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CSL COORDINATED SCIENCE LABORATORY

ANNUAL PROGRESS REPORT 1982-83

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UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

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This report summarizes all sponsored research activities that occurred in the Coordinated Science Laboratory during the period July 1, 1982 to June 30, 1983. The summaries are categorized into nineteen technical areas. A comprehensive list of faculty, graduate students, publications, and supporting agencies during this period of time is included.

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COORDINATED SCIENCE LABORATORY

UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

ANNUAL PROGRESS REPORT 1982-83

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PUBLICATIONS

1. HIGH SPEED DEVICES

Book Chapters

1.1 H. Morkoç, "Modulation doped $Al_xGa_{1-x}As$/GaAs heterostructures," in <u>The Technology and Physics of Molecular Beam Epitaxy</u>, E. H. C. Parker and M. G. Dowsett (eds.), Plenum, New York, July 1984.

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       "Molecular beam epitaxial double heterojunction GaAs/$Al_xGa_{1-x}As$ bipolar
       transistors with high current gains," Workshop on Compound Semiconductor
       Microwave Materials and Devices, San Antonio, TX, Feb. 21–22, 1983.

2.   SEMICONDUCTOR MATERIALS AND DEVICES

Book Chapter

2.1   G. E. Stillman, L. W. Cook, T. J. Roth, T. S. Low and B. J. Skromme,
       "High purity material," in GaInAsP Alloy Semiconductors, T. P. Pearsall
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19.   CLIMATE AND CROP STUDIES

Journal Article

19.1 P. Handler and E. Handler, "Climate anomalies in the tropical Pacific Ocean and corn yields in the U.S.," _Science_, vol. 220, pp. 1155–1156, June 1983.

1. HIGH SPEED DEVICES*

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Work on the growth of GaAs and AlGaAs homo- and heterojunction structures by MBE has continued while the growth of GaAsSb systems by MBE has been initiated. In addition, modeling of modulation doped FETs or MODFETs, along with their characterization and optimization both at 300 and 77 K, has progressed very rapidly. Bias dependence of MODFETs, light sensitivity, and threshold voltage shift with temperature and bias were investigated in detail. A new project, wide bandgap emitter heterojunction transistors was initiated and extremely high current gains were obtained. As in the past, GaAs/AlAs and GaAs/AlGaAs superlattices were investigated by Raman, photoluminescence, and x-ray measurements.

In the MBE growth area, dependence of incorporation rates of Ga and Al on the substrate temperature and group V/III ratio was analyzed. At 700°C substantial Ga reevaporation was observed. With even less than 1% of a monolayer of Al, Ga desorption can be suppressed. Likewise excess As overpressure also suppresses the Ga desorption. These results are important because of their relevance to high quality heterointerfaces.

Modulation doped FETs having 1 μm gate lengths were fabricated and characterized. In collaboration with the University of Minnesota, a model predicting the current voltage and capacitance voltage characteristics of MOD-FETs was developed. Using the experimental data and the model developed, average electron velocity in the channel was determined to be about 1.8-2 x 10^7 cm/s at 300 K and about 3 x 10^7 cm/s at 77 K. Since these values are comparable to those for undoped GaAs, the modulation doping provides electrons for current conduction without degrading the properties of GaAs. Using the model, a design criterion was produced and applied to optimize the MODFETs. Transconductances as high as 275 mS/mm at 300 K and over 400 mS/mm at 77 K have been obtained. Maximum drain current levels approaching 300 mA/mm have been observed. Using an automatic network analyzer, S-parameters as well as the maximum available gain (13 dB at 10 GHz with N-off MODFETs) have been measured as well.

Heterojunction npn bipolar transistors with base thicknesses ranging from 500 Å to 2000 Å and base doping ranging from 5 x 10^{17} cm^{-3} to 10^{19} cm^{-3} were grown and fabricated. Because of the particular fabrication concerns, both the emitter and collector region were made of $Al_{0.5}Ga_{0.5}As$ wide gap material. Devices with emitter area of 10 x 60 μm and collector area of 50 x 60 μm exhibited current gains of 500 for a base doping of 10^{19} cm^{-3} and thickness of 500 Å, and 1700 for a base doping of 5 x 10^{18} cm^{-3} and thickness of 1000 Å. The gain was about 900 for a base thickness of 2000 Å and a doping of 10^{18} cm^{-3}.

Using a strained superlattice at the heterointerface, much improved interfacial properties as determined from transport parallel to the interface have been obtained. In some cases, the improvement in mobility was almost 10-fold. Using this concept, inverted modulation doped structures, bipolar transistors, and double heterojunction lasers were fabricated. Current threshold densities of about 630 A/cm^2, the lowest obtained in conventional lasers, have been observed. It is expected that by using the standard cavity length, 400 μm, instead of 280 μm which was used, much lower thresholds can be measured.

Optical characterization of GaAs/AlAs and GaAs/AlGaAs superlattices with sizes between 25 Å and 100 Å have also been investigated. Full width at half

maximum values of about 4 meV have been observed, indicating   excellent   crys-
talline   quality.   Investigations   are under way to explain the triplet peaks
observed in the excitation spectra.

2. SEMICONDUCTOR MATERIALS AND DEVICES

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2.1 Introduction

The goal of this work is the evaluation of the potential of high-purity InP and InGaAsP for optical and microwave device applications. The work supported by JSEP in particular is an investigation of the hydride growth technique for InGaAsP. The hydride technique is of interest because all four gas phase constituents are controlled independently in contrast to the halide technique, and because of the difficulty of growing the InGaAsP compounds by MOCVD or MBE.

With other support, LPE growth of InP and InGaAsP is also being studied, and the properties of the hydride-VPE and LPE epitaxial layers are compared. The techniques used in this work to characterize the material include the measurement and analysis of Hall coefficients and resistivity measurements over the 4-350 K temperature range to determine the total concentrations of electrically active donors and acceptors. The influence of the growth conditions on the identity and concentration of the acceptor species incorporated in the epitaxial layers is studied through photoluminescence measurements over the 1.5-20 K range. Deep levels, and the influence of different growth parameters on the concentrations and energy levels of these centers are studied through DLTS measurements. The crystalline quality and degree of lattice

match are studied with an x-ray diffractometer purchased with partial support
using JSEP funds. The residual shallow donor impurities in InP are studied
using far infrared Fourier transform measurements of photothermal ionization
photoconductivity on high purity epitaxial InP.

2.2 Vapor Phase Hydride Growth*

The majority carrier mobility at 77 K is the most common figure of merit
cited for this group of III-V semiconductors. The carrier concentration and
mobility are generally derived from the Hall coefficient and resistivity.
There is a danger in using the 77 K mobility as the sole indication of sample
purity because the measurement technique averages over the sample. When
proper caution is exercised, the 77 K mobility is a useful measure of the sam-
ple quality.

In Table 2.1 we have listed the Hall data and carrier concentration for
five of the best GaAs and five of the best InP epitaxial layers grown in the
VPE system. The InP sample with $\mu_{77K} = 71,000 \text{ cm}^2/\text{V-sec}$ is the highest mobil-
ity InP grown by the hydride technique that has been reported to date. In
addition to the InP the vapor phase system has also produced high purity GaAs
indicating that all four of the source materials are of sufficient purity to
grow high purity quaternary.

The electrical characteristics and lattice mismatch of some of the ter-
nary InGaAs samples grown in the vapor phase system are shown in Table 2.2.
The carrier concentrations are higher and mobilities are lower than expected
from source materials which have produced the high quality binaries, InP and
GaAs. The crystalline quality of the ternary layers is studied with a double
crystal x-ray diffractometer. InP has a relatively low congruent evaporation
temperature, 360°C. Above this temperature the vapor pressure of phosphorus
increases rapidly relative to indium, resulting in a phosphorus-depleted
indium-rich surface unsuitable for epitaxial growth. This thermal damage
occurs at temperatures far below those encountered in VPE growth. For epitax-
ial InP a 2 min in situ vapor etch was sufficient to provide a specular sur-
face and was adequate for growth. The diffractometer was utilized to

Table 2.1

High Purity VPE GaAs and InP Hall Data

Material	Carrier Concentration		Mobility (cm^2/V-sec)	
	n_{77K}	n_{300K}	μ_{77K}	μ_{300K}
GaAs	3.3×10^{13}	2.5×10^{13}	83,300	8,200
GaAs	3.3×10^{14}	2.5×10^{13}	72,900	6,000
GaAs	3.9×10^{13}	2.2×10^{13}	84,000	6,600
GaAs	1.7×10^{14}	1.7×10^{14}	88,700	5,200
GaAs	2.2×10^{14}	2.3×10^{14}	74,000	5,900
InP	5.2×10^{14}	6.7×10^{14}	71,000	3,270
InP	3.5×10^{14}	4.2×10^{14}	60,000	3,400
InP	1.9×10^{14}	1.5×10^{14}	60,000	2,920
InP	4.8×10^{14}	6.2×10^{14}	57,500	3,800
InP	5.2×10^{14}	5.7×10^{14}	54,000	4,330

Table 2.2

VPE InGaAs/InP

Material	Carrier Concentration		Mobility (cm^2/V-sec)		Mismatch $\frac{a_{epi} - a_{sub}}{a_{sub}}$
	n_{77K}	n_{300K}	μ_{77K}	μ_{300K}	$\frac{\Delta a}{a}$
InGaAs/InP	1×10^{16}	7×10^{15}	3,000	4,000	non-uniform
InGaAs/InP	6×10^{16}	1.3×10^{16}	2,200	6,500	$+8 \times 10^{-3}$
InGaAs/InP	6×100^{15}	4.4×10^{15}	6,800	18,200	$+1 \times 10^{-3}$
Best Reported VPE InGaAs/InP	1×10^{15}	1×10^{15}	10,000	35,400	

characterize the growth surface further. Substrates which had undergone the 2 min etch and had good surface morphology had broad x-ray diffraction peaks (> 20 arc sec) indicating some thermal damage still present. The theoretical half width of 10 arc seconds ($CuK\alpha_1$ <+400,-400> reflection) was obtained for non-thermally damaged crystals and some which were etched for longer times (4 minutes). Since in vapor growth the quality of the epitaxial layer is much more sensitive to the substrate morphology, as contrasted with MBE or LPE, eliminating this source of damage is critical to the VPE growth of high purity InGaAsP/InP.

2.3 Impact Ionization in InP*

The InP/InGaAsP alloy system has proven to be most suitable for fabrication of long wavelength (1.0 - 1.6 μm) optoelectronic sources and detectors. For wide bandwidth applications, high sensitivity avalanche photodiodes (APD's) are employed. Such APD's can be realized by utilizing an InP/InGaAs heterostructure with separate absorption and multiplication regions. The multiplication takes place in InP and is characterized by the impact ionization coefficients α and β, for electron and hole initiated ionization respectively. These coefficients are the inverse of the statistical mean free paths between impact ionization events. An accurate knowledge of α and β is essential for optimal APD design. Figure 2.1 shows the ionization data for (100) InP covering a wide range of the electric field values. The statistical process of secondary pair production introduces an additional component of noise into the detection process characterized by the "excess noise" factor. This factor is directly related to the ratio of the ionization coefficients of the semiconductor and decreases as the ionization ratio is enhanced. In (100) InP, α and β are given by

$$\alpha(E) = 3.45 \times 10^5 \exp[-(1.04 \times 10^6/E)^{1.54}] \tag{2.1}$$

$$\beta(E) = 3.80 \times 10^5 \exp[-(1.01 \times 10^6/E)^{1/46}] \tag{2.2}$$

where E is the peak electric field. The ratio β/α decreases from 4.0 to 1.3
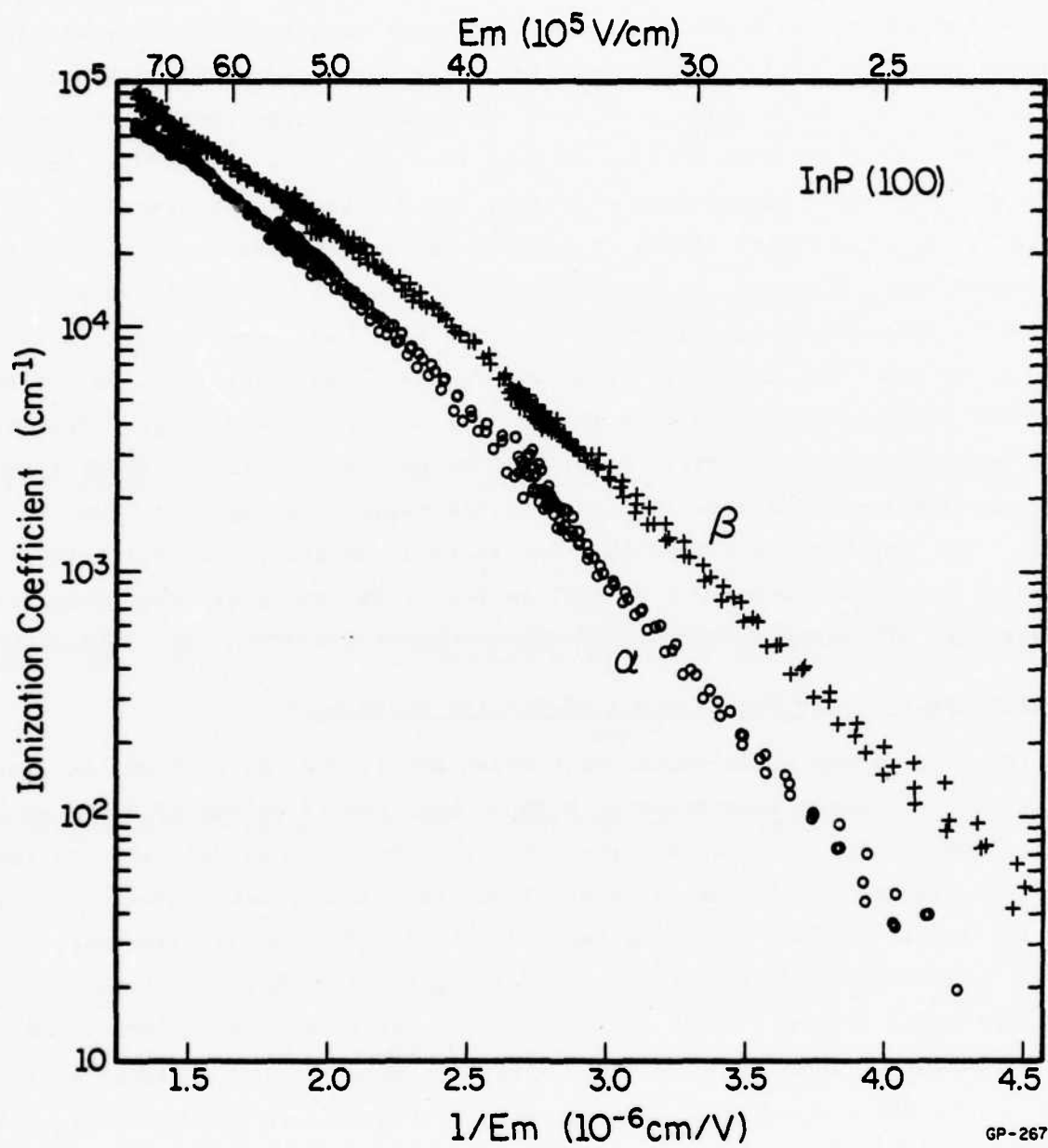
Fig. 2.1 Impact ionization coefficients for ⟨100⟩ oriented InP.

as the electric field is increased from 2.4 to 7.7 x 10^5 V/cm.

Some coefficients have been measured along the ⟨111⟩ orientation. Extension of the techniques used for impact ionization measurements along the ⟨100⟩ orientation to the ⟨111⟩ is difficult primarily due to problems with polishing and etching the (111)A surface of InP. We have developed techniques for successful polishing and mesa etching in this face and were therefore able to fabricate the APD structures necessary for ionization measurements. These special structures (inset of Fig. 2.2) allow access to both sides of the junction for pure electron and hole injection into the high field region. The ionization data are plotted in Fig. 2.3 along with bands indicating the ⟨100⟩ data given in Fig. 2.1. The ratio of β/α was found to be identical in both ⟨100⟩ and ⟨111⟩ orientations over the covered electric field range. The absolute magnitude of the coefficients, however, differ slightly due to a 5% discrepancy between the electric field values measured along the two directions. We can therefore conclude that there is no preferred orientation for fabrication of low noise APD's in InP, as far as the ratio of the ionization coefficients are concerned.

2.4 Photoluminescence Measurements of Shallow Acceptors*

Low temperature photoluminescence measurements are being used to study the residual acceptor impurities in undoped high purity epitaxial GaAs and InP layers. Our recent work concentrated on identifying some of the residual acceptors in undoped InP whose chemical identity is unknown. Several shallow acceptor levels in InP, including those due to Zn, Cd, and Mg, have been identified previously by means of photoluminescence measurements on lightly back-doped epitaxial layers. Other levels have not yet been firmly identified by this technique, such as the "A_1" acceptor, which is the dominant residual level in LPE InP and has also been reported in PH_3-VPE and LEC material. Its identity was originally conjectured to be either Si, Mg, or C, but it has generally been assumed to be C based on chemical considerations.
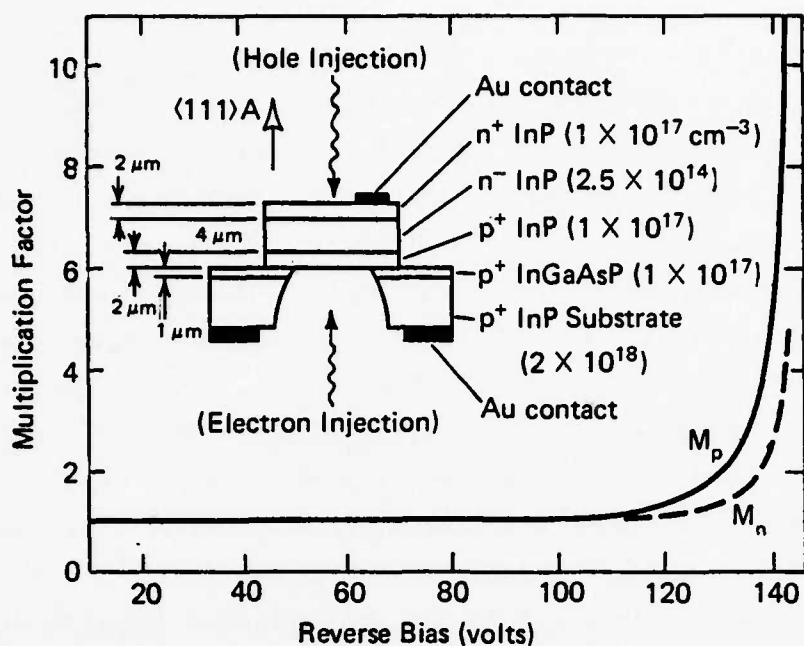

Fig. 2.2 Multiplication factors for holes and electrons as a function of
reverse bias with the device structure (inset).

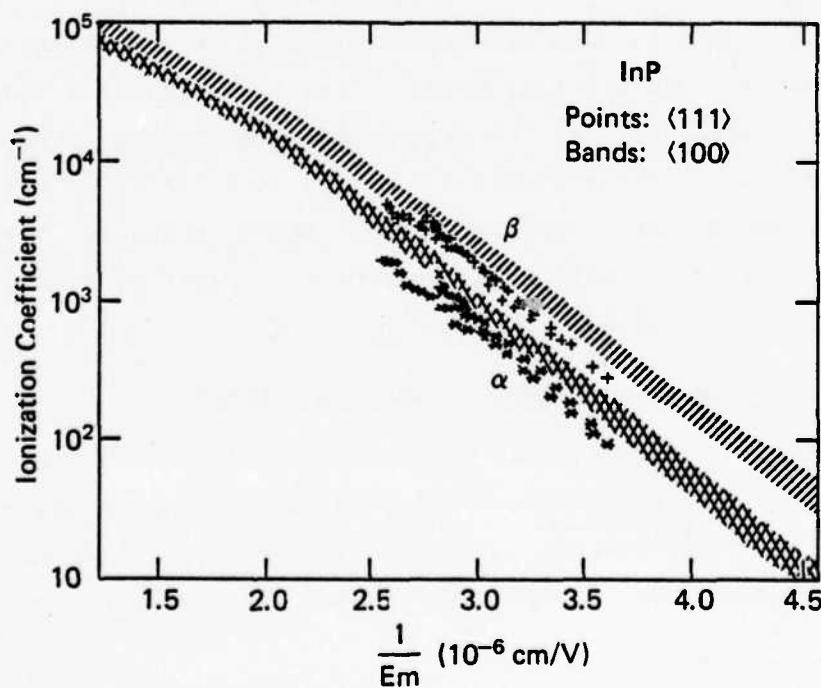Fig. 2.3 InP impact ionization coefficients for both ⟨111⟩, points, and
⟨100⟩, bands, orientations.

In collaboration with members of Dr. Ben Streetman's laboratory in CSL, we have performed low dose (10^{10}–10^{12} cm^{-2}) ion implantations of C and Be into high purity LPE, VPE, and LEC InP samples in order to prepare lightly doped specimens containing known quantities of these acceptors. Encapsulation with PSG and subsequent anneals at 730°C for 30 min. were used to activate the impurities and remove damage. Both the implanted samples and control samples, which were either unimplanted and annealed or implanted with B and annealed, were then characterized using low-temperature (1.7–20 K), high resolution (0.2 Å) photoluminescence measurements. Prominent donor-to-acceptor (D°–A°) and conduction band-to-acceptor (e–A°) peaks appeared in the spectra of the C-implanted samples at 1.3749 and 1.3795 eV, respectively, as shown in Fig. 2.4, and in the Be implanted samples at 1.3783 and 1.3824 eV, as shown in Fig. 2.5. The positions of the peaks in the Be-implanted samples are virtually coincident with the positions of the peaks due to the A_1 acceptor in undoped material, while the C peaks occur at a position where no acceptor levels have been reported in unintentionally doped high purity InP. These results lead to the unexpected conclusion that C is not present as a residual acceptor in high purity VPE, LPE, or LEC grown InP.

Low dose Si implants were performed into high purity epitaxial layers but did not produce any new acceptor peaks. Possible candidates for the chemical identity of the A_1 acceptor therefore include Be or Mg, whose ionization energy we measured as being within 0.3 meV of that for A_1 or Be; conceivably, another as-yet unreported acceptor species could also be responsible. A lightly Sn-doped LPE sample was measured but gave no evidence of any new acceptor peaks attributable to Sn.

