar spacing, the satellite peak intensities $I_{\pm}$ will in general not be equal. The amplitude of modulation, u, can be calculated from the measured ratios $I_{\pm}/I_B$.

Figure 3.1 shows x-ray spectra from three superlattice films grown at an Ar pressure of 15 mTorr. The layer thicknesses were 29, 20 and 16 Å as determined from the displacements of the satellite peaks from the Bragg peaks.

Figure 3.2 is a plot of I_- normalized to I_B as a function of Λ for films grown at Ar pressures of 1 and 15 mTorr. Similar results were obtained for I_+. In all cases the line intensities were corrected for their angular dependence using the procedure described in reference 5. Figure 3.2 shows that the sputtering pressure, and hence ion bombardment energy [6], had a large effect on the rate of interlayer diffusion during film growth. I_-/I_B increased and the minimum wavelength decreased as the pressure was increased from 1 to 15 mTorr.

We presented a simple analytical model in reference 1 which accounted for the effects of ion bombardment enhanced diffusion during the growth of superlattice structures. Ion bombardment results in an excess lattice defect density $N_v(x)$. These defects are produced near the surface since the extrapolated ion range from LSS theory [7] for Ar^+ bombardment of (In,Ga)Sb is on the order of one lattice spacing for ion energies up to $\sim$ 300 eV. Most of the defects will be annihilated at the surface; however, some of them will diffuse inward and be trapped as the film surface progresses and we assume that those will be annihilated at a rate proportional to their density. If $D^*(x)$ is proportional to $N_v(x)$, then

$$D^*(x) = D_o^* \exp(-x/\delta) \qquad (2)$$

where D_o^* is the value of the enhanced diffusion coefficient at x = 0 and δ is a characteristic diffusion length of the defect. No assumptions are made regarding the exact diffusion mechanism; however, if a double defect, e.g., a divacancy or a vacancy - interstitial pair, is required then $D^*(x)$ will be given by the product of two exponentials which can simply

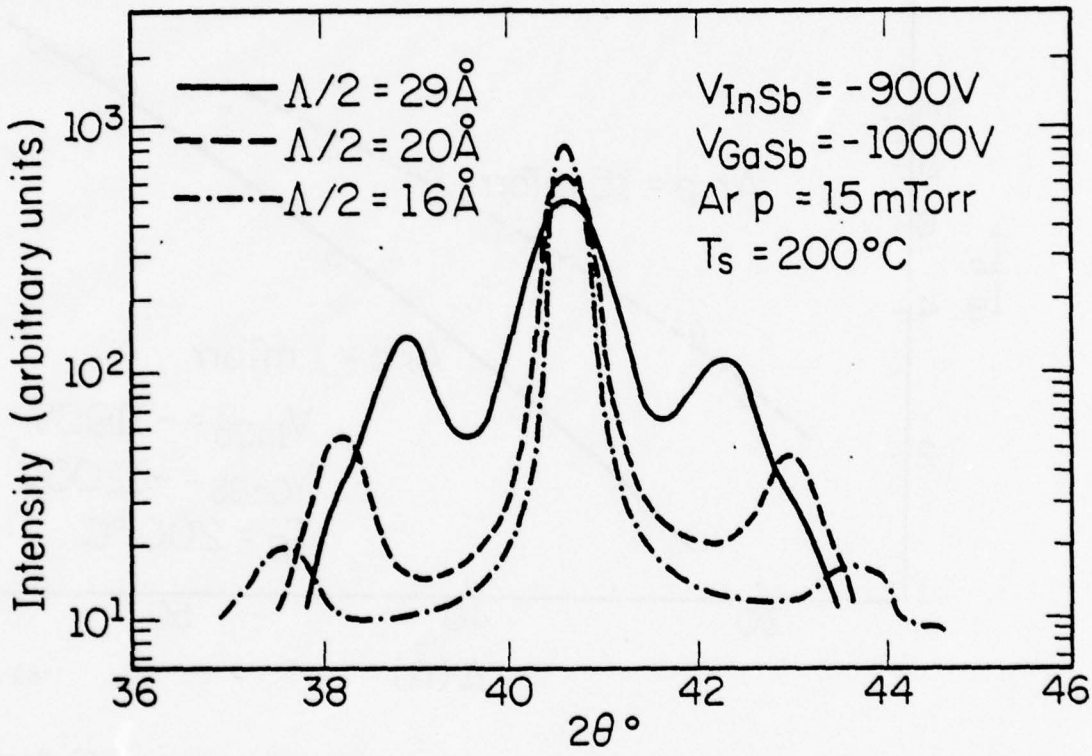

Figure 3.1 X-ray diffraction spectra from three InSb/GaSb superlattice structures grown on InSb-coated Corning 7059 glass at 250°C.

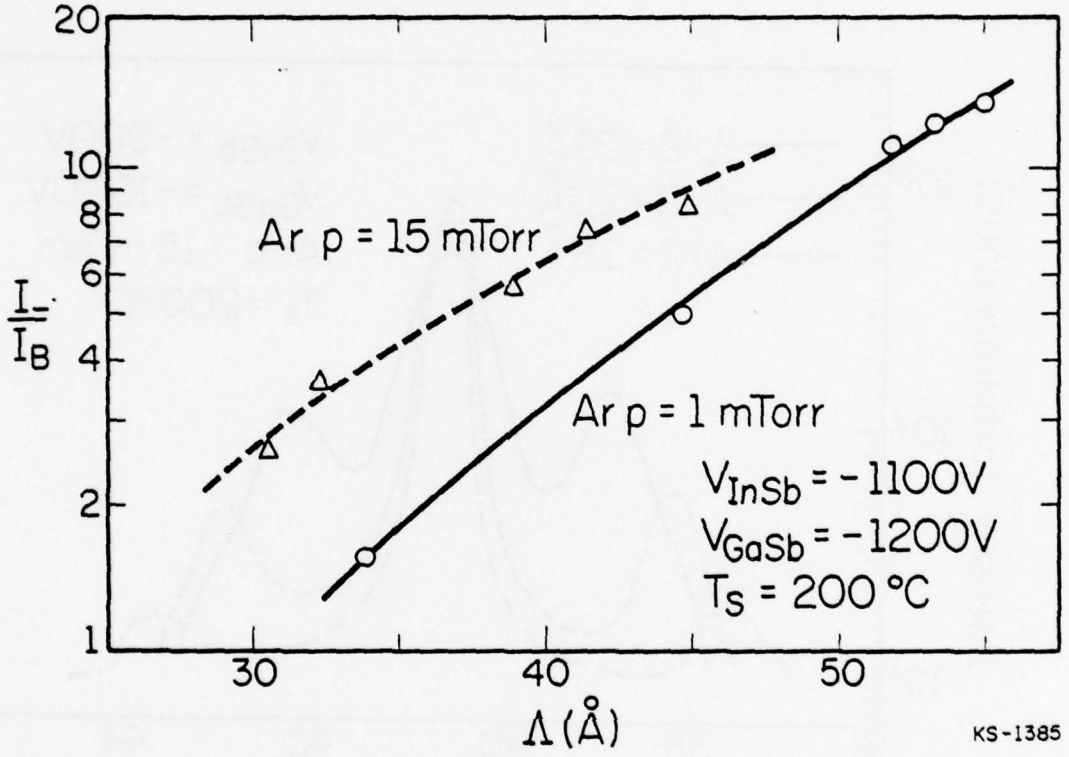

Figure 3.2 The satellite peak intensity normalized to the (220) Bragg peak intensity versus the period of the composition modulation in superlattice films grown at 1 and 15 mTorr.

be written as another exponential with a different characteristic diffusion length. $D^*(x)$ can be related to the experimentally determined amplitude of the composition wave through the diffusion equation written in differential difference form and the coefficient of the Fourier component of the composition wave corresponding to the order of the satellite measured. The relationship can be expressed as

$$\ell n\left(\frac{\pi u}{2}\right) = \frac{D_o^* \delta \beta(h)}{v} \left[\exp\left(-\frac{\Lambda}{2\delta}\right) - 1\right] \qquad (3)$$

where $\beta(h)$ depends only on the crystallographic direction and v is the average film growth rate.

Figure 3.3 shows the experimentally measured values of u vs Λ are well described by equation (3) for both 1 mTorr and 15 mTorr Ar sputtering pressures. The values of D_o^* obtained from this analysis are 3×10^{-17} cm^2/sec and 6×10^{-17} cm^2/sec for the high and low pressure cases, respectively. These results thus explain the dependence of Λ_{min} and u on Ar pressure. The accuracy of δ is poor, but equation (3) can be fitted by values of δ on the order of 1000 Å. The value of $D^*(x)$ averaged over the region of ion bombardment enhancement is given by D_o^*/e and is 2.2×10^{-17} cm^2/sec for the 1 mTorr case and 1.1×10^{-17} cm^2/sec at 15 mTorr. These values should be compared with the thermal interdiffusion coefficient (see section 3.3.1) of $\sim 10^{-22}$ cm^2/sec at the film growth temperature of 250°C [2].

An UHV multiple ion-beam system is presently under construction (described in the 1978 JSEP Proposal) which will be used to obtain more refined results in which the ion energy, impingement angle, and ion flux distribution will be accurately controlled.

3.2.2 Effect of Ion Bombardment on Elemental Sticking Probabilities During Film Growth*

Recent work has demonstrated that low energy ion bombardment can have important effects in extending the growth temperature range over which stoichiometric III-V compounds and alloys may be formed. The

*This work was supported by the Joint Services Electronics Program (U.S. Army, U.S. Navy, and U.S. Air Force) under Contract DAAB-07-72-C-0259.

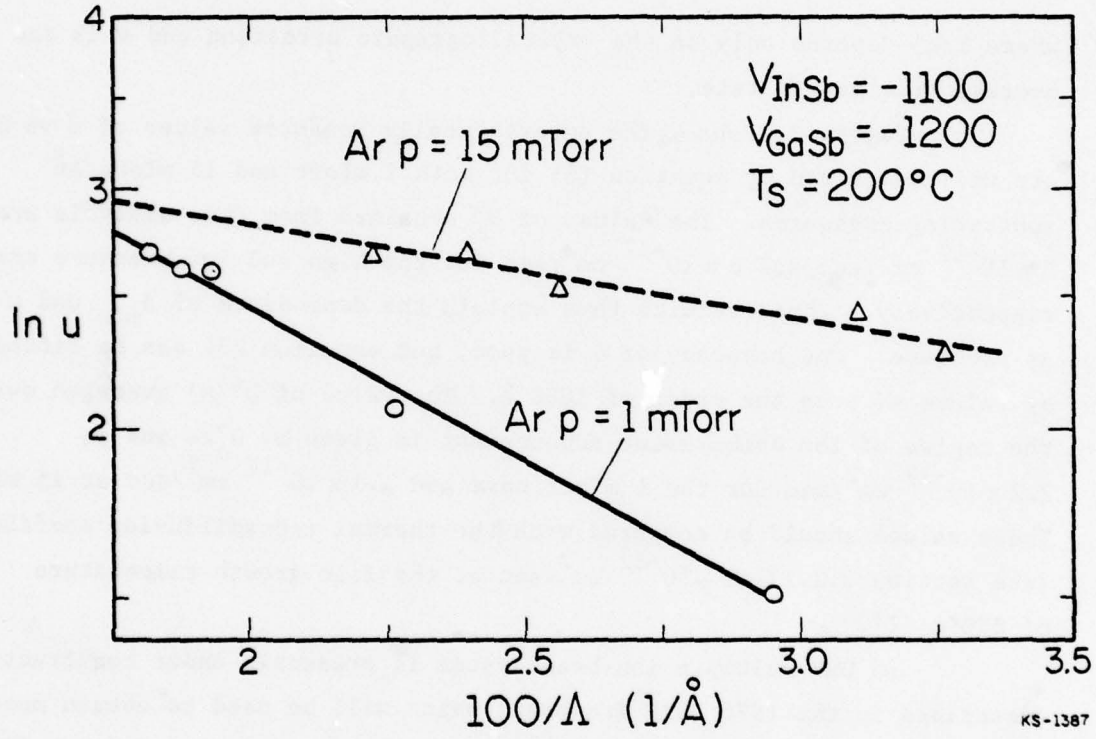

Figure 3.3 The amplitude versus the inverse of the period of the composition modulation in superlattice films grown at 1 and 15 mTorr.

dotted curve in Figure 3.4 was calculated from results on thermodynamic elemental sticking probabilities of Sb on InSb given in references 8 and 9. The Sb to In impingement flux ratio was 2.33. The solid line is our results for InSb sputter deposited under conditions in which the induced bias on the growing film is $\sim$ -75 V with respect ot the positive plasma. (The applied substrate bias, V_s, was zero in this case.) At low temperatures (< 300°C), where the thermodynamic sticking probability of both In and Sb is $\sim$ unity, the induced substrate bias decreases the Sb sticking probability to $\sim$ 0.7 giving an Sb:In ratio of 1.65 in the deposited film. The lowest growth temperature at which stoichiometric films can be obtained is also decreased from $\sim$ 415°C to $\sim$ 395°C. Preliminary data show that further decreases in the incorporation probability of excess Sb in films grown at low temperatures occurs with increasing negative applied bias on the substrate until at $|V_s| \geq$ - 75 V, deposited films are stoichiometric at any growth temperature for the impingement flux ratio used in these experiments. In the high temperature region where Sb is lost by evaporation, there is also preliminary data to show that ion bombardment again extends the stoichiometric region.

While it is emphasized that these are preliminary results with more data required, we believe that these data are reasonable in view of our work on preferential sputtering effects (see JSEP 1976/1977 Progress Report). We are presently extending our preferential sputtering models to handle compounds. However, as a general observation from our overall work on ion-surface interactions during film growth, it is reasonable to expect that the elemental sputtering rates for precipitated metal phases (Sb in this case) will be larger than the corresponding rate from the compound and that there should be a relationship between ion bombardment conditions, elemental impingement ratios (and absolute rates), and film growth temperatures. This area is being pursued and we believe it will not only lead to enhanced control over film composition and growth conditions but also to a better understanding of metastable crystal growth (see section 3.3.2).

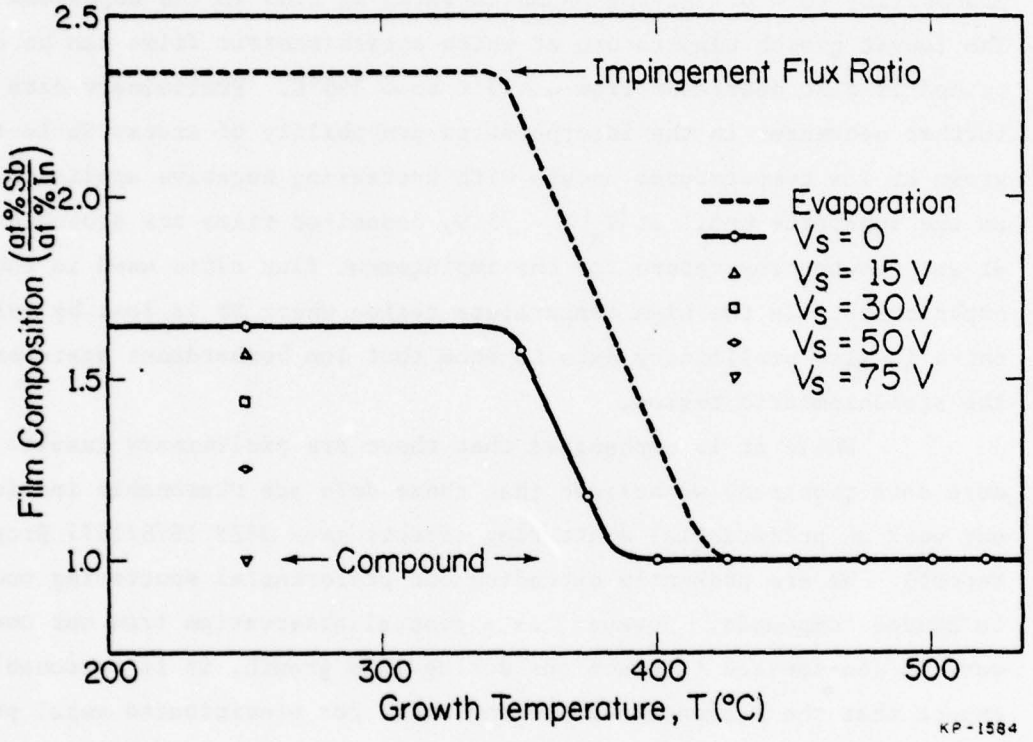

Figure 3.4 Measured Sb to In concentration ratios plotted as a function of growth temperature for evaporated films and plotted as a function of growth temperature and substrate bias for sputtered films. In all cases, the ratio of Sb to In species impinging at the substrate was seven to three.

3.2.3 Chemical Sputtering*

Ion bombardment, in addition to causing physical sputtering and affecting other physical processes such as diffusion (see section 3.2.1) and absorption (section 3.2.2) can also stimulate surface chemical reactions leading to so called "chemical sputtering." This is an important effect in other materials areas in addition to film growth--such as plasma etching, a recently developed technology in semiconductor device fabrication. In chemical sputtering, a gas phase species reacts with the target to form a volatile species which is desorbed. The ion bombardment stimulates this reaction and physical and chemical sputtering may occur in parallel.

In the present work, TiC is sputtered in a mixed Ar + O_2 rf glow discharge. The ion species bombarding the target are primarily Ar^+ and O_2^+. The bombardment itself leads to physical sputtering of TiC. In addition, the oxygen ions dissociate upon striking the surface and react with the target producing volatile CO and CO_2 as well as TiO_2. The degree to which these reactions are driven depends upon the O_2 partial pressure and the ion bombardment flux and average energy. The evolution of CO and CO_2 is followed using a quadrapole mass spectrometer. At a total pressure of 15 mTorr, the evolution of CO and CO_2 increases from the background level to saturation as the oxygen concentration is increased from 0.07 to 7%. Films deposited with >4% oxygen are essentially pure TiO_2 with no carbon detectable. The role of ion bombardment on the rate kinetics of such surface reactions is being investigated.

3.2.4 X-ray Photoelectron Spectroscopy (XPS) and Auger Electron Spectroscopy (AES) Investigations of Ion Bombardment and Preferential Sputtering Effects in Y_2O_3-doped ZrO_2†

Y_2O_3-doped ZrO_2 and CeO_2 are important fast anion conductors and oxygen catalysts. We have recently been successful in growing the first thin films of these materials in the stabilized cubic structure with high ionic conductivity [10]. However, the utility of these films in oxygen sensing applications depends strongly on their surface properties.

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*This work was supported by the National Science Foundation under Grant DMR 76-20640.

†This work was supported by UOP Incorporated, Des Plaines, IL.

XPS and AES studies are presently being carried out in which surface and near-surface chemical information is required. The latter is obtained in conjunction with sputter etching. However, it has been found that ion bombardment itself causes profound physical and chemical changes in the exposed surface. The electronic structure, phase stability, and catalytic activity can be greatly affected either beneficially or deleteriously depending on the conditions of the experiment. The most interesting case is that of Y_2O_3-doped CeO_2 in which Ce may be reduced from the +4 to the +3 state. This decreases the solubility of Y_2O_3 which is then preferentially sputtered. However, no reduction is observed in the remaining Y_2O_3 for Ar^+ bombardment energies up to 900 eV. In addition to "chemical shifts" in core state electron binding energies, changes in valence band structure are also being followed and related to the film surface properties.

3.3 Crystal Growth by Sputtering

3.3.1 GaSb and InSb/GaSb Superlattice Structures*

Single crystal p-type GaSb films have been grown by rf sputtering on semi-insulating (100) GaAs substrates at growth temperatures as low as 300°C. Temperature dependent (8-600°K) Hall effect and resistivity measurements were used to determine the concentration and ionization energies of defect levels in the films. In all cases, the results could be fitted analytically using three acceptor levels, one very shallow and the other two deeper in the forbidden band. A large number of films were grown under a wide variety of deposition conditions allowing us to determine the origin of these levels and to relate their concentrations to film deposition conditions as a diagnostic technique. The deepest level occurred at 80 $\pm$ 5 meV above the valence band (VB) edge and was associated with threading dislocations originating at the film-substrate interface. The measured concentration of this level ranged from 1×10^{17} to 1.5×10^{16} cm^{-3} for the conditions investigated, decreasing with film thickness and growth temperature. A detailed analysis of the results showed that approximately 1 in 40 sites along the dislocation line were electrically active.

*This work was supported by the Joint Services Electronics Program (U.S. Army, U.S. Navy, and U.S. Air Force) under Contract DAAB-07-72-C-0259.

An intermediate level was found at 40 ± 5 meV above the VB edge and was shown to be related to Sb vacancies or equivalent Sb-deficient point defect complexes. The concentration of this level increased with film growth temperatures and decreased with an increase in the Sb to Ga impingement ratio during growth. Concentration variations between 3×10^{17} and 1×10^{16} cm^{-3} were observed. The Sb to Ga impingement flux was varied using three target schemes: sputtering from a stoichiometric GaSb target, sputtering from a $Ga_{0.3}Sb_{0.7}$ target, and using two targets-GaSb and Sb- in a multitarget sputtering [11] configuration. The results of this study are being extended to include ion bombardment effects on elemental sticking probabilities in order to extend the range over which such effects can be measured (see section 3.2.2).

A net concentration of very shallow acceptors with an ionization energy of < 1 meV was always observed in these films. The measured concentrations were also related to Sb deficiencies but were compensated by residual shallow impurity levels which correlated with system base pressure and the purity of the Ar sputtering gas. We believe that the compensating donors are oxygen due to the dissociation of water vapor in the discharge. Group VI substitutional impurities are known to result in very shallow levels in both GaSb and InSb.

Single crystal InSb/GaSb superlattice structures were also grown using multitarget sputtering in order to investigate the effects of ion bombardment on enhanced interdiffusion (see section 3.2.1). In addition, the effects of film growth parameters on the defect structure, abruptness, and coherence of sputtered heterojunctions was also investigated [2]. The layer thicknesses studied ranged from 12 to 70 Å and the polycrystalline to single crystal "transition temperature," T_c, was found to decrease with decreasing average film-substrate lattice mismatch and modulation period, Λ. The Λ-dependence, shown in Figure 3.5, resulted from a decrease in the coherence between layers and the associated increased amount of plastically accommodated strain which occurred with increasing layer thickness.

Increasing the film growth temperature, T_s, and decreasing the period of the composition modulation also resulted in a decrease in the density of microtwins and low angle dislocation boundaries which were observed in all films. Single and multiple {111} twins were identified.

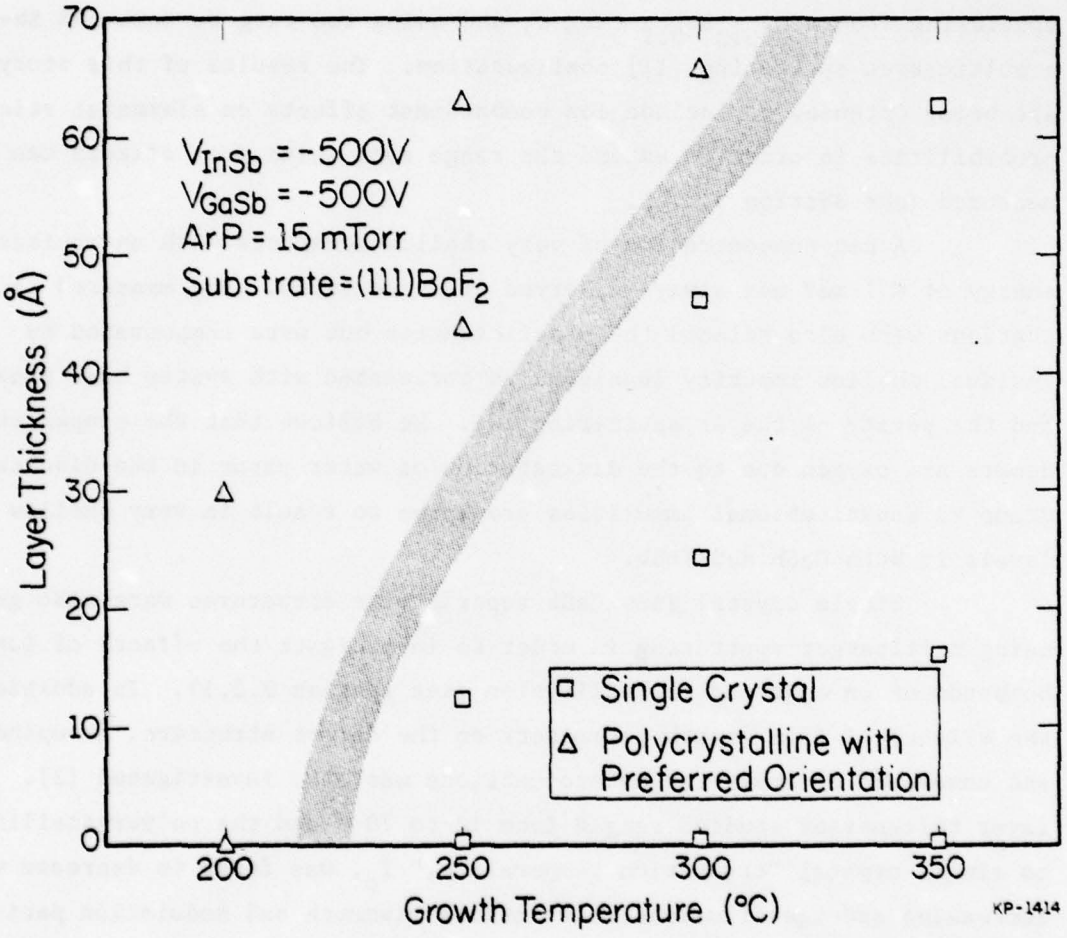

Figure 3.5 InSb/GaSb superlattice film crystallinity vs layer thickness and growth temperature.

For a given set of growth conditions on cleaved BaF_2 and NaCl substrates, a significant decrease in T_c and structural defect densities could be achieved by coating the substrates with thin (< 300 Å) single crystal InSb layers which were deposited and annealed in-situ immediately prior to superlattice film growth.

In addition to ion bombardment enhanced diffusion studies, measurements of themal interdiffusion at InSb/GaSb interfaces were also made. The standing wave x-ray technique discussed in section 3.2.1, and in more detail in reference 2, was used to monitor the rate of change in the period of the composition modulation as a function of post-annealing time and temperature. The diffusion constant, $\tilde{D}_o$, was found to be 4×10^{-14} cm^2/sec with an activation energy of 0.8 eV [2].

3.3.2 Growth of Metastable In(Sb,Bi) Alloys*

We have recently reported the first results on the growth of thin film $InSb_{1-x}Bi_x$ semiconducting alloys [12]. $InSb_{1-x}Bi_x$ solid solutions combine a narrow bandgap semiconductor with a semimetal allowing the possibility of varying the bandgap from that of InSb ($\simeq$ 0.23 eV at T = 0°K) to a metallic phase by increasing x. Such a material would have applications as a medium to far-IR detector. In the only detailed crystal growth study reported up to now on In(Sb,Bi), Jean-Louis et al. [13-15] used the Czochralski technique to grow bulk single crystals. They found a solid solubility limit of 2.6 mole % InBi and an extrapolation of their optical measurements predicts a semiconductor to semimetal transition at 6.8 mole % InBi. The low solid solubility is due primarily to the fact that InBi exists in a tetragonal structure while the alloy crystallizes in the cubic sphalerite structure of InSb.

We have used multitarget sputtering to grow polycrystalline metastable $InSb_{1-x}Bi_x$ films with InBi concentrations up to $\sim$ 12 mole %, which exceeds the reported solid solubility limit by more than a factor of four. The films were deposited on substrates which rotated through separate InSb and Bi discharges maintained at an Ar pressure of 15 mTorr.

*This work was supported by the Joint Services Electronics Program (U.S. Army, U.S. Navy, and U.S. Air Force) under Contract DAAB-07-71-C-0259.

The relative target voltages were used to control the composition of the deposited films and were chosen such that the deposition rate was always less than a monolayer per target pass. The film growth temperatures investigated were 135°C and 165°C and a (110) preferred orientation was obtained in films grown on Corning 7059 glass substrates. All solid solution films were stoichiometric within the accuracy of our electron microprobe, ~ 0.5 atomic %. The incorporation probability of Bi was found to decrease with increasing Bi impingement flux and with increasing growth temperature as shown in Figure 3.6.

We believe that, following the initial nucleation stage, $InSb_{1-x}Bi_x$ film growth by MTS proceeds in the following manner. A slightly Sb-deficient InSb layer, whose average thickness is less than one monolayer, is deposited. The growing film is then rotated into the Bi discharge and only those Bi atoms that can find available In atoms are incorporated. At the growth temperatures used, however, some excess Bi remains on the surface. This excess Bi then competes with impinging Sb for In atoms deposited in the InSb discharge thus decreasing the net Sb incorporation probability and allowing the growth of metastable alloys. As the film growth temperature is increased for a given set of InSb and Bi fluxes, the amount of excess Bi remaining on the surface after the growing film rotates through the Bi discharge decreases, resulting in an increase in the net Sb incorporation probability.

Ion bombardment, and possibly the average kinetic energy of depositing species, also plays a role in controlling the elemental incorporation probabilities and the solid solubility limits. Recent results show that these latter parameters may be varied by changing the sputtering pressure and the substrate voltage. This work is thus providing further data for understanding ion bombardment effects on elemental sticking probabilities (see section 3.2.2).

The single phase $InSb_{1-x}Bi_x$ alloys deposited on glass were found to be n-type with the room temperature carrier concentration and electron mobility increasing monotomically from ~ 10^{17} cm^{-3} to ~ 10^{18} cm^{-3} and ~ 70 cm^2/V-sec to ~ 150 cm^2/V-sec respectively as the InBi concentration increased. The electron mobility also showed an increase with increasing T_s.

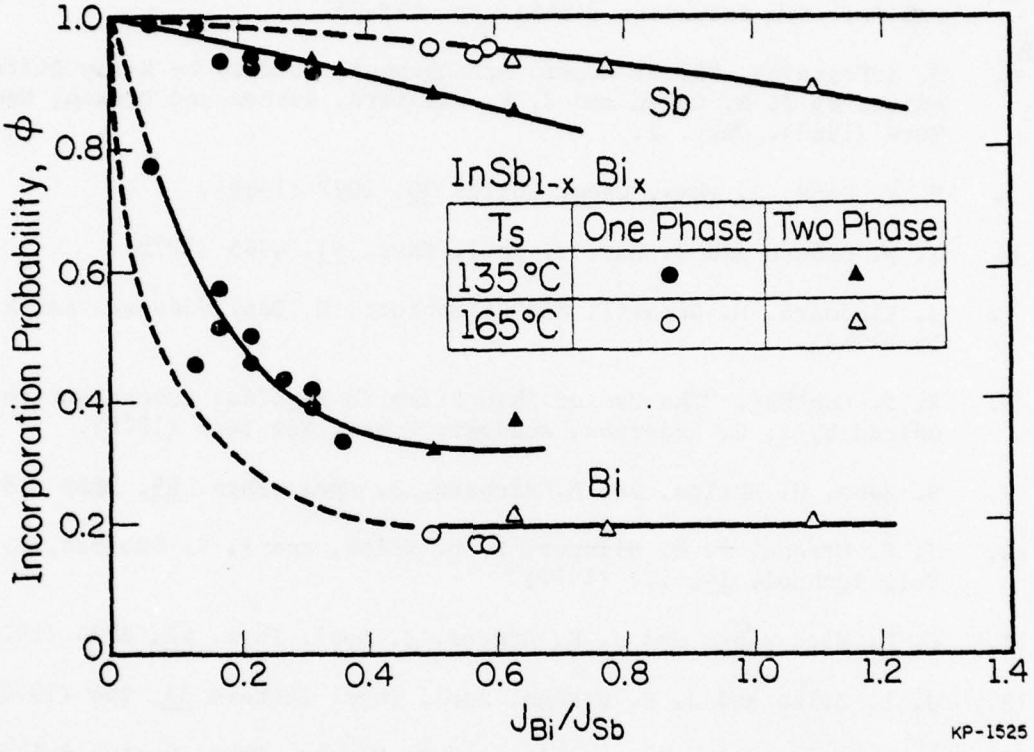

Figure 3.6 The incorporation probabilities of Sb and Bi during the growth of MTS - deposited $InSb_{1-x}Bi_x$ films plotted as a function of the ratio of Bi to Sb impingement fluxes.

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4.1 Introduction

The long range objective of this research is to originate and analyze new microacoustic wave principles that will lead to significant device applications. The work has been focused on the development of more universal and complete transducer models, fundamental studies of surface acoustic wave scattering, and the development of a new class of microwave acoustic devices based on nondispersive waves propagating along a substrate edge.

4.2 Line Acoustic Waves in Lithium Niobate*

Line Acoustic Waves (LAW's) are edge mode waves which propagate along and are confined to the edge of an infinite quarter space (wedge). They are of interest for their nondispersive and diffractionless properties as well as the high power densities obtainable due to the tight spatial confinement.

Previous work with LAW's has been hindered primarily because of fabrication difficulties associated with the realization of suitable flaw-free guides. Chemical etching techniques have been used to obtain wedge structures in Quartz and Lithium Niobate; however, edge quality has limited the operating frequency of such devices to the low VHF range. Moreover, fabrication of transducers for generating line waves has also presented problems because interdigital structures tend to be multimoded and difficult to build next to the edge of a crystal.

*This work was supported by the Joint Services Electronics Program (U.S. Army, U.S. Navy, and U.S. Air Force) under Contract DAAB-07-72-C-0259.

We have provided a solution to the problem of wedge fabrication by the use of crystal cleaving techniques [1]. The structure formed by the intersection of a cleavage plane with the top polished surface of the crystal is found to be an ideal guide for LAW propagation. Freedom from defects and wedge angle uniformity are obtained, making the use of such structures feasible for VHF and UHF frequencies. A transducer suitable for generating line waves has been found which discriminates against multi-mode excitation and reduces resolution requirements significantly [2]. The single phase transducer with one electrode per wavelength reduces the resolution requirements by a factor of four when compared to a double electrode interdigital structure operating at the same frequency. Figure 4.1 shows a single phase transducer oriented near the edge of a cleaved guide structure.

LAW devices have been built at frequencies up to 220 MHz on $LiNbO_3$. Laser probe measurements of propagation velocity and field distribution are found to agree with theoretical predictions [1] and the cleaved edges are shown to be suitable for LAW propagation at high frequencies [2]. Experimental work also indicates that the single phase transducer suppresses MEL reflections in addition to selectively exciting the LAW mode.

Drawbacks to the use of LAW propagation for practical applications still lie primarily in the area of fabrication. Lithium Niobate does not cleave easily and work is being done to increase the yield of quality edges. Long transducers necessitate extremely small alignment tolerances (approaching 100 micro-radians). The single phase transducer in its present form has a significant amount of unactive capacitance, hence its electrical Q is somewhat higher than that obtained from an interdigital structure.

Due to the diffractionless property of LAW's, high quality delay lines and resonators appear to be an ideal application for LAW's. The high power densities obtainable could give rise to parametric applications.

Cleaved edges have been shown to be excellent guides for LAW propagation at frequencies much higher than those previously reported for wedge guides. A suitable transducer for generation of such waves has been

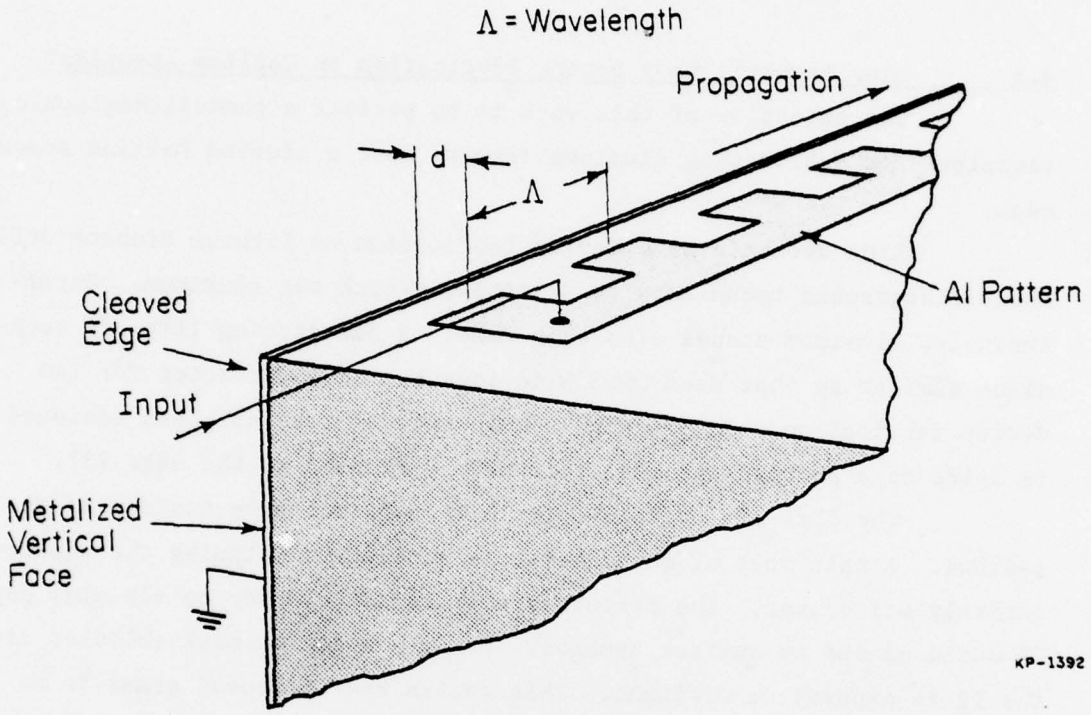

Figure 4.1 Single phase transducer.

tested and found to perform well. Because of the dispersionless, diffraction-free properties of LAW's they appear to be well suited for signal processing applications. Areas of future investigation should include the problem of quality edge yield and improvement of the coupling efficiency of LAW transducers.

4.3 Line Acoustic Wave Device Fabrication on Gallium Arsenide*

The objective of this work is to perfect a photolithographic technique for fabricating aluminum fingers near a cleaved Gallium Arsenide edge.

Line acoustic wave device fabrication on Lithium Niobate utilized photolithographic techniques to selectively etch the aluminum. Unfortunately, aluminum etches also etch GaAs. A non-etching lift-off technique similar to that used for SAW devices has been perfected for LAW device fabrication. In practice a high success rate has been achieved in spite of a photoresist (PR) thickness variation at the edge [3].

The lift-off technique for line acoustic wave devices is as follows. A thin coat of photoresist is applied by spinning the substrate entirely off center. The preferred edge leads in order to minimize any PR build up due to surface tension. Using a negative mask (blocked field) the PR is exposed to UV light. This causes the unexposed areas to be slightly undercut. After developing, examination of the image determines if the final device will be error free (Figure 4.2). This feature gives the lift-off technique its high success rate. Aluminum is evaporated over the photo resist pattern at near normal incidence (see Figure 4.3). The slight undercutting produces distinct edges for pattern sharpness and insures that the two regions of aluminum are not connected. Note that the PR may be only as thin as the evaporated Al thickness. Therefore the PR build up near the edge does not hinder device fabrication (see Figure 4.2). The device is then immersed in acetone and ultrasonically

*This work was supported by the Joint Services Electronics Program (U.S. Army, U.S. Navy, and U.S. Air Force) under Contract DAAB-07-72-C-0259.

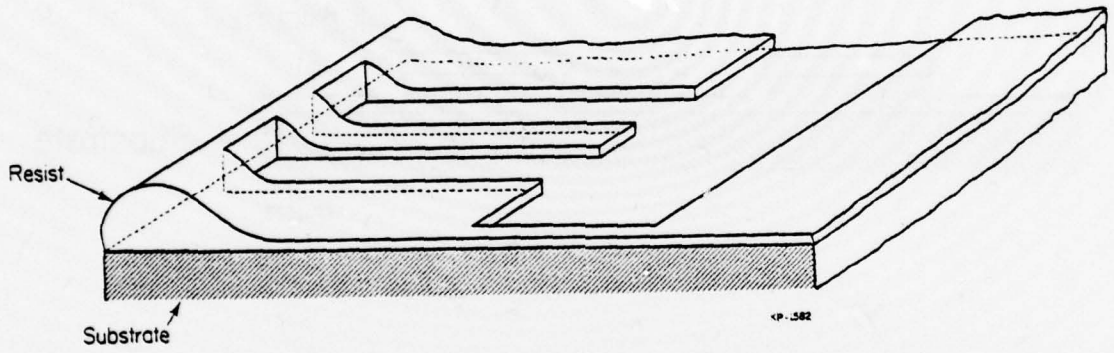

Figure 4.2 Photoresist pattern.

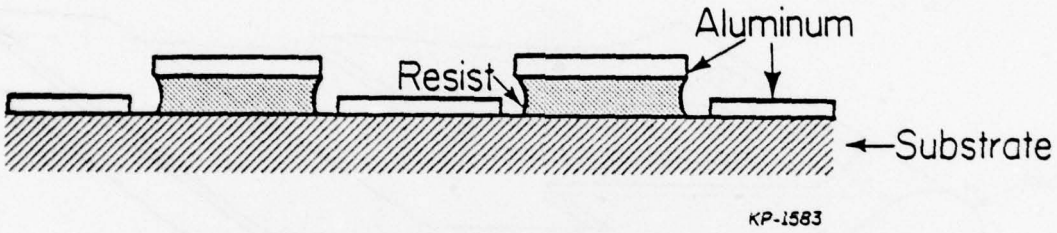

Figure 4.3 Photoresist pattern after aluminization.

cleaned until all of the PR and un-needed Al are lifted. A final Al evaporization on the cleaved face produces the needed vertical ground plane.

This process requires that the Al be deposited at near normal incidence and that there is no deposit on the face which is perpendicular to the source. The Al makes contact over the edge using this two step evaporization.

This technique has produced exceptionally sharp aluminum patterns close to the cleaved GaAs edge with no shorts, pinholes, or broken fingers. The technique is limited only by the photoresist thickness and pattern finger width. The former limitation allows electrode thickness to be only as great as PR thickness (3000 to 15,000 Å), while the latter causes fingers to be as thin as the UV undercutting permits.

An experimental line acoustic wave device has been fabricated on GaAs. It consists of two 150 wavelength single phase transducers separated by 20 wavelengths. The device has a center frequency of 74.7 MHz and 3 db bandwidth of .320 MHz [4].

In conclusion, the lift-off technique has been applied to the fabrication of line acoustic wave devices on GaAs resulting in Al patterns which are sharp and error-free. Although the finger width and thickness are limited by photoresist thickness, the high success rate makes this process a prime candidate for future LAW work.

4.4 A Model for Multitrack Non-Periodic Multistrip Couplers*

Multistrip couplers are commonly analyzed by determining the normal modes of the coupler from field theory [5]. This technique is applicable only to periodic couplers and becomes complicated for a large number of tracks.

An analytical technique has been developed that views the coupling as a process of regeneration by each strip in succession. The regeneration is calculated from a simple equivalent circuit model for the

*This work was supported by U.S. Air Force under Contract F33615-75-C-1291 and by Joint Services Electronics Program (U.S. Army, U.S. Navy, and U.S. Air Force) under Contract DAAB-07-72-C-0259.

interdigital transducer. Since the analysis proceeds on a strip-by-strip basis, slow variations in periodicity are accounted for. Additional physical insight is gained from the interpretation of the coupling in terms of a simple equivalent circuit.

