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SOLID STATE ELECTRONICS LABORATORY

JSEP FINAL REPORT

January 11, 1991 through January 10, 1994

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

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STANFORD ELECTRONICS LABORATORIES • DEPARTMENT OF ELECTRICAL ENGINEERING
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JSEP Final Report

Period of January 11, 1991 - January 10, 1994

Department of Electrical Engineering
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Joint Services Electronics Program
(U.S. Army, U.S. Navy and U.S. Air Force)
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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 January 11, 1991 through January 11, 1994. This report summarizes the areas of research, identifies the most significant results and lists the dissertations, publications and presentations sponsored by the contract (DAAL03-91-C-0010).

Key Words and Phrases: Nanostructure, quantum well, quantum dot, reactive ion etching, diamond, superconductors, Si-Ge, wireless, video-on-demand, discrete multitone modulation, cyclic correlation, neural network, image compression

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This work was supported by the Joint Services Electronics Program, contract DAAL03-91-C-0010. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies either expressed or implied, of the U.S. Government.

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 DAAL03-91-C-0010. 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. Because of the rapid changes and opportunities in mobile and wireless communicaitons, two new units were inititiated in data compression algorithms, modulation and low power decoders. A third unit was switched from neural networks to begin examining cycostationarity in wireless communications systems. In addition, three of the seven semiconductor materials and processing units changed during the course of the program to focus on nanostructure fabrication and devices. Thus, the program at the end of the three year period had a significantly different focus than at the outset and attests to the vitality and flexibility afforded to the JSEP program. The new units and changes were not a reflection of quality, but of new opportunities and a conscious decision to focus JSEP funds on seeding new ideas and projects which could lead to larger programs with conventional DoD funding, and which would be greatly enhanced by some initial results or proof of concept. The JSEP flexibility provides great leverage in seeding such new ideas in the interim period when virtually nothing could 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. Investigation of Transport in Quantum Dots (J. S. Harris)
   b. Physics and Applications of Ultra-Small Structures (R. F. W. Pease)
   c. Reactive Ion Profiling of Heterostructures (C. R. Helms)
   d. Electronic Structure and Interfacial Properties of High Temperature Superconductors (W. E. Spicer)
   e. Semiconductor Laser Structures for Optical Interconnects (S. S. Wong)
   f. Quantum Computing (J. D. Plummer)
   g. Applications of SiGe in MOS Technologies (K. C. Saraswat)

2. Information Systems
   a. Signal Processing for Wideband Digital Protable Communications (T. H. Meng)

b. Wideband Data Transmission Techniques (J. M. Cioffi)
c. Fast Arithmetic Computing with Neural Networks (T. Kailath)
d. Image Compression, Data Compression and Network Information Flow (T. Cover)

2. SIGNIFICANT RESULTS

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

- *Quantum Wires in Si*

Fabrication of precise dimension quantum wires and dots is required to understand and exploit quantum structures in Si. High resolution e-beam patterning, precise etching and oxidation have been developed to create quantum wires of < 5nm diameter and aspect ratios of >200. These structures have been utilized to investigate fundamental energy states in Si and nanosturctures, electron-hole recombination and light emission and election emission into vacuum. The negative result of light emission from these structures suggests that surface treatement may be playing a greater role than quatum confinement in porous Si sturctures.

- *Application of SiGe in MOS Technologies*

Low temperature processing is becoming increasingly important for large area displays. Si films become amorphous when deposited below 600°C, thus limiting the quality of low temperature films for thin film transistors (TFT) and poly gates for MOSFETs. Poly SiGe films have been deposited by LPCVD at 500°C with 1/5 the sheet resistance of poly Si films. A new H^+ ion implantation process has been demonstrated to passivate grain boundaries in TFTs on glass and to reduce the dark current in TFTs.

- *Low Power Compression Algorithm and Custom IC*

Limited bandwidth and portability place severe and conflicting demands upon portable communications equipment, particularly where video information is required. A new data compression algorithm was developed which could be implemented with much lower computational energy than current approaches. A custom IC was designed, fabricated and tested in a portable communication device with a color display for full-motion video over a wireless link at 500 Kbps which utilizes only 10mW of power, compared to 1-2W for currently available decoders.

- *Discrete Mulitone Modulation for Digital Transmission*

Discrete multitone modulation was developed at Stanford and recently adopted by the American National Standards Institute (ANSI) as the standard for high-speed multimedia transmission over twisted-pair copper lines.

3. SEMICONDUCTOR MATERIALS, PROCESSES AND CIRCUITS

3.1 Investigation of Transport in Quantum Dots

Scientific Objective:

With recent developments in e-beam lithography techniques, it has become possible to fabricate devices with minimum feature sizes less than 100nm. The two dimensional electron gas (2-DEG) structure implemented in AlGaAs/GaAs technology is already a well developed system for studying these nanoscale devices. Because of the future promise of such devices for ultra-high density electronics, emphasis shifted toward these structures midway through the program after the student supported on Investigation of High Speed Heterojunction Bipolar Transistors completed his disertation. Our goal is to study the two dimensional array aspects of coupling between dots, quantum transport and Coulomb blockade in two dimensions.

