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JSEP FINAL REPORT

May 1, 1985 through April 30, 1988

J. S. Harris
Principal Investigator
Program Director
(415)723-9775

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Period of May 1, 1985 - April 30, 1988

**Department of Electrical Engineering
Stanford University
Stanford, CA 94305**

**Joint Services Electronics Program
(U.S. Army, U.S. Navy and U.S. Air Force)
Contract DAAG29-85-K-0048**

**J. S. Harris
Principal Investigator
Program Director**

Monitored by U.S. Army Research Office

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Abstract

This is the final report of the research conducted at Stanford Electronics Laboratories under the sponsorship of the Joint Services Electronics Program from May 1, 1985 through April 30, 1988. This report summarizes the areas of research, identifies the most significant results and lists the dissertations, publications and presentations sponsored by the contract (DAAG29-85-K-0048).

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1. INTRODUCTION

This report summarizes the activities in the research programs at the Stanford Electronics Laboratories sponsored by the Joint Services Electronics Program under contract DAAG29-84-K-0047. This contract is monitored by the Army Research Office, Research Triangle Park, North Carolina.

This report covers a period of significant change in the Stanford JSEP program. Three of the six initial projects were new, and during the course of the three year program, two new projects were initiated in the second year and one of the initial projects was completely changed in the third year. Thus, the program at the end of the three year period had fewer than half of the initial projects. This was not a reflection of needed change from the quality of the projects, but a conscious decision to focus JSEP funds on seeding new ideas and projects which could lead to larger programs with conventional DoD funding, but would take one to two years to proceed through the proposal process. The JSEP flexibility provides great leverage in seeding such new ideas in the interim period when virtually nothing would otherwise occur.

The research program is divided into main areas:

- Semiconductor Materials, Processes and Circuits
- Information Systems

The work units and tasks within each of the above areas are summarized below, together with the investigator responsible for the unit.

1. Semiconductor Materials, Processes and Circuits

- a. Quantum Well and Reduced Dimensional Semiconductor Systems (yr 1&2) and Molecular Beam Epitaxy of High T_c Superconductors (yr 3) (J. S. Harris)
- b. Ultra-Submicron Devices (R. F. W. Pease)
- c. GaAs/Integrated Circuits (B. A. Wooley)
- d. Complementary MOS Device and Material Physics at 77°K (J. D. Plummer and K. C. Saraswat)
- e. The Chemical and Electronic Structure of Refractory Metal GaAs Interfaces (C. R. Helms, I. Lindau and W. E. Spicer)
- f. The Study of Crystal Properties Using Channeling Radiation (R. H. Pantell)

2. Information Systems

- a. Coding for Spectrally Constrained Channels (J. M. Cioffi)
- b. Real Time Statistical Signal Processing (T. Kailath)

2. SIGNIFICANT RESULTS

The most significant accomplishments, as determined by the JSEP Principal Investigator and Director, are summarized as follows:

- *Molecular Beam Epitaxy of High T_C Superconductors*

The objective of this project is to investigate the growth of the new perovskite high temperature superconductors by molecular beam epitaxy (MBE). The layered nature of the Cu-O makes MBE an attractive approach to synthesize these materials. This work was carried out in collaboration with the MBE group at the Varian Research Center, where the MBE system is located. Superconducting films were deposited and a 90°K superconducting transition was obtained on annealed DyBaCuO films. We demonstrated that molecular O₂ was not incorporated into the MBE films and that to achieve in-situ films, one would have to utilize a more reactive O source. Using an O plasma source and shuttering the Ba and Dy to force a layering to match the desired DyBaCuO structure, we obtained a variety of perovskite materials with stoichiometry very close to the desired superconducting phase. In-situ films with ~ 60°K transitions were obtained in this manner. The most encouraging observation was that by shuttering, metastable phases of these materials could be realized which have not been observed by other growth techniques, suggesting that indeed, "engineered" structuring might be possible. It also demonstrates that the "architectural engineer" growing these structures must know precisely what to build, as other than the superconducting phases can readily form. This work was the first to demonstrate that these materials could be grown by MBE, which was not at all obvious, and it has resulted in a number of publications and an invited paper at the International MBE Conference.

