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August, 1977

Submitted by: R. T. Chien
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H. V. Krone

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1. Surface Studies

Journal Articles

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17. Population/Food/Weather Studies

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COORDINATED SCIENCE LABORATORY
SUMMARY OF
PROGRESS REPORT FOR JULY 1976 THROUGH JUNE 1977

1. Surface Studies

Several projects have been successfully completed, setting the stage for a heavier concentration upon surface effects on semiconductors. The possibility of creating monatomic layers at a surface by electron beam writing on molecularly held gases has been thoroughly explored, with particular emphasis on the thermal stability and chemical characterization of the layers. This promises to be a useful approach, which will be pursued further. Separate studies of the role of structural defects in promoting chemical reactions on solids have been concluded. These studies point to lattice steps as being highly effective in catalyzing molecular dissociation in a few specific systems. Considerable progress has also been made in the examination of atomic clusters on metal surfaces, which are of interest for understanding processes occurring in thin films. The statistics governing cluster behavior have been extensively developed and experimental studies of cluster energetics have been initiated.

2. Thin Films

The overall objective of this program is to investigate ion-surface interactions which have a controlling effect on the nucleation and growth kinetics, chemistry, and physical properties of alloy semiconducting films grown by sputtering. In support of this objective we have developed multitarget rf sputtering (MTS) techniques which allow independent control over elemental sputtering rates during steady state deposition. A model has been developed and verified to predict film composition distributions, both through the film and across the film, as a function of sputtering variables. Single crystal $In_{1-x}Ga_xSb$ films have been grown by MTS, and Sb sticking probabilities have been determined.

Energetic particle bombardment of the substrate and film which occurs during bias sputtering has been investigated. A combination of diffraction and electron spectroscopy techniques were used to study ion bombardment enhanced interdiffusion and chemical mixing at sputter deposited superlattice and film-substrate boundaries. An analytical model which accounts for interdiffusion has been developed to predict preferential elemental sputtering from alloy targets. The model is presently being applied to preferential resputtering during film growth.

3. Microwave Acoustics

The long range objective of this research is to originate and analyze new microacoustic wave principles that have significant device implications. Progress towards the specific objectives of achieving smaller substrates, more accurate performance, and higher frequencies has been achieved.

The substrate size reduction is important for applications where high power density, multiple channels, or integration with semiconductor devices is important. The line acoustic waves (LAW) are nondispersively confined in two dimensions so that the acoustic active area is reduced by orders of magnitude below that of surface waves. Theoretical and experimental developments regarding the LAW propagation and excitation have been devised. Small size and accurate performance has been achieved by utilizing monolithic I.C. thin film capacitors in conjunction with microacoustic wave devices. High frequencies with low resolution requirements are best achieved by using the transducer at the harmonic responses. The capacitively coupled transducers and the new excitation analysis techniques represent significant steps toward accurate harmonic frequency operation.

4. Millimeter Wave Integrated Circuits

Considerable progress, both in the theoretical analysis of millimeter-wave guiding systems and in experimental implementation of various components, has been made. On the theoretical side, the "equivalent-dielectric approach" has been generalized and applied to a number of configurations. A more complete, multiple-mode type extension of this analysis is in progress. Such an extension will be useful for predicting the higher order mode characteristics of planar guides. Experimental efforts were directed towards the design, fabrication and intensive testing of various guides using automated recording equipment. Major concentration was placed on homogeneous inverted strip guide, which evolved as a useful modification of the previous quartz-teflon inverted strip guide. Also, a new tapered dielectric guide, based on the principle of parabolic index-profile optical fiber, was successfully designed and tested. In line

with our ultimate goal of building fully integrated, dielectric-based communication systems, the implementation of both passive and active components was carried-out. In addition to building passive components, like couplers and directional filters, significant results have been achieved in constructing an integrated Impatt oscillator. Our immediate goal is to achieve integration of a mixer-local oscillator unit.

5. Electromagnetic Radiation and Scattering

The Spectral Domain Approach has been used in the analysis of several problems previously handled by GTD or other asymptotic methods. Use of the Spectral Domain Approach allows treatment of problems not previously tractable, and provides reliable results in areas (shadow boundaries, etc.) where asymptotic methods may break down. In addition, an iterative method employing the spectral domain approach has been developed which allows improvement of the available GTD solution. Finally, a spectral domain test has been devised to check the accuracy of existing asymptotic solutions, and the test has been applied to solution of the source - region problem of a slot radiating on an infinite circular cylinder.

6. Plasma Physics

The experimental study of wave-wave coupling in a beam-plasma system is being pursued, following the completion of our theoretical work on the problem. The experiment has resulted in the discovery of several interesting effects. In addition, two new experiments are being planned in the area of plasma turbulence. One will study the first and second order probability distributions of the wave potential in a turbulent ion-acoustic instability. The other new experiment will investigate the theoretically predicted possibility of turbulent stabilization of a beam-plasma instability.

7. Rarefied Gas Dynamics

Under our long range plans to use the kinetic theory treatment to solve gas dynamics problems under non-equilibrium conditions, we have solved the Boltzmann as well as the Krook equations for an evaporation-effusion problem which has applications in the design of space experiments, certain meteorology tests, and nuclear reactors. We have also studied the development of Monte Carlo techniques to analyze the separation process in aerodynamic isotope enrichment devices.

8. Computational Gas Dynamics

Under our long range plans to solve directly the basic gas dynamics equations for complex flow problems, we have undertaken the task of studying nonlinear free surface problems. We have developed a hybrid time-dependent finite element - finite difference method and used it to solve the pressure distribution and the submerged body problems. We have also applied a time-dependent finite difference method to solve a three-dimensional problem of an accelerating strut.

9. Semiconductor Physics

Properties of ion implanted layers in elemental and compound semiconductors are studied. These include recrystallization effects, electrical activation, impurity profiles, and optical properties. Encapsulants for annealing GaAs are examined, and the nitrogen isoelectronic trap in ternary alloys is studied as a "model" deep level in these materials.

10. Digital Systems

Research in Fault-Tolerant Digital Systems covers the following three areas: (1) Fault-Tolerant Distributed Systems, including modeling of loosely coupled distributed systems and the development of design principles for reliable systems with high performance, (2) Self-Checking Systems, including new results on the interconnection of totally self-checking modules and self-checking using time rather than space redundancy, and (3) Methods of Fault Simulation and Testing, including the develop-

ment of a functional block level simulation language as a tool for fault analysis of microprocessors and other systems, and the development of diagnostic test procedures for semiconductor memories and microprocessors.

Research in Switching Theory and Design Languages deals with methods for minimizing programmable logic array realizations, the development of an algebra to aid in the realization of switching functions using a particular MOSFET package, and the completion of the development of a high-level system design language which, through its syntax, aids the designer in avoiding deadlocks or hang-up of the resulting control structure.

Research in Pipelined Processing covers five broad areas: model development, control of pipelines, effective design procedures, applications, and performance evaluation. Specific studies for this year are reported in the following areas: (1) Memory Management, including optimal dynamic allocation in a demand paging virtual memory, (2) Processor Organization, including an analysis of memory addressing architecture, trade-offs for multiple instruction stream processors, and direct execution processors, and (3) System Organization, including the evaluation of highly concurrent single stream systems, and multiprocessor systems, implementation trade-offs, and the design and construction of a multiple microprocessor system for computer architecture research.

Research in Data Bases and Retrieval Systems reports some new results on the extension of existing data models to generalize the applicability of the results and on the worst case and average cost measures for updates.

11. Display, Memory and Communication System Research

A demonstration of graphic communication system concepts has been developed using second generation intelligent terminals and distributed processing. The demonstration has been conducted using existing data communication networks such as ARPANET. Initial concepts relating to the human interface to graphic communication systems have been developed.

Low cost video/data disk concepts are being explored. A high speed, random access readout servo system design has been developed. Techniques for generating, storing and manipulating large bi-level images in the context of future communication systems have been developed and demonstrated.

12. Information Science

The work in computational techniques has been continued in two main directions: (1) Parallel computation, where new efficient procedures have been designed for sorting, matrix inversion, and solution of a number of graph problems; (2) Computational geometry, where new significant results in planar problems have been obtained on the medial axis and the kernel of a simple polygon; in multi-dimensional geometry, in the determination of a densest hemisphere. Finally, a general FFT-like algorithm has been developed to compute the discrete Fourier transform over a finite field.

In the area of data compression, the emphasis has been on universal schemes for variable rate sources, where we have demonstrated the existence of such schemes with single-letter fidelity criteria. Additional results concern the modeling of information sources and the compression of continuous-time sources.

Further research on estimation and filtering of signals and systems with uncertainties has produced significant results in three major areas: (1) Singular perturbation techniques applied to stochastic systems; (2) combined detection-estimation schemes; (3) decision-directed estimation schemes for fading channels.

Finally, in the area of multi-user digital communication systems, our research has concentrated on an asynchronous phase-coded spread-spectrum multiple-access (SSMA) communication system. We have identified the key code parameters that determine the communication performance of such a system, and have obtained several analytical results and efficient computational algorithms for these parameters. Other research on multiple-user communications has been an information-theoretic study of a single transmitter/many receivers system called a broadcast channel.

13. Advanced Automation

Progress has been made in a number of areas, including visual information processing and recognition, automatic manipulation and assembly, computer-aided decision making, natural language understanding, and human-computer interaction. Work in vision has resulted in vastly improved low-level processing for feature extraction and image compression, a novel parallel processing scheme for vision, and new methods for three-dimensional modelling and recognition using binocular views. Assembly and manipulation research has led to a novel, sensitive tactile sensing system, a system which allows arm control in the BASIC language and new routines for arm control via fast visual position feedback. In the area of computer-aided decision making, there are new results in planning and problem solving for inconsistent environments. Natural language research has led to the PLANES system which gives casual users access to a large data base, and to improved methods for dealing with general natural language. Work on human decision making and human-computer interaction has provided new data and models for allocating responsibility between humans and computers in multi-task situations, and for human performance in computer-aided fault diagnosis. A queueing network model for library networks has been developed and applied to the design of an interlibrary information system.

14. Information Retrieval Research

During the 1976-1977 time period the Information Retrieval Research Laboratory (IRRL) has conducted research on several aspects of information retrieval problems. Major projects include the following:

1) A hybrid approach to fact identification in natural language text using keyword and AI techniques;
2) A feasibility study for an automatic data base selector; and
3) A feasibility study for developing a union list of serials based on non-standardized machine-readable records.

15. Analog and Digital Circuits

In the Analog and Digital Circuits Group progress is reported for several areas of investigation. First, progress is reported on some simple but effective algorithms for the design verification of integrated circuit layouts. Due to their simplicity, these algorithms could easily be implemented on a minicomputer artwork system. Secondly, progress on the distortion analysis of transistor circuits is reported. In particular, the effect of the dc operating point on transistor amplifier distortion was studied. Thirdly, progress on the study of some novel digital filter structures which offer improved noise and sensitivity performance is reported. The structures are multiple feedback structures which show considerable promise in significantly reducing the wordlength in narrowband filters. Progress is also reported on a fourth project which is concerned with the reduced order modeling of large systems. The system is partitioned into subsystems and error minimization techniques are used to find a reduced-order all-pole model of each subsystem. Topological formulas are used to find the approximate behavior of the overall system. Lastly, progress is reported on the use of singular perturbation methods in the analysis of coherency in dynamic power systems and in the analysis of nonlinear oscillator problems

16. Decision and Control

Several projects have led to many results involving various aspects of control analysis, synthesis, and optimization. The key directions are control and decision strategies for systems under imperfect information, interactive software and microprocessor hardware for control systems, multimodel approach to structural uncertainty in large scale system theory, Stackelberg strategies for multicontroller systems, optimization methods, and system structural properties of stability, controllability and observability.

17. Population/Food/Weather Studies

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

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

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1.1 Semi-Conductor Surface Chemistry*

During the past year, two projects have been brought substantially to completion. In the first of these, the creation of monatomic overlayers by electron bombardment of a molecular gas has been explored. This effort is of interest, both for the fundamental information it may yield about the properties of chemisorbed gases, and for its possible technological implications in device fabrication. The initial studies have been carried out on a metal surface. However, having established the feasibility of the technique, applications to other substrates are planned. The second effort has focussed upon the role of defects in chemisorption. For the first time, direct evidence for the effect of a single step in accelerating the dissociation of gases has been obtained.

1.1.1 Formation and Stability of Surface Layers

Formation of surface layers by electron bombardment of adsorbed gases has been under continuing study. The aim is to reach an understanding of the factors affecting the thermal stability of such layers, which may be of use in high density devices. Work has been concentrated on a prototype system - nitrogen on the (110) plane of tungsten - for which preliminary studies were already reported last year [1].

Localized deposits of nitrogen are formed by electron beam writing, following the sequence illustrated in Figure 1.1. The surface

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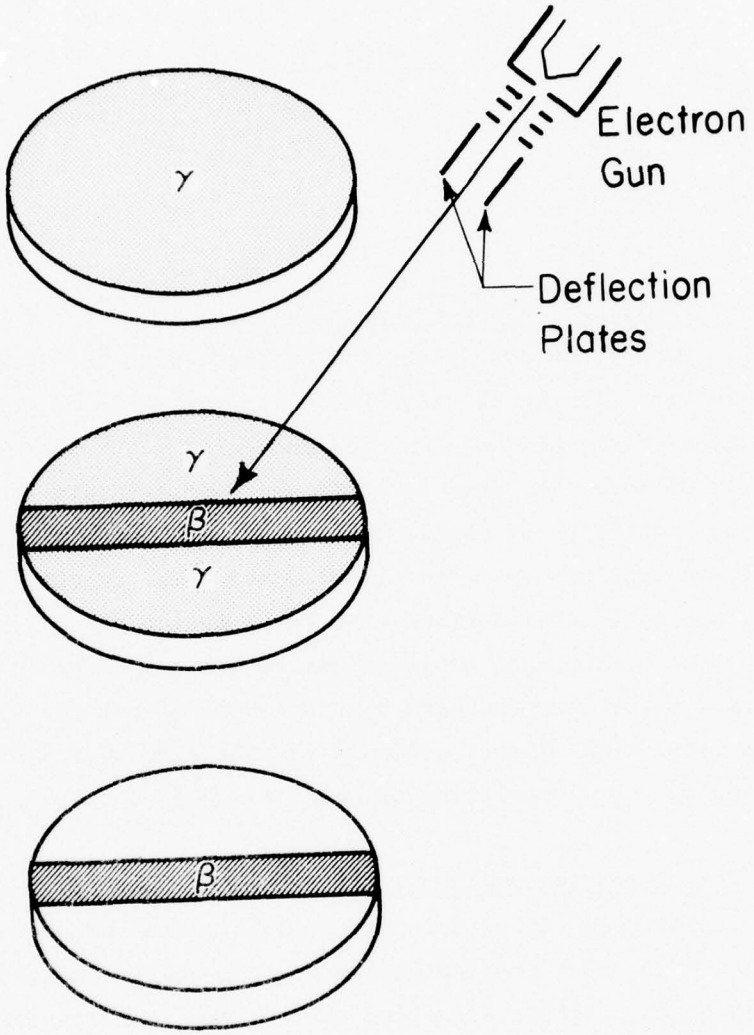

Figure 1.1 Creation of monatomic layers by electron bombardment.
Top - molecular γ-nitrogen adsorbed at T < 100°K on W(110)
Center - irradiation by electron beam, bringing about binding of nitrogen atoms
Bottom - warming to room temperature removes molecules, leaving behind a stable layer.

at low temperatures, $T < 100°K$, is exposed to molecular nitrogen, and a layer made up primarily of molecular γ-nitrogen is formed. This is irradiated by electrons, bringing about dissociation of the nitrogen into the atomic β-state, which is firmly affixed to the substance. The molecular gas is then removed from the surface by gentle warming.

Measurements have been completed to characterize the nature of these deposits, as well as the losses from them by surface diffusion or evaporation. Diffusion has been examined at initial nitrogen concentrations of 0.55 and 0.41 of a monolayer. The diffusion coefficient D is given as usual by the Arrhenius expression

$$D = D_0 \exp -\Delta E_m^{\ddagger}/RT \quad ,$$

where $\Delta E_m^{\ddagger}$ is the barrier to the diffusion and D_0 the prefactor, which provides some information about the dynamics of motion. The temperature dependence of the diffusion is shown in Figure 1.2. At an initial coverage of .55 monolayers, surface diffusion occurs over a barrier of 21.0 ± 2.2 kcal/mole, and with a prefactor $D_0 = 4.7 \times 10^{-2}$ cm^2/sec. At the lower starting concentration, the barrier is 21.3 ± 2.8 kcal/mole, with a prefactor $D_0 = 8.8 \times 10^{-2}$ cm^2/sec. The differences in these measurements are small and within the standard deviations of the results. No pronounced dependence upon the concentration of the starting deposit is evident; furthermore, diffusion appears to be entirely normal, and does not seem to be affected by the presence of steps or other defects on the (110) plane.

Evaporation of the nitrogen deposits formed by electron bombardment has also been examined. This has been done by observing concentration changes in the center of an extensive deposit of electron bombarded nitrogen, where transport by diffusion is unlikely to cause any significant depletion. Auger measurements have been used to sample the concentration after successive intervals at predetermined temperatures in the range above $T \approx 1000°K$. Desorption from such layers has been compared in Figure 1.3 with desorption from layers formed by ordinary dissociation at room temperature. The energy for desorption is comparable: 79.2 ± 5.1 kcal/mole for electron bombarded material and 76.9 ± 2.9 for ordinary nitrogen. That the chemical nature of the deposit formed by the different

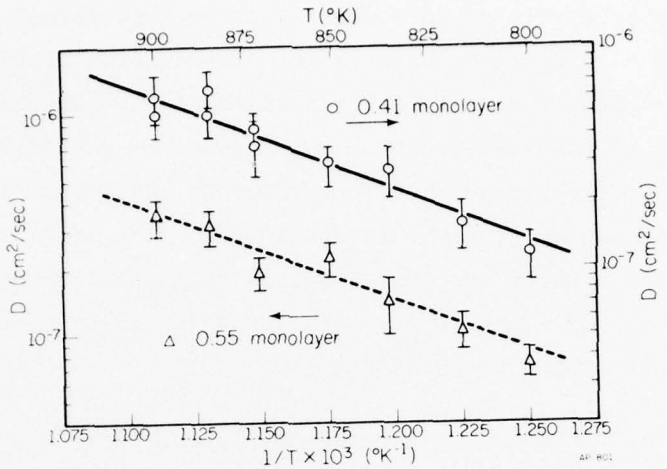

Figure 1.2 Temperature dependence of surface diffusion coefficient in nitrogen layers on W(110) at different initial concentrations.

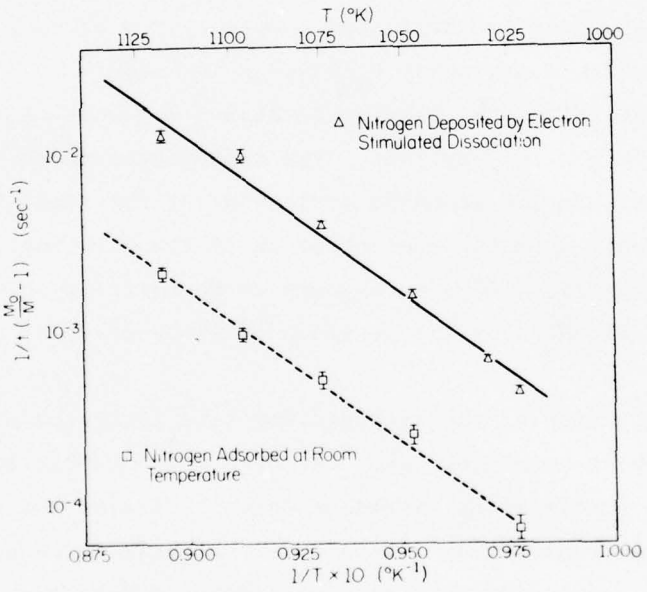

Figure 1.3 Temperature dependence of nitrogen evaporation from layers formed by electron stimulated dissociations and by ordinary adsorption at room temperature.

techniques is much alike has also been shown by contact potential studies, which reveal essentially no change in the electron emission when nitrogen adsorption occurs by either process.

Attempts have been made to infer the structure of nitrogen layers on the tungsten (110) using low energy electron diffraction. Layers formed by chemisorption at room temperature are limited to approximately a quarter of a monolayer. At that concentration, electron diffraction indicates a p(2 x 2) overlayer with all half-order spots split. This suggests an arrangement of nitrogen in which nearest neighbor sites are unfilled. Islands with the nitrogen atoms arranged in this manner are separated from each other by antiphase boundaries in the [100] direction, as indicated in Figure 1.4.

The structure of the higher concentration layers obtained by electron bombardment is not as clear. Depending upon the conditions of preparation, different LEED patterns have, in fact, been obtained. An unequivocal determination of the atomic arrangement at the surface is not possible from the data available. However, a likely structure for the overlayer usually obtained by electron bombardment is shown in Figure 1.5.

These measurements suggest that the primary difference between ordinary nitrogen overlayers, formed by thermal dissociation with the surface at room temperature, and layers produced by electron bombardment of molecularly bound gas, lies in the higher concentration achieved in the latter. The stability of layers produced by electron bombardment is limited primarily by surface diffusion, which occurs at temperatures in the range around 800°K. Evaporation is of concern only at significantly higher temperatures. On the smooth (110) plane of tungsten, on which all of these studies have been carried out, the ratio of the diffusion energy to the desorption energy is rather smaller than found in the past on higher index planes [2]. This is of interest for the understanding of chemisorbed layers. It does not appear to pose a practical problem, however, for the possible utilization of electron bombardment induced layers in devices. Although we have considered here a special case, namely the behavior of nitrogen on tungsten, electron bombardmend should make possible the formation of a variety of monatomic layers on solids; the possibilities inherent in this technique of forming surface layers will be explored further.

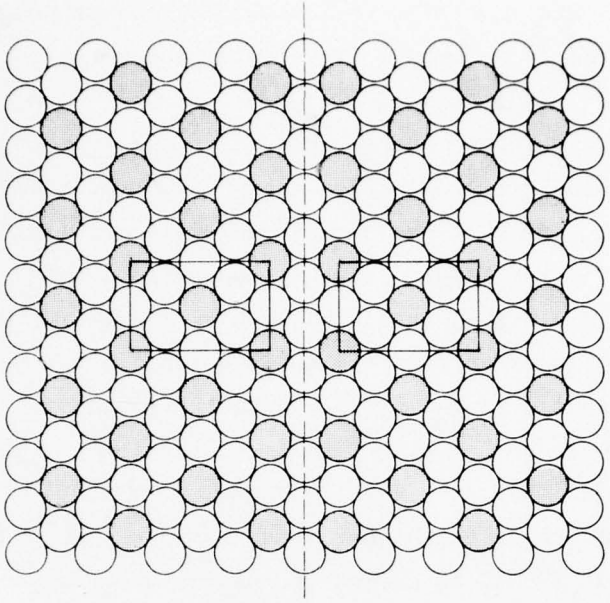

Figure 1.4 Arrangment of nitrogen chemisorbed in thermal process on W(110).

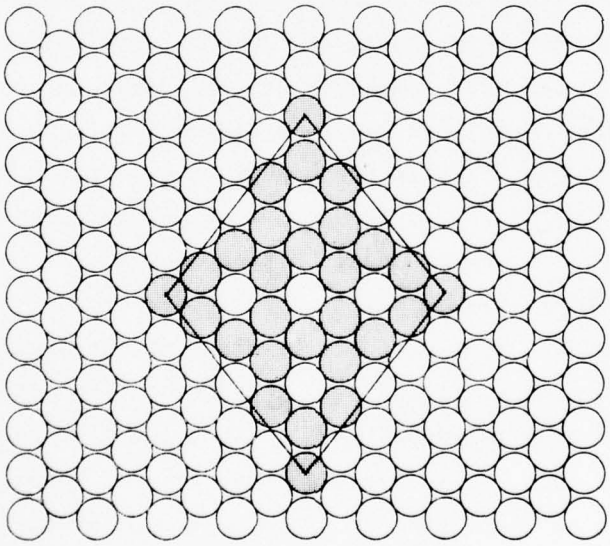

Figure 1.5 Possible structure of nitrogen overlayer produced by electrons stimulated dissociation.

1.1.2 Surface Structure and Reactivity

The role of structural imperfections in surface reactions has long been of interest [3]. In the past, however, it has been difficult to prepare perfect surfaces, or surfaces with well-characterized defects on them, to isolate the chemical effects of such imperfections. We have recently completed a series of studies to probe chemisorption of simple diatomic gases on perfect surfaces. This has been done using field emission from a selected area of a single crystal plane, using equipment previously described [4]. Adsorption affects the work function ϕ of the surface under study, and this change can then be used as an empirical indicator of adsorption.

Of particular concern has been the reactivity of densely packed planes in the dissociation of gases at a surface. In the interaction of hydrogen with tungsten, for example, it has been known for some time [4] that the (110) plane is relatively unreactive by comparison with the rougher surfaces surrounding it on a field emitter. Chemisorption does, however, occur eventually on this densely packed plane, once the remainder of the field emitter has been saturated. A very similar phenomenon occurs on rhenium, on which the basal plane shows an even more remarkable lack of reactivity when initially exposed to hydrogen [5], as in Figure 1.6. Such behavior has been rationalized on the assumption that chemisorption does not occur on the perfect surface itself, but rather on surrounding steps and other structural imperfections. The dissociation products then covers the flat surfaces by surface diffusion from the dissociation sites. The processes actually involved in adsorption on these perfect surfaces have now been clarified in two different ways - by preadsorption studies, and by measurements on surfaces with purposely introduced defects.

In Figure 1.7 is shown the work function of a W(110) plane on exposure to molecular hydrogen. As already indicated, at low temperatures, changes on this plane occur only when the remainder of the emitter has essentially stopped adsorbing. It has also been shown that N_2, which is rather more strongly bound on tungsten than hydrogen, does not immediately cover the (110) - it goes to the rough surfaces instead. Hydrogen adsorption has now been examined on a tungsten emitter previously exposed

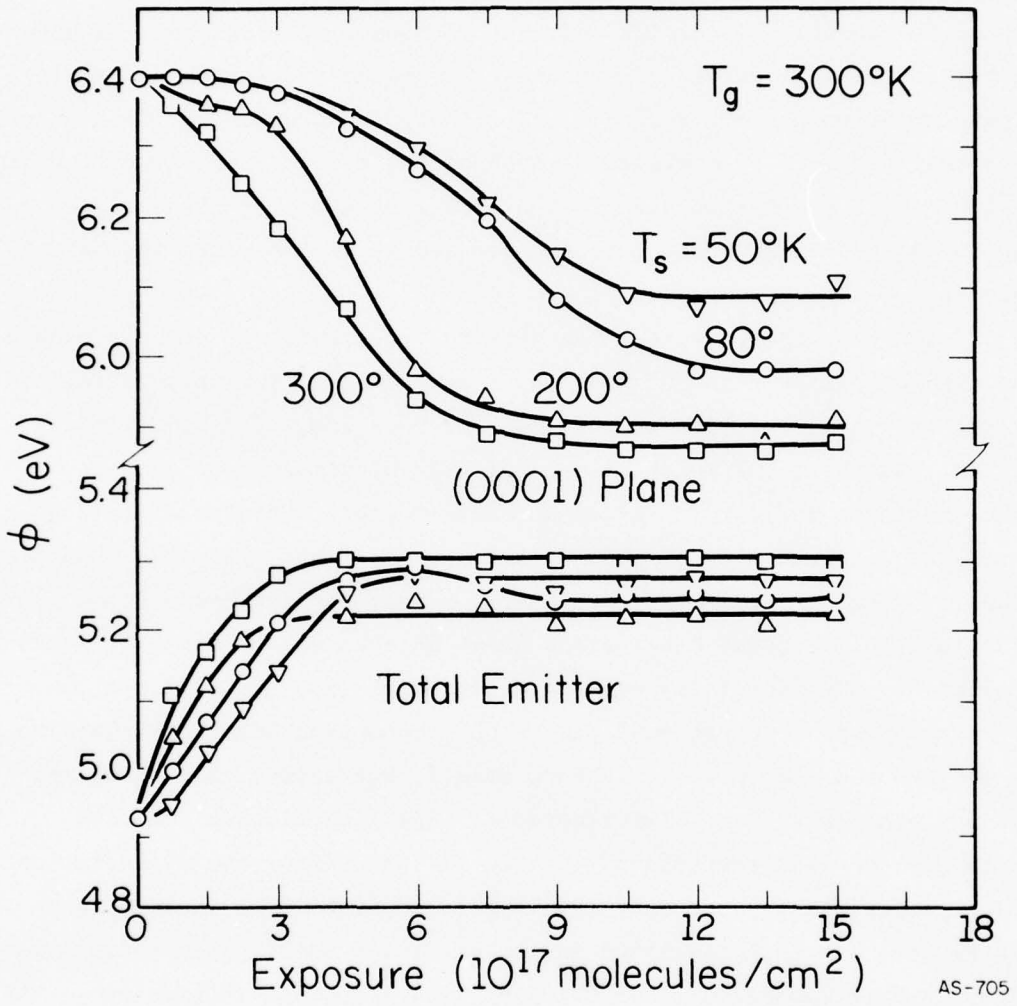

Figure 1.6 Hydrogen adsorption on (0001) plane of rhenium, compared to adsorption on total emitter dominated by rough planes.

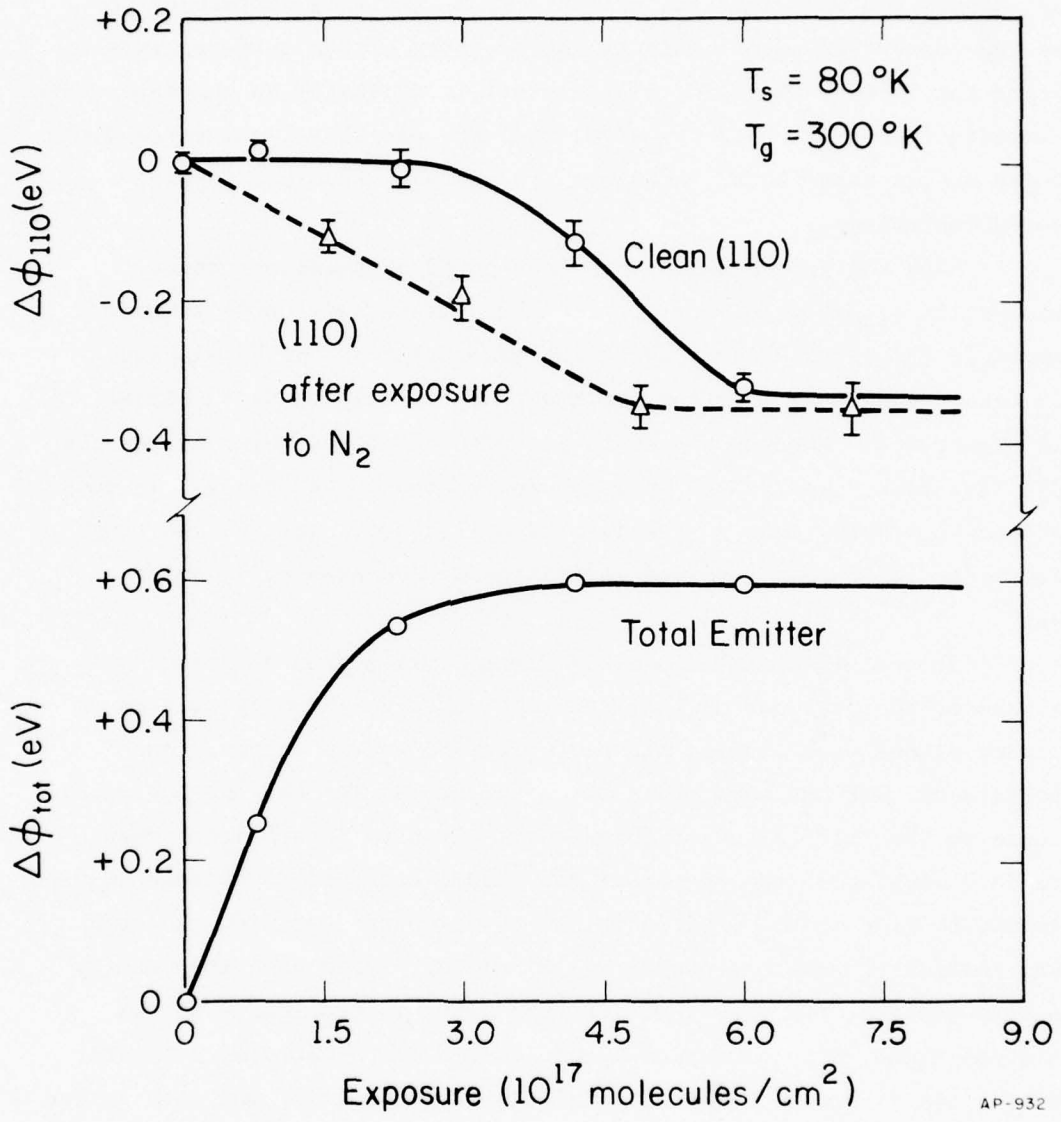

Figure 1.7 Hydrogen adsorption on W(110) plane of clean emitter, and on emitter with peripheral areas covered by nitrogen.

to nitrogen, so as to cover the areas surrounding the (110). The adsorption of hydrogen on such an emitter proceeds quite differently than on a virgin surface. As is apparent in Figure 1.7, the hydrogen immediately changes the work function of the (110). The only difference in these two adsorption experiments is in the state of the surfaces surrounding the (110) - the (110) plane itself is initially in the same state. The immediate adsorption on the (110) when the periphery is covered with nitrogen proves that the surroundings are actively involved in the dissociation process.

Much the same behavior has been noted on rhenium. There, chemisorption of nitrogen does not occur at all on the (0001) at room temperature [5]. Hydrogen or deuterium adsorption on the basal plane again takes place only when the remainder of the emitter is saturated, as in Figure 1.8. However presaturation with nitrogen, which leaves the (0001) face free, changes the hydrogen adsorption dramatically. It occurs immediately, proving that on rhenium, as well as on tungsten, the rough surfaces are intimately involved in filling up the atomically smooth planes.

That dissociative chemisorption on such planes is actually catalyzed by the presence of lattice steps has been shown by studies on low index planes with a small cluster preformed at the center. An indication of what has been found in these studies for the adsorption of hydrogen on the (110) plane of tungsten is given in Figure 1.9. When there is a cluster in the center of the plane, exposure to hydrogen causes an immediate rise in the work function, to be contrasted with the lack of any initial change on a perfect (110) plane. After hovering briefly on a high plateau, the work function then drops in two stages to its saturation value. The processes involved on a (110) carrying a cluster have been identified by computer simulation. The initial increase is due to direct chemisorption on the cluster edges. The work function subsequently decreases, as the (110) terraces are filled in by the catalytic action of the steps. Finally, in the last stage, the top of the clusters is covered by hydrogen.

The details of this work will be available soon. However, it is already clear from these studies that lattice steps can play a pro-

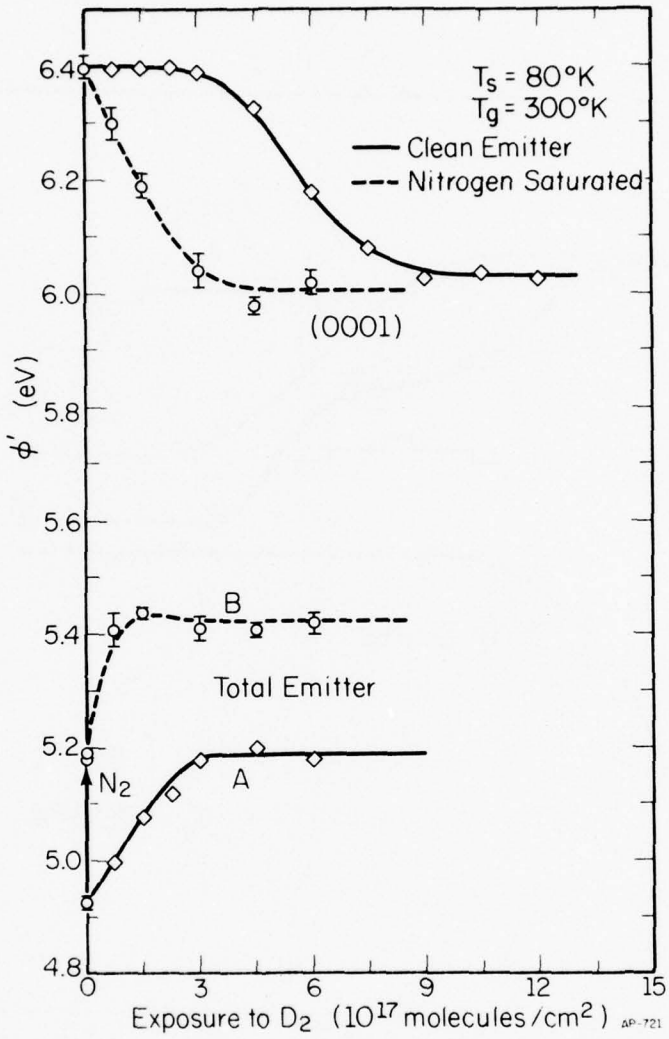

Figure 1.8 Deuterium adsorption on basal plane of clean and nitrogen saturated rhenium emitter.

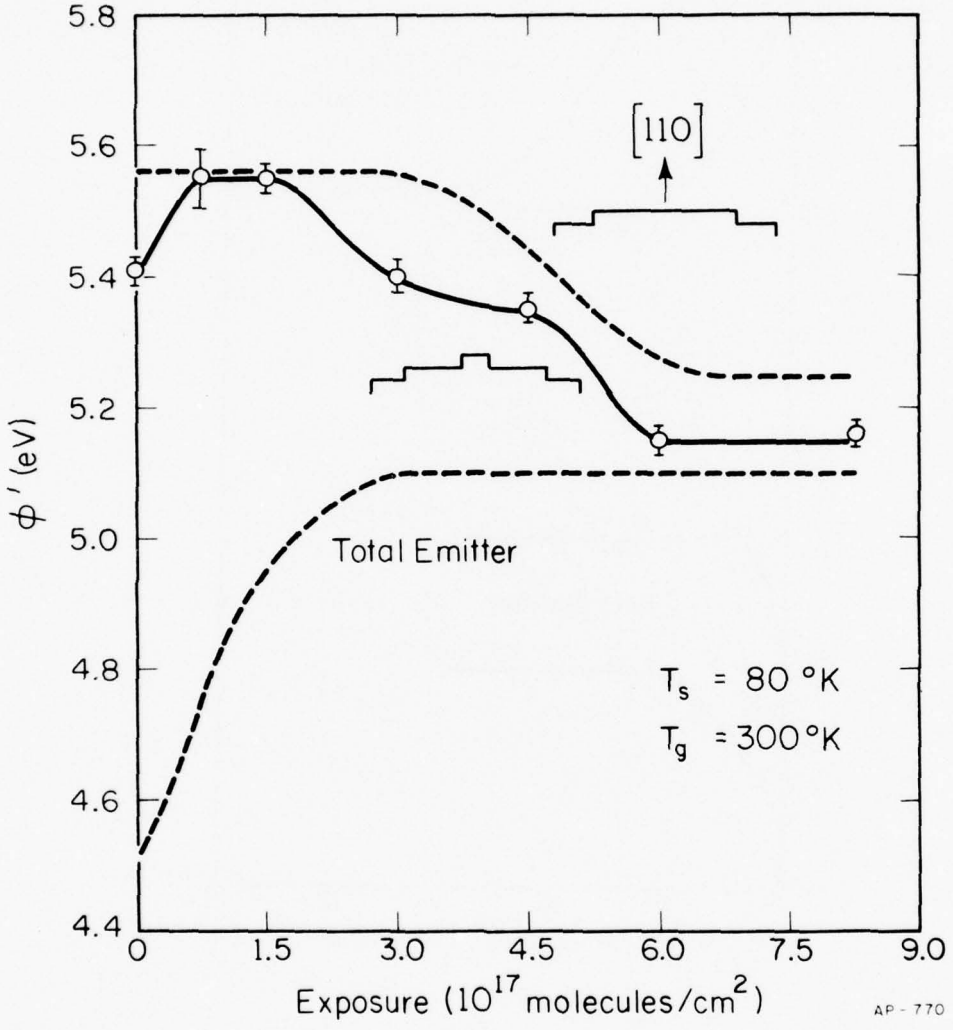

Figure 1.9 Hydrogen adsorption on perfect (110) plane of tungsten (top dashed curve) and on (110) with a small cluster at center (solid curve).

found role in catalyzing the reaction of gases on a solid; it is also clear from other work soon to be completed that these dramatic effects are limited to a few transition elements.

1.2 Atomic Exploration of Crystal Surfaces*

Work has been concentrated upon characterizing the surface behavior of atomic clusters. These are of interest in both the nucleation and growth of thin films; using the field ion microscope, it is for the first time possible to obtain quantitative data on their properties. In support of direct observations of such clusters, an extensive analysis of cluster statistics has been carried out [6]. The first problem examined is the extent to which the diffusion of dimers is affected by dissociation.

We have worked out the mean square displacement for dimers that can exist in an infinite number of states or configurations. If transitions between these states are governed by the rates α_i and β_i, shown in Figure 1.10, then the mean square displacement $\langle (\Delta x)^2 \rangle$ is given by

$$\langle (\Delta x)^2 \rangle = 4t\alpha_0 \frac{(1 + \sum_{i} \prod_{j=1}^{i} \alpha_j/\beta_j)}{(1 + \sum_{i} \prod_{j=0}^{i} \alpha_j/\beta_{j+1})} .$$

That dissociation can have an important effect on the mean square displacement, even if only a negligible percentage of the dimers is dissociated, is evident from estimates for a system modeled on the properties of rhenium on tungsten [7], with the potentials shown in Figure 1.11. The crucial parameter is the dissociation rate α_1. The barrier $\Delta E^{\ddagger}_{\alpha_1}$ opposing dissociation can be approximated by

$$\Delta E^{\ddagger}_{\alpha_1} = cE_2 + \Delta E^{\ddagger}_{\alpha} \qquad 0 < c \leq 1,$$

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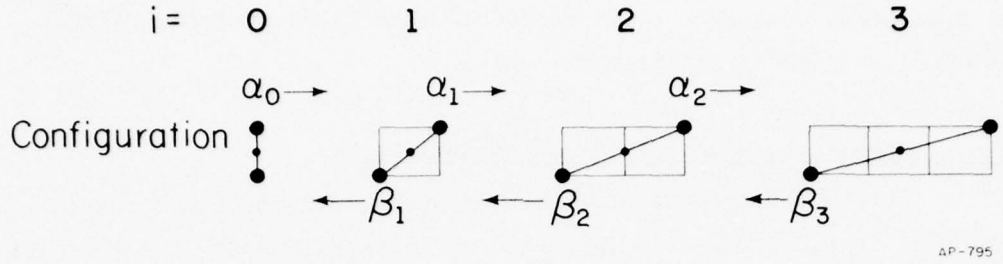

Figure 1.10 Rate constants for transitions between different dimer configurations.

