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ANNUAL REPORT ON ELECTRONICS RESEARCH AT THE UNIVERSITY OF TEXA--ETC(U)
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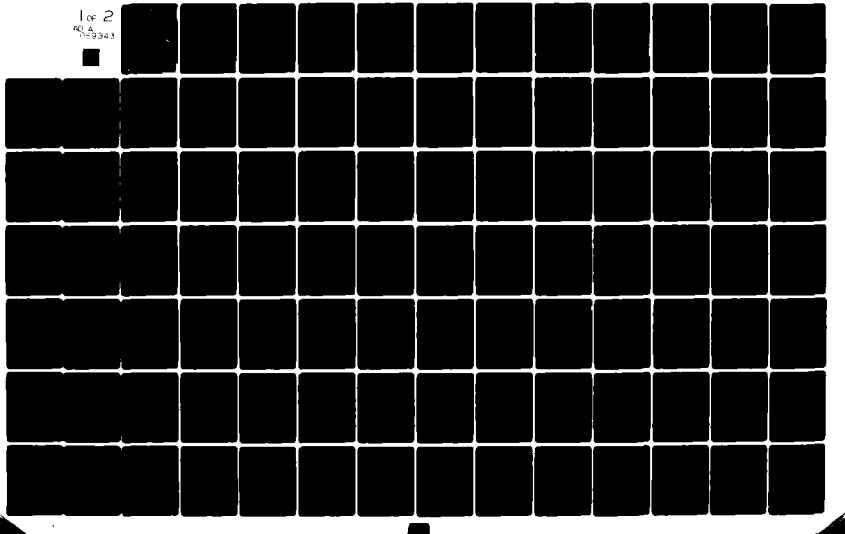

Annual Report on Electronics Research at The University of Texas at Austin

No. 27

For the period April 1, 1979 through March 31, 1980

JOINT SERVICES ELECTRONICS PROGRAM

Research Contract AFOSR F49620—77—C—0101

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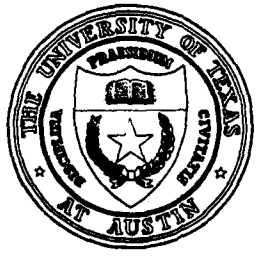

ELECTRONICS RESEARCH CENTER

Bureau of Engineering Research
The University of Texas at Austin
Austin, Texas 78712

The Electronics Research Center at The University of Texas at Austin consists of interdisciplinary laboratories in which graduate faculty members, Master and PhD candidates from numerous academic disciplines conduct research. The disciplines represented in this report include information electronics, solid state electronics, quantum electronics, and electromagnetics.

The research summarized in this report was supported by the Department of Defense's JOINT SERVICES ELECTRONICS PROGRAM (U.S. Army, U.S. Navy, and the U.S. Air Force) through the Research Contract AFOSR F49620-77-C-0101. This program is monitored by the Department of Defense's JSEP Technical Coordinating Committee consisting of representatives from the U.S. Army Research Office, Office of Naval Research and the U.S. Air Force Office of Scientific Research.

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Submitted by Edward J. Powers
on behalf of the faculty and staff
of the Electronics Research Center

Technical Editor: Steven I. Marcus

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(12) 112

ELECTRONICS RESEARCH CENTER

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Austin, Texas 78712

ABSTRACT

This report summarizes progress on projects carried out at the Electronics Research Center at The University of Texas at Austin and which were supported by the Joint Services Electronics Program. In the area of Information Electronics progress is reported for projects involving (1) nonlinear filtering and estimation, (2) electronic multi-dimensional signal processing, (3) electronic computer system design and analysis and (4) electronic computer software systems.

In the Solid State Electronics area recent findings in (1) basic solid state materials research and (2) research on instabilities and transport near surfaces and interfaces of solids are described.

In the area of Quantum Electronics progress is presented for the following projects: (1) nonlinear wave phenomena, (2) atomic and molecular electronic processes and (3) high power laser systems.

In the Electromagnetics area progress in (1) electromagnetic signal analysis and identification, and (2) Guided-Wave Devices for the far infrared-mm wave spectrum is summarized.

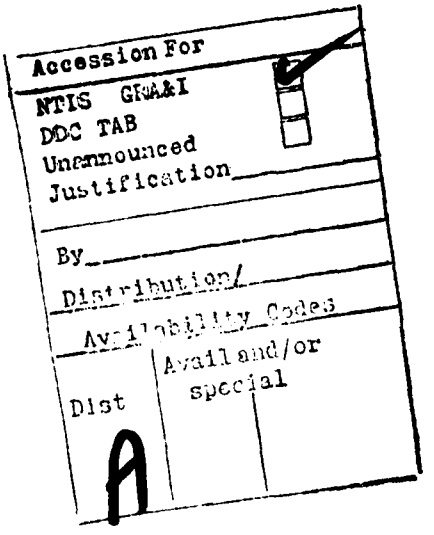

TABLE OF CONTENTS

PERSONNEL AND RESEARCH AREAS

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*Denotes persons who have contributed to JSEP projects, but who have not been paid out of JSEP funds (e.g., students on fellowships).

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Advanced Degrees Awarded

Nader Bagherzadeh, EE, M.S., August 1979, "Quantized and Linear Detection"

John M. Beall, Jr., EE, M.S., May 1979, "Digital Bispectral Analysis of Nonlinear Effects in a RF-Excited Glow Discharge Plasma"

Hyokang Chang, EE, Ph.D., May 1979, "Design and Implementation of Two-Dimensional Recursive Digital Filters"

Mark A. Chonko, EE, M.S., May 1979, "A Feedback Controlled System for the Precise Measurement of Weak Current-Voltage Non-Linearities"

Kang Min Chung, EE, Ph.D., December 1979, "Infrared Nonlinear Optical Processes in Molecules"

Don Halverson, EE, Ph.D., August 1979, "Discrete Time Detection of Signals in Dependent Non-Gaussian Noise"

Jae Y. Hong, EE, M.S., May 1979, "Development of a Plasma Fluctuation Diagnostic Based on Digital Time Series Analysis"

Advanced Degrees Awarded, Cont.

Kai Hsu, EE, Ph.D., December 1979, "On Discrete Time Centralized and Decentralized Estimation and Stochastic Control"

Michael Kelley, Physics, Ph.D., December 1979, "Determination of the Molecular Structure of Dimolybdenum-Tetracetate and Investigation of the Temperature Dependence of the Molecular Structure of Sulfur-Hexafluoride by Gas Phase Electron Diffraction"

Wha-Joon Lee, EE, M.S., December 1979, "Synthesis of Fan Filters by Piecewise Separable Decomposition"

Rafael A. Lemus (Mazariegos), EE, M.S., May 1979, "Synchronization of Concurrent Transactions in a Distributed Database Management System"

Douglas L. Michalsky, EE, M.S., December 1979, "A Relative Efficiency Study of Some Popular Detectors"

Ernesto Pacas-Skewes, EE, Ph.D., May 1979, "A Design Methodology for Digital Systems Using Petri Nets"

Bharat Deep Rathi, EE, M.S., December 1979, "The Design of Intelligent Controllers--Using the Move Processor"

Man Ho Tong, EE, M.S., May 1979, "Crash Recovery in Distributed Systems"

*Randall O. Withrow, EE, M.S., May 1979, "A Digital Data Acquisition System Used in the Determination of the Spectral Index of Turbulent Fluctuation Data"

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PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES, AND REPORTS

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES, AND REPORTS

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*J.W. Keto, "Electron Beam Excited Mixtures of O_2 in Argon, II. Electron Distributions and Excitation Rates," accepted for publication in J. Chem. Phys.

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*R.W. Bené, R.M. Walser, G.S. Lee and K.C. Chen," Is First Phase Nucleation at Metal-Semiconductor Interfaces a Electronically Induced Instability?", submitted to J. Vac. Soc. Technol., 1980.

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PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES, AND REPORTS

*M.F. Becker, R.M. Walser, J.G. Ambrose, and D.Y. Sheng, "Picosecond, 1.06 Micron Laser-Induced Amorphous Phases in Thin, Single Crystal Silicon Membranes," submitted for publication.

*K.M. Chung, G.J. Mauger, and M.F. Becker, "Third Harmonic Generation and Multiphoton Absorption in SF_6 at 193K," submitted for publication.

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J.P. Stark, "An Approximate Analytical Demonstration of the Famous Darken Experiment," Met. Trans., in review.

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*L.W. Frommhold, J.W. Keto, and M.H. Proffitt, "Collision-Induced Light Scattering by the 3He Diatom," in preparation for Phys. Rev. Letters.

J.S. Turner, "Homogeneous Bifurcation Phenomena in Oscillating Chemical Reactions. A Model Study of the Belousov-Zhabotinskii Reaction," J. Chem. Phys., in preparation.

J.S. Turner, "Thermodynamics, Dissipative Structures, and Self-Organization in Nonequilibrium Chemistry," J. Nonequil. Thermodynamics, invited review, in preparation.

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*L.W. Frommhold, J.W. Keto, and M.H. Proffitt, "The Diatom Polarizability from Collision Induced Scattering Measurements of the Helium Isotopes, ^3He-^3He, ^4He-^4He," in preparation.

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES, AND REPORTS

TECHNICAL PRESENTATIONS AND LECTURES

1979 IEEE International Conference on
Acoustics, Speech and Signal Processing
Washington, D.C.
April 2-4, 1979

*J.K. Aggarwal and H. Chang, "Stabilization of Two-Dimensional Recursive Filters."

Workshop on Computer Analysis of
Time-Varying Imagery
Philadelphia, PA.
April 5-6, 1979

J.K. Aggarwal and J. Roach, "On the Ambiguity of Three-Dimensional Analysis of a Moving Object from Its Images."

J.K. Aggarwal, R. Jain and W. Martin, "Segmentation Through the Detection of Changes Due to Motion."

J.K. Aggarwal and W. Martin, "Occlusion in Dynamic Scene Analysis."

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Dallas, Texas
April 21, 1979

G.L. Wise, "Nonlinear Transformations of Random Processes."

IEEE MTT Symposium
Orlando, Florida
April 29-May 2, 1979

B.S. Song and T. Itoh, "A Distributed Feedback Dielectric Waveguide Oscillator with a Built-in Leaky-Wave Antenna."

C. Chang and T. Itoh, "Spectral Domain Analysis of Dominant and Higher Order Modes in Fin-Lines."

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PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES, AND REPORTS

1979 IEEE International Conference
on Plasma Science
Montreal, Quebec, Canada
June 4-6, 1979

Y.C. Kim, E.J. Powers, J.Y. Hong, J.R. Roth, and W.M. Krawczonek, "Fluctuation-Induced Transport in a Bumpy Torus Plasma."

Y.C. Kim, E.J. Powers, R.O. Withrow, and J.R. Roth, "Spectral Index Determination of Dispersive Fluctuations."

J.R. Roth, W.M. Krawczonek, E.J. Powers, J.Y. Hong, and Y.C. Kim, "The Role of Fluctuation-Induced Transport in a Toroidal Plasma with Strong Radial Electric Fields."

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Circuits and Systems
Philadelphia, Pennsylvania
June 17-19, 1979

*D.R. Halverson and G.L. Wise, "On Polynomial Nonlinearities for Detection in ϕ-Mixing Noise."

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and National Radio Science Meeting
Seattle, Washington
June 18-22, 1979

*Y.C. Kim and E.J. Powers, "Amplitude and Phase Modulation of a Wave due to Nonlinear Wave-Wave Interactions."

*E.J. Powers and Y.C. Kim, "Bispectral Study of Nonlinear Wave-Wave Interactions."

IEEE International Symposium on
Information Theory
Grignano, Italy
June 25-29, 1979

T.J. Wagner and L.P. Devroye, "The Asymptotic Convergence of Kernel Rules."

IEEE International Symposium on
Information Theory
(continued)

T.J. Wagner and L.P. Devroye, "Distribution-Free Performance Bounds for Potential Function Rules."

Technical University of Darmstadt
Darmstadt, West Germany
June 26, 1979

T. Itoh, "New Millimeter-Wave Circuit Approach."

Technical University of Aachen
Aachen, West Germany
June 28, 1979

T. Itoh, "Dielectric Waveguide Techniques for Millimeter-Wave Integrated Circuits."

University of Duisburg
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I. INFORMATION ELECTRONICS

INFORMATION ELECTRONICS

Research Unit IE9-1. NONLINEAR FILTERING AND ESTIMATION

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A. OBJECTIVES AND PROGRESS: This research unit is concerned with analytical investigations of the statistical aspects of nonlinear systems. Specifically, the design of nonlinear systems for signal detection, the analysis and design of nonlinear estimators, the nonparametric estimation of regression functions, the stability of stochastic systems, and the performance of adaptive delta modulators have been investigated.

Nonlinear Systems for Signal Detection: The objective of this research effort was the analysis and design of nonlinear systems for the discrete time detection of signals in corrupting noise. We were concerned with the situation where the sampled data were not mutually independent, thus taking the problem away from the usual statistical framework and putting it into a more realistic engineering framework. In practical signal processing situations, data is often sampled at a rate high enough to rule out the assumption of mutually independent samples.

Some recent work addressed this situation by studying the design of memoryless detectors for a constant signal in m-dependent noise. By memoryless detection, we refer to a zero memory nonlinearity followed by an accumulator whose output is fed into a threshold comparator which announces the detection decision. In [1] we extended this technique to the case where the corrupting noise was assumed to be ϕ-mixing. Modeling the noise as a ϕ-mixing process allows a great deal of flexibility in the dependency structure of the noise and, loosely speaking, only requires a "decrease" in the dependency as samples are more widely separated in time. In this work, a detailed analysis of the detector was made and various consequences of approximating the optimum zero memory nonlinearity were investigated. In [2] the work done in [1] was extended to the case where the signal was random and not constant. In this extension, the signal was required to be a ϕ-mixing random process, an extremely weak restriction.

The situation considered in [3] and [4] was also concerned with memoryless detection of a constant signal in additive ϕ-mixing noise. However, in this work we constrained the zero memory nonlinearity in the memoryless detector to be a polynomial. With this constraint, the design of the detector was considerably simplified. For example, the method given in [1] involved the solution of an integral equation of nonstandard form. However, when the nonlinearity was constrained to be a polynomial, the technique simplified and involved only a system of linear algebraic equations, which can be solved in a straightforward manner with the use of a digital computer. Also, it was shown that in many situations, the performance of a polynomial memoryless detector approached the performance of the optimal memoryless detector as the degree of the polynomial became sufficiently large.

In [5] we considered the design of nonlinear systems for the nonparametric detection of constant signals in additive m-dependent noise. Nonparametric detectors are appealing because they offer a fixed structure which will maintain a constant false alarm probability over a wide class of noise distributions. Both the small sample and large sample situations were considered, and discrepancies between these two situations were discussed.

The investigation of nonlinear systems for signal detection is continuing. The research in this area was complemented by the Grant AFOSR-76-3062 from the Air Force Office of Scientific Research.

Nonlinear Estimation: This research is concerned with a number of basic questions in the area of state estimation for nonlinear dynamic stochastic systems. The estimation problem involves the extraction of information about the state of the system from nonlinear noisy measurements. The eventual objective is the design and analysis of high-performance optimal and suboptimal estimators which operate recursively in real time.

Aside from the linear (Kalman) filter, there are few known cases in which the conditional mean (the minimum variance estimate) of the system state given the past observations can be computed recursively in real time with a filter of fixed finite dimension. However, in [6] we have proved that for certain classes of discrete-time systems, described either by a finite Volterra series or by certain types of state-affine realizations, the minimum variance estimator is recursive and of fixed finite dimension. Furthermore, these optimal estimators possess the interesting property of being driven by polynomials in the innovations. This phenomenon

does not occur in continuous time, and it may have significance in the design of suboptimal estimators.