- *Ultra-Submicron Devices*

MESFETs with gate lengths down to 65 nm and transconductances as high as 330 mS/mm were fabricated. A study of transconductance vs gate length revealed no evidence of increased effective saturation velocity due to velocity overshoot phenomena for gate lengths down to 90 nm. MODFETs with GaAs and InGaAs channels were also fabricated with gate lengths as small as 55 nm. The GaAs channel MODFETs had transconductances as high as 415 mS/mm, and the InGaAs MODFETs had transconductances as high as 315 mS/mm. GaAs channel MODFETs were found to have a maximum effective saturation velocity of 1.95×10^7 cm/s at a gate length of 150 nm. The occurrence of this maximum effective saturation velocity near a gate length of 150 nm agrees with the predictions of Kizilyalli et. al. The techniques for ultra-short gate lengths are now being used to process lateral quantum devices. A lateral double barrier resonant tunneling MODFET has been fabricated where the depth of the central well is tunable with a stacked gate configuration.

- *Real Time Statistical Signal Processing*

The goals of this research program have been to study the direction-of arrival (DOA) estimation and adaptive beamforming problems and in particular to focus on innovative techniques that have computational and performance advantages over existing methods. Of special interest is the beamforming problem in the presence of "coherent" interference as can arise in "multipath" and "smart" jammer environments. A new concept was introduced, called the "smoothed rank profile", which can be exploited to completely determine the source coherency structure in the presence of coherent signals. The key idea here was to employ a signal-free covariance matrix in determining the optimum weight vector, in an attempt to account explicitly for the underlying signal model. Using this approach, two different versions of an optimum uniform linear beamformer were obtained that completely eliminate the signal cancellation phenomenon associated with signal coherency.

- *Coding for Spectrally Constrained Channels*

We have developed a coding method, called "vector coding", that allows the design of error-correcting codes that have both good distance properties and allow the spectral shape of the transmitted code words to be specified. Basically, the method combines filtering and coding together in one entity. On all channels that we've investigated, this vector coding achieves the maximum possible transmission rate practically achievable, often called the "cut-off rate".

3. SEMICONDUCTOR MATERIALS, PROCESSES AND CIRCUITS

3.1 QUANTUM WELL AND REDUCED DIMENSIONAL SEMICONDUCTOR SYSTEMS AND MOLECULAR BEAM EPITAXY OF HIGH TEMPERATURE SUPERCONDUCTORS

The initial objective of this project was to investigate heterojunction, quantum well and superlattice concepts and their application to new electronic devices with superior performance to devices based upon current semiconductor device principles. The properties of carrier transport and storage in various regions of these ultra-small, 3-dimensionally confined structures are not well understood and their application to an entirely new generation of electron devices is in its infancy. High magnetic fields provide an alternate means to achieve electron confinement, and hence, reduced dimensionality. Investigation of the current-field characteristics of very lightly doped gallium arsenide samples at liquid nitrogen temperatures revealed that parallel magnetic fields have profound effects on the mobility of warm electrons. Large magneto-impurity effects at 4K confirm the dominance of impurity impact ionization over the conductivity in this material up to relatively large electric fields. These results provide insight into the physics of one-dimensional electron transport. Eight publications and a completed Ph.D. dissertation resulted from this effort.

Near the end of the second year, the 1 or 2-dimensional nature of the new high T_c superconductors provided an incentive to utilize the capabilities of MBE to grow and investigate electron transport in these materials. In collaboration with the MBE group at Varian Research Center and with the superconductivity group in the Applied Physics Department at Stanford, we embarked on an effort to make thin films of the new high temperature superconductors by MBE. Superconducting films were deposited and a 90°K superconducting transition was obtained on annealed DyBaCuO films. We demonstrated that molecular O_2 was not incorporated into the MBE films and that to achieve in-situ films, one would have to utilize a more reactive O source. Using an O plasma source and shuttering the Ba and Dy to force a layering to match the desired DyBaCuO structure, we obtained a variety of perovskite materials with stoichiometry very close to the desired superconducting phase. In-situ films with ~ 60°K transitions were obtained in this manner. The most encouraging observation was that by shuttering, metastable phases of these materials could be realized which have not been observed by other growth techniques, suggesting that indeed, "engineered" structuring might be possible. It also demonstrates that the "architectural engineer" growing these structures must know precisely what to build, as other than the superconducting phases can readily form. This work was the first to demonstrate that these materials could be grown by MBE, which was not at all obvious, and it has resulted in a number of publications and an invited paper at the International MBE Conference.