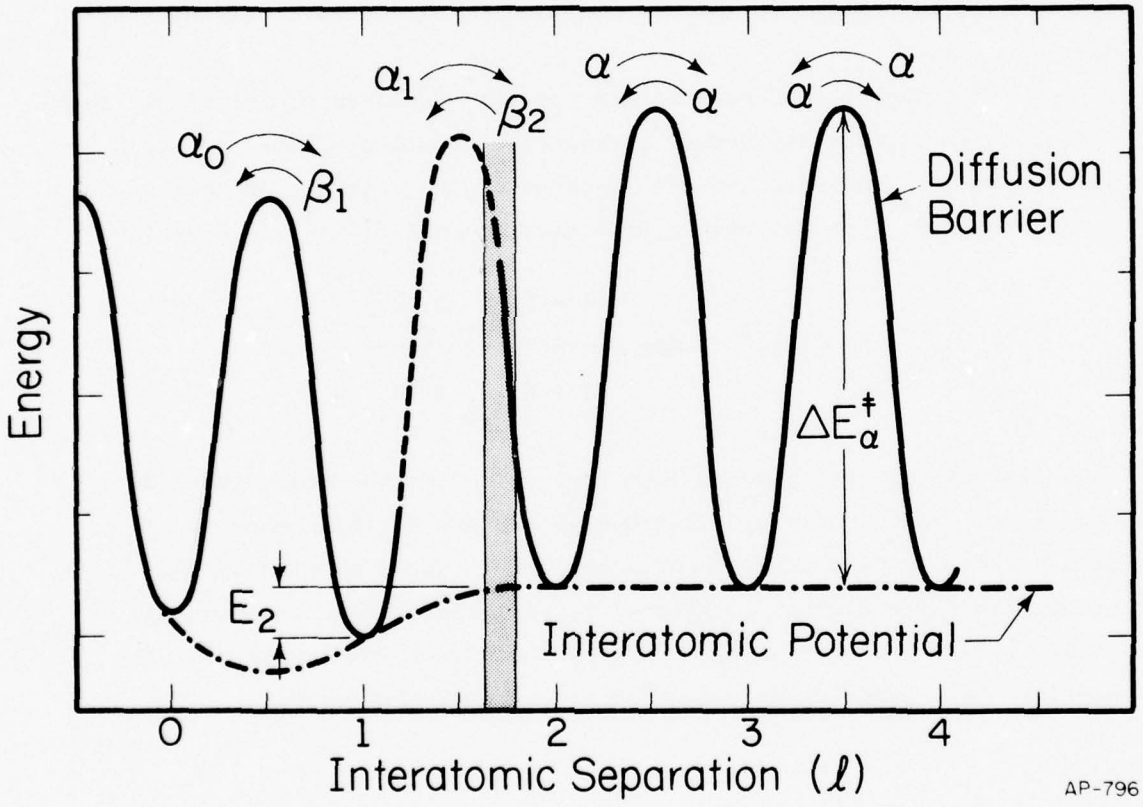

Figure 1.11 Potentials for dissociating dimer, modeled on behavior of Re on W(211). Shading indicates separation at which atomic interactions have become vanishingly small.

where $\Delta E_{\alpha}^{\ddagger}$ is the barrier to single atom motion and E_2 the energy difference between dimers in the staggered configuration and dissociated dimers. Estimates of the mean square displacement are now readily accessible. As shown in Figure 1.12, the specific assumptions about the rate of dissociation α_1 have the largest effect when the fraction dissociated, $[1 - (P_0 + P_1)]$, is very small. However, the absolute effect of dissociation upon the mean square displacement is essentially linear in the amount dissociated. With the formalism now developed, it is straightforward to correct experimental data for such effects.

In addition to the mean square displacement of clusters, the distribution functions governing the statistics of clusters are of interest as well. These have been been worked out explicitly for simple nondissociating dimers. Although the analytical expressions are complicated, the physical behavior is simple. Consider the probability p_X that after a time interval t the center of mass of a dimer be at a distance X from the origin. This probability is displayed in Figure 1.13 for different values of the constants a and b governing the rate of jumping from the straight to the staggered configuration and vice-versa. When the two rates are alike, the behavior of the center of mass is similar to that of an ordinary random walk and follows a Gaussian curve. However, when the rates of jumping are different, the probabilities show pronounced oscillations in going from even to odd sites.

Also important is the behavior of more complicated clusters, such as trimers. Although these pose special statistical problems, trimers are significant as a guide to the properties of higher aggregates. Considerable experimental information about trimers has been obtained in this laboratory. An analysis of trimer diffusion has therefore been carried out which should, in the future, allow a detailed examination of the diffusion process.

Experimental work has been concentrated upon establishing the energetics of interactions between atoms at a surface. This has been done in two ways: from observations of the distribution function and from measurements of dissociation. The former are especially interesting. Studies have been made of rhenium atoms in adjacent rows of the tungsten (321) plane. As indicated in the model in Figure 1.14, the (321) plane

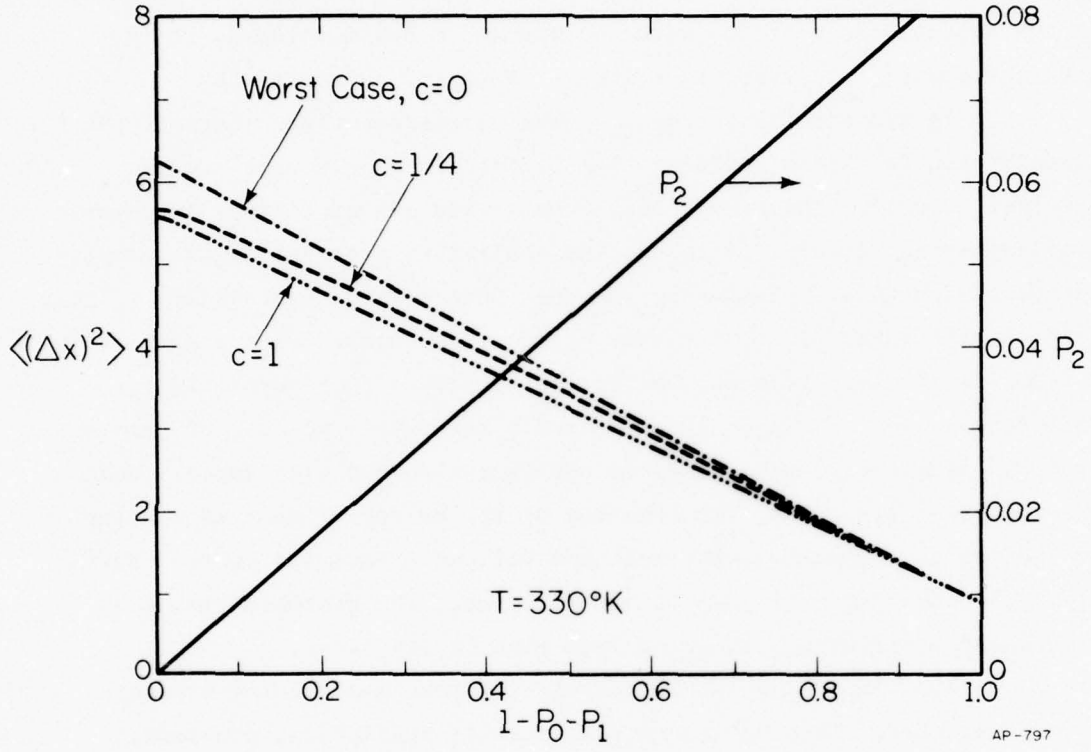

Figure 1.12 Effect of dissociation upon the mean square displacement of dimers. Fraction dissociated = $1 - P_0 - P_1$. Potentials as suggested in Figure 1.11.

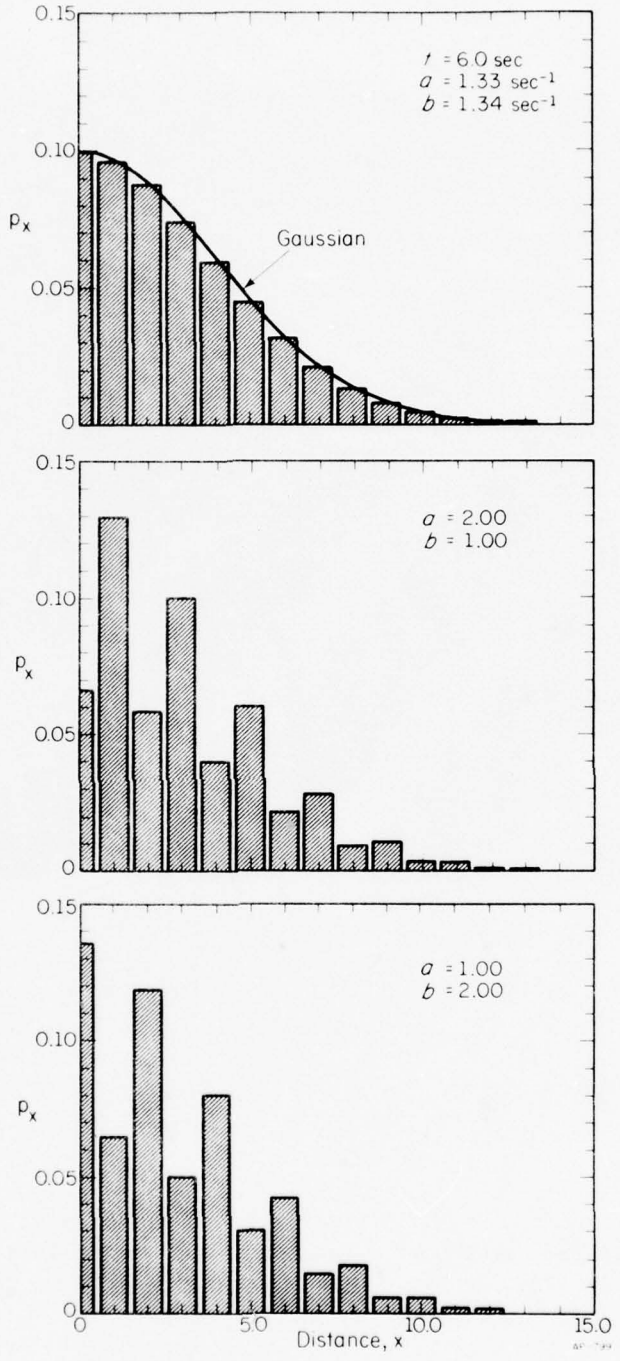

Figure 1.13 Probability of a non-dissociating dimer reaching a distance x from the origin at a time t, for different values of the jump rates a and b.

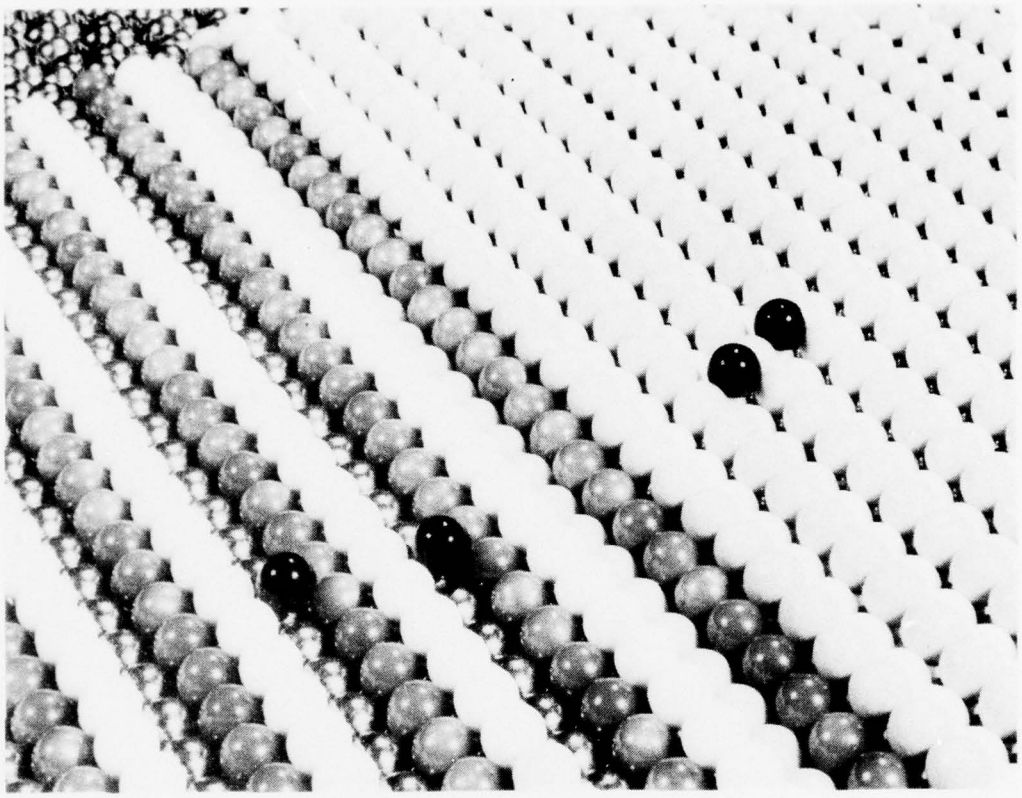

Figure 1.14 Hard-sphere model of a body-centered cubic lattice, showing (211) plane on the right and (321) on the left.

is made up of close-packed rows at a spacing (7.08 Å) somewhat larger than that of the (211) plane (4.47 Å). On this surface it has been possible to measure the equilibrium distribution of atoms as a function of the distance X between the atoms, projected along the close-packed rows. The probability p_X of finding two atoms separated by this distance is given by

$$p_X = C(2 - \delta_{X0})(L - X) \exp - W_X/kT,$$

where C is a normalization constant, δ_{X0} is Kronecker's symbol, L stands for the number of sites available in a row, and W_X represents the effective energy of interaction between atoms. From measurements of the probability p_X, it is therefore in principle possible to derive information about the strength of the forces operating between atoms.

In Figure 1.15 are shown actual measurements of the pair distribution function for rhenium atoms on the W(321). It is evident that at small distances there is a deficiency of pairs compared to what is expected for a random distribution of atoms; at somewhat larger spacings there is a slight excess. The observations suggest that there may be repulsive interactions operating between rhenium adatoms even at relatively large interatomic separations. These effects, as well as the dissociation of dimers on the (211) plane, are the subjects of continuing studies.

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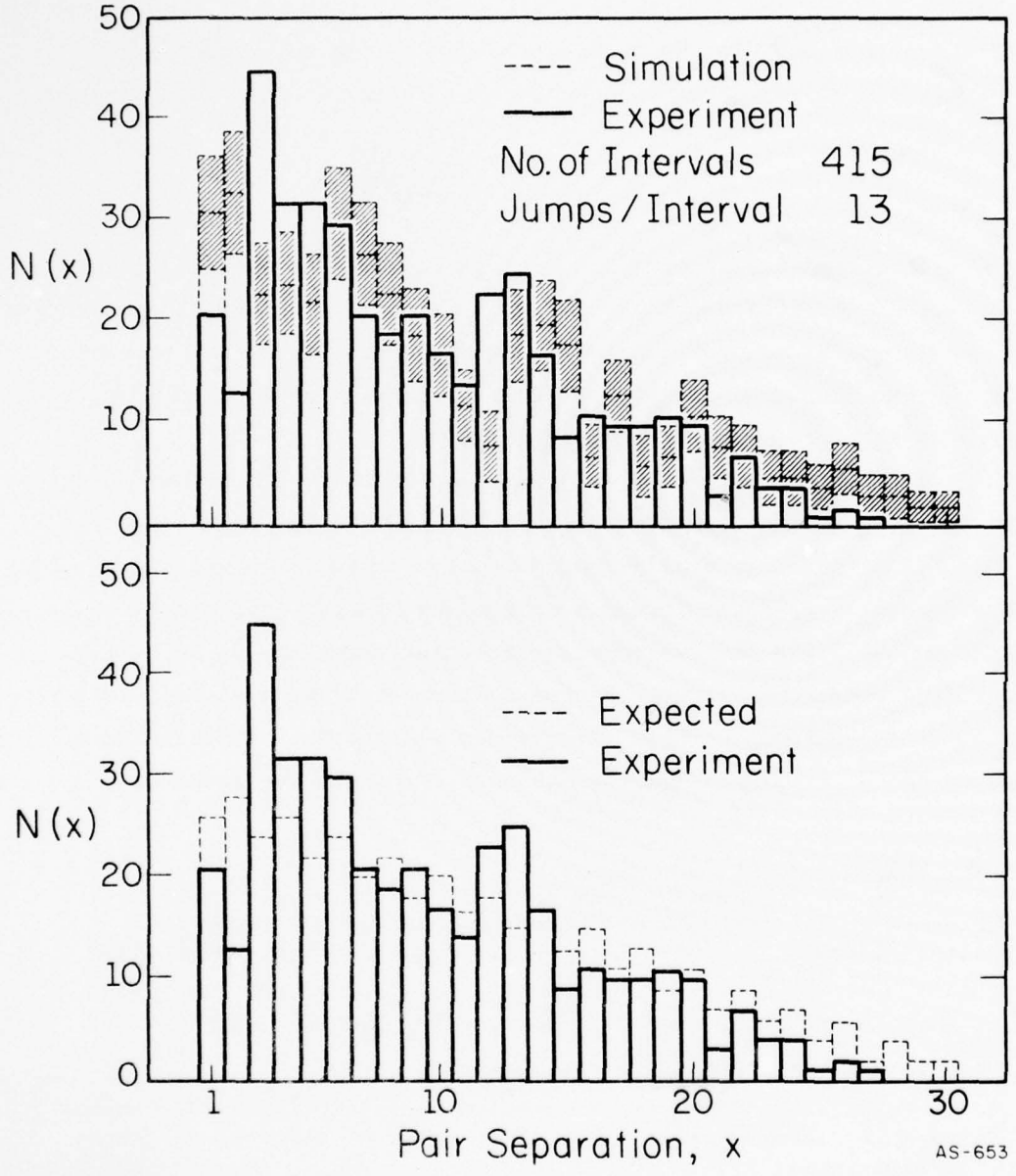

Figure 1.15 Distribution of Re pairs in adjacent channels of W(321).
Top - comparison of experiments with Monte Carlo simulation for pairs without interactions.
Bottom - experiments compared with random distribution. N(X) gives the number of pairs at a separation X.

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2.1 Introduction

The overall objective of this program is to investigate ion-surface interactions which have a controlling effect on the nucleation and growth kinetics, chemistry, and physical properties of alloy semiconducting films grown by sputtering. In support of this objective we have developed multitarget rf sputtering (MTS) techniques which allow independent control over elemental sputtering rates during steady state sputtering. Glow discharge optical spectroscopy (GDOS) has also been developed in this laboratory as an in-situ probing technique for obtaining real time analysis of the discharge, including the composition of sputtered species. Analytical models have been developed to predict preferential elemental sputtering rates and altered layer profiles in alloy targets as well as preferential elemental resputtering rates and ion bombardment enhanced diffusion in the growing film. Such calculations are supported by physical measurements. Deposited film properties, discharge probe measurements, and in-situ chemical analysis during growth are combined to yield information on elemental sticking probabilities, nucleation kinetics, impurity incorporation and site distribution, and film microstructure.

2.2 Ion-Surface Interactions

2.2.1 Preferential Elemental Sputtering*

Preferential removal of high yield species occurs during the initial stages of alloy sputtering. This continues until a steady state

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is reached at which the chemical composition of sputtered material is equal to the bulk target composition. A chemical gradient will then exist between the surface and the bulk, the width of which defines the so-called "altered layer" thickness. Preferential sputtering has been observed in a wide variety of alloys (see reference 1 for a summary).

The absolute magnitude and the time variation in the altered layer thickness and chemical profile during the transient sputtering period are of importance both to crystal growth studies and as basic parameters in sputtering and ion damage theory. Such information is also necessary in predicting film chemistry under conditions of bias sputtering. Preferential sputtering and altered layer thickness is a function of energy, mass and angle of incidence of bombarding ions; lattice atom masses and crystal structure and orientation; and target temperature and elemental diffusivities. Phenomenological models have been proposed to predict steady state surface compositions [2,3] and to estimate steady state altered layer thicknesses [4,5], but all such models have neglected diffusion effects and have assumed a steady state altered layer profile which is either rectangular or which is separable into a time dependent amplitude function and a time independent spatial function. Our approach has been to formulate the general problem in terms of mass balance accounting for both normal and ion enhanced diffusion. The problem is then to solve the differential diffusion equation

$$\frac{\partial\theta(x,t)}{\partial t} = \frac{\partial}{\partial x}\left[\tilde{D}(x)\,\frac{\partial\theta(x,t)}{\partial x}\right] \tag{1}$$

under the boundary conditions

$$\int_{x_o}^{\infty}\frac{\partial}{\partial t}\left[\theta(x,t)\rho(\theta)\right]dx = \theta(x_o,t)\left[\rho(\theta)v(t) - iS_A(\theta)\right] \tag{2}$$

$$\theta(x,t=o) = C(x) \tag{3}$$

$$\theta(x,t) \to C(x) \text{ as } x \to \infty \tag{4}$$

where $\theta(x,t)$ is the surface composition at time t after sputtering a distance x, $\tilde{D}$ is the ion bombardment enhanced diffusion coefficient,

$\rho(\theta)$ is the atomic density of the surface, $C(x)$ is the original concentration at position x, $v(t)$ is the surface recession velocity at time t, and $S_A(\theta)$ is the sputtering yield of A as a function of surface composition.

In principle an exact solution of the above equations can always be found provided that the functional dependencies of $\tilde{D}(x)$, $S_A(\theta)$, and $\rho(\theta)$ are known. In practice, experimental results are generally not available. Some information on $S(\theta)$ exists for the Cu-Ni system and experimental values of $\theta(t \rightarrow \infty)$ are available. We have therefore used Cu-Ni as our first model system. To handle $\tilde{D}(x)$, we have considered the altered layer to be composed of two regions as shown schematically in Figure 2.1. The first region is chemically homogeneous due to ion bombardment mixing effects. The thickness δ of this liquid-like layer is related to the damage distribution function as defined by Sigmund [6], and depends on the energy and incidence angle of the ions, the ion and lattice atom masses, the target stopping power, and the threshold energy for lattice atom displacements. For large values of the ratio v/D^*, the altered layer thickness X_c reduces to δ. Thus a measurement of X_c under these conditions, i.e. for high sputtering rates and low target temperatures, gives the value of δ for a given ion-target system at a given value of ion energy and incidence angle.

Laplace transforms have been used to solve equations (1)-(4) and some initial results for a 50/50 Cu-Ni target under 1 keV Ar^+ bombardment at a flux density of 1×10^{14} ions/cm^2 sec are given in Figures 2.2 and 2.3. Figure 2.2 shows the surface composition of Ni as a function of sputtering time for several values of $\tilde{D}$, while Figure 2.3 is a plot of the altered layer profile as a function of sputtering time (i.e. ion dose). Auger electron spectroscopy is being used to experimentally determine surface compositions as a function of time for different sputtering conditions, thus allowing $\tilde{D}$ to be calculated from the model. Similar computational techniques will then be used to investigate preferential sputtering in alloy semiconductors. In parallel with this work, section 2.2.2 below summarizes experimental efforts designed to directly measure $\tilde{D}$ as a function of both substrate

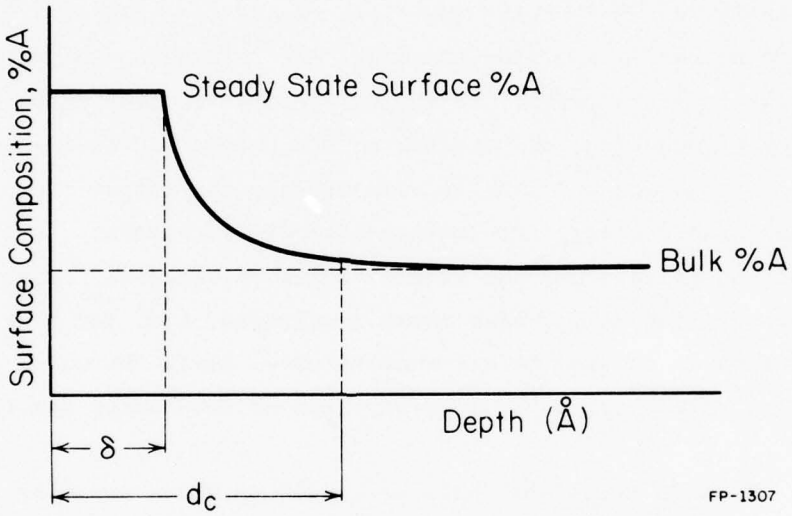

Figure 2.1 Change in composition as a function of depth surface due to ion bombardment.

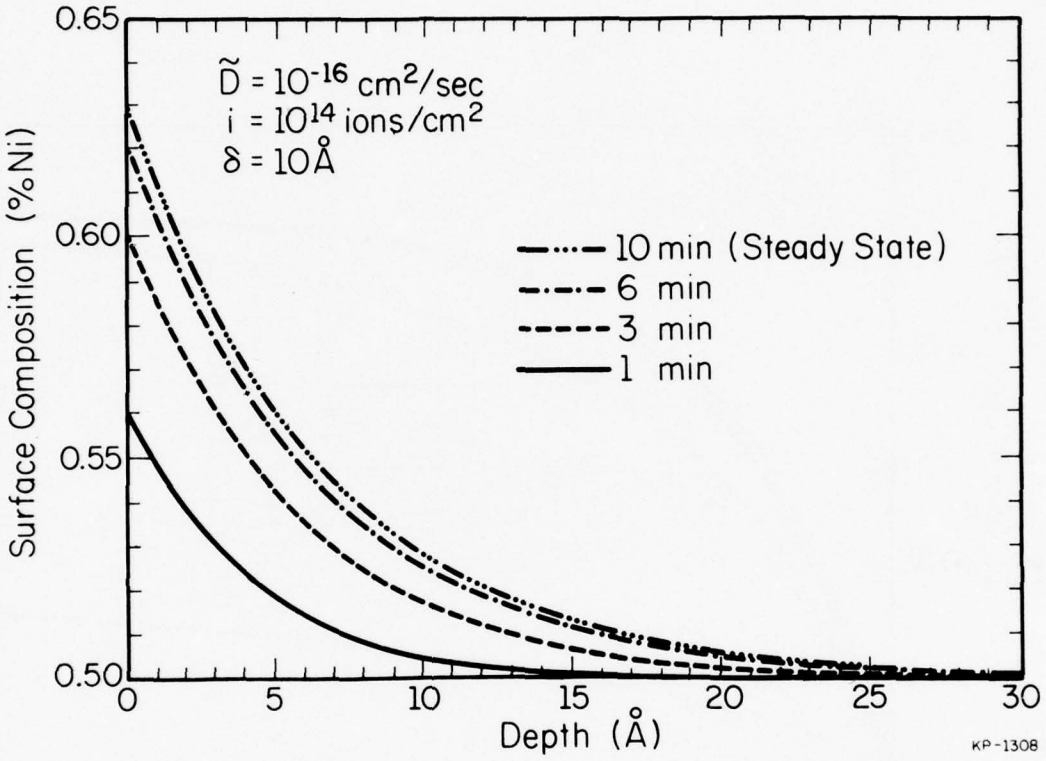

Figure 2.2 Altered layer composition profiles during transient sputtering of a 50/50 Cu-Ni alloy.

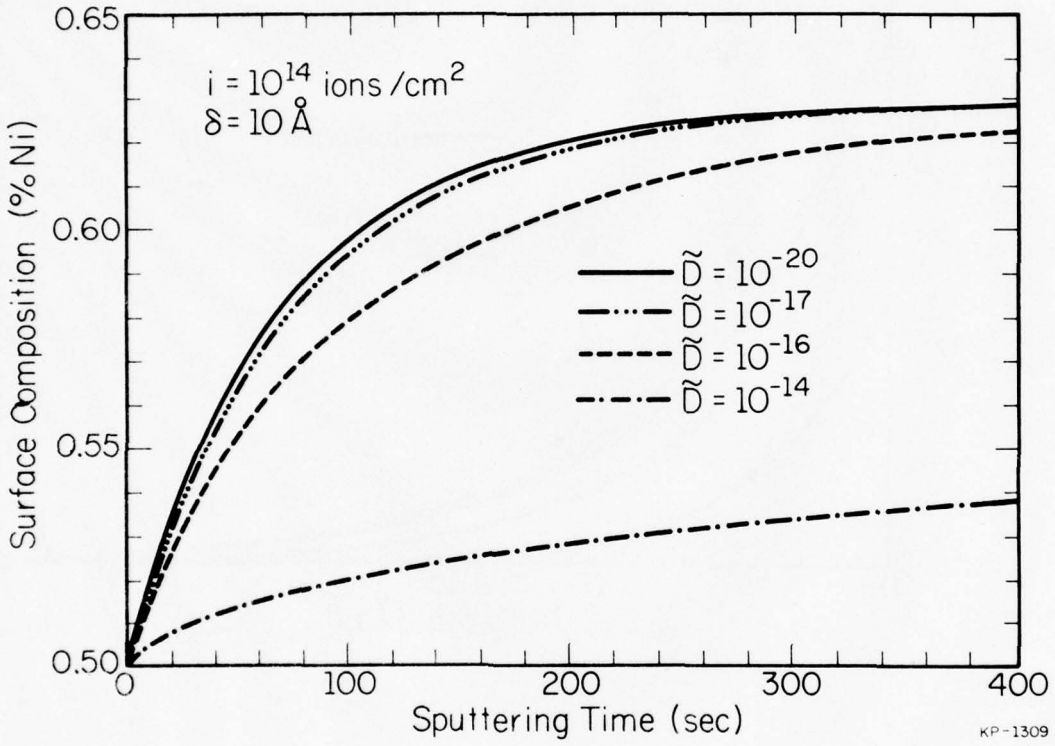

Figure 2.3 Effect of interdiffusion coefficient $\tilde{D}$ on the transient sputtering time of a 50/50 Cu-Ni alloy.

temperature and ion bombardment using sputtered superlattice structures.

2.2.2 Ion Bombardment Enhanced Interdiffusion*

Elemental interdiffusion at sputtered InSb/GaSb layer boundaries is being investigated as a function of film growth temperatures, ion bombardment during growth, and post annealing conditions. For this work, superlattice structures with layer thicknesses ranging from 12.5 to 50 Å have been deposited by MTS (see section 2.3.1) on both InSb coated Corning 7059 glass slides and ⟨100⟩ oriented single crystal Si wafers. InSb/GaSb interlayer diffusion is then studied using x-ray diffraction techniques in which the intensity of satellite peaks around the Bragg reflection peaks are monitored as a function of annealing time [7].

Diffraction theory [8,9] predicts satellite peaks at angles of $\theta_{\pm}$ about the Bragg reflection at θ_B when the diffracting crystal planes are stacked with a small wavelength sinusoidal modulation in atomic scattering factors and/or interplanar spacing. θ_B is the Bragg angle for the average film composition. The angles $\theta_{\pm}$ are related to the x-ray wavelength λ and the modulation period Λ by

$$\sin \theta_{\pm} = \sin \theta_B \pm \frac{\lambda}{2\Lambda} \qquad (5)$$

A non-sinusoidal periodic modulation, such as a square wave, can be represented by a Fourier series of increasing harmonic frequencies resulting in higher order satellites at increasing separations from θ_B. When the sample contains a modulation in both the scattering power and the interplanar spacing, the satellite peak intensities $I_{\pm}$ will in general not be equal.

Figure 2.4 shows x-ray spectra from two multilayer films grown on InSb-coated 7059 glass at 250°C. The layer thicknesses calculated from the satellite spacings were 18 Å and 23 Å. The average film

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

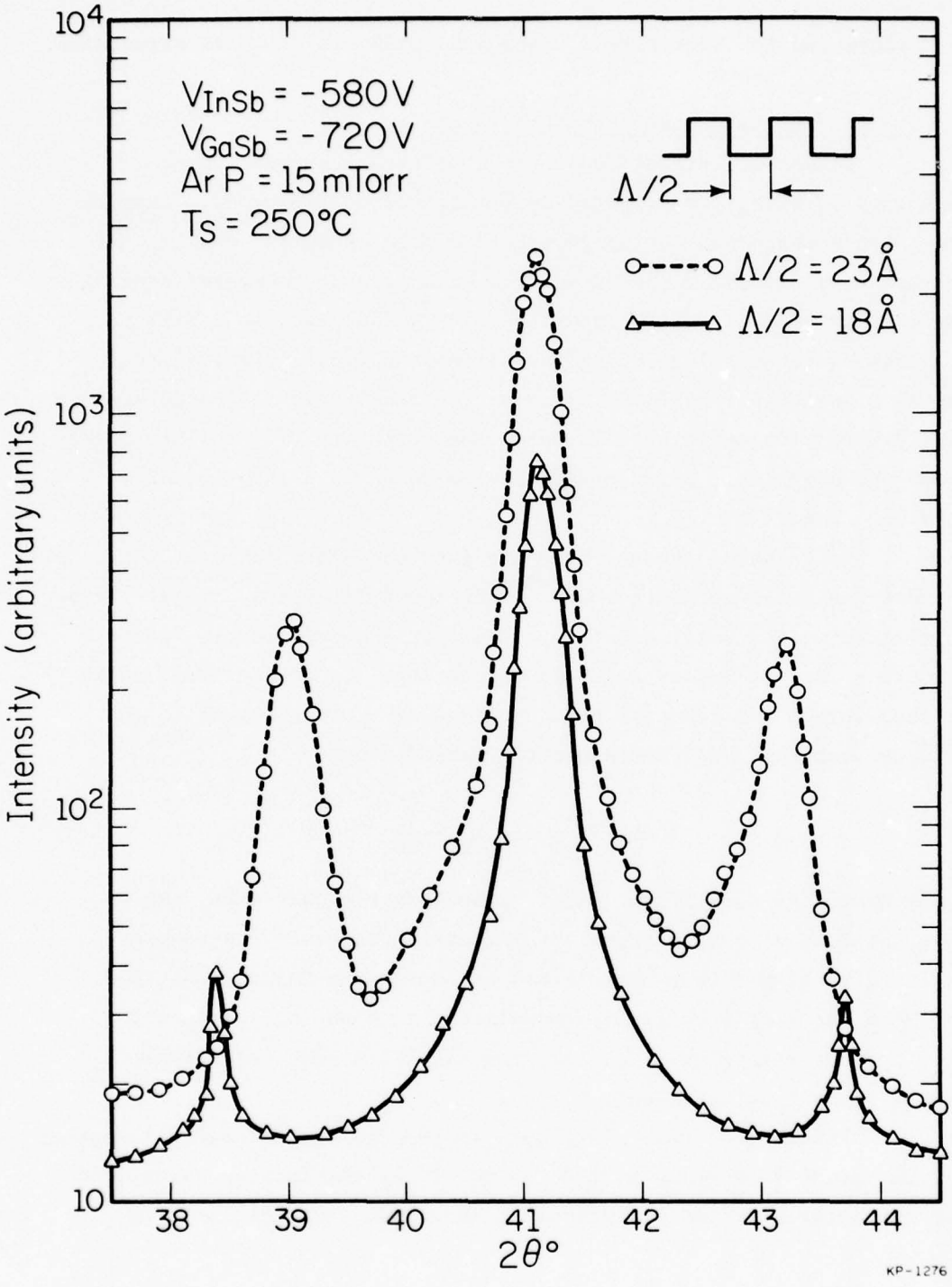

Figure 2.4 X-ray spectra from InSb/GaSb superlattice structures grown on InSb-coated 7059 glass at 250°C.

composition was determined from the position of the Bragg peak to be, assuming Vegard's law, $In_{0.49\pm.09}Ga_{0.51\pm.09}Sb$. This is in good agreement with predictions from standardized InSb and GaSb deposition rate curves.

The satellite peak intensities decay upon annealing and following an initial transient period during which recrystallization and grain growth may occur, the satellite peak intensity at time t may be related to the initial intensity I(0) by [10,11]

$$\ln \frac{I(t)}{I(0)} = - 2\beta(h)\, \tilde{D}t. \qquad (6)$$

$\tilde{D}$ is an interlayer diffusion coefficient and $\beta(h)$ is a geometric factor, which for cubic crystals is given by

$$\beta(h) = \frac{1}{a^2} \sum_p [1 - \cos\{\underline{k}(h)\cdot\underline{X}(p)\}]. \qquad (7)$$

In the above expression, a is the lattice constant, $\underline{X}(p)$ is the nearest neighbor vector, and $\underline{k}(h)$ is the wave vector of the composition modulation. Note that for large values of $\underline{k}(h)$, $\beta(h)$ approaches $|\underline{k}(h)|^2$.

Samples grown at 250°C on InSb-coated 7059 glass with layer thicknesses of 18 and 21 Å respectively were used in the diffusion studies. Annealing of the encapsulated samples was carried out in air at 320°C for times ranging up to 300 h. The results for I_- are plotted in Figure 2.5. After an initial non-linear decay due to structural changes in the films, the slope of I vs annealing time attained a constant value as predicted by equation (6). From the data in Figure 2.5, a diffusion coefficient of 3.9×10^{-21} cm^2/sec was calculated for the 21 Å layer film and 5.1×10^{-21} cm^2/sec for the 18 Å layer film. The agreement is within experimental uncertainty. Analysis of I_+ intensity results also showed excellent agreement.

Recently, similar results have been obtained for InSb/GaSb structures on Si where strong preferred orientation is observed. Presently we are using x-ray analysis of sputtered superlattices to investigate the dependence of $\tilde{D}$ and the activation energy $\tilde{Q}$ on ion bombardment and film growth temperature. Initial results have indicated

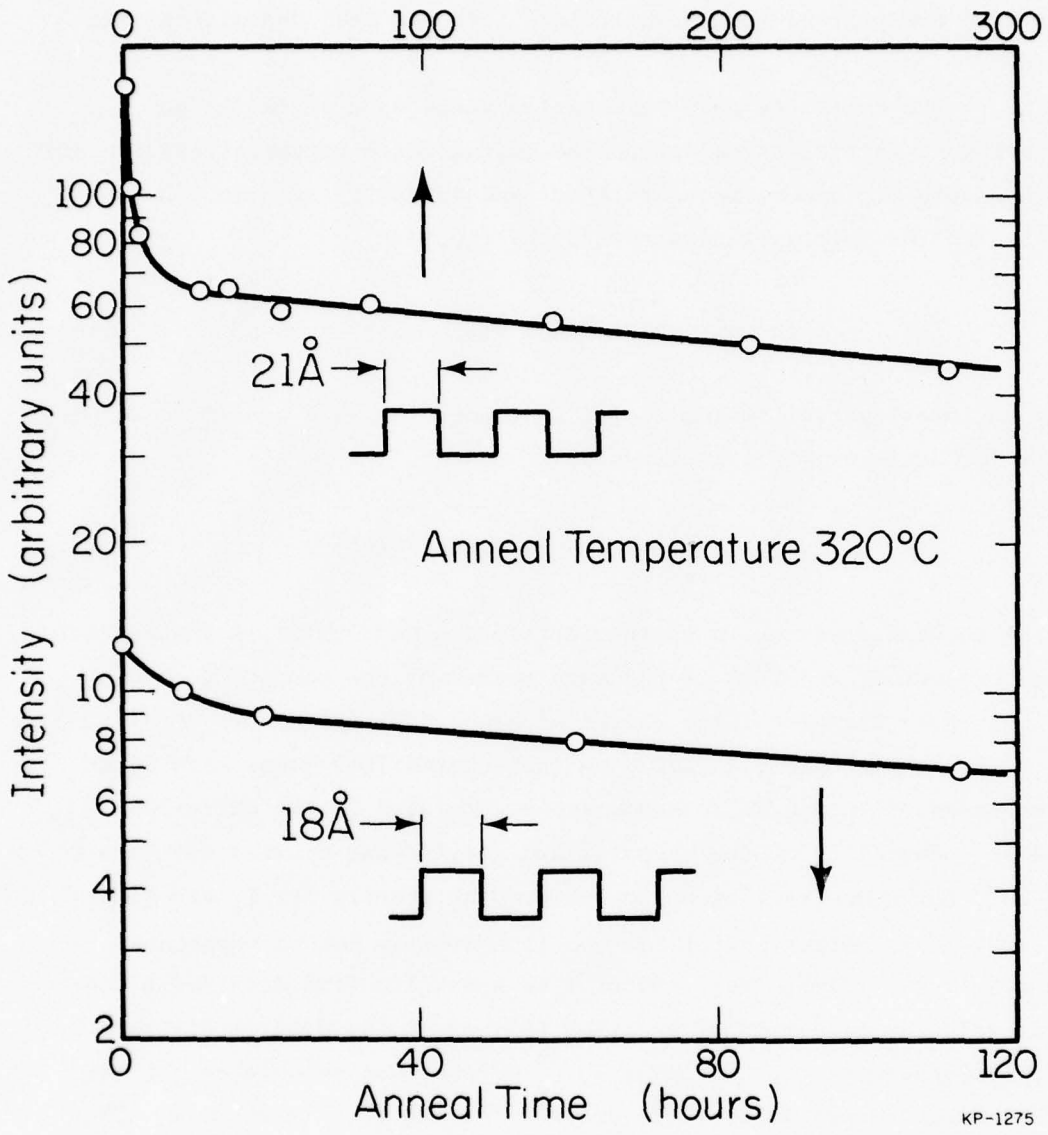

Figure 2.5 A plot of the satellite intensity as a function of annealing time at 320°C for samples with layer thicknesses of 18 Å and 21 Å respectively.

significant increases in $\tilde{D}$ with increasing ion bombardment flux during film growth at elevated temperatures.

2.2.3 The Nature of the Transition Region Formed Between the Film and the Substrate During Crystal Growth Under Ion Bombardment*

The chemistry and microstructure of the interfacial layer formed between rf bias sputtered TiC films and steel substrates have been investigated as a function of substrate growth conditions using auger electron spectroscopy and transmission electron microscopy [12]. Chemical information was obtained using point-by-point independent micro-stylus and auger measurements. A dc bias (V_s) ranging from 0 to -1000 V was applied to the steel substrate during the initial 5 min of film deposition. It was found that under bias sputtering conditions in the presence of small partial pressures of oxygen, C was preferentially resputtered as oxygen was incorporated. A transition region was thus formed between the steel substrate and the bulk TiC film.

A transition layer profile is shown in Figure 2.6 for a film grown at a substrate temperature, T_s, of 120°C and V_s = -1000 V. Electron diffraction in conjunction with auger spectroscopy was used to determine the phases present. The distribution of these phases was, in order, Fe, $FeTiO_3$, TiO_2, and TiC. The width of the transition region, w, which ranged up to 3000 Å, increased with increasing V_s. w was not particularly sensitive to the substrate temperature during growth (T_s) except at high values of V_s where one might expect to obtain ion bombardment enhanced diffusion. Increased film substrate adhesion previously observed to be related to both V_s and T_s are explained by the formation of a wide chemically graded transition region in which successive phases exhibit mutual solud solubility.

