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Annual Progress Report

for

Join Services Electronics Program

Contract N00014-84-K-0327

for the period

1 April 1986 through 31 March 1987

G.L. Report No. 4287

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Edward L. Ginzton Laboratory
Stanford University
Stanford, CA 94305

For the Faculty of the Edward L. Ginzton Laboratory
Professor S. E. Harris
Director

October 1987

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Section I

Introduction

This is the annual progress report for the JSEP Program of the Edward L. Ginzton Laboratory at Stanford University for the period 1 April 1986 through 31 March 1987. The research activities were organized into four work units:

Work Unit 85 − 1   Picosecond Optical Electronic Measurements
(Professor D. M. Bloom)

Work Unit 85 − 2   Optical and Nonlinear
Optical Studies of Single-Crystal Fibers
(Professor R. L. Byer)

Work Unit 85 − 3   Scanning Optical Microscope
(Professor G. S. Kino)

Work Unit 85 − 4   Metal-Vacuum-Metal Tunneling
or Scanned Tunneling Microscopy
(Professor C. F. Quate)

The central theme of our work at Ginzton is the development of new material and device technologies, along with novel techniques for characterization and measurement, that will allow ultra-high speed electronic and optical processing of information. The different work units of this proposal interconnect the physics and technology of linear and nonlinear optical materials and fibers with new measurement tools which provide unprecedented spatial and temporal resolution. The following paragraphs summarize each of these work units.

Professor Bloom's work has been concerned with developing laser techniques for obtaining both time and frequency domain measurements of high speed electrical circuits. His efforts have been concerned with both electrooptic voltage sampling in gallium arsenide and with real time charge sampling in silicon. Using these techniques Bloom and his students have demonstrated 2 p.s. time resolution, and circuits with response into the 100 GHs range. A particularly exciting achievement during this contract period was the development of the charge sensing technique in

silicon. This concept has in turn allowed the development of a very simple silicon optical modulator with extraordinary potential.

The overall objective of Professor Byer's program is the growth, fabrication and characterization of single crystal optical fibers. The program is concerned with the development of both passive devices, such as polarizers, filters, and high-temperature light guides, as well as active devices such as frequency doublers and optical parametric oscillators. The basic technique that Byer uses is to focus the output of a CO_2 laser onto the tip of a source rod into which is dipped a seed crystal; he then pulls the seed crystal and feeds the source rod at different speeds. The process thereby allows the growth of a fiber whose cross-section is smaller than that of the source rod by the ratio of the two speeds. The particular achievement of the Byer group has been insitu characterization which has allowed the growth of both sapphire and $LiNbO_3$ fibers with diameter variations as small as 0.05%.

During the last year and a half Professor Kino has re-directed his efforts from the study of very high frequency acousto-optic taps for optical fibers, to the development of a new type of real-time scanning optical microscope. This microscope operates by illuminating an objective lens by light from a 20μm diameter pinhole. This illuminates a spot on the object, the reflective light from which then passes back through the same objective lens and the same pinhole to a detector. If the object is moved out of focus the reflected light of the pinhole is defocused and does not pass through. The depth of field is therefore approximately the confocal depth of the focusing lens. The Kino microscope has a measured depth of field of 600 nm. Also, because of the double use of the same lens, a transverse resolution almost twice that of a conventional microscope is obtained. This is about 200 nm in the Kino microscope. Applications to integrated circuits as well as to biological systems are under way.

Professor Quate's work is aimed at developing the technology and studying the applications of the Scanning Tunneling Microscope and the Atomic Force Microscope, both of which allow unprecedented imaging on an atomic scale. The scanning tunneling microscope uses a tip that has a single atom at its extremity. The Force Microscope is an outgrowth of the STM, which does not require tunneling electrons and which thereby allows the examination of insulators. The extraordinary accomplishments of this program include the operation of the STM in air at atmospheric pressure with high scanning speeds, the first demonstration of the Atomic Force Microscope, and the first measurement of the energy gap in high temperature superconductors. The Force Microscope is also being used to study magnetic materials. This study could perhaps lead to storage and retrieval on an atomic scale.

The publications and oral disclosures, as well as the invited papers, patents and honors are included as sub-sections of each of the individual work units.

Work Unit 85-1

Title: Picosecond Optical Electronic Measurements

Principal Investigator: D. M. Bloom

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A. Introduction

Our work on this contract has followed two distinct but related paths: electrooptic voltage sampling of gallium arsenide integrated circuits and real-time optical detection of charge in silicon integrated circuits.

The electrooptic sampling effort been directed at improving the performance and ease of use of the sampler in making time- and frequency-domain measurements in the low picosecond and mm-wave regions. We have incorporated a wafer probe station in the sampler that has allowed testing of circuits in wafer form, thus eliminating expensive and time-consuming high frequency packaging. The system has demonstrated a time resolution of 2ps or a bandwidth of greater than 100GHz with microvolt sensitivity. We have measured propagation delays, signal distortion and microwave scattering parameters in digital and analog circuits. This work received initial support from the JSEP. On-going work in this area is being funded by the AFOSR and the AFWAL.

The silicon charge sensing effort, supported through this JSEP contract, was pursued initially as an extension to silicon of electrooptic sampling. However, because the silicon lattice is not electrooptic, a different optical interaction was needed. We found that

the free-carrier plasma/optical interaction produces a
large refractive index change and our silicon probe was
developed using this interaction. In the plasma-optical
effect the polarizability of free carriers in the
semiconductor perturb the index of refraction which can
be detected in a Nomarski-type optical interferometer.
For example, we have demonstrated the real-time optical
detection of charge modulation in silicon bipolar
integrated circuits at 50MBit/sec. The probe has proved
to be highly non-invasive and so sensitive that our
results suggested the development of a silicon optical
modulator based on the effect. To this end, we have
been awarded a new JSEP contract to develop a high speed
silicon optical modulator based on currently available
bipolar process technology.

B. Summary of Principal Accomplishments

The principal accomplishments of this work unit
were:

1) Development of our electrooptic sampler to make
signal delay, distortion, and scattering
measurements with 2ps resolution or in a 100GHz
bandwidth on digital and analog GaAs integrated
circuits in wafer form.

2) Development of an optical probe for the real-time
measurement of charge modulation in silicon
integrated bipolar circuits; detection of 25MBit/s
signals in a silicon bipolar transistor in a
detection bandwidth of 200MHz with a sensitivity of
better than $2 \times 10^8 carriers/cm^2/\sqrt{Hz}$. Spatial
resolution is approximately $3\mu m^2$.

3) Initial concept of a silicon optical modulator for
use at $1.3\mu m$ wavelength based on free carrier
plasma/optical effect.

C. Discussion

Our electrooptic sampling system was developed for non-contact optical probing of IC voltages on GaAs integrated circuits[1-2]. An infrared probe beam, focused throught the IC substrate, senses a voