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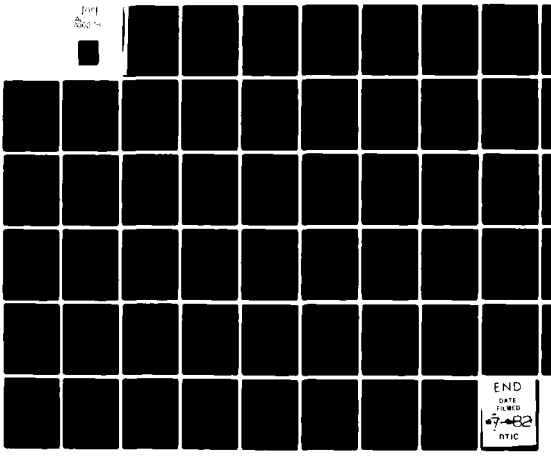

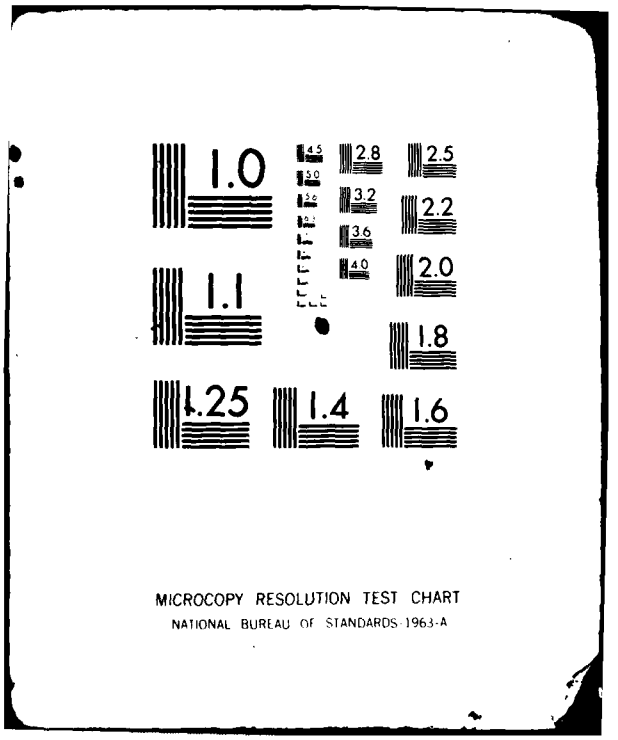
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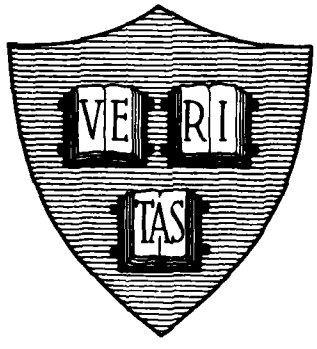

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I.1 Electronic Transport in Polycrystalline Semiconductors. D. Montgomery, and H. Ehrenreich, Contract N00014-75-C-0648; Research Unit 1.

The electrical transport properties of polycrystalline and amorphous semiconductors are of importance in connection with photovoltaics and semiconductor electronics, particularly as it applies to computers. The focus of the present work, which is just beginning, is on the electrical properties of polycrystalline silicon. At present, the problem of conduction in silicon in the presence of a scattering mechanism such as that produced by

the phonon interaction or by impurities and a few grain boundaries arranged in simple geometrical configurations is being examined. Since silicon can in fact be produced in this form, a comparison of these results with experiments might shed some light on the details of the potential model that should be used to describe the grain boundary.

The details of the electron-hole recombination process at a grain boundary are also being examined theoretically. This extension of the Hall-Shockley-Read theory might provide insight concerning the distribution of trapping levels within the band gap in the vicinity of the grain boundary.

It is hoped to extend this work to transport in an array of microcrystals by the use of an effective medium theory. For the present, however, the aim of the research effort is somewhat more modest: by identifying the parameters to which the theory is most sensitive, quantities such as the barrier heights and trap distributions, we hope to suggest interpretable experiments whose results could be used to refine existing models after comparison with a sufficiently general theory of the present form.

I.2 Electronic Structure of Interfaces. A.E. Carlsson, H. Ehrenreich, and K.C. Hass, Contract N00014-75-C-0648; Research Unit 1.

The objective of this work is to explore criteria for the existence of semiconductor interface states in a general, qualitative way in order to isolate the essential physical features that are responsible for these states. This effort is motivated by the fact that such states can have large and often deleterious effects on device properties. A model Hamiltonian approach is used in this work. This has the advantage that general features can be deduced directly from closed analytic expressions which leads to immediate physical insight. This approach should be contrasted to

many other theoretical efforts which have used computationally complex and therefore untransparent methods to make quantitative predictions concerning specific but nevertheless idealized interfaces.

We have already made considerable progress in understanding the conditions under which band gap interface states are found at semiconductor heterojunctions and grain boundaries.[1] A tight-binding bulk semiconductor Hamiltonian, which is a generalization of the Weaire-Thorpe form in that it has a more reasonable band-edge density of states behavior, has been used as the basis of this work. The effects of the interface are described by multiple scattering theory. Interface states are shown to be absent at perfect covalent heterojunctions and grain boundaries. Large interface band edge discontinuities further inhibit their formation. Band gap interface states may be present at polar heterojunctions and heterojunctions containing either uniformly weakened bonds or isolated localized defects.

The analytic conditions for the existence of those states are illustrated by means of density of states calculations using parameters appropriate within the limitations of the model for the Si grain boundary and the Si-SiO_2, Ge-GaAs, and AlAs-GaAs interfaces. A theorem placing bounds on the allowed spectrum at the interface extends these results to non-abrupt interfaces and more realistic bulk semiconductor Hamiltonians. The general features of the results obtained by these various approaches are in basic agreement with previous experimental and theoretical work.

At present this work is being extended in several directions. We would like to obtain a better understanding of the effects of interface defects on the electronic structure. Interface formation is known to be susceptible to chemical complexing effects and dissociation of the substrate

material, resulting in morphologies which are far from planar. The extension of such nonplanar effects over as little as two monolayers can have profound effects on the electrical properties since interface states at even low concentrations can play a major role in influencing device properties.

Our previous work treated both uniform bond weakening along the entire interface plane or the case of single weakened bonds. These results will be generalized in two directions. The first involves finite concentrations of such interface defects located in a plane. This can be accomplished using a generalization of the ATA and CPA techniques developed for random binary alloys,[2] which permit interactions among defect states to be taken directly into account. The second extension involves a study of the electronic structure of a heterojunction in which one side consists of a perfect semiconductor and the other one contains a large number of broken bonds or vacancies. Since interface behavior is frequently determined by the first few atomic layers, this model should provide a reasonable representation of at least some aspects of non-planar effects.

Carlsson's Ph.D. thesis[3] contains some preliminary results concerning the electronic structure at Schottky barriers utilizing a modified form of a rather untransparent formalism due to Garcia-Moliner and collaborators. As another part of the effort we hope to utilize a self-consistent version of this formalism to obtain some insight into such practically important questions as to the reasons for Schottky barriers being consistently smaller than what would be theoretically expected.

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1. A.E. Carlsson, H. Ehrenreich, K.C. Hass, and H.U. Baranger, "Conditions for the Existence of Germanium Interface States," submitted to *Physical Review* B, February 1981.

2. C.D. Gelatt, Jr., and H. Ehrenreich, *Physical Review* B10, 398 (1974).

3. A.E. Carlsson, Ph.D. Thesis, Harvard University, 1981 (unpublished).

I.3 Laser-Induced Disequilibrium in Superconducting Films. A.D. Smith, W.J. Skocpol, and M. Tinkham, Contract N00014-75-C-0648 and NSF Grant DMR-79-04155; Research Unit 2.

We have completed a tunneling study of the effect of laser-induced electronic disequilibrium in superconductive films. In the first series of experiments,[1] the small changes in tunnel current resulting from illumination with chopped laser radiation were measured and inverted (using a newly developed technique) to determine the changes in quasiparticle population in the two films. The results showed that the changes were well modeled by a small change in the effective electronic temperature, T*. An asymmetry in the I-V curves in these measurements pointed to the existence of a new thermoelectric effect[2] in tunnel junctions, which effectively produces a tunnel current proportional to the difference in T* in the two films caused by irradiation of only one of the films. This tiny current was then measured directly at zero bias using a SQUID picoammeter, allowing a more complete and systematic study to be made. A simple theory of this effect was developed, based on the energy-dependence of the tunneling probability, together with analysis of nonequilibrium populations by the Rothwarf-Taylor equations. This theory not only accounts for the sign, magnitude, temperature dependence, and laser-power dependence of the observed thermoelectric

current, but it also offers a possible explanation of long-standing discrepancies between earlier experimental results on point contacts and previous theories.

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2. A.D. Smith, M. Tinkham, and W.J. Skocpol, "A New Thermoelectric Effect in Tunnel Junctions," *Phys. Rev.* B22, 4346-4354 (1980).

I.4 Nonequilibrium Switching Phenomena. D.J. Frank, W.J. Skocpol, and M. Tinkham, Contract N00014-75-C-0648; Research Unit 2.

We are investigating the time scale for the appearance of a voltage drop along superconducting microstrips when their critical current is exceeded suddenly. A variety of experimental arrangements have been developed which are suitable to measure the 2-200 nsec times, which occur in Al, as a function of the temperature and the current pulse magnitude. These techniques have been tested on dirty Al strips and yield preliminary results which agree in general magnitude with those of Pals and Wolter,[1] except that we observe some increase in the delay times for temperatures within 4% of T_c. This observation is at least qualitatively in agreement with theoretical expectations. We also tentatively find delay times that are in agreement with the predicted dependence on current[2] when the current pulse is only slightly larger than the critical current.

