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An annual report of the JSEP (Joint Services Electronics Program) in Electromagnetics Solid State Electronics, Materials and Devices, Quantum Electronics, and Information Services in presented. In addition, results of the research to date are summarized and significant accomplishments are indicated.

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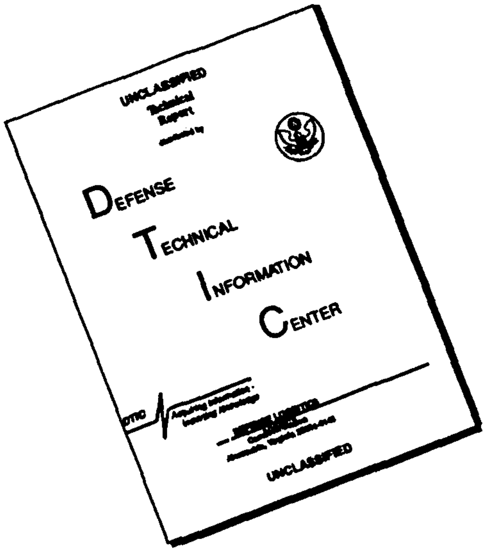

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G. Franklin		one-output controller."
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W. T. Nye	M80/23	"Dynamic arrays via a modified ratfor preprocessor."
M. A. Bhatti T. Essebo W. Nye K. S. Pister E. Polak A. Sangiovanni-Vincentelli A. Tits	M80/14	"A software system for optimization based interactive computer-aided design."
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V. Borkar P. Varaiya	M79/69	"Identification and adaptive control of Markov Chains."
E. Polak A. L. Tits	M79/52	"A globally convergent implementable multiplier method with automatic limitation."
E. Polak D. Q. Mayne	M79/48	"Algorithms for computer aided design of control systems by the method of inequalities."
R. W. Coen R. S. Muller	M79/36	"A uniform channel IGFET."
E. Polak	M79/33	"An implementable algorithm for the optimal design centering, tolerancing and tuning problem."
D. J. Allstot	M79/30	"MOS switched capacitor ladder filters."

University of California, Berkeley — Electronics Research Laboratory

Joint Services Electronics Program — September 30, 1982

Work Unit No.: SSD-83-3 — Last Year's No.(s): SSD-82-3

Title: New Techniques for Wide-Dynamic-Range Signal Processing Using Monolithic Integrated Circuit Technology

Senior Principal Investigator(s):

R. W. Brodersen	(415) 642-1779
P. R. Gray	2-5179
R. G. Meyer	2-8026
D. O. Pederson	2-3539

Scientific Objective

To investigate new techniques for signal processing with maximum dynamic range using monolithic integrated-circuit technology. The project will encompass noise characterization, system design, new circuit topologies and a coordinated program of technology research.

State of the Art

Monolithic integrated-circuit technology has profoundly affected the field of signal processing. Functions such as A/D and D/A conversion[1], filtering[2], and digital signal recovery[3] are examples where monolithic technology has become the preferred method of realization in many systems. However, the prevailing approach to the design of such systems is the selection of an arbitrary available technology, often developed for other purposes, followed by research into methods of realizing the desired function.

Our research has shown the need and the potential for a more unified approach to the realization of signal processing circuits which maximizes the advantages inherent in monolithic fabrication. For example, several methods of monolithic filter realization require amplifiers with very high input impedances[2,4]. These can be realized in such diverse technologies as NMOS, CMOS, BiMOS, BiFET or GaAs and the appropriate technology is not always obvious. In addition, many other critical device parameters have widely differing values in different technologies, providing the designer with an enormous number of potential parameter combinations. These include gm/I and gm/C ratios, parasitic capacitance and many others. These parameters can be varied at the process level if the system requirements are included as inputs at that level.

Progress and Publications Since Last Major Proposal

Our earlier work on the fabrication, characterization and modeling of generalized multi-layer monolithic structures allowed us to realize a unique monolithic process incorporating high-frequency JFET structures with independently-accessible gates. Extensive characterization on a range of devices has been undertaken and verified the advantages of these structures for a wide range of high-frequency signal processing areas. In particular, it appears possible to advance the state of the art significantly in the realization of high-frequency monolithic filters and real-time signal processing. Experimental high-frequency filters using this process are currently in fabrication. These filters incorporate very-wide-band operational amplifiers (unity gain beyond 100 MHz) made possible by the unique JFET structures described previously. This project will continue with further work in combining advanced fabrication techniques and new system concepts with the ultimate goal being the realization of unique methods of high-speed signal processing using arbitrary combinations of analog and digital techniques.

A second aspect of our work has involved new techniques to achieve

We have designed a far-submicron copy of a superconducting interferometer that we are making as a part of our analog-to-digital converter project. It appears possible to reduce the area by a factor of about 150. We are currently considering choices of ways of defining Josephson junction areas.

Recent Publication With JSEP Support

"Silicon-coupled Josephson Junctions and Super-Schottky Diodes with Coplanar Electrodes," R. C. Ruby and T. Van Duzer, IEEE Trans. on Electron Devices, vol. ED-28, pp. 1394-1397, November 1981.

Recent Publications Without JSEP Support

"Hillock growth on lead films upon cycling to cryogenic temperatures," C.Y. Fu and T. Van Duzer, J. Vac. Sci. Technol., 17, pp. 752-754, May/June 1980..

"Josephson digital devices and circuits," T. Van Duzer, IEEE Trans. Microwave Theory and Techniques, MTT-28, pp. 490-500, May 1980.

"Digital Applications of Josephson Junctions," T. Van Duzer, Proc. Symposium on Processing and Devices, Stanford University, May 1, 1982.

"Asymmetrical Three-Junction Superconducting Quantum-Interference Device," S. H. Dong, R. E. Jewett, J. W. Spargo, and T. Van Duzer, submitted for publication.

"Fabrication and Properties of High-J_c Lead-Alloy Junction," Y. Tarutani and T. Van Duzer, submitted for publication.

Government Scientific Contacts

The principal investigator instigated the initiation of a biannual workshop on Josephson digital circuits and was its first chairman. This workshop brings together the governmental, academic, and industrial groups working in this field. He was also elected as vice-chairman of the Applied Superconductivity Conference in 1980. Both of these relationships bring him extensive interaction with scientific personnel from the Office of Naval Research, the Naval Research Laboratory, the National Bureau of Standards and other governmental agencies.

Significant Accomplishments

The most significant recent accomplishment was the demonstration of the required performance of the new LEBES system. A considerable effort was required to eliminate problems that prevented the 0.1 µm accuracies demanded of it. We are presently completing the programming necessary to permit circuit layouts made on our CAD system to be fed into the pattern-generation control of the LEBES system. This will make possible very fast changes in the circuit designs. We are also working on a program for making proximity-effect corrections in the electron-beam exposures since our small exposed regions will be affected significantly by nearby exposures.

Proposed Research Program

We will conduct studies to determine the feasibility of fabricating useful superconductive electronic devices with feature sizes in the far-submicron size range. With our new electron-beam lithography system, we can make, for example, logic gates and memory cells. Under other sponsorship, we have developed the technology for making such circuits in larger size. Some of the techniques used in the larger size devices will be usable in the smaller sizes only with considerable effort. Others must be replaced entirely. For example, the present method of using a silicon monoxide mask to define the size of the Josephson junctions will probably have to be replaced or realized in an entirely new way.

In addition to the fabrication innovation required for these sizes, important questions of physics of the devices must be attacked. The line widths will be on the order of the penetration depth and some features will be comparable with the coherence length. In which situations are these lengths going to set limits on operation? For example, the paired-electron-fluid characteristic of superconductors has a significant amount of inertia and this acts like an inductance. This inductance can be useful in some circumstances, but could set performance limits in others.

Analysis of the behavior of these devices, taking account of the new physical effects that arise because of the sizes being comparable with the superconductor characterizing parameters, will be carried out with our simulation programs. It will be possible to handle distributed effects as arrays of lumped elements to get accurate representation.

Interaction with Other Work Units

This program of studying miniaturization forms a part of a larger effort on various aspects of Josephson digital circuits. A program has been initiated to develop a high-speed A/D converter and this will use Josephson junctions and circuits of conventional size that can be made by photolithography. In that work, we expect to demonstrate superconductive integrated circuits containing some tens of Josephson junctions. We also have an NSF-sponsored project to study the use of coplanar junctions (both electrodes are in the same plane) with special emphasis on a structure we developed here that involves electron-pair coupling through a highly doped surface of a semiconductor. These may prove to be valuable for miniaturization and that aspect will be considered.

Our work on Josephson devices and their frequent need for submicron dimensions has given our group a high degree of familiarity with electron lithography and we have published several papers in that field. This expertise will be supported by the microfabrication interest of Professors A. R. Neureuther and W. G. Oldham, as well as the large body of knowledge in our integrated circuits group (SSD-84-1).

University of California, Berkeley — Electronics Research Laboratory

Joint Services Electronics Program — September 30, 1982

Work Unit No.: SSD-83-2 — **Last Year's No.(s):** SSD-82-2

Title: Study of the Effects Limiting Realization of Far-Submicron Superconductive Electronic Structures

Senior Principal Investigator(s): T. Van Duzer (415) 642-3306

Scientific Objective

The objective of this work is to investigate the fundamental factors that limit the size of superconductive devices and circuits.

State of the Art

There is currently interest in two fields that appear destined to converge. Electron-beam lithography has made possible the fabrication of devices and circuits having feature sizes on the order of 0.1 micrometer and smaller. A parallel development is the demonstration of the potential of systems using Josephson junctions as the active elements[1]. In some cases the two fields have already met. This has largely been in the formation of very small weakened regions between two larger sections of superconductive material to form Josephson junctions. Some very small-area tunnel junctions have also been made[2]. To date, no work has been reported on theoretical or experimental examination of the effect of making circuits such as memory cells or logic circuits in which all feature sizes approach the characteristic lengths that appear in the theory of superconductivity. These characteristic lengths are called the "penetration depth" and "coherence length." The former is the 1/e distance of decrease of magnetic induction from the surface of a bulk superconductor. The latter is roughly the size of the Cooper electron pair, which, in thin films, is largely dominated by the mean free path of the electrons. For superconducting loops, one often refers to magnetic flux quantization; the loop must contain an integral number of flux quanta. For loops of small cross section, the quantization is of the so-called "London fluxoid." If circuits are made of sufficiently small cross section, quantization must be considered in the latter terms.

Tunnel junctions have so far been the most common active element in logic circuits and would form a part of this study. Our group has reported the use of semiconductor-barrier devices that appear to have promise for applications in SQUID magnetometry, millimeter-wave detection and mixing, and digital circuits. No consideration in depth has yet been given to the effect of reducing the dimensions of these structures to the 0.1 micrometer size range.

Progress and Publications Since Last Major Proposal

Our device-fabrication efforts under other sponsorship have involved the realization of structures in which far-submicron (approximately 0.1 micrometer) features are required to obtain Josephson effects. These have included constricted-thin-film devices and a structure in which an interrupted superconductive film strip lies on a highly doped silicon surface. We have also developed a strong base for numerical analysis of the properties of superconductive devices and circuits. We have developed the technology of making resist-patterned oxide-barrier junctions and circuits and can work on extending it to the far-submicron range.

An electron-beam lithography system (Perkin Elmer - ETEC LEBES system) has been purchased and all acceptance tests have been successfully performed. With this machine we are able to write 0.1 μm lines and achieve level-to-level registration of 0.1 μm. Work is in progress to improve repeatability of the 0.1 μm features by achieving tight control on all of the several determining factors.

University of California, Berkeley Electronics Research Laboratory

Joint Services Electronics Program September 30, 1982

II. B. Basic Research in Solid State Electronics - Devices Coordinator: Professor T. Van Duzer

General

Since 1960 solid-state device research and integrated circuit research have been carried out in a common facility in the Electronics Research Laboratory. We have long maintained and observed the obvious benefit; everyone enjoys a more complete, flexible experimental capability. Further, as a consequence of sharing experimental facilities, there has been a beneficial contact between research in apparently quite different fields. One result is a significant transfer of technique, accelerating progress in experimental technology for all concerned. More subtle results are the development of larger research goals in common.

An excellent example of the interaction of different research groups is the research in electron-beam lithography initiated by Professor Van Duzer and his students nearly 10 years ago to make very fine geometries in Josephson junction structures. This background stimulated work by Professors Neureuther and Oldham to explore advanced lithographies for integrated circuits.

The fabrication facility continues as the focal point for the collaboration between the device, design, and technology research activities in solid-state electronic devices. Recent additions to the laboratory have included a Riber molecular-beam epitaxy system, an electron-beam lithography system for precision multi-level structures, and a Plasmatherm parallel plate plasma/reactive ion dry-etching system.

The proposals contained herein are all advanced device basic studies which use the common laboratory facilities in the experimental phase. They have in common the state-of-the-art techniques required for successful fabrication. Such processes as molecular beam epitaxy, ion implantation, high-resolution lithography, plasma etching, and ion milling will be used, as well as more standard processes such as diffusion and thin-film deposition. The research proposals also have in common certain intermediate and long-term goals. In general the intermediate goals are the basic study and development of simple devices and device models which will point the way toward the long-term goal of more powerful, cheaper, denser circuits.

The most basic studies in this proposal are the investigations in advanced lithography. Progress in all the device studies depends in large measure on advances in the definition of the structures. The electron-beam studies are aimed at an analytic understanding of the factors controlling the ultimate performance of electron-beam lithography systems. The results of such studies would make possible, for example, the application of the extensive Monte Carlo and experimental energy deposition characterization to a wide class of new structures, including, e.g., Josephson superconductor devices. The proposed photolithographic studies similarly promise to aid in the advance of the integrated-circuit and transducer state of the art.

The proposal on Josephson device studies is aimed at exploring the factors limiting the performance of these devices in the far-submicron size range. Van Duzer and co-workers have demonstrated that they can perform submicron lithography in a modified scanning electron microscope. They have also constructed a number of novel working Josephson structures. They now propose to combine the technologies and make really small circuit cells to explore the problems in this new domain of device size. A number of fundamental theoretical fabrication problems will be encountered and resolved in the course of these studies; it promises to be a very exciting time in the Josephson effect research.

Another proposal deals with techniques for realizing wide-dynamic-range signal processors with integrated circuits. System design and new circuit topologies will be worked out to optimize the technology choices, with parameter choices at process level. Proper noise characterization is essential to achievement of wide dynamic range and forms an important part of the proposed project.

In the final project in solid-state devices a study will be done on piezoelectric polymer-film materials in order to optimize them for transducer applications. The polymers will be formed by plasma-initiated polymerization which makes possible a wide range of process control. It makes possible the formation of relatively mono-disperse, high-molecular-weight polymers. The plasma method also permits polymerization of monomer films in the presence of an electric field, thereby eliminating constraints to their use in transducers and integrated circuits.

tools, especially with the increasing interest in deep wavelengths. A high data rate system is critically needed in order to extract model parameters for existing and new resist technologies.

Several studies of the limits of lithography have been made. These have generally been done on the basis of exposure dose limitations [6] or image contrast [7,8,9]. Such studies have contributed to the understanding of the general importance of various lithography parameters. However, most of the studies of lithography limits have not included the consideration of development effects and are often of questionable practical value. For example, it is at first sight attractive to create a resist with infinite contrast. However, in the presence of the finite edge slope of typical optical images and vertical standing waves for silicon substrates, a resist with infinite contrast would wash out laterally along standing wave peaks long before punching through to the substrate surface. The availability of combined exposure and development simulation [4] now allows these effects which limit the practical use of photolithography to be accurately explored [10,11]. The capability to model multiple process step line edge profiles [12], will allow the developer and compatible processing effects to be examined even more completely at a composite process level. As advances in both the process modeling tools and the fabrication technologies occur, it will be possible to more clearly define the limits of practical lithographic performance.

To realize the benefits of high resolution lithography, alignment and registration techniques must be developed which are accurate to within a fraction of the smallest replicated feature. Automated alignment using amplitude detection with complementary patterns is capable of 0.1 accuracy [13] and the use of phase sensitive grating techniques shows even greater potential [14]. Optical projection printing systems now under development are using alignment schemes based on bright field [15] and dark field [16] techniques as well as modifications of grating techniques [17], and even off-axis prealignment with laser interference controlled stepping [18]. The variety of alignment techniques presently being tried is indicative of the poor understanding of the alignment problem. The role of the alignment mark shape (3 dimensions), resist pile up and interference effects of thin film overlays confuse mark design. The tradeoffs in selecting the alignment wavelengths, bright or dark field imaging, or alternatively grating techniques are so complex that as yet no standard approach can be predicted.

All of these approaches depend on the quality of the signals diffracted from wafer marks and the imaging of the optics which collect and process the signals. The basic properties of the signals diffracted from wafer marks can be explored using either simple physical approximations or, if necessary, rigorous electromagnetic methods such as are used in the analysis of diffraction gratings [19]. The effect of the signal collection optics can be assessed through suitable modification of simulation algorithms such as those used for imaging mask patterns on wafers [4]. The problems which may be attacked with this array of analytical tools includes: (1) signal quality from typical IC process alignment marks, (2) design of optimum alignment marks, (3) understanding of alignment time and accuracy tradeoffs in bright field imaging vs dark field imaging, vs grating alignment techniques.

Alignment in electron beam direct writing systems is potentially considerably more accurate, but still presents rather formidable problems. This is particularly true for production use where wafer marks are restricted to be process compatible and are frequently overcoated with resist. Typical production alignment mark signals in the presence of resist coating have been studied experimentally [20]. Theoretically, Monte Carlo techniques have been extended to non-planar topography and used to a limited extent to examine backscattered electron signals from alignment marks [21-24]. It has also been found that for selective etched silicon alignment marks that the total backscattered energy signal can be characterized by means of a simple universal curve [23,24]. There is still, however, a pressing need for more complete basic data on the angular distribution of backscattered electrons from various wafer marks and especially for a tractable means of modeling these results.

The key issue in both optical and electron beam alignment is overall system performance. A typical measure of performance is the signal to noise ratio which in turn determines the feedback data rate. Since signal strength as well as alignment signature quality must be considered, this leads to some interesting tradeoffs. For example, in optical lithography dark field alignment produces a higher quality signal signature, but only at a much reduced level compared to the clear field approach. Similarly, in electron beam lithography higher quality signatures are available from collecting only the electrons which exit the substrate at near grazing angles, but the number of these electrons decreases rapidly with the angle. The role of the wafer mark properties and electron collection system on the resultant signal to noise ratio can be a dominant factor in the optimization of overall system performance. In both optical and electron beam lithography there is a need to understand the alignment process in terms of models which can characterize these signal generation and collection tradeoffs. Thus there is a critical need both in optical and electron beam lithography to include the generation and collection of alignment signals into system considerations in optimizing overall performance.

Progress

An apparatus for making in situ measurements of resist film thickness during development or etching has been constructed. It is based on monitoring the reflectivity at 6328 A which varies with thickness change due to interference. The reproducibility of the initial system has been upgraded through improved optics and developer temperature control. The data collection and analysis has been automated. Presently the system is being used to explore processing parameter effects such as prebake temperature, developer temperature, and batch to batch variations.

An extensive Monte Carlo and experimental study of alignment signals from tapered Si steps, including resist coating, has been completed. Fundamental aspects of the electron scattering distribution in energy, space and angle both within the wafer and in the backscattered signal have been published by Y. C. Lin (Ph.D. thesis). As an extension of that work, Albert Chen is applying the unique e-beam alignment capability to explore critical fabrication technology issues in IC devices and circuits. A lithography test mask set is being developed and used to characterize the resolution, linewidth control and alignment of the new ETEC direct writing e-beam system. CMOS devices of the lightly doped drain type will be fabricated using hybrid optical and e-beam lithography. The goal is to show the advantage of e-beam lithography in component matching for linear circuits and demonstrate the use of its unique alignment ability as a tool for systemically exploring critical parameters in device structures.

Y. C. Lin, A. R. Neureuther and W. G. Oldham, "Alignment signals from symmetrical silicon marks for electron beam lithography," ECS Journal, accepted.

M. Exterkamp, W. Wong, H. Damar, A. R. Neureuther and W. G. Oldham, "Resist characterization: Procedures, parameters, and profiles," SPIE, vol. 334, Optical Microlithography, paper No. 24.

M. Exterkamp, "A system to characterize positive photoresist," M.S. thesis, Department of Electrical Engineering and Computer Sciences, University of California, Berkeley.

D. Kim, W. G. Oldham and A. R. Neureuther, "Characterization of resist development: Models, equipment, methods, and experimental results," Kodak Microelectronics Seminar, San Diego, CA., October 21-22, 1982.

Significant Accomplishments

A set of guidelines for designing e-beam alignment marks, including resist coating effects, has been published. The in situ resist development measurement system has been fully automated and gives reproducible results. Data on resist processing parameters (bake, temperature, concentration, batch) has been obtained.

Proposed Research

Characterization of the Limits of Resist Performance

The in situ development rate system will be significantly upgraded and used to quantitatively study development effects for a variety of lithographic applications such as ion, e-beam and x-ray exposure. The apparatus will be augmented so that controlled and reproducible experimental conditions can be obtained. Especially important parameters are the developer flow rate and temperature. Puddle, tank, agitation and flow types of developing conditions will be emulated. Automatic data reduction for extracting the etch rate vs. chemical concentration of photoactive compound in optical resists will be developed. The system will be used to make characterizations of ion, e-beam and x-ray resists. Here the emphasis will be on studying second order effects beyond the simple etch rate vs. dose model.

The exposure and development measurement tools will be used to establish resist model parameters of practical interest and to characterize changes in these as a function of processing parameters and resist modifications. Several examples of current interest are the behavior of AZ1350J in strong (351) and organic developers and the change in characteristics for the new striation fee version (AZ1450). The properties of AZ1350J used as a negative resist by means of image reversal are also of key interest. The modification of the model parameters inherent in process steps such as post exposure baking or the addition of adhesion promoters will also be explored.

To more clearly determine the practical limits of lithographic performance we will establish the relationship between the resist model and performance, assess the capability of various resist technologies, and explore other basic limiting effects. The importance of the resist model parameters on performance will be studied to obtain feedback as to which parameters are significant and how they might be optimized. For example, the standing wave effects can be suppressed to some extent through appropriate modifications of the absorption parameters. An investigation of new lithography strategies such as multilayer and inorganic resists with plasma development will be made to assess from a practical point of view their potential improvement in lithographic performance. Other basic effects such as thermal degradation and blistering which may limit the exposure intensity in serially exposed optical steppers and e-beam systems will also be explored.

<u>Optimization of Alignment Signals for VLSI</u>

Methods of characterizing the effects of wafer mark properties and signal collection optics on optical alignment signal signatures will be explored. The quality of signals diffracted from wafer marks will be considered by simple approximate physical methods and by more rigorous diffraction grating integral equation numerical analysis techniques [18] if necessary. The effects of the optics used in the collection of alignment signals will be simulated through the extension of the image capability of program SAMPLE [4]. This composite set of analytical tools will be used to understand the role of the mark illumination, mark shape, imaging approach and detector in the context of the entire alignment system.

Various optical and electron beam alignment schemes will be examined from an overall system point of view. Particular emphasis will be given to the role of the models for the generation of alignment signals from alignment marks and for the effects of the signal collection system. The signal to noise ratio and other performance figures of merit will be evaluated and used in comparison studies. We will attempt to identify optimum alignment mark features and signal collection system parameters for the dark field, clear field and grating type alignment approaches. Similarly, for electron beam systems we will attempt to optimize the alignment mark shape and collection angles. Special emphasis will be given to the problem of the degradation of system response with resist overcoating of the alignment marks.

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University of California, Berkeley — Electronics Research Laboratory

Joint Services Electronics Program — September 30, 1982

Work Unit No.: SSD-83-1 — Last Year's No.(s): SSD-82-1

Title: Critical Problems in Lithography and Their Impact on Practical Performance

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Scientific Objective

The objective of this proposal is to attack the problems limiting photo and electron beam lithography and to predict the limits of practical lithography performance as advances are made in the technology. The two problems selected are characterizing the limits of resist performance and the optimization of alignment signals for VLSI. We are constructing automatic systems for determining both development and exposure model parameters of resist materials. The dependence of resist parameters and lithographic performance on process parameters will be investigated both for new resist technologies, and for modifications in existing technologies. We will also use resist profile quality studies as well as basic resist parameter tests to assess the practical limits of lithographic performance. The optimization of alignment signals for VLSI will be based on a study of the fundamental effects of the scattering of electrons or diffraction of photons by various alignment mark features. Where possible the alignment and focus signals for various wafer marks will be characterized by using simple empirical, universal models for the components of the marks. System considerations, such as the signal to noise ratio, will be examined from the point of view of optimizing the wafer mark geometry and signal detector system.

State of the Art

Automatic measurement systems for determining both the exposure and development parameters of positive type photoresist were first established a number of years ago at IBM [1]. The exposure measurement approach, which is based on monitoring the change in transmission during UV exposure, is currently being widely adopted. A system of this type has been developed at U. C. Berkeley with appropriate improvements such as full bleaching exposure [2]. The IBM system for determining the development rate parameters is based on an in situ scanning reflectance measurement. This system is much more complicated than the exposure measurement system but a commercial system which is an option on a "Film Thickness Analyzer" is available for about $100,000. The data rate of this system limits its use to etch rates less than about 300 A/s. Alternative approaches to produce a less expensive, more accurate, dedicated system are also being made. At U. C. Berkeley in situ capacitive probes [3] and remaining resist absorption techniques [2] have been investigated. The major problems with these approaches are obtaining experimental control over developer flow rates and geometrical areas, and reducing sources of noise in measured signals. There remains a pressing need for a more versatile and more universally applicable automatic system capable of quantitatively measuring general development parameters.