In [7] we have investigated nonlinear discrete time estimation and stochastic control problems in which the observations take a finite or countable number of values. The approach involves the application of recent developments in martingale theory, resulting in a generalization of the work of Segall, Brémaud, and Van Schuppen. General methods for constructing system models and deriving optimal estimators are presented, and the previously obtained estimation equations of the researchers mentioned above are exhibited as special cases. The key concept is the use of modern martingale theory and the judicious choice of certain sigma-algebras and martingales. Real time finite-dimensional recursive estimators are derived and constructed for systems in which the state is a finite state Markov process. In addition, these methods are also applied to stochastic control problems involving finite state Markov processes.

In [8] and [9], by employing the finite dimensional estimators which we derived previously [10], we have for the first time been able to analyze the performance of suboptimal estimators and the tightness of estimation lower bounds for a nonlinear system by comparison with the optimal estimator. A system for which we can construct the optimal estimator was studied; the optimal estimator, extended Kalman filter (EKF), constant gain extended Kalman filter (CGEKF), best linear estimator (BLE), and Bobrovsky-Zakai lower bound were compared both analytically and via Monte Carlo simulations. The results indicated that the performance of the EKF is virtually as good as that of the optimal estimator, and the Bobrovsky-Zakai lower bound is tight for very high signal-to-noise ratio but is less effective for large values of state and observation noises. As far as suboptimal filter design is concerned, the CGEKF is probably preferable, in most of the cases studied, to the optimal estimator and the EKF, due to its simple computational requirements.

In a study related to the robustness of nonlinear filters, we have also considered some questions of convergence of the inputs and outputs of nonlinear stochastic systems. Consider a nonlinear system with a given input and the corresponding output. If a sequence of inputs converged to that particular input, it would often be of interest to know when the corresponding sequence of outputs converged to the particular output. In one sense, we might estimate the desired output of the system by the output due to an estimate of the desired input. In [11] we considered this problem in a stochastic framework. We considered the output convergence properties of Borel measurable (but not necessarily continuous)

mappings defined on separable metric spaces. General results were presented pertaining to the L_p convergence of the outputs of systems when subjected to sequences of input random quantities converging in various modes.

The research in this is continuing and has been complemented by Grant AFOSR-79-0025 from the Air Force Office of Scientific Research and Grant ENG 76-11106 from the National Science Foundation.

Nonparametric Estimation of Regression Functions: It is reasonable to expect that with a large amount of empirical data we could achieve a good estimate of a regression function. However, with a large amount of data, we may be faced with computational burdens in processing them. Therefore, a recursive method of estimation may seem attractive. In this research effort we investigated distribution-free consistency results for the recursive nonparametric regression function estimation problem.

Assume that (X,Y), (X_1,Y_1), $\cdots$, (X_N,Y_N) are independent identically distributed $\mathbb{R}^d \times \mathbb{R}$ - valued random vectors with $E\{|Y|\} < \infty$. Consider estimating the regression function

$$m(x) = E\{Y|X = x\}$$

from the data, (X_1,Y_1), $\cdots$, (X_N,Y_N). We proposed the following estimate. Break the data up into disjoint blocks of lengths $b_1,b_2, \cdots, b_n$, and among all X_i in the j-th block, find the one that is closest to x using the ℓ_q norm $\|\cdot\|$ on $\mathbb{R}^d$ (in case of a tie, pick the X_i with the lowest index i). Call the corresponding $\mathbb{R}^d \times \mathbb{R}$ - valued random vector (X_j^*, Y_j^*). The dependency on x is suppressed for the sake of brevity.

If $\{\{w_{n1},\cdots, w_{nn}\}, n \geq 1\}$ is a triangular array of positive weights, then we estimated m(x) by

$$m_n(x) = \frac{\sum_{j=1}^{n} w_{nj} Y_j^*}{\sum_{j=1}^{n} w_{nj}} \qquad (1)$$

when $N = b_1 + \cdots + b_n$ observations (X_i,Y_i) were available.

Notice that when $w_{ni} = v_i$ for all n, i, then the computation in (1) can be performed recursively. That is, there is no need to store all the observations (X_i,Y_i), and if we are not satisfied with m_n we can collect more observations and update our estimate. Also, (1) retains the flavor of the nearest neighbor estimates, but the processing burden arising from the ranking procedure is less. The conditions which we put upon b_n and w_{ni} were weak:

$$b_n \xrightarrow{n} \infty ,$$

$$\sup_{1\le i\le n} w_{ni} \Big/ \sum_{j=1}^{n} w_{nj} \xrightarrow{n} 0 .$$

In [12] we investigated which consistency properties of m_n hold without additional restrictions on the joint distribution of (X,Y). Also in [12] the discrimination problem was considered and the first distribution-free strong Bayes risk consistency result in the literature was given.

In addition, some previous research on nonparametric estimation and discrimination performed under this unit was published during the past year [15,16].

The research in this area was complemented by the Grant AFOSR 76-3062 from the Air Force Office of Scientific Research.

Stochastic Stability: The objective of the work in stochastic stability was a tractable method to determine the stochastic stability of linear systems with multiplicative noise, that is, systems described by equations of the form

$$\dot{X}(t) = \left[A + \sum_{i=1}^{n} B_i f_i(t)\right] X(t)$$

where the $f_i(t)$ are random processes. Notice that the noise is multiplicative instead of additive, accounting for the nonlinear structure of the system. Such systems are popular models for many practical problems, such as circuits with random parameters and the effect of switching jitter on sampled data system performance. In the case that the noise processes are jump processes, such models find application in modeling faulty systems, or systems subject to abrupt random changes. A major concern is the stability of such systems. The objective of this work was the establishment of useful methods for determining when the statistical moments of the state components tend to zero.

A new method for investigating the stochastic stability of the above form of system was introduced. It is based upon the use of the characteristic functional of a random process. That is, if X(t) is a random process, its characteristic functional is given by

$$\Phi_X(\mu) = E\left\{\exp\left[i\int X(t)\mu(dt)\right]\right\},$$

where μ is a suitably restricted generalized measure. It was shown that for certain types of bilinear systems, the characteristic functional afforded a convenient method for investigation of stochastic stability. In particular, this method was particularly appropriate for situations where the noise processes were filtered Poisson processes. This form of noise provides a good model for a wide variety of phenomena such as shot noise, ELF and VLF atmospheric noises, and other random sporadic events such as the noise generated by a faulty component. The results of this research are given in [13], where several examples are presented.

The research in this area was complemented by the Grant ENG 76-11106 from the National Science Foundation.

Adaptive Delta Modulation: This investigation is concerned with how the adaptive delta modulator (ADM) of Figure 1 performs with a stationary Gaussian input X(t). The measure of performance is the limiting average squared error between the input X(t) and its digital approximation Y(t), namely,

$$\lim_{T\to\infty} \frac{1}{T}\int_0^T \left(Y(t)-X(t)\right)^2 dt . \qquad (2)$$

Assuming that X(t) is Gauss-Markov and making an assumption about the time averages of $\{X(t),Y(t)\}$, it was shown that (2) is the same as

$$\lim_{N\to\infty} \frac{1}{N}\sum_{n=1}^{N} \left(X(nT)-Y(nT)\right)^2 . \qquad (3)$$

The impact of this result is that in simulating the adaptive delta modulator, the points $X(0),X(T),X(2T),\cdots$ are the only ones that need to be generated in order to estimate (2). A simulation study revealed that the ADM achieves its best performance for PQ=1 and $1.002 < P < 1.1$. While this performance is essentially equal to that of the ordinary delta modulator

(P=Q=1) with an optimally chosen Δ (which depends on T_o and X(t)), the ADM achieves its performance regardless of the initial Δ used, the sampling time T_o, and the distribution of the underlying Gauss-Markov-process X(t) ([14]).

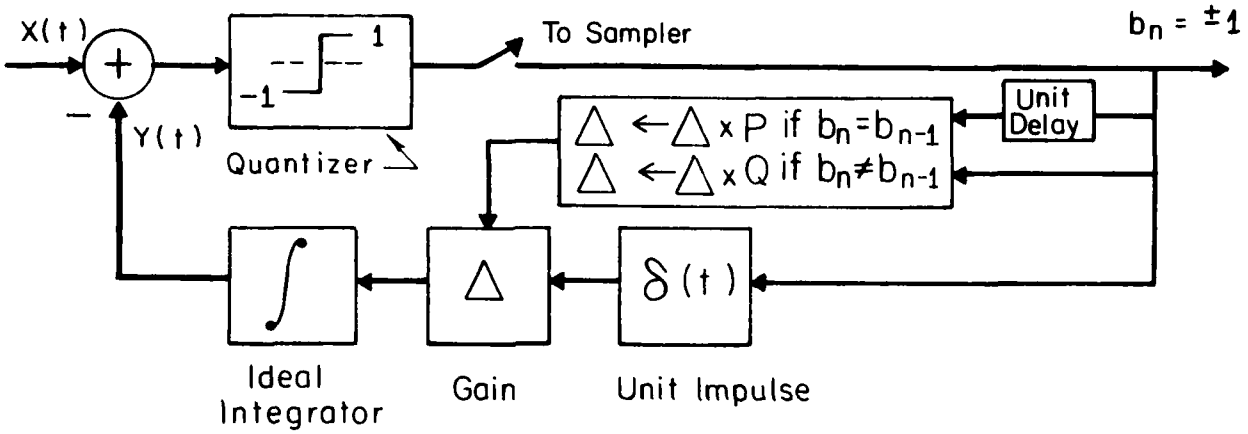

Figure 1. Adaptive Delta Modulator

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Research Unit IE9-2 ELECTRONIC MULTI-DIMENSIONAL SIGNAL PROCESSING

Principal Investigator: Professor J.K. Aggarwal (471-1369)

Graduate Students: N.C. Huang and S. Park

A. PROGRESS: The broad objective of this research unit is to develop new and efficient techniques for the processing of two-dimensional (2D) images and shift-variant signals. Significant progress has been made in the synthesis and implementation of 2D recursive digital filters. In addition, we have made some progress in the analysis and synthesis of linear shift-variant digital filters.

Linear shift-variant (LSV) digital filters are a generalization of linear shift-invariant (LSI) digital filters and are important in processing seismic trace and speech signals whose frequency content changes significantly with time. By using LSV digital filters, we can change filter characteristics at each time instant as desired. In [1] we have investigated some fundamental properties of recursive LSV digital filters in both the time and frequency domains. We present the notion of a generalized transfer function and discuss the frequency characteristics of shift-variant digital filters in terms of the generalized transfer function. In the time domain, the necessary and sufficient conditions for a filter to be realizable as an LSV difference equation have been examined in terms of its impulse response. Furthermore, several techniques to obtain difference equations from realizable impulse responses are also proposed. From the properties of the impulse response, we derive the relationship between the class of systems characterized by LSV difference equations and the class of systems characterized by rational generalized transfer functions. In doing so, we have established some basic notions regarding LSV digital filters.

The synthesis of 2D recursive digital filters is primarily concerned with the problem of approximating the specified frequency characteristics in magnitude and/or phase by 2D stable rational polynomials. In the past, the difficulties with spectral factorization and stability in two-dimensions has led to synthesis techniques in which these difficulties could be alleviated by synthesizing a filter in separable form. In 1978, Hirano and Aggarwal developed a synthesis technique for approximating nonseparable frequency characteristics by sums and products of separable transfer functions. We have generalized this technique to synthesize 2D separable fan filters. In general, an ideal fan filter has triangular pass or stop regions, and its frequency

characteristic is nonseparable. We have developed an approach to decompose the triangular pass or stop regions into several rectangular sections. With this approach, the nonseparable frequency characteristics can be approximated by the combination of several separable transfer functions. The results of this effort are documented in [2]. One major advantage of the present technique is that the difficulties associated with 2D nonseparable fan filters can be avoided by using such an approximation.

Another approach to the synthesis of 2D recursive digital filters, which in a certain sense mimics the synthesis philosophy of one-dimensional (1D) recursive filters, involves the spectral factorization of 2D magnitude-squared functions. However, synthesis techniques for 1D filters do not generalize easily to 2D filters. In one-dimension the stabilization of unstable filters can be carried out by using least square inverse polynomials. In two dimensions, however, there are two forms of least square inverse polynomials: planar least square inverse (PLSI) polynomials of causal form, and PLSI polynomials of semicausal form. It is now known that PLSI polynomials of causal form do not lead to the stabilization of 2D unstable filters. The reason for this is that 2D causal recursive filters are inadequate for the synthesis of filters with arbitrary magnitude functions. Therefore, we have developed a new procedure [3] for synthesizing 2D semicausal recursive filters by taking advantage of PLSI polynomials of semicausal form which can be spectrally factored in an approximate way. The new procedure requires only the single operation of finding the PLSI polynomials of semicausal form; this procedure is much simpler and more accurate than the previous methods. In addition, we present a new stabilization procedure [4] which offers an effective means for stabilizing 2D unstable filters when incorporated with any stability checking algorithm in the literature. Furthermore, we propose a new measure of the amplitude distortion due to stabilization to help judge the acceptability of the amplitude response of the resulting filter.

In general, semicausal recursive digital filters require much more storage than causal recursive filters. The problem of implementing semicausal recursive filters has been investigated and reported in [5]. We first generalize the state-space implementation scheme for causal transfer functions to semicausal transfer functions. We then present a method for simplifying the exact implementation, since it requires an output frame much larger than the input frame. Finally, we give an example which compares the output signal from the simplified implementation with the output signal from the exact implementation.

The paper [6] published in the book edited by J.K. Aggarwal reviews recent developments of 2D recursive digital filters in terms of semicausality and spectral factorization, thus establishing a fundamental theory of 2D recursive filters. In addition to the work documented above, the paper [7] has been accepted for publication.

This has been a brief summary of the principal results we have achieved in the past year. Several aspects of the problems are still under investigation. Specifically, the research concerning the analysis and synthesis of LSV digital filters will be continued. The applications of LSV digital filters for the processing of LSV digital signals will be considered. Furthermore, the results on the one-dimensional LSV digital filters will be generalized to two-dimensional LSV digital filters which have potential applications to space-variant images.

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INFORMATION ELECTRONICS

Research Unit IE9-3 ELECTRONIC COMPUTER SYSTEM DESIGN AND ANALYSIS

Principal Investigators: Professor S.A. Szygenda (471-7365)
Professor E.W. Thompson

Graduate Students: Rodney Barto, Rafael Lemus, Don Ross and Richard Von Blucher

A. OBJECTIVES AND PROGRESS: Logic simulators can perform several useful functions for the design engineer [1]. By simulating his circuit he can verify the correctness of his design and determine whether it possesses any undesirable behavior due to device delays, without having to build any hardware. He can also examine its performance under fault conditions and devise tests to locate devices that have failed. The increasing proliferation of digital devices in common machines makes their correct operation in both normal and fault conditions much more important. The rising cost of manpower makes any device that can hold down development costs look very attractive. Logic simulators can fill these needs and are a potentially useful tool for the design engineer [2].

In order for a logic simulator to be useful it must possess two attributes. First, it must accurately predict the operation of the logic circuit being simulated. Second, it must do this in a cost effective manner. These requirements are interrelated, as will be shown.

A logic simulator performs its functions by constructing a working model of the network under consideration [3,4]. The devices, Boolean and sequential gates, that the network is constructed from must be modeled as must the topology of the network, that is, the interconnections of the devices. The network topology is stored in a set of tables that the simulator creates. The most difficult job of the simulator is to model the devices in the network and the electrical activity that they produce.

Even though logic devices are considered to be binary valued, that is, producing outputs that are either logic 0 or logic 1, in reality they are all analog in nature. As such, they are capable of a considerable amount of non-binary behavior. Signals propagate through them in finite delay times, and this produces undersirable logic level behavior, such as hazards. The effects of output loading and improperly terminated connecting lines will produce poorly defined rising

and falling edges. All this activity should be modeled by the simulator.