2.5 Fourier Transform Spectroscopy of Shallow Donors*

The technique of photothermal ionization Fourier transform spectroscopy continues to be of use in characterizing the residual shallow donors which limit the purity of high purity undoped epitaxial material in the InGaAsP system. The mechanism for the process of photothermal ionization, represented
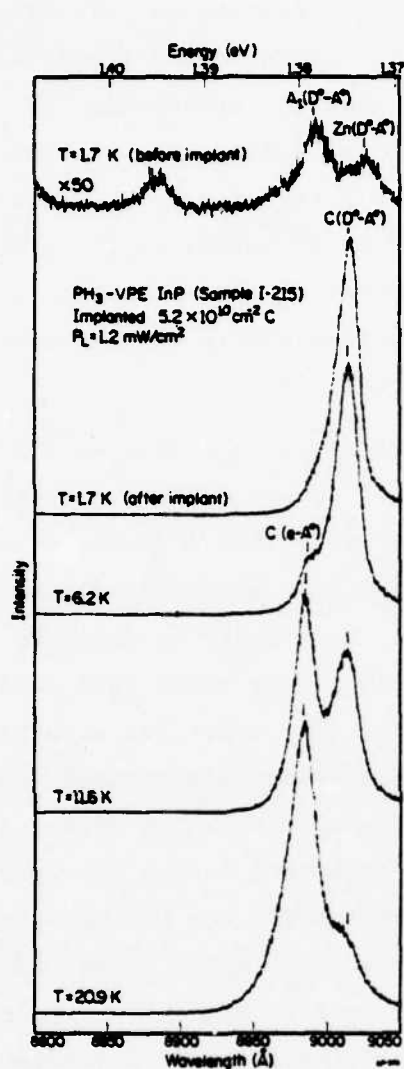
Fig. 2.4

Low temperature photoluminescence spectrum of a hydride VPE InP sample, both before (at 1.7 K) and after (at four different temperatures) implantation with ^{12}C.
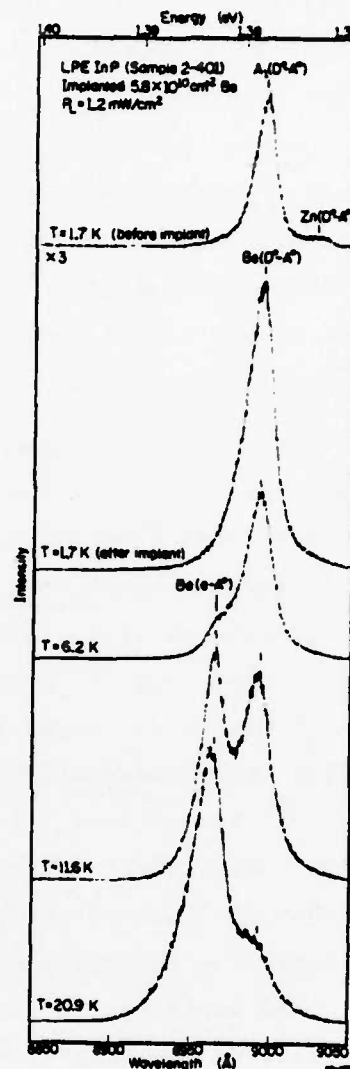
Fig. 2.5

Low temperature photoluminescence spectrum of a LPE InP sample before and after implantation with ^{9}Be.

schematically in Fig. 2.6, can be understood by considering an electron ini-
tially occupying a donor ground state. The temperature of the sample is 4.2 K
so that few electrons are in the conduction band. Absorption of a far
infrared photon of appropriate energy can induce a transition to one of the
donor excited states, from which the still bound electron may be excited to
the conduction band by absorption of phonon(s), contributing to the electrical
conductivity of the sample. A photothermal ionization spectrum then consists
of a plot of photoconductive response versus photon energy or wavenumber, and
contains peaks at the various donor transition energies.

The ground state energies of shallow donors in InP are very nearly hydro-
genic but the energy of the donor ground state energy differs slightly from
the value predicted from hydrogenic theory, and since this difference is donor
species dependent, each hydrogenic transition in a photothermal ionization
spectrum contains several closely spaced peaks. Each peak corresponds to a
particular donor species present, and has an amplitude which is a measure of
the relative concentration of that donor species. The multiplet structure is
most easily resolved at high magnetic fields (greater than about 3 T) in the
1s–2p (m = –1) transitions. For this reason, the spectra which appear in this
paper show only these transitions. The photothermal ionization spectra of
Fig. 2.7 show the donor peaks present in high purity VPE and LPE InP grown in
our laboratory. The LPE samples typically show three donor peaks labeled A,
B, and C. The amplitudes of these peaks are related to but not proportional
to the relative concentrations of the associated donors. For example the
photoresponse of the sample at the energy of peak B is largely due to the
Stark broadened low energy tail of peak C. By numerically fitting a sum of
individual peaks of the characteristic shape with adjustable amplitudes to the
spectra, it was possible to determine the typical relative concentrations of
donors A, B, and C in LPE samples as approximately 0.2 to 0.1 to 0.7. The
spectra for the VPE samples show only the peaks A and C in the very different
relative concentrations of 0.7 to 0.3.

Carefully controlled doping experiments have been performed by several
research groups to identify various donor species with the associated photo-
thermal ionization peaks for GaAs. Such experiments are difficult because of
the small range of donor concentrations between that of the purest material
which can be grown by a given technique and that for which impurity
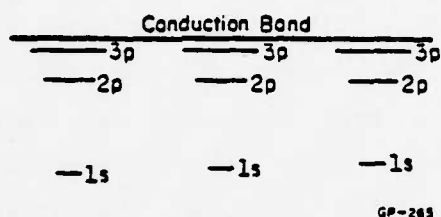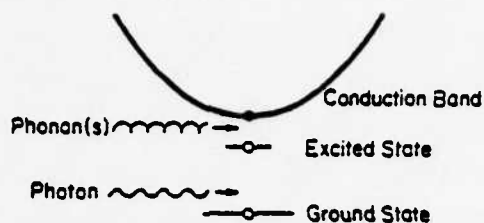
Fig. 2.6 Two representations of the photothermal ionization process:
(a) illustrating the multistep photon-phonon(s) excitation, and
(b) Illustrating the difference in ground state (1s) energies
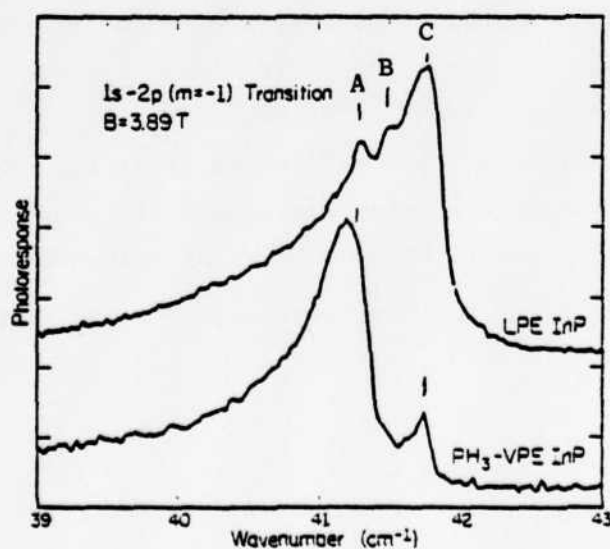for 3 donor species.

Fig. 2.7 Photothermal ionization spectra for InP grown by LPE and hydride VPE
(PH$_3$-VPE).

interactions degrade the spectra by broadening and distorting the spectral peaks. Until recently, nearly all InP grown was of insufficient purity to resolve these peaks and so far, very few donor identification experiments have been performed for InP. Using intentionally doped LPE grown InP, Stradling has identified photothermal ionization peaks for Sn, Si, and S. This work indicates that the peaks A and C are Si and S respectively, but these identifications should be regarded as tentative.

In collaboration with the staff at the Advanced TRIGA nuclear reactor at the University of Illinois, high purity n-type GaAs samples grown by a variety of epitaxial techniques were transmutation doped with a low fluence of thermal neutrons to produce Ge and Se impurities from the host Ga and As atoms, respectively. Samples were chosen having low concentrations of Se and Ge donors and Ge acceptors prior to doping. Photothermal ionization spectra (as shown in Fig. 2.8), and photoluminescence spectra, as well as Hall effect data, were recorded before and after neutron doping and subsequent low temperature anneals. The high purity of these samples and low neutron dose, together with the low noise and high resolution of the measurements, has allowed the precise identification of the Se and Ge donor peaks in the photothermal ionization spectrum of GaAs through an accurate determination of their 1s–2p(m=–1) transition energies. Comparison of the relative concentrations of shallow donors and acceptors, obtained from the photothermal ionization and photoluminescence spectra, with the values of N_D and N_A determined from the Hall effect data, allowed the activation of Se and Ge to be measured. The observation of Ge_{As} acceptors after doping and of the incomplete activation of Se as donors have been interpreted in terms of transmutation induced recoil of the Se and Ge due to γ-ray and $\bar{e}-\bar{\nu}_e$ pair emission during β decay.
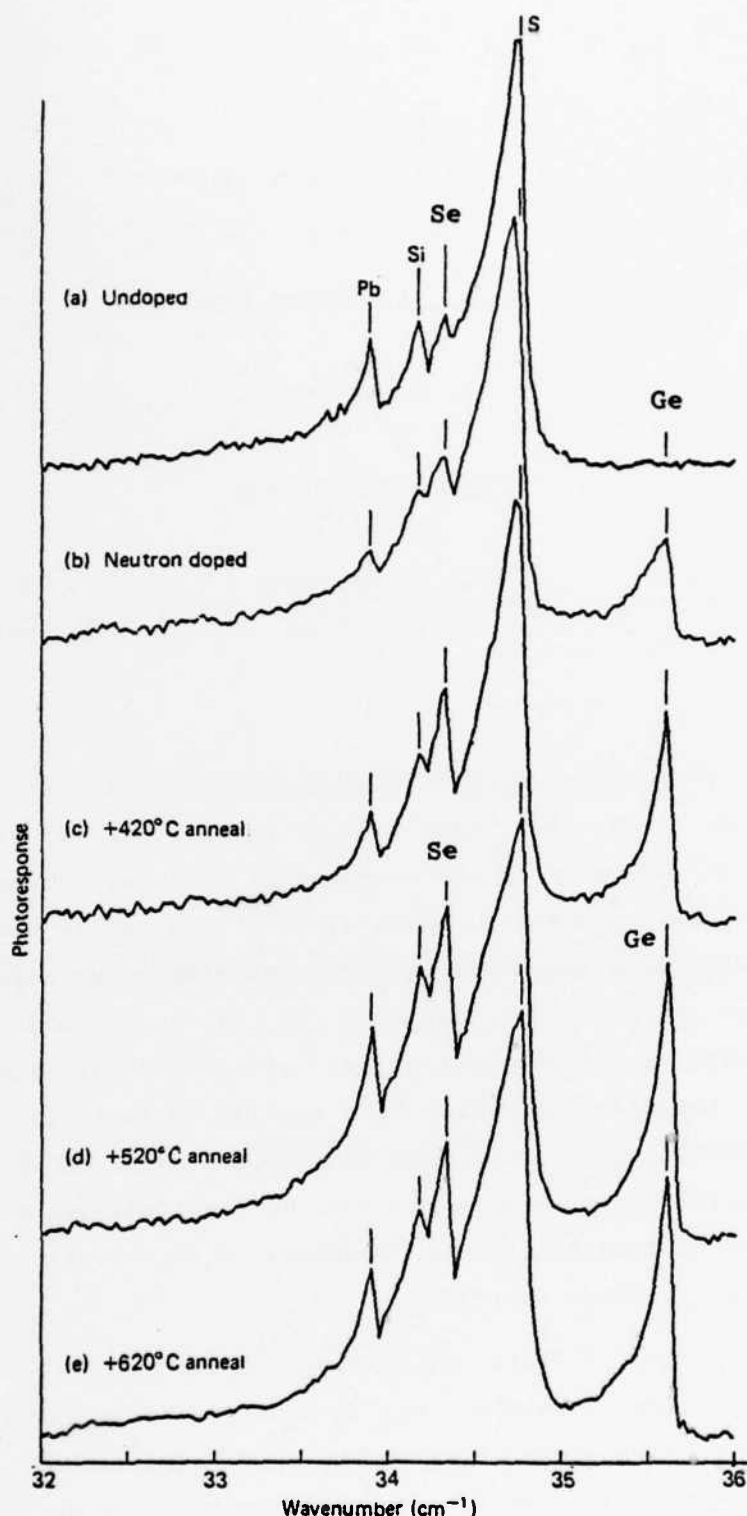
Fig. 2.8   Sequence of photothermal ionization spectra of the 1s–2p(m=–1) transitions of the high purity LPE sample grown by C. A. Stolte at
Hewlett–Packard, recorded at B=4.97 Tesla before and after transmutation and after each step in a sequence of 10 minute anneals at
successively increasing temperatures. Since the energy of the Se
donor peak is known, the higher energy peak (coincident with the X_3
residual donor peak) that appears in the spectrum after transmutation must be associated with Ge donors. The peak amplitudes in
these spectra also show a plateau in activation of transmutation
generated Se and Ge donors as a function of temperature, but this is
not an indication of 100% activations.

3. QUANTUM ELECTRONICS*

Faculty and Senior Staff

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Research in the area of quantum electronics presently falls into two main categories. Work under the direction of Prof. J. R. Tucker is devoted to studies of quantum phenomena in the response of nonlinear tunnel junctions to very long wavelength radiation. This research has led to the development of new millimeter wave receivers which approach quantum noise limited sensitivities; and these devices are expected to have a dramatic impact in radio astronomy and future space communications systems. The same concepts of photon-assisted tunneling have also been applied to interpret the dynamics of charge-density wave motion in the "one-dimensional" metals $NbSe_3$ and TaS_3. Recent experimental results strongly support the tunneling model proposed by John Bardeen, and continuing research addresses fundamentally new problems of collective charge transport in solids.

The group directed by Profs. J. T. Verdeyen and J. G. Eden focuses on the production of excited molecules and free radicals by plasma discharge and ultraviolet lasers, with application to the growth and etching of semiconductor surfaces. Advanced diagnostics, which include microwave and laser induced fluorescence, mass spectrometry and optical spectroscopy, are utilized to probe the kinetics of excited states and their interactions with semiconductor materials. Although the results are expected to provide insight into processing technologies used in industry, the emphasis here is on fundamental studies

of excited state chemistry in plasma discharges. Recent research has achieved insight into the process of silane dissociation and deposition onto silicon substrates. Work on etching of silicon in an NF_3 discharge has yielded information on electron and ion densities that can be used to understand the dynamics of the dissociation and the role played by F ions in the etching process.

3.1 Millimeter and Submillimeter Wavelength Photon Detectors

The scientific objective of this research is the study of photon-assisted tunneling phenomena, with application to the development of quantum detectors at very long wavelengths.

A new generation of ultra-low noise millimeter wave receivers is currently under development. These devices utilize remarkable quantum effects in the tunneling of single-electron quasiparticles between two superconductors, which were predicted on the basis of photon-assisted tunneling theory [R1]. When operated in the quantum regime at millimeter wave frequencies, heterodyne mixers using superconductor-insulator-superconductor (SIS) tunnel junctions were predicted to be capable of achieving [R2]:

(1)   conversion gain-simultaneous amplification in the process of frequency down-conversion of the incoming signal.

(2)   quantum limited mixer noise temperatures $T_M \sim h\omega/k$.

Taken together, these results imply that practical receivers can be constructed which approach the limiting sensitivity imposed by the quantum nature of the radiation. That is, it should be possible to detect individual quanta at millimeter wavelengths, and eventually extend this technique into the submillimeter and microwave regions as well. There has been great progress toward engineering these receivers during the past year. An extensive review has recently been published by Phillips and Woody [R3]. We have extended the theory to include an analysis of series arrays of tunnel junctions, and to project the future performance of harmonic mixers of this type [3.1]. Very recently, A. R. Kerr and M. J. Feldman of the NASA Institute for Space Studies in New York reported a receiver noise temperature $T_R = 68$ K ≈ 10 $h\omega/k$ for operation at 115 GHz on a radio telescope. This noise temperature is a factor of 3 lower than previous state-of-the-art Schottky diode receivers, and by utilizing the conversion gain effect they expect to achieve noise temperatures

$T_R \sim 20$ K ~ 3 $\hbar\omega/k$ in the relatively near future. Since required integration times for a radiometer scale with T_R^2, this represents a current improvement of about one order-of-magnitude, and the clear potential for a factor of 100 increase in the capability of millimeter wave astronomical receivers. This development is expected to have a revolutionary impact on the science of radio astronomy, and eventually on deep space communications as well.

The second area in which photon-assisted tunneling phenomena are being studied is in characterizing the motion of charge-density waves (CDW's) in the "one-dimensional" metals $NbSe_3$ and TaS_3. CDW conduction represents the second example of charge transport in solids by a macroscopically occupied quantum state, superconductivity being the first. John Bardeen proposed that this CDW conduction takes place by a Zener-type collective tunneling process [R4], and that the ac response of these materials can be characterized by the same photon-assisted tunneling theory developed for the SIS tunnel junctions [R5]. This extremely controversial hypothesis implies that we are observing quantum effects in the MHz frequency region where $\hbar\omega \sim 10^{-6}kT$ at temperatures as high as $T = 200$ K. This is theoretically possible only because very large numbers of electrons are acting together, so that the total energy of the condensate is large compared to thermal energies. Another implication of this theory is that these CDW materials will be an extremely important system in which to test ideas of macroscopic quantum tunneling. We have performed extensive experiments on $NbSe_3$ and TaS_3 to measure their dc and ac conductivity, and their rectification and harmonic mixing properties. The results [R6] comprise, we feel, compelling evidence for the tunneling interpretation of CDW conduction. We are continuing a very extensive experimental program in this area, and are also pursuing a fully microscopic formulation of the theory.

3.2 Plasma Deposition

Although the deposition of amorphous semiconductor films from a glow discharge is a well-known technology, little is known of the kinetics of the discharge, and their relationship to the deposition process. In the last year, a research program was started with the goal of understanding the properties of the plasma in a glow discharge deposition system, and determining what effect these properties have on the deposited films.

A capacitively coupled, r.f. excited discharge geometry, similar to those used in commercial systems, was chosen for these studies. Two aluminum electrodes contained in a 4 inch outer diameter pyrex vacuum chamber, are driven by a signal generator and r.f. amplifier. These studies utilized silane diluted in helium, with the percent silane in the gas mixture variable from 0 to 10%.

Early studies have been concerned with the ionization and excitation of helium and silane by electrons in the discharge. Measurements of the electron density in the plasma are of critical importance in understanding these processes. The density of electrons in the plasma was studied both in helium, and in SiH_4/He mixtures, using a microwave bridge operating at 10 GHz. In this technique, a microwave beam traversing the plasma is compared with a reference beam, and the phase shift measured is directly proportional to the electron density in the plasma. Typical measurements show electron densities in the mid 10^{10}/cm^3 range for one Torr of helium excited by 10 watts of r.f. power. Measurements on silane/helium mixtures show significantly lower electron densities than in pure helium, indicating that silane or some of its dissociation products attach electrons forming negative ions. In fact, the density of electrons in silane/helium mixtures is so small, that for concentrations above 1% silane, no phase shift can be measured with the current interferometer. This is particularly surprising since the open circuit d.c. bias and the short circuit bias current of the two discharges are comparable.

The emission from the plasma has been studied as a function of space between the electrodes and time within the r.f. excitation. Measurements of light emission from the discharge as a function of distance between the electrodes indicates that there are dark spaces of roughly the same length adjacent to both electrodes. At high pressures the dark area between electrodes fills in; at low pressures the dark area becomes more pronounced indicating that in many respects the plasma in a parallel plate r.f. discharge is analogous to the negative glow in a d.c. discharge.

Temporal resolution of the emission from the plasma is achieved using a box-car integrator. Emission from the plasma shows two distinct peaks over an r.f. cycle; one during the positive half-cycle and one during the negative half-cycle. However, the two peaks are not equal in magnitude. Emission from

the 501.6 nm line of helium is slightly larger during the positive half-cycle than during the negative half cycle. The temporal asymmetry in emission possibly points to a similar asymmetry in dissociation of silane and deposition of silicon on the substrate.

3.3 Plasma Etching

Our work in the area of plasma etching has included a detailed study of the plasma characteristics of various etchant gas discharges. Some of the properties which have been investigated are the dissociation of the parent gas by the discharge, electron density, composition (neutral and ionic), and excited states. By examining these microscopic properties along with the more conventional macroscopic parameters such as gas flow rate, power input, etch rate and anisotropy, it should be possible to gain a greater understanding of the extremely complicated etching kinetics.

Our most recent results are to be published in the Proceedings of the 6th International Symposium on Plasma Chemistry and will be summarized only briefly here [R7] (a copy of this has been forwarded to JSEP). These results are concerned with the NF_3 discharge, the products of which can etch Si approximately 6000 Å/min and with a selectivity of 20:1 for etching silicon over SiO_2. Using mass spectrometry, microwave interferometry, and optogalvanic spectroscopy, it has been shown that:

(1) The NF parent gas can be quite effectively (> 50%) dissociated by the discharge.

(2) The electron density in the NF_3 discharge is one to two orders of magnitude smaller than that of a similar discharge in Ne or CF_4.

(3) Large negative ion densities are probably present in the NF_3 discharge — F^- and F_2^- are the species present with the former being the predominant ion. (These negative ions could play an important role in the etching process) [R8].

(4) A doubly peaked optogalvanic signal [R9,10] due to photodetachment has been observed.

At the present time our work is continuing with a further examination of the optogalvanic signal and an attempt to formulate a model which can explain the temporal behavior observed. It is currently believed that the initial

peak is due to a sudden collection of photodetached electrons while the latter is a function of the plasma potential which changes due to the excess electron population. Preliminary experiments observing the floating potential of probes placed near the discharge do indicate a significant perturbation of the plasma potential on the time scale of the secondary optogalvanic peak.

Another area of investigation involves coupling the discharge, microwaves and the laser. An excimer laser is used to photodetach the negative ions in the NF_3 discharge and it is hoped that the excess electron density produced can be monitored with microwave interferometry. This technique, if successful, could be used to obtain quantitative limits on the negative ion densities present.

3.4 Laser CVD

This work has concentrated on exploiting the unusual characteristics of the ultraviolet excimer lasers to grow semiconductor films from the vapor phase. Polycrystalline and single crystal Ge films have been grown on a number of substrates and the film growth rates and carrier mobilities for poly-Ge are comparable to the best values in the literature.

Recent work has focussed on understanding the gas phase kinetics that result in the growth of the film. Emission spectroscopy, laser induced fluorescence and spontaneous Raman scattering are being used to study the temporal and spatial histories of the GeH_2 and H_2 radicals and various electronic excited states of Ge and GeH. Current results point to the GeH_2 radical as the dominant species and the one that is probably responsible for film growth.

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4. SEMICONDUCTOR PHYSICS

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4.1 Introduction

This research involves the study of basic properties of semiconductors, methods of device processing, and new device concepts. Both theoretical and experimental methods are employed in each of these categories. We are examining a variety of hot electron·.phenomena and their effects on present and future device performance, especially in connection with modulation doping. We are studying ion implantation and annealing of Si and III-V compounds, including laser and electron beam processing. These experimental studies include examination of defects arising from implantation and annealing. Several aspects of this work are done in collaboration with other units, particularly the studies of materials grown by VPE (Unit 2).

4.2 Electron and Incoherent Beam Processing of Semiconductors*

In the previous reporting period we have examined swept line electron beam annealing (SLEBA) of implanted Si. During this period, we have applied the same annealing technique to Be-implanted GaAs. The temperature distributions during SLEBA have been theoretically calculated using Monte Carlo and Green's function techniques. Comparative studies of SLEB and furnace annealed planar Be-implanted GaAs junctions have been made.

Single crystal Si films have been grown on SiO_2 covered Si substrates by zone melting and recrystallization from windows in the oxide to the underlying crystalline Si. A scanned narrow graphite strip heater has been used for the purpose. The recrystallized films consist of single crystal grains about 1 mm wide and extending indefinitely along the scan direction. These grains contain low angle grain boundaries at about 25 μm intervals. These, however, have a negligible effect on the electrical properties of the films. B and P implantation into these films have been studied by Hall profiling and secondary ion mass spectrometry. Electrical activation and carrier mobility in these films approaches bulk Si values over a wide range of doses. Junction studies made on these films show that leakage currents are slightly higher in these films than in bulk Si, because of the low angle grain boundaries intersecting the junction.

4.3 Furnace Annealing of Compound Semiconductors*

In the previous reporting period, anomalous diffusion of impurities in implanted InP was observed. Correlated diffusion of implanted dopants (e.g., Be, Mg or Si) and background impurities (e.g., Fe or Cr) was reported.

Studies of correlated diffusion have been extended to GaAs. Implanted S exhibits defect enhanced diffusion behavior and low electrical activation. The redistribution of implanted S during annealing is inhibited (for anneal temperatures up to 800°C) by a sufficiently high level of Si, irrespective of whether the latter is introduced during crystal growth or by co-implantation. Substantial improvements in peak donor concentration are achieved by S and Si co-implants as compared to separate S or Si implants. S and Ar co-implantation causes damage enhanced diffusion of S for low Ar doses, but little diffusion for amorphizing Ar implants. However, extremely poor electrical activation of implanted S is achieved in this case.

4.4 Electronic Transport at High Energies*

We have developed previously a quantum Monte Carlo simulation which includes a realistic bandstructure and uses a quantum field theoretic scheme to calculate the electron-phonon interaction. This numerical simulation has been used to simulate with one parameter set all important hot electron effects in silicon and a large number of hot electron phenomena (impact ionization, transient transport) in GaAs, InP, and InAs. Below a few examples are given of the large variety of results which have been obtained. Table I shows the set of electron phonon coupling constants for silicon which describes simultaneously deviations from Ohm's law velocity saturation, impact ionization, and the emission of hot electrons from silicon into silicon dioxide.