Research Highlights:

A "Quantum Dot" is a submicron region of a semiconductor which confines some relatively small number of electrons. In such small quantum dots, one may see significant electron-electron interaction effects, such as Coulomb blockade. Meirav demonstrated that the conductance of a single quantum dot was periodic with the electron density in the dot with a period was proportional to the charging energy required to add a single electron to the dot. This occurs because the tunneling of an electron is "Blocked" due to the "Coulomb" repulsion with the charge already existing in the dot.

In prior work, the transparency of the tunnel barriers coupling the dot to the leads is adjusted by independent gates and another gate is used to adjust the electron density. Such gated structures require large areas and would be very difficult to implement in any type of two-dimensional array. Since we are interested in ultra-high density application of single electron devices, we have developed an approach where a <u>single</u> gate is utilized to both form the quatum dots and control their electron density in the entire two dimensional quantum dot array (200 X 200 dots). The arrays were made using standard modulation doped AlGaAs/GaAs 2DEG structures with an electron mobility of roughly 200,000 cm^2/Vs and a sheet density $3.5x10^{11}$ cm^{-2} at 4.2 K. To form the dots, "plus sign" patterns were formed by e-beam lithography and wet-etching through the 2DEG layer in these plus sign regions. A single Cr/Au gate was deposited over the whole array. A small negative gate voltage starts forming the barriers by depleting the carriers in the channel regions between the plus sign arms, while the dots remain filled with electrons.

The devices were measured in a dilution refrigerator between 20 and 700° mK. The current-voltage (I-V) curves as a function of the gate voltage V_g in these arrays showed multiple hysteresis loops, depending upon the inter-dot coupling. As the gate voltage becomes more negative, the width of these loops increases and new loops begin to appear. An interesting observation is that all hysteresis loops are counter clockwise, even for loops within loops. We also observe that the switching voltage and the width of each hysteresis loop decreases with increasing temperature. It is possible to see the dissociation of big loops into smaller ones and their disappearance at different temperatures, all lower than 700° mK. There is an apparent tradeoff between the gate voltage and temperature; at 700° mK, if the gate voltage is made 20-30 mV more negative, one can recover the hysteresis, however the ratio of the loop width to the switching voltage is smaller than that at 20° mK, which points to the total disappearance of the effect at high enough temperatures. Indeed, at 4.2°K, there is no hysteresis at all in the transport characteristics of the array. These are the first measurements on a large two-dimensional quatum dot array and the results are qutie astonishing. Further work is required to understand the tranport, but there is a marked similarity to results at high magnetic fields where it is believed that Wigner crystalization is occuring. Such a result would be exciting in a laterally structured quantum dot array.

3.2 Physics and Applications of Ultra-Small Structures

Scientific Objective:

As the device dimensions continue to move from the micrometer regime to the nanometer regime in the present trend of silicon VLSI technology, there is a greater need to understand the physics and the technologies related to ultra-small silicon structures. Many interesting electrical and optical properties of nanometer size silicon systems have been predicted from quantum mechanical considerations. These include the transition from an indirect to a direct material which makes the material optically active [L.T. Canham, *Appl. Phys. Lett.* **57**, 1046 (1990)], the enlargement of the energy band gap, the reduction of dielectric constant [R. Tsu, et. al., *NATO ASI Series* **244**, 203 (1993)], the decrease of doping efficiency [R. Tsu, et. al., *Appl. Phys. Lett.* **64**, 1806 (1994)], and the decrease of carrier mobility [G.D. Sanders, et. al., *Phys. Rev. B* **48**, 11067 (1993)]. It is therefore the goal of this research project to explore this fascinating boundary of solid state physics and atomic physics. At this boundary, many concepts taken for granted in a bulk material can no longer be applied. However, the technologies developed in this project will aid the precision control of device structures used in many present and future VLSI systems.

Research Highlights:

To this end, a reliable technology has been developed to fabricate sub-5 nm silicon nanostructures. With the dramatic phenomenon of self-limiting oxidation discovered in this effort, sub-5 nm silicon nano-wires with an aspect ratio of more than 200 to 1 can be fabricated in a controllable fashion. The process involves a combination of high resolution electron beam lithography, anisotropic reactive ion etching, and thermal oxidation. Novel transmission electron microscopy techniques were also developed to examine the crystalline structures of the silicon nano-wire in various view angles (side view, planar cross-sectional view, and longitudinal cross-sectional view). The resolution achieved with this technique is 0.19 nm. This allows for precise measurements of the nano-wire dimensions. In addition, the oxidation progression of the nano-wires were characterized and the self-limiting oxidation phenomenon was found.