There are two basic types of logic simulators in use today. The most common is the logic level simulator. This type models logic signals as being either logic 0, logic 1, or unknown, and some will have representations of rising and falling signals and hazards. The most accurate of these will have a number of possible signal representations. Delay modeling capabilities range from simulators that assume each gate has one time unit of delay, to those allowing each gate to have an unique ambiguous delay.

The second type of simulator models the electrical activity of the network. Each gate is modeled by considering the transistor circuit that it is made from. The MOTIS simulator [5], which is of this type, has capability of representing 64 signal levels and is thus more accurate than the logic level type mentioned above.

The more accurate a simulator is the slower it performs its simulations. The most common measure for simulator speed is the number of gate evaluations per second (GES). This is the number of gate output values the simulator can calculate in one second. Logic level simulators can perform from 400 to 4,000 GES, while the MOTIS simulator can perform 400 GES. Since only 10% to 20% of a network is active at any time, most simulators are event driven. Such a simulator will evaluate a gate only if it is active; this saves considerable amounts of simulation time.

The limitation on simulator speed stems mostly from the fact that all simulators in use today are computer programs run on general purpose computers. The common computer architecture does not provide a natural framework for the complex data structures a logic simulator requires. The purpose of this work was to design and validate a computer architecture for logic simulation. This architecture incorporated into its hardware the building blocks of a software simulator. Thus the tables and flows of data required by a simulator are natural to the computer, rather than defined and maintained by a computer program. The simulator would run with the aid of a host computer, that would load the simulator and handle its output.

There were three objectives in this design. First, the computer resulting from this design should be faster at simulation than a software simulator. The "hardware" simulator should be at least one and possibly two orders of magnitude faster than a software simulator. Second, the hardware simulator should be more accurate than a software simulator. The computer should support, yet not be limited to, the MOTIS

type of simulation. Third, the initial cost of the hardware simulator should be comparable to the initial cost of a software simulator.

The constraints on this design fall into two categories. The first category limits the components which can be used in the design and the second limits the extent of the design itself.

1. Constraints on Hardware Used

The decision was made at the beginning of the design to limit the components used to those that are readily commercially available. There would, therefore, be no designing of custom made integrated circuits or other devices. The logic family chosen for the control circuitry is the TTL family. There are two reasons for this. First, the initial cost of TTL logic is much less than that of the faster ECL logic. Second, it is much less expensive to construct a circuit with TTL than with ECL. This is because the higher speeds provided by ECL make the design of interconnections in the circuit much more critical than they are with TTL.

The major memories are constrained to operate at speeds obtainable with standard MOS memory ICs. It would be possible to build the memories with TTL or ECL ICs, but the cost of this would be prohibitive.

The processors of the computer, the units that do the actual work, may be made of either TTL or ECL. The former would be preferable, for reasons mentioned above. None of the processors, however, will be physically large, and thus, would not be either expensive or difficult to build with faster logic.

These hardware limitations placed a heavy demand on the design. Any increase in speed will be obtained by virtue of an improved architecture, not from the use of faster logic. The larger of the computers a software simulator may run on rely more heavily on the use of the faster logic families for their speed increases.

2. Constraints on the Design

There are a number of items of the design that were not dealt with in this study. All of them result from the fact that the purpose here is to present only the basic architecture of the computer, not a design for a finished product.

B. SIMULATOR DESIGN OVERVIEW AND RESULTS: The major functional blocks of the simulator are shown in Figure 1. Each table that a simulator requires is confined in a separate memory. These are the Fan-in Memory (FIM), Fan-out Memory

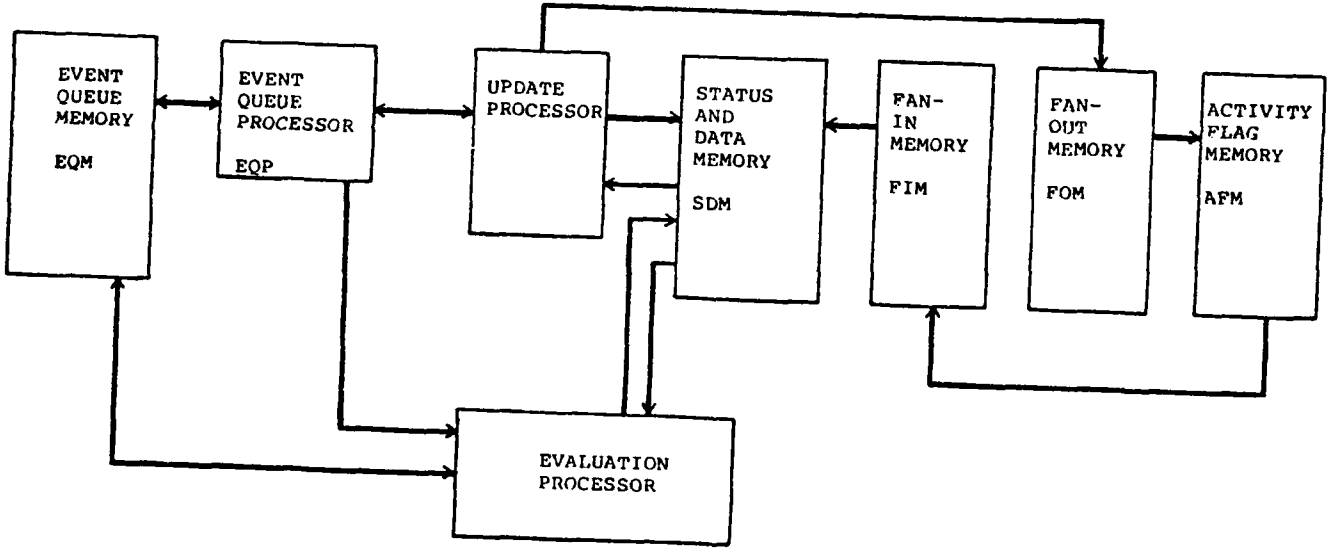

Figure 1: MAJOR FUNCTIONAL BLOCKS

(FOM), Status and Data Memory (SDM), Activity Flag Memory (AFM), and Event Queue Memory (EQM). The FIM contains a list of the inputs to each gate, and the SDM contains its static and dynamic data such as value, type, and number of inputs. The FOM and AFM are used to allow the simulator to be event driven. The EQM is used to schedule events.

The simulator operates in two phases, Evaluation and Update. Each of these involves a separate processor, the EVAL and UPDATE processors, respectively. The Event Queue processor has only minimal duties to perform in its handling of the EQM.

During the Evaluation phase, gates that require evaluation have their input values sent from the SDM to the EVAL processor. This phase makes use of the interleaved nature of the FIM and SDM. The FIM can provide the addresses of the inputs to a gate to the SDM at a high rate since they are accessed 16 at a time and sent in a word serial, bit parallel manner over a high speed data path. The SDM is interleaved 8 ways and can thus provide the input values to the EVAL processor in a relatively short amount of time. The EVAL processor itself can be optimized for the type of gate modeling desired.

During the Update phase, events scheduled during the Evaluation phase occur. The information for these events is stored partly in the SDM and partly in the EQM. The UPDATE processor is a 7 stage pipeline capable of handling gates at the rate of four gates in each cycle time of a SDM block. During this phase, the fanouts of active gates are followed by sending the contents of the FOM to the AFM. During the Evaluation phase, the AFM is searched for active gates, and their addresses sent to the FIM. Further details of the design are provided in Reference 6.

A possible implementation of the simulator, in which all of the memories were constructed from NMOS integrated memory circuits was presented. The speeds at which the various components operated were compatible with TTL control circuitry. The simulator was shown to be capable of performing from 10,000 to 200,000 gate evaluations per second depending on complexity of the devices modeled. This is from one to two orders of magnitude faster than software simulators.

Because the simulator has not been designed to gate level, only a cost estimate of the major memories can be made. This estimate is still meaningful, since these units form the bulk of the machine.

Prices for the ICs for the major memories were obtained in March of 1980. NMOS dynamic RAMs made by the Nippon Electric Company were selected for the FIM, FOM, AFM, and

SDM. The total cost of these components was $17,750. The EQM could be constructed from memory made by the Electronic Memory and Magnetics Corporation at a cost of $1,536. This brings the total memory components cost to $19,286. A reasonable estimate for the total system cost would be two to three times the memory cost, roughly $60,000 to $90,000. This compares favorably with software simulators which cost from $40,000 to $170,000.

The estimates given here must be viewed in light of the following considerations. First, the performance of the machine is largely dependent on the efficiency of the EVAL processor. Its performance was given here assuming it would perform evaluations much as a software simulator would, using stored programs. It is quite likely that special hardware could be designed to speed up the EVAL phase considerably.

Second, the cost estimates given here are for one machine. In a production effort, where several simulators were to be built, the cost of components would decrease. Current demand for software simulators and the growth of the digital electronics industry could justify such a product effort.

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INFORMATION ELECTRONICS

Research Unit IE9-4 ELECTRONIC COMPUTER SOFTWARE SYSTEMS

Principal Investigator: Professor Raymond T. Yeh

Graduate Student: T. William Mao

A. PROGRESS: This work is concerned with an approach to distributed programming and involves the design and validation of a programming language for a distributed environment where many processors cooperate to complete a single task. The processors share no common memory and communicate with each other through hardware busses. This environment can be seen as an abstract model of many networks and microprocessor networks.

We considered the design of a distributed language, DLCP, which draws most of its features from Algol-descendent languages such as Pascal. The basic components in the language are processes, which are assumed to be executed in parallel. Strong emphasis is placed on communication facilities for processes. Since no shared variables exist, communication is by message passing. To simplify the implementation of the language, we further assume that the distributed environment does not support automatic buffering of messages. Information exchange therefore must be totally synchronized. Communication Ports (CP), [1,2] influenced by Hoare's communication sequential processes [3], were proposed as a generalized mechanism for both information exchange and synchronization among processes. During communication, the processes behave as if they merge into a single process. To provide greater concurrency, another feature was introduced to allow early disconnection of communication. CP also provides compiler-time message type checking and a run-time mechanism to schedule call acceptances. Many examples have been given showing the equivalence of CP and the communication and synchronization features of other proposed languages.

In order to formally define the semantics of DLCP, Hoare's deductive system of axioms and assertions was extended to include distributed programs. Semantic rules were developed to define the semantics of CP. We also developed proof rules which, when combined with semantic rules, can be used to prove functional correctness of distributed programs written in DLCP. In proving functional correctness, the invariant property, which is essential to the verification of multi-process programs, was identified. The invariant property is generally considered to be a property global to the whole

program, and requires all assertions in the program to meet a condition, called speed independence. We show that invariance may be proven only if a subset of the program assertions are speed independent. The effort to discover proper assertions and invent auxiliary variables for proving a program was thus reduced. Further, the deductive system was proved to be consistent with a state machine model of program execution, which assumes machine states instead of logical assertions as elements.

Finally, the feasibility of implementing DLCP on a processor network was assessed. An algorithm, using message send and receive as primitives, was developed to enable a process in DLCP to communicate with other processes efficiently. The runtime support system needed to interface a process with the processor it resides and other processes was considered. A prototype of such a system, embedding the algorithm, is designed, illustrated, and coded in Concurrent Pascal.

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II. SOLID STATE ELECTRONICS

SOLID STATE ELECTRONICS

Research Unit SS9-1. BASIC SOLID STATE MATERIALS RESEARCH

Principal Investigators: Professor R.W. Bené (471-1225)
Professor R.M. Walser (471-5733)
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Graduate Students: S. Chao, K.C. Chen, L. Lancaster, G.S. Lee, H.Y. Yang

A. OBJECTIVES: Our main objectives are to develop an understanding of the kinetically selected reaction paths and phases at low temperatures and to increase our understanding of the relationships between atomic rearrangements and electronic, magnetic and optical properties of the interface region in thin film reaction couples. In previous studies we have hypothesized the existence of a glassy membrane layer which forms initially upon metal deposition on a Si or Ge surface [1,2,3], and which acts as the controlling element in compound nucleation. We have observed the formation of a disordered layer for ultrathin deposits of metals on Si [4,5] and have shown that the possible existence of a modified disordered region (behaving as a negative U glass), even after compound nucleation, is consistent with Schottky barrier results[6].

Some of our present objectives are to check and extend these hypotheses by correlating surface resistance, magnetic moments (EPR), noise and dielectric response measurements with transmission electron diffraction indications of thin film structure. Also, ellipsometric studies are being used to obtain the depth resolved optical constants (and optical spectra over limited wavelength ranges) to correlate with the preceding measurements.

B. PROGRESS: We have found that nucleation of the first compound phase out of the initially formed disordered phase at low temperatures (room T) is quite possibly due to an electronic instability in the interfacial glassy region. We have made measurements on the Co-Si system, where we find that the onset of Co_2Si nucleation occurs after a deposition of a critical effective thickness of Co which depends on substrate preparation. (In general, the cleaner the substrate, the smaller the critical thickness.) This same critical thickness is just the thickness at which the surface disordered region attains metallicity (defined by $\frac{dR_s}{dT} \geq 0$) over two dimensions or less, indicated by the value of R_s where this occurs ($\approx 10^4 \frac{\Omega}{\square}$).

Since the first stages of Co_2Si nucleation appear

to occur in separate islands, the compound formation does not produce the metallicity-- rather, metallicity apparently stimulates compound nucleation. As a further check on this interpretation we have deposited thin Co films on Si substrates which had been doped into degeneracy, i.e., which were metallic to start with. We find compound (Co_2Si) nucleation down to the thinnest Co which we can experimentally sputter. Thus the critical thickness, which typically occurs at about 70 sec. deposition for 4-10 Ωcm Si, has been suppressed below 5-10 sec deposition for degenerately doped Si. It should be noted that we have used both n and p type Si (doped with four different impurities) and both (100) and (111) faces with substantially the same results.

The implication of the above experiments is that in the Co-Si system, first phase nucleation (compound) is triggered when the interfacial atoms are in contact with a metallic region (of two dimensions or less in the case of deposition on high resistance Si). In other words, first nucleation is an electronically induced instability [7]. If this interpretation is true in general or just for the near noble metals, interacting with Si (Ge), is very important for a microscopic understanding of the reaction path being followed in these systems leading to first nucleation. As an example, this may have a bearing on the differences observed in the metal-metal nucleation rule(s) where the eutectic is still important as in metal-Si or metal-Ge systems, but the first phase is not generally a congruent one (unlike metal-Si or metal-Ge systems). An objective then is to extend these measurements to other systems to determine the generality of the results.

We have followed, by means of multiple angle-of-incidence ellipsometry, the formation and subsequent evolution of the glassy layer at the Co/Si interface. The measurements are consistent with an optical model made up of a bulk Si substrate, a glassy, Co-rich Si surface layer, and a surface layer containing oxygen, Si and Co. The glassy layer was found in all samples onto which Co was sputtered down to < 20 sec. sputtering time. This r.f. sputtering potential was 2 kV. For sputtering times up to ~70 sec., the optical constants of the glassy layer at 6328Å, measured by multiple angle-of-incidence ellipsometry show values in the range characteristic of amorphous Si. For greater sputtering times the optical constants are more characteristic of a metallic glass [8]. The transition from semiconducting glass to metallic glass appears to be very abrupt, and in work presently under way we are making ellipsometer measurements at different locations on a substrate with spatially

varying thicknesses of sputtered Co, in order to determine how rapidly the optical constants vary in the immediate vicinity of the transition. The observed change in optical constants occurs at close to the same amount of deposited Co where sheet resistivity measurements indicate a change from semiconducting to metallic behavior[5].