3.2 ULTRA-SUBMICRON DEVICES

We are using electron beam lithography combined with GaAs technology and MBE to study the physics and device possibilities associated with one, two, and three-dimensionally confined electrons. An existing custom ultra-high resolution electron beam column has been adapted for device fabrication. These modifications include a stage that will hold 2 and 3 in. wafers for ease in later processing and a custom pattern generator that facilitates fine line lithography and has an alignment accuracy of 100nm.

As a precursor to the fabrication of quantum devices, a GaAs process sequence has been established by fabricating MESFETs and MODFETs with sub-tenth micron recessed gates on MBE grown wafers. The gate was defined with UHREBL using a thin (70 nm) layer of PMMA resist. Before deposition and liftoff of the gate metal, the gate recess was formed with a citric acid etch that did not attack the PMMA unlike the more common etchants.

MESFETs with gate lengths down to 65 nm and transconductances as high as 330 S/m have been fabricated. A study of transconductance vs gate length revealed no evidence of increased effective saturation velocity due to velocity overshoot phenomena for gate lengths down to 90 nm. A strong variation in the drain source saturation current, I_{dss} , with gate length was determined to be the result of citric acid etch rate dependence on the size of the resist opening. A lower etch rate resulted in a more shallow etch depth and a thicker active channel. I_{dss} could be predicted for any device to within +10% by examining the extent of etch undercut in a high performance SEM.

MODFETs with GaAs and InGaAs channels have been fabricated with gate lengths as small as 55 nm. The GaAs channel MODFETs had transconductances as high as 415 S/m, and the InGaAs MODFETs had transconductances as high as 315 S/m. GaAs channel MODFETs were found to have a maximum effective saturation velocity of 1.95×10^7 cm/s at a gate length of 150 nm. The occurrence of this maximum effective saturation velocity near a gate length of 150 nm agrees with the predictions of Kizilyalli et. al.

Work has begun on the first lateral quantum device, a lateral double barrier resonant tunneling MODFET. The depth of the central well is tunable with a stacked gate configuration. The confinement and tunneling characteristics of the electrons in the central quantum wire will be studied as a function of temperature, electric and magnetic fields. This structure has device potential as a high speed three terminal resonant tunneling transistor. Work is also underway on lateral surface superlattices. A literature review of research on this topic has been completed. The lateral surface superlattices to be built first involve various combinations of grid and grating stacked gates in a MODFET. The device applications include

tunable photon detectors, high frequency oscillators, and high speed switching transistors.

On a related topic of high resolution electron beam lithography, work is underway on a Monte Carlo simulator to study space charge effects in an electron gun. The electron-electron interactions near the source where the particle velocity is small and the charge density is high significantly contribute to the energy spread of the electrons. This energy distribution results in lateral beam broadening and a larger chromatic disc of confusion. Both of these effects increase the minimum achievable spot size and hence affect the lithographic resolution. Novel data structures are being incorporated in the Monte Carlo code to increase either the speed of simulation or the number of particles that can be simulated in a given time. The sophisticated graphics capabilities of the Mac II are being utilized to provide a intuitive interpretation of the physics that is usually lacking in numerical simulations.

3.3 GaAs ON SI INTEGRATED CIRCUITS

This program was initiated at the midpoint of the program to explore the potential of GaAs on silicon integrated circuit technology. Areas in which the monolithic formation of GaAs devices on a silicon integrated circuit chip may have a significant impact on system performance include the receiver electronics for fiber-optic communication links, high-speed sample-and-hold systems, and high-speed data and signal acquisition systems. The initial vehicle for this research is a receiver front-end for optical fiber communications that combines a GaAs metal-semiconductor-metal photodetector with a silicon bipolar preamplifier. The photodetector is formed in epitaxial GaAs that is grown selectively on the silicon substrate. The design and fabrication of the silicon preamplifier have been completed, and we have successfully demonstrated the selective growth of GaAs films by means of a process that is compatible with the prior integration of circuits in the substrate. We are now pursuing research into the "back-end" process integration for such technologies.