Currently, the central focus of this work is on probing the electronic structures and developing possible device applications of the silicon nano-wires. Preliminary Raman spectroscopy of the nano-wires yields a lower phonon energy and a wider spread of the spectral width, which is consistent with the stress state and the expected shorter lifetime of phonons in these confined quantum systems. A device structure consisting of a metal/oxide/Si nano-wire system has also been implemented and demonstrated to yield field emission current consistent with the strong electric field at the oxide/Si nano-wire interface. In short, these nano-wires are ideal field emission structures. Although no photoluminescence signal was detected from these structures at this time (most likely the result of excess non-radiative recombination centers), a workable light-emitting device structure has been conceived. This device utilizes a transparent conductor to inject high energy tunneling electrons through the oxide barriers and into the silicon nano-wires. Because of the direct contact to the oxidized nano-wires and the domination of tunneling current in these wires over that of the planar regions, the pumping efficiency of excited carriers is expected to be better than that of a photoluminescence system. Moreover, the lack of primary excitation photons in this electrical pumping scheme should also improve the detection limit of the spectrometer. All of these are expected to contribute to the understanding of ultra-small silicon systems.

3.3 Reactive Ion Profiling of Heterostructures

Scientific Objective:

The principal focus of this work has been to study the effect of oxygen and hydrogen on diamond surfaces using Electron Energy Loss Spectroscopy (EELS) and Auger Electron Spectroscopy (AES).

Research Highlights:

Studies have shown that the introduction of oxygen in diamond growth environments improves diamond quality, increases growth rates, and reduces the lower temperature limit at which diamond films can be grown. If the surface is subjected to overly energetic oxygen ions, the displacement of carbon atoms and the breaking of bonds can occur, causing a diamond to graphite transition at the surface. This transition is seen by the appearance of a π plasmon feature in the EELS spectra. This research has shown that 200 eV oxygen ion bombardment removes surface damaged layers, recovering diamond EELS features in the surface region. Higher energy oxygen ion bombardment does not produce surfaces as ideal as the 200 eV case. This process leaves approximately .5 monolayers of oxygen on the surface.

Removal of this residue can be achieved by an anneal in ultra high vacuum which causes the oxygen to desorb as CO and CO_2. In this project, oxygen on the diamond surface has been correlated with an 8.5eV loss feature in the EELS spectra. (This is in addition to the diamond surface and bulk plasmons at 34 eV and 22 eV respectively). The 8.5 eV loss feature is seen to decrease with anneal time. There is still a small loss feature present at 8.5eV when AES data shows that no oxygen is present, implying that bulk diamond also contributes to this loss feature.

An unchanging π plasmon feature in the EELS spectra shows that annealing oxygenated diamond in vacuum does not reduce the amount of graphitic carbon on the surface. In contrast, when oxygenated diamond is annealed in atomic hydrogen, the EELS spectra shows a significant reduction in the π plasmon feature. This can be attributed to the selective etching of non- diamond carbon by atomic hydrogen.

3.4 Electronic Structure and Interfacial Properties of High Temperature Superconductors

Scintific Objective:

Our research has focussed on the electronic structure and interfacial properties of high temperature superconductors. The primary technique that we have applied to the study of the high temperature superconductors is angle-resolved photoemission spectroscopy (ARPES), which gives direct **k**-dependent information about the density of states of a material. Due to the short escape depths of the photoelectrons from the sample surface, it is also very surface sensitive, with probe depths on the order of 5-15 Å. One of the key aspects of our studies has been the use of very high energy resolution (approximately 30 meV) which has allowed us to study the very low energy scale properties such as the Fermi surfaces and superconducting excitations. Development of a new system with better than 5 meV resolution is underway in our lab, and will be used in future studies.

Research Highlights:

A. Studies of the low energy excitations and Fermi surfaces

We have performed the most detailed studies of the band structure (E vs. **k** relationships) and Fermi surfaces of a variety of the cuprate superconductors. These studies have uncovered a number of very important and interesting trends which are helpful for our understanding of these materials. First, all the cuprate superconductors have well-defined Fermi surfaces with similarities to predictions of one-electron band theory calculations. However, a number of them show very strong nesting features, which are expected to have significant effects on the interactions between the electrons. The highest T_c material has stronger nesting features than the lower T_c materials. The measured E vs. **k** relationships diverge quite a bit from the band theory predictions, the most striking piece of evidence being the observation of very flat bands at the (π,0) point in the Brillouin zone. In the p-type superconductors, we have found these bands are pinned very near the Fermi energy E_F, while in the n-types they are far below E_F. This may account for the very different physical properties that are observed in the p- and n-type superconductors.