We are also interested in extending the measurements to shorter sputtering times. Using the data now available, the ellipsometrically determined glassy layer thickness does not extrapolate to zero for very small sputtering times, and the optical constants do not extrapolate back to the values of the Si substrate. Immediate future work will concentrate on very low sputtering times, and on times corresponding to the semiconducting glass-metallic-glass transition.

Out of our multiple angle-of-incidence ellipsometry measurements has also come a useful criterion for matching the complexity of the optical model (number of layers with unknown thicknesses and optical constants) to the available experimental precision in measuring the ellipsometer azimuth angles. If f is the minimum sum-of-squares after completion of a least-squares fit between model and experiment at N angles of incidence and E is the mean measurement error, the value of $x = f/(2NE^2)$ can be used to determine model adequacy. If $x \gg 1$, the model chosen does not have enough variable parameters to explain all the measurements. If $x \ll 1$, the model is so complex that it is being forced to fit random fluctuations in the measurements. A value $x \approx 1$ suggests that model complexity and experimental precision are about optimally matched.

This work is being continued and extended as indicated in our objectives and is being combined with work in SS9-2 on Instabilities and Transport Near Surfaces and Interfaces of Solids. Although the initial objectives of these two studies were loosely connected, they have grown in the direction of very strong coupling and we feel at this time it makes sense to combine them so that we may more easily express our overall objectives and the relationship of individual studies to these objectives. The new combined study is entitled "Solid State Reactions, Instabilities and Transport Associated with Surfaces and Interfaces of Solids."

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Research Unit SS9-2. RESEARCH ON INSTABILITIES AND TRANSPORT NEAR SURFACES AND INTERFACES OF SOLIDS

Principal Investigators: Professor R.M. Walser (471-5733)
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Professor J.P. Stark (471-1504)
Professor J.S. Turner (471-7253)

Graduate Students: E.M. Aly, J. Ambrose, S. Park, D. Sheng

A. OBJECTIVES: The broad objective of this work is to understand the relationship between atomic rearrangements and electronic instabilities at surfaces and interfaces of solids. These atomic rearrangements of interest are solid phase surface chemical modifications that alter the interfacial behavior of electronic devices of, for example, ohmic contacts and Schottky barriers. These surface instabilities may be relieved by mass transport and surface diffusion as in electromigration, or via surface phase transitions including crystallization and compound formation.

At present the research in this unit is being concentrated on: (1) understanding the fundamental origin of these electronic surface instabilities in model systems, and (2) exploring the effect of various experimental parameters on the relaxation of the instability. Ultimately both activities should lead to an increased understanding of how improved or alternative electronic device structures can be synthesized.

In the last year, three model interface systems--mercury-silicon (Hg/Si), amorphous silicon-crystalline silicon (α-Si/c-Si), and platinum-silicon (Pt/Si) have been studied. The rationale for these studies and the results obtained are discussed in the next section.

B. PROGRESS: Our previous research [1-7] has led to the general hypothesis that solid phase surface transitions are electronically initiated by the critical fluctuations of redistributed, or delocalized, bond charge. Much of the present work is directed toward developing support for this hypothesis. The questions being addressed in each model interfacial system, and the results obtained on each are discussed separately.

1. Mercury-Silicon. The fundamental electronic properties of Hg/Si interfaces are being studied by measuring their capacitance-voltage and current-voltage terminal characteristics as a function of several parameters. We believe the

Hg/Si system will allow us to study the fundamental nature of an electronically driven surface instability without important competing effects.

First, because Hg/Si is a completely immiscible system, the relaxation of the surface instability should be unaffected by binary chemical association at other than the interface itself. Secondly, controlled variations in the properties of the solid phase Hg/Si interface should be more readily achieved by "quenching" through the convenient bulk Hg freezing point at -38°C. In more highly soluble, e.g., eutectic forming binary metal-silicon systems, controlled quenching is difficult to achieve because of the "low-dimensional" or interfacial critical point behavior.

In our experiments we are searching for evidence of dynamically stable "organized" interface states at the liquid phase Hg/Si interface. These "organized" or collective interface states should bear a close relationship to the laterally inhomogeneous "Guoy layer" at the electrical double layer of electrodes in electrochemical cells.

We have completed initial measurements on the DC I-V measurements of liquid Hg/Si at 300°K for n and p type silicon substrates with bulk resistivities varying from 0.008 Ω-cm to 35 Ω-cm. The data show that a transition from very low resistance ohmic interfaces (.008 Ω-cm) to extremely high resistance blocking interfaces occurs with a transition in behavior occuring for substrate resistivity of $\sim$ 1Ω - cm at a bias voltage of $\sim$ 100 - 500 mV. The bias voltage at which the transition from ohmic to blocking occurs decreases with increasing substrate resistivity.

Using electronic techniques, we have examined the first and second derivatives of DC I-V curves for possible evidence of the organization of collective interface states in the vicinity of the transition bias. Such peaks have been found but insufficient data are available for discussion at present.

We interpret the results obtained thus far to indicate the possible detection of dynamically stable collective interface states generated by field-dependent electrohydrodynamic interface modes. In our model the variation of the substrate resistivity is used to dynamically adjust the overall charge transfer so that the average interface charge approaches a critical concentration for supporting the collective interface state.

At the present we are making additional measurements of this type at various temperatures above the Hg freezing point to characterize the sensitivities of the interface mode selectivity at various proximities to the critical point.

We then plan to attempt to freeze these states in by "quenching" and characterize their behavior relative to the parameters of the quench.

2. Amorphous Silicon - Crystalline Silicon (α-Si/c-Si). We are presently using picosecond 1.06μ laser pulses to study the c-Si → α-Si phase transition. Initially we have concentrated on studying the correlation between the energy deposition parameters and the structure as determined by TEM and SEM. We have recently reported the first observation of a picosecond induced c → α phase transition in silicon with near band gap photons [8].

Recent reports of laser-induced amorphous phases in crystalline silicon due to picosecond .532μ and .266μ radiation [9] and nanosecond .266μ radiation [10] raise questions regarding the dynamics of such a transition. These results may not be adequately described by equilibrium heat-flow analysis for several reasons.

These unanswered questions led us to an investigation of the laser interaction with thin (1.5μ and <300 nm) silicon films. The transparency of such films facilitates the study of optical absorption and transient effects as well as TEM without intermediate thinning. In the experiments we report here, transient effective absorption coefficients greater than 100 times the small signal value were observed. In addition, we have made the first observation of the laser-induced amorphous phase with picosecond radiation at 1.06 microns. Previous models based on heat-flow and fast quench rates have not predicted this behavior. We suggest that localization of the excitation and the free carriers is required to explain our results.

The thin silicon samples were prepared from low resistivity (111) Si wafers which had 1.5 micron epitaxial layers of intrinsic Si. The wafers were then masked to expose an area of approximately 0.5 cm^2 to be electrochemically etched. The selective etch left the 1.5 micron epilayer intact. Further thinning of selected areas to thicknesses less than 300 nm was done by ion beam milling.

The laser pulses were supplied by a passively mode-locked Nd:YAG laser. Single pulses were selected, and they had an average FWHM duration of 38 psec. At the sample, the pulses were focused to intensities from less than 0.3 GW/cm^2 more than 10 GW/cm^2. The Si substrates were free standing in air and at room temperature. In addition to intensity, other experimental parameters were the number of laser pulses incident on a single location (from one to >1000) and sample thickness. Transient optical absorption, optical microscopy, and SEM were used with the 1.5 micron thick samples while the <300 nm

samples were prepared specifically for the TEM.

The results of various irradiations are best described as a function of laser intensity. Below the threshhold for any permanent change for large numbers of pulses, 0.5 GW/cm^2, the transient absorption coefficient was measured to be more than 100 times the small signal value. This figure is based on Beer's law absorption over the entire 1.5 micron film thickne s. If the absorbing region was localized near the film surface, the local absorption coefficient would be even greater. Typically about 50% of the incident laser energy was absorbed. The small signal absorption correlated well with the sample thickness and known absorption at 633 nm.

Just above the threshold for permanent change, small areas within the laser beam profile changed from orange and transparent to black, opaque and grainy. These regions were located at the beam entrance face of the sample. The threshold for single shot effects was 1 GW/cm^2 compared to 0.5 GW/cm^2 for multiple pulses. TEM diffraction shows the characteristic α-Si rings (not polycrystalline). The actual amorphous region overlays a region which is still single crystal.

For higher intensities the size of the amorphous area increased until it filled the entire laser beam profile. This behavior was essentially the same for multiple pulse or single pulse experiments, more pulses at lower intensity being equivalent to fewer higher intensity pulses. Another effect observed at higher intensities was a similar amorphous layer on the exit face of the sample. In the 1.5 micron thick samples, a region of single crystal silicon could be clearly observed by optical microscopy between the two amorphous surface layers.

At the highest intensities used ($\sim$ 10 GW/cm^2), the films repeatedly punctured and cracked. There is no evidence of any liquid or melt morphology present at the laser irradiated site for this case. The question of whether a liquid phase existed in our experiments is doubtful but not conclusively eliminated.

- Our most important conclusion is that spatial energy concentration is required to achieve sufficient excitation to amorphize the surface silicon layer. The observed absorption coefficient of greater than 1000 cm^{-1} is not readily explained by free carrier absorption. For an interband absorption coefficient of 10 cm^{-1}, carrier densities will be in the range of 10^{18}-10^{19} cm^{-3} for the laser intensities in these experiments. Such carrier densities are insufficient to account for a >1000 cm^{-1} free carrier absorption coefficient. We suggest that higher carrier densities

may be present but are spatially localized at the surface of the sample. The observed surface amorphous layers tend to confirm such a surface localization hypothesis. Further experiments are planned to elucidate the dynamics of this localization process.

Finally, we speculate that these laser-induced amorphous phases in silicon are an example of the classical nucleation and growth process. Evidence of the irregular amorphous regions at low intensities growing larger for higher intensities or more pulses is very suggestive of nucleation and growth from heterogeneous sites.

3. Platinum-Silicon (Pt/Si). There are two main objectives of this research. The first is to investigate the first phase nucleation which occurs between thin films of platinum and single crystal silicon substrates at room temperature.

The second is to study the possible effects that an applied D.C. electric field to the sample during sputtering would have on the reaction path leading to solid phase silicide nucleation at the interface between the deposited platinum and silicon substrate. Thin platinum films are rf sputtered onto a clean, cold, n-type, 4-10 ohm-cm, and (100) oriented single crystal silicon substrates. Films with deposited platinum corresponding to thicknesses between 10Å and 40Å were prepared by sputtering at 2kV rf at 20 m Torr argon pressure (80Å/min). The range was covered in about 5Å steps.

The as-deposited Pt-Si couples were chemically thinned and then structurally characterized using Transmission Electron Diffraction (TED). In addition Auger electron spectroscopy was employed for depth profiling and Auger peak shape studies. Also, sheet resistance measurements for different sample thicknesses were monitored in the temperature range of 300°K down to 15°K.

All measurements suggest that the transition from semiconducting to metallic behavior occurs at about 40Å for the ultrathin platinum films on silicon crystal.

Thin platinum films in the equivalent thickness range $10Å \leq t \leq 35Å$ produce amorphous surface regions as indicated by transmission electron diffraction (TED). The present experiments indicate that the stability of the glass (amorphous layer) is dependent on the thickness of the deposited platinum layer. The glass is stable for thicknesses less than 35Å and unstable with respect to the nucleation of α-Pt_2Si for greater thicknesses at room temperature with no applied field. α-Pt_2Si polycrystalline rings are found by TED at a minimum deposited metal thickness of 40Å.

For the same metal thickness (40Å) and never below this thickness, Auger electron spectroscopy measurements with depth profiling show a splitting in the (92-ev) silicon peak and shifting of this peak to a slightly lower energy value [11]. The splitting and the shifting are most likely due to the formation of platinum silicide. At the same time, the platinum depth profile has shown a nearly constant concentration of Pt over the range where that splitting and shifting of the silicon peak occurs. Sheet resistance measurements are also consistent.

Since Pt_2Si is the most stable congruently melting silicide in the Pt-Si binary phase diagram, our results here are in agreement with the first phase nucleation rule for the transition metal silicides [1,4].

We have also studied the reaction path in the Pt-Si system when a D.C. field of about 10 volts is applied across the sample during sputtering of the platinum. The same three types of measurements have been used to analyze the results, TED, Auger and sheet resistance. The applied field stimulates the transition from the amorphous glassy layer of Pt-Si to the crystalline Pt_2Si. Namely, we find that the Pt_2Si is formed consistently at platinum layer thicknesses of about 25Å as compared to 40Å with no D.C. field.

Ahilea and Hirch [12] have discussed the application of an electric field on an evaporated thin metal film during its preparation. They contend that the electric field induces electric dipoles which stabilize the growing compound. The measurements we have made are in agreement with their predictions. Bené [13] reports that during the deposition of Co on Si, the silicide transformation is stabilized when doped degenerate silicon is the substrate. The latter suggests that the electric dipole model is incomplete and that the transition metal-silicon thin film follows a more complicated nucleation path.

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III. QUANTUM ELECTRONICS

QUANTUM ELECTRONICS

Research Unit QE9-1 NONLINEAR WAVE PHENOMENA

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A. PROGRESS: This research unit is concerned with analytical and experimental studies of nonlinear wave interactions in physical systems. The work may be subdivided into two areas: (1) the development of digital time series analysis techniques useful in analyzing and interpreting fluctuation data generated by *nonlinear wave interactions* in various media, and (2) *nonlinear optics* in the infrared spectral region in molecular gases.

1. Nonlinear Wave Interactions. The objective of this work is to develop digital time series analysis techniques that may be used to analyze and interpret experimental fluctuation data associated with nonlinear wave phenomena. During the past year, our research has focused on the following topics: (a) the relationship between the experimentally measured bispectrum and coupling coefficients which are determined by the physics of the nonlinear interaction, (b) understanding simultaneous amplitude and phase modulation of a (carrier) wave propagating in a nonlinear dispersive medium in terms of nonlinear wave-wave interactions between the sidebands and a low frequency wave, (c) investigating the effects of dispersion on three wave interactions with particular emphasis on the implications in nonlinear optics, and (d) initiation of work concerned with developing suitable digital analysis techniques to handle statistically nonstationary fluctuation data. The major thrust of the first two topics involves the development of theoretical models which describe various facets of nonlinear wave modulation in a general sense and which also provide a means by which to interpret digital time series analysis results in terms of the physics of nonlinear wave phenomena.

a. The Bispectrum and Nonlinear Wave Coupling. As waves propagate through a nonlinear dispersive medium, a temporal and/or spatial variation (i.e., modulation) of the wave's (complex) amplitude may result from competition between the dispersiveness and the nonlinearity of the medium. By considering a spatial variation of the wave's amplitude in terms of three wave coupling, we found [1] that the biphase, the phase

of the bispectrum, is determined by the characteristic scale length of amplitude variation due to nonlinear coupling and the phase of the coupling coefficient. Furthermore, when the coupling coefficient is real and positive, the sign of the skewness coefficient [1], which is determined by the biphase, can be explained in terms of nonlinear wave characteristics. That is, if the wave's amplitude is growing in the direction of propagation, a negative skewness results and if the amplitude is decaying, a positive skewness results. In addition, we have considered [1] the power variation of a wave in terms of the bispectral power transfer function, which involves the coupling coefficient and the bispectrum. When the coupling coefficient is known a priori, one can experimentally determine the direction and the amount of power transfer over a spectrum due to nonlinear wave coupling by utilizing bispectral techniques. We have confirmed [1], using digital bispectral techniques [2], the above theoretical results using density fluctuation data from an rf-excited glow discharge.

b. Wave Modulation in a Nonlinear Dispersive Medium: A model describing simultaneous amplitude and phase modulation of a carrier wave propagating in a nonlinear medium has been developed [3] in terms of nonlinear wave-wave interactions between the sidebands and a low frequency wave. We solved the wave coupling equation by transforming it into a recurrence form and obtained a solution for the amplitude of the sidebands in terms of the coupling coefficient. When the coupling coefficient has a slow dependence on the wavenumber, we found that the carrier wave undergoes amplitude and phase modulation with modulation indices determined by the coupling coefficient and the amplitude of the low frequency wave. However, the ratio of the AM index to PM index was found to be independent of the amplitude of the low frequency wave and is solely determined by the coupling coefficient. Also, we found that an asymmetric distribution of sidebands results from wavenumber dependence of the coupling coefficient. That is, when the coupling coefficient is an increasing function of wavenumber, the lower sidebands are dominant over the corresponding upper sidebands. Furthermore, the amplitude modulation and the frequency deviation with respect to the carrier frequency are out of phase by π when the lower sidebands are larger than the upper sidebands, and the amplitude modulation and the frequency deviation are in phase when the upper sidebands are larger than the lower sidebands.