The interest in resist exposure and development parameter data has increased recently due to the public availability of the user oriented SAMPLE for simulating the projection printer resist line edge profiles [4]. The exposure parameters at several wavelengths and development rate parameters for a few of the popular resists are available in the literature [5]. However, the available data is lagging far behind the resists and developers of interest today. This gap is likely to widen further with the greater diversity of processing conditions and imaging

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becomes an important problem as it definitely will affect the property of the grown film. Thermal conversion of the conduction type (n into p or p into n), probably due to redistribution of the deep-level impurities[18-20], has been reported in the literature, and in our laboratory we have observed a similar effect in O-implanted and Cr-doped GaAs. We plan to use the analytical instruments of the MBE system to provide information on the diffusion of impurities in the films grown by the MBE process on semi-insulating GaAs. Recently we have obtained from Dr. T. Ranganath of Hewlett-Packard some high-purity semi-insulating GaAs wafers. The electrical properties of the films grown on Cr-doped and high purity SI GaAs wafers will be compared.

Insofar as microfabrication technology and device studies are concerned, our work on MBE will be concentrated on three basic topics. One area of great interest is visible lasers. The work of Tsang[21] has clearly demonstrated the importance of a high Al cladding layer to minimize carrier diffusion across the barrier and thus reduce the threshold current. We plan to use x = 0.65 for Al in the cladding layer, and x between 0.20 and 0.30 for Al in the active layer to determine the effect of satellite valleys and thus the ultimate limit of short wavelength lasers. Professor Nishizawa of Tohoku University has obtained an external efficiency 1-3% in (GaAl)As LED's at 6650 Å with x = 0.30. The advantages of using quantum well structures will be examined. Factors concerning the difference in the effective masses of the central valley Γ and the satellite valleys X CB electrons as well as possible means of raising the X valley minima will be investigated.

The second area of our current interest is the metal-semiconductor contact, a subject of fundamental importance to semiconductor devices. Although impressive results based on the MBE technology have been reported over a wide range of subjects[22], the contact problem has not been extensively studied. The two-chamber (growth and analytical) arrangement of most MBE systems limits what one can do in making and studying metal-semiconductor contacts. As reported in the Progress and Publication section, we are in the process of adding a metallization chamber to our MBE system. This metallization chamber will enable the deposition of refractory metals and provide the future possibility for low-energy ion beam epitaxy. Questions important to the physics and metallurgy of a metal-semiconductor contact include the possible existence of a separate phase similar to silicide in the case of Si and the possibility of introducing a diffusion barrier for certain metals. We propose that our work on the metallization chamber be continued as preparation for a basic study on metal-semiconductor contacts.

We plan to use the analytical instruments of the MBE system to monitor the surface condition of a semiconductor before metal deposition and to determine the interface structure after metal deposition. We propose that the interface properties of metal-semiconductor contacts prepared under controlled deposition conditions be studied for use either as ohmic contacts or as Schottky barrier diodes. The AES analyzer will enable us to detect possible contaminants[23] on the substrate surface prior to MBR growth[23] as we have already done and to determine the interface composition[23] after MBE growth and subsequent processing of the grown films. The atomic structure of the interfaces will be investigated by ion beam channeling and high resolution cross sectional TEM

The third area of proposed research is three-dimensional device architecture. As discussed in the Progress and Publications section, we have started work on deep impurity implantation in Si using MEV ions, and obtained very encouraging results. We propose that the work on deep implantation in Si be continued. We also propose that work on three-dimensional GaAs IC be initiated. As a feasibility study, high Al, undoped layers will be grown to see whether or not the layers are suitable for use as the isolation between two vertical device structures. Next, GaAs layers will be grown on both sides of the isolation layer and deep dopant implantation will be made to determine the quality of the electrical connection made by implanted MEV ions. In terms of the final device structure, heterojunction bipolar transistors appear to be most promising among the many devices considered for high speed IC applications[24]. The DH structure makes possible the combination of a low base resistance and a high emitter efficiency.

To complement the Riber MBE system which will be used for III-V semiconductor studies, we are currently developing a home-made Si MBE system to fabricate multilayer epitaxial structures. The combined information obtained from both studies will provide us a more complete picture of the MBE growth process and a better understanding of superlattice electronic properties. Investigations on the following modulated structures have been planned:

(1) Homoepitaxy -- abrupt dopant profiles for Si.

(2) Heteroepitaxy -- (a) $Si/Si_{1-x}Ge_x$ multilayers

(b) Si/silicide multilayers.

We are currently seeking funding for the ultrahigh vacuum evaporation chamber. A dual source with separate E-gun controls is proposed for the deposition of binary phases. The dopants will be generated by Knudsen-type cells or low energy implantation (e.g., the Cullatron source). Processing and evaluation of some simple devices such as the metal base transistor[17] and emitter-coupled logic[25] will be performed at microfabrication facilities of the Electronics Research Laboratory.

Interaction with Other Units

Close interaction is expected with the work in microfabrication under SSD-84-1, SSD-84-2, with the work on material characterization under SSM-84-1 and SSM-84-2, and with the work on injection lasers under QE-84-1.

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of the chamber and on the installation of the equipment on the chamber will start in the Fall Quarter.

Work on MBE on Si has also begun. So far we have completed the assembly of an ultrahigh vacuum deposition chamber which has a base pressure of ≈ 1 X 10^{-10} Torr. The deposition chamber will be separated from the evaporation chamber with a gate valve. During evaporation, the evaporant fluxes will enter the deposition chamber via an orifice with the gate valve opened. Decoupling of the two chambers will ensure better substrate cleanliness prior to deposition. In addition, vacuum in the deposition chamber can be maintained at much lower pressures during the evaporation cycle since both chambers are differentially pumped.

A Hall-effect measurement system has been completed. The set-up has anodic stripping capability which will enable us to profile both the carrier concentration and the mobility of the MBE grown layers.

Recent demonstration of the permeable base transistor[16] shows the feasibility of hetero-epitaxial growth of device-quality semiconductor films on metal. This hetero-epitaxy should lead to possible other novel high speed devices such as the metal base transistor.[17] Such possibilities will be explored for both GaAs and Si.

To fabricate three dimensional device structures, lateral definition of the device features becomes a necessity. To complement the MBE technique, we have done preliminary studies to investigate the feasibility of using high energy (MeV) ion implantation to modify the electrical properties of semiconductors. The major advantages of high energy ion implantation are: (1) the ions can penetrate microns deep into the semiconductor with a relatively low dopant and damage distribution near the surface; (2) the lateral definition of device features can be done by conventional masking techniques.

So far, we have performed implantations with the following ion-target combinations: As -Si, B - InP and Si - GaAs. The Si studies have been completed and the results are encouraging. We have been able to predict the formation of amorphous regions using LSS theory and the effect of substrate temperature during implantation is reasonably well-understood (see paper 1, publication list). Examination by spreading resistance measurements, Rutherford backscattering spectrometry, SIMS and cross sectional TEM shows that the top two microns of the Si are monocrystalline even after a high implantation dose of 2 x $10^{15}/cm^2$. No redistribution of the dopant (As) was observed during the post-implantation annealing steps - 550°C for solid phase epitaxial growth followed by a 900°C annealing for electrical activation (see paper 2, publication list). The III-V semiconductor samples are under current investigation by similar techniques and the experimental results will soon be available. Plans for the near future include proton and oxygen implantations into GaAs to fabricate isolation regions.

The masking technology for high energy implantation has also been explored and we have established a standard procedure to delineate masking features using tungsten as the ion absorber. The W films were sputtered down onto the semiconductor substrate and etched by a SF_6/O_2 plasma using a planar RIE system. Vertical walls of the W films can be achieved with line features on the order of a couple of microns.

Publications

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Proposed Research Program

The availability of an MBE system should greatly enhance our experimental capabilities in the area of microstructure engineering. We have planned the MBE system not merely as a facility for growing thin films, but also as a research tool for studying materials problems important to electronic and optical devices of micron and submicron dimensions. In the MBE system we have the growth chamber is separate from the analysis chamber. This separate arrangement makes the MBE system useful for both film growth and film analysis. We propose the following two main subjects for research: (1) to study and to develop the MBE growth process as a microfabrication technology, and (2) to investigate and to correlate the properties, including interface and surface properties of the film grown under different growth conditions.

The controllability of the thickness, the composition and the doping concentrations of the films grown by the MBE process has been demonstrated in a number of experiments, including super-lattices and DH injection lasers. However, there are other important aspects of the MBE growth process which have not been extensively investigated. We plan to study the effects of growth conditions on the incorporation of electrically and optically active impurities. Both the substrate temperature and the vapor pressures of Ga, As and Al are important growth parameters. The substrate temperature affects the grown film through its effect on (1) mobility of deposited surface atoms, (2) escaping probability of deposited atoms, and (3) diffusion of impurities incorporated into the film. By varying the temperature and pressure we hope to be able to find an optimal growth condition for the (GaAl)As system. As stated in the Progress and Publications section, we have already started growing GaAs and (GaAl)As films under different growth conditions by varying the Ga and Al oven temperature and the substrate temperature. We propose that this work be continued and that the mobility, the doping concentration and the activation of the dopants as electrically active donors and acceptors be measured as a function of the growth condition.

Besides temperature and pressure, another important variable in the growth condition is the substrate itself. One distinct advantage of GaAs over Si is the availability of semi-insulating GaAs substrates upon which electronic and optical devices can be built. It is well known that GaAs can be made semi-insulating by compensation either through deep donors known to be oxygen-related centers or through deep acceptors known to be Cr-related centers. Since many GaAs devices such as FET's and lasers require processing of the wafer at high temperatures such as MBE growth of multilayer structures, the effect of diffusion of impurities in and out of the wafer, as well as in and out of the grown film,

$$d^2N/dt\,ds = 3.5 \times 10^{22} P/(MT)^{1/2} \qquad (2)$$

where P is the partial pressure, M is the molecular weight, and T is the background gas temperature. Take CO as an example which has M = 28 AMU. At a typical growth rate r_g = 1 μm/hr., the product ξP must be smaller than 7×10^{-15} in order to ensure $C < 10^{14}$ cm^{-3}. This simple calculation tells us that we must be extremely careful with contaminants with high sticking coefficients and high vapor pressure. It is important, therefore, for us to have analytical equipment, such as CMA and SIMS, to perform chemical analysis of the grown film and to use electrical measurements, such as transient capacitance-voltage spectroscopy, to characterize the incorporated impurities.

Both the MBE and the MO-CVD growth techniques are capable of producing high-quality films as demonstrated in multiple quantum-well (MQW) heterostructure lasers.[6,7] Recent results on photoluminescence indicate, however, that while Al-Ga disorder alloy clustering seemed to have taken place at the MQW heterostructure interfaces in the MO-CVD films,[8], no evidence of clustering showed in the MBE films.[9] The experiment is an example of the need of employing a multitude of experiments in characterizing and comparing films grown by different processes and under different conditions. Even though lasers of low threshold current densities have been reported using the LPE, MBE, and MO-CVD growth processes, defect formation and impurity distribution during either epitaxial growth or subsequent processing remain the topics of intensive study.[10] Defect formation and impurity redistribution not only will affect initially but also may gradually degrade the device performance.

Recently interest in the MBE growth technology has extended to Si. Iyer et al.[11] have proposed a model to explain the dopant incorporation characteristics of MBE grown Si. The smearing of doping profile is explained in terms of a time constant required by the dopants to reach a steady-state concentration. Using "flash-off" and "build-up" techniques, extremely abrupt doping profiles for layers as thin as ≈ 200 A have been achieved. This extra control on the dopant concentration may enable us to incorporate heavily doped or highly resistive layers into the MBE grown Si.

Hetero-epitaxial structures of $Si/CoSi_2/Si$[12] and Si/Ge[13] have also been demonstrated by solid phase epitaxy. Since the recyrstallization takes place during subsequent annealing cycles, solid state reactions have created interfaces[14], and extended regions of misfit dislocations adjacent to the interface.[15] We believe that such interfacial imperfections can be eliminated or minimized by the MBE technique with coevaporation to form the silicide phase and the $Si_{1-x}Ge_x$ solid solution. Moreover, MBE growth can be achieved at substrate temperatures substantially lower than the annealing temperatures required for solid phase epitaxial growth.

Progress and Publications
Under JSEP

The Riber 400 MBE system has been in operation for almost one year. A leak in the cryoshroud was found. The cryoshroud was re-welded and the leak was fixed. A leak in the bellows for the HEED screen shutter was also detected. The shutter mechanism on our system was of an old design. We consulted Dr. D. Collins of Hewlett-Packard and Dr. P. Luscher of Varian, and made a new shutter similar to Varian's design. Had we ordered a replacement shutter from Riber, over six months would have been wasted (they did not have one in stock). Both leaks had kept the base pressure in the middle 10^{-10} range and were difficult to locate. Now that the MBE system is functioning properly, it is under operation almost continuously.

We have made numerous runs, first growing GaAs films and now growing (GaAl)As films on both semi-insulating and n^+ GaAs. At first, undoped GaAs films were found to be n-type of moderate resistivity. Since we changed the As source to one bought from a different vendor, the grown films unintentionally doped have been consistently of high-resistivity p-type in agreement with the results reported in the literature. The Phi scanning Auger spectrometer purchased through JSEP funding was used to detect the presence of contaminants on GaAs and thus to establish a proper cleaning procedure for GaAs surface. The Bell Lab. procedure of etching in H_2SO_4:H_2O_2:H_2O and then oxidizing in de-ionized H_2O has resulted in a substantial reduction of the carbon peak to a magnitude more than 10 times smaller than the oxygen peak. However, it was found that improper cleaning left a sulfur peak of a fair strength.

SEM photographs were taken for each run to determine empirically the growth rate. The Ga temperature was varied between 980°C and 1020°C and the substrate temperature between 590°C and 640°C. Growth rates between 1 µm/hr. and 1.7 µm/hr. were obtained. The n-type films were Sn doped and the p-type films were Be doped. (GaAl)As films with Al content between 0.14 and 0.19 were grown. The value of x was obtained by comparing the relative strengths of the Ga and Al AES signals. The renovation work currently under way at the Electronics Research Laboratory for the new microfabrication facility has caused some interruption of the operation of the existing equipment and delayed our processing of the grown films for a systematic evaluation of the electrical properties of the grown films. All the films showed good HEED patterns and excellent surface morphology (the surface appears spotless and mirror-like).

Besides Hall and resistivity measurements, experiments under preparation include photoluminescence (PL) and deep-level transient spectroscopy (DLTS). Once the equipment, ordered through both industrial and JSEP funding, is on hand, which is expected shortly, characterization of the grown films will commence. In the meantime, we have planned the addition of a metallization chamber to the Riber MBE system. Xerox has donated to us (through the goodwill of Dr. R. Burnham) a vacuum chamber taken from their old Phi MBE system. We'll convert the chamber into a metallization chamber, and have already received from NSF partial funding toward the purchase of the ancillary equipment, such as E-gun evaporator and ion pump, for the conversion. Work on the design of the chamber has been completed, and actual work on the modification

University of California, Berkeley **Electronics Research Laboratory**

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Work Unit No.: SSM-83-3 **Last Year's No.(s):** SSM-82-3

Title: Molecular Beam Epitaxy and its Applications to Studies of Materials Aspects of Microstructure Engineering

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Scientific Objective

Recent advances in thin-film growth technology have opened exciting opportunities, not only in the development of new device structures, but also in our quest for a better understanding of material properties. The objectives of this research program are (1) to master the MBE growth technology for III-V compound semiconductors and for Si, and to develop the associated processing techniques, such as etching and masking, suitable for the MBE process, and (2) to analyze, to characterize, and to correlate the properties of the materials grown under different growth conditions. Our goals are to seek an optimal approach and to develop the needed technology for fabrication of devices of micron and submicron dimensions where interface and surface properties are expected to play a crucial role.

State of the Art

Over the last several years, significant progress has been made in the thin-film technology based on epitaxy for the fabrication of optical and microwave semiconductor devices. The three basic methods are liquid-phase epitaxy[1] (LPE), vapor-phase epitaxy[2] (VPE), including metal organic chemical vapor deposition[2] (MO-CVD, a form of VPE), and molecular beam epitaxy[3] (MBE). Among the three, LPE is the most extensively used, especially in the fabrication of double-heterostructure (DH) injection lasers. While the LPE technology has some distinct advantages over the VPE and MBE technology, it has its limitations. One obvious disadvantage is the lack of control on the film thickness and the impurity profile due to the fast growth rate. Another serious drawback is the impossibility of monitoring film growth and having the growth process temporarily stopped for analytical examination of the grown film. The MBE technology provides the answer to these problems and seems well suited as a research tool for the fabrication and study of semiconductor devices of micron and submicron dimensions.

One problem for which we must find a solution if we are to improve the quality of epitaxially grown films of compound semiconductors is the incorporation of unwanted impurities during the growth process. For example, a dominant shallow donor[4] was found in LPE-grown (GaAl)As and this impurity was thought to be sulphur introduced into the melt with aluminum. Contaminants[5] such as transition metals were reported to be present in MBE-grown GaAs. The total contamination incorporated in a MBE-grown film may be written as

$$C = (\xi/r_g)\,(d^2N/dt\,ds) \qquad (1)$$

where C is the impurity concentration, ξ is the sticking coefficient, r_g is the growth rate, and $d^2N/dt\,ds$ is the number of contaminant gas molecules striking the growth surface per cm^2 per sec. From kinetic theory of gases,

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causes such as carrier diffusion across the carrier can not be ruled out. Possible laser structures with built-in barriers will be explored. We propose that the study be extended to include probable indirect effects of hot carriers. Also, particular attention will be paid to the special chemical and growth properties of the quaternary compound so that what we learn from laser fabrication can be applied to other device fabrication. Recently, two vertical configurations have been proposed for the GaAs FET, one utilizing an etched V groove[19] and the other utilizing Be ion implantation[20]. We propose that laser studies also be made on the structure utilizing LPE growth over an etched channel. We choose this structure because we can learn from it both the etching and growth properties pertaining to a V groove. Further, special attention will be paid to lattice match in the groove region, as any mismatch will certainly show in the laser performance.

As mentioned in the section on Progress and Significant Accomplishments, we have started MBE growth of $Ga_{0.47}In_{0.53}As$ films on InP substrates. Both the HEED pattern and surface morphology are good. We propose that MBE growth be extended to $Al_{0.47}In_{0.53}As$. Our aim is to study the properties of the heterostructure of (GaIn)As and (AlIn)As lattice-matched to InP, for modulation doped FET and quantum-well lasers. As a basic topic for study of interface physics, we also plan to investigate ways to make ohmic contacts to and Schottky barriers on the two ternary compounds. Experiments to determine the doping concentration by the C-V measurement and to find the carrier mobility by Hall measurements are standard procedures in the IC laboratory. Now we have the new capability of determining the composition and impurity concentration in highly doped samples by the AES analyzer. Once the ion-etching package and the DLTS set-up become operational, we will depth-profile the impurity concentration in the MBE grown layer and across the semiconductor-metal interface to correlate the depth-profile measurement with the electrical (DLTS C-V and Hall) measurements. Also, as mentioned earlier in the section on state of the art, in view of the covalent nature of III-V compounds[15,16], an interface material is needed in order to significantly change the barrier height of a Schottky diode. Suitable metals such as Pt, which forms a silicide on Si, will be tried on the quaternary compound, and again the depth-profile measurement will be made to determine the interfacial composition and to correlate it with the electrical properties of the metal-semiconductor contact.

Interaction With Other Work Units

Close interaction is expected with the work units on MBE and on ion-implanted semiconductors, and frequent consultation is also anticipated with other work units, mainly in the IC and device area, for electrical measurements.

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truly outstanding but unexpected. Although we believe uniform carrier distribution to be an important factor, other probable explanations are being studied. In the meantime, experiments are being carried out on lasers with similar but slightly modified structures to ascertain the controlling factors for the observed behavior.

We have also started MBE growth of $Ga_{0.47}In_{0.53}As$ films on InP substrates. After many adjustments in the growth conditions, recently we have been able to obtain good HEED pattern from, and good surfacemorphology of, the grown film. Because of the scheduled shut-down of the laboratory in October, we have concentrated our effort in MBE film growth. The electrical properties of the grown ternary films together with the x-ray determination of the lattice constants will be measured in the month of laboratory shut-down.

Proposed Research

As discussed in the section on state of the art, the quaternary $(Ga_{1-x}In_x)(As_{1-y}P_y)$ compound and the ternary $Ga_{0.53}In_{0.47}As$ compound have outstanding properties, as laser material for the former, and as photodetector and FET material for the latter. These materials, compared to the GaAs/(GaAl)As systems, are still in the infant stage of investigation, even though rapid progress is being made in material and device studies. In our laboratory, we have acquired expertise in the GaAs/(GaAl)As material through our work on the injection laser and have gained experimental skills in measurements of electronic properties of semiconductors through our work on integrated circuits. During the past year, we have gained enough experience in MBE growth of GaAs and (GaAl)As films on GaAs substrates and are currently expanding our activities to growing $Ga_{0.47}In_{0.53}As$ films on InP substrates. We plan to use the LPE facility to grow the quaternary $(Ga_{1-x}In_x)(As_{1-y}P_y)$ compound films and the MBE facility to grow the ternary $Ga_{0.47}In_{0.53}As$ and $Al_{0.47}In_{0.53}As$ films on InP substrates.

As mentioned in the sections on Progress and Significant Accomplishments, we have already successfully grown LPE layers of quaternary compounds of excellent quality and achieved lasing action at the fiber zero-dispersion wavelength (1.3 µm) in stripe-geometry lasers. What is exciting is that we are able to obtain single wavelength operation even close to the threshold in stripe-geometry lasers. The mode spectrum is pure without any detectable side wavelengths. This outstanding behavior is not expected from the laser theory of Gordon based on amplified and filtered spontaneous emission. Currently, we are investigating the laser behavior in several basic stripe-geometry structures with slight variations. We propose that this study be continued with the aim to understand the physical mechanism leading to single wavelength (that is, pure longitudinal mode) operation of the quaternary laser.

Besides single wavelength operation, another important problem concerning quaternary lasers is temperature sensitivity. We have made a survey of the literature and analyzed the experimental results reported by several groups (see M.S. report by Kojima). The probable mechanisms include Auger recombination, carrier leakage across the barrier, interband absorption, and hot-carrier effect. Although Auger recombination is believed to be the major cause for sensitivity to temperature, other outstanding properties and for their relatively unexplored status. Our research efforts will be concentrated at first on those aspects for which we have acquired expertise and then extended to areas which, we think, are important and in which we can make significant contributions.

Progress and Publications

In the previous progress reports, we mentioned that we had started LPE growth of InP films on InP substrates and fabricated a few stripe-geometry lasers. We were able to achieve lasing action in a majority of the lasers tested. With a 10 μm stripe width, a surprisingly small threshold current as low as 180 mA has been obtained. Since then, we have made a great number of stripe-geometry lasers and taken x-ray measurements of the lattice constants of the grown layers. The threshold current depends to a great extent on how well the quaternary (GaIn)(AsP) layer is lattice matched to the InP substrate. The wafer showing the low threshold current actually has a lattice mismatch almost comparable to the resolution of the x-ray measurement and smaller percentage-wise than that of the $Ga_{0.7}Al_{0.3}As$ film relative to the GaAs substrate. However, we had problems with reproducibility. The nonreproducibility of the results was due to lack of control in the accuracy required in the weight of GaAs and InP charges relative to the In melt. A microbalance to accurately weigh the GaAs and InP charges was purchased through industrial funds. Now that the melt composition and the growth temperature are accurately controlled, we are able to obtain lattice-matched (GaIn)AsP films for the 1.3 μm laser routinely and consistently. In the meantime, we have performed experiments on Zn diffusion into InP, and obtained consistently good results. We have developed, in conjunction with Zn diffusion into GaAs, an ampoule which minimizes zinc deposition onto the sample during cooling. The zinc diffusion process is now under control.

Publications Under Partial JSEP Support

S. Wang, "Novel Semiconductor Lasers for Integrated Optics," paper 31, vol. 317, pp. 93-98, SPIE Conference Proceedings, Conference on Integrated Optics and Millimeter and Microwave Integrated Circuits. (1982).

S. Wang, H. K. Choi and I. H. A. Fattah, "Studies of Semiconductor Lasers of the Interferometric and Ring Types," Jour. Quantum Electron., vol. QE-18, pp. 610-617, (1982).

K. Kojima, "Temperature Dependence of the Threshold Current of (GaIn)(AsP) Lasers," M.S. Report (1982).

Significant Accomplishments

Very recently, a great deal of attention has been given to the longitudinal mode spectrum of semiconductor lasers and to ways of achieving single longitudinal mode operation. In our laboratory we have devised a simple structure for the 1.3 μm (GaIn)(AsP) laser and achieved single longitudinal mode operation. Even at currents very close to the threshold, the laser shows a pure, single wavelength. This result is phenomenon, called velocity overshoot, makes compound semiconductors extremely attractive for ultra-high frequency applications.

Among III-V compounds, the GaAs/(GaAl)As system has been most extensively studied for both laser[1] and FET[2] applications. For the laser, a great deal of attention has been focused on stabilizing the mode by incorporating a two-dimensional waveguide in the structure, and remarkable progress has been made on the GaAs/(GaAl)As laser. Many lasers exhibiting linear light-versus-current relation, stable transverse and lateral mode pattern, and single longitudinal mode operation have been developed at several laboratories. These include the buried-heterostructure (BH) laser[3,4], the channeled-substrate-planar (CSP) laser[5,6], and the laser utilizing thickness variation in the grown layer to provide waveguiding in the lateral direction[7-10]. Among the lasers referenced here are the IRW laser[7], the CJSF laser[7] and the narrow DCC-CSP laser[6] being developed and studied in our laboratory. Recently, the research interest has shifted from the GaAs/(GaAl)As laser toward the quaternary (GaIn)(AsP)/InP laser which covers the spectral range where optical fibers have exhibited minimum loss (around 1.55 micrometers) or zero dispersion (around 1.3 micrometers). Because the development of the quaternary laser is relatively recent, many problems including mode stability and temperature sensitivity have not been fully investigated and are yet to be overcome.