B. Studies of the superconducting energy gap

We have performed detailed studies of the low energy excitations in the superconducting state of the 85°K superconductor $Bi_2Sr_2CaCu_2O_8$ (Bi2212). As in conventional superconductors, we found that a gap (the superconducting energy gap) exists in the excitation spectrum. However, we found that the superconducting gap in the HTSCs behaves very differently from that in conventional superconductors. The order parameter (gap) in conventional superconductors, has s-wave symmetry, implying that the gap is isotropic or nearly isotropic in **k**-space. We discovered that the gap in Bi2212 has a huge anisotropy, and the details of this anisotropy match very closely what is expected for a d-wave symmetry order parameter. The order parameter symmetry is one of the key pieces of information we need to know before we reach an understanding of the mechanism of the superconductivity, and if it is in fact d-wave, then the mechanism is expected to be very different from that in conventional superconductors. In addition to the huge gap anisotropy, we uncovered some other interesting effects, such as anomalous spectral weight transfer at the superconducting transition and surface superconductivity.

C. The metal/superconductor interface and the proximity effect.

We performed a number of studies on the metal/superconductor interface. One of the highlights of these studies was one on the proximity effect, which is a phenomenon in which Cooper pairs (the superconducting charge carriers) will leak from a superconductor to a normal metal if the electrical contact between the two is good. The normal metal will then become a superconductor itself, that is, it will obtain the excitation spectrum of a superconductor. We have searched for the proximity effect in an original and unique way, which makes use of the surface sensitivity of photoemission spectroscopy. We prepared junctions of the highest attainable quality in a number of different geometries, and then directly searched for the effects of a superconducting gap in the surface layer (gold) with high-resolution, temperature-dependent photoemission spectroscopy. We did not observe such an effect, but were able to place an upper limit of approximately 5 meV on its existence, which is well below the superconducting gap value of approximately 20-25 meV in the bulk high T_c superconductor.

D. Studies of thin film superconductors

We have recently begun applying the techniques developed for the study of single crystal superconductors to the study of artificially structured thin film samples. We have obtained MBE grown $Bi_2Sr_2CaCu_2O_8$ samples from Varian Associates, and have performed ARPES measurements on them. The results are very consistent with those taken on cleaved single crystals.

3.5 Semiconductor Laser Structures for Optical Interconnects

Scientific Objective:

The objective of this work is to study the interplay between geometry and physics in a semiconductor laser in order to achieve high brightness optical emitter structures for applications in optical data communication.

Research Highlights:

Typically, the width of a conventional (Fabry-Perot) laser diode is constrained to be on the order of tens of microns it if is to operate with a single lateral mode (i.e., diffraction-limited), as beyond this width internal self-focusing, or filamentation, effects force multi-moded operation. Consequently, single stripe AlGaAs/GaAs lasers are only capable of roughly one hundred milli-watts continuous-wave (CW) output power in a diffraction-limited spot. However, proper implementation of the well-known unstable resonator structure, with its inherent strong lowest-order lateral mode selectivity, can suppress filamentation in a diode laser and hence overcome these limitations.

We have fabricated unstable resonator diode lasers in a wide-stripe (100 microns), half-symmetric configuration with one flat and one concave mirror. The resonant structure is defined using reactive-ion-etching (RIE). The silicon tetrachloride-based RIE process we have developed consistently produces cavity mirrors with AFM-measured RMS surface roughness values of approximately 3.5 nm, which is less than 1/65 of the wavelength. This yields only a small increase in threshold current due to scattering relative to that of a cleaved-cavity laser. Devices with a variety of geometric magnifications have been measured, and beam quality and brightness have been found to improve dramatically with increasing magnification. Devices with a magnification of 9 have been measured with a lateral M2, beam quality factor, values of 1.25 at single facet output powers of 275 mW. This is favorably compared to the lateral M2 of greater than 10 for conventional wide-stripe gain-guided lasers, and the lateral M2 of 1.1-1.2 for 100 mW narrow-stripe index-guided diode lasers. Spectral near-field measurements of these devices confirmed single lateral mode operation. This is the first time such ideal characteristics have been realized with a highly manufacturable RIE process.

We are currently developing a numerical model for these devices based on a Huygens integral formulation of beam propagation. we believe that previously published simulations by others of similar devices are substantially flawed. Recently we have also experimentally demonstrated an alternative configuration to achieve improved brightness, the temperature-induced unstable resonator diode laser.

3.6 Quantum Computing

Scientific Objective:

The goal of this project is to develop an accurate and efficient numerical simulator for modeling quantum-effect electronic devices such as the resonant tunneling diode. This statement of purpose indicates the continued evolution of the project from a general study of quantum computing (the use of quantum-effect device to perform computation) to a focus on a single area of quantum computing research: the development a numerical simulator for quantum devices. The result of our effort is a software tool called SQUADS (Stanford QUAntum Device Simulator). SQUADS allows simulation using either of two formulations of quantum mechanics, the transmission matrix method (TMM) and the Wigner function method (WFM), each with its own advantages. Both the I-V characteristic and transient behavior can be simulated for arbitrary 1-D quantum-sized structures in any characterized material system.