The accuracy of the simulation is shown in Fig.4.1, which displays Ning's result for the emission probability of hot electrons into silicon dioxide. The excellent agreement between experiments and theory could only be achieved due to the inclusion of quantum effects (collision broadening) and band structure (second conduction band).

The impact ionization rate can be understood with similar precision not only for silicon but also for GaAs, InP, and InAs. Fig. 4.2 shows results for InP. The experimental results have been obtained by the work of Unit 5. Notice the absence of an anisotropy in both theoretical and experimental results. Details of transient transport are described in the next section.

4.5 Transient Phenomena in III-V Compound Semiconductors**

In the last few years, attempts have been made to construct new types of semiconductor devices which are capable of ever higher speed. Most of the predicted advantages are based on the high field-transient transport properties of III-V compounds and the associated higher drift velocities. These may give rise to the possibility of high current-low power applications. It has been the purpose of our study to obtain details of the (transient) transport
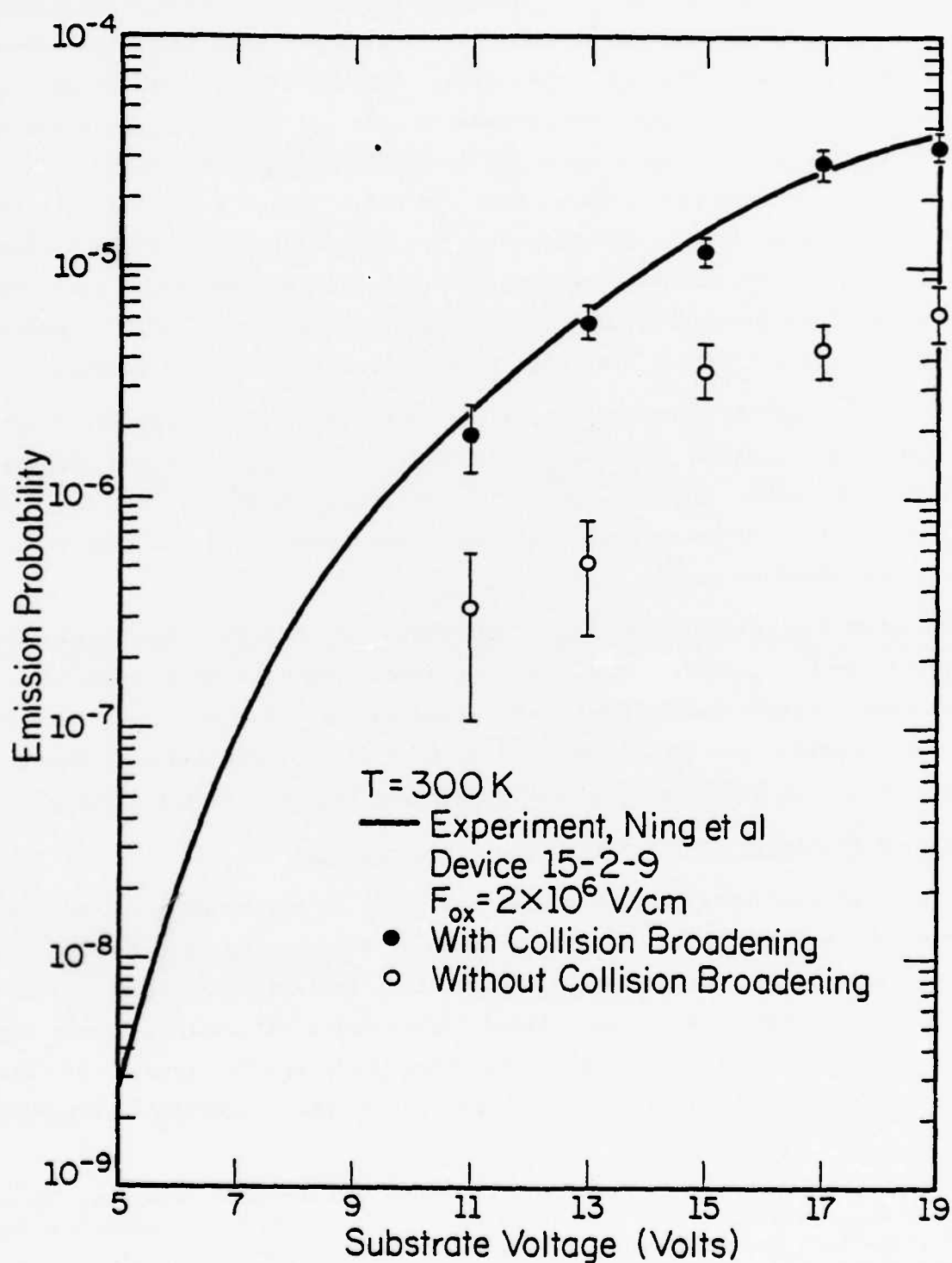
Fig. 1: Calculated and measured emission probability as a function of the substrate voltage.
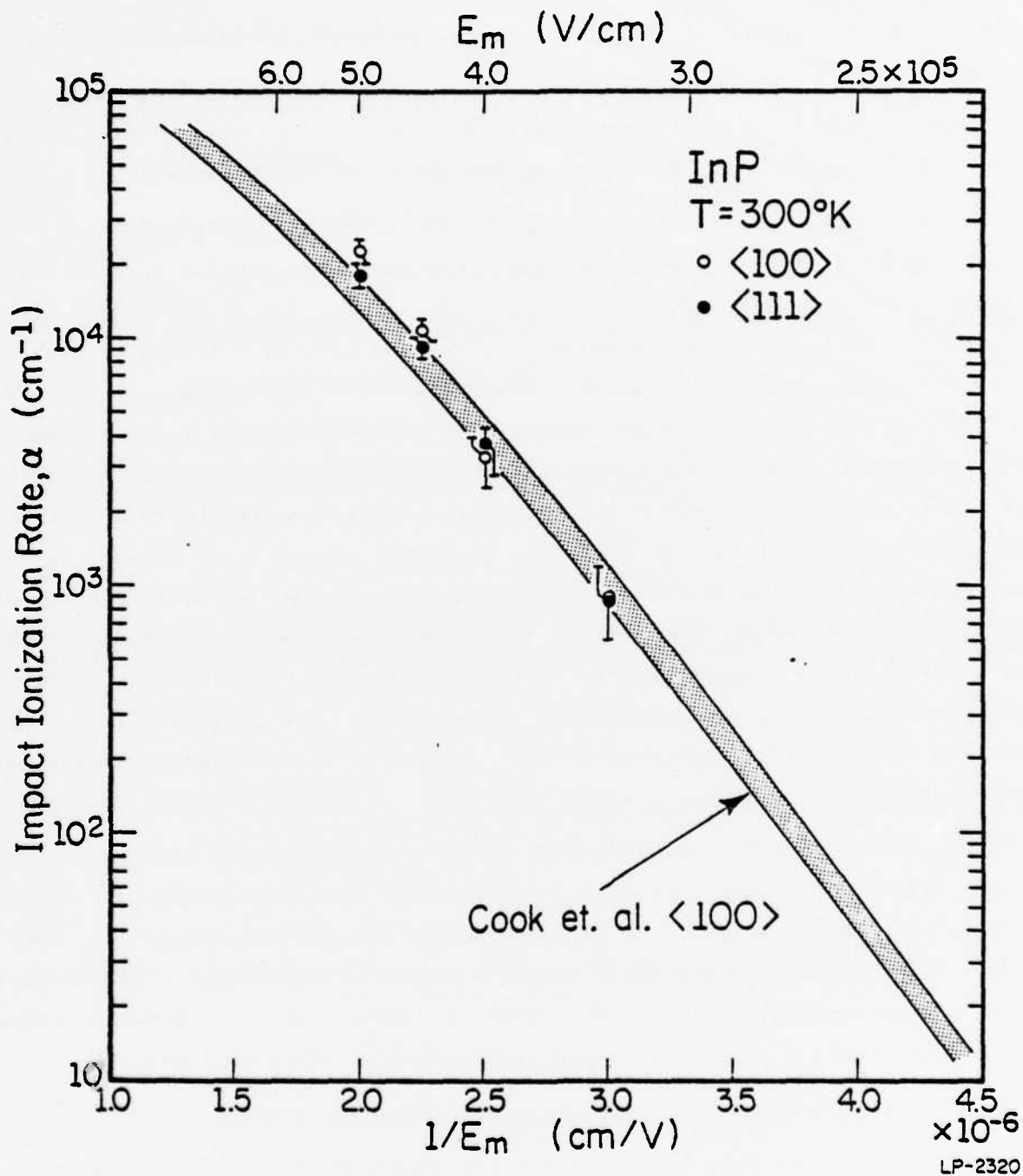
Fig. 2: Impact ionization rate in InP as a function of inverse field. The shaded area corresponds to experimental results of Cook and Stillman. The circles are calculated by our Monte Carlo simulation. The error bars are based on convergence error estimates.

properties of InAs, GaAs, and InP. The study included collision-free trans-
port, high energy injection and velocity enhancements, and impact ionization
phenomena in the context of their importance for device performance.

The III-V semiconducting compounds encompass a wide range of materials
with very different physical properties. many of these properties play a sig-
nificant role in the high field transport behavior of the material.

Representative of the large disparity in transport properties of the
III-V compounds are GaAs, InP, and InAs. The impact ionization rate in these
materials is vastly different over a wide range of applied fields. The elec-
tron drift velocities have a wide range of values as well. It has been known
for some time that very high steady state drift velocities can be attained in
GaAs. This has sparked much interest in practical device applications of
GaAs. By use of velocity overshoot, it is possible to achieve extraordinarily
high drift velocities and currents through a very small distance and at low
power levels. Velocities more than four times the steady state value can be
achieved under certain conditions in device size, applied electric field, and
initial electron energy. Recently InP has been considered as a candidate for
high speed device applications based on velocity overshoot. Velocity
overshoot can be attained over a much wider range of applied fields and
launching energic in InP than in GaAs, making it a more promising material
for device considerations.

Fig. 4.3 shows a comparative study of the average transit time through a
device 1500 Å long for InP, GaAs, and InAs vs. the applied electric field.
The electrons are injected at an optimum energy (for highest speed) as shown
in the figure. The steady state velocity of InP is also shown. Notice that
overshoot can improve the speed by about a factor of 3. However, this
improvement prevails only in a rather small range of electric field.

4.6 Electronic Transport in Layered Heterojunction Structures*

Several projects have been attacked and completed in this project area,
which can only be described briefly because of lack of space.
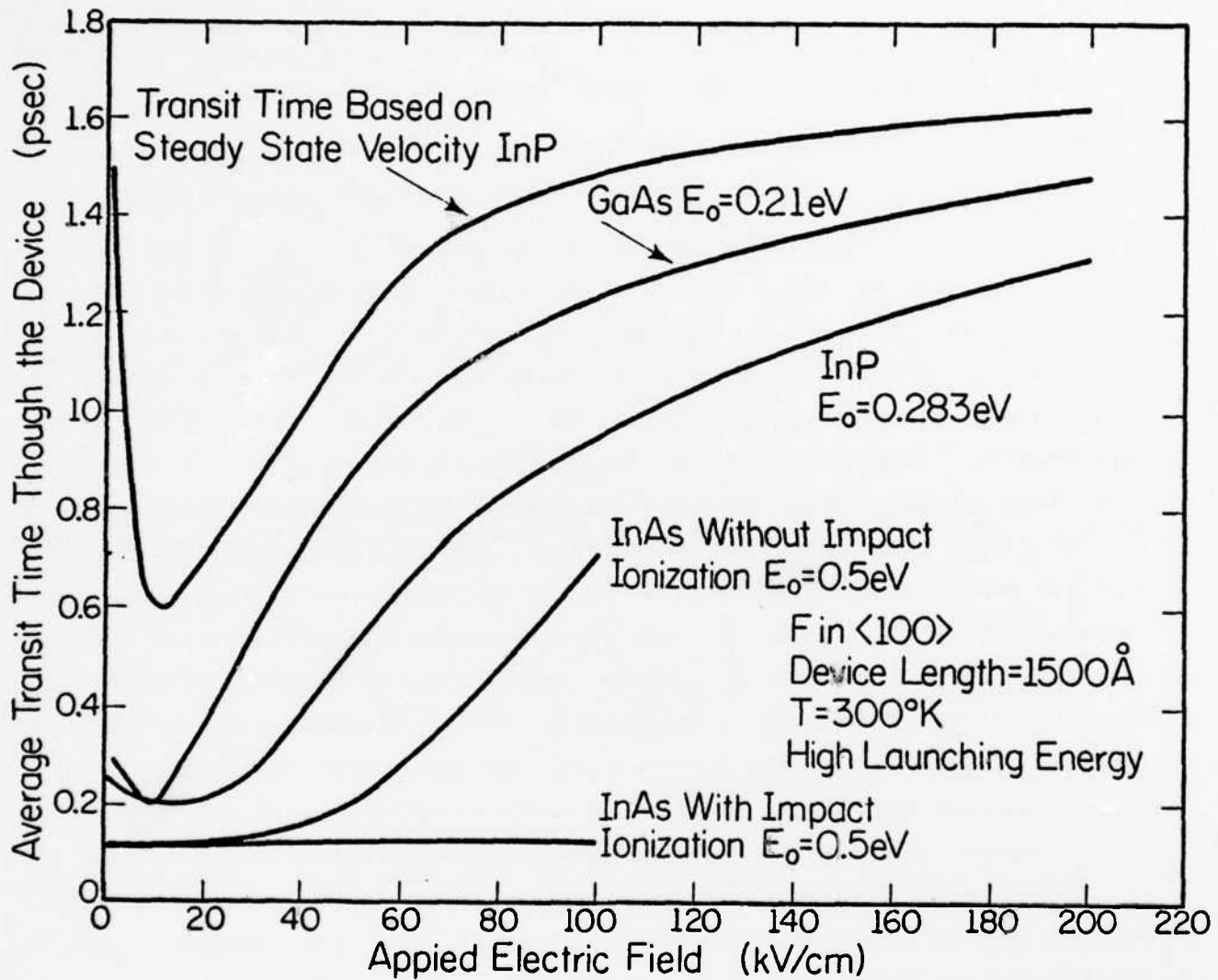
Fig. 3: Average transit time through a device of 1500 Å as a function of applied electric field for GaAs, InP, and InAs at high launching energy and 300 K.

(i)   We have developed a model for the index of refraction of superlattices.

(ii)   We have applied deep level transient spectroscopy (DLTS) studies to quantum well structures and shown that quantum wells represent models of giant deep traps. As a consequence, we were able to deduce band edge discontinuities from the DLTS measurements.

(iii) We have demonstrated the universality of <u>real space transfer</u> by showing that it exists also in InGaAs-GaAs and in GaAs-GaAsP layers.

(iv)   We have used our new high magnetic field facilities to study quantum well heterojunction (QWH) laser operation in strong magnetic fields.

In contrast to the results of experiments on homojunction and double hetero-junction diodes in which the active region behaves as bulk crystal, the behavior of QWH diodes is governed by the qnasi-two-dimensional density of states, a result of the quantum size effect. In the earlier experiments, the emission energy corresponds to transitions from donor to acceptor states (homojunction diodes with a heavily compensated active layer) or to transi-tions from the conduction band to acceptor states (donble heterojunction diodes). For the QWH diodes of onr work, however, the transitions are from electron subbands of the conduction band to the heavy-hole or light-hole sub-bands of the valence band. The laser emission exhibits a linear shift to higher energy with increasing magnetic field B for B perpendicular to the plane of the QW; the energy is independent of B for B parallel to the plane of the QW. Simultaneously, the threshold current for lasing with B perpendicular to the quantum-well layers is reduced, while it is nnaffected with B parallel to the layers. The reduction of the threshold current is a manifestation of the further quantization of the 2-D electron gas by the magnetic field. These observations provide direct experimental proof that the electron gas is quasi-two-dimensional nnder lasing conditions.

5. THIN FILM PHYSICS*

Faculty and Senior Staff

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                      M. A. Ray

5.1 Semiconductor Crystal Growth from the Vapor Phase: Ion-Surface, Plasma, and Laser Stimulated Reactions

We are studying energetic particle-surface interactions and stimulated gas phase reactions which control the nucleation and growth kinetics, chemistry, and physical properties of compound and alloy semiconductors grown from the vapor phase by UHV ion beam sputtering, plasma-assisted chemical vapor deposition, accelerated beam MBE, and laser-induced chemical vapor deposition. The common feature of these techniques is that crystal growth proceeds under non-equilibrium thermodynamic conditions through the production of highly reactive gas phase species: excited atoms, metastables, radicals, and ions. Such species transfer energy to the growth surface upon condensation, thereby altering the surface reactivity as well as adsorption and adatom diffusion kinetics; allowing film growth at lower temperatures, a wider range in controlling doping concentrations and tailoring film properties, and the growth of unique metastable materials. This work is being pursued from both an analytical and an experimental point of view to establish a detailed understanding of fundamental film growth mechanisms. We have recently published two invited review papers in this area. Results from this research have a wide range of applications in addition to crystal growth, including the active

research fields of reactive ion etching, ion beam lithography, microchemical analysis, plasma chemistry, and laser-materials interactions.

5.2 Ion/Surface Interactions

We have developed general models for predicting elemental incorporation probabilities and depth distributions of both thermal and accelerated species incident upon growing film surfaces during vapor phase deposition. Trapping (low energy implantation), scattering, re-evaporation, and preferential sputtering are accounted for. More recently we have added terms for collisional mixing and segregation of dopants. As discussed briefly below, the use of these models in analyzing experimental data not only leads to a more detailed understanding of film growth processes but also gives predictive capability in designing new experiments or considering the growth of new materials.

5.2.1 Growth Kinetics

Ion/surface interaction effects have been found to greatly affect the growth kinetics of sputter deposited single crystal GaAs. Experiments were carried out on (100) GaAs substrates as a function of deposition rate R, growth temperature T_s, incident As/Ga flux ratio J_{As}/J_{Ga}, and ion acceleration voltage V_s. Atomic Ga and As beams were obtained by sputtering from a single crystal undoped GaAs wafer while the simultaneous evaporation of arsenic from an effusion cell provided an As_4 overpressure. The film growth rate R was found to depend not only on the Ga flux, as in thermal evaporation, but also on the ratio of the incident arsenic to gallium fluxes and the film growth temperature. These additional dependences are related to the effect of the steady state As surface coverage Θ_{As} on the average Ga atom surface binding energy $\langle U_{Ga} \rangle$ and hence on the secondary sputtering yield due to induced low energy ion bombardment of the growing film. A model was developed to relate Θ_{As} to film growth parameters and thus to allow predictions of R which exhibited good agreement with experimental results. From this analysis, $\langle U_{Ga} \rangle$ was found to increase from 3.5 to 4.9 eV/atom as Θ_{As} was increased from 0.2 to 0.6, corresponding to Ga-stabilized and As-stabilized surfaces, respectively.

5.2.2 Elemental Incorporation Probabilities and Depth Distributions

Achievable doping concentrations of many important dopants in MBE films grown under practical conditions have been limited by low thermodynamic sticking probabilities. However, acceleration of these dopants to relatively low energies, a few hundred eV, has been shown by several investigators to result in enhancements in net incorporation probabilities in GaAs and Si of up to eight orders of magnitude. We reported similar effects for S doping of sputter deposited GaAs last year.

We have extended our general model for calculating incorporation probabilities and depth distributions of thermal dopants in single crystal films grown from the vapor phase (see results reported last year for Sn segregation in GaAs) to account for accelerated dopants. We have calculated the incorporation probability σ of As in MBE grown (100) Si as a function of acceleration energy E_i and film growth temperature T_s. Terms accounting for the thermal sticking probability, low energy implantation, diffusion, surface segregation, desorption, and preferential sputtering were included in the calculation. The results agreed very well with experimental data from Ota at Bell Laboratories who measured σ_{As} for $400 < E_i < 800$ eV and $600 < T_s < 1100^{\circ}$C. In addition we were able to calculate variations in As depth distributions in the near-surface region as a function of growth conditions. This latter information, not available experimentally, is very useful as a guide to crystal growers for device fabrication.

5.2.3 Growth of Single Crystal Metastable Semiconductors

As reported last year, we are carrying out the first detailed study of the growth and physical properties of new single crystal metastable semiconductors. The key feature in stabilizing the growth of these materials is the controlled use of low energy ion bombardment during deposition to modify elemental sticking probabilities and adatom diffusivities and to promote collisional mixing. The research described in sections 5.1 through 5.2.2 above has provided a much better understanding of the growth of these unique materials. During the past year we have concentrated our efforts on the study of $(GaAs)_{1-x}Ge_x$ because of the importance of the end-members, the interest in Ge/GaAs heterostructures, and the fact that it is representative of a new subclass of potentially important alloys, $(III-V)_{1-x}(IV_2)_x$.

Epitaxial metastable $(GaAs)_{1-x}Ge_x$ alloys with compositions ranging from x = 0 to x = 1 have been grown on (100) GaAs substrates by ion beam sputtering in an ultrahigh vacuum system. Electron channeling, double crystal X-ray diffractometry, and X-ray topography analyses indicate that the films are of very high crystalline perfection. Either n-type or p-type conduction, with n and p varying over several orders of magnitude, could be obtained by varying the film composition, the growth temperature, and the As overpressure during deposition. The equilibrium GaAs-Ge pseudobinary phase diagram has been determined by differential thermal analysis to be a simple eutectic with an invariant temperature and composition of $880^{\circ}C$ and 18 mole % GaAs.

Optical absorption measurements show an unusually large negative bowing in the direct Γ-point bandgap E_o as a function of film composition. E_o decreases rapidly with increasing x on the GaAs rich side but varies much more slowly with x on the Ge-rich side. The results are not well described by the conventional virtual crystal model which would treat $(GaAs)_{1-x}(Ge_2)_x$ as a compound of average cations $Ga_{1-x}Ge_x$ and average anions $As_{1-x}Ge_x$ and would predict nearly parabolic bowing. In collaboration with Professor Jack Dow (Physics, UIUC), a model including a zincblende to diamond structure order-disorder phase transition was developed to explain the results. An order parameter was calculated and used in an empirical sp^3s^* tight binding modified virtual-crystal approximation to the band structure. The model explains the general features observed.

The above described model also has also been used to calculate the valence band densities of states in the alloys as well as the structure of the higher lying conduction bands vs x. We are presently checking these calculations using x-ray photoelectron spectroscopy (XPS) in collaboration with Dr. Tery Barr at UOP and spectroscopic ellispsometry in collaboration with Professor Paul Raccah (Physics, UICC). The initial XPS results show agreement between measured and calculated s and sp peak splitting.

We have very recently carried out preliminary crystal growth experiments in new metastable $(III-V)_{1-x}(IV_2)_x$ systems as well as $Ge_{1-x}Sn_x$.

5.2.4 Reactive Ion Etching of GaAs

The first detailed study of the reactive ion etching (RIE) of GaAs has been carried out by our group. We investigated the RIE of (100) GaAs in pure CCl_2F_2 and CF_4 discharges as well as in mixtures of Ar and CCl_4, CCl_2F_2, or CF_4. Anisotropic etching with removal rates, R, of up to 800 nm/min have been obtained in reactive discharges operated at a pressure of 40 mTorr and a target voltage of -3kV. The physical sputtering rate in pure Ar discharges operated under the same conditions was only 40 nm/min. A combination of in-situ optical emission and absorption spectroscopies have been used to show that in both pure and dilute (up to 90 mole % Ar) halocarbon discharges, physical sputtering of atomic Ga and As is not a primary etching mechanism for GaAs, although ion bombardment does play a critical role in the overall process. Transient glow discharge optical spectroscopy measurements demonstrated that while R increased with increasing Cl/F ratios in the etch gas, the steady state carbon concentration at the GaAs surface also increased indicating that carbon accumulation is not the rate limiting step to etching. Rather, the rate limitation is provided by the desorption kinetics of gallium halides which we believe are ejected primarily (except in pure CCl_4) through ion-assisted processes as the reduced radicals GaF_x and/or $GaCl_x$ (x=1 or 2).

A phenomenological model has been developed which provides a qualitative description of the etching behavior of GaAs in mixed halocarbon/inert gas discharges. The model, in combination with measurements of the etching rate, optical emission and absorption intensities, and relative carbon surface coverages, also allows a determination of rate limiting mechanisms. A further result of the model is that an estimate can be made of the efficiency of utilization of adsorbed halide species in the overall etching process.