2.3 Crystal Growth by Sputtering

2.3.1 Decoupled-Plasma Multitarget rf Sputtering**

Multitarget sputtering was developed (see Progress Report, 1976)

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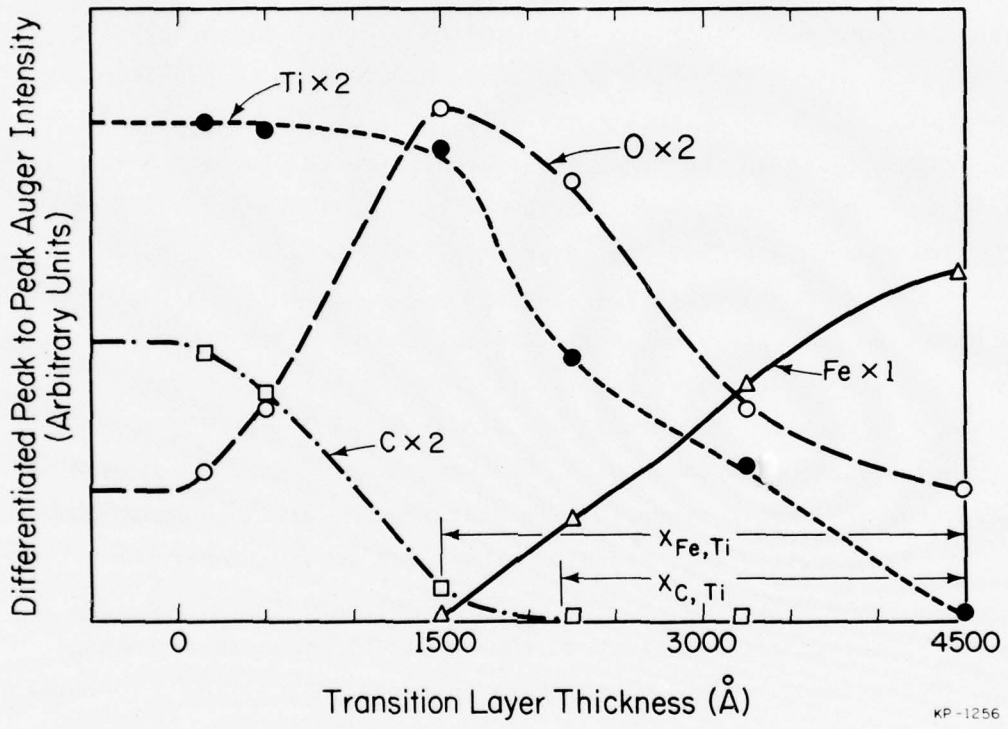

Figure 2.6 Point by point depth profile of TiC - Steel interface. TiC was deposited at T_s = 120°C, V_s = -1000 V.

in order to have a technique for growing alloy semiconducting films in which one has independent control over elemental sputtering rates. With MTS it is possible to grow single crystal films of single phase alloys with any desired composition or compositional spatial variation. The substrate is continuously rotated through two or more electrically or physically isolated sputtering discharges and the film is formed by sequential deposition of material from each target. Results from work discussed in section 2.2.2 showed that for InSb and GaSb targets, in order to obtain chemically homogeneous $In_{1-x}Ga_xSb$ films, the layer thickness deposited per target pass had to be on the order of, or less than, 1 monolayer for the growth conditions investigated.

During the past year we have developed a model for quantitatively predicting the chemical composition and film thickness distributions of alloy films deposited by MTS [13]. The film thickness distributions deposited from each target are expressed in terms of deposition variables such as applied target voltage, target radius, sputtering pressure, substrate rotation radius, rotation rate, and target-substrate separation. A schematic diagram defining these parameters is given in Figure 2.7. The vol % of element j at rotating coordinates (x',y') on the substrate plane is just given by

$$\text{vol \% } j\ (x',y') = \frac{m\ \lambda_j(x',y')}{\lambda_T(x',y')} \times 100 \qquad (8)$$

after m rotations where $\lambda_j(x',y')$ is the normal film thickness deposited per target pass at (x',y') from the jth target and λ_T is the total deposited film thickness at (x',y'). $\lambda_j(x',y')$ can be written as

$$\lambda_j(x',y') = \frac{1}{\omega}\ \eta_j\ R_j(o,o)\ G_j(x',y') \qquad (9)$$

where $R_j(o,o)$ is the measured deposition rate at (x'=o,y'=o), η_j is an experimentally determined constant which is a function of geometry and sputtering pressure, and $G_j(x',y')$ is the film thickness distribution function in the rotating coordinate system which is essentially a transformed von Hippel function. Measured and calculated film thickness distributions are shown to be in good agreement along both

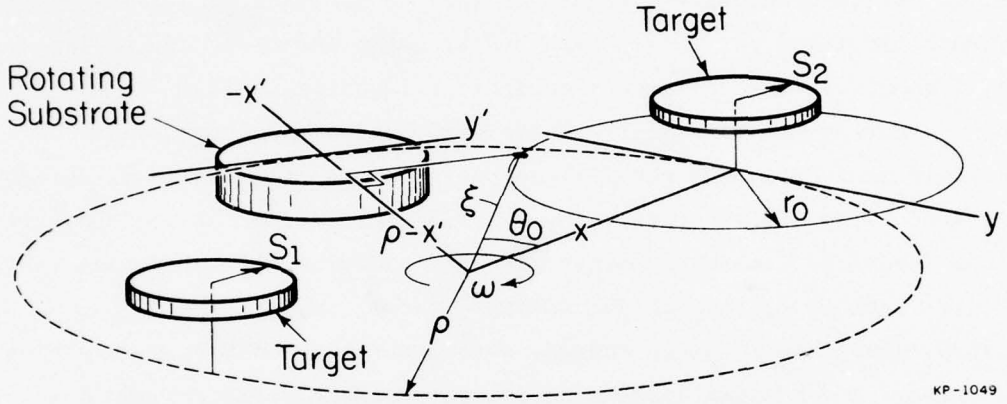

Figure 2.7 A schematic diagram defining the geometric relationship between the target and the rotating substrate in a multitarget rf sputtering system.

x' and y' axes in Figures 2.8 and 2.9. Deposited film thickness is uniform to within 5% over 30 cm^2. Figure 2.10 shows the agreement between measured and predicted $In_{1-x}Ga_xSb$ film composition.

2.3.2 $In_{1-x}Ga_xSb$ Film Growth*

Single crystal $In_{1-x}Ga_xSb$ films have been grown by MTS at temperatures much lower than those reported by other techniques [14,15,16]. Substrate heating due to particle bombardment and plasma radiation have been accounted for. A sharp increase in the crystalline transition temperature occurs for films containing greater than 75 mole % GaSb and is related to the sharp increase in the equilibrium solidus temperature in this composition range. Studies of the nucleation characteristics of these films is presently being carried out. The possible effects of particle bombardment during sputter deposition on film nucleation characteristics, such as an increase in preferred adsorption sites, have been reviewed by the author [17].

The sticking probabilities of impinging species during film growth by MTS is also being investigated. The n-type carrier concentration in InSb and In-rich $In_{1-x}Ga_xSb$ films varies from $\sim 5 \times 10^{16}$ cm^{-3} to 5×10^{-18} cm^{-3} depending on sputtering conditions. The donor states in this concentration range have been shown to be related to Sb vacancies. Indium sticking probabilities as a function of T_s and V_s have been determined in the MTS system using a known impingement flux of In and Sb atoms from an InSb target and varying the impingement flux of additional In from a pure In target. The measured carrier concentration in deposited films was found to decrease with increasing excess In impingement until a minimum value was reached for a given set of deposition conditions. Further increases in In flux eventually lead to the precipitation of metallic Sb.

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

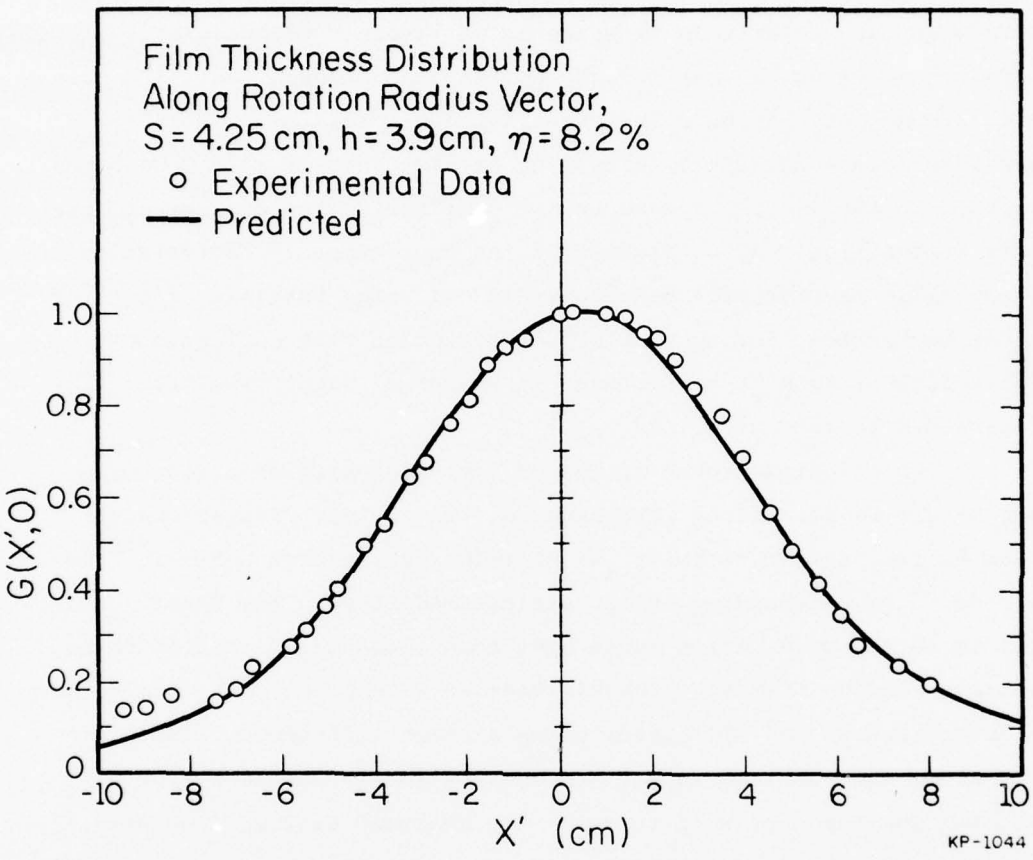

Figure 2.8 Rotating substrate thickness distribution along the x' axis for rf sputter-deposited InSb. The film was deposited at V = 1000 V, p = 15 mTorr (2 Pa), ω = 3 rev/min, and h = 3.9 cm.

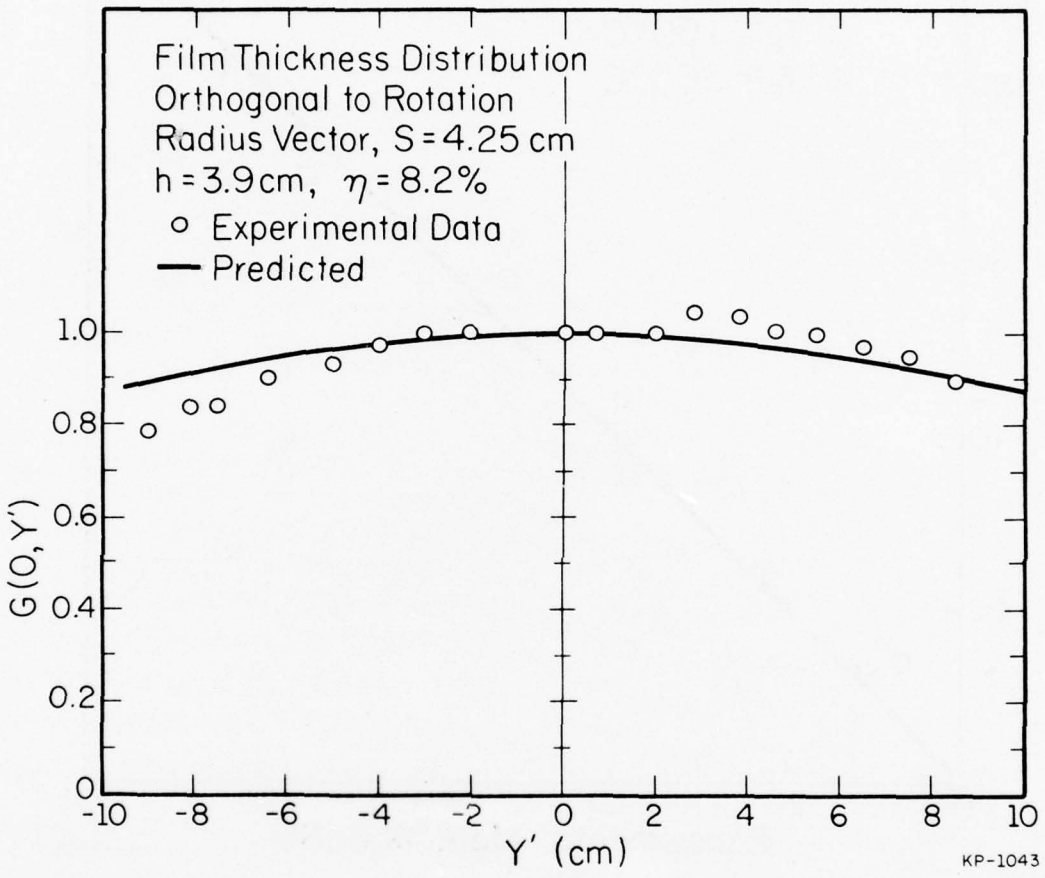

Figure 2.9 Rotating substrate thickness distribution along the y' axis for rf sputter deposited InSb. The film was deposited with V = 1000 V, p = 15 mTorr (2 Pa), ω = 3 rev/min and h = 3.9 cm.

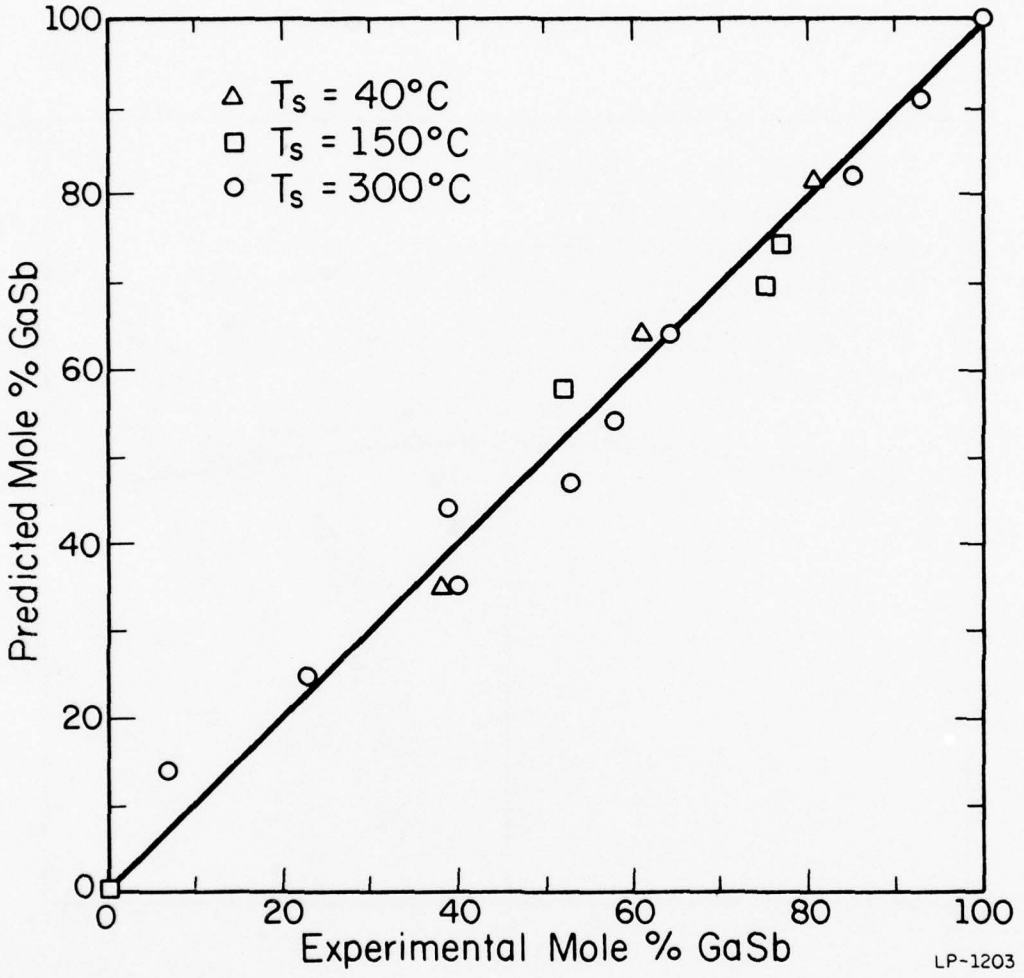

Figure 2.10 Measured $In_{1-x}Ga_xSb$ alloy composition as a function of the predicted composition.

The incorporation rate and mechanisms of both reactive and noble gases in sputtered films and their effects on film properties is also being investigated.

2.3.3 Growth of Doped ZrO_2 and CeO_2 Fast Anion Conductors by Sputtering*

The deposition rate, chemistry, microstrucutre, and optical and electrical characteristics of rf sputter-deposited Y_2O_3-doped ZrO_2 and CeO_2 films have been investigated as a function of applied substrate bias V_s. All films were deposited in Ar at a pressure of 20 mTorr (2.67 Pa). The deposition rate of both materials initially increased with V_s and then decreased as V_s/V_t exceeded ~ 0.08, where V_t is the target voltage. In the doped ZrO_2 films, the O/Zr ratio, microstructure, and ionic conductivity activation energy were dependent upon V_s. For $V_t = -500$ V, deposited films were approximately stoichiometric at $V_s \simeq -70$ V, while films grown at $-V_s < 60$ or > 80 V were oxygen deficient. Films grown at $-V_s \leq 40$ V had a very columnar microstructure, while films deposited with $-V_s > 60$ V appeared quite dense with little structure visible in fracture cross-section electron micrographs. Electrical measurements indicated ionic-transference numbers within 1% of unity at temperatures $T \leq 180^{\circ}C$. Linear Arrhenius plots of measured film resistance versus T in the range 150-550°C yielded activation energies in the range 0.9-1.15 eV and indicated a single-conduction mechanism. All doped ZrO_2 and CeO_2 films exhibited high optical transmission over most of the visible and near-infrared spectrum. The refractive index decreased with increasing oxygen content and agreed reasonably well with published values for pure ZrO_2 films. Further details may be obtained in reference 18.

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3.1 Introduction

The long range objective of this research is to originate and analyze new microacoustic wave principles that have significant device implications. Progress towards the specific objectives of achieving smaller substrates, more accurate performance, and higher frequencies has been achieved.

The substrate size reduction is important for applications where high power density, multiple channels, or integration with semiconductor devices is important. The line acoustic waves (LAW) are nondispersively confined in two dimensions so that the acoustic active area is reduced by orders of magnitude below that of surface waves. Theoretical and experimental developments regarding the LAW propagation and excitation have been devised. Small size and accurate performance has been achieved by utilizing monolithic I.C. thin film capacitors in conjunction with microacoustic wave devices. High frequencies with low resolution requirements are best achieved by using the transducer at the harmonic responses. The capacitively coupled transducers and the new excitation analysis techniques represent significant steps toward accurate harmonic frequency operation.

3.2 Analysis of Line Acoustic Wave Propagation in Piezoelectric Crystals*

Line acoustic waves are guided along an edge formed by 2 semi-infinite stress free surfaces. These waves are characterized by strong

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

energy confinement, zero diffraction, and non-dispersive propagation, all of which are important for signal processing applications and are particularly important if the microwave acoustic devices are to be integrated with solid state semiconductor components. The line acoustic wave analysis uses an orthonormal basis set for the expansion of the field quantities. This method has been applied in the past only to cubic crystals. A general formulation of the technique has been derived for arbitrarily oriented wedges in general Triclinic piezoelectric crystals with both open and short circuit electrical boundary conditions [1]. Using the properties of stress free boundaries the Laguerre Function orthonormal decay constants are set so that only a few terms are required and compact analytical expressions are obtained to describe the complete electrical and acoustic field distributions. The theoretical velocities and field distributions have been verified by comparing measured values on 40° and 90° edges of Lithium Niobate. High quality edges needed for the experimental evaluation of line acoustic waves have been achieved by cleaving the crystals along crystalographic axes. Edges of sufficiently high quality to operate at frequencies approaching 1 GHz appear to be feasible [2].

This technique has been used to derive the line acoustic wave field distributions for a significant number of materials. Distributions for line acoustic waves on lithium niobate are contained in a paper submitted for publication [1] along with a complete detailed description of the theoretical analysis.

3.3 Line Acoustic Wave Transducer Analysis*

The analysis described in Section 3.2 has demonstrated the existence of non-dispersive line acoustic waves defined along the edge formed by two stress free surfaces. Surface acoustic wave interdigital transducer analysis techniques cannot be applied directly to line waves because the field distributions along the transducer elements are not

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

uniform. Expressions for the line acoustic wave radiation conductance of interdigital transducers located along the edges have been derived using the analytical expressions for line acoustic wave field distributions developed in Section 3.2. The calculated values are found to be in good agreement with the experimental results. The radiation conductance forms the basis for theoretical modeling interdigital line acoustic transducers. The detailed derivation of the expression for the radiation conductance of an apodized line acoustic wave transducer is described in a paper accepted for publication [3].

3.4 Analysis of Surface Waves in Layered Anisotropic Piezoelectric Substrates*

Surface wave solutions in piezoelectric crystals are usually obtained using an iterative search procedure for SAW velocity such that electrical and mechanical boundary conditions are simultaneously satisfied. This procedure is rather difficult, especially in layered structures where boundary conditions must be satisfied at several interfaces and generally requires sophisticated time consuming convergence techniques. In addition, the results are typically numerical values which provide little physical insight and are difficult to use in the analytical analysis of the microacoustic wave devices.

A simple noniterative method for obtaining the SAW Field distributions in piezoelectric crystals covered with anisotropic layers has been derived. The advantages of the method are:

1) It is simple to program and the solution is not interactive. To find the SAW velocity and field distribution requires the diagonalization of an 18×18 matrix which takes only a few seconds on a computer.
2) The boundary conditions are incorporated into the field equations and automatically accounted for. This makes it convenient to account for the complex boundary conditions such as those encountered in layered structures. Anisotropic piezoelectric layers can be taken

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into account and second order effects such as mass loading are accurately predicted.

3) Field distributions are obtained as linear combinations of orthonormal functions making it more convenient to perform further manipulations to obtain reflections, power flow, mode impedance, and transducer excitation functions.

The details of this derivation and the results for a series of materials is shown in detail in a paper submitted for publication [4]. This work shall be particularly important for the analysis of micro-acoustic wave devices monolithically implemented and covered with dielectric and semiconductor layers.

3.5 Integrated Circuit Capacitor Controlled Response of Acoustic Transducers*

Apodization is the most widely used technique for adjusting the tap weight of wide band surface acoustic wave interdigital transducers. It has been found to be less than optimum for many applications and is particularly unsuited for very small configurations as required in monolithically integrated solid state microacoustic wave devices.

Tap attenuator techniques utilizing integrated circuit capacitors to adjust the coupling strength of equal length taps have been devised as an alternative [5]. The thin film integrated circuit capacitors are superimposed on top of the propagation path so that no extra substrate area is required and accurate, wide dynamic range tap weight control is achieved. The complete analysis of this weighting technique is described in [6] and the accuracy of this technique is demonstrated by a configuration utilizing two capacitively weighted transducers with an acoustic beamwidth of 5 wavelengths operated without the benefit of a multistrip coupler to suppress the bulk acoustic waves. The selectivity of this filter response is in excess of 75 dB with an insertion loss of approximately 15 dB [7]. Filters with shaped factors as low as 1.08 and insertion losses as low as 10 dB have been achieved

*This work was supported by U.S. Air Force under Contract F 33615-75-C-1291.

utilizing this technique [8]. These results show that SAW structures implemented with capacity weighted transducers have substrate area requirements five times less than the requirements for apodized transducers. The technique is directly applicable to line acoustic waves because the tap weights are not altered by non-uniform beam profiles.

3.6 Harmonic Analysis of Microacoustic Wave Transducers*

Surface acoustic wave transducers with capacity weighted structures provide nearly theoretically ideal response at the 3rd harmonic and significant responses at the 5th and 7th harmonics. These results are very encouraging and lend optimism that future interdigital structures will achieve higher harmonic operation and make it possible to use photolithographically generated interdigital transducers for GHz frequency devices.

In an effort to expand this potential and evaluate the deviations from the theoretical, an experimental analysis technique has been devised which measures a time domain excitation function for SAW transducers. This time domain excitation function is defined as the instantaneous surface acoustic wave amplitude displacement distribution resulting from a voltage impulse applied to the transducer. Theoretical descriptions of the SAW source fields produced by an interdigital transducer have recently been derived. The experimentally measured excitation function provides measured field distributions resulting from the interdigital transducer source fields. This is particularly important in the analysis of transducers to be operated at higher harmonics so that the effects of the beam structure and the interdigital transducer environment can be accounted for in the design. This analysis is described in detail in a paper submitted for publication [9].

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

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4.1 Introduction

During the past grant period we have made considerable progress towards devising new passive components and guiding systems for millimeter-wave integrated circuits. We have also designed and tested a complete working model of a millimeter wave oscillator circuit using an impatt diode as the source. On the theoretical side, we have extended the "equivalent dielectric constant" or the EDC approach, which, although extensively used in the literature to analyze planar dielectric waveguides, was found to be inadequate for certain polarizations of the dominant E-field. We have termed the new approach the "equivalent permeability constant" method, and have tested its usefulness for a number of configurations for which the equivalent dielectric constant approach was not satisfactory. We are currently working towards a further extension of both of these methods. The extension will be based on a full-wave, multiple-mode type of analysis and is expected to be useful for accurately predicting the higher order mode characteristics of planar waveguides. We note that these characteristics are not accurately derived from either the "equivalent dielectric" or the "equivalent permeability" approach, although they both seem to work reasonably well for the lower order modes, depending on the polarization of the dominant component of the E-field. In addition, we have theoretically designed and experimentally confirmed a new tapered dielectric waveguide of the planar kind that has characteristics similar to a graded index fiber with parabolic index profile used in optical

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

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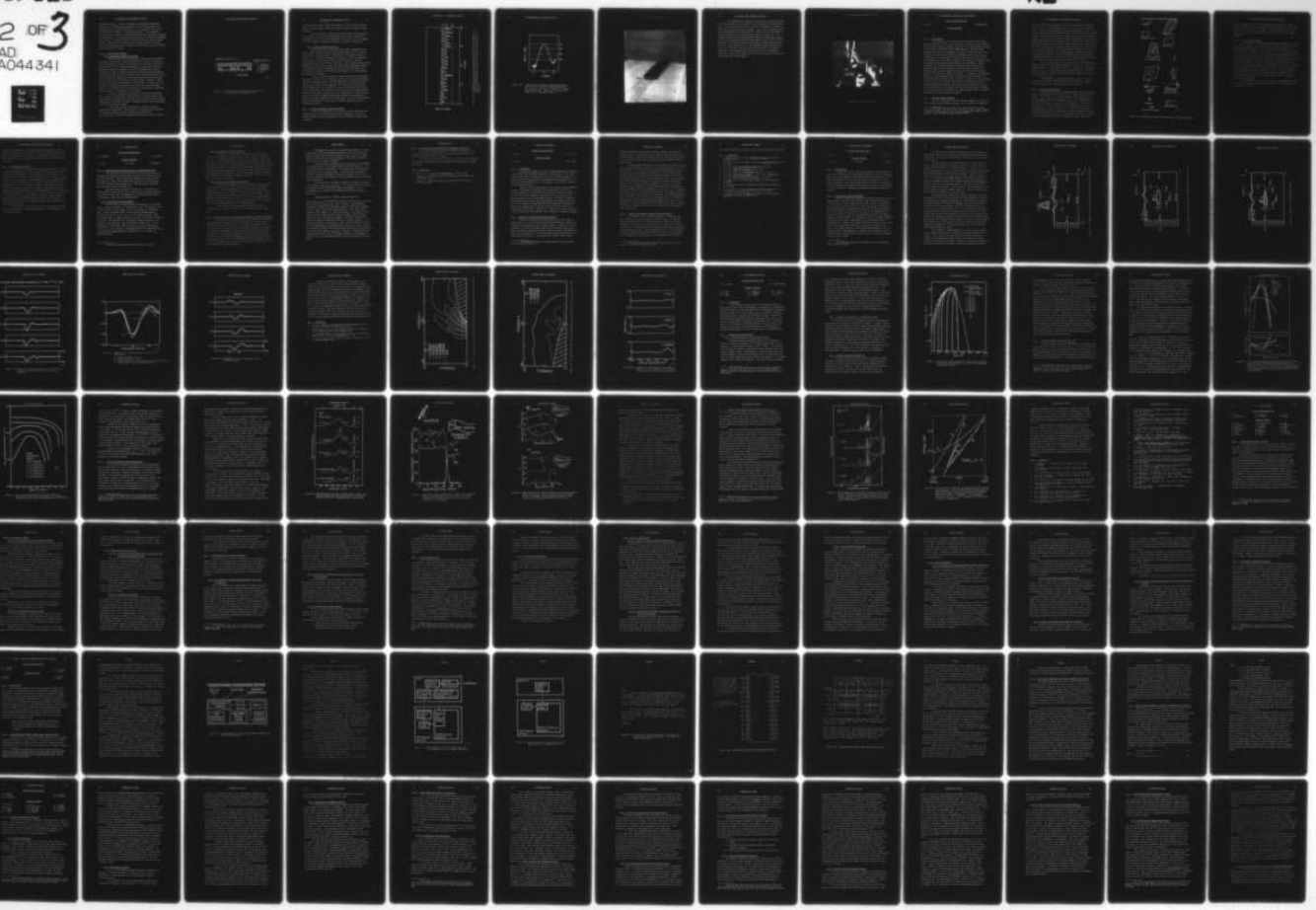

integrated circuits. We have discovered a new waveguide design that supports a single propagating mode, and yet has the advantage that its dimensions are not impractically small, as for instance, in the case of planar monomode waveguides of conventional design. These waveguide designs have been tested on a probing bench which was specifically designed for this purpose. The operation of this bench has been virtually automated, thus making it extremely efficient for rapidly evaluating new waveguide designs. The design of a millimeter wave integrated mixer circuit has been completed and the various component parts of the circuit are currently being fabricated and tested.

4.2 New Waveguide Designs

4.2.1 Homogeneous Inverted Strip Guide

During the previous grant periods we had extensively studied the QT (quartz-teflon) guide. Keeping in mind that the ease of fabrication will be an important criterion in determining the usefulness of the waveguide designs, we have concentrated during the present grant period on homogeneous types of waveguides called the HIS (homogeneous inverted strip) guides, which are made entirely from a single dielectric material. This type of design is not only desirable from a mechanical point of view, it also offers the possibility of convenient fabrication of complicated circuits through injection molding or other similar techniques. Figure 4.1 shows the typical cross-section of the HIS guide. The ribs serve the function of supporting the guide on the ground plane and have minimal effect on the characteristics of the waveguide since they are removed far from the centers of concentration of the field.

In order to rapidly test the effect of varying the parameters of the guide on its performance characteristics, we have designed a near-field probing arrangement that is capable of providing us with such useful information as the guide wave number, multimode contents and field confinement in the guided wave region.

A non-trivial problem encountered in the course of doing experimental measurements is the coupling of the guide to the oscillator. A "prism-type" coupler has been developed for launching the dielectric guide. Although the coupling characteristics of this type of

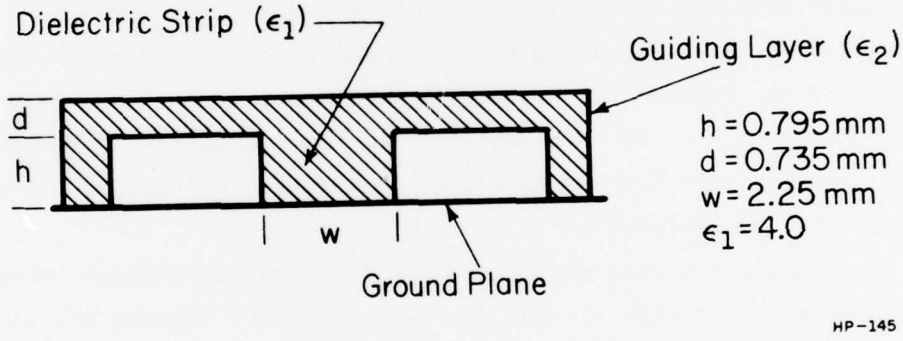

Figure 4.1 Cross section of Homogeneous inverted strip dielectric wave integrated circuits.

launcher are quite good, further work remains to be done in this area in order to achieve enhanced efficiency and less leakage of unwanted direct radiation.

Both longitudinal and transverse measurements of the near-field characteristics of various waveguides have been carried out using the measurement set-up. A typical longitudinal field plot is shown in Figure 4.2a and a sample of transverse variation is plotted in Figure 4.2b.

4.2.2 Effective Graded Index Fiber

Most recently we have successfully designed a homogeneous dielectric guide that mimics the well-known graded index fiber, so successfully used as an optical guide. The geometry of the guide is shown in Figure. 4.3. A significant feature of the design is that the parameters of the guide were theoretically derived before fabrication and the experimental results were found to verify the overall guiding characteristics predicted by the theoretical work. The design shows considerable promise from the point of view of machinability and ease of fabrication, and a more rigorous theoretical and experimental analysis of the tapered guide is planned for the future.

Finally, we have discovered a rather interesting and unexpected phenomenon in the process of studying the effects of varying the parameters of various waveguide designs. We have found that by deliberately introducing a very narrow air gap underneath the bottom layer of dielectric and the ground plane, it is possible to alter the characteristics of the guide substantially, particularly from the point of view of supportability of higher order modes. Specifically, the introduction of a small air gap allows us to design a monomode guide whose dimension are comparable to those of the guides supporting two or more modes. We plan to theoretically analyze this phenomenon in more detail using the methods that we are developing currently.

4.3 Passive Components and Active Devices

Since our ultimate goal is to build a receiver using dielectric waveguides and associated active and passive components, we have been testing a number of passive components, such as directional couplers and resonators.

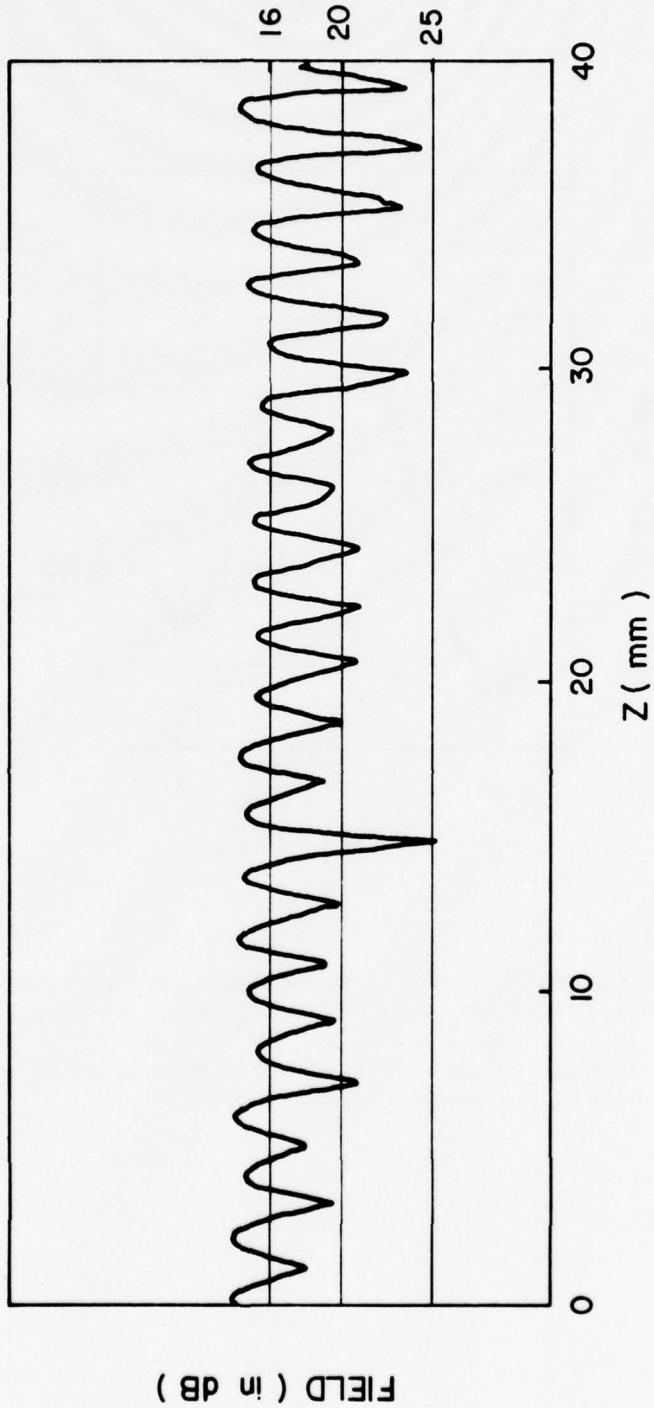

Figure 4.2a Longitudinal field patterns obtained experimentally at 79 Ghz for an effective graded-index guide (H = 1.5 mm, h = 1 mm, 2w = 10 mm, ϵ_r = 4, about an 0.07 mm air gap). Pattern is indicative of single mode operation.

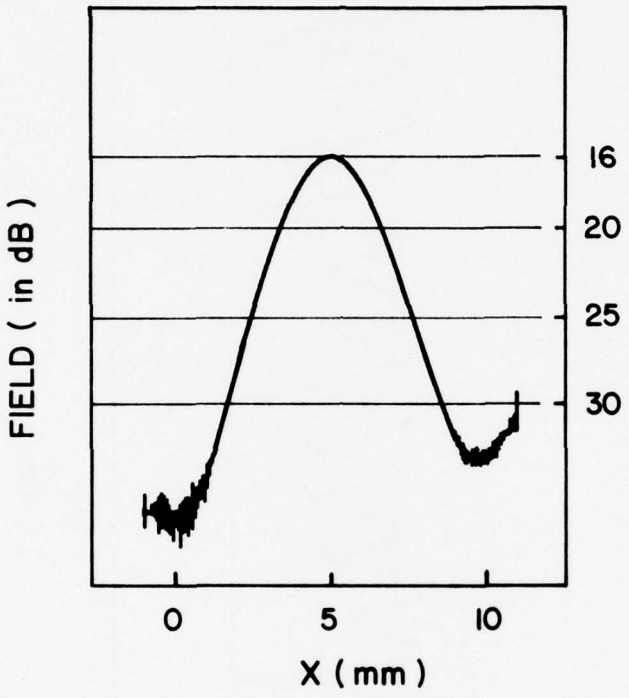

Figure 4.2b Transverse field patterns obtained experimentally at 79 Ghz for an effective graded-index guide (H = 1.5 mm, h = 0.5 mm, 2w = 10 mm, ϵ_r = 4, above an 0.07 mm air gap). The field is down by 10 dB within $\pm$ 4 mm of the guide center.

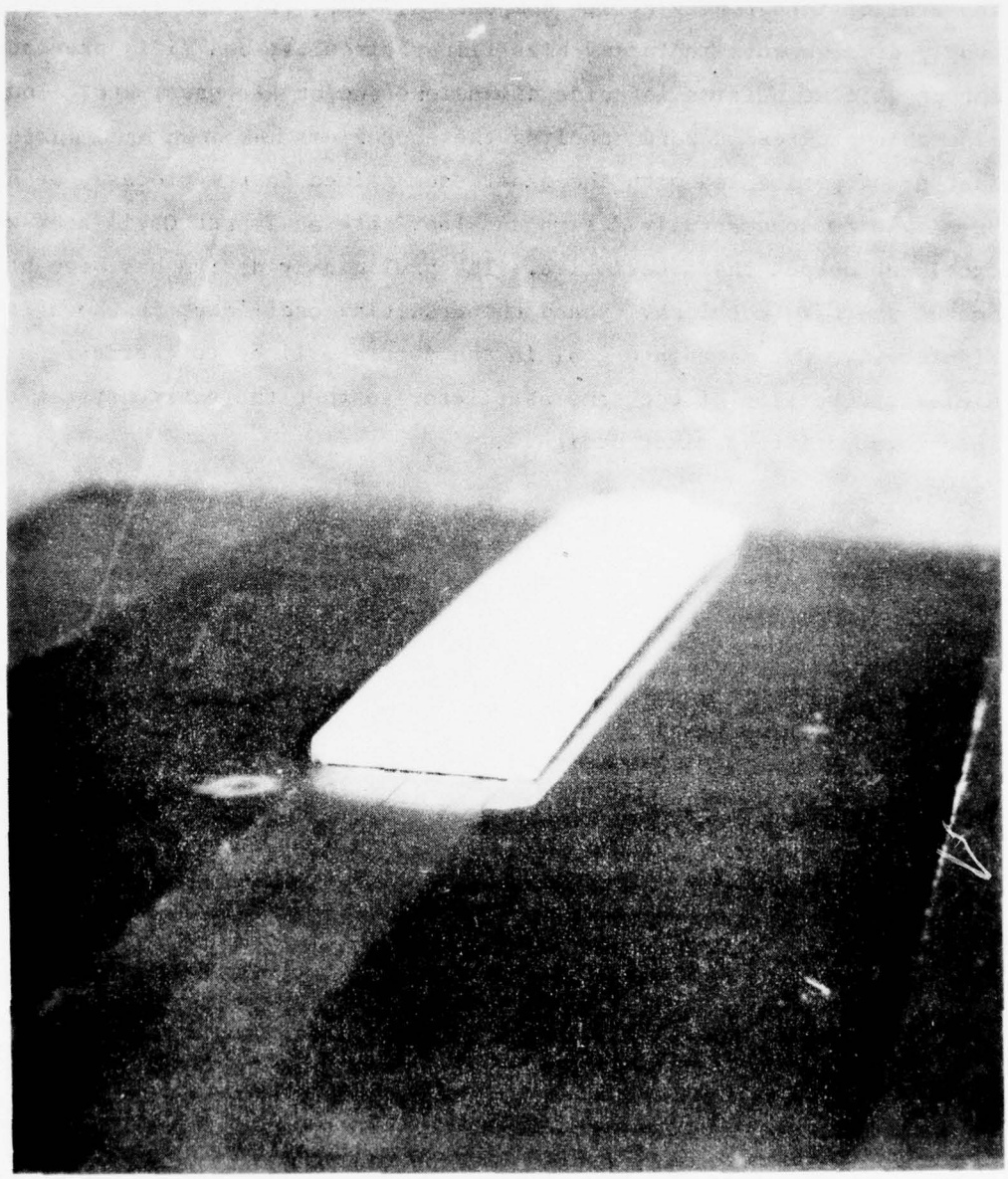

Figure 4.3 Effective graded index guide.

In designing active components, we have been striving toward the goal that the active devices should be truly integrated in the dielectric guide. We have addressed ourselves to some of the important problems in the area of integrating active components, viz., (i) heat sinking; (ii) DC supply arrangements-including bias filter circuits; and (iii) presence of abrupt discontinuities in guide dimensions and/or air gaps, etc. Considerable progress toward handling these problems has been made during the last grant period, and with the experience gained in the process, we have been able to successfully design and fabricate an Impatt Oscillator with excellent output characteristics. The preliminary design has been based on the use of a metal cavity and the resulting oscillator is shown in Figure 4.4. Our immediate goal in the future will be to fabricate a dielectric version of the same oscillator so that the entire system can be incorporated into a mixer design.