Research Highlights:

Progress over the past year has been mainly characterized by numerous incremental advances in the capabilities, flexibility, and robustness of SQUADS. However, one more important new feature is the ability to enforce current continuity at the device boundaries. Investigation of the importance of this effect has thus far largely been ignored by others in quantum device simulation research. The standard approach is to assume an equilibrium (i.e., zero current) distribution of carriers at the device boundaries. On the other hand, maintaining current continuity across the boundaries requires a more time-consuming iterative simulation of the quantum system. We have yet to fully evaluate the significance of enforcing current continuity, but initial I-V curve simulations show only a small effect on device operation (up to 10% difference in current) in both WFM and TMM simulations.

Several improvements in SQUADS mainly affected the TMM part of the simulator. The first of these was the incorporation of a faster Airy function calculation routine, which is used for the most accurate TMM simulations. This change improved the speed of these simulations from about 10 times slower than the standard TMM simulations to about 3-4 times slower, making them feasible for a greater fraction of simulations. During this reporting period, we also generated a 70-page technical reference for the math and theory underlying the TMM part of SQUADS. From this work, we improved the robustness of the simulator by considering various failure modes and how to protect against them (i.e., not terminate execution) while still giving accurate results. This work also helped us implement a more accurate discretization (called node-centered regions) of the energy band profile without slowing down the simulation. Finally, producing the reference allowed us to see how the code could be tightened (e.g., by combining similar functions) for improved ease of maintenance and upgrading in the future.

There were also improvements in SQUADS which mainly affected the WFM part of the simulator. The memory requirements of WFM simulations can be enormous, so one important change was the adoption of dynamic memory allocation, by which SQUADS allocates arrays with exactly the dimensions needed, rather than allocating the largest size expected (with larger sizes previously requiring a recompile). This reduced both the memory usage and execution time for the typical simulation. Our efforts to tune the WFM part of SQUADS over the past year have netted an additional 40% decrease in simulation times. Finally, we spent significant effort determining when our WFM simulations were accurate, or perhaps more accurately, when they were not. For example, using a first order approximation to spatial derivatives was found to be generally not accurate enough to capture the physics of quantum devices, while a second order derivative is usually sufficient.

Although SQUADS uses two very different formulations of quantum mechanics as alternate foundations for implementing a numerical simulator, code is shared whenever possible. This allows functionality to be implemented once and be immediately available to both simulation methods (for example, this is how both self-consistency and boundary current continuity were implemented). Thus, we now list improvements in SQUADS that are shared by both the TMM and WFM simulation methods. These include an energy band offset model which

includes strain dependence (important for SiGe devices), an algorithm to give a more accurate initial guess of the energy band profile for faster self-consistent simulations, and allowing linearly graded and/or doped layers for more accurate device specification. Several improvements were intended to make SQUADS simpler to use, including separating the material system specification from the device/simulation specification file, and implementing command-line options to allow execution of different modes of SQUADS (e.g., TMM or WFM; single bias, I-V curve, or transient) without modifying the simulation specification file.

3.7 Applications of Si-Ge and Germanium Films in MOS Technologies

Scientific Objective:

- To fabricate MODFET structures on high Ge content SiGe hetrostructures and to assess their utility in high-speed transistor applications.
- To develop a low thermal budget, low cost, low manufacturing cycle time and reliable technology to fabricate high performance CMOS thin-film transistors (TFTs) in poly-GeSi and poly-Si on low cost substrates, such as glass, for active-matrix liquid crystal display (AMLCD) applications.

Research Highlights:

1. Hetrostructure MODFETs

Work has proceeded on the integration with a silicon substrate of high-performance n-channel heterostructure field-effect devices using germanium-rich GeSi with Ge alloy fractions from half to unity. The goal is to combine the high intrinsic electron mobility of germanium and the carrier confinement available with band-structure engineering in the Ge-Si system. Success with the use of graded-alloy epitaxy to isolate the defects associated with the transition between silicon and germanium lattice constants has been achieved. Other methods are also under current investigation. Rapid thermal nitridation treatment followed by CVD-oxide deposition is being investigated as a means to achieve high-quality gate insulators.