Finally, the fact that ion/surface interactions are essential for etching in fluorine-containing discharges has significant technological implications. Ion bombardment not only provides directional etching, but the formation of GaF_3 on the side walls (which receive relatively little ion irradiation) acts as a natural etch stop and sidewall taper can be adjusted by changing the F/Cl ratio in the discharge.

5.3 Laser Stimulated Chemical Vapor Deposition[*]

In collaboration with Prof. Eden of the Electrical Engineering Dept. at UIUC, we have grown the first polycrystalline Si and Ge films on amorphous SiO_2 substrates (average substrate temperatures < $120^{\circ}C$) by the photodissociation of SiH_4/N_2 or GeH_4/He mixtures, respectively, using pulsed ArF (193 nm) and KrF (248 nm) excimer lasers. For both Si and Ge, the film growth rate exhibited a strong dependence on laser wavelength and beam intensity I where 1 $\lesssim I \lesssim 10$ MW $- cm^{-2}$. Optical absorption and emission experiments were carried out as a function of photon fluence and position to determine the gas phase reaction paths, rate limiting steps, and the excitation state of radicals produced. Surface reactions are being studied by splitting off a fraction of the pump beam passing parallel to the substrate and using it to probe the surface.

Single crystal Ge and Si films have now been grown in our new ultra-high vacuum, load-locked LCVD system. In addition, we have recently carried out the first experiments using laser induced plasmas in UHV as the source for primary ion deposition of single crystals. This technique offers real promise for low temperature growth with good control of dopant incorporation.

6.   ACOUSTIC CHARGE TRANSPORT*

Faculty and Senior Staff

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M. Needham

6.1 Objective

A new type of signal processing device which provides the monolithic realization of high speed signal delay and distributed signal sensing functions in GaAs has been demonstrated [6.2]. Electron transport is accomplished in a buried channel epitaxial GaAs structure using the traveling wave electric field of a Surface Acoustic Wave (SAW) generated directly in the GaAs.   Sense electrodes located on the surface of the device provide non-destructive sensing of the signal charge packets as they propagate through the channel.   Very powerful monolithic signal processors will be feasible on GaAs because the conventional GaAs I.C. technology can provide gain and control while the Acoustic Charge Transport (ACT) device provides the compact, low power, fast memory required for signal processing.

The objectives of this research are to: 1) investigate the charge injection, transport and detection processes in the ACT device so that the fundamentals of device operation may be well understood, and 2) study the material and device structure properties which influence the operation of the ACT device.

6.2 Acoustic Reflection Control in GaAs

A technique for controlling the Surface Acoustic Wave reflectivity of metallic electrodes in GaAs has been demonstrated [6.1]. The principle of reflection control is based on a layered bimetal electrode geometry. In general, the bimetal approach permits an adjustment of electrode reflectivity from zero to some maximum value determined by the electrode height and the properties of the metals. The bimetal technique is useful for optimizing the SAW propagation characteristics of metallized surfaces in GaAs microwave acoustic devices.

6.3 Acoustic Charge Transport Theory

A theory is developed which describes the fundamental charge transfer characteristics of basic buried channel GaAs structures which are illuminated by large amplitude Surface Acoustic Waves. Simple closed form expressions are obtained for packet charge density and boundary shape in terms of the channel parameters. It is shown that four sets of numerically generated and normalized curves are sufficient for the determination of the transport characteristics of a wide range of channel potential geometries. The dependence of diffusion induced transfer inefficiency on charge load and wave potential is investigated. The results indicate that high speed acoustic charge transport is capable of supporting typical buried channel charge loads at very high transfer efficiency.

6.4 Experimental Performance of the Acoustic Charge Transport Device

First generation ACT devices were studied and the primary sources of operational limitations in these devices have been identified [6.2,6.3]. The performance of second generation ACT devices is enhanced by design improvements which provide precise channel definition and charge injection structures. High speed electron transport has been observed in second generation devices with transfer efficiencies exceeding 0.996 per transfer, and signal bandwidths of 60 MHz. Possible sources of transfer inefficiency in the ACT device have been studied and it is concluded that a significant improvement in transport performance may be obtained by further device refinement. Experimental measurements of transport charge capacity are in good agreement with the transport theory described previously. The onset of diffusion limited

transfer efficiency, measured at large charge loads, is also in good agreement with the theory.

6.5 Non-destructive Charge Sensing in the ACT Device

A simple lumped circuit model has been developed to describe non-destructive charge sensing by floating electrodes in the ACT device. The basic operation of non-destructive charge sensing has been demonstrated experimentally using an 8-tap ACT tapped delay line. Experimental measurements of detection sensitivity are in good agreement with the simple model. Two important characteristics of floating electrode detection have become evident from this work: 1) Nearly perfect non-destructive behavior may be obtained if the induced sense electrode voltage is much less than the SAW channel potential, and 2) The energy dissipated in the sense load is sourced by the acoustic wave, not the signal charge [6.3].

The nearly perfect sense operation obtained from the floating electrode structure should permit large time-bandwidth product signal processing operations since, in principle, thousands of taps may be implemented in the ACT device without signal degradation.

7. SURFACE STUDIES

Faculty and Senior Staff

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7.1 Studies on the Silicon-Metal Interface*

Much of our work has been aimed at establishing the atomic events in the formation of silicon overlayers on metals. As part of this effort, we have examined the structure of silicon layers on W(110), using the field ion microscope to gain a view of the surface on the atomic level. Our previous studies showed that on this plane, silicon formed very open layers with strings of atoms in the [1$\bar{1}$0] direction separated by three spacings along [100]. It has now been possible to demonstrate that the structure of the overlayers is highly dependent upon the concentration. This is apparent in the sequence of field ion microscope shots in Fig. 7.1. On depositing a monolayer of silicon and equilibrating it at 340 K, the layer appears densely packed. After removing atoms from it by field evaporation and reequilibrating, the loosely packed structure previously observed is restored. If the number of silicon atoms is further reduced, this layer disorders and disintegrates into a tangle of chains.

Measurements have also been started on silicon on the (211) plane of tungsten, which is made up of deep channels. When a fraction of a monolayer of silicon is deposited on this plane and warmed to room temperature, as in Fig. 7.2, the silicon atoms appear to occupy every other site in the surface
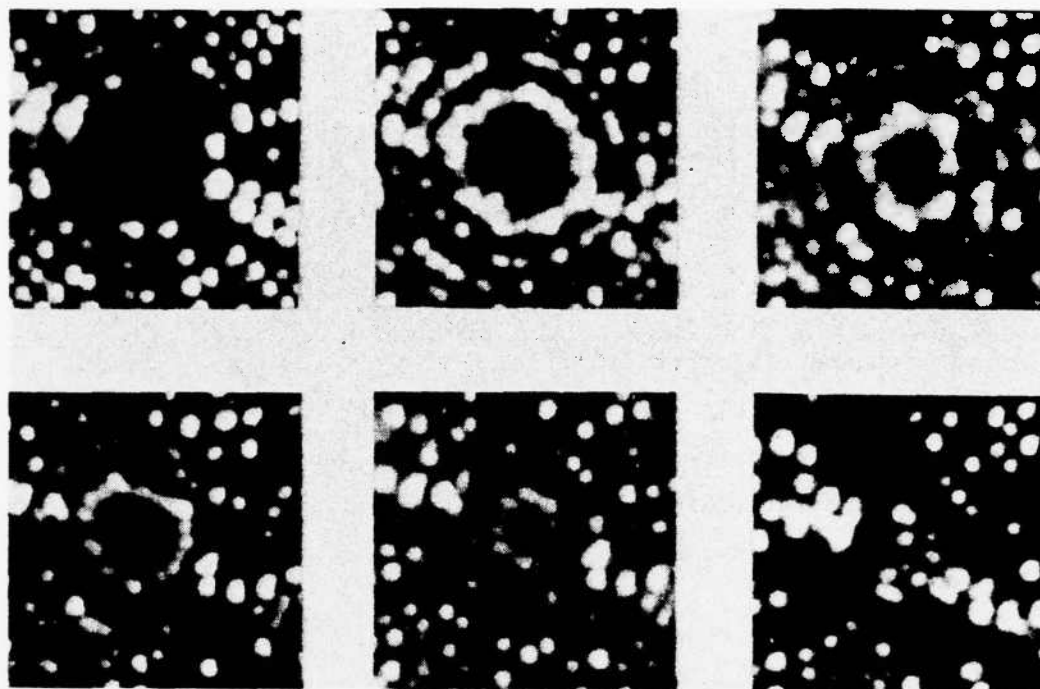
Fig. 7.1 Transformation of silicon layers on W(110).

Top Left: Clean tungsten surface. Center: Dense silicon monolayer obtained by equilibration at $T_E = 340$ K. Right: Number of silicon atoms has been reduced by field evaporation.

Bottom Left: Same layer, but now loosely packed after reequilibrating at 340 K. Center: Additional silicon atoms have been field evaporated. Right: Reequilibrating this layer brings about disordering.

Fig. 7.2   Silicon monolayer on W(211).

      Left: W(211) plane with a small number of silicon atoms on it.
           Note the horizontal rows of the substrate.

      Right: Rectangular array, formed on equilibrating half a monolayer
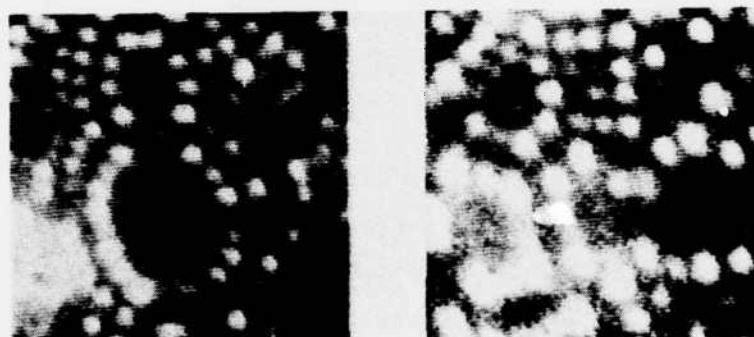   of silicon.

Fig. 7.3   Silicon multilayers on W(211).

      Left: Bare (211) plane of tungsten.

      Right: Surface after deposition of more than 10 layers, and equili-
           brating at 1100 K. Vertical ridges are now evident at right
           angles to the horizontal rows of the tungsten substrate.

END
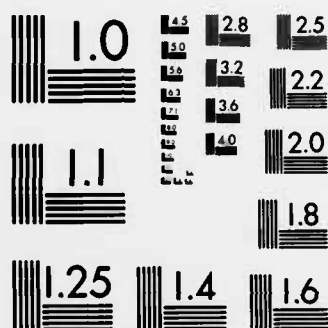
channels, forming a structure with a rectangular unit cell. On adding further
silicon, as for example in Fig. 6, ridges appear at right angles to the direc-
tion of the close-packed rows of the underlying tungsten. After several
layers of silicon have been deposited on the surface, the spacing between
these ridges seems to enlarge and the structure engulfs additional planes as
well. These layers are nicely ordered, as has been confirmed on stripping
them away atom by atom using pulsed field evaporation. Close to the tungsten
interface the image of the layers changes to the previously observed rectangu-
lar arrangement, until finally the silicon is removed and a well-ordered
tungsten surface is left behind. It appears that the interface between sili-
con and tungsten, on this plane at last, is sharp on the atomic level and all
layers are well-ordered.

As part of the overall effort these atomic studies will be complemented
by more macroscopic observations on large-scale single crystals. Eventually,
this should provide a link between the results of the very detailed measure-
ments on silicon on metals in the field ion microscope and more traditional
studies, using low energy electron diffraction and Auger techniques. In order
to measure transport in an overlayer on a large-scale single crystal, a spa-
tially localized deposit is first created. Studies of the spreading out of
this deposit at more elevated temperatures then can provide detailed informa-
tion about surface diffusivities. To implement such studies, we have assem-
bled a computer controlled system, a schematic of which is shown in Fig. 7.4.
With this system the sample can be moved to obtain a spatial scan of the sur-
face concentration using Auger spectroscopy. The rapid recording and storage
of these spectra on the computer make it feasible to complete several concen-
tration profiles before significant contamination of the surface can occur.

The diffusivities must then be deduced from these concentration profiles,
and that is not a standard problem. In the past we have shown that given
several profiles, it is possible to obtain enough information about both the
time and space derivatives of the concentration to deduce the diffusivity,
even when it is dependent upon the concentration. However, in order to have
spreading over a large enough distance, it is usually necessary to heat the
surface to a temperature at which not just diffusion, but also evaporation may
occur. The problem of disentangling the diffusivity under these circumstances
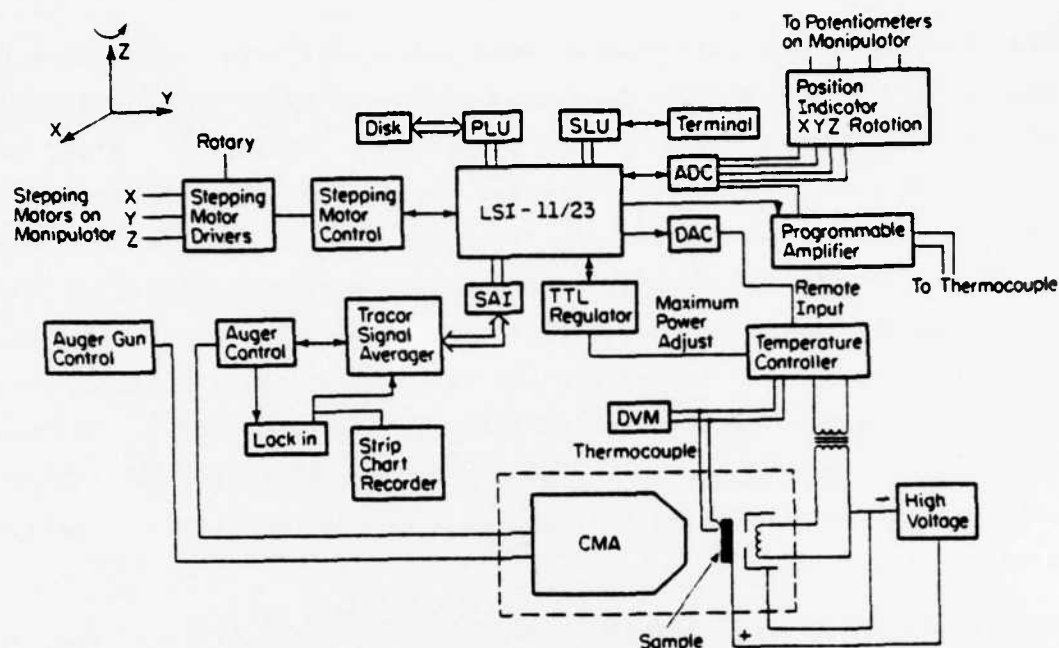is more difficult. Nevertheless, as is apparent from Fig. 7.5, we have

7. SURFACE STUDIES

Fig. 7.4   Computer control system for diffnsivity   stndies   using   cylindrical
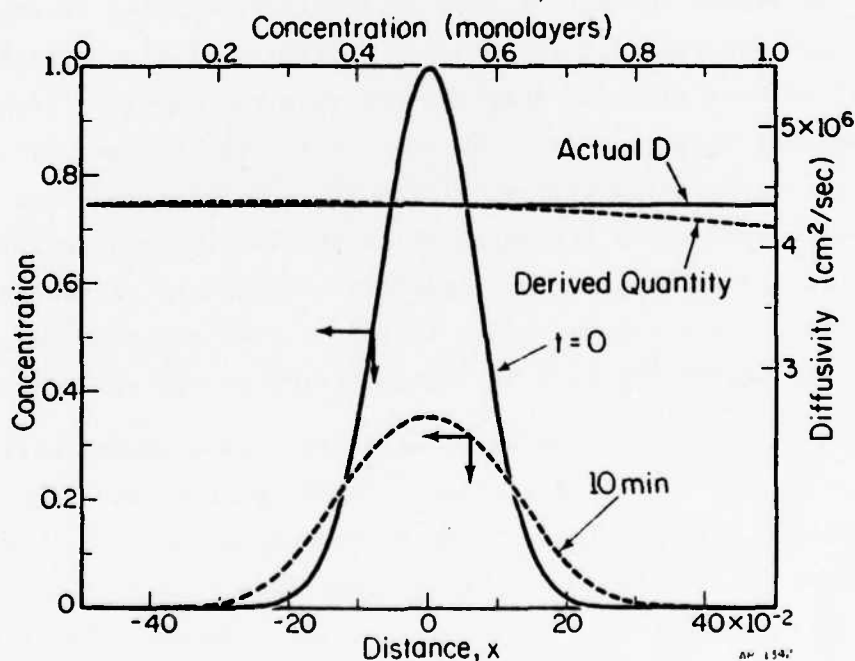mirror Anger analyzer.

Fig. 7.5   Concentration profile after both evaporation   and   diffusion.   Eva-
poration   rate   =   .011 n^2exp-(80-5c) x 10^3/RT.   Dashed curve shows
diffusivity derived from profile   after   10   min.   eqnilibration   at
1100 K.   c = concentration in monolayers.

devised methods which are capable of yielding reliable values of the dif-
fusivity (if it is independent of concentration), even when there is competi-
tion from evaporation. We expect these techniques to provide an interesting
comparison with the more detailed studies in the field ion microscope.

7.2 Atomic Exploration of Crystal Growth and Reactivity*

The interaction of metal atoms with lattice steps is important in under-
standing the growth of crystals from the vapor. Nevertheless, no detailed
information is available about such interactions on metals. Recently we have
for the first time been able to obtain quantitative data on atomic binding in
the vicinity of a step by taking advantage of the field ion microscope's abil-
ity to image individual atoms. The idea of the experiments is simple. In an
equilibrium system the probability of finding an atom at a site i as against
some reference position O is

$$P_i/P_0 = \exp(-F_i/kT) \ ,$$

where F_i is the free energy with the atom at i compared to its value at the
reference position. Measurements of the occupation probability at all the
atomic sites on W(211) planes of different size have been made. In Fig. 7.6
are displayed the results for a plane 12 sites across.

The behavior recorded here is quite different from expectations based on
traditional models. The tungsten atom is bound more strongly at the sites
closest to the edges, where the number of neighbors is smaller than at the
center. The edges also exert a significant effect upon binding over an appre-
ciable range, extending as far as four sites away from the end. These effects
turn out to be highly specific to the chemical identity of the adatom. With a
rhenium adatom, for example, the binding does not have its maximum value at
the ends, as with tungsten, and differences between center and end positions
are much smaller. It appears that atomic interactions are considerably more
complicated than envisioned in the past.

Concomitant with these measurements of surface phenomena on the atomic
level we have been drawing to a close our observations of surface diffusion
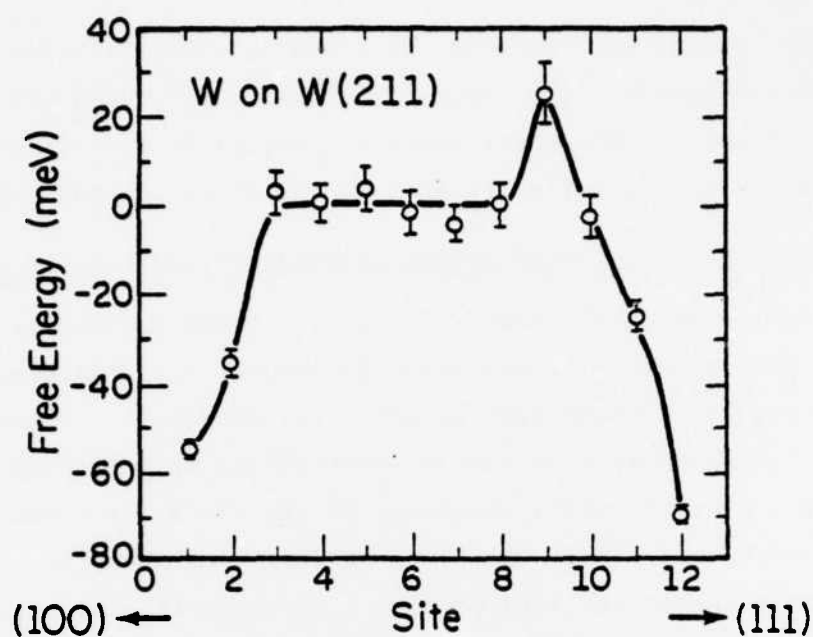
Fig. 7.6 Free energy for tungsten adatom at different sites of a [$\bar{1}$11] channel on W(211).
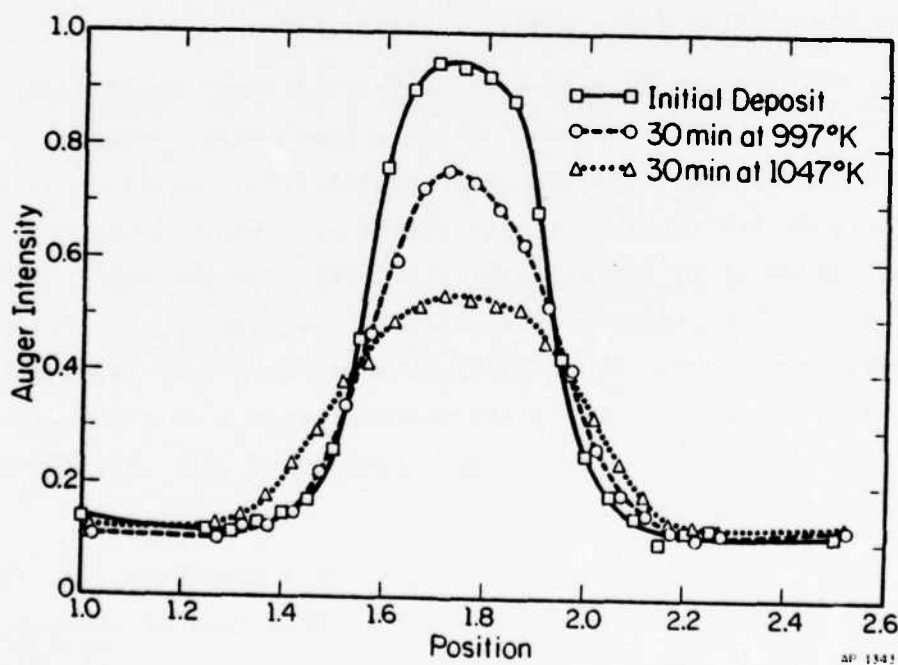

Fig. 7.7 Concentration profiles for nitrogen on W(100).

for gases on macroscopic crystal surfaces.   Work   has   been   concentrated   on
W(100), as on this plane diffusion of gases has not been detected in the past.
In a series of careful examinations, shown in Fig. 7.7,   spreading   out   of   a
nitrogen deposit has actually been detected.   On W(100) diffusion only occurs
at reasonably high temperatures, in the vicinity of 1000 K, where   evaporation
removes a significant portion of the gas layer, to a considerable extent mask-
ing the spreading of nitrogen over the surface.

Quantitative determination of the diffusion characteristics on this   sur-
face will be of particular interest, to establish the importance of structural
effects on the migration of gases.   To make such an attempt   reasonable,   good
data on evaporation will first have to be generated, and such an effort is now
underway.

8.   ELECTROMAGNETIC COMMUNICATION, RADIATION AND SCATTERING

Faculty

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Graduate Students

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8.1 Millimeter-wave Integrated Circuits*

During the last grant period we have concentrated on four major directions in the area of millimeter wave research. First, we have been carrying out extensive analytical, numerical and experimental studies of discontinuities in planar waveguides with a view to determining their equivalent circuits and using these equivalent circuits for the design of filters, couplers, etc. Various techniques including the spectral-iterative method, the mode matching method and the spectral-Galerkin method are being investigated for solving the discontinuity problems.   Conventional techniques for solving discontinuity problems in closed, empty waveguides are not suitable for the types of problems under consideration here and new approaches are being investigated.

Second, a new form of waveguide for millimeter waves, viz. the suspended H-guide, has been developed.   The guide appears to have many desirable features such as ease of fabrication, integrability, low loss and suitability for designing waveguide components such as couplers. It also shows good promise for leaky wave antenna designs. We plan to investigate the suspended H-guide antenna problem in the near future.

Third, we have been developing the components of a 220 GHz Imaging Radar. New concepts, including the use of overmoded waveguides, are being implemented in the design of waveguides as well as dielectric antennas that are compatible with the overmoded waveguides. We have built and tested various components of the system at 84 GHz and are planning to experimentally verify the design at 220 GHz during the following year.