In a collaboration with the IBM Watson Research Center, they have recently finished fabricating an integrated circuit with Josephson junction pulsers and samplers on it. This high speed circuitry should enable us to

resolve the 100 psec time scales expected in In and Sn. We are now developing the technique to fabricate In microstrips on these IC's, and we plan then to do the experiment, in collaboration with IBM.

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2. M. Tinkham,"Heating and Dynamic Enhancement in Metallic Weak Links," to be published in the Proceedings of the Maratea Conference on Nonequilibrium Superconductivity, Phonons, and Kapitza Boundaries.

I.5 Theory and Fabrication of Superconducting Point Contacts. G.E. Blonder, and M. Tinkham, Contracts N00014-75-C-0648 and N00014-77-C-0085; Research Unit 2.

An understanding of the noise and high frequency response of superconducting point contacts is predicated on an understanding of the d.c. I-V curve. Collaborating with Teun Klapwijk, who spent last year here on sabbatical from the Delft Technical University, we have been developing such a theory. Our approach is based on quantum mechanical solutions to the Bogoliubuv equations, with special care devoted to a proper definition of the appropriate transmission coefficients at interfaces in the presence of Andreev reflections. Our computer-generated plots agree quite nicely with experimental I-V curves from the available literature. As a natural consequence of this approach, including multiple Andreev reflections, we can also explain the "subharmonic gap structure" that appears in many superconducting devices with a constricted metallic region.[1] In contrast to earlier efforts at explaining this structure, our approach gives a natural explanation of what features are observed in asymmetric junctions, as well as of the equivalence of odd- and even-subharmonic peaks.

In addition, we have been pursuing an experimental program to develop photolithographic technology suitable for making three-dimensional point contacts. By using an anisotropic etch, a small, pyramidal hole is defined in a wafer of silicon. This is used as a matrix for a later metal evaporation. Although this work is in a very early stage, we have reason to expect that these devices will display good thermal cycling and stability.

Reference

1. See, for example, M. Octavio, W.J. Skocpol, and M. Tinkham, *IEEE Trans. Magnetics* MAG-13, 739 (1977).

I.6 Production and Characterization of Amorphous Semiconductors. D.A. Anderson, J. Blake, P. Ketchian, D.K. Paul, and W. Paul, Contracts N00014-75-C-0648, NSF DMR-78-10014 and NSF DMR-77-24295; Research Unit 3.

Amorphous semiconducting films of Si, $Si_{1-x}H_x$, Ge, $Ge_{1-x}H_x$, $Si_{1-x-y}Ge_xH_y$, GaAs, and $(GaAs)_{1-x}H_x$ have been produced by r.f. sputtering of crystalline targets by Ar onto substrates of 7059 glass, quartz, Al and c-Si held at suitable temperatures between 0°C and 400°C. The preparation parameters varied have included the substrate temperature, the partial pressure of Ar, the partial pressure of H, the r.f. power, and the partial pressure of dopant gases such as O_2, PH_3 and B_2H_6. We have also produced the same alloy films in a separate apparatus by the d.c. glow discharge decomposition of appropriate mixtures of SiH_4, GeH_4, SiF_4, H_2, AsH_3 and $Ga(CH_3)_3$.

The films are analyzed chemically, as required, by electron microprobe, and depth profiles determined by SIMS. X-ray examinations are used to verify amorphicity. The density is determined on chosen samples by floating

the sample in a liquid whose density may be varied, and the thickness is found using a Sloan Dektak profiling apparatus. The H contents are determined best by ^{15}N nuclear reaction analysis, but cruder estimates have been made either from H-evolution on heating or by infrared vibrational absorption.

These films have been used for measurements of transport, phototransport, photoluminescence, optical absorption, field effect, drift mobility and capacitance-frequency. A coherent self-consistent explanation of these data has been sought. In subsequent sections, only those measurements supported by the JSEP will be described.

I.7 Study of Conditions for the Optimum Configuration of Pseudogap States in Amorphous $Si_{1-x}H_x$ Alloys. D.A. Anderson, G. Moddel, S. Oguz, M.A. Paesler, P. Viktorovich, and W. Paul, Contracts N00014-75-C-0648, NSF DMR-78-10014 and NSF DMR-77-24295; Research Unit 3.

We have continued to examine the connection between the density of states distribution in the pseudogap and the film preparation conditions. The density of states distribution is measured directly by capacitance-frequency measurements or inferred indirectly from measurements of transport, phototransport, optical absorption and photoluminescence. The optimum state distribution depends on the end in view, as we emphasized in last year's report. The preparation parameters varied have been substrate temperature, partial pressure of hydrogen, partial pressure of argon, r.f. sputtering power, gas flow rates, substrate bias, and chemical and plasma cleaning procedures, as was also detailed last year. We have continued to evaluate the chemical content, and its profile through the film, using secondary ion

mass spectroscopy and the hydrogen content from H-evolution and I.R. absorption. We have also extended our structural measurements by TEM, SEM and STEM (at M.I.T.) measurements.

In general, our studies during this report period confirm our report of last year. Substrate temperatures above 400°C result in decreased H-incorporation, with the result that any improved healing effect on the network is more than offset by the reduced defect compensation by H. We find optimum reduction of gap states for $p_H \geq 0.8$ mTorr, and have determined during the year that the flow rate of H can vitally affect the film composition and properties, even while the partial pressure of H is held constant (the flow rate can be varied independent of p_H by changing the pumping speed). The argon pressure we have used has usually been 5 mTorr, but we have confirmed that the Ar incorporation depends, *inter alia*, on Ar pressure, and the result of this for film disorder and properties has still to be evaluated. The substrate d.c. bias has been found to be an important parameter in the modification of ionic bombardment which presumably affects the disorder in the film. Fine tuning of this to give optimum results is difficult, because too little bombardment can result in films which incorporate weakly bound debris, while too much can create too much disorder. Experiments along these lines continue. Finally, we have continued the study of the incorporation of O, C, N and other contaminant species and its modification by pre-sputtering plasma cleaning. A major result of this study has been the establishment that there is always a build-up of contaminant near the substrate-film interface; an offshoot of this realization has been the study of techniques to bury the contaminant in an interfacing film (between substrate and a-Si:H). This has resulted in the measurement, for the first

time anywhere, of a very substantial field effect response in sputtered a-Si:H.[1]

The results of variation of film preparation conditions for the properties have been incorporated in a number of papers.[2-10] Thus, the results for the increase in the main PL peak near 1.4 eV and the incidence and magnitude of a defect-related peak near 0.9 eV have been reported, as well as the temperature dependence of the PL magnitude, which depends critically on the extent of the tail to the conduction band density of states.[2,6] The conditions leading to increased gap state density attributable either to new Si-H configurations or to H-catalyzed defects were reported in references 3, 8 and 10. Reference 9 compared photoemission results carried out by one of the authors (B. von R.) earlier at Stuttgart with new photoconductivity results in order to establish variations in gap state density on an absolute energy scale. The Oguz and Paesler study[4] examined the evolution of H from a-Si:H in two separate regions of temperature and found the activation energies and diffusion limitations on the two quite different processes involved. Finally, reference 7 examined the changes in oscillator strength of several Si-H vibrational absorptions in the infrared caused by He-ion bombardment, and their subsequent alteration on annealing. This study established the danger of careless use of the integrated I.R. absorption as a measure of H-content in samples of possibly different defect density, and has led to a more informed choice of which vibrational mode can be used for H content estimation.

I.8 Study of Transport in a-Si:H Alloys. D.A. Anderson and W. Paul, Contracts N00014-75-C-0648 and DOE-DEACO-379-ET-23037; Research Unit 3.

The results of four years study of transport properties have been written up for publication during this report period. Conductivity and thermopower as a function of temperature for films produced under different conditions of substrate temperature and partial pressure of hydrogen were analyzed as a group. Large numbers of films investigated provided sufficient statistics that reliable conclusions could be drawn concerning the results.

In low H-content films, the properties are dominated by a single (hydrogenated) phase of a-Si and the data show great consistency over a wide range of deposition conditions. We interpret this result to mean that the states near the conduction band edge are affected little by H-incorporation and that the transport takes place at a well-defined energy level, which appears to be independent of the deposition conditions of sputtering, and indeed of the deposition method.

There are nevertheless several anomalies that occur, both in our studies and in parallel studies of others or both glow-discharge and sputtered material, viz. (1) a decrease in slope of the activated log σ vs. $1/T$ relation at high temperatures, (2) a difference between the activation energies for conductivity and thermopower, (3) an anomalously high intercept at $1/T = 0$ for the curve of thermopower versus $1/T$, which is not in accord with any theory available, and (4) a high value of σ_0, the pre-exponential in the expression for the conductivity, $\sigma = \sigma_0 \exp[-E_\sigma/kT]$. We have proposed that the first three of these anomalies can be explained on a model of a film composed of two phases, one the (island) phase of hydrogenated

a-Si where dangling bonds are compensated by H and the second (tissue) a highly-hydrogenated, highly-defected phase which connects the growth islands. We suppose that the islands and tissue have different chemical constitution, structure, electronic band structure and transport properties, and offer what we consider to be plausible rationalization of the above anomalies as caused by the changing relative importance of the conductance of the two phases.[13] This model has received major support from our demonstration, based on it, that there exists a range of high T_s and moderate p_H where the anomalies either disappear ((1) and (3)) or are minimized ((2)). These preparation conditions are postulated to give films where the volume is connective tissue between islands is cut to a minimum.