For the field-effect transistor, the emphasis is on low power and high speed, and a power/speed product around 20 fJ and a propagation delay around 100 ps have been reported by several laboratories (see papers appearing in the special issue of MTT, Reference 2).To further advance the FET technology, several important problems need to be overcome and have received prominent attention. One of the steps used in the fabrication of the FET is ion implantation. It is found, however, that considerable degradation of the doping profile takes place during annealing of Cr and S implants[11-13]. Although anodic oxidation has been tried on compound semiconductors[14], the interface-state density is considerably higher than that at Si/SiO_2 interface. For lack of a suitable insulator, most FET's are made of Schottky-barrier gates in the form of MESFET. However, the barrier height formed on Si and GaAs is generally not as high as we hope to have. Theoretical studies[15,16] have shown that the degree to which the barrier height at a metal-semiconductor interface is influenced by the metal work function is strongly dependent on the ionicity of the semiconductor. Because Si and GaAs are covalent the barrier height in these two materials is not expected to change much with the metal, as confirmed by experimental data[15]. Therefore, an interface material, such as silicide for silicon, must be found for compound semiconductors between the metal and the semiconductor.

Recently, the ternary compound $In_{0.53}Ga_{0.47}As$ has generated considerable interest, not only as a photodetector for the quaternary (GaIn)(AsP) laser, but also as a FET[17]. Theoretical calculations[18] of the low-field mobility and the peak drift velocity in the ternary compound show that $\mu = 9700\ cm^2/v\text{-}s$ and $v_m = 2.8 \times 10^7$ cm/s are higher than the corresponding values in GaAs and InP, even with alloy scattering being taken into account. The quaternary (GaIn)(AsP) and the ternary $In_{0.53}Ga_{0.47}As$ compounds offer exciting research opportunities for their

University of California, Berkeley — Electronics Research Laboratory

Joint Services Electronics Program — September 30, 1982

Work Unit No.: SSM-83-2 — Last Year's No.(s): SSM-82-2

Title: III-V Compound Semiconductors: Material-Property and Device Studies

Senior Principal Investigator(s): S. Wang (415) 642-4134
C. Hu 2-3393

Scientific Objective

We propose to study the properties of the quaternary compound (GaIn)(AsP) and the ternary compound $Ga_{0.47}In_{0.53}As$ concerning LPE and MBE growth, lasing characteristics, ohmic-contact formation, and Schottky-barrier height. The quaternary compound is important for its spectral coverage best suited for fiber optical communications, and will be studied as laser material. The ternary compound is promising for its theoretically predicted high mobility and peak drift velocity. Our objectives are to find the dominant factors affecting LPE and MBE growth, lattice mismatch, impurity concentration, contact resistance and Schottky-barrier height in these materials, and to correlate the material properties, such as lattice mismatch, doping profile and material-composition profile, with the device performance, such as lasing characteristics, turn-on voltage, and I-V characteristics, and with the electrical measurements, such as carrier concentration and mobility.

State of the Art

III-V compound semiconductors possess many distinct and unique advantages as an electronic and optical material. Most of the compounds of smaller gap energy such as InAs and InSb, have very small electron mass and thus exceedingly high electron mobility. Some of the compounds of larger gap energy, such as InP and GaAs, can be made semi-insulating by compensation either through deep donors or through deep acceptors. The compounds are almost completely miscible except in some systems where a small miscibility gap exists. The mixed compounds can be lattice-matched to a given substrate, for example $(Ga_{1-x}In_x)(As_{1-y}P_y)$ to InP, by properly choosing the relative composition signified by x and y. The miscibility and the possibility of lattice-match of these compounds enable us to build electronic and optical devices with materials different from the substrate and thus to take full advantage of the material properties, for example (GaIn)As on InP, with the former for its high mobility and the latter for its semi-insulating property.

Most of the compounds are direct-gap semiconductors and hence attractive candidates as materials for lasers and photodetectors. In compounds where the energy gap is direct, the energy separation between the central valley (the direct gap) and the satellite valleys (above the central valley) of the conduction band varies from compound to compound. This variation offers various possibilities for mixed compounds. For mixed compounds with relatively small separation, for example 0.36 ev in GaAs, we expect the material to exhibit the so-called transferred-electron or Gunn effect. For mixed compounds with relatively large separation, we expect that the material should be able to attain a much higher drift velocity than the value limited by the transferred-electron effect. The possibility of a high drift velocity makes these materials attractive candidates for FET. In any case, on a time scale shorter than the intervalley-scattering time, the electron drift-velocity is expected to continue to grow with increasing applied field to values beyond those limited by the transferred-electron effect. This

B. Modeling Channel Hot-Electron Emission

Channel hot-electron emission is expected to be a principal problem affecting the reliability of short channel MOS devices for VLSI.

Modeling of this phenomenon has been hindered by the large number of variables involved and the inability to verify the individual building blocks of the model[12-14]. We propose to develop a relatively simple ballistic transport model, whose central premise is the verified and accepted "lucky electron model"[2] originally introduced for hot-electron emission into the substrate. The modifications needed for channel hot-electron emission are to require that an electron gains sufficient energy from the field, and that it be redirected by acoustic phonon scattering toward the Si/insulator interface before suffering an energy-robbing, intervalley-phonon scattering. Also included are the scattering in the finite distance between the channel electrons and the interface and in the image-force potential well in the oxide. The only device-dependent input to the model is potential distribution in the channel along its length, which may be obtained from approximate analytic formulas or from computer models of the device.

This model should be able to predict the dependence of the channel hot-electron emission rate on V_g, V_{ds}, channel length, gate-oxide thickness, and the channel doping profile. We have developed a preliminary version of such a model[11], but much more needs to be done. The final model would likely make use of the multi-dimensional device simulation programs being developed elsewhere to calculate the surface potential distribution between the source and drain.

Even the preliminary model has suggested several intriguing concepts that we propose to study experimentally in parallel with refinement of the model. The ballistic "lucky electron" model suggests that if the drain-source potential is kept below 2.5 volts, the channel hot-electron emission is very small -- regardless of how short the channel may be. If this is borne out by experiments, it could have far-reaching impact on the physical limitations of very short channel FET's.

Another concept suggested by the model is that the hot-electron emission is almost uniquely determined by the maximum field strength in the channel. If so, it should have a one-to-one correlation with the substrate current, which has been theoretically correlated to the maximum field, E_m:

$$I_{sub} = I_d A e^{\beta E}$$

where A and β are material constants.

The correlation between channel hot-electron emission and I_{sub} would allow us to do device characterization and accelerated reliability tests of the hot-electron instability by simply measuring I_{sub}. This procedure would supplement or possibly replace the long-term stress tests, which are the only available means of assessing the device instability associated with hot-electron phenomena.

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attain the energy needed to surmount the 3.2 eV barrier at the Si/SiO_2 interface and enter the oxide.

Progress and Publications

Without JSEP support, we have already studied Fowler-Nordheim tunneling into SiO_2 grown from poly-Si and observed electron trapping[9] (C. Hu, Y. Shum, T. Klein, E. Lucerno. Appl. Phys. Lett., July 15, 1979). We have developed a method for determining the trap cross-section and density distribution[10] (C. Hu, D. Y. Joh, Y. Shum, T. Klein, IEDM, Dec. 1978, pp. 229-232), together with a ballistic model of hot channel electron transport and emission into SiO_2[11] (C. Hu, IEDM, Dec. 1979, pp. 22-25). We have carried out extensive studies on gate currents in avalanching gated diodes[12] (R. Amantea and R. S. Muller, Jap. Jour. Appl. Phys., vol. 16, Suppl. 16-1, pp. 205-210, 1977), and have built special resistive-gated MOSFET's to assure uniformity of injection along the channel[13] (P. K. Ko and R. S. Muller, IEDM, 1979, pp. 506-507).

A paper, "Correlation Between Substrate and Gate Currents in MOSFETs" (S. Tam, P. Ko, C. Hu, R. S. Muller) has been accepted for publication in the November 1982 issue of IEEE Trans. on Electron Devices. Also accepted for publication in IEEE Electron Devices Letters is a paper entitled "Hot-Electron Induced Excess Carriers in MOSFETs" (S. Tam, F. C. Hsu, C. Hu, R. S. Muller, P. Ko). Another paper has been submitted to IEEE Electron Devices Letters, "dv/dt Breakdown of VDMOSFET."

Significant Accomplishments

We have identified the mechanism of minority carrier generation in the substrate as photo-carrier generation. The photons are generated in the high field region in the transistor channel by hot electron bremsstrahlung radiation. These photons have an average decay length of 780 μm and can cause DRAM refresh time degradation and even logic circuit malfunctions throughout the chip. Furthermore, present techniques such as the use of guard ring (psuedo collector) are ineffective in stopping the photons. The rate of photons emission is found to be $2 \times 10^{-5} I_{sub}/q$.

We have also derived and proven a power law relationship between channel hot-electron gate current and the substrate current. This should significantly simplify the testing for device reliability since the gate current can now be deduced from the measured substrate current, which is larger than gate current by 10^{10}.

Proposed Program

Two topical areas will be investigated simultaneously: (A.) trap density and cross-section distributions in gate insulators, and (B.) models for hot electron emission from MOSFET channels.

A. Trap Density and Cross-section Distributions

The two parameters linked most closely to electron trapping and device stability are trap density and capture cross-section. Below, we describe a method that determines the trap density per unit cross-section as a continuous function of the capture cross-section $N(\sigma)$ - - a task hitherto untenable.

From first-order rate processes, the density of filled traps $N_f(\sigma)$ increases according to

$$\frac{dN(\sigma)}{dF} = \sigma[N(\sigma) - N_f(\sigma)] \qquad (3)$$

The solution of (3) is

$$N_f(\sigma,F) = N(\sigma)(1-e^{-\sigma F}) \qquad (4)$$

The shift in the C-V or I-V curves, ΔV is related to the filled trap density by

$$\Delta V = \frac{d_t Q}{\varepsilon} = \frac{qd_t}{\varepsilon}\int_0^\infty N_f(\sigma,F)d\sigma \qquad (5)$$

$$\frac{d\Delta V}{dF} = \frac{qd_t}{\varepsilon} = \int_0^\infty \frac{dN_f(\sigma,F)}{dF}d\sigma$$

$$= \frac{qd_t}{\varepsilon}\int_0^\infty \sigma N(\sigma)e^{-\sigma F}d\sigma \qquad (6)$$

Clearly, $\frac{d\Delta V}{dF}$ is the Laplace transform of $\frac{q}{\varepsilon} d_t\, \sigma N(\sigma)$. The distribution $N(\sigma)$ can be obtained by taking the inverse Laplace transform of the measured $\frac{d\Delta V}{dF}$. If $\frac{d\Delta V}{dF}$ can be approximated by an analytic function, the inverse transformation is often easy to carry out. Otherwise, numerical techniques can be employed.

We propose to use this method to investigate the dependence of trap densities and cross-section distributions on the growth conditions for the insulator, the exposure to radiation, of the MIS system, and the annealing conditions used in the fabrication process. Even the more conventional characterization techniques have not been applied to the most promising insulators in submicron devices. We propose to study the traps in very thin (< 300 Å) SiO_2, thermal as well as CVD nitride, SiO_2 grown on poly-Si -- both as-deposited and laser-annealed.

University of California, Berkeley — Electronics Research Laboratory

Joint Services Electronics Program — September 30, 1982

Work Unit No.: SSM-83-1 — **Last Year's No.(s):** SSM-82-1

Title: Hot-Electron Injection and Trapping at Si-Insulator Interfaces

Senior Principal Investigator(s): C. Hu (415) 642-3393
R. S. Muller 2-0614

Scientific Objective

The objective of this work is to characterize and understand hot-electron injection and trapping at the interface between silicon and overlying insulator layers, and to investigate means of gaining control over these phenomena. It is also our objective to study other related hot-electron phenomena such as minority carrier injection into the substrate and breakdown in the Si/SiO_2 system.

State of the Art

Hot electrons can be injected into silicon dioxide in several ways. An important example is channel hot-electron injection[1], which occurs with increasing likelihood as MOSFET channels are shortened and which imposes practical constraints on the operating voltage of short channel MOSFET's[2,3]. Injection can also take place through internal photoemission[4], Fowler Nordheim tunneling at high fields[5], and avalanche breakdown near the Si surface[6]. Once a conduction electron enters the oxide, it can be captured by traps in the SiO_2 band gap formed by impurities or defects. The buildup of trapped charge Q is often monitored by measuring the change of the flat band voltage ΔV_{FB} - usually through C-V measurements. If the approximate location of the traps is known, then we can determine Q from Q = V_{FB}, where d_t is the centroid of the trapped charge measured from the metal-SiO_2 interface. It is clear that the technique senses the internal field at the Si/SiO_2 interface created by charge Q. This method, however, cannot be reliably applied to studying SiO_2 grown from poly-crystalline Si. One other technique can sense the field at the interface - the photocurrent-voltage[7] technique. This method, however, is inconvenient to use. We propose to measure the change in the internal field due to Q by measuring the shift of the I-V curve. In other words, the Fowler-Nordheim injection is used both as the mechanism of electron injection, and as a means of measuring Q.

Using a first-order, rate-process model, it can be shown[8] (given a trap density N and capture cross section σ) that:

$$Q = q\, N(1-e^{\sigma F}) \tag{1}$$

$$F = \frac{J(t)}{q}\, dt \tag{2}$$

where J is the current density and F is the electron fluence. Hence, an established procedure is to measure Q as a function of F and then to extract N_t and σ from the data by curve fitting with Eqs. 1 and 2. As a result, only discrete values of σ have been reported for traps in SiO_2 grown from single crystal Si without regard to possible spreads of σ over a finite range.

Finally, a quantitative model of channel hot-electron injection is presently not available. It has only been established that as electrons move from source to drain, they become sufficiently heated so that some

In parallel with this effort, a research program on metal-compound semiconductor contact is discussed under SSM-3.

Besides Si and GaAs, a great deal of attention has been paid recently to the quaternary compound (GaIn)(AsP) and the ternary compound $Ga_{0.47}In_{0.53}P$, the former for its spectral coverage as a laser for fiber optical communication, and the latter for its high electron mobility and peak drift velocity. Compound semiconductors have many distinct advantages over silicon. Compounds of larger gap energy can be made semi-insulating by compensation and compounds of smaller gap energy have very high electron mobility. The miscibility and the possiblity of lattice-match of these compounds enables us to build electronic and optical devices with materials different from the substrate and thus to take full advantage of the material properties. A research program on the LPE growth of the quaternary compounds, the quaternary-compound laser, and the metal-quaternary compound contact is presented under SSM-2 entitled "III-V Compound Semiconductors: Material Properties and Device Studies."

In summary, three research programs are proposed in MBE technology, in interface studies and in the quaternary compound (GaIn)(AsP). The main objectives are: (1) to study the characteristics of the MBE process and to explore potential use of the MBE process for fabricating submicron electronic devices; (2) to determine the electrical and material properties of a metal-semiconductor interface and to study the effects of interface properties on the device performance; and (3) to develop the processing technology for the quaternary compound and to explore the possible use of the compound for integration of electronic and optical devices.

principal tool for analysis. Eventually we hope to determine optimum design criteria for such receivers.

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University of California, Berkeley — Electronics Research Laboratory

Joint Services Electronics Program — September 30, 1982

II.A. Basic Research in Solid State Electronics - Materials — Coordinator: Professor S. Wang

General

Two important aspects of material research concerning microstructure engineering are control of growth and doping process, and understanding of interface problems. In the Electronics Research Laboratory, we have developed extensive expertise in silicon technology and, to a lesser degree, in GaAs technology. Processing steps such as lithography, impurity diffusion, plasma etching, ion beam milling, ion implantation, and liquid-phase-epitaxy (LPE) have been widely and routinely used. Recent advances in thin-film growth technology, especially chemical vapor-phase deposition (CVD) and molecular beam epitaxy (MBE), have opened new options in the fabrication of submicron electronic devices. Through JSEP funding, we recently purchased a Riber MBE system and a scanning Auger microprobe (SAM), and have ordered equipment for photoluminescence (PL) and deep-level transient spectroscopy (DLTS) experiments. These facilities greatly enhance our experimental capabilities in thin-film growth and in interface studies. A great deal of our research effort will be focused on developing the capabilities of the MBE system and the SAM instrument, and applying these capabilities to thin-film growth and analysis.

It is conceivable that fabrication of future submicron electronic devices will involve a combination of several growth and processing steps, such as MBE, ion implantation, laser annealing, and heat treatment. It is our plan to develop the capability not only in growing thin films under controlled conditions, but also in determining the impurity distribution and composition profile in the grown films before and after the various processing steps. Processing and growth steps, such as ion implantation and MBE, either introduce lattice defects or involve high doping concentration beyond the solid-solubility limit, or both. These problems must be investigated. Since the MBE technology has been most developed for GaAs/(GaAl)As and since we already have extensive experience with LPE growth of GaAs/(GaAl)As films, our initial effort on the MBE system will deal mainly with GaAs/(GaAl)As materials. A research program on the MBE process is presented under SSM-3 entitled "Molecular Beam Epitaxy and its Application to Studies of Material Aspects of Microstructure Engineering."

As the dimension of electronic devices is reduced further and further, the interfaces of a device are expected to play a more and more important role in affecting the device performance. Even for silicon devices which have been most extensively studied, many important interface problems remain to be understood and overcome. One such problem relates to hot-electron injection and trapping at the interface between silicon and overlying insulator layers. A major effort will be focused on the development of an understanding of interface traps in both their properties and in their effects for modeling. A research program on determining trap density and cross section and on modeling channel hot-electron emission is presented under SSM-1 entitled "Hot-Electron Injection and and Trapping at Si/Insulator Interfaces."

Theory and Techniques, March 1983.

Government Scientist Contact

(a) We have an ongoing project with U.S. Army MERADCOM intended to apply principles of antenna design to development of MM-wave imaging arrays. (b) Attended meeting on "Integrated Optics and MM and Microwave Integrated Circuits," November, 1981, which had Army participation.

Significant Accomplishments

D. B. Rutledge completed his Ph.D. with JSEP support in June, 1980. He is presently an Assistant Professor at California Institute of Technology. From his work and collaborations there resulted a new type of detector array and a novel microbolometer for infrared detection. This detector consists of a thin bismuth bolometer film with dimensions much smaller than a wavelength. The small size of the detector results in reduced NEP and faster response. A video NEP of 1.6×10^{-10} $W/Hz^{1/2}$ is obtained at 119 μm, remaining within a factor of 10 of this value for modulation frequencies up to 25 MHz. When used as a mixer, the device is predicted to have an NEP of 3.5×10^{-18} W/Hz. It is easily fabricated with conventional planar processing techniques and can be replicated in arrays. The device is expected to be most useful when the radiation to be detected is spatially coherent.

In recent work we have studied coplanar waveguide (CPW) as a basis for integrated circuits operating below 100 GHz [16,17]. Preliminary results indicate that the radiation loss of unenclosed CPW is adequately low. Tunable resonators and bandpass filters have been designed and tested at 5 GHz. These results are significant because they open a way to tunable, integrable local oscillators for monolithic receivers.

Proposed Research

The most promising basic component for millimeter-wave IC's appears to be the dielectric "slab-coupled" or "ridge" waveguide. Although this type of guide was proposed and studied earlier[1,2], it appears not to have found applications until now, and thus has not been extensively analyzed. Existing theory is highly approximate, due to the fact that the guide boundaries do not fall on coordinate surfaces. Precise theoretical analysis is posssible but requires laborious computation. Our intention is to make use of both approximate and computational techniques, but to supplement them with simulation experiments at X-band. By this means it will be possible to obtain dispersion curves for variously shaped guides of this family and compare them with theory. Electromagnetic field distributions will also be studied.

When the guides are adequately characterized, we shall go on to study their potential use as a basis for other components. For example, it seems logical to create a hybrid coupler by bringing two of these guides close together, so they couple through the fringing fields of their common slab. However, this raises significant electromagnetic questions. We must determine whether the guides can be curved (in order to bring them together and separate them) without excessive radiation loss. Radiation losses will depend on the dimensions of the guide and this dependence must be studied. The design of such a coupler will also require detailed knowledge of the fringing fields. Thus before such a coupler can be effectively designed, theoretical and experimental studies of the guided fields must be made.

An interesting alternative to the use of curved guides is the possible introduction of abrupt double bends, such as are used in hollow metal waveguides. The basic idea here is to obtain the desired deflection by using a sequence of two bends, the reflection of the second of which is used to cancel the reflection of the first. "Fine-tuning" of such a structure can be applied by perturbing the shape of the guide. This approach will be studied as a way of obtaining more compact bands with possibly reduced radiation loss.

An especially interesting application of the dielectric guides is their use in resonators. There is a serious need for new radiation sources in this region of the spectrum, especially integrable ones, and these new sources will need integrable resonators. Evident ways of producing resonators based on slab-coupled guides includes (a) circular "racetrack" resonators with hybrid couplers; (b) "open-circuited" sections of guide with perpendicular cleaved end-faces; or (c) guides with periodic distributed-feedback structures. All of these, when looked at more closely, are relatively sophisticated structures, for which careful analysis will be required. Related problems we also propose to study are (a) how can such resonators be tuned? and (b) how can active elements be coupled to them to create oscillators? In regard to (a), we plan to study perturbation of phase velocity caused by presence of adjustable external dielectrics in the fringing fields. With regard to (b), two possibilities are being investigated. One is the use of metallic couplers such as have been used with mixer diodes in earlier work; the other is incorporation of large-area devices directly in reduced-height guides, with electromagnetic coupling. It is hoped that enough understanding of the requisite structures can be gained to make new mm-wave sources a practical possibility.

During the last year we have proceeded with our program of characterization of the "rib" waveguide. By means of probe measurements dispersion characteristics have been determined. More recently we have worked on optimal design of the V-coupler used to couple diodes to the guide. We plan to continue this work and to develop design rules for this unusual and useful component. In particular, our objective is to reduce the coupling loss between diode and guide, by optimal choice of the coupler and guide dimensions.

When design of the V-coupler has been completed we shall proceed to the previously-described design studies of hybrid couplers and resonators. The resonator studies, especially, are urgently needed for development of monolithically-integrated radiation sources. Development of the semiconductor devices is being carried on concurrently under other support.

Our recent success with devices based on CPW encourages us to proceed with analysis of other system elements. In particular, we need to study the special filters and tuning elements required for a low-loss receiver front end. We will continue to use 5-GHz simulation as aa

University of California, Berkeley — Electronics Research Laboratory

Joint Services Electronics Program — September 30, 1982

Work Unit No.: EM-83-2 — Last Year's No.(s): EM-82-2

Title: Millimeter Wavelength Electromagnetic Structures

Senior Principal Investigator(s):	S. E. Schwarz	(415) 642-5684
	K. K. Mei	2-4106
	D. J. Angelakos	4-7200

Scientific Objective

This project is based on the emergence of a new level of millimeter-wave technology, based on use of semiconductor integrated circuits. The electromagnetic structure to be used in this region of the spectrum will probably have to be quite different from those used in existing microwave technology. Appropriate structures (a) should contain little or no metal, as the latter introduces resistive losses; (b) should have dimensions in the range feasible for existing microfabrication technology (loosely speaking, .0002 - 1.0 cm). (c) should yield desired structures without undue fabrication complexity; and (d) should lend themselves to low-cost replication and integration into systems. The scientific objective of this project is thus the realization and analysis of novel antenna and waveguide structures for use in this emerging application.

State of the Art

Conventional millimeter-wave technology at present makes use of hollow metal waveguides. The resulting structures work well in most cases but suffer from problems of cost, size, and fragility; moreover, they become progressively smaller and more difficult to construct as wavelength decreases into the near-millimeter region. The most promising alternative appears to be the slab-coupled dielectric waveguide[1]. No exact theory of these guides exists. There is an approximate theory[2], or, alternatively, numerical methods exist[3] that can, at some cost in time and effort, be used in specific cases. Until now these guides have not been adapted for millimeter-wave use, but similar guides have been considered for use in integrated optics[4,5]. In our own earlier work[6] we demonstrated the use of these guides in millimeter-wave IC applications by using them as the basis for tapered dielectric antennas. Other possible guiding structures have been proposed[7-12], but these seem less advantageous due to fabrication difficulty and/or metallic loss. Open structures are also posssible[13] but these are large and lack rigidity. A non-integrated millimeter-wave dielectric antenna was devised by Shiau[14] using empirical formulas due to Mallach and Kiely[15].

At frequencies below 100 GHz metallic lines appear to be preferable. Our work emphasizes coplanar waveguide.

Progress and Publications

Publications Under JSEP and Other Support

C. Yao, S. E. Schwarz and B. J. Blumenstock, "Monolithic integration of a dielectric millimeter-wave antenna and mixer diode: an embryonic millimeter-wave IC," to appear in IEEE Trans. on Microwave Theory and Techniques, August 1983.

T. Wang and S. E. Schwarz, "Design of dielectric ridge waveguides for millimeter-wave integrated circuits," to appear in IEEE Trans. Microwave

K. K. Mei, J. F. Hunka and S.K. Chang, "Recent developments of the unimoment method," International Symposium on Recent Developments in Classical Scattering, Columbus, Ohio, June 1979. To be published as a chapter in Recent Developments in Classical Scattering, edited by V. K. Varadan, Academic Press. J. F. Hunka, "Scattering of two bodies of revolution," to be published in Journal of Electromagnetics, July-September 1981.

K. K. Mei, "Recent developments in the Unimoment Method," URSI 20th General Assembly, Abstracts Sessions of Commissions, p. 390, Washington, D.C, Aug. 1981.

J. F. Hunka and K.K. Mei, "Scattering by two bodies of revolution," IEEE Antennas and Propagation Symposium and USNC/URSI 1980 Meeting, Quebec City, Canada, June 1980.

B. Publications under Other Sponsorship

H. Kao and K. K. Mei, "Scattering by advanced composite bodies of revolution", USNC/URSI Conference, Seattle, Washington, June 1979.

S. Coen and K.K. Mei, "Inverse scattering of layered media," USNC/URSI Conference, Seattle, Washington, June 1979.

S. K. Chang and K. K. Mei, "Generalized Sommerfeld integrals and field expansions in two-medium half-spaces," IEEE Trans. on Antennas and Propagation, vol. AP-28, no. 4, pp. 504-512, July 1980.