Using digital complex demodulation techniques, we investigated [3] wave modulation of a self-excited wave in an

rf-excited glow discharge and found the following agreements with the theoretical model: first, the amplitude modulation and the frequency deviation are out of phase by approximately π, which is consistent with the power spectra displaying dominant lower sidebands. Next, the amplitude and phase modulation indices are increased as the amplitude of the low frequency wave increases, but the ratio of AM index to PM index is insensitive to the rms value of the low frequency wave in agreement with the theoretical model. Finally, the frequency deviation is proportional to the square of the modulation amplitude, which supports the fact that the amplitude and phase modulation are interrelated to each other through a nonlinear (i.e., amplitude dependent) dispersion relation.

c. Three Wave Interactions in Dispersive Media. During the investigation of a theoretical model to describe wave modulation in a nonlinear dispersive medium, we found that the effects of the dispersion may be important in certain cases. Thus, we numerically investigated [4] the effects of dispersion on the nonlinear interaction of three waves. Solution of this problem may be very important for understanding optical parametric amplification of ultra short pulses, and plasma heating by the lower hybrid wave. Specifically, three wave optical interactions in homogeneous nonlinear dispersive media were studied with a complementary use of analytic and numerical methods [4]. The main emphasis of the study was to investigate the effects of dispersion in the picosecond substructure generation in optical parametric processes. In a 3-wave interaction at optical frequencies ω_1, ω_2, ω_3 satisfying the resonance condition (i.e., $\omega_3 = \omega_1+\omega_2$), we found that the presence of dispersion in the medium leads to the generation of picosecond multipulsed substructure in the pulse profiles. Both the degenerate ($\omega_1=\omega_2=\omega_3/2$) as well as the nondegenerate ($\omega_1 \neq \omega_2$) parametric amplification processes are studied. For all the cases, a specific and realistic situation involving a $LiNbO_3$ crystal illuminated by a pulsed laser of intensity $10^{14} W/m^2$ is considered. The time envelopes of the initial pulses are chosen to be Gaussian with a full width at the half maximum of 30 psecs. The existence of the picosecond substructure in the pulse profiles, predicted by the present study, is in good agreement with the experimental observations of Kryukov et al. [11].

d. Analysis of Nonstationary Fluctuations. Wave modulation is intrinsically a nonstationary process. Thus, we have initiated an effort to understand the statistical characteristics of nonstationary fluctuation date. In our preliminary attempts to

get a handle on this problem, we utilize a two frequency coherence function $\Gamma^2(\omega_1,\omega_2)$, i.e.,

$$\Gamma^2(\omega_1,\omega_2) = \frac{|<\Phi(\omega_1)\Phi^*(\omega_2)>|^2}{<|\Phi(\omega_1)|^2><|\Phi(\omega_2)|^2>}$$

where $\Phi(\omega)$ is the Fourier transform of the fluctuation data and $< >$ denotes an expected value. The two frequency coherence function measures the degree of mutual coherence between two spectral components and is bounded by zero and unity. If a random fluctuation is regarded as a superposition of random oscillations, stationarity requires each oscillation to be uncorrelated to each other when $\omega_1 \neq \omega_2$ [5]. Therefore, any deviation from stationarity will result in a nonzero value of two frequency coherence functions at $\omega_1 \neq \omega_2$. We are presently utilizing digital techniques to compute the two-frequency coherence function for a variety of fluctuation data from different physical systems. In addition, we found [6] that the complex energy density function may provide a systematic framework with which to describe nonstationary fluctuation data. The complex energy density function, which is defined in terms of the analytic signal and its Fourier transform, corresponds to the signal energy density at a given instant and frequency. Much work remains to be done, concerning the practical digital implementation of this concept and how it may be exploited in the analysis and interpretation of nonstationary fluctuation data.

2. IR Nonlinear Optics. The objective of the continuing research in infrared nonlinear optics is to study new types of molecular optical nonlinearities at infrared wavelengths. Optical third harmonic generation is used to probe the nonlinear susceptibility and multiphoton absorption of molecular gases. A current problem in this field is to obtain a more wide ranging and fundamental understanding of why some molecules and which molecules have large nonlinear susceptibilities, particularly at cryogenic temperatures. At high laser intensities various competing or limiting processes, primarily multiphoton absorption, occur which reduce the efficiency of the third harmonic process. The study of these limiting processes is another facet of the overall objective.

We have recently concluded a several year study of the high energy resonant excitation of SF_6 gas using third harmonic generation techniques. The saturation of the linear and nonlinear properties of SF_6 has now been observed at 193K

and 293K over a wide range of laser intensities (from 10 to over 200 MW/cm^2). The entire study was carried out at a pressure of 0.2 torr which, during the laser pulse, is a collisionless regime. Since the nonlinear susceptibility of SF_6 is strongly affected by multiphoton resonances [7] and by population depletion and redistribution, third harmonic generation was selected as a means to study these two effects. Experiments were conducted in which the third harmonic generation spectrum for SF_6 was measured at intensities above and below the molecular dissociation threshold [8,9]. Evaluation of the data indicated that the discrete state population, which contributes most strongly to the third harmonic nonlinearity, was being depleted by one- and two-photon processes depending on the excitation frequency. Based on these experimental results, we hypothesize the existence of one- and two-photon transitions from the discrete vibrational states below 3000 cm^{-1} to the quasi-continuum (Q.C.) of states of higher energies. It is therefore likely that three-photon resonances from the ground state are damped by one-photon transition to the Q.C. The subsequent measurements at 193K were made to confirm this hypothesis [10]. At 193K the hot band population is significantly reduced and the ground state population correspondingly increased. Evaluation of the results is much simpler for this reason. Some resonances were observed to shift slightly with temperature, but the low temperature results fit the same model as we proposed earlier.

Study has begun on the two-photon resonant gas deuterated methane, CD_4. This molecule was selected because of an unusually strong and narrow two-photon resonance accessible to the 9.6μ and of the CO_2 laser. The resonance is Raman active and obeys the selection rule of $\Delta J = 0$. This in turn generates only a single narrow Q-branch for two-photon resonant absorption. Calculations indicate that a large third harmonic susceptibility should result. Currently this effort is just entering the experimental phase. A new dewar has been constructed to facilitate these measurements over a wide range of temperatures.

This work is also supported by a grant from AFOSR (AFOSR 78-3712). The work will continue in the coming year with emphasis being placed on molecules with narrow strong resonances, molecules with discrete fundamental resonances, and cryogenic temperature effects.

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Research Unit QE9-2. ATOMIC AND MOLECULAR ELECTRONIC PROCESSES

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A. INTRODUCTION: Atomic and molecular processes a) form the basis for the understanding of gaseous matter, and b) have important applications to high-priority technologies like lasers, energy conversion, high-altitude reactions, combustion, and electronic devices. In principle, complete theoretical answers to relevant questions lie in Schrödinger's equation and its solutions. However, rigorous solutions are known only for H. Every heavier system involving more than two particles has to be approached through approximations. Obviously, the coarseness of the approximations increases with the number of particles involved. If a very large number of particles interact simultaneously, then collective phenomena become predominant, and the solutions lie in the thermodynamic domain. Our research efforts here have been concentrated on dilute systems so that only two-body interactions are important. In this research area many approximate solutions are known, but their validity and range of convergence can be judged only by comparison with experimental results. Therefore, this group is fundamentally concerned with precision measurements, although the interpretation of data repeatedly requires detailed theoretical and computational studies.

Our research unit has concentrated its efforts toward a threefold approach--high energy electron scattering, electron impact spectroscopy and collision induced light scattering. The first two topics are supervised by Dr. Fink, and the latter by Drs. Frommhold and Proffitt. The high energy electron scattering experiment led to investigations of the molecular structures of several compounds, of intramolecular potential functions and of electron charge densities. These studies were sponsored by JSEP for many years. The results were presented to the NSF and they are presently supporting this work. The papers referenced [1-6] are all based on high energy electron scattering, and due recognition for the previous support of the JSEP is given. At present, electron impact spectroscopy is being developed here, with particular emphasis on electronic excited states. The excitation will occur optically and the probing will be carried out by low energy electron scattering. Collision-induced

light scattering was used to measure the invariants (trace and anisotropy) of the diatom polarizability tensor of the rare gases, often for the first time. In this way, particularly for the lighter gases, rigorous comparisons with ab initio calculations of the diatom polarizabilities were possible. New data concerning the virial expansion of light scattering by real gases are thus obtained [21].

Since the research efforts of the group have evolved along these parallel lines, the objectives and progress are reported consecutively. Section 1 is devoted to electron scattering, Section 2 to collision-induced light scattering.

B. OBJECTIVES AND PROGRESS

1. Electron Scattering. Low energy elastic electron scattering in the energy range of 10 eV-1000 eV is a research tool used to study the dynamic response of an atom or molecule to an incoming electron. If the electon is very slow, then the induced distortion in the charge density is adiabatic [7]. The consequence for the cross sections is a strong enhancement at small angles, due to the long range dipole field, which the targets produce to shield themselves from the perturbing field generated by the incoming electron. When the electron energy is increased the overall angle cross sections decrease, indicating a nonadiabatic dynamic response of the molecule [8]. At very high incident energy the electron cloud is too slow to adjust to the incoming perturbation, and the cross sections reflect the static potential. It is the latter process we have utilized heavily and were able to exploit to such an extent that we could determine the static distribution of the electrons involved in the molecular bond forming process [9]. (This research is now supported by NSF.) We are now extending our research to the medium and low energy range.

Electrons which interact with atoms and molecules in the 10 - 1000 eV range have a very high probability of exchanging energy with the target [10]. If the molecules are in the ground state, then the electron can only lose energy and excite the target. Inelastic electron scattering, when measured in the smallest scattering angles, follows the optical selection rules, and therefore the cross sections lead to oscillator strengths and obey sum rules [11]. The angular dependence of the various spectral lines is characterized by the vibrational progression to which this transition belongs [12]. Therefore, the identification of overlapping series is rather straightforward and a valuable supplement to the highly resolved but very confusing optical spectra. If the molecule is in an excited state then, the scattering electron

can deexcite the target and carry off the excess energy (super elastic scattering) [13,14]. The spectrum of the scattered electrons on the high energy side will reflect the distribution of the excited states while the electron was passing through. Since the experiment is carried out on a gas jet, the collisional deexcitation processes are avoided and only the intramolecular energy transfer pathways will be exhibited. There are two interesting features on which we plan to focus our attention. First, due to the anharmonicity of the molecular potential in the excited state, there always occur mode couplings which greatly influence the chemical reactivity of the excited species. Furthermore, at a Fermi-resonance, due to the L-S coupling mechanism, the molecules can transfer energy from one multiplet to another, often coupled with a change of the geometrical configuration [15,16]. With the availability of powerful lasers the excited states can be produced abundantly, and this will open the door to many possibilities in studying fundamental problems like relaxation processes and applied issues like laser chemistry or laser isotope separation.

Developing the field of superelastic electron scattering is equivalent to a new field of spectroscopy in which the high resolving power of optical spectroscopy is utilized in the excitation of a specific molecular state by resonance absorption. At the same time the deexcitation via electron scattering opens the opportunity to study singlet-triplet conversions, vibrational mode coupling, and potential curve crossings due to the selection rules as they apply to scattering processes. This technology has been successfully tested on Na and Ba vapors and therefore looks very promising for the extension to molecular gases [13,14].

Our study on the electron gun facility has been concluded. Our telefocus gun is working at the space charge and Boersch-effect limit [17,18]. We could show that the theory by Zimmerman describes accurately the thermodynamical relaxation process in the electron beam [19]. The 127° electron analyser works very well; however, a new concept in designing hemispherical analysers looks so promising that we are presently building two prototypes in our machine shop [20]. We hope to gain significantly on the transmitted electron beam intensity without loss of resolution. In order to keep all the electron optics to be used at the optimal setting, we are adapting various ray tracing programs to our CDC-computer facilities. These results will be a constant guide for the composition of the electron optical arrangements.

In order to pump the molecules into the electronic excited state, we are building an Ar^+ pumped mode-locked dye

laser. This system will produce 5-7 psec pulses with a repetition rate of 80 MHz. The peak power will be several hundred watts; therefore, frequency doubling can be achieved relatively efficiently. The laser system is equipped with a cavity dumper which allows us to vary the repetition rate while integrating the pulse intensity. This laser system provides us with photons from 8000 - 2000 Å, tunable and quasistationary (since the lifetime of many molecular electronic states is on the order of μsecs). During the last year we have developed a new correlator which allows us to measure directly the pulse width. The results are presently summarized in a manuscript to be published in Rev. Sci. Inst.

This work will be continued in 1980-81. In the next report we intend to show the first inelastic electron spectra and absolute measurement of the number of excited states which can be reached under the various pumping conditions in NO_2 and I_2.

2. Collision-Induced Laser Light Scattering. The goal of our collision-induced laser light scattering work is the consolidation of a large body of often conflicting experimental, semi-empirical and computational data concerning diatom polarizabilities. The term "diatom" is meant to emphasize the collision-induced nature of the incremental polarizability due to exactly two interacting atoms or molecules (monomers) of a gas, which is typically near atmospheric density. Consequently, the various second virial coefficients of the dielectric Clausius-Mosotti relation, the refractive Lorentz-Lorenz relation, and the field-induced birefringence (Kerr effect) of gaseous matter are intimately related research topics of great interest to us [21]. In the past, much effort was devoted to the basic understanding of collision-induced dielectric properties of gases, and to the measurement of certain moments of the depolarized collision-induced light scattering of the heavier rare gases, which are relatively easy to measure (by our new standards). The emphasis of our work, on the other hand, has been the investigation of such properties of the diatoms of the light gases (as ^3He, ^4He, Ne, etc.), for which sometimes very accurate ab initio computations of collision-induced polarizabilities exist, which are, however, largely untested by real experiments [21]. At the same time, we were also aiming to measure new properties, such as polarized collision-induced scattering, which were generally believed to exist but thought hard to obtain. We mention here that diatom polarizabilities are tensors. The invariants, trace and anisotropy, are responsible for polarized and depolarized scattering of light, respectively. The diatom

tensor is determined if both invariants are known. The goal of our work then is to measure these invariants, particularly for the light gases, and compare the results with the ab initio calculations of the same quantities where these exist. For gases heavier than neon, various approximate computational schemes were previously employed to estimate the diatom polarizabilities. The numerical results are often of an uncertain accuracy, and different semi-classical methods do not always give consistent results. Therefore, our aim is to also obtain accurate diatom polarizabilities for these gases and to provide new experimental tests for these important computations. Other empirical data based on the various second virial coefficients of the dielectric, refractive and field-induced birefringent properties of rare gases will also be critically compared with our new data [21].