This model has been extended to explain the results for films of high H-content. Here it is supposed that the tissue material may dominate the transport and give rise to high magnitude, unactivated conductivity and relatively T-independent, high magnitude (mV range) thermopowers. It should be said that this type of model is consistent with our ideas on how thin films grow from vapors, and that under certain conditions, the resulting structure may be seen in TEM and SEM micrographs. However, over much of the range of the present studies direct structural examination reveals no microstructure--not wholly unexpectedly since it is supposed to occur on a scale of 10-30 Å. As a result of this division of our p_H range on the basis of nondominant/dominant microstructure, we have stated to examine the other properties we measure for confirmation of our transport deductions.

I.9 Photoconductivity in Amorphous $Si_{1-x}H_x$ Alloys. D.A. Anderson, G. Moddel, and W. Paul, Contract N00014-75-C-0648; Research Unit 3.

Measurements of the photoconductivity spectral dependence have been continued and extended to a wide range of a-Si:H samples, leading to low energy absorption data and hence information about how the joint density of states giving rise to it varies with other sample properties. Correlations have been found between the height of an absorption feature seen at low energies, the midgap state density as determined by capacitance/conductance measurements, the slope of an exponential absorption tail and the bandgap size, both for sputter and silane decomposition produced a-Si:H, and contrasted with a-GaAs:H and A-SiGe:He alloys.

The temperature dependence of the photoconductivity and its decay after illumination is cut off has been studied, yielding values for a drift-mobility which appears activated. Combining these results with the temperature and intensity dependence of photoluminescence yields quantitative parameters involved in the radiative recombination process and the state distribution just below the conduction band edge. Measurements of the photoconductivity magnitude and decay time as a function of intensity have been combined with the temperature dependences to show likely paths for nonradiative recombination, leading, finally, to a basis for an overall model of recombination.

Publications of the Research Reported in Sections I.7 to I.9

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15. D.A. Anderson and William Paul, "Transport Properties of a-Si:H Prepared by Sputtering III (in preparation).

I.10 X-Ray Scattering in Liquid Crystals. J. Collett, E. Chason, L. Sorenson, and P.S. Pershan, Contracts N00014-75-C-0648, NSF DMR79-23597 and NSF DMR79-19479; Research Unit 4.

In collaboration with Professors J.D. Litster and R. Birgeneau of M.I.T. we carried out an X-ray diffraction study of the smectic-B liquid crystal 40.8 Å. Previous studies on these more ordered smectic phases were ambiguous on the difference between liquid crystalline and true three-dimensional crystals. In a previous publication, Birgeneau and Litster[1] proposed a model that could serve to distinguish between these phases. The material 40.8 had previously been widely studied and was generally accepted as being of the smectic-B character. The principal result of the investigation was that for this material the phase identified as smectic-B was in fact a full three-dimensional crystal with long-range order. Superimposed on the long-range order, however, was a very large degree of diffuse scattering corresponding to considerable short-range disorder in these materials.

The manuscript on this subject was submitted to the 8th International Liquid Crystal Conference in Kyoto held in July of 1980.[2] In addition to the discovery of the long-range order in this particular material we carefully investigated the phase transition between the smectic-A and B phases. Previously a number of authors had believed this transition to be continuous with considerable pre-transition effects. We demonstrated unambiguously the transition was first-order and that apparent pre-transition effects could be simulated by trace impurities that provided a finite width to the coexistence region.

A second X-ray study was carried out in collaboration with Drs. Als-Nielsson and D. Moncton at the Risø National Laboratory in Denmark and at

the Synchrotron in Hamburg. The shape of a Bragg peak associated with the smectic-A order has been theoretically predicted to be qualitatively different than that of true crystals.[3] In this work we 1) showed that the shape of the Bragg peak associated with the layer spacing is essentially unchanged between the A and the B phases. The intensity in the B phase is up by about a factor of 3, but otherwise there is almost no difference; 2) we were able to carry out this type of experiment at the Synchrotron at Hamburg demonstrating that with the use of synchrotron radiation the same high resolution experiments that could only be done with a rotating anode machine in a matter of weeks can be done at synchrotrons in a matter of minutes. We are currently fitting the data from this experiment and will prepare a publication for the next fiscal year. Preliminary indications are that the elastic constants obtained from the observed line shapes are consistent with $B \sim (\Delta t)^{0.3}$. Critical scattering at the high temperature side of the transition was also measured.

We have initiated a collaborative experiment with the group at M.I.T. (R.J. Birgeneau) to measure X-ray diffraction structures of freely suspended thin films of various ordered smectic phases. An oven for this purpose has been constructed and tested, a linear detector purchased at M.I.T. has been made operable and preliminary measurements have been taken to demonstrate that we have adequate signal-to-noise. In the next report period we hope to investigate a series of phases in materials closely related to 40.8 Å.

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I.11 Light Scattering from Thin Smectic Films. L. Sorenson, and P.S. Pershan, Contracts N00014-75-C-0648, NSF DMR79-23597, and NSF DMR79-19479; Research Unit 4.

Following earlier work by Rosenblatt, *et al.*[1] we are continuing to study the orientation of fluctuations in thin smectic films. The earlier studies measured the intensity variations as one applied a strong electric field to the sample. We are currently instrumenting to measure the spontaneous, thermal fluctuations in the presence of a small, steady biasing field. We will repeat the earlier studies of critical fluctuations near the high temperature transition to a tilted phase from one in which the molecules are normal to the layers. We will also study the phase transition that occurs at lower temperatures when the film undergoes a transition from what is essentially a two-dimensioanl fluid to one of more ordering. Results of this latter study should bear on theoretical studies on melting in two dimensions.[3]

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I.12 Elastic Properties of Liquid Crystals. M. Fisch, L. Sorenson, and P.S. Pershan, Contracts N00014-75-C-0648, NSF DMR79-23597, and NSF DMR79-19479; Research Unit 4.

The experimental apparatus to measure surface modes in smectic liquid crystals is now operating according to design. A set of measurements have been made on the material 4-N-octyloxy-4'-cyanobiphenyl (80CB). This material, along with a number of others, is believed to have a continuous (second order) phase transition between the nematic and smectic-A phases. Consequently, physical parameters such as the interlayer elastic constant, B, are expected to go to zero continuously as one approaches the phase transition from the smectic-A side. All previous measurements to confirm this belief have either been indirect using either the "undulation instability technique,"[1,2] or correlation time measurements of the Rayleigh scattered light.[3,4] In any case by any of these techniques one does not measure B directly but rather one measures the correlation length which is the ratio of B to a K constant.

Although one suspects that the quantity K does not vary significantly with a direct measurement of B is desirable. The surface scattering developed here provides the first direct measurement of B that is sufficiently precise that one can follow the temperature dependence to within .01°C of the transition.

We have evaluated the technique by repeating the measurement on a number of different samples at both different heights and scattering angles. All of these yield the same value of B. The best fit to the temperature dependence produces $B \sim (\Delta t)^{\phi}$ where ϕ is equal to $.31 \pm .02$. A manuscript describing preliminary results on this work was presented at the 8th

International Liquid Crystal Conference held in Kyoto in July 1980. That paper is to be published in the Proceedings of the Conference.

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I.13 Forced Rayleigh Scattering in Smectic Liquid Crystals. P.S. Pershan and D.B. Carlin, Contracts N00014-75-C-0648, NSF DMR79-23597, and NSF DMR79-19479; Research Unit 4.

We have developed a forced Rayleigh scattering system, based on a technique developed in this laboratory for multilamella lipid samples,[1] for diffusion constant measurements in liquid crystals. Electronic component failures which were a major source of delay during this past year have been largely overcome.

We have tested the system on bulk samples of both iodine in toluene and isotropic 40.8 liquid crystal. We have determined thermal diffusion constants in these materials with fair reproduciblity. Mixing of homodyne and heterodyne signals has caused occasional spurious results and has necessitated the development of a phase-locked heterodyne detection system.

While signal strengths in the bulk samples has been strong, the $\sim 10^{-5}$ thickness reduction of a freely-suspended thin film sample[2] promises commensurate decreases in signal strength. Determinations of thermal conductivity will be correspondingly difficult in thin film samples and has not yet been seen.

We are currently engaged in an attempt to observe the permeation mode in an aligned bulk sample of smectic 80CB. Direct observation of this mode has never been reported. It is predicted to have molecular transport coefficients of $\sim 10^{-3}$ to 10^{-4} smaller than thermal diffusion.[3] An oven has just been constructed incorporating two stages of temperature control and permanent magnets for sample alignment in permeation mode experiments.

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I.14 Raman Scattering in Lyotropic Liquid Crystals. S.A. Asher, P.S. Pershan and T. Urabe, Contracts N00014-75-C-0648, NIH 5-R01-GN-24, 081-02; Research Unit 4.

We have previously developed techniques to make single crystals of dipalmitoyl-phosphatidyl choline-water mixtures for a narrow range of conditions. Polarized Raman spectra have been taken on these samples and analyzed to the point that we can determine the relative orientation of the chain axes through the crystallographic axes. X-ray measurements were also

carried out in the same material. Up to 15 orders of the long spacing were observed and 14 separate reflections corresponding to in-plane structure was observed. On the basis of this result, we were able to identify the unit cell of this crystal as monoclinic with lattice parameters 8.02, 10.54 and 49.3 Å with an angle of 85° between the two short dimensions. A manuscript on this work was submitted to the 8th International Liquid Crystal Conference at Kyoto in July of 1980.[1]

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II. QUANTUM ELECTRONICS

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II.1 Nonlinear Four-wave Mixing in Vapors. A. Bogdan, M. Dagenais, M. Downer, Y. Prior, and N. Bloembergen, Contract N00014-75-C-0648; Research Unit 5.