T. M. Kvan and K. K. Mei, "The internal fields of a layered Radome excited by a plane wave," IEEE AP International Symposium, Los Angeles, June 1981, pp. 608-611.

H. Chang and K. K. Mei, "Scattering of EM waves by buried or partly buried bodies of revolution," IEEE International Symposium, Los Angeles, June 1981, pp. 653-656.

Government Scientist Contact

Professor Mei is in frequent contact with scientists of the Army who are interested in the work of electromagnetic scattering.

Significant Accomplishments

We have positively demonstrated that the Unimoment Method is a powerful computational technique to solve scattering problems involving inhomogeneous material targets[5], and that an iterative technique following the Unimoment Method is an economical approach to solve two-body scattering problems[1]. In an effort to solve two-body scatterings near an air-ground interface, we have investigated a new addition theorem involving Sommerfeld integrals. This investigation has been successful, using the theory of analytic continuation. We are now in a position to implement the new addition theorem to find scattering by two bodies, where one may be above and the other under the ground.

Proposed Research Program

Our research has already shown that the two metal body scattering can be computed accurately and economically. Our new objective is to extend the study to multi-body scattering involving lossy ground. We shall also study scattering and radiation properties of wire structures which are partially buried in a lossy ground, or the multi-medium scattering, and two-body scattering where one body is above and other under the ground. Recently we have also included the work of time domain approach to electromagnetic scattering. We have formulated a numerical algorithm, so that the time domain finite difference technique may be conforming to the curved boundaries of the scatterer. We have already demonstrated the feasibility of the conformal TDFD method and intend to further exploit the successes. Experimental verification of the computation of scattering by buried objects is planned and will be included in this research effort.

Interaction with Other Work Units

The techniques developed in this research will be applied to other work units in the proposal, such as EM-84-2.

References

(1) J. F. Hunka, "Electromagnetic scattering by two bodies of revolution," Ph.D. Dissertation, Department of Electrical Engineering and Computer Sciences, University of California, Berkeley, 1979.

(2) K. K. Mei, J. F. Hunka and S. K. Chang, "Recent developments of the unimoment method," International Symposium on Recent Developments in Classical Scattering, Columbus, Ohio, June 1979. To be published as a chapter in Recent Developments in Classical Scattering, edited by V. K. Varadan, Academic Press.

(3) D. J. Angelakos and N. Kumagai, "High-frequency scattering by multiple spheres," IEEE Trans. on Ant. and Prop., vol. AP-12, no. 1, January 1964, pp. 105-109.

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University of California, Berkeley — Electronics Research Laboratory

Joint Services Electronics Program — September 30, 1982

Work Unit No.: EM-83-1 — Last Year's No.(s): EM-82-1

Title: Conformal Time Domain Finite Difference Method of Solving Scattering Problems

Senior Principal Investigator(s): D. J. Angelakos (415) 642-7200
K. K. Mei 642-4106

Scientific Objective

The objective of this research is to complete the study of the multiple scattering near lossy ground using the Unimoment Method and to develop the time domain solutions of scattering problems.

State of the Art

Multiple scattering near lossy ground is a problem now solvable by the Unimoment Method and it is completed[1,2]. The time domain solution of the scattering problem has hitherto been solved using a rectangular space grid, which does not conform well to the geometry of the target. Our new approach using a conformal grid and a new radiation boundary condition will literally open up a new area for research.

Progress and Publications Since Last Major Proposal

1. Experimental System

Considerable experimental results have been obtained on high-frequency scattering by multiple spheres[3]. These were primarily back scatter measurements because bistatic measurements involved considerable difficulties; consequently, a refinement of the equipment was undertaken.

A semi-automated radar cross-section measurement system has been developed where it is possible to obtain scattering data to be used as verification of the numerical results. The system consists of an indoor image ground plane with a CW microwave system operating in the x-band. It utilizes the well-known null balance technique for extracting the scattered field. A process computer is linked to the system via a network analyzer which is used as a coherent detector. The measurement system employs a reciprocal measurement technique (RMT) which enables one to obtain bistatic scattering data[4]. The process computer stores and removes inherent errors in the system and processes the data in a variety of formats.

The measurement system has proven successful in verifying previous numerical analysis endeavors[1]. The accuracy of the system has been shown to be reliable for cross-sections on the order of the wavelength squared.

2. Computation

The program of scattering by two bodies body of revolution near lossy ground is near completion.

A. Publications under JSEP

J. F. Hunka, "Electromagnetic scattering by two bodies of revolution," Ph.D. Dissertation, University of California, Berkeley, 1979.

(2) Mei, K. K., "Unimoment method of solving antenna and scattering problems," IEEE Trans. on Antennas and Propagation, vol. AP-22, no. 6, Nov. 1974, pp. 760-766.

(3) Stovall, R. and K.K. Mei, "Application of a unimoment method to a biconical antenna with inhomogeneous dielectric loading," IEEE Trans. on Antennas and Propagation, vol. AP-23, no. 3, May 1975, pp. 335,342.

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(10) Chang H. O. and K. K. Mei, "Scattering of EM waves by buried or partly buried body of revolution," IEEE Antennas and Propagation International Symposium. Los Angeles, pp. 653-656, June 1981.

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(12) Taflove T, and M. E. Brodwin, "Numerical solution of steady state electromagnetic scattering problems using time-dependent Maxwell's equations, IEEE Trans. Microwave Theory and Tech., vol. MTT-23, pp. 623-630, August 1975.

(13) Merewether, D. E., "Transient currents induced on a metallic body of revolution by an electromagnetic pulse," IEEE Trans. Electromagnetic Compatibility, vol. EMC-13, pp. 41-44, May 1971.

University of California — Electronics Research Laboratory

Joint Services Electronics Program — September 30, 1982

I. Basic Research in Electromagnetics — Coordinator: Professor K. K. Mei

Basic research in electromagnetics at ERL presently consists of two parts. One is the development and application of computational techniques to electromagnetics, and the other is the basic research in theory and experimentation of electramagnetics at submillimeter wavelengths. These two reseach acitivites are described in the following.

Computations in Electromagnetics

Research in electromagnetic theory was traditionally done within the regime of applied mathematics. Since the advent of high speed digital computers, we have seen more and more emphasis on the computational research being done in applied electromagnetics. In the early 1960's the main thrust of electromagnetic related computation was in integral equation approaches[1]. The integral equation was a natural choice in radiation problems because the radiation conditions at infinity could easily be satisfied by using proper Green's functions. Although the integral equation method is not too well adapted to problems involving fat bodies and dielectric bodies, early investigators were still quite happy with it, because even with its limitations it was possible to solve many problems which were hitherto unsolvable. As more and more problems were solved, researchers began to look for alternatives to the integral equation approach, which might be better than the integral equation method in solving fat, dielectric or even inhomogeneous bodies. This effort is represented by the unimoment method which was developed by K.K. Mei and his associates at ERL[2], and the several publications that follow[3,4] indeed show that the differential equation approach can be very efficient in regions where the integral equation method is clumsy and impractical. This method is currently being used to investigate the scattering by buried dielectric obstacles, a project now supported outside the JSEP.

The unimoment method is not only good in solving scattering by dielectric bodies, it is also an excellent technique for solving scattering by perfectly conducting bodies. A simple illustration shows how it works. Consider the scattering by a conducting spheroid. Outside a circumscribing sphere, the solution is expressed in classical spherical harmonics with undetermined coefficients, and inside the sphere the solutions are generated by solving the finite element equations. The expansion coefficients on both sides of the sphere are determined by enforcing the continuity conditions on the sphere. It is interesting to see that the finite element mesh area becomes larger if the spheroid becomes thinner, and it becomes smaller if the spheroid becomes fat. That means the unimoment method is efficient (more precise) for a fat scattering that a skinny scatterer. The integral equation methods works just the opposite way, i.e., the surface area of the scatter increases as the scatter becomes fatter and hence requires more computation.

We have already succeeded in using the unimoment method to solve scattering by dielectric bodies[5], and it is apparent that it should work even better when applied to a single fat metal scatterer. We have also completed two-body scattering involving two metal scatterers[6,7].

With the support of ARO? the unimoment method has been successfully applied to scattering by submerged targets and to partially buried targets[10]. Other applications of our computational skills are considerable, but our intention is to develop new basic techniques rather than to solve problems. Our new direction is to approach Maxwell's equations in time domain.

The direct time domain solutions of Maxwell's equations were first attempted by Yee[11]. In recent years, even though Yee's method has been extensively applied to scattering problems involving complex-shaped targets[12,13], the basic approach has not been improved. Basically, Yee's method is a finite difference time domain (FDTD) technique, which applied finite difference both in space and time. The disadvantage of this method is that the space mesh must be right rectangular, thus a circle must be composed of small rectangles. This is both theoretically and practically unsatisfying.

Our approach to the time domain problem is to use complete quadratics in space mesh, so that the mesh can conform with the contour of the scatterer. In addition, we have also tried a new "radiation condition" on the technique which shows great promise in terminating the mesh close to the scatterer. We have excellent success in trying our new approach to simple scattering problems in two dimensions. We are very hopeful that this new development will open a new door in electromagnetics.

Electromagnetics at Submillimeter Wavelengths

Radio, microwave, submillimeter wave and light are all electromagnetic waves. The only difference between them is the frequency. However, both in theory and application they are dealt with quite differently. For example, the guided transmission of radio is mostly by coaxial lines, of microwave by metal waveguides, and of light by beams or dielectric waveguides. There are borderline frequencies where different transmission methods can be used. That indeed is the case at submillimeter waves to low infrared waves.

Under the previous sponsorship of JSEP we investigated both metal and dielectric structures such as antennas and wave guides at low infrared frequencies. It has turned out that the metal guide, while lossy, is an excellent device to concentrate electromagnetic power to a very small region, much less than a wavelength. The bulk of any submillimeter device has to consist of dielectric material as antennas and guides. Hence, our effort for the next period will emphasize the application of dielectric guiding structures and couplers at mm waves.

References

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A. 1982-1983 JSEP PROJECTS:

AS OF 31 AUGUST 1982

2. RESEARCH PROJECTS

A. 1981-1982 JSEP Projects: as of 31 August 1982

Project No.	Project No.	Title	Investigator(s)
I.	ELECTROMAGNETICS		
	EM-83-1	Electromagnetic Scattering by Multiple Targets and Targets in Multiple Media	D.J. Angelakos K.K. Mei
	EM-83-2	Millimeter Wavelength Electromagnetic Structures	S.E. Schwarz K.K. Mei D.J. Angelakos
II.	SOLID STATE ELECTRONICS		
	A. Materials		
	SSM-83-1	Hot-Electron Injection and Trapping at Si/Insulator Interfaces	C. Hu R.S. Muller
	SSM-83-2	III-V Compound Semiconductors; Material Property and Device Studies	S. Wang C. Hu
	SSM-83-3	Molecular Beam Epitaxy and Its Applications to Studies of Materials Aspects of Microstructure Engineering	S. Wang N. Cheung
	B. Devices		
	SSD-83-1	Critical Problems in Lithography and Their Impact on Practical Performance	A.R. Neureuther W.G. Oldham
	SSD-83-2	Study of Effects Limiting Realization of Far-Submicron Superconductive Electronic Structures	T. Van Duzer
	SSD-83-3	New Techniques for Wide-Dynamic-Range Signal Processing Using Integrated Circuit Technology	R.W. Brodersen P.R. Gray R.G. Meyer D.O. Pederson

RESEARCH PROJECTS - continued

Project No.	Title	Investigator(s)
II. SOLID STATE ELECTRONICS		
B. Devices (cont.)		
SSD-83-4	Research on Electronic Systems Composed of Polymer Films and Planar Si Devices for Transducer Applications	D.W. Hess R.S. Muller
III. QUANTUM ELECTRONICS		
QE-83-1	Functional Analysis of Novel Semiconductor Lasers for an Integrated-Optical-Network Viewpoint	J.R. Whinnery S. Wang
QE-83-2	Millimeter and Infrared Heterodyne Mixing and Detection	T.K. Gustafson S.E. Schwarz T. Van Duzer
IV. INFORMATION SYSTEMS		
ISS-83-1	Large-Scale and Nonlinear Circuits Study	L. O. Chua E. S. Kuh
ISS-83-2	Control of Large Sytems	C.A. Desoer P.P. Varaiya
ISS-83-3	Computer Optimization of Electronic Circuits	A. Sangiovanni-Vincentelli R.G. Meyer E. Polak

3. Consolidated List of JSEP Published Papers and Memorandums through 31 August 1982.

1. INTRODUCTION

During the period 1 May 1982 through 30 April 1983, the Electronics Research Laboratory (ERL), University of California, Berkeley, is receiving support for its basic program from the Joint Services Electronics Program (JSEP), sponsored by the Departments of the Air Force (Air Force Office of Scientific Research), Army (Army Research Office), and Navy (Office of Naval Research), under contract F49620-79-C-0178.

This annual report is an updating report; hence it covers the period 1 September 1981 through 31 August 1982. Significant Accomplishments, where applicable, appear in the project reports (section A). In particular, the three most significant accomplishments, as determined by the Director, are summarized as:

i. Project SSM-83-1 - Hot-Electron Injection and Trapping at Si/Insulator Interfaces

We have identified the mechanism of minority carrier generation in the substrate as photo-carrier generation. The photons are generated in the high field region in the transistor channel by hot electron bremsstrahlung radiation. These photons have an average decay length of 780 μm and can cause DRAM refresh time degradation and even logic circuit malfunctions throughout the chip. Furthermore, present techniques such as the use of guard ring (pseudo collector) are ineffective in stopping the photons. The rate of photons emission is found to be $2 \times 10^{-5} I_{sub}/q$.

We have also derived and proven a power law relationship between channel hot-electron gate current and the substrate current. This should significantly simplify the testing for device reliability since the gate current can now be deduced from the measured substrate current, which is larger than gate current by 10^{10}.

ii. Project SSO-83-3 - New Techniques for Wide-Dynamic-Range Signal Processing using Monolithic Integrated Circuit Technology

(a) During the past year we have made considerable progress in research on new methods for the design and implementation of high-frequency switched-capacitor filters for communications. We have designed and fabricated a sixth order bandpass switched capacitor filter with center frequency of 250kHz, bandwidth of 10kHz, and clock rate of 4MHz. The unique circuit approach incorporates fully differential signal paths, identical resonators, and cascode differential CMOS operational amplifiers.

(b) We have devised new topologies for switched capacitor filters in NMOS technology, which utilize positive feedback to overcome the limited gain achievable in NMOS single-stage amplifiers. A sixth order elliptic filter with center frequency at 250kHz was fabricated and tested. The effects of intermodulation at high signal levels in amplifiers of this type are now being investigated.

(c) Our research in high-frequency bipolar monolithic circuits has resulted in the realization of a new monolithic amplifier topology. A number of circuits have been fabricated incorporating unique dual-gate FET structures and giving bandwidths of 50MHz, gain of 66 dB and slew rates of 125v/usec.

iii. Project QE-83-1 - Functional Analysis of Novel Semiconductor Lasers for an Integrated-Optical-Network Viewpoint

We have acheived longitudinal mode stability over an extended temperature range and in the tandem-cavity laser, the amount of internal refelction required to overcome gain variation is only of the order 10^{-3}. The smallness of the reflection means that the internal-reflection scheme should be applicable to most index-guided lasers. Recently, we have extended the concept to lasers involving coupled lateral modes. Not only was single longitudinal-mode operation achieved, but also a temperature range as large as 30°C was observed in which the laser wavelength was locked to one longitudinal mode.

The report contains:

A. 1982-1983 JSEP Projects: as of 31 August 1982

B. Consolidated List of JSEP Published Papers and Memorandums through 31 August 1982

During this time period 1 September 1981 - 31 August 1982, there are currently an additional 23 Journal papers being processed: in press, in review, submitted and being prepared. Further, there have been 11 Conference papers presented (or to be presented).

JOINT SERVICES ELECTRONICS PROGRAM

ANNUAL PROGRESS REPORT (CONTRACT F49620-79-C-0178)

(1 September 1981 - 31 August 1982)

by

D.J. Angelakos

Report No. UCB/ERL 82/1

30 September 1982

ELECTRONICS RESEARCH LABORATORY

College of Engineering
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maximum possible dynamic range in bipolar and MOS analog amplifiers and signal-processing circuits. Our work in this area has focussed initially on methods of achieving maximum dynamic range in switched-capacitor filters. In such devices, the fundamental limit on dynamic range results from thermal noise in the MOS switch transistors used in the filter structure, but monolithic switched-capacitor filters produced to date have not approached this limit because of the dominant effects of flicker noise in the MOS transistors making up the operational amplifiers[2,5]. Our research has resulted in a new differential chopper-stabilized technique which removes this 1/f noise, resulting in experimental fifth-order filter prototypes with dynamic range in excess of 105 dB. This is more than 15 dB higher than previously reported performance obtained from such filters[6]. We expect to continue this work with the objective of exploring the maximum theoretical dynamic ranges achievable, and formulating detailed theories of the noise performance of such filters.

Significant Accomplishments

(1) A new high-frequency bipolar monolithic process has been devised and extensively characterized for both low-frequency and high-frequency parameters. This research has led to new circuit configurations for high-frequency monolithic filters, switches and amplifiers which are currently being fabricated.

(2) A new chopper stabilized differential filtering technique was developed, and a monolithic prototype fabricated. This prototype has been extensively characterized, demonstrating dynamic range and power supply rejection performance well beyond any previously published levels. An extensive theoretical analysis of the sources of noise in switched capacitor filters has been carried out, resulting in a better understanding of the fundamental limitations on dynamic range as a function of energy storage element values. These results have been subsequently applied to the bandpass case, with important conclusions regarding the dynamic range of high-Q bandpass filter structures.

(3) During the past year we have made considerable progress in research on new methods for the design and implementation of high-frequency switched-capacitor filters for communications. We have designed and fabricated a sixth order bandpass switched capacitor filter with center frequency of 250kHz, bandwidth of 10kHz, and clock rate of 4MHz. The unique circuit approach incorporates fully differential signal paths, identical resonators, and cascode differential CMOS operational amplifiers.

(4) We have devised new topologies for switched capacitor filters in NMOS technology, which utilize positive feedback to overcome the limited gain achievable in NMOS single-stage amplifiers. A sixth order elliptic filter with center frequency at 250kHz was fabricated and tested. The effects of intermodulation at high signal levels in amplifiers of this type are now being investigated.

(5) Our research in high-frequency bipolar monolithic circuits has resulted in the realization of a new monolithic amplifier topology. A number of circuits have been fabricated incorporating unique dual-gate FET structures and giving bandwidths of 50MHz, gain of 66 dB and slew rates of 125v/μsec.

A. Publications under JSEP

D. J. Allstot, R. W. Brodersen and P. R. Gray, "MOS switched capacitor ladder filters," IEEE J. Solid-State Circuits, vol. SC-13, no. 6, Dec. 1978, pp. 806-814. Received the 1980 IEEE W. R. G. Baker Prize Paper Award.

S. K. Lui and R. G. Meyer, "High-frequency bipolar-JFET-I^2L process," Digest of Technical Papers, 1980 International Electron Device Conference, Washington, December 1980.

S. K. Lui and R. G. Meyer, "High-frequency bipolar-JFET-I^2L process," IEEE Trans. on Electron Devices, accepted for publication.

K. C. Hsieh and P. R. Gray, "A low-noise chopper stabilized differential switched capacitor filtering technique," Digest of Technical Papers, 1981 International Solid State Circuits Conference, New York, NY, February 1981.

P. R. Gray, R. W. Brodersen, D. A. Hodges, T. Choi, R. Kaneshiro and K. C. Hsieh, "Some practical aspects of switched capacitor filter design," Digest of Technical Papers, 1981 International Symposium on Circuits and Systems, Chicago, April 1981.

K. C. Hsieh, P. R. Gray, D. Senderowicz and D. G. Messerschmitt, "A low-noise switched capacitor filtering technique," IEEE J. Solid-State Circuits, December 1981.

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S. K. Lui and R. G. Meyer, "High frequency-JFET-I^2L process," IEEE Trans. on Electron Devices, vol. ED-29, no. 8, August 1982.

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S. K. Lui, R. G. Meyer and N. Kwan, "An ion-implanted sub-surface monolithic Zener diode," IEEE J. Solid-State Circuits, vol. SC-14, no. 4, August 1979, pp. 782-784.

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Proposed Research Program

The research described above on high-frequency monolithic structures has shown the benefits of combining research in advanced fabrication techniques and new system concepts in a coordinated approach. We propose to continue this research by concentrating on new methods of high-frequency signal processing using high-frequency monolithic structures. Our present work on high-frequency filters will be extended to examine the possibility of filters operating beyond 100 MHz and the process requirements to achieve this end. The initial vehicle will be high-frequency silicon technology, but the results obtained should have implications beyond this to other technologies such as GaAs.

Specific problems to be addressed include choice of optimum circuit configurations and identification of process parameters with maximum impact on ultimate circuit performance. For example, fast settling amplifiers are required and the form of circuit used is closely related to device parameters such as f_T, g_m and parasitic capacitance[7]. These parameters are all process-dependent and it is not yet apparent which of these is the most important. Thus both process research and circuit research are essential parts of the overall program.

During the first year of this program, our understanding of noise mechanisms in switched capacitor filters has greatly improved. We now are able to predict a priori the noise behavior of switched capacitor filters once the device noise parameters are known. We are now extrapolating these results to attempt to draw general conclusions regarding noise limitations in high-Q bandpass switched capacitor filter applications. These filters will become quite important in high frequency communications applications. We are currently fabricating a number of prototypes of such filters which will allow us to compare our theoretical results with experimental observations.

Switched capacitor filters have found wide application in communication systems. However, internally-generated distortion in these circuits is a major limitation on the dynamic range achievable and prevents their implementation in a number of critical applications. At present, no published theory of distortion in switched-capacitor filters exists. The development of such a theory is a first step towards the ultimate realization of switched-capacitor filters with distortion and noise levels below -90 dB at operating signal levels.

We have begun research on this topic and have identified four potential sources of distortion in such filters. Work is proceeding via analytical and computational methods to investigate and characterize the distortion sources and their interaction in the sampled-data environment. A new analytical approach has given some excellent preliminary results in predicting distortion due to capacitive nonlinearities. Since existing CAD tools are inadequate for the simulation of low levels of distortion in sampled-data systems, research is also proceeding in this area. A new computational technique has been devised and implemented which enables the simulation of nonlinear phenomena not previously reported. This has enabled us to investigate the influence of active-circuit parameters on the filter distortion performance. Future work will be directed towards consolidating and extending these results, followed by an investigation of optimum filter topologies for minimum distortion performance.

Another aspect of this research will focus on the problem of dynamic range in high-Q switched capacitor filters. We have determined that from a fundamental standpoint, high-Q switched capacitor filters must suffer in dynamic range relative to lowpass filters of the same bandwidth by a factor equal to the square root of the ratio of the center frequency to the bandwidth. For filters with Q on the order of 100, this is a severe limitation, giving typical dynamic range on the order of 70 dB as opposed to 90 dB for lowpass filters. We propose to study alternate filter architectures which achieve better dynamic range performance. The use of decimation through a cascade of lower Q filters appears to be a promising avenue for achieving better dynamic range.

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University of California, Berkeley · Electronics Research Laboratory

Joint Services Electronics Program September 30, 1982

Work Unit No.: SSD-83-4 Last Year's No.(s): SSD-82-4

Title: Research on Electronic Systems Composed of Polymer Films and Planar Si Devices for Transducer Applications

Senior Principal Investigator(s): D. W. Hess (415) 642-4862
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Scientific Objectives

We propose to investigate the technology for, and the chemical and physical behavior of electronic systems that are composed of polymer-film materials and integrated-circuit devices. The objectives are to define the materials and interface properties and to evaluate the technologies that may ultimately find application in new and improved transducer devices.

Major Task:

Investigate the control of piezoelectric properties in polyvinylidene fluoride and poly-acrylonitrile that can be achieved with plasma-based techniques. The purpose of this effort will be to develop novel methods for the production of piezoelectric polymer thin films directly from monomer sources, thereby eliminating many of the constraints inherent in incorporating such films into solid state devices. This study is based upon current work in our laboratory which demonstrates the feasibility of preparing films of vinyl polymers from monomer sources.

State of the Art

The above task is proposed in order to apply newly developed polymer formation technology[1,2] to poly-vinylidene fluoride, a polymer material that has very interesting and useful piezoelectric properties[3,4], and to poly-acrylonitrile. Plasma polymerization[1,2] techniques have been demonstrated for certain vinyl monomers in bulk condensed phases, but has not been attempted for thin film formation. Our experience with piezoelectric films, particularly with ZnO, has given us a background in exploitation of this property in novel transducers. We expect to show that the plasma polymerization processes can permit tailoring of the piezoelectric activity of the film in order to optimize certain transducer behavior.

Progress to Date

Three important experimental systems have been assembled to characterize piezoelectric polymer films. The first system is a laser interferometer. This interferometer is similar to a Michelson interferometer, but uses optical heterodyning to provide a linear, sensitive output signal capable of detecting 0.1 Angstrom mechanical displacements. Data taken from this system will be used to determine piezoelectric activity of polymer films.

The second experimental system is a multistate Thermally Stimulated Discharge spectrometer[5]. This spectrometer experimentally determines the activation energy of each charge trapping mechanism in addition to giving the amount and type of polarization.

Finally, an apparatus for measuring the pyroelectric properties of polymer films has been developed. A polymer sample is placed in an environmental chamber and the temperature is ramped up or down with respect to time at a fixed rate. The reversible current produced as the temperature is changed is used to calculate one of the pyroelectric coefficients of the sample. It has been shown that pyroelectric activity is often related to piezoelectric activity of the polymer sample[6].

Progress is being made on an improved model that describes the macroscopic behavior of piezoelectric films. The main points of this model are that it is thermodynamically consistant and that the fundamental material properties are defined in sufficiently fundamental quantities that the behavior of the film on a macroscopic level can be related to the microscopic properties of a film which are determined by molecular spectroscopy. To date the model recovers linear piezoelectric theory and clearly points out the assumptions inherent in linear theory.