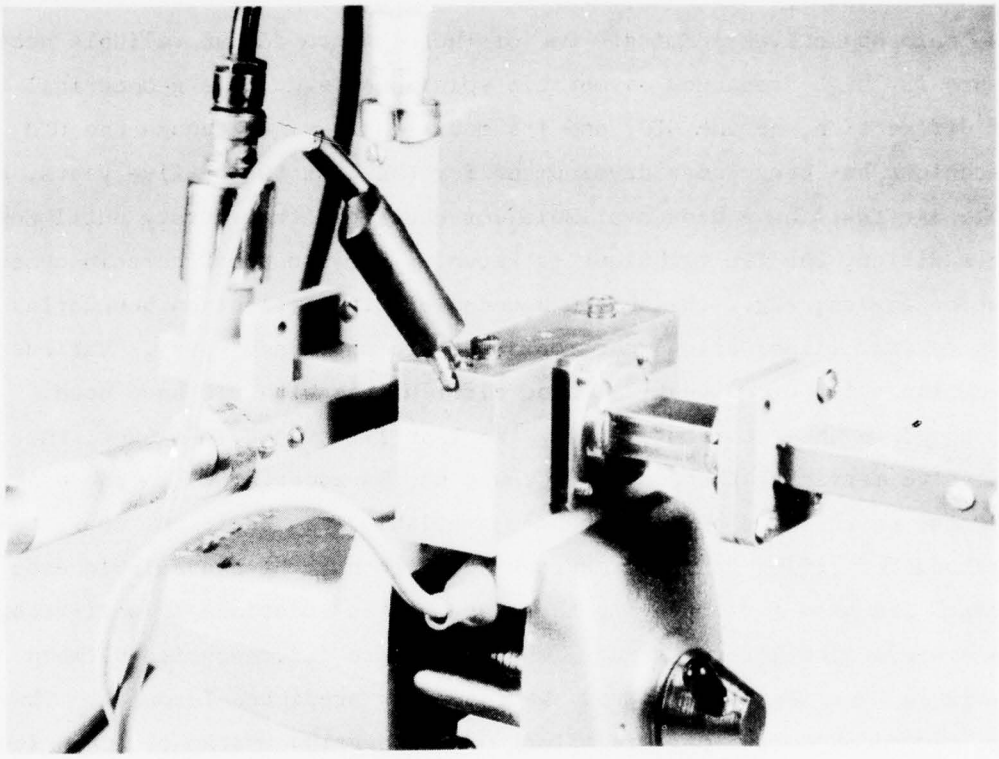

Figure 4.4 Impatt oscillator.

5. ELECTROMAGNETIC RADIATION AND SCATTERING* 5

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M. Tew

5.1 Introduction

This project was initiated this past year with the following two main objectives in mind. One of these was to devise reliable accuracy tests for high frequency asymptotic solutions, e.g., the geometrical theory of diffraction, or the GTD, and its modifications. Although the GTD technique has been under development for the last twenty-five years, no reliable tests have been available for checking its accuracy until now. In addition, the GTD technique is known to break down at certain observation angles, e.g., the shadow boundaries, the reflection boundaries, and for general illumination functions that are not plane waves. Various techniques for circumventing these difficulties with GTD have been proposed in the literature during the last five years. However, the relative merits of these methods could not be ascertained in the past because no reliable tests have been available. In addition, no systematic methods for refining high frequency solution have been available even though the need for improving these asymptotic solutions is well-recognized. Such needs occur, for instance, when there are discrepancies between reliable experimental data and theoretically predicted formulas. Thus, the second objective of this effort was to develop systematic techniques for carrying out these improvements by combining high frequency asymptotic techniques with integral equation methods.

5.2 Spectral Domain Approach

The key to improving the high frequency asymptotic solutions is the use of the Spectral Domain Approach. In this method, the scattered

*This work was supported by the Joint Services Electronics Program (U.S. Army, U.S. Navy, and U.S. Air Force) under Contract DAAB-07-72-C-0259, the Army Research Office Grant (ARO DAAG 29-77-G-0111, and National Science Foundation Grant (NSF ENG76-08305).

fields are represented in terms of the Fourier Spectrum of the induced current density on the scatterer, rather than as ray fields emanating from it. The correspondence between the spectral approach and the widely-used ray method has been established in the regions where the key approach is valid. The similarity ends there though,since the spectral approach continues to work even when the ray approach breaks down, e.g., for non-planar incidence waves or for grazing angles of incidence. The non-planar incident wave problem is of interest in many practical situations, as for instance, for the case of an antenna mounted on the wing of an aircraft, or a ship-based platform. The grazing incidence problem also occurs in many practical situations, e.g., a radar system illuminating the wing of an aricraft from the side. The spectral domain approach represents a fundamental advancement in the theoretical technique and has been found to be valuable for handling practical problems of this nature.

Yet another situation of practical interest is described as the "shadow boundary - shadow boundary interaction," which occurs when one diffracting ege is at the shadow boundary of a second one. Conventional GTD and some of its modified versions are known to break down in this situation; however, the spectral approach has been shown to apply quite well for this case also.

A comprehensive report describing these aspects of spectral work has been prepared. This material will also appear as a chapter of a forthcoming book to be published by the Academic Press.

5.3 Iterative Improvement

The problem of iteratively improving high frequency asymptotic solutions have been developed and applied to a number of practical geometries. (See Figure 5.1.) A few examples of such geometries are: (i) rectangular cylinder, which models a tower, or a supporting strut for a reflector feed; (ii) smooth convex surface, e.g., a fuselage of an aircraft or a body of a missile; (iii) trapezoidal plate, e.g., an airplane wing or a missile stabilizer. In each of thes cases, the available GTD solution needs improvement at certain observation angles, or is inadequate because of lack of availability of canonical solutions. The spectral domain approach has been applied to these problems and

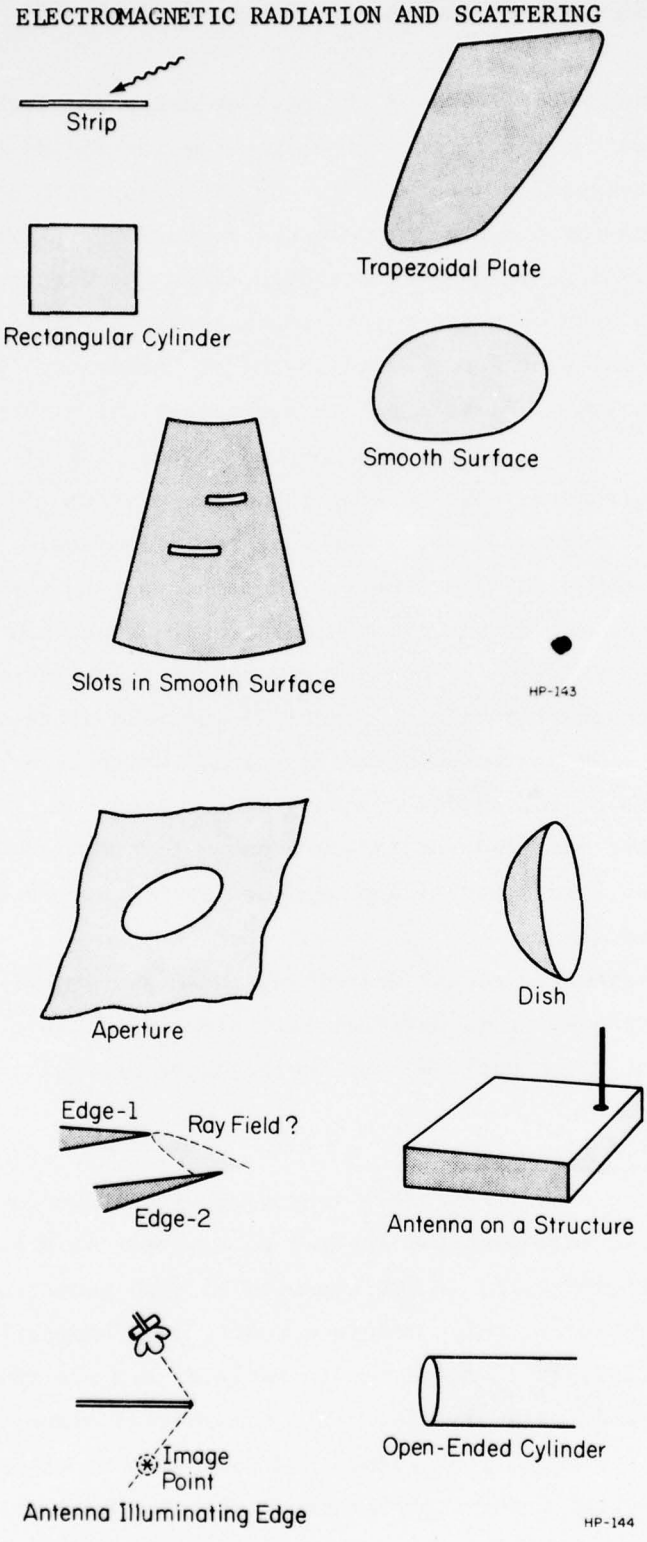

Figure 5.1 Illustrative geometries for application of spectral method.

systematic improvement of the GTD solution has been obtained. What is more, the improved solutions have been tested for boundary condition and their accuracy verified in this manner. As mentioned earlier, need for such a test has been recognized for a long time, but none was available until now.

5.4 Source Region Problem

In contrast to the scattering problems described above, a number of practical geometries of interest involve radiating sources mounted on an object whose dimensions are large compared to the wavelength. An example of such a structure is one or more slots on a conical or cylindrical surface, e.g., a missile. The computation of mutual coupling between two slots and the radiation patterns of slots in the conformal array configuration is of great practical interest. Unfortunately, the conventional high frequency solutions are inaccurate in the axial direction where the mutual coupling between two circumferential slots is the largest, and hence, the interest is also greater. Recently, two solutions have been published that purportedly solve this problem. We have applied our spectral domain test to these solutions and have convincingly demonstrated that one solution is far superior than the other, and that both can be further improved.

Future efforts on this project will be devoted towards further generalizing the spectral approach and applying it to other geometries of practical interest.

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6.1 Nonlinear Wave-Wave Interactions in a Beam-Plasma System

The experimental study of nonlinear wave-wave interactions in a beam-plasma system has been continued, and new and interesting results have been obtained. There are important advantages in using a system consisting of a weak, cold, electron beam injected into a cold plasma to study wave-wave coupling effects [1]. The experimental system has been described in detail elsewhere [2].

The observations include the effects of: 1) excitation of stable harmonics by an unstable mode, 2) excitation of unstable harmonics by a weakly unstable mode, 3) enhancement of a spontaneous spectrum by a driven wave. These cases are detailed below.

6.1.1 Excitation of Stable Harmonics

A wave at the most unstable mode, with frequency, ω_1, has been seen to excite its harmonic at a frequency $\omega_0 = 2\omega_1$. The harmonic, being linearly stable, does not appear at all in the absence of the driving wave. A most interesting effect here is that the maximum harmonic excitation occurs, not at $\omega_1 = \omega_p$ (ω_p is the plasma frequency), where the unstable wave is strongest, but at $\omega_1 \simeq 0.9\ \omega_p$. This may be explained as follows. The amplitude E_0 of the harmonic depends strongly on the nonlinear coupling constant V_{011} and the linear growth rate κ_1 of the driving wave. Theoretical results show that V_{011} has a deep minimum just where κ_1 is at a maximum. The consequence of these competing stimuli can be that the maximum harmonic excitation occurs at a value of ω_1 different from ω_p.

*This work was supported by the University of Illinois.

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*This work was supported by the University of Illinois.

6.1.2 Excitation of Unstable Harmonics

An alternative to the process described in (6.1.1) is the excitation of a harmonic at frequency $\omega_0 = \omega_p$ by a driver at frequency $\omega_1 = \omega_p/2$. The computed coupling constant is very strong for this interaction, and we have indeed observed a powerful excitation. In this case, the driving wave, known as a phantom driver, does not approach observational threshold, and almost all of the power is thrown into the harmonic. This process has potential application in the area of high frequency microwave or submillimeter wave production, as an electron beam is used to amplify waves at harmonics of a driving frequency. Moreover, the driver does not have to be strong to begin with.

6.1.3 Enhancement of Spontaneous Spectrum

With our experimental system, one can excite either a broadband spontaneous spectrum, where the unstable waves grow from thermal noise level, or coherent, monochromatic waves produced by externally modulating the beam (as described in 6.1.1 and 6.1.2), or both. If both spontaneous and modulated spectra are present, they may influence each other by nonlinear wave-wave coupling. We have in fact observed that a spontaneous unstable spectrum is significantly enhanced by the switching on of an unstable modulated wave at a nearby frequency.

The theoretical and experimental study of the effects described above, and possibly others, will be continued in the coming year.

6.2 Investigation of the Statistical Properties of Plasma Turbulence

Work has begun on the measurement of the first and second order probability density functions of the wave potential in the stationary plasma turbulence resulting from an ion acoustic instability. This is an extension of some previous work in which some exploratory measurements of the first order probability density of the turbulent wave potential were made [3]. The study is being made using ion acoustic turbulence because it is one of the most fundamental and best investigated examples of plasma turbulence and is of considerable practical importance. However, the techniques and the underlying theoretical considerations are not restricted to ion acoustic turbulence.

The experiment consists of a low pressure discharge in helium within which resides spontaneously generated ion acoustic turbulence. Langmuir probes biased at space potential measure an electron current which is proportional to the wave potential. The unstable waves have frequencies in the range of 4-40 MHz.

The first order probability density, $P_1(\varphi_1,\underset{\sim}{r}_1,t_1)$ is obtained by sampling at time t_1 the waveform from a probe at position $\underset{\sim}{r}_1$. The nanosecond samples are stretched to a few microseconds and displayed on a multichannel pulse height analyser. The preliminary measurements revealed a Gaussian distribution in the wave potential of the fully developed turbulence, and deviations from the Gaussian close to the onset of the instability.

We are presently preparing to measure the second order probability density, $P_2(\varphi_1,\underset{\sim}{r}_1,t_1;\ \varphi_2,\underset{\sim}{r}_2,t_2)$. To do this we first note that in a stationary state P_2 depends only upon the difference $t_1 - t_2 = \tau$. Furthermore, P_2 is related to the conditional probability $Q(\varphi_1,\underset{\sim}{r}_1;\ \varphi_2,\underset{\sim}{r}_2,\tau)$ by

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

$Q(\varphi_1,\underset{\sim}{r}_1;\ \varphi_2,\underset{\sim}{r}_2,\tau)$ is the probability that φ has the value φ_2 at $\underset{\sim}{r}_2$ given that it had the value φ_1 at $\underset{\sim}{r}_1$ a time τ earlier. This conditional probability is measured by passing the sampled waveform from a probe at $\underset{\sim}{r}_1$ into a single channel pulse height analyser. The single channel analyser selects samples of a given amplitude φ_1. The output from the single channel analyser is used to gate the samples from a different probe at $\underset{\sim}{r}_2$ into a multichannel analyser. The signals from the two probes are sampled at times that differ by a variable interval, τ. The multichannel analyser only receives a pulse from the probe at $\underset{\sim}{r}_2$ when a pulse of amplitude φ_1 is received from the probe at $\underset{\sim}{r}_1$ a time τ earlier. By changing the setting of the single channel analyser and thus the value of φ_1, the function $Q(\varphi_1,\underset{\sim}{r}_1;\ \varphi_2,\underset{\sim}{r}_2,\tau)$ is obtained. No measurements of P_2 have yet been made. We are currently assembling the equipment required to do so, and preliminary results should be available in the near future.

6.3 Electron-Beam Stabilization by Ion-Acoustic Turbulence

The study of the possibility of a laboratory experiment to investigate proposed mechanisms for electron beam stabilization by ion-acoustic turbulence has been continued.

The apparatus to be used in testing the validity of the proposed stabilization mechanisms has been designed and some parts have been made and tested.

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7.1 Introduction

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

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

7.2 Study of an Evaporation-Effusion Problem*

Nonlinear evaporation-effusion problems have a wide range of applications, e.g., in the design of spacecraft experiments, certain such problems require accurate kinetic theory treatment. Ytrehus [8,9] of the University of Trondheim, Norway formulated these problems using a Mott-Smith type Ansatz, solved the Boltzmann transport equations for Maxwellian molecules, and compared his calculations with available experimental and other theoretical results. He indicated that further study of these

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

problems using more accurate kinetic theory treatment is necessary to study the effect of different boundary conditions and collision laws. We have undertaken a joint research effort with him and Wendt of Von Karman Institute for Fluid Mechanics to study these problems under a NATO Research Grant.

Under the joint effort, we have successfully simulated the half space evaporation-effusion problem by solving the Boltzmann as well as the Krook equations for a two-wall emitting and absorbing problems studied by us [6]. There are computational difficulties in solving directly the Boltzmann equation for any half-space problem; therefore, the success of our attempt would be of basic interest and could lead to similar attempts to study the half space problems by using the accurate kinetic theory approach. The solutions obtained establish the validity of Ytrehus' simple and useful approach to make parametric studies of such problems and the conditions under which theoretical calculations can be correlated with others as well as with experimental results. The results obtained by us and Ytrehus were presented at 10th Rarefied Gas Dynamics Symposium, Aspen, Colorado in July, 1976 and were published [10,11]. We have been making further numerical studies of these problems for large mass rate in order to study the simulation near the limiting mass rate. A meeting will be held in Brussels in August, 1977 to review the accomplishments of our joint study.

7.3 Study of Aerodynamic Isotope Enrichment Devices[†]

The objective of this research program is to develop Monte Carlo techniques for analyzing the separation process in aerodynamic isotope enrichment devices. We have performed a number of numerical experiments to study the statistical errors of a Monte Carlo technique and the role of intermolecular collisions and the gas surface interaction on the separation process. These experiments have led to the proposal of a hybrid approach in which the efficiency as well as the resolution of the computation can be improved. This approach would be useful to

[†]This work was supported by the Sandia Laboratories under Contract U.S. Sandia Lab ERDA SB-04-8802.

solve certain gas mixture problems, e.g., those encountered in pollution.

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T. J. Akai D. R. Hall S. H. Lee

8.1 Introduction

The objective of this research program is to solve numerically the basic inviscid and viscous gas dynamic equations for complex problems using large scale computers. Our studies of the implementation of finite difference methods on ILLIAC IV and of methods of solutions of fluid dynamic problems on large scale computers have led to our research effort to solve potential flow problems with boundary conditions - in particular, free surface problems - using both finite difference and finite element methods.

8.2 Study of Free Surface Problems*

We shall consider the potential flow around a partially or fully submerged body. The free surface for this type of flow is unknown and is to be found as a part of the solution to the problem. The unknown position of the free surface leads to a nonlinear boundary condition at the surface; therefore, despite the linearity of the potential equation, it is not possible to use powerful tools such as the superposition of solutions, the Green's function, and eigenfunctions which are commonly applied to linear problems. The treatment of the full nonlinear boundary condition and the complex flow geometry and flow features remains a formidable task. Computational methods have been developed to deal with some of the computational difficulties and have been used to solve several free surface problems. These methods have advantages as well as problems in their implementations. Accurate solution of more complex problems depends on the success of future efforts in further development of computational schemes.

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

We shall describe briefly our progress in the development of computational methods for solving steady and unsteady nonlinear problems. Specifically, we plan to study the surface waves and the forces induced by these waves.

We have developed a time-dependent finite element scheme [1] to deal with the geometrical complexity and the free surface boundary condition of the nonlinear free surface problems. In this scheme, the finite element method is used to make the field calculation and the finite difference method is used for the time evolution. The mesh system is numerically generated in an optimum way by using a method developed by us [1,2]. We have used this hybrid method to solve three problems: a pressure distribution moving with a constant speed, a moving submerged elliptic cylinder, and a moving hydrofoil. These three problems are shown schematically in Figs. 8.1, 8.2, and 8.3. The initial mesh system for the hydrofoil problem is shown in Fig. 8.4. We shall describe very briefly numerical solutions of these problems.

The computational domain of the pressure distribution problem is bounded by the free surface and three cut-off boundaries. The downstream boundary is expanded periodically to contain the whole region of disturbance within the computational domain. The evolution of surface elevation for Fr = Froude number = $(4\pi)^{-1/2}$ is displayed in Fig. 8.5. In Fig. 8.6, the nonlinear results at t = 2 is compared with the linear calculation and the solution by Haussling and Van Eseltine [3]. These results show that the local steady state solution can be achieved by the proposed time dependent approach and indicates that the numerical scheme developed yields reasonable numrical schemes for the free surface problem. The condition of the conservation of energy was found to be preserved through the computation. Such a finding serves as a useful check for evaluating the numerical results.

The problem of a submerged body is of basic interest because of the additional difficulty in treating the boundary condition at the surface. Upon completion of the study of the pressure distribution problem, we have applied the hybrid scheme to the submerged elliptic cylinder and the hydrofoil problems. Figure 8.7 shows the development of the surface elevation with respect to time for the hydrofoil problem.

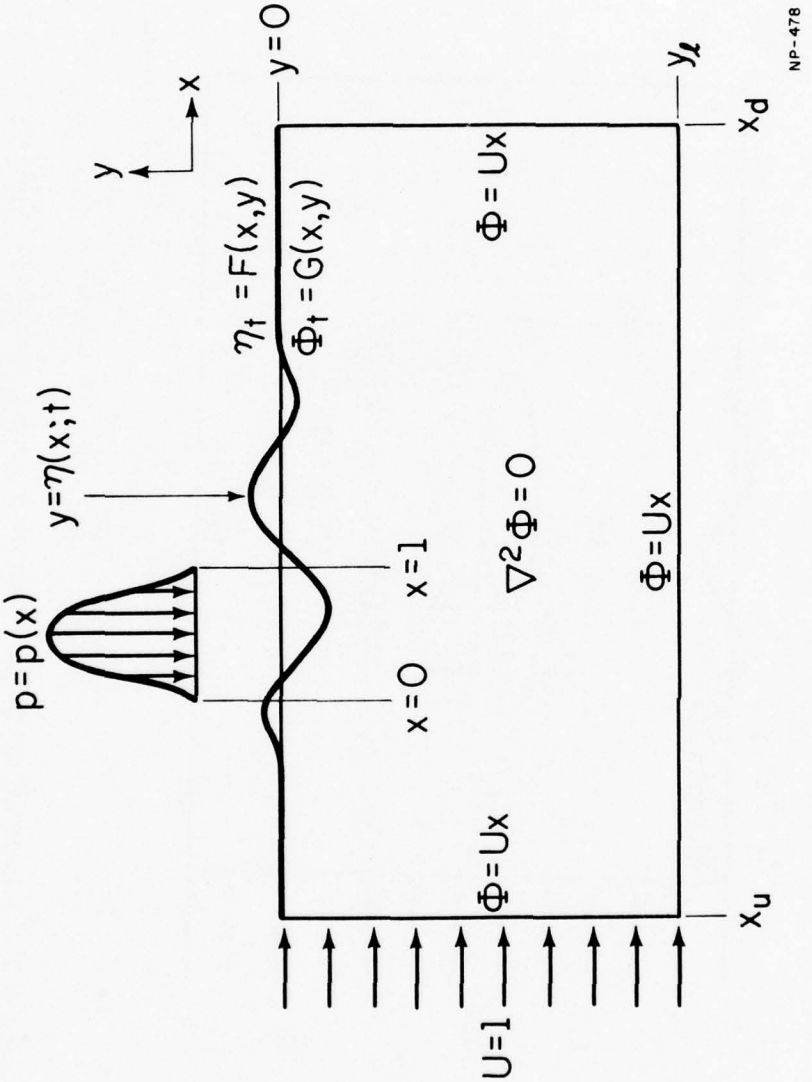

Figure 8.1. Schematic of the two-dimensional pressure distribution problem.

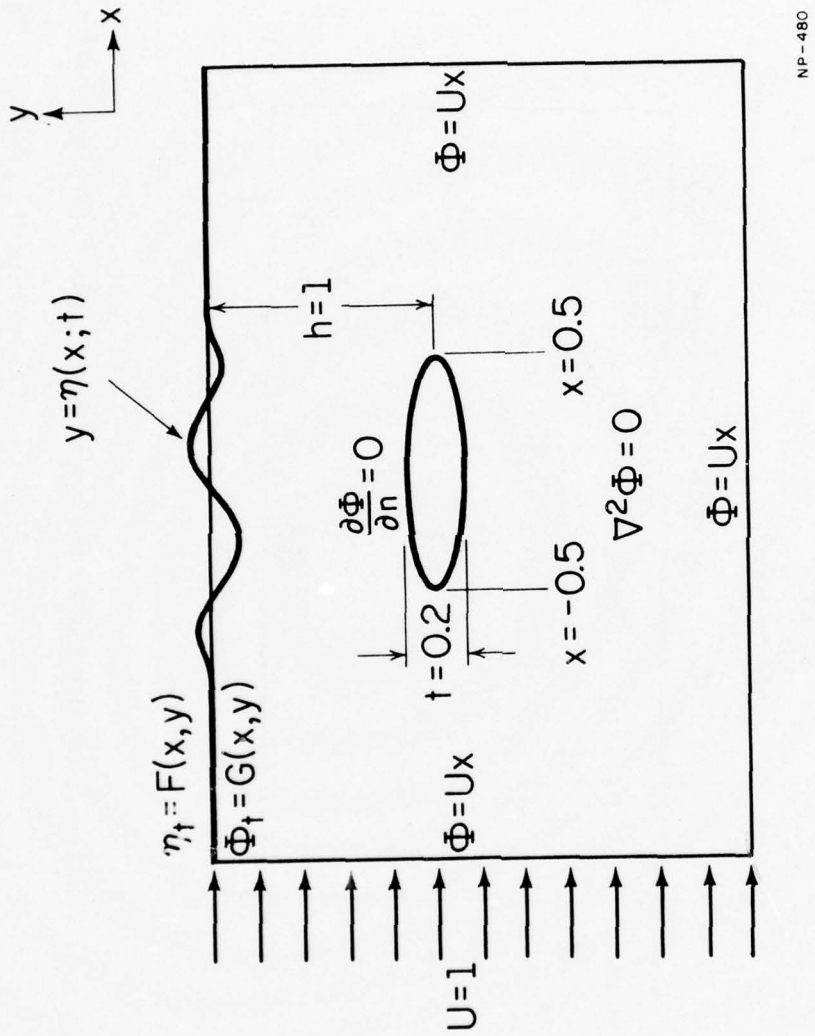

Figure 8.2. Schematic of the problem of a moving submerged elliptic cylinder.

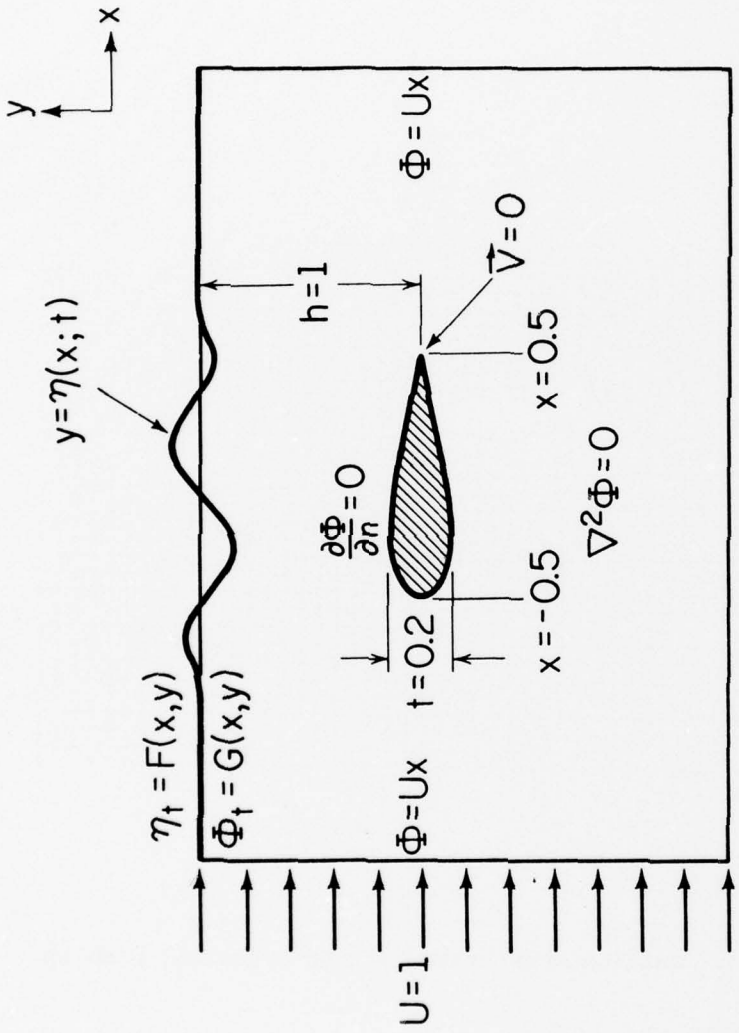

Figure 8.3. Schematic of the hydrofoil problem.

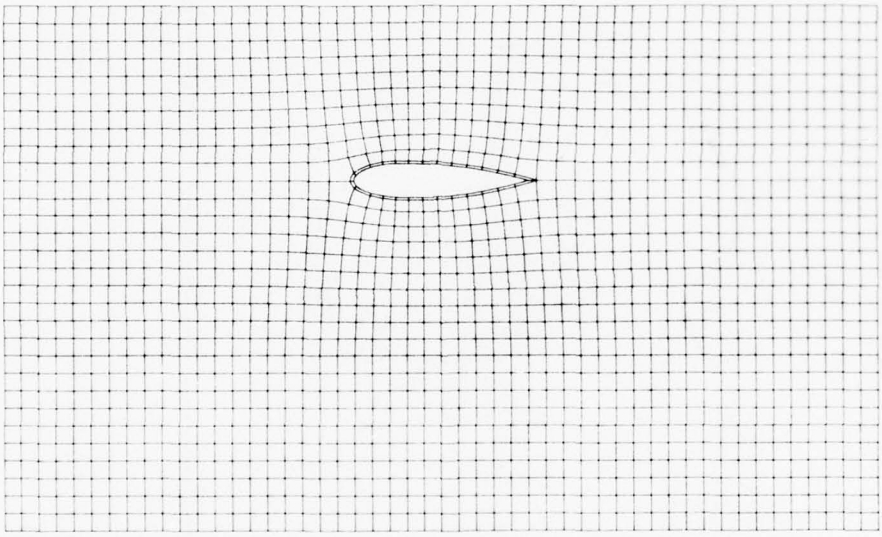

Figure 8.4. Initial mesh system of the hydrofoil problem.

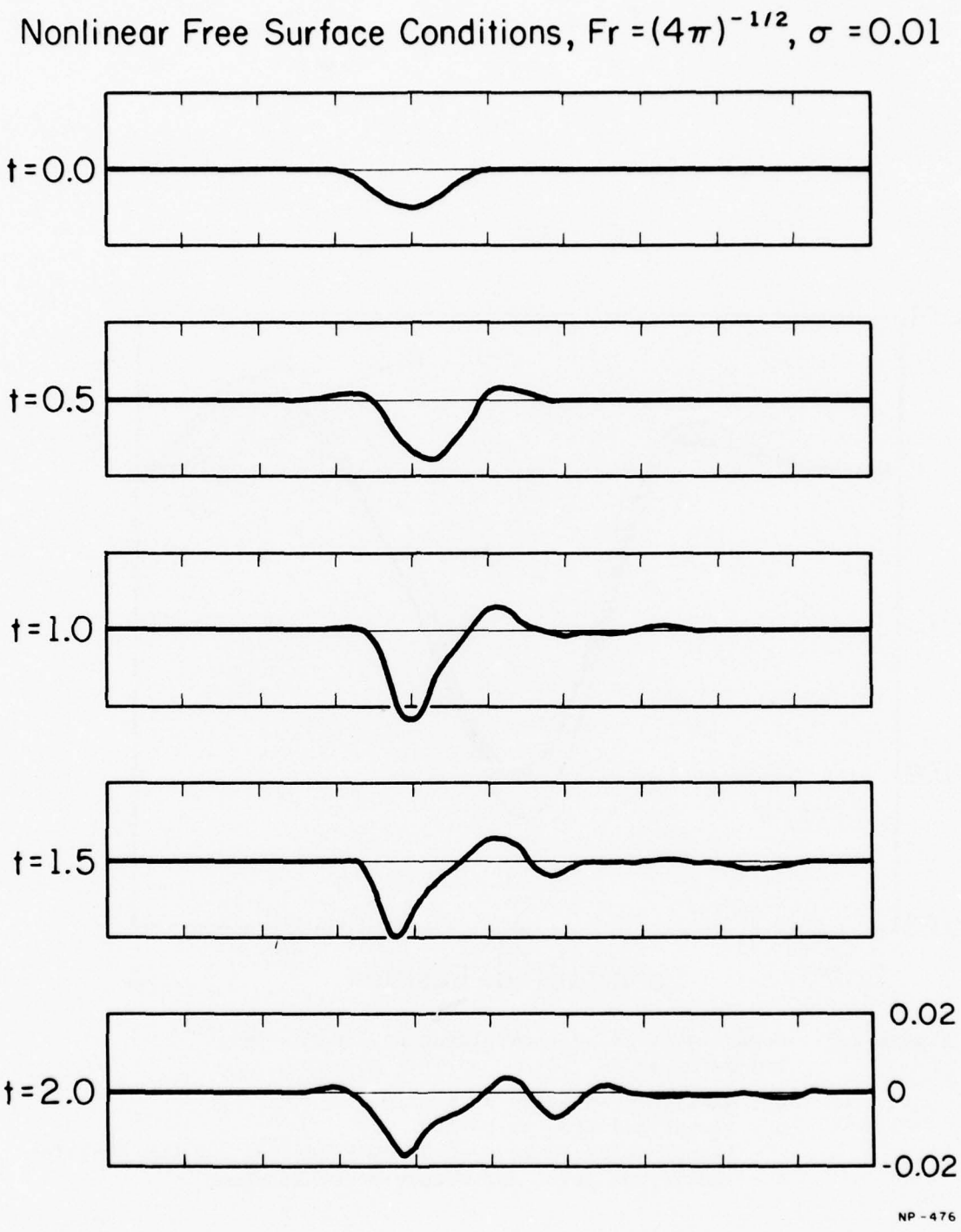

Figure 8.5. Evolution of surface elevation for $Fr = (4\pi)^{-1/2}$ and $\sigma = 0.01$ as computed with nonlinear free surface conditions.

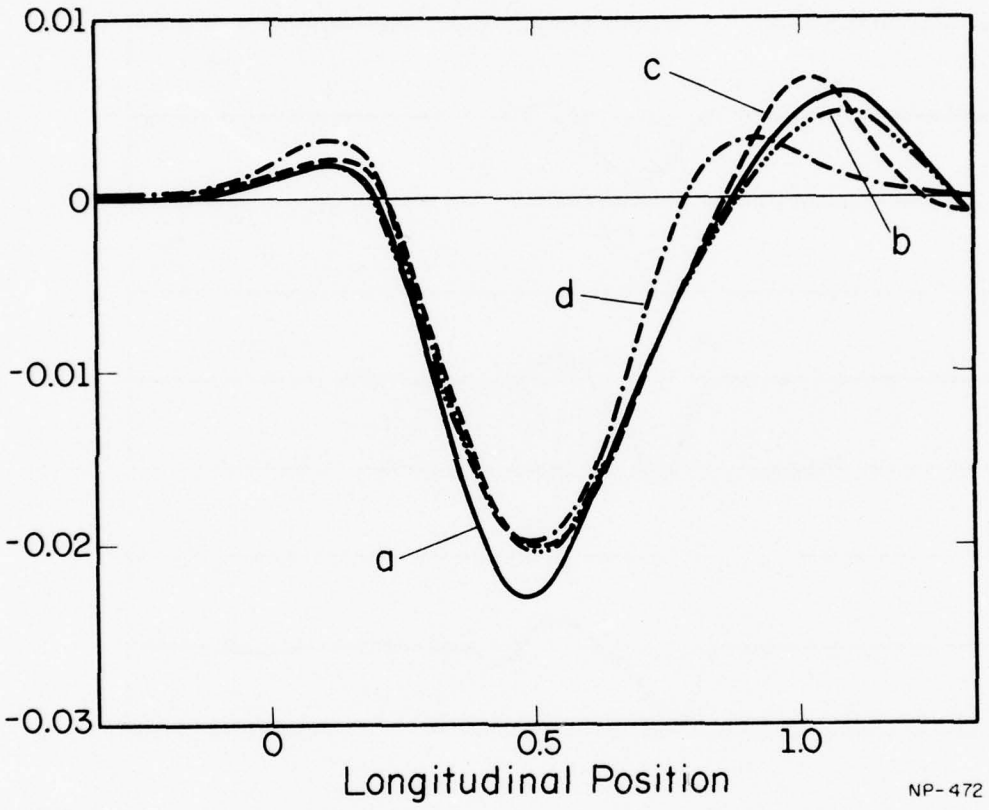

Figure 8.6. Comparisons of surface elevation for $Fr = (4\pi)^{-1/2}$ and $\sigma = 0.01$.

a - Nonlinear solution at $t = 1.0$
b - Linear solution at $t = 1.0$
c - Linear solution at $t = 0.96$ by Haussling and Van Eseltine
d - Linear analytic, and steady-state solution

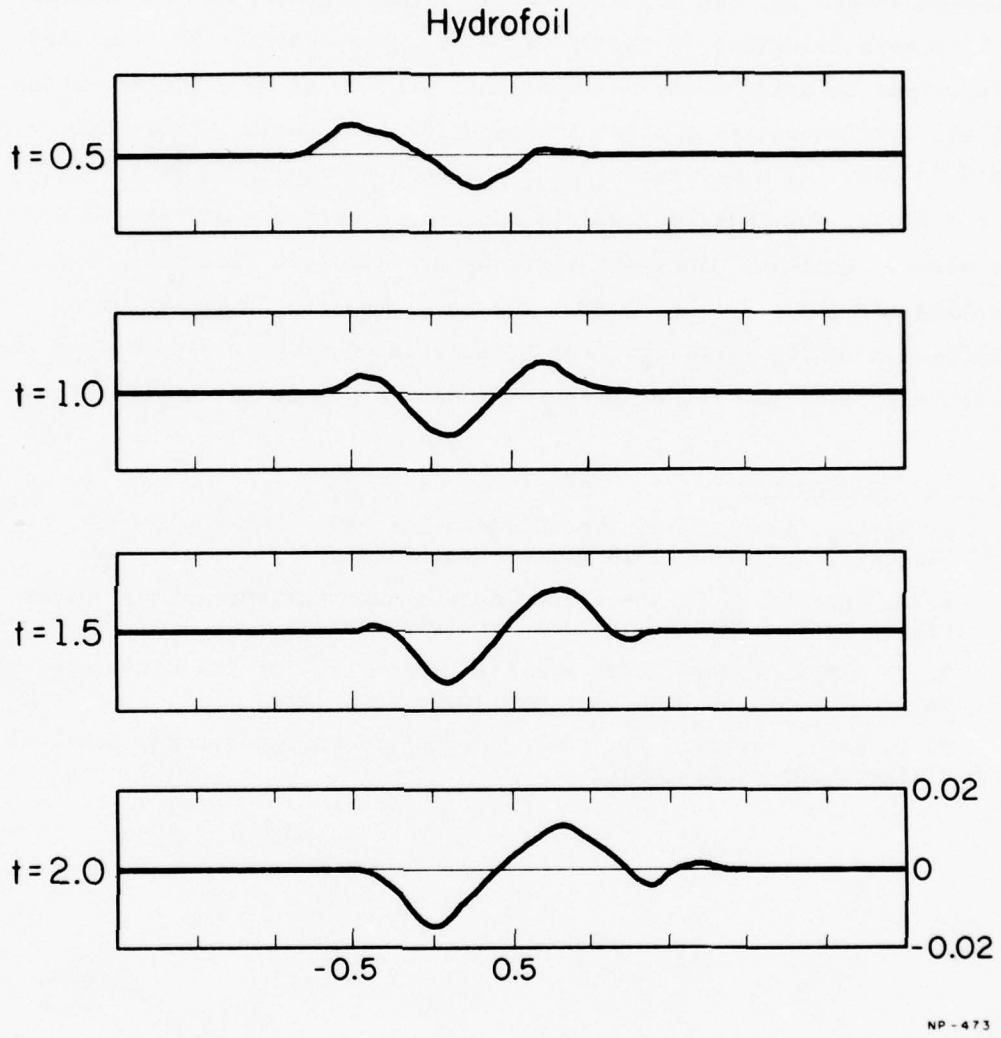

Figure 8.7. Development of surface elevations for the hydrofoil problem.

We have also developed an explicit time-dependent finite difference scheme [4] to solve the free surface problem. Explicit schemes may be more favorable for solving large scale problems on super computers which have more stringent implementation requirements. The proposed method and the solution obtained for the pressure distribution problem were described in the previous progress report. We have used this scheme to solve a three-dimensional problem of an elliptic cylindrical, surface-piercing strut accelerating from rest. Figure 8.8 and 8.9 show the wave formation at the ends of the strut at t = 0.05. At t = 0.058, wave breaking was found to occur near the downstream end of the strut. Profiles along the strut before and just after the wave breaking are shown in Fig. 8.10. The wave breaking is caused by a combination of the short wavelengths associated with low speeds and the relatively large amplitudes associated with high initial acceleration.

8.3 References

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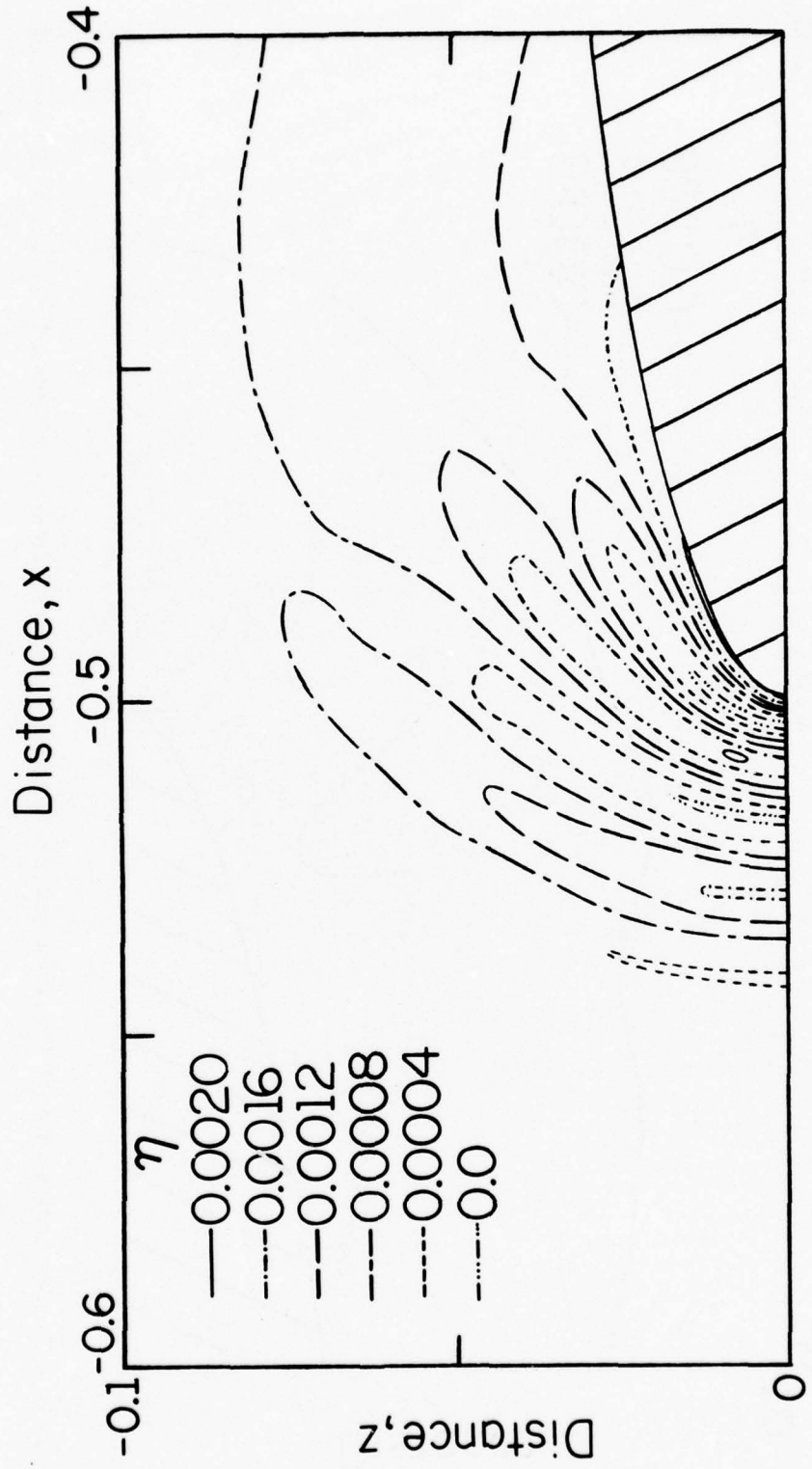

Figure 8.8. Contour plots of the free surface position near the upstream end of the strut at t = 0.05.