Fourth, we have developed a new method of detecting and resolving multiple modes in an overmoded waveguide. The method has been extensively and successfully tested on the computer and will shortly be verified experimentally. When adequately proven, the technique should be very useful for investigating multimoded waveguides.

8.2 Electromagnetic Scattering and Radar Target Identification*

For the past year we have been investigating the application of the spectral-iterative and spectral-Galerkin techniques to the solution of a number of different types of scattering problems. These include conducting scatterers with and without edges, homogeneous, inhomogeneous and lossy and dielectric scatterers, conducting scatterers coated with resistive material, and single or multiple screen frequency selective surfaces, both of infinite and finite extent. The solutions to these problems are useful in the study of RCS of radar targets, target recognition, design of radomes and biomedical applications. We have placed particular emphasis on the analytical aspects of the spectral-iterative technique, especially from the point of view of determining the convergence properties of the iterative procedure. We have discovered the bounds of certain parameters, e.g., the sampling rate of the FFT and the material properties of the material for which convergence is guaranteed. We have also been attempting to develop a theoretical understanding of the divergence of the iteration procedure when such divergence occurs. In addition, we have recently developed a modification of the spectral-iterative technique, one that combines the spectral-domain formulation with an iteration procedure based on the conjugate gradient method. The method appears to be very powerful as it is able to handle large arbitrary-shaped

scatterers, be they perfect conductors or penetrable dielectric types. Furthermore, the convergence of the iteration procedure can be guaranteed and consequently the method is highly reliable. Extensive research into the scope and limitations of this new technique is currently underway. The results of the forward scattering problems are being coupled with the inverse algorithm we have developed in order to investigate the effect of systematically modifying a radar target with a view to reducing its RCS.

9. PLASMA PHYSICS*

Faculty and Senior Staff

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Graduate Student

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9.1 Statistical Properties of Plasma Turbulence

The objective of this research is to study the statistical properties of plasma turbulence. The system under investigation is the positive column of a dc-discharge in helium which is unstable with respect to the spontaneous excitation of ion acoustic waves. Electric field fluctuations of the turbulent wave field are picked up by a Langmuir probe and their probability distribution are measured by a fast sampling method. Close to onset the fluctuations are Gaussian. As the instability level increases the probability density becomes more and more non-Gaussian. The maximum deviation from Gaussian behavior is a function of the neutral helium pressure. At relatively high pressure ($p \approx 0.1-0.2$ Torr) it occurs at 1.2-1.5 times the onset current, whereas at low pressure ($p \approx 0.05$ Torr) the current of maximum non-Gaussian behavior can be as large as 10 times the onset current. At very high turbulence levels the fluctuations become again Gaussian.

Phase correlations between Fourier components resulting from wave-wave coupling terms are suspected to be the primary cause for the observed behavior; it has not been possible, however, to predict the probability distribution from assumed models of turbulence.

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10. RAREFIED GAS DYNAMICS AND COMPUTATIONAL GAS DYNAMICS

Faculty and Senior Staff

S. M. Yen

Graduate Students

R. Chamberlain   S. H. Lee

10.1 Rarefied Gas Dynamics

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 the Coordinated Science Laboratory [R1] to solve directly the Boltzmann equation and has been used by the Boltzmann group to solve the Boltzmann equation for several rarefied gas flow problems under a wide range of non-equilibrium and boundary conditions [R2-R7]. The solutions we have obtained yielded detailed microscopic and macroscopic non-equilibrium properties, most of which have never been treated and studied before. We have also studied numerical solutions of other kinetic equations and other numerical methods to solve rarefied gas flow problems, including the direct simulation technique.

Nonlinear evaporation-condensation problems are encountered in such diversified areas as upper atmosphere meteorology, the cooling of nuclear reactors, design of space experiments, petrochemical engineering, vacuum technology, and the interaction of high power laser radiation with metal surfaces. The treatment of these problems requires first the consideration of vapor kinetics problems characterized by the nonequilibrium vapor motion in a Knudsen layer at the interphase boundary. Under a joint research effort, we have successfully solved the evaporation problem [R8]. Studies have also been made for the condensation problem [R10,10.3]. The non-equilibrium vapor near a condensing surface differs from that near an evaporating surface and its behavior is more complex. Our Boltzmann solutions yield distinct non-equilibrium behavior in the Knudsen layer of condensing vapor. The non-

equilibrium behavior as well as the condensation rate as a function of pressure ratio was found to depend strongly on the substance parameter $\hat{\beta}$ which is proportional to the ratio of the latent heat and its liquid surface temperature. Figure 10.1 shows the Knudsen layer characteristics exhibited by the temperature profiles for the evaporation and condensation problem for two values of mass transfer parameters, $\hat{\beta} = 2.68$ and 10.21. (Evaporation Knudsen layer near $\hat{x} = 1$, and condensation Knudsen layer near $\hat{x} = 0$.) For the case of $\hat{\beta} = 2.68$, the temperature profile is nearly anti-symmetrical with the temperature at the mid-position ($\hat{x} = 1/2$) equal to the average value ($\hat{T} = 1/2$); therefore, the two Knudsen layers are similar in non-equilibrium behavior. For the case of $\hat{\beta} = 10.21$, the temperature profile is no longer anti-symmetrical. In fact, the evaporation Knudsen layer dominates the flow region. The condensation Knudsen layer is very small. The temperature at the mid-position is only slightly above that of the condensation interface.

10.2 Naval Hydrodynamics*

Free surface wave problems encountered in naval hydrodynamics are characterized by complexities in flow geometry, flow features and boundary conditions. These complexities have led to several computational difficulties: accurately accommodating the free surface geometry, satisfying the boundary condition uniformly over the free surface, creating the radiation boundary condition and implementing the boundary condition at the contact line of the free surface with the solid surface of a partially submerged body.

In the initial phase of our study, we have developed two time-dependent numerical schemes with Eulerian grid systems for solving steady and unsteady potential flows for nonlinear free surface problems. In one method [R12,R13], we use the finite element method to deal with the geometrical complexity and the free surface boundary condition of the nonlinear free surface problems. We have also developed an explicitly time-dependent finite difference scheme [R12,R14]. In both numerical schemes the computational domain is expanded downstream periodically during the computation as the disturbance on the free surface is propagated close to the downstream boundary. Therefore, the undisturbed condition is applied on the cut-off downstream boundary.
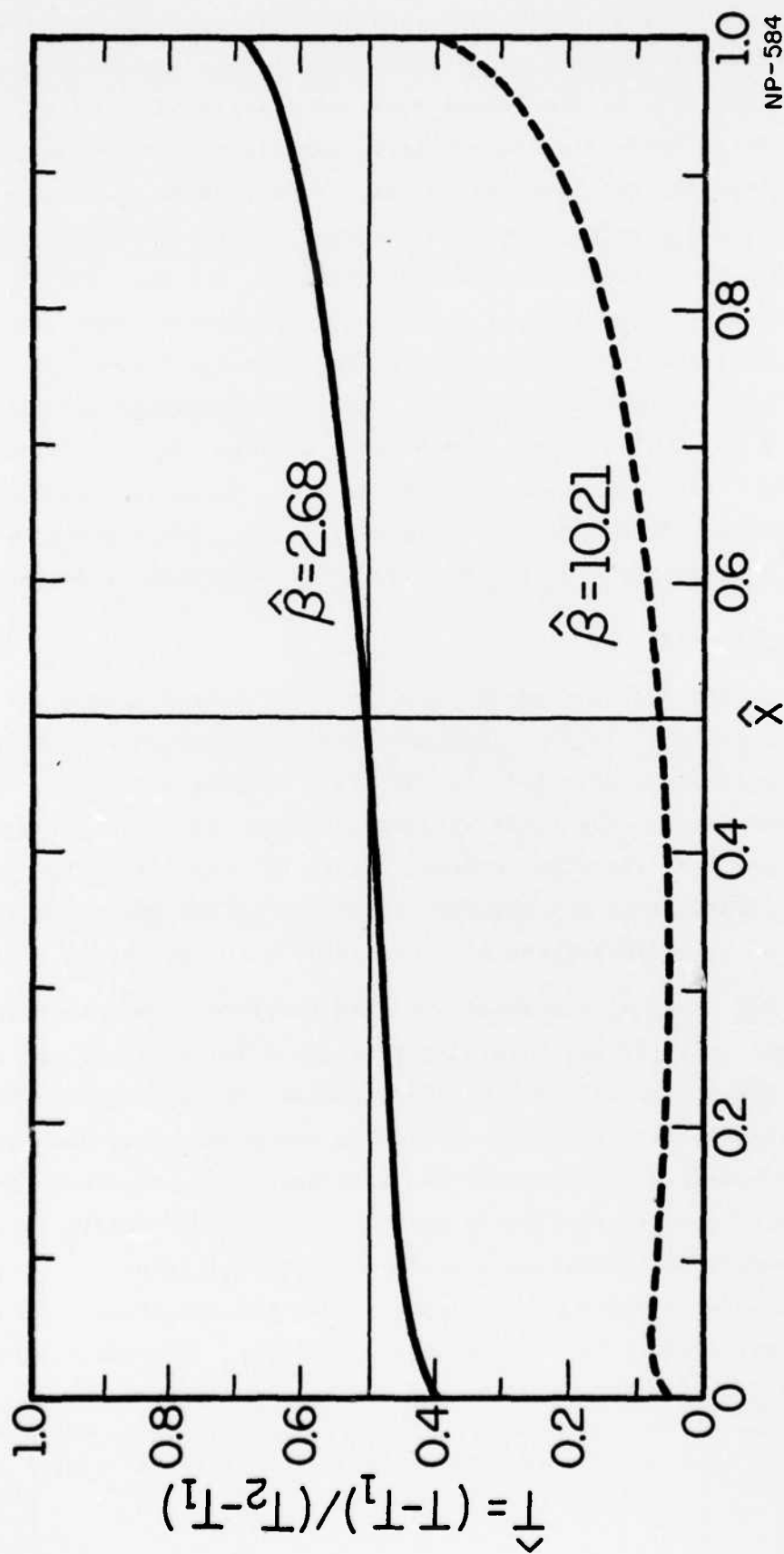

Fig. 10.1 Comparison of evaporation (near $\hat{x} = 1$) and condensation (near $\hat{x} = 0$) Knudsen layer characteristics exhibited by the temperature profile obtained from the Boltzmann solution for two substance parameters, $\hat{\beta} = 2.68$ and 10.21.

In order to obtain the longer time and steady state solutions, we use a fixed downstream boundary set close to the disturbance so that we can increase the computation efficiency by dealing with a small computational domain. The second phase of our study has been focused on the application of our numerical schemes to the nonlinear free surface problems with a fixed, small computational domain. We have used Orlanski's method [R15,R16] to implement the open boundary condition at the outflow boundary and damping in our time marching schemes to treat the high frequency errors that appear in the solution and inhibit accurate treatment of the open boundary condition. Transient and steady state solutions have been obtained for the pressure distribution and the accelerating strut problems [R17].

We are now in the third phase of our research. The objective of the study in this phase is to apply our method to the ship wave problem. We have chosen the hull of Wigley shape as our first problem. The numerical method we use has the following features:

(1) the mesh system accommodates both the free surface and the hull surface,

(2) the nonlinear free surface condition is satisfied accurately, and

(3) the computation efficiency for the field calculation is increased by using the conjugate gradient method.

We have been focusing our attention on the accurate treatment of hull surface conditions. The abrupt change in surface slope near the bow and stern causes high frequency oscillations which destroy the solution. These oscillations could not be removed by filtering only $2\Delta x$ waves since wave lengths longer than $2\Delta x$ are also being excited. The remedy found was to smooth the body at the bow and stern so that the slope changes continuously from points on the body to points off of the body. The treatment of hull surface condition leads to other computational difficulties that concern major aspects of the numerical method, namely, the implementation of nonlinear free surfce conditions, the design of an appropriate mesh system to accommodate the flow geometry, and finding an accurate and efficient method to solve the elliptic equation for the flow field. We have studied the application of the conjugate gradient method to obtain the potential flow solution of the ship wave problem. The method is being applied to the linear Wigley problem in which the implementation of the free surface and hull conditions are simplified. Figure
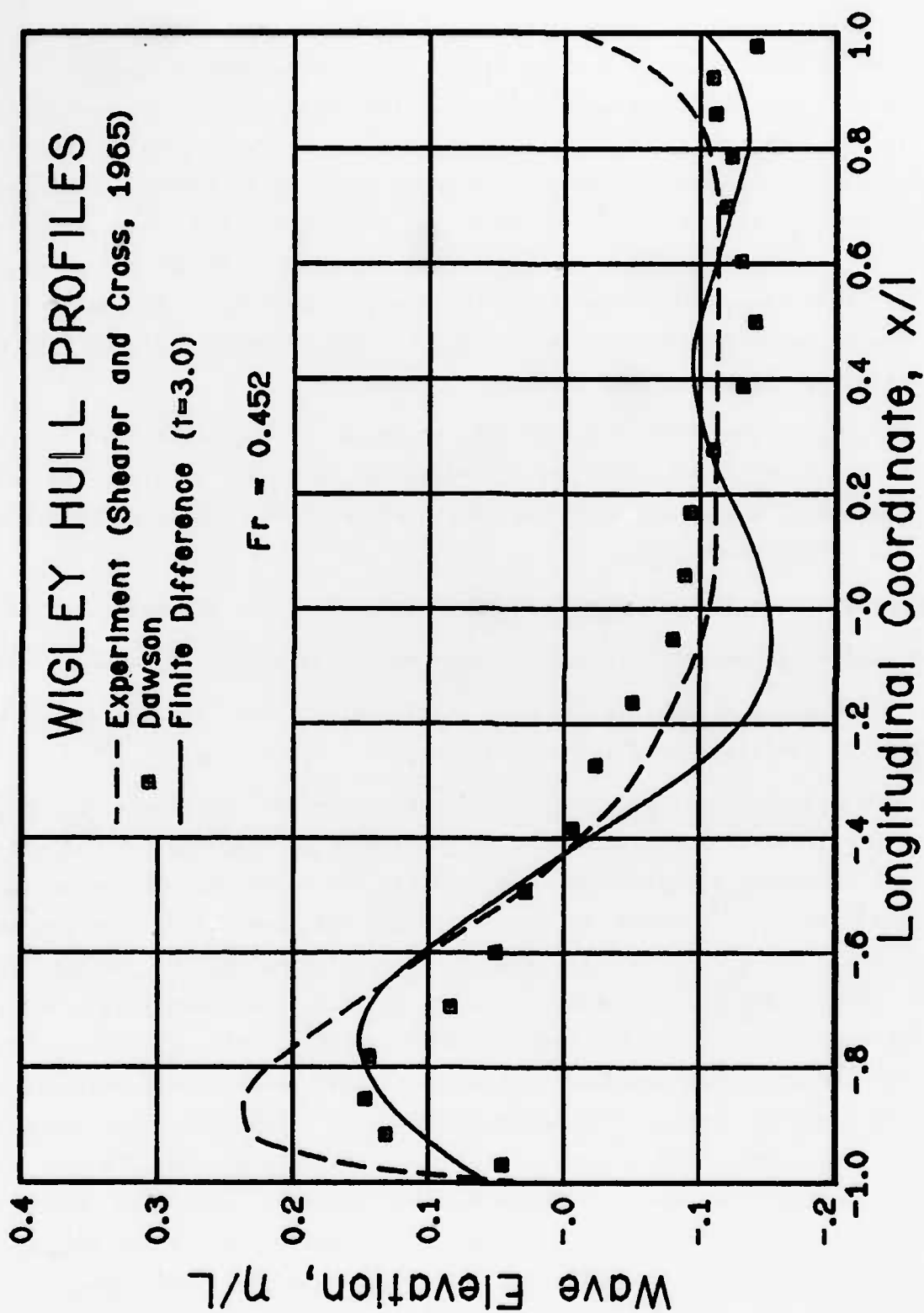
Fig. 10.2 Comparison of Wigley hull - wave profiles for Fr = 0.452.

10.2 shows the comparison of our calculation of the surface wave profile for the linear case for Fr = 0.452 with an experiment [R18] and a linear calculation by Dawson [R19].

10.3 Aerodynamics

The objective of this research program is to use a single method to solve directly the Euler and the Navier-Stokes equations in the entire compressible flow regime: subsonic, transonic and supersonic. Our initial effort is to study the numerical solution of compressible flow over an axi-symmetric tri-conic body. We used the implicit factored scheme which was developed by Warming and Beam [R20] to solve the Navier-Stokes equation. We developed and used a mesh generation system designed for the triconic body. We studied the implementation of surface boundary conditions and the effect of damping on the numerical solution.

We have obtained Euler solutions for M_∞ = 0.5 to 2.75 and Navier-Stokes solutions for M_∞ = 0.5 (Re = 1000, 10,000 and 100,000), M_∞ = 0.8 (Re = 16,000) and M_∞ = 0.95 (Re = 190,000). The mesh size is 31 x 65. The mesh system is refined near the solid surface for the viscous calculation and in the regions with shock waves for both the inviscid and viscous flow calculations. Results obtained exhibit detailed flow field characteristics [10.1]. The surface pressure distributions are in agreement with experiments.

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11. COMPUTER SYSTEMS

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11.1 A Simulation Model for Physical Failures in MOS VLSI Circuits*

Detailed studies of the effects of physical failures on MOS VHSIC cir-
cuits at the circuit level have revealed the existence of abnormal failure
modes. Unfortunately, such studies are not practical for complex VLSI
modules. It is therefore desirable to have logical models for describing the
behavior of MOS circuits under failures. Classical switching theory fails to
account for some key structural and logical properties of MOS circuits, such
as the bidirectional transmission gate. Switch-level simulation models have

emerged as efficient logic design tools for MOS circuits. However, these models cannot be used to describe the behavior of MOS circuits under physical failures typically observed in the field.

We have developed a technique to analyze the logical effects of physical failures in MOS circuits with the help of a multi-valued algebra. The advantage of our method over existing ones is that it is directly based on physical failures and not on any simplified fault models. The algebra was based on the results of extensive simulations using the SPICE circuit simulation program. Using the algebra, we have implemented an MOS logic simulator in PASCAL under VAX-11/UNIX. To improve the simulator performance, the MOS circuit is partitioned into groups of transistors that are connected in a certain manner. Also, a static labeling algorithm has been developed, which determines the order in which various groups are solved. This ensures a single pass simulation algorithm for combinational circuits. For sequential circuits the feedback loops are identified, and the algorithm enforces that the groups in the feedback loops are solved before groups that fan out from the loop are simulated. This results in a considerable amount of speedup since the time for obtaining a solution increases linearly with the number of devices in the circuit. The partitioning and labeling times increase as the square of the number of devices in the worst case. However, since these are static overheads, once they are completed for a circuit, they need not be repeated for multiple simulations of the circuit under various failures. The results of our simulator have been verified by circuit-level simulations on some typical MOS circuits such as programmable logic arrays, decoders, registers, and random combinational logic. Using the simulator based on our algebra, we have developed some reasonably accurate functional-level fault models for VLSI modules.

11.2 Testing of Complex Circuits*

Our functional level test generation approach has been successfully applied to testing of a variety of structures.

A canonical set of test patterns for lookahead adders with the regularity for easy on-chip generation has been found for arbitrarily structured carry-lookahead adders. Approximately $2N^2$ test patterns are required to test any N bit carry-lookahead adder for physical failures at any computational node including single and multiple stuck-at faults, and bridging between outputs. Additionally, it was found that nodes implemented with AND-OR-INVERT cells or PLA's are tested for a wider variety of failures related to their particular structure. The lookahead cells implemented with AND-OR-INVERT structure may fail to any function that is all positive or negative in its input variables. If the lookahead cells are implemented using PLA's, the test will detect any failure which does not increase the number of product lines. The test sequence can be generated on-chip using one of two methods. The first method involves the construction of two N bit shift registers, two N bit latches, and $O(N)$ gates to produce the test patterns and result vectors. The second method uses the bit-wise functions of the ALU to generate a test sequence for the adder section of the ALU. This method reduces the extra hardware to a small test pattern/result vector generator program in ROM.

We have found a new and systematic method to generate tests for microprocessors. A functional level model for the microprocessor is used and it is represented by a reduced graph. A new and comprehensive model of the instruction execution process is developed. Various types of faults are analyzed and it is shown that with the use of appropriate code words all faults can be classified into three types. This gives rise to a systematic procedure to generate tests which is independent of the microprocessor implementation details. Tests are given to detect faults in any microprocessor, first for the Read Register instructions, and then for the remaining instructions. These tests can be executed by the microprocessor in a self-test mode, thus dispensing with the need for an external tester.

A new technique for testing MOS circuits under realistic physical failures has also been found. It was found that physical failures cause logic behavior which cannot be modeled by a "stuck-at" model; nevertheless, most of these failures were shown to be detectable by stuck-at tests. Cases were shown for which test generation based on MOS circuit structure produces a much simpler test set than one based on the gate level descriptions.

11.3 Concurrent Error Detection in Information Transfer and Storage Modules*

We have developed functional fault and error models for typical physical failures in various forms of information transfer and storage modules implemented with MOS technology. Based on these models, we have developed comprehensive methods for detecting the errors caused by physical failures. The error detection is designed to take place concurrently with the normal use of the modules. Models and methods of error detection have been proposed for a variety of classical memories and interconnection networks.

The proposed methods of error detection for memories have particular promise for the large number of read-only memories currently utilized in many VLSI digital systems. The development of the functional fault models for these memory modules has shown that all of the errors caused by typical physical failures in fine-geometry and very dense MOS integrated circuits can be detected by a systematic encoding over the address and stored data with a unidirectional error-detecting code. This scheme detects errors caused by a modeled physical failure in any part of the memory, which includes the address decoders and multiplexers, and not merely in the memory cells as with classical methods of error detection.

Similar methods of encoding the address and data have been shown to be applicable to a variety of interconnection network topologies and control structures. When these networks are implemented with 2x2 crossbar switches, the schemes guarantee the detection of any errors caused by a physical failure in the switches, the interconnecting links, or the network control. These techniques are particularly applicable to environments in which the detection of errors caused by transient or intermittent faults must be guaranteed.

11.4 Design of Fault-Tolerant Adders and Multipliers*

We have developed a new method of achieving fault-tolerance in arithmetic units using redundancy in time. For error correction in an adder, the adder unit is physically divided into three identical sub-units, and three computation steps are performed with the same set of operands; however, each computa-

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tion step is performed on a different configuration of the adder. A sequence comprising the number of the segments, showing disagreement in result, has been devised to distinctly locate the faulty unit. Two different schemes for subsequent extraction of the correct result were developed. For error correction in a multiplier, each of the two operands is split into two equal parts and four multipliers with appropriate number of bits generate the partial products. These methods are able to correct all functional errors in the adder/multiplier from faults confined to one of those sub-units. This fault model is more general than the traditional stuck-at-fault model and thus is more appropriate for VLSI circuits.

11.5 Transient Fault Analysis for Retry Techniques*

We have developed a few fundamental results related to the problem of system recovery from transient faults using retry techniques. A probabilistic model for the activity of faulty periods was developed and a fault analysis was carried out to decide the optimum length of the retry period, T. Distribution functions have been derived to represent the case of false alert, where a transient fault is flagged as permanent, and the case of a miss, where too many faults coexist thus overcoming the checker's capability to detect them. These derivations were compared with the results of a simulation program representing the model used. The agreement between the analysis and simulation was found to be quite good.

11.6 Fault Tolerant Bus Communication Protocols for Computer Systems*

Bus systems form the communication medium for computers, and a great deal of effort has been devoted to detecting errors which occur as information is transferred from one module to another. We have studied the problem of correctly transferring information in the presence of faults. The lines of a bus are grouped together into two classes: synchronous address and data lines, and the control lines which govern the action of the synchronous lines.

The fault model which is assumed for the synchronous lines includes not only the classical stuck-at fault, but also bridging faults and transient faults. Algorithms were developed which use time redundancy to guarantee

correct transfer of information in the presense of a single fault. The algorithms require either one or two retrys, depending on the type of fault.

The knowledge of the behavior of the control lines permits dual-rail control signals to be used to guarantee continued operation in the presense of single faults. The expected levels of the signals as the protocol sequences through its actions allow identification of lines which are stuck at an incorrect value; the incorrect line can then be ignored as the module continues to function. Several algorithms were developed to convert state machines for single-rail control signals to state machines which accommodate dual-rail signals. The system cost associated with this technique consists of the additional lines needed for dual-rail control signals and for implementing the time redundant transfer algorithms, and the additional hardware needed to implement the algorithms. For a standard bus this means about a 40% increase in the number of lines and approximately doubling the hardware dedicated to the bus control function.

11.7 Availability and Fault Tolerance in Distributed Systems*

In a distributed computing system made up of different types of processors, each processor in the system may have different performance and reliability characteristics. In order to take advantage of this diversity of processing power, a modular distributed program should have its modules assigned in such a way that the applicable system performance index, such as execution time or cost, is optimized. We have found an algorithm for making an optimal module to processor assignment for a given performance criterion. A computational model is used to characterize distributed programs, consisting of tasks and an operational precedence relationship. This model allows us to describe probabilistic branching as well as concurrent execution in a distributed program. The computational model, along with a set of seven program descriptors, completely specifies a model for dynamic execution of a program on a distributed system. The optimal task to processor assignment is found by an algorithm based on results in Markov decision theory. The algorithm is completely general and applicable to N-processor systems.

We have also developed a general model to analyze the behavior of algorithms which redistribnte the workload of a failed processor to the remaining good processors in a distribnted system. It was discovered that snch algorithms should be used with cantion since they have the capability of making the entire system unstable; instability arises since the increased workload directed toward the good processors conld drive one or more of these into overload, resulting in a serious degradation of system performance. Using the general model we have studied a class of load redistribution algorithms which nse various techniques to redistribnte workload, an have derived closed-form expressions for the performance of the system. We have also derived criteria which, if adhered to, will guarantee stability in the event of failure. This is the first time that closed form expressions have been fonnd for complex models in this area of research.

Finally, we have stndied the problem of distribnting the control of the hardware resources in a distributed system. This is a difficnlt problem since at any time, several controllers may observe different and inconsistent views of the global system state. A specific problem in distribnted control is that of distributed schednling, where each processor makes a decision as to what portion of the workload should be processed locally and what portion shonld be directed to less-loaded processors. We have defined a totally new distributed scheduling algorithm which not only performs well in a distribnted environment, but is also able to adapt itself to fluctuations in the workload. Using a general purpose distributed system simnlator, we have shown the performance advantages of this new algorithm over the random, ronnd robin, and shortest qneue algorithms.

11.8 Design and Evaluation of Modules*

The reliability of a microprogram control unit (MCU) can be improved by means of concurrent error detection (CED) in the control nnit. We have developed an integrated approach to the design and implementation of an MCU with CED capability, nsing the Am2910 microprogram sequencer as a fnnctional model. An MCU layont has been completed for cnstom nMOS-VLSI technology. This is nndergoing detailed evaluation and redesign prior to fabrication.

We have designed an integrated digital filter system using residue number arithmetic which achieves high data rates and which identifies faulty hardware modules concurrent with normal filter operation. The system is designed to continue operating under module failure through an extendible technique which includes some redundant filter modules. Design and nMOS mask layout are complete for all functional units. Each design has been optimized for performance with the aid of transistor-level simulation tools. Our design methodology further requires the masks for each unit to undergo a series of verification steps at various levels. These include design rule checking of the mask layouts, timing analysis using transistor and capacitor information extracted from the layouts, and verification of functionality from the extracted transistor information. The chip has been submitted for fabrication.

We have completed the layout of an address generation chip which generates 16-bit addresses indexing the elements of an array which can be referenced in nested loops with up to 8 levels of nesting. The chip was designed in cooperation with ESL, Inc. We have checked the entire chip for design rule violations and all the violations have been corrected. Circuit simulation of most of the chip cells was done using SPICE, which provided the data used to predict the chip cycle time. Logic simulation verified the correctness of the chip control. The chip will be submitted to ESL for fabrication.

11.9 Adaptive Interpretation as a Means of Exploiting Complex Instruction Sets*

Many issues affect performance of computer systems. In this research we concentrated on the effect of instruction set architecture on the performance potential of a computer system. These are key issues when considering what instruction set is most appropriate for the support of high-level languages on general purpose machines. Two possible approaches are so-called complex instruction sets, such as those of the VAX and IAPX 432, and the "reduced" instruction set of the RISC I microcomputer, which is expected to have performance similar to that of a VAX 11-780.

We have proposed a method of instruction set interpretation that takes
advantage of the architectural features of complex instruction sets. This
method has been simulated executing real programs and, in the case of the VAX
instruction set, has resulted in a typical improvement of a factor of two,
assuming the same cycle time as the VAX 11-780. The technique exploits the
context available in a complex instruction and retains this information for
use in subsequent execution of that instruction. Since this context is avail-
able only within a single instruction, low-level instruction sets cannot bene-
fit from this technique. In this sense, the reduced instruction set machines,
as implemented in RISC, are at their architectural limits; while complex
instruction sets such as the VAX are far from theirs. For these reasons, com-
plex instruction sets can have a significantly greater performance potential
than a reduced instruction set for a given technology.

11.10 A New Processor Architecture for Reducing Procedure Call Overhead*

A structured programming language makes frequent use of procedures for
ease in understanding. In addition, each procedure call or return instruction
may require several memory references for storing and restoring registers.
These two points show that procedure calls are a significant part of a
program's execution time. A method for reducing this overhead in single chip
processors was devised. It uses a number of on-chip stacks, each associated
with one particular register. In a procedure call or return, registers are
saved or restored in one machine cycle by being pushed or popped onto their
respective stacks simultaneously. A mask allows selected registers to be
restored while leaving others unchanged during a return. In the event that
the level of procedure nesting exceeds the depth of the stack, the overflow
from the bottom of the stack is transferred to memory. A return after an
overflow has occurred does not bring this data back to the bottom of the
stack; instead, the data is brought back to the top of stack registers when an
underflow occurs. This reduces the number of overflows in a program.

We have developed a model to provide a rough estimate of the performance
of this processor as a function of high level language (HLL) statistics and
the parameters of the proposed machine. In particular, these parameters

include the number of parallel stacks and the depth of each stack, the principal attributes of the proposed system. Our model uses the frequency of each type of HLL statement, the number of variable references in each statement, the distribution of variables in registers and memory, the number of formal parameters and local variables in a procedure, and the typical assembly language representation of each statement. It also provides a performance comparison between traditional architectures and the proposed architecture by changing some of the parameters. Preliminary results show that a significant performance gain can be achieved. Work is continuing on improving the model and specifying the architecture.

11.11 Performance Evaluation of Pipeline Computers*

We have developed a unified methodology for modeling instruction flow in pipelined computers at a discrete-time level where localized flow perturbations are fully accounted for. Flow perturbations within pipelined computer systems fall into two distinct categories: those which are inherent to machine parameters such as cache miss, memory access conflict, long function computation, etc., and those which are inherent to machine load, i.e., data dependency and branch dependency. Function Unit pipelines have been modeled effectively with the assumption that their degree of external system interaction is minimal. We have addressed the more difficult case of Instruction Unit pipelines which do interact heavily with memory and are fully subject to system load abnormalities.

We have introduced the notion of a probabilistic variable-time segment to develop a new class of models called residual-time models which solve for pipeline performance degradation due to the first class of perturbation. These models are discrete-time models which are event driven in philosophy and which cause the automatic generation of a (well formed) Eigenvalue problem whose solution is the steady-state distribution of machine state. These models thus require independent job-load statistics for their solution, and we have developed a set of trace transformations which provide these statistics.

The VAX 11/780, the IBM 801, and the Amdahl 580 have all been modeled in a straightforward fashion using this approach. A more complex hypothetical machine was formulated to fully test the extensibility of the technique, and this technique was compared against classical modeling techniques. It was found that classical modeling techniques provided good performance estimators only when the system was heavily bottlenecked, and the residual-time model was found to provide good estimators regardless of system balance.

12. APPLIED COMPUTATION THEORY*

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12.1 Introduction

Current technology requires the development of efficient computational techniques and the analysis of the capabilities of various models of computation. We are concerned with the resources - such as time, equipment, memory, interconnection - that are used or needed in the algorithmic solution of given problems. This dynamic discipline, known as concrete computational complexity, not only contributes to a fundamental understanding of computing, but is also extremely relevant to both hardware and software applications. It is only natural that the great technological innovations represented by Very-Large-Scale-Integrated (VLSI) Circuitry have had a substantial impact on this field, opening new horizons and posing challenging problems. Much of our current research (organized below in four subsections) has been motivated by this revolution.

12.2 VLSI Computation

In our ongoing investigation of the sorting problem, we have developed in detail an area-time (AT^2) optimal VLSI architecture for bitonic sorting. The cube-connected-cycles (CCC), which is optimal for bitonic merging, is suboptimal for bitonic sorting; however, a significant variant of the CCC, called the "pleated-CCC" is optimal for both problems. Crucial to this performance is the idea of "folding" the cycles, so that the cycle lengths can be dynamically tailored to the current demand of the computation. The pleated-CCC has performance $AT^2 = \theta(q^2 n^2)$ for stably sorting n records of size q in the time range $\theta(q \log^2 n) \leq T \leq \theta(q n/(q+\log n))$. The existence of an optimal sorter for $T = o(\log^2 n)$ is still a major open problem. We have shown, however, that by judiciously combining well-known parallel architectures - such as the orthogonal-trees and the CCC - significant performance improvements can be obtained in the "fast" sorting range, with $T \varepsilon [\log n, \log^2 n]$.

We are also investigating the problem of designing an $[AT^2]$-optimal n-bit integer multiplier with $T = \theta(\log n)$ and making progress in developing a unifying framework for systolic computations.

12.3 Layout Theory and Design Aids

It is crucial to the growth of VLSI that we develop better and more automatic techniques for the layout of VLSI circuits. Since most placement and routing tasks currently involve empirical techniques and even some manual intervention, we are working to develop a theory of VLSI layout. We have studied in detail the subproblem of channel routing. Extending our previous work, we have determined an algorithm to route multiterminal nets, using three conducting layers, in a channel of width at worst only twice the density; moreover, for the subcase of two-terminal nets this algorithm degenerates to the optimal channel width (i.e., density). The latter algorithm produces the layout track-by-track; we have also developed an alternative algorithm which produces the layout column-by-column, gracefully adapts to two-terminal net problems and, in addition, in all cases yields a channel width strictly less than twice the problem density. We also have developed an improved algorithm for two-layer channel routing, where wires are allowed to run on top of each other. In addition, we are examining the routing of four-sided channels.

Although the problem of determining three-layer wireability from a "layout" is NP-complete, we have shown that any layout can be wired using four layers. Thus, we have an algorithm for four-layer routing of a four-sided channel.

12.4 Distributed Computing

We have developed new asynchronous algorithms for solving selection problems on distributed systems. Our algorithm to select the median in a uni-directional ring has message complexity $O(N^{1+e})$ for any $e > 0$. This result fits naturally between known message complexities for related problems in rings; the easier problem of finding the maximum can be solved with $O(N \log N)$ messages, and the harder problem of sorting all the values can be solved with $O(N^2)$ messages. Our algorithm can be implemented on the discrete torus and on circulant graphs with the same message complexity. Furthermore, we have designed novel algorithms for selecting the maximum in distributed systems with more communication links.

12.5 Data Structures / Information Retrieval

Buddy systems are often used for nonpreemptive storage allocation. We have analyzed the worst case performance of both binary and Fibonacci buddy systems. For both unrestricted and allocation-only request sequences we have derived exact bounds on two measures of fragmentation.

13. ADVANCED AUTOMATION

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13.1 Understanding and Representing Natural Language Meaning*

This project is concerned with judging the plausibility of natural language sentence meanings, with representing meaning and context, and with novel processing mechanisms for natural language understanding.

Progress was made on representing event descriptions, spatial relationships, time, and causality. "Event shape diagrams," a new representation form for dealing with sequences and concurrency of events, have been used in understanding scene and event descriptions. In this work, we view language as

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having meaning consequences at many levels, ranging from the stimulus/response like meaning levels of idiomatic language use, to the expansion of language into a time-ordered structure of perceptual predicates with values. Such structures can, for example, function as templates to be compared with visually generated scene descriptions, or may be used as instructions for driving the robot arms.

We have in addition been researching a parallel, analog model for knowledge integration and decision-making in the context of natural language processing. The model involves dynamically constructing an unstable weighted network of possibilities, while concurrently sifting and stabilizing the network such that the best interpretation is highlighted. The model has been successfully applied to a natural language processing task. We are also working on a computer system that models a reader's point of view, taking into account characters' knowledge and belief states and affective responses.

13.2 An Expert System that Integrates Language, Perception and Learning*

We have been building computer expert systems which have the ability to describe what they see in natural language, which can respond appropriately to natural language instructions or questions about their perceptual world, and which can learn from experience. We are using a simple world of table top scenes, two robot arms equipped with elementary touch sensors, and a binocular vision system, to build and test our theories. A specialization of the language system described in section 13.1 is used in conjunction with the specialization of the learning system of section 13.4 for the robot arm domain and a special vision system. The vision system will produce a stream of perceptual predicates with values. These perceptual predicates (near, in, supported by, etc.) are ordered in "importance," and trigger higher level "event schemas" (e.g. grasping, aligning, dropping) that succinctly encode numbers of simpler perceptual predicates. Particular problems include the choice and generation of predicates, generation of predicate values from raw scene data, object identification, modeling "importance" or "salience," and the matching event schemas with the perceptual stream that is both incomplete and includes extraneous information.

The overall system will be capable of being taught actions and words to describe them by being led around while watching with its vision system and correlating the sensory/motor data with natural language commentary.

Also as part of this project, we are developing a mechanism modeling expert systems for simulating the operation and diagnosis of problems in a gas turbine engine.

13.3 Cognitive and Linguistic Universals*

We have been using a variety of techniques to learn what aspects of natural language are universal, and which are particular only to certain languages; we have programmed a system to represent and reason about temporal relationships in text or discourse. We have studied English, Spanish, Basque, Mandarin, Chinese, Burmese, Jinghpaw and other southeast Asian languages, as well as several American Indian languages. Some universal features identified and detailed so far include the division of the world into stative, durative and punctual verbs and nouns (object words); "case grammars" for verbs, expressing relationships between verbs and nominal phrases such as agent or actor, object of an action, instrument, source, destination, beneficiary, etc.; methods for expressing tense (past or retrospective, present or witness, and future or modal) as well as aspect (action in progress, completed, beginning, ending, etc.); and the sharing of the same words or syntactic constructions for both temporal and spatial relationships (i.e. in, before, near, at, and so on in English). We are also converting a complete machine-readable dictionary so that it can be used with our parsers to select appropriate word senses, assign case roles, and to discover and denote causal relationships.

13.4 Explanatory Schema Acquisition**

The schema learning group is exploring artificial intelligence techniques that will enable a computer system to learn general world knowledge in the form of "schemata" through its interactions with an external environment. A schema is a data structure that specifies, in conceptual terms, how a

particular real world situation is likely to progress and why. Intelligent behavior requires an extremely large number of these schemata.

One computer system has been completed. Currently, there are three more systems under development. These are building on what we learned from the first. The domain areas for the three projects are 1) learning to process natural language texts, 2) learning to prove NP completeness problems in computation theory, and 3) learning to perform robot arm tasks.

This represents a departure from the usual approaches to machine learning. First, it is very knowledge-based. That is, the system must possess much knowledge before it can acquire new knowledge. Furthermore, it is capable of one-trial learning. The results so far are very promising. Explanatory schema acquisition takes us a large step closer to building a large intelligent system capable of learning on its own.

13.5 Computer Vision*

Further progress was made in the ongoing project on perceptual segmentation of dot patterns. Algorithms were developed for segmentation of patterns containing curvelike clusters and clusters with varying densities [13.23].

Progress was made towards developing a robust algorithm to compute scene depth by performing efficient two-dimensional matching of features in a given stereo pair of images [13.14].

The problem of collision avoidance and trajectory planning for three dimensional objects was investigated. Algorithms were developed based on octree and septree decompositions of objects [13.8,R1].

The use of the Voronoi tessellation of the plane was demonstrated for representation and secure transmission of images [13.15].

13.6 Acquisition, Representation, and Manipulation of Three-Dimensional Time-Varying Information*

The goal of this project is to develop and study techniques for acquiring, representing, and manipulating 3-D time-varying scenes. During the last 6 months, our efforts have been concentrated on the representation aspect of the problem, in particular we have in mind applications to collision avoidance in robotics.

We are looking into efficient ways of discrete volume representation. Specifically, we are studying space quantization using hexagonal prisms (which are more isotropic and more efficient — in the nyquist sampling rate sense — than the conventional cubes); hierarchical representation using septrees; and efficient algorithms for updating septrees after object motion.

In the future, we will continue our work on representing volumes by hexagonal prisms and septrees, and start to investigate techniques for the transformation between 2-D and 3-D information.

13.7 Hierarchical Control and Monitoring with Conceptual Levels**

This work deals with the use of knowledge-base architecture and planning control mechanisms to perform an intelligent monitoring task in the flight domain. The conceptual levels architecture is a new approach to hierarchical planning. The conceptual levels architecture is a semantic approach which makes planning in a complex domain more tractable by partitioning and organizing the domain knowledge into conceptual levels.

The flight domain knowledge is presently organized into four conceptual levels: the route level, the trajectory level, the flight-control level, and the aircraft subsystem level. These levels form a form/function hierarchy which is based on composition instead of the more common class/member relationship.

The conceptual levels architecture is unique because it enables the planner to focus its attention to only the knowledge within a level. This is

because a level is determined by a causal framework, a causal mini-world which is complete by itself. In addition to localizing the planner's attention, the levels also provide the ability to do recovery planning based on a change in the context at any level. This property is unique and desirable in real-world problem-solving.

The work accomplished thus far consists of the design of a semantically oriented planning architecture, an initial design of the four planners corresponding to the four levels, and an initial design of the inter-level planning-control mechanism. This mechanism controls the planning process over the levels hierarchy. Problems and issues currently under investigation include (1) focus of attention, (2) vertical problem decomposition, (3) planning control, (4) inter-level teleological consistency, (5) domain knowledge representation, and (6) partial planning.

13.8 Mechanism Modeling and Automatic Diagnosis*

The purpose of this work is two-fold. First, we will develop models of understanding of mechanisms, about their operating principles, structure-function relationship and hierarchical interaction. Secondly, we shall exploit these mechanism models for intelligently diagnosing multiple faults.

As a typical case study we have developed some initial understanding models for a generic refrigeration system in terms of such concepts as heat-transfer and circulation. With the help of these concepts models we can analyze any schematic of a refrigerator and identify the relevant components which are pertinent to an operation, such as circulation. We can then easily construct the circulation subsystem as an abstraction.

In a more abstract direction, we have established a systematic process of substructure recognition which facilitates mechanism understanding. By simplifying the physical model through composition of substructures which perform a unit function, and treating the substructure as a single new functional component, the amount of physical detail can be greatly reduced and a composition hierarchy can be imposed over the physical model. Furthermore, this hierarchy

enables explanation at various levels of detail. Substructure recognition is
based on satisfaction of semantic constraints on component parameter rela-
tions, as well as syntactic constraints on the physical structure, and can
vary in different contexts.

Finally, in the direction of diagnoses, we are studying an important sub-
class of multiple failures, called "dependent failure" cases, in which a pri-
mary failure can trigger subsequent secondary failures. Two new concepts are
introduced into this diagnostic approach: (1) the observed symptom, which
serves as input to the diagnosis process, is a time-sequence of "qualitative"
events, and (2) occurrences of secondary failures are treated as timely events
which can be explicitly reasoned from mechanism models.   To reason about
dependent failures, we construct state-transition models which are capable of
encoding component knowledge such as time-related constraint characteristics
and failure causalities.   Based on the structure knowledge and component
models, a qualitative reasoning process, called "predictive analysis", is
developed to analyze the time-elapsed behavior of a fault-asserted mechanism.
With the ability to reason with deep-level mechanism model, a computer-based
real-time diagnosis system has been implemented to reject or to justify fault
hypotheses by qualitatively matching predicted mechanism behaviors with
observed time-elapsed symptom.

13.9 Air Traffic Control, Problem-Solving, and Learning*

Engineering an expert system for air traffic control requires accomplish-
ing two difficult tasks: automating conflict resolution, and delivering air-
craft to their destinations in an expeditious and fuel efficient manner.   The
central planning problem is one of handling interacting goals in a domain
where the knowledge base contains both detailed mathematical models of air-
craft and heuristic route planning knowledge.

The mathematical models are computationally too complex for the human
controllers who are the domain experts, but their heuristic knowledge is based
on simplified aircraft performance models. Thus to acquire the expert
knowledge through advice-initiated learning we developed a qualitative reason-

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ing approach that embodies both levels of abstraction and a naive understanding of Newtonian physics. The computer can rationalize the controller's heuristics through their relation to the aircraft models, and determine why its own solution is inferior.

The planning mechanism must handle goal interactions based on priorities, constraints, and possibilities. This requires an approach that explicitly represents planning meta-knowledge, and limits search by using default plans. We are producing a planning system that centers around goal interaction and default plan modification.

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14. INFORMATION RETRIEVAL

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14.1 Introduction

During the 1982-1983 time period, we conducted in information retrieval a number of research and development projects and participated in the University of Illinois' online search service. Major activities included analysis of database data; a test of the feasibility of automatically determining the overlap between bibliographic databases; development of a computer-readable databases directory; and participation in the University of Illinois' online search service.

14.2 Analysis of Database Data*

Our staff maintains a body of information about commercially available databases called the Database of Databases. We have continued to study various statistical characteristics of this population based on the material in our database. Such statistics and analyses are useful both to researchers in the area and to the users and producers of databases.

The particular information developed in the studies performed in the last year considered the age, size, type (scientific, medical, etc.), and source (government, private, etc.) of the databases covered. At present, 773 databases are covered by our Database of Databases, but any given study might include only a specified subset of those depending on the needs of the study.

The most recent analyses are for the years 1980 and 1981.

Analyses are performed using the Bell Labs statistical package $\underline{S}$.   Data are extracted from our files and cleaned – missing values are supplied and validity checked – before being read into the S environment. We use special macros to perform the special tabulations and summaries we need. These provide output suitable for use with the UNIX tbl and nroff utilities.

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

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

14.3 Federal Emergency Management Agency Database Requirements Assessment and Resource Directory Model*

We identified and analyzed word-oriented (bibliographic, textual, directory, etc.) databases relevant to various units within the Federal Emergency Management Agency (FEMA).

The use of computer databases instead of manual searching saves time, an important factor in emergency situations. Computer databases usually provide more timely information and allow one-step searching of complex topics tailored to meet individual needs. A directory indicating which databases contain information of interest to FEMA would be a valuable resource for all FEMA units. This project developed a methodology for compiling such a directory and also provided a model as a sample directory.

Databases of potential relevance to FEMA were identified and, after discussion with FEMA personnel, the fifteen judged to be most relevant to the most FEMA areas of interest were selected. Subject profiles that reflect the interests of all individual FEMA units were developed in conjunction with appropriate FEMA personnel. Profiles were used to test the fifteen databases online. The databases were ranked by subject coverage, amount of information, and type of information based on the online search results. We created a sample FEMA Database Directory based on the analysis of the fifteen databases and including samples of citations from each database.

14.4 Directory of Computer-Readable Databases*

The 1984 edition of Computer-Readable Databases — A Directory and Data Sourcebook is currently in preparation. The 1982 edition by Professor Martha E. Williams, Lawrence Lannom and Carolyn Robins was published by Knowledge Industry Publications, Inc. It contains 1500 pages of data about databases. The first edition of this book was edited by Martha E. Williams and Sandra Rouse and published in 1976 by the American Society for Information Science. Updates were issued in 1977 and 1978 and a total revision was published by Knowledge Industry Publications, Inc. in 1979.

Organization

The Directory is organized alphabetically by database name and includes an introduction and four indexes: Subject Index, Database Name/Acronym/-Synonym Index, Producer Index and Processor Index.

Information on each database follows the general format: (1) Basic Information; (2) Producer/Distributor/Generator Information; (3) Availability and Charges for Database Tapes; (4) Subject Matter and Scope of Data on Tape; (5) Subject Analysis/Indexing Data; (6) Data Elements Present on Tape; (7) Database Services Offered; and (8) User Aids Available.