Significant Accomplishments

Our laboratory now has the analytical tools to measure the piezoelectric, pyroelectric, and charge trapping mechanisms in polymer films.

Update of Current Period

Films of polyvinylidene-fluoride have been plasma deposited directly on silicon wafers previously coated with aluminum electrodes. These films are being analyzed for piezoelectric activity, pyroelectric activity, and charge trapping and polarization using the techniques previously described.

Proposed Research

The overall goal of this research is the investigation of process techniques suitable for the production of piezoelectric polymer transducers with high piezoelectric activity and long-term stability. Plasma polymerization techniques appear to offer a novel fabrication method for forming such films. Ultimately, we intend to develop a predictive model that will be useful in optimizing polymer properties for specific transducer applications.

Molecular dipole orientation is considered a primary factor affecting piezoelectric activity. Physical properties such as polymer length, molecular weight distribution, and the amount of polymer chain crosslinking may all influence dipole orientation. These physical properties can also affect polymer chain relaxation, which may be important in maintaining stable piezoelectric activity.

Plasma polymerization techniques offer the ability to vary a number of processing parameters, e.g., plasma power and duration, monomer concentration, and substrate temperature. It has been found that certain combinations of these processing variables can produce extremely high molecular weight linear polymers with a relatively monodisperse molecular weight distribution[1,2]. Preliminary studies will determine how changes in processing variables affect the physical properties of the polymer films. Once these dependencies are established, polymer films can be produced covering a wide range of physical properties. The polymers will then be further characterized as functions of their piezoelectric activity. In addition to producing polymers with unique physical properties, plasma polymerization techniques offer the distinct advantage of allowing monomer films to polymerize in the presence of an electrical field. This feature will be exploited in an attempt to align molecular dipoles in the monomer films as polymerization proceeds. Such procedures may eliminate the current requirements of stretching and poling operations needed to impart piezoelectric activity to polymer films.

Piezoelectric activity will be determined using the interferometer previously described. This will be done by electrically driving the piezoelectric film with a known voltage and measuring the resulting mechanical movement using the interferometer. In addition to measuring the magnitude of piezoelectric constants, the phase difference between the driving voltage and the resulting mechanical displacement can be used to calculate piezoelectric relaxation as a function of frequency.

Additional analytical techniques will be used to characterize the various polymer films. Molecular and crystalline structure and composition will be investigated using infrared and x-ray spectroscopy. Charge storage mechanisms will be studied using the previously described thermally stimulated discharge system.

Some investigators have concluded that surface polarization and charge carrier injection from the electrodes is important in determining piezoelectricity in polymer films[7]. This hypothesis will be tested by depositing polymer films on silicon substrates and metallizing the opposite side of the polymer film. The capacitance and/or the current in the resulting semiconductor-polymer-metal composite will be measured as a function of applied voltage. Such studies will be used to determine charge conduction mechanisms and interface properties of the piezoelectric polymers.

The model we have developed is based on general continuum mechanics that forms a foundation for describing nonlinear and dissipative materials in thermoelastic systems[8]. We have modified this work to include electrical effects, and plan to continue this work to model nonlinear piezoelectric materials. This work will ultimately be used to help design polymer films optimized to specific transducer applications.

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University of California, Berkeley **Electronics Research Laboratory**

Joint Services Electronics Program **September** 30, 1982

Work Unit No.: QE-83-1 **Last Year's No.(s):** QE-82-1

Title: Functional Analysis of Novel Semiconductor Lasers from an Integrated-Optical-Network Viewpoint

Senior Principal Investigator(s): J. R. Whinnery (415) 642-1030
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University of California, Berkeley — Electronics Research Laboratory

Joint Services Electronics Program — September 30, 1982

III. Basic Research in Quantum Electronics and Optics — Coordinator: Professor S. Schwarz

General

We propose to perform research in quantum electronics in the following areas: (1) novel and complex semiconductor laser radiation sources, and (2) analysis, comparison, and evaluation of novel infrared/millimeter-wave radiation detector systems.

At present, semiconductor lasers, though well-advanced, are still unable to perform efficiently as components in coherent, single-mode optical communication systems. Single-mode operation and tunability are difficult to obtain. In part 1 of this proposal we discuss new methods for solving these problems through the use of structures more advanced than the Fabry-Perot resonators used at present. We expect that the proposed structures will also facilitate combination of several interacting lasers into networks. If successful these ideas may bring about significant increases in the usefulness of semiconductor lasers for a large number of scientific purposes.

Radiation detection in the infrared/millimeter-wave region of the spectrum is important for scientific, astronomical, defense, and communications uses. At present our ability to utilize this portion of the spectrum is rather poor --- at both lower frequencies (microwave) and higher frequencies (optical) technology is much more advanced. One reason for this is that neither conventional microwave nor optical devices lend themselves well to this wavelength region. However, several interesting new devices show considerable promise: these include cryogenic Josephson and SIS junctions, metal-barrier-metal (MBM) junctions, and planar ("surface-oriented") Schottky diodes. Part 2 of this proposal is concerned with comparative development and assessment of these novel devices, as components for detection systems. One expects that some devices will be better-suited to some applications while other devices are better suited to others, but the concept of "well-suited" is not a simple one. It involves tradeoffs between possibly competing advantages such as noise-equivalent power or noise temperature, conversion efficiency, bandwidth, response time, frequency of operation, durability, cost, and compatibility with other components. We propose to continue our comparative study of the principles and potentialities of these new devices. Because in some cases the devices themselves are not well understood or seem susceptible to improvement, the systems research will be supported as necessary by basic physical device studies and efforts at fundamental device improvements. It is hoped that the results will allow us to designate the most promising approaches. We then plan to fabricate and test prototypes of the most promising detection systems, in order to verify our conclusions and bring them to the attention of other scientists who can use them.

Scientific Objectives

We propose to explore and to study novel and complex semiconductor-laser structures for tunability and traveling-wave operation. Theoretical analysis based on scattering-matrix formulation will be carried out to gain insight on possible modes of oscillation in complex laser structures and to guide us in the search for new laser structures. Experimental techniques using LPE and MBE will be developed to fabricate the various structures. Our objectives are (1) to advance the semiconductor-laser technology beyond its present state as an individual coherent optical source, (2) to explore new modes of operation for a semiconductor laser other than the simple Fabry-Perot mode, and (3) to study laser performance when interacting with other lasers or an integrated-optical network.

State of the Art

In recent years important advances in semiconductor lasers have been reported in the attainment of linear light-output versus input-current relation, stable transverse and lateral mode pattern, and single longitudinal mode operation. Equally impressive are achievements in guided-wave optical circuit elements such as directional couplers, filters, switches, isolators and modulators. There is beginning to be some important work in combining the lasers with the waveguide elements, such as the array[1] and coupled multiple stripe[2] work, and the combination of lasers and transistors[3], but most of the work to date has been restricted to the consideration of the individual devices. Much more needs to be done in combining the waveguide networks with the lasers to achieve tuning, mode control and increased power output. A combination of wave and network analysis is required to optimize these interactions.

One major advance in semiconductor-laser technology is the incorporation of two-dimensional waveguiding in the transverse plane of the laser structure. During the past few years, many lasers exhibiting stable transverse and lateral mode pattern and single longitudinal mode operation have been developed at several laboratories. These include the buried-heterostructure (BH) laser[4,5], the channeled-substrate-planar (CSP) laser[6,7], and the laser utilizing thickness variation in the grown layer to provide waveguiding in the lateral direction[8-11]. Among the lasers referenced here are the IRW laser[8], the CJSF laser[8] and the narrow DCC-CSP laser[7] developed and studied in our laboratory. All the lasers mentioned above oscillate in well defined cavity modes in all three directions, transverse, lateral, and longitudinal. This fact facilitates the application of waveguide-network theory to semiconductor lasers and makes possible an analysis of laser structures more complex than the simple Fabry-Perot structure which has been almost exclusively employed in the semiconductor lasers thus far.

In the meantime, remarkable progress has also been made in the fabrication and control of modes in optical waveguides. Low-loss, single-mode waveguides have been reported in GaAs[12] and $LiNbO_3$[13], and active waveguide devices using coupled guides and Y junctions either alone or in the Mach-Zehnder interferometer configuration have been developed. These advances further support our view that single-mode guided-wave technology is ready for the exploration of new and complex semiconductor-laser structures and the development of simple integrated optical systems involving the source and other optical elements.

Although single longitudinal mode behavior has been achieved in most index-guided lasers, this behavior is maintained only for a limited range of temperature. Because the gain-peak wavelength λ_m and the resonance wavelength λ_ℓ for the longitudinal mode change at a different rate as the temperature changes, the laser wavelength hops from one longitudinal mode λ_ℓ to a neighboring one λ_ℓ' as soon as λ_ℓ' becomes closer to λ_m than λ_ℓ. Mode hopping occurs for every 1 to 1.5°C change in temperature for lasers with a longitudinal mode spacing $\Delta\lambda_\ell$ about 3 Å. The transition from λ_ℓ to λ_ℓ' generally takes place within a finite temperature interval about 0.2°C. In the transition region, a laser oscillates at both λ_ℓ and λ_ℓ'. What is even worse is that an unusually large amount of noise is generally observed. This excess noise presents a serious problem in many applications such as audio-disk laser pick-up[14].

The scattering matrix used extensively for microwave networks[15], provides a natural way for studying the interconnection of integrated-optics devices, since these (like microwave networks) are distributed electromagnetic systems with identifiable modes, interacting with input and output ports. Most emphasis in the literature has been on passive junctions[16], but as shown in the papers of the Publication List, we have found it a powerful formulation for studying the combination of lasers and various possible components, including curved guides for which radiation and transmission losses must be minimized[17]. The known theoretical limitations on scattering-matrix parameters tell much about what can or cannot be done with the interconnections.

Progress to Date

Our work on control of mode behavior in semiconductor lasers has come to a successful conclusion. This has resulted in a series of papers which were reported in the last proposal. Now that we have acquired an understanding of how to achieve lateral-mode stability and single longitudinal-mode operation and have developed the capability of fabricating index-guided lasers which oscillate in a well-defined cavity mode, we can continue the new, and perhaps more exciting phase of our research on combining semiconductor-laser technology and waveguide-network techniques (developed for microwaves) for exploration of this relatively unexplored area.

As stated in the last progress report, we have embarked on a new program of study on the use of scattering matrix formulation to analyze the proper modes of several complex laser structures and to explore possible advantages of these lasers. The laser structures investigated include (1) a laser with coupled cavities in tandem, (2) an interferometer laser with a curved branch waveguide attached to a straight Fabry-Perot cavity, and (3) a ring laser with a straight waveguide attached to a circular cavity. The results of the analyses can be found in papers 1 and 2 of the publication list. In the meantime, we have carried out the experiments on the two lasers (1) and (2) mentioned above. The experiments have indeed confirmed our theoretical prediction. The experimental results as well as the theoretical background can be found in papers 3 to 6 of the publication list. A brief summary of the highlights is given below.

As mentioned in the State of the Art section, one serious problem with the Fabry-Perot laser is mode hopping. This problem arises because of lack of mode selectivity of the Fabry-Perot cavity. If a laser is made of two cavities, interference between the fields in the two cavities provides a physical mechanism in mode selection. For both the tandem-cavity laser and the interferometric laser, the longitudinal modes of the composite cavity can be classified into two groups: (1) the coincidence resonance modes (CRM) for which the longitudinal modes of the individual cavities are at resonance simultaneously, and (2) the nonresonant modes (NRM) for which the longitudinal modes of the individual cavities are off their respective cavity resonance. For the CRM's, the threshold gain needed for lasing action is a minimum, and one of the CRM's closest to the gain peak is expected to lase. The CRM's are few in number and thus far apart in wavelength. In between two CRM's lie many NRM's. The coincidence-resonance condition for the tandem-cavity and the interferometric laser provides a built-in selection mechanism for the longitudinal modes.

Insofar as longitudinal mode stability is concerned, the important quantity is the spacing $\Delta\lambda_{CRM}$ between the coincidence resonance modes. Because $\Delta\lambda_{CRM}$ is much larger than the spacing $\Delta\lambda_{\ell}$ between the longitudinal modes in a simple Fabry-Perot laser, longitudinal mode stability can be maintained in the tandem-cavity laser and the interferometric laser over a much larger temperature interval than the simple Fabry-Perot laser. Experimentally, a range at $\Delta T \simeq 7^{o}C$ has been achieved as compared to $\Delta T \simeq 1$ to $1.5^{o}C$ in Fabry-Perot lasers. During this temperature range, the lasing wavelength changes with temperature at a rate of 0.7 $Å/^{o}K$ which is the rate for the resonance condition of CRM governed by d(nL)dT where n is the refractive index and L is the overall length. We believe that the temperature range can be further extended by a proper choice of the relative length of the two cavities.

The coupling of lasers by waveguide networks has been studied in two ways. In the first, there is a coupling connection between laser stripes on a single GaAs chip, similar to that used by Scifres et al.[2]. The laser currently being fabricated has three stripes. The roles of different coupling means, different mechanisms of transverse mode control for the laser, and various spacings are being studied. The second method utilizes external coupling, with the individual stripes coupled to fibers by standard techniques, and those coupled to a mutual fiber through the evanescent fields outside the core. The fibers are positioned by v-grooves, selectively etched in silicon, and the cladding etched away until the desired degree of coupling is obtained. Analysis shows that positioning is fairly critical, but not impossible. The positioning of the etched single-mode fibers is very difficult because of their fragility, but the related work of Digonnet and Shaw on fiber couplers[18] shows that fabrication can be controlled.

Dispersion in integrated optics circuits has been studied in view of the short pulses[19] now being produced by semiconductor lasers. The short distances result in negligible dispersions even for picosecond pulses in most practical circumstances, but there are special circumstances in which this is not the case. The geometrical dispersion of microstrip and coplanar waveguides introduces distortion of picosecond pulses in a few millimeters[22], and material dispersion for semiconductors waveguides operating near the band edges may also be an issue.

Publications Under Combined Sponsorship

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Significant Accomplishments

As reported in papers 3-6 in the publication list and summarized in the Progress-to-Date section, we have achieved longitudinal mode stability over an extended temperature range. In the tandem-cavity laser, the amount of internal reflection required to overcome gain variation is only of the order 10^{-3}. The smallness of the reflection means that the internal-reflection scheme should be applicable to most index-guided lasers. Recently, we have extended the concept to lasers involving coupled lateral modes. Not only was single longitudinal-mode operation achieved, but also a temperature range as large as 30°C was observed in which the laser wavelength was locked to one longitudinal mode.

Proposed Research Program

As discussed in the State of the Art review, in order to explore new applications for semiconductor lasers and to extend microwave techniques to guided-wave optics, it becomes necessary that we study lasers with complex structures for performing functions other than merely providing coherent radiation. Furthermore, since a laser is only a part of an optical system in practical applications, analytical methods must be developed so that the laser performance can be analyzed in the frame of an optical network.

In spite of the progress made in improving the performance of semiconductor lasers, tunability of the laser wavelength has not been achieved. We propose that the tandem-cavity laser and the interferometric laser be studied for wavelength tunability and controlled wavelength switching. An estimate based on the electrooptic coefficient in GaAs indicates that a tunable range for the laser wavelength in the neighborhood of 3Å should be possible. For wavelength switching, the range should be much larger, probably on the order of 50 to 100Å.

Besides tunable lasers, another subject of considerable interest and practical importance involves lasers with built-in mode coupling to provide wavelength stability. Our work on the tandem-cavity laser and the interferometric laser has shown that the interference between the longitudinal modes of two coupled cavities can be used to advantage in wavelength stabilization. A coupled-cavity laser automatically selects a wavelength at which the fields in the coupled cavities interfere constructively. We propose that the work on the tandem-cavity laser be continued to establish a design criterion for the laser. At the same time, we plan to apply the concept of coupled modes to lateral modes. Preliminary results are very encouraging. As reported earlier, a stable-wavelength temperature range as large as 30°C has been observed. We propose that work on coupled-lateral-mode lasers be continued. Theoretical studies on the behavior of the laser are in progress for comparison with the experiment.

Another subject which we are currently investigating concerns the possibility of operating a semiconductor laser in a traveling-wave mode instead of a standing-wave mode as in the conventional Fabry-Perot laser. As mentioned in the Progress to Date report, we have analyzed various possible combinations of the circular and straight guides, and found one particular combination very promising. One obvious, and potentially important, advantage is the possibility to minimize the effect of optical feedback on the dominant circulating mode. Such feedback has been the cause for induced pulsation in semiconductor lasers when coupled to an optical fiber. We propose that our present work on the traveling-wave laser be continued. We select the curved inverted-ridge (IR) waveguide for the experimental ring laser structure for two reasons. It can be fabricated by growth over an etched channel, with which we are familiar in fabricating straight IR waveguides. Second it is possible to incorporate reversed biased p-n junction in the laser structure for double current confinement as we did in the DCC-CSP laser. However, for a circular cavity, the index difference must be large enough in order to keep the radiation loss small. This is an important design consideration which needs further work for its implementation.

The work on coupled semiconductor lasers for phase control, power combining and tuning will be continued with coupling introduced both on the laser chip, and externally. For the former method, evanescent coupling between laser stripes will be compared with direct connections between the stripes by various methods. The optimum coupling for phase locking without introducing undesirable relaxation oscillations will be investigated[21]. The work on external coupling will presently concentrate on the continuation of fiber couplings described under "Progress to Date," but will also consider coupling through a series of Y junctions in lithium-niobate guides. since the design of these is well worked out.

The work on dispersion will extend the current work on the microstrip configuration[20] to the coplanar configuration also[23]. Work so far has been on the geometric dispersion resulting from coupling to substrate modes, but loss dispersion, and the effect of material dispersion for guides operating near the band edge will be investigated.

Interaction with Other Work Unit

Frequent consultation is anticipated with the work unit on electromagnetics concerning wave propagation in dielectric waveguides.

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University of California, Berkeley — **Electronics Research Laboratory**

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Work Unit No.: QE-33-2 — **Last Year's No.(s):** QE-32-2

Title: Millimeter and Infrared Heterodyne Mixing and Detection

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Scientific Objective

In this project we propose a study of radiation detection systems involving direct detection and superheterodyne mixing techniques using various nonlinear devices for mixers and detectors. The wavelength range of interest is the entire band of frequencies from millimeter through far infrared, that is, 10 mm to 10 microns wavelength. It is of particular interest to understand which techniques are favored - - in the framework of realistic receiver systems - - for application in various parts of the frequency range. The investigation will involve coupling of radiation to devices with impedance matching, selection of the best devices and obtaining their characteristic parameters, and a study of optimal coupling to intermediate-frequency amplifiers. Objectives include low-noise receiver performance, plus other advantages such as wideband response and, for some devices, room-temperature operation. The novel devices in question (being developed partially under other sponsorship) include planar Schottky diodes, super-Schottky diodes, cryogenic SIS and Josephson junctions, metal-barrier-metal diodes, and novel configurations of other, more convenient detectors. Attention will be given to principles of coupling to multiple-device arrays.

State of the Art

The noise temperatures of mixer-IF amplifier combinations have been surveyed for the frequency range 1 GHz (wavelengths of 30 cm to 0.3 cm) [1]. Room temperature mixers are usually Schottky diodes in this range and their best noise properties are typified by a measurement by Kerr [2] at 100 GHz; assuming an IF amplifier with a 15° K noise temperature, the single-band noise temperature for the mixer-IF amplifier combination is about 550° K. Equivalently, this is a minimum detectable power of 0.76×10^{-20} W/Hz. That value was then further reduced by nearly a factor of two by cooling the diode (essentially the same results are achieved at T = 18° K or T = 77° K).

To achieve large reductions of noise temperature for frequencies in the several-millimeter wavelength range, superconductive devices must be used. There are two general categories. In one, the Josephson effects are employed, and in the other, the nonlinearity that comes with single-particle tunneling in superconductors. The best results obtained with Josephson devices have mixer noise temperatures in the range of 20-50 times the liquid-helium bath temperature with conversion efficiencies in the range of 0.5-1.4. Mixer noise temperature of 54° K with conversion efficiency of 1.4 at 36 GHz [3], and 140° K with conversion gain of 2.4 at 140 GHz [4] have been achieved. Opinion now is that the Josephson devices have too much noise down-converted into the IF range by beating of the RF noise with the many harmonics of the LO signal and the Josephson oscillations. Still, Taur estimates from detailed computer calculations that a receiver noise temperature of 70° K should be achievable for a SSB receiver at 100 GHz, assuming an IF amplifier with a 20° K noise temperature [5].

Considerable emphasis is now being placed on the "quasiparticle" (single particle) tunneling devices, also known as NIS and SIS junctions. This has grown out of the realization that very strong nonlinearities of the I-V characteristic are available for classical resistive mixing through the use of devices that function at millivolt levels where a sharp change of slope results from the existence of the superconducting energy gap. The experimental work has been further inspired by the quantum-mechanical analysis of Tucker [6] showing that an SIS mixer can be expected to give quantum-limited detection sensitivities at high frequencies (> 70 GHz). It has also shown that conversion gain can be expected from these devices. The earliest of the quasiparticle devices was the super-Schottky diode, which is a Schottky diode with the metal electrode replaced by a superconductor. These showed the best diode noise temperature ever seen at 10 GHz [8]. In the usual configuration, the series resistance leads to a parasitic conversion loss which increases strongly with frequency so that usefulness of the device is limited to wavelengths longer than several millimeters. In the normal metal-insulator-superconductor NIS tunneling device, the Schottky barrier is replaced by that of the insulator, and the series resistance is largely eliminated. The same applies in the case of the superconductor-insulator-superconductor SIS junction; in this device, the nonlinearity is stronger but it also has Josephson current which can add noise. Results to date on the SIS and NIS junctions have been excellent [9]. Experiments with SIS junctions at 36 GHz have demonstrated the predicted conversion efficiency. The single-sideband value of 0.7 (or 1.4 in DSB) is greater than can be expected from classical mixing theory. The mixer noise temperature of 3° K (SSB) is very close to the photon noise limit $h\nu/k_b$ = 1.7° K. These experiments were done with lead-alloy oxide-barrier-junctions. It would be advantageous to use a more rugged system such as niobium on thin silicon membranes.

The highest frequency at which the quasiparticle mixers have been reported is 115 GHz where a conversion efficiency of 0.2 and a mixer noise temperature of less than about 80° K were deduced from a receiver noise temperature of 470° K. One part of our work is aimed at making an antenna-coupled mixer at one millimeter wavelength; the first measurements will be at 70 GHz. Carrying the advantages of these devices to the submillimeter wavelength range is a large and important task.

At wavelengths near 10 microns, extrinsic and intrinsic photoconductive and photovoltaic detectors can be used as mixers. Minimum detectable power near the quantum limit (about 10^{-20} watt for 1 Hz bandwidth) has been demonstrated [9,10]. Although results have been impressive, it is difficult to obtain IF bandwidths much larger than 1 GHz with such mixers. Moreover, they all require refrigeration, at least to 77° K. As one goes toward longer wavelengths, mixers are more difficult to make. A detectable power of 3×10^{-16} W at 119 μm using an extrinsic Si mixer at 2° K has been reported [11]; in another experiment with an extrinsic GaAs mixer at 4° K, a detectable power of 10^{-14} watt was reported at 337 μm [12].

In principle, one should be able to do much better than this at wavelengths around 0.1 mm, using resistive diode mixers at room temperature. Minimum detectable powers on the order of kTB, or 4×10^{-21} watt/Hz, are theoretically possible. But results achieved to date fall short of theoretical limits: with Schottky diodes, for example, room-temperature detectable powers of 10^{-9}, 10^{-12}, and 5×10^{-15} W/Hz at 118, 170 and 337 microns, respectively [13,14]. One experiment has also been deposited and coupling is through the wall.

A thorough study of the dependence on doping level of the etch rate of boron-doped silicon in ethylenediamine-pyrocatechol-water has been completed and the work has been submitted for publication.

Quasiparticle SIS mixers for the millimeter range are also being developed. Here our approach has centered on unifying the SIS junction with an antenna structure, the latter to provide efficient coupling. A typical design consists of a sandwich-type vee antenna with four SIS junctions in series at its terminals. Performance approaching theoretical quantum limits is expected near 70 GHz. At higher frequencies the capacitance of the junctions becomes a problem, and a novel method has been developed to tune reactance out (see proposal). With this scheme it should be possible to use the antenna-coupled SIS at frequencies up to 300 GHz. This work is continuing.

In order to test receivers near this higher frequency, a 230 GHz isotopic methyl fluoride laser has been constructed. The CO_2 pump laser is now working well and the FIR laser itself is being perfected.

This JSEP grant has supported some exploratory research with planar Schottky diodes. The design of these diodes has been developed and analyzed. Considered as video detectors, these diodes are expected to have NEP higher than that of non-planar diodes by a factor of about ten. This drawback is compensated by the greater ruggedness and integrability of the planar diodes. Practical development is now being carried on further under non-JSEP support.

We have shown that efficient coupling of radiation at 36 GHz into thin film metal-barrier-metal junctions can occur. Sensitivities within a factor of about three to five of Schottky barrier junctions can be obtained for direct detection at 36 GHz. The noise was 1/f limited up to a few tens of megahertz when a bias was applied. The characteristics of this noise spectrum are attributable to impurity noise and can possibly be alleviated by better fabrication of the barrier material. In the absence of the 1/f spectrum (high frequency or zero bias), the noise was Johnson or shot in nature.

Heterodyne detection at 36 GHz and harmonic mixing using a 72 GHz signal were also performed. Conversion losses were respectively about ten to twenty db greater than that reported for commercially available detectors. However, an optimum design for the harmonic mixing experiment was not used.

These experiments, the results of which are described in detail elsewhere [15], provide strong evidence that the metal-barrier-metal structure would be superior to Schottky barriers at higher frequencies: frequencies above which the spreading resistance results in inferior performance for the Schottky devices. We have thus initiated a study of the fundamental characteristics of metal-barrier-metal junction structures at shorter wavelengths.