The experimental approach of our work differs in some ways from all other work in the field. 1) The generally adopted "method of moments" was abandoned in preference to procedures based directly on the intensity and shape of the observed continua. The rigorous evaluation of the spectral distributions is supported by our wavemechanical computations of the spectra, which make use of accurate interatomic potentials and "models" of trace and anisotropy. In this way, the very serious problem of interference by the intense Rayleigh line is completely avoided. 2) The sensitivity of our research apparatus is the highest reported as yet in the literature. As a consequence, our measurements are done at the smallest gas densities, and hence are affected the least by three-body or higher interference. In some important cases, this particular fact gives rise to different spectra, and therefore to new results specific for diatom interactions and free to the highest degree from three-body contributions. 3) Finally, we make use of polarization optics to also obtain the polarized collision-induced components, thereby providing for the first time, complete data for the determination of the diatom polarizability tensor invariants. We mention that as a routine, absolute intensity calibrations are obtained for all spectra taken, typically now at an accuracy of 5% or better.

In our collision-induced scattering work, most recently we were able to obtain the diatom spectrum of the rare isotope of helium, ^{3}He [22]. Both a polarized and a depolarized spectrum are obtained, similar to (but significantly different from) the ^{4}He diatom spectra reported earlier [23-25]. We mention that these two isotopes make very different gases, not only on account of their different masses.

The diatom spectra appear to be very different too, on account of the symmetries related to the nuclear spin. The common isotope (^{4}He) is a boson. Consequently, collisional pairs of only even angular momentum quantum states are allowed, whereas for the ^{3}He diatom the odd states completely dominate the situation (much like in normal hydrogen, ortho-H_2 is three times more abundant than para-H_2). And yet, their electronic structure, and hence their diatom polarizabilities, are the same! The resultant, very different spectra must therefore, be fitted with the same polarizability invariants, which in fact we were able to demonstrate [22]. This new work in ^{3}He is most of all an impressive consistency check of the general approach and methods of our work, and emphatically demonstrates the soundness of it. Furthermore, since at the same time the precision of our calibrations could be improved, a superior overall precision of the inferred diatom polarizabilities of helium was obtained. Elsewhere, this work has already stimulated new and very accurate ab initio calculations of the dynamic diatom polarizability of helium, which for the first time will account rigorously for the frequency dependencies.

The first polarized collision-induced diatom spectra of the neon [26,27] and the argon [28] diatoms could also be obtained, and from them, accurate empirical models of trace and anisotropy for these gases. An interesting frequency dependence of the argon diatom polarizability was observed by comparing (on an absolute intensity scale) the diatom spectra excited by three different laser frequencies (5145Å, 4880Å, and 4579Å). It is known that the anisotropy of a pair is given by a leading term, plus a correction term. The leading term is of the form $6\alpha^2/r^3$ (with α = atomic polarizability; r = internuclear separation), which in essence describes the distortion of the local fields by the collisional perturber. The frequency dependence of this leading term is that of α^2, and as is well known, it is quite weak. At close range, the need of an added correction term has long been known. Usually a form like $A \cdot \exp(-r/r_o)$ is found useful; this in essence accounts for electronic overlap at close range. Almost nothing is known about the frequency dependence of this correction term. If we are interpreting our recent observations correctly, the frequency dependence of the correction term must be rather substantial, and certainly much stronger than hitherto assumed. Furthermore, for the first time this relatively small correction, which must be calculated on the basis of wavemechanics, can be studied with little interference from the leading term. A few more months of work are required to arrive at the correct interpretation of this observation, but we mention that extensive tests have already

indicated the validity of this surprising result.

C. FOLLOW-UP STATEMENT: Unexpectedly, in collision-induced light scattering an interesting frequency dependence was recently observed [28]. This effect is intriguing because it is almost certainly associated with the wave mechanics of the atomic interaction, but not with classical electrodynamics and the (trivial) local field distortions. In recent years for the case of the argon diatom, theory showed that the electronic overlap contributions are rather small, at least at zero frequencies of the field. Experiments at 5145Å seemed to be supporting this conclusion. However, our new experiments at 4880Å and 4579Å indicate the need for a significant overlap correction at these frequencies, much larger than hitherto thought. The older results at 5145Å thus appear to be only coincidentally in support of the theory at zero frequencies. This situation, we think, warrants some more activities in this field before moving on to the nonlinear collision-induced diatom polarizabilities (susceptibilities).

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QUANTUM ELECTRONICS

Research Unit QE9-3. HIGH POWER LASER SYSTEMS

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A. PROGRESS: This research unit is concerned with the physics of energy transfer in gaseous, high power laser systems and with optical components for high power laser beam analysis.

1. Energy Transfer in Laser Systems. One objective of this unit is the use of time dependent spectroscopic techniques to identify the primary energy transfer processes in high-energy laser systems. Initial research has concentrated on studies of electron beam pumped mixtures of oxides and rare gases. This work is now concluded. New experiments have been directed at studies of recombination rates in high-density rare gas discharges. This information is pertinent to nearly all types of high-power excimer lasers which use rare gases as a buffer in the energy absorption process. We have now obtained very exciting data on recombination processes at high densities.

Electron Beam Excited Mixtures of Oxygen and Argon. We have now completed both experimental studies and theoretical modeling for electron beam excited mixtures of argon and oxygen. Previously we showed from qualitative models of our data that the primary mechanism for populating the $O(^1S_0)$ state in the discharge is charge transfer from the molecular argon ion to O_2.

Important to any direct measurements of the energy transfer rates to oxygen is a knowledge of energy transfer to "impurities" which result from electron dissociation of oxygen molecules. In single shot experiments starting with a mixture of pure argon and oxygen, a significant amount (2% at 10 atm total gas pressure when using a Febetron 706) of dissociation occurs during the pulse. When using very small and continuous electron beam currents (less than 100 $\mu A/cm^2$) as in our experiments, we found that significant amounts of $O(^3P)$ and O_3 were produced under particular experimental conditions; hence we felt it necessary to model accurately the amounts of $O(^3P)$ and O_3 produced. We have also measured the concentrations of $O(^3P)$ and O_3 by determining their quench rates of $O(^1S_0)$ from measurements of the fluorescence decay time at 557.7 nm. We find that our model calculations are in good agreement with these measured quench rates, and they also explain the observed dependence of the

$O(^1S)$ fluorescent intensity on argon and oxygen pressures and beam current. This work has been submitted for publication [1].

In our model calculation, we used our measured energy transfer rates but as well had to assume a significant electron dissociation of O_2 to obtain agreement between model calculations and our experiments. We have now completed calculations of the electron energy distribution function, excitation rates, dissociation rates, and electron impact vibrational heating that result from the stopping of the electron beam in the gas [2]. These calculations show that dissociative excitation of ground vibrational O_2 is insufficient to explain the experimental rates for dissociation. Also, we find that the calculated electron vibrational excitation rates are significantly greater than the known rate of cooling by V-T relaxation to argon atoms.

With an accurate model of the electron beam excited argon and oxygen discharge, we can find conditions enabling the study of energy transfer from argon ions and excimers to both O_2 and O_3. These are determined by measuring the loss rate of ions and excimers as a function of time after termination of the electron beam as a function of O_2, O_3, and argon pressure. The measured bimolecular and termolecular rates, which are submitted for publication [3], are summarized in Table I.

Table I

Energy transfer rates. The error bars for ozone are relative and do not include errors in the quench rate of $O(^1S_0)$ measured in Ref. 4.

	This Work (10^{-10} cm^3/sec)	Ref. 5 (10^{-10}cm^3/sec)	Ref. 6 (10^{-10}cm^3/sec)	Ref. 7 (10^{-10}cm^3/sec)
$Ar_2^*+O_2$	0.46±0.26	2.6		
$Ar_2^*+O_3$	46±6			
Ar^*+O_2	0.8±.6		1.2±1.2	1.2
[illegible]	[illegible]±30			
	[illegible] sec)		(10^{-30}cm^6/sec)	

Dissociative Recombination in Argon at High Pressures. In a recent progress report [8] we summarized preliminary results and the experimental approach for studying dissociative recombination rates in argon at pressures from 10 Torr to 1000 Torr. We have now extended these results to pressures up to 20,000 Torr by monitoring the repopulation of the $Ar_2^*(^{3,1}\Sigma_u^+)$ excimer which radiates at 125 nm. For pressures above one atmosphere, each excited atomic state resulting from dissociative recombination results in the production of one excimer state, which for small excited state densities produces a photon at 125 nm. At higher pressures then, we can monitor the rate of recombination as a function of time in the late afterglow by observing the production of photons at 125 nm. We find that the effective rate of recombination for electrons increases monotonically with pressure. Our measured rates are in agreement with other workers at low pressures [9], while at the highest pressure of 10,000 Torr we observe a factor of 17 increase in the recombination rate coefficient over that measured at 10 Torr.

Werner et al. [10] first suggested the possibility for the increase in the rate of dissociative recombination at higher pressures in order to explain the experimental dependence of the rare gas excimer laser gain as a function of pressure. They suggested the increased rates of recombination could be explained by the formation of trimer ions, e.g., Ar_3^+, at higher pressures. Werner et al. [10] measured the electron density as a function of increased gas pressure at fixed electron beam current. Measured electron densities in our experiments are in good agreement with these results.

In contrast to the model proposed by Werner et al. for the increased recombination rates, our data suggest that dissociative recombination is enhanced by collisions in a termolecular reaction. For illustration we show in Fig. 1 a comparison of our data with a model which assumes that the formation of trimer ions is in equilibrium with the dimer ions with an equilibrium coefficient measured by Turner and Conway [11]. As observed in Fig. 1 this model is inconsistent with the data. This does not imply that cluster ions are not formed; rather it suggests that their formation alone will not explain the increased rate of recombination.

Bardsley [12] has suggested dissociative recombination can proceed directly through dissociative molecular states or indirectly through vibrationally or rotationally excited rydberg molecular levels. In experiments on shorter time scales we believe we observe a delay in production of dissociative atomic states characteristic of intermediate states. We also observe dependences upon electron density which are explainable by a variation in the ratio of direct to indirect

recombination. The research is now directed to the identification of these intermediate states using state-selective photo excitation. In building apparatus for these experiments we have developed improvements in blumlein-driven lasers [13] and an optical autocorrelator [14] to be used in adjustment of a mode-locked laser for kinetic studies. Two papers related to our studies of dissociative recombination are in preparation [15,16].

Our research on electron beam excited mixtures of argon and oxygen and on dissociative recombination in argon at high densities is completed. New efforts directed toward the identification of intermediate states in dissociative recombination using state-selective photoexcitation will be carried out under the JSEP Research Unit QE80-2, "Structure and Kinetics of Excited State Molecules."

2. Laser System Components. A second objective of this research unit is the characterization and optimization of beam sampling techniques for high energy lasers. The use of the grating rhomb (parallel grating pair) to obtain amplitude and phase distributions in laser beams has been studied. The objective was to determine analytically the inherent aberrations in rhomb systems and develop an optimum configuration. In addition, a deconvolution algorithm should be devised which can correct data already taken using an arbitrary rhomb system containing aberrations.

Final work on this problem was completed and published [17] during the past year. The inherent aberrations were analyzed for the case of a two-grating rhomb laser beam sampler used in high energy laser systems. Although plane wave fronts are sampled without aberration, spherical or more complex wave fronts suffer 1-D phase and displacement deviations. An inverse filter description that employs the angular spectrum concept for the incident and sampled beams has been developed. An inverse filter is easily synthesized and may be used to deconvolve the aberrations from a sampled data set. In addition, an optimization was performed in order to minimize phase errors in the sampled beam and to develop design criteria. Some practical examples show that, in an optimized system, the aberrations are often negligible, and deconvolution is seldom necessary.

Work on this problem is now complete and it does not appear in our currently proposed research.

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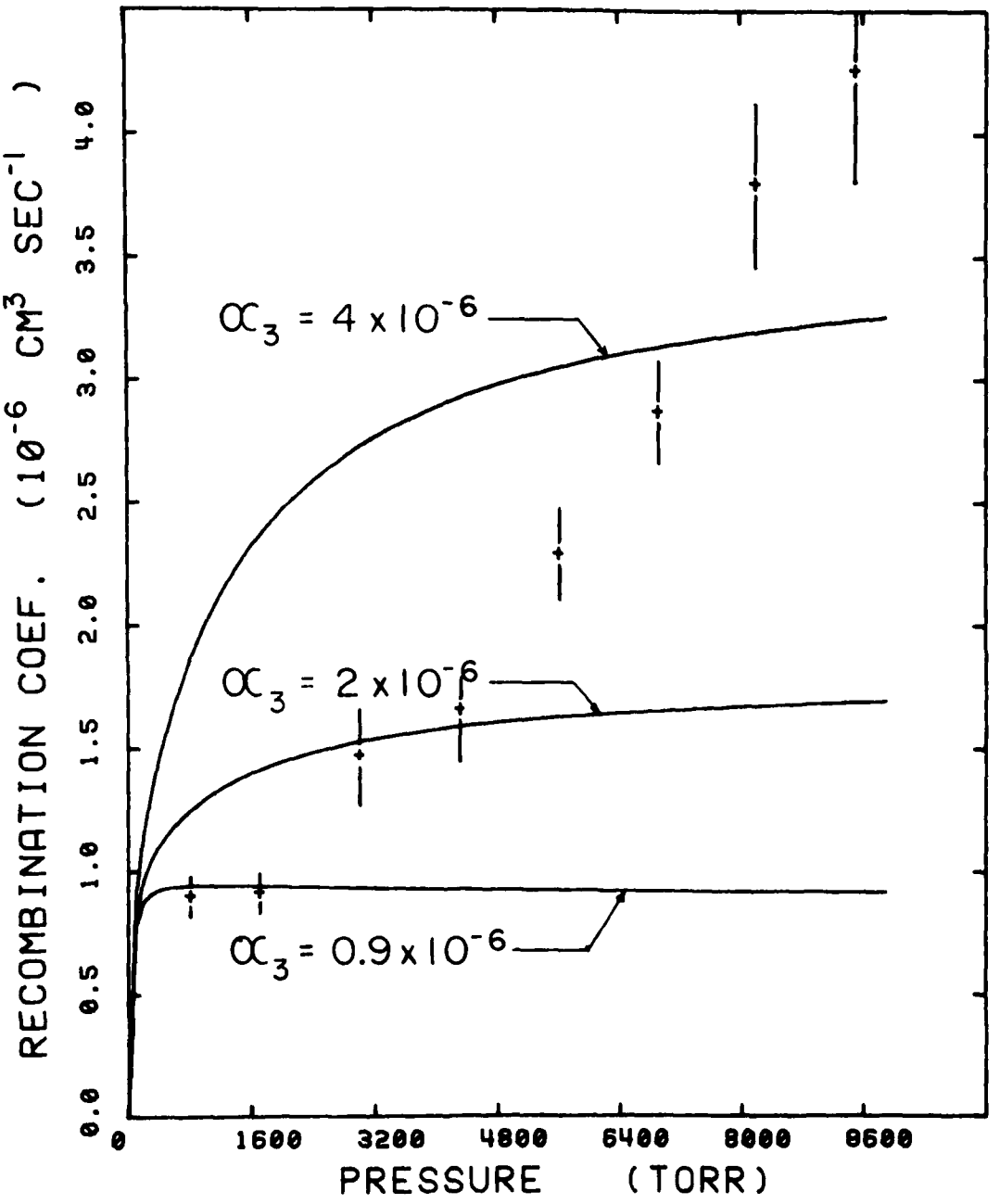

Fig. 1. The effective electron recombination for three trimer ion recombination coefficients compared with our measured values which are shown as crosses. For reasons described in Ref. 16 the rate coefficients are measured by extrapolating to zero electron density to avoid effects of electron collisions.

IV. ELECTROMAGNETICS

ELECTROMAGNETICS

Research Unit EM9-1 ELECTROMAGNETIC SIGNAL ANALYSIS AND IDENTIFICATION

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A. OBJECTIVE AND PROGRESS: Many targets to be detected by radar have inherent metal-to-metal contacts which are observed to exhibit nonlinear junction effects which, in turn, may result in new frequency components (such as harmonics and cross-products) appearing in the backscattered field [1]. The objective of this work is to investigate the possibility of gaining additional signature information characterizing a nonlinear target by appropriately analyzing and interpreting the incident and backscattered radiation. Clearly classical linear spectral analysis techniques are of limited value in analyzing signals scattered by a nonlinear target. Our approach to this problem is to build upon our own experience in applying higher spectral concepts to nonlinear wave phenomena [2,3] and to utilize various aspects of work done by others in nonlinear systems [4]. The concept of impulse response (or equivalently, its Fourier transform known as the transfer function) has been utilized to characterize the features of linear targets [5]. To quantitatively characterize the higher order nonlinear scattering features of a target, we have utilized the nonlinear systems concept of higher order impulse responses and their Fourier transforms, higher order transfer functions. In this case we may consider the incident radiation as the "input" to to a nonlinear system and the scattered radiation as the "output." In contrast to much of the nonlinear systems work involving the time domain [4], we have focused on the frequency domain [6] where the "input"-"output" relation is modelled with aid of a hierarchy of linear, quadratic, cubic, etc., transfer functions. We have also shown how the concept of higher order transfer functions may be utilized to characterize the linear and nonlinear features of a target with the aid of linear, quadratic, cubic, etc., scattering cross sections. As an example of how the concept of higher order scattering cross sections may be applied, we have utilized these concepts to extend the radar equation to nonlinear targets [7]. Specific details follow.

Nonlinear Transfer Functions: Our starting point is based on the work of Barrett [8] who showed that, if the input $x(t)$ is a zero-mean stationary Gaussian process, the output $y(t)$ may be expressed by the following orthogonal representation:

$$y(t) = \int_{-\infty}^{\infty} h_1(t-t_1)x(t_1)dt_1 + \iint_{-\infty}^{\infty} h_2(t-t_1,\ t-t_2)\Big\{x(t_1)x(t_2) - \langle x(t_1)x(t_2)\rangle\Big\}dt_1dt_2$$

$$+ \iiint_{-\infty}^{\infty} h_3(t-t_1,\ t-t_2,\ t-t_3)\Big\{x(t_1)x(t_2)x(t_3) - x(t_1)\langle x(t_2)x(t_3)\rangle - x(t_2)\langle x(t_3)x(t_1)\rangle - x(t_3)\langle x(t_1)x(t_2)\rangle\Big\}dt_1dt_2dt_3 + \ldots \quad (1)$$

where the pointed brackets denote statistical averaging and the nth kernel h_n may be regarded as the nth order impulse response characterizing the nonlinear features of the system. Fourier transforming Eq. (1), we obtain:

$$Y(f) = \int_{-\infty}^{\infty} H_1(f_1)X(f_1)\delta(f-f_1)df_1$$

$$+ \iint_{-\infty}^{\infty} H_2(f_1,f_2)\Big\{X(f_1)X(f_2) - \langle X(f_1)X(f_2)\rangle\Big\}\delta(f_1+f_2-f)df_1df_2$$

$$+ \iiint_{-\infty}^{\infty} H_3(f_1,f_2,f_3)\Big\{X(f_1)X(f_2)X(f_3) - X(f_1)\langle X(f_2)X(f_3)\rangle - X(f_2)\langle X(f_3)X(f_1)\rangle - X(f_3)\langle X(f_1)X(f_2)\rangle\Big\}\delta(f_1+f_2+f_3-f)df_1df_2df_3 + \ldots \quad (2)$$

where H_n, the n-dimensional Fourier transform of h_n, is the nth order transfer function, and X(f) and Y(f) are the Fourier transforms of the input and output, respectively. The presence of the terms in pointed brackets insures that Eq. (2) is an orthogonal representation. Note also that $\langle X(f_1)X(f_2)\rangle = P_x(f_1)\delta(f_1+f_2)$ for a stationary random fluctuation, and where $P_x(f)$ is the power spectral density of x(t) [9]. Thus, the terms in the pointed brackets correspond to degenerate type situations where $f_1=-f_2$, $f_2=-f_3$, or $f_1=-f_3$, etc.

Since each term in Eq. (2) is orthogonal to the other terms, the output power spectral density $P_y(f)$ is given, up to third order, by the relatively simple expression:

$$P_y(f) = |H_1(f)|^2 P_x(f) + \int_{-\infty}^{\infty}\int |H_2(f_1,f_2)|^2 P_x(f_1)P_x(f_2)\delta(f_1+f_2-f)df_1df_2$$

$$+\int_{-\infty}^{\infty}\int\int |H_3(f_1,f_2,f_3)|^2 P_x(f_1)P_x(f_2)P_x(f_3)\delta(f_1+f_2+f_3-f)df_1df_2df_3 \quad (3)$$

Of particular interest is the fact that $H_n(f_1,f_2,f_3,\ldots f_n)$ may be determined by multiplying Eq. (2) by $X^*(f_1)X^*(f_2)\ldots X^*(f_n)$ and carrying out a statistical average. The asterisk denotes a complex conjugate. For example, the first three transfer functions are given by:

$$H_1(f) = \frac{P_{yx}(f)}{P_x(f)}$$

$$H_2(f_1,f_2) = \frac{1}{2!}\frac{P_{yxx}(f_1,f_2)}{P_x(f_1)P_x(f_2)} \quad (4.a)$$

$$H_3(f_1,f_2,f_3) = \frac{1}{3!}\left\{\frac{P_{yxxx}(f_1,f_2,f_3)}{P_x(f_1)P_x(f_2)P_x(f_3)}\right. \quad (4.b)$$

$$\left.-\left(\frac{H_1(f_1)}{P_x(f_3)}\,\delta(f_2+f_3) + \frac{H_1(f_2)}{P_x(f_1)}\,\delta(f_3+f_1) + \frac{H_1(f_3)}{P_x(f_2)}\,\delta(f_1+f_2)\right)\right\} \quad (4.c)$$

Note that all the transfer functions are expressed in terms of nth order cross spectra, $P_{yx..x}(f_1,f_2,\ldots f_n)\delta(f_1+f_2+\ldots f_n-f)=\langle Y(f)X^*(f_1)\ldots X^*(f_n)\rangle$. Of special interest is the fact that such spectra can be computed directly from the Fourier transforms X(f) and Y(f) of the raw time series data [2].

Eq. (2) models, in the frequency domain, the linear, quadratic, and cubic relationship between two fluctuating quantities x and y. Of particular importance is the fact that Eq. (2) is an orthogonal representation, which in turn indicates that to third (i.e. cubic) order Eq. (2) is the best model in a least mean-square-error sense. The overall "goodness of fit" of the model can be obtained by computing a squared coherence function $\gamma^2(f)$, which can be expressed as $\gamma^2(f) = \gamma_1^2(f) + \gamma_2^2(f) + \gamma_3^2(f)$, where $\gamma_1^2(f)$, $\gamma_2^2(f)$ and $\gamma_3^2(f)$ are quantitative measures of the degree of linearity, quadraticity, and "cubicity" of the model. The quantity $\gamma^2(f)$ represents the fraction of power present in the actual output which is accounted for by the model. Similarly, $\gamma_1^2(f)$, $\gamma_2^2(f)$, and $\gamma_3^2(f)$ represent the fraction of power present in the output which is associated with the linear, quadratic, and cubic nature of the model. Expressions for the linear, quadratic, and cubic coherency spectra are given below:

$$\gamma_1^2(f) = \frac{|P_{yx}(f)|^2}{P_y(f)P_x(f)} \tag{5.a}$$

$$\gamma_2^2(f) = \frac{1}{2!}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\frac{|P_{yxx}(f_1,f_2)|^2}{P_y(f)P_x(f_1)P_x(f_2)}\,\delta(f_1+f_2-f)\,df_1\,df_2 \tag{5.b}$$

$$\gamma_3^2(f) = \frac{1}{3!}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\frac{1}{P_y(f)P_x(f_1)P_x(f_2)P_x(f_3)}\Big|P_{yxxx}(f_1,f_2,f_3) \tag{5.c}$$

$$- \Big\{P_{yx}(f_1)P_x(f_2)\delta(f_2+f_3) + P_{yx}(f_2)P_x(f_3)\delta(f_3+f_1)$$

$$+ P_{yx}(f_3)P_x(f_1)\delta(f_1+f_2)\Big\}\Big|^2\,\delta(f_1+f_2+f_3-f)\,df_1\,df_2\,df_3$$

Nonlinear Radar Cross Sections: We now procede to build upon the conceptual framework of nonlinear transfer functions to generalize the idea of radar cross section so that it might quantitatively describe both the linear and nonlinear features of a target. The general concept of a nonlinear radar cross section should possess the following features: (1) It should, in the linear limit, reduce to the familiar linear radar cross section, (2) It should indicate that due to the nonlinear aspects of the target various frequencies in the incident signal "mix" to yield a variety of new frequencies (including harmonics and intermodulation cross-products) in the scattered signal, (3) It should be capable of separately quantifying the degree of nonlinearity associated with the quadratic, cubic, etc., features of the target, (4) It should reduce, in the appropriate limit, to the concept of harmonic radar cross sections [10] where it is known that the amount of power scattered from a nonlinear target is a nonlinear function of the incident power.

Let $S_i(f)$ [$wm^{-2}Hz^{-1}$] denote the power flux spectral density incident upon a target, and let $P_s(f)$ [wHz^{-1}] denote the power spectral density of the scattered signal (measured at the target), which is assumed to be reradiated isotropically. Recalling that, in general, radar cross sections relate the incident flux density to the power scattered isotropically, and utilizing Eq. (3) where $S_i(f)$ is the "input" and $P_s(f)$ the "output" of our nonlinear system, we arrive at the following expression relating $S_i(f)$ and $P_s(f)$.

$$P_s(f) = S_i(f)\sigma_1(f) + \iint S_i(f_1)S_i(f_2)\sigma_2(f_1,f_2)\delta(f_1+f_2-f)df_1df_2 + \iiint S_i(f_1)S_i(f_2)S_i(f_3)\sigma_3(f_1,f_2,f_3)\delta(f_1+f_2+f_3-f)df_1df_2df_3 + \ldots \quad (6)$$

The quantities $\sigma_1(f)$, $\sigma_2(f_1,f_2)$ and $\sigma_3(f_1,f_2,f_3)$ are the radar cross sections representing the linear, quadratic, and cubic features of the target. Note that σ_1, σ_2, σ_3 have the physical dimensions of m^2, $w^{-1}m^4$, $w^{-2}m^6$, respectively. In general, the dimensions of the nth order cross section $\sigma_n(f_1,f_2,f_3,\ldots f_n)$ are $w^{1-n}m^{2n}$. The fact that the dimensions of the "nonlinear"

cross section involves w (watts) is a manisfestation of the fact that the amount of power (at the "mixing" frequencies) scattered by a nonlinear target is a function of the incident power level. For example, the second term on the RHS of Eq. (6) indicates that the amount of power scattered at the sum frequency $f = f_1 + f_2$, is dependent on the product of the power flux density of both f_1 and f_2. The quadratic cross section $\sigma_2(f_1,f_2)$ is a quantitative measure of the strength of this quadratic interaction. Analogous statements may be made concerning the third term on the RHS which models the cubic features of the target.

To demonstrate the utility of the nonlinear cross section $\sigma_n(f_1,f_2,f_3,\ldots f_n)$ we now procede to develop the so-called "nonlinear" radar equation which relates the power spectral density $P_r(f)$ of the received signal to the power spectral density of the transmitted signal $P_t(f)$. To do this, we make use of the fact that

$$S_i(f) = \frac{P_t(f)}{4\pi R^2} G_t(f), \tag{7.a}$$

$$P_r(f) = \frac{P_s(f)}{4\pi R^2} G_r(f) \frac{\lambda^2}{4\pi} \quad . \tag{7.b}$$

where $G_t(f)$ and $G_r(f)$ are the gains (at frequency f) of the transmitting and receiving antennas, respectively. Combining Eqs. (6) and (7) we obtain the nonlinear radar equation,

$$P_r(f) = \frac{G_r(f)}{4\pi R^2} \frac{\lambda^2}{4\pi} \frac{P_t(f)}{4\pi R^2} G_t(f)\sigma_1(f)$$

$$+ \frac{G_r(f)}{4\pi R^2} \frac{\lambda^2}{4\pi} \iint \frac{P_t(f_1)}{4\pi R^2} \frac{P_t(f_2)}{4\pi R^2} G_t(f_1)G_t(f_2) \cdot$$

$$\sigma_2(f_1,f_2)\delta(f_1+f_2-f)df_1df_2$$

$$+ \frac{G_r(f)}{4\pi R^2} \frac{\lambda^2}{4\pi} \iiint \frac{P_t(f_1)}{4\pi R^2} \frac{P_t(f_2)}{4\pi R^2} \frac{P_t(f_3)}{4\pi R^2} G_t(f_1)G_t(f_2)G_t(f_3) \cdot$$

$$\sigma_3(f_1,f_2,f_3)\delta(f_1+f_2+f_3-f)df_1df_2df_3 + \cdots \tag{8}$$

The first term on the RHS, which models the linear scattering features of the target, is the usual (linear) radar equation. The next two terms indicate how the radar equation is modified by the quadratic and cubic nature of the target. Note the linear term possesses the well known $1/R^4$ range dependence, whereas the quadratic and cubic terms vary as $1/R^6$ and $1/R^8$, respectively. We further note that when $f_1=f_2=f_3=\ldots f_n$, Eq. (8) reduces to the harmonic radar equation. In this case, Eq. (8) indicates that the scattered 2nd and 3rd harmonic power are proportional to the square and cube of the incident fundamental frequency power, respectively.

Comparing Eqs. (3) and (8), we arrive at the following relationships between the linear and nonlinear scattering cross sections and linear and nonlinear transfer functions,

$$|H_1(f)|^2 = \frac{\lambda^2}{4\pi} \frac{G_r(f)}{4\pi R^2} \frac{G_t(f)}{4\pi R^2} \sigma_1(f) , \tag{9.a}$$

$$|H_2(f_1,f_2)|^2 = \frac{\lambda^2}{4\pi} \frac{G_r(f_1+f_2)}{4\pi R^2} \frac{G_t(f_1)}{4\pi R^2} \frac{G_t(f_2)}{4\pi R^2} \sigma_2(f_1,f_2) , \tag{9.b}$$

$$|H_3(f_1,f_2,f_3)|^2 = \frac{\lambda^2}{4\pi} \frac{G_r(f_1+f_2+f_3)}{4\pi R^2} \frac{G_t(f_1)}{4\pi R^2} \frac{G_t(f_2)}{4\pi R^2} \frac{G_t(f_3)}{4\pi R^2} \sigma(f_1,f_2,f_3) , \tag{9.c}$$

and so on.

B. SUMMARY: To describe the nonlinear features of a scattering object we have utilized the concept of nonlinear transfer functions. This in turn allowed us to generalize the concept of radar cross section, in that the linear, quadratic, and cubic scattering characteristics of the object may be quantitatively described by the linear, quadratic, and cubic cross sections. Furthermore, it was demonstrated that by introducing the concept of nonlinear cross sections, one could modify the radar equation to include the nonlinear features of a target.

It was shown that when an "input" is Gaussian, but nonwhite, the nonlinear transfer function and hence the nonlinear cross sections can be determined by computing the power spectrum of the input, and higher order cross spectra

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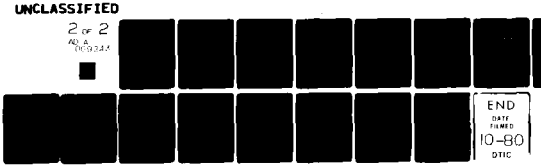

between the input and output. Some of the practical aspects of implementing these ideas in order to determine the linear and nonlinear scattering cross sections from measurements of the incident and scattered signals are currently being investigated.