3.4 COMPLEMENTARY MOS DEVICE AND MATERIALS PHYSICS AT 77K°

The overall objective of this work was to explore the feasibility of operating silicon CMOS integrated circuits at LN₂ temperatures. It has been known for many years that device parameters like mobility are significantly improved at cryogenic temperatures. However, circuit and system performance cannot be predicted, based on device parameters alone. As a consequence, our program has investigated a broad range of device, technology and circuit issues. We were able to show that CMOS structures can be optimized for low temperature operation, with a significant performance improvement. We also showed that it is quite possible to design bipolar transistors which operate effectively at LN₂ temperatures, contrary to the view held by many. A detailed analysis of circuit performance at low temperatures revealed that interconnects are generally not a limiting factor. Device

characteristics are usually the speed limiting factor at low temperature and their improved properties lead to an overall circuit performance improvement about 2 times. Finally, we conducted several fundamental investigations into device physics at LN₂ temperatures. We showed that hot carrier effects can be a problem at low temperatures if supply voltages are not reduced; that non-ideal base currents in bipolar devices can be worse at low temperatures if trap densities are high; and we characterized electron and hole mobility and the dominant scattering mechanisms at low temperatures. Overall, the program resulted in a clear understanding of the advantages and disadvantages of cryogenic CMOS circuit operation.

3.5 THE CHEMICAL AND ELECTRONIC STRUCTURE OF REFRACTORY METAL GaAs INTERFACES

Over the past three years significant progress has been made in understanding the chemistry and pinning behavior of Ti-GaAs interfaces.

Titanium reacts with GaAs to form TiAs and a variety of Ti:Ga alloys. The dominant diffusing species are Ti and Ga, consequently a layered growth morphology, Ti_xGa_{1-x} - TiAs - GaAs, is observed. The TiAs - GaAs interface is stable up to a minimum of 800°C. The Ti:Ga alloys are significantly less stable. Anneals involving ultra-thin films or high temperatures result in the formation of TiAs and free gallium, which segregates to the film surface and agglomerates or evaporates.

For UHV-cleaved surfaces a limited reaction is observed upon deposition and substantial interdiffusion is observed for annealing temperatures as low as 200°C. Interfacial oxides retard the reaction, with no TiAs formation observed until about 350°C.

The as-deposited barrier height is roughly 0.69 eV, similar to previously observed pinning positions for low-electronegativity metals. Thin interfacial oxides have a minimal effect on the barrier height. Annealing results in an increased barrier height (~0.80 eV) which is stable up to at least 550°C. The increase, occurring at 200°C for intimate contacts and 350°C for contacts with interfacial oxides, coincides with the onset of significant metal-substrate interdiffusion and the formation of a uniform TiAs-GaAs interface. This is consistent with the Advanced Unified Defect Model which predicts that excess gallium, liberated by the formation of TiAs, would tend to push the interface Fermi level towards the valence band maxima. The potentially high work function of the TiAs phase in contact with the GaAs may also be important in determining the barrier height of the reacted contact.

3.6 THE STUDY OF CRYSTAL PROPERTIES USING CHANNELING RADIATION

The purpose of the program is to investigate the properties of crystals in which relativistic electrons or positrons are channeled. We have demonstrated the use of this technique to measure crystalline potentials, to observe the effect of nitrogen platelets on the diamond lattice, to observe and quantify electron-induced damage effects in certain materials, to determine thermal vibrational amplitudes, and to measure channeling lengths in III-V compounds, alloys and superlattices.

During this program, a new channeling-radiation beamline was installed on the Mark III electron linear accelerator at Stanford University. Previous channeling experiments used a beamline at the Lawrence Livermore National Laboratory, but the Livermore accelerator is no longer operating. The new Stanford beamline has been used to measure channeling spectra at high currents for the first time. In the high-current experiments, we have channeled electrons through the (100) and (110) planes of silicon. Previous experiments have shown that defects form very slowly in silicon, and, despite hours in the high-current beam, our measured spectra display the expected channeling peaks.