An initial experiment [16] has demonstrated the coupling of 118 μm radiation to an edge metal-barrier-metal structure situated at the center of an eleven wavelength antenna. Although the sensitivity of detection was not high, the coupling principles first suggested by Hwang et al. [17] were established for M-B-M junctions. The edge structure for the junction [18] had an area of $\approx 10^{-10}$ cm^2 which is comparable to a point contact junction. Thus the RC time constant corresponded to a wavelength much shorter than 118 μm. This initial detection experiment established that coupling to planar junctions is possible and that fundamental investigations of a variety of mixing and detection experiments at shorter wavelengths are possible. Recently a more sophisticated coupling structure has been incorporated. This involves the chemical etching of a silicon substrate at an angle to form a prismatic coupling element along the edge of the substrate. The linear antenna structure of the tunneling junctions are then fabricated on the substrate such that the primary lobes are directed into the substrate and through the etched edge forming the prism. These lobes should have enhanced gain since those directed directly into free space from the antenna should be suppressed by the phase matching criteria.

Publications

The following papers acknowledged partial or total JSEP support:

(1) "Characteristics of Integrated MOM Junctions at D.C. and at Optical Frequencies," IEEE Jour. Quantum Elec., QE-14, 159 (1978).

(2) "Electronic Resonance of CARS," Phys. Rev., 18 (1978).

(3) "Photo-Induced Currents in Metal-Barrier-Metal Junctions," Radiation Energy Conversion in Space, ed. by K. W. Billman, 1978. (Vol. 61 of Progress in Astronautics and Aeronautics Series.)

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(5) "Small Area Metal-Oxide-Metal Junctions as Picosecond Photoemissive Detectors," in Picosecond Phenomena, Springer Series in Chemical Physics, vol. 4 (ed. by C. V. Shank, E. P. Ippen, and S. L. Shapiro).

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(8) "A Phototransistor with Concentric Electrodes on the Si Substrate," IEEE Electron Device Letters, EDL-2, 200 (1981).

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(11) "Fabrication of Thin Film Screen Below 1000 Å, Proc. Symposium on Josephson Junctions, Saitama, Japan, February 1982.

(12) "(100) Silicon Etch-Rate Dependence on Boron Concentration in Ethylenediamine-Pyrocatechol-Water Solutions," submitted for publication.

(13) "Planar Multimode Detector Arrays for Infrared and Millimeter-Wave Applications," IEEE J. Quantum Electronics, QE-17, 407-414 (March 1981).

(14) "Monolithic Integration of a Dielectric Millimeter-Wave Antenna and Mixer Diode: An Embryonic Millimeter-Wave IC," IEEE Trans. Microwave Theory and Technioues, (August 1982).

(15) "Antennas and Waveguides for Far-Infrared Integrated Circuits," IEEE J. Quantum Electronics, QE-16, 508-516 (May 1980).

The following doctoral theses were completed by students receiving support from JSEP:

"Characteristics of Metal-Oxide-Metal Devices," Moriehai Heiblum. The abstract is as follows:

In the past ten years, metal-oxide-metal (MOM) devices, in their point-contact configuration, have been used for harmonic-, sum- and difference-generation at frequencies up to the near infrared, as well as for detection of visible radiation.

Because of the lack of mechanical stability of point-contact configuration, planar MOM devices are desirable. Earlier efforts, however, have resulted in devices with undesirably large area. In this work I report a new integrated device with area comparable to that of the point-contact configuration ($\sim 10^{-10}$ cm^2), which we name "Edge MOM." Fabrication methods and detection characteristics at DC and at 10.6, 3.39, and 0.6328 μm are described. A detailed description of the Edge MOM junction and its behavior under the influence of impinging radiation is given.

An extension of the MOM to an MOMOM is suggested in part two of the work. The suggested MOMOM has the theoretical capability of amplifying optical signals.

In order to find the limitations of the MOMOM, hot-electron devices such as: MOM-vacuum-metal, MOM-semiconductor, and MOMOM are theoretically investigated. As a result a proposed structure with effective interaction area $(10^{-10}-10^{-8})$cm^2 and oxide thickness on the order of 10 A is proposed, which might have a transfer ratio of 0.3 - 0.5.

Different coupling mechanisms such as: wave-guiding, antenna, and surface-plasmon coupling are looked into and frequency limitations are estimated.

"Metal-Barrier-Metal Junctions for Millimeter Wave Mixing and Detection," Charles William Slayman. This thesis has the following abstract:

Metal-barrier-metal (MBM) junctions were used to mix and detect millimeter wave radiation. The MBM junctions used in this work were of the stable thin film type with areas of roughly 1 μm x 1 μm and fabricated using conventional photolithographic techniques.

The devices tested were predominantly of the Ni-NiO-Ni variety.

A brief review of 1) the theory of the nonlinear current vs. voltage (I-V) characteristic of the MBM, 2) the equivalent circuit of the device, and 3) the processing steps used to fabricate the Ni-NiO-Ni junctions is presented. Devices of different impedances were produced by varying the processing procedure. The I-V characteristic, dynamic resistance R_{dyn}, and nonlinearity I"/I' were measured for the different devices. It was found that the nonlinearity was not dependent on the processing parameters. The low temperature (77° K) characteristics of an $Al-Al_2O_3-Ni$ and a Ni-NiO-Ni junction were measured. Between 4.2° K and 77° K, the I-V characteristic of the Ni-NiO-Ni junction did not change.

A brief introduction to the possible noise mechanisms in MBM junctions is presented. Any two terminal device (both of whose electrodes obey Fermi-Dirac statistics) that displays shot noise under bias will display shot noise at zero bias equivalent to the thermal noise of a resistor. This fact was experimentally observed in a 940Ω Ni-NiO-Ni junction. Under bias, however, the device displayed a $1/f^{1.1}$ noise spectrum up to 100 kHz and the RMS noise current was found to be proportional to the bias current and not the square root of the bias current.

Detection experiments were performed at 36 GHz with Ni-NiO-Ni junctions ranging from 180 Ω to 12.3 Ω. The detected signal saturated at power levels above 10 μW. The millimeter wave response was studied under short pulse (60 ns) and long pulse (6 μs) conditions for a normal and a burned Ni-NiO-Ni device. The sensitivity of the junction was found to increase threefold at 77° K. A comparison of the performance of the various Ni-NiO-Ni junctions to point contact MBMs and commercial Schottky detectors is made.

Fundamental mixing between two 36 GHz klystrons and harmonic mixing between a 36 GHz klystron and a 73 GHz klystron was performed using various Ni-NiO-Ni junctions. Mixer conversion loss and noise temperature were studied as a function of bias and local oscillator (LO) drive. Though the Ni-NiO-Ni diodes are not as sensitive as Schottky mixers and detectors, different MBM systems might ultimately prove to be more nonlinear.

"High-Speed Photodetectors with Interdigital Mesa Structures on Si Surfaces," Dennis Cheng-wei Chen. This thesis has the following abstract:

Silicon photodetectors were fabricated to convert incident optical radiation into electrical signals. The symmetrical lateral photodetectors devised and studied in this work were made over interdigital mesa structures with areas of 0.5 mm x 0.5 mm using the anisotropic-etching technique.

A brief review of the fundamentals of junction photodetectors is first presented. Concept of the lateral pnp photodetector is then introduced. Detectors with different dimensions were fabricated. The I-V curves were examined and exhibited phototransistor characteristics. Pulsed-light responses were measured with various laser sources. Rise time and FWHM (full width at half maximum) of the impulse response were observed to be 100 ps and 190 ps, respectively. The noise characteristics are also studied.

Finally, the avalanche breakdown mechanism was included to realize an avalanche phototransistor. Characteristics of this novel device were measured and are discussed.

Compatibility with the existing monolithic planar processing makes these detectors interesting for optoelectronic applications.

"Submillimeter Integrated-Circuit Antennas and Detectors," David B. Rutledge. This thesis has the following abstract:

Integrated-circuit techniques promise to make possible reliable submillimeter devices and arrays. This thesis discusses three different integrated-circuit antennas. The first is an evaporated V-antenna in a sandwich of crystal-quartz substrates. This was the first evaporated submillimeter antenna to have a predictable pattern, and it has been successfully tested in a plasma interferometer at 119 µm. The second is a dielectric-waveguide antenna, made by anisotropic etching of silicon. This antenna has been integrated with a Schottky diode. The final antenna is a multimode, tunable array of 400 microbolometers. This approach gives efficient coupling between a source and the detectors. The array achieves a D of $2 \times 10^8 cmHz^{1/2} W^{-1}$ at 1.4 mm with a modulation frequency of 1 MHz.

Significant Accomplishments

We have gained an improved understanding of the processes involved in the fabrication, by the two-step etching procedure, of silicon membrane Josephson devices. Successful devices have been made and tested.

A technique was developed for formation of silicon walls 1.0 µm high and < 0.1 µm thick by preferential etching. These are being made for super-Schottky diodes and Josephson junctions.

The ethylenediamine-pyrocatechol-water etchant is used to form thin membranes of silicon having controlled thickness. We have carefully measured etch rate vs. boron doping as an aid to thickness control.

A new approach to tunable quasiparticle mixers has been devised. The novel features of this design are (a) use of an integral planar antenna to improve coupling, and (b) use of an electrically-tunable variable reactance to cancel device capacitance. The SIS junctions have now been fabricated and testing is ready to begin.

The usefulness of metal-barrier-metal junctions as millimeter-wave mixers has been demonstrated experimentally. Results indicate that their mixer noise temperatures are comparable to those of Schottky diodes, although conversion efficiency is less.

Working tunneling junctions have been fabricated on Si substrates with prismatic coupling structures incorporated. A co-planar strip line has also been fabricated to couple microwave i.f. (20 GHz) from the tunneling junction to semi-rigid co-axial cable and into a microwave spectrum analyzer. The co-planar structure matches the microwave i.f. system to the tunneling junction.

Research efforts relating to the development of such tunneling junctions in a planar configuration have also contributed significantly to the development of planar configurations of conventional photodetectors, and also the incorporation of tunneling junctions into such detectors to limit the dark current. This effort has acknowledged partial JSEP support.

A study of dielectric waveguides as components for millimeter-wave systems has been completed and submitted for publication.

Proposed Research Program

Research on the use of the phenomena of superconductivity in the proposed work for detection and mixing will take three paths. Microfabrication of the silicon-coupled structures will continue in order to improve the control of their electrical characteristics. A new coupling concept in the form of a microstrip-type of electrode arrangement to minimize the effect of the capacitance of the substrate will be evaluated. Devices will be tested as mixers at 36 GHz and 90 GHz to prove the assertion of reduced parasitics. This will give a guide to the frequency limitations of this type of structure so we can evaluate whether it can be used in the submillimeter-wavelength range. The choices of metals will be such as to realize both Josephson and super-Schottky behavior. The superconductor used will, at first, continue to be the lead-indium alloy. One of the virtues of the silicon membrane barriers is that high-T_c materials should make satisfactory electrodes, thus making it possible to fabricate rugged mixers that can operate in the temperature range where small simple refrigerators are available. Thus the use of such other materials will be studied to see if there are unexpected phenomena.

Super-Schottky and Josephson devices made using a thin vertical membrane as the coupling agent between two sections of a superconducting strip will also be tested as a detector and mixer at 90 GHz.

A theoretical model of the semiconductor barrier Josephson junction will be developed. We have already partially evaluated one proposed model and find that important aspects of the electrical properties are not described. The new work will make use of the phase-slip model that has had success in describing other simpler types of Josephson junctions. The extra complications in the semiconductor barrier structure are that it is physically inhomogeneous, having Schottky barriers at each of the interfaces of the semiconductor with the superconductors and a degenerate region between them.

We also plan to continue with studies of quasiparticle mixers for the 70-300 GHz range. The design we are pursuing, developed conceptually during the last reporting period, will now be described. A planar vee antenna is deposited on a quartz substrate [17]. At its terminals we construct four lead-indium SIS junctions in series. (Four are used to increase impedance, so it approximately matches the antenna source impedance.) A parallel-conductor transmission line (nearly lossless because it is made of superconductor) is constructed in parallel with the set of junctions. At the other end of this line is a larger SIS junction dc biased with an adjustable current less than the critical current. This junction acts as an inductor, whose reactance can be varied by varying the current. This reactance is transformed by the transmission line, and the transformed reactance appears in parallel with the mixer diodes. By adjusting the dc bias current and choosing the size of the tuning junction and length of the transmission line, we expect that the capacitance of the mixer junctions can be canceled. This will allow us to use the SIS mixer at frequencies higher than has been possible until now. If the new design approach is successful it should find important uses, especially in astronomy. Observations of new phenomena should also be possible. In particular, the predicted quantum effects of Tucker [6] should only become observable at frequencies above 100 GHz; our technique for canceling capacitance should allow such observations to be made.

A considerable amount of information has been obtained by investigation of the detection characteristics of metal-barrier-metal junction structures. This includes the recent work involving 36 GHz detection [15] using waveguide coupling as well as 118 µm detection utilizing quasi-optical coupling [16]. The 36 GHz work demonstrated virtually 100% coupling of the incident radiation. It also provided verification of detection based upon rectification by the current-voltage characteristic of the junction. The 118 µm detection demonstrated that antenna theory can be applied to the quasi-optical coupling and that slowing of the guided mode along the antenna occurs and must be considered, as pointed out by Hwang et al. [17].

The detection and mixing characteristics of metal-barrier-metal structures are expected to be superior to other devices at shorter wavelengths. In addition, fundamental characteristics of such microstructures should be investigated at high frequencies to avoid thermally induced signals or other low frequency signals which could mask the tunneling signal. Nontheless, thermal effects should be minimized since both the tunneling characteristics and antenna coupling characteristics can change, the latter through substrate loss primarily. Thus proper choice of the substrate is important as well as electrode shapes which maximize conduction of heat away from the junction.

To observe the high frequency characteristics a convenient choice is an investigation of harmonic mixing utilizing the 28 µm output of a water vapor laser and the 9.3 µm band output of a CO_2 laser. The IF frequency is in the 20 GHz frequency range and can be detected directly with a high frequency spectrum analyzer. All of the experimental apparatus to do this experiment is in hand. In addition, such a harmonic mixing experiment has been accomplished with point contact metal-barrier-metal structures [19]. It can be argued that this was a direct demonstration that currents flowed across the junction at a frequency corresponding to 9.3 µm and consequently established the fundamental requirement for lumped components at near infrared wavelengths. No similar mixing has been accomplished with planar fabricated metal-barrier-metal junction structures, primarily because of the coupling and thermal aspects.

We wish to initially use the quasi-optical prismatic coupling scheme which we have developed and described in previous sections. Detailed coupling characteristics and signals expected are to be calculated. An approximate estimate of the signal expected has already been made and indicates that the experiment is feasible.

Thus far we have been pursuing the microfabrication of edge M-B-M's on a silicon substrate as detailed in the previous two sections. We plan in the near term to demonstrate direct detection at 28 μm and 9.3 μm utilizing such junction structures. Electron lithography will be considered for the fabrication of edge junctions with a smaller area (and therefore a smaller RC time constant) for the detection at 9.3 μm. Subsequent to the direct detection experiments, the harmonic mixing experiment will be attempted. Of primary interest is the behavior of the IF signal detected as a function of both the bias across the junction structure and the angles at which the radiation at 28 and 9.3 μm are incident.

The results of the mixing experiment will provide a measurement of the coupling characteristics and fundamental knowledge concerning the basic phenomena responsible for the high frequency voltage-current characteristics of the tunneling mixing devices. It is possible that improved nonlinearity could allow quantum effects to be observed [16,19,20]. We plan to investigate a variety of junctions expected to have improved nonlinear characteristics for both direct detection and heterodyne mixing. We are also interested in other antenna configurations which have the potential to improve coupling. The geometry of the junctions also lend themselves to possible enhancement of the radiation field in the region of the junction structure by the fabrication of various types of resonant structures at both 9.3 and 28 microns.

The motivation to improve the tunneling and coupling characteristics and to enhance the fields in the region of the junction are expected to result in new microstructure approaches to radiative interactions with solids. The efforts have also stimulated a considerable effort in related areas such as picosecond detectors in various microfabricated devices.

Triode-like M-B-M-B-M structures have been considered in some of our earlier work as potential amplifiers or oscillators at millimeter frequencies or higher. Such devices still appear to have promise, and althou they will not occupy a major portion of our attention under this contract, we plan to continue exploratoiy studies insofar as they are related to the work proposed above.

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University of California, Berkeley **Electronics Research Laboratory**

Joint Services Electronics Program September 30, 1982

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Title: Large-Scale and Nonlinear Circuits Study

Senior Principal Investigator(s): L. O. Chua (415) 642-3209
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University of California, Berkeley Electronics Research Laboratory

Joint Services Electronics Program September 30, 1982

IV. Basic Research in Information Systems Coordinator: Professor C.A. Desoer

General

About twenty years ago, the unity of the basic concepts and techniques underpinning the fundamental study of circuits, control systems and communication systems became apparent and became known as system theory. With rapidly increasing power and decreasing cost of computing, these concepts and techniques were applied to larger and larger systems. This commonaltiy of basic theoretical tools and approaches still exists today and as the size of the system under study increases, the nature of the problem changes.

These features are particularly apparent in the first pair of topics which cover respectively large circuits and large control systems. In each of these topics we see a fundamental interweaving of decomposition techniques -- such as diakoptic analysis, graphic decomposition by strongly connected components and minimum essential sets, and decentralized control by creation of a hierarchy --, modeling techniques -- piecewise linear and spline approximations -- and analytical techniques.

The third topic is a bold project aimed at stepping out of the by-now-traditional use of simulation for computer-aided electronic circuit design and reaching for a more sophisticated level where the simulation is coupled with up-to-date optimization algorithms to direct the design toward a minimum of a previously chosen objective function or towards the display of a trade-off curve (or surface), so that the engineer, using additional data not present in the mathematical formulation, can choose what he deems to be optimum. A significant feature of the optimization algorithm is that inequality constraints may easily be imposed, a fact which we consider crucial in engineering design.

To anyone who studies these three proposals it is clear that in the course of the work there will be ample opportunities for interaction and cross-fertilization, both through normal informal contacts and through regular seminars.

Scientific Objective

Our objective is to continue our research efforts on large scale and nonlinear circuits which were initiated several years ago. The many tools and results that we have developed so far continue to serve as a foundation for our future research and will be used to attack several interrelated fundamental problems in this relatively unexplored but important area.

State of the Art

Network theory played a major role from the early 40's to the 60's in the development of the present day communication systems. The main thrust of network theory then was directed at the analysis and synthesis of linear circuits which can be characterized by a relatively small number of differential equations. Although in recent years many authors have published papers on nonlinear circuits and large-scale networks, the extent of the development of large-scale nonlinear circuits, both in theory and applications, is nowhere near the kind of maturity in classical network theory. The advances during the past decade in elecronic devices and integrated circuits, coupled with the immense impact of computers on circuit analysis and design, have drastically changed the nature of the problems faced by circuit theorists. While anlysis of circuits is still the key problem, it is more difficult in view of the size and complexity of the circuit and the inherent nonlinearity which exists in most electronic devices. Furthermore, the scope and significance of "circuit analysis" has been much broadened. Theory and techniques developed from large-scale networks and nonlinear circuit analysis can often be used in other types of large-scale network and system problems; for example, computer networks, power networks and complex control systems.

It should be noted that because of the size and complexity of LSI and VLSI, the objectives and approaches in analysis are considerably different from those of the classical network theory. First, computation becomes a key element in the study of any large circuit or system. The development of efficient algorithms is crucial. While theoretical results are essential, often one must also depend on heuristics. Second, the study of the structure of a large circuit and the property of interconnection is important. Frequently, large problems need to be divided into smaller sub-problems in order to facilitate analysis, data storage and computation. Third, design is usually accomplished by experience as a first step and improved on by repeated analysis. Fourth, such problems as reliability study, tolerance analysis, diagnosis and testing are important and should be kept in mind in the overall design process. The last item constitutes a new area of research which was not a part of classical network theory. All these indicate that there exist a large variety of problems of a circuit-theoretic nature which need to be studied.

Progress and Publications Since Last Major Proposal

The following is a summary of research progress in the area of nonlinear and large-scale networks which were published since the last major proposal.

1. Research Progress on Piecewise-Linear Analysis and Piecewise-Linear Algebra

Piecewise-linear techniques have been used extensively in circuits and systems theory to model dc nonlinear characteristics of electronic devices, and to study a large class of nonlinear resistive networks. In 1977, Chua and Kang introduced new analytical representations for one-dimensional piecewise-linear functions[1]. This piecewise-linear representation was subsequently generalized to the multi-dimensional case: it is applicable for any m-dimensional piecewise-linear function which is affine over convex polyhedral regions bounded by linear partitions[2]. This generalization results in a tremendous amount of data compression, thereby allowing large-scale piecewise-linear equations to be stored in significantly less computer memory space. Application of this result to the modeling and analysis of large-scale networks is presently under investigation.

A new algorithm has recently been developed for solving piece-wise-linear equations of nonlinear electronic circuits.* Unlike other methods, this algorithm guarantees that all solutions will be found in a finite number of steps. The method depends crucially on the above cited development which allows a multi-dimensional piecewise-linear function to be represented in a closed canonical form. This highly compact representation requires only a minimum amount of computer storage and is responsible for the efficiency of the algorithm

Although motivated originally by analysis problems, the piecewise-linear representation in reference 2 led naturally to important applications in nonlinear circuit synthesis. In particular, systematic methods for synthesizing nonlinear networks having a prescribed scalar or multidimensional piecewise-linear function have been developed[3]. In the scalar case, precision active-circuit building blocks using operational amplifiers, transistors, diodes, and resistors have been derived for realizing piecewise-linear driving point and transfer characteristic plots. In the multidimensional case, methods have also been obtained for realizing a multiterminal nonlinear network having a multidimensional piecewise-linear transfer function. Moreover, these methods have been generalized by synthesizing nonlinear n-ports having a prescribed multidimensional piecewise-linear driving-point function. Although most of the basic building blocks are grounded active networks, converter networks have been developed for transforming such grounded networks into floating networks having the same properties. By slight modifications of these converter networks, other useful conversion properties have also been developed.

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*L. O. Chua and Robin L-P. Ying, "Finding all solutions of piecewise-linear equations," ERL Memo UCB/ERL M81/54, 23 July 1981.

More recently, this multidimensional piecewise-linear representation has led to the partial resolution of a heretofore unsolved conjecture first posed in 1978[4]. In a recent paper[5],* we have proved that every reciprocal n-port resistor represented by our n-dimensional piecewise-linear function is realizable by a nonliner circuit containing only 2-terminal piecewise-linear i resistors and a reciprocal linear element, such as a (p+q)-port transformer. This result thereby resolves one of the many fundamental questions raised in reference 6. In particular, we have proved the following:

Theorem 1. n-port Reciprocity Criteria

A piecewise-linear n-port described by

$$i_1 = a_1 + b_1 v_1 + \dots + b_{1n} v_n + \sum_{k=1}^{m_1} g_{1k} | \alpha_{1k_1} v_1 + \dots + \alpha_{1k_n} v_n - \beta_{1k} |$$

$$\vdots$$

$$i_n = a_n + b_n v_1 + \dots + b_{nn} v_n + \sum_{k=1}^{m_n} g_{nk} | \alpha_{nk_1} v_1 + \dots + \alpha_{nk_n} v_n - \beta_{nk} |$$

is reciprocal if and only if

a) $b_{ji} = b_{ij}$

b) $m_j = m_i$

c) $\alpha_{jk_1} = \alpha_{ik_1}$, $k = 1,2,\dots,m_j$

$$\vdots$$

$\alpha_{jk_n} = \alpha_{ik_n}$, $k = 1,2,\dots,m_j$

$\beta_{jk} = \beta_{ik}$, $k = 1,2,\dots,m_j$

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*The second author (David J. Curtin) was supported by the JSEP Contract F44620-71-C087.

Theorem 2. Reciprocal n-port Synthesis Criteria

A piecewise-linear n-port satisfying the above reciprocity criteria can be synthesized using only passive piecewise-linear 2-terminal resistors and a (p+q)-port transformer if and only if the set of algebraic conditions given in reference 5 is satisfied.

Both theorems 1 and 2 could not be proved without using our multidimensional piecewise-linear representation whose explicit analytical representation was crucial in constructing the piecewise-linear algebraic proof.

Recently, we have developed two approaches for realizing a (p+q)-port transformer using operational amplifiers.* Unlike iron-core transformers, our realization is valid from dc to a relatively high frequency, limited only by the op amp's frequency response.

2. Research Progress on Qualitative Nonlinear Network Analysis

Among the many important unsolved problems posed in the last major proposal concerning the foundation of nonlinear circuit theory, the following are some of the recent results published on this subject.

a. Implications of Capacitor-only Cutsets and Inductor-only Loops in Nonlinear Networks[7]

Let N be an autonomous dynamic nonlinear network. Let N_{RG} be the associated resistive subnetwork obtained by open circuiting all capacitors and short circuiting all inductors. We have proved the following results in reference 7.

(1) Suppose that N_{RG} has only isolated operating points. Then N has only isolated equilibria, if and only if, there are no capacitor-only cutsets and inductor-only loops.

(2) If the above condition is violated, then there are a continuum of equilibria even if the operating points are isolated.

(3) Let M be the set of equilibria. Then each trajectory is constrained to lie on an affine submanifold M^*, which depends on the initial state, such that $M \cap M^*$ has only isolated points. Hence, each trajectory behaves as if it has only isolated equilibria. The space M^*, because of its nature, can be considered as the minimal dynamic space of the network.

The above results are of special relevance to the computer simulation of nonlinear electronic circuits[8]. The presence of inductor-only loops and capacitor-only cutsets could lead to serious numerical problems during integration. These issues have been the subject of several heated debates[9,10] almost 20 years ago. The results presented in [7] provide a definitive and rigorous resolution of the fundamental issues raised in references 9 and 10.

*L. O. Chua, G. N. Lin and J. J. Lum, "The (p+q)-port transformer," ERL Memo UCB/ERL M81/41, 11 June 1981.

b. Dynamics of Josephson-Junction Circuits[11]

Although seemingly esoteric, the electromagnetic properties of Josephson junctions have been used in applications ranging from the measurement of minute computers with pico second switching times.