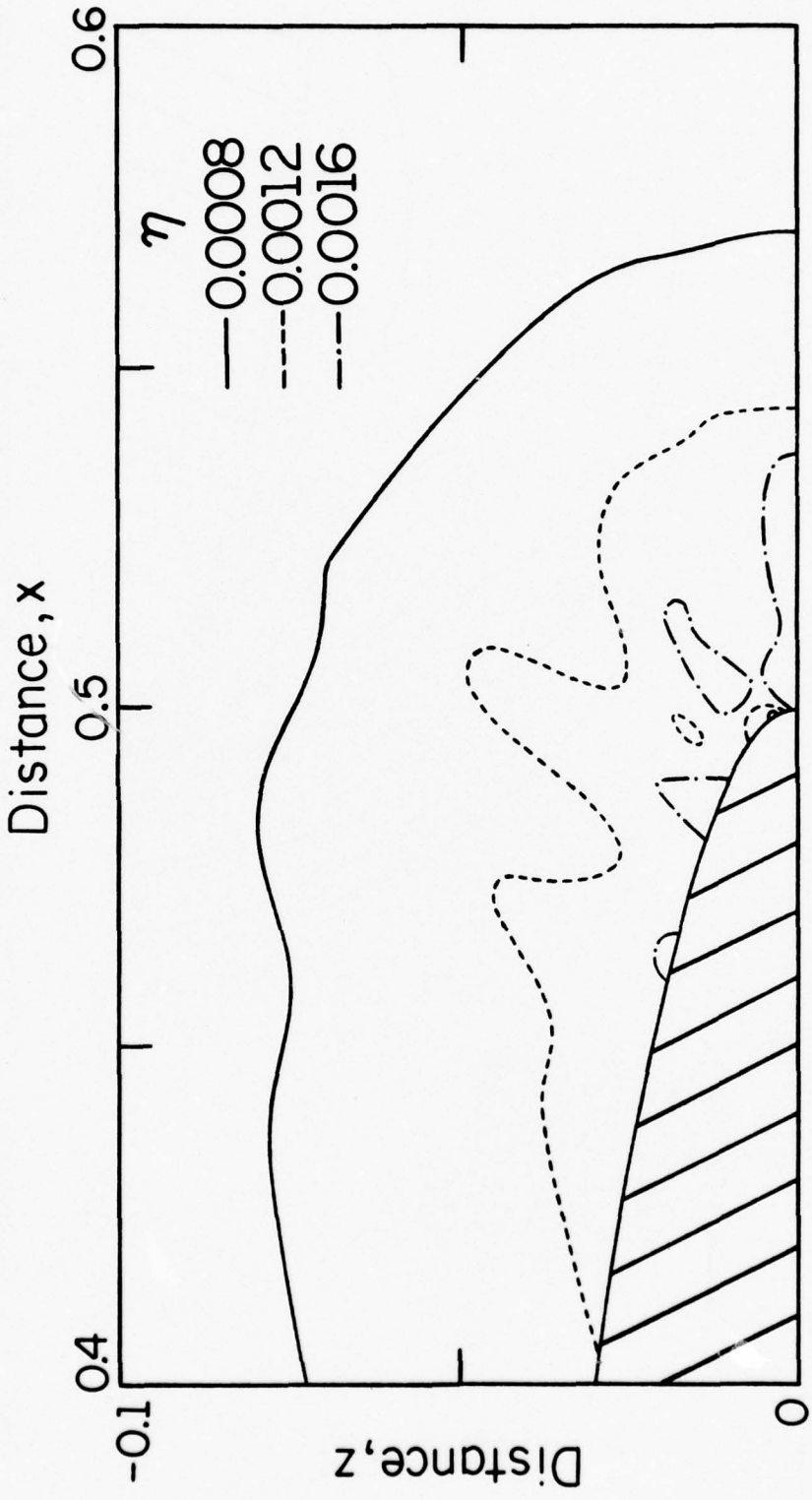

Figure 8.9. Contour plots of the free surface position near the downstream end of the strut at t = 0.05.

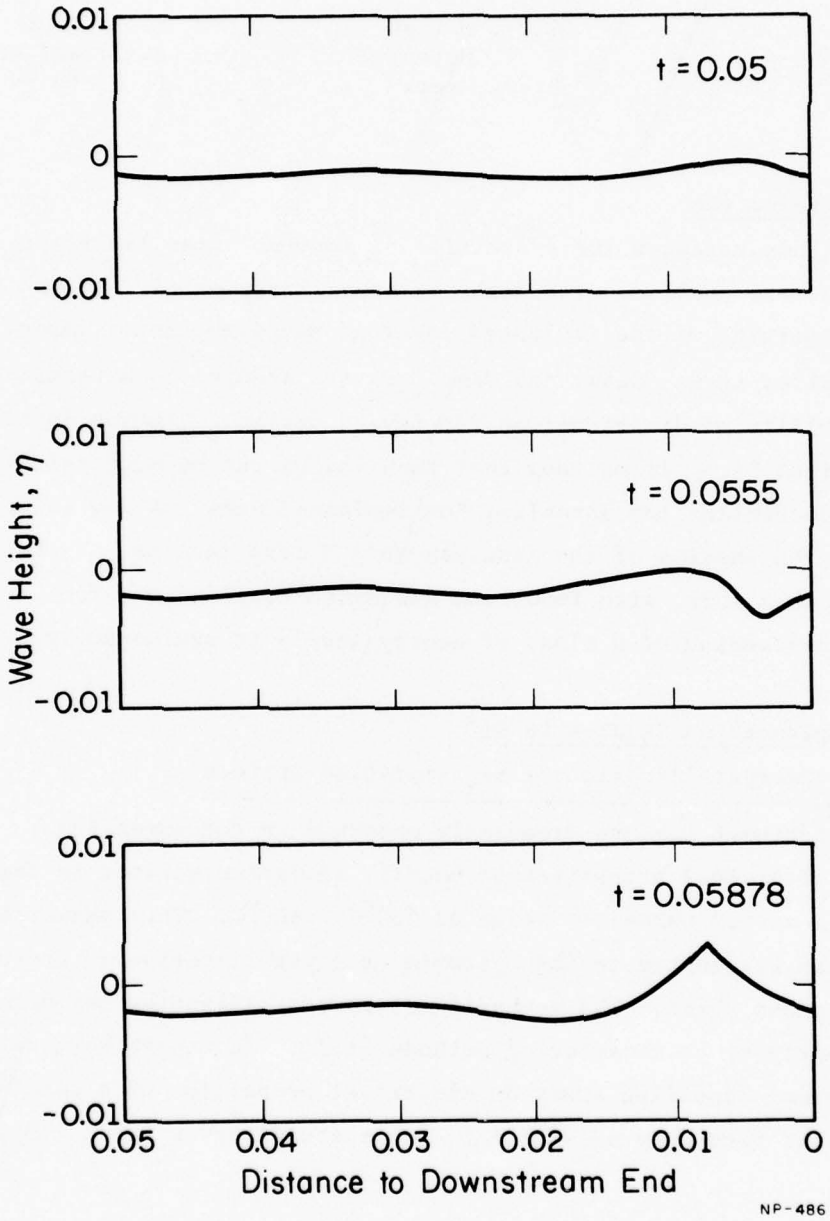

Figure 8.10. Sequence of wave profiles at the surface of the strut vs. the distance s along the arc of the strut prior to and after wavebreaking.

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9.1 Introduction

In this research the properties of ion-implanted layers in semiconductors are studied, with emphasis on exploration of fundamental materials properties of the implanted layers. Measurements of implanted impurity profiles in Si, GaAs, and $GaAs_{1-x}P_x$ are studied to determine the predictability of distributions for device design. Studies on rf plasma deposited Si_3N_4 films show that such layers can be successfully used as an encapsulant for annealing ion implanted GaAs. A new interpretation of the physics of the isoelectronic N trap in $GaAs_{1-x}P_x$ has emerged from this work, with important and basic implications for improved understanding of a class of energy levels in semiconductors.

9.2 Implantation Studies in Si*

9.2.1 Recrystallization of BF_2-implanted silicon

A dominant feature frequently observed in the annealing behavior of electrical properties of heavily implanted silicon is the presence of a marked annealing stage at $550^{\circ}C \sim 600^{\circ}C$. This annealing stage has been attributed to the epitaxial recrystallization of a continuous amorphous phase. The mechanism of recrystallization has been studied recently by backscattering methods [1,2]. We report here the first isothermal annealing study on electrical properties of a continuous amorphous layer formed by BF_2-implant. This study serves two purposes,

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(1) to study the recrystallization mechanism as it affects electrical properties, and (2) to investigate BF_2-implanted layers to compare with B-implanted layers. We have made a detailed electrically active profile study of BF_2-implanted layers annealed isothermally at 550°C. This measurement is done by a double a.c. Hall measurement system in conjunction with successive layer removal techniques. Figure 9.1 shows the electrically active region grows from the underlying crystalline silicon substrate gradually to the surface. It also shows that the heavily damaged crystal silicon immediately below the continuous amorphous layer is not activated electrically even after 550°C annealing for 100 minutes. This clearly demonstrates the different annealing mechanism for a continuous amorphous layer compared with a heavily damaged crystalline region.

9.2.2 Fluorine distribution in a BF_2-implanted layer

The critical dose for a BF_2^+-implant to form a continuous amorphous layer in Si is much less than for a B^+-implant. However, the outdiffusion and redistribution of fluorine atoms during annealing could have significant effects on carrier mobility and reverse leakage current. We have performed SIMS measurements on the fluorine distribution, and find that fluorine tends to diffuse out from silicon after the sample is annealed at 600°C or higher temperatures. The damage created by fluorine and boron atoms seems to hinder this outdiffusion. Therefore, the fluorine accumulates at these regions of damage during annealing. At 900°C, a large fraction ($\sim$ 36%) of this implanted fluorine diffuses out, and after 1100°C annealing, 99% of the fluorine has diffused out. Possible effects of residual fluorine have yet to be determined.

9.2.3 Studies in arsenic implanted Si

It has been observed that when arsenic is implanted through the edges of tapered oxide layers into silicon, a stable high defect density region exists near the taper and that this damage cannot be annealed out even at 1000°C [3]. TEM [3] and backscattering studies [4] have provided indirect evidence that recoiling oxygen atoms are responsible for the residual damage. We have used low temperature

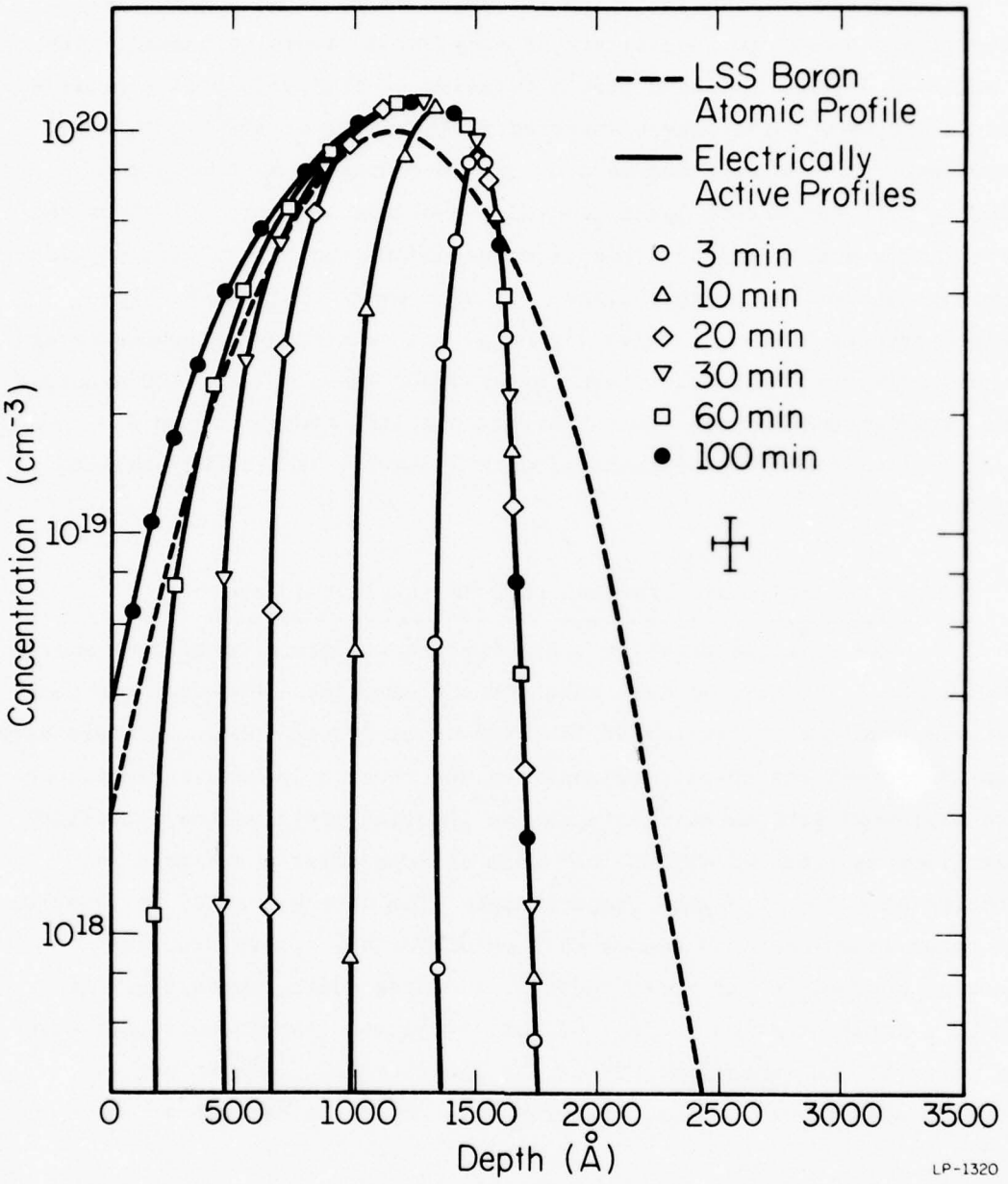

Figure 9.1 Electrically active profiles for ⟨100⟩ silicon implanted with 150 keV BF_2^+ to a dose of 1 x 10^{15} cm^{-2} and annealed isothermally at 550°C.

photoluminescence and, by monitoring the 0.79 eV oxygen dependent radiative center, have shown that considerable oxygen recoil takes place when As is implanted through a thin oxide layer [5].

More recently we have studied the effect of recoil-implanted oxygen on the transport properties of silicon implanted with arsenic to fluences of 10^{15} cm^{-2} and 5 x 10^{15} cm^{-2}. Sheet resistivity and sheet Hall coefficient measurements following various annealing stages indicate identical recovery for through-oxide and bare surface implants. Comparison of impurity profiles obtained from secondary ion mass spectroscopy (SIMS) and glow discharge optical spectroscopy (GDOS) with free carrier profiles obtained from differential Hall measurements show identical activation for through-oxide and bare surface As implants for both 600°C and 1000°C anneals. Additionally, the mobility values obtained from bare surface and through-oxide implanted samples agree very well with the values expected for As doped silicon [6]. It is generally believed that residual damage observed in through-oxide implanted samples is caused by random nucleation during recrystalization of the implantation-induced amorphous layer, due to a reduction in epitaxial growth rate of the implanted layer by the presence of excess recoiled oxygen atoms. The results of our transport studies are in substantial agreement with the above model.

9.3 Beryllium-Implanted GaAs and $GaAs_{1-x}P_x$*

In recent years, considerable attention has been given to the implantation of Be in GaAs [7-10] and $GaAs_{1-x}P_x$ [11,12] to form p-type layers with high electrical activation and efficient luminescence. It has been demonstrated that device quality p-n junctions exhibiting extremely low leakage currents and high breakdown voltages [10,13,14] can be fabricated by Be implantation. For example, we have recently shown

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

that typical Zn-diffused $GaAs_{0.6}P_{0.4}$ diodes have reverse leakage currents $\sim$ 50 times those obtained in equivalent diodes made by Be implantation [14]. Lateral Zn diffusion under the nitride mask creates lattice degradation observable by scanning electron microscopy. Such lateral diffusion and degradation is not observed for Be-implanted diodes. We have recently made mesa-etched GaAs diodes by Be-implantation having breakdown voltages of $\sim$ 100 V and leakage currents of $\sim$ 1 nA at $\sim$ 50 V. These results are important to the development of numerous devices requiring junctions in these materials, including the emerging field of GaAs integrated circuits.

In examining the properties of Be-implanted layers, a thorough study of the electrical and optical activation of Be-implanted GaAs for a wide range of implant doses and anneal temperatures and times has been carried out. We have employed low temperature ($5^{o}K$) photoluminescence to study the optical activation of implanted Be and residual damage not evident in electrical properties. Profiles of the electrically active carrier distribution have been obtained by performing differential resistivity and Hall effect measurements in conjunction with chemical etching for removal of successive layers. Details of our luminescence measurements [8] and double ac Hall measurements [15] are given elsewhere.

Studies of photoluminescence at $5^{o}K$ indicate that an anneal at $900^{o}C$ is required for Be-implanted GaAs to obtain optimum activation and to remove residual lattice damage [8]. Results of electrical measurements, however, indicate good electrical activation and mobility recovery at considerably lower temperatures. In fact, 900^{o} annealing of heavily-doped material results in Be diffusion, as discussed below.

In Fig. 9.2, we show carrier concentration and mobility profiles for a Be fluence of 1×10^{15} cm^{-2} at 250 keV. The samples were annealed for 1/2 hr with Si_3N_4 encapsulation at the temperatures shown. In this case the highest hole concentration occurs for the $700^{o}C$ anneal with an activation of 75%, although the $600^{o}C$ profile is quite similar with an activation of 70%. In contrast with the results at low concentrations, a drastic redistribution of the implanted Be is found at $800^{o}C$ in this higher fluence case. The activation has been reduced to 50%, and

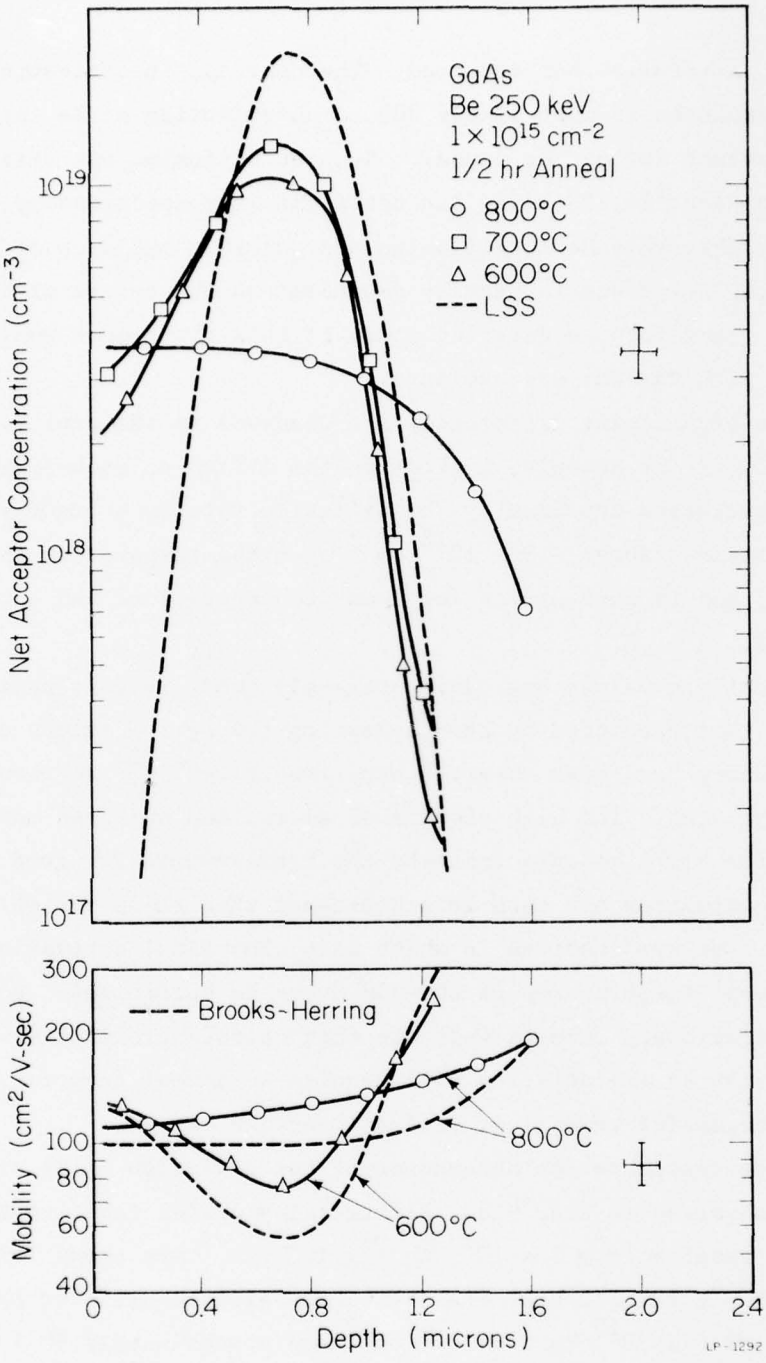

Figure 9.2 Net acceptor concentration and mobility profiles obtained from differential Hall effect measurements on GaAs implanted with a 1 x 10^{15} cm^{-2} fluence of Be and annealed for 1/2 hr at the temperatures shown. The as-implanted theoretical distribution (LSS) and Brooks-Herring mobility curves are superimposed.

significant indiffusion has occurred. The decrease in activation at higher temperatures is most likely due to outdiffusion of Be into the Si_3N_4 encapsulant during the anneal. Such outdiffusion was first observed by Comas and Plew [16,17] using secondary ion mass spectroscopy (SIMS). It is likely that this Be outdiffusion and possible build-up of Be near the GaAs-Si_3N_4 interface is heavily dependent on the nature of the Si_3N_4 films used. Therefore, a detailed study of this phenomenon would require comparisons with various encapsulants.

No significant differences are observed in the profiles for 800 and 900°C 1/2 hr anneals, indicating the diffusion mechanism is highly concentration dependent. The diffusion rate is extremely fast for concentrations above $\sim 5 \times 10^{18}$ cm^{-3} when the temperature is near or above 800°C, and is much slower for lower concentrations and anneal temperatures.

Mobility values are again extremely good, in this case slightly higher than that predicted by Brooks-Herring theory. Numerous variations from this theory have been observed experimentally [18], so these results are not surprising. The high electrical activation and high mobility found even for 600°C anneals indicate the requirements for good electrical activation are much less stringent than those for optical activation. For applications in which only electrical activation is desired, anneal temperatures of 600-700°C may be sufficient. However, the photoluminescence results indicate that optoelectronic devices fabricated with Be implantation will require an anneal temperature of 900°C for successful removal of residual lattice damage.

The concentration dependence of the diffusion of Be at 900°C is readily observed in Fig. 9.3. Electrical profiles for five 250 keV Be fluences ranging from 5×10^{13} to 1×10^{15} cm^{-2} are shown following anneals at 900°C for 1/2 hr. The activation efficiencies for the three lower doses of 5×10^{13} to 2×10^{14} cm^{-2} are approximately 90-100%, and the profile tends to flatten and diffuse in only slightly as the dose is increased. These fluences correspond to peak implanted impurity concentrations of less than $\sim 5 \times 10^{18}$ cm^{-3} as given by LSS. For implanted impurity concentrations above this value, the activation is observed to decrease rapidly to 65% for a 5×10^{14} cm^{-2} fluence and

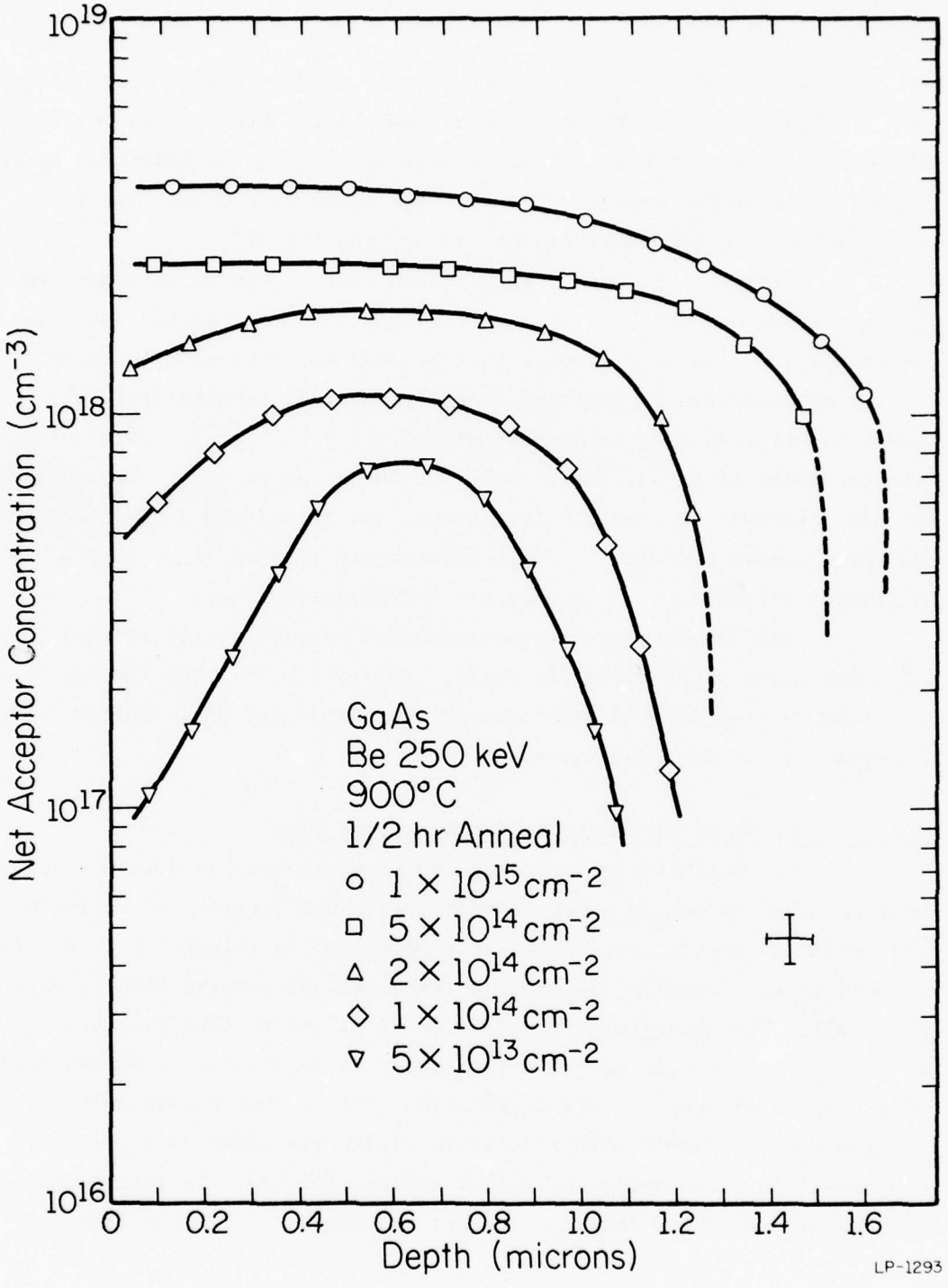

Figure 9.3 *Net acceptor* concentration profiles obtained from differential Hall effect measurements on GaAs implanted with Be to the doses shown and annealed for 1/2 hr at 900°C.

to 50% for a 1×10^{15} cm^{-2} fluence. Deeper indiffusion is also observed for the higher doses. The diffusion front in the higher dose profiles shown in Fig. 9.3 is believed to be extremely sharp, as indicated by the dashed lines in the curves. The profiles shown in Fig. 9.3 are in agreement with preliminary studies using SIMS [16,17].

Ilegems [19] has recently shown that Be can be incorporated in GaAs grown by molecular beam epitaxy (MBE) to form device quality p-type layers. He also reports that Be does not diffuse significantly at low concentrations. We have recently examined samples from Bell Laboratories with high Be concentration ($> 2 \times 10^{19}$ cm^{-3}). Preliminary studies indicate the diffusion behavior in MBE grown and implanted samples is not dependent on concentration alone, but depends in a complex manner on the presence of defects. More experiments to shed light on the diffusion behavior of Be in GaAs are presently underway.

Similar carrier concentration and atomic profile studies have been performed in Be implanted $GaAs_{(1-x)}P_x$ ($x = 0.4$). The results are the same as that in GaAs and indicate that implanted Be is a good acceptor in the GaAs-GaP system.

9.4 Study of Encapsulants for Annealing GaAs*

Ion implantation produces considerable lattice damage which must be annealed out in order to restructure the lattice and activate the implanted impurities. While this procedure is relatively straightforward in Si, annealing a compound semiconductor such as GaAs is more difficult. The incongruent evaporation of Ga and As from GaAs at temperatures in excess of 600°C [20] makes it impossible to anneal bare GaAs samples without surface degradation. It is thus necessary to encapsulate the sample with a suitable dielectric layer or to perform the anneal in a carefully controlled ambient [21,22]. In the present work we have used low temperature photoluminescence (PL) and Auger

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

electron spectroscopy (AES) to investigate the annealing-encapsulation properties of chemical vapor deposited SiO_2 and rf plasma deposited Si_3N_4 layers on GaAs.

The SiO_2 layers used in this study were deposited by thermal oxidation of silane, with the sample maintained at $\sim 450^{o}C$. All Si_3N_4 layers were prepared by rf plasma deposition from reaction of silane with nitrogen, with samples maintained at $\sim 450^{o}C$. Those nitrides labeled A were deposited in a system where silane and nitrogen were mixed prior to initiation of the rf plasma. Those labeled B were prepared by first initiating a nitrogen plasma and then introducing the silane separately from the plasma region and over the surface of the sample.

Figure 9.4(a) illustrates that when a sample is annealed with SiO_2 encapsulation, a broad luminescence band is observed with a peak at 1.356 eV. In an earlier work we have shown that this defect band is related to Ga outdiffusion [23]. This observation is substantiated by the AES depth profile of the oxide on a similarly treated sample (Fig. 9.5). A detectable Ga signal is observed in the surface Auger spectrum (see inset). Since the sample was encapsulated on all sides during the anneal, the presence of Ga at the surface clearly indicates diffusion of Ga from the substrate through the SiO_2 layer. However, no Ga was detected within the SiO_2 layer itself. Presumably, this is due to a solid solubility of Ga in SiO_2 below the Auger detection limit ($\sim$ 0.5 atomic %).

The PL spectrum from a sample annealed with Si_3N_4(A) is presented in Fig. 9.4(b). This spectrum also clearly indicates Ga loss from the GaAs. The lower energy peaks associated with the 1.356 eV band in Fig. 9.4 are phonon replicas of the main zero-phonon peak. These peaks are separated by $\sim$ 36 meV, the LO phonon energy in GaAs [24]. Figure 9.6(a) shows an AES depth profile for a similar sample annealed with Si_3N_4(A) encapsulation. A relatively strong Ga signal is observed at the Si_3N_4 surface and a uniform Ga level is seen throughout the encapsulant. As discussed earlier, Si_3N_4(A) was prepared by premixing silane and nitrogen prior to the formation of the plasma. The AES data also show the presence of a uniformly high level of oxygen within

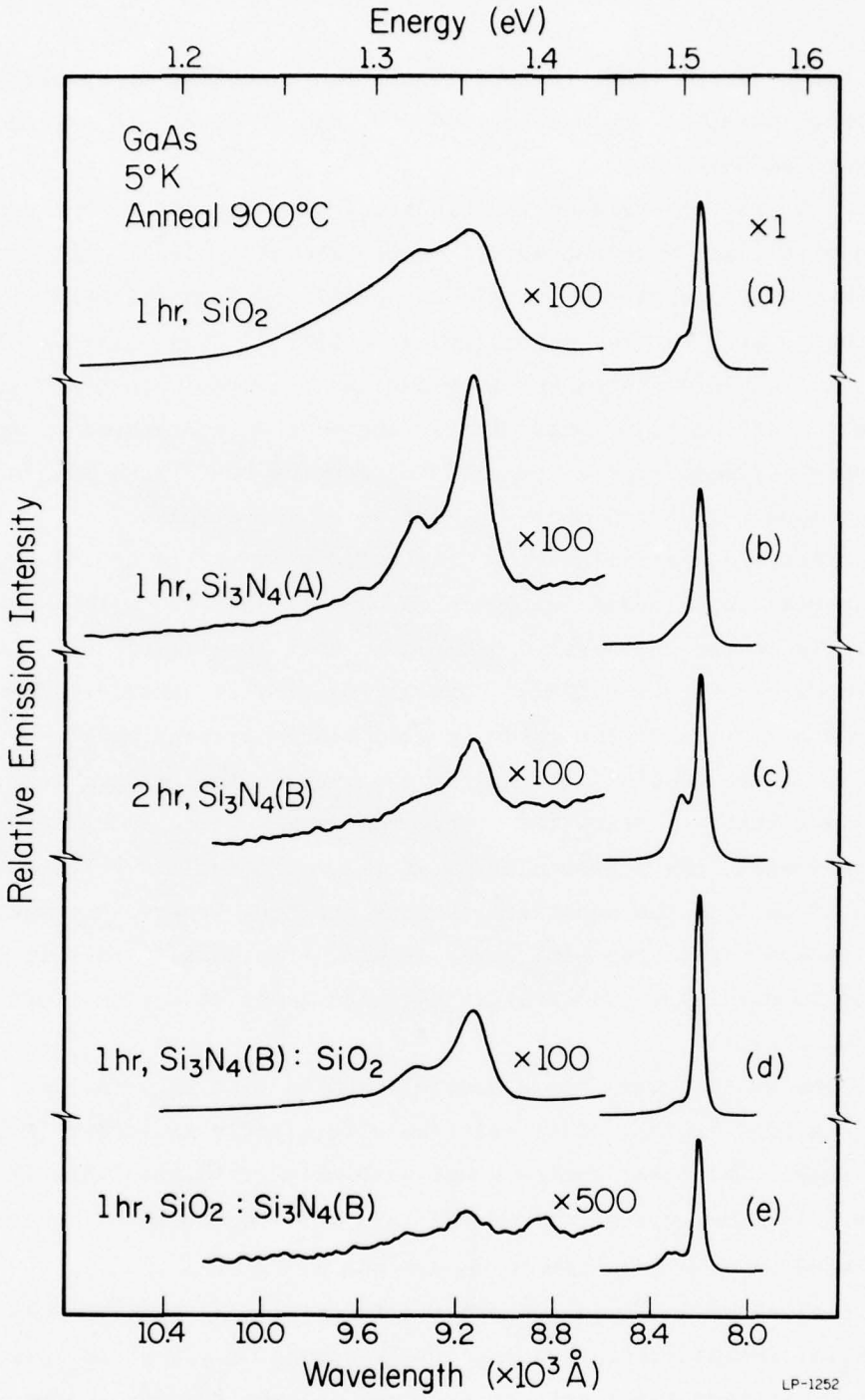

Figure 9.4 Photoluminescence spectra from GaAs samples annealed with various encapsulants. The scale factors are indicated relative to the 1.52 eV bandedge peak for each sample.

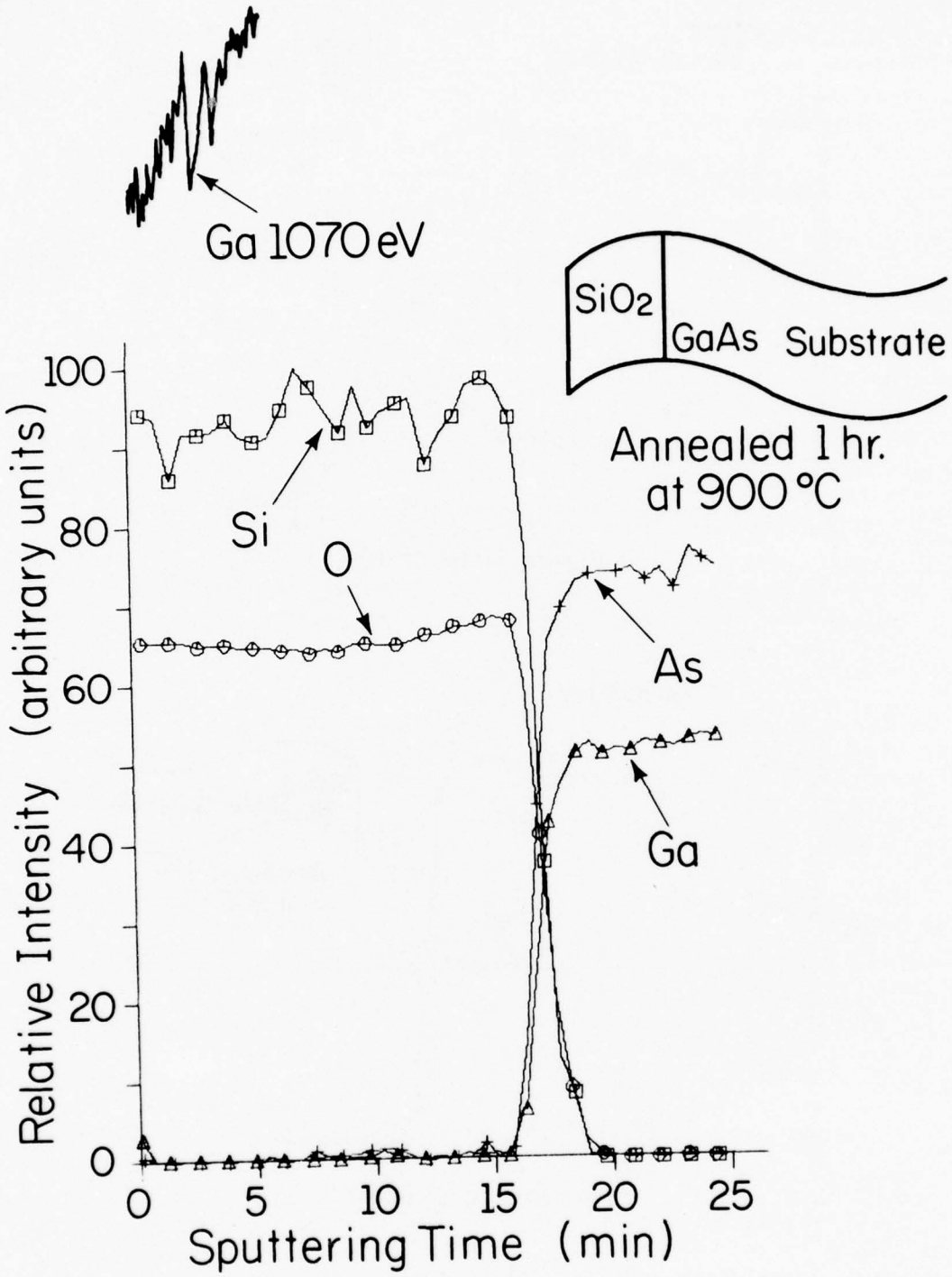

Figure 9.5 Auger depth profile obtained from a GaAs sample encapsulated with SiO_2 and annealed at 900°C for 1 hour. The inset illustrates the Ga Auger spectrum observed at the SiO_2 surface prior to sputtering.

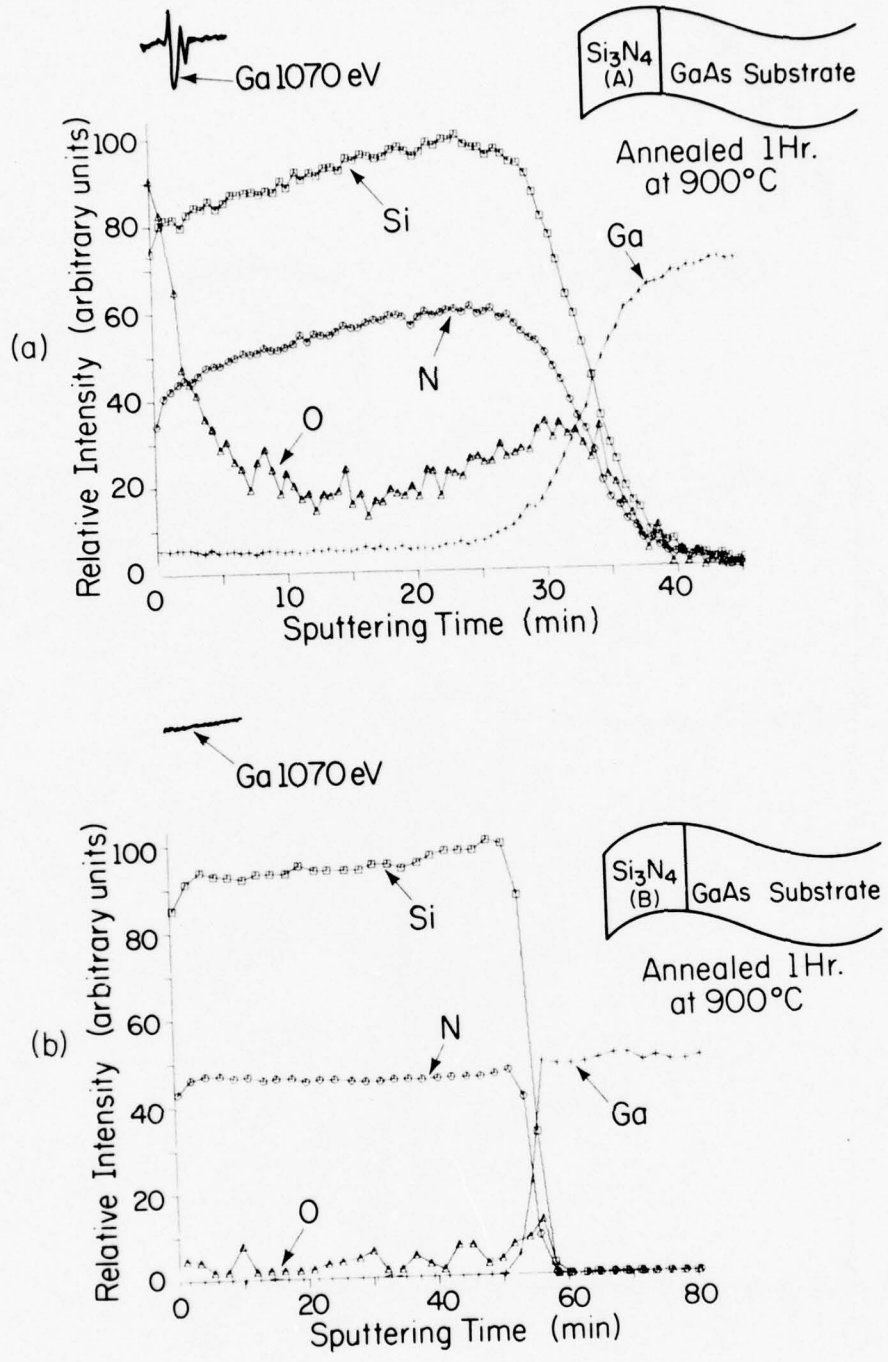

Figure 9.6 Auger depth profiles obtained from GaAs samples encapsulated with: (a) Si_3N_4(A), and (b) Si_3N_4(B) layers and annealed at 900° for 1 hour. The insets illustrate the Ga Auger spectra at the Si_3N_4 surfaces prior to sputtering.

the film. Both PL and AES data clearly show the outdiffusion of Ga through such nitride layers.