The technique correctly predicts the response of a strip-coupled unidirectional transducer as described in Reference [6]. It is presently being applied to the design of multistrip-couplers for converting surface acoustic waves to line acoustic waves in Lithium Niobate.

4.5 Generalized Transducer Model*

The objective of this model development is to determine the response of generalized interdigital transducers at fundamental and harmonic frequencies taking into account the effects of neighboring electrodes. The previously developed impulse response model assumes the electrodes to be point sources with variable strengths and provides the approximate frequency response by a simple Fourier transformation of the tap weights. The former model is simple and useful but does not account for interactions with neighboring electrodes and does not provide accurate harmonic response. A more accurate analysis is obtained by solving for the charge distribution under each electrode individually from field theory [7-11] taking into account neighboring electrode effects; this charge is then treated as a distributed source for the surface wave. A significant advancement in the application of this approach is the work of Smith and Pedler [7] where the Fourier transforms of the charge distribution on an electrode are tabulated as a set of polynomial coefficients for all possible sequences of electrode voltage of +1 and -1. In the general case when the electrodes are allowed to take on any voltage, this method is unwieldy and it is necessary to start from field theory for every new set of voltages. The simplicity of the impulse response model is lost in this approach.

*This work was supported by U.S. Air Force under Contract F33615-75-C-1291 and by Joint Services Electronics Program (U.S. Army, U.S. Navy, and U.S. Air Force) under Contract DAAB-07-72-C-0259.

In an infinitely long uniform single electrode interdigital transducer, the charge distribution on each electrode is identical. The transducer response is then written as the product of the array factor from the impulse response model and the element factor which is the Fourier transform of the charge distribution on one electrode. In general, with an arbitrary sequence the charge distribution on each electrode is different because of neighboring electrode effects and a simple separation of the transducer response into an element factor and an array factor is not possible.

If the array has uniform spacing, the charge distribution induced into an infinite shorted array by one electrode is used as the single tap excitation function. This charge distribution is only scaled by the electrode voltage and since the distribution is a complete solution of the field equations, the charge distribution on the total transducer is a superposition of the charge distribution induced by each of the electrode voltages. The Fourier transform of the charge distribution induced by a single electrode voltage is defined as the element factor and the Fourier transform of the electrode voltages is defined as the array factor. Then the transducer response can be written as a product of an element factor and an array factor. The magnitude and phase of the electrode voltages is completely arbitrary.

Many practical transducer structures may be modeled as a periodic array with a specified electrode voltage sequence. In a direct coupled transducer (which includes withdrawal weighting with shorted electrodes and multiphase unidirectional transducers) the strips are connected directly to either of two bus-bars while in the capacity-coupled transducer each electrode is connected through a capacitive voltage divider. An apodized transducer is conceptually divided up into channels and considered as a number of direct coupled unapodized transducers connected electrically in parallel.

In each case the capacitance, radiation conductance and transfer function, are related to the electrode voltage sequence, providing an extension of the impulse response model that is valid at the harmonics and takes neighboring electrode effects into account.

4.6 Time Domain Analysis of Reflections

An accurate model of SAW reflector arrays is an essential tool in designing for a desired response. While such a model is currently in use, experimental determination of actual reflector parameters tends to be susceptible to other device responses. It is therefore desirable to devise a straight-forward measurement system which can differentiate the reflector response from other response mechanisms.

Reflector gratings have traditionally been analyzed in terms of their frequency response using a mismatched transmission line model [12-14]. Reflector stripes are considered to have normalized characteristic impedance z, while free surface gaps are represented by a normalized characteristic impedance 1. The theoretical transmission matrix (T-matrix) of the array is calculated by cascading the T-matrices of each successive gap-stripe section, and is then converted to a scattering matrix. The reflection coefficient represents the reflectivity of the array so that the frequency response is found by plotting reflection coefficient versus frequency. Appropriate model parameters are experimentally determined from an examination of the measured bandwidth and phase slope of the device. Accurate measurement of these characteristics can be difficult, however, since device losses, direct transducer response, and RF coupling provide broadband distortions.

By applying a time domain analysis technique similar to that used in the analysis of SAW transducers, much of the difficulty in the determination of device parameters can be overcome. The analysis is based on the transmission line model described above, but the theoretical (or measured) frequency response is Fourier transformed to the time domain for interpretation.

Near the center frequency of a high reflectivity array little energy reaches the end of the array, but significant energy of off-frequency signals does penetrate to the end. The lack of interactive reflections at the end of the array causes it to act as a highly localized discontinuity to such signals, resulting in the occurrence of a sudden

*This work was supported by U.S. Air Force under Contract F33615-75-C1291 and by Joint Services Electronics (U.S. Army, U.S. Navy, and U.S. Air Force) under Contract DAAB-07-72-C-0259.

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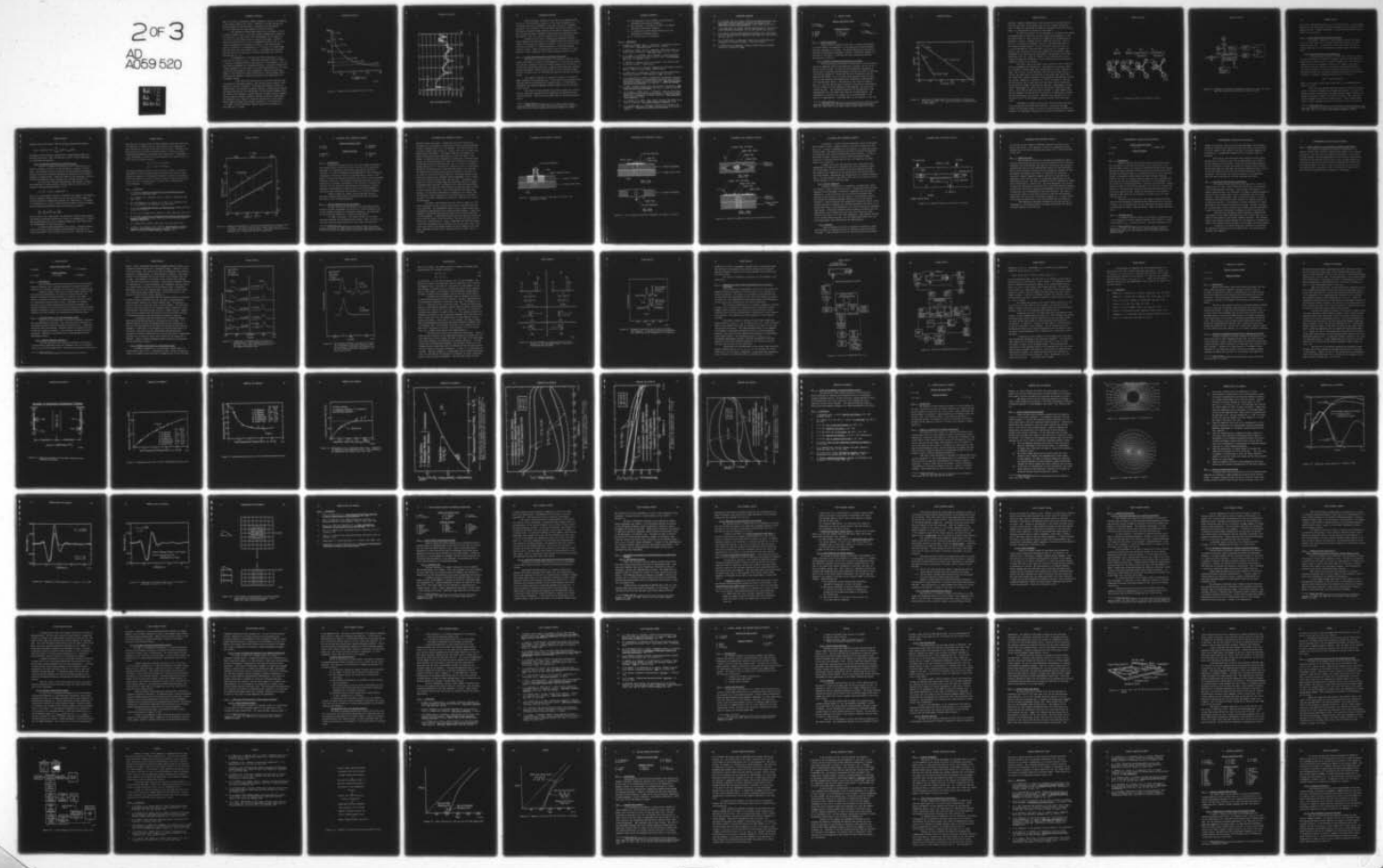

jump in an array's reflectivity impulse response at time t_j, corresponding to the overall length of the array. Assuming $\lambda/4$ stripes and gaps, the center frequency of the array may be calculated from the equation $f_o = N/t_j$, where N is the total number of reflector stripes.

The interactive reflections within the array produce a series of impulse response nulls. For a given center frequency the location of the first null, t_n, has a one-to-one correspondence to $|R|$, where $R = (z-1)/(z+1)$ is the reflectivity of a single stripe edge. For small values of reflectivity $\Delta z = (1-z)$ is approximately equal to 2R, so that z may be considered as a function of t_n and f_o. This relationship, plotted in Figure 4.4, is independent of N as long as N is large enough that the first null occurs before time t_j. The dashed lines represent the lower limit of Δz which may be read from the graph for a given N, ensuring that $t_n < t_j$.

Of significance is the fact that uniform attenuation in an array does not affect t_n or t_j. Nonuniform attenuation does not affect t_j and has a negligible effect on the position of the minimum, t_n, for any loss factors acceptable in a resonator reflector. The curve of Figure 4.4 is thus indepenent of such losses so that the determination of Δz is valid in spite of the presence of array attenuation. With an accurate knowledge of z the theoretical array reflectivity at center frequency may be calculated and compared to measured reflectivity for determination of attenuation losses.

A test device was constructed to verify the principles and practicality of the above analysis. The reflector array consists of 800 shorted Al stripes on ST-Quartz. Transducer and reflector stripes are ~4000 Å thick. The reflector frequency response is masked by RF coupling, introducing uncertainty into the analysis of the original frequency data. The effect of RF coupling is removed from the reflector response, however, when the impulse response envelope is obtained by Fourier transforming the frequency data. Figure 4.5 shows the superposition of the experimental impulse response with measured parameters f_o = 98.38 MHz and z = 0.99224, and the theoretical impulse response with parameters f_o = 98.52 MHz and z = 0.9922.

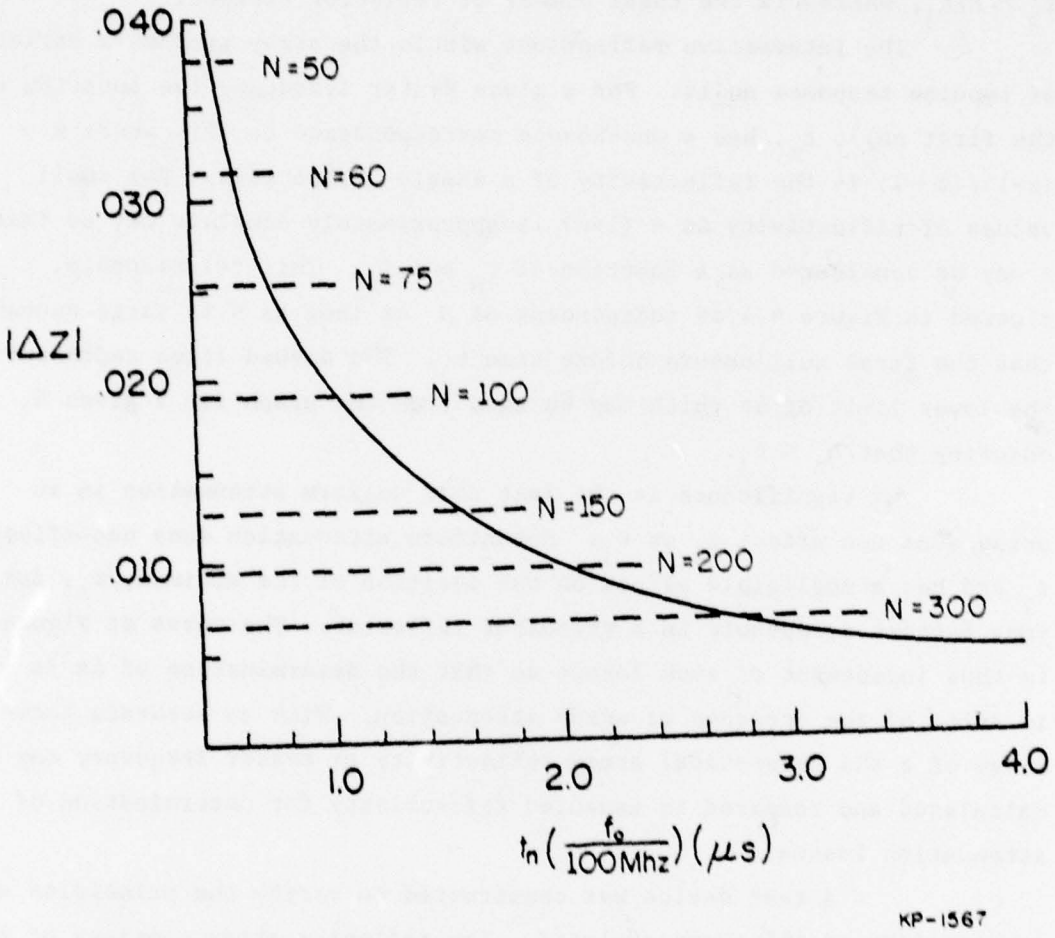

Figure 4.4 Characteristic mismatch versus null time.

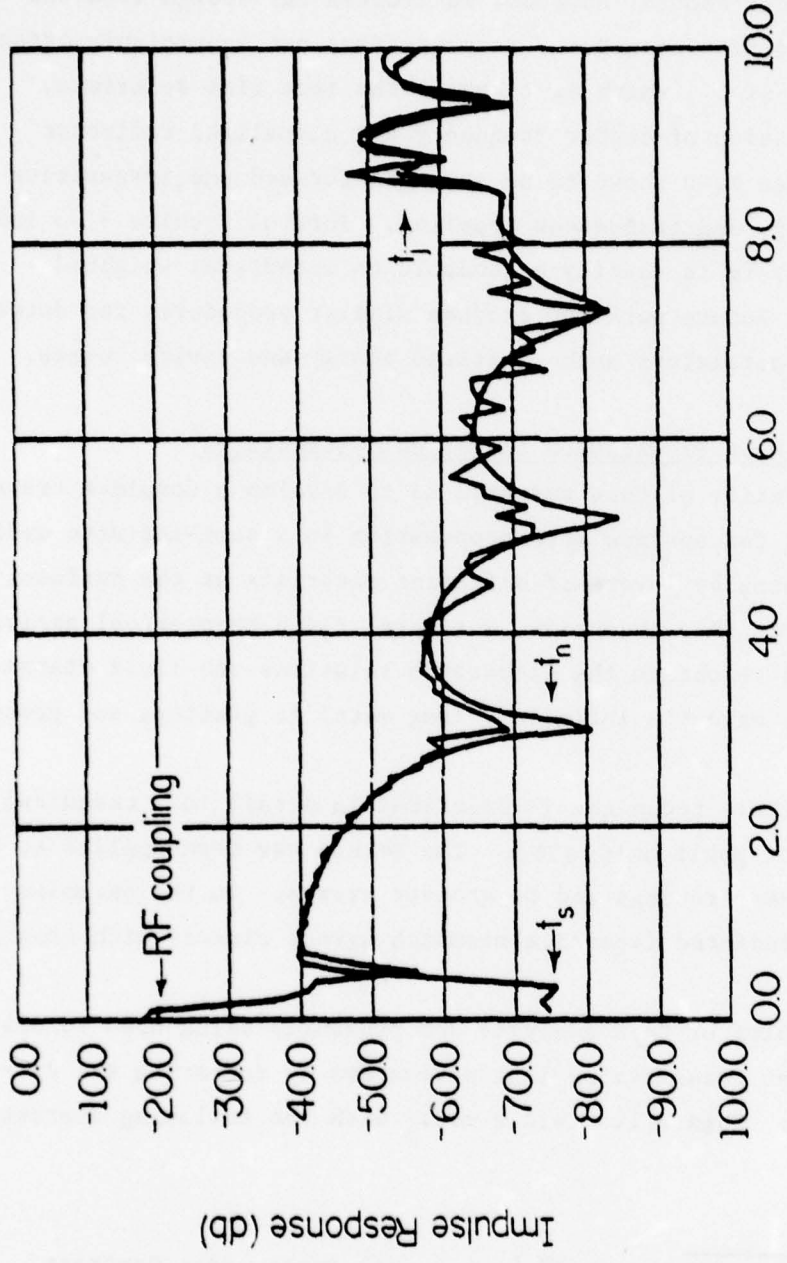

Figure 4.5 Theoretical and experimental reflection impulse response magnitude.

Direct transducer response on this device was suppressed with the use of a unidirectional transducer as the output transducer [15]. If a unidirectional output transducer is not used, the direct transducer response is also localized in the time domain and does not affect t_n or t_j. The output transducer should, however, be located far enough from the array so that the direct transducer response does not appreciably affect the apparent value of t_s, which is taken as the zero time reference.

Determination of center frequency and normalized reflector stripe impedance has been shown to be straight-forward and insensitive to losses, RF coupling, and transducer coupling. Initial results also indicate that the analysis is readily extendable to withdrawal weighted reflector arrays. Future work may produce similar procedures for determination of other parameters such as stored energy and device losses.

4.7 Surface Wave Propagation in Periodic Structures*

The objective of this research is to develop a complete transmission line model for surface wave propagation in a semi-infinite medium with periodic loading by layers of different materials at the surface. As a first step towards this objective, a general field theoretical analysis has been developed to obtain the dispersion relations and field distributions of surface waves in infinitely long metallic gratings and grooved arrays.

The analysis technique is described in detail in a technical paper submitted for publication [16]. The method has been applied to thin and thick metallized gratings and to grooved arrays. In the examples considered, the predicted impedance mismatch agrees closely with experimental results.

The results of this analysis are presently being used to determine the equivalent transmission line parameters by comparing the dispersion relations. This will yield a model with the following characteristics:

*This work was supported by U.S. Air Force under Contract F19628-78-C-0040 and by the Joint Services Electronics (U.S. Army, U.S. Navy, and U.S. Air Force) Program under Contract DAAB-07-72-C-0259.

(1) The equivalent circuit elements are analytically determined from material parameters.

(2) The technique is applicable to layers of different materials of arbitrary thickness.

(3) It accounts for stored energy effects due to the excitation of evanescent modes.

(4) It is valid over all frequencies.

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5.1 Surface Chemistry*

Recent work has centered on two areas - electron beam studies of surface layers, and examination of the mechanism by which polyatomic molecules decompose at a surface. The former effort has become heavily involved in assembling new equipment; however, considerable progress has been made in the latter, in defining the steps controlling molecular dissociation on crystals.

5.1.1 Kinetics of Molecular Decomposition on Solids

The dissociation of molecules colliding with a solid constitutes one of the important events in heterogeneous reactions, such as the formation of surface films. We have been investigating the mechanism of this process, using molecular beam methods to probe the effect of exciting solid and gas separately. Recent work has been concentrated upon the reactions of methane. In an all glass system specially built for this study, we have examined the decomposition of methane and deuteromethane on a tungsten field emitter. The results of this study are shown in Fig. 5.1. Both CH_4 and CD_4 must be thermally activated for chemisorption to occur; however, in the temperature range examined, CH_4 reacts more rapidly than CD_4. The activation energy for the decomposition of the deuteromethane is 2-1/2 times larger than for ordinary methane. The differences in reactivity are largely due to the differences in the barrier to chemisorption. A detailed model for this behavior is not yet

*This work was supported by the National Science Foundation under Grant DMR 76-82088 and by the Joint Services Electronics Program (U.S. Army, U.S. Navy, and U.S. Air Force) under Contract DAAB-07-72-C-0259.

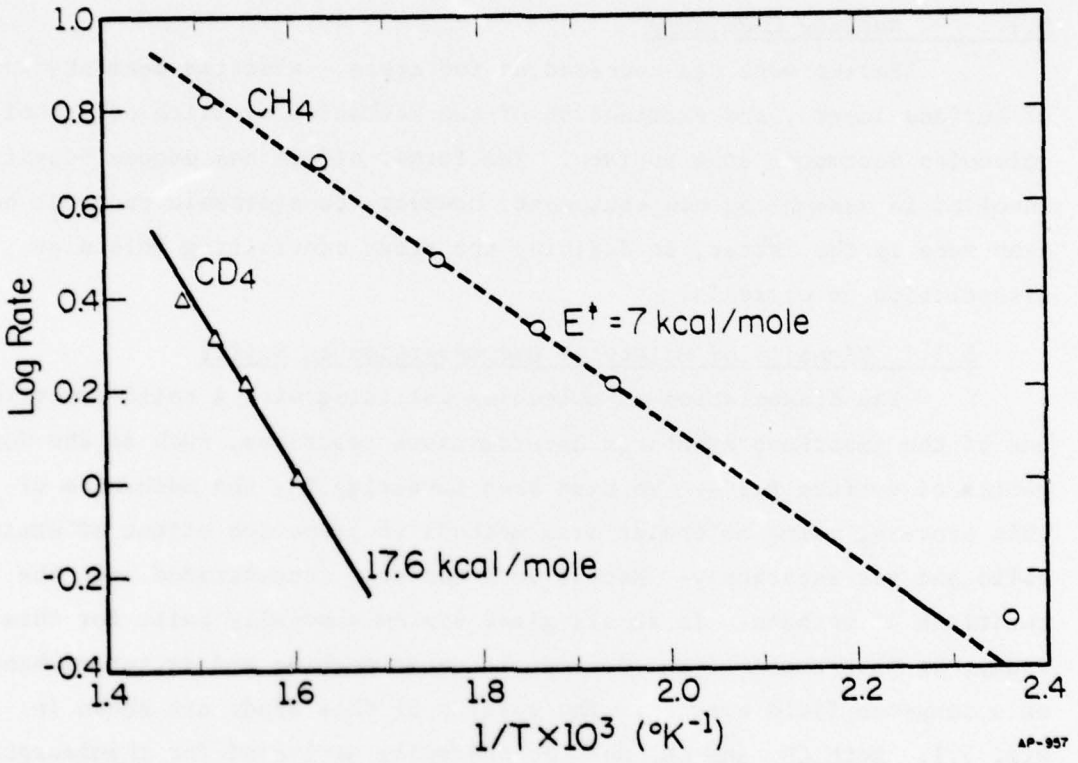

Figure 5.1 Dependence of chemisorption rate of methane on rhodium upon the gas temperature. E^* = activation energy for decomposition at the surface.

available. However, qualitatively, these results are in accord with the view that excitation of the methane molecule into a higher vibrational state, in which the interatomic distances are extended beyond some critical value, is a prerequisite to reaction at the surface.

In order to directly test the importance of vibrational excitations in enhancing surface reactivity, we have carried out experiments to test the effectiveness of laser irradiation in enhancing the decomposition of methane at a surface. Methane has four vibrational modes [1], shown in Fig. 5.2. Of these, the asymmetric stretch ν_3 and the bending mode ν_4 are strongly infrared active. For CD_4, the first vibrational state of ν_4 can be populated by irradiation with a CO_2 laser [2]. However, the energy of this transition is quite low compared with the barrier height determined in our molecular beam experiments, and excitation of the first vibrational level of ν_4 does not appear to be the dominant step in the surface decomposition of methane. We have concentrated upon exciting the asymmetric stretch of CH_4 instead.

The 3.39 μ line of the He-Ne laser overlaps the P(7)F transition of the ν_3 fundamental of methane [3]. Unfortunately, helium-neon lasers are available in limited power only, insufficient to excite a molecular beam. For our work, we have therefore built the system shown in Fig. 5.3. In this, the laser beam is focused down a long narrow tube, whose walls are coated with a freshly evaporated film of rhodium, the material selected for testing. Methane at a pressure of $\approx 10^{-3}$mm is admitted to the tube, and the reaction rate is monitored, with and without laser irradiation, by observing the change in the pressure with time. Measurements are done using a Pirani gauge [4], which does not perturb the system under examination. At 10^{-3}mm, the mean free path of methane is large compared with the tube diameter, so that the first collision of a vibrationally excited molecule should occur at the walls. With the laser available to us, we can excite 4×10^{-5} of the methane molecules into the first vibrational level.

Experiments on methane dissociation with and without excitation by the helium-neon laser have been completed. Irradiation does <u>not</u> produce any detectable change in the rate at which methane dissociates on rhodium. Our experiments indicate that the reaction probability of methane

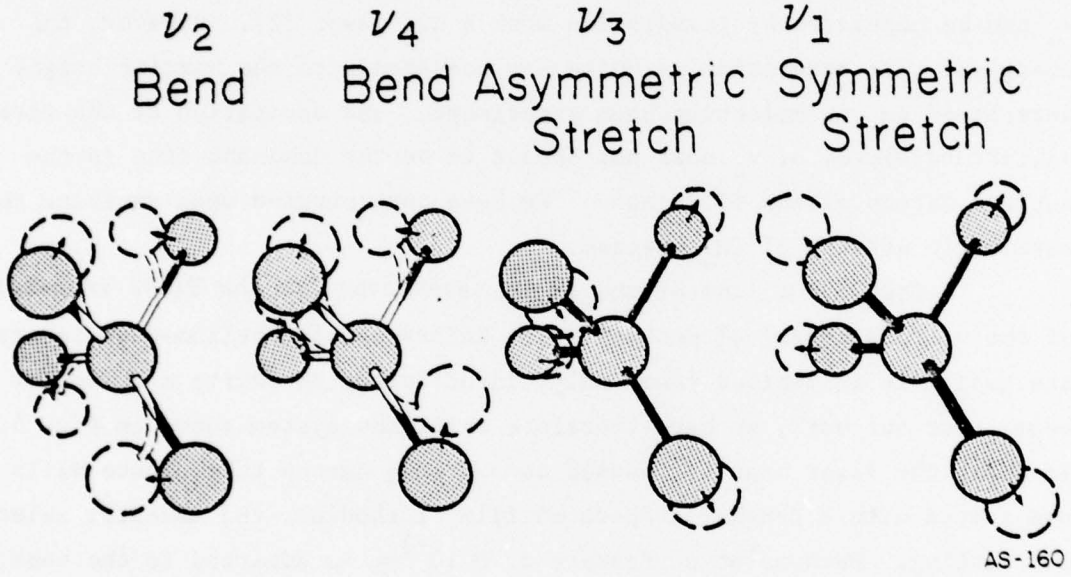

Figure 5.2 Vibrational modes of the methane molecule.

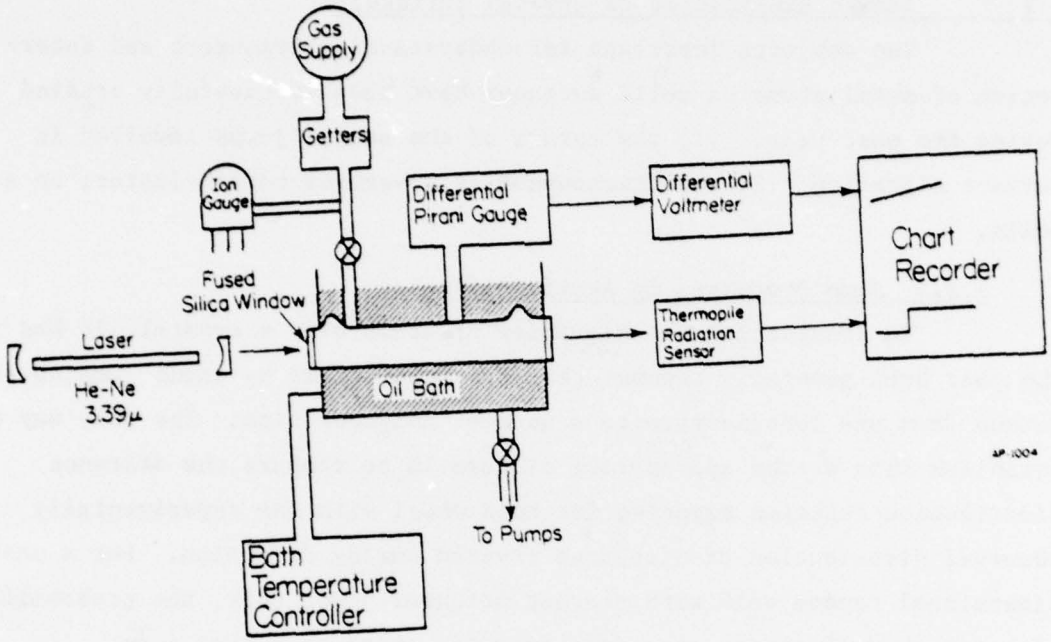

Figure 5.3 Schematic of system for studying the effects of laser excitation upon the dissociation of methane at a metal surface.

in the first vibrational state of ν_3 is less than 6×10^{-5}. It thus appears that this is not the excited state which dominates the dissociation of the methane molecule. Further experiments, in which other excitations will be probed, are in progress.

5.2 Atomic Exploration of Crystal Surfaces*

Two subjects important for understanding transport and interaction of metal atoms on solid surfaces have been successfully studied during the past year: (1) the nature of the atomic jumps involved in surface migration; (2) the thermodynamics governing metal clusters on a solid.

5.2.1 Jump Processes in Atomic Diffusion

In considering the migration of atoms over a crystal, it has in the past been generally assumed that movement occurs by atoms jumping at random from one lattice site to a nearest neighbor site. The only way to establish this as the appropriate picture is to compare the distance distribution function expected for this model with the experimentally observed distribution of distances covered during diffusion. For a one-dimensional random walk with nearest neighbor jumps only, the probability of being at a distance x spacings from the start at a time t is

$$P_x(t) = \exp(-2\alpha t) I_x(2\alpha t) \quad ,$$

where α is the rate at which jumps occurs and I_x is the modified Bessel function of order.

That this distribution adquately accounts for the data available on the (211) plane of tungsten has already been shown [5]. In order to estimate possible contributions from jumps covering larger distances, the distance distribution function for walks with jumps to other than next nearest neighbors sites has been worked out [6]. If, for example, atomic jumps to nearest neighbor sites occur at the rate α and to next nearest

*This work was supported by the National Science Foundation under Grant DMR 72-02937 and by the Joint Services Electronics Program (U.S. Army, U.S. Navy, and U. S. Air Force) under Contract DAAB-07-72-C-0259.

neighbor sites at the rate β, then the distance distribution becomes

$$P_x(t) = \exp[-2(\alpha + \beta)\, t\,] \sum_{n=-\infty}^{+\infty} I_n(2\beta t)\; I_{x-2n}(2\alpha t) \; .$$

An analysis of the statistics required for a quantitative measure of β has been carried out. This confirms that on W(211), double jumps make no significant contributions.

5.2.2 Dissociation Equilibrium of Adatom Clusters

Clusters of adatoms are believed to play an important role in material transport, as well as in the nucleation of films on solid surfaces. The cohesion of such clusters has not been adequately examined in the past, and we have therefore undertaken an examination of the thermodynamics of surface dimers. Chosen for study was the system Re_2 on W(211), for which considerable kinetic information is already available [5].

The basic idea underlying thermodynamic measurements is simple. The probability of finding atoms in adjacent channels of the (211), at a distance i spacings from each other, is [7]

$$P_i = C(2 - \delta_{i0})(L - i)\exp(-W_i/kT) \; .$$

Here C is a normalization constant, L represents the length of the channels, and most important from our point of view, W_i gives the free energy increase on moving two adatoms from infinity to a separation i. If adatoms at a separation $i \geq 2$ do not interact with each other, so that such dimers can be considered dissociated, then the ratio P_1/P_D is given by

$$\frac{P_1}{P_D} = \frac{2}{L-2} \exp\left(\frac{S_1}{k}\right) \exp\left(-\frac{E_1}{kT}\right) \; ,$$

where S_1 and E_1 are, respectively, the entropy and internal energy difference between dissociated clusters and clusters in configuration 1. Experimental measurements of P_1/P_D at different temperatures thus should yield the thermodynamics of dimer dissociation.

In practice such measurements are not easy. A detailed kinetic study of the rate at which changes in the probability distribution of dissociating dimers occurs has been carried out [8]. From this it appears

that the ratio of P_1/P_D can be seriously perturbed during the quench from the temperature at which dimers are equilibrated to the temperature at which observations are made in the field ion microscope. Techniques have been worked out to avoid these problems, making it possible to obtain significant thermodynamic information about dissociation. Measurements of P_1/P_D, determined as a function of the temperature, are shown in Fig. 5.4. These yield the internal energies

$$E_1 = -3.7 \pm 1.1 \text{ kcal/mole},$$

$$E_0 = -2.3 \pm 1.2 \text{ kcal/mole}.$$

The entropy changes for dissociation are not yet available. From the measurements of the dissocation energy we conclude that indirect interactions are important in affecting the behavior of atoms at the surface. Further measurements to probe the nature of these interactions are underway as part of a continuing effort to reach a better understanding of atomic phenomena on thin films.

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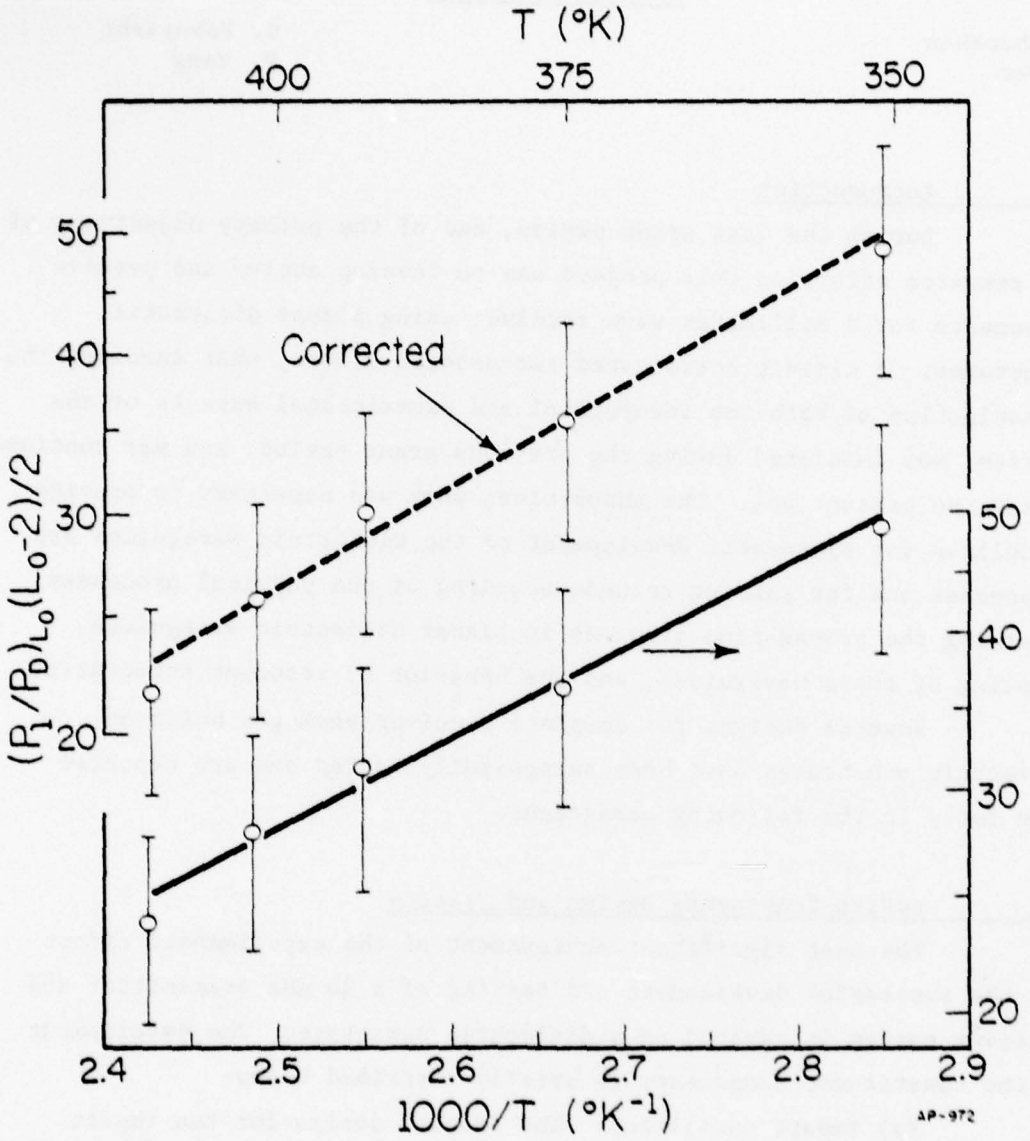

Figure 5.4 Temperature dependence of dissociation equilibrium for rhenium dimers on W(211). Top curve (y-axis at left) shows dissociation data corrected for distortion during quench. Error bars indicate standard deviation due to statistical errors in observations.

6. MILLIMETER WAVE INTEGRATED CIRCUITS*

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6.1 Introduction

During the last grant period, one of the primary objectives of the research effort in this project was to develop active and passive components for a millimeter wave receiver using planar dielectric structures. A closely coordinated two-pronged effort, that involved the investigation of both the theoretical and experimental aspects of the problem, was initiated during the previous grant period, and was continued during the present one. The theoretical work was necessary to provide guidelines for systematic development of the dielectric waveguides and components and for gaining an understanding of the physical processes governing the propagation of waves in planar dielectric waveguides, coupling of these waveguides, and the behavior of resonant structures.

Several designs for complete receiver packages built on dielectric substrates have been successfully tested and are reported more fully in the following paragraphs.

6.2 Active Components Design and Testing

The most significant achievement of the experimental effort was the successful development and testing of a 30 GHz transmitter and receiver system integrated on a dielectric substrate. The development of the constituent components is briefly described below:

(a) Impatt oscillator: The initial design for the impatt oscillator employed the conventional metal cavity. Next, the cavity was partially opened by removing the walls, and a dielectric block was

*This work was supported by the Joint Services Electronics Program (U.S. Army, U.S. Navy, and U.S. Air Force) under Contract DAAB-07-72-C-0259 and by the Army Research Office Grant (ARO DAAG 29-77-G-0111).

inserted in this open cavity. Though this oscillator worked quite satisfactorily, the geometry of the dielectric-diode interface appeared to have a profound effect on its performance. The third generation of oscillator design, shown in Fig. 6.1, retains even less of a metal waveguide than its predecessor. The Impatt diode was stud-mounted on a copper ground plane, which served both as a heat sink and d.c. bias ground. A planar dielectric waveguide of rectangular cross-section was placed over the ground plane and a small hole was drilled in the guide through which the diode could protrude. An r.f. filter of cylindrical design comprising of $\lambda/4$ sections was connected to the top of the diode through the cylindrical hole in the dielectric guide. The oscillator was tunable with a movable short placed at one end of the guide, and the power was extracted from the other end. The latest version of the oscillator eliminates the elaborate filter arrangement as well as much of the metal shield near the diode (see Fig. 6.2). In addition, a very simple but effective biasing scheme was constructed with only a small rectangular metal plate and a cylindrical pin. The plate was attached to the top of the dielectric and joined to the bias pin, which, in turn, pressure contacted the diode. This version had the following useful features: (i) electrical and mechanical tunability; (ii) control over the operation (center) frequency by cavity modification; (iii) metal enclosure; (iv) total integration on dielectric substrate; and (v) ease of fabrication.

(b) Mixer: The objective here was to build a mixer on a dielectric substrate so that it would be structurally compatible with the local oscillator. The arrangement shown in Fig. 6.3 was evolved after considerable experimentation with various mounting schemes. A metal post attached to the ground plane passed through a hole drilled in the dielectric waveguide. A diamond-shaped metal plate was deposited around the post on the top surface of the dielectric, such that the metal post was electrically isolated from it. Next, a GaAs beam-lead diode was mounted in the small gap between the cylindrical post and the metal plate. This plate also served as the common terminal for the IF amplifier and diode bias. Mechanical tuning was once again provided by movable short at the end.

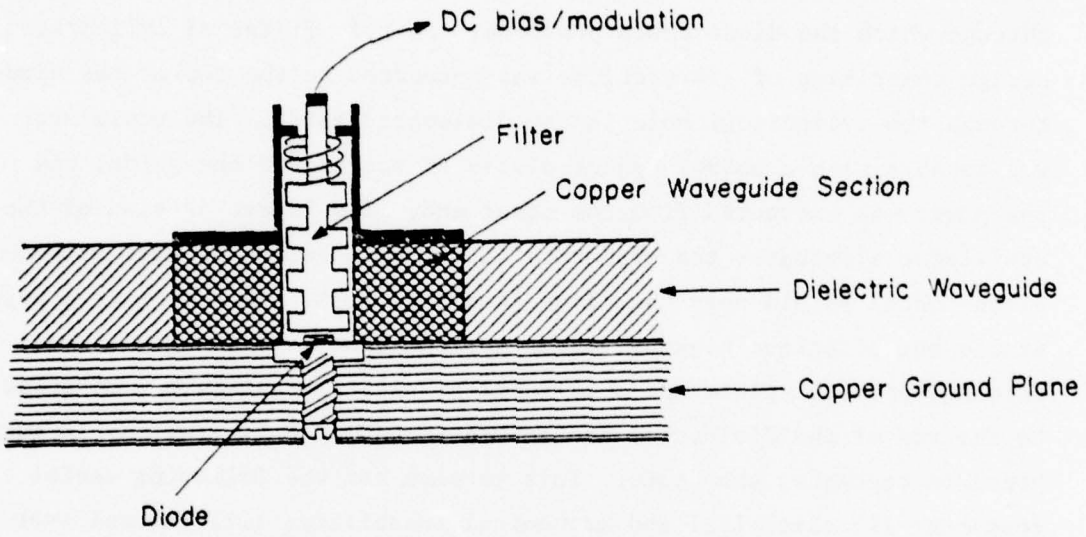

Figure 6.1 Dielectric waveguide type Impatt oscillator with cylindrical filter.