Maintenance

During 1982-1983 we worked on transferring the underlying database from the DEC/10 to the Lab's new VAX 11/780. New formatting and maintenance procedures needed to be devised. We have also begun data collection for the next

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*This work was partially supported by Knowledge Industry Publications, Inc.

(1984) edition. We anticipate making data gathering/maintenance an ongoing operation.

14.5 University of Illinois Online Search Service*

The Online Search Service is a service provided for students, faculty, and staff of the University by the Library and our group. Information retrieval services are provided by accessing computer-readable databases from the following search systems: Bibliographic Retrieval Services, DIALOG Information Systems, New York Times Information Bank, System Development Corporation, and the National Library of Medicine.

In addition to serving as one of the locations where searches are conducted, we contributed to the Service by providing monthly financial and usage reports to the Library administration and by providing expert advice in the use of information retrieval services. The financial and usage reports were generated by internally produced software on an Alpha Microsystems microcomputer and are based on accounting data provided by the online vendors and the Library.

14.6 Automatic Duplicate Detection of Journal Articles Appearing in Multiple Databases — A Feasibility Study**

Duplicate journal articles can be detected via computer algorithms. Consequently, database overlap can be measured automatically. This study dealt with the following databases and subject areas: Agricola (agriculture); BIOSIS Previews (biosciences); CA Search (chemistry); Commonwealth Agricultural Bureaux (agriculture); COMPENDEX (engineering); Excerpta Medica (medicine); INSPEC (engineering [physics/electrical engineering/computers]); Medline (medicine); Science Citation Index (all of the previous).

From among these databases, candidates for matching were selected on the basis of subject matter where overlap was likely to be significant, i.e., a medical database vs. another medical database, etc. (18 pairs of databases were matched). We included 1977 publication year items that appeared in journal articles (operationally defined as an item having a volume or issue number

and an initial page). Algorithms were developed that overcame the problems of varying tape formats, abbreviation conventions, transliterations, presentation of compound names or names with particles in differing formats, spelling errors, etc.

A key (truncated version of the citation) was created for each article and alternate keys were created to handle special problems (e.g., particles in last names and transliterations). An initial match (pass-1) was done using minimal elements within the key (first three characters of the last name and first page) to pull out possible matches. Bigrams (contiguous character pairs with spaces and punctuation eliminated) were created for the title and author(s) of each citation; bigram strings were matched and values generated for each pair.

Thresholds for bigram pair scores were established through sampling. Pairs with scores above the threshold were judged to be duplicates. The match results were tested by sampling 2% (each 50th pair) of all database matches; 77,670 pairs were visually inspected and judged as duplicate/nonduplicate, and error rates per database pair were established. Error rates for the algorithm ranged from 0% to .58%, for an overall rate of .16%. The extent of duplication between databases was found to be higher than anticipated and ranged from 7.5% to 74%.

14.7 Comparative Analyses of Online Retrieval Interfaces*

We have begun an NSF-sponsored project to test the suitability for novice use of different styles of retrieval system interface. Three approaches are to be compared: (1) a "conventional" command-driven Boolean interface like those used by existing retrieval services; (2) a "direct dialogue" Boolean interface based on menus and limited options like the interface designed here in a previous project studying transparency aids; and (3) a "consulting" associative interface in which the system asks the user for suggestions, advice, and evaluations to use in performing a search. All three interfaces will use a backend retrieval system supporting Boolean and associative searching using a spreading activation model. Work during this time period has centered on system design and capabilities specification.

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15. COMMUNICATIONS

Faculty and Senior Staff

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15.1 Multiple-Terminal Digital Communications*

This research topic includes various problems in spread-spectrum communications and random-access communications networks. The topics that were investigated during the past year include the performance of direct-sequence spread-spectrum multiple-access (DS/SSMA) communications systems, local throughput of spread-spectrum packet radio networks, the effects of multipath on spread-spectrum communications, communications in the presence of jamming, error control coding for multiple-access systems, adaptive transmission strategies and routing in mobile radio networks, balanced scheduling in packet-synchronized spread-spectrum networks, and dynamic routing schemes for networks with continuous traffic and for networks with time-varying but deterministic inputs. Progress in this research is described in the subsections

that follow.

15.1.1 Spread-Spectrum Multiple-Access Communications Systems

We have investigated the effects of partial correlation on the performance of DS/SSMA systems. Investigation has focussed on systems in which the number of chips N per bit is either relatively prime to the period p of the signature sequences, and on systems in which N is a divisor of p. Our results deal primarily with the mean-square multiple-access interference and the signal-to noise ratio. We have found that in systems in which N and p are relatively prime, the resulting loss of control of sequence phases leads to an increase in the multiple-access interference of about 15 percent over systems in which p = N and which employ signature sequences in their optimal phases. On the other hand, systems in which N is a divisor of p perform in a similar manner to systems in which p = N. It is, of course, difficult to optimize phases for sequences of long period. However, we have derived a method of sequence design which enables us to construct long sequences and achieve the desired performance without any optimization of phases.

We have designed classes of quadriphase sequences for use in DS/SSMA systems using QPSK or offset-QPSK modulation. Our results enable us to design sets of sequences containing 2(N+1) sequences of period N for which the maximum magnitudes of the periodic correlation functions are bounded by $3(N+1)^{1/2} + 5$. Here, N is a multiple of 4, and N + 1 is a prime or prime power. It is also possible to design smaller sets of sequences for which the autocorrelation properties are nearly ideal. These sets are analogons to the maximal connected sets of binary m-sequences.

We began an investigation of the multiple-access capability of frequency-hopped (FH) spread-spectrum communications and the throughput of FH spread-spectrum radio networks. Analytical and numerical results have been obtained for the maximum number of simultaneous transmissions for a given bit error rate, and for the local throughput of such networks when M-ary modulation and Reed-Solomon error correcting codes are employed. If the codeword error probability is constrained to be less than 0.1, the FH system has a higher local throughput than the standard ALOHA scheme. The latter is not of any use in practical military channels with jamming and fading.

We have investigated the possibility of DS/SSMA communication over the low frequency (LF) band. In the proposed scheme, each user is assigned M orthogonal signature sequences, and thus transmits $\log_2 M$ bits of information when any sequence is used to modulate the carrier. Each signature sequence is a polyphase sequence with as many as 100 different phases. Such a scheme can work on the LF band because the long times associated with the LF band allow for the use of quite complicated signal sets. A locally optimum receiver has been derived for such a communication system operating in a mixture of Gaussian and impulsive noise. The receiver consists of a bandpass correlator followed by a sampler, a zero-memory nonlinearity, and M discrete-time matched filters. When the interference in the receiver is dominated by the multiple-access noise or by the Gaussian component, the receiver operates primarily in the linear region of the nonlinearity, and its performance can be approximated by that of an equivalent linear receiver. The error probability for the linearized receiver has been computed using a method based on characteristic functions, and also by an approximation that can be justified heuristically on the basis of the central limit theorem. We have also designed two classes of signal sets that can be used in such systems.

15.1.2 Effects of Fading on Frequency-Hopped Spread-Spectrum Communications

One of the topics in that we have investigated recently is the mathematical characterization and modeling of selective fading channels. The main application envisioned at present is for use in performance analysis of FH spread-spectrum communications. As a result, it is necessary to obtain a model for the entire "channel" as seen by the data modulation: a frequency hopper, a fading channel, and a dehopper.

A FH system and a fading channel were modeled together as a time-varying random process. It was shown that from the point of view of the binary FSK transmitter and receiver, noncoherent frequency-hopping over an ideal (infinite bandwidth, nonfading) channel can be characterized as time-selective fading. The degree of time-selectivity is greater for fast-frequency-hopped (FFH) systems than for slow-frequency-hopped (SFH) systems. Thus, the frequency deviation must be larger for the FFH than for the SFH system in order to meet a given co-channel interference criterion. If the communications channel is time selective, additional spacing between frequency slots may be

necessary to obtain the same level of performance. Results on the minimum frequency spacing have been obtained for various models of correlation functions for a purely time-selective channel. If the channel is frequency selective, it is of interest to know the minimum spacing between frequency slots necessary so that the fading of signals occupying different slots is independent. Using an example of a purely frequency-selective channel, lower bounds on the frequency spacing have been obtained.

In order to gain a thorough understanding of the effects of the fading process on the bit error probability, the system performance in the absence of multiple-access interference was first considered, and the results were applied to the evaluation of the FH/SSMA communications system. The effects of time-selective fading on DPSK communications was considered for several data pulse shapes and a variety of fading channel models. It was found that while the system performance strongly depends on the characteristics of the channel Doppler spread, the time-selective nature of the channel is not a limiting factor for typical values of mean-squared Doppler spread.

The investigation of the effects of frequency-selective fading on DPSK signaling resulted in a number of important conclusions. It was found that channels which are even slightly frequency selective can significantly degrade performance, and that the limiting error probabilities for typical values of mean-squared delay spread may be unacceptably high. Secondly, it was shown that the system performance is highly dependent on the data pulse waveform as well as the characteristics of the channel delay spectrum. It was further shown that useful bounds on the average error probability can be obtained in terms of a measurable second-order channel parameter. Finally, it was demonstrated that this channel parameter can be used to approximate the performance of systems operating with a channel which can not be fully characterized and aid in the selection of pulse waveforms and modulation schemes for use in frequency-hopped spread-spectrum systems.

We have investigated the performance of a class of fast-frequency-hopped SSMA communication schemes proposed for mobile radio communications. A suitable receiver model has been derived for such schemes. The receiver is an optimum receiver in the presence of nonselective Rayleigh fading, but is suboptimal for the classical nonfaded channel. Bounds on the probability of

error for such a receiver have been obtained for the nonfaded (additive Gaussian noise) channel and the nonselective Rayleigh faded channel. We have also studied the performance of this receiver when it uses hard decisions instead of soft decisions on each hop. These results indicate that the new suboptimal receiver structure is superior to the original receiver considered earlier by others. Furthermore, in the presence of Rayleigh fading, the receiver using hard decisions is not significantly poorer in performance as compared to the optimum receiver. The latter is, of course, much harder to implement.

15.1.3 Communication in the Presence of Jamming

We have investigated the problem of communication in the presence of hostile jamming in game-theoretic terms. The players in the game are the coder and the jammer, and the payoff function is Shannon's mutual information. Under certain restrictions, the players have simultaneously optimal (saddlepoint) strategies. These strategies are generally memoryless, and so in an information-theoretic sense, the commonly used technique of interleaving is superfluous. For binary coding and PSK modulation, uniform Gaussian jamming is generally inferior to pulsed jamming. However, if a modest amount of bandwidth expansion is tolerable, suitable coding can neutralize a pulsed jammer. For FSK modulation, our studies used channel capacity as the payoff function, and we investigated the problem for the case of partial-band jamming (as might be found in a FH system) and nonselective fading. We found that there is an optimal code rate that minimizes the energy per bit required to achieve reliable communication. Furthermore, for code rates of 0.5 or less, uniform jamming is the optimal jamming strategy. We have also studied the performance of several explicit coding/diversity schemes in the presence of optimal jamming, and we have evaluated the relative merits of interleaved vs. non-interleaved coding schemes in the presence of general interference phenomena including jamming, fading and other RFI.

15.1.4 Direct-Sequence Spread-Spectrum Communications for Packet Radio Networks

In order for direct-sequence spread-spectrum modulation to be useful in packet radio networks, it is necessary to employ a large set of signature sequences with good correlation properties. The crosscorrelation values must be small in order to provide multiple-access capability, and the autocorrela-

tion values must be small in order to enhance the capture effect for the reception of random access transmissions and to permit reliable communication in the presence of multipath interference. For networks in which groups of mobile terminals are somewhat clustered, the crosscorrelation is important only for those terminals in the same group. Thus, we need a large set of sequences with several subsets. All sequences in the set must have good auto-correlation properties, but the crosscorrelation is crucial only among those sequences in the same subset.

Because of the specifications of the signal format for the DARPA packet radio network, we have investigated the Gold sequences of period 127. By carefully selecting subsets of twelve sequences each, we were able to obtain sequences with the desired properties. In particular, although the autocorrelation values for these Gold sequences can be as large as 43, our set uses phases of the sequences which have autocorrelation values no larger than 23. In addition an algorithm was developed to obtain sequences which give low bit error rates in the presence of multiple-access interference. We have shown that a saving of more than 1 dB can be obtained by proper selection of the phases of the Gold sequences of period 127. For smaller sets of sequences of shorter period, the effect is even more dramatic: nearly 3 dB can be saved in the case of three Gold sequences of period 31.

Because of the severe specular-multipath fading that arises in mobile radio networks in urban areas, we have investigated the effects of such fading on the performance of coherent and noncoherent direct-sequence spread-spectrum communications. Our early work on this subject considered only receivers with standard matched filters. This work has been expanded to consider receivers which employ post-detection integration or RAKE-type filters.

Receivers of greater complexity than the simple correlation receiver have been considered for the reception of direct-sequence spread-spectrum communications over the specular multipath channel. Results have been obtained on the performance of a receiver which has complete knowledge of the number of channel paths and of the delay, phase, and signal strength associated with each of the paths. In this receiver the simple correlator is cascaded with a transversal filter; consequently the receiver is matched to the actual channel output rather than the transmitted signal. The effects of multiple-access

interference, intersymbol interference, and thermal noise in the receiver have been considered. This work has in turn provided valuable insight into the problem of sequence selection for packet radio systems which must operate in a specular multipath environment. Since it may be difficult to determine and utilize the complete characteristics of the channel, which is necessary for coherent reception and combining, we are also investigating the performance of noncoherent and differentially coherent reception.

15.1.5 Random Access Techniques

A main result of our research in random access communications has been to suggest and analyze algorithms which allow several stations in a mobile communication network to lock into a time-division multiple-access (TDMA) communication mode. The algorithms are designed to operate even when the identity and the total number of the other users is unknown and feedback information is limited. Algorithms based on ALOHA random access as well as a tree algorithm were studied. Our research provides a generalization of TDMA which is appropriate in the face of a fluctuating population of users, such as typically encountered in a mobile communication network.

A bounding technique inspired by the state-space approach of stochastic control was developed. It is used to establish an upper bound of time-slotted multi-access broadcast channel using feedback information consisting of a 0, 1, or e to denote a slot with zero, one, or at least two packets, respectively. Related bounds based on an information theoretic analysis have also been obtained.

New results have been obtained in the development of numerical evaluation and bounding techniques for the analysis of routing in a packet-switched communications network. A general lower bound was obtained for the delay in a queue in terms of the average arrival rate. The novel feature of the bound is that no special structure (such as stationarity or a renewal property) is assumed on the arrival process so that it can be applied to bound buffer delay within rather complex networks.

15.1.6 Transmission Strategies in Radio Networks

A viable access strategy for a mobile radio network is to attain network-wide synchronization with resolution small compared to packet

transmission times and to govern packet transmission times with a schedule. Certain transmission schedules called uniformly most balanced schedules were shown to exist which are optimal simultaneously under a variety of criteria. The problem of finding such schedules is equivalent to a network flow problem with convex cost. Efficient decentrizable algorithms of deterministic and of stochastic type were given for computing the schedules. A preliminary performance analysis was also given.

Recently we proposed and analyzed new adaptive transmission strategies for mobile radio networks. Local throughput in a mobile radio network is roughly defined as the rate at which packets are propagated in specified directions in local network regions. A key factor determining local throughput in an ALOHA or spatial TDMA network with randomly spaced stations is the transmission radius used by the stations. We have shown that allowing the transmission radius to depend on the desired direction of propagation can significantly increase local throughput. Analysis was also completed which indicates that the local throughput capabilities of a radio network can be effectively used only if adequate routing strategies are employed.

15.1.7 <u>Routing and Control in Communication Networks</u>

Substantial progress was recently achieved dealing with optimal dynamic routing in communication networks. New characterizations of optimal state-dependent routing strategies were obtained for the continuous traffic network model proposed by A. Segall for linear cost with unity weighting at each node and for constant inputs. The concept of <u>flow relaxation</u> was introduced and was used to transform the optimal routing problem into an <u>initial flow</u> optimization problem with convex cost and linear constraints. Three algorithms were given for open-loop computation of the optimal initial flow. The first is a simple iterative algorithm based on gradient descent with bending and it is well suited for <u>decentralized</u> computation. The second algorithm reduces the problem to a series of max-flow problems and it computes the exact optimal initial flow in $O(N^4)$ computations where N is the number of nodes in the network. The third algorithm is based on a search for successive <u>bottlenecks</u> in the network. Many extensions of this work are under investigation.

In other research we have recently considered stochastic control models for a Markov network with two queues. The controls govern routing and service

priorities and can depend on state feedback. Optimal controls described by switching curves in the two dimensional state space were shown to exist. Finite horizon and long run average cost problems were considered and value iteration was a key tool. An example was given which shows that nonconvex value functions can arise for slightly more general networks. A single station control problem with nonconvex value functions was then considered to indicate how switch structure might be established more generally. A novel approach using policy iteration and stochastic coupling was used to establish optimality of threshold.

Some of our research has been in computational probability methods which are applicable to communication network analysis. In one paper, the invariant probability distribution was found for a class of birth-and-death processes on the integers with passes and one or two boundaries. The invariant vector has a matrix geometric form and is computed by solving a non-linear matrix equation and then finding an invariant probability distribution on the boundary states. Levy's concept of watching a Markov process in a subset was used to decouple the computation of distributions on the boundary and interior states.

In other research on general probability methods, bounds of exponential type were derived for the first-hitting time and occupation times of a real-valued random sequence which has a uniform negative drift whenever the sequence is above a fixed level. The only other assumption on the random sequence is that the increments satisfy a uniform exponential decay condition. The bounds provide a flexible technique for proving stability of processes frequently encountered in the control of queues. Two applications were given. First, exponential-type bounds were derived for a GI/G/1 queue when the service distribution is exponential type. Secondly, geometric ergodicity was established for a certain Markov chain in $\mathbb{R}^2$ which arises in the decentralized control of a multi-access, packet-switched broadcast channel.

15.2 <u>Signal Detection, Estimation, and Filtering</u>*

The overall purpose of this research effort is to develop effective sta-
tistical signal processing procedures for applications in communications and
control. Specific areas currently under investigation include the development
of robust detection, estimation and filtering procedures for operation in un-
certain statistical environments, the study of techniques for efficient digit-
ization of signal detection systems, the development of effective receivers
for multiple-access digital communications, and the analysis of multistage
decision processes. Progress in these areas is described briefly in the fol-
lowing subsections.

15.2.1 <u>Robust Signal Processing in Uncertain Statistical Environments</u>

In general, the area of robustness deals with the design of systems and
procedures which are relatively insensitive (in terms of performance) to small
deviations from an assumed model. Robust techniques are of interest in a wide
variety of applications including radar, sonar, and seismology, inasmuch as
inaccurate models are the norm for such situations; and robustness has been
studied widely in the contexts of communications, control, and inferential
statistics. The basic assumption for the analytical study of robustness in
detection and filtering is that the statistics of signals and/or noise are not
known exactly, but rather are known to be within some (usually nonparametric)
classes representing uncertainty in the underlying model. The primary tech-
nique for designing a robust system is to seek a system achieving the best
worst-case performance over the relevant uncertainty classes; i.e., the pri-
mary design philosophy is minimax. Within this context several detection,
estimation and filtering problems have been considered recently under this
project, and these are described in the following paragraphs.

One area in which several minimax and robustness results have been
obtained is that of state estimation and control for linear dynamical systems
with uncertain statistical behavior. In particular, minimax results have been

developed for steady-state linear-quadratic control [15.14] of time-invariant systems and for finite-interval estimation and regulation [15.24,15.47] of time-varying systems. Along these same lines the problem of robust filtering and smoothing of stationary processes with uncertain spectra has also been considered. Specific results include a general study of robust causal solutions for the Wiener-Kolmogorov problem [15.23] and an analysis of the effects on performance of spectral uncertainty in stationary linear filtering [15.21]. A related study treats the development of jam/antijam strategies for data transmission through the Gaussian test channel with an intelligent jammer [15.3].

Another aspect of robustness in which several results have been obtained recently is that of robust signal detection. Specific results in this area include the development of robust detectors for the (nonlinear) detection of signals in additive dependent noise with uncertain first-order distribution [15.18], the design of matched filters for digital transmission through uncertain channels [15.16,15.25], and the design of signals for this latter problem [15.26]. Also, [15.13] considers a design technique known as the segment method as an alternative to minimax for designing binary decision systems within uncertainty.

In addition to the above new results, two survey papers on robustness topics have been prepared [15.12,15.46]. The topics of these surveys include robust signal processing for communication systems [15.12] and robust data quantization [15.46].

15.2.2 Digital Detection Systems

In addition to the robustness work surveyed in the above subsection, several other aspects of the design and analysis of signal detection systems have been considered recently. Progress in this area is described briefly in the following paragraphs.

One area in which recent progress has been made is that of designing efficient systems for detecting signals in dependent non-Gaussian noise backgrounds. For example, optimum detection of signals in weakly dependent noise is considered in [15.17]. It is shown here that, for a moving-average dependence model, efficient detection can be achieved by reshaping the independent-noise optimum detection nonlinearity with an additive linear

correction term. An investigation of several commonly used noise models indicates that the resulting performance improvement is most significant for impulsive types of noise. In [15.11] similar modified structures are considered for detecting signals in ϕ-mixing noise. It is demonstrated that the ϕ-mixing model with only the mixing coefficients given is not sufficiently descriptive of dependence structure to admit a design that is uniformly better than the independent-noise design. (This is in contrast to the moving-average model of [15.17].)

A number of other problems have also been studied during this reporting period. These include a study of companding approximations for evaluating signal detection performance with quantized data [15.28], an evaluation of the efficiencies of truncated sequential hypothesis tests [15.19], and a study of the effects of statistical dependence on the efficiency of sequential detection systems [15.50]. Further work includes a study of the effects of reduced complexity on quadratic detection [15.32,15.52], an analysis of the effects of noise dependence on direct-sequence spread-spectrum communications receivers [15.57], and a novel derivation of the output signal-to-noise ratio for quadratic receivers and fading channels [15.27].

16. ANALOG AND DIGITAL CIRCUITS

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16.1 Hierarchical Simulation and Design Verification of VLSI Circuits and Systems*

In this research unit a study was initiated on the use of partitioning and tearing algorithms for the analysis of large scale circuits and systems. In this approach the circuit is partitioned into subcircuits, each subcircuit is solved separately, and then the subcircuit solutions are combined to obtain the solution of the entire circuit. The purposes of tearing a system are fourfold. First, one can save on computer storage if identical subcircuits are created, because the sparse matrix pointers need to be stored for only one of the identical subcircuits. Secondly, computation time is saved because the sparse matrix pointers need to be generated for only one of the identical subcircuits. Further, computer time is saved by exploiting subcircuit latency, that is, subcircuits that are inactive in a given time interval can easily be bypassed in the solution. Thirdly, the use of tearing methods in the analysis of large systems allows for the parallel processing of the subcircuits. Finally, tearing facilitates the use of reduced-order or macromodels in the analysis.

In our research work, simulation techniques at three levels have been under investigation. At the circuit level, the simulation program SLATE now runs under the UNIX operating system on the VAX 11/780. Also better MOS transistor models have been incorporated.

At the timing level, we have developed a new modified Gauss-Seidel-type method based on prediction to analyze partitioned circuits that could include feedback loops and bilateral interconnections among the subcircuits. The method uses analysis sequencing (or selective trace) to analyze the circuit at every time point in "one-sweep", i.e., it uses only the first iteration in the relaxation process. During the analysis sequencing any values of the not-yet solved variables, corresponding to feedback loops or bilateral interconnections, such as floating capacitors, are predicted by using an explicit integration formula. The stability, convergence and accuracy properties of the method have been studied in detail and found to be superior to the standard Gauss-Seidel method used in MOTIS. The method has been programmed into a computer program called PREMOS for the simulation of MOS circuits [16.23,16.27]. For small circuits, the speed of PREMOS is about ten to thirty times faster than SPICE. For large and very large circuits the speed enhancement is expected to be substantially greater.

At the logic level, algorithms have been developed for generating symbolic logic expressions at any node in a MOS transistor circuit in terms of the input nodes [16.14,16.19]. A PASCAL program has been written to generate these expressions from a net list of the transistors and their interconnection.