Figure 9.4(c) displays the PL spectrum obtained from a sample with Si_3N_4(B) encapsulation, annealed at 900°C for 2 hours. A weak 1.356 eV band is seen. In a sample annealed with such an encapsulant for 1 hour, the intensity of the 1.356 eV band was very weak. The absence of a strong defect PL band even after the 2 hour anneal suggests that Si_3N_4(B) effectively suppresses Ga outdiffusion. In AES studies, no Ga signal could be detected either in the surface spectrum or in the depth profile of this nitride [Fig. 9.6(b)]. It is also interesting to note that the oxygen level in Si_3N_4(B) was low, barely above the detection limit of ~ 0.1 atomic %. This is at least an order of magnitude lower than the oxygen level observed in Si_3N_4(A).

Anneal studies were also carried out using a multi-layered dielectric sandwich as the encapsulant. Figure 9.4(d) shows the PL spectrum obtained when a Si_3N_4(B)/SiO_2 dielectric layer (with SiO_2 in contact with the GaAs) was used as the encapsulant. The 1.356 eV band is observed, although the intensity of this band is weaker than in spectrum 9.4(a). The AES data failed to show any Ga either at the surface or within the dielectric layer. However, when the anneal was repeated with a Si_3N_4(A)/SiO_2 layered encapsulant, AES depth profiles clearly showed the presence of Ga both at the surface and within the nitride layer. GaAs samples encapsulated with SiO_2/Si_3N_4(B) were also annealed. As expected, PL (Fig. 9.4e) and AES data indicated negligible outdiffusion of gallium from the substrate. No Ga pileup was observed at the oxide-nitride interfaces in any of the cases studied.

These studies lead to the following conclusions:

(1) SiO_2 encapsulant on GaAs permits Ga loss during annealing at 900°C.

(2) Attempts to deposit Si_3N_4 layers by premixing silane and nitrogen result in silicon oxynitride films which also permit Ga outdiffusion during annealing.

(3) Si_3N_4 layers prepared by introducing silane separately from the nitrogen plasma region allow negligible Ga outdiffusion. Such films can be successfully used to encapsulate GaAs for post-implant annealing.

9.5 Study of the Nitrogen Isoelectronic Trap in $GaAs_{1-x}P_x$*

We reported last year extensive studies of ion-implanted N in GaP and $GaAs_{1-x}P_x$, which led to a new interpretation of N-related luminescence in the ternary alloy [25,26]. In further studies during the past year we have established the nature of phonon participation and developed model calculations of the N bound states in these materials.

Figure 9.7 illustrates the strong increase in exciton-phonon interaction for the N_X state of isolated nitrogen as the alloy composition is varied from GaP into the ternary. Increased optic and acoustic phonon coupling, local mode broadening, and accompanying Stokes (or Frank-Condon) shift between emission and absorption are evident with increasing GaAs mole fraction. We have performed emission linefits to the recombination spectra over much of the alloy diagram to identify the phonon cooperation [27]. The increased electron-phonon interaction and the deepening of the binding energy for the N_X (or A-line) state is indicative of increased lattice relaxation about the N center in the alloy. These features are discussed extensively elsewhere in terms of the data [27] and theoretical treatment [28].

In collaboration with Hsu and Dow in the Physics Department we have described the N trap in terms of an extended Koster-Slater model which includes the effects of both the central-cell atomic pseudopotential difference and the spatially extended lattice distortion surrounding the substitutional N impurity [28]. Results of this model calculation are shown in Fig. 9.8 compared with the experimental data. Fitting parameters of the model to the data near $x = 0.35$, the theory yields a spatially localized state N_X which evolves continuously from the A-line of GaP, and a spatially diffuse excited state N_Γ at higher energy in direct bandgap compositions. In addition, the theory gives good agreement with the observed composition dependences of luminescence

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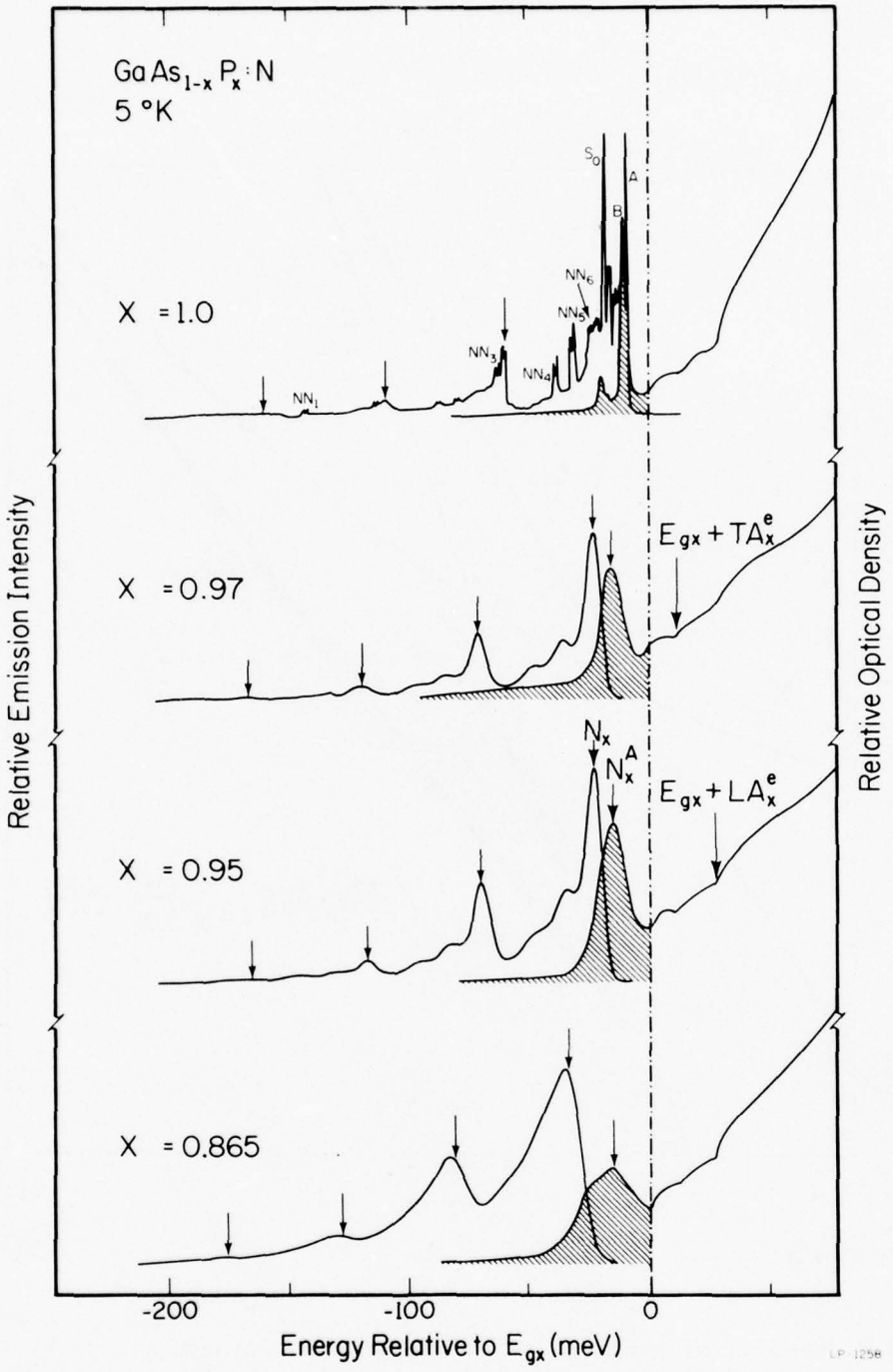

Figure 9.7 Photoluminescence and absorption (shaded) on the N trap in GaP and $GaAs_{1-x}P_x$, illustrating Stokes shift of N_X in the ternary. The spectra are aligned according to the free exciton edge (E_{gx}). Arrows indicate the N_X peak and the optical phonon replicas.

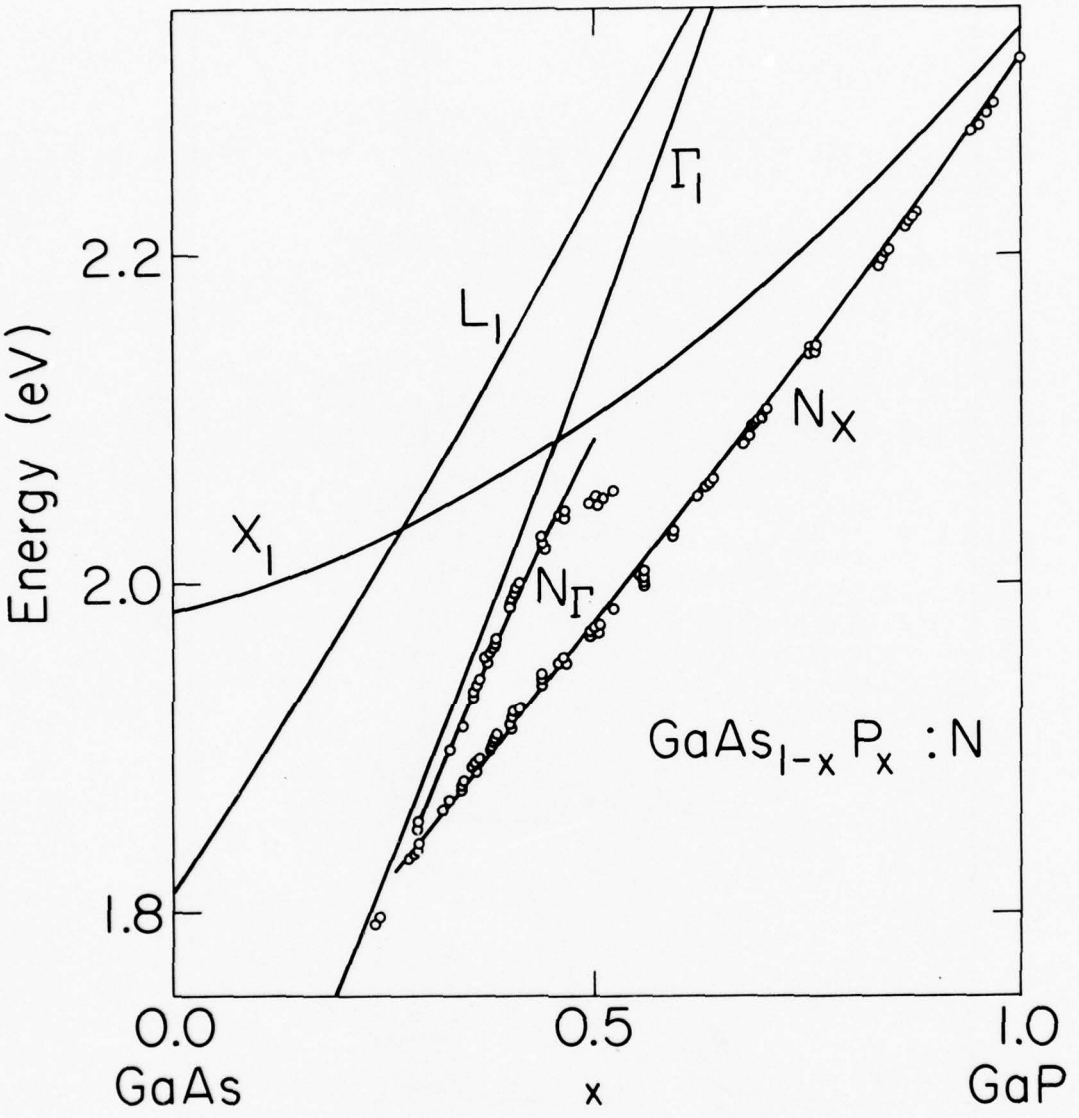

Figure 9.8 Results of model calculations of the nitrogen states N_Γ and N_X in $GaAs_{1-x}P_x$. The solid lines labeled N_Γ and N_X indicate energy levels for these states computed using an extended Koster-Slater model. Experimental PL peak positions are shown by the circles for comparison. The approximate positions of the X_1, L_1, and Γ_1 bandedges are also shown as a function of composition.

intensities, pressure effects, and radiative lifetime. Recent work suggests that the reported low temperature disappearance of NN pairs in the ternary [26] is related to ternary lattice relaxation, in that long-range exciton transfer present in GaP is decreased in the alloy where the emission-absorption overlap is reduced as displayed in Fig. 9.7.

We have examined ion implanted N in (Al,Ga)As over much of the alloy composition range, and find results similar to that in Ga(As,P). An interesting result of these studies is that properties such as lattice coupling to the impurity and binding energy at the trap state vary within a ternary system and between systems as expected from the changes in known mechanical properties of the lattice. Clearly, lattice distortion about the N center is of paramount importance in determining its properties as a deep radiative level. Furthermore, we have shown that the N trap is a "model" deep level (despite its proximity to the X_1 bandedge in GaP) and that the ternary alloys offer an excellent opportunity for studying details of deep levels in semiconductors.

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10.1 Fault-Tolerant Digital Systems*

A digital system is called fault-tolerant if failures either do not affect the correct operation of the system ("fault-masking") or if failures are indicated as soon as their effect begins to invalidate the outputs ("self-checking").

Research is divided into two broad areas: (1) Fault-Tolerant Distributed Systems, including a study of modeling various types of loosely coupled distributed systems to analyze their performance under failures and the development of design principles for reliable systems with high performance; (2) Self-Checking Systems, including new results on the interconnection of totally self-checking modules having dissimilar fault behaviors and hence employing dissimilar codes, and the use of redundancy in time rather than space ("self-checking alternating logic"), and (3) Methods of Fault Simulation and Testing, including the development of a functional block level simulation language and programming system to serve as a tool to study the behavior of microprocessors and other logic systems under various faults, and the development of diagnostic test procedures for semiconductor memories and microprocessors.

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

10.1.1 Fault-Tolerant Distributed Systems

10.1.1.1 Modeling the Reliability and Performance of Loosely Coupled Distributed Systems

A broad study is being made of loosely coupled distributed systems for various applications requiring fault-tolerance. The parameter of interest is the overall performance of the system under failures. The study deals with modeling various types of systems and analyzing their performance under failures and also finding design principles for reliable systems with high performance.

Simple systems which are periodically checked have been modeled. For one type of system for example, the optimum time after which the diagnosis should be periodically run has been found to be approximately the geometric mean of the time for diagnosis and the Mean Time Between Failures. Systems with imperfect diagnosis are being studied. Since the time a system spends in the working, recovery and failed states is of importance in calculating the performance, semi-Markov models are being used so that these times can be made quite arbitrary and real systems can be modeled more accurately.

10.1.1.2 Analysis and Design of Diagnosable Distributed Systems

Existing approaches for diagnosis in systems often do not give sufficient insight into the design of diagnosable systems. In some cases the optimal design approach is a formidable graph - theoretic problem, the solution of which can be obtained only for the simplest of configurations.

The present work aims to consider arrays of microcomputers or networks of facilities interconnected in such a way that neighboring units have the capability to test a given unit, partially or completely. The conditions under which a complete test may be performed on such a system, the identification of faults, and the techniques to achieve proper system reconfiguration in the event of a fault will be among the aspects to be considered. The major factors in the study include minimization of global requirements in the system, practicality of design procedures, and ease of implementation.

10.1.2 Self-Checking Systems

10.1.2.1 Interconnections of Self-Checking Modules

This study considers the design of totally self-checking (TSC) systems that are made up of blocks whose fault behavior is different from one another. Consequently different codes will be mentioned and their associated circuit structure discussed in some details.

Systematic and non-systematic codes that are used to protect against unidirectional errors are shown to have the same basic structure. Indeed they can be produced using the same generating rules expressed in terms of products of lattices. The structure of non-systematic unordered codes, more precisely fixed-weight codes, is examined; it is shown that these codes have codewords that can be effectively classified in terms of congruence, cycling and complementation classes. These results can be used to provide guidelines to solve the problem of finding partitions associated with the design of minimal checkers. Growth and existence tests are related to the design of TSC checkers and are used to show the non-existence of two-level checkers for Berger codes (a class of systematic unordered codes). Some practical suggestions for, and some limitations on the use of unordered codes under different fault models are described.

In the area of arithmetic checking it is shown that well-known arithmetic codes and checking structures are essentially TSC provided some basic guidelines are followed and some increase in the hardware is tolerable.

The different fault models are unified by a brief study of code translation and methods to use codes to their best advantages.

A report is being readied on those topics.

10.1.2.2 Self-Checking Alternating Logic

One of the approaches to improving the reliability of digital logic is to use a time-redundant scheme for dynamically checking the logic. Self-checking alternating logic (SCAL) uses an additional time period for each input to determine if the complemented output results when the complemented input is applied.

Work has been done in (1) improving techniques of determining whether self-dual combinational circuits are self-checking, (2) designing

sequential machines which are SCAL, (3) developing techniques of converting arbitrary circuits to SCAL through the use of specific SCAL modules, and (4) providing system level design approaches. A report is in preparation.

10.1.3 Fault Simulation and Testing

10.1.3.1 A Functional Level ALGOL68 Based Integrated Circuit Representation Library Package

The need for a fault simulator which can handle large scale digital systems has encouraged the development of a functional block level simulation language. A package of library routines and definitions is being developed which allows the use of a subset of the programming language ALGOL68 to model microprocessors or other logic systems and to study their behavior in the presence of faults. The library package will provide a large amount of flexibility in the description of the system block structure, the representation of data, and in the representation of the characteristics of the individual functional blocks.

The library package is almost complete. The simulation driver and the system representation facilities are ready. A few user interface routines remain to be prepared before full scale testing and operation of the package can begin.

10.1.3.2 Testing of LSI Circuits

Research in the area of LSI circuit testing deals with the development of diagnostic test procedures for semiconductor memories and microprocessors. Test procedures have been developed for testing memories by specifying faults on a "functional" level [1,2]. These procedures are capable of detecting a wide variety of faults associated with memories, including decoder faults, stuck-at-1 or 0 cells and faults which cause transitions in one cell to change another. These test procedures are $\mathcal{O}(n.\log_2 n)$ where n is the number of cells in memory. They are thus of a much smaller length than the classical test procedures of comparable fault coverage which are $\mathcal{O}(n^2)$. The new test procedures have been successfully implemented in various computer systems and have been used to detect and locate faulty chips. They have been found to be particularly useful for periodic checkout of memory systems. Further attempts are being made

to increase the fault coverage by suitably modifying the $\mathcal{O}(n.\log_2 n)$ procedures, and simpler test procedures are also being sought.

A fault model for the control unit of a microprocessor is being developed. The effect on the diagnostic routines of faults in both the control unit and in the functional units like the register file, stack, and the ALU is under study.

10.2 Switching Theory and Design Language*

Research in this area deals with methods for minimizing programmable logic array realizations, the development of an algebra to aid in the realization of switching functions using a particular MOSFET circuit package, and the completion of the development of a high-level digital system design language which, through its syntax, aids the designer in avoiding deadlocks or hang-ups of the resulting control structure.

10.2.1 An Algorithm for Minimizing Programmable Logic Array Realizations

Since Programmable Logic Arrays (PLAs) are being increasingly used in logic design, an efficient algorithm which performs multiple-output AND-OR logic minimization is desired. Classical methods involving multiple output prime implicants are practical only for small numbers of inputs (under 6) and outputs (under 4). Therefore, a new branch and bound algorithm has been found for logic problems with up to 16 inputs and 8 outputs. The algorithm makes a series of locally optimum decisions using the concepts of switching theory to derive a first solution. After finding the first solution, it backtracks to consider alternative decisions, modifying gate inputs and successively improving the solution. If run to completion, the algorithm finds the minimum gate solution. At each point the maximum improvement obtainable from continuing to run the algorithm to optimum is known.

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The algorithm has been coded in SAIL and many test problems of a wide range of complexity have been carried out. The efficiency of the algorithm was found to be highly problem dependent. It works particularly well for problems with scattered prime implicants. In a fast shifter problem with 13 inputs and 8 outputs and 74 product terms, the optimum of 68 gates was found in less than 3 minutes on the DEC-10. On the other hand, for a 5 input, 5 output function with 31 product terms, an 18 gate solution was found in just over a minute; no improvement was found in another 20 minutes. In this case, the lower bound on the number of gates was 14. To the extent that most control functions for processors, for example, have a large number of inputs and outputs, but scattered implicants, the algorithm described would be very useful for automatic minimization. A detailed report is under preparation.

10.2.2 Realization of Switching Functions Using a Certain Type of MOS Package

This study centers around a MOSFET circuit package similar to the commercially available Fairchild 3102 package. Switching functions that may be realized using this package have been studied. An algebra, called the P-S algebra, has been developed to determine whether a given switching function is realizable in a series-parallel form using the least number of elements in the package. The realization in the case of bridge form circuits has also been studied. The P-S algebra has also been found to be useful when an optimal or near-optimal realization is required for a function which does not possess a minimal realization.

10.2.3 Digital Systems Design Language

It is our contention that most computer hardware design languages (CHDLs) are useful only as documentation aids. It is interesting to note that one of the most popular, called ISP [3] started out as such.

We have completed the specification of a CHDL (a report will follow shortly) which has the following properties:

1. Sufficient scope to describe multiprocessing systems.
2. Syntactically correct programs describe systems which have deadlock-free control structures.

The control problem associated with multiprocessing systems is, in general, quite complex, and the opportunities for creating a control structure which can hang-up are great. Hence, specifying a CHDL so that this pitfall can be avoided by staying within the bounds of the syntax, gives the user a true design tool which is more than just an aid for documentation. A report (R-759) has been published; another is in preparation.

10.3 Pipelined Processing*

This research is concerned with the design, control, applications, and efficiency of pipelined processors. Pipelining, i.e., overlapped execution, can provide more throughput of a central processor to achieve a balanced system. In contrast to full parallelism through duplication of resources, whose cost rises approximately linearly with increased throughput, pipelining never costs more than full parallelism and is generally significantly less expensive. Several commercial computers have used pipelined architecture and a continuing trend in favor of pipelining for general purpose computation is expected. This research represents a first attempt at a comprehensive and effective methodology for the design, control, application, and performance evaluation of pipelined processors and other pipelined structures.

A pipeline is considered to be a collection of segments of hardware which can operate simultaneously. Each segment performs a specified part of a particular computation. Any set of segment use patterns may be specified. For each computation the segment use pattern must be fully known. This determinacy requirement limits the complexity of a computation which may be considered as a task for the pipeline. A more complex computation is treated as an assemblage of tasks. The task arrival pattern within an assemblage of tasks may be nondeterministic. The nature of pipelines for which deterministic information is available is now well known due to our previous research. Recent emphasis has been on non-deterministic system level problems.

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Research is divided into five broad areas: model development, control of pipelines, effective design procedures, applications, and performance evaluation. Specific studies for this year are reported in five groupings: memory management, processor organization, system organization, circuit technology evaluation, and an experimental multiple microprocessor system.

10.3.1 Virtual Memory Management

An algorithm has been discovered for computing an optimal dynamic allocation which minimizes the space-time cost in a demand paging virtual memory. The problem is represented by a graph computed from a trace of the program. Another algorithm is available to reduce the size of the graph.

After the reduction, the optimal allocation is found by determining the maximum flow in the remaining graph. For the class of graphs considered, the worst case complexity for finding the maximum flow is $\mathcal{O}(N'^3)$ where N' is the number of nodes in the graph after reduction.

These algorithms have been implemented and used to collect data for a variety of programs. The memory allocations resulting from our algorithm have been compared with those from an optimal static allocation algorithm and from two known dynamic heuristic algorithms: the Page Fault Frequency algorithm and the Damped Working Set algorithm. Comparisons have been made for a variety of page sizes and secondary memory speeds. These algorithms are substantially more accurate than the only other known approach to this problem. Results indicate that, except for programs which have nearly constant size working sets of known size and change between them abruptly, dynamic (automatically adaptive variable size allocation) algorithms offer marked advantage over the best achievable static allocation. Furthermore improved, implementable dynamic heuristics are needed, as known heuristics are very sensitive to their parameter values and proper parameter tuning procedures are not known.

Details may be found in report R-754.

10.3.2 Processor Organization

10.3.2.1 Analysis of Memory Addressing Architecture

Program execution is separated into a computation process and an addressing process. The addressing process generates the memory reference stream for the computation process. The memory reference stream of the computation process is then modeled probabilistically and its information content derived. Techniques have been developed for analyzing the effectiveness of the addressing process. Comparisons of this effectiveness have been made with respect to information theoretic bounds for a given trace. Such comparisons have shown that conventional addressing processes place a large and mostly unnecessary load on the system.

Several techniques for analyzing particular aspects of addressing architectures and CPU/Memory traffic have been developed. Areas of improvement for addressing architecture, compilers, and memory architecture have been examined for achieving performance enhancement of the addressing process. For example, our results indicate that it is possible to build an LSI memory chip that not only would relieve the CPU of most of the load imposed by the computation process (thereby speeding up execution time), but would also only require only one address pin; trading-off increased chip complexity for reduced interchip bandwidth. The extent of this increased complexity has been evaluated and appears to be reasonable for the performance gains achieved. Several more moderate approaches and their performance cost characteristics have been analyzed as well. Very significant performance gains can be achieved only if the memory can take advantage of second order information in the memory reference stream. These results become increasingly important as memory address space and LSI memory chip density increase.

10.3.2.2 Architectural Tradeoffs for Multiple Instruction Stream LSI Processors

Although implementation of ever larger and more powerful processors is feasible in LSI technology, state-of-the-art microprocessors at best are only minor modifications of outdated last generation minicomputer architecture. This research is concerned with a careful evaluation of a broad range of trade-offs involved in LSI CPU architecture in a total system context. Our goal is to define and evaluate cost-

effective architecture and their appropriate implementations, so as to make best use of increased chip area to enhance total system performance, while conserving the number of pins on a chip.

A pipelined architecture, which allows concurrent multiple instruction stream execution within a simple chip, provides an efficient method of obtaining high processing bandwidth with relatively few pins. A methodology has been developed which, beginning with a desired instruction set, determines necessary interconnection paths, the placement and quantity of logic units to obtain efficient parallelism, and a final logic block level layout for a pipelined nulti-processor specifically suited for LSI implementation. Such a processor requires only a very simple shared control structure and few registers per instruction stream. These properties are particularly important for an LSI implementation. The feasibility of such a system is thus demonstrated.

So that alternative multichip organizations may be evaluated, if a single chip is infeasible, various partitioning methods were studied based on reduction of pin requirements. Two methods were found to be clearly superior: a register partition and a bit slice partition. It has been determined that the register partition is best with a processor which has a large number of control lines compared to the data word width and a bit slice partition is best when the word width is large. It was also found that a combination of the two methods works best when a high degree of partitioning is required. Conventional multiple single stream processor organizations and time slice partitions were found to be unattractive.

The final section of this research compared the performance of a pipelined processor with one data register against a single processor with many data registers. (This is relevant to determine the cost effective means of LSI implementation.) It was found by analyzing program traces from several IBM 360 programs that the performance of a multistream pipelined CPU with only one data register per stream far exceeded the performance of a single processor with many data registers. The two alternative systems are of comparable cost in LSI implementation.

It has therefore been concluded that additional area within LSI processor chips is used most cost effectively by a pipelined multi-

processor architecture, rather than a single processor architecture with more general purpose registers. Partitioning studies show that this basic result holds true even if multichip organizations are necessary.

10.3.2.3 Directly Executed Languages

Computer processing of a typical user job may be decomposed into two distinct phases. Users generally submit algorithms to the computer represented in some high-level source language which, to facilitate execution, is first translated into some equivalent intermediate language representation. This first phase is typically performed by a compiler or sequence of compilers. The intermediate text may then be executed by an emulator, which interprets the intermediate text statements. This interpreter is usually executed directly by the machine hardware. This second processing phase thus consists of the actual performance of the user's algorithm through interpretation of the intermediate text. The intermediate text generated by the compiler is called a "directly executed language" or DEL, since it is "directly executed" by the interpreter.

Typically, the interpretive stage of this process is performed by a microprogrammable host processor, with microprogram control store used to contain the interpreter program. Thus, the first phase of this research has been the investigation of a microprogrammed control structure for a pipelined multiple instruction stream processor. The organization under consideration consists of multiple DEL instruction streams being interpreted independently by the distinct streams of the pipelined host processor. This research has demonstrated that high performance with a substantially reduced cost/performance ratio can be achieved by utilizing a single interleaved control store to hold the microprocessor for all streams. Additional design procedures were developed for the specification of branch resolution times, for analyzing the effect of branch resolution faults on performance, and for the appropriate addition of dummy time delay segments to enhance overall system performance.

The second phase of this research examines DEL implementation in pipelined and non-pipelined architectures. In this case, the DEL programs are resident in a large, relatively slow main memory, and the interpretation is performed by a microprogrammed host processor. By considering DEL instructions to be sequences of primitive operations, it

has been possible to develop mathematical models to describe the space-time behavior of programs as a function of the DEL selected. Space costs in this model correspond to memory requirements in both main and control stores, while time cost is proportional to program execution time. By using these models, we will investigate the space-time characteristics of various DELs. In addition a methodology for determining an optimal DEL with respect to space-time costs and a particular primitive architecture is being formulated.

10.3.3 System Organization

10.3.3.1 Evaluation of Highly Concurrent Single Stream Systems

In the design and operation of complex computer systems, performance evaluation is absolutely essential in order to predict the effects of system parameter changes on system performance. However, at various stages of the design or optimization process, performance evaluation of varying levels of detail and acceptable accuracy are needed. Typically, accuracy and detail are much more important towards the end of the design process than the beginning.

In this study, we propose a hierarchy of system models covering a range of complexity, to be used in the optimization of a computer system. Accuracy is traded off against computation cost along the hierarchy. As a case-study, we chose the CPU-memory subsystem of the IBM 360 Model 91 as the base system to be optimized. This system is sufficiently complex and well documented in the literature.

The hierarchy we have constructed consists in the main of three models - a deterministic trace-driven simulation model, a queueing network model and a regression model. The trace-driven model is an extension of the work reported in CSL Report R-717, and yields, through simulation, highly accurate empirical data about system and resource throughput on program traces run on it. These are used to calibrate, i.e., fix-the parameters of, the queueing network model, which is of considerably less computational complexity. Regression is used to calibrate either the queueing model parameters, or the system performance itself, as functions of the system parameters of interest.

The optimization will use higher-level models (i.e. those of less complexity) for performance prediction. After each optimization iteration, the optimum performance prediction of the higher level model will be validated by comparison with the trace-driven model prediction for the "optimum" system. The procedure will halt when a match is obtained, otherwise the higher level model will be recalibrated in the new region of interest, and another iteration of the optimization process will be carried out.

The trace-driven model has been constructed and a calibration procedure for calibrating the queueing network model has been developed. Procedures for relating the model parameters to system parameters, predicting performance using the queueing network model, system optimization and recalibrating the queueing model at the new predicted optima are being developed.

10.3.3.2 Evaluation of Multiprocessor Systems

Accurate models have been developed for many of the parts of a computer system. Often, however, these models have been quite complex and their combination into a single system model has not been accomplished. Research has recently been initiated to develop an overall system model to describe the performance and cost of a complex system.

The goal of this research is to identify cost-effective systems by trading off number of processors, number of jobs sharing primary memory, size of primary memory, "rotation" speed of secondary memory, number of "sectors" in secondary memory, page size and possibly other parameters given the page fault characteristics of jobs. This research will employ a judicious mixture of analytic, queueing theoretic, and simulation techniques. In contrast to other research in the field and most of our own previous work, this research uses known results and concentrates on the multivariate nature of the total system problem.

10.3.4 Design Considerations and Trade-Offs in MOS/LSI

In order to be cost-effective, digital circuits implemented in MOS large scale integration (LSI) are designed with close regard to optimality. Three criteria - power dissipation, chip area (cost), and

speed - are balanced to produce a final circuit. Current practice involves a significant amount of simulation to determine the most satisfactory trade-offs. This project was concerned with the prediction of optimal values of certain design parameters for a given function of the above three criteria.

This research first developed a simplified model for MOS/LSI circuits. Using this model, equations were derived for circuit speed, power dissipation, and area. These equations were expressed as functions of the channel dimensions of MOS transistors and of the degree of pipelining in the circuit.

These three equations, and their pairwise products, were then optimized. The functional relationships between the equations and the parameters were examined. The effects and trade-offs of particular design choices were described.

The results of this research are available as CSL Report R-764.

10.3.5 A Multiple Microprocessor System for Computer Architecture Research

Basic design and construction of the AMP-1, a multiple microprocessor system, has been completed. The system uses eight Motorola 6800 microprocessors with time multiplexed shared busses between the processors and 1K by 8 bit memory modules. The present 14 modules are being expanded to the full 64 modules. The entire system runs as a peripheral to a DEC-10 which can start and stop processors and access the AMP-1 read-write memory. DEC-10 software includes AMP-interaction routines and an M6800 cross assembler. Fairly complex single processor code has been run and some simple multiprocessor code has been run as well. Some debugging of certain multiprocessor interactions needs to be completed.

The system is being expanded to include memory protection hardware which will protect the execution of debugged code running concurrently with undebugged code and will detect certain hardware failures. Performance monitoring hardware is also being added to collect run time data about system performance. The data collection hardware can be interrogated by the system. Realistic multiprocessor system and user code is being developed.

We have already learned much about strengths and weaknesses of present day microprocessor design when used in such a system. Further results will evaluate system performance as a function of the number of processors used, the processor - memory speed balance, number of memory banks, and alternative memory address interleaving schemes. Virtual memory studies and other system level considerations may be developed by emulation. Studies of this system for general purpose job loads and several special purpose applications are being planned.

10.4 Data Bases and Retrieval Systems*

Fundamental properties of data bases and computer-implemented data systems are being investigated. At present the primary emphasis of the research is on updates and the interaction of update costs with other system costs. An extension of a data model developed by Elias [4-7] and Welch [10] is used in order to expand the applicability of the results beyond a particular data problem. Similarly a general computer model reflecting the capabilities and costs of most available computers is used in order to expand the applicability of the results beyond systems implemented on a particular currently available computer. Appropriate worst case and average cost measures have been found for updates. The type of update most thoroughly analyzed has been a total update in which the new data base is specified independently of the previously recorded data base. When the new data base can be chosen from a finite collection of possible data bases, expressions have been found for the optimal update cost minimized among the many alternative systems which could be used. These results have been submitted for publication [8]. Current research is directed toward updates in which the new updated data base is a minor modification of the recorded one. Additions, deletions, and changes of table entries are examples of such updates. In order to find minimal cost systems for such updates, it is necessary to consider situations in which the number of possible different data bases is unbounded. Preliminary results have been accepted for conference presentation [9].

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

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11.1 Introduction

The research program of the display, memory and communication system group is concerned broadly with the evolution of computer-based information and communication networks in which users interact through communication consoles and networks which support both visual and audio teleconferencing and digital information, i.e. interactive electronic mail. Our work is being focused specifically on finding efficient techniques for generating, storing and transmitting documents, imagery and data in future command and control systems and in crises management activities. The goal is to find and evaluate new electronic device and computer system concepts which offer the potential of reducing the cost and accelerating the development of such systems. The report of work is divided into three major activities:

- demonstration of graphic communication system concepts
- mass storage techniques for communication consoles
- bi-level image generation, storage and manipulation techniques

11.2 Demonstration of Graphic Communication System Concepts

When proposing the concept of graphic communication via computerized mail systems, it is often difficult for people who are not familiar with highly interactive graphic systems to visualize exactly how such a scheme would work. As a result we have created a set of computer programs

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which demonstrate how such a system will function. This effort has also provided the group with the opportunity to clarify many of the underlying principles which we feel are missing in many other systems currently being proposed.

For a system to support computer-based mail activities it must allow the user to easily create messages, to transmit these messages to other users, and to be able to examine messages received from other users. Generally, the system text editor is used to create messages (text files), which are analogous to the documents contained in an envelope sent through the US postal service.

To create the envelope, a special program, which we will call the mail system, prompts the user for the receiver's name and address. Other features such as identification headers and multiple copy mailing services are often provided. The text file is then formatted with this information and transmitted to the receiver. The receiver can then use the mail system to read and file their mail.

The principle objective of our demonstration is to indicate the feasibility of sending not only alpha numeric information over such mail systems but also graphic information e.g. drawings, graphs, bar charts, map etc. We felt that it was important to demonstrate this to DARPA in order to strengthen our proposal. In view of the limited resources available, we devised an approach which uses current ARPANET services to support the demonstration and does not require any changes in that system. The approach was realized and a demonstration is currently available. A number of demonstrations have been given both at the University and in Washington. The following paragraphs describe the nature of our approach.

Previous efforts at CSL, CERL, and RHRC have produced a design for PDP-11 based graphic communication terminals which use the plasma display panel and direct touch input [1]. Figure 11.1 is a block diagram of the terminal configuration. Several of these terminals have been built and are available at the University and in the Washington DC area. The terminal can operate as a PLATO terminal, and ASCII/graphic terminal or as a stand-alone, desk-top computer system. Thus the terminal can use PLATO services to create graphic mail and then can connect to the ARPANET via CAC using the UNIX mail system to send the mail to another

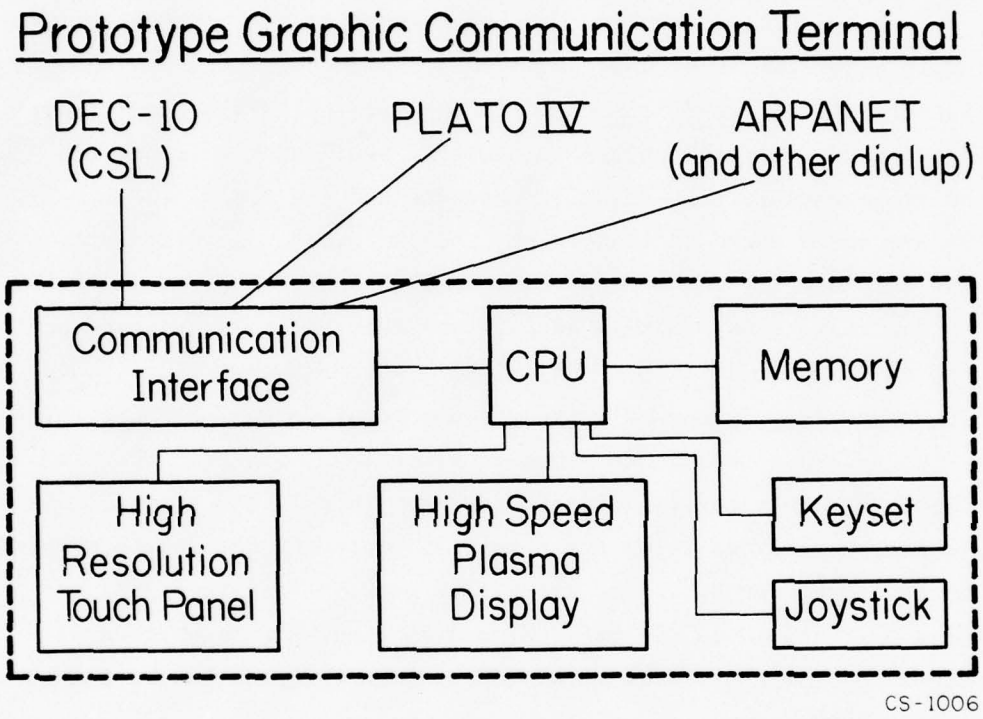


Figure 11.1 Block diagram of the PDP-11 based graphic communication terminal configuration.

such terminal at a remote location. A system diagram is shown in Figure 11.2.

After a graphic message is created (currently using the PLATO editor but eventually a terminal-based graphic editor) the message is converted into PDP-11 executable binary form. Figure 11.3 illustrates the editor/binary/terminal relationship. The image data must then be formatted such that it can be transmitted over the ARPANET using the UNIX mailer, i.e. it must be converted to a pure text file. To accomplish this the encoding algorithm sends only standard alpha-numerics and linefeeds. The characters: # \ @ DEL (177 octal) and the sequence of linefeed, period, linefeed all have special meanings and must be avoided. To accomplish this, the image data is mapped 4 bits/character onto A-P (101-121 octal). Linefeeds are added every 32 characters, the character ~ is used as a header and \ is used as an "end of transmission" character.

The characters are then sent by the terminal to a program running on the CAC UNIX system which puts them into a standard text file. Once this file is created, it can be mailed to any point on the ARPANET.

To replay a message received at a terminal, the user must signal the terminal to enable the image data decoder. This is done with a special key press recognized locally by the terminal. Once the decoder is enabled, it begins to search for a ~, i.e. the header mark. After the ASCII formatted data is received by the terminal and decoded, the graphic message can be viewed by the user. This message can then be saved in the terminal and/or transmitted on to some other remote terminal.

Figures 11.4a, b, and c illustrates the type of message that is sent in a typical demonstration of the graphic mail system. These figures were produced directly from the terminal display.

Another activity which we pursued during the period of support was the consideration of graphic editing concepts. Graphic mail systems will be of little use to the average worker if he/she is required to master complex computer languages in order to create graphic messages. Thus, efforts have been made to develop some general guidelines relative to the design of graphic editors for mail systems.