It has been predicted that coherent signals can be generated and exhibit extra resonances induced by an incoherent collision process.[1,2] In the absence of pressure there is destructive interference between two coherent pathways. However, in the presence of collisions this interference is eliminated, giving rise to a coherent signal.

The four-wave mixing (4 WM) experiments are performed in Na vapor in the presence of He buffer gas. We have studied two of these pressure induced resonances as a function of He pressure. One resonance shows an enhancement in our generated intensity at the frequency $2\omega_1 - \omega_2$ when the difference in frequency, $\omega_1 - \omega_2$, between two of the dye lasers corresponds

to the difference in energy between the $3^2P_{1/2}$ and $3^2P_{3/2}$ states of Na. The other resonance occurs when $\omega_1 = \omega_2$. In both cases our lasers are tuned near the P-doublet, but none of the incident frequencies (ω_1, ω_2) or their combinations $(2\omega_1, \omega_1 - \omega_2, 2\omega_1 - \omega_2)$ are exactly resonant with any material energy levels. To observe these resonances a three-dimensional phase matching geometry is employed[3] which allows our generated signal to be spatially separated from our incident lasers even in the degenerate frequency case.

Over the past year, we have successfully demonstrated these effects using a nitrogen laser pumped dye laser system.[4,5] To perform detailed lineshape studies these experiments were repeated on a cw dye laser system (purchased with JSEP funds). Due to the lower power and much narrower linewidth these lasers can be timed much closer to resonance (well within the impact approximation). Excellent agreement with theory is observed and papers have been submitted on this work.[6,7]

Work is currently being performed on an as yet unreported type or pressure induced resonance--a Raman type resonance which can occur between two equally populated levels. The two levels we use are the $F = 1$ and $F = 2$ hyperfine levels of the $^2S_{1/2}$ ground state of Na.

With the upgrading of one of our cw dye lasers (JSEP funding) to obtain two actively stabilized cw dye lasers we will be able to study the degenerate and hyperfine resonances in more detail. In addition it should be possible to study a pressure induced resonance in two photon absorption in Na when one of our lasers is timed between the $3P^{1/2}$ and $3P^{3/2}$ and the other laser is timed from there up to the 5S or 4d levels. It is believed that these new pressure induced effects will provide novel spectroscopic information about collisional interactions.

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Papers Presented

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N. Bloembergen, "Coherent Four-Wave Mixing Induced by Incoherent Collisions," Invited Paper presented at the 11th Winter Colloquium on Quantum Electronics, Snowbird (Utah), January 1981.

II.2 Two-Photon Absorption in Lanthanide-Doped Crystals. M. Dagenais, M. Downer, R. Neumann, and N. Bloembergen, Contract N00014-75-C-0648; Research Unit 5.

Our earlier observations[1] of direct two-photon absorption in the Gd^{3+} ion embedded in a LaF_3 crystalline host have been extended to include measurements with the actively stabilized dye laser (purchased with JSEP funds) operating in the single-mode configuration. With the sample at liquid helium temperature, inhomogeneous linewidths as narrow as 7 GHz were observed. Quantitative measurements of the shift of the line positions with temperature and line broadening from phonon-electron interactions were also made with the single-mode system. These new results, which were presented at two conferences,[2,3] demonstrated the value of two-photon absorption experiments for extending high-resolution spectroscopy in lanthanides to excited states in the ultraviolet region of the spectrum.

Our major interest has centered on the intensities of the two-photon transitions from the $^8S_{7/2}$ ground state of Gd^{3+} to three excited states. Quantitative measurements of the relative integrated intensities of the three multiplets were made with a continuous wave dye laser operating broadband. The polarization dependence of the two-photon absorption intensities was studied in detail, and strong anisotropics were observed. It was realized that these measurements provided a new and sensitive test of the standard theory of lanthanide transition intensities formulated by Judd and Ofelt in 1962.[4] Our observations revealed serious discrepancies with theoretical predictions. A report on these observations, including possible explanations of the discrepancies, has been accepted for publication in Physical Review Letters.[5] We believe that this publication will stimulate considerable theoretical interest, and open up a new experimental field of nonlinear spectroscopy in lanthanides.

Future plans include measurements of two-photon intensities in other lanthanide ions, and high-resolution studies using the technique of fluorescence line narrowing. The latter experiment will employ the recently purchased spectrum analyser to analyse the fluorescence following two-photon excitation of the $^8S_{7/2} \rightarrow {}^6P_{7/2}$ transition in Gd^{3+}.

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II.3 Picosecond Laser Induced Phase Transformation on Semiconductor Surfaces. R. Yen, J.M. Liu, and N. Bloembergen; Contract N00014-75-C-0648, Research Unit 6.

In the preceding reporting period we have published a paper showing that an amorphous layer can be formed on the surface of a single crystal of silicon by irradiating the surface with a picosecond laser pulse at 532 nm or 266 nm.[1] These experiments were performed in air on untreated silicon

surfaces which ordinarily have a native surface oxide layer of about ~10 Å to 20 Å thickness.

It has recently been suggested that ambient oxygen could have a profound effect on the formation of amorphous silicon because the absorbed oxygen impurity could retard the silicon regrowth rate during resolidification and thus facilitate the formation of the amorphous layer. In order to settle this question, the following experiment has been performed. A 10 nsec ruby laser pulse was used to prepare atomically clean silicon surfaces in ultra-high vacuum. With picosecond Nd:YAG laser pulses, the amorphous patterns formed on the atomically clean silicon surfaces were compared with those formed in air and other ambient conditions. Results show that the picosecond laser-induced phase transition of silicon does not depend on the ambient conditions, nor on the native surface oxide layer of silicon.[2]

Experiments are planned to determine the role, if any, of the so-called "plasma-annealing" mechanism during our pulsed laser annealing experiments.

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II.4 Picosecond Laser Induced Nonlinear Photoemission from Metals. R. Yen, J.M. Liu and N. Bloembergen, Contract N00014-75-C-0648; Research Unit 6.

This research has been fully reviewed in the recently completed Ph.D. thesis of R. Yen.[1] It was presented in part at the Eleventh International Conference on Quantum Electronics in June, 1980. Multiphoton photoelectric emission has proven to be an effective tool for studying the physical mechanism of the photoemission process. Specifically the dependence of the multiphoton photocurrent on the incident angle and state of polarization of the laser pulses has been studied. From this dependence photoelectrons that originate from the bulk and those that originate from the surface can be distinguished.[1,2,3] Experiments carried out with 30 picosecond at 1.06 μm pulses at intensities higher than 10^9 watts/cm^2, show the influence of heating of the tungsten metal surface layer.

Instead of four photons necessary to overcome the work function, thermally excited electrons can now be liberated by the absorption of only three photons. With computer simulation good agreement between the theory and the observations of anomalous behavior at very high intensities has been obtained.

The theory also predicts that the characteristic time for heat exchange between the conduction electrons and the lattice lies in the range of 1-10 picosecond. With a laser pulse of duration shorter than a few picoseconds, it should be possible to heat the electron gas, which has a small heat capacity, to a very high temperature, while the lattice remains cool. Efforts are presently under way to observe such effects experimentally. Such anomalous heating effects would be important in elucidating the dynamics of solid state electron-phonon interactions.

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II.5 Laser-Plasma Interaction. P.R. Kolodner and E. Yablonovitch, Contract N00014-75-C-0648 and ED78-S-02-4631; Research Unit 7.

This study of resonance absorption of laser light has been completed. A detailed report of the findings, over the past three years has been presented in the Ph.D. Thesis of P.R. Kolodner. He has joined the Bell Telephone Laboratories, Murray Hill (NJ). Professor E. Yablonovitch has left Harvard University and is now with the Exxon Research and Engineering, Linden (NJ).

Evidence has been found for a nonrandom process which emits a monoenergetic burst of suprathermal electrons of 1 to 2 picoseconds duration. A brief account of this work has been published. A more detailed report has been prepared and submitted for publication in the Physical Review. This research project is herewith terminated.

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II.6 Time Resolved Infrared Double Resonance Spectroscopy. R. Sharp and N. Bloembergen, Contracts N00014-75-C-0648 and N00014-78-C-0531; Research Unit 7.

In a continuation of experiments designed to investigate the dynamics of intramolecular vibrational energy randomization, we have used the advanced infrared laser technology of our laboratory to complete a unique infrared double resonance experiment on SF_6. Thirty picosecond CO_2 laser pulses from two independently tunable CO_2 lasers were utilized in a standard pump and probe arrangement to obtain the time resolved spectra. Pumping the N_3 vibrational mode of the SF_6 molecule with the P20 CO_2 wavelength, we have probed changes in the absorption spectrum in a time resolved manner throughout the entire N_3 band and observed interesting features not previously obtained in nanosecond pulse experiments. The results of this work, to be published in a forthcoming paper,[1] indicate a sharp hole burned at the excitation wavelength, in addition to the usual redshifting of the absorption spectrum due to anharmonicity. The sharp holeburning feature, unobserved in nanosecond pulse work, indicates the collisionless domain in which the picosecond pulse experiments are conducted is essential to observing truly intramolecular vibrational relaxation effects.

In the true resolved data of the SF_6 work, two distinctly different forms of behavior are observed. Fast transients, which rise and fall with the excitation pulse, are associated with saturation in the bottlenecked discrete states. Slower phenomena, which appear to behave in accordance

purely with the integrated energy of the pump pulse, are associated with quasicontinuum excitation. These effects give further support for the quasicontinuum model.