In closing, we reiterate that the (possible) measurement of higher order nonlinear scattering cross sections appears to provide a very systematic and quantitative way with which to describe the scattering characteristics of nonlinear targets. Knowledge of such higher order cross sections should provide additional information which may be utilized in the classification and identification of a target. Secondly, knowledge of linear and nonlinear scattering cross sections will enable one to predict the power spectrum of the scattered signal in terms of the power spectrum of the incident signal.

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Research Unit EM9-2 GUIDED-WAVE DEVICES FOR THE FAR INFRARED-mm WAVE SPECTRUM

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A. RESEARCH OBJECTIVES

This work has as its overall objective the identification, analysis, and finally, the prototype demonstration of useful semiconductor waveguide devices for production and control of radiation in the frequency range from ten to a few hundred gigahertz. This part of the spectrum is uniquely suited to a number of DoD needs, but its exploitation will require a mix of designs, some using concepts first developed in integrated optics, and others adapting microwave techniques. This research focuses on use of the Gunn and IMPATT mechanisms for radiation sources, and on use of carrier injection and the field effect for electronic active guided wave devices such as modulators, active filters and beam deflectors. For the most part, the device concepts being studied are compatible with planar waveguide integrated circuit technology.

B. PROGRESS

In the first year of research under this unit, our investigations have proceeded in a number of directions, which are detailed in the following.

1. Distributed Gain Mechanism. In conventional two or three terminal active devices such as Gunn, IMPATT or FET, microwave amplification takes place in the direction of the dc bias. For instance, in a Gunn device a gain is expected in the direction from one electrode to another due to negative mobility [1] around the transit time frequency without dipole formation [2] ($n_0L < 10^{12}cm^{-2}$), or even with dipole formation [3] ($n_0L > 10^{12}cm^{-2}$); here n_0 is the carrier concentration and L the device dimension.

As opposed to these conventional approaches, we envisage the situation in which growing waves propagate in the axial (z) direction in Figure 1, perpendicular to the dc bias, if the device has sufficient length. In fact, it was reported that one can have gain in the axial (z) direction when the transverse carrier transit angle is around 2π or its multiples in IMPATT or n-GaAs type Gunn structures [4,5].

Some experimental work on a n-GaAs device with coplanar electrodes has been reported in [6].

Strictly, these types of problems are time-dependent and three-dimensional, but there has been no explanation of transverse transit angle dispersion even in the simplified time-independent one-dimensional case. This transverse transit angle dispersion has a critical effect on the gain and propagation characteristics of planar structures.

In the previous work on distributed gain devices [4,5] it was assumed that the device is uniform in one transverse dimension. Hence, no guided wave effect has been investigated. On the other hand, the work of coplanar type describes only a special case, and no general treatment of this class of devices is reported [6].

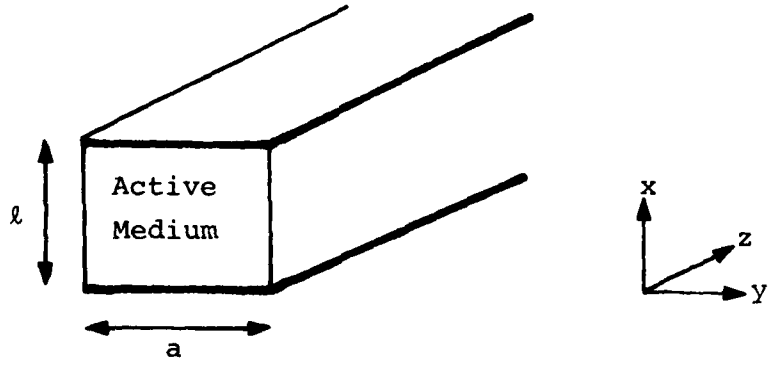

Figure 1. Parallel strip waveguide with active medium.

These new structures are expected to have several unique features that make them potentially advantageous in millimeter-wave applications. They are:

(a) The device structures conform to planar fabrication technology, and hence, may be useful in monolithic IC development.

(b) Since the gain mechanism is distributed along the axis, the device is considered to be an active waveguide. This may lead to flexible design possibilities. Depending on how the gain device is terminated, it may work either

as an amplifier or as an oscillator.

(c) Wide-band performance, such as wide band electronic tuning, may be attained. This is because the propagation characteristics (the phase constant and the gain) are controlled by the dc bias, and small changes in these characteristics result in cumulative phase shift or gain in the axial direction.

(d) Since at least one of the device dimensions is large compared to the wavelength, the fabrication may be more cost effective at higher frequencies.

Basic Mechanism for Distributed Gain. We have concentrated mainly on the Gunn-type devices. For basic understanding of the gain phenomena, we reviewed the one-dimensional analysis used by Yokoo and Ono [5]. In Figure 1 we apply the dc bias along the x direction in such a way that no domain is formed ($n_0L < 10^{12}cm^{-2}$). If we assume that the fringing effect is negligible, all the field lines are parallel along the x axis and are inside the active medium. Then the field becomes uniform in y and the problem is reduced to one dimension. The dispersion relation in this case becomes $\beta^2 = -j\omega\mu_0 \ell Y(\omega)$, where ℓ is the path length and $Y(\omega)$ is the driving point admittance per unit area.

The real part of β is the phase constant, whereas the imaginary part gives either loss or gain. It was found that gain is exhibited when the total transit angle is around 2π or its multiples.

Simplified Analysis for Planar Distributed Gain Structures. Up to now, we have reviewed the simplest structure which is assumed to have uniform transverse carrier transit angle, and hence, no dispersion. In many more practical structures, however, transverse carrier transit angles are non-uniform. These structures include microstrip, slot-line and coplanar transmission line arrangements. These structures can be easily implemented by planar technology and are useful for high microwave and millimeter-wave applications. In these devices, the contour of the region in which an n-GaAs medium exhibits gain depends on the bias voltage. It is, therefore, expected that the dc bias strongly affects the propagation and gain characteristics due to transit angle dispersion caused by different carrier transit paths in the transverse direction.

To investigate this two-dimensional effect, we

divided the cross sectional structure into infinitely many dc current elements (constant flux) as shown in Figure 2(a). Within the small tubes labelled 1, 2, ---, the flux is constant and uniform. Therefore, we can model the structure (coplanar type here) with a parallel combination of time independent one-dimensional structures denoted by 1, 2, --- as described in Figure 2(b). The propagation constant of the composite structure is obtained by combining those of the individual one-dimensional structures.

Our initial investigation indicates that the results based on the simplified model qualitatively agree well with those obtained experimentally [6]. In addition, this analysis lends itself to clear understanding of the gain mechanism in planar structures. We find that the gain is created only in a portion of the cross sectional region while the rest of the region causes loss. Therefore, this analysis may be useful for optimum design of the device.

Maximum Possible Frequency of Operation. During the early stages of space-charge build-up in two-valley semiconductors exhibiting negative conductance, the time rate of the space charge growth is given by [7,8]

$$Q(x,t) = Q(x-vt,0) \exp\left(\frac{t}{\tau_D}\right)$$

where

$$\tau_D = \frac{\varepsilon_s}{qn_o|\mu_D|}$$

is the dielectric relaxation time. Typically in n-GaAs with density $n_0 = 10^{15}cm^{-3}$, mobility $\mu_D = -2400\ cm^2/v\text{-}sec$, and relative dielectric constant $\varepsilon_s = 12.5$, τ_D is about 2.88 psec [9]. That is, it takes about 2.88 psec for space charge to grow up to the e^1 level.

On the other hand, the negative differential mobility is due to the intervalley carrier transport caused by optical-phonon scattering. The carrier transport is the transfer of conduction electrons from a high-mobility low-energy valley to a low-mobility high-energy valley. This scattering time is on the order of psec [7]. In other words, negative differential mobility does not exist until intervalley scattering is completed.

Therefore, if the sum of this scattering time and

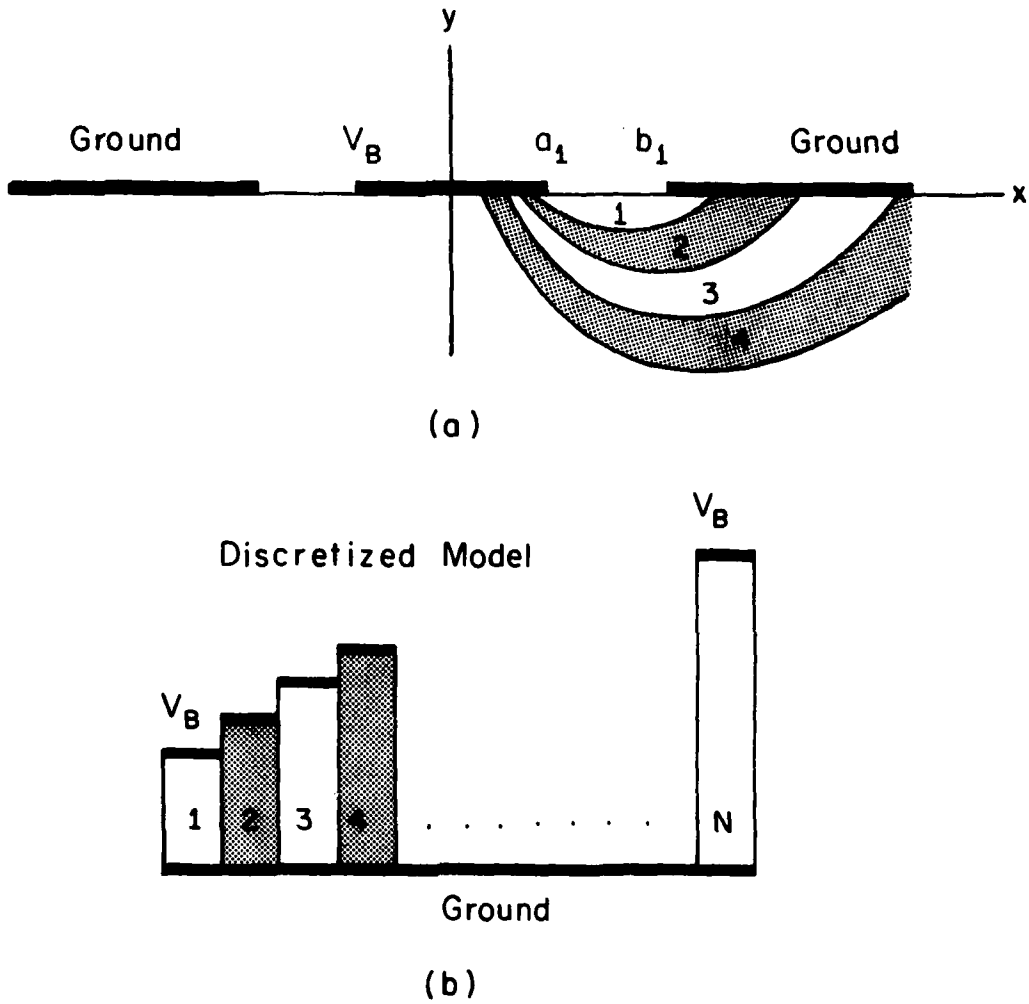

Figure 2. Coplanar Waveguide

the dielectric relaxation time is larger than the half-cycle period, the amplification due to negative differential mobility is unlikely to occur. When we operate around 10 GHz, this limitation is negligible, but 100 GHz lies nearly at the edge of the maximum operating frequencies. As an example, for the amplification to occur at 100 GHz, the sample length L must be 1 μm or so. But in order to satisfy the accumulation layer limitation ($n_0 L < 10^{12} cm^{-2}$), n_0 must be smaller than $10^{16} cm^{-3}$. When $n_0 = 10^{15}$, τ_D is on the order of a few psecs [9].

Hence, if the medium is uniform and space charge nucleates exactly at the cathode interface, the operation at 100 GHz is considered feasible. Space charge nucleation at the cathode interface is also believed to be possible when we make the anode larger than the cathode as in microstrip or coplanar structures.

Besides this time limitation, another limitation we have to consider is the power limitation. If we reduce sample length in order to increase operating frequencies, the capacitance increases. Hence, we also have to reduce sample area to avoid breakdown [10].

Comparative Study. Based on the simplified analysis presented above, we calculated qualitative performances of both microstrip and coplanar type distributed Gunn devices. It is found that the microstrip type electrode arrangement generally provides higher gain per unit axial length, whereas the stability for the bias fluctuation is better in the coplanar arrangement [11]. This is because more fluxes contribute to the generation of gain at the same time in a microstrip arrangement, while relatively fewer fluxes contribute to the gain over a wider bias range in the coplanar structures.

Prototype Design. We obtained a GaAs material with the epi-layer of 5 μm thickness with doping density of $n_0 = 2.7 \times 10^{-14} cm^{-3}$. By using a computer program, we obtained design data for the electrode pattern. A mask based on the design has just been delivered. Currently we are working on the adapter which provides both RF and bias connections to the device.

2. Control Devices. We have continued our investigation of adaption to millimeter-wavelengths of the multilayer dielectric waveguide phase-shifter concept originally studied for use at higher frequencies [12,13]. In the millimeter-wave region of interest, carrier injection is expected to produce refractive index changes on the order of 0.1 or more, but accompanied by significant losses introduced by scattering

of the injected carriers. The frequency regime of interest, therefore, lies between the short wavelength region where free carrier dispersion is dominant, and the microwave region where injected carriers drive a section of the semiconductor into metal-like optical behavior [14].

Some recently completed preliminary calculations indicate that a multilayer dielectric waveguide structure can be specified which utilizes a very thin (much less than a wavelength) active layer to minimize free carrier scattering loss, while still retaining sensitivity of effective index to active layer refractive index of near unity. These calculations will be carried forward to yield a design of a loss-minimized carrier-injection-controlled phase shifter with a GaAs active layer, with estimates of phase shift/unit length, insertion loss, and required drive power.

3. MO-CVD Facility. Since much of the analytical work has pointed toward devices based on layered semiconductor structures particularly GaAs (and perhaps $Ga_xA\ell_{1-x}As$), we have begun construction of a system to deposit epitaxial layers of those materials with controlled composition and doping, by metal organic chemical vapor deposition [15]. This method, while incapable of the ultra precise thickness control provided by molecular beam epitaxy, gives layers of high crystalline quality. Since the waveguide theory scales as d/λ where d is film thickness and λ is the wavelength, the precise thickness control necessary for optical waveguide structures should not present a problem in the millimeter-wave regime. When the system is constructed, the compositional profiles and optical properties of layers made with it will be characterized by means of Auger electron spectroscopy and ellipsometry. Once characterized, the system will be employed to fabricate layered semiconductor waveguide structures such as those described here.

C. FOLLOW-UP STATEMENT

This research is being continued under the 1980-83 JSEP Contract.

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

This report summarizes progress on projects carried out at the Electronics Research Center at The University of Texas at Austin and which were supported by the Joint Services Electronics Program. In the area of Information Electronics progress is reported for projects involving (1) nonlinear filtering and estimation, (2) electronic multi-dimensional signal processing, (3) electronic computer system design and analysis and (4) electronic computer software systems. →

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In the Solid State Electronics area recent findings in (1) basic solid state materials research and (2) research on instabilities and transport near surfaces and interfaces of solids are described.

In the area of Quantum Electronics progress is presented for the following projects: (1) nonlinear wave phenomena, (2) atomic and molecular electronic processes and (3) high power laser systems.

In the Electromagnetics area progress in (1) electromagnetic signal analysis and identification, and (2) Guided-Wave Devices for the far infrared-mm wave spectrum is summarized.