An important feature of this radiation is its time structure. In an rf linear accelerator, the electrons are tightly bunched at the peak of each microwave period. For the Mark III, these electron bunches (micropulses) are 0.5 to 1 ps long and are separated by 350 ps. This pattern continues over the 3- μ s duration of the klystron pulse (the macropulse), and these pulses repeat at 15 Hz. As a result, while the average current is microamperes, the peak current is typically 60A. This is the only intense source of picosecond x-rays known (synchrotron radiation from storage rings has pulse durations from 0.1 to 2 ns), and like synchrotron radiation, it is narrow band, tunable and highly directional. We are now considering various experiments using this beam as a source to take advantage of its unique features.

4. INFORMATION SYSTEMS

4.1 CODING FOR SPECTRALLY CONSTRAINED CHANNELS

This project was initiated in the second year of the program. Work on this project can be decomposed into three main categories: analysis of VC, application of VC methods to the ISDN digital subscriber loop, and reduction of implementational complexity through the use of block equalization methods. Each of these categories will be subsequently summarized in more detail. Basically, we have been able to demonstrate that VC achieves the highest possible coding gain, on any linear gaussian noise channel, for finite complexity of

implementation. We have also extended vector coding to the very important case where several digital communication channels are co-located and crosstalk interference dominates performance measures. Again, here we can show that gains are as high as can be practically achieved. Additionally, we have developed a theory of block (as opposed to symbol) equalization that can be used to reduce implementation complexity to well within acceptable levels.

4.2 REAL TIME STATISTICAL SIGNAL PROCESSING

The goals of this research program have been to study the direction-of arrival (DOA) estimation and adaptive beamforming problems and in particular to focus on innovative techniques that have computational and performance advantages over existing methods. Of special interest is the beamforming problem in the presence of "coherent" interference as can arise in "multipath" and "smart" jammer environments. Two signals are said to be coherent (or fully correlated) if one is a scaled and time-shifted version of the other. Another area of interest is to develop numerically robust fast algorithms for Recursive Least-Squares adaptive filtering.

Coherence among source signals or between signal and interferences as arising in multipath and jamming environments, causes great difficulties in the modern high-resolution "eigenstructure" or "subspace" techniques for direction-of-arrival estimation and beamforming. In previous research, we had obtained a spatial smoothing (or subarray averaging) technique to restore the dimensionality of the signal subspace. More recently, new refinements of this technique have been developed. A new concept was introduced, called the "smoothed rank profile", which can be exploited to completely determine the source coherency structure in the presence of coherent signals.

Following an alternative route, new optimum beamforming techniques were developed for coherent signals. The key idea here is to employ the signal-free covariance matrix in determining the optimum weight vector, in an attempt to account explicitly for the underlying signal model. Using this approach, two different versions of an optimum uniform linear beamformer were obtained that completely eliminate the signal cancellation phenomenon associated with signal coherency.

There are two much-studied adaptive methods of solving the minimum-mean-square filtering problem. One solution is a stochastic Gauss-Newton method, which leads to the recursive least-squares (RLS) algorithm. In contrast, the so-called least-mean-square (LMS) algorithm also attempts to minimize the mean square of the error signal, but does so by employing an approximate technique. The advantages of RLS algorithms over LMS

algorithms in aspects such as convergence speed and tracking behavior are well-known. However, in practice the use of the LMS algorithm is widespread due to its computational simplicity and robustness. More recently, two groups of fast RLS algorithms have been introduced that have a computational complexity of the same order of magnitude as that of the LMS algorithm. The fastest group, the fast transversal filters (FTF), therefore emerged as a most promising adaptive filtering technique. However, these FTF algorithms were plagued by exponential instability of the propagation of numerical errors. Now, over the last reporting period, substantial progress has been achieved in this long-standing problem. A stabilized FTF algorithm has been proposed, involving the introduction of computational redundancy and numerical error feedback, that is only 28% more expensive than the fastest (but unstable) FTF algorithm.