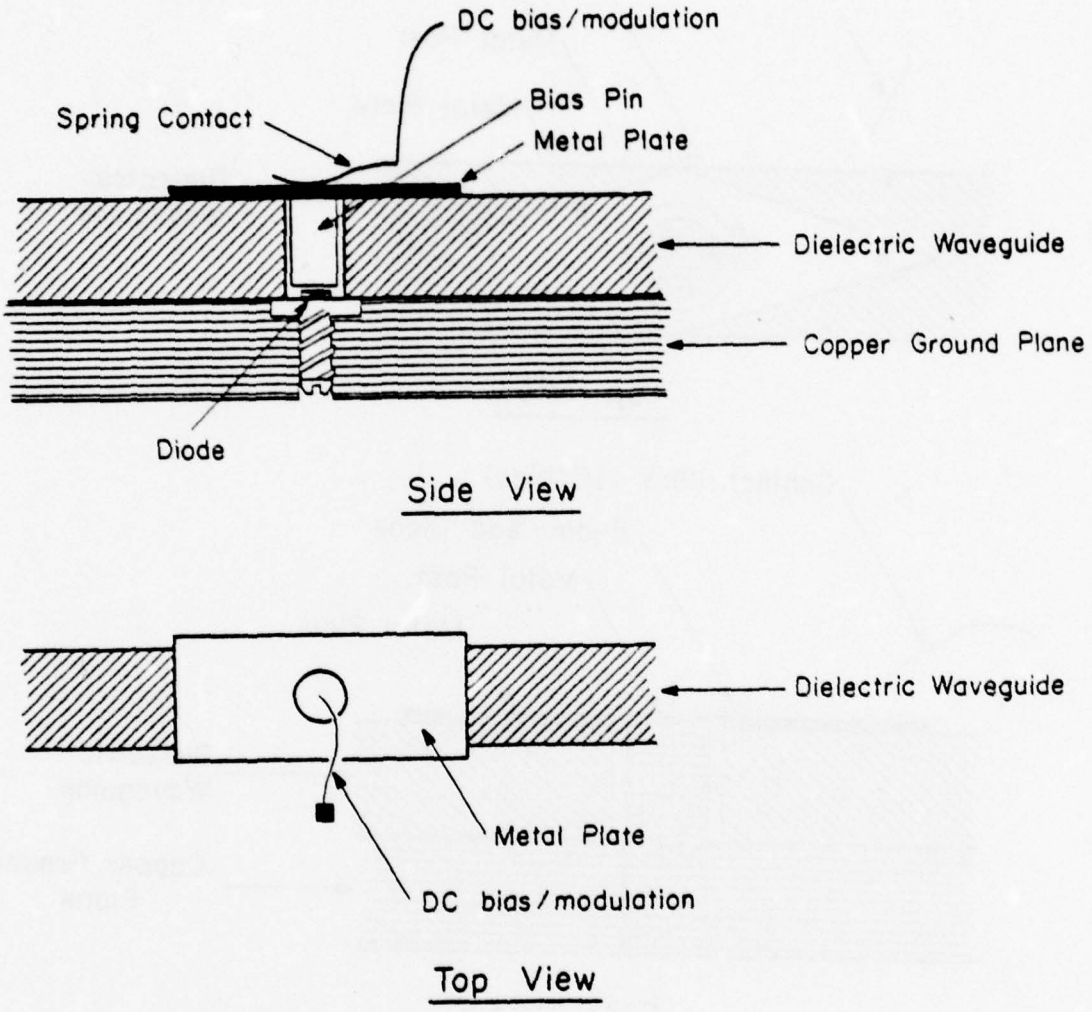

Figure 6.2 Fully integrated dielectric waveguide type Impatt oscillator.

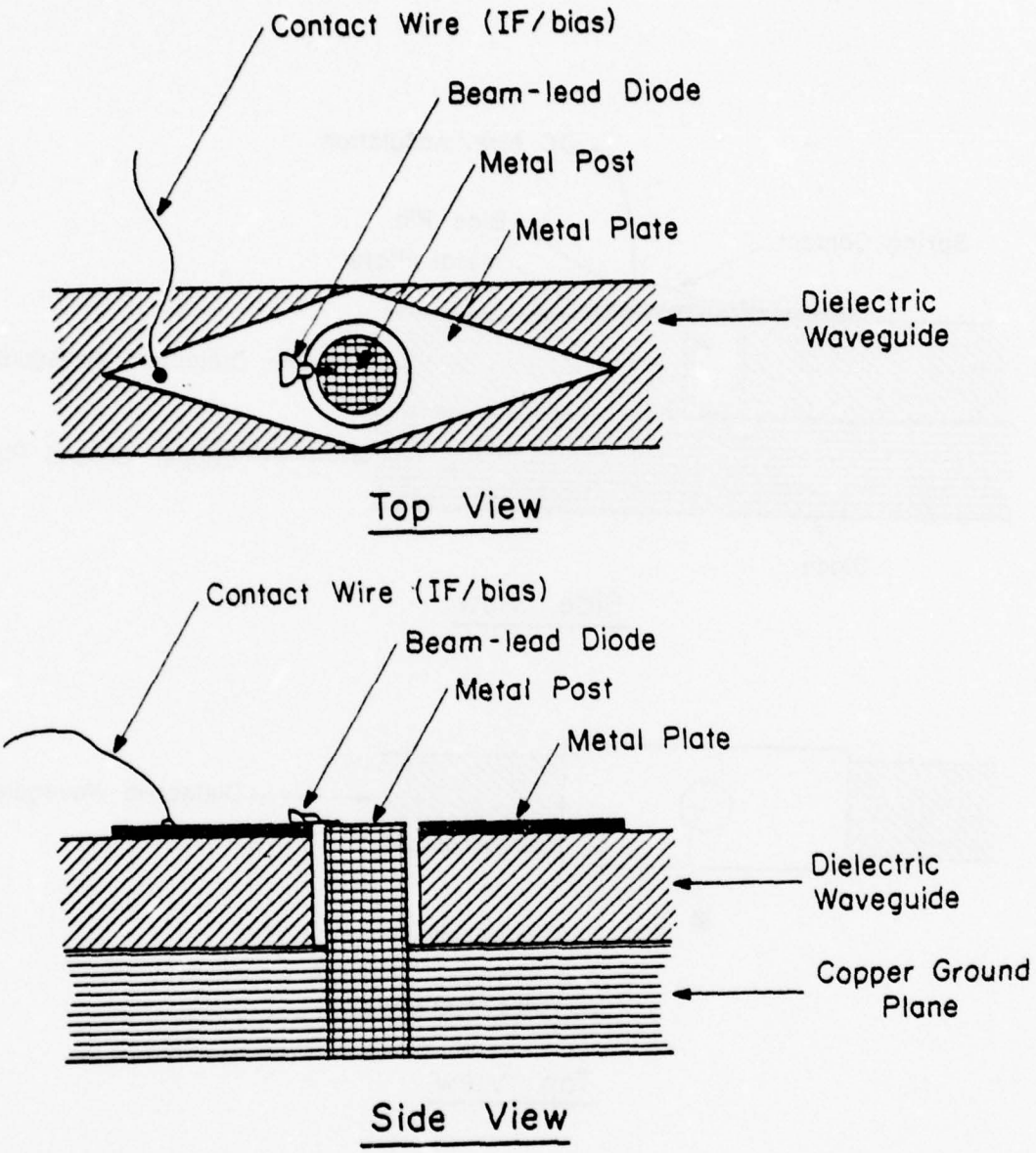

Figure 6.3 Dielectric waveguide based mixer using beam-lead diode.

(c) Receiver: A local oscillator and mixer circuit was designed and developed to share a common dielectric guide and a ground plane (see Fig. 6.4). A coupler arrangement for the received r.f. signal was incorporated as shown. The precise tuning of the local oscillator was achieved by varying the power supply bias and movable short position. In some of the latter versions, the mixer diode was forward-biased for higher sensitivity. The mixer output was fed into an IF amplifier and subsequently into a detector.

A number of receiver and transmitter pairs operating in the neighborhood of 30 GHz carrier frequence have been successfully tested. The tuning range for these receivers was typically between 5-500 MHz. The characteristic parameters of the system and the individual devices have been studied. Improvements and modifications are currently underway. One of the major thrusts of the future effort will be to develop receiver systems operating in the 60-90 GHz range.

6.2.1 Passive Components

Essential components of an integrated, millimeter-wave system are couplers, filters, and ferrite devices. Considerable effort has been expended on the development of dielectric components that are mutually compatible. A sweep oscillator and the associated instruments were acquired during the period, and has enabled us to conveniently measure and evaluate the frequency-dependent characteristics of the passive components. Several couplers were designed and extensively tested. Since the open dielectric waveguides are typically multimoded, the effect of the higher-order modes on the performance of the various devices was thoroughly investigated. Preliminary findings reveal no adverse influence since the experimental results compare quite well with the theoretical values derived on the basis of a single mode propagation. Some modified versions of the uniform planar waveguide, e.g. the graded-index guide, have also been investigated, both theoretically and experimentally.

6.2.2 Antennas

From an application as well as theoretical viewpoints, design and development of compatible dielectric antennas present considerable challenge. A small testing facility for performing antenna measurements

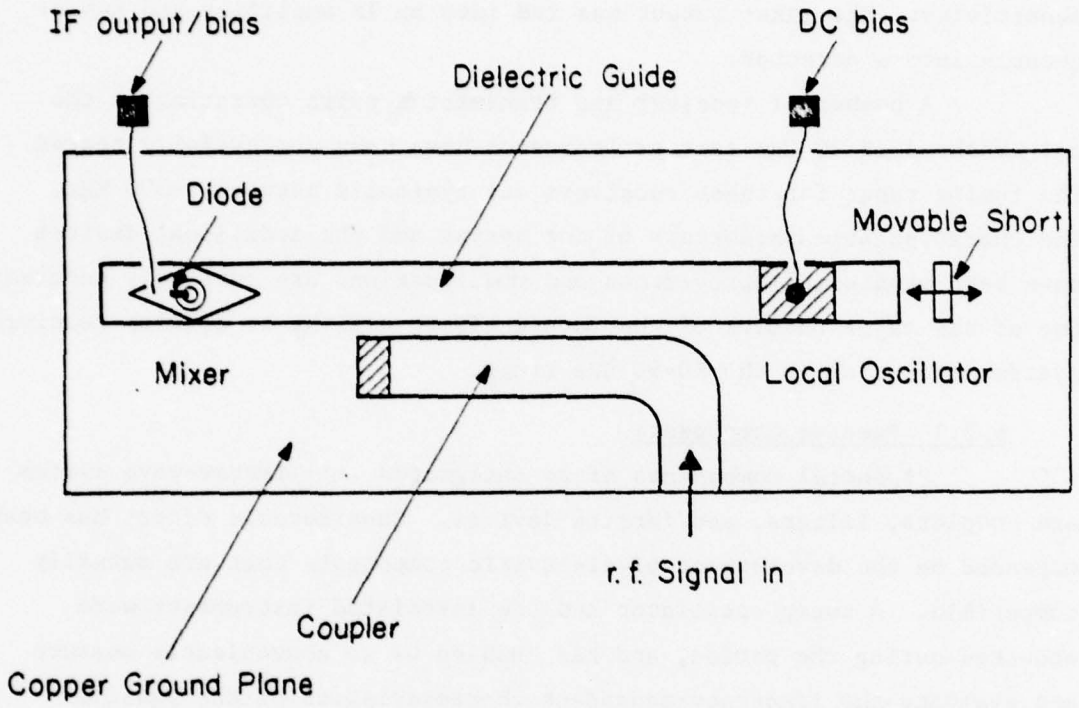

Figure 6.4 Integrated receiver on dielectric substrate.

was constructed and a number of different versions of dielectric rod antenna were tested. Some important criteria for designing dielectric antennas which have been established and further work is being continued in this area.

6.3 Theoretical Work

Three different methods for analyzing the propagation characteristics and determining the modal field distributions in open dielectric waveguides have been developed and numerical results have been obtained. A generalized version of the mode-matching analysis has been employed to derive the characteristic equation and the propagation constants of both the dominant and higher order modes. We show that the "effective dielectric constant" approach, commonly employed for open dielectric waveguides is the limiting case of a single mode approximation in the mode-matching method. The newly introduced "effective permeability method" can be interpreted in a similar way. Two other approaches, one of which is useful for refining the results derived via the mode matching technique, and the other for directly computing the propagation constant without the intermediate step of mode-matching, have been developed. The latter is particularly useful for non-planar structures where the mode-matching method does not lend itself to convenient application. Numerical results illustrating the application of the three methods have been obtained.

The theoretical approaches developed for the open dielectric waveguides are sufficiently general and should prove useful for optical and quasi-optical circuits as well.

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7.1 Introduction

Important progress has been made during the last grant period and considerable success has been achieved in the application of the Spectral Domain concept to a variety of scattering and radiation problems. The spectral domain approach introduced during the previous grant period appeared to show good promise as a candidate for the so-caller "resonance region" of frequencies, where neither the high frequency asymptotic solutions nor the low frequency moment methods are useful. Bridging this important gap has been recognized by researchers in electromagnetics as one of the most challenging problems in radiation and scattering. Another important feature of the spectral approach is its ability to evaluate the accuracy of the asymptotic solutions derived from the application of the ray optical methods or GTD. Before the introduction of the spectral approach or STD, there was no systematic or reliable means for accomplishing this task.

During the last grant period, the spectral approach has been applied to the problems of conformal arrays, diffraction by an edge with a corner, e.g. an airplane wing, and the computation of source radiation in the presence of smooth conducting bodies. These are briefly described below.

7.2 Conformal Arrays

An important problem arising in the design of conformal arrays is the computation of mutual impedance between slots located on a smooth curved surface, e.g., a missile nose-cone. Since the dimensions of the

*This work was supported by the Joint Services Electronics Program (U.S. Army, U.S. Navy, and U.S. Air Force) under Contract DAAB-07-72-C-0259 and by the National Science Foundation under Grant NSF ENG76-08305.

surface are typically large in terms of the wavelength, high frequency asymptotic techniques are employed to derive the surface current induced by a slot located on the surface of the body. The mutual impedance can be derived in a straightforward manner once this surface current is available.

More than one GTD solution has been reported for the surface current and it is difficult for a user to decide which one of these is the most accurate for his purpose. Using the spectral domain approach we have successfully attacked the problem of evaluating these solutions and have developed two tests that can reliably identify the most accurate of the three asymptotic solutions that have been published in the literature. What is more, an iterative procedure for systematically improving these solutions has also been developed and tested.

7.3 Scattering from Corners in Thin Plates

The spectral domain approach has been employed to assess the contribution of a scalar corner diffraction coefficient to satisfaction of the surface boundary condition. In performing a GTD analysis of a complex scattering body, the investigator is likely to combine diffraction from curved and straight edges as well as diffracted rays from curved surfaces. Since complex bodies often include sharp corners, a vertex diffraction coefficient would be most desirable to complete analysis of an arbitrary scatterer. Investigation of vertex scattering of a vector field has not yet resulted in an easy-to-use form. Acoustic scattering by a quarter-plane (scalar incident wave), however, has been successfully studied by Albertsen, resulting in a GTD-type diffraction coefficient.

This work used the Spectral Domain Approach to determine the contribution of the corner diffracted rays to the surface field, and its effect on satisfaction of the surface boundary condition. The iterative nature of the Spectral Domain Approach was also employed to systematically improve the solution for waves incident at both normal and oblique angles.

In addition, the corner diffraction coefficient as published by Albertsen was found to have some slight errors, and some corrective measures were suggested.

7.4 Source Radiation in the Presence of Smooth Convex Bodies

The problem of computing the radiation characteristics of sources located in the vicinity of smooth convex objects, e.g., airplane fuselage or a nose-cone, has very important applications in such areas as radar and EMC. We have demonstrated that the presently available GTD solutions for the radiated far field are in error and have derived new and accurate solutions by solving canonical problems that do not ignore the important effect of torsion in the ray trajectory as it travels on the smooth surface along gedesic paths. The theoretical results have been verified by comparison with experimental measurements.

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8.1 Introduction

Two interesting studies have been completed in nonlinear beam-plasma interactions, and a proposed experiment on probability density functions in ion-acoustic turbulence has moved out of the planning stage.

Anomalous harmonic generation by a beam-plasma instability has been observed experimentally, and a model involving nonlinear wave-particle interactions has been proposed to account for the effect. A theory of parametric instability of plasma waves and ion-acoustic waves in a beam-plasma system has been devised. Experiments on sideband excitation by an unstable beam-plasma wave have been performed, and excellent agreement has been found with the parametric instability theory. Diagnostic equipment essential to the proposed experiment on ion-acoustic turbulence has been obtained, and preliminary tests have been made.

8.2 Nonlinear Effects in a Cold Beam-Plasma System

Research has continued apace on nonlinear processes associated with the beam-plasma instability. The cold beam-plasma system and the experimental appratus have been described previously [1,2]. Significant new results have been obtained. Anomalous harmonic generation has been studied and a model put forward. A new parametric instability has been discovered. Theoretical calculations are in good agreement with the experimental results.

8.2.1 Anomalous Harmonic Generation

Previous experiments have shown that harmonics are excited in the beam-plasma system when either the fundamental wave or the harmonic itself is at the most unstable mode. This occurs by wave-wave coupling [3].

*This work was supported by the University of Illinois.

However, recent experiments show that an anomalous harmonic signal can be produced even when neither wave is strongly unstable. Figure 8.1 illustrates the effect. The traces on the left are fundamental wave radiation intensity vs plasma density, for fixed modulation frequency. The plasma density can be determined from the delay time τ and increases from left to right. The parameter x is distance of the receiving horn from the point where the beam enters the plasma. On the right is harmonic intensity vs plasma density. For short distances, the fundamental intensity peaks at a plasma density such that the wave frequency, which is externally determined, is at the most unstable mode. The harmonic, however, peaks at a significantly higher plasma density, so that the wave has a frequency less than that for strong instability.

Figure 8.2 demonstrates that the anomalous harmonic is produced by means distinctly different from the wave-wave coupling mechanism which generates harmonics at the most unstable mode. The harmonic is found to peak at two different values of plasma density. The peak which occurs at the same density as the fundamental peak is produced by wave-wave coupling. The anomalous peak occurs at a higher density. Computations of linear growth rates and nonlinear coupling constants show that the anomalous harmonic cannot be produced by wave-wave coupling.

An explanation has been proposed for the anomalous harmonic which takes nonlinear wave-particle interactions into account. It is believed that the velocity fluctuations which exist on the beam as a result of external modulation, the means by which beam-plasma waves are launched, is sufficient to electrostatically trap the beam particles at the outset. This means that the space-charge fluctuations which accompany the velocity fluctuations are so great that there is significant distortion of the particle orbits, which results in the production of harmonics. There is general agreement between theoretical calculations and the experimental results.

8.2.2 Parametric Excitation in a Beam-Plasma System

Parametric instability is an intensively studied subject in plasma physics today [4,5]. A high-intensity wave, called the pump wave, excites two daughter waves which would be damped except for the nonlinear

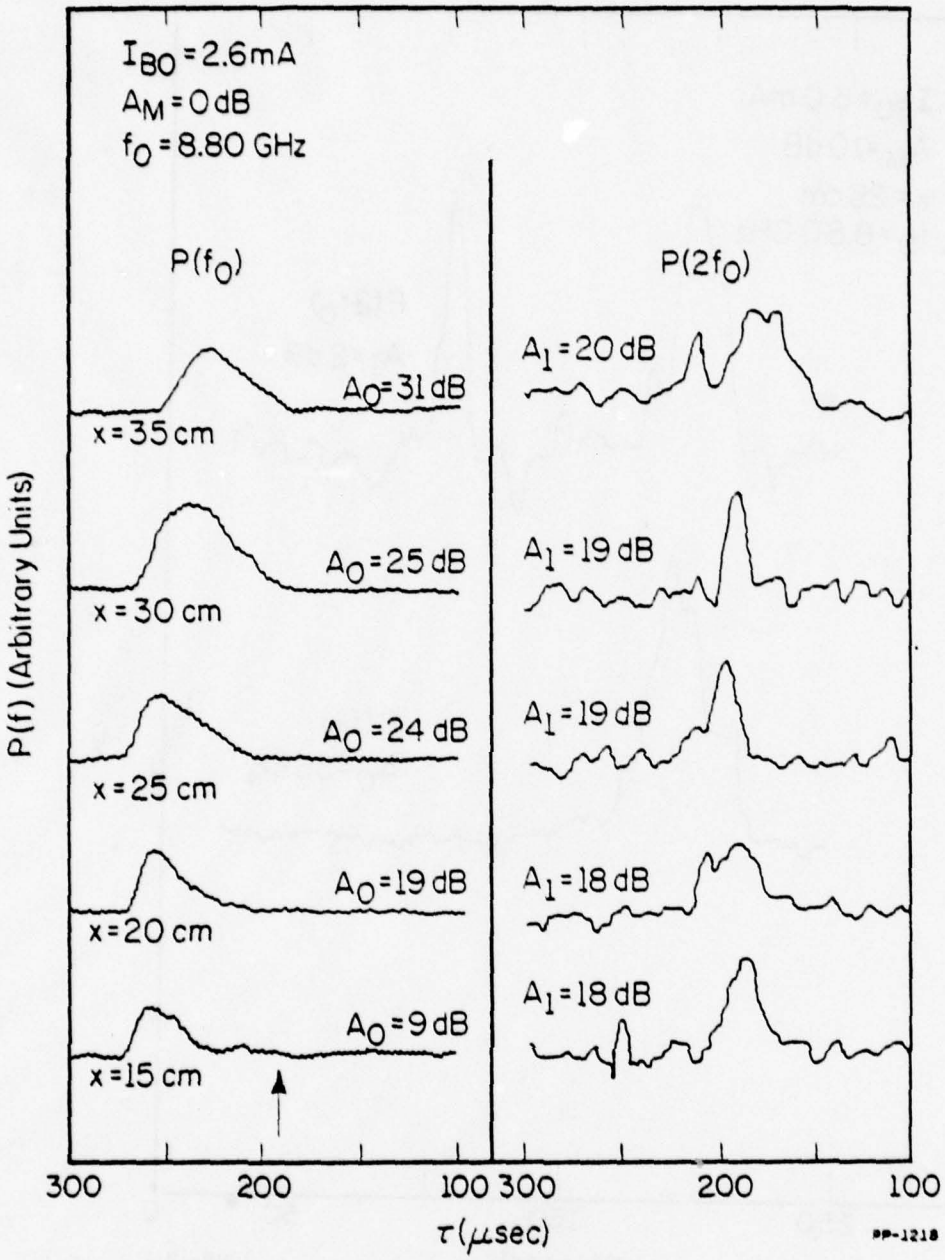

Figure 8.1 Fundamental and harmonic wave intensities vs plasma density. The fundamental traces are on the left. Arrow marks the average position of the anomalous harmonic peak.

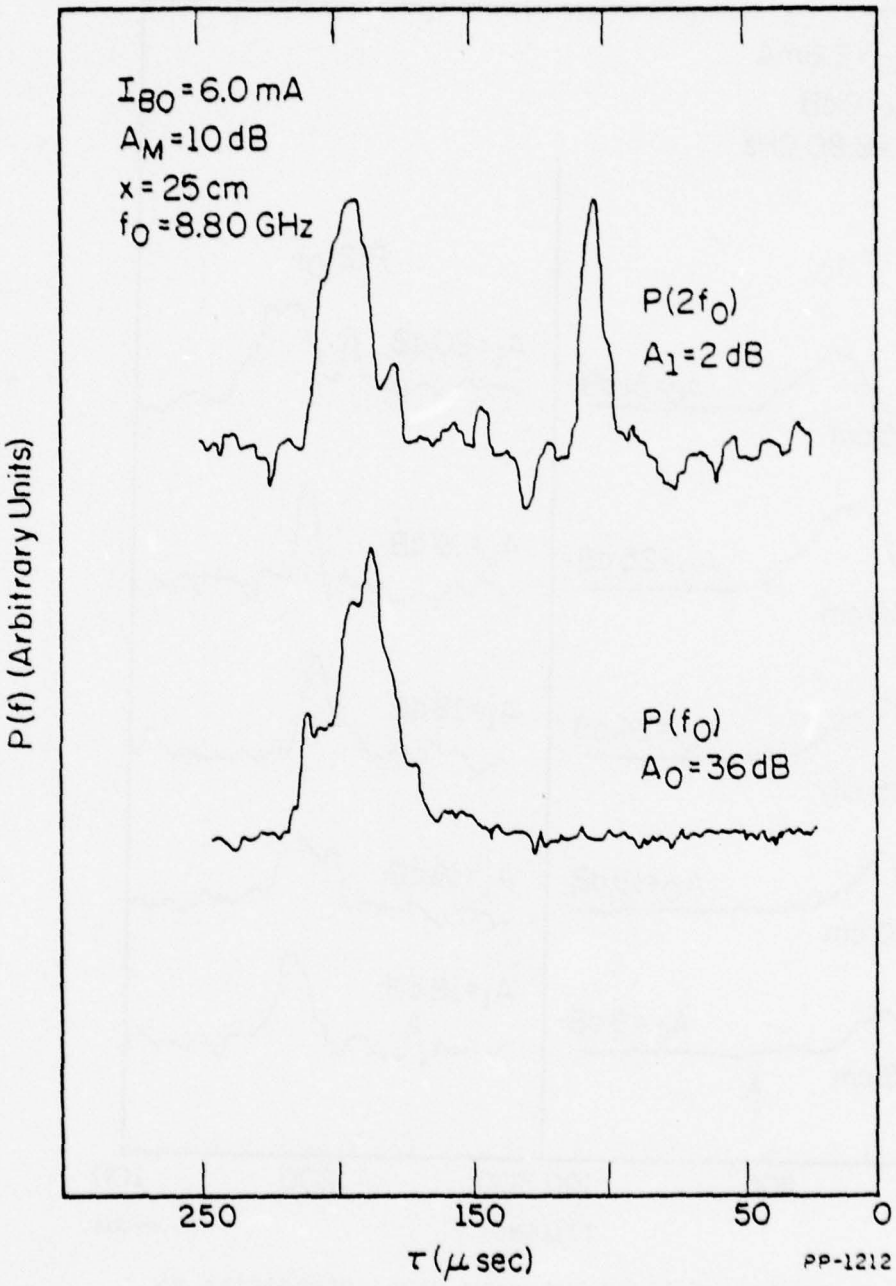

Figure 8.2 The anomalous harmonic, on right in top trace, is not produced by wave-wave coupling. Wave-wave coupling is responsible for harmonic peak on left, which occurs when fundamental is at most unstable mode.

action of the pump. The daughter waves are capable of reaching large amplitudes when the resonance conditions:

$$\omega_0 = \omega_1 + \omega_2 \ , \tag{1a}$$

$$k_0 = k_1 + k_2 \ , \tag{1b}$$

are satisfied. ω is the wave frequency, and k is the wavenumber. The subscript 0 refers to the pump wave, and the subscripts 1 and 2 refer to the daughter waves. This process is believed to be instrumental in the stabilization of instabilities, by transferring energy from an unstable wave to other modes. Also possible is plasma heating, accomplished by transfer of energy from the daughter waves to particle thermal motion.

A theoretical and experimental study of parametric excitation in the beam-plasma system has been completed. The most unstable mode of the beam-plasma instability is employed as the pump. The daughters consist of a plasma wave and an ion-acoustic wave. Because the beam-plasma wave has a much smaller wavenumber than the other two modes, the resonance condition (1b) requires that $|k_p| \simeq |k_i|$. In principle, four different processes are possible, as shown in Fig. 8.3. The coupling constants for parametric excitation in this system were computed, and it was found that Case I, where one of the two daughter waves is backscattered, is parametrically unstable. Since Case II is not unstable, the theory predicts that a large-amplitude beam-plasma wave should develop a sideband on the low-frequency side. The frequency separation of the sideband from the main wave is predicted to be equal to the frequency of an ion-acoustic wave, i.e., slightly less than the ion plasma frequency.

The theoretical results were confirmed by experiment. Figure 8.4 shows the fine structure of the beam-plasma instability spectrum for a helium plasma and for a neon plasma. The peak on the right is the beam-plasma wave, whose frequency is determined by an external modulator. The peak on the left is the predicted sideband. The frequency separation of the sideband from the beam-plasma wave is different for the two gases because of their different ion plasma frequencies - a result of the difference in ion mass. That the sideband is a plasma mode, and not another beam-plasma wave, was confirmed by the technique of incoherent microwave scattering, which is used to measure wavenumbers. The experiment showed that the

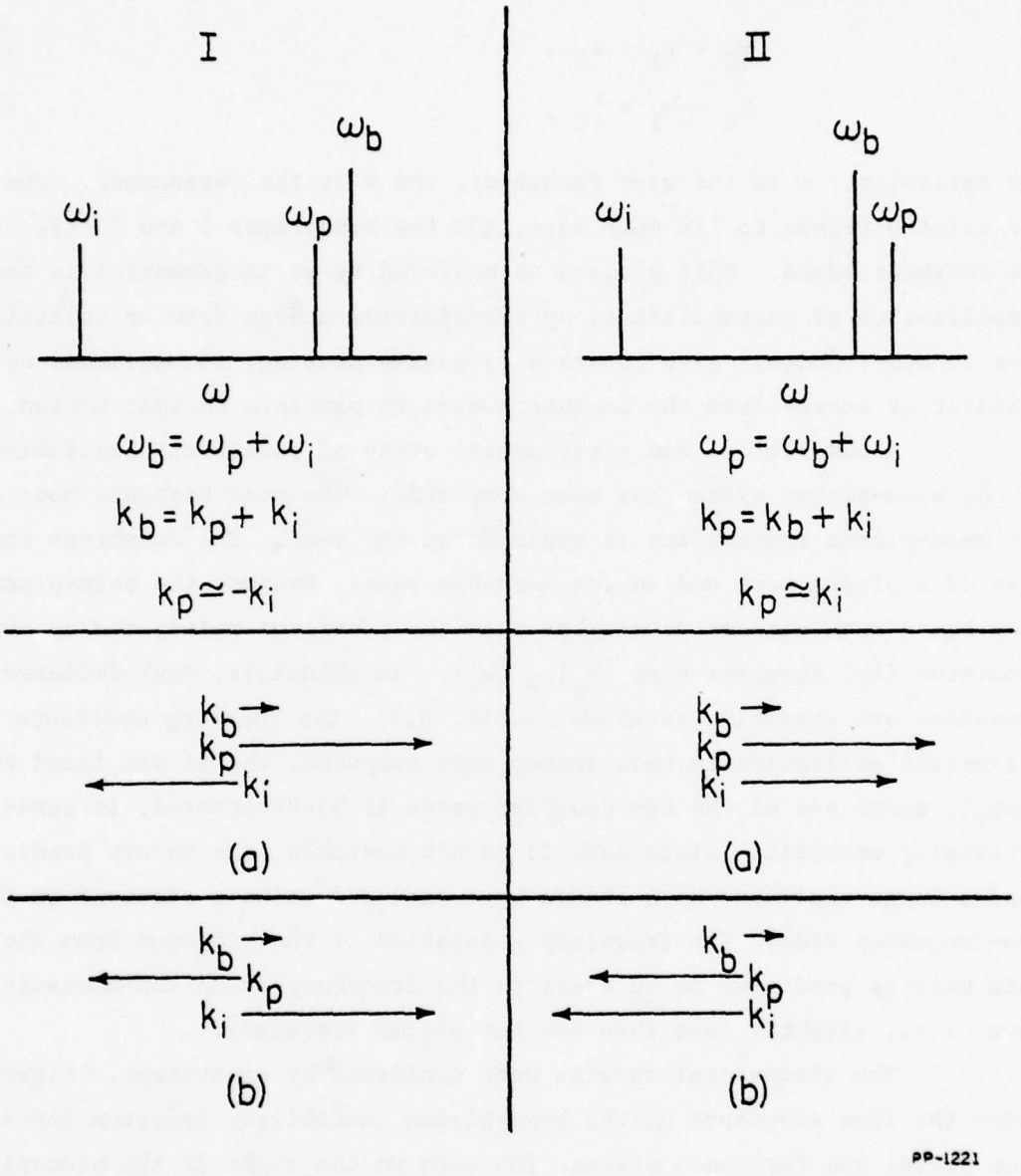

Figure 8.3 The four parametric coupling processes which are possible in the beam-plasma system. Only Case I is parametrically unstable.

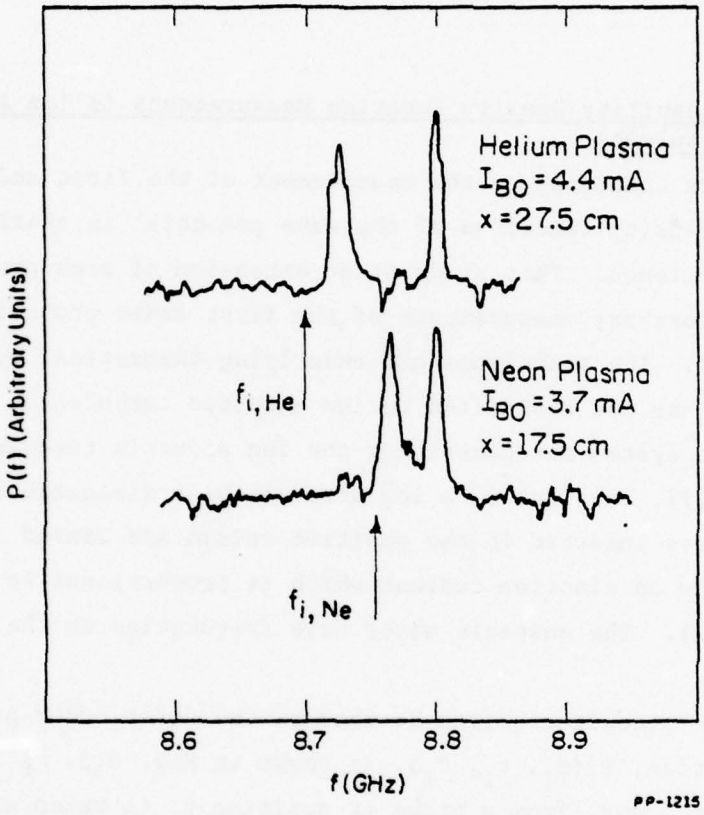

Figure 8.4 Sidebands produced by helium and neon plasmas. The difference in frequency separation establishes the connection of the sideband with ion dynamics.

sideband did not have a wavenumber characteristic of beam-plasma waves. The spectrum of the parametrically excited sideband and the required pump wave threshold intensity were in good agreement with theoretically determined values.

The results on parametric excitation will be published in the coming year.

8.3 Probability Density Function Measurements in Ion Acoustic Turbulence

Work continues on the measurement of the first and second order probability density functions of the wave potential in stationary ion acoustic turbulence. This study is an extension of some previous work in which exploratory measurements of the first order probability density were made [6]. The techniques and underlying theoretical considerations of this work are not restricted to ion acoustic turbulence.

The system for generating the ion acoustic turbulence, described elsewhere [6,7], consists of a low pressure D.C. discharge in helium. Langmuir probes inserted in the positive column and biased at space potential draw an electron current which is proportional to the turbulent wave potential. The unstable waves have frequencies in the range of 4-40 MHz.

The circuit required to measure the first order probability density function, $P_1(\varphi_1, \underset{\sim}{r}_1, t_1)$, is shown in Fig. 8.5. A 350 ps duration sample of the signal from a probe at position $\underset{\sim}{r}_1$ is taken at time t_1 by the sampling oscilloscope. The sample-and-hold output of the sampling oscilloscope is converted into positive pulses of a few microseconds duration. The pulses are then amplified and displayed on a multichannel pulse height analyzer. The resulting display is $P_1(\varphi_1, \underset{\sim}{r}_1, t_1)$. Preliminary measurements revealed a Gaussian distribution in the wave potential of the fully developed turbulence, and deviations from the Gaussian near the onset of the instability.

Preparations for the measurement of the second order probability density function, $P_2(\varphi_1, \underset{\sim}{r}_1, t_1; \varphi_2, \underset{\sim}{r}_2, t_2)$, by utilizing the circuit shown in Fig. 8.6 are near to completion. To understand the measurement, first note that in a stationary state, P_2 depends only on the time

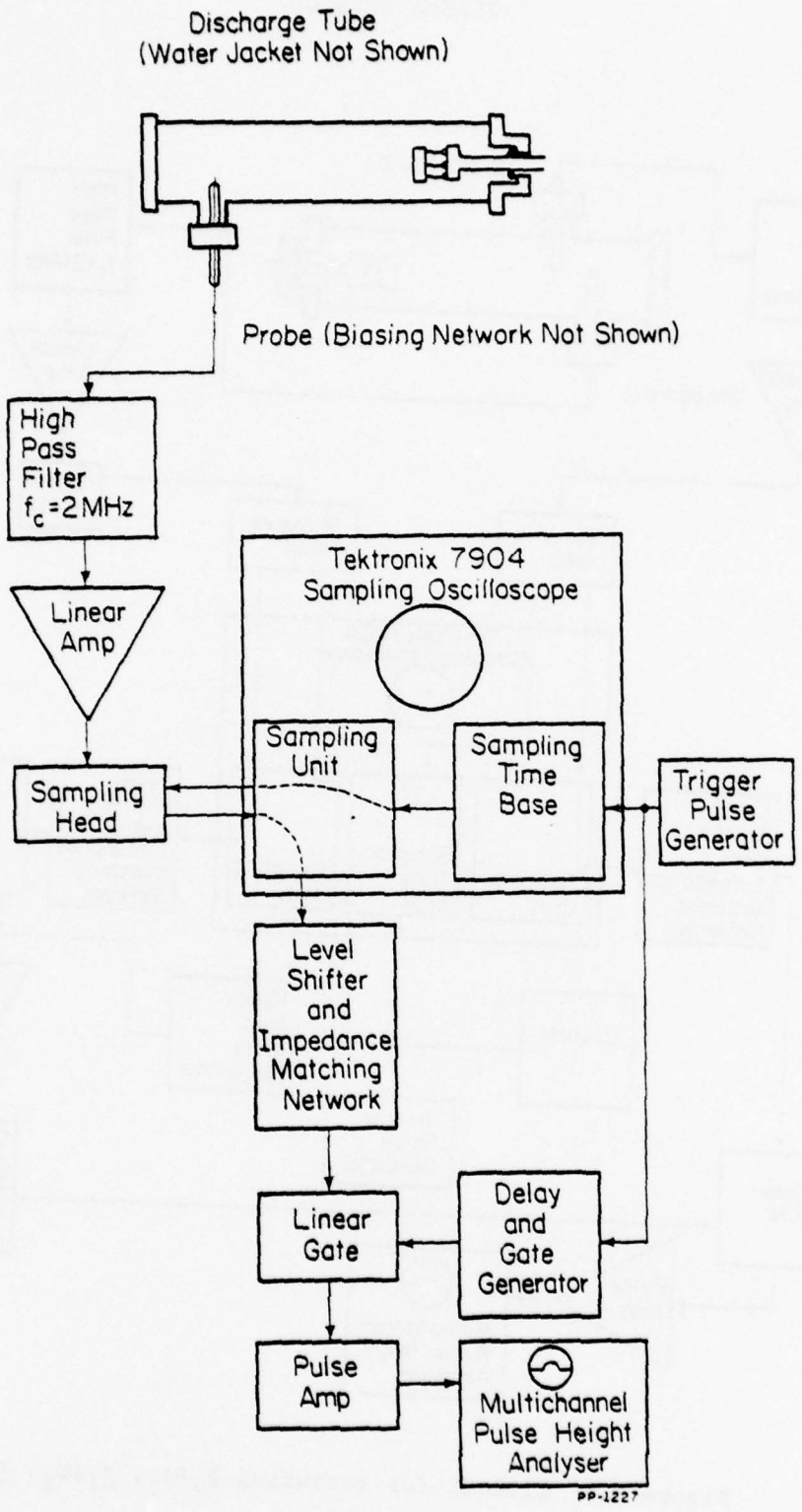

Figure 8.5 Circuit for measuring $P_1(\varphi_1, \underset{\sim}{r}_1)$.

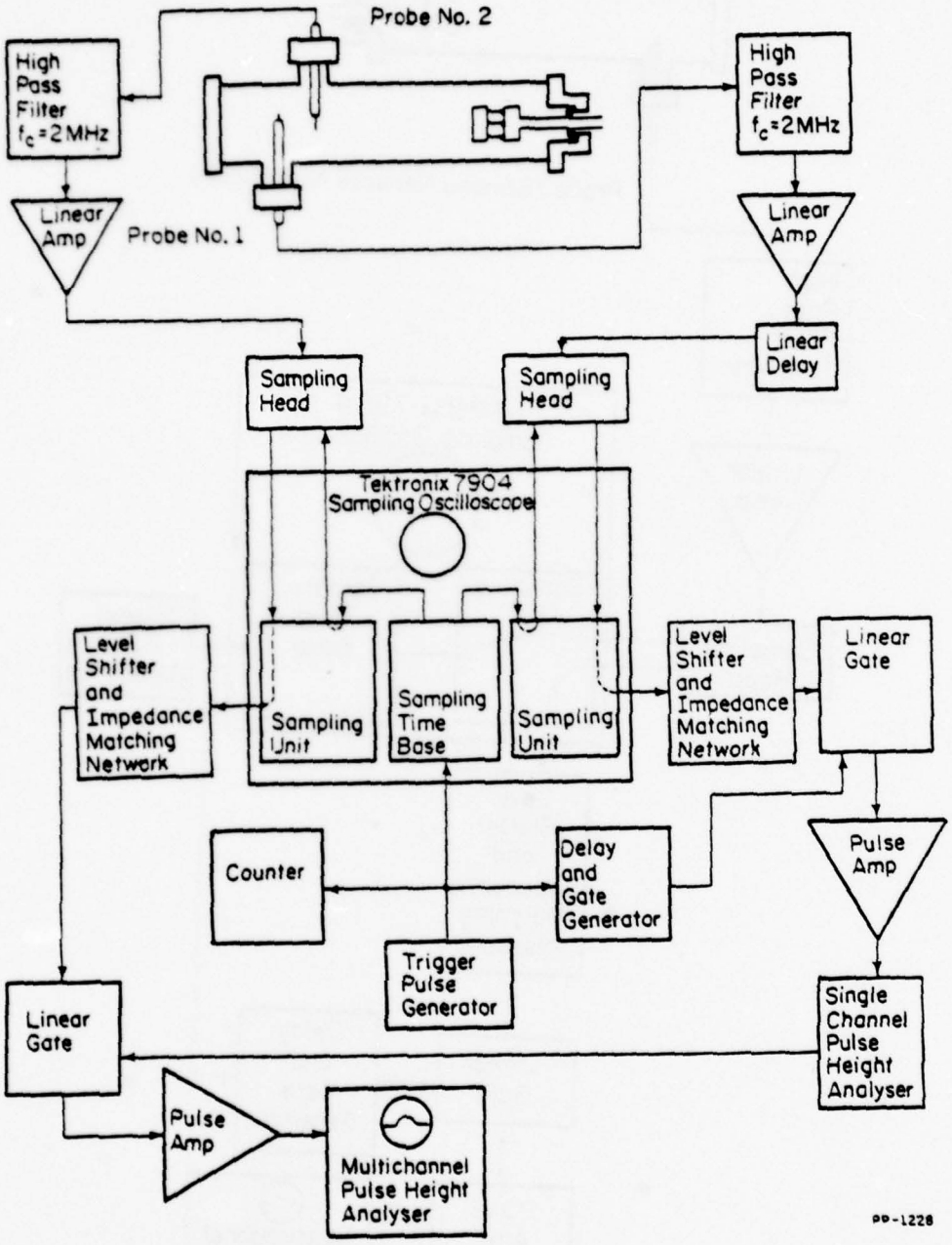

Figure 8.6 Circuit for measuring $P_2(\varphi_1, \underset{\sim}{r}_1; \varphi_2, \underset{\sim}{r}_2; \tau)$.

difference, $t_1 - t_2 = \tau$. Furthermore, P_2 is related to the conditional probability, $Q(\varphi_2, \underset{\sim}{r}_2 | \varphi_1, \underset{\sim}{r}_1, \tau)$ by:

$$P_2(\varphi_1, \underset{\sim}{r}_1; \varphi_2, \underset{\sim}{r}_2; \tau) = P_1(\varphi_1, \underset{\sim}{r}_1) Q(\varphi_2, \underset{\sim}{r}_2 | \varphi_1, \underset{\sim}{r}_1, \tau).$$

Q is the probability that φ has the value φ_2 at position $\underset{\sim}{r}_2$ given that it had the value φ_1 at positiom $\underset{\sim}{r}_1$ a time τ earlier. The conditional probability is measured by passing the samples of the delayed signal from a probe at $\underset{\sim}{r}_1$ into a single channel pulse height analyser. The analyser selects pulses of a given amplitude φ_1. The output of the single channel analyser is used to gate the samples from the probe at $\underset{\sim}{r}_2$ into a multichannel analyser. Thus the multichannel analyser only receives a pulse from the probe at $\underset{\sim}{r}_2$ when a signal of amplitude φ_1 has occurred at position $\underset{\sim}{r}_1$ a time τ earlier.