Although much has been published concerning Josephson-junction circuits, these articles are either quantum-mechanical analyses of the Josephson effect or sundry reports of experiments which reveal some very remarkable phenomena associated with circuits containing Josephson junctions. Those who have ventured to solve the differential equations of Josephson-junction circuits have necessarily restricted themselves to approximate methods, or the use of approximate analog models. The situation remains somewhat unsatisfactory from the circuit theorist's point of view, as only a very limited insight is available into the general circuit behavior of the devices.

Our research on Josephson-junction circuits was conerned mainly with developing a unified qualitative theory of the phenomena associated with Josephson-junction circuits. Some recent progress has been reported[11]. In particular, the features of the d.c. I-V characteristic of a Josephson junction have been explained rigorously in terms of the flows on a cylindrical phase space. The junction phase difference ϕ attains an equilibrium point in the supercurrent regime, and acts like a current-controlled oscillator in the finite voltage regime. The hysteresis in these characteristics is due to the coexistence of an equilibrium point and a periodic solution.

For the a.c. excited Josephson junction, the dynamics are described for a simpler circuit model as trajectories on the surface of a torus. Using the concept of a turning point to define the various possibilities of periodic flows on the torus,, the character of harmonic and subharmonic oscillatory waveform has been derived. Furthermore, the existence of almost periodic waveforms has been established. The presence of constant-voltage steps is related to the structural stability of the turning point, which roughly means that the character of a periodic oscillation is not affected by small enough perturbations in the excitation. An algorithm is given in reference 11 to numerically determine the heights of these constant voltage steps.

A precise interpretation is also given in reference 11 showing how an a.c. excited junction is subject to synchronization phenomena, and that the step height is merely the entrainment range, or locking range, of each synchronization event. It is also shown how synchronization, in general, can be geometrically interpreted as closed trajectories on an integral manifold which can be smoothly transformed into an n-dimensional "torus."

c. Theory of Symmetry in Nonlinear Circuits[12,13]

Simple group-theoretic concepts have been used successfully in references 12 and 13 to develop a rigorous and comprehensive theory of symmetry for nonlinear elements and circuits. This theory does not rely on geometrical arguments or other ad hoc techniques normally invoked in such studies. This theory also unifies all forms of symmetry, including rotation, reflection and complementary symmetry into a single framework. It also includes all known nonlinear symmetry principles as special cases. Moreover, a general method for identifying all symmetry characteristics possessed by a nonlinear multiterminal element or circuit has been obtained. Some of the results that have been obtained concerning symmetry in a nonlinear element are:

(1) Several algorithms for synthesizing a nonlinear multiport or multiterminal element having any prescribed form of symmetry have been derived. In particular, various examples have been used to illustrate how these algorithms can be used to derive well-known symmetrical nonlinear circuit modules such as push-pull amplifiers, complementary-symmetric amplifiers, rectifiers, modulators, etc.

(2) A reduction algorithm has been developed which allows a complicated symmetric element to be analyzed by a much simpler reduced element.

(3) A general principle has been derived for applying symmetry to achieve frequency separation in nonlinear communication circuits where the even harmonic components are separated from the odd harmonic components.

d. Passivity in Dynamic Nonlinear n-ports

In this research* we have succeeded in stating rigorously the energy-based concepts which are fundamental to nonlinear network theory, passivity and losslessness, and clarifying the way they enter the input-output and the state-space versions of the subject. We examined the conflicting definitions of passivity which exist in the literature and demonstrated the contradictions between them with several examples. We proposed a particular definition of passivity which avoids these contradictions by eliminating the dependency on a state of "zero stored energy," and we showed that it has the appropriate properties of representation independence and closure. We applied it to several specific classes of n-ports and derived equivalent passivity criteria. The exact conditions are given under which this definition is equivalent to one based on a internal energy function, and we used the concept of an internal energy function to provide a canonical network realization for a class of passive systems.

e. Geometric Properties of Dynamic Nonlinear Networks

In this research,** we have derived several basic results on

*J. Wyatt, Jr., L.O. Chua, J. W. Gannett, I. C. Goknar and D. N. Green, "Energy concepts in the state-space theory of nonlinear n-ports: Part I - Passivity," IEEE Trans. Circuits and Systems, Vol. CAS-28, Jan. 1981, pp. 48-61.

**T. Matsumoto, L. O. Chua, H. Kawakami and S. Ichiraku, "Geometric properties of dynamic nonlinear networks: transversality, local solvability and eventual passivity," IEEE Trans. Circuits and Systems, Vol. CAS-28, Maay 1981, pp. 406-428.

dynamic nonlinear networks from a geometric point of view. One of the main advantages of a geometric approach is that it is coordinate-free, i.e., results obtained by a geometric method do not depend on the particular choices of a tree, a loop matrix, state variables, etc. Therefore, the method is suitable for studying intrinsic properties of networks.

We have shown that transversality of resistor constitutive relations and Kirchhoff space is a sufficient condition for the configuration space to be a submanifold. Our main result states that a network is locally solvable, i.e., the dynamics of a network is well defined in the sense of Definition 3, if and only if, capacitor charges and inductor fluxes serve as a local coordinate system for the configuraton space. In other words, if all the variables in a network are determined as functions of capacitor charges and inductor fluxes, at least locally, then the dynamics is well defined. Conversely, if the dynamics is well defined, then all the variables in a network are determined as functions of capacitor charges and inductor fluxes. Because of its coordinate-free property, our main result also says that if the dynamics is well defined in terms of some coordinate system, then it must be well defined in terms of capacitor charges and inductor fluxes. Conversely, if the dynamics is not well defined in terms of capacitor charges and inductor fluxes, then there is no choice of variables in terms of which the dynamics is well defined in the sense of Definition 3. This shows that capacitor charges and inductor fluxes are the fundamental quantities in describing the dynamics of networks. Perturbation results are given which guarantee transversality and local solvability. Finally, several other perturbation results are given which guarantee eventual strict passivity of dynamic nonlinear networks. They explain why the voltage and current waveforms of almost every network of practical importance are eventually uniformly bounded.

3. Research Progress on Circuit Layout and Routing

During the past year a major effort has been made on the routing aspect of circuit layout. The work includes three distinct problems, namely:[13]

(i) Global wiring and the Steiner problem,

(ii) Generalized channel routing, and

(iii) A new approach to 2-layer routing.

(i) The problem of global wiring is of theoretical interest and has significant practical value. It represents an important step in automatic layout of master-slice and building-block chips. We have developed a heuristic algorithm to solve the minimum Steiner tree problem with rectilinear distance. This will be a key part of the general program which we are developing on global wiring.

(ii) We have extended our early work on channel routing to include channels which have cyclic constraints[16]. A new program is being developed based on a totally different approach on 2-layer routing. The preliminary result is encouraging. In special cases the resulting channel width could be smaller than the traditional lower bound of maximum density.

(iii) In the traditional approach to automatic routing of 2-layer printed circuit board, a unidirectional method is used. This depends on the strategy of using one layer for horizontal connection and the other for vertical connection. The interconnection between layers is made through via holes. In a new approach, we have demonstrated that it is possible to save about half of the vias required in the traditional approach[14]. On the other hand, it is difficult to control the congestion between pins and vias. However, by using a different via assignment procedure, we can offer more flexibility in routing[15].

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Significant Accomplishments

The major results have been summarized under Sections 1, 2d and 2 e.

Proposed Research Program

Although much progress has been obtained since our last major JSEP proposal entitled "Large-scale and nonlinear circuits study," many of the problems proposed in that proposal have not yet been pursued. Others are still under continuing research*. We proposed therefore to continue our research along the lines described in our last major proposal. The following is a summary of the proposed research program:

1. Piecewise-linear analysis of general nonlinear networks. While piecewise-linear analysis has been proven to be a powerful method for analyzing large, nonlinear resistive networks, its application to circuits with capacitors and inductors has not been found useful. Preliminary studies have indicated that a source of difficulty lies in the noncommutative property of matrix multiplication. However, we believe that techniques can be developed to deal with special classes of nonlinear dynamic systems. In particular, the concept of decomposing a general RLC nonlinear circuit into three subnetworks should be explored. Also, the problem of matching boundary conditions at discrete time needs to be Investigated.

2. Spline approximation. While the piecewise-linear approximation has the distinct advantage of reducing a nonlinear problem into a linear one over a given region, thus greatly simplifying the computation, it does not yield the desired accuracy for certain problems. To improve accuracy, spline approximation can be used. On the other hand, with spline functions, one needs to solve nonlinear equations over each region. The technique developed in Katzenelsen's algorithm which involves the crossing of simple boundaries cannot be used directly. We propose to study the use of spline functions in solving nonlinear resistive network problems. It is possible that a combined piecewise-linear and spline function method can be devised.

3. Simplicial interpolation. In our most recent work on piecewise-linear analysis, we introduced the method of simplicial interpolation for approximating an n-valued function. A key first step is to select an n-dimensional rectangle in a bounded set in which the solutions lie. The method of simplicial subdivision provides a systematic way to tesselate an n-dimensional rectangle into simplices. With this, the necessary computation in piecewise-linear analysis which deals with boundary crossing becomes greatly simplified. However, further work is needed, both in determining the bounded set and in choosing a suitable initial grid. The present algorithm uses simplices of the same size until an approximate solution is found. More work is needed in increasing the efficiency of computation.

The method of simplicial approximation has also been found useful in tolerance analysis of large scale circuits[1,2]. The method proposed by Director and Hachtel locates and approximates the boundary of the feasible region of a design space with a simplex of boundary hyperplanes. It gives solution to the tolerance assignment problem, and thus

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*That proposal was written from a long-range planning point of view and included many more basic research problems than we were prepared to pursue. This was done in order to provide a better perspective on the relationship between the various proposed topics of research.

is capable of evaluating a given design. The computation steps required are substantially less than those of the Monte Carlo method.

It is clear that simplicial approximation is a powerful tool for studying many types of large-scale circuit and system problems. The unique feature of the method lies in its computational elegance and simplicity. Yet, for each type of application, different techniques must be developed. We propose to generalize its applications and study many of its salient features.

4. Diakoptic analysis of dynamic nonlinear networks. Our recent work on large-scale networks has shown that there exists a one-to-one correspondence which equates any form of diakoptic or codiakoptic analysis to a special case of generalized hybrid analysis. This result unifies both diakoptic and codiakoptic analysis into a simple circuit-theoretic concept independent of any linearity assumption. In other words, this concept should be applicable also for nonlinear and dynamic networks. To obtain this generalization, we propose to develop algorithms for decomposing a large system of nonlinear ordinary differential equations -- such as those associated with nonlinear LSI circuits -- into several subsystems coupled to each other in a form analogous to the decomposition of a generalized hybrid matrix into a bordered block-diagonal, or a bordered block triangular form. This decomposition step is not only convenient, but is in fact essential when a very large system of state equations has to be solved. Indeed, even using the most advanced sparse matrix technique, the computer cannot handle large systems of nonlinear differential equations effectively.

Various decomposition methods will be exploited and the relative computational efficiencies compared against each other. Since each method decomposes the solution process into several stages, each involving a relatively small system of equations, it can be implemented via the so-called "small-computer approach;" namely, one can either apply the overlay techniques to "stack" the decomposed solution states, or apply parallel computation techniques to speed up the solution process.

We also propose to develop methods for investigating the qualitative behaviors of large-scale nonlinear dynamic networks by analyzing the beahviors of the decomposed subnetworks. For example, if each subnetwork is asymptotically stable, or completely stable, can we conclude that the same property holds in the original network? Our preliminary study on this important question shows that the qualitative properties of the decomposed dynamic subnetworks are not generally preserved in the original network. However, we were able to prove that many properties are preserved if additional assumptions of a topological nature are imposed[3]. We propose, therefore, to apply the recent techniques developed[4,5] to derive corresponding results for large-scale dynamic nonlinear networks.

5. Qualitative analysis of nonlinear communication circuits. With the exception of amplifiers and active filters where nonlinearities are undesirable, most communication circuits such as oscillators, mixers, and frequency converters are inherently nonlinear in the sense that their operation depends crucially upon the presence of at least one

nonlinear element[6]. In fact, even some "linear" input-output systems such as the parametric amplifier must be designed around a nonlinear element. Although nonlinear circuits can now be analyzed with the help of computer simulation programs[7], the resulting information is often inadequate from the designer's point of view. Indeed, there are many questions of a non-numerical nature which are more vital to the proper operation of the system.

For example, depending on the initial condition, it is well-known that nonlinear circuits can exhibit several distinct modes of operation. In fact, one perennial problem that confronts designers of parametric amplifiers and frequency converters is the sudden burst of unwanted subharmonic oscillations. Unfortunately, unless the designer knows what initial conditions would give rise to such ancmalous operations, the existence of spurious operating modes may not be detected by computer simulation. Such information could be obtained, however,by carrying out a qualitative anlysis of the associated system of nonlinear differential equations[8].

There are many other important questions of a qualitative nature which the circuit designer must answer in order to arrive at a good design. Some of these questions are: Will the circuit be stable or will it oscillate (except in the case of an oscillator)? If the circuit is stable, what are the different modes of dynamic operation? Will there be a unique steady state response? If so, how fast does the transient decay to the steady state? What are the effects of noise and parasitic elements on the operation of the circuit? In the case of amplifiers, what are the dominant distortion terms and how can they be calculated efficiently? In the case of frequency converters, how are the frequency and power related to each other? Is it possible to derive a generalized form of frequency-power relationships analogous to either the Manley-Rowe or Page-Pantell type for nonlinear devices modeled by more than one type of circuit elements? How can conversion efficiency be improved? How do we design an optimally matched nonlinear circuit?

While answers to some of these questions have been given for specific circuits containing diodes and transistors[9,10], they are generally rather ad hoc in nature and depend heavily upon the network topology and the devices being used. Since future communication circuits are certain to contain such modern microwave devices as Gunn diodes, IMPATT's, GaAs FET's, etc.[11], it is essential that more unified methods be developed. We propose therefore to continue our research in this area with the ultimate objective of developing such a unified theory.

6. Piecewise-linear algebra. Research on piecewise-linear analysis over the past decade has been concerned mostly with the development of efficient computer algorithms and the investigation of the existence and uniqueness of solutions. Very little attention has yet been given to the algebraic operations on equations involving piecewise-linear functions because such functions have so far been represented as a collection of systems of linear equations, each holding over a prescribed region in space. Our recent discovery of an explicit analytical formula for representing piecewise-linear functions of one

variable[12] shows that the class of all networks containing piecewise-linear two-terminal elements can be described using only two basic nonlinear building blocks; namely, the "absolute-value function" $y = |x|$, and the "sign function" $y = \text{sgn}\ x$. Using this representation, the equilibrium equations of networks containing two-terminal piecewise-linear elements can now be written in analytic form. This is analogous to writing equilibrium equations for linear networks in matrix form. The analysis of linear networks is an easy task, mainly because of the availability of "matrix algebra" as a tool of analysis. Unfortunately, no corresponding tools are available for analyzing nonlinear networks because of the infinite variety of nonlinearities that must be considered. However, by restricting the class of nonlinearities to include only the "absolute value function" and the "sign function," it is quite hopeful that such an algebra would automatically allow any piecewise-linear function of one variable* and we would have in fact developed an algebra for analyzing networks containing piecewise-linear elements.

The development of a "piecewise-linear algebra" would make it possible to carry out a symbolic analysis of networks containing piecewise-linear elements. In particular, various nonlinear network functions of practical interest -- such as the driving-point and transfer characteristics -- can be derived in symbolic form. Another application of the piecewise-linear algebra would be to derive design equations where the important design parameters are preserved in symbolic form. This in turn would allow a sensitivity analysis to be made via algebraic operations alone.

To summarize, we propose to apply our newly discovered analytical representation to develop a piecewise-linear algebra for analyzing and designing circuits containing piecewise-linear elements.

7. Computer-aided circuit analysis, design and layout. Recent advances in microelectronics have created an urgent need of new approaches to circuit analysis, design and layout. This research project is concerned with two problem areas, namely: (a) piecewise-linear circuit analysis and simulation, and (b) theoretical studies of layout for integrated circuits and printed circuit boards.

(a) Piecewise-linear circuit analysis and simulation

The idea of piecewise-linear analysis first introduced by Katzenelson in 1965 has been fully developed by us, and a complete theory of piecewise-linear analysis is now available. The theory has broad applications in nonlinear circuits and systems. The method has advantages over conventional methods, for example, in calculating driving-point or transfer characteristics of circuits with negative slopes. Yet circuit simulation based on the piecewise-linear method has not been widely used. There are two main reasons, namely: the problem of corner crossing, and the lack of study of convergence.

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*We have good reason to believe that the same technique could be generalized to allow piecewise-linear functions of many variables.

Recently, two notable approaches emerge which will greatly enhance the power of the piecewise-linear method.

The first which is developed by us is the use of simplicial approximation. With simplicial approximation we can simplify the task of computing the solution curve. There remain two problems to be investigated, namely: the corner-crossing problem and the problem of choosing the size of the initial complex. Both will affect the convergence of the method.

The second approach is to use ideal diodes and linear resistors only in modeling. This has the advantage that transition between regions can be handled by linear programming. Furthermore, the ideal diode model fits naturally to timing, logic and function simulation. Much more work needs to be done with this approach. For example, the problem of sensitivity and tolerance has never been attacked. Also, the problem of fault diagnosis in ideal diode cicuits is worth studying because it is simpler than fault diagnosis of analog circuits and could possibly take advantage of the technqiues well-known in digital circuits.

(b) Layout study

With the advent of VLSI, the problem of layout has reached a new dimension. We believe it is highly important to develop theoretical concepts on what could be done. Recent literature is by and large restricted to program development and almost void of analytical results. Many problems need to be investigated.

The problem of placement is perhaps the most important and difficult. Existing work deals with either placement of uniform modules or small analog circuits. Nowadays, in custom LSI, modules of various shapes and sizes with thousands of interconnections need to be considered. Thus, net list alone, which gives information on connection, is not enough for optimum placement. It is necessary to consider both the geometries and the topological specifications. We believe that graph theoretical concepts are essential in algorithm development.

A related problem is to predict the size of a chip from the geometric and topological information. As chips become more dense, the percentage of space needed for routing will further incease. The task of chip planning is fundamental to IC design. Of course efficient routing is implied in chip planning. Although methods of channel routing and global routing are available, no optimum results exist. In this connection, we have recently developed highly efficient channel routing algorithms based on graph theoretical considerations. More such studies will be carried out, for example, in channel routing with more than two layers.

Finally there is a need to develop circuit simulation programs directly from layout information. This involves the modeling of devices as well as parasitic elements.

Interaction With Other Work Units

We anticipate interacting with the CAD efforts of Professors Polak and Sangiovanni-Vincentelli, as well as the large-scale system research of Professors C. A. Desoer, P.P. Varaiya, R. W. Brodersen et al. (Work units ISS-83-2 and SSD-83-4 respectively).

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University of California, Berkeley — Electronics Research Laboratory

Joint Services Electronics Program — September 30, 1982

Work Unit No.: ISS-83-2 — Last Year's No.(s): ISS-82-2

Title: Control of Large Systems

Senior Principal Investigator(s): C. A. Desoer (415) 642-0459
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Scientific Objective

The overall long term objective is to design control structures for unknown systems subject to random disturbances. The class of structures being investigated is the so-called "adaptive feedback control" laws, the unknown system is any countable state Markov chain whose unknown transition probabilities are parameterized. Also to be studied is the practically important case where the "real" system does not belong to the class of a priori selected models. In conjunction with this work, deterministic system design methods and evaluations are also investigated.

State of the Art

Over the past twenty-five years engineers have invented a variety of procedures for designing control strategies. The sophistication of these strategies has grown with the increase in the use of computers which enables the implementation of complicated strategies in real time (feedback control). But all these procedures rest on the assumption that the information available about the system and the calculation of the choice of control which is based on this information is centralized, that is it takes place in a single system.

As engineers began to consider the control of large systems* (e.g., power systems, communication networks) in a scientific manner, it became clear that "classical" procedures of design are inapplicable to the problem of Combinatorial Complexity. As the number of variables describing the system increases, the amount of computation necessary to apply classical control strategies grows even faster, soon exhausting the capability of existing and foreseeable computing capability. It was soon recognized that a way of dealing with this complexity is to insist on decentralized control strategies[1-4]. After this recognition, research has proceeded in three directions. First, there has been the attempt to derive design principles applicable to a fairly general class of decentralized controllers[5,6]. But this attempt was soon frustrated by a new difficulty, Informational Complexity**. As soon as information and control is decentralized, the information available and the effectiveness of the decision taken by each controller depend upon the decisions taken earlier by other controllers. This "simultaneity" reproduces the Combinatorial Complexity at another level and renders inapplicable existing techniques of controller design. The difficulties created by Informational Complexity are not well understood. On the one

*Systematic attention to the control of large systems began less than ten years ago. An indication of this is given by the fact that the IEEE Control Systems Society established its Technical Committee on Large Scale Systems in 1969, its first editorial on large systems appeared in 1974, and its first Special Issue on Large Systems in April 1978.

**We are indebted to Professor Y. C. Ho (personal communication) for his conceptualization of these two kinds of complexity.

hand we have several counterexamples of decentralized control problems which appear quite innocent, but whose optimal strategies are extremely complex[7,8,16]. On the other hand, we now know a (small) class of decentralized information structures for which optimal control strategies do have a simple structure[4].

The second direction of research has led to the search of optimum decentralized controllers for what have been called quasi-static control problems[9]. For these problems optimum·controllers can have a simpler structure since only "steady state" behavior is of interest. Some very interesting solutions have already been proposed for the control of network flows[10] and for routing messages in a communication network[11].

Whereas the second direction described above seeks to reduce complexity by simplifying the control task (attention to steady state and ignoring transient behavior), the third direction reduces complexity by restricting a priori the structure of the class of decentralized controllers. In designing fixed structure controllers which guarantee adequate response against random disturbances, the attempts to date have been ad hoc [12-15]. It seems clear that considerable advance can be made if fixed structure decentralized controllers are investigated more systematically. This prediction is bolstered by the results recently obtained in the study of decentralized linear feedback controllers which guarantee adequate response against "deterministic but unknown" disturbances.

With the goal of designing robust controllers for large scale systems, the following approaches are relevant. First there is a very considerable literature on the stability of interconnected systems based on the Lyapunov method. In terms of generality of the results and of technical sophistication, the paper of Rasmussen and Michel deserves special mention[17]. Second, the problem can be approached from the input-output point of view: given the input-output properties of the subsystem and the topology of the interconnection, describe the I/O properties of the overall system. Under the joint sponsorship of NSF and JSEP we conducted a thorough investigation of this problem[18]. We refer the reader to its 46 item reference list. Recently we produced an improved formulation of the problem which led us to necessary and sufficient conditions for stability, even for the nonlinear case. The goal of this research is to study the input-output properties of the overall system. The advantage of the approach, namely graphical decomposition, is that it applies equally to nonlinear time-varying just as well as linear time-invariant systems, either lumped or distributed. The graphical decomposition technique operates as follows: the digraph of the interconnected subsystem is decomposed into an acyclic interconnection of strongly connected components and then a minimal essential set is extracted to further simplify the analysis of the strongly connected components.

On the decentralized control of large systems, especially as it relates to tracking and disturbance rejection, the work of Davison[19,20] deserves special mention. We used it as well as graphical decomposition techniques to investigate the eigenvalue assignment and stabilization problem of linear time-invariant interconnected systems[21]; one main result is that we can achieve eigenvalue assignment provided we operate at the column subsystem level, whereas if we restrict ourselves to summation node level, examples show that eigenvalue assignment cannot be achieved in general, whereas we prove that we can achieve stabilization[21].

On the more specific topic of tracking and disturbance rejection, the considerable literature and several approaches used are reviewed in reference 22. Furthermore, the principal results are given a streamlined self-contained derivation in reference 23. Unfortunately, all this literature considers only linear, usually lumped systems and discusses robustness of the servocompensators only within that class[24]. The effect of <u>nonlinear</u> plant perturbation on optimal control design has recently been examined in references 25,26; in the broader aspect of I/O stability in references 27-29.

Only one recent report treats the tracking problem for nonlinear systems[30].

Adaptive control strategies are increasingly being suggested as an appropriate solution to the situation where the system to be controlled is not known and is subject to random disturbances. Adaptive control is a compromise between two extreme alternatives. The first: <u>assume</u> the unknown system is equal to a "nominal" system, may give a performance which is unacceptably degraded; the second: formulate the problem as a Bayesian decision problem and solve it by Dynamic Programming, while formally optimal, it cannot be "solved" except in the most trivial instances.

In adaptive control, one identifies the unknown system using previous data: and then uses the control assuming the current estimate of the unknown system to be the true system. As time progresses, and more data is collected, the uncertainty regarding the system declines and the performance improves. The crucial question is how fast this improvement in the knowledge and performance of the system occurs. Previous research has been primarily focused on linear systems.

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Progress and Relevant Publications Since Last Major Proposal

A. Under Combined Sponsorship

1. Control of Markov Chain Models

We have completed the first phase of the research. Our work (and of others in the field) is summarized in [a]. This research dealt with the control of Markov chains when the transition probabilities are not known a priori. Then the function of control action is to simultaneously learn the system parameters and to guide the system in a desired fashion. The strategy adopted to do this is adaptive control. Here at each time instant the past observations are used for parameter estimation and the next control action assumes that the estimate is true.

Two ideas for estimation have appeared. The original one is to use the maximum likelihood estimate (MLE). Kumar has modified this by multiplying the likelihood function by a term that corresponds to the reward. The resulting estimates have some desirable properties not enjoyed by the MLE.

Convergence of estimates is guaranteed when the parameter set is finite but not when it is infinite. Nevertheless, Kumar's modified MLE produces a control which is optimal. The problem of finding conditions to ensure parameter convergence seems rather difficult.