5. JSEP SUPPORTED DISSERTATIONS

1. T. J. Shan, "Array Processing for Coherent Sources," Ph.D. Dissertation, Stanford University, Department of Electrical Engineering, December 1986.
2. M. D. Williams, "The Effect of Chemical Reactivity and Charge Transfer on Gallium Arsenide (110) Schottky Barrier Formation," Ph.D. Dissertation, Stanford University, Physics Department, December 1986.
3. E. S. Hellman, "Hot Electron Resistance and Magnetoresistance in High Purity Gallium Arsenide, Ph.D. Dissertation, Stanford University, Department of Electrical Engineering, May 1987.
4. J. O. Kephart, "Beyond the Continuum Potential Approximation: Channeling Radiation from Nonideal Crystals," Ph.D. Dissertation, Stanford University, Department of Electrical Engineering, August 1987.
5. Albert Karl Henning, "Hot Carrier Effects In CMOS Field Effect Transistors At Cryogenic Temperatures," Ph.D. Dissertation, Stanford Univeristy, Department of Electrical Engineering, August 1987.
6. R. Roy, "ESPRIT - Estimation of Signal Parameters via Rotational Invariance Techniques," Ph.D. Dissertation, Stanford University, Department of Electrical Engineering, August 1987.
7. Jason C.S. Woo, "Operation Of MOS and Bipolar Transistors at Liquid Nitrogen Temperature," Ph.D. Dissertation, Stanford Univeristy, Department of Electrical Engineering, September 1987.

6. JSEP SUPPORTED PUBLICATIONS

The following publications are listed in order of projects.

1. "Energy-Momentum Relation for Polarons Confined to One Dimension," E. S. Hellman and J. S. Harris, Jr., *Phys. Rev. B.*, **33**, 8284 (1986).
2. "Quasi-One Dimensional Polaron Effects and Current Inhomogeneities in Sequential Phonon Emission," E. S. Hellman, J. S. Harris, Jr., C. B. Hanna and R. B. Laughlin, *Physica* **134B**, 41 (1985).
3. "Polaron Transport in Quasi-One Dimensional Semiconductor Heterostructures," E. S. Hellman and J. S. Harris, Jr., *Surface Science*, **174**, 459 (1986).
4. "The Mechanism of Current Modulation by Optic Phonon Emission in Heterojunction Tunneling Experiments," C. B. Hanna, E. S. Hellman and R. B. Laughlin, *Phys. Rev. B*, **34**, 5475 (1986).
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6. E. S. Hellman and J. S. Harris, "Polaron Transport in Quasi-One Dimensional Semiconductor Heterostructures," *Surf. Sci.*, **174**, 459-465 (1986).
7. E. S. Hellman and J. S. Harris, Jr., "Polynomial Kinetic Energy Approximation for Direct-Indirect Heterostructures," *Superlattices and Microstructures*, **3**, 167-169 (1987).
8. E. S. Hellman and J. S. Harris, Jr., "Hot Electron Transport Parallel to Strong Magnetic Fields in Gallium Arsenide," to be published in *Solid State Electronics*.
9. C. Webb, S.-L. Weng, J. N. Eckstein, N. Missert, K. Char, D. G. Schlom, E. S. Hellman, M. R. Beasley, A. Kapitulnik and J. S. Harris, Jr., "Growth of High T_c Superconducting Thin Films Using Molecular Beam Epitaxy Techniques," *App. Phys. Lett.*, **51** (15) 1191, October 12, 1987.
10. C. Webb, S.-L. Weng, J. N. Eckstein, N. Missert, K. Char, D. G. Schlom, E.S.Hellman, M. R. Beasley, A. Kapitulnik, and J. S. Harris, Jr., "Growth of High T_c Superconducting Thin Films Using Molecular Beam Epitaxy Techniques", *Appl. Phys. Lett.* **51**, 1191 (1987).
11. E. S.Hellman, D. G. Schlom, N. Missert, K. Char, J. S. Harris, Jr., M. R. Beasley, A. Kapitulnik, T. H. Geballe, C. Webb, S.-L. Weng and J. N. Eckstein, "Molecular Beam Epitaxy and Deposition of High T_c Superconductors", *J. Vac. Sci. & Tech. B* **6**, 799 (1988).
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