By changing the setting of the single channel analyser (φ_1) and the delay time (τ), the function Q is obtained. By counting the total number of samples taken and the total number which enter the multichannel analyser, $P_1(\varphi_1, \underset{\sim}{r}_1)$ can be measured simultaneously with Q.

During the past year, our efforts have been concentrated on the assembly of the equipment needed to measure P_2. The discharge tube and its surrounding water jacket have been modified to accept two radial probes, one fixed and the other movable in three dimensions with micrometer adjustments. In addition, a viewport has been added to allow measurement of the ion temperature in the discharge. The ion temperature will be determined by measuring the Doppler broadening of the ion emission lines. The small broadening expected will be measured with a Fabry-Perot interferometer.

In addition to major changes in the discharge tube, there has been considerable upgrading of the electronic equipment. A new regulated power supply for the discharge has been installed in order to reduce the amount of ripple in the discharge current. The procurement and construction of the sampling network is now completed and tests are being made to insure linearity and stability of the network by sampling known determinant waveforms. The system has been found to be sensitive to slight noise or distortion on the test signal. Measurement of P_2 will begin upon completion of the movable probe assembly.

A recent paper [8] suggests that the average behavior of a system before and after a given fluctuation amplitude φ_0 occurs, i.e. $\langle\varphi(t)|\varphi(0) = \varphi_0\rangle$, can be used to study the nonlinearity of the system. The information contained in this quantity is a subset of the information contained within $P_2(\varphi_1, \underset{\sim}{r}_1; \varphi_2, \underset{\sim}{r}_2 = \underset{\sim}{r}_1, \tau)$. Since only one probe is required (because $\underset{\sim}{r}_2 = \underset{\sim}{r}_1$) measurement of this quantity will begin in the very near future.

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9.1 Introduction

Rarefied gas dynamics deals with nonequilibrium gas flow problems in which microscopic treatment according to kinetic theory is necessary to determine the effect of intermolecular collisions and gas surface interactions on both the microscopic and macroscopic gas flow properties. Such rarefied gas flow problems occur in aerodynamics, electronics, aeronomy, environmental fluid dynamics, and other related fields.

The aim of this research program is to develop numerical methods to solve a wide range of problems under conditions far from and near thermal equilibrium. A Monte Carlo method has been developed at CSL [1] to solve directly the Boltzmann equation and has been used by the CSL Boltzmann group to solve the Boltzman equation for several rarefied gas flow problems under a wide range of equilibrium and boundary conditions [2-7]. The solutions we have obtained yielded detailed microscopic and macroscopic nonequilibrium properties, most of which have never been treated and studied before. We have also studied other numerical methods to solve rarefied gas flow problems, e.g., the direct simulation technique.

9.2 Study of an Evaporation Problem* and a Condensation Problem

Nonlinear evaporation-effusion problems are encountered in such diversified areas as upper atmosphere meteorology, the sodium cooling nuclear reactors, design of space experiments, petrochemical engineering, vacuum technology, and the interaction of high power laser radiation with metal surfaces. Ytrehus [8] of the University of Trondheim, Norway formulated at one dimensional problem, solved the Boltzmann transport equations for Maxwellian molecules for this problem, and compared his

*This work was supported by NATO Research Grant 1075 and by the University of Illinois.

calculations with available experimental and other theoretical results. His work stimulated further study of this problem using more accurate kinetic theory treatment in order to find the effect of different boundary conditions and collision laws. We have undertaken a joint research effort with him and Wendt of Von Karman Institute of Fluid Mechanics to study these problems under a NATO Research Grant. The major contribution of Wendt is in the experimental phase of the study.

Under the joint effort, we have successfully simulated the half-space evaporation-condensation problem by solving the Boltzmann as well as the Krook equations for a two-wall emitting and absorbing problem [9] first suggested to us by Cheremissine and studied by us [6] in detail. The simulated problem is shown schematically in Fig. 9.1. There are computational difficulties in solving directly the Boltzmann equation for any half-space problem; therefore, the success of our attempt would be of basic interest and could lead to similar attempts to study the half space problems by using the accurate kinetic theory approach.

The solutions obtained establish the validity of Ytrehus' simple and useful approach to make parametric studies of such problems and the conditions under which theoretical calculations can be correlated with others as well as with experimental results. The results obtained by us and Ytrehus were presented at the 10th Rarefied Gas Dynamics Symposium, Aspen, Colorado in July, 1976 and were published [10,11]. We have made further numerical studies of the Krook solutions for large mass rate in order to study the simulation near the downstream limiting Mach number of 1. Figures 9.2 and 9.3 show respectively the variation of the downstream speed ratio and that of the backscattered mass flux with the "wall" downstream pressure ratio. It seems that Ytrehus' approach is also valid for large speed ratios. A paper summarizing these results will be presented at the 11th Rarefied Gas Dynamics Symposium, Cannes, France in July, 1978.

The solution of the two-wall emitting and absorbing problem includes that of the condensation problem which also has a wide range of applications. Figures 9.4 and 9.5 show respectively the condensation rate and the downstream speed ratio. We show the flow behavior in the Knudsen layers in Figures 9.6, 9.7, and 9.8.

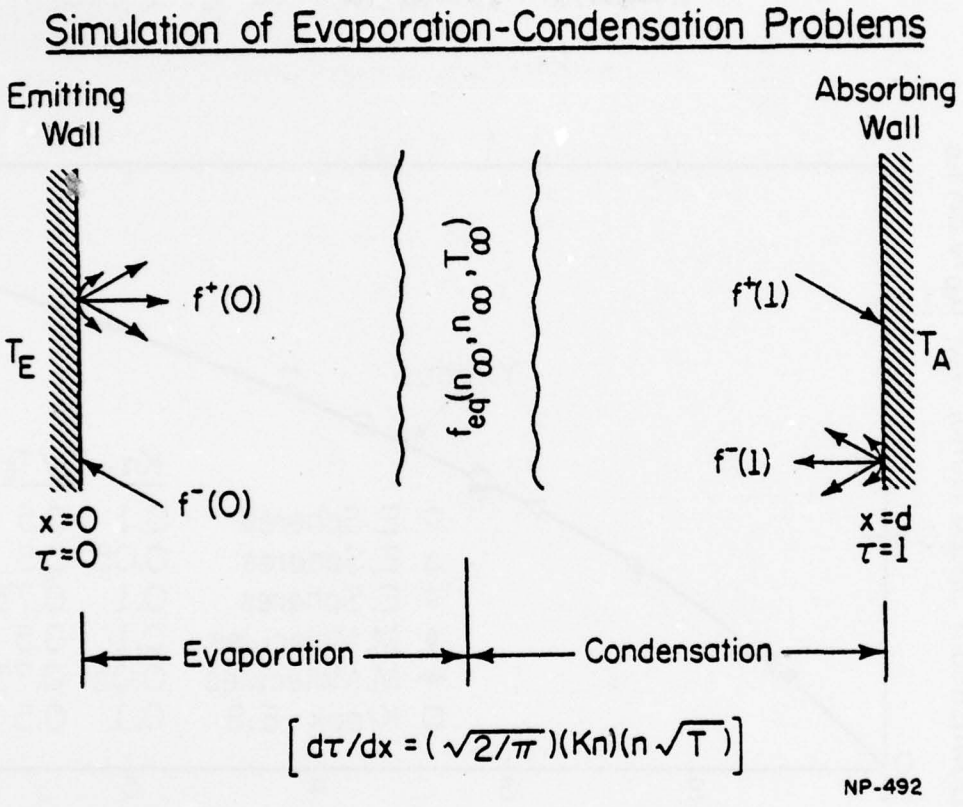

Figure 9.1 Numerical simulation of half-space evaporation and condensation problems.

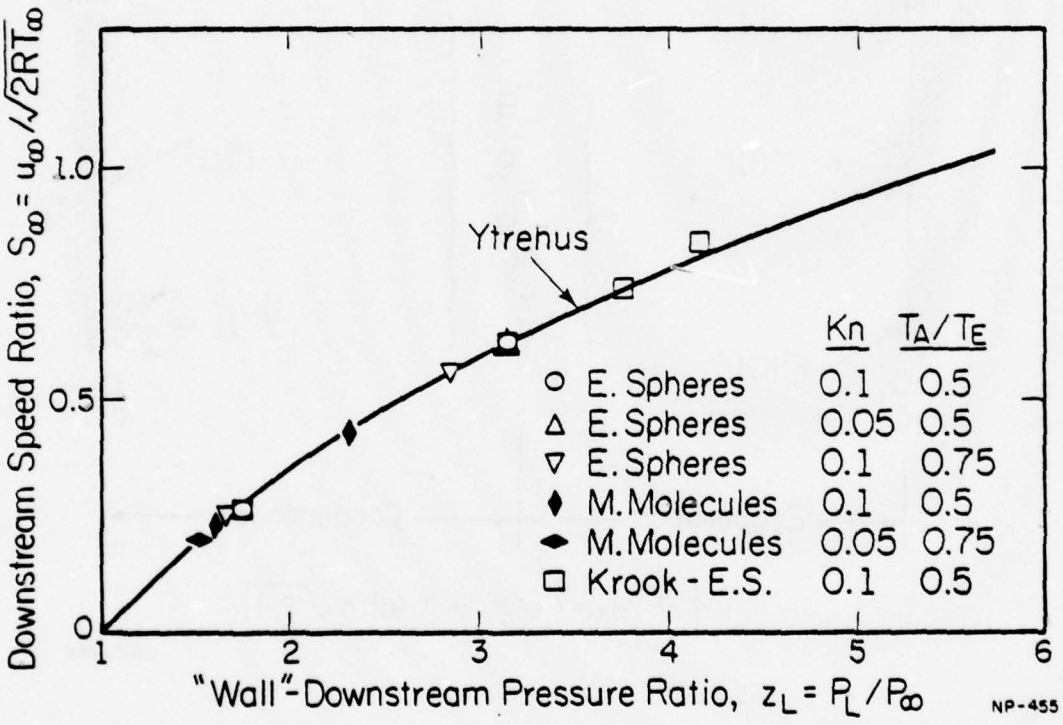

Figure 9.2 Downstream speed ratio vs "wall" downstream pressure ratio.

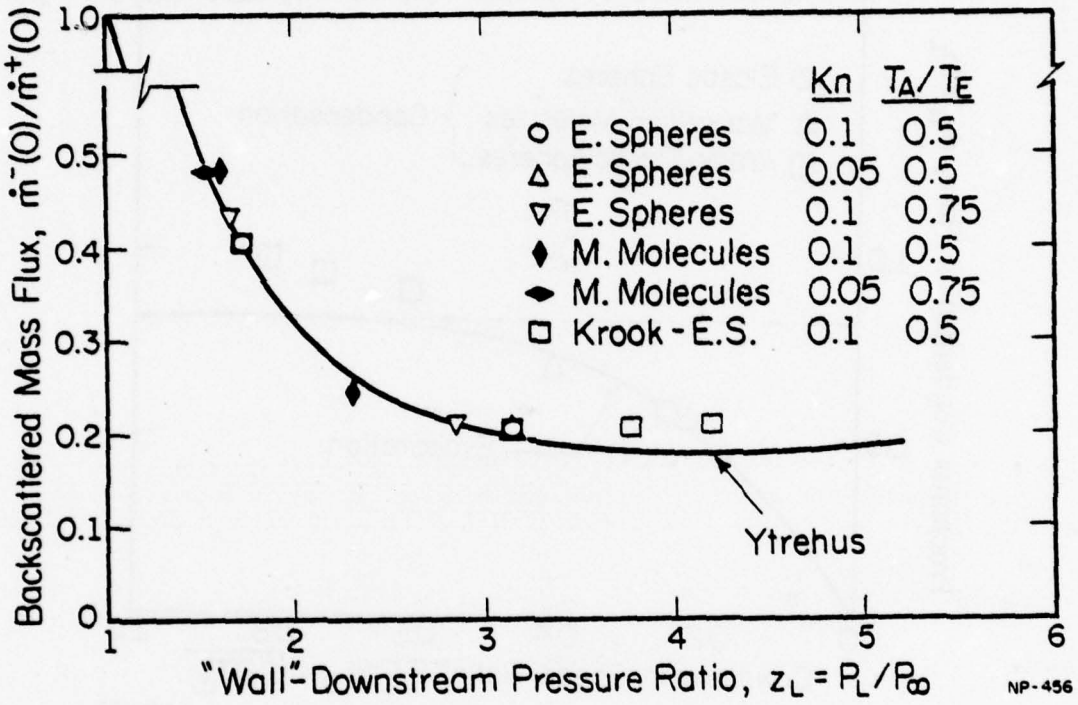

Figure 9.3 Backscattered mass ratio vs "wall" downstream pressure ratio.

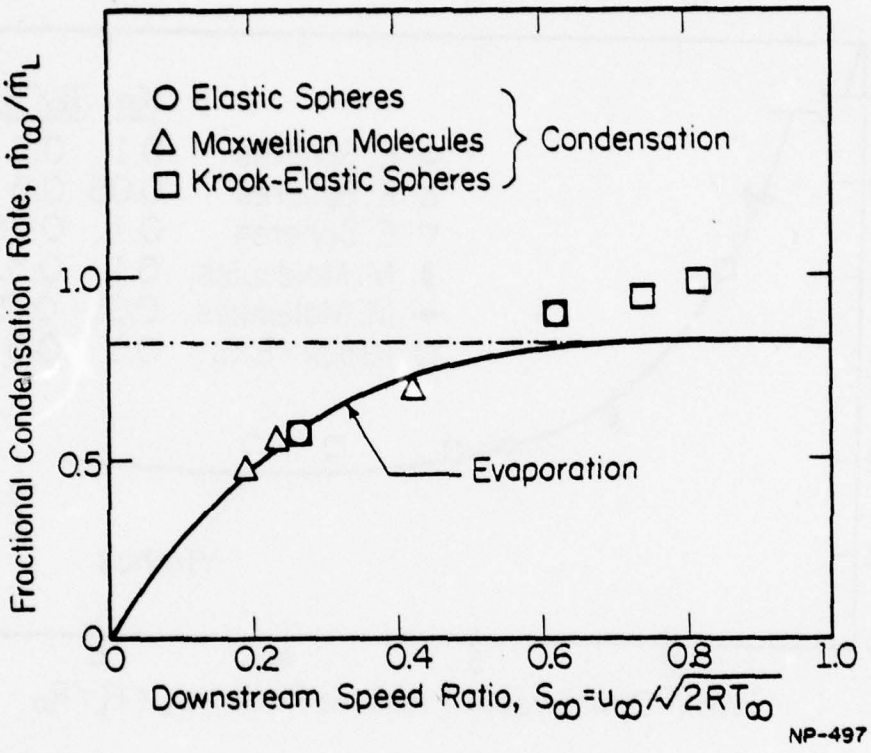

Figure 9.4 Condensation rate vs downstream speed ratio. Comparison of condensation and evaporation rates. (The variation of the evaporation rate shown by the solid line.)

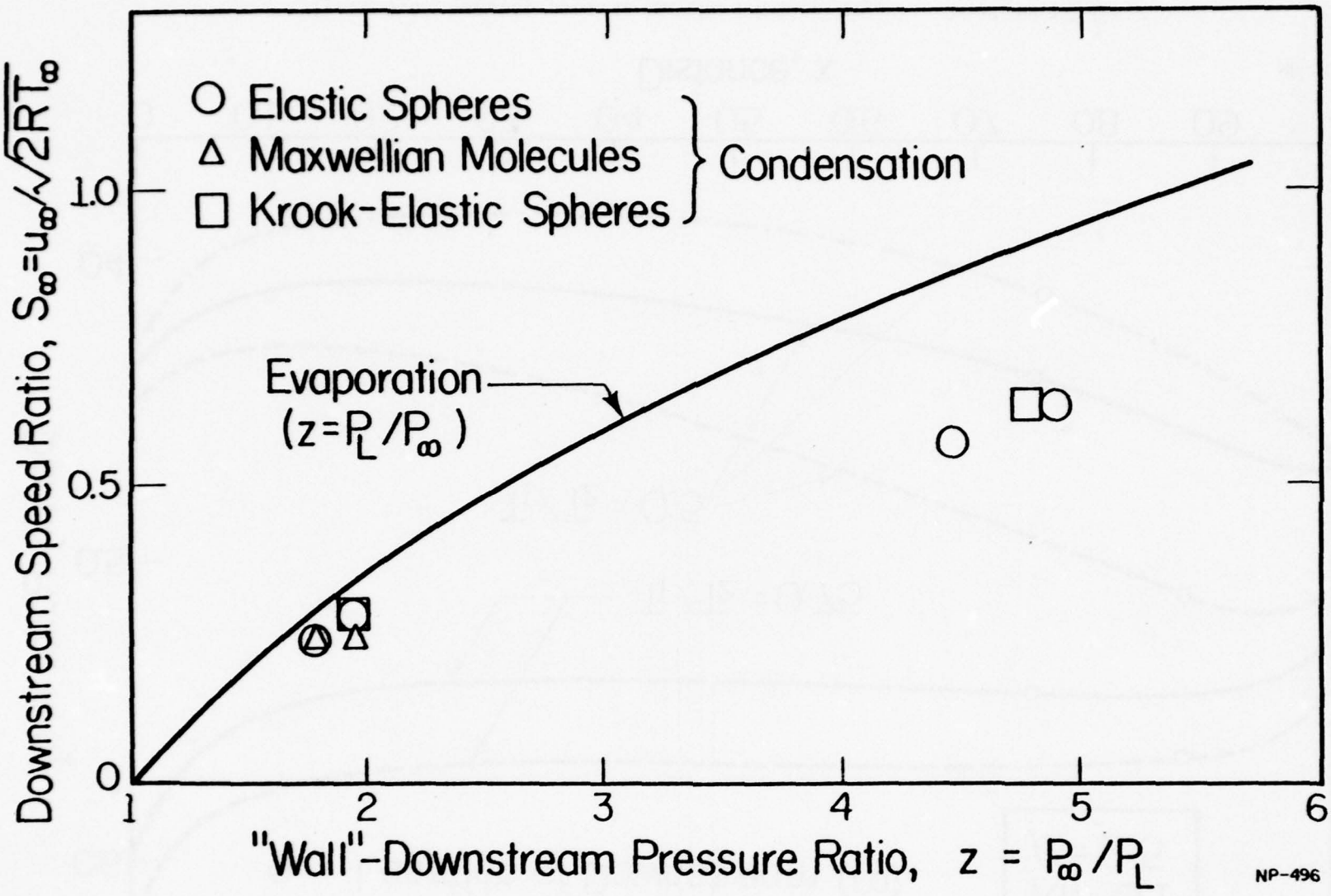

Figure 9.5 Downstream speed ratio vs "wall" - downstream pressure ratio. Comparison of the results for the condensation with those for the evaporation. (Note: $z = P_\infty/P_L$ for condensation and $z = P_L/P_\infty$ for evaporation.) (The variation of the downstream speed ratio shown by the solid line.)

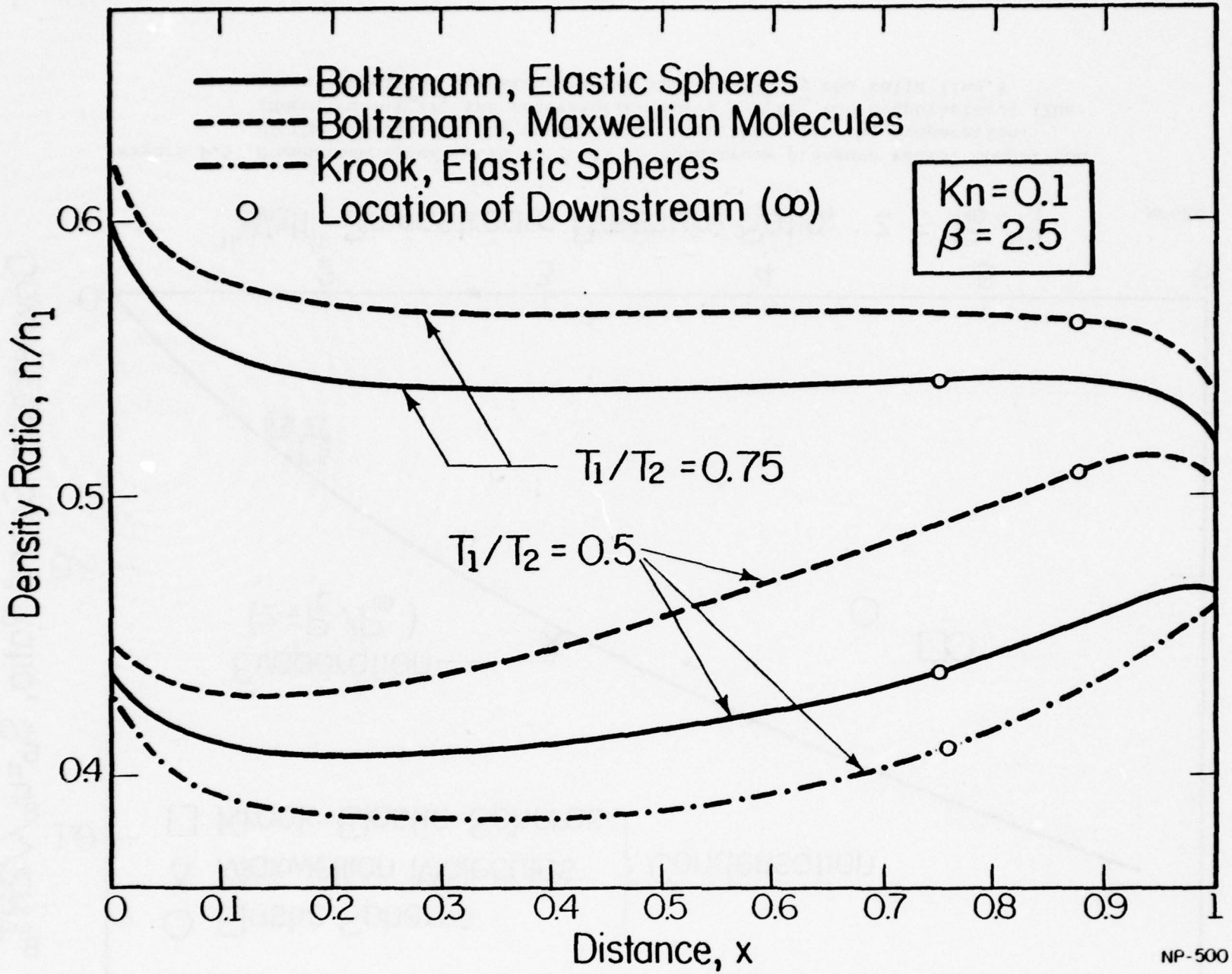

Figure 9.6 Density profile in the Knudsen layers. Knudsen layers:
(1) Adjacent to the evaporation surface: $x = 0$ to x_∞,
(2) Adjacent to the condensing surface: $x = 1$ to x_∞.

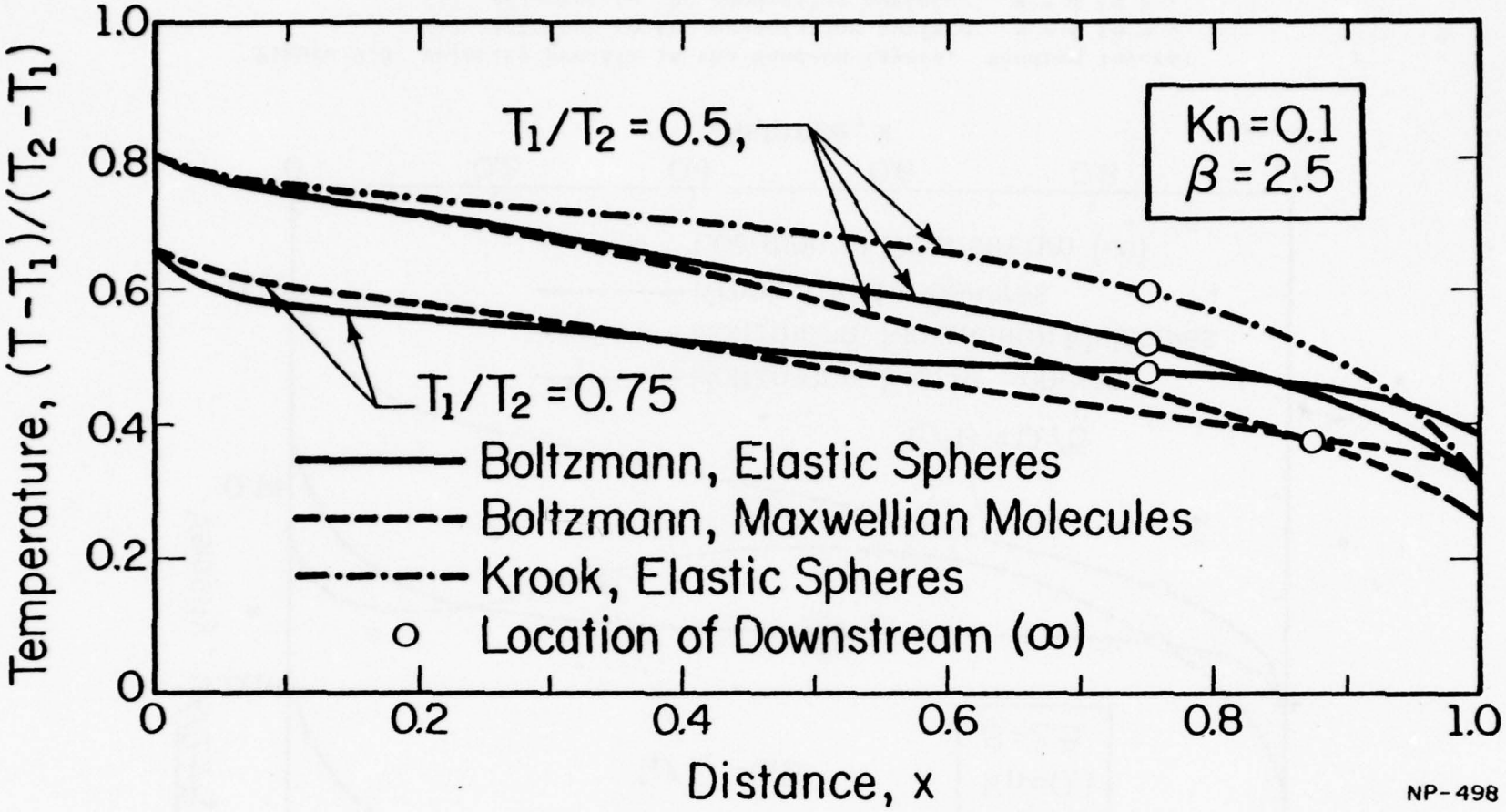

Figure 9.7 Temperature profile in the Knudsen layers. Knudsen layers:
(1) Adjacent to the evaporating surface: $x = 0$ to x_∞,
(2) Adjacent to the condensing surface: $x = 1$ to x_∞.

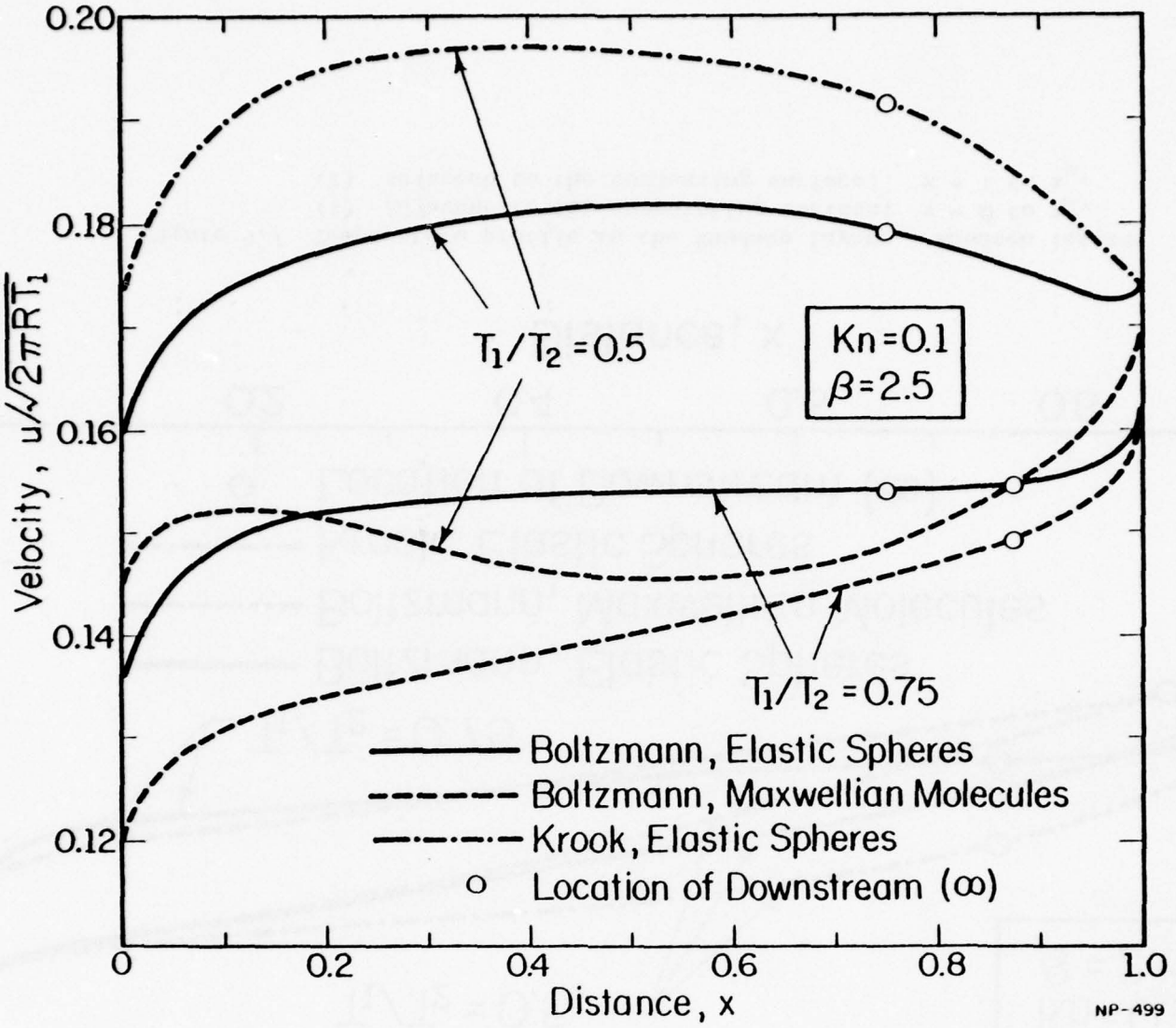

Figure 9.8 Velocity profile in the Knudsen layers. Knudsen layers:
(1) Adjacent to the evaporating surface: x = 0 to x_∞,
(2) Adjacent to the condensing surface: x = 1 to x_∞.

9.3 Study of Aerodynamic Isotope Enrichment Devices

The objective of this research program is to develop Monte Carlo techniques for analyzing the separation process in aerodynamic isotope enrichment devices. We have developed a hybrid approach in which the efficiency as well as the resolution of the computation of the separation process can be improved. This approach would be useful to solve certain gas mixture problems, e.g., those encountered in pollution.

9.4 References

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10.1 Introduction

The objective of this research program is to solve numerically the basic inviscid and viscous gas dynamic equations for complex problems. We have studied the application of finite element, finite difference and hybrid methods to problems of complex geometries and boundary conditions. We shall report our research efforts on the numerical generation of optimum mesh systems, the numerical solution of nonlinear free surface problems and the numerical solution of viscous flow problems of complex geometrics.

10.2 Numerical Generation of Optimum Mesh Systems*

The objective of this study is to develop an efficient finite element method for fluid flow problems by using an optimum grid system generated by a numerical transformation. We have made a parametric study of the effect of mesh systems on the accuracy of the numerical solutions and, on the basis of this study, have formulated a set of criteria to select the shape and the structure of elements in a mesh system to minimize the discretization errors. We have developed two methods that meet these criteria to generate numerically optimum mesh systems for finite element as well as finite difference computations.

The first of the two methods to generate the optimum mesh system has been reported [1]. The second method which is a modification of the first involves the numerical transformation by solving two Laplace equations. It may be looked upon as an attempt to find an orthogonal transformation of elliptic-cylindrical type for a domain of arbitrary geometry. This method does not work for bodies with concave corners;

*This work was supported by the National Science Foundation under Grant ENG 75-15050 and Grant ENG 77-20436.

however, it is more suitable for bodies with sharp edges as airfoils. Figures 10.1 and 10.2 show respectively the mesh systems for an internal flow around a circular cylinder and an external flow around an airfoil.

The design criteria and the numerical generation of optimum finite element meshes were presented at the Sixth International Conference on Numerical Methods in Fluid Dynamics, June 20-25, 1978, Tbilisi, USSR [2].

10.3 Study of Free Surface Problems*

There are three major problems associated with the numerical solution of free surface problems: to accommodate accurately the free surface geometry, to satisfy the boundary condition uniformly over the free surface and to treat the radiation boundary condition. Computational methods have been developed to deal with these problems and have been used to solve several free surface problems. However, computational difficulties are encountered in the application of these methods to problems under certain conditions. On the other hand, each of these methods have advantages over others in the solution of a particular class of problems. Our research on the computational methods using the Eulerian approach [3] has led to several conclusions concerning further studies:

(1) The time-dependent approach can be used to solve the initial phase of development of free surface flows. In computation of larger time, study has to be made to reduce the accumulation of diffusive error.

(2) The finite element method can be used to reduce the interpolation error; however, the implementation of this method is more complex. In order to increase computation efficiency for complex problems, we should consider a hybrid method that combines the finite element and finite difference grid systems.

(3) On the basis of consideration of error accumulation, the steady state approach is more favorable. However, the treatment of radiation boundary condition should be studied.

*This work was supported by the National Science Foundation under Grant ENG 77-20436.

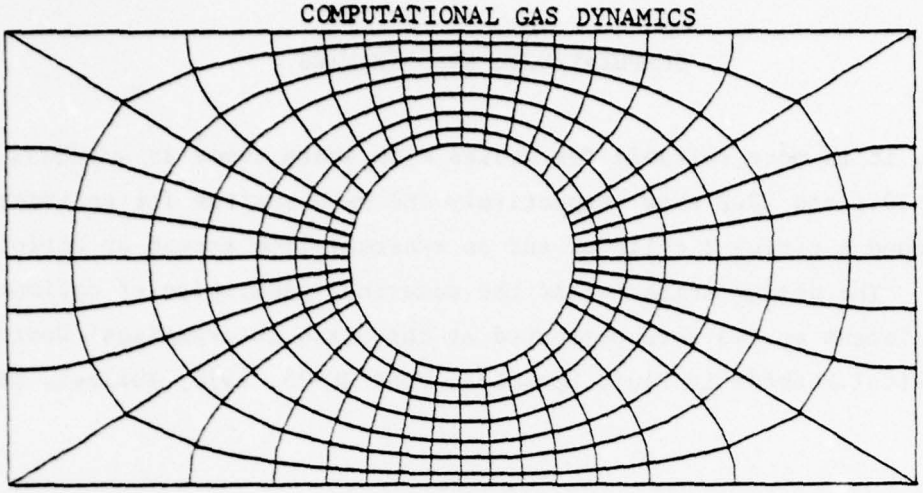

Figure 10.1 Optimum mesh system - an internal flow.

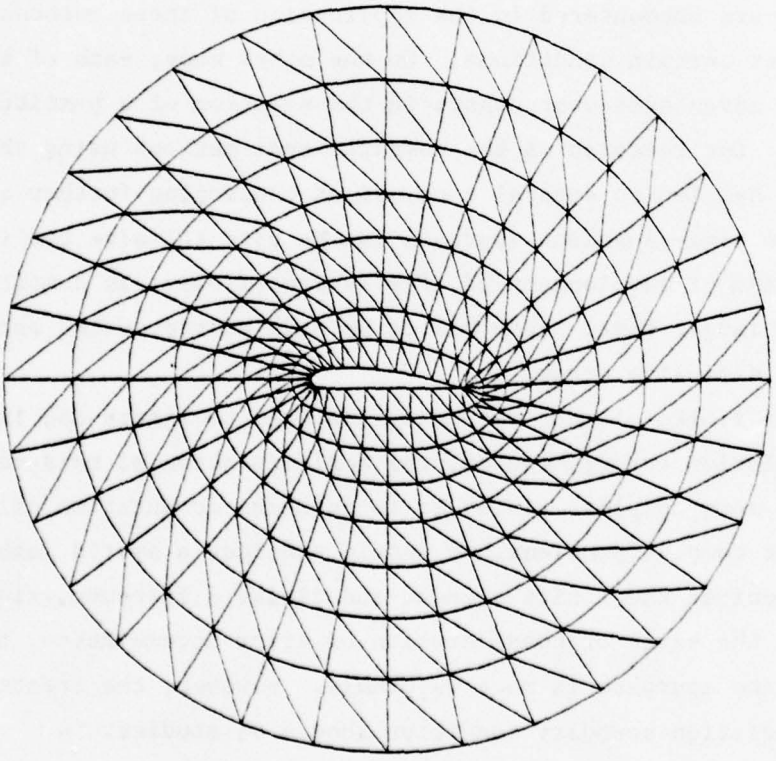

Figure 10.2 Optimum mesh system - airfoil.

Our current research tasks are summarized as follows:

(1) Study further the application of the two-dimensional problem of pressure distribution by obtaining the numerical solutions at a larger Froude number and at different depths: Previous solutions [4,5] were obtained for Froude number of $1/\sqrt{4\pi}$ and at y = -1 [4] and y = -2 [5]. New solutions were obtained for Froude number of $1/\sqrt{2\pi}$ at these two heights. Figure 10.3 shows the comparison of wave resistance at two Froude numbers as well as the comparison with linear results by Haussling and Van Eseltine [6,7]. The wave heights at t = 2 and 3 are shown in Fig. 10.4 and the comparison of wave height at t = 2 with the linear calculation, Fig. 10.5.

(2) Study the numerical errors due to the implementation of free surface condition in the time-dependent scheme by performing numerical experiments on a parabolic system characterized by that condition.

(3) Study the implementation of radiation boundary condition in the steady state approach by performing several numerical experiments on the pressure distribution problem: The results of these experiments indicate that several factors must be taken into consideration in implementing the radiation boundary condition at a fixed downstream boundary.

(4) Study the application of a hybrid method to increase the computation efficiency for field calculation: Fig. 10.6 shows an example of a hybrid mesh in which the finite difference method is to be used in the outer region and the finite element method, the inner region.

(5) Study the numerical solution of the unsymmetrical hydrofoil problem by more accurate implementation of the Kutta condition.

10.4 Study of Viscous Flow Problems

A research effort has been initiated to solve the Navier-Stokes equations for problems of complex geometrics using the finite element method. A computer program has been written to solve the viscous flow problem around an airfoil using the mesh system as shown in Fig. 10.2.

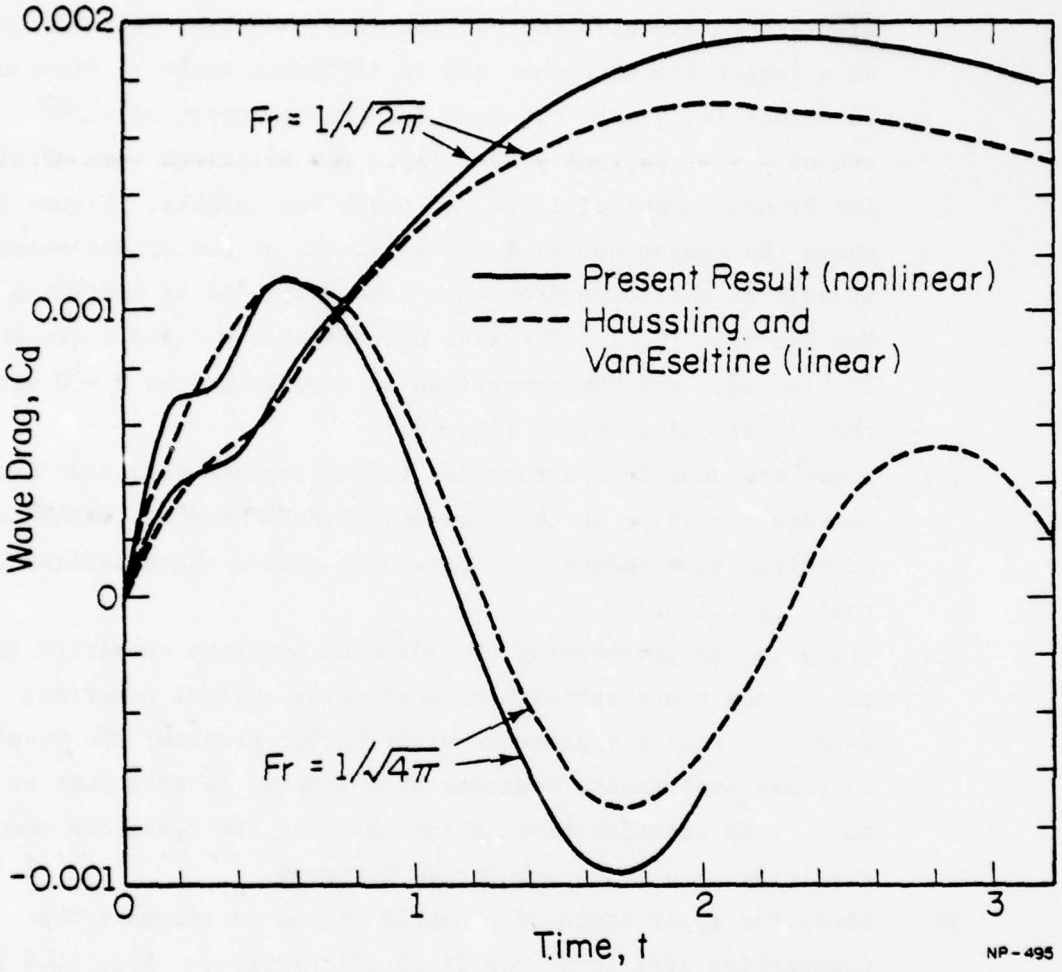

Figure 10.3 Comparison of wave drag at Fr = $1/\sqrt{4\pi}$ and $1/\sqrt{2\pi}$.