16.2 Technology Mapping*

Technology mapping is defined as the transformation of a circuit design, completed in a base process technology, into similar designs in an evolution of that technology. The aim is to preserve the functional integrity of the design and to verify with design verification tools that the transformed design meets performance specifications. The work involves the generation of electrical models from layout, the recommendation of pertinent hierarchical

simulation techniques and the conditions of their use, and the establishment of principles for modifying circuit layout to meet electrical needs.

Presently an extraction program has been written in PASCAL for NMOS circuits. The program extracts the net list of transistors and interconnect wires from the CIF layout file and constructs circuit models for the transistors as well as the interconnect wires. The output data is in SPICE format so that a circuit or timing simulation can be performed [16.24]. In addition, a timing simulator has been written for NMOS circuits which is basically a logic simulator with a table look-up approach for delay estimation [16.18]. The delay information is determined by performing circuit simulations on basic circuit primitives.

16.3 Switched-Capacitor Filters - Structures and Statistical Design*

Switched-capacitor (SC) circuits provide one of the most practical means for realizing high-precision voice-band filters in monolithic form. Currently most of the SC design techniques can be categorized into two basic approaches. The first approach is based on simulating either the operation or the node voltages of the LC ladder networks [R1] - [R3]. The second approach is based on cascading a variety of bilinear and biquadratic SC circuits [R4] - [R5]. The ladder-based circuits have superior sensitivity performance as compared with cascade circuits when realizing low-pass and bandpass filters with flat passbands. However, when both filtering and equalization is to be performed, the sensitivity advantage of the ladder-based realization over the cascade realization can be lost.

Our research has been concerned with developing new SC structures which combine the low-sensitivity nature of multiple-loop feedback (MF) topologies [R6] and the modularity and flexibility of the cascade approach. A user-oriented program has been developed for design and optimization of such MF SC structures. The optimized structures obtained in this manner are less sensitive or at least comparable to the ladder-based structures when realizing flat-passband filters. Furthermore, the optimized MF structures are less sensitive than the cascade structures when performing both filtering and

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equalization.

In the area of statistical circuit analysis and design, several variance reduction techniques have been studied with respect to their application in estimating circuit yields [16.15]. It has been shown that given an approximation of the region of acceptability with a given accuracy, importance sampling techniques deteriorate rapidly as the dimensionality of the parameter space increases. However, modest reductions in the variance of the yield estimator can be obtained with stratified sampling techniques. Also, a practical method has been proposed for the implementation of the control variate method. This method may be the most useful in a general purpose statistical circuit analysis program. Finally, a new approach to Monte Carlo based yield maximization has been investigated [16.16]. In a variety of passive, active, and switched-capacitor filter circuits, it has been shown that a quadratic model can be used to approximate the responses over a parameter grid several standard deviations in length. Thus, the circuit yield for different design values can be estimated using correlated sampling and the quadratic model. This method is very efficient if line search techniques are used to find the maximum yield along a given search direction. Several filter examples show that the global behavior of the quadratic model is good and that it is very effective for yield maximization.

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17. DECISION AND CONTROL

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17.1 Control and Decision Strategies for Systems under Imperfect Information*

Uncertainties arise because of unknown system parameters, unknown signal environments, and hardware tolerances. Related complexities arise in situations involving multiple system performance criteria in complex systems. Two approaches, one deterministic but unknown, and the other stochastic, are being followed.

Design of multivariable control systems that remain stable for a range of plant operating conditions has received major attention. Conditions for robustness have been obtained in terms of singular values of comparison sensitivity matrices or return difference matrices [17.57,17.56].

Adaptive control is a promising approach for control of poorly known systems. Fundamental work in a time-scale approach to adaptive control has led to important advances in adaptive observers and design of adaptive systems in the presence of parasitics (unmodeled high-frequency dynamics) [17.21,17.35,

17.20,17.50,17.51]. A major study of this approach has been produced [17.6], and has already stimulated other researchers.

Singular perturbation techniques originated in our group continue to attract major attention. Our recent survey [17.63] lists more than 400 publications in this active field. Important new work includes extension of time scale properties to classes of nonlinear systems [17.52].

Finally, several results in the control of stochastic multi-decision-maker systems have been obtained. For example, the possibility of using self-tuning for Nash strategies has been investigated, and a simple algorithm has been developed [17.45].

17.2 Nonlinear Systems*

Various topics in nonlinear oscillator theory, the behavior of phase locked loops, the properties of certain nonlinear nonautonomous control systems, and the chaotic fluctuations of several nonlinear systems were studied. We describe each, and give a brief indication of future work, in turn.

A. Nonlinear Oscillators: Levinson and Smith first established, in a now classic paper [R1], the existence of periodic solutions of the generalized Lienard equation, under relatively mild assumptions, by exhibiting an annulus in the phase plane, free of singularities, into which all trajectories entered and none left. By far the most difficult part of their proof was the construction of the outer boundary of the annulus; they did this by a very careful accounting of the changes in the total energy of the system when following a particular trajectory. We have succeeded in finding another outer bound without using an energy "budget", thereby obtaining a considerably simpler proof than in [R1]. A paper describing this work has been accepted for publication in the Journal of Mathematical Analysis and Applications [17.34].

B. Phase-locked Loops: A manuscript giving the theory for the locking and the tracking of deterministic phase-locked loops to single frequency inputs, and the response of the phase-locked loop to multiple inputs, was prepared, but not sent to the journals since the multiple input results seemed so bizarre to us. We have started both an experimental program and a digital

computer simulation to test our theory. Thus far our predictions have been confirmed. Work is continuing on this topic.

C. <u>Nonlinear Control Systems</u>: Kevorkian [R2] gave a method for assigning a set of subsystems and couplings, namely a "structure" to a dynamical system. This assignment, which has proven useful in stability studies, can be extended to include control systems. The extension, shown to be useful for a class of control problems, is being investigated.

D. <u>Chaotic Fluctuations</u>: Computer simulations of two low-order systems have been run; each system exhibits chaotic fluctuations for particular initial conditions. Both systems, intended to serve as simple models of power systems, may be useful in the study of power system stability and "hunting". We propose to investigate these, and other similarly simple models, further.

17.3 <u>Implementation Constrained Decomposition and Hierarchical Control</u>*

Major activities during this reporting period have been focused on decentralized control, hierarchical multiple decision making, order reduction and model simplification, and decomposition methods. A summary of some of our results in these areas follows.

In [17.13,17.14,R3 and 17.41] we have studied different classes of stochastic minimax optimization problems which arise in the transmission of messages over channels with partially unspecified noise statistics and which may be subjected to unknown jamming noise. Different transmission schemes have been developed in these papers, which lead to satisfactory worst-case performance while retaining a simple structure for transmitters and receivers. In [17.13] a thorough analysis of the so-called "Gaussian test channel" is made in the presence of jamming noise. In [17.14], continuous-time channels are considered, where the objective has been to transmit a Gaussian stochastic process under a minimum mean squared error distortion measure and in the presence of jamming noise and with feedback allowed between the receiver and the transmitter. In this case the minimax transmitter and receiver policies have been obtained in closed form, and the least favorable probability distribution for the unknown jamming noise has been shown to be Gaussian and correlated

with the transmitted signal. In [R3] and [17.41], extensions of these results have been investigated in the context of models which are different from these, and again implementable closed-form expressions have been obtained for minimax transmitter-receiver policies. Furthermore, in [17.39] some mathematical questions have been addressed, which arise in the existence of saddle-point solutions for minimax stochastic optimization problems.

Spectral decomposition of stiff partial differential operators for distributed systems having a small parameter ε has been studied. Also, using the asymptotic properties of the eigenvalue-eigenvector pairs of the aforementioned operators, asymptotic approximations of the solutions of three classical stiff boundary value problems (namely elliptic, parabolic and hyperbolic) are constructed. Third, a numerical analysis of several examples of such problems is undertaken using finite-dimensional approximations. It is found that the two methodologies give comparable results. However, the first is more tractable because it alleviates the inherent stiffness of the problems at hand and requires less computation. Details may be found in [17.9].

Work continues on chained aggregation, a method for order reduction in large scale systems. A summary of recent work may be found in [17.7]. The concept of near-unobservability, which is related to the geometric structure exposed by chained aggregation, is developed in [17.55].

Stackelberg strategies are receiving continued attention for hierarchical multiple decision making [17.2,17.1].

17.4 Robust Team Optimal and Leader-Follower Policies for Decision Making in C^3 Systems*

This project has addressed fundamental issues in deterministic and stochastic decision problems which involve multiple goals, multiple decision makers, hierarchies in decision making, informational decentralization and possible discrepancies between the perceptions of different decision makers of the outside world and the underlying objective(s). In addition to an investigation of existence, uniqueness and derivation of optimal policies for such problems, sensitivities of these policies have been analyzed, with respect to

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changes in the underlying data.

In [17.43] and [17.44], we have studied the sensitivity of leader-follower policies in two-agent deterministic decision problems with respect to variations in the values of some parameters describing the objective functionals, for both Stackelberg and team problems. In [17.43] we introduce an appropriate sensitivity function and introduce the notion of a "robust" incentive scheme for the agent at the top of the hierarchy (leader) as one that minimizes, in addition to the usual (standard) Stackelberg performance index, this sensitivity function. Such an approach has applications in decision problems wherein the leader does not know the exact values of some parameters characterizing the follower's cost functional, and seeks to "robustify" his optimum policy in the presence of deviations from the nominal values. In [17.43] we have provided an in-depth analysis of such incentive design problems, obtained some explicit results for general convex cost functionals, and presented some illustrative examples. In [17.44], on the other hand, we have studied a general class of "nominal" team problems with two agents and with a hierarchical decision structure, where we have also allowed one of the decision makers to have a slightly different perception of the overall team goal, with this slight variation not known by the other agent who is assumed to occupy the hierarchically dominant position. This leading agent is assumed to have access to dynamic information, and his role is to announce a robust policy (incentive scheme) which would lead to achievement of the overall team goal in spite of the slight variations in the other agent's perception of that goal. In the paper we have obtained such robust policies for the leading agent, for general cost functionals with convex structure, and have also shown that in some special cases this robust feature of the incentive scheme is maintained regardless of the magnitude and nature of the variations.

In [17.38,17.40] we have studied a class of decision problems in which the probabilistic description of the stochastic variables is perceived differently by different agents. We first show that when the decision makers have different probabilistic models of the stochastic environment, the resulting decision problem is a nonzero-sum (multi-criteria) stochastic game, even if the decision makers have a single common goal quantified in exactly the same way (say by a cost functional). Hence, even for team problems the corresponding solution concept (team-optimal solution) will have to be

modified when discrepancies exist in the perception of the agents of the prob-
abilistic model of the decision process. The currently available theory of
nonzero-sum stochastic games is not applicable to such problems, and a brand
new theory has to be developed. This is what is accomplished in these two
papers, for two agent problems with static information patterns. We have
introduced the concept of "stable equilibrium solutions" for decision problems
with multiple probabilistic models, and have obtained sufficient conditions
for existence and uniqueness of such equilibria (under a symmetric mode of
decision making) when the objective functionals are quadratic and the decision
spaces are general inner-product spaces. Furthermore, for the special case of
Gaussian distributions in both discrete and continuous-time problems, we have
presented in [17.40] some explicit stable equilibrium policies.

In [17.65], we continue our earlier work on Stackelberg dynamic games and
consider a subclass of such problems in which the leader has informational
advantage over the follower, in the sense that the leader can observe the
follower's actions at each stage (before he (the leader) acts) either per-
fectly or partially. Under a feedback Stackelberg solution concept which
takes this informational advantage into account, we have studied derivation of
optimal affine policies and have investigated the conditions under which such
a solution coincides with the global Stackelberg solution. A second set of
results obtained in [17.65] involves an analysis of existence and derivation
of causal real-time implementable global Stackelberg solution in dynamic games
when the leader is allowed to use memory policies.

In [17.42] and [17.4], we have addressed the important problem of
developing a general equilibrium theory for discrete and continuous-time
dynamic games with varying (symmetrical and asymmetrical) modes of play, i.e.,
for games in which the solution concept itself and the leadership is deter-
mined by past actions of the players and the outcome of some (stochastic) pro-
cess. In [17.4] we study stochastic systems with structural and modal uncer-
tainties described by a finite state jump process, and introduce a new concept
of equilibrium (which we call "strong equilibrium") which encompasses both the
feedback Nash and feedback Stackelberg solution concepts for the special cases
of deterministic discrete-time games with symmetrical and asymmetrical modes
of play, respectively, and also provides a convenient framework for the intro-
duction of a feedback Stackelberg solution concept in deterministic

differential games. For the general class of stochastic nonzero-sum dynamic
games with structural and model uncertainties, and under the feedback closed-
loop information, we obtain the optimality conditions in both discrete and
continuous time. We also study certain special cases, which are further dis-
cussed in [17.42] along with some illustrative examples.

17.5 Control Strategies for Complex Systems for Use in Aerospace Avionics*

Several advances in both cooperative and noncooperative multi-decision-
maker situations have been obtained. A summary may be found in [17.2]. A
multimodel solution to a class of stochastic team problems has been obtained
[17.60].

Fundamental results in adaptive control of systems with reduced models
are described in [17.6]. Error analyses for adaptive observers in the pres-
ence of parasitics are given in [17.21]. A time-scale framework for analysis
of actuator and sensor parasitics is presented in [17.35].

An application of chained-aggregation techniques to decomposition of a
class of nonlinear systems is presented in [R4]. A revealing geometric
analysis of chained aggregation has been developed, and details may be found
in [17.23] and [17.53].

17.6 Integrated Flight Control Systems**

This project has analyzed the relationship between open and closed loop
transfer functions in multivariable systems. A parameterization of the open
loop transfer function using the singular value decomposition is introduced.
Feedback properties of the closed loop system are determined in terms of the
parameters of the open loop system. Through these results, the effect of
known structured plant modeling errors on the feedback properties of a system
can be determined. The result also provides insight into the fundamental
structure of multivariable feedback systems.

17.7 Large Scale Systems*

During this reporting period a major new research area in multiple time scale studies of networks and Markov chains has been opened. The approach provides analytical tools to reveal the time-scale properties inherent in classes of networks, and thus provides a scientific basis for defining subsystem hierarchies and decompositions. See [17.5,17.58,17.46]. The approach is an outgrowth of our development of singular perturbation techniques and concepts [17.63,17.52]. Extensions to nonlinear systems have also begun [17.27,17.52,17.58].

Singular perturbations provide a time-scale approach to modeling and control. A different approach, based on system structure as viewed through the system output, is chained aggregation. Advances in chained aggregation during this reporting period include structural decomposition techniques [17.53], three-control-component design [17.23] for hierarchical control of large scale systems, and an information-induced multimodel solution to a multiple-decision problem [17.30,17.62].

Other new results in the multiple-decision-maker framework [17.2] have been obtained. A stochastic Nash solution in a multimodel situation is reported in [17.29]. Decentralized stochastic adaptive Nash games are studied in [17.15], and self-tuning leader-follower (Stackelberg) games in [17.16]. Team-optimal Stackelberg strategies for systems with slow and fast modes are reported in [17.31].

17.8 Power System Reduced Order Modeling**

Consistent reduced order models of single machines have been developed through time scale decomposition. Models including stator transients, full damper and field windings have been systematically reduced to obtain models of any desired order. Several of these models were shown to be identical to the classical machine models while others have been shown to be new models containing improved dynamic characteristics. Correction terms to the classical

models have been derived to provide improved response while maintaining low order models. These single machine models represent a new approach to power system machine analysis.

Multimachine reduced order models have also been developed using singular perturbation methods. The aggregation of field flux has been demonstrated on a five machine model. Work is continuing on the aggregation of damper windings.

Details may be found in [17.10] and [17.37].

17.9 Advanced Power System Stability Methods*

Fast methods for computing critical clearing times of power systems are being developed. Direct energy methods are being used with various trajectory approximations. The Potential Energy Boundary Surface (PEBS) method was used to provide linear sensitivities of energy margins to total load. These sensitivities were then used in an optimal load flow to compute the stability constrained maximum loadability and maximum interchange capability of a power system. Work on modal energy and single machine energy functions is continuing. The emphasis of this approach is on observing the flow of energy through the network and machines. This energy balance must satisfy certain physical constraints which may ultimately be representable as a type of energy transportation problem.

Details are given in [17.22,17.32,17.48].

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       (to appear).

18.   DIGITAL SIGNAL AND IMAGE PROCESSING

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18.1 New Directions in Multidimensional Signal Processing*

Under JSEP sponsorship we have made significant progress in nonlinear image restoration, two-dimensional windowing, image reconstruction from frequency offset Fourier data, and band-limited signal extrapolation.

We have developed image restoration algorithms which use the theory of least squares estimation with order constraints to produce monotone increasing or decreasing estimates in the neighborhoods of edges. These computationally efficient algorithms retain sharp edges in the original image while reducing noise considerably. A separate threshold parameter can be chosen based on expected edge heights to help tune the algorithms to the particular image being processed. We are currently applying the same order-constrained least squares methods to the problem of edge detection.

Windowing is a common operation in multidimensional signal processing. In certain systems such as spotlight mode synthetic aperture radar and computer-aided tomography with missing projection data, the required window shape is irregular, i.e., not circular or rectangular. We have developed a

method for designing optimal 2-D windows with regions of support having an arbitrary shape. Our method formulates the window design as an eigenvalue problem and uses the power method for its solution. Indications are that these new windows will provide better performance in a number of systems.

Our work in image reconstruction from frequency offset Fourier data is motivated by the situation in synthetic aperture radar where the magnitude of a complex signal f is reconstructed with good accuracy from samples of the Fourier transform of f located in a small region considerably displaced from the origin. Ordinarily the offset of the Fourier data would preclude a high resolution reconstruction of $|f|$, however, we have conjectured that if the phase of f is random enough, then a good reconstruction will be possible. In an attempt to better understand this imaging mechanism we have conducted a series of image reconstruction experiments both with and without random phase for a number of different Fourier data locations. For the frequency offset locations, the random phase reconstructions are strikingly superior to the reconstructions without random phase. Analytical results have also been obtained which support this conclusion. In the future we are planning to learn more about the image phase in synthetic aperture radar and related systems with the ultimate goal of developing optimal estimation procedures for Fourier-offset image reconstruction.

Motivated by the missing cone problem in 3-D image reconstruction in non-destructive testing and computer-aided tomography, we have been looking into some of the fundamental issues in band-limited signal extrapolation. We believe that the two major reasons for the failure of existing algorithms (when applied to practical problems) are discretization errors and noise. We are therefore concentrating our research on these two factors.

The major results we have obtained during the past year include:

(1) Development of a unified viewpoint (in terms of 4 basic models) which clarify the confusion existing in the current literature about continuous and discrete extrapolations.

(2) Generalization of the discrete Cadzow algorithm and proof of the convergence of the discrete solutions to the continuous solution.

(3) Alternative formulations of the extrapolation problem in the presence of noise (which may lead to robust algorithms).

(4) Linking results on extrapolation in the signal processing literature to those in mathematics (integral equations, Hilbert space).

Our future research plans include:

(a) Finding bounds on discretization errors.

(b) Finding robust extrapolation algorithms in the presence of noise.

(c) Studying the related problem of phase retrieval.

18.2 Tomographic Image Reconstruction*

The convolution-back projection algorithm has long been a popular approach for reconstructing images from projections in computer-aided tomography. The advent of efficient procedures for computing general integer-order Hankel transforms, though, makes another algorithm, dubbed the Hankel transform reconstruction algorithm (HTRA), computationally viable. The HTRA expands the 2-D Fourier transform data into a series of circular harmonics and then performs a series of Hankel transforms on these harmonics to give a series of circular harmonics representing the reconstructed image. We have simulated the HTRA and shown that it compares favorably, in terms of speed and image quality, to the standard convolution-back projection algorithm. We are presently developing faster algorithms for computing the series of Hankel transforms required in the HTRA.

One approach to enhanced reconstruction in spotlight mode synthetic aperture radar and computer-aided tomography with partial data is to estimate portions of the missing data by various forms of 2-D bandlimited extrapolation algorithms. Two new algorithms have been proposed: (i) the projection-slice algorithm (PSA) and (ii) the angular iteration method (AIM). The PSA algorithm involves calculating projections of successive image estimates, and then using this data to reconstruct the image. Each time projection estimates are calculated, the measured projections are substituted into the positions where they are known. The AIM algorithm is based on the periodicity of the projec-

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tions with respect to angle. At each radius, the data is periodic in angle, and hence a special form of bandlimited extrapolation can be used, provided a reliable angular band-limit can be estimated. Experiments have successfully shown that the PSA and AIM algorithms can individually improve quality in the reconstructed image beyond that obtained assuming zero data. It has also been shown that the two algorithms can be combined for cases where improved resolution is worth the price of considerably extra computation.

18.3 Motion Estimation with Application to Robotics*

The objective of this project is to develop and study techniques for acquiring information about three-dimensional time-varying scenes from sequences of two-dimensional images. The motivation behind our basic research in this area is the use of computer vision in robotics. We are especially interested in trajectory planning of mobile robots.

During the past year, our research has concentrated on the determination of 3-D motion and structure of a rigid body based on 2 or 3 time-sequential images (central projections). This is done in 2 steps. In step 1, feature correspondences are found over the images. Then, in step 2, a set of equations is solved for the motion/structure parameters. Most past work used points as features in step 1, and required the solution of simultaneous non-linear equations in step 2 (which entails convergence and uniqueness problems). The major results we have obtained include:

(1) Simple linear algorithms for determining 3-D motion/structure using point correspondences, and theoretical results on uniqueness of solutions.

(2) Algorithms for 3-D motion/structure determination using straight-line correspondences.

(3) Algorithms for corner point detection and matching, with application to motion estimation.

(4) Algorithms for detecting and matching straight-line patterns, with applications to motion estimation.

In the future, our research will proceed along the following lines:

(a) To study some of the unresolved theoretical issues concerning solution uniqueness, especially for the straight-line correspondence case.

(b) To study the numerical stability of our algorithms for both the point and the line correspondence cases and to find robust motion/structure determination algorithms.

(c) To develop algorithms for point and line detection which give results to sub-pixel accuracy.

(d) To study the case of multiple rigid and nonrigid body motion.

18.4 Number Theoretic Concepts for the Realization of Failure Resistant Signal Processors in VLSI Circuit Technology*

This research involves a study of modular digital processor architectures that are suitable for VLSI realization. The objective is to develop modular structures for important signal processing kernels (convolution, FFT, recursion, etc.) with features that are advantageous for VLSI realization. In particular, residue number system (RNS) arithmetic and number theoretic transforms (NTTs) are being studied for their capability to realize high-speed modular processors that are easily partitioned for VLSI layout, and which provide an inherent form of error isolation due to the lack of interdigit carry. The following are some of the more important results that have been obtained recently:

(1) An RNS error checker which had been proposed earlier was constructed from discrete components and tested with a 68000 microprocessor system. It was observed that single digit errors originating within the error checker itself were detected and located in the same manner as errors in the incoming data.

(2) Many of the observed self-checking properties of the proposed RNS error checker were proved theoretically [R1].

(3) A VLSI layout was completed for a mod 11 module of a finite impulse response (FIR) digital filter using a ROM-accumulator architecture. The

IC is currently being fabricated at a silicon foundry.

(4) Error properties and correction algorithms have been analyzed for quadratic residue systems capable of realizing complex arithmetic [R2].

Present efforts are in progress to analyze computational efficiency and error properties for a recursive realization of an FIR structure in the RNS. This is a generalization of a new structure that was proposed several years ago [R3], and which has an attractive capability for VLSI realization.

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19. CLIMATE AND CROP STUDIES*

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An ongoing study is continuing to relate climate anomalies in one part of the world at a prior time to crop growing conditions in other regions of the world at some later times. A number of interesting climate-crop patterns have been found which have a high probability of repeating themselves every 3-7 years.

The climate-crop patterns can also be used as a means of crop forecasting. Varions types of time series analysis have been developed for recognition of these climate-crop patterns. Some of the crop time series contain data starting in 1866. A paper describing the relationship of corn yields in the United States to anomalons sea surface temperatnres in the eastern tropical Pacific Ocean has been published in <u>Science</u>. A second paper on this subject has been submitted to <u>Agricnltural Meteorology</u>. A third paper associating the effect of volcanic aerosols on subseqnent global climate has been submitted to <u>Science</u>.

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