In order to investigate the nature of intramolecular vibrational relaxation more completely, we are now undertaking experiments which involve pumping one infrared active band and probing the absorption in a different band in the same molecule. These experiments are designed to observe the nature of energy randomization from one vibrational mode to another in the molecule. Such experiments should give further insight into the feasibility of mode selective laser chemistry, a subject of intense interest to the synthetic laser chemist, as evidenced by the recent issue of Physics Today, November 1980, which contains four review articles on the subject.

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II.7 Infrared Multiphoton Excitation of Excited Electronic States in Molecules. Jeff Y. Tsao, Itamar Burak, and N. Bloembergen, Contract N00014-75-C-0648; Research Unit 7.

The infrared multiphoton excitation of ground electronic states is a well-studied phenomenon. This work extends the phenomenon to excited electronic states, thereby adding a very sensitive detection tool, visible fluorescence, to current diagnostics.

Using a synchronized infrared-visible double resonance system based on our picosecond CO_2 and Q-switched ruby laser pulses, we were able to

induce the first known direct infrared multiphoton pumping of excited electronic states, in NO_2[1] and biacetyl.[2]

Since then, we have concentrated our efforts on the related phenomenon of inverse electronic relaxation (IER), in which the infrared multiphoton pumping of the ground electronic state may also lead to population in the excited electronic state. We were able to settle the controversy over the origin of the IR multiphoton induced luminescence in CrO_2Cl_2, showing that CrO_2Cl_2 dissociates sequentially in an intense IR field, and that the parent as well as at least two dissociation fragments undergo IER and luminescence.[3,4]

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II.8 Multiphoton Vibration Excitation. J.G. Black, E. Yablonovitch, T. Simpson, and N. Bloembergen, Contracts N00014-75-C-0648 and N00014-78-C-0531; Research Unit 7.

The systematic study of the energy deposition by 100 nanosecond and 500 picosecond CO_2 laser pulses in a variety of molecules has been completed. A simple, low-cost laboratory computer interface was constructed.[1] Such computer interfaces are now used in several other research projects in our laboratory. The averaged energy absorbed per molecule and the dissociation rate has been measured as a function of energy fluence and peak intensity

results have been obtained for SF_6, CF_3I, CF_2HCl, C_3F_7I and CF_3-CO-CF_3. They confirm the general ideas about quasi-continuum absorption and bottlenecking in a systematic manner. Detailed results may be found in the Ph.D. Thesis of T.G. Black. Dr. Black has joined the Xerox Research Laboratories in Rochester, NY. A condensation of the thesis is in preparation for publication in the scientific literature.[3]

It is obvious that diatomic molecules have no vibrational quasi-continuum of levels, and they cannot be dissociated by monochromatic IR radiation in a collisionless process. There is still an outstanding question about the behavior of triatomic and other small polyatomic molecules. For OCS (sulfur carbonyl), collisionless dissociation was reported some years ago, but never confirmed. Absorption data indicated a saturation of the absorbed energy per molecule. These results were clearly inconsistent with each other. We have investigated the OCS molecule under collisionless conditions with ultrashort CO_2 laser pulses. Our peak energy fluence (250 Joules/cm^2) and our peak intensity (3×10^{11} watts/cm^2), were considerably higher than used previously. We have found no evidence for dissociation even under these extreme conditions. The average amount of energy absorbed is less than one photon per molecule under the same conditions. The absorption increases, however, with intensity and does not show a saturation behavior. Previous absorption data were apparently influenced by rotational hole filling by collisions. Under collisionless circumstances the ratio of the Rabi frequency to the width of the rotational band is of importance. A manuscript on these new observations has been prepared.

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III. INFORMATION ELECTRONICS CONTROL AND OPTIMIZATION

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III.1 Estimation Theory. R.W. Brockett, Contract N00014-75-C-0648; Research Unit 8.

The idea of looking at nonlinear filtering problems by applying nonlinear system theory to the conditional density equation appears now to be a firmly established part of the literature. New results on this problem were discussed at the NATO/ASI meeting on Stochastic Systems in June 1980. In Ref. 1 there is a systematic discussion of this point of view together with new results on the structural properties of Lie algebras which can arise in connection with nonlinear filtering. In a recent paper,[2] Hijab has investigated a certain stochastic control problem with incomplete observations. This appears to be one of the very few interesting problems in combined estimation and control which can be solved.

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III.2 Nonlinear Systems. R.W. Brockett, Contract N00014-75-C-0648; Research Unit 8.

In his thesis[1] Wong develops, in a systematic way, a series of important connections between the methods of (linear) functional analysis and the analysis of finite dimensional nonlinear control system. The cornerstones of this approach are the Volterra series, approached from the point of view Carleman linearizations and the idea of a Fock space. Wong develops a new class of invariants for the characterization of nonlinear systems. These invariants have important implications for nonlinear identification problems as well as the study of the input-output behavior of nonlinear systems.

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III.3 Linear Systems. R.W. Brockett, Contract N00014-75-C-0648; Research Unit 8.

The area of automatic identification of systems is one which is of great importance in adaptive control. As has been pointed out before, the various relevant spaces of linear models are not well understood. In

papers[1,2,3] below new results, bringing us significantly closer to the point where we put fundamental limitations on what can be accomplished using adaptive control, are established. In particular, it is shown in Ref. 3 that because of certain complications in the geometry of the space of linear models, there exist no algorithm in a certain natural class which will automatically identify the input-output characteristics of a linear system of a specified complexity. On the other hand, the new methods available in nonlinear estimation theory give as a second tool to use on identification problems. In unpublished work[4,5,6] we have shown how this combination can lead to new results not available from either point of view alone.

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III.4 Incentive as a Many-Person Optimization Problem. Y.C. Ho, G.J. Olsder, T.S. Chang, L. Servi, and P. Luh, Contracts N00014-75-C-0648 and NSF ENG78-15231; Research Unit 9.

The idea of declaring a reward (punishment) for a decision maker according to his particular choice of action in order to induce certain "desired" behavior on the part of the decision maker is known as incentive (threat). This practice is age old. However, only in recent years have the notions been formalized. The person who declares the incentive (a contingency contract which says I shall do this if you do that) is known as the "leader," the decision maker who receives the incentive based on his action is the "follower." Viewed in this light, the incentive problem can be formulated as a multi-person Stackelberg game problem with a nonclassical information structure. The exploration of the conceptual basis and the applications of this basic problem constituted a major part of our effort in optimization research for the past year.

The overall approach has been to view the incentive problem as a coupled control problem involving two or more persons. First the deterministic version of the problem is analyzed. In particular, the role of dynamics and information structure is detailed. The basic concepts developed is then extended to stochastic case where its relationship to the economic literature is pointed out.

(i) Incentive Pricing for Utilities

The research work was initiated by peak load problems of electric systems. The initial phase of the effort involved a broad survey of the literature in the areas of electricity pricing and load management.

From a game theoretic point of view, pricing problems are Stackelberg games where the utility company plays the role of the leader, and customers

play roles of followers. Several pricing schemes were analyzed. In recognizing the limit of the peak load pricing formulation and the persuasive breakthrough in microelectronic technology, we formulate the Load Adaptive Pricing problem as a closed-loop Stackelberg game.

The central part of the Load Adaptive Pricing problem is "incentive." Incentive problems were then studied and a unified treatment and some new results were developed.

Load Adaptive Pricing problem was then solved for a particular producer consumer model. We demonstrated that the utility company can induce customers to behave cooperatively to achieve the team optimum and the society is better off under Load Adaptive Pricing than under peak load pricing. As the number of cycles approaches infinity, our results show the solutions converge and the system is stable.

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(ii) Stochastic Incentive Problem

An incentive problem can be roughly described as follows. Let us consider a firm with two divisions (agents) which makes decisions based upon their private information and self-interests. The authority (leader) in the firm hopes that divisions could exchange information and cooperate as a team to optimize the firm's operation as a whole. To achieve his goal, the authority then announces a certain kind of incentive scheme, e.g., performance-dependent bonus, to influence divisions' decisions indirectly so that they could behave like a team.

The problem is nontrivial because the leader cannot determine if the divisions have acted correctly based on their private information. He must somehow induce the truth so to speak. Secondly, the divisions also face a stochastic decision problem in which the information structure is nonclassical. These difficulties combined with system dynamics makes the problem very challenging.

If there are enough noncooperative agents, we showed that, under relatively mild conditions, the leader could successfully induce the agents to behave like a team all the time. Moreover, there typically exist infinite number of feasible incentive schemes. We proposed a systematic way to pick up one of the feasible schemes to fulfill the balanced budget requirement, if such a scheme exists. We also discussed the noise robustness property and schemes with expected surplus. Finally, we applied our method to solve a class of closed-loop stochastic Stackelberg dynamic game which is considered to be unsolvable before.

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III.5 Electrical Networks and Resource Allocation Algorithms. L. Servi, Contracts N00014-75-C-0648, N00014-79-C-0776, and NSF ENG78-15231; Research Unit 9.

An investigation was conducted[1,2] to explore the ties between resource allocation algorithms and electrical networks. The result was a proof of an isomorphism between the differential equations governing the resource allocation algorithms and the differential equation governing some electrical networks. This theorem was used in two different ways: First, the isomorphism between the two areas permitted the use of intuition and knowledge of (well-studied) electrical networks to simplify several proofs of properties of the resource allocation algorithms. Secondly, the ties led to the first known application of incentive structures to a resource allocation algorithm.