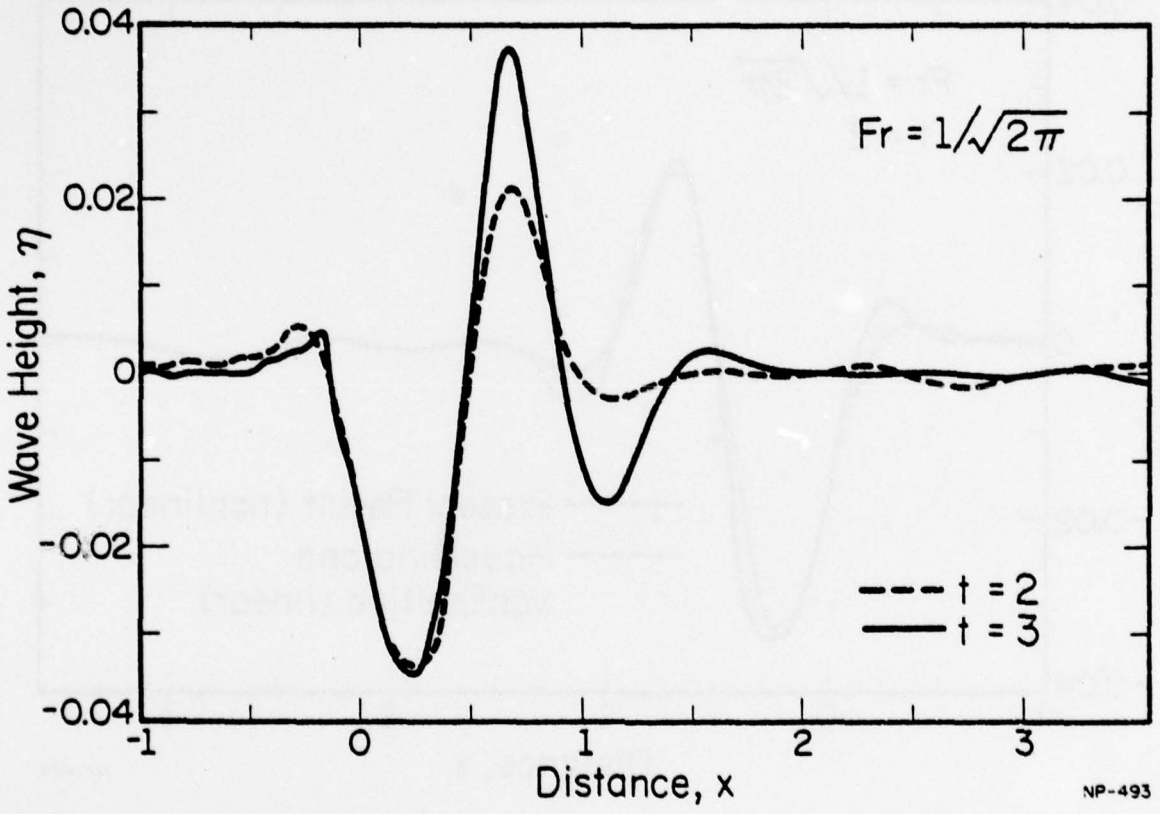

Figure 10.4 Comparison of wave height at t = 2 and 3. Fr = $1/\sqrt{2\pi}$.

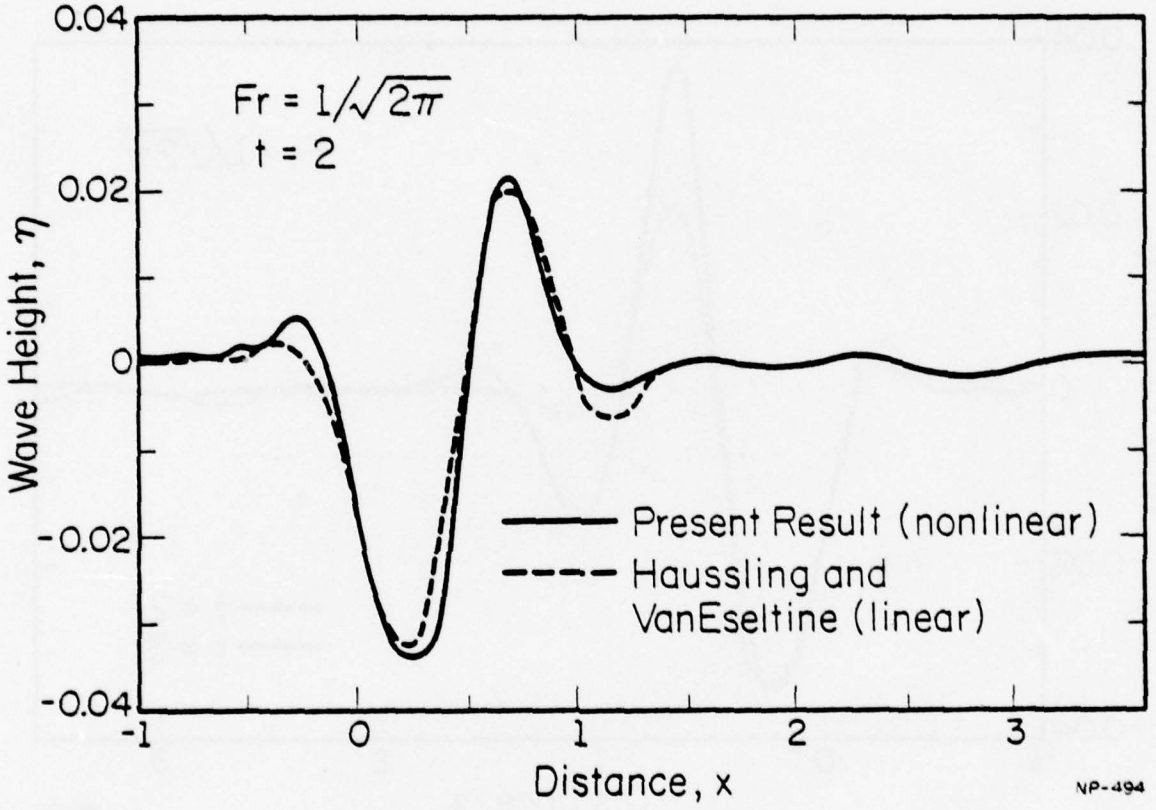

Figure 10.5 Comparison of the wave height at $\underline{t} = 2$ with that of the linear calculation. $Fr = 1/\sqrt{2\pi}$.

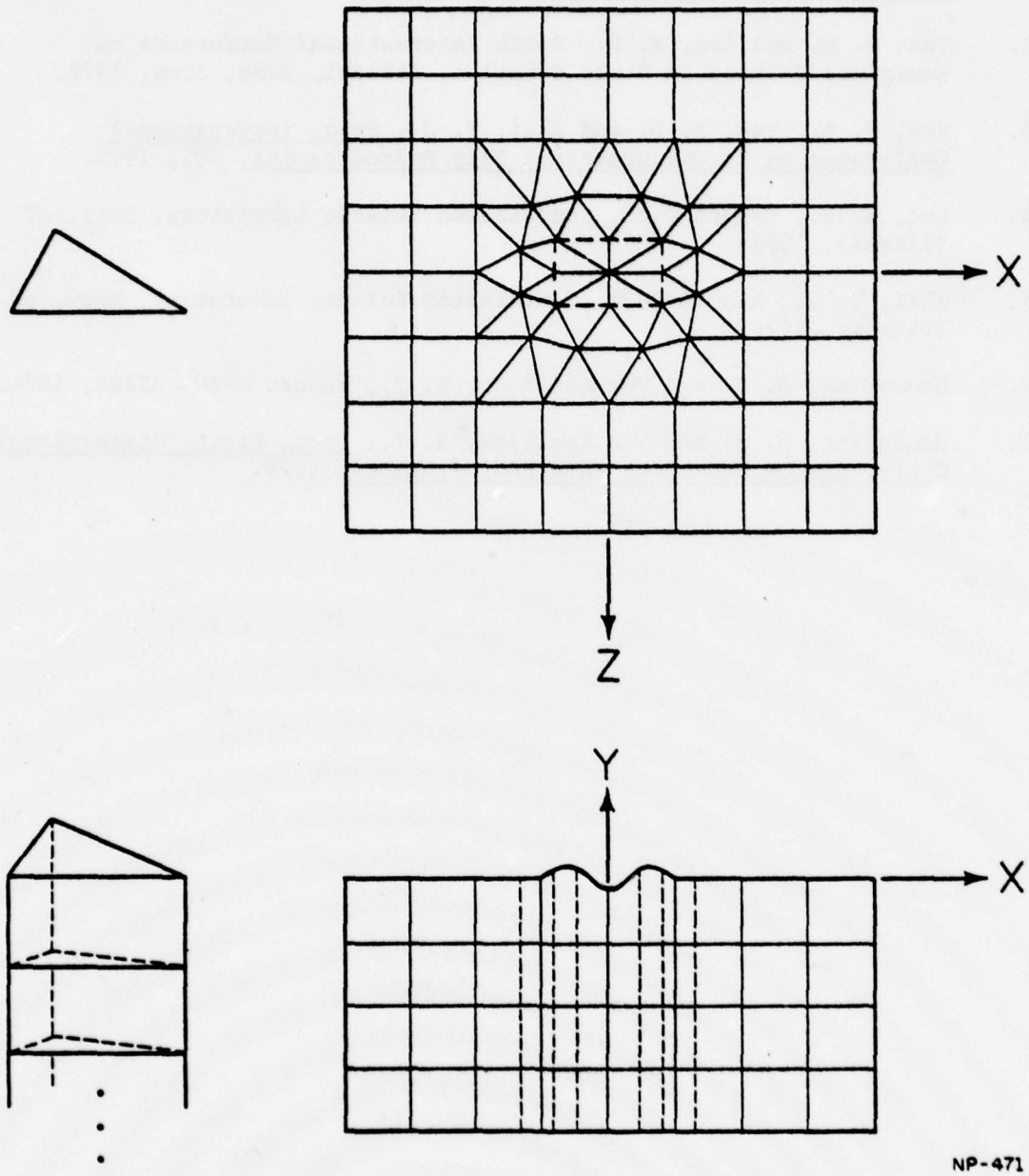

Figure 10.6 A grid system for implementation of a hybrid method. Inner region for finite element method. Outer region for finite difference method.

10.5 References

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11.1 Fault-Tolerant Distributed Systems*

Loosely coupled distributed systems can be conveniently made to tolerate faults by designing them so that failure in one part of a system will not cause the entire system to fail. Such a system should have mechanisms to locate faulty units and to reconfigure around such units. Research in this area can be divided into two broad classes: testing of the units of a system (which are assumed to be built from LSI blocks like microprocessors and memories), and techniques for achieving high reliability and performance in a distributed system.

11.1.1 Testing of LSI

Testing techniques at a higher, functional level for memories and microprocessors were studied. Tests were designed to be easily applied by users; thus tests for microprocessors, for example, were obtained as instructions for the microprocessor rather than as arbitrary input vectors.

In memory testing, an efficient $O(n)$ algorithm (where n is the number of cells in the memory) to detect all faults in a functional model was constructed [1]. Existing algorithms to detect the same set of faults were $O(n^2)$. This fault model was also extended to incorporate more complex faults. An $O(n \cdot \log_2 n)$ algorithm was developed to detect faults in this extended fault model. Additional algorithms were also developed

*This work was supported by the Joint Services Electronics Program (U.S. Army, U.S. Navy, and U.S. Air Force) under Contract DAAB-07-72-C-0259.

to detect pattern sensitive faults in memories, as well as to locate faults on a memory board. Improvements were also made to existing algorithms [2]. (See Section 11.4.3 for a practical application.)

The task of fault detection in microprocessors is very difficult because of their complexity. We have developed a general model for microprocessors at the register transfer level in terms of their control and data processing sections. We have also developed a fault model on a functional level which takes into account a large number of failures, including faults in instruction decoding, control commands, data transfer mechanisms, data storage facilities, and the arithmetic and logic unit. A set of test procedures was developed to detect all faults in the fault model [3]. Tests were generated for an existing 8-bit microprocessor used internally at Hewlett-Packard. The generated tests were validated with the use of the TESTAID simulator. The test set for the microprocessor was found to be capable of detecting all the detectable single stuck-at faults, and many others which cannot be characterized as stuck type faults. Work is continuing in generalizing the microprocessor models and extending the functional level fault models.

11.1.2 Distributed Systems with High Reliability and Performance

Techniques to achieve high reliability as well as performance in distributed systems and ways of modeling distributed systems were studied.

When digital systems are built in a modular fashion with multiple distributed processors which share data, the contamination of data in the system by the failure of a single processor becomes a problem. This becomes worse when it is not possible or practical to have a global supervisor which detects failures and removes the failed units. A new technique for distributed systems, called roving diagnosis, which does not use a global supervisor or dedicated redundancy was found [4]. A model was found for calculating the reliability and performance of a system with a given topology and diagnosis and reconfiguration policy. A particular system with the proposed scheme was compared with systems using classical redundancy. It was found that the performance of the proposed scheme is much better than that of the redundant systems, while

the reliability for some requirements is close to that obtained by using redundancy. Related results on roving diagnosis can be found in Section 11.2.

The use of semi-Markov processes in the modeling of computer system performance was studied. A new performance measure was defined, in the semi-Markov framework, which incorporates a measure of system throughput and system availability. These general techniques were applied to modeling a gracefully degradable shared resource multiprocessor (such as the AMP system - see Section 11.4). The model was used to discover the effects of several system parameters (number of processors, mean detection latency, mean repair time, probability of an undetected global fault, ect.) on overall system performance. In addition, the implementation of a resource guardian (used to protect shared memory) was modeled. From these studies a set of design guidelines for shared resource multiprocessors has been established.

11.2 Concurrent Self-Diagnosis and Reconfiguration in Large-Scale Systems*

11.2.1 Self-Checking Systems

Codes that are used to protect against unidirectional errors have been studied, particularly the class of fixed-weight codes. Such codes have codewords that can be effectively classified in terms of congruence, cycling, and complementation classes. The capabilities of unordered codes are defined with respect to circuit structure and fault models. Self-checking concepts are adapted to arithmetic circuits and checkers and it is shown that these circuits are totally self-checking provided some broad design rules are followed and some increase in hardcore is allowed [5,6].

Further results on applying alternating logic, that is, time-encoded rather than space-encoded information, to the design of self-checking systems have been obtained, particularly memory efficient

*This work was supported by the Joint Services Electronics Program (U.S. Army, U.S. Navy, and U.S. Air Force) under Contract DAAB-07-72-C-0259.

approaches to the design of sequential machines, new techniques for the design of checkers, and system level design approaches to self-checking alternating logic systems [7,8,9,10,11].

11.2.2 Detection of Fault-Free Units in a System

The identification of a faulty unit by its neighbors in a system was first attacked by means of the connection assignment approach for the case when a unit is capable of completely testing another one [12]. A more general case was considered in [13,14].

A system is defined to be d-fault diagnosable with repair if and only if there exists a sequence of applications of a test set and repairs of identified faults that allow all faults (at most d in number) originally present to be identified. In certain applications, as in airline reservation systems, it may not be desirable to have any faulty units around, so that the integrity of the data base can be maintained. Under such circumstances, the only acceptable solution may involve the identification of all faults on one application of the test sequence (called d-fault diagnosability without repair). This condition has been shown to be very demanding in terms of nodes and interconnections required.

An alternative approach to this problem is being investigated. Instead of designing systems in which at least one faulty unit can be identified after an application of the test sequence, one could design systems in which at least one fault-free unit can be identified after an application of the test sequence. (The fault-free units could then proceed to execute tasks vital to the integrity of the system, while further diagnosis is continued on that part of the system known to contain the fault.)

A diagnostic graph may be associated with every system to show the masking interrelationships between the faults in the system. In a single-mask-per-test (SMPT) system every test for a fault is invalidated by (i.e., gives unreliable results in the presence of) at most one other fault in the system. Some interesting results for such systems are:

- In a SMPT system which has a strongly connected diagnostic graph, the number of fault-free units that can be identified after application of the test-sequence must be zero or at least two.

- A fault-free unit is identifiable in a strongly connected SMPT system if and only if the system is diagnosable with repair. (The maximum number of faults that can be present is assumed the same in both cases.)
- In a connected SMPT system, if a fault-free unit cannot be identified for some set of test results, then the system is not diagnosable with repair either.

A single-test-per-fault (STPF) system is defined as one in which there is at most one complete test for each fault (there may be many faults which invalidate a test, however).

- For STPF systems a measure called the system implication index I(S) may be defined. If $I(S) > \lfloor (d+2)^2/4 \rfloor$ then, under the assumption that no more than d faults can be present, at least one fault-free unit can always be found.

A paper on this work is in preparation.

11.2.3 Self-Diagnosis and Roving Diagnosis

The design of systems capable of continuous self-diagnosis by using a principle called "roving diagnosis" is being studied. In essence, roving diagnosis requires one part of a system to be diagnosing another part while the remainder of the system continues normal operation. The part of the system most recently diagnosed as fault-free now takes its turn to diagnose another part. Thus, there is a subsystem involving the diagnosed and diagnosing units which apparently roves through the system until no part of the system remains undiagnosed. The roving diagnosis approach is an attempt to overcome several problems common to non-roving schemes. These problems are:

i) The reliability of some implied global mechanism, required for diagnosis, is never questioned.

ii) The system, especially in multiple redundant schemes, is utilized far below its potential, although its reliability can be made quite high for an arbitrary but limited time.

iii) The entire system, or at least a major portion, has to be shut down for diagnosis.

The extent to which the roving diagnosis approach is capable of alleviating the above problems depends greatly on the assumed fault model for the system. Thus, there exist faults whose identification is beyond the capabilties of even a global arbiter. The basic model for the system is the system diagnostic graph [13]. In general, there may be more than one unit required to test any given unit. Hence by looking at the diagnostic graph for the system it is not always immediately obvious whether diagnosis by roving is possible. It can be shown, however, that if the diagnostic graph for the system contains a particular kind of graph, called a roving graph, then the system can perform roving diagnosis.

The success of the roving diagnosis scheme depends to some extent on the ability to test certain distinguished nodes in the system, identifiable from the roving graph, called the initial nodes. Algorithms for minimizing the number of initial nodes in certain types of systems have been developed. Various schemes by which the initial nodes themselves may be tested, with almost no hard-core requirement, are being evaluated.

Associated with the problem of locating faulty units in systems is the problem of reconfiguring the system around the faults so that the system may continue operation, possibly with a degradation in performance. Two questions must be asked about the system, once the fault has been detected:

(i) Can all the nodes which were formerly communicating with the faulty node be informed about the existence of the fault?

(ii) Can the system continue useful operation once the faulty node has been effectively removed from the system?

Answers to these questions are presented and the problem of reconfigurability and reusability is related to some known graph-theoretic problems. (See also Section 11.1 where probabilistic models for roving diagnosis are discussed.) A paper on this topic is in preparation.

11.2.4 Reliable Interconnection Networks

Modularization of computing systems allows reduction of large design and debugging problems to a set of smaller, more manageable problems; it not only aids in designability but helps reduce obsolescence because modules can be replaced to improve system performance without

having to redesign the complete system. However, in recent years computing modules have become more autonomous and in many cases are computers in their own right, and the complexity and controllability of networks required to interconnect the computing modules may become limiting factors in system size. Connection networks may in fact become the prime source of errors in the systems. High reliability systems can make even further demands on the connectivity requiring new connections to be made under certain fault conditions. A form of interconnections among modules is therefore required that is simple, expandable, controllable, testable and in short more reliable than the system components. A design technique for such an interconnection network in which the design parameters are connectivity requirements, module complexity, and concurrent job capability has been studied and is reported in [15].

11.2.5 Design Languages

Control structures created for multiprocessing systems are usually quite complex and assuring that they will not deadlock is a difficult task. Specifying a computer hardware design language so that this pitfall can be avoided by staying within the bounds of the syntax (in the spirit of "an ounce of prevention...") gives the system designer a design tool that is more than just an aid for documenting the principles of operation of a system. The specifications of a computer hardware design language that has sufficient scope to describe multiprocessing systems and has the property that syntactically correct programs describe systems that have deadlock-free control structures have been formalized. The model used assumes that the system partitions into a data structure, in which actions are represented as register transfers, and a hierarchically organized asynchronous control structure, which coordinates the actions in the data structure. This work is reported in [16].

11.3 Computer Architecture*

11.3.1 Fixed-Cycle Resources for a Pipelined Processor

This research has centered on the performance of functional resources that are used by a single multiple-stream pipelined processor. Such resources include arithmetic functional units and the modules that compose an interleaved memory. The functional requirement of such resources is that they perform some operation and resynchronize their results with the associated stream in the pipelined processor.

In some instances, a replicated or pipelined resource can be used to achieve the required performance. However, in this research a single non-pipelined unit with a fixed cycle time is being investigated as a lower cost alternative. This resource is characterized by a cycle time, c, and a deadline, d, which if missed results in a penalty of the non-compute pass through the pipeline.

The performance of this type of resource for various resource scheduling techniques has been determined through the use of Markov modeling and some model reduction methods. It can be shown that very high performance can be obtained when effective use is made of the available deadlines. This high performance can be obtained with a relatively simple scheduling discipline. Although optimal scheduling algorithms have been developed only for certain restrictive cases, the development of a model to upper bound system performance has shown that under most circumstances a FIFO-based algorithm yields nearly optimal performance. An extension to these models has allowed the consideration of resources with access times less than their cycle times.

To verify the results of our analytic models a simulator has been programmed. In addition, it has allowed the evaluation of various scheduling disciplines and request behaviors that could not be modeled analytically.

Various applications for this type of resource have been examined including an implementation of a cost-effective control store which attains high performance through the use of interleaving.

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*This work was supported by the Joint Services Electronics Program (U.S.Army, U.S. Navy, and U.S. Air Force) under Contract DAAB-07-72-C-0259 and by the National Science Foundation under Grant MCS73-03488A01.

Such an organization is most directly relevant to multiple stream processors, which execute several programs simultaneously, yet require only a single shared microprogram store with our implementation. Additional design constraints were developed for the specification of branch resolution times and for the addition of dummy segments to enhance overall system performance. The cost design trade-offs for interleaved memories with deadlines were also examined. In addition, the performance of parallel processor-memory configurations was contrasted to systems with skewed requests and deadlines with the resultant elimination of the expensive crossbar switch. Formal mechanisms for evaluating performance with all of the above considerations have been developed.

A conference paper on portions of this research has been accepted [17] and a comprehensive CSL report is in preparation.

11.3.2 Stochastic Scheduling for Parallel Pipeline Processors

Analytic models of parallel pipeline processors are being investigated to determine optimal scheduling strategies and performance estimates. The model assumes that an instruction stream is to be served by a parallel pipeline processor. Each instruction execution results in a sequence of resource utilization requests necessary to serve the instruction. However, the execution of an instruction may overlap in time with that of previous and successive instructions. Thus, throughput is limited by competition among instructions for shared resources.

Markov modeling techniques have been applied to this pipeline scheduling program to describe system behavior. Initially, models of system behavior are excessively complex. However, system models are simplified ignoring elements of system behavior which do not affect performance [18].

An optimization technique based on Markov decision theory has been discovered which chooses a scheduling policy maximizing system performance under an assumed stochastic model of instruction arrivals. This procedure specifies a scheduler which efficiently shares resources among concurrently executing instructions. Further work has shown that adaptive scheduling policies can also be defined which adjust to time varying instruction arrival patterns. A report is in preparation.

Much of the theory described above can be applied to a variety of stochastic scheduling problems. While work in [18] concentrates on low level resource sharing, we are currently formulating models of resource sharing at higher levels in the hierarchy of system control. For example, a memory can be viewed as a shared resource to be partitioned among concurrently active tasks. Again, we seek optimal scheduling strategies and performance measures.

The above work provides a means of analyzing the performance of a prospective architecture. A more difficult problem is that of determining an architecture which is optimal according to some measure of cost and performance. We have studied relatively simple problems in this area, and while optimal solutions exist, the problem was found to be NP complete [19] indicating that heuristic techniques for suboptimal solutions should be pursued.

11.4 Computer System Organization*

11.4.1 Modelling of Multiple Processor Virtual Memory Systems

Work is continuing on the modelling of the performance of multiple-processor virtual memory computer systems. The models are expressed as functions of the number of processors, configuration of secondary drum memory, number of jobs in the system, page size, fault rate, overhead time per fault, memory size, and paging strategy. Several models for portions of the overall problem have been developed.

One analytic model describes the operation of P parallel processors executing with an infinite number of jobs available, each of which faults according to an exponential distribution.

A second analytic model deals with a finite number of jobs, J, and determines the number of jobs that fault on P processors in time T. Analysis of this model provides the number of jobs arriving at secondary memory each sector time unit. These results may be used to simplify greatly a simulation model for processor-drum performance.

*This work was supported by the Joint Services Electronics Program (U.S. Army, U.S. Navy, and U.S. Air Force) under Contract DAAB-07-72-C-0259.

A decomposition of the total computer system into two models is being developed. The first model concerns program behavior, paging and allocation strategy, and average memory allocation allowed per job. The output of this model would describe the faulting behavior of individual jobs. This fault descriptor would become one of the inputs to the second model, along with system configuration parameters such as number of processors, drum memory parameters and the number of jobs. Using the second model, which is currently being developed, it will be possible to study the effects of various system configurations as a function of program behavior, which is difficult to characterize in general.

A computer simulation of the second model has been written and is being used to aid in the understanding and characterization of the effects that specific parameters have on system performance. In addition to modelling the various system parameters, the simulation allows variations in the fault descriptor, such as two classes of jobs with different faulting behavior. A significant amount of data has been collected from the simulator and results are being analyzed for the purpose of obtaining functional relationships and reducing model complexity.

Once the results of the second model are known, a more goal-directed formulation of the first model, which will then be more tractable, will be developed.

11.4.2 Multiple Access Memory Systems

As part of our continuing investigation into the performance of interleaved memories in a multiprocessor environment, we have been studying the effect of the memory reference behavior and techniques for modelling and analyzing it. We have considered a system consisting of N processors connected to M memory modules through a cross-bar switch. All processors are assumed to have identical memory referencing behavior which is as follows: let the modules be numbered from 0 through M-1. If a processor last referenced module i, then with probability P_k it next references module $(i + k)_{\text{mod } M}$ where $P_0 + P_1 + \ldots + P_{M-1} = 1$. We have validated this model of reference behavior with measurements and have developed an accurate, though approximate, closed form solution for the memory bandwidth. This solution, too, has been experimentally

validated. Furthermore, we have demonstrated that the model of program behavior can be further simplified to yield a two-parameter model without sacrificing accuracy appreciably. These results have been written up and are being submitted for journal publication. They will also appear shortly as a CSL Technical Report.

11.4.3 The AMP-1 Multiple Microprocessor System

The AMP-1 was designed and implemented to perform experiments dealing with performance evaluation of alternative system configurations within the selected class of architectures. The system memory has been expanded to a full 64K bytes of shared memory. Several design changes and modifications of system timing have markedly improved the state of the system.

A memory diagnostic algorithm developed at CSL (see Section 11.1.1),has been implemented as a reentrant program for the AMP-1 system. When run on all eight processors, eight distinct areas of memory can be diagnosed simultaneously. This program was essential for bringing up the memory. Chip and PC board problems were located rapidly and repaired resulting in a very efficient process. Continued problems with bussed signals on the second chassis, which contains the expanded memory, are being solved. The system was modified to include active redriving of the busses between chassis. Total system reliability improved greatly and jobs which use no more than 14K of memory can now be run using the full range of system configurations.

Some preliminary results have been obtained with a multitasked program for Gaussian elimination. An operating system is being implemented. A study of memory protection for such systems has been completed. Memory protection is now being implemented on the system so that undebugged programs can run simultaneously with debugged programs without interference. A design for a flexible but simple data collection device for evaluating system performance has been completed and is being implemented.

An invited position paper on microprocessor-based computer systems was presented at Midcon '77 [20].

Plans for the immediate future include attaining fully reliable operation of the expanded memory, completion of the operating system and other support software, intensive evaluation of the multitasked Gaussian

elimination program and other programs for a variety of system configurations, completion of the memory protection and performance data collection hardware, an examination of the performance of AMP-1 on Finite Element Methods software, a modification of the hardware to allow user-defined local memory rather than fixed processor-allocated local memory, and a study of properties of concurrent, modular programming languages and software.

11.4.4 Levels of Program Representation vs. Computer Organization

The issue of high level language support is treated in a systematic top-down manner. Program representations are categorized into three classes with respect to a host processor: high level representations, directly interpretable representations and directly executable representations. The space of intermediate languages for high level language support is explored and it is shown that whereas the ideal intermediate language from the point of view of execution time is a directly executable one, the best candidate from the viewpoint of memory requirements is a heavily encoded directly interpretable representation. The concept of dynamic translation is advanced as a means for achieving both goals simultaneously; the program is present in the memory in a compact static representation, but its working set is maintained in a dynamic representation which minimizes execution time. The architecture and organization of a universal host machine, incorporating this strategy, is outlined and the potential performance gains due to dynamic translation are studied. A report on this topic is being submitted for publication.

11.5 Modelling and Evaluation of Large Computer Systems*

11.5.1 Applied Queueing Theory

The performance evaluation of computer systems is closely bound to the ability to form reasonable models of the system and to then evaluate the model analytically. For these purposes, queueing theory is

*This work was supported by the Joint Services Electronics Program (U.S. Army, U.S. Navy, and U.S. Air Force) under Contract DAAB-07-72-C-0259.

a very important tool. The goal of this research is to develop a queueing theory which is robust and of general applicability. A first step in developing such a theory is to understand the behavior of queueing systems and to isolate the factors that do, in fact, affect this behavior. To this end we have been constructing a general queueing simulator. We have also been actively investigating a property of certain queueing systems termed "local balance" which allows analytical evaluation to proceed with great ease. Our efforts have been directed to understand, in a more fundamental sense, what gives rise to this property.

A General Queueing Simulator

We are in the process of constructing a very general simulator for queueing networks which we intend to use as a vehicle for our future research. This simulator is being written in SIMULA and possesses the following features:

i) an arbitrary topology and number of queues may be simulated,
ii) any number of servers may be specified for each queue,
iii) any arbitrary service discipline may be specified for each queue,
iv) any arbitrary deterministic or stochastic arrival process may be specified,
v) the routing behavior and the service requirements for each arrival to the network may each be specified by arbitrary deterministic or stochastic processes,
vi) statistics may be output selectively to obtain exactly as much information as is required.

In conjunction with a package of programs for the numerical analysis of queues, which we intend to develop in the future, this simulator will give us the ability to study queueing networks of any desired structure and complexity.

Investigations into Local Balance Networks

Our study of queueing networks that satisfy local balance was, as a first step, directed towards understanding the underlying cause for the existence of the product form solution which is useful in obtaining tractable analyses for complex systems. We have ascertained that the product form solution is a consequence of two factors which are explained below:

i) The existence of a cellular decomposition of the Markov chain for the queueing network, and

ii) a topological equivalence between the cells into which the chain is decomposed and the network in question.

A cellular decomposition is one in which the arcs of the (infinite) Markov chain are partitioned into disjoint finite subsets termed cells. The set of arcs in a cell must form an ergodic Markov chain and the relative probabilities of the nodes (states) in a cell are then easily obtained. Whereas an arc may belong to but a single cell, a node may be associated with more than one cell. The relative probabilities of nodes which are not in the same cell may be obtained via a sequence of nodes (possibly just one) which is selected such that each node is associated with the cells corresponding to both its predecessor and successor nodes in the sequence. A cellular decomposition exists if the relative probability of two cells is the same irrespective of which sequence of nodes is used to compute it. In the event that a cellular decomposition of the Markov chain exists and if all the cells and the queueing network too have the same topology then it can be shown that the queueing network will possess a product-form solution.

We have, furthermore, derived a small number of theorems from which all the product-form results follow as corollaries, thus providing a unifying framework for the work reported in [21-25]. These results are currently being written up and will be submitted shortly for journal publication.

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12. DISPLAY, MEMORY, AND COMPUTER TERMINAL RESEARCH*

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12.1 Introduction

The research program of the Display, Memory, and Computer Terminal Architecture Group is concerned broadly with computer-based information and communication systems in which users interact through a variety of tactile and audio input devices. Its goals are to devise human interface, terminal architecture, and system structure specifications for improving the efficiency of these information and communication systems. The report of work is divided into a description of each of the three major activities:

1. Interactive facsimile communications
2. Terminal-based mass memory
3. Display device research

12.2 Interactive Facsimile

In this area, our objective is to define those characteristics of face to face human interaction in a professional discussion that should be preserved in a teleconferencing system. Typical remote conversations would include discussion about diagrams, schematics, or other images which each user would see on a local display. Each user could position a cursor in all the other displays to point at important image features. In this type of communication we feel it is not important to see the other person's face. We believe the interactive communication system needs to support the following operations:

*This work was supported by the Joint Services Electronics Program (U.S. Army, U.S. Navy, and U.S. Air Force) under Contract DAAB-07-72-C-0259.

1) Input and transmit high contrast line images
2) Support remote pointing
3) Multiplex voice, image, and pointer data on a single low bandwidth communication channel

12.2.1 Bilevel Image Techniques

Previous research has shown that bilevel techniques such as ordered dither provde good image quality on a wide variety of display devices [1-3]. We have continued our investigation of adaptive ordered dither and constrained average techniques [4] as they apply to high contrast diagrams since much of the imagery in professional communication is basically line drawings or text. We have found that adaptive dither and constrained average perform well because both methods provide edge enhancement and some immunity to average background intensity variations. We shall continue our investigation of data compression methods such as 2-dimensional pattern matching [5] and bit interleaving [6] for transmitting these bilevel images. We will also examine some current facsimile algorithms for their application in the remote conferencing system.

12.2.2 Pointing

An important characteristic of face to face communication is the ability to point at an image that all the participants can see. We conducted a survey of the participants in a remote conference at Bell Laboratories and are currently analyzing the results. Preliminary findings indicate the people did not need to see a television image of the remote speaker but would like to have a speaker controlled pointer in the local slide screen.

While we could simply send an image of the speaker using animated ordered dither [7], our low bandwidth requirement dictates we instead locate the actual pointer and periodically transmit a single coordinate. We are continuing our investigation to determine whether a simple means of visual pointer detection is feasible. We also hope to develop techniques for using a touch sensitive digitizer over the image to control a remote cursor.

Part of our investigation concerns the physical appearance of the remote cursor. Our experiments indicate a set of concentric circles

provides a good cursor for some applications. We also investigated an inverted video cursor which was not as effective as the circular one in complex images.

12.2.3 Data Multiplexing

In teleconferencing a two way audio channel is mandatory. Our survey results have shown the conference participants feel that a poor audio channel limits the usefulness of the teleconference system. In addition, Chapanis has shown a two way audio information exchange is nearly as efficient as face to face communications [8]. Our objective in this area is to define ways of multiplexing the audio, image, and pointer data on a single low bandwidth communication line. We feel that a switched mode is the most efficient for sending image data since the largest amount of time in a teleconference is probably voice only. Data for these images can be transferred during no voice periods or upon manual command of the user. Our work so far indicates that the use of a single control character code would provide a means of signalling a switch from voice to data modes.

The pointer updates could be handled as data, but we have been looking into methods which significantly reduce the necessary bandwidth. One technique we have developed relies on the fact that two consecutive digitized voice samples are seldom complements of each other. Pointer updates can be transmitted as the number of data bytes between voice data markers generated by a voice sample followed by its complement. At the receive end, the average of the two nearest neighbor samples can be substituted for the missing voice sample with very little recovered voice distortion. Our experiments are continuing into these methods of remote pointer data transmission.

In all of our experiments, we are assuming the voice data is digitized at 8000 samples per second using the μ255 or A-law compander. With these restrictions, our results are applicable to both the Bell System T1 and the CCITT 64KB/s standard digital channel.

12.2.4 Terminal Simulator

The goal of the terminal simulator research unit is to construct a minicomputer based graphics terminal to support our remote conferencing

experiments. This PDP11/10 intelligent terminal has been described previously [9]. During the second half of 1977, we designed and built a display multiplexor which allows the terminal to independently drive up to four 512 x 512 plasma display panels. Currently two are connected. The terminal software was modified such that any full panel image may be stored under local program control. This set up permits us to simulate various terminal to terminal communications links with having to construct special hardware communications circuits.

To simulate the voice channel, an analog switching interface has been built. Currently this interface allows us to control in software the interaction between the data and the voice on a single communication channel. We will use this experimental configuration to simulate our interactive facsimile terminal. Thus far, we have learned that the pointer data should not be bufferred for a no voice period but should be sent as soon as possible. We have also determined that the remote cursor should not jump from one location to another, but should follow a smooth trace between locations to avoid confusing the remote user. Using this terminal simulator we shall test the validity of our assumptions concerning teleconferencing characteristics and guage the difficulty of realizing these system features in an actual network.

12.3 Terminal Based Mass Memory

The objective of this research is to devise techniques for realizing a low cost 10^{10} bit local mass store for use with processor-based terminals. In our view, the most practical approach is to use optical video disk technology that is presently receiving great attention for use in home entertainment systems [10]. These systems store 10^{10} bits on a 30 cm diameter disk of thin plastic. The emphasis of our research is to find a system configuration that will allow worst case access time for any information on the disk to be less than 100 ms and still maintain low cost. Figure 12.1 shows the optical system that we have studied to achieve a 10^{8} bit disk system. The thin plastic disk is rotated at 30 revolutions per second. Note that the laser beam can be deflected to any track of the disk by rotation of the deflection mirror. This is the only moving part of the system other than the disk. The

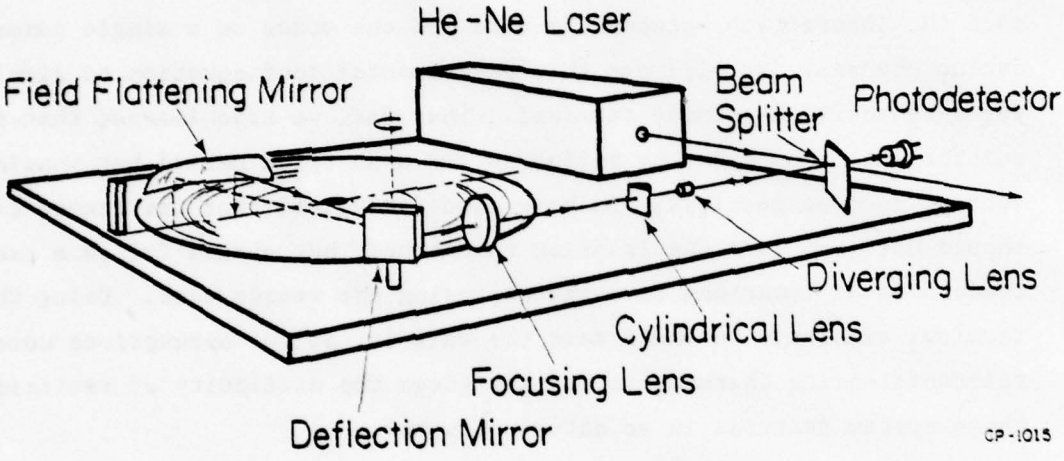

Figure 12.1 Optical layout for the 10^8 bit per disk, optical memory system.

light reflected from the disk is measured by a single photodetector that always remains stationary. Thus with this optical system the access time is limited by the inertia of the deflection mirror and the rotation rate of the disk. The low cost feature is retained by designing the optical system so that no special purpose a-spheric components are required.

A major challenge with this system is the design of the servo amplifiers that control the deflection mirror. Because the mirror must access any of 5000 tracks, the demands of the servo system are more than 100 times greater than those of typical video disk systems. We have determined the major noise and error sources and have worked out various techniques for reducing or eliminating them.

A second problem area is that of data encoding techniques that are tolerant to the noise generated by the dust particles that will always be present on the disk. Two approaches were studied; one analog and one digital. The analog approach was designed to accept both digital data and analog audio frequency signals. The audio was of interest for storing a large dictionary of recorded spoken words. The rapid access of this disk playback system would than allow the computer to talk directly to humans by concatenating the recorded words into sentences. Because the bandwidths of the disk system is much greater than that of audio, a frequency division multiplex system was used to encode the audio. Upon playback a receiver would tune to a different subcarrier for each revolution of the disk. In this way a full second of audio could be stored on one track by encoding 30 subcarriers with ahort audio segments 1/30 of a second long. This analog technique has the advantage that dust on the disk will not totally destroy the information but will only reduce the signal to noise ratio slightly. This is because the audio information is spread out over large areas of any one track.

The digital technique simply puts a dot on the disk for a one and leaves it blank for a zero. This has the disadvantage that a piece of dust that covers the dot will cause a total loss of the bit. As a preliminary solution we used a single error correcting hamming code. This very significantly increased the performance of the system but it did not correct all errors since large dust particles that covered two bits could not be corrected. We feel that the technique of spreading out the bits

of a word on the disk so that the largest dust particles will cover only one bit on any word will solve this problem.

The digital system worked very well even with the simple error correction. We demonstrated the recording and playback of very high quality digitized audio. We also demonstrated playback of digital data that drives a computer graphics terminal. Since the speed of this terminal is usually limited by a 1200 bps telephone line, the rapid access and playback rate of the optical disk increased the terminal speed at least four times.

12.4 A Real Time Curve Tracer for the AC Plasma Display Panel

The value of the charge transfer curve for characterizing the electronic behavior of the AC plasma display has been known for many years [11-13]. However, actual quantitatively measured curves have rarely been used by engineers and researchers because of the required tedious measurement process. The problem of how to measure the fundamental output parameter, namely the wall charge, has recently been solved in our lab with a circuit technique that allows real time measurement of the wall charge from a single cell in commercially available panels [14]. This paper presents the application of computer control to the tedious measurement problem. The result is a system that displays the wall charge transfer curve of a single plasma cell in real time. The value of this system is that it allows the engineer to rapidly assess the consequences of design and parameter changes. This sould greatly accelerate the understanding of the device.

Figure 12.2 shows the basic system. The computer controls the output of the power supply for the sustain generator so that software can vary the peak amplitude of the sustain waveform. The timing and duty factor of the sustainer is manually controlled. The wall charge signal is sent back to the PDP-11/10 for processing. The transfer curve and the envelope of the wall charge are each displayed on two 512-60 plasma panels. The keyset allows experimental control and selection of different algorithms for the data processing. System software allows the minicomputer and the displays to act as either a PLATO or an ASCII graphics terminal [9]. Thus the facilities of the PLATO system can be used for software editing, assembly, storage, and loading.

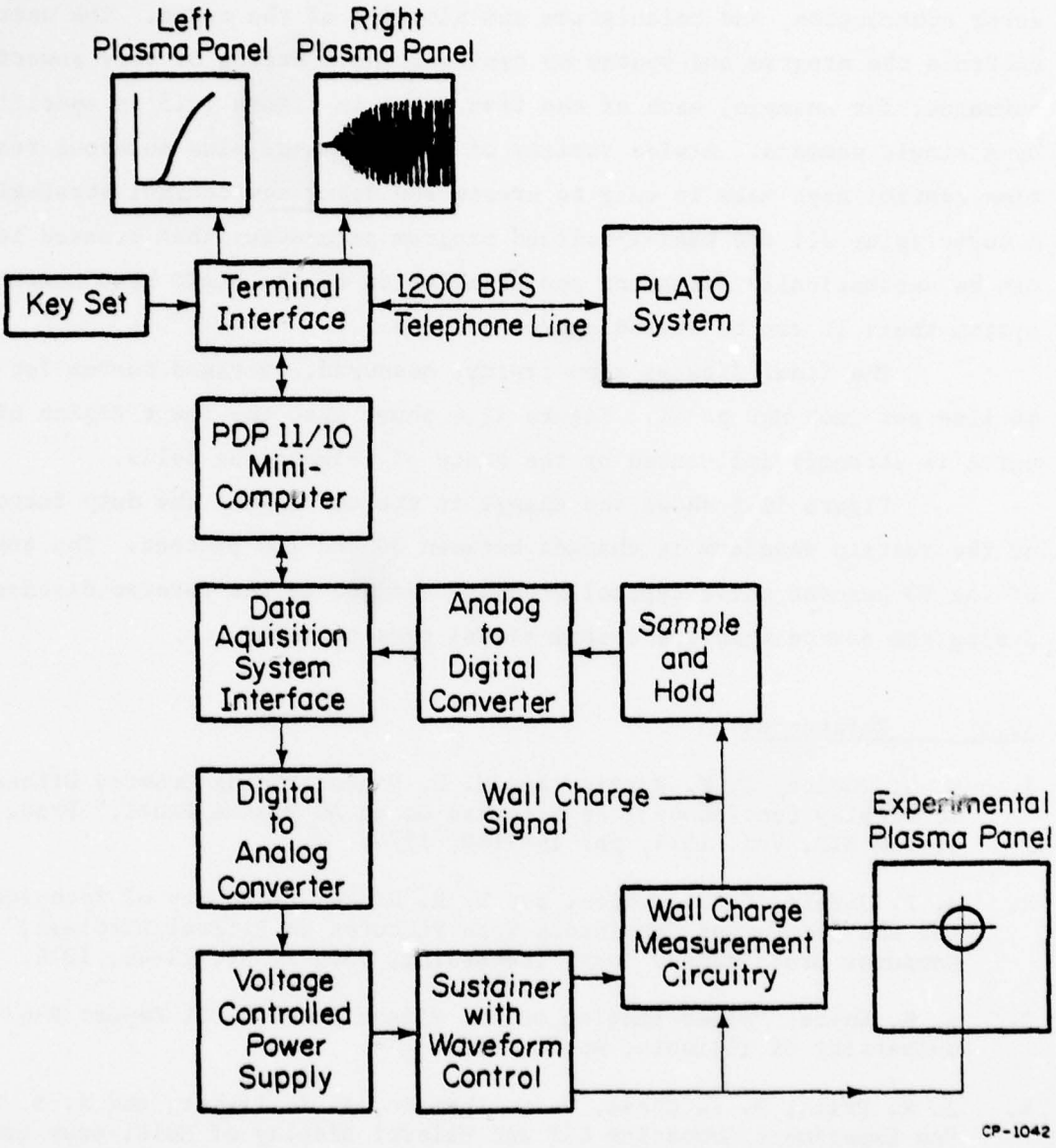

Figure 12.2 A block diagram of the real time curve tracer.

Figure 12.3 shows a block diagram of a program that will cause the system to draw wall charge transfer curves. The four major program steps are sustain voltage control and data collection, error calculation, error subtraction, and calculation and plotting of the curve. The user controls the program and system by typing a short string of very powerful commands; for example, each of the five steps in Figure 12.3 is specified by a single command. A wide variety of such commands plus numerous real-time control keys make it easy to create and debug new control strategies. A curve (plus all the user-specified program parameters that created it) can be automatically formatted and transferred to the PLATO host computer system where it can be stored and/or printed.

The final figures show typical measured, averaged curves for a 60 line per inch MgO panel. Figure 12.4 shows that the lower region of the curve is strongly influenced by the state of neighboring cells.

Figure 12.5 shows the change in the curve when the duty factor of the sustain waveform is changed between 50 and 100 percent. The top of the 50 percent curve typically bends over due to the reverse dischage during the period when the system signal goes to zero.

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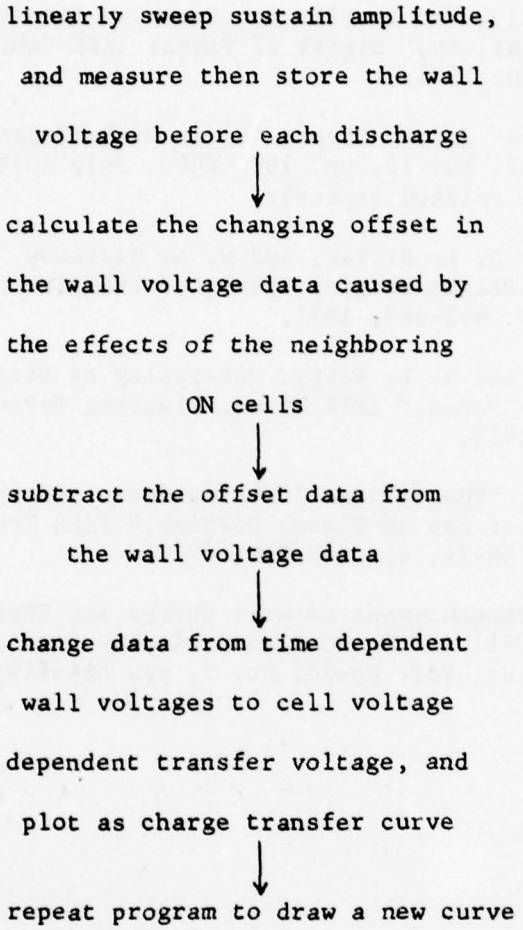

Figure 12.3 Program to continually draw charge transfer curves.

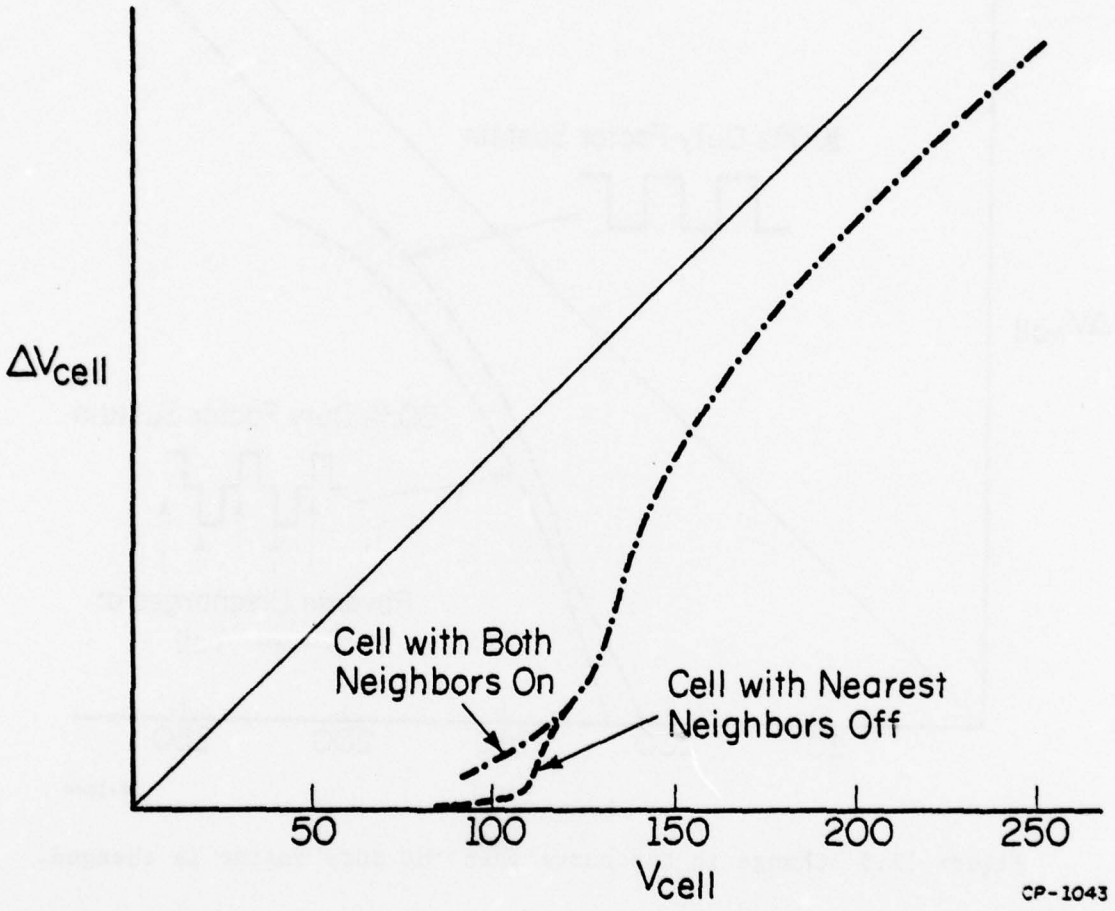

Figure 12.4 Data collected for a 60 line per inch MgO plasma panel.

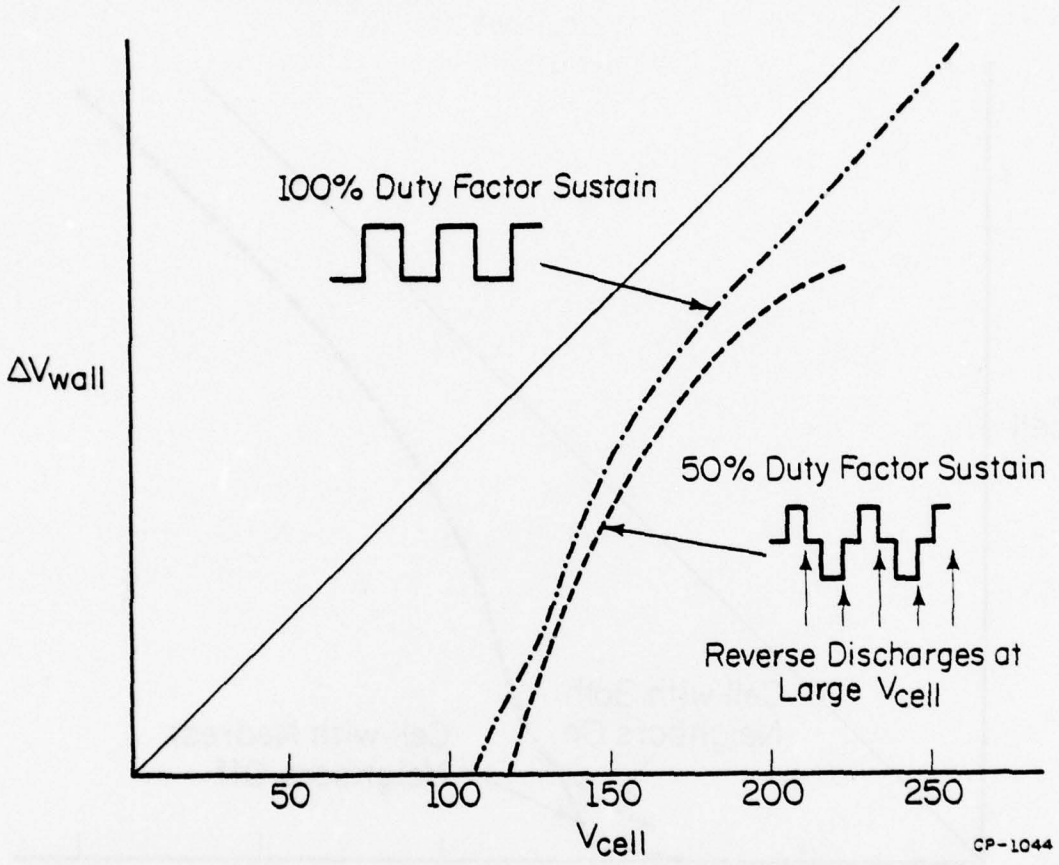

Figure 12.5 Change in the curve when the duty factor is changed.

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13.1 Introduction

Interesting new results have been obtained in the analysis and design of efficient computation techniques for a variety of applications. By far, most of our studies have been in the area of computational geometry, which, as is well-known, is extremely relevant to a large spectrum of practical applications, ranging from computer-aided design to operations research. However, investigations have been undertaken, and some of them completed, in other areas, such as parallel computation, storage management, circuit complexity, and algebraic computation. These areas will now be individually reviewed.

13.2 Computational Geometry

In three-dimensional geometry, we have solved a problem of long standing, i.e., how to find the intersection of two convex polyhedra, with n vertices in total, in time less than $O(n^2)$. We have developed an algorithm [1] to (i) test whether their intersection is empty, and (ii) if so, to find a separating plane, while (iii) if not, to find a point in the intersection and explicitly construct their intersection polyhedron. The algorithm runs in time $O(n\log n)$. The part of the algorithm concerned with (iii) (constructing the intersection) is based upon the fact that if a point in the intersection is known, then the entire intersection is obtained from the convex hull of suitable geometric duals of the two polyhedra taken with respect to this point.

*This work was supported by the National Science Foundation under Grant NSF MCS76-17321 and by the Joint Services Electronics Program (U.S. Army, U.S. Navy, and U.S. Air Force) under Contract DAAB-07-72-C-0259.

This technique can then be used to optimally solve another interesting problem, i.e., the construction of the common intersection of a set of n half-spaces in three-dimensional space in time O(nlogn)[2]. The intersection, if nonempty, is presented as a convex polyhedron. The algorithm is summarized as follows: (i) the half-spaces are placed in two sets depending upon whether they contain or do not contain the origin; (ii) the half-spaces in each of these sets are dualized to points, and the convex hulls of the dualized sets are obtained in time O(nlogn); (iii) since the half-space intersection is nonempty if and only if these two convex hulls are disjoint, a separating plane is found, also in time O(nlogn) using the previous techniques; (iv) after applying a linear spatial transformation which maps the separating plane to infinity, the convex hull of the union of the two transformed convex hulls is the transformed intersection of the half-spaces. A significant consequence of this result is that a three-variable linear, or convex, programming problem can be asymptotically solved faster than by the Simplex algorithm, in the worst case.

As regards planar geometry, our results can be conveniently grouped into the categories of proximity, point-location, triangulations, and reachability.

In the category of proximity problems, we have shown that the nearest neighbor for all vertices of an n-vertex convex polygon can be obtained in time O(n) [3]. This is a surprising result, since no method faster than O(nlogn) is known for constructing the Voronoi diagram of a convex polygon. (The Voronoi diagram for a set S of points is a partition of the plane into regions, so that each region is the locus of the points closest to a given $P \in S$ than to any other member of S.) It has also been shown that the Voronoi diagram for a set S of n points in any L_p-metric ($1 \leq p \leq \infty$) can be constructed in time O(nlogn); this generalizes a number of previous results in L_1, L_2, and L_∞ [4]. Another interesting generalization is the notion of Voronoi diagram for a mixed set of points and line segments; it is shown that this diagram is also obtainable in time O(nlogn) [4], thereby solving the medial axis problem of a simple polygon faster than was previously known [5].

In the category of point-location problem, the original algorithm of Lee and Preparata has been modified to show that a set of k points can be located in the planar subdivision induced by a straight-line planar graph with n vertices in time $O(k\log k) + O(n) + O(k\log n)$, given a preprocessing time $O(n\log n)$; this indicates that for a wide range of k (typically when $k = O(n)$) the new algorithm has a better worst case performance [6]. An entirely new approach has been developed to the single point location problem: Based on a simple partition of each edge of the given n-vertex graph G into $O(\log n)$ segments, a practical algorithm has been designed which locates a point with less than $6\lceil\log n\rceil$ comparison on a searchable data structure which is constructed in time $O(n\log n)$ and is stored in $O(n\log n)$ memory locations [7].

In the category of triangulations in the plane, we have successfully completed the investigation of the following problems: (i) A simple n-vertex polygon can be triangulated in time $O(n\log n)$, by first decomposing in time $O(n\log n)$ the given polygon into a collection of special polygons, called monotone, which can be individually triangulated in time proportional to their numbers of edges [8]; (ii) The so-called "greedy triangulation" of a set of n points can be obtained in time $O(n^2\log n)$, versus the $O(n^3)$ previously known best algorithm [9]; (iii) The minimum triangulation of a convex polygon can be obtained in polynomial time $(O(n^3))$, thereby showing that, at least in special cases, this problem is not NP-complete [9]; (iv) The Delauney triangulation procedure has been successfully generalized to sets of points and segments [4].

Finally, in the category of reachability problems, we are studying the problem of computing the shortest path between two given points in the plane in the presence of obstacles; these obstacles are realistically simple geometric figures, such as line segments, circles, polygons, etc. Presently it has been demonstrated that when the obstacles are n parallel line segments, the shortest path is computable in time $O(n\log n)$ [4]; investigations on more general obstacle characterizations are in progress.

13.3 Storage Management

Efficiency of storage management in algorithms which use arrays is often enhanced if the arrays are stored in a proximity-preserving manner, that is, array positions which are close to one another in the array are also stored close to one another in the memory structure. It has been shown that any scheme that stores arrays in a linear memory, in both the worst and the average case, induces unbounded loss of proximity, but arrays can be stored in binary trees with bounded loss of average proximity [10]. We have investigated the effect of introducing duplication of items of a square array A on the average path length between the images of any two records adjacent in A under a mapping from A into the set of leaves of a complete binary tree. It is shown that with the appropriate choice of duplications, in some arrays the average path length can be decreased by as much as 12% without using a deeper tree than needed in the absence of duplication [11].

13.4 *Other Efficient Computational Techniques*

We have considered the theoretical problem of improving the time and space bounds for $n \times n$ boolean matrix multiplication. Using modular arithmetic, we have obtained new results for two important computation models, such as the logarithmic cost RAM having no multiply-divide instructions (which can also be realized as a boolean network), and the RAM using indirect addressing for table look-up [12].

As regards parallel computation, we have refined our preliminary investigation of the problem of parallel inversion of an $n \times x$ matrix and obtained the following results [13]; given an algorithm which multiplies two $n \times n$ matrices in $O(\log n)$ parallel steps on $n^{\alpha}/\log n$ processors, an $n \times n$ matrix can be inverted in $O(\log^2 n)$ parallel steps on $n^{\alpha+1/2}/(\log^2 n)$ processors. Presently the best value of α is $\log_2 7$.

Finally, we have considered the problem of designing fast combinational networks subject to various constraints on modules available, fan-in, and fan-out. Particularly, the major problem is the construction of networks of either NAND or NOR gates (with various fan-in limits) which realize the function represented by any given boolean expression using operators in the complete boolean basis B2. The investigations

represent a complex extension of restructuring techniques previously used for boolean as well as arithmetic expressions [14]. The main objective is to provide a methodology for convenient design of combinational networks. The techniques obtained are not merely existence proofs but are algorithmic and could, for example, be implemented in the form of computer programs to convert expressions with very large numbers of literals to networks meeting the indicated bounds. These results are the subject of a forthcoming technical report [15].

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14.1 Natural Language Understanding*

Our overall goals are to generate, develop and demonstrate programs which will allow a casual user (i.e., one with little or no special programming knowledge) to use a computer effectively and confidently; the same ideas should also allow more sophisticated users to communicate with a computer through language much more like natural language.

14.1.1 PLANES-Natural Language Question-Answering System

A number of features were added to the PLANES data base question-answering system [1-3]. New features allow a user to (a) input his own definitions, e.g. "from now on the United States of America means USA"; (b) ask questions including comparatives, e.g. "Did plane 37 fly more hours than plane 23 during July?"; (c) make exclusion statements, e.g. "from now on only consider planes 2 and 29"; (d) get access to HELP files at any time by typing a single character, and return to the prior context easily. The HELP files were considerably expanded, and a convenient display form was devised with different types of information in different boxes on a CRT screen.

*This work was supported by the Office of Naval Research under Contract No. N00014-75-C-0612.

An extensive testing and evaluation program for PLANES was begun and the results of this testing were used both to debug and improve the old PLANES system and to provide hard information for the design of a new system which would dramatically improve on and replace PLANES. The evaluation has included (a) a complete analysis of the PLANES data base (a portion of the Navy 3-M (Maintenance and Material Management) data base, Mechanicsburg, PA); (b) the devising of a novel testing protocol and scoring system for PLANES, including classifying schemes for user requests and system answers [4]; (c) the running and evaluation of tests of PLANES by a number of users. In addition, a check list of natural language features to be addressed in general was assembled.

14.1.2 Browsing and Alerting

A new browsing and alerting system named BROWSER [5] has been largely designed and partially programmed. BROWSER operates on the 3-M data base, and automatically develops classification rules for situations of interest; these rules will eventually be used by alerting "demons" to watch incoming data and notify users when the situations of interest arise. Work completed so far includes a detailed study and the hand running of a number of concept discovery experiments on the 3-M data base, the design of models of the 3-M data base, and the coding of the basic controlling program and a number of heuristics for BROWSER.

14.1.3 ATNs (Augmented Transition Networks)

ATNs are used extensively for parsing in PLANES and other natural language programs. Our research has led to an improved, exportable ATN package which we have supplied to a number of research groups at other locations. [6,7] describes our ATN interpreter and an ATN compiler and can also serve as a user's manual for our ATN system; [7,8] describes NETEDI, an ATN editor which can be used to easily expand ATNs. Other research on the use of lookahead and "bottom-up parsing" has led to speed-ups of nearly two orders of magnitude in general ATNs. Other recent work has led to a system which automatically produces indexed documentation on ATNs as well as a more powerful interpreter which can accept general patterns on ATN arcs.

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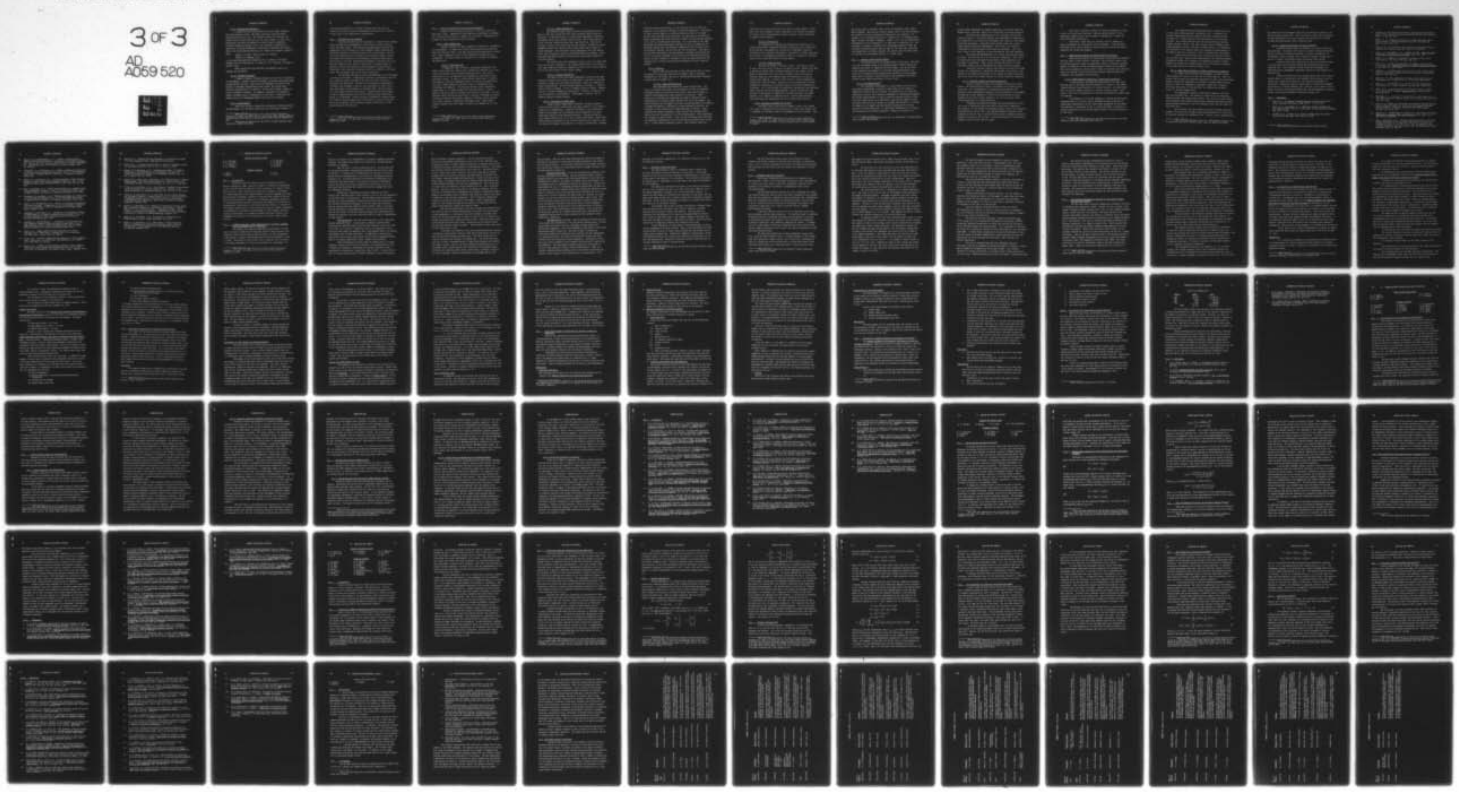

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14.1.4 Language and Perception

A system has been written which can accept simple sentences describing physical scenes and answer questions involving spatial reasoning and inference [9]. The program is based on an analysis of English spatial prepositions 9e.g. on, in, above, under, to, near, etc.). Prepositions and nouns are defined in terms of spatial primitives, including coordinate systems (2-D or 3-D, Euclidean, cylindrical or spherical), projection operations, figure-ground boundaries for objects, object size and relational matrices, etc. Suppose the program is given as input:

"Jenny is at home. Jenny's home is in Urbana.
Urbana is on highway I-74."

It will answer appropriately questions like "Is Jenny in her home?" (Probably but not necessarily), "Is Jenny on I-74?" (No), and "Is Jenny in Urbana?" (Yes).

Other related work [9] describes developmental aspects of language and perception.

14.1.5 Automatic Planning*

A number of general software packages were written to facilitate AI programming. A memory structure building, retrieving, and manipulating package has been written. This allows AI programmers to encode a wide variety of knowledge representation types easily, and allows these different representations to interact. We have also studied a number of areas in automatic planning. For example, a mechanism is designed to enable concurrent plans to communicate to each other. Constraints and design criteria for organizing subgoal trees were also studied.

14.1.6 Miscellaneous†

Other work includes a comparative evaluation of existing parsers and development of a new parser which will use "intelligent failure"; a

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*This work was supported by the Joint Services Electronics Program (U.S. Army, U.S. Navy, and U.S. Air Force) under Contract DAAB-07-72-C-0259 and by the Office of Naval Research under Contract N00014-75-C-0612.

†This work was supported by the Office of Naval Research under Contract No. N00014-75-C-0612.

computational approach for modeling literary "point of view" in narrative [10]; and a process intercommunication facility to allow two or more jobs to run cooperatively simultaneously.

14.2 Manipulation and Assembly*

Work has continued on the development of a robot control system which facilitates the programming of robot tasks in terms of vision, touch, and other senses. This system allows manipulator position and orientation to be controlled via visual feedback, while observing the manipulator dynamics to identify external forces and torques. The use of visual feedback allows a relaxation of positional accuracy requirements which are influenced by the mechanical stiffness, high inertia, and friction of the arm. Manipulator performance is improved since less power is needed for fast motions, sensitivity to external forces is improved, and delicate operations can be performed at greater speed. Furthermore, since position is measured relative to objects in the workspace, the environment need not be so well controlled.

The software implemented allows the manipulator to be programmed in terms of constraints. A manipulator position is described by specifying a reference point, attached to the arm, and a goal position or constraint for that point. Similarly, an orientation is described by reference lines attached to the arm and constraints for those lines. Force and torque are described by a reference point and the desired force and torque vectors at that point. A split-screen stereo adapter for the TV camera provides two views of scene and allows depth information to be extracted. Visual servoing is achieved by specifying both the reference and goal positions or orientations in terms of data from the vision processor, and by tracking features of the arm or of the object being moved by the arm.

*This work was supported by the Joint Services Electronics Program (U.S. Army, U.S. Navy, and U.S. Air Force) under Contract DAAB-07-72-C-0259.

14.3 Visual Information Processing and Recognition*

Research was performed in the areas of low-level vision and high-level vision. Segmentation algorithms were investigated and methods for correlating stereo pairs of images were developed. Techniques were studied for scene recognition using 3-D models.

14.3.1 Image Segmentation

Several varieties of image segmentation schemes were implemented and investigated. A comparative study of edge detectors has been done. Resulting from this study, a new edge detection system has been developed. Also a region aggregation and a contour aggregation system have been implemented. All these systems are designed to be feasible in hardware implementations.

14.3.1.1 Edge Detection

A comparative study of Hueckel, Yakimovsky, Rosenfeld, and simple linear difference edge detector systems was completed [11]. Also a Brice and Fennema region growing system was tested. The results indicated that all the approaches are comparable to the simple linear difference system. In order to achieve better sensitivity, a multiple edge detector system was implemented which is based on the application of several linear difference detectors, each of a difference size (ascending size sequence). The smallest detector with a significant output (that is, an output greater than that predicted by a noise model for the given detector), signals the presence of an edge. Then the detector "best" fitting the given edge is selected, disabling all others. Using this technique very gradual changes of intensity can be detected if no rapid intensity changes mask the gradual ones. Small single operator systems tend to be unable to detect slow changes due to local noise.

*This work was supported by the Joint Services Electronics Program (U.S. Army, U.S. Navy, and U.S. Air Force) under Contract DAAB-07-72-C-0259.

14.3.1.2 Region Aggregation

The problem of edge point connection was approached from the point of view that connections which form connected regions should be preferred. To achieve this goal, a region based aggregation system was implemented which passes several sizes of disks over an edge detection array (the array containing edges after edge detection). Regions are allowed to form in areas where edges are not present. Because the region homogeneity disks are initially quite large, broken edge strings are easily connected. Each successive region aggregation pass uses smaller disks, thus refining old regions and forming smaller new regions. Rules have been made which prevent old regions from being merged together in successive passes.

The results after this aggregation system is run on a given edge data set are quite remarkable. Even large contour breaks can be mended. Also some classes of subjective contours are closed (i.e., contour implied but not actually present in the original image).

14.3.1.3 Contour Aggregation

The output of both the region aggregation system and the edge detection system are still arrays of edge points. This data is read and converted to edge lists and vertex coordinates. Edges are examined for mutual connectedness. If the connected property is present, a "macro"-edge or string is formed. If not, a probable vertex is formed. Probable vertices are then examined for authenticity. Vertices of degree 2 or less are removed as uninformative. Then degree 2 vertices are re-formed at points of high curvature.

14.3.2 Correlation of Image Pairs

Using a single image analysis approach, an edge extraction process was built which carries with each edge a measure of its contrast (equally, its significance). With this information, less significant edges can be brought into consideration by the extrapolation of more significant edges by using planning heuristics. The main interest in this contrast depiction is in its use in stereo correlation. Depth information should be available at the earliest possible level (that is, without waiting for higher level symbolic, or region, correlations), although

region-free based correlations at the intensity level are much too expensive to be considered feasible on sequential machinery. Correlation of these contrast edges on a row-by-row basis was found to be highly effective and reasonably time-efficient, and imposing the constraint of global consistency and smooth continuity allows a relaxation-type approach to be used in solidifying the depth-map. It is felt that all the edge extraction and depth measurements required of a pair of images will be attainable within about 30 seconds of computation (ten for each of the two intensity analyses, and ten more for the correlation). Failings of the low-level description and unreliability of global correlations were felt to be the main drawbacks of an earlier three dimensional modeling system, and this research is intended to clear up these problems as preliminary work to further developing and extending the object modeling process.

14.3.3 Modeling

Work in this area has been in three directions--that of reconstructing 3-D scenes from stereo sets of images, that of automatic recognition of 3-D scenes, and that of finding graph matching techniques to match parts of images [12].

14.3.3.1 Image Reconstruction

Two techniques were studied for scene reconstruction. The first, or multiple view method, was developed to utilize the combined information from bulk correlation and three or more stereo images to construct three-dimensional edge features or structures. These structures are obtained by projecting into space a piecewise-linear representation of intensity edges obtained from one of the images. The second technique was developed to utilize a narrow angle pair (2-3 degrees) of images and symbolic correlation to ensure matching reliability and efficiency in the construction of edge depth maps of scenes. A new technique for dynamic smoothing of edge contours was developed which permits accurate triangulation at narrow viewing angles while preserving the integrity of sharp corners. Also, two new techniques were developed for piecewise approximation of 3-D and 2-D digital contours with circular arcs. In both stereo techniques, objects with prominent edges are

preferred, but no other restrictions are made on surface shape. In this sense, the work represents a major advancement over previous techniques for stereo vision which generally restrict objects to have plane faces or simple curved surfaces.

14.3.3.2 Recognition

In recognition a technique was developed for matching a 3-D scene reconstruction containing piecewise-linear edges (e.g. constructed by the multiple view method) to a stored wire frame model, based on utilization of 3-D features and geometric constraints. Further techniques were studied for implementing efficient search in occluded and cluttered scenes, and in cases where there are many models.

14.3.3.3 Graph Matching

Work was performed to identify, explore, and develop a theory of model manipulation as it applies to computer vision. Efforts were made to develop a unified theory of model manipulation for computer vision which is applicable to the real world. Further efforts were made to formalize shape and color features which are invariant to occlusion, location and lighting. A result of this work is a unified approach to dealing with color and depth. Many of the vision tasks which are being attempted by computer use a relatively small set of model manipulation techniques. All of the methods for combining, intersecting, and modifying models involves the use of graph matching. Initial studies have been started for the purpose of developing a rigorous definition for graph matching as it applies to computer vision. Several graph matching algorithms have been implemented and are currently being analyzed.

14.3.4 Networks of Automata for Vision*

The basic idea of this work on computer vision is as follows [13]: given a digitized television picture of a scene, each picture cell is embedded in a hexagonal array of programmable cellular automata. Once

*This work was supported by the Joint Services Electronics Program (U.S. Army, U.S. Navy, and U.S. Air Force) under Contract DAAB-07-72-C-0259 and by the Office of Naval Research under Contract N00014-75-C-0612.

the picture data is embedded, these cells can "broadcast" their information outward. They can also receive signals other cells have broadcast. This method of picture processing is potentially very powerful. For instance, we can program these cells to respond so as to recognize lines, edges, corners, and axes of symmetry. Shapes also will be recognized by programming the cells differently. As each pass is completed (i.e., the broadcast is allowed to continue for a prearranged length of time) the resulting information can be used as input for the next pass, where the cells might have a different program. The overall goal for this system is to be able to distinguish objects in a visual scene.

14.4 Computer Aided Decision Making

Two research efforts are being pursued in this area. The first is on the conceptual design of an onboard computer software system for enhancing the safety of commercial airline flights. The second effort is the conceptual development of a software system which, from a description of an analog circuit, automatically produces a testing program which drives a digitally controlled bed of test equipment in testing printed circuit board realizations of that circuit.

14.4.1 The SECURE System*

The conceptual development of a system which uses artificial intelligence methodology to enhance flight safety in the cockpit of commercial airliners has been started. The objective is to reduce the possibility of pilot error caused by inadequate or misleading information. The design considerations are that it does not increase the pilot workload, but rather serves as an additional, untiring crew member [14,15]. Its basic functions are to monitor all systems with respect to all phases of flight, and to suggest possible recovery procedures from system failures or course deviations. It should have knowledge of all systems, the instruments and recovery procedures. Because its purpose is to

*This work was supported by the U.S. Department of Transportation under Contract DOT-OS-80020.

provide Safety Enhancement by CompUter REasoning, it has been named the SECURE system. Work was begun on two systems and an aircraft simulator.

The design and implementation of an instrument verification system was begun. A five-level approach was established for determining the consistency of an output of an instrument with respect to the outputs from other instruments. Algorithms which provide values for a given flight parameter have been implemented. This allows, for instance, estimations of altitude based on more than one instrument. The first level, which is the comparison of these estimations, has been completed.

The design and implementation of a script based monitor system was begun. The notation for a script has been formalized. Three levels of scripts have been implemented to describe a flight operation from preflight to postflight. These scripts provide the context in which instrument readings can be interpreted and system failures diagnosed

Finally,an aircraft simulator was written to control the flight dynamics of a hypothetical, simplified, three-engine jet airliner. The outputs of the simulator correspond to the outputs of flight instruments and can be altered to simulate failures or out-of-calibration conditions.

14.4.2 Automatic Analog Test Program Generation

Initial design was begun on an automatic analog test program system. The system accepts as input a description of an analog circuit along with a set of manufacturer's acceptance specifications, and produces a test program which sequences a bed of automatic test equipment. The approach we have adopted is to have the system develop an understanding of the circuit and to generate a set of tests based on this understanding much as a technician would.

Techniques are being investigated for partitioning the circuit into a set of functional subcircuits built around active components. For instance, it will isolate and recognize op-amp circuits as integrators, differentiators, and the like. One algorithm which we developed looks promising in that it uses a recursive series-parallel component absorption approach to partition the circuit. It has the capability of determining feedback loops over more than one stage.

Given such a partition, methods are being investigated to trace a fault to a particular subcircuit. Ways are being studied to select appropriate signals, and to select points of application, in order to trace down faulty subcircuits.

Given that a fault lies in a specific circuit, methods are being investigated for locating the faulty components. Included among these methods are circuit theoretic analyses applied locally, and direct impedance and voltage measurements.

14.5 Human Decision Making and Human-Computer Interaction

Human decision makers are increasingly interacting with computers and this trend is quite likely to continue. This situation leads to the interesting question of what are appropriate modes of interaction between humans and computers and how can human-computer interaction be enhanced. This section summarizes research efforts aimed at answering these questions within the domains of multi-task decision making, computer-aided fault diagnosis, and management decision making.

14.5.1 Human-Computer Interaction in Multi-Task Situations*

In many systems, the human has responsibility for many tasks. This may lead to the human being overloaded or, at least, to the human's responsibilities being limited so as to avoid overload. It seems reasonable to consider computer aiding as a solution to this problem. This leads to the issue of deciding how to allocate responsibility between human and computer.

One approach is to use the computer as a backup decision maker, assigning tasks to it as the load on the human becomes excessive and taking away responsibility as the load becomes manageable for the human. This approach is attractive in that it allows the human to maintain an overall perspective for the system without having to actually perform all of the tasks.

*This work was supported by the National Aeronautics and Space Administration under NASA-Ames Grant NSG-2119.

This approach has been investigated from a theoretical point of view using a queueing theory formulation [16]. A procedure for optimally determining when the computer should be utilized has been developed [17]. These ideas are now being studied in two realistic settings. One of these settings involves the monitoring of multiple dynamic processes [18,19]. The other setting involves computer-aided flight management [20-22]. The goal of these efforts is to demonstrate the usefulness of the approach while also gaining an understanding of the human's abilities to perform in such a computer-aided environment.

Several new efforts have also recently been initiated within this research area. These include investigations of airborne management information systems [23], prospects for mathematical models of human behavior in realistically complex tasks [24], and analytical evaluation of the effectiveness of predictor displays [25].

14.5.2 Human Decision Making in Computer-Aided Fault Diagnosis*

As complex systems become more automated, the humans within these systems will come to fill the role of trouble-shooter. This will require that displays and procedures appropriate to that role be developed. However, despite the large body of literature on human problem solving, there is a lack of a fundamental knowledge of human fault diagnosis abilities, especially as these abilities are affected by the availability of various computer aids.

Two experimental studies of human fault diagnosis abilities have been performed [26]. The effects of problem size, forced-pacing, computer aiding, and training were studied. The results of these studies were described using a model of human fault diagnosis that employs several pattern-evoked heuristics as well as elementary ideas from the theory of fuzzy sets [27].

More recently, the task scenario and fuzzy set model have been extended to allow study of human trouble-shooting abilities in tasks that include both feedback and redundancy [28]. Further, recent experimentation

*This work was supported by the U.S. Army Research Institute for the Behavioral and Social Sciences under Grant No. DAHC 19-78-G-0011.

has studied the fault diagnosis abilities of maintenance trainees in an FAA certificate program [29]. Other extensions to this work in progress include development of new task scenarios and extensions of the model of human decision making in fault diagnosis tasks.

14.5.3 Interactive Modeling of Library Networks*

A queueing network model for analysis of library networks has been developed. It predicts the effects of request routing and document delivery policies on network performance in terms of probability of satisfying a request, average time to satisfy a request, average cost to satisfy a request, and average network processing loads [30-33].

During the past year, application of the library network model to a case study of the Illinois Library and Information Network was completed [34]. Also completed was the design and development of a model-based online management information system for interlibrary loan networks [35].

Efforts initiated this year include application of the library network model to a case study of the Suburban Library System, an interlibrary loan network which utilizes a particularly high degree of automation. Further new efforts include study of alternative reimbursement policies in library networks [36], extension of the library network model to resource allocation problems [37], and investigations of general design issues within management information systems [23].

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15.1 Introduction

During the 1977-1978 time period the Information Retrieval Research Laboratory (IRRL) conducted a number of research and development projects and directed the operation of the University of Illinois' online search service. Major activities included the following: development of a hybrid approach to fact identification in natural language text using Keyword and AI techniques; analysis of data base data; design of an automatic data base selector; design of an integrated man/machine interface to facilitate network resource utilization; development of a directory on transnational corporations for the United Nations; design of a system for the automatic generation of a state-wide union catalog; computer assistance in development of an index and bibliography of electroorganic synthesis reactions; development of a computer-readable data base directory; and management and direction of the University of Illinois' online search service.

15.2 A Hybrid Approach to Fact Identification in Natural Language Text Using Keyword and AI Techniques*

The research was aimed at improving the performance of information retrieval systems by enriching the inverted index structure with linguistic data extracted during index building. We have concentrated on approaches to several sub-problems within the broad framework of such a system. The purpose of this project was to identify tools to produce a noticeable improvement in retrieval performance at a reasonable cost

*This work was supported by the Joint Services Electronics Program (U.S. Army, U.S. Navy, and U.S. Air Force) under Contract DAAB-07-72-C-0259.

and was not intended as an advancement on AI natural language processing research. Our system would exhibit only superficial, rapidly applied knowledge of language.

Work was done in several subproblem areas. We have done work on the parsing problem, using minimal techniques derived directly from AI research. A second area of concentration has involved a new information retrieval paradigm based on the notion of "spreading activation networks" [1]. The third subproject concentrated on production of an associative data base system to be used for storing the dictionaries used by the parser and sentence templates for parser use, as well as the actual data derived by the system from natural language data bases for subsequent retrieval.

Conventional information retrieval techniques are often based on the "inverted index," which contains a list of all the appearances of each word used in the data base. Our enrichment would include the addition of syntactic/semantic information derived during processing plus new retrieval processing techniques to use the richer data structure. The goal system would also identify limited kinds of facts in the data base and add them to a knowledge store. In the time and function framework of this project we did not directly consider fact identifications, storage and retrieval, but only tools that would be useful in approaching our goal system.

Text processing. The text processing phase of the system has several responsibilities. It must build a complete inverted index, indicating for each word used in the file the locations in the text where it is used. For a file of n words this task is of complexity n log n, and can be done either by insertion into a tree-shaped index or by sorting and merging lists of term occurrences. In addition to inverting the terms we will also invert other aspects of the natural language document, such as its author, publication source, subject and references.