2. Thin Film Transistors

Manufacturing of low cost, high resolution AMLCDs requires high performance driver circuits to be fabricated on glass substrates at process temperatures < 575°C. Amorphous Si MOS TFTs can be fabricated on glass but lack performance. Poly-Si TFTs have good performance but requires processing at ≥600°C. Adding Ge to Si lowers processing temperatures for deposition, doping, recrystallization, grain boundary passivation, allowing TFT fabrication at lower temperatures using conventional technology. CMOS TFTs have been fabricated in Si and GeSi using conventional thermal technology without exceeding 550°C with excellent properties (high on current and low leakage). For better crystallization and dopant activation rapid thermal processing using lamps and excimer laser processing allow shorter times at higher temperatures resulting in lower thermal budget, improved device performance and reduced manufacturing cycle time. Further improvement in TFT performance and reduction in cycle time has been demonstrated through the use of RTP and excimer laser for crystallization and dopant activation. Traps in grain boundaries and within the grains in poly-GeSi and poly-Si cause severe device degradation. A new method has been developed to passivate these traps by ion implantation of H+. Several novel device structures have being developed to reduce leakage, increase mobility (and thus on current). Issues related to the reliability of gate dielectric are being investigated and best method to form it is being explored. Finally, process technology is being developed which will simplify processing, reduce manufacturing cycle time and cost.

4. Information Systems

4.1 Signal Processing for Wideband Digital Portable Communications

Scientific Objective:

The goal of this project is the development of an integrated approach to the design of a portable video-on-demand system capable of delivering high-quality image and video data in a wireless communication environment. The research is focused on both the algorithm and circuit design techniques developed for implementing a portable video compression/decompression system at power levels that are two orders of magnitude below existing solutions.

Research Highlights:

A portable video-on-demand system requires a bandwidth far greater than broadcast video, as each user can subscribe to different video programs at any time in any place. Because of the large bandwidth requirement, for both storage and transmission, data compression must be employed, thus requiring real-time video decoding in the portable unit. The key concern for portability is reduction of power consumption to allow for extended battery life.

In this project we have developed compression algorithms with a compression efficiency similar to or better than industry standards but require minimal computation energy in their hardware implementations. Our decoder prototype achieves real-time video decoding at a power level of 10 mW, compared with comparable industry decoder chips dissipating 1 to 2.5W. Examples of algorithmic trade-offs for energy conservations are the development of a vector quantization scheme that allows on-chip computation to eliminate off-chip memory accesses, the use of channel-optimized data representations to avoid the error control hardware that would otherwise be necessary, and the coding of internal data representations to further reduce the energy consumed in on-chip data exchanges. The architectural and circuit design techniques used include the selection of a filter bank structure that minimizes the energy consumed in datapath, the data shuffle strategy that results in reduced internal memory size, and the design of digital and analog circuits optimized for low supply voltages. Our hardware prototype is a video decoding chip set for decompressing full-motion video transmitted through a wireless link at 500 Kbps to 1 Mbps range, which is incorporated into a light-weight hand-held portable communication device with a color display.

4.2 Wideband Data Transmission Techniques

Scientific Objective:

Discrete Multitone Modulation (DMT) has been recently demonstrated to be a high-performance cost-effective technology for high-speed digital transmission over severely band-limited channels. In particular, the DMT transceiver (which was developed and patented by the

Cioffi group at Stanford) has been adopted by the American National Standards Institute (ANSI) as a standard for a high-speed multimedia transmission service on twisted-copper lines known as the Asymmetric Digital Subscriber Line (ADSL) service.

Research Highlights:

Our research over the past year has focused on two directions. First, we investigated two techniques to improve further the performance of the DMT transceiver towards achieving theoretical performance limits on twisted-copper lines. These two techniques are geometric-SNR-based equalization and shaping. Second, we explored the application of the DMT technology to other more challenging transmission environments; namely the Cable Television (CATV) network and Rayleigh-fading wireless channels and compared its performance with that of single-carrier transceivers.

Optimum Finite-Length Equalization for DMT

For highly--dispersive channels, the length of the cyclic prefix (needed to eliminate interblock interference in the DMT) is large resulting in a significant bit rate loss, especially for a moderate--size input block. We investigated the use of equalization to reduce the cyclic prefix overhead by optimally shortening the channel impulse response duration. In particular, we showed that the optimum equalization criterion in conjunction with the DMT is maximizing the {geometric SNR} which we have cast as a constrained nonlinear optimization problem and solved using iterative numerical techniques. Extensive computer simulations have demonstrated that the use of equalization results in a substantial performance margin improvement over the case of no equalization. An additional increase in margin is achieved by designing the equalizer based on the geometric SNR criterion as opposed to the traditional mean square error criterion.

Combining Shaping with DMT

A straightforward approach for selecting the input constellation points during each DMT symbol period is to use the bits allocated to each subchannel to independently select a complex point from a square or circular constellation. However, better power efficiency is obtained by selecting the constellation point from a spherical region, and we refer to this gain as shaping gain. While a number of shaping approaches have been proposed for single--carrier systems, the application of shaping to DMT modulation is complicated by the variation in the number of bits and amount of power allocated to the different subchannels. We showed how single--carrier shaping techniques may be extended to the multicarrier case, allowing on the order of an extra 1.0~dB of gain to be obtained. The combination of shaping with sophisticated coding techniques allows a DMT system to approach the fundamental limits of band--limited channels.

Application of DMT to Multimedia Transmission on CATV

We have studied two candidate methods for transmitting digital multimedia signals on the

CATV network: single-carrier modulation with equalization and multicarrier modulation. Simulations show that, on channels likely to exist on the cable network, the achievable bit rate of multicarrier systems is higher than the rates achievable by single-carrier systems with equalization for a fixed system complexity. Conversely, for a given bit rate, the complexity of multicarrier modulation is significantly less than the complexity of single-carrier systems with equalization. Furthermore, multicarrier modulation is well-suited for both broadcast and duplex operation over the cable network. The subchannels created by multicarrier modulation provide a flexible platform for the transmission of signals with radically different bandwidth and error protection requirements, such as digital video and digital voice. Finally, a multicarrier system can be easily expanded when services requiring additional bandwidth are desired by users.

Single-Carrier vs. Multicarrier on Rayleigh-Fading Channels

The European Broadcast Union (EBU) has adopted multitone modulation for its Digital Audio Broadcast (DAB) System. This use of multitone modulation by the EBU has sparked new interest in wireless multitone modulation. The U.S. is now testing competing DAB systems: one a multitone system; the other, a single-carrier system using a decision feedback equalizer (DFE). We compared the performance of these two systems on a Rayleigh-fading channel before and after coding. We found that before coding, the single-carrier system can achieve better performance due to diversity. After coding, given a slowly fading channel such that there is no effective time-interleaving, the multitone system can now achieve diversity and performs as well if not better than the DFE. With a fast-fading channel, the DFE will have better diversity than the multitone before and after coding. However, this result assumes perfect knowledge of the channel, and does not include tracking issues which are pertinent when the channel is changing rapidly.

4.3 Fast Computing with Neural Networks

Scientific Objective:

The aims of this project have been in the two areas described below.

Neural Networks:

This research was focused on examining new methods of computing using artificial neural networks, performing complexity analysis of neural networks with discrete and continuous output units, investigating the application of wavelet theory to the systematic synthesis of neural networks, exploring the use of pruning techniques to enhance the generalization capabilities of neural networks, and studying the robustness properties of neural network learning algorithms to model uncertainties and lack of statistical information.

Cyclostationarity in Communications and Sensor Array Processing:

This effort was in the area of communications, with an eye towards future research in wireless communications, exploiting our extensive prior research on sensor array processing.

The first step was to study the consequences of the most commonly encountered signal structure in communications, namely cyclostationarity, to the problems of direction-of-arrival (DOA) estimation and blind identification of possibly non-minimum phase communication channels.

Research Highlights:

Neural Networks

We have studied the consequences of using discrete output neural networks to perform arithmetic operations such as multiplication and division, and have studied the trade-offs between the depth and size, i.e., speed and hardware cost) of such implementations. In particular, we have shown that it is possible to multiply two 64 bit numbers with a neural network using 8 propagation delays, whereas the best known AND/OR logic gate implementation with the same amount of hardware requires 30 delays. We have also studied the computational power of neural networks with continuous outputs, and have shown that for highly oscillating functions such as parity, continuous outputs give us no advantage over discrete linear threshold elements.

We have investigated the application of wavelet theory to the recursive synthesis of neural networks and have proposed a modification of the Matching Pursuit (MP) algorithm, called Orthogonal MP, that has the additional property of maintaining the full backward orthogonality of the residual (error), and which may be useful for this purpose. Since the generalization capability of a synthesized neural network depends on the of the neural network, we have proposed a network pruning algorithm (Optimal Brain Surgeon - OBS) that removes a network's excessive weights, and readjusts the remaining ones so as to minimize the increase in training error, thereby improving the network's generalization performance.

A very important question in neural network training is the robustness of the learning algorithms with respect to model uncertainty and lack of statistical information. In this regard we have shown that the celebrated LMS algorithm (extensively used in adaptive filtering) and Backpropagation (extensively used in neural networks) are optimal and locally optimal, respectively. This result explains the inherent robustnes of these algorithms, since it guarantees that they will yield small estimation errors for all possible small disturbances and/or modelling errors.

Cyclostationarity in Communications and Sensor Array Processing

Conventional sensor array processing methods such as MUSIC and ESPRIT rely on the spatial properties of the signals impinging on a sensor array, and have the disadvantage of ignoring the temporal properties of the signal and assuming them to be narrow band. In many communication applications the signals cannot be assumed narrow band and exhibit a certain structure known as cyclostationarity. We have shown that by exploting this structure and using "cyclic correlations" the data exactly obey a narrow band model (even though the original signals may not have been narrow band) and that therefore we may estimate the source DOAs using conventional narrow band techniques.