2. Design of Deterministic Control Systems

Fundamental studies in nonlinear feedback systems have been completed: a general theory of multi-input multi-output nonlinear feedback systems has been completed and published[h]. It gives a complete generalization of the theory that H. S. Black presented for the linear time-invariant single-input single-output feedback system. In addition, it gives a completely general demonstration that the linearized inverse return difference is the quantity that controls the degree of desensitization to plant and/or output disturbances. It is also shown to play a key role in linearizing the I/O map of the closed-loop system.

The streamlining of the theory of the generalized Nyquist criterion and its generalization to the distributed case has been published[i]. We hear that the method has been programmed and is being used at TRW in Los Angeles, and at Aerospace Corporation, El Segundo, CA. The features of our generalized Nyquist criterion are that (a) it applies to the distributed case, and (b) it does not require any reference to Riemann surfaces, branch cuts, etc. that previous derivations required.

An interesting approach to the study of linear feedback systems due to Zames has been adapted to the problem of designing multivariable feedback systems with stable plants. This design method is revolutionary in that (a) it is based on the global parameterization of the four transfer functions pertaining to the problem, and (b) the stability of the design is easily checked without having recourse to such things as Nyquist diagrams etc. The design algorithm allows complete freedom - modulo, of course, the C_+ - zeros of the plant - in the choice of I/O map: therefore we can diagonalize the I/O map, assign zeros independently to each channel, assign poles independently to each channel and achieve tracking requirements [8].

As a result of these studies, we developed a straightforward algorithm for the design of single-input single-output systems [ℓ].

The algebraic methods have been extended to square or rectangular, discrete-time or continuous-time, lumped or distributed plants. A report of this work is in preparation and is submitted for the American Control Conference 1983 [m]. The ν-parameterization method has been extended to simple unstable plants. This will be presented at the CDC 1982 [n].

We studied carefully the problem of robust stability: first we gave a much more general proof of a result surmised by Doyle and Stein [o]. Then we developed a completely general study of robustness where there are no constraints on the kind of perturbation the plant may experience [p].

C. Significant Accomplishments

The spread of computer-assisted control has increased the possibility of implementing adaptive controllers which "tune" the control inputs to automatically detected changes in operating conditions. Considerably more work needs to be done, and this will take several years, before adaptive controllers can be implemented on a routine basis.

Work on statistical identification has shown us that it is possible to design experiments to identify an unknown system, and engineers have developed many methods for controlling a known system. The aim of adaptive control is to carry out both tasks - identification and control - concurrently. Our investigations, and the work of others, have proved that, in principle and under precisely stated conditions, this is indeed possible. Others have shown that adaptive controllers will operate satisfactorily for linear systems of the form:

$$\sum a_i y_{t-i} = \sum b_i u_{t-i} + \sum c_i w_{t-i}$$

where y_t, u_t, w_t are the output, input and white noise and the a_i, b_i, c_i are unknown parameters. Our work has resulted in conditions for the satisfactory control of systems of the form:

$$x_{t+i} = f(x_t, w_t, u_t, \theta)$$

where x_t is a discrete state, and θ is the unknown parameter.

We have studied the case when x_t belongs to a countable state space, θ ranges over a compact set and, at each t, θ is estimated by the maximum likelihood estimator θ_t. It is shown that if θ_t converges to θ^*, then θ^* correctly identifies the closed-loop system, but not necessarily the open-loop dynamics. Moreover, θ_t need not converge at all. However, if an arbitrarily small random component is added to the control, then the true parameter is identified with probability 1. These results are presented in [q].

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Proposed Research Program

The general outline of the research program in large scale systems is a long term program in the course of carrying it through: there are certain innovations that have to be pursued because it is intuitively clear that they will have important -- though unknown at present -- effects on the Large Scale Systems research program

Over the coming period we plan to develop our work in adaptive control along the following directions:

The research done so far uses a so-called "passive" learning in which the fact that the system parameters are unknown does not affect the control used. Such a strategy may perform poorly for short horizon problems.

Recently some fundamental breakthroughs have been achieved for the classical multi-armed bandit problem (see [b,c,d] and the references there). The dynamic structure in bandit problems is simpler than the general Markov structures we have investigated; however, bandit problems consider discounted cost functions, i.e., they include "transient" behavior, while our problems only considered "steady state" behavior.

For determinate systems the proposed research will attempt to extend the results on the bandit problems to more complex dynamics. The most promising extension seems to be to consider a set of bandits operating in a common Markovian environment.

(1) We will vigorously pursue the extension of the new design algorithm: we believe that we should be able to give a completely algebraic theory of design which would be applicable to square or rectangular, discrete-time or continuous-time, lumped or distributed plants.

(2) We will critically reexamine Youla's parameterization to see whether some dramatic simplification as occurred in the stable plant case cannot be caused to occur for the unstable plant case. If not, we propose to investigate the best stabilization method.

(3) We will devélop extensions of the technique to large scale systems.

Interaction with Other Units

We shall continue to interact with the research project of L. O. Chua and E. S. Kuh on nonlinear circuits and with E. Polak on computer optimization of electronic circuits.

University of California, Berkeley | **Electronics Research Laboratory**

Joint Services Electronics Program | **September** 30, 1982

Work Unit No.: ISS-83-3 | **Last Year's No.(s):** ISS-82-3

Title: Computer Optimization of Electronic Circuits

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Scientific Objective

This project is a continuation of Project ISS-83-3, Computer Optimization of Electronic Circuits. Our chief objective remains the development of an interactive, optimization-based, computer-aided design methodology for the design of electronic circuits. To this end, we propose to continue developing specialized, dovetailing, single and multi-objective optimization algorithms, circuit simulation techniques and device models. In addition, since the development of progressively more complex systems makes sense only if these systems can be maintained, we propose to perform research on system diagnosability and fault analysis.

The optimization algorithms to be developed must be capable of solving complex, nondifferentiable, semi-infinite optimization and trade-off problems which arise in electronic circuit design when tolerances, trimming, and distributed constraints are taken into account. Our simulation procedures must be capable of producing not only circuit responses, but also the derivatives of these responses with respect to design parameters. In addition, they must have special variable precision features which result in a reduction of computing time at low precision, so that an optimization algorithm can call such a procedure with low precision when far from a solution and increase precision adaptively, as a solution is approached. The effect of such variable precision computation is to considerably reduce computing times. Since production tolerances can be imposed on only a very small number of device parameters, and since the optimization algorithms become extremely inefficient when tolerances on a large number of parameters are specified, device models must be developed in terms of production parameters by making use of the fact that the variation of many circuit parameters can be expressed in terms of variations of production parameters.

Finally, our theoretical work will be implemented and experimentally evaluated in an interactive-computer aided design facility which we are developing.

State of the Art

Optimization-based computer-aided design is certainly not a new phenomenon, see for example [B9,B11,B13,B15,B20,C1,K1,K2,P7,H16]. However, until quite recently, its use was severely limited by the fact that the available optimization algorithms were not able to solve design problems with tolerances, trimming and distributed constraints, such as those imposed on frequency or transient responses [B20]. The reason for this is that such a design problem frequently assumes the form

$$\min\{f(x) \mid g^i(x) \le 0,\ i = 1,2,..,I;\ \max_{w \in W} h^j(x,w) \le 0,\ j = 1,2,..,J;$$

$$\max_{e \in A}\ \max_{s \in S}\ \min_{t \in T}\ \max_{k \in K}\ z^k(x,e,s,t) \le 0\} \qquad (1)$$

where $g^i(.)$ represents simple constraints on the nominal design vector x, $h^j(.,.)$ represents nominal frequency (or time) dependent constraints on impedances or gains, etc., and z represents the requirement that performance be maintained in the presence of production errors e which can be counteracted by adjusting the trimming parameters t. The variable s may represent time or frequency or temperature, etc. The above problem is easily recognized as a non-differentiable, semi-infinite optimization problem, i.e., about as difficult an optimization problem as one cares to think of.

Although there is a fairly large literature on algorithms for various classes of semi-infinite and nondifferentiable optimization problems, see e.g., [B25,B26,B27,D8,D9,G6,G7,G8,H12,M10,P14,P16,P17a,H1,T1], we find that many of these algorithms are either conceptual (i.e., involve operations that one is not able to perform) or address themselves to very restrictive classes of problems, such as those with one-dimensionally convex constraint sets [B9,B11,B13,B15]. As far as general purpose, implementable algorithms are concerned, there appear to be only three [P14,G6,T1] which solve the simpler case of (1) when there are no tolerance and trimming constraints present, two [G6,P4] which allow for tolerances and only one [P5] which solves (1) in its complete generality. All of these three algorithms were co-authored by E. Polak.

In addition to the difficulties mentioned above, the use of optimization techniques in electronic circuit design was, and still is, severely handicapped by the fact that existing simulation codes, e.g. the ones described in [K1,J6,Z2], which must be called for function and derivative evaluation, have inadequate provisions for derivative calculations. For example, if we consider a sample of the best known computer aided analysis programs, such as ASTAP [A6], CIRCUS [D7], ECAP [E2], NET 2 [M7], SCEPTRE [B61], SUPERSCEPTRE [S12], SPICE 2 [N3] and BELAC [G12], we find, quite typically, that ASTAP computes no sensitivities, SPICE 2 computes only small-signal sensitivities, and none of them compute temperature sensitivity. We are now beginning to develop an effort to extend these programs so that required derivatives will also be computed. In addition to the simulation programs mentioned above, programs based on tearing algorithms [B28,C9,H5,H6,K8,M14,R1,S3-S8,S10,S11,W5], and on model approximation and decoupling [C6,F1] are also being considered for extension since they are more efficient in large-system applications.

As specialized optimization algorithms began to be developed for electronic circuit design, such as [P4,P5], it became obvious that existing device models were completely incompatible with the need of keeping the total number of toleranced variables small. Quite recently R. G. Meyer was able to show that more suitable models can be developed, because many of the important variables are correlated, and that their behavior can be expressed in terms of a reasonably small number of variables the tolerances on which can be controlled in the production process, such as sheet thickness, resistivity, device scaling factors, epitaxial doping, etc.

As far as fault diagnosis is concerned, we find theoretical results for the diagnosability of linear circuits and systems [B1,B3,B4,E3,L1,N1,R2,R3,S1,S2,S11,T1,T4-T6]. Some preliminary results for the diagnosability of memoryless nonlinear circuits and systems were co-authored by A. Sangiovanni Vincentelli [S12]. However, there appear to be no diagnosability results for dynamic nonlinear circuits and systems.

Progress and Publications Since Last Major Proposal.

A. Under JSEP

1. Existing semi-infinite optimization algorithms used in engineering design are very reliable. However, since they are only first order methods, they are rather slow. Now, engineering design via optimization involves a great deal of time-consuming simulation and hence, in conjunction with first order methods, can be quite expensive in computer time. Obviously, there is a great need for faster methods. Professor E. Polak, in collaboration with Professor D. Q. Mayne of Imperial College, London, and Andre Tits, a graduate student, have made a considerable amount of progress in devising superlinearly converging algorithms for solving nonlinear semi-infinite optimization problems encountered in engineering design. Their work is reported in the following papers.

D. Q. Mayne and E. Polak, "A quadratically convergent algorithm for solving infinite dimensional inequalities," University of California, Berkeley, Electronics Research Laboratory Memo No. UCB/ERL M80/11, 1980. To appear in J. of Appl. Math. and Optimization.

E. Polak and A. Tits, "A recursive quadratic programming algorithm for semi-infinite optimization problems," International Symposium on Semi-infinite Programming, University of Texas, Austin, September 8-10, 1981, also to appear in J. of Appl. Math. and Optimization.

E. Polak and A. Tits, "On Globally stabilized quasi-newton methods for inequality constrained optimization problems", 10th IFIP Conference on System Modeling and Optimization, New York August 31-September 4, 1981.

D.Q. Mayne and E. Polak, "A superlinearly convergent algorithm for constrained optimization problems", Mathematical Programming Study 16, On Constrained Optimization, pp. 45-61, 1982.

2. We have made a great deal of progress in constructing an interactive computing system for optimization-based computer-aided-design. Our present package, DELIGHT, offers an extremely high level language for very rapid and easy optimization program writing; extreme modularity, which permits very simple assembly of algorithms and problems from blocks; easy interface to simulation and system definition packages such as SPICE; various interrupt and restart features; powerful graphics; etc. Our progress to date on this system is desclibed in:

W. Nye, E. Polak, A. Sangiovanni-Vincentelli and A. Tits, "DELIGHT: an optimization-based computer-aided-design system," University of California, Berkeley, Electronics Research Laboratory Memo UCB/ERL M81/19, 1981; Proc. IEEE Int. Symp. on Circuits and Systems, Chicago, Ill, April 24-27, 1981.

3. In our earlier work on design centering, tolerancing and tuning

problems, we discovered that these problems are inherently nondifferentiable. An examination of the literature showed that there was very little available by way of nondifferentiable optimization algorithms. It was therefore clear that the art of constructing nondifferentiable optimization algorithms would have to be considerably extended if these algorithms are to become a realistic tool in engineering design. Professor E. Polak, in collaboration with Professor D. Q. Mayne of Imperial College, London, and Y. Wardi, a graduate student, have studied the possibility of obtaining nondifferentiable optimization algorithms by extension of differentiable optimization algorithms. Their results are most encouraging and are reported in:

E. Polak, D. Q. Mayne and Y. Wardi, "On the extension of constrained optimization algorithms from differentiable to nondifferentiable problems," University of California, Berkeley, Electronics Research Laboratory Memo No. UCBERL M81/78, 1981, also to appear in SIAM J. on Cont. and Opt.

E. Polak and D.Q. Mayne, "Algorithm Models for Nondifferentialble Optimization", University of California, ERL Memo UCB/ERL No. M82/34, May 1982.

E. Polak, "Semi-infinite Optimization in Enginering Design", International Symposium on Semi-infinite Programming, Univ. of Texas, Austin, Texas, Sept. 8-10, 1981.

4. Professor Polak has shown that nondifferentiable, design centering, tolerancing and tuning problems can be decomposed into a sequence of differentiable optimization problems via outer approximations. As a result, the arsenal of computational tools available for their solution is much enlarged.

E. Polak, "An Implementable Algorithm for the Design Centering, Tolerancing and Tuning Problem", J. on Opt. Th. and App., Vol. 35, N. 3, Nov. 1981.

5. Professor Polak in collaboration with Y. Wardi, a graduate student has presented a theory that enables one to make some sense in a number of optimization problems defined on function spaces, where either the problems themselves have no solutions or algorithms construct sequences in solving them that have no accumulation points in the spaces in which they are defined. The tools used to achieve this result are minimizing sequences.

E. Polak and Y. Wardi, " A Study of MInimizing Sequences", University of California, Berkeley, ERL Memo M82/22, March 1982.

6. Professor A. Sangiovanni-Vincentelli has co-authored three survey papers dealing with various design aids for VLSI. These papers are as follows:

R. Newton, D. O. Pederson, A. Sangiovanni-Vincentelli and C. Sequin, "Design aids for VLSI: The Berkeley perspective," IEEE Trans. on

Circuits and Systems, July 1981.

G. Hachtel and A. Sangiovanni-Vincentelli, "A survey of third generation simulation techniques," IEEE Proc., November 1981.

R. Brayton, G. Hachtel and A. Sangiovanni-Vincentelli, "A survey of optimization techniques for integrated circuit design," IEEE Proc., November 1981.

7. Professor A. Sangiovanni-Vincentelli and V. Visvanathan, a graduate student, partly in collaboration with Professor of R. Saeks of Texas Technological University, have made a considerable amount of progress in the area of diagnosability of nonlinear circuits and systems. Their work is reported in the following papers:

V. Visvanathan and A. Sangiovanni-Vincentelli, "Diagnosability of nonlinear circuits and systems, Part I: The DC case," Special joint issue of IEEE Trans. on Computer and IEEE Trans. on Circuits and Systems on Design for Testability, November 1981.

R. Saeks, A. Sangiovanni Vincentelli and V. Visvanathan, "Diagnosability of nonlinear circuits and systems-Part II: Dynamical systems," Special joint issue of IEEE Trans. on Conputers and IEEE Trans. om Circuits and Systems, on Design for Testability, November 1981.

V. Visvanathan, "Applications of Differential Sensitivity to Large-Perturbation Problems: Diagnosability and Model Simplification", PhD Thesis, University of California, Berkeley, 1982.

8. Professor A. Sangiovanni-Vincentelli and E. Lelarasmee, a graduate student, partly in collaboration with Dr. A. Ruehli of IBM T.J. Watson Research Center, have developed a new family of relaxation based methods for large scale circuit simulation. It has been possible to characterize the convergence properties of these methods and to show that for a large class of circuits, i.e. MOS digital circuits, the method will always converge to the solution of the circuit equations. An experimental computer program called RELAX, has been written. Its performances are impressive: using the same models, RELAX has computed with the same accuracy transient responses of MOS digital circuits about 70 times faster than SPICE2. This research has been awarded a best paper award at the 1982 Design Automation Conference and the D.J. Sakrison Memorial Award given to E.Lelarasmee for outstanding research done by a graduate student in the Department of EECS, University of California, Berkeley. The papers where these results have been reported are:

E. Lelarasmee, A. Ruehli and A. Sangiovanni-Vincentelli, "The Waveform Relaxation method for time domain analysis of large scale integrated circuits", IEEE Trans. on Comp. Aided Des. of Int. Circ. and Syst., vol CAD-1,No. 3, pp.131-145, July 1982.

E. Lelarasmee, A. Sangiovanni-Vincentelli and A. Ruehli, "A New Relaxation Technique for Simulating MOS Digital Integrated Circuits" Proc. 1982 Int. Symp. on Circ. and Syst., pp. 1202-1205, Rome, May 1982.

E. Lelarasmee and A. Sangiovanni-Vincentelli, "RELAX: A New Circuit Simulator for Large-Scale MOS Integrated Circuits" Proc. 19th Design Automation Conference, pp. 682-690, Las Vegas, June 1982.

E. Lelarasmee, "The Waveform Relaxation Method for the time domain analysis of large scale integrated circuits: Theory and Applications", PhD Thesis, University of California, Berkeley, 1982.

Significant Accomplishments

1. We have made important progress in devising superlinearly convergent algorithms for the solution of semi-infinite optimal design problems.

2. We have developed a comprehensive theory of diagnosability for dynamical nonlinear circuits and systems.

3. We have made a considerable amount of progress in developing DELIGHT, a highly sophisticated interactive computing system for optimization-based computer aided design of engineering systems and, in particular, of electronic circuits.

4. We have developed a new family of relaxation-based methods for the simulation of large scale circuits that may open an entire new vista on circuit simulation.

Proposed Research Program

Introduction

The research which we propose to carry out is in four parts, three of which must be kept highly co-ordinated, while the fourth one is rather independent of the others. The three coordinated parts of our research are: (i) the development of optimization algorithms for single and multi-objective optimization problems corresponding to electronic circuit design problems with simple inequality constraints, semi-infinite inequality constraints, and max min max ... type of constraints which results from specifications on nominal parameter values, frequency responses, tolerancing and trimming, etc.; (ii) the developement of efficient simulation codes which compute not only responses but also various sensitivities and whose precision can be modulated as a means of controlling computing time; and (iii) the development of device and circuit models which allow to express system behavior in terms of a very small number of fundamental variables which can be controlled in the production process. The stand-alone part of our research is devoted to developing a comprehensive theory of fault diagnosis for nonlinear circuits and systems.

Our research results will be tested, evaluated and fine-tuned in our interactive computing facility which is currently being used to develop a multidisciplinary, optimization-based computer-aided design methodology. The power of the DEC 11/780 computer and the availability of sophisticated, interactive graphics features makes this facility an ideal medium for this type of experimental work.

Optimization Algorithms for Interactive Electronic Circuit Design.

a) Single-Objective Optimization

To accomodate most, if not all the important requirements of electronic circuit design, the optimization problem to be considered must be at least as complex as the following one

$$\min f(x) \mid g^{i}(x),\ i = 1,2,..,I;\ \max_{w \in W} h^{j}(x,w) \leq 0,\ j = 1,2,..,J;$$

$$\max_{e \in E}\ \max_{s \in S}\ \min_{t \in T}\ \max_{k \in K}\ z(x,e,s,t) \leq 0 \qquad (1)$$

where f, g^{i}, h^{j} and z^{k} are all continuously differentiable and W, S, E R, and $T \subset R^{p}$ are compact sets. At the present time, there are only two approaches possible to such a problem, one based on outer approximations of the constraint set and the other one on inner approximations of the constraint set [G6,P5,D16,S13].

(i) Outer approximations can be used to decompose (1) either into a sequence of nondifferentiable problems, as was done in [P6], or into a sequence of differentiable problems, as was done in [P5]. While, in general, it is preferable to decompose a difficult problem like (1) into an infinite sequence of differentiable problems, the price paid in [P5] for obtaining a sequence of differentiable problems was that these problems may have a very large and possibly ill conditioned set of constraints. Since our ability to handle nondifferentiable problems has considerably improved since [P5,P6] were written, we propose to examine the advantages of decomposing (1) into a sequence of nondifferentiable, but hopefully quite well conditioned problems. In particular, since the resulting nondifferentiable optimization problems have a very special structure, we hope to devise efficient algorithms for their solution.

(ii) Introduced for circuit design by Director and Hachtel [D16], inner approximations algorithms have made a very favorable initial impression on CAD users. Their main advantages are that they result in particularly simple subproblems and that whenever computation is suspended, the designer has at least a feasible design at his disposal. At present, their main disadvantages are that they only make sense for convex constraints and that there are no reasonable constraint dropping schemes to limit the growth of complexity of the resulting subproblems, which severely limits the precision with which they can solve a problem. Consequently, there remain a number of important unanswered questions. In particular, it is important to determine whether they can be extended to nonconvex problems and whether one can develop constraint dropping schemes that are as efficient as those proposed for outer approximations algorithms. We propose to address ourselves to these questions.

b) Multiobjective optimization

We have an ongoing effort in multiobjective optimization, which is used in electronic circuit design for performing trade-offs. There are a number characterizations of non-inferior (i.e. trade-off) point surfaces [C10,D2,M1,P3,P11]. Quite recently, we have obtained a number of interesting quantitative results on the efficient exploration of such surfaces [P8,P8a]. One of the major obstacles to the use of multi-objective optimization in design is the lack of meaningful methods of multidimensional information display. We propose to attack this problem in conjunction with developing efficient strategies for trade-off surface exploration.

Circuit Simulation

This part of the project is devoted to the development of simulation techniques and codes which are compatible with our optimization algorithms. The most urgent task is to extend at least one high quality simulation code so that it will yield the required derivatives. Since SPICE 2, which was developed at Berkeley, is such a code and since it already has some sensitivity computation features, such as for d.c. small-signal sensitivities, it is an ideal starting point for such a project. We note that some theoretical results for computating time domain sensitivities have already been obtained [D13], however, these results are not easily implemented within the context of existing simulation programs, such as SPICE 2. Moreover, they promis to be very expensive in terms of computer time and storage requirements.

We therefore propose to develop and implement, as an extension of SPICE 2, an algorithm for time domain sensitivity analysis which makes use of a number of the intermediate computations, involving jacobians, required by the integration of the circuit equations.

Device Modeling

The major task in this area is to develop device models which lead to efficient computations in the context of optimization-based computer-aided design. In particular, emphasis will be placed on reducing the number of variables on which tolerances must be placed, since computing costs go up exponentially with this number. In particular, we shall attempt to develop appropriate models for complex MOS digital and analog circuits. The modeling process will be iterative, in that our new models will be tested experimentally against existing models and against actual circuit performance.

Fault Diagnosis of Nonlinear Circuits and Systems

Our results, reported in [V1], yield a necessary and sufficient condition for the diagnosability of nonlinear memoryless systems described by the equation:

$$y = f(u,a) \quad (2)$$

where $f(.,.)$ maps $R^p \times R^n$ into R^q . The condition involves a rank test on the matrix:

$$R_w(a) = \int_{-\infty}^{\infty} \cdots \int_{-\infty}^{\infty} [df(u,a)/da]^T [df(u,a)/da] w(u) du \quad (3)$$

where T the denotes transpose and $w(.)$ is a continuous scalar valued function selected to ensure the existence of the integral.

As a further step, we studied the diagnosability of nonlinear dynamical circuits [S13]. Most such systems can be described by implicit algebraic-differential equations of the form

$$h(\dot{x}(t),x(t),y(t),u(t),a) = 0 \quad \text{for all } t \geq 0 \tag{4}$$

The theory and techniques developed for resistive circuits can be applied to this case by by extending them to a function space setting. Among other things, this involves replacing the Jacobian and its transpose by the Frechet derivative and its adjoint. The difficulty in computing the Frechet derivative makes the above approach numerically very difficult. To deal with this complication, we propose to examine the possibility of replacing the original system by a discrete-time approximation, i.e., a discrete-time dynamical system of the form:

$$h(\dot{x}(t_n),x(t_n),y(t_n),u(t_n),a) = 0, \quad \text{for } n = 0,1,2,\ldots \tag{5a}$$

$$\dot{x}(t_n) = \sum_{i=0}^{k} b_i \, x(t_{n-i}) \tag{5b}$$

The above form is of particular interest in electronic circuit design since the simulation of electronic circuits requires the solution of equations of the form (5a,5b) for a set of discrete time increments b_i as well as the time points t_{n-i}, which are chosen according to the particular backward differentiation formula used in the simulator. By using a discrete approximation to the continuous dynamical system, we will be able to couple algorithms for diagnosis with existing efficient simulators, such as SPICE 2. An additional important simplification in the diagnosis of systems of the form (4), will result from the fact that the Frechet derivative can be replaced by time-domain sensitivities which are much easier to compute.

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E. Lelarasmee	M82/40	"The waveform relaxation method for time domain analysis of large scale integrated circuits: theory and applications."
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E. Polak Y. Y. Wardi	M82/22	"A study of minimizing sequences."
L. O. Chua E. W. Szeto	M82/27	"Higher-order nonlinear circuit elements: circuit theoretic properties."
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T. Lee W. Nye A. Tits	M81/69	"The design of digital filters using interactive optimization."
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