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III.6 Estimation in the Presence of Uniformly Distributed Measurement Noise. Y.C. Ho and L. Servi, Contracts N00014-75-C-0648, N00014-79-C-0776, and NSF ENG78-15231; Research Unit 9.

A study was undertaken to examine the convergence properties of a new recursive estimation algorithm[1] which found the minimum error variance estimate of a system, absent of disturbance noise, with observations that were masked by uniformly (not Gaussian) distributed noise. For a special

case it was found that the error variance was asymptotically proportional to the inverse of the *square* of the number of observations in contrast to the Kalman filter (which is the minimum *linear* error variance algorithm) for which the error variance is asymptotically proportional to the inverse of the number of observations.

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III.7 Optimization and Control of Manufacturing Networks. R. Suri, Contracts N00014-75-C-0648, N00014-79-C-0776, and NSF ENG78-15231; Research Unit 9.

Our recent research has been directed towards the modelling, control and optimization of a new class of automated manufacturing systems, the so-called Flexible Manufacturing System (FMS)*. FMS's have been widely recognized as the key to improved productivity in certain manufacturing sectors. However, while we have developed the technology to *construct* these systems, our ability to *analyze* and optimize their performance remains relatively primitive. Lack of ability to control the performance of an FMS in an optimal fashion means that, while several advanced (and expensive) systems have been installed, their full potential is not being harnessed. Thus it is clear that the availability of analytical tools would prove

*Other terms for these systems are Computerized Manufacturing Systems (CMS), Integrated Computer-Aided Manufacturing (ICAM), and Advanced Batch Manufacturing Systems (ABMS).

extremely useful to users of FMS. Our research on this topic has focused on two main issues: (i) developing good analytic models for predicting FMS behavior, and (ii) developing theoretical and computational tools for optimization and control of FMS operation.

With respect to analytic models of FMS, previous researchers had suggested the possibility of using analytical queueing models for FMS, although there was no theoretical basis for doing so. Our recent analytic results on queueing network models[1,2,3] in fact provide such a basis. Our results also have other uses: they explain why classical queueing models have worked well for many real-world systems that violate some classical assumptions; they enable derivation of sample statistics of performance measures of networks; and they enable precise bounds to be placed on the behavior of certain nonclassical networks.

For the optimization and control of FMS's, we have studied the theoretical issues, and also developed algorithms and computational tools. A summary of our work in this area can be found in Ref. 4. In Ref. 5, we study the optimal feedback control of an FMS, while in Ref. 6, we develop a sub-optimal but efficient algorithm for real-time control of an FMS.

Based on an analytical approach, our techniques have given much better results than previously proposed heuristics.[6] Our methods and results show the scope for achieving still better results in the future.[4]

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III.8 Stochastic Realization Theory. P.E. Caines and D.F. Delchamps, Contract N00014-75-C-0648; Research Unit 10.

At one level, stochastic system theory addresses the problem of modeling physical phenomena as inputs and outputs of stochastic dynamical systems and analyzing the actual processes based on a knowledge of the properties of the systems modeling them. Stochastic realization theory, on the other hand, concerns itself with examining for a given stochastic process the set of *all* models which take on a certain form--usually linear and finite-dimensional--and thereby gaining insight into the process and the possible models for it. In recent years, the notion of a state space stochastic realization for a wide-sense stationary process has been developed and refined by many workers (see refs. 1-6). In our work, we have sought to link certain disparate approaches to the problem under the condition that the given process has a rational spectrum. The connections established in Ref. 7 illuminate important structural characteristics of stochastic processes. In particular, the theory has applications in linear

estimation theory and identification. During the past year, with a view toward applications in nonlinear estimation and control, we have sought to extend the main results of stochastic realization theory to cover certain classes of stochastic processed defines on manifolds.

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III.9 Stochastic Adaptive Control. P.E. Caines and D.J. Dorer, Contracts N00014-75-C-0648 and NASA NCC2-39; Research Unit 10.

Basic techniques for the control of linear state space systems, for example state feedback, require accurate prior knowledge both of the form of the system to be controlled and the associated matrix coefficients. The system matrix coefficients must be determined through a combination of

physical considerations and the process of parameter identification, that is the statistical estimation of model coefficients from experimental measurements of system response.

When the parameters of a linear system change or cannot be accurately determined without extensive experimentation, control systems which adapt, or make an update of the control, using measurements of system outputs have advantages over a fixed linear feedback law.

Recursive adaptive control algorithms, which both estimate the linear system coefficients and update the control associated control law have been studied. The system and control law are presented in discrete time, that is sampled data form, and the control laws are of recursive type, requiring only a fixed number of computations to perform the coefficient update and generate the control signal. The system inputs, outputs, and parameters are in the form of stochastic processes. This allows for the effects of unmeasured system noise and stochastic time variation of the system coefficients. A formulation of this type becomes necessary since, in practice, measurements on a system involve noise and need to be treated mathematically as stochastic processes in order to evaluate system performance under realistic conditions.

Under suitable restrictions on the noise inputs and parameter variation, an algorithm previously studied in Ref. 1 for the fixed parameter case will stabilize a stochastically varying system with additional system noise. The performance of this algorithm is evaluated in terms of an expected mean square tracting error. One feature of this approach is that the parameter estimates, which are only used inside the control computation, may not converge in any useful sense.

More specifically, the results of Ref. 1 on the tracking performance of adaptive algorithm have been extended to the case where the underlying system parameters vary according to a random law, or martingale stochastic process, rather than remaining constant. For a stochastic tracking algorithm, that is a control designed to follow or track accurately a prescribed signal, one measure of performance can be obtained by evaluation of the expected square tracking error. Under suitable restrictions on the system noise and stochastic parameter variation, an adaptive algorithm initially studied in Ref. 1 for the fixed parameter case, has been shown to cause the closed loop system, which includes the randomly varying portion, to track a bounded reference signal. More precisely, if the parameters are represented by convergent martingale processes with values satisfying a matrix positive real condition, then the average asymptotic expected square tracking error of the closed loop system assumes the value of the associated limiting fixed coefficient stochastic system.[5]

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IV. ELECTROMAGNETIC PHENOMENA

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Research in the area of electromagnetic radiation is directed toward the solution of practical problems through the complete understanding of the underlying physical phenomena. This involves the coordinated application of modern analytical, numerical, and experimental techniques and the use of high-speed computers and precision instrumentation. Application is also made of modeling techniques and the principle of similitude. Most practically significant problems in this area are sufficiently complicated that extensive computation and measurement are often required to justify approximations that are usually necessary. Where possible, general formulas are obtained and verified experimentally so that the phenomenon under study can be understood physically in analytical form and not just as a set of numbers.

The researches are concerned primarily with the properties of antennas and arrays and of the electromagnetic fields they generate in various practically important environments that lead to difficult problems with complicated boundary conditions. Examples include dipoles, traveling-wave antennas and arrays, crossed dipoles and loops near the boundary between two media such as air and earth or sea water, and rock and sea water; dipoles in finite

bodies composed of dielectric, conducting or layered materials; active and passive loops near the surface of the earth or with dissipative cores; and the fields in the complicated geometry of electromagnetic pulse simulators with and without scattering obstacles.

IV.1 Theoretical and Experimental Study of the Scattering from an Obstacle Above the Earth. H.-M. Lee, T.T. Wu, R.W.P. King, and L.C. Shen, Contracts DAAG29-79-C-0109 and N00014-75-C-0648; Research Unit 11.

The scattered electromagnetic field from a conducting loop located above water has been studied.

Measurements of the scattered field at a wavelength of 20 cm were completed. The data involved the scattered field strengths and phases from a set of eighteen loops with circumferences varying from 11 to 36 cm at heights ranging from about 1 to 20 cm. The axis of the loop was held normal to the water surface when its scattered fields were measured. The experiment was carried out above the water tank in the penthouse on McKay Lab. The height variation was achieved by changing the water level of the tank while everything else, including the loop, the transmitting and the receiving antennas, was held fixed. Thus the relative phase for the incident field at the center of the loop from the transmitting antenna was always a constant.

A surface current distribution in the form of Tchebichef polynomials across the width of the loop, multiplied or divided by a square-root factor, was assumed. This factor allowed the surface current component along the circumference of the loop to have a square-root singularity at the edges of the loop while allowing the component across the width of the loop to vanish as the square-root of the distance from the edges. Such a current distribution was obtained for the problem of scattering by the same loop in free

space using an iterative method. Hence it was assumed that the presence of the water changed only the expansion coefficients.

Many of the terms in the solution involved integrals similar to the famous Sommerfeld integrals. Numerical integrations which were very time consuming had to be carried out. The results compared favorably with the experimental measurements.

Efforts have been made to find good approximations to the Sommerfeld integral. Professor Wu devised a method to obtain a uniform approximation of the Sommerfeld integral over almost all distances from a radiating dipole in water. It seems that a systematic expansion of the integral in appropriate small parameters can be achieved. A breakthrough in this area would make possible the analytic solution of this problem in a manner similar to that in the free-space scattering problem.

The field scattered from a straight wire arranged horizontally in air over the earth when illuminated by a plane wave incident at an arbitrary angle is more difficult to determine accurately than the field scattered from a circular loop. However, when the horizontal wire is at a height d that is in the range $0.01 \leq d/\lambda_0 \leq 0.15$ (where λ_0 is the wavelength in air), the theory of the horizontal-wire antenna over a dissipative half-space is applicable.[1,2] In this range the induced currents can be determined using the generalized transmission-line formulas, and from them the scattered field can be calculated. The currents have been obtained in this manner and a program for calculating them and the scattered field is being written.