While building the inverted index the program must do a simple linguistic analysis of the text it processes. The parsing must be able to handle most sentences, identifying noun groups, modifiers, verbs, agent/object relationships, conjunctions, and so forth. It must also be able to do some analysis across sentence boundaries, such as resolving a

fair percentage of pronoun references. Yet the system must operate efficiently (not adding significantly to the cost of the inversion) and in those caes where it cannot complete analysis of a sentence must be able to identify the parts of the sentence it has handled correctly. Our parsing work has been based on Sheldon Klein's early work [2]. The basic idea is to use "closed class words," which are only used in one way in natural language (such as articles, pronouns, and prepositions) as anchors for a very simple, sequence-oriented parsing process. Suffix tests are used to assign words to probable classes and then context frames and phrases and clause building procedures are used for disambiguation. This can be done in linear time, and therefore is much cheaper than the n log n inversion process. The goal of this processing is to assign a syntactic class to each use of each word and to agglomerate word groups to establish syntactic/semantic relationships within a sentence that could be stored in the index in addition to the raw words themselves. Thus if "genetic engineering" occurred in an article the system could index it under "engineering," "genetic," and "engineering modified by genetic," recognizing that the phrase relationship was useful and should be saved.

The text processing phase could also include fact identification. This would be done by associating procedure with words in the dictionary so that appearance of a particular word would trigger a procedure that would look for particular words or types of words to fill in "slots" in a "frame" associated with a particular kind of fact. These procedures would be associated with particular forms or syntactic uses of specific words and also with generic classes of words. The dictionary would relate words to word classes and to uses.

At present our research on the text processing phase has centered on building a parser based on Klein's work and an associative store to be used for storing dictionary and index data. The parse operates with a limited dictionary and linguistic knowledge base. Use of the data base rear end to store an expanded amount of underlying knowledge was deferred for budget reasons. Work on the fact recognition problem has been on a conceptual level, considering the data structures and knowledge needed. We believe the knowledge should form a generalized, consistent structure for world knowledge, linguistic knowledge, and knowledge derived from

data processed. Thus the case frame describing the word types needed to describe an occurrence of a word and the frame describing a fact should be structurally similar. Our work has indicated that the needed structure will include the features of a procedural systemic grammar [3] and a self-defining semantic network [4].

Retrieval processing. To use the enriched data structure a new retrieval paradigm will be needed. We have considered simply using an augmented Boolean query that would allow specification of roles and case information for words or occurrence of specific word relationships in a text passage (such as "engineering" modified by "genetic"). We have also investigated the use of a spreading activation network model in which all data would be stored in a network whose nodes represented documents, words, authors, journals, and so forth and whose links indicated the use of a given word in a given location, the publication of a document in a given journal, the use of a given word to modify another, and so forth. The retrieval process would involve the activation of specified nodes and a cyclic spreading of activation from active nodes to their neighbors. Stopping, quenching, and selection criteria would be used to identify a result set [5]. This research has so far produced a pilot system that has shown some success on a limited sample data base, indicating that unaugmented results may be notably improved by this paradigm's query modification capability.

The associative data base. Both processing and retrieval activities require the availability of an associative storage system. We have incorporated those needs into our development of EARL (Entity And Relationship Language), a data base management system based on the Entity-Relationship model of data [6]. The core of EARL, including the associative capabilities needed for this research, has been implemented in a prototype version, and allows the storing of n-tuples and their retrieval by value along any of their components. Development of EARL, and of all pilot programs in this research, has been done in SAIL on the DEC SYSTEM-10. The associative retrieval capability allows EARL to retrieve items matching a partial content specification. Thus, for instance, possible phrase templates may be retrieved by specifying the classes of known words in the templates slots (instantiation). The

instances are retrieved sequentially, for sequential testing, or as a set, for best-match testing.

15.3 Analysis of Data Base Data*

The IRRL maintains a body of information about commercially available data bases called the Data Base of Data Bases. On this NSF contract we have studied various statistical characteristics of this population based on the material in our database. Such statistics and analyses are useful both to researchers in the area and to the users and producers of such databases.

The particular information developed in the studies performed in the last year considered the age, size, type (scientific, medical, etc.), and source (government, private, etc.) of the data bases covered. At present 365 data bases are covered by our data base of data bases, but any given study might include only a subset of those due to missing or unavailable data. We are currently updating the database to provide those particular data for all data bases covered.

The software used in this research consisted of a program framework containing slots into which logic could be inserted to perform specific data selection, cleanup, and analysis. The data was first extracted from the database by our data access program USER and written into a file of (tag,value) pairs. The analysis programs read that file and select the tags of interest. Some effort was made to overlap multiple analyses by re-using data selected and cleaned for prior use.

Cross tabulations are made based on defined groupings or actual values; depending on the data involved. Thus, cross tabulations were done involving both raw year of origin versus grouped size and grouped year of origin versus grouped size. Statistical summaries included means, limits, and standard deviation for raw data plus correlation coefficients for raw data and grouped data. Detection of bad data included identification of records containing illegal or missing values.

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*This work was supported by the National Science Foundation under Grant No. NSF77-SP-0986.

The work involved in this project also provides us with a framework for further studies of the data bases available to researchers today. We are currently updating the data base and improving the coverage and consistency of data fields that are likely to be important in future studies.

15.4 Automatic Data Base Selector*

This project evaluated the feasibility of an automatic Data Base Selector to rank a set of data bases according to their applicability to a given user query, based on data base vocabulary statistics (Term Occurrence File) modified according to a mathematical model (Term Equivalence Model).

The Data Base Selector consists of a file containing the vocabulary (with frequencies) from 20 major data bases, programs for data management and file generation, programs for query processing, and a mathematical model for normalizing the variability (differing numbers of years worth of files, controlled versus uncontrolled terminology, hierarchical and multilevel vocabularies, etc.) found in multiple natural language bibliographic data bases.

A Data Base Selector would be of use to data base users, data base producers, and data base processors. It would help users or searchers allocate resources to searching data bases most appropriate to queries. It would help processors and producers carry out data base comparisons, vocabulary comparisons, and vocabulary compatibility studies. No merged file of a large number of data base vocabularies has been studied before and the number of potential uses of such a file may be considerably larger than those mentioned here.

The Data Base Selector has as major components a master data file called the Term Occurrence File, a software package for file management (file generation, update, delete, etc.) called FIL, a mathematical model for normalizing term occurrence data in various data bases called Term Equivalance Model, and a Query Processor to accept queries, match

*This work was supported by the National Science Foundation Under Grant NSF SIS-76-01990.

them against the Term Occurrence File, submit term occurrence data to the Term Equivalence Model, and provide histogram rankings of data bases as output.

The selection of a file structure for the Term Occurrence File for the Data Base Selector project was made with two major objectives in mind. First, the amount of time needed to search the file for a given term must be minimized and second, the file must be as compact as possible, due to the limited availability of on-line storage space. The first objective is the one of primary importance to the project itself. However, since there are a number of ways to organize a file for fast searches, the second objective actually dictated which structure would be used.

The Term Occurrence File is organized as an indexed sequential file. The terms in the file are kept in lexicographic order according to the EBCDIC collating sequence. Although our machine uses ASCII rather than EBCDIC, we decided to use the EBCDIC sequence because the data base vocabulary tapes supplied to us had the terms sorted according to that sequence. In order to allow for efficient searching, term entries in the file are grouped into fixed length segments, with an index entry generated for each segment. A term can be located by searching the index to determine in which segment it is to be found. That segment can then be accessed directly and searched sequentially for the specified term.

An important aspect of the file structure design is that it allows most operations involved in locating a term to take place in main storage. The segment to which a term belongs can be quickly determined by searching the index with a binary search algorithm. The appropriate segment can then be brought into main storage where it can be searched sequentially. In order to facilitate this searching, term entries are not allowed to cross segment boundaries. This means that there will generally be some unused space at the end of each segment, but the amount of space lost is not significant since the size of a file segment is large relative to the size of a term entry. Keeping the index in main storage and reading entire segments of the file into main storage for searching greatly decreases the number of input operations and therefore the amount of time needed to search for a term.

The Term Occurrence File is created by a series of merge operations. Since the terms are kept in lexicographic order and since the vocabulary tapes are also ordered, a fairly straightforward merge operation suffices to add a data base's terms and count information to the file. The merge program puts the terms and counts into the internal format used for term entries, groups the entries into segments, and generates the index as it creates the new file.

The term equivalence model is based on using the occurrences of a term in a data base and then normalizing that number with various factors, and then applying various weights which are defined by both the system and the user to arrive at a relative measure of the relevance of a term or query to a data base.

Normalizations which are applied include: for the length of time which the data base covers, for the number of index terms and tokens used in a field, for the distribution of a term over the data bases. Weights can be assigned to a field in a data base to increase or decrease its important by the user or by the system.

Sets are combined using the notions of fuzzy set theory. The association of a term to a field in a given data base is described by a value between zero and one (inclusive) representing degree of membership of that term in the data base.

The selector does the following: queries using Boolean and ("*"), and or ("+") are accepted and evaluated and the results returned, giving the individual associations of terms with each db and the association of the whole query with each data base. It is important to note that the values for the query are derived from the associations of the individual terms ONLY. In other words, because we do not have the facility to calculate the values for Boolean combinations of terms and then calculate the association, we first calculate the association, then calculate the Boolean combination.

Sets may be assigned names with the assignment operator. Individual terms may be weighted by multiplying them by a constant. Fields may be weighted by assigning the field name a weight. For instanct "auth←5" will weight occurrences in the author field 5 times more heavily for every term. Weighting factors can be any real number, including decimals.

The Selector has been implemented and tested on a set of queries, using various combinations of normalization factors and various rules for evaluating Boolean operators in fuzzy logic. The results have been mixed. The Selector has obtained correlations of around .72 with actual search results in some versions. One version selected the top two data bases, as ranked by search results, with precision and recall of .89. We feel that these results are promising, and that further testing is definitely warranted, to determine the most powerful combination of factors. The effectiveness of the normalizations, in particular, should be tested in an environment in which comparable data bases are involved. The testing done in this project was biased somewhat by the data provided and by the differences between the TOF and the data bases available for searching.

15.5 An Integrated Man/Machine Interface to Facilitate Network Resource Utilization*

For the first time in history computerized information retrieval is widespread and economically viable. Evidence of this is shown in the volume of machine-readable records, data bases, on-line software packages, vendors, search services, and searches. The major portion of the currently published scientific and technical literature can be identified through computer searches because the references are in computer-readable form. The majority of the world's currently published abstracting and indexing literature is in computer-readable form. There are more than 300 publicly available data bases containing approximately 52 million records (citations). Thirty-three million of these records are now available through the various on-line system ventors in the U.S., Canada and Europe. Some of the major vendors include: the National Library of Medicine (NLM), Lockheed Information Service (LIS), System Development Corporation (SDC), Bibliographic Retrieval Service (BRS), the Canada Institute for Scientific Information (CISTI), and the European Space Agency (ESA). These on-line service organizations use a variety of

*This work was supported by the National Science Foundation under Grant No. NSF DSI 77-26886.

sophisticated on-line software packages such as ELHILL, DIALOG, ORBIT, STAIRS, CAN-OLE AND RECON. Services from the data bases, through the on-line vendors, are provided by dozens of centers, libraries and brokers and they conduct more than 1.2 million retrospective searches per year.

Unfortunately there are no standards governing the format of data bases, the elements and vocabularies included in them, or the on-line systems for searching them. The lack of standards imposes requirements on searchers to become familiar with the variety of existing data bases, vocabularies, access protocols, system features and command languages as well as to keep up-to-date with changes made in all of them.

Many of the differences and variations can be made less apparent by developing translators or transducers for converting the procedures or conventions or terminology of one system into equivalent procedures, conventions and terminology of other systems. These converters or translators would make systems appear alike to the searcher and made data bases function as if they used the same vocabulary. Such aids would make the differences transparent to the users thus, they can be called Transparency Aids. An integrated collection of transparancy aids can be said to comprise a Transparent System. The aids then are the Transparency Subsystems.

By the removal of the differences between data bases and systems the systems become easier to use; they become more user-oriented. As they become more user oriented the requirement for intermediary searchers decreases and we begin to approach the day when most searching will be done by end users (those that pose the search questions).

The proposed research program would increase the transparency of retrieval steps by making the discreteness of separate tasks less obvious and by making the variety of systems and data base differences less obvious. Specifically, we will: (1) design a generalized model for a Transparent System, (2) analyze the alternative factors affecting the Transparency Interface, (3) develop a skeletal user-oriented terminal, and (4) integrate Transparency Subsystems.

The Transparent System will be comprised of: the interface programs; the command languages used by the Transparent System; the transparency aids or subsystems that perform various functions, such as conversion of command languages or selection of data bases; the data files

containing descriptive and statistical data about data bases; and the connections to the data bases or network resources. The model of the Transparent System will show the relationship between and among all of these. The alternatives study will show advantages and disadvantages of various model configurations, and the user-oriented terminal development together with the subsystem integration will demonstrate the advantages of a Transparent System by showing how the subsystems will interact in performing their functions.

15.6 UN Directory on Transnational Corporations*

In early 1977 we were contacted by the United Nations Centre on Transnational Corporations concerning the feasibility of preparing an "International Directory of Sources of Information on Transnational Corporations." The emphasis was to be on machine-readable sources of information and the format similar to the Computer-Readable Bibliographic Data Bases--A Directory and Data Sourcebook by Williams, M. E. and Rouse, S. E. Investigation of our own files, for machine-readable sources, and of the University of Illinois Library, for printed sources, provided us with an estimate of 80-150 possible sources. These were divided into three groups: hardcopy (printed) compilations; machine-readable numeric or factual data bases and; machine-readable bibliographic data bases. It was understood that these sources were not all specifically about transnational corporations but were sources that contained some substantial information, either factual or bibliographic, on transnational corporations.

On the basis of this initial investigation, we agreed to compile such a directory and deliver one camera-ready copy to the UN by December 31, 1977.

Methodology

(1) A search was conducted of the catalogs and secondary sources of the University of Illinois libraries and the University of Chicago Regenstein Library in order to construct a preliminary list of appropriate hardcover sources.

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*This work was supported by the United Nations Centre on Trans-National Corporations under Contract No. UN CON-77-161.

(2) A search of available sources and directories to compile a similar preliminary list of machine-readable sources. Our own personal contacts in this area were also utilized. Copies of both preliminary lists were provided to the UN.

(3) Modification of the questionnaire used for gathering and inputting data on bibliographic data bases for Computer-Readable Bibliographic Data Bases--A Directory and Data Sourcebook.

(4) Design of a questionnaire for gathering and inputting data on numeric data bases and hardcopy sources.

(5) Gathering data on hardcopy publications from locally available sources and by telephone for U.S./Canadian publishers and by correspondence for non-U.S./Canadian publishers. The preliminary list of sources was finalized during this process. Some publications were dropped as inappropriate as they were examined or as more information became available on them while others were added, especially through checking the references in appropriate publications. In addition, each publisher was queried as to the current state or probability of a machine-readable version of the hard copy publication. Our preliminary list of machine-readable sources was somewhat increased by this process.

(6) Gathering data on machine-readable sources from our own files and by telephone for U.S./Canadian data base producers and by correspondence for non-U.S./Canadian data base producers. The preliminary list of sources was finalized during this process. As was the case with the printed sources, some data bases were dropped from the original list of candidates while others were added.

(7) Editing data for consistency of format and content description.

(8) Initial design and creation of controlled vocabulary for the creation of a variety of indexes to provide additional points of access to the information in the directory.

(9) Design of output format for the final printing of the Directory.

(10) Modification of existing programs for the input, manipulation, and output of the data gathered for the Directory.

(11) Inputting data into the IRRL Data Base of Data Bases. The IRRL data base management system, EARL, was used for data manipulation. The CSL DEC Systems 10 computer was used for all computer work.

(12) Initial listing, proofreading and editing of data in machine-readable form. Subsequent proofreading and editing cycles were performed as needed to work the data into its final form.

(13) Generation of five different indices to provide additional access points to data contained in the Directory.

(14) Printing one camera-ready copy on a ComData terminal. This final copy was submitted to the UN on December 30, 1977.

Contents and Format

The final version of the International Directory of Data Bases on Transnational Corporations consists of 139 sources of information divided into three major sections, five indices and one appendix. The major sections are:

(1) Hard Copy Sources -- 67 total

(2) Bibliographic Data Bases -- 43 total

(3) Numeric Data Bases -- 29 total

Sections 1 and 3 include data obtained specifically for this Directory. The majority of the material in section 2 was taken from Computer-Readable Bibliographic Data Bases--A Directory and Data Source-book. Indices include: A Name/Acronym/Synonym Index, a Subject Index, a Geographic Index, a Subject Index with Geographic subdivisions and Geographic Index with Subject subdivisions. The last two indices conatin exactly the same material but with differing arrangments allowing access from either subject or geographic entries. All index entries refer back to one or more individual data base/sources.

Each data base/source starts on a new page. In addition to page numbers, a short name or acronym for the appropriate data base is noted in the upper right portion of each page for easy access. Up to nine major categories of information are provided for each data base/source. (Not every category is appropriate for each of the three major divisions.) The nine categories are entitled:

(1) Basic Information

(2) Producer/Publisher or Producer/Distributor/Generator Information

(3) Availability and Charges

(4) Subject Matter and Scope

(5) Subject Analysis/Indexing Data

(6) Bibliographic Data Base Elements or Items in Data Base and Associated Data Elements

(7) Search Programs

(8) Data Base Services Offered

(9) User Aids Offered by Data Base Producer

A ten page introduction provides definition of all data elements used in the Directory which are not self-explanatory. A one page appendix lists additional sources which were either not appropriate to the format of the Directory, e.g., journals, or which we were unable to examine directly or obtain sufficient information on but which we considered strong candidates for inclusion. The final version of the Directory sent to the UN contains 386 numbered pages. Publication of the Directory as a UN document in the near future is likely.

15.7 Automatic Generation of a Statewide Union Catalog*

The result of the "State-wide Union Catalog Feasibility Study" was the development of a prototype system called IUCS (IRRL Union Catalog System). IUCS was developed by testing various techniques for matching records against large test files of machine-readable records from major institutions that maintain their catalogs in machine-readable form. Overall the IUCS involves four major steps: (1) a pre-processing step which converts incoming files into IUCS form; (2) a first pass screen which matches records according to an efficient title-date matching key; (3) a second pass screen which provides more refined matching of the potential duplicates located in the first pass; and (4) a post-processing step which merges the new records into the existing MASTER file to create a union catalog.

Test Files

The machine-readable files of MARC-like records used to test the IUCS were provided by Northwestern University (NW), the University of Chicago (UC), Northern Illinois University (NIU), and the Ohio College

*This work was supported by the Illinois State Library under Grant No. ISL FY 76-III-D.

Library Center (OCLC). The records from OCLC were records generated for one anonymous large university in the midwest. Records used for testing all aspects of the system included only those from NW, UC, and OCLC. NIU was unable to provide full bibliographic records because of technical difficulties. NIU experienced difficulty in converting their catalog card image records to MARC format. We wrote and tested a program that converted their catalog card images to a format suitable for use with the Library of Congress recognition program but apparently NIU was unable to get the LC program to run. Since we needed to be able to identify specific fields for the IUCS and since NIU was not able to provide the field identification we were unable to include the NIU file in the IUCS test. We did, however, use their records of LC card numbers in order to check LC number overlap between files.

In order to insure a reasonable degree of overlap between the records of the cooperating libraries we extracted a time-distinguished sample consisting of records for items entered into the files for the 1974-75 time period. The files used in the full scale test included 73,552 records from OCLC, 57,728 records from NW and 22,857 records from UC.

Development of IUCS Screens for Matching Records

IUCS was planned to be a multiscreen system for matching records in which the first screen would be a broad screen that would pull out the candidate duplicate records. A set of finer screens would be used for verifying pairs of records as duplicates, rejecting pairs as non-duplicates or indicating a need for manual checking to verify or reject pairs.

Development of the broad screen or first pass in the IUCS involved the design of a fixed-length code based on information from the titles and dates of the records in the files to be matched. This code, called a matching key, should be efficient and effective. That is, it should provide a fast, inexpensive match and it should not fail to match records that are the same. Various key elements from the title portion of records were selected and tested, using entropy measures to determine the discrimination power of the key, and candidate title keys were determined. Although the title keys would work well in most cases, it was necessary to add "date" to the key in order to discriminate among multiple identical

titles such as "Proceedings" or "Collected Works." The result of tests on title-date keys produced the title-date (TD) key which is based on selected alpha characters from the beginning and end of titles plus date information.

The TD key is used for the first pass matching of files. Results of this matching step are then subjected to finer screening in a second pass procedure. The second pass includes three procedures: (1) matching of authors; (2) matching of titles using Harrison keys (which are bit string representations of the titles) and Hamming distances; and (3) matching of paging. The author match allows any combination of main and added entry. Harrison keys, which are bit strings representing the character strings of the titles, are generated for each title. The Harrison keys for two records, which are candidate duplicates, are then compared. The comparison does not involve a character by character comparison but indicates the extent of differences between titles. The comparison involves calculating the Hamming distance between title bit strings. Hamming distance is a representation of the differences in the two bit strings derived from the titles. It is the sum of the number of instances of non-match in the bit strings. The more differences there are between two titles, the greater the Hamming distance will be. By allowing Hamming distances up to eight for the IUCS second pass screen, we were able to overcome small variations in the recording of titles and a certain number of typographical errors.

The third procedure involved in pass 2 is the match on paging. There again we did not want to require exact matches but matches within a range. This is done because of the variant ways in which pages are counted and recorded.

Testing the Effectiveness of IUCS

The adequacy of any scheme for creating a union catalog can be measured in terms of the two cardinal errors that may occur. Records that do not relate to the same item may be erroneously identified as duplicates- these are mismatches -- and records that truly relate to the same item may not be identified as duplicates -- these are missed matches. Of the two types of errors, mismatches are more serious because they result in information being permanently lost. If a new record is mismatched (said to match even though it does not) with a record in the MASTER catalog it

is then discarded because it is assumed not to be a new record. In order to determine the mismatch rate of IUCS we selected 3,686 record pairs that had been matched by IUCS. Manual examination of the 3,686 pairs indicated that two records were mismatched and they were very closely related bibliographically. One was a result of a cataloging error and hence is not really an error as far as IUCS is concerned. The other is a duplicate according to the IUCS definition. A minor change in IUCS would accommodate this type of mismatch getting through. Thus the mismatch rate of IUCS, based on examination of 3,686 records is .054% and with a minor change in the system (checking the authorship statement or the 700 fields for indications of translation) it would be reduced to almost zero. Simple screens such as LC matches, ISBN matches or use of search keys produce considerable numbers of mismatches.

Errors due to missed matches result in an unnecessary expansion of the union catalog. These are less serious in that information is not lost, it is merely unnecessarily recorded twice.

In order to determine the percentage of matches missed by IUCS, we used all possible means for matching records in the OCLC and NW test files and developed a set of duplicates that, as far as we could determine contained 100% of the true duplicates in the file. Based on matching within this set, the effectiveness ratings (in percentages) of LC, ISBN, IUCS-TD, and combinations were: LC, 74.90; ISBN, 56.58; IUCS-TD, 97.10; LC/ISEN, 80.74; IUCS-TD/ISEN, 98.17; and IUCS-TD/LC/ISBN, 99.62. Missed matches were missed for a variety of reasons. In a similar test of a restricted file, the distribution of missed matches fell into four categories. Variations in titles (addition or substitution of words, use of German abbreviations, typographic errors, etc.) accounted for 81% of the errors. Variation in year of publication data accounted for 12.3% of the errors. Variation in paging accounted for 5.8% of the errors and variation in author data accounted for < 1%.

Cost of Operating IUCS

An important factor in evaluating any system is the cost of running the system. Our programs were written in the SAIL language and were run on the CSL's DEC system-10. Computer costs for the full scale preparation and merging of records from OCLC, NW, and UC were recorded.

Costs are related to the four major processing steps: pre-processing, pass 1, pass 2, and post-processing. Using nighttime rates (which are approximately 10% of day rates), the cost of pre-processing was $20.68, the cost for pass 1 processing was 8.62, the cost of pass 2 processing was $11.57, and the cost for post-processing was $1.45, for a total cost of $42.20.

Because our runs involved 154,000 records we extrapolated our actual costs to simulate a comparison of 200,000 records in a "new" file with a million record MASTER file. Assuming a 25% overlap, the nighttime cost would be $70.90 (or $592.55 during the day). If the overlap were 50% the cost for nighttime processing would be $96.88 (or $769.49 during the day). On top of these costs one would have to add the personnel cost for manual checking of 1.1% of the duplicates located. Approximately 1.1% of duplicates are pairs that IUCS prints out for manual verification.

15.8 Swann Bibliography of Electroorganic Synthesis Reactions 1801-1975*

Staff at the Information Retrieval Research Lab (IRRL) are collaborating with a group of staff and students in the Department of Chemical Engineering (under Professor Richard Alkire, P.I.) to compile and index the Swann Bibliography of Electroorganic Synthesis Reactions, 1801-1975. Financial support for indexing the bibliography came from ERDA, The Electrochemical Society and nine chemical companies.

Approximately 14,000 citations involving electrosynthesis reactions, including original scientific publications, patents, reviews, books, lab manuals and dissertations are compiled by Dr. S. Swann, Department of Chemical Engineering, University of Illinois during the past fifty years. These citations provided the raw data for the bibliography.

Methodology

1) Literature Searching

When available the abstracts for the citations were examined and abstracted from Chemical Abstracts or Dissertation Abstracts.

*This work was partially supported by the Energy Research and Development Administration under Contract: U.S. Argonne NL 31-109-38-4003 and 9 chemical companies.

2) Coding Reactions

Synthetic reactions appearing in the abstracts were then analysed and coded according to a scheme that described the major types of electroorganic synthetic reactions. The compounds synthesized were named according to CA nomenclature and their molecular formulas determined. Common or trivial names were also provided. One staff member from IRRL participated in this portion of the project.

3) Computer Generation of the Bibliography

The computer generation of this bibliography was carried out at IRRL under the direction of Professor Martha E. Williams.

a. Data Entry Form

A data entry form was designed with tags for the following data elements:

i. Type of publication
ii. Reaction class
iii. Class of book
iv. Authors
v. Publication year
vi. CA (Chemical Abstracts) number
vii. Journal citation
viii. Title
ix. Translated title
x. Notes (includes molecular formulas, product names, synonyms)

Data that has been analysed and coded was transcribed onto the data entry forms by students. Proofreading strategies were established to avoid errors. The forms were then sent to be keypunched and verified.

b. Software Requirements and Implementation

The project required software to build and maintain the data base of bibliographic citations and to generate the citation listing and various indexes from it. A review of the requirements and budget led to a fairly simple data base design, allowing maintenance to be done using the system text editor, rather than a special purpose editing program. Programs were required to check the format and, to some extent, the content of the input data, to generate a formatted data base file from the input data, to generate the citation listing in the

desired format, and to generate the desired indexes to the citation listing. A utility program was also written to read input data from magnetic tapes. The programs were written for the CSL DEC System 10, using the SAIL programming language, an ALGOL derived language suitable for writing well-structured programs.

The format checking program (FORMAT.SAI) verifies the presence of required data elements in the expected places, checks the validity of certain fields by comparison to tables of acceptable values, checks for sequencing of input items for each record, and flags errors or possible errors in a formatted listing for manual verification. This program is a straightforwarded line by line check of the input file, subjecting each line to a sequence of tests determined by the type of line read and expected.

After the citations have been edited to correct errors found by FORMAT, they are formatted by the program CITFMT.SAI. This formatting consists of taking the raw input lines and attaching a sortkey based on the reaction under which the citation is to be listed, sorting, and adding an initial line to each citation containing descriptive information.

If the new batch is to be added to a combined file the program CITMRG.SAI is used to perform the merge based on the previously assigned sortkey.

When a batch or a combined file is ready for printing the program CITPRO.SAI is used to generate the citation listing and index files. CITPRO performs conversions of citation numbers to listing numbers and generates a citation listing structured by type of citation and reaction class described. The appropriate fields are extracted and transformed to suitable index entries, then written to specific index files for subsequent sorting and listing. The indexes generated are selected by the user.

c. Editing

Printouts of the citations and indices were proofread and edited online using the DEC System-10 editor, SOS.

Organization of the Bibliography

The bibliography is arranged with citations grouped according to the nature of the chemical reaction reported. Within each reaction category citations are arranged according to type of publication and within these subcategories citations are listed in chronological order by year.

Access to the bibliography is provided by four indices:

i. Author Index
ii. Product Name Index
iii. Product Molecular Formula Index
iv. Product Synonym/Common Name Index

Publication

The bibliography will be published under the auspices of The Electrochemical Society. Publication in the form of a hard-bound book is anticipated by late 1978. A computer tape of the citations and indices will also be available at that time.

15.9 Directory of Computer-Readable Bibliographic Data Bases*

The Computer-Readable Bibliographic Data Bases--A Directory and Data Sourcebook, compiled and edited by Professor Martha E. Williams and Sandra Rouse, was published in 1976 by the American Society for Information Science. Updates to the Directory were issued in April 1977 and April 1978. A new directory including data that is relevant as of December 1978 is planned for publication in January 1979. Unlike its predecessor, the new directory will be published in bound rather than looseleaf form. The computer generation of the printed product is supported by the American Society for Information Science Methodology.

Data Collection

1. Data base processors in Europe and North American were contacted by mail for information on the data bases they provided access to.

*This work is partially supported by the American Society for Information Science.

2. The 13 page questionnaire designed for the first directory was revised to achieve a more consistent format and expanded to include non-US data. For the first time the questionnaire was computer-generated with the information that we had for the data bases covered by the first directory. Existing data entries need only to be verified or changed and missing information supplied by the data base producer.
3. The questionnaires will be mailed to the data base producers and after a few weeks US and Canadian producers will be contacted by telephone for verification of the data and assistance with questions they may have.
4. Information on the availability of new data bases was obtained from the published literature and contacts with data base processors/producers. The producers of new data bases were interviewed first by phone. The completed questionnaire was then mailed to them for verification and if necessary followed up by telephone. Only online data bases that were publicly available were treated fully. Data bases available for internal use only or which are only offline will be listed separately.
5. Returned questionnaires were checked and data entries standardized.

Data Entry

1. Data will be entered online into the data base of data bases file using the DBIN program.
2. Data entries will be printed out, verified or corrected and edited online using the DBEDIT program.

Organization

The directory will be organized alphabetically by data base name and will include an introduction and four indices: Subject Index, Data Base Name/Acronym/Synonym Index, Producer Index and Processor Index.

Information on each data base follows the general format:

1. Basic Information
2. Producer/Distributor/Generator Information

3. Availability and Charges for Data Base Tapes
4. Subject Matter and Scope of Data on Tape
5. Subject Analysis/Indexing Data
6. Data Elements Present on Tape
7. Data Base Services Offered
8. User Aids Available.

15.10 University of Illinois Online Search Service*

During the past year, the University of Illinois Online Search Service, under the general supervision and coordination of IRRL, expanded its services to the students, faculty and staff of the University. With the cooperation of the University Library, searching is now available at six different locations around the campus, with request for passwords and/or terminals pending which should bring the number up to nine by the fall of 1978. One additional location, the University Library School, uses the systems available through the search service for classroom use only. Locations where searching is offered to University students, faculty and staff include IRRL, Reference Room of the Main Library, Chemistry Library, Biology Library, Education and Social Sciences Library and Physics Library.

Online systems available through the Search Service include Lockheed's DIALOG, System Development Corporation's ORBIT, the Bibliographic Retrieval Service system and TRIS-On-LINE through Battelle. Individual data bases available from these systems total 108. Negotiations are currently in process to add the New York Times Information Bank by the fall of 1978.

Use of all systems during FY78 is given in the following table. The costs given represent the total amount paid by the University to the online vendors concerned. Approximately 52% of this was recovered from the users of the Search Service through the charging of fees.

*This work was supported by the State of Illinois.

USE OF ALL SYSTEMS FY78

System	Hours	Cost
BRS	507.68	$14,487.27
LRS	47.60	4,115.89
SDC	5.65	387.45
TRIS	.83	86.01
TOTAL	561.76	$19,076.62

The total connect hours used represent 1192 individual searches, a search being defined as a single session at the terminal, regardless of the number of data bases or systems accessed. Of these, 517 were conducted and paid for, at least in part, by University faculty, students or staff. The remaining 675 were conducted by IRRL or Library staff for internal use. The bulk of these were conducted by Library staff either as practice as they learned to use the system or for general reference or verification work.

Beyond providing general direction and coordination, IRRL performs the following specific tasks related to the Online Search Service: negotiation of contracts with online vendors; training of new searches; consultation on system problems or difficult searches; promoting the service to the University community through brochures, posters and demonstrations; keeping statistics on all aspects of the Search Service; all accounting work associated with collecting fees and paying bills. In addition, we are currently working on an automated accounting system, which we hope to have in full operation by the fall of 1978.

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16.1 Data Compression and Information Transmission*

The research on variable-rate compression for discrete-time sources has been expanded to include weakly- and strongly-universal variable-rate data compression. In particular, the first results on weakly-universal variable rate compression (which appear in our paper [2]) give all of the previously established results (e.g.,[1]) on variable-rate universal data compression as special cases. The main advantage of the weakly-universal universal approach is that no prior probability is needed for the class of sources in question. In spite of this, the classes of sources which are covered by our results are sufficiently general to include any class Λ of conceivable interest which has a uniform bound on its rate-distortion functions (i.e., $R_\theta(D) \leq r$ for each θ in the class Λ where $r < \infty$). In addition, alternatives to this restriction on the rate-distortion function in the form of restrictions on the source memory are given in [2].

We have also studied strongly-universal variable-rate data compression and have established sufficient conditions for the existence of strongly-universal compression schemes. Such compression schemes, when they exist, are more powerful than weakly-universal methods; however, only relatively specialized classes are strongly-universally encodable.

Research has been initiated on the construction of universal variable-rate source codes. The approach is based on mismatch bounds for

*This work was supported by the National Science Foundation under Grant NSF ENG-75-20864 and by the Joint Services Electronics Program (U.S. Army, U.S. Navy, and U.S. Air Force) under Contract DAAB-07-72-C-0259.

variable-length noiseless source codes [3] and continuity properties of relative entropy. Such constructions have been obtained for the class of all binary memoryless sources, and extensions to the class of all discrete memoryless sources and the class of all discrete n-th order Markov sources appear to be fairly easy to obtain.

We have begun a new research project on channel coding theory for both discrete- and continuous-time channels with memory. The class of channels considered (the $\bar{\rho}$-continuous channels) is sufficiently general to include all previous discrete-time channel coding theorems. The extension of $\bar{\rho}$-continuous, discrete-time channel coding theory to continuous-time channels should follow along the lines of our work on continuous-time sources [4,5].

16.2 Robust Digital Detection and Estimation*

Research in this area may be divided into two basic parts, the first dealing with robust detection and quantization schemes, and the second is concerned with combined estimation detection schemes for uncertain signals and systems.

16.2.1 Robust Detection and Quantization

Progress relating to the decision and signal-detection aspects of this research can be divided into three categories: results for optimum data quantization in signal detection systems, results relating to robust signal detection and filtering, and results involving memoryless decision-making systems.

In the first of the above categories, general design procedures have been studied for the selection of optimum quantization strategies for general discrete-time decision/detection applications where independent sampling is used (as in [6-8]). These results are being applied to achieve designs for specific detection models in which signals are represented as random (i.e., noncoherent) quantities (as in [9]). Further

*This work was supported by the National Science Foundation under Grant NSF ENG78-05880, the Army Research Office under Contract DAAG-29-76-G-0154, and by the Joint Services Electronics Program (U.S. Army, U.S. Navy, and U.S. Air Force) under Contract DAAB-07-72-C-0259.

results in this area involve the extension of the independent-sampling design strategies to the case where statistical dependence is present among data samples [10]. The results here are direct generalizations of the independent-sampling results, although the design strategy in this case is more difficult numerically. To supplement the analytical work in this area, a numerical investigation is currently being conducted for a class of non-white Gaussian noise processes.

In the second of the above categories, two aspects of the design of robust systems have been investigated. In particular, results have been obtained which yield a general design strategy for signal-detection and other decision-making systems whose performance will be insensitive to unknown deviations in noise or other data statistics [11]. This work differs from earlier related work (for example, [12,13]) in that a more general class of problems is considered here and an alternate performance criterion based on a generalization of signal-to-noise ratio is applied to facilitate design tractability. A related aspect of the robustness problem which has been considered involves the design of Wiener-type filters which exhibit performance insensitivity to general types of deviations from nominal signal and noise power spectra for filtering stationary processes. These latter results are generalizations of earlier filtering results based on bounding spectra and on other particular spectral uncertainties. Papers describing both of these studies are currently undergoing review.

The third aspect of this research involves the extension of recent results [14] in the design of memoryless signal detection systems for operation in dependent noise environments. Specifically these previous results have been extended to include a more general binary decision problem in which dependence among data samples can be modeled by any of a number of mixing conditions (e.g., m-dependence, ϕ-mixing). The new results, which are based primarily on large-sample-size performance optimization, lead to a design strategy which can be reduced to the solution of a conventional Fredholm-type integral equation. This work relates to the quantization work discussed above in that the quantizer-detectors for dependent data are of the memoryless type studied here.

16.2.2 Estimation-Detection Schemes for Uncertain Signals

Progress in detection-estimation for uncertain signals may be classified into three parts. The first is concerned with the development of a detection-estimation scheme for the estimation of Poisson-driven processes. The signal model is assumed to be linear with Poisson white noise input whose mark is unknown. The optimal scheme is not implementable by a finite dimensional filter, hence a suboptimal scheme is proposed which is based on the detection of the incident process and then estimating its mark, with prescribed delay. The resulting scheme is implemented approximately in a recursive fashion. Its performance is analyzed approximately with the result that it is superior in the mean-squared error (MSE) sense then the optimal linear scheme for low intensity of the Poisson input. The scheme has also been extended to the vector case as well. It has been simulated to verify the implementation consideration of the algorithm and to validate its performance as compared to the analytical expression derived approximately. The details have been reported in [15].

The second part is concerned with detection-estimation schemes for discrete-time linear systems with uncertainties modeled by Markov switching parameters or observations. A suboptimal scheme for the state estimation of such systems using a prescribed number of detectors was shown to be superior in terms of complexity and implementation consideration to existing suboptimal schemes at no sacrifice in the performance. The simplicity of the scheme is particularly evident for low or high transition probabilities of the switched parameters. Additional research of such models has been devoted to the case when the transition probabilities are not known, and hence may be suitable for modeling time varying parameter changes which may be slow or fast. Both optimal and suboptimal schemes have been proposed, and conditions for the convergence of the resulting estimators have been derived [16]. Further research into additional simplification of the schemes and analysis of their performance is in progress.

The third part is concerned with the application of the singular perturbation model to estimation and filtering. Multiparameter singularly perturbed systems with unknown perturbation parameters are investigated, as an extension to [17]. The use of innovations testing with several filters

composed of slow and fast parts in multiple time-scales leads to the determination of the highest order necessary to achieve a prescribed incremental MSE. A finite series expansion in the perturbation parameter, of system states and their estimates has been proposed. The conditions for the series to be composed of completely slow filters are derived, and the maximum number of terms in the series is found. The resulting scheme is simpler to implement than the composite system due to the use of only one time scale (the slow one), with particular savings when the number of the fast variables is relatively high. Applications to various stochastic systems are in progress.

Finally, several modification of the detection-estimation scheme [18] for signals with uncertainty represented by bounds have been studied, such as the extension to the dynamic case [19], and the explicit derivation of an approximate algorithm for the system performance and design.

16.3 Multiple-User Digital Communication*

During the past year, we have continued our work on spread-spectrum multiple-access (SSMA) communication systems [20,21], periodic sequences for SSMA communications [22-28], and multiple-user information theory [29,30]. In addition a new research project on SSMA communication via fading channels [31] was begun.

16.3.1 Spread-Spectrum Multiple-Access Communications Systems

Analytical results have been obtained for quadriphase direct-sequence spread-spectrum multiple-access (QDS/SSMA) communications over additive white Gaussian noise channels. In this work [21], two different modulation schemes were considered and were shown to yield different signal-to-noise ratios at the receiver output. In one modulation scheme, the quadriphase modulation is achieved by coherently adding two different orthogonal biphase DS/SSMA signals. In the other, the data signal is modulated directly onto two orthogonal but otherwise identical quadriphase-coded carriers. The signal-to-noise ratio for the orthogonal biphase

*This work was supported by the Army Research Office under Grant DAAG-29-78-G-0114, by the Joint Services Electronics Program (U.S. Army, U.S. Navy, and U.S. Air Force) under Contract DAAB-07-72-C-0259, and by the National Science Foundation under Grant ENG75-22621.

DS/SSMA system with K transmitted signals is given in terms of the cross-correlation parameters for the 2K binary signature sequences. For the system with direct modulation onto quadriphase-coded carriers, however, this signal-to-noise ratio can be written in terms of the complex cross-correlation parameters for the K complex quadriphase signature sequences.

Recently, we have discovered that the two different modulation schemes described above are both special cases of a very general QDS/SSMA signal design in which non-orthogonal quadriphase coded carriers are allowed. It appears that any QDS/SSMA modulation technique of practical interest is a special case of this general QDS/SSMA signal format. We have analyzed this general QDS/SSMA system for an additive white Gaussian noise channel and have deduced all of our previous results [21] on QDS/SSMA.

16.3.2 Spread-Spectrum Communication via Fading Channels

In a direct-sequence spread-spectrum multiple-access (DS/SSMA) communications systems with an additive Gaussian noise channel, the output of each of the synchronized correlation receivers consists of a desired signal component, K-1 interfering signals due to the other transmitters, and an additive channel noise component. The signal-to-noise ratio at the output of the correlation receiver has been analyzed [20] for an additive white Gaussian noise channel. This signal-to-noise ratio has been shown to be an accurate measure of the average bit error probability. In the definition of signal-to-noise ratio, the noise is taken to be the K-1 interfering signal components plus the channel noise component. It has been shown [20,24] that the signal-to-noise ratio is completely specified by the aperiodic autocorrelation functions for the K binary signature sequences, and the channel noise spectral density.

In the present paper we consider binary DS/SSMA communication via fading channels. The type of fading considered is Rician fading; that is, for a single transmitted signal, the received signal consists of a strong specular signal (the desired signal) plus a weaker diffuse or Rayleigh-fading component. For fading that is not Rician (i.e., no strong specular component), the direct-sequence form of spread-spectrum communication would not generally be useful, since it could not be coherently demodulated.

For DS/SSMA via a Rician fading channel, each correlation receiver output consists of a desired signal (due to the specular component) plus noise. The noise consists of a "self-clutter" term (due to the diffuse fading component), K-1 interfering signals, and the additive channel noise. Each of the K-1 interfering signals have both a specular component and a diffuse component. Two types of Rician fading are considered, time-selective fading and frequency-selective fading. It is shown that the signal-to-noise ratio is completely specified by the aperiodic autocorrelation function for the signature sequences, the autocorrelation function for the fading process, and the thermal noise density. The signal-to-noise ratio is an important performance measure in its own right; moreover, we conjecture that it is an accurate measure of the error probability.

16.3.3 Design and Analysis of Sequences

There are a number of important electronic systems engineering problems which require sets of sequences with good correlation properties. Our work on the design and analysis of sequences has been primarily motivated by applications to multiple-access communications but our results are applicable to other areas such as multiple-terminal system identification, ranging, tracking,etc. Results in this area include a set of identities and bounds involving crosscorrelation and autocorrelation parameters of sequences [22,24,26]. These results enable us to achieve substantial reductions in the computational effort required to determine correlation parameters of interest in the SSMA problem [22]. The same identities lead to a number of interesting techniques for the construction of sequences with good correlation properties. Our methods can be used to construct sequences with optimal autocorrelation properties, uncorrelated sequences, and long impulse-equivalent sequences [27,28]. We have also studied the behavior of correlation parameters of random, binary sequences [23] which provides information on the asymptotic behavior of these parameters. Finally, we have initiated a study of M-ary sequences with good Hamming correlation properties, which can be used as hopping patterns for frequency-hopped SSMA communication systems. Preliminary results are reported in [25].