Most currently available editors are precise, general purpose programs which often prove difficult to use, especially by those who are

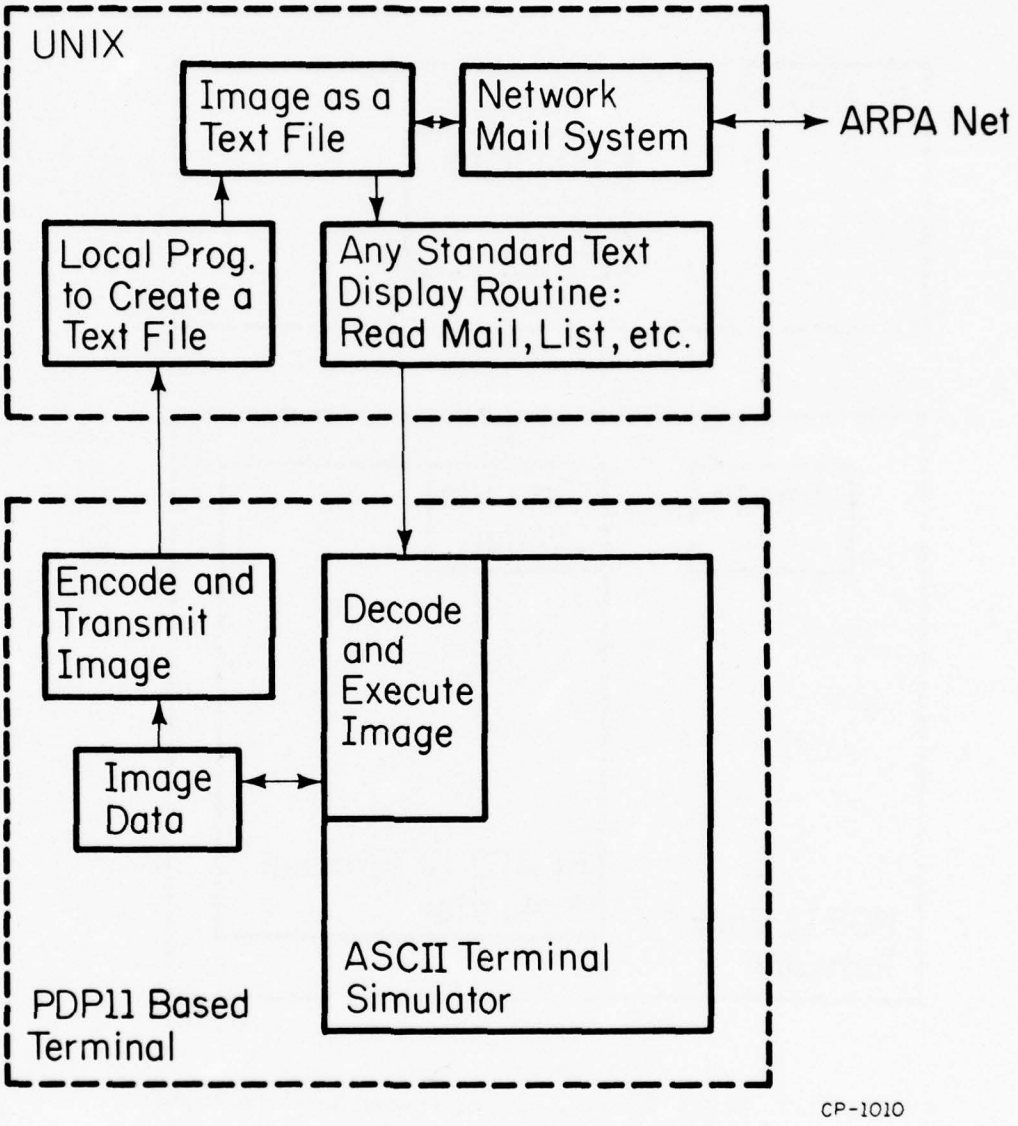


Figure 11.2 Block diagram of the system used to send and receive graphic mail in the DARPA demonstration.

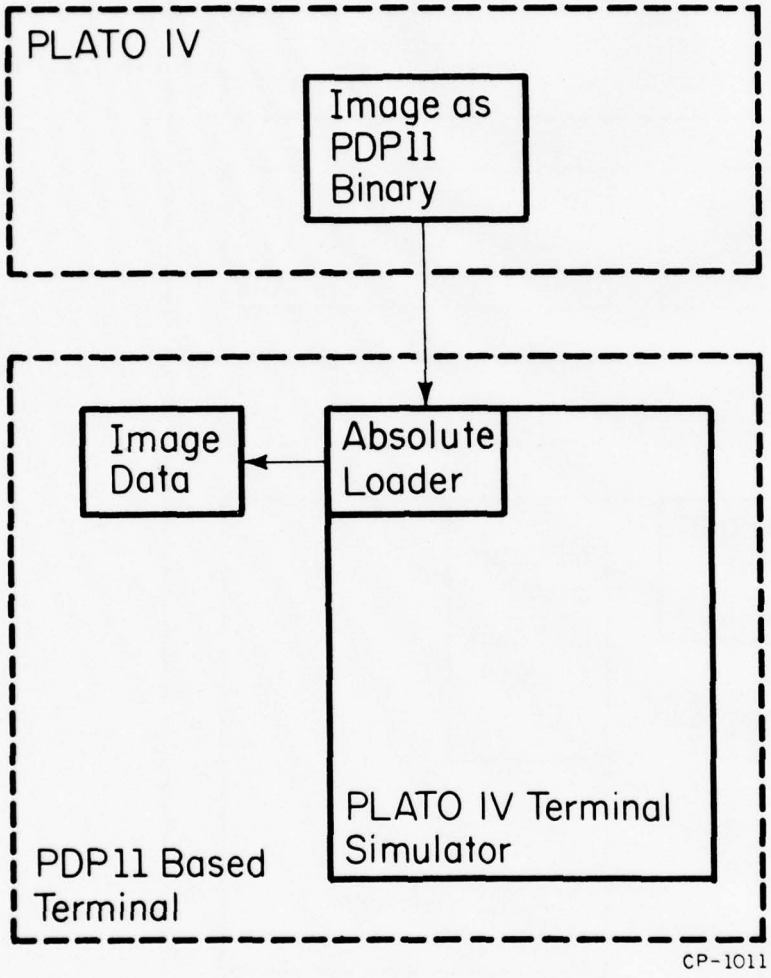


Figure 11.3 Block diagram of the system used to create graphic mail for the DARPA demonstration.

Lynn,

Sorry to hear you are having problems with the system. I think the schematics are correct, but I am including the pinouts for the EA 9002 just in case.

I am sending the timing diagrams so you can start debugging right away. Hopefully we've only blown some standard TTL chip you can get there.

In case it is the microprocessor, I am sending a new chip and the complete specs out UPS blue as soon as I finish here. Let me know if there is anything else I can do for you. I should be back on the system after lunch.

Maureen

Figure 11.4a First page of a three page message sent through the ARPANET in the DARPA demonstration. The figures are direct screen copies.

We use the wait sync strobe (WAS) to set up the single step mode. It puts out a negative going synch pulse at the end of each instruction cycle.

All signals are TTL compatible, with V_{CC} = 5V

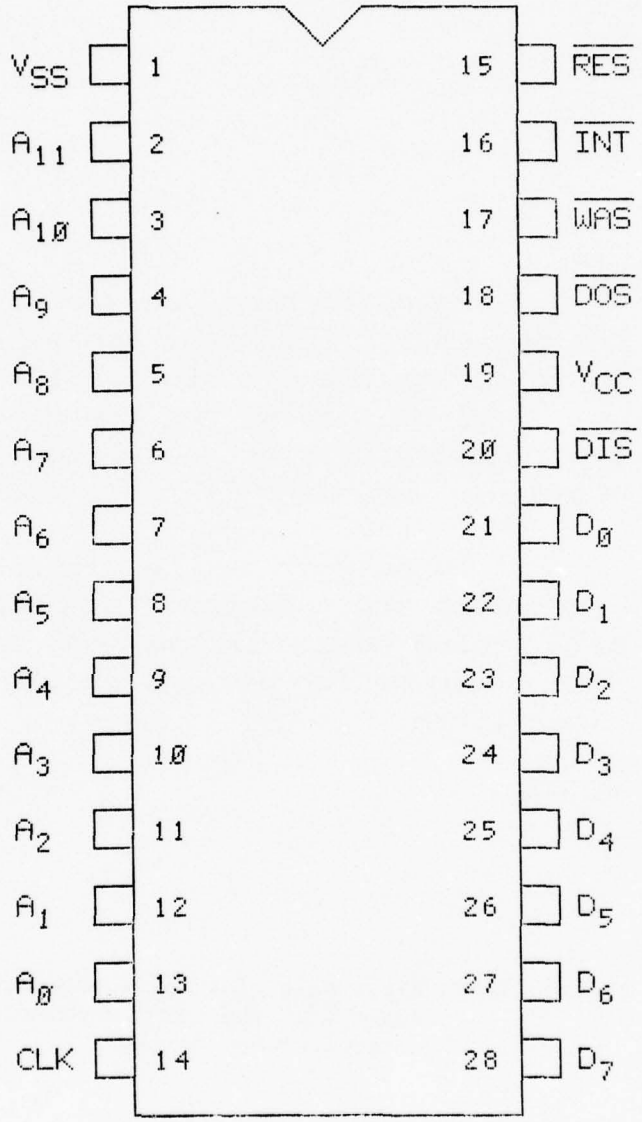
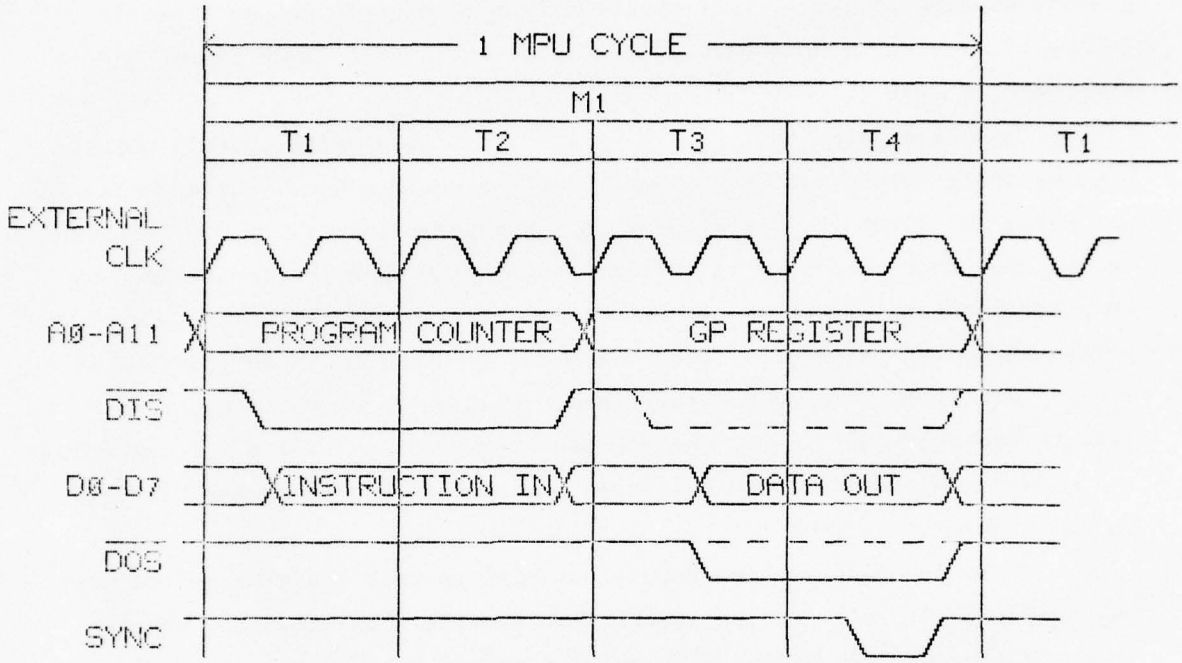


Figure 11.4b Page two of the three page demonstration message.



We have had some problems with noise on the DIS line during T3, so you might check that for single byte instructions first.

Since we are running at the maximum clock frequency, the duty cycle is critical. The minimum phase definition for a 250ns period is 140ns high and 60ns low. You can run the system with 300ns square wave to test everything but the display driver if you like.

Figure 11.4c Page three of the three page demonstration message.

not familiar with computer languages or who are infrequent users. The DARPA and NSF proposals present a number of new ideas for object oriented graphic editors. Throughout the research period we have tested some of these ideas via small scale programs which support particular types of graphic editing activity. One specific example of this was an investigation of editing techniques using the high resolution touch panel developed at CERL [2].

As indicated earlier, it is important to develop systems which are, by their nature, self-explanatory and natural to use. For example, in analyzing the human factors elements of an interactive system, it is useful to consider what people do in a similar situation when not constrained by computer hardware. Leaving out verbal description for the moment, the most common method of interacting with graphical information is to point at it. Objects are often circled or underlined, notation is drawn or written next to the relevant figure, changes are discussed in terms of transforming and moving subsections. New boundaries and locations are marked directly on the drawing.

To interact with a computer display in this manner requires some way to "draw" directly on the screen. To provide this function, we are investigating the use of the high resolution touch panel developed by P. Van Arsdall. This touch panel is able to resolve some of 256 x 256 points (30 pts/inch), both single point or a tracking mode. It is activated by pressing the surface with a passive probe such as a finger. The touch panel is flat and transparent, and was designed to mount directly on the front of the plasma display panel.

A set of programs using the high resolution touch panel with local, high speed displays was developed during the period and was demonstrated to a number of visitors. In one sequence the user indicated an area of interest by circling the location on a map. The map was then expanded to show a more detailed view of the area.

In the context of an object oriented graphics editor, the user circled figures to be grouped as objects. If the area was initially too densely drawn to pick out exactly what is wanted, the area was expanded first. Free hand drawings was used to enter some figures, and a touch driven cursor was provided for more detailed work.

Besides the demonstration, a paper titled "Use of a High Resolution Touch Surface in an Interactive Graphics System" has been written and is being considered for submission to appropriate publications.

11.3 Mass Storage Techniques for Graphic Communication Consoles

The objective of this research is to devise techniques for realizing a low cost 10^{10} bit local mass store for use with processor-based communication consoles. In our view, the most practical approach is to use optical video disk technology that is presently receiving great attention for use in home entertainment systems [3]. These systems can potentially store up to 10^{10} bits of digital information on a 30 cm diameter disk of thin plastic. The emphasis of our research is to find a system configuration that will provide a worst case access time for information on the disk of less than 100 milliseconds and still maintain low cost.

A simple optics system for the playback system has been found and tested that uses low-cost, off the shelf optics. It allows a diffraction limited focused laser beam to be deflected by a simple galvanometer controlled mirror. The beam can be deflected to any one of 5000 tracks on the disk in a time that is limited only by the inertia of the small deflection mirror. This system measures the reflectivity of the disk. The reflected laser beam goes to a single small area detector that is stationary for all deflections of the beam. This optics system also has the advantage that the spatial information of the reflected beam allows the detector to sense the position of the laser beam relative to the track on the disk. This information is essential for feedback to the servo system that keeps the beam centered on the track. This servo system has been designed and demonstrated on the playback system with the optics system discussed above. Because of the random access features of this memory system, the full rotational range of the mirror deflects the beam across 5000 tracks. This is 100 times the resolution required by the video disk home entertainment systems. Thus the success of this servo system is an important milestone in demonstrating that standard galvanometers can be controlled to the required high precision by feeding back only the position of the laser beam relative to the track.

A second major control problem in this system is deflecting the galvanometer from one track to another in a minimum time. To do this job and that of controlling the data flow, an 8080 microprocessor system was interfaced between the disk system and a high speed computer. Digital algorithms for controlling the galvanometer were then modeled using the CSL hybrid and digital computers. Although a satisfactory solution has not been found, considerable insight has been gained on the important factors of the problem so that a workable solution is expected shortly.

The system for recording disks has been refined so that disks with various different formats can be made on a routine basis. Equipment for an encoding and decoding system has been constructed that allows intelligible audio words to be recorded and played back. The advantages and shortcomings of this and other coding schemes are now being investigated.

11.4 Bilevel Image Generation, Storage, and Manipulation Techniques

During the past year we continued our research in the area of bilevel image generation [4,5], storage [4,6,7], and manipulation. A new form of ordered dither, adaptive ordered dither [8], has been developed that adds edge enhancement capability to the ordered dither algorithm. A system for generating ordered dither animation through a conditional replenishment scheme has been devised [9,10].

The ordered dither technique [4,5] compares each multi-level input picture element (pel) intensity with a fixed position dependent threshold level to determine whether the corresponding display element should be energized. Since each pel is mapped onto a single display element, the algorithm is capable of recovering both high and low spatial resolution with the same algorithm [5]. We have developed an adaptive dither algorithm that includes a factor to provide edge enhancement by compressing the dither threshold levels together [8]. The adaptive dither algorithm is shown in Equations (1) and (2).

If

$$I\,x\,y > T\,x\,y \text{ then } P\,x\,y = 1 \qquad (1)$$

then $P\,x\,y = 0$

$$T\,x\,y = (D\,x\,y - A\,x\,y) + A\,x\,y \qquad (2)$$

where:

A x y is the local intensity average

D x y is the basic dither threshold

I x y is the multi-level pel intensity

P x y is the display element state

σ is the edge enhancement factor

Edge enhancement is controlled by varying σ over the range (0,1). If σ equals 0 then pure edge enhancement results since each pel is compared to the local average. If σ equals 1, unmodified ordered dither is realized.

We are continuing to examine adaptive dither as a means of enhancing bilevel image quality without increasing the complexity of the algorithm significantly. It should be possible to automatically set σ based on a first pass through a grey scale image file so that high contrast drawings use a small σ, and continuous tone images use a near 1. A more ambitious idea would be to dynamically determine σ based on local image features so that only desired portions of the image would be enhanced. Once digitized these images can be compressed using one of several techniques for long term storage [4,6,7].

To represent bilevel image animation or motion, one could simply display bit maps at a 30 Hertz rate. However, since ordered dither uses a position dependent set of thresholds, display points energized in one frame are likely to be energized in the following frame. We have designed and constructed a conditional replenishment imaging system [10] that produces animation on a relatively slow display device by only transmitting those pels that change state from one frame to the next. A display buffer controls the update generation so that no pel updates are lost. The system uses either a vidicon camera or a modified television for video input. Slow movement is reproduced well on a plasma panel running at 50,000 updates per second, while rapid motion leaves a smear until subsequent frames clean up the image background. We feel this conditional replenishment technique will be an important one for animation sequence generation in computer networks and computer aided instruction systems.

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12.1 Efficient Computation Techniques*

In the past year we have continued our investigations of specific aspects of the design and analysis of computer algorithms, and have obtained several significant results. Specifically we have concentrated our efforts in the areas of parallel computation and computational geometry. Our results in these areas - as well as in the design of algorithms for algebraic problems - will now be briefly summarized.

12.1.1 Parallel Computation

In most of our research in the past year we have adopted as a realistic computation model a system with an arbritary number of identical processors, each capable of random-accessing a common memory with no alignment penalty. Store, fetch, and arithmetic operations have unit costs, and fetch conflicts are disallowed when appropriate.

Within this model, we have developed a family of parallel sorting algorithms [1] of the "enumeration type," which consist of the following phases: (i) count acquisition: the keys to be sorted are subdivided into subsets and for each key we determine the number of smaller keys (count) in every subset; (ii) rank determination: the rank of a key is the sum of the previously obtained counts; (iii) data rearrangement: each key is placed in the position specified by its rank. The basic novelty of the algorithms is the use of parallel merging to implement

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count acquisition. By using Valiant's merging scheme, we show than n keys can be sorted in parallel with n logn processors in time Clogn; in addition, if memory fetch conflicts are not allowed, using a modified version of Batcher's merging algorithm to implement phase (i) we show that n keys can be sorted with $n^{1+\alpha}$ processors in time (C'/α) logn.

We have also considered the problem of the number of processors to be used in the fast parallel matrix inversion. According to a recent result by Csanky, there is an algorithm for inverting an n X n matrix in time $O((\log n)^2)$ with $O(n^4)$ processors. By a careful analysis of the parallelism of the problem, we have succeeded in by-passing some redundant operation, thereby achieving the same time performance (which is conceivably optimal) with $O(n^{3.31})$ processors [2].

Finally, we have considered graph problems. A careful analysis shows a great wealth of parallelism which can be profitably exploited by an appropriate computation system to drastically reduce computation time. Within the aforestated model, algorithms which run in time $O((\log n)^2)$ have been developed to solve each of the following problems for graphs with n vertices: (i) finding a minimum spanning tree of a connected, weighted graph [3], (ii) finding the biconnected components, (iii) the bridge connected components, (iv) a shortest cycle, (v) a set of fundamental cycles of an undirected, connected graph, (vi) finding the dominators and, (vii) a shortest cycle in a directed graph [4]. The number of processors needed to execute each algorithm is bounded above by a polynomial in n. It is shown that $2\lceil \log n \rceil \pm c$ is a lower bound on the time required to solve each of these graph problems. Thus the algorithms obtained have time complexities which are optimal to within a factor of logn.

12.1.2 Computational Geometry

It is an established fact that the solution of geometric problems is extremely relevant to a large spectrum of practical applications. In this general area we have obtained a number of interesting results.

We have studied the problem of obtaining the medial axis - also known as "skeleton", or "prairie fire" - of an n-edge single

polygon, not necessarily convex. With a substantial improvement over previously known techniques, we have developed two algorithms, which apply respectively to convex and nonconvex polygon. Both are based on a technique which reduces the given problem to an analogous one of smaller size and require a number of operations respectively proportional to $O(n\log n)$ and $O(n^2)$ [5].

We have also refined our preliminary investigation of the so-called "densest hemisphere" problem, which is stated as follows. Given a set K of n points on the unit sphere S^d in d-dimensional Euclidean space, find a hemisphere of S^d which contains a largest subset of K; equivalently, given a set K'of n d-dimensional vectors find a d-dimensional vector which has nonnegative (or positive) dot product with a largest number of members of K. We have obtained the following complementary results: (i) a discretized version of the original problem, restated as a feasibility question, is NP-complete when both n and d are arbitrary (hence, it is practically intractable); (ii) when the number d of dimensions is fixed, there exists a polynomial time algorithm which solves the problem with a number of operations $O(n^{d-1}\log n)$ [6].

In another study, we have analyzed the problem of finding the kernel K(P) of a simple n-vertex polygon P, which is defined as the locus of the points internal to P from which all vertices of P are visible. Equivalently, K(P) is the intersection of appropriate half-planes determined by the polygon's edges. Although the intersection of n generic half-planes is known to require time $O(n\log n)$, we show that one can exploit the ordering of the half-planes corresponding to the sequence of the polygon's edges to obtain a kernel finding algorithm which runs in time $O(n)$ and is therefore optimal [7].

Finally, we have obtained several miscellaneous results which have been collected in a "Notebook" entitled "Step into Computational Geometry" [8]. In this report, a merge type algorithm is illustrated for computing the medial axis of a convex polygon and its analogy to the Voronoi diagram problem is pointed out. We have also shown (i) how the order-1 Voronoi diagram construction can be profitably used to speed-up the solution of the "smallest bomb" problem; (ii) that the two closest vertices of a convex polygon with n vertices can be found in time $O(n)$,

and (iii) that k points can be collectively located in a planar subdivision faster than they would be one at a time.

12.1.3 Algorithms for Algebraic Problems

We have devised a new method for computing the Discrete Fourier Transfrom (DFT) of a sequence of n elements over a finite field $GF(p^m)$ with a number of bit operations $O(nm \log(nm) \cdot P\ q))$ where P(q) is the number of bit operations required to multiply two q-bit integers and $q \tilde{=} 2\log_2 n + 4\log_2 m + 4\log_2 p$. This method is uniformly applicable to all instances and its order of complexity is not inferior to that of methods whose success depends upon the existence of certain primes. Our algorithm is a combination of known and novel techniques. In particular the finite-field DFT is at first converted into a finite field convolution; the latter is then implemented as a two-dimensional Fourier transform over the complex field. The key feature of the method is the fusion of these two basic operations into a single integrated procedure centered on the Fast Fourier Transform algorithm. Details are given in [9].

We have also devised a method for the computation of the FDT over $GF(2^m)$, which is more efficient that the direct method for computing the DFT. However, the order of complexity of this method is inferior to that of the method of [9]. Investigation shows that this method (which we call a Semi-Fast Fourier Transform Algorithm) is considerably superior to that of [9] for fields of order 2^{11} or less, because of the overheads involved in the latter method. The Semi-Fast Fourier Transform Algorithm is also superior to the usual Fast Fourier Transform Algorithm for fields of these sizes. Details are given in [10]. All these algorithms, as well as other efficient algebraic algorithms, have obvious applications to decoding techniques for algebraic codes. Some results in this direction are given in [11-13].

12.2 Data Compression Theory and Techniques*

Most of the research effort during the past year was devoted to the study of variable-rate universal data compression subject to a fidelity constraint. In this form of data compression, the rate of transmission is allowed to vary (e.g., as a function of the actual source) but the average distortion as measured according to a fidelity criterion is constrained to be less than some prescribed level. We have been able to demonstrate the existence of such universal data compression schemes for very general classes of sources with a single-letter fidelity criteria [14-16]. We have also investigated a new class of fidelity criteria (subadditive) which are more general than the single-letter criteria [20].

In addition to the results summarized above, we have obtained new results on mathematical modeling of information sources [17,19] and data compression for continuous-time sources [18].

12.2.1 Variable-Rate Data Compression

If a variable rate code of block length n is applied to source θ, the average rate $\bar{r}_n(\theta)$ and average distortion $\bar{\rho}_n(\theta)$ are the two most important measures of performance. If it is desired that $\bar{\rho}_n(\theta) \leq D$, the best that one could hope for is that $\bar{r}_n(\theta)$ converge to $R_\theta(D)$ in the limit as n increases. Here, $R_\theta(\cdot)$ is the rate-distortion function for source θ and D is some prescribed nonnegative distortion level. For a collection of Λ of sources, $\bar{r}_n(\theta) \to R_\theta(D)$ is actually a convergence of a sequence of functions on Λ and the form or type (e.g., pointwise, uniform, mean) of the convergence becomes an important issue.

For a single source θ, this is the classical source coding problem of Shannon which has been solved by Shannon (1959); Gallager (1968); and Berger (1968) for discrete memoryless; discrete ergodic; and discrete-time, continuous-amplitude (abstract alphabet) ergodic sources, respectively.

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For a collection Λ of ergodic sources or for a stationary non-ergodic source (these two problems are essentially equivalent), results were previously obtained for discrete sources and for totally-bounded alphabet, discrete-time sources [14]. Loosely speaking, these results are for almost uniform convergence of $\overline{r}_n(\theta)$ to $R_\theta(D)$; that is, there is a set $\Lambda' \subset \Lambda$ such that $\overline{r}_n(\theta) \to R_\theta(D)$ uniformly on Λ' and Λ' can be selected to have arbitrarily high probability. (Even more loosely speaking this says that there is a code for which it is highly likely that nature will choose a value of θ for which the code performs well.)

Our new results in this area focus on two different directions of improvement of this universal variable-rate data compression theorem. First, for applications to practical data compression problems the restriction in this theorem to totally bounded alphabets is a serious handicap (it excludes Gaussian sources, for example). Second, it is desirable to strengthen the form of convergence of $\overline{r}_n(\theta)$ to $R_\theta(D)$.

In [15] we improve the Pursley-Davisson theorem to allow for two classes of source alphabets, each of which is more general than the totally-bounded metric space alphabet. These are separable Hilbert space alphabets and metric space alphabets for which every closed, bounded set is compact. For example, Gaussian sources are included under each of these two classes. Also included is the (Hilbert) space of all functions f on [0,T] for which f^2 is integrable. This is of considerable importance for continuous-time source coding applications. Based on a preprint of [15], Professor J. Kieffer has recently extended our results to even more general alphabets in his paper, "A Generalization of the Pursley-Davisson Mackenthun Universal Variable-Rate Coding Theorem" (accepted for publication in the IEEE Transactions on Information Theory).

In our recent paper [16] extension in another, perhaps more important, direction involves the improvement of the form of convergence of $\overline{r}_n(\theta)$ to $R_\theta(D)$. The strongest form (strongly universal coding) requires that for any $\varepsilon > 0$ there exists an N such that for all $n \geq N$, $|\overline{r}_n(\theta) - R_\theta(D)| < \varepsilon$. A somewhat weaker form (weakly universal coding) requires only that $\overline{r}_n(\theta) \to R_\theta(D)$ pointwise on Λ. The distinction between these two forms is one of uniformity of convergence on Λ. Both these forms are independent of any probability measure on Λ and hence are improvements on the Pursley-Davisson-Mackenthun theorem, even as generalized by Kieffer.

Finally, we have some very recent results [20] on source coding relative to a subadditive fidelity criterion. This is a first step in an attempt to consider more general distortion measures than the usual single-letter fidelity criterion. The subadditive fidelity criterion is of interest for systems which suffer from insertions and deletions in addition to errors.

12.2.2 Theory of Continuous-Time Information Sources

Our main contributions in this area have been addressed to the characterization of continuous-time information sources and the information theory of such sources. Our paper [17] on the continuity of stationary continuous-time information sources establishes the equivalence of two popular forms of continuity for metric-space valued processes. The mathematical modeling of continuous-time sources is discussed.

In a paper [18] coauthored by Professor Robert Gray of Stanford, we investigate data compression for both ergodic and nonergodic continuous-time sources. This result is based on an application of the Gray-Davisson theorem for discrete-time sources to the segmented continuous-time source. It should be mentioned here that the full generality of such results as the Gray-Davisson theorem (for fixed-rate coding) and the Pursley-Davisson-Mackenthun theorem (for variable-rate coding) is needed for the application to continuous-time sources. If we segment a sample function from a continuous-time source with real-valued outputs, then we get a discrete-time source which has an abstract alphabet (e.g., the alphabet may be $L_2(0,T)$, the set of all squared-integrable functions on the interval $(0,T)$).

12.2.3 Information Singularity of Discrete-Time Sources

Information singular discrete-time random processes, as defined by Berger (1975), are processes which are deterministic in an information-theoretic sense. An important problem addressed by research in information singularity is the determination of the amount of information conveyed by a random process in the presence of measurement inaccuracies in other forms of noise. This leads to the consideration of the information content of a random process (e.g.,signal) in the presence of another random process (e.g., noise) and suggests investigation of the decomposition of a process

into information singular and information bearing components. With this in mind, Berger defined a process to be strongly information singular with respect to a second process if it is deterministic even when corrupted by a second process. In [19] and [21] we show that a class of processes investigated by Berger and strongly information singular relative to any stationary Gaussian process with bounded spectral density.

12.3 Estimation, Detection and Filtering of Signals*

The research in this area has been concerned primarily with the study of detection-estimation schemes for signals or systems containing uncertainties in either the model or the parameter values. The modeling and analysis of signals or systems with different modes, such as fast and slow modes, have also been investigated using the singular perturbation techniques, with the objective of applying estimators to such signals. The results obtained during the past year may be divided into three principal areas:

(i) Singular perturbation techniques applied to stochastic systems.

(ii) Combined detection-estimation schemes for uncertain signals or systems.

(iii) Decision-directed estimation schemes for fading channels.

12.3.1 Singular Perturbation Techniques

The singular perturbation approach has been shown to be widely applicable not only to control problems in deterministic setting, but also to estimation and control of stochastic systems with fast and slow modes. Such a methodology also applies to the representation and estimation of signals with narrow- and wide-band components. Related earlier results in the estimation and control for stochastic singularly perturbed systems may be found in [24-26]. The approach has since been generalized in a unified manner to the multi-parameter singularly perturbed stochastic linear system [27]. In this case a model with several perturbation

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parameters is considered, which may represent a system with multiple time-scales in its time constants, or signals with different degrees of narrow- and wide-band components. In particular, the analysis is useful to the study of the limiting behavior of fast or slow systems whose stochastic inputs may be faster or slower than the system modes. The outputs of such systems may in turn be processed for the purpose of estimation or control by slower or faster filters. The study of the multiparameter singularly perturbed stochastic linear systems considered the limiting properties of such systems, and the resulting approximations when such signals are used as inputs to faster or slower systems. The multiple time scale approximate linear filter for estimating the states of such systems was also derived resulting in simplified implementation and reduced computational burden. The details of the study and its application to the filtering problem may be found in [27].

Another study in the singular perturbation area has been the application of the robust detection-estimation scheme considered in [28] to a singularly perturbed system with unknown perturbation parameter [29]. The general scheme has been shown to have simple implementation and a robust performance in the Incremental Mean-Squared Error (IMSE) sense. Its application to the singularly perturbed case results in further simplification in implementation, with improved performance in the IMSE sense over the full system with fixed parameter value, or the reduced system when the perturbation parameter is set to zero. Such an application results in a robust estimation scheme for systems of unknown order. The formulation may also apply to the problem of tracking or filtering for a maneuvering vehicle having a wide range of maneuver intensities such as very slow to very fast.

12.3.2 Combined Detection-Estimation Schemes

In addition to the application to singularly perturbed system, the study of combined detection-estimation schemes for the estimation of signals or systems with variable uncertainties in general has continued. Two such problems have been considered utilizing two different signal or system models and appropriately different performance criteria.

The first considers the estimation of stochastic signal whose model is assumed to be driven by the derivative of a jump process input

rather than the usual white Gaussian noise input. The objective is to derive an estimation scheme which would perform equally well under widely ranging rates of jumps in the input process. First, an estimation scheme is proposed which is based on detecting the jumps in the process, and then by estimating the jump instants and magnitudes it derives an estimation of the desired signal or the system state. It can be shown that such a scheme, while suboptimal in minimum MSE sense, performs better than the best linear filter when the rate of jumps is low. At the other extreme, the best linear scheme is optimal in the MMSE sense for such processes as the rate of jumps tends to infinity. Thus, two schemes are obtained which perform well for low and high rates of jumps, i.e., for slow and fast processes. Eventually, a combined detection-estimation scheme is to be considered in order to combine the two extreme schemes via a detector so that the resulting estimate may have robust performance when the rate of jumps of the process is variable or unknown. The details of the first scheme and its comparison with the linear filter is to be presented in [30].

The second considers an alternative performance criterion to the weighted minimax MSE cost used in [31] for the construction of state estimators for dynamic systems with uncertainties. The original scheme in [31] concentrated on the static case, while the present work emphasizes the recursive structure for dynamic discrete-time system. The approach is still based on assuming a set of bounds on the systems parameters. However, the performance criterion is a weighted MSE conditional on the observations as well. The resulting state estimator is implemented as a weighted average (dependent on the observations) of a number of MMSE filters. The resulting scheme is recursive, and the selection of each filter parameter is performed with every new observation data. The estimator is shown to converge under fairly wide conditions to a MMSE estimator matched to a value of the unknown parameter which lies in the same bounding set as does the true parameter value. A simulated example indicate that the performance of this system is superior to the usual minimax scheme. Its implementation for the recursive case is computationally simpler and less constrained in structure than the original scheme considered in [31]. Furthermore, it is more potentially applicable to

cases of time varying uncertainty in dynamic systems, and such extensions are under investigation. The details of the scheme and its analysis are reported in [32].

12.3.3 Decision-Directed Estimators for Fading Channels

This topic in the area of detection-estimation differs from the topic discussed above not in techniques but in applications. While the first emphasized the problem of estimation (for tracking or control) in signals or systems, the latter is concerned with receiver design for digital communication systems when the channel contains uncertainties in the form of fading. The emphasis in this case is therefore on detection and not estimation. The proposed receiver for such a channel is constrained to have memory, and the memory is embodied in the estimator which is used to determine the channel fading parameters. Those estimates are then employed by an optimized zero-memory detector to determine the received data bit. On-off keying is considered as a special case of general binary communication systems over such channels. The detector structure, optimization, and performance is investigated in [33]. The estimator is assumed to be given and to have large memory to allow for asymptotic results to be obtained. The receiver performance is then shown to be superior to the usual memoryless receiver in terms of error probability. The estimator to be used in conjunction with the detector is considered in [34]. The estimation criterion which is suitable for minimum probability of error is derived. The structure of the estimator is assumed to be a finite memory linear functional of observations, but also dependent on the detector previous decisions via decision feedback. Two different cases are considered corresponding to orthogonal signalling and on-off keying are considered. The estimator performance is then evaluated in terms of MSE and speed of convergence as a function of memory size. Other nonparametric and robust detection schemes for nonclassical channels are under investigation.

12.4 Multi-user Digital Communication Systems*

Our research has concentrated on an asynchronous phase-coded spread-spectrum multiple-access (SSMA) communication system. We have identified the key code parameters that determine the communication performance of such a system, and have obtained several analytical results, upper and lower bounds, and efficient computational algorithms for these parameters. Other research on multiple-user communications has been an information-theoretic study of a single transmitter/many receivers system called a broadcast channel.

12.4.1 Multiple-Access Communication Systems

We have identified the key cross-correlation parameters that determine the maximum error probabilities and the signal-to-noise ratios (SNR) in SSMA systems [36, 43]. We have numerically evaluated these parameters for several classes of sequences that have been proposed for use in SSMA systems; such as m-sequences and Gold sequences [38]. We have also studied some of these cross-correlation parameters for random binary sequences. The parameters then are random variables and we have determined their means and variances. The results indicate that, for long sequences, the cross-correlation parameters will, with high probability, be approximately equal to the mean [46].

While numerical evaluation of correlation parameters for a small number of sequences of moderate length is relatively straightforward, such evaluation requires far too much computation for larger sets of long sequences that are employed in many SSMA systems. We have obtained several analytical results and bounds on the correlation parameters and have discussed efficient computational algorithms to assist in the selection of good sets of sequences [35,39,42,44]. In particular, we have related key cross-correlation parameters to the autocorrelation functions of the sequences. Since autocorrelation functions have been more thoroughly studied than cross-correlation functions, this result is of considerable theoretical interest. Moreover, since for a set of K sequences, there

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are $\binom{K}{2}$ cross-correlation functions as compared to only K autocorrelation functions, this result also provides a more efficient method of computing the cross-correlation parameter. We have also used this result to obtain bounds on the correlation parameters and to study trade-offs between desirable cross-correlation and autocorrelation properties of sequences [42,44].

The key result relating cross-correlations and autocorrelations has been generalized in a number of different ways. These generalizations have led to new methods for constructing classes of sequences with a variety of useful correlation properties. In particular, a method of constructing new classes of multivalued sequences, whose out-of-phase periodic autocorrelations are exactly zero, has been devised. A technique for constructing long impulse-equivalent (in the sense of Huffman) sequences has been discovered. Also a method for constructing two arbitrarily large sets of sequences, such that any sequence in one set is uncorrelated with any sequence in the other set, has been devised [47,49].

We have studied the correlation spectra of Gold sequences from the viewpoint of algebraic coding theory and obtained the cross-correlation spectrum of an m-sequence in the Gold code and any other Gold sequence. We have also studied other classes of cyclic codes for applications in SSMA systems. Some classes of codes discovered by Kasami appear to be most promising. In many cases, they can be used to provide a few sequences with maximum cross-correlation magnitude that is approximately one-half of the bounds on Gold sequences, or a large class of sequences (which includes the Gold sequences as a subset) with the same bound as the Gold sequences. Cross-correlation parameters for these sequences have been evaluated [37,40].

12.4.2 Multiple-Source/Multiple-Receiver Information Transmission

We briefly mention some very recent results on a particular multiple-terminal communication system known as the broadcast channel. This work is directed toward establishing the computability of the set of all achievable rates for a system with two separate message streams which are to communicate with two receivers over a broadcast channel. Each receiver is interested in the information from only one of the sources.

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The broadcast channel problem, first introduced by Professor Thomas Cover of Stanford, remains unsolved in two respects: the capacity region is unknown and certain regions which are achievable are not known to be computable. Our papers ([41,45,48]) make contributions to both of these open problems.

12.5 Data Transmission Systems*

As a continuation of our past efforts, we have been mainly concerned with the development of design techniques for spectrum shaping coding schemes. The objective of spectrum shaping is primarily the removal of power from the extremes of the allocated band, since this is basically the cause of intersymbol interference. In line with this remark and within the general approach of utilizing powerful heuristics, we have used the Taylor expansion of the power spectrum at f = 0; the most significant nonzero term of this expansion for balanced, counter-encodable codes, is that of second-order, whose coefficient is referred to as Δ. A rather sophisticated code synthesis algorithm has been developed, based on the heuristic Δ, for codes whose autocorrelation sequence is finite. Using this technique we have obtained several coding schemes which are superior to previously known corresponding design [50].

Additional results consist in the development of a computation procedure for code spectral density which is more efficient than any previously known for this task, since a deeper analysis of the problem reveals that previously reported methods performed a considerable amount of redundant work [51].

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13.1 Visual Information Processing and Recognition*

In an effort to develop a powerful computer system for the processing of visual image data, we have made progress in several areas. Several low level feature extraction programs have been implemented and integrated into the vision system, and other programs are being developed to increase the overall feature extracting ability of the system. Methods for developing three-dimensional models have been developed along with methods for matching these models to three-dimensional representations of objects obtained from stereoscopic views of scenes. As an application of this system, we are studying methods which extract features from visual data as a means of compressing the data for transmission and subsequent reconstruction of a scene.

13.1.1 Low Level Vision

A system for visual shape recognition is being implemented which has the following capabilities: (a) edge extraction, (b) area classification, (c) simple contour identification, (d) compound contour

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identification, (e) stereo correlation, (f) correlation of features in time, and (g) visual knowledge representation. Programs have been written to embody the first four capabilities. An interesting quality was found between contour-edge processing algorithms and area-region processing algorithms. The Mach band phenomenon has been studied and a model for it has been developed within the context of the overall system. Algorithms for "following" simple contours and for finding corners have been implemented [1]. Work has begun to incorporate the remaining three capabilities.

We have also begun investigating the use of parallel methods for visual processing. A parallel model for a general low-level task-free vision system was developed [2]. The scheme of the model involves (a) finding the local features (e.g., line or edge segments), (b) propagating information describing each local feature outward with decreasing strength from the location of the feature, (c) looking for and noting significant intersecting messages in a "transform space," (d) retransforming from the points in transform space to allow selection of "important" features and suppression of "unimportant" ones, and to allow grouping of features into lines, edges, regions, etc. The scheme can be layered to aid in handling regions and textures.

13.1.2 Three-Dimensional Modeling and Recognition

Progress has been made in the designing of programs which analyze multiple-view images of scenes and which construct three-dimensional computer models of objects. As part of this effort, programs developed at Edinburgh have been brought up on our PDP-10 system and have been further improved [3].

Improvements to the three-view method of depth extraction have been made. These include the incorporation of two-dimensional intensity templates from the original images in addition to edge gradient data for matching. Spatial contiguity is used to permit efficient incremental tracking of three-dimensional edges by limiting the field of search for the matching of edge points along chains. A non-linear smoothing algorithm which preserves the sharpness of angular bends has been developed for use on edge chain data in two and three dimensions.

Results have been obtained on the three-dimensional matching of objects with curved edges to wire frame prototypes. The basis for the matching is the relative three-dimensional location, orientation, and length of edge features extracted by stereo image comparison [4]. A new technique for fitting curves with piecewise circular segments has been developed for possible use in the matching of piecewise circular wire frame structures. Strategies for matching three-dimensional shapes in occluded scenes have also been treated.

In the area of image segmentation minimal spanning tree techniques have been extended to permit vertex cues to be used in body finding in complex scenes [5]. With this approach the non-linear smoothing algorithm allows the precise determination of the nature of vertices for use in Guzman-like object isolation. This a priori isolation into bodies thus aids considerably in model matching and spatial contiguity heuristics.