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IV.2 Scattering by a Thin-Wire Cross. R.W.P. King and B.H. Sandler, Contracts N00014-75-C-0648 and DAAG29-79-C-0109; Research Unit 11.

The currents and charges induced in a right-angled cross of thin wire have been determined analytically when the arms of the cross have arbitrary lengths but the exciting field is normally incident.[1] They have also been determined when the active field is incident at an arbitrary angle but only for the equi-arm cross and *only in zero-order*.[2] This approximation does not take account of the effect of cross coupling. A complete first-order analysis has now been carried out for a cross with arms with different and unrestricted lengths excited by a field arriving from any angle and polarized in any direction.[3,4] Detailed graphs are provided for the currents in and the scattered fields of an equi-arm cross when the angle of incidence is 45°, the electric field is polarized perpendicular to the horizontal member of the cross, and the arm lengths are in the range $kh \leq 3.5$ which includes one even and two odd resonances. The effect of changes in the length of each of the vertical arms has been determined for both normal and non-normal incidence, and the critical conditions relating to three-arm and four-arm types of oscillation have been discussed.

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IV.3 Numerical and Analytical Determination of Fields of Antennas near an Interface between Two Half-Spaces with Significantly Different Wave Numbers. T.T. Wu, R.W.P. King, B.H. Sandler, and L.C. Shen, Contracts N00014-75-C-0648 and N00014-79-C-0419; Research Unit 11.

The theoretical tools available for the study of the propagation of electromagnetic waves in a region composed of two half-spaces filled with two different material media include 1) the general complex integrals originally due to Sommerfeld for the field of an infinitesimal dipole parallel or perpendicular to the plane boundary, and 2) simple formulas due to Baños for restricted, nonoverlapping ranges that approximate the field. A detailed numerical evaluation of the general integrals for the radial electric field due to an electric dipole in a half-space of earth or water bounded by air has been carried out and compared with Baños' approximate formulas.[1] Numerical calculations have also been made of the field and the Poynting vector in both regions quite close to the dipole in order to illuminate the excitation of a lateral wave by a dipole.[2] More extensive numerical computations of the six components of the electromagnetic field are in progress.

A great step forward in the analytical treatment of lateral waves has recently been achieved by T.T. Wu who derived a new single formula that accurately represents the exact general integrals for the radial electric field over the complete range of frequencies and distances. Computations of E_ρ from this quite simple formula agree with the corresponding values

obtained numerically from the general integrals. The importance of the availability of this formula in the study of not only the propagation but also the reflection and scattering of lateral waves at boundaries and surface irregularities cannot be overestimated. The derivation of comparable formulas for the other components of the field is planned.

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IV.4 Lateral-Wave Propagation and Modeling of the Lithosphere. M.F. Brown, J.T. deBettencourt, J.M. Dunn, R.W.P. King, L.C. Shen, and T.T. Wu, Contracts N00014-79-C-0419 and N00014-75-C-0648; Research Unit 11.

An experimental study of lateral-wave propagation along the boundary between salt water and air (modeling the ocean and the lithosphere respectively) is in progress. During the past year experiments were conducted to study the effects of surface irregularities and discontinuities of various types. Rectangular styrofoam sheets of different sizes were placed in the path of the lateral wave at different depths in the salt water to form air "square wells." The results are widespread in nature, but all attest to the indestructibility of the lateral wave. Studies of deep wells for two thicknesses show that the reflection before the obstacle is much greater for the thicker styrofoam slab. Nevertheless, the character of the propagating wave remains unchanged at distances beyond the perturbing effect of the obstacle. Work is currently in progress to study the effects of wedge-shaped obstacles,

whose geometry is more characteristic of mountains. An investigation will then be made of the inverse effect of "walls" of salt water extending upward into the air in the path of the lateral wave. A theoretical treatment of idealized surface irregularities is also planned to provide a basis for the interpretation of observed effects. A paper describing the apparatus, available theoretical solutions, and preliminary measurements correlated with theory was presented during the year.[1]

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IV.5 Transmission and Reception with Embedded Bare and Insulated Antennas. R.W.P. King, S. Prasad Hinchey, and B.H. Sandler, Contract N00014-75-C-0648; Research Unit 11.

An experimental and theoretical study has been made of the properties of insulated antennas embedded at a considerable depth below the surface of a living organism or of the earth.[1,2] Special attention has been given to devising methods of transmitting power for localized radiation or heating. Four different insulated coaxial lines and antennas with interesting and useful properties when inserted in a hole in a general dissipative medium have been studied. These are the insulated coaxial line with extended inner conductor, the insulated center-driven dipole with choke section, the insulated sleeve dipole, and the series-connected insulated transmission-line antenna. Measurements of the currents on the insulated, series-connected, transmission-line antenna have been completed. They are in good agreement

with theory. Measurements of the currents on the insulated center-driven dipole with choke section and on the insulated sleeve dipole are in progress. The insulated conductor embedded in an electrically dense, conducting or dielectric medium has been shown to be a versatile device for communication or heating. It is readily adapted to use in bore holes or close to a boundary for lateral-wave transmission. It can be operated as a resonant element or as a traveling-wave antenna and, with appropriate dimensions, is useful at frequencies ranging from the highest to moderately low ones.

An earlier study of the electric field in a three-layered half-space when illuminated by an incident plane wave has been completed.[3] The layers have the properties of skin, fat, and muscle. The impedance and voltage across the load of a dipole antenna is discussed when this is located in each of the three layers and in the air near the surface. Bare and insulated antennas are considered over a frequency range up to 3 GHz with layer thicknesses of skin from 0.2 to 1.0 cm, and of fat from 0 to 1.5 cm. The transmitting problem is discussed as well as application of the results to finite bodies.

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IV.6 Theoretical and Experimental Study of Electromagnetic Fields and Antennas in Dissipative and Dielectric Cylinders. R. Bansal, Contract N00014-75-C-0648; Research Unit 11.

The investigation of the induced electromagnetic fields inside a finite dielectric cylinder illuminated by a plane wave is nearing completion. The experimental study of the electric field in the interior of a cylinder of water (height = 50 cm, radius = 8.64 cm) at three frequencies (100, 300, and 600 MHz) for the conductivity range $0 < \sigma < 3.5$ S/m was the subject of a recent conference paper.[1] During the past year, effort was focussed primarily on the development of a fast and inexpensive analytical-numerical solution. By taking advantage of the fact that water has a large (in general complex) relative dielectric constant, we have been able to "decouple" the internal absorption problem from the external scattering problem. We first solve the external problem numerically using a surface integral-equation solution, adapted from a fast moment-method algorithm,[2] and compute the tangential magnetic field $\vec{H}_{tan}$ on the surface of the cylinder. This $\vec{H}_{tan}$ then serves as the boundary condition for an analytical eigenfunction solution of the internal problem. Since the internal problem is solved analytically, it has been possible to incorporate the central conducting tube in our theoretical model without significantly increasing computation time or labor. (The conducting tube was required in the experimental setup to shield the transmission lines leading to the probes.) The basic procedure can be iterated for improved accuracy. Some computations for the salt-water cylinders have been carried out, and the theoretical results are in good agreement with the corresponding experimental data. The application of the method to the distilled-water case is complicated by the possibility of internal "resonances" in the cylinder. Suitable modifications in the

procedure are currently under investigation. A paper discussing the theoretical method has been submitted recently for presentation.

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IV.7 The Loop Antenna with a Cylindrical Core. R.W. Burton, R.W.P. King, E. Burton, B.H. Sandler, and T.T. Wu, Contract N00014-75-C-0648 and Southeastern Center for Electrical Engineering Education (SCEEE); Research Unit 11.

The electromagnetic field of an electrically small loop antenna with a cylindrical core can be evaluated approximately from the field of a loop around an infinitely long circular cylinder. The infinitely long cylinder may be conducting or insulating. Measurements made with an electrically small half-loop over a ground plane at a high frequency with cylinders of water having widely different conductivities have been applied, with the help of the principle of similitude, to a very large loop around a mountain at a very low frequency. The measurements indicate that, at least for the field in the plane of the loop, the cylinder of matter can be approximated by an image loop with an empirically evaluated current. Confirmation of this hypothesis awaits the numerical calculation of the general integrals for the field for both sets of conditions.

IV.8 Antennas in Matter. R.W.P. King, M. Owens, and T.T. Wu, Contracts N00014-75-C-0648, F19628-76-C-0057, and F44620-72-C-0021; NSF Grant ENG 75-14455; Research Unit 11.

The results of current and past researches, supported by the above Contracts and Grant, on bare and insulated antennas in and over dissipative or dielectric media have been integrated into a three-part book.[1] The book presents a full treatment of a sequence of research that has become increasingly important in recent years--the use of *underground antennas* for communication with miners and subway trains and for the geophysical exploration of the earth's crust; *underwater antennas* for communication with and between submarines and divers and for oceanic research, including telemetry from areas beneath the polar icecaps; and *antennas embedded in or near living organisms* for biomedical telemetry and diagnostics in tissue and layered media with electromagnetic properties as diverse as those of fat, muscle, and bone. The book has been designed to serve a dual purpose: the first and third parts, covering fundamentals and measurements, form a self-contained introduction for undergraduates and researchers in geophysics and bioengineering; the second part provides a detailed presentation of the theory of the subject for graduate students and researchers in electrical engineering and physics. The approach integrates analytical, numerical, and experimental methods for the solution of a variety of problems involving antennas and electromagnetic wave propagation in or near matter.

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IV.9 The Resistive Bifurcated Parallel-Plate Waveguide. H.M. Shen, Contract N00014-75-C-0648; Research Unit 11.