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17.1 Fault Analysis of Analog Circuits*

As systems become more and more complex the need for good fault diagnostic procedures becomes more obvious. In recent years much work has been done on the fault analysis of digital circuits, primarily because the increase in the size of these circuits has necessitated good fault tests. The two state nature ("1" or "0") of digital circuits has also made them more amenable to the development of reasonably simple and reliable test procedures. In contrast, research on fault diagnostic procedures for analog circuits has not been as productive. The difficulty lies in the practical restriction that connections cannot be broken on the circuit board. This means that currents cannot be measured reliably. With only voltage measurements available, typically an infinite number of fault conditions in the circuit could give rise to the observed voltage errors. To further complicate the problem a circuit's responses to a stimulus are nonlinearly related to its parameter values.

To begin this research project a survey was made of methods which have been proposed for the fault analysis of analog circuits, such as, fault dictionary techniques, sensitivity and optimization methods, functional or signal tracing techniques, short-circuit admittance parameter measurements, and the bilinear transform approach. The advantages and disadvantages of each of these methods were investigated and the results were presented in an invited paper at the IEEE Electro/78 Convention [1]. In addition, new approaches were sought for the isolation of faults in analog circuits. Initially all nodes were assumed to be

*This work was supported by the Joint Services Electronics Program (U.S. Army, U.S. Navy, and U.S. Air Force) under Contract DAAB-07-72-C-0259.

accessible and methods were investigated for the calculation of the circuit parameter values from node voltage measurements. In the case of resistor circuits which contain only a single faulty element it was shown that the faulty resistor can be identified as the one with the largest voltage change [2].

Further research was done on the calculation of circuit parameter values from the node voltage measurements. This work led to a new method by which circuit element values can be easily calculated from node voltage measurements [3,4]. Presently the application of this method for the fault analysis of electronic circuits is being investigated.

17.2 Reduced-Order Modeling by Error Minimization and Topological Formulas*

Previously an approximating function $F_a(s)$ was computed for a given function F(s) which satisfied the frequency constraints

$$\text{(I)} \quad F(j\omega_1) = F_a(j\omega_1)$$

and

$$\text{(II)} \quad F(0) = F_a(0).$$

Though such an approximating function is very easily obtainable from knowing only $F(j\omega_1)$ and F(0), several reasons lead us to modify it so that an approximating function $F_a(s)$ will have the same value as a given function F(s) not at $\omega = 0$ but at another prespecified frequency ω_2. In other words, a new approximating function $F_a(s)$ of a given function F(s) will satisfy

$$\text{(I)} \quad F(j\omega_1) = F_a(j\omega_1)$$

and

$$\text{(II)} \quad F(j\omega_2) = F_a(j\omega_2)$$

where ω_1 and ω_2 are any two specified frequencies. One form of such an approximating function $F_a(s)$ is

*This work was supported by the National Science Foundation under Grant ENG 75-14100 and by the Joint Services Electronics Program (U.S. Army, U.S. Navy, and U.S. Air Force) under Contract DAAB-07-72-C-0259.

$$F_a(s) = \left[\frac{A + jB}{(s - p_o)(s - \bar{p}_o)}\right]^r$$

where A and B are real constants. It is found that such a function always exists for any given function F(s). Also when a given function is a quotient of polynomials, then the error by this approximating function $F_a(s)$ at a frequency ω will be small if the distances between p_o and the zeros and the poles of F(s) are small compared with the distance between p_o and $j\omega$.

When a large scale system consists of blocks each of which is represented by a network function, one way of approximating the overall response of the system is by approximating the network function of each block. Another way to approximate the response is by the use of topological relationships between the overall response and the network functions of each block so that one can approximate the numerator and the denominator of overall response. This latter method allows us to develop several modified forms of the approximating function $F_a(s)$. One of the modified forms is

$$F_a(s) = \frac{[(A + jB)(s - z_o)(s - \bar{z}_o)]^r}{[(s - p_o)(s - \bar{p}_o)]^t}$$

where p_o is a prespecified pole. Another form is

$$F_a(s) = \frac{A}{(s - \alpha)^t[(s - p_o)(s - \bar{p}_o)]^r}$$

where α is a real constant. The properties of these approximating functions and the application of these approximating functions in the analysis of large scale systems will be published soon [5].

17.3 High Performance Structures for Recursive Digital Filters*

Speed and accuracy of a recursive digital filter are limited by the computational complexity of the filter arithmetic, and by the finite

*This work was supported by the National Science Foundation under Grant No. INT 76-84216 and by the University of Illinois.

wordlengths that must be used in practical filters. Both arithmetic roundoff error and errors created in the filter response due to coefficient quantization are highly sensitive to the structure of the network used to realize the transfer function. The complexity of the arithmetic operations depends on the recursive equations, as well as on the number representation used to encode the internal states of the filter. The first objective of this research is to investigate low sensitivity multiple feedback structures that are flexible enough to realize transfer functions with both poles and zeros. The second objective is to evaluate different number codes in an effort to find codes that simplify the mechanization of multiplication and addition. Low sensitivity implies that the filter can operate with short wordlengths. Reduced computational complexity leads to simplified hardware, improves operating speed, and lower overall cost. Since fault tolerance is also important in high performance systems, the study of number codes has included a search for number representations that provide error detection and correction capability.

A new multiple feedback lowpass recursive filter structure has been compared to other low sensitivity structures on the basis of roundoff noise at the filter output. In particular, comparative studies included the second-order direct form cascade structure, the second-order coupled form cascade structure, a new low sensitivity multiple feedback structure which is a modification of the Vaughan-Pope and Bruton structure and a wave digital filter of Fettweis [6]. The new multiple feedback structure showed considerably less roundoff noise than the direct form cascade structure. It was similar in roundoff noise performance to the coupled form structure and the wave digital filter for narrow-band lowpass filters. A computer program that was developed for computing coefficient sensitivities is now being used to compare the coefficient sensitivities of these structures.

In addition, a new class of recursive architectures was derived by applying residue number coding to the recursive difference equations [7,8]. One particularly interesting structure that resulted from this procedure consists of a parallel interconnection of second order sections, where each second order section is made up of L parallel residue subfilters and L is the number of residue digits used to represent the internal

states. It was described in [9] how concepts from combinatorial digital filters can be combined with the residue architecture to form a highly efficient hybrid structure. A new technique for scaling in residue number systems was discovered that enables the recursive difference equation to be implemented efficiently in four specialized classes of residue systems. New results were obtained in applying residue techniques to adaptive filters [10], in residue input-output translation, and in fault detection in residue filters [11]. The primary advantages of the residue number architectures are high speed table look-up arithmetic using semiconductor memories, high precision without a sacrifice in operating speed, and overall low cost that results from an abundant use of read-only memories [12,13].

17.4. New Structures for Switched Capacitor Integrated Filters*

Switched capacitors can be used to replace resistors in active filters for achieving fully integrated sampled data recursive filters [14]. The response of this type of filter depends on the switching rate and the ratios of capacitances. Since the ratio of capacitances can be precisely controlled (whereas absolute values cannot), and since capacitors, MOS switches, and operational amplifiers can be integrated on the same substrate, the switched capacitor approach is a promising way of mass-producing precise, low cost integrated filters.

Sampled data filters of this type have been successfully designed by applying switched capacitor transformations to conventional active filters in the state variable configurations [15]. In these filters, the analog integrators are replaced by sampled-data accumulators. An analysis of these sampled data accumulators using z-transform theory revealed that the parallel switched capacitor integrator is actually a realization of a discrete-time integrator derived by a forward Euler difference approximation. Similarly, it was found that the series switched-capacitor integrator corresponds to a backward Euler difference approximation. Since it is well known from digital filter theory that the Euler approximations seriously distort the frequency response of the filter in transforming from

*This work was supported by the University of Illinois.

the analog to the digital domain, it was concluded that other switched capacitor structures should be investigated.

A new circuit was proposed that transforms a state variable second-order analog filter into a sampled data filter with a transmission zero at half the sampling frequency [16]. The circuit was a result of attempting to transform the analog filter by means of the bilinear z-transformation, which is known to preserve the frequency response of the analog filter. Although the filter did not represent a true bilinear version of the original filter, it did have a zero at half the sampling frequency, and it yielded significantly improved characteristic for both lowpass and bandpass filters. This improvement was predicted by computer analysis and was later verified by experimental measurements taken from a laboratory model constructed with discrete circuit components.

Further results were obtained [17] in the form of a new switched-capacitor integrator that truly represents a bilinear sampled data integrator and that requires less hardware than another design [19]. This new integrator can be used to produce true bilinear sampled data state variable filters. It also has potential as a replacement for the Euler integrators in the sampled data ladders of Jacobs et al. [18] that are of interest because of their low sensitivities. The one problem that still remains is that the new integrator does not accommodate a differential input, as needed in the ladder filters. The search continues for a switched-capacitor bilinear integrator with a differential input so that sampled-data ladders can be designed with the desirable features of the bilinear z-transform.

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18.1 Introduction

Several projects have led to many results involving various aspects of control analysis, synthesis, and optimization. The key directions are in decentralized control of large scale systems; multi-models in large scale systems; structural properties of systems including sensitivity, controllability, and observability; model simplification by singular perturbation methods and chained aggregation methods; stochastic control of systems containing parameter uncertainty; control of systems with multiple decision makers; and optimization methods.

18.2 Sensitivity Adaptive Feedback with Estimation Redistribution*

When a control law is to be designed for an uncertain system with unknown parameters, two roles of the control signal have to be considered: one is the effect of the control signal on the estimation of the unknown plant parameters and/or state variables, and another is the attainment of the control objective. This dual role of the control was first pointed out by Feldbaum [1]. In general, these two roles of the control are conflicting. Therefore the design of a dual controller requires that a compromise be made between the estimation and control

*This work was supported by the U.S. Air Force Office of Scientific Research under Grant AFOSR-73-2570, by the Joint Services Electronics Program (U.S. Army, U.S. Navy, and U.S. Air Force) under Contract DAAB-07-72-C-0259, and by the National Science Foundation under Grant INT-77-20969.

objectives. The optimal solution to the dual control problem is achieved through the use of a closed-loop controller. This is the only controller that can attempt a compromise between its two objectives, since it anticipates that future measurements will be taken. The problem of getting the closed loop control law leads in general to a nonlinear problem and only approximate solutions can be obtained. Much effort has been made to obtain tractable methods of solution [2-4]; some are approximations to the optimal solution and others use the conflicting characteristic of the dual property of the control.

We have developed a new way of formulating a stochastic adaptive control problem that incorporates a cost assignment for the estimation effort that automatically redistributes the estimation budget in a rational way. In this approach a fixed budget for estimation is considered. The estimation effort is redistributed according to the accuracy required to achieve a given control objective. Greater estimation accuracy results in a greater cost. Parameters which have greater influence on the state of the system require more accurate estimation than those whose effect on the state is less significant. The cost of estimation has been explicitly considered before [5] but the novel features in our work are the explicit inclusion of the cost of estimation through a sensitivity function approach, and more importantly, the redistribution of the parameter estimation accuracies to improve overall control performance.

We have considered the problem of designing feedback control laws for a class of multi-input-multi-output discrete time stochastic systems with unknown parameters. The optimization is performed so that a measure of the total energy the control spends in estimation does not exceed the budget available for estimation. We have obtained a feedback solution for the control that explicitly takes into account the accuracy of the estimation and that redistributes the estimation effort so that the overall performance of the system is improved. We call this control Sensitivity Adaptive Feedback with Estimation Redistribution (SAFER) control, and details are given in [6].

18.3 Sensitivity Reducing Compensators Using Observers*

A desirable property of any control design is that it be insensitive to small variations in the parameters of the controlled plant. The mathematical model can only approximate the physical problem so that the assumed values of parameters for the design may be different from the actual parameter values upon implementation. Also, most systems suffer from some forms of unmeasurable or unpredictable variations due to the degeneration of physical components and adverse environmental effects. The potential benefits of using state feedback to improve sensitivity can be evaluated by comparing the sensitivity of the closed-loop design to a nominally equivalent open-loop control. The development of these concepts has led to the definition of the comparison sensitivity operator [7] which directly relates the open-loop and closed-loop sensitivities, and a sensitivity reduction criterion giving sufficient conditions for a particular feedback control law to guarantee sensitivity reduction in comparison to the open-loop control [7,8].

Necessary and sufficient conditions for satisfaction of this comparison sensitivity reduction criterion have been derived for full state feedback control laws [9], and more recently for output feedback controls using dynamic compensators [10]. In both instances it is shown that sensitivity reduction is directly related to some optimal control.

We have developed an extension of [10] to the particular case of output feedback systems which use state observers to implement dynamic compensation of the plant. It should be noted that implementing a full state feedback law using an observer to estimate the unmeasured states, where the state feedback gains satisfy the sensitivity reduction design of [9], will not in general satisfy the output sensitivity reduction criterion. This is evident from the results of [10]. A comprehensive design procedure has been developed and its application through the use of an interactive software implementation has been carried out for a simple aircraft control example [11,12].

*This work was supported by the U.S. Air Force Office of Scientific Research under Grant AFOSR-73-2570, by the Joint Services Electronics Program (U.S. Army, U.S. Navy, and U.S. Air Force) under Contract DAAB-07-72-C-0259, and by the National Science Foundation under Grant ENG-74-20091.

The design procedure using observers is an improvement over the design with arbitrary compensator dynamics as described in [10] for the following reasons. First, the design of the observer is well known and by placing the poles of the observer the designer is selecting poles of the overall feedback system. Second, the dynamic order of the reduced order observer is less than the maximal bound on the dynamic order of the compensator designed by the methods of [10]. Finally, the use of observers leads to a useful interpretation of the sensitivity weighting matrix [11, 12].

18.4 Chained Aggregation*

Chained aggregation is a reduced order modeling procedure which retains the subsystem dynamics which are strongly observable in the available outputs. It transforms the system to the Generalized Hessenberg Representation (GHR) which is used to detect weakly observable subsystems and to define a collection of plausible reduced order models. If the weakly observable part cannot be simply neglected, GHR also defines a subset of model parameters appropriate for adjustment.

For a linear time invariant system

$$\dot{x} = Ax + Bu, \qquad y = Cx, \tag{1}$$

where $x \in R^n$, $u \in R^m$, a reduced r_i-th order state $z_1, r_1 < n$, is defined as $z_1 = Cx$, the aggregation matrix C is partitioned as $C = [C_{11}\ \bar{C}_{11}]$, where $\det C_{11} \neq 0$. The transformation

$$z = Tx, \quad T = \begin{bmatrix} C_{11} & \bar{C}_{11} \\ 0 & I_{n-r_1} \end{bmatrix}, \quad z = \begin{bmatrix} z_1 \\ z_2 \end{bmatrix} \tag{2}$$

of (1) yields

*This work was supported by the National Science Foundation under Grant ENG-74-20091, by the Electric Energy Systems Division of the Department of Energy under Contract EX-76-C-01-2088, and by the Joint Services Electronics Program (U.S. Army, U.S. Navy, and U.S. Air Force) under Contract DAAB-07-72-C-0259.

$$\dot{z} = \begin{bmatrix} F_{11} & F_{12} \\ F_{21} & F_{22} \end{bmatrix} z + \begin{bmatrix} G_{11} \\ G_{12} \end{bmatrix} u \quad . \tag{3}$$

and (1) is said to be completely aggregable with respect to C if $F_{12} = 0$. If so, the resulting tandem configuration has no feedback from the residual z_2 into the aggregate z_1, and the residual subsystem is unobservable from z_1. The more general case needing the chained aggregation occurs when (1) is not completely aggregable. In chained aggregation the term $F_{12}z_2$ is viewed as the output of the residual subsystem and used to enlarge the aggregate state $z_1 = y$. A transformation analogous to (2) is then applied to the residual, producing a new aggregate subsystem and a new residual. The process is repeated until the system is expressed in the Generalized Hessenberg Representation. The GHR determines a collection of candidate structures of the reduced order models and singles out parameters whose adjustment, if necessary, will compensate the influence of the interaction between the aggregate and the residual. A restricted QL algorithm is developed for this purpose. Thus model reduction consists of: (i) transforming the system into the GHR, (ii) selecting from the GHR a structure and a set of adjustable parameters, (iii) using the restricted QL algorithm for the adjustment of these parameters. The derived models describe the dynamic behavior observed through the available measurement, require the adjustment of only a subset of parameters and at the same time retain the structure of the subsystem strongly observable through the outputs. For details see [13-16].

18.5 Singular Perturbation*

In this well-known approach a parameter μ is introduced such that at $\mu = 0$, only the slow, and at $\mu > 0$ both the slow and fast phenomena are modeled. One of the new research directions uses this approach for time scale separation in optimal regulator design. This

*This work was supported by the Joint Services Electronics Program (U.S. Army, U.S. Navy, and U.S. Air Force) under Contract DAAB-07-72-C-0259, by the Electric Energy Systems Division of the U.S. Department of Energy under Contract EX-76-C-01-2088, by the National Science Foundation under Grant ENG-74-20091, and by the U.S. Air Force Office of Scientific Research under Grant AFOSR-73-2570.

has been accomplished for linear systems [17] and for the nonlinear system in the form

$$\dot{x} = a_1(x) + A_1(x)z + B_1(x)u \tag{1}$$

$$\mu\dot{z} = a_2(x) + A_2(x)z + B_2(x)u \tag{2}$$

where $x \in R^n$, $z \in R^m$ are the "slow" and "fast" states and $u \in R^r$ is the control. It is of practical interest that synchronous machine models are of this type [18]. A guaranteed region of asymptotic stability of (1), (2) has been determined in [19] and a near optimum two time scale design has been developed in [20,21], applicable to some essentially nonlinear systems.

Another research direction deals with the singularly perturbed stochastic control problem [22,23] in which the meaning of fast variables is not always clear due to the white noise model used in the system representation. The problem has since been reformulated to allow the fast modes to serve as a model for well-defined variables in the stretched time-scale, with non-negligible contribution to the slow modes of the system. The new formulation is made possible by the introduction of additional scaling in α, β, γ, and δ powers of μ, as in the LQG problem

$$\dot{x} = A_1x + \mu^{\alpha}A_{12}z + B_1u + G_1w \tag{3}$$

$$\mu\dot{z} = A_{21}x + A_2z + B_2u + \mu^{\beta}G_2w \tag{4}$$

$$y_1 = C_{11}x + C_{12}z + v_1 \tag{5}$$

$$y_2 = C_{22}z + \mu^{\gamma}v_2 \tag{6}$$

$$J = \frac{1}{2}\begin{bmatrix} x \\ z \end{bmatrix}' \Gamma \begin{bmatrix} x \\ z \end{bmatrix}_{t=T} + \frac{1}{2}\int_0^T [x'Q_1x + 2x'Q_{12}z + \mu^{\delta}z'Q_2z + u'Ru]dt \tag{7}$$

where y_1, y_2 are the observations and w, v_1, v_2 are white Gaussian noise vectors with finite covariances in the slow time-scale. The objective here is to determine the relative values of the parameters α, β, γ, δ which result in meaningful approximate variables and a finite performance index. For example, in the case $\alpha = 0$ and $\mathrm{Re}\,\lambda(A_2) < 0$ the following set of values will yield meaningful fast and slow variables $0 \leq \beta \leq \frac{1}{2}$, $\gamma \geq \beta$, $\delta \geq (1-2\beta)$. When $\gamma > \beta$ the fast states observations are noise-free,

while when $\delta > (1-2\beta)$ the fast states are not of interest to the control problem. Two extreme cases of β are of particular interest. If $\beta = 0$, the fast states represent parasitic wide-band processes which appear as an additional input noise in both the system and the observations, and are of no consequence to the performance index. If $\beta = \frac{1}{2}$, the fast states behave as a regular Gauss-Markov process in the stretched time scale t/μ, and hence may represent important fast varying stochasitc phenomena. Of course, the case $\beta > \frac{1}{2}$ degenerates to a deterministic problem.

In general the fast states may be partitioned into several substates with different values of the appropriate parameters. Extension to a hierarchy of multiple time scales may be performed as in [23].

18.6 Well-Posedness of Singularly Perturbed Nash Games*

If two or more decision makers control the same system each with a separate performance index, it is necessary to examine the effect of singular perturbation on their strategies. Specifically, consider a Nash equilibrium of a nonzero-sum differential game for a linear plant with two decision makers using linear state feedback and quadratic performance indices. Let the strategies be obtained for lower order models, one for a slow game and one for a fast game. The slow game neglects the fast modes and the fast game assumes the slow variables to be constant. A composite control synthesized from the two lower order games is then applied to the high order plant. The performance indices using these approximate controls are compared to the true Nash performance indices as the singular perturbation parameter of the plant tends to zero. If these limits are equal, the lower order game problems are said to be well-posed. Otherwise they are ill-posed.

It has been shown by counterexample that the usual procedure when applied to the nonzero-sum game leads to an ill-posed reduced order game [25]. However, for the zero-sum case, the reduced order game is well-posed [26].

*This work was supported by the Division of Electric Energy Systems, U.S. Department of Energy under Contract EX-76-C-01-2088, by the National Science Foundation under Grant ENG 74-20091, and by the Joint Services Electronics Program (U.S. Army, U.S. Navy, and U.S. Air Force) under Contract DAAB-07-72-C-0259.

If the performance indices do not depend on the fast components of the fast state variables, the usual singular perturbation is well-posed even for nonzero-sum games [25]. This performance index is physically consistent with the assumption that fast modes are inadequately modeled and even neglected in the calculation of the controls.

In cases where the performance indices contain fast modes, a well-posed reduced order game has been formulated for designing the approximate Nash controls. In contrast to the full separation possible in control problems here the order reduction is hierarchical [25]. The fast game is solved first. A composite control consisting of a slow component yet to be determined, and a fast component whose feedback gain is obtained from the fast game, is then substituted in the high order plant model. Upon setting the singular perturbation parameter to zero, a reduced order slow game is obtained. However, this slow game differs from the usual one in that the system matrices now depend on the fast game solution. A reduced order composite control utilizing this modified slow game is shown to be well-posed [25]. This hierarchical reduction is somewhat analogous to leader-follower strategies [27] where the fast modes correspond to the follower and the slow modes correspond to the leader.

Investigation of the necessary conditions for closed-loop Nash solutions in [28] has shown that the cause for ill-posedness is that the neglecting of the fast modes excludes them from the feedback information available to the decision makers in solving the slow game. Since Nash solutions are different for different feedback information structures, a solution of the full order game using feedback from the fast variables does not tend to a solution of the slow game where this information is lost. Thus, such phenomena are not restricted to Nash strategies, but can be expected in other situations when open and closed loop solutions differ.

18.7 Multi-Modeling of Large Scale Systems*

The concept of multi-controller strategies with nonclassical information patterns expresses a basic fact that a controller has neither complete nor instantaneous access to other controllers' measurements and decisions. This project extends the notion of nonclassical information patterns by introducing a new concept of multi-modeling. It expresses a related and perhaps more basic fact that different controllers have different information about the system structure and dynamics and therefore use different simplified models of the same large scale system. These models may differ in parameter values, signal uncertainties, and, more critically, in their basic structural properties.

A strong motivation for the multi-modeling approach is found in multi-area power systems. The controller operating in an area employs a detailed model of his area only and a "dynamic equivalent" of the remainder of the system. Other controllers behave similarly in their own areas. Thus the same power system appears in different forms to different controllers. Present power system practice suggests that even if the controllers were given a complete model of the system, they would still use different simplified models to match their individual needs.

Interconnected subsystems often interact through their slow dynamics while the coupling of their fast dynamics is limited. It can be assumed then that each decision maker neglects the fast dynamics of all the other subsystems. Such a situation can be modeled by

$$\dot{x} = f(x) + \sum_{j=1}^{N} F_j(x)z_j + \sum_{j=1}^{N} B_j(x)u_j \qquad (1)$$

$$\varepsilon_i \dot{z}_i = g_i(x) + \sum_{j=1}^{N} G_{ij}(x)z_j + B_{ii}(x)u_i \ , \qquad (2)$$

where $\varepsilon_i > 0$, $i = 1,\ldots,N$ are the small parameters, one per subsystem. However, the model known to the i-th decision maker is

*This work was supported by the Electric Energy Systems Division of the U.S. Department of Energy under Contract EX-76-C-01-2088, by the National Science Foundation under Grant ENG-74-20091, and by the Joint Services Electronics Program (U.S. Army, U.S. Navy, and U.S. Air Force) under Contract DAAB-07-72-C-0259.

$$\dot{x} = \bar{f}_i(x) + \bar{F}_i(x)z_i + \sum_{j=1}^{N} \bar{B}_j(x)u_j \tag{3}$$

$$\varepsilon_i \dot{z}_i = \bar{g}_i(x) + \bar{G}_i(x)z_i + B_{ii}(x)u_i \tag{4}$$

and it is consistent with what would have been obtained by assuming $\varepsilon_j = 0$, $i \neq j$, and neglecting the fast interactions, G_{ij}, $i \neq j$. The fundamental problem is to determine how a control strategy based on (3), (4) will behave when applied to (1), (2). This problem has been approached in two ways. In [29] it is assumed that G_{ij}, $i \neq j$ are $0(\varepsilon)$ and it is shown that the behavior of the actual system is $0(\varepsilon)$ close to the behavior expected by the decision makers. In the more difficult case [30] when G_{ij} are not $0(\varepsilon)$ but are limited in some sense, a block D-stability condition is shown to be sufficient to guarantee stability of the resulting feedback system. The work is in progress on further nonlinear and stochastic generalizations of these results.

18.8 Large Scale Systems*

One can associate a matrix, the occurrence or primitive connection matrix, and, correspondingly, a directed graph, with every dynamical system describable by the set of equations

$$\dot{x}_k = f_k(x_1,\ldots,x_m, t), \quad k = 1,\ldots,m \tag{1}$$

The maximally strongly connected subgraphs of the directed graph play an important role in analyzing the behavior of the system (1). In particular if the dynamical system is written in canonical structural form, where the state variables are identified with the branches of the maximally strongly connected subgraphs of the direct graph, then under mild conditions one can infer that if the isolated subsystems are asymptotically stable the entire system is stable. Here the subsystems are defined to be those portions of (1) which correspond to separate maximally strongly connected subgraphs of the directed graph. One obtains various stability results by making differing assumptions concerning

*This work was supported by the Joint Services Electronics Program (U.S. Army, U.S. Navy, and U.S. Air Force) under Contract DAAB-07-72-C-0259.

the stability of the isolated subsystems. Similar but weaker results can be obtained by considering the observability and controllability of the subsystems of (1). This work is being prepared for publication.

18.9 Constrained Stochastic Power Flow Analysis*

A major component of the planning strategy for large scale power systems is the evaluation of system performance for specified network loading. Stochastic power flow analysis has been proposed as a method to evaluate a large quantity of different load schedules in one load flow algorithm. Significant progress has been made in this approach [31]. Current stochastic power flow methods do not include the finite ranges of Tap-Changing-Under-Load transformers and generator excitation systems. These constraints can have a significant effect on the statistical distribution of power system voltages in response to multi-schedule uncertain loading. A method of multiple linear transformations and the multivariate Gram-Charlier series is being developed as a viable approach [32]. Statistical distributions are described by the joint moments of the random loads which facilitates their transformation through multiple linear transformations. The multiple linear transformations represent the various linearizations of the power flow equations when voltage control variables are constrained.

The evaluation of system performance under large excursions in network loading is frequently complicated by the lack of a real solution. The use of linear load flow techniques does not account for the possibility of load flow failure, and thus produces non-conservative results. A fast detection scheme for predicting linear load flow failure has been developed for pure D.C. systems [33]. The method exploits the quadratic form of the power flow equations in rectangular coordinates, and tests for negative discriminants at critical proposed operating points. This work is being extended to accommodate full A.C. systems.

*This work was supported by the Division of Electric Energy Systems of the U.S. Department of Energy under Contract DOE EC77-S-02-4345, and by the National Science Foundation under Grant NSF ENG 78-05594.

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Faculty and Senior Staff

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19.1 Introduction

a. This program is concerned with the use of computer-generated graphics in teaching a number of interrelated disciplines dealing with population. Under this program for the NSF, we are distributing the DEMO-GRAPHICS software to universities and colleges throughout the USA. The purpose is to provide innovation in the teaching of these subjects through the use of computers. Thus far, the population program has been introduced into more than 38 universities and colleges and has been used in many classes and demonstrations. This coming fall the material will probably be used by thousands of students.

The mode of information transfer is primarily through the use of computer-generated graphics and also includes the use of other types of visual materials, such as slides, transparencies, and booklets derived from the computer-generated graphics. In addition, user manuals, teachers' guides and other printed materials are also available. The programs are now running on a number of computer systems and are almost machine independent, thus enabling wide use. We plan to extend the use of the materials to additional educational institutions and to many other disciplines. We have run a number of workshops for teachers and graduate students as an introduction in the use of DEMO-GRAPHICS in their various disciplines.

b. A second program is concerned with developing long range forecasting techniques for weather and climate. The forecast range varies from a few months to a few years. In addition to the common meteorological variables, crop data has been found to be a useful indicator of long range weather trends.

19.2 Programming

For the NSF contract we have ten programs written in BASIC which can be run on almost any computer-output device combination.

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*This work was supported by the National Science Foundation under Grant SED 76-18446.

1. Index Program - a descriptive listing of all distributed programs.
2. Data Base Query Program - a data printout of all the demographic information utilized by the programs for each country.
3. Population Projections Program - population projections for any of the 136 available countries plus 10 user-defined regions. Ten population indicators may be projected; age composition bar graphs and line graphs are included.
4. Population History Program - historical data and population projections for the 136 countries and 10 user-defined regions.
5. General Purpose Program - population data for the 136 countries and 10 user-defined regions with which projections of any population-related quantity may be made.
6. International Migration Program - population projections for any of the 136 countries and 10 user-defined regions, with the option of including net migration figures.
7. Cereal Program - projection of cereal supply and demand for 136 countries.
8. Two-Sex Population Projection Program - population projections, including a user option to vary vital rates for each sex separately.
9. Adding Your Own Data - an opportunity to include other countries or regions (states, cities, etc.) to the data base for use with the other DEMO-GRAPHICS programs, except the Cereal Program.
10. Creating a Bloc - an option which permits the user to combine the data for two or more countries to permit regional population studies.

The computer programs are about 20k bytes in length and are very similar to the PLATO programs. User manuals have been written for instructors using the program in their courses, and a number of demonstration modules illustrate how computer-assisted instruction can transfer certain concepts associated with population to the student. We have established a Newsletter for users of the program to obtain feedback and interchange ideas between instructors. We have distributed tapes to over 90 institutions throughout the United States, Canada, the Mideast and Europe. In time we believe most of these institutions will be using the system.

At the present time, the following institutions are using the program: University of Akron, Arizona State, Augustana College, Bowling Green State, University of California (Berkeley), University of California (Santa Barbara), California State University - Chico, University of Chicago, University of Cincinnati, Dartmouth College, University of Delaware, University of Denver, Eastern Kentucky University, Duke University, Emory University, Fullerton College, University of Georgia, Hope College, Illinois State University, University of Illinois, Iowa State, Kansas State University, University of Maryland, Michigan State University, New Mexico State University, University of North Carolina, Oberlin College, Old Dominion University, University of Pittsburgh, University of Rochester, University of Tennessee, Tennessee Technological University, Tuskegee Institute, University of Utah, University of Western Ontario, University of Wisconsin-Green Bay, University of Wisconsin-Madison and Western Washington State College. Some of the institutions now using the program have also shown the program to other people and are acting as secondary sources of distribution.

During the most recent meeting of the Population Association of America we held a seminar attended by over 23 people on the use of the programs in demographic education. The seminar was well received and may be repeated again next year.

19.3 Long Range Weather Forecasting

During the past two years a new program has been initiated to determine whether it is possible to develop a system which would allow one to forecast climate or weather six months to two years in advance. Some preliminary success has been obtained using worldwide crop production and yield data as well as a number of unique meteorological variables. The program has been relatively successful in that a number of predictions have been made which have, in fact, occurred. While the program is still in its infancy, we hope by including additional variables and new mathematical techniques that we will be able to improve the reliability of the forecasts to the point where they will become an important tool in long range weather forecasting.

APPENDIX A

SUMMARY OF TRAVEL

Date of Travel	Personnel	Places of Visit	Purpose
1977			
6/27-7/1	Gernot Metze	Los Angeles, California	To present papers entitled "Design of Totally Self-Checking Combinational Circuits" and "A New Fault Model for LSI Modules" at the 1977 International Symposium on Fault-Tolerant Computing.
7/10-7/15	Ben G. Streetman	Meridian, New Hampshire	To present a paper entitled "Nitrogen Trap in $GaAs_{1-x}P_x$ at the Gordon Research Conference on *Line and Point Deflection Semiconductors.*
7/14-7/16	R. T. Chien	Raleigh, North Carolina	To discuss JSEP research with Dr. Jimmie Suttle at the Army Research Office.
7/29-8/20	Raj Mittra	Palo Alto, California	To discuss space applications of millimeter waves with NASA/JPL at California Institute of Technology.
8/2-8/4	R. T. Chien	San Francisco, California	To participate in the Joint Services Electronics Program Topical Review at Stanford Electronics Lab.
8/2-8/4	J. E. Greene	San Francisco, California	To present a paper entitled "Growth of InSb and (InGa)Sb Thin Films by RF Multitarget Sputtering" at the Joint Services Electronics Program Topical Review at Stanford Electronics Lab.
8/2-8/4	Ben G. Streetman	San Francisco, California	To present a paper entitled "Studies of Deep Level Impurities in $GaAs_{1-x}P_x$ and $Al_{1-x}Ga_xAs$ at the Joint Services Electronics Program Topical Review at Stanford Electronics Lab.

SUMMARY OF TRAVEL (continued)

Date of Travel	Personnel	Places of Visit	Purpose
8/20-8/27	H. Harlyn Baker	Boston, Massachusetts	To present a paper entitled "Three-Dimensional Modelling" at the 1977 5th International Joint Conference on Artificial Intelligence.
8/20-8/27	Cliff Geschke William Brew	Boston, Massachusetts	To present a paper entitled "A Variable Capacitance Touch Sensor" at the 5th International Joint Conference on Artificial Intelligence.
8/20-8/26	Larry Peterson David Chen Rod Fletcher Y. C. Pan	Boston, Massachusetts	To present a paper entitled "Image Compression and Reconstruction Using Feature Extraction" at the 5th International Joint Conference on Artificial Intelligence.
8-21-8/25	David Burr Charles Jacobus Steve Nelson Michael Selander	Boston, Massachusetts	To present a paper entitled "A System for Stereo Computer Vision with Geometric Models" at the 5th International Joint Conference on Artificial Intelligence.
8/22-8/25	R. T. Chien	Boston, Massachusetts	To present a paper entitled "Using and Re-Using Partial Plans" at the 5th International Joint Conference on Artificial Intelligence.
9/28	Carl M. Panasik	Indianapolis, Indiana	To obtain repair of Tektronix computer output hard copy unit.
10/9-10/16	Richard A. Flower	Ithaca, New York	To present a paper entitled "Bounds on Update Algorithms" at the IEEE International Symposium on Information Theory.

SUMMARY OF TRAVEL (continued)

Date of Travel	Personnel	Places of Visit	Purpose
10/9-10/11	K. V. Vaidyanathan	Atlanta, Georgia	To present a paper entitled "Study of Encapsulants for Annealing of GaAs" at the Fall Meeting of the Electrochemical Society.
10/11-10/14	Piero Maestrini	Ithaca, New York	To present a paper entitled "Arithmetic Codes in Residue Number Systems" at the IEEE International Symposium on Information Theory.
10/25-10/28	Supriyo Datta	Phoenix, Arizona	To present a paper entitled "Analysis of Acoustic Waves in General Piezoelectric Wedges Using Ortonormal Functions" at the IEEE Group on Sonics and Ultrasonics.
10/25-10/28	Bill Hunsinger	Phoenix, Arizona	To present a paper entitled "Capacitive Tap Weighted SAW Transducers" at the IEEE Sonic and Ultrsonic Symposium.
10/25-10/28	Don Malocha	Phoenix, Arizona	To present a paper entitled "Capacitive Tap Weighted SAW Transducers with Reduced Losses" at the Ultrasonics Symposium.
11/1-11/4	Gernot Metze	Hyannis, Massachusetts	To participate in The 1977 Automation Testing Conference.
11/6-11/9	Harold V. Poor	Monterey, California	To present a paper entitled "Optimum Data Quantization for a General Signal Detection Problem" at the 11th Annual Asilomar Conference on Circuits, Systems, and Computers.

SUMMARY OF TRAVEL (continued)

Date of Travel	Personnel	Places of Visit	Purpose
11/7-11/11	J. E. Greene	Boston Massachusetts	To present a paper entitled "Optical Spectroscopy for Glow Discharge Sputtering Diagnostics and Process Control" at the American Vacuum Society National Symposium.
11/7-11/11	Jon Culton	Boston, Massachusetts	To participate at the American Vacuum Society National Symposium.
11/8	Edward S. Davidson	Chicago, Illinois	To present a paper entitled "Toward a Microprocessor Based Computer System" at the MIDCON.
11/20-11/21	R. T. Chien	*Raleigh-Durham*, North Carolina	*To discuss JSEP research with Dr. Jimmie Suttle* at the Army Research Office.
12/2	Gerald T. Marcyk	Des Plaines, Illinois	To present a paper entitled "Impurity Profiles in Semiconductors Measured by Glow Discharge Optical Spectroscopy" at the American Vacuum Society.
12/7-12/12	Dimitri Bertsekas	New Orleans, Louisiana	To present a paper entitled "Alternative Theoretical Framework for Finite Horizon Stochastic Optimal Control" at the IEEE Decision and Control Conference.
12/12-12/14	W. K. Jenkins	Atlanta, Georgia	To attend an ARO sponsored Review of Georgia Tech's Program on 2D Digital Signal Processing.
12/12	Larry J. Peterson Michael Selander	Northbrook, Illinois	To see a demonstration of a display device at EMI Medical Institute.

SUMMARY OF TRAVEL (continued)

Date of Travel	Personnel	Places of Visit	Purpose
12/14	A. Y. Cho	Summit, New Jersey to Urbana, Illinois	To attend the Coordinated Science Laboratory Annual JSEP Review at the request of the Director.
1978			
1/25-2/2	R. T. Chien	Salt Lake City, Utah & San Francisco, California	To present a talk at the Workshop on Automatic Test Program Generation (Salt Lake City) and attend JSEP Reviews at Stanford and Berkley.
2/22-2/24	R. T. Chien	Pacific Grove, California	To present a paper entitled "Time Varying Images and 3-D Modelling" at the Engineering Foundation Conference on Vision.
3/3-3/9	Dimitri Bertsekas	Bromwoods, Missouri	To participate in the Washington University's Workshop on Current Topics in Communications.
3/5-3/8	Michael Pursley	Bromwoods, Missouri	To present a paper entitled "Representation Theory for Broadcast Channels" at the Washington University's Workshop on Current Topics in Communications.
3/26-3/29	Donald Wolford	Washington, D. C.	To present a paper entitled "Resonant Raman Study of N-Doped $GaAs_{1-x}P_x$ Alloys" at the American Physical Society Spring Meeting.
3/27-3/30	Franco Preparata	San Antonio, Texas	To participate in the Workshop on Science of Design (of Computing Systems) sponsored by U. S. Naval Laboratory, San Diego, California.

SUMMARY OF TRAVEL (continued)

Date of Travel	Personnel	Places of Visit	Purpose
3/28-3/31	A. H. Haddad	Baltimore, Maryland	To present a paper entitled "Adaptive Estimation in Linear Systems with Unknown Markovian Noise Statistics" at the Johns Hopkins Conference on Information Science and Systems.
3/28-3/30	H. Vincent Poor	Baltimore, Maryland	To present papers entitled "A Robustness Property of Signal-to-Noise Ratios" and "Optimum Quantization for Memoryless Detection in m-Dependent Noise" at the Johns Hopkins Conference on Information Science and Systems.
3/29-3/30	J. A. Abraham	Baltimore, Maryland	To present a paper entitled "Roving Diagnosis for High Performance Digital Systems" at the Johns Hopkins Conference on Information Science and Systems.
3/29-3/30	Gernot Metze	Baltimore, Maryland	To present a paper entitled "Alternating Logic: Self-Checking Logic Using Redundancy in Time" at the Johns Hopkins Conference on Information Science and Systems.
4/3-4/8	Robert T. Chien	San Diego, California	To present a paper entitled "On the Use of Deductive Models for Automatic Test Programs for Analog Circuits" at the Industry/Joint Services Automatic Test Conference and Workshop and visit McDonnell-Douglas Aircraft.
4/4-4/6	T. N. Trick	San Diego, California	To present a paper entitled "Modeling for Fault Analysis" at the Automatic Test Program Group Workshop.

SUMMARY OF TRAVEL (continued)

Date of Travel	Personnel	Places of Visit	Purpose
4/10-4/12	W. K. Jenkins	Tulsa, Oklahoma	To present a paper entitled "Techniques for Residue-to-Analog Conversion for High Data Rate Digital Filtering" at the International Conference on Acoustics, Speech, and Signal Processing.
5/1-5/3	Dimitri Bertsekas	New York, New York	To present papers entitled "Multicommodity Flows and Distributed Computation" and "On the Theory of Dynamic Programming and Stochastic Control" at the TIMS/ORSA Joint National Meeting.
5/7-5/8	R. T. Chien	Alexandria, Virginia	To attend the JSEP Laboratories Director's Meeting.
5/14-5/23	T. N. Trick	New York, New York	To present a paper entitled "Analog Circuit Fault Analysis" at the International Symposium on Circuits and Systems.
		Boston, Massachusetts	To present an invited paper on "Computer Algorithms for Analog Circuit Fault Analysis" at ELECTRO/78.
5/15-5/21	W. K. Jenkins	New York, New York	To present a paper entitled "A Comparison of Residue Number Multipliers and 2's-Complement Multipliers Implemented by Stored Multiplication Tables" at the IEEE International Symposium on Circuit and Systems and Workshop on Digital Signal Processing.
5/30-6/1	W. K. Jenkins	Columbus, Ohio	To present a talk at a Workshop on Application of Residue Number Coding to Digital Computers.

SUMMARY OF TRAVEL (continued)

Date of Travel	Personnel	Places of Visit	Purpose
5/31-6/2	Harlyn Baker Charles Jacobus	Chicago, Illinois	To attend the IEEE Computer Society Conference on Pattern Recognition and Image Processing.
6/4-6/7	Michael Pursley	Toronto, Canada	To present an invited paper entitled "Quadriphase Spread-Spectrum Multiple Access Communications" at the IEEE International Conference on Communication.
6/4-6/6	Dilip V. Sarwate	Toronto, Canada	To present a paper entitled "Hopping Patterns for Frequency-Hopped Multiple-Access Communications" at the IEEE International Conference on Communication.