13.1.3 Visual Image Compression and Reconstruction

Research in a new area was begun in order to investigate a novel concept in image data compression for transmission bandwidth reduction. Several experiments were carried out to gain insight into the effectiveness of using feature extraction algorithms for purposes of image compression and reconstruction [6,7]. This approach potentially offers significant advantages over standard data compression techniques and could achieve compression ratios on the order of one hundred-to-one. Furthermore, this approach is compatible with time sequential techniques which offer possibilities of further compression.

Aerial photographs, characterized by regions of relatively constant intensities and long boundaries of straight and curved lines were digitized for the experiments. Our present approach is to extract straight and curved edge segments from the digitized data and to fit circular arcs to the segments. Initial results have yielded compression ratios in the range of one hundred-to-one. Currently we are improving the edge following and arc fitting routines in order to improve the appearance of the reconstructed images. Further research will focus on region growing and texture extraction techniques in order to improve the quality of the reconstructed pictures.

13.2 Manipulation and Assembly*

Progress was made in the area of robot arm manipulation. We now have a system with limited touch sensing capabilities. Progress was made both in software control for the manipulator and in the implementation of hardware for touch sensing.

The software necessary to control the CSL robot arm was developed during the past year. These programs fall into two classes. First, a servo supervisor program has been written. It is interrupt driven and performs functions such as positional error integration and differentiation, trajectory segment splicing and hardware failure detection.

Secondly, a set of interface routines has been written which allows the manipulator to be controlled by programs written in BASIC. These routines allow BASIC to examine the status of the manipulator as well as to perform coordinated motion sequences.

A touch sensor was constructed to allow control of the hand's gripping force [8]. This sensor operates by measuring the change in capacitance of two parallel plates separated by a compressible foam dielectric.

Research into designing a force sensitive arm with visual position feedback has begun. The necessary fast vision routines have been written, and the problems of specifying an assembly task in terms of primitive visual relations are being investigated.

13.3 Computer Aided Decision Making*

Progress was made in the area of computer aided decision making. Emphasis was on developing the ability to make and carry out plans in environments in which inconsistencies may be observed. The use of partial plans in a computer planning and execution monitoring system was investigated. The key results are [9,10]:

1. A local strategy for modifying partial plans can be used successfully if it is possible to distinguish a partial failure from a partial success.
2. A fixed local strategy for all goals is not sufficient to distinguish the above. Consequently, a specific search strategy must be constructed for each individual goal encountered.

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3. A problem solver can largely overcome the problems of an inaccurate world model if it can experiment in the real world and if it can determine how to ignore troublesome information.

These results are specifically applied to the domain of inconsistent environments. It was shown that a strategy based on local considerations, backed by global analysis is often sufficient in an inconsistent environment.

Investigations have begun on how to manage concurrent, cooperating processes, such as in the CADM system in which five cooperating processes are run simultaneously. A manager program is under construction for the efficient coordination of concurrent jobs.

13.4 Natural Language

Our overall goal is to generate and develop ideas which will allow a casual user (i.e. one with no special programming knowledge) to use a computer effectively and confidently, with a minimum of training prior to use and a minimum of frustration during use. We are approaching this goal in two ways. First, we have built a system called PLANES [11, 12] which gives a casual user access to a large data base of aircraft flight and maintenance data via the typing of natural English requests. Second, we are doing basic research on more general techniques for representing the meaning of natural language and on procedures for extracting particular meanings from English passages. Our work will lead in the short run to a powerful system to interface a user with the Navy 3-M data base in Mechanicsburg, PA, and in the long run to a broad range of programs for dealing with areas involving language (e.g. intelligence data, news accounts, strategy or planning data, etc.).

13.4.1 A Natural Language Data Base Model and System*

(1) We have completed a model for a natural language data base system [13] which we believe to be superior to any model currently proposed; requests need not be grammatical, a user may omit information to

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be understood in context, complex language structures can be used, and new words and question types can be added quite easily. Our current model has evolved by trial and error from earlier models [14,15].

(2) We have implemented and tested the model in the PLANES system. We have added to PLANES a number of features to help a user learn to use the system and recover from any difficulties he may be having with the system. During the past year we have also added a new larger data base and completed a relational query system to interface it with the natural language processor as described in [16]. Initial work on a browsing system was completed and documented [17]. The PLANES system is described in detail in [12].

13.4.2 Exportable System Packages

Portions of PLANES have been generalized and collected into packages of exportable functions. One package is an expanded ATN (Augmented Transition Network) System (ATNs are used in many language processing systems). The package includes an ATN editor for easily building and expanding ATNs [18], an optimizing ATN compiler for making ATNs more rapid and compact, and improved facilities for handling phrases, word roots, and automatic backtracking. This work is described in [19]. Another package* can improve programs by source-to-source transformation (i.e. by writing a new program in the same language as the original. Improvements are based both on static replacement of program constructs and dynamic evaluation of programs and modification in places where the most time is being spent. The package works on LISP programs, and has been used to improve PLANES code; it is described in [20].

13.4.3 General Natural Language Understanding†

We have continued and initiated general natural language research, centered on understanding and representing language with visual content. Specific interests include developing an adequate set of semantic primitives [21], making spatial inferences, understanding

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metaphors and analogies, understanding previously unknown words in context [22], and mediating between declarative and procedural internal knowledge representations.

Other work* has explored techniques for making inferences in natural language dialogs [23]. Attention has centered on problems of modelling a speaker's intent and dealing with the dialogue material appropriately in the light of the speaker model.

13.5 Human Decision Making and Human-Computer Interaction

13.5.1 Human-Computer Interaction in Multi-Task Situations†

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

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

This approach has been investigated from a theoretical point of view using a queueing theory formulation [24]. A procedure for optimally determining when the computer should be utilized has been developed [25]. These ideas are now being studied in two realistic settings. One of these settings involves the monitoring of multiple dynamic processes [26]. The other setting involves computer-aided flight management [27]. The goal of these efforts is to demonstrate the usefulness of the approach while also gaining an understanding of the human's abilities to perform in such a computer-aided environment.

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13.5.2 Human Decision Making in Computer-Aided Fault Diagnosis*

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

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

13.5.3 Interactive Modeling of Library Networks†

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

During the past year, the model has been applied to analysis of a regional network within the Illinois Library and Information Network [28]. Further, it is being used as the basis of a design of a model-based online management information system for interlibrary networks [29].

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14.1 Introduction

During the 1976-1977 time period the Information Retrieval Research Laboratory (IRRL) conducted research on several aspects of information retrieval problems. Major projects include the following: development of a hybrid approach to fact identification in natural language text using keywords and AI techniques; a feasibility study for an automatic data base selector; and a feasibility study for developing a union list of serials based on non-standardized machine-readable records.

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

This research is aimed at improving the performance of information retrieval systems by enriching the inverted index structure with linguistic data extracted during index building. We have concentrated on approaches to several sub-problems within the broad framework of such a system. The purpose of this project was to produce a noticeable improvement in retrieval performance at a reasonable cost and was not intended as an advancement on AI natural language processing research. Our system would exhibit only superficial, rapidly applied knowledge of language.

Work done so far has been in several areas. We have done work on the parsing problem, using techniques derived directly from AI research. A second area of concentration has involved a new information retrieval paradigm based on the notion of "spreading activation networks" [1].

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Work has also been done on an associative data base system to be used for storing the dictionaries to be used as well as the actual data derived by the system from natural language data bases.

Conventional information retrieval techniques have often been based on the "inverted index," which contains a list of all the appearances of each word used in the data base. Our enrichment would include the addition of syntactic/semantic information derived during processing plus new retrieval processing techniques to use the richer data structure. The goal system would also identify limited kinds of facts in the data base and add them to a knowledge store.

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

While building the inverted index the program must do a simple linguistic analysis of the text it processes. The parsing must be able to handle most sentences, identifying noun groups, modifiers, verbs, agent/object relationships, conjunctions, and so forth. It must also be able to do some analysis across sentence boundaries, such as resolving a fair percentage of pronoun references. Yet the system must operate efficiently (not adding significantly to the cost of the inversion) and in those cases where it cannot complete analysis of a sentence must be able to identify the parts of the sentence it has handled correctly. Our parsing work has been based on Sheldon Klein's early work [2]. The basic idea is to use "closed class words," which are only used in one way in natural language (such as articles, pronouns, and prepositions) as anchors for the parsing process. Suffix tests are used to assign words to probable classes and then context frames and phrase and clause building procedures are used for disambiguation. This can be done in linear time, and therefore is much cheaper than the n log n inversion process. We are

working on extending Klein's system to include a larger vocabulary, to use a word class probability based on previous experience, and to handle compound sentences. The goal of this processing is to assign a class to each use of each word and to establish syntactic/semantic relationships within a sentence that could be stored in the index. Thus if "genetic engineering" occurred in an article the system could index it under "engineering," "genetic," and "engineering modified by genetic."

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

At present our research on the text processing phase has centered on building a parser based on Klein's work and an associative store to be used for storing dictionary and index data. The parse is currently operating with a limited dictionary and linguistic knowledge base pending availability of the data base rear end it needs to store its underlying knowledge. Work on the fact recognition problem has been mostly on a conceptual level, considering the data structures and knowledge needed. We believe the knowledge should form a generalized, consistent structure for world knowledge, linguistic knowledge, and knowledge derived from data processed. Thus the case frame describing the word types needed to describe an occurrence of a word and the frame describing a fact should be structurally similar. Our work has indicated that the needed structure will include the features of a procedural systemic grammar [3] and a self-defining semantic network [4].

Retrieval processing. To use the enriched data structure a new retrieval paradigm will be needed. We have considered simply using an augmented Boolean query that would allow specification of roles and case information for words or occurrence of specific word relationships in a text passage (such as "engineering" modified by "genetic"). We have also been investigating the use of a spreading activation network model in

which all data would be stored in a network whose nodes represented documents, words, authors, journals, and so forth and whose links indicated the use of a given word in a given location, the publication of a document in a given journal, the use of a given word to modify another, and so forth. The retrieval process would involve the activation of specified nodes and a cyclic spreading of activation from active nodes to their neighbors. Stopping, quenching, and selection criteria would be used to identify a result set [5]. This research has so far produced a pilot system that has shown some success on a limited sample data base. Large scale testing awaits the completion of the associative store.

The associative store. Both processing and retrieval activities require the availability of an associative storage system. We have incorporated those needs into our development of EARL (Entity and Relationship Language), a data base management system based on the Entity-Relationship model of data [6]. The core of EARL, including the capabilities needed for this research, is nearing completion. It will allow the storing of n-tuples and their retrieval by value along any of their components. Development of EARL, and of all pilot programs in this research, is being done in SAIL on the DEC SYSTEM-10.

14.3 Automatic Data Base Selector*

This project will determine the feasibility of an automatic Data Base Selector that will operate on user query terms and provide a relative ranking of data bases according to their applicability to the query based on data base vocabulary statistics (Term Occurrence File) as operated on by a mathematical model (Term Equivalence Model).

The Data Base Selector will consist of a file containing terminology from 20 major data bases, programs for data management and file generation, programs for query processing, and a mathematical model for normalizing the variability (differing numbers of years worth of files, controlled versus uncontrolled terminology, hierarchical and multi-level vocabularies, etc.) that is found in multiple natural language data bases.

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The Data Base Selector will be of use to data base users, data base producers, and data base processors. It will help users or searchers determine file appropriateness for queries. It will help processors and producers with data base comparisons, vocabulary comparisons and vocabulary compatibility problems. No merged file of a large number of data base vocabularies has been created before and the number of potential uses of such a file may be considerably larger than those mentioned here.

The Data Base Selector will have as major components a master data file called Term Occurence File, a software package for file management (file generation, update, delete, ect.) called FIL, a mathematical model for normalizing term occurrence data in various data bases called Term Equivalence Model and a Query Processor that will accept queries, match them against the Term Occurrence File, submit term occurrence data to the Term Equivalence Model and provide histogram rankings of data bases as output.

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

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

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

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

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

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

Sets are combined as fuzzy sets, that is membership of a term in a field is conceived and quantified as a value between zero and one (inclusive) representing degree of membership of that term in the data base.

The selector will do the following: queries using Boolean and, ("*"), or ("+") will be accepted and evaluated and the results returned giving the individual associations of terms with each db and the association of the query with data bases. It is important to note that the values for the query are derived from the associations of the individual terms ONLY. If for example there are two data bases and terms A' and B' have association matrices of .6 and .7 and .3 and .4 respectively, then A' * B' will have the value (.3 .4) and A' + B' the value (.6 .7). In other words, because we do not have the facility to calculate the values for Boolean combinations of terms and then calculate the association, we first calculte the association, then calculate the Boolean combination.

Sets may be assigned names with the assignment operator. If you wish to name A*B glub, say glub ← A*B. Individual terms may be weighted by multiplying them by a constant, e.g., "glub*3" triples glub's association values. For later use for instance one could say "glub ← glub*3" to avoid always including the weighting factor. Fields may be weighted by assigning the field name a weight. For instance "auth ← 5" will weight occurrences in the author field 5 times more heavily for any term. So far this cannot be applied selectively to terms in a query with different weights. In other words, "glub*(auth ← 2)+stub*(auth ← 1)" is legal, but does not quite have the effect one might wish. Weighting factors can be any real number, thus including decimals.

Possible additions: Improved field weighting for intra query use, improved diagnostics (there are 0 now), more operations, e.g., "not", a quote operator for odd terms (and dates which are now treated as numerical factors), < , >,....

14.4 Automatic Generation of a Statewide Union Catalog*

The Illinois State Library Union Catalog Project is primarily concerned with locating and pairing duplicate records in machine-readable bibliographic files. That is, machine-readable files containing the information found on catalog cards in libraries.

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The creation and maintenance of union catalogs (a single file containing the records and holdings for more than one library) has always been a goal of librarians, primarily to aid in interlibrary loan activities. When bibliographic records were maintained on cards, printing or typing of extra cards and interfiling them in a large union card catalog was an expensive, labor intensive, chore. For this reason, few large union catalog projects have been attempted, despite their usefulness as a resource sharing device. As more and more libraries convert their catalogs to a machine-readable format, the desirability of having a machine algorithm for combining these files into union catalogs is increasing.

The basic question is whether the computer can identify two (or more) bibliographic records as matches with an accuracy approaching that of a human card filer. This problem can be viewed as a special case of pattern matching with noise. The noise in this situation consists of typographic errors and variations in cataloging practices.

The algorithm we have developed proceeds in two steps. First, a combined file is partitioned using an alphanumeric character key derived from the title and the year of publication. Then the records in each partition having two or more records are compared with each other using several other fields with a variety of keys and matching criteria.

The key used for the initial partitioning is an alphanumeric character key generated by concatenating characters from selected positions in the title such as the first and third letters of the first word, the first letters from the second and third words, etc. The positions used in the key were selected by studying the distribution characteristics of the individual positions. Entropy (information theoretic entropy), normalized for file size, was utilized as a single figure measure of merit. Since 43 different characters were retained in the titles (A-Z, Ø-9, #, !, $, %, &, ?, and blank), the formula used to calculate the entropy for a single character position was

$$- \sum_{i=1}^{43} P_i \log_{fs} P_i$$

where p_i equals the frequency of occurrence of the ith character in that position and fs is the size of the file being tested.

Based on an analysis of such figures and some heuristics and testing of actual keys, the best 8 character key for partitioning bibliographic records on the basis of the title string was determined to contain:

1. The 1st and 3rd letters of the 1st word.
2. The 1st letters of the 2nd and 3rd words.
3. The 1st letters of the 2nd and 3rd words from the end of the title.
4. The 4th letter from the front and the 2nd letter from the end of the last word.

This determination is, of course, file dependent. But the entropy figures from which it is derived remained remarkably consistent over several different file sizes from two different files.

The efficacy of this key is vital since the amount of work in the second stage grows with the square of the partition size.

In the second stage, authorship is matched in a straight forward fashion (a string match of the first five characters) and the full title and paging are matched. Full title matching is not done by straight character by character matching but is implemented using bit strings mapped from the title character strings and a "degree of match" calculated using Hamming distance between bit strings. The bit string representation was first proposed by Harrison [7] and was independently developed at IRRL by Thom Hickey [8]. We are hashing trigrams into 72 bits (two DEC-10 machine words). Using the Hamming distance between these Harrison keys allows us to determine a cutoff value such that most titles that differ only because of typographic errors can be counted as matches.

Testing these algorithms on large files containing a bibliographic control number (Library of Congress card number) we estimate that only 1.25% of the duplicate pairs will be missed. On the other side, only one example of the algorithm matching non-duplicate records has been found.

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15.1 Design Verification of LSI Circuits*

Work is being performed in two areas of design verification for large-scale-integrated circuits. The first area is commonly referred to as design rule verification, that is, in the layout of integrated circuit masks certain design rules should be obeyed, such as minimum width and spacing of figures, alignment of figures, etc. If these design rules are violated the yield and reliability of the circuit may be very poor. We have developed a very general set of commands to check for design rule violations in a variety of integrated circuit technologies. The commands are REDUCE, EXPAND, SPACE, WIDTH, RWIDTH, ALIGN, and RALIGN. The titles of the commands have obvious connotations. REDUCE and EXPAND reduce or expand respectively a file of figures by a given tolerance. The command SPACE checks the spacing between figures and notes violations, and the command WIDTH checks the minimum width of figures and notes violations. The command ALIGN is used to check the alignment of contacts within diffusions, the alignment of metal over contacts, and the alignment of gates for MOS transistors. The commands RWIDTH and RALIGN are specialized to handle rectangular figures, whereas the other commands will handle any polygon with right angles. The algorithms used to implement these commands are relatively simple compared to other design rule checking algorithms [1], so that similar operations can be performed with less memory requirement allowing the algorithms to be implemented on a mini-computer artwork system. A CSL report which describes these algorithms will be completed shortly.

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The second area of design verification under investigation is algorithms for checking continuity in LSI layouts. The purpose of this work is to locate open and short circuits in LSI layouts before fabrication. Also, once all the mask features have been cataloged with respect to the circuit nodes to which they are connected, then the values of the parasitic circuit parameters can be calculated and the effect of these parasitic elements on the circuit performance can be computed. Often these parasitic elements determine whether or not the circuit will function and how fast is can operate. Due to the magnitude of the data base in LSI circuits, the first problem studied was the optimum partition size with which one should work. The results of this study were surprising in that they predicted a small partition consisting of less than one hundred mask features. This result can be found in the following references [2,3].

15.2 Distortion Analysis of Communication Circuits*

This work is concerned with the analysis of large and small signal distortion in electronic circuits. Under consideration are the modeling of distortion effects in electronic circuits, the effect of bias on distortion, and distortion analysis in the case of interfering signals. This past year progress was made on the effect of dc bias on transistor amplifier distortion. It was found that third-order distortion in bipolar transistor amplifiers can be nearly eliminated by biasing the transistor appropriately. The study included the effect of the base-emitter junction exponential nonlinearity and the collector-base junction avalanche breakdown phenomenon. The interaction between these two distortion mechanisms was studied in depth and bias regions were found in which a cancellation of the two distortion mechanisms was observed [4,5].

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15.3 Novel Structures for Digital Signal Processing*

There are many hardware structures with which one can realize a specified functional description of a digital signal processing system. The purpose of this work is to examine the relative merits of various structures in terms of speed, accuracy, and cost. Of particular interest is the analysis of roundoff noise and limit cycles in various digital filter structures. Narrowband lowpass filters synthesized with the cascade structure require very long wordlengths to achieve a given accuracy. This requirement increases the cost and reduces the speed of the system. Under study are some new structures which significantly improve the performance of these systems. In particular, a new multiple feedback structure has been proposed which offers significant improvement in performance [6,7]. In the cited references a comparison is given of the roundoff noise behavior of this new structure versus some of the more commonly used structures.

15.4 Reduced-Order Modeling by Error Minimization and Topological Formulas†

The general problem is the representation of a system of high order, such as a power system. For initial studies, the system is assumed to be linear, and is represented by a network function, F(s). We seek an approximate representation of the system of lower order which may be used for simulation and analytical studies. Most of the effort in the past has made use of the various forms of Pade approximation, the most familiar being the continued-fraction or Cauer expansion. However, in these methods identification with specific parts of the system is lost, and it is not possible to insure stability.

In the method under study, we approximate F(s) by a reduced-order network function $F_a(s)$ such that with $s = j\omega$ there is no error at $\omega = 0$ and at one additional frequency which may be chosen, ω_o. The form of $F_a(s)$ is an all-pole function with complex conjugate poles of suitable

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multiplicity. The method is then applied to a quotient of polynomials, F_1/F_2 and a procedure has been found to approximate this function by applying to F_1 and F_2 that previously applied to F(s) to obtain F_{1a}/F_{2a}.

In applying the method to the order reduction of the network function description of a large-scale system, the system is divided into subsystems each described by an input-output relation. The subsystems and the overall system are related by topological equations. For example, the driving-point impedance is given by the quotient

$$\frac{\pi \text{ 2-tree admittance products}}{\pi \text{ complete-tree admittance products}}$$

where each admittance function has the form

$$\sum_{(i,r_i)}\left(\frac{k_{i,r_i}}{(s - p_i)^{r_i}} + \frac{\bar{k}_{i,r_i}}{(s - \bar{p}_i)^{r_i}}\right) + \sum_{(j)} a_j s^j$$

Here the poles, p_i, are those of the subsystem and not the overall system. The approximation method applied to the overall system will be the same as that applied to the subsystems. In other words, if the poles of each subsystem are known, the approximation of the overall system function can be achieved without knowing the poles and zeros of the overall system. The approach is being used in a form implemented on the simulation program LINSYS to study a variety of systems.

15.5 Analysis of Coherency in Dynamic and Transient Stability Studies Using Singular Perturbation Methods*

A problem to which model order reduction techniques may be applied to advantage is that of the analysis of coherency in dynamic power systems. It has long been recognized that synchronous machines which are electrically "close" to one another will often behave virtually as a unit during and following a power system disturbance. However, until recently, no concentrated attack has been made on the problem of establishing which machines will behave coherently as a result of a given disturbance.

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In general, "tight" coupling of synchronous machines suggests that these machines will behave as a unit. In addition, when the coupling is not ideal, these machines will exhibit intermachine high frequency oscillations. These two facts imply that in the case of coherent synchronous machines, there exists a separation of frequencies (in the linearized sense). In a recent result [8], singular perturbation techniques have been extended to the case of frequency separation. It appears that analysis of coherency can be approached and further studied via singular perturbations.

15.6 Almost Discontinuous Oscillations: The Generalized Multivibrator*

The behavior of a general free-running multivibrator circuit has been investigated. The circuit contains two three-terminal nonlinear active devices drawing control current and subject to saturation; The circuit also contains various passive circuit elements, some of which are parasitic. The active devices are described by sufficiently general functions so that tubes and transistors are readily included. Furthermore the circuit is not assumed to be symmetric.

The operation of the multivibrator is governed by a system of nonlinear differential equations which is a higher dimensional generalization of the van der Pol relaxation oscillator equations.

The methods of singular perturbation theory have been applied to show under what circumstances the multivibrator will, and under what circumstances it will not, oscillate. The period and waveform of the oscillations have also been obtained, and found to be in agreement with experiment.

This work, done in collaboration with P. J. Ponzo, of the University of Waterloo, has been submitted for publication.

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16.1 Introduction

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

16.2 Control and Decision Strategies for Systems Under Imperfect Information*

The problem of controlling a stochastic system containing unknown parameters has been the subject of numerous studies as is shown by recent surveys. One general approach involves the estimation of the unknown parameters and the state of the system and the design of a control law that satisfies a given performance criterion. The accuracy of the estimators will be in general a function of the control, while the quality of the control will be a function of how accurately the system is known.

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Thus a controller must find a compromise between the estimation and control objectives. The exact solution of this problem is theoretically extremely difficult and computationally not feasible at the present time. An alternative to this situation has been obtained by subsuming the estimation objective to the control objective. We have developed a procedure for controller design for discrete time stochastic systems with unknown but constant parameters [1].

A performance index that is quadratic in both the state and the control over N periods is considered. This performance index is minimized with respect to the feedback control gain matrix, the estimation dynamic matrix, and the filter gain matrix. The last two matrices are introduced for the computation of the estimate of the state. It is important to note that both the identification and the state estimation are performed so that a control objective is satisfied, in contrast with other approaches reported in the literature in which the parameters are estimated with a particular objective different from the objective of the control.

The controller design uses the apriori statistics of the unknown parameters instead of relying on an on-line parameter identification scheme during the optimization procedure. The procedure is particularly advantageous when the number of stages is small. For the long term, when several successive N-stage periods are considered, self-tuning properties can be obtained by monitoring long term trends in the statistics of the plant parameters and changing control design values to correspond to the new statistics.

The procedure has been extended to time-varying systems [2]. A sensitivity approach for the same general problem has been investigated and reported recently [3].

Another approach to parameter and model order uncertainties is the singular perturbation method. Among new singular perturbation results are conditions for complete separation of slow and fast regulator designs [4]. A second-order approximation of the optimal performance is achieved without the knowledge of the small singular perturbation parameter. A new asymptotic method is developed for a class of nonlinear singularly perturbed optimal regulator problems [5]. The resulting near-optimal feedback control can stabilize essentially nonlinear systems. It is implemented

in two-time-scales, with the feedback from the fast state variables depending on slow state variables as parameters. Stochastic control problems are solved for linear singularly perturbed systems [6-8]. A two time scale trajectory optimization algorithm has been developed and tested [9,10].

16.3 Interactive Software and Microprocessor Hardware for Control Systems*

An important step in the search for new analytical design and optimization methods in control and estimation theory is experimentation with proposed methods in a computer simulation environment. As an efficient mechanisms for achieving this an interactive software system has been developed for control system design, which incorporates possibilities to readily try various proposed optimization algorithms. Design experience with such a software interactive facility is providing a much needed human feedback for modifications and improvements in the suggested analytical methods.

The final stage is system implementation using microprocessor hardware. We have completed an adaptive estimator and an adaptive controller and experimented with them in real time [11,12]. The interactive software is taking part in a redesign based on microprocessor performance during a simulated operation.

Typical control algorithms for nonlinear feedback control are being implemented on microprocessors [13]. As a case study, a time-optimal control algorithm is used to perform a video disc scanner [14,15].

16.4 Multimodel Approach to Structural Uncertainty in Large Scale System Theory†

The aim of this project is to enlarge the scope of decentralized control, multi-person game, and team theory to incorporate the multi-model behavior of decision makers, that is, situations in which the decision

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makers are using different reduced order models of the same large scale system. These models differ not only in parameter and signal uncertainties, but, more critically, in their basic structural properties.

A strong motivation for this problem statement is found in multi-area power systems. The controller operating in an area employs a detailed model of his area and only a reduced order "dynamic equivalent" of the remainder of the system. Other controllers behave similarly in their own areas. Thus the same power system appears in different forms to different controllers.

Along with the ubiquitous "curse of dimensionality," the main sources of complexity delineating the border between ordinary and large scale control problems were considered to be: first, that the decision makers have different objectives and, second, that they use different measurements.

During this year major advances have been made in both conceptual formulation and analytical treatment of multi-model situations and multiple controller strategies. A chained aggregation procedure has been developed and forms the basis for a systematic construction of reduced order models. Multi-model situations are being treated as multi-parameter perturbation problems possessing time scale hierarchies and decoupling properties. New results in singular perturbation theory make it applicable to wider classes of stochastic and nonlinear systems. This research on modeling and near optimum control is accompanied by new developments of leader-follower strategies for decentralized control of large scale systems. For detailed treatment see [16].

16.5 Stackelberg Strategies for Multicontroller Systems*

Leader-follower strategies were first considered by von Stackelberg in connection with static duopoly problems in economics [17]. The concept was extended and developed for dynamic systems by Cruz and co-workers [18-21,23]. It has been extended to stochastic discrete-time

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systems also [22]. More recently it has been suggested as an approach for the control of multilevel systems [26].

During the year we have developed explicit strategy for a general linear-quadratic discrete-time two person game [24]. Explicit conditions have been derived for open-loop Stackelberg strategies for multilevel systems [27]. Closed loop strategies which are restricted to be linear have been investigated [25]. Finally, stochastic multilevel systems where one decision-maker is a coordinator have been investigated for various information structure configurations [29].

16.6 Optimization Methods*

Our work on optimization methods have centered on two main areas:

1) Computational algorithms for deterministic optimization (nonlinear programming and optimal control).
2) Dynamic programming and stochastic optimal control.

In the first area we have investigated Lagrange multiplier methods for constrained optimization, approximation methods for non-differentiable optimization and ill-conditioned problems, and decomposition methods for large scale nonconvex optimization problems. We have obtained convergence and rate of convergence results for Newton type Lagrange multiplier methods. We have constructed a combined multiplier and Lagrangian method that maintains the best characteristics of both methods. We have proposed a general method for approximating ill-behaved optimization problems by a sequence of well behaved problems and have analyzed the convergence properties and quality structure underlying the corresponding methods. Finally we have proposed a method for convexifying nonconvex optimization problems in a way that separable structure-essential for the application of decomposition algorithms is maintained.

In the second area we have expanded the class of policies traditionally used in stochastic optimal control models originally

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proposed by Blackwell, to include all universally measurable policies. We have shown that by working within this class all the measurability difficulties that have plagued theoretical investigations in stochastic optimal control can be resolved satisfactorily. In particular we have been able to dispense with the unnatural notion of p-optimality that has been deemed so far an essential ingredient of theoretical analysis of discrete-time stochastic optimal control problems. For further details see [30-36].

16.7 System Structure: Stability, Controllability and Observability*

Given the real, continuous-time description of a dynamical system $\dot{x}_k = f_k(x_1,\ldots,x_n,t)$, $k = 1,\ldots,n$, one can associate a square matrix, $C = [c_{ij}]$, the occurrence matrix, and a directed graph (a digraph), C with the system [37,38].

The occurrence matrix C is reducible if it can be transformed by symmetric row and column permutations into quasi-triangular form; C is in canonically unique quasi-triangular form (cuqtf) if each of its diagonal submatrices is irreducible. If C is in cuqtf, then the diagonal submatrices C_{kk} of C correspond to the maximally strongly connected (msc) subgraphs of the digraph, G. The off-diagonal matrices $C_{ij}(i = j)$ correspond to a set of edges of G with common orientation, to directed cut sets or edge disjoint unions of directed cut sets, as are zero matrices [38].

The dynamical system is in canonical structural form (csf) if C is in cuqtf, and the state variables have been labelled correspondingly. The isolated subsystems of a dynamical system are the uncoupled systems corresponding to the msc subgraphs of G.

We have shown that, subject to some mild conditions on the f_k, if each isolated subsystem is exponentially stable, and if the coupling between subsystems is bounded, then the entire system is exponentially stable [38]. Furthermore the system remains exponentially stable if the magnitude of the coupling increases, but not so rapidly [38]. These

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results have been generalized to asymptotically stable subsystems. A complete description of the solutions in terms of isolated subsystem behavior can be given for linear time-invariant systems.

We have also obtained, recently, necessary structural conditions for controllability and observability of dynamical systems.

This work is being prepared for publication.

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17.1 Introduction

a. This program is concerned with the use of computer-generated graphics in teaching a number of interrelated disciplines. In one program directed at foreign nationals we conduct seminars in population awareness and the impact of rapid population growth on the social and economic conditions of their countries. Over the past seven years over 14,000 people have seen the program. In addition, under the program for the NSF, we are distributing the population software programs to universities and colleges throughout the USA. The purpose is to provide innovation into the teaching of these subjects through the use of computers. Thus far the population program has been introduced into over twenty universities and colleges and has been used in many classes and demonstrations. This coming fall the material will probably be used by hundreds, if not thousands, of students.

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

17.2 Programming

During the past year we have continued our training program in Washington, D.C. where three instructors have contributed to AID seminars, training of new staff for AID and various members of the State Department. We have also acted as a data source for various governmental agencies concerning population data and the provision of hardcopy printouts of the PLATO screen.

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For the NSF contract also we have programmed four new programs into BASIC which can be run on almost any computer-output device combination. The programs are:

1. Population Projection
2. Population History
3. General Purpose Model
4. Food Model

The programs are about 20k in length and are very similar to the PLATO programs. User manuals have been written for instructors using the program in their courses and a number of demonstration modules illustrate how computer-assisted instruction would transfer certain concepts associated with population to the student. We have established a Newsletter with users of the program to obtain feedback and interchange of ideas between instructors. Some of the institutions now using the program have also shown the program to other people and are acting as secondary sources of distribution.

During the most recent meeting of the Population Association of America we held a seminar attended by over 40 people on the use of the programs in demographic education. The seminar was well received and will be repeated again next year. In the fall we plan to demonstrate the program at the annual meeting of the American Sociological Association.

Many of the present users have requested special programs which they believe would be especially useful to them and we are in the process of programming them for later distribution.

17.3 Long Range Weather Forecasting

During the past year a new program has been initiated to determine whether it is possible to develop a system which would allow one to forecast climate or weather 6 months to two years in advance. Some preliminary success has been obtained using worldwide crop production and yield data as well as a number of unique meteorological variables. The program has been relatively successful in that a number of predictions have been made which have turned out to have been realized. An example of some of the successful forecasts are listed below:

Date Forecast	Successful Forecasts	
February 1, 1977	Continuation of California drought.	April, 1977
February 1, 1977	Rain in March and April which would moderate the drought in Central USA.	April, 1977
November 9, 1976	Little precipitation in Midwest and Great Plains during the winter of 1976-77.	February, 1977
November 9, 1976	Severe winter in 1976-77. More severe than in 1962-63.	February, 1977
November 9, 1976	Frost with damage to citrus in Florida during winter of 1976-77.	
	Most probable dates: Nov. 22 $\pm$3, Dec. 21 $\pm$ 3, Jan. 18 $\pm$3, Feb. 8-16	January 18, 1977
July 1, 1976	Poor monsoon in India	September, 1976
July 1, 1976	Poor Chinese crop	December, 1976
January, 1976	Minimum in polar ice cap in the Barents Sea	April, 1976
November, 1975	1976 summer drought in Central USA	August, 1976
July 1, 1975	Coffee frost in Brazil	July 18, 1975
February 1, 1975	1975 Russian crop failure	July 4, 1975

While the program is still in its infancy and only about 60% of the forecasts are valid, we hope by including additional variables and new mathematical techniques that we will be able to improve the reliability of the forecasts to the point where they will become an important tool.

APPENDIX A

SUMMARY OF TRAVEL

APPENDIX A*

SUMMARY OF TRAVEL

Date of Travel	Personnel	Places of Visit	Purpose
1976			
7/27-7/28	P. V. Kokotovic	West Lafayette, IN	To participate in the Joint Automatic Control Conference.
8/1-8/5	Kaj Stolt	State College, PA	To participate in the Field Emission Symposium.
8/2-8/6	R. T. Chien	Stanford, CA	To participate in the Joint Services Electronics Program Lab Directors and the Annual JSEP Review at Stanford University.
8/8-8/13	Will McLevige	Boulder, CO	To present a paper entitled "Electrical and Photoluminescence Properties of Be Implanted GaAs and $GaAs_{0.62}P_{1.38}$" at the International Conference on Ion Implantation in Semiconductor and other Materials.
8/8-8/13	K. V. Vaidyanathan	Boulder, CO	To present a paper entitled "Impurity Distribution of Ion-Implanted Be in GaAs by SIMS, Photoluminescence and Electrical Profiling" at the International Conference on Ion Implantation in Semiconductors and Other Materials.
8/8-8/13	Charles Jacobus	Rindge, NH	To present a paper entitled "An 8 Bit Microprocessor Identifies Second Order Transfer Function" at the Algorithms for Image Processing Conference.

*This travel suported in part by the University of Illinois.

SUMMARY OF TRAVEL

Date of Travel	Personnel	Places of Visit	Purpose
8/15-8/19	E. S. Davidson	Fort Collins, CO	To participate as a panel member of the DISE Workshop on Microprocessors and Education.
9/21-9/29	Michael B. Pursley	Stanford, CA	To present a paper entitled "Recent Advances in Coding for Multiple-Access Communication Systems" at the International Telemetering Conference.
9/22-9/25	J. B. Cruz, Jr.	Warrenton, VA	To participate in the Workshop on Decision and Information for Tactical Command and Control sponsored by DoD (at the request of Drs. Chien and Knausenberger).
9/26-9/29	B. G. Streetman Gerald Marcyk Donald J. Wolford	St. Louis, MO	To participate in the AFOSR International Symposium on GaAs.
9/28-10/1	Bill J. Hunsinger	Annapolis, MD	To present a paper entitled "Application of Unidirectional Transducers to Resonator Cavities" at the IEEE Sonics and Ultrasonics Symposium.
9/28-10/1	R. T. Chien	Los Angeles, CA	To present a paper entitled "Cost Effective Coding Implementations for Computer Communication Systems" at the International Telemetering Conference.

SUMMARY OF TRAVEL

Date of Travel	Personnel	Places of Visit	Purpose
10/8-10/10	Gernot Metze	East Lansing, MI	To participate in the IEEE Design Automation Workshop and chair a session.
10/11-10/14	Andrew White	New York, NY	To present a paper entitled "Animated Dither Images on the AC Plasma Panel" at the IEEE & SID 1976 Biennial Display Conference.
10/13-10/15	Gernot Metze	East Lansing, MI	To chair a session, and present a paper entitled "Design of Self-Checking Networks" at the Design Automation Workshop.
10/21-10/22	H. R. A. Roefs	Montreal, Canada	To present a paper entitled "Correlation Parameters of Random and Maximal Length Sequences for Spread-Spectrum Multiple-Access Communications" at the 1976 IEEE Canadian Conference on Communication & Power.
10/25-10/29	R. T. Chien	Washington, D. C.	To participate in the Symposium on Science and the Future Navy.
11/2-11/5	Jacob Abraham	San Juan, Puerto Rico	To present a paper entitled "Distributed Systems: An Alternative Form of Redundancy" at the IEEE Workshop on Distributed Fault-Tolerant Computer Systems.
11/2-11/5	Gernot Metze	San Juan, Puerto Rico	To present a paper entitled "Use of Self-Checking Networks for Distributed Systems" at the IEEE Workshop on Distributed Fault-Tolerant Computer.

SUMMARY OF TRAVEL

Date of Travel	Personnel	Places of Visit	Purpose
11/3-11/5	D. Bertsekas	Miami, FL	To present a paper entitled "Equivalent Stochastic and Deterministic Dynamic Programming Models" at the Joint National Meeting of ORSA/TIMS.
11/18-11/24	M. E. Van Valkenburg	Pacific Grove and Cupertino, CA	To present a paper entitled "Advances in Circuit Theory: The Past Decade and Future" at the Asilomar Conference and to discuss research with officials of Hewlett-Packard in Cupertino.
11/21-11/24	Wataru Mayeda	Pacific Grove, CA	To present a paper entitled "Topological Formulas for Logic Networks" at the Asilomar Conference.
11/21-11/24	A. H. Haddad	Pacific Grove, CA	To present a paper entitled "On Singular Perturbation in Stochastic Dynamical Systems" at the Asilomar Conference.
11/21-11/25	R. T. Chien	Albuquerque, and Las Cruces, NM and Los Angeles, CA	To discuss research with personnel of White Sands Missile Range, New Mexico State Univ., Hughes Aircraft and Sandia Laboratories.
11/30-12/1	Cliff Geschke	Chicago, IL	To participate in the 4th NSF/RANN Production Research & Technology Conference.
11/30-12/3	Harland G. Hopkins	Clearwater, FL	To present a paper entitled "An 8 Bit Microprocessor Identifies Second Order Transfer Function" at the 1976 IEEE Conference on Decision and Control.
12/5-12/8	Ben Streetman	Washington, D.C.	To present a paper entitled "Photosenors on GaAsP," at the International Electron Device Meeting.

SUMMARY OF TRAVEL

Date of Travel	Personnel	Places of Visit	Purpose
1977			
3/10-3/12	Steven Shreve	Lexington, KY	To present a paper entitled "Universally Measurable Policies in Stochastic Optimal Control" at the Regional Midwest Conference on Stochastic Control at the University of Kentucky.
3/21-3/24	Don Wolford	San Diego, CA	To present a paper entitled "Luminescence and Absorption Properties of the N isoelectronic Trap in $GaAs_{1-x}P_x$" at the American Physical Society Conference.
3/28-3/30	Gernot Metze	Baltimore, MD	To participate in a Johns Hopkins University Workshop on Intermittent/ Transient Fault Analysis.
3/29-3/31	A. H. Haddad	Baltimore, MD	To chair a session and present a paper entitled "Estimators for Signal Detection in Fading Channels" at the 1977 Conference on Information and Systems.
4/20-4/22	Andrew White	Chicago, IL	To participate in the IEEE Workshop on Picture Data Description.
4/20-4/22	Larry Peterson	Chicago, IL	To present a paper entitled "Image Compression with Feature Extraction and Reconstruction" at the IEEE Workshop on Picture Data Description and Management.

SUMMARY OF TRAVEL

Date of Travel	Personnel	Places of Visit	Purpose
4/21-4/23	Clifford Geschke	Milwaukee, WI	To participate in the IEEE Milwaukee Symposium on Automatic Computation and Control.
4/23-4/27	M. E. Van Valkenburg	Phoenix, AR	To participate in the IEEE International Circuits and Systems Symposium.
5/2-5/5	R. T. Chien	Cambridge, MA	To participate in the JSEP Review at Harvard and MIT and the JSEP Laboratory Director's Meeting.
5/3-5/7	W. R. Perkins	Boston, MA, Montreal & Toronto	To present a paper entitled "Chained Aggregation of Linear Time-Invariant Systems" at the JSEP Topical Conference at Harvard, to attend the IEEE Optimization and Control Conference in Montreal and discuss research with faculty members of the Electrical Engineering Department at the University of Toronto.
5/3-5/7	Dimitri Bertsekas	Boston, MA	To present a paper entitled "Theoretical Foundations of Stochastic Optimal Feedback Control" at the JSEP Topical Conference at Harvard.
5/3-5/5	J. B. Cruz, Jr.	Boston, MA	To present a paper entitled "Decentralized Stackelberg Stretegies" at the JSEP Topical Conference at Harvard.

SUMMARY OF TRAVEL

Date of Travel	Personnel	Places of Visit	Purpose
5/3-5/4	P. V. Kokotovic	Boston, MA	To present a paper entitled "Singular Perturbations in Control Theory" at the JSEP Topical Conference at Harvard.
5/25-5/26	Gernot Metze	Charlotte, NC	To participate in the Seventh Annual Multi-valued Logic Symposium as Program Chairman.
5/31-6/3	David L. Waltz	Amherst, MA	To present a paper entitled "A Model for Low-Level Vision" at the Workshop on Vision.
6/5-6/9	Kaj Stolt	Ithaca, NY	To present a paper entitled "Computer Simulation of Small Dislocation Loops in fcc Crystals" at the Application of Field Ion Microscopy to Materials Science Conference.
6/12-6/19	William B. Rouse	Cambridge, MA	To present a paper entitled "Queueing Model of Pilot Decision Making in a Multi-Task Flight Management Situation" at the 13th Annual Conference on Manual Control.
6/19-6/25	Raj Mittra	San Francisco, CA	To present a paper entitled "A Diffraction-Theoretic Interpretation of Geometric Optical Methods with Application to High Frequency Scattering and Radiation Problems" at the IEEE AP-S/URSI Conference.
6/22-6/25	Nelson Wax	San Francisco, CA	To participate in the International Joint Automatic Control Conference.