Often in a guided-wave system, higher mode electromagnetic waves are excited by a nonuniform structure, and it is desired to absorb them without affecting the principal mode. This can be achieved with a bifurcating resistive sheet. A detailed analysis has been made of an infinite parallel-plate waveguide bifurcated by a resistive sheet of finite length.[1] A TEM wave propagates in the z-direction together with some of the lower TM and TE modes. After the space has been divided into three regions, the series solutions in them are matched across the boundaries. Then, the eigenequation is used to determine the propagation and four sets of equations are solved for the unknown coefficients. The series solutions converge rapidly and are readily applied to obtain conditions of maximum absorption. It is found that with a proper choice of surface resistance and length of plate the reflection coefficient for the TM wave can be made very small.

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IV.10 Electromagnetic Fields and Currents and Charges on Cylinders in a Parallel-Plate Transmission Line. D.J. Blejer, T.T. Wu, R.W.P. King, and H.M. Shen, Mission Research Corporation Subcontract SC-0082-79-0009 and Contract N00014-75-C-0648; Research Unit 11.

EMP simulators consisting of a central parallel-plate region and tapered input and load sections are well known to provide a high quality of simulation of an incident plane wave at all frequencies for which the spacing

of the parallel plates is a small fraction of the wavelength. In this range the electromagnetic properties of the simulator are those of the well understood two-conductor transmission line in which TEM waves propagate from the generator to the terminating impedance, radiation from the structure is negligible, and reflections at the junctions of the tapered and parallel-plate sections are insignificant. When the terminating impedance is equal to the characteristic impedance of the structure, the standing-wave ratio (SWR) is small and most of the power supplied by the generator is dissipated in the termination.

At higher frequencies for which the wavelengths of interest are comparable with the parallel-plate spacing, radiation becomes a dominant instead of negligible property of the structure which now behaves more like an antenna than a transmission line. Significant reflections occur at the junctions of the parallel plate and tapered sections and at their edges so than only a small fraction of the input power actually reaches the terminating load. Most of it is radiated since the electromagnetic field, instead of being bound quite close to the conductors, now extends far out in space. The representation of the field between the parallel plates by a TEM mode becomes inadequate and higher modes are required. An earlier experimental study of the field in the Harvard model simulator at the high frequency of $f = 625$ MHz showed that, due to strong radiation loading when the plate spacing h is greater than a wavelength, the SWR in the parallel-plate region was quite low (less than 2.0).[1]

In an intermediate frequency range when $h \lesssim \lambda$, neither the transmission-line termination nor the radiation loading is effective in maintaining a low SWR in the parallel-plate region. In particular, when $f = 271$ MHz and $h = 75$ cm $= 0.67\lambda$, the SWR is generally of the order of 5 to 6 and, in

addition, a very deep minimum (notch) is observed with an associated SWR as high as 25. An experimental investigation has been conducted to study the electric field throughout the parallel-plate region of the Harvard model simulator at f = 271 MHz.[2,3] Attention has been directed to determining the origin of the deep minimum and to devising means for eliminating it and reducing the otherwise quite high SWR.

It is shown that the isolated deep minimum or "notch" is due to the mutual cancellation of the imaginary parts of the TM_{01} and TEM modes. The effects on the SWR and the deep minimum of changes in the magnitude and location of the terminating resistance are investigated. Also studied are the introduction of a bifurcating plate, resistive modal filters, and series aprons. It is shown that with the proper adjustment of the last named, the "notch" can be eliminated and the SWR reduced to near two over the entire mid-frequency range. Since the low-frequency and high-frequency ranges already have low SWR's, the simulator has been made effective over the entire frequency band in the sense that the SWR is low.

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V. SIGNIFICANT ACCOMPLISHMENTS REPORT

V.1 Theory of Subharmonic Gap Structure in Superconducting Contacts.
G.E. Blonder, and M. Tinkham; Research Unit 2, SOLID STATE ELECTRONICS.

Superconducting point contacts and other microscopic metallic constrictions are interesting from a purely conceptual standpoint as well as from the point of view of a versatile experimental technique with device applications. It is surprising, therefore, that even the d.c. I-V curves of these devices have remained imperfectly understood even after many years of application and attempts at explanations. This situation has been changed during the past year by a general theory of micro-constrictions which we have developed in collaboration with Dr. Teun Klapwijk, who spent the year here on leave from Delft Technical University.

Our approach is based on solutions to the quantum mechanical Bogoliubov equations, with special care devoted to a proper definition of transmission coefficients at the constriction. The key observation is that a quasiparticle in the barrier is able to change repeatedly, via Andreev reflections, from electron-like to hole-like states. For a clean interface and in the presence of an applied voltage V, the quasiparticle gains an energy eV from each of many multiple reflections, and the curious subharmonic gap structure is the result. In contrast to earlier efforts at explaining this structure, our approach gives a natural explanation of which features are observed and which are not, in asymmetric junctions, as well as accounting naturally for the equivalence of odd- and even-subharmonic peaks in symmetric junctions,

an outstanding difficulty of previous theories. A dirty interface, such as an oxide barrier, makes higher-order reflections less likely, decreasing the strength of the subharmonic gap structure. In the limit of a high barrier, our results reduce continuously and naturally to the usual tunnel junction I-V curves.

Our computer-generated plots agree quite nicely with experimental results in the available literature. It is especially important that our conceptual approach has such wide applicability and allows correct, qualitative reasoning without recourse to complex formalism.

V.2 Standing Waves and Notches in a Parallel-Plate Type of EMP Simulator and Their Reduction. T.T. Wu, R.W.P. King, and D.J. Blejer; Research Unit 11, ELECTROMAGNETIC PHENOMENA.

When a nuclear explosion occurs in the atmosphere, a powerful outward-traveling pulse of electromagnetic radiation is generated that can have dangerous effects on aircraft or missiles in its path. In order to study these effects and the means to avoid them, very large simulators have been constructed in which aircraft and missiles are exposed to electromagnetic pulses. Recent experiments on the Harvard model simulator have led to a method which significantly improves their performance.

In order to serve the intended purpose, the electromagnetic pulse or wave in a simulator must closely resemble that due to an explosion in the atmosphere. Unfortunately, the pulses generated in existing full-sized simulators have not completely satisfied this basic requirement in that significant unwanted reflections occur at the higher frequencies contained

in the spectrum of the pulse. These distort the active field and with it the magnitude and nature of the observed effect on obstacles illuminated by it.

With a small model simulator constructed at Harvard, a systematic study has been in progress to reduce or eliminate the undesired reflections and their effect on objects located in the electromagnetic field. This has been done at individual frequencies selected from all parts of the spectrum characteristic of the properly scaled pulse. Because the shape of the simulator is analytically simple only in the low-frequency part of the spectrum where transmission-line theory is a good approximation, much of the work has been experimental. Specifically, the electromagnetic field throughout the model simulator has been measured directly both in the absence and presence of metal obstacles in the form of cylinders and crossed cylinders and flat plates.[1-3]

From a systematic accumulation of data and their interpretation in terms of mode theory, the origin of peculiar, very deep minima or "notches" in the field at discrete frequencies and locations in the simulator has been determined. It has also been shown that the simulator behaves like a properly matched transmission line with a low standing-wave ratio *only* at the low end of the frequency spectrum. At the high end, it has the properties of a horn antenna, but also with a fairly low standing-wave ratio due to a high level of radiation. In the intermediate range of frequencies, neither radiation nor the resistive termination is effective as loads so that the standing-wave ratio is undesirably high.

To reduce this high standing-wave ratio, a novel device called a series apron has been developed and tested. When properly adjusted, it greatly reduces the standing-wave ratio at the intermediate frequencies, yet has

little effect on the high- and low-frequency ends of the spectrum. This device simultaneously eliminates the deep minimum or "notch." In this manner undesired reflections have been greatly reduces so that the field in the simulator has been brought much closer to the required traveling-wave distribution characteristic of the field propagating outward from a nuclear explosion.

The importance of this accomplishment is brought out by measurements and calculations of the currents and charges induced on electrically thick cylinders when located in the simulator. These have been shown to have magnitudes and distributions that are very different when the cylinder is excited by a traveling wave than when excited by a standing wave, especially when this has a deep minimum or "notch."

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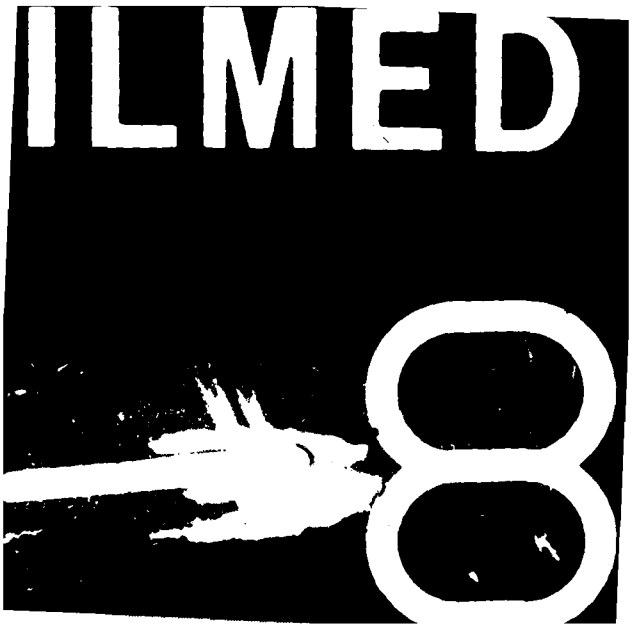
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