It is well known that a non-minimum phase linear time-invariant channel driven by wide-sense stationary input cannot be identified from the second order statistics of the channel output. However, we have shown that if the input is cyclostationary, then second order statistics of the output suffice to identify the channel, and have proposed time-domain and frequency-domain algorithms for doing so. When extended to the case of multiple antennas, we have shown that if the input is wide-sense stationary then the channels corresponding to each antenna may be identified using second order statistics alone, and have proposed an algorithm for doing do. The trick is that valuable phase information can be obtained from the cross-correlation of the various antenna outputs.

4.4 Image Compression, Data Compression and Network Information Flow

In 1990 we proposed five research areas in image compression. These areas included the successive refinement of information (progressive transmission), adaptive data compression and rate distortion theory for images.

Our work on the successive refinement of information included the paper by Cover and Equitz, "The Successive Refinement of Information," *IEEE Transactions on Information Theory*, 1991. This paper established necessary and sufficient conditions for achieving several points on the rate distortion curve. Thus for many sources, like Gaussian sources, Bernoulli sources with a Hamming distortion criterion and others, an optimal method was found for describing a source so that additional descriptional information would still be optimal. This hierarchical technique describes random sources in such a manner that the description is optimal no matter when it is stopped.

This paper placed second in consideration for the best paper prize in information theory for the period 1991-1992.

An experiment has been run to determine the limits of the noisy compression of images. The indications of this experiment are that currently available data compression algorithms can be further improved by an order of magnitude. However, in order to achieve this, the image compression algorithms will have to be able to "see" the image as well as people do. Part of this work was announced in DCC (Data Compression Conference) March 1994.

JSEP Supported Dissertations

1. D. Costa, “Microwave and Low-Frequency Noise Characterization of Npn AlGaAs/GaAs Heterojunction Bipolar Transistors,” Ph.D. Dissertation, Stanford University, Stanford, CA, December, 1991.

2. W. S.-K. Fu, “Femtosecond and Quasi-Steady State Optical Non-linear Physics of GaAs/AlAs Type II Quantum Wells,” Ph.D. Dissertation, Stanford University, Stanford, CA, August 1992.

3. B. O. Wells, “Analysis of the Gap in High Temperature Superconductors Using Photoemission Spectroscopy,” Ph.D. Dissertation, Stanford University, Stanford, CA, August 1992.

4. D.S. Dessau, “ Photoemission Studies of High-Tc Superconductors: Doping Dependences, Fermi Surfaces, Superconducting Gaps, and Metal-Superconductor Interfaces,” Ph.D. Dissertation, Stanford University, Stanford, CA, December 1992.

5. K. Y. Siu, “Complexity Issues in Circuits for Neural Computation,” Ph.D. Thesis, Stanford University, Stanford, CA, May 1991.

6. G. Xu, “Fast Subspace Decomposition and Its Applications, Ph.D. Thesis, Stanford University, Stanford, CA, September 1991.

7. L. Ekroot, “Process Entropy,” Ph.D. Dissertation, Stanford University, Stanford, CA, 1991

8. J. Roche “Distributed Information Storage,” Ph.D. Dissertation, Stanford University, Stanford, CA, 1992.

9. S. Pombra, “Non-White Gaussian Multiple Access Channels with Feedback,” Ph.D. Dissertation, Stanford University, Stanford, CA, 1992.

10. A. Nobel, “On Uniform Laws of Averages” Ph.D. Dissertation, Stanford University, Stanford, CA, 1992.

11. M. Troutt, “The Algebraic Structure of Trellis Codes” Ph.D. Dissertation, Stanford University, Stanford, CA, 1992.

12. R. Keller, "Chemical Methods to Modify Defect Populations in Gallium Arsenide" Ph.D. Dissertation, Stanford University, Stanford, CA, 1993.

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2. W. Liu, D. Costa, and J. S. Harris, Jr., "Comparison of the Effects of Surface Passivation and Base Quasi-Electric Fields on the Current Gain of AlGaAs/GaAs Heterojunction Bipolar Transistors Grown on GaAs and Si Substrates", *Appl Phys. Lett.* **59**, 691 (1991).
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5. D. Costa, W. Liu, and J. S. Harris, Jr., "Direct Extraction of the AlGaAs/GaAs Heterojunction Bipolar Transistor Small-Signal Equivalent Circuit", *IEEE Trans.on Elect. Dev.* **38**, 2018 (1991).
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7. W. Liu, D. Costa and J. S. Harris, Jr., "Derivation of the Emitter-Collector Transit Time of Heterojunction Bipolar Transistors", *Solid State Elect.* **35**, 541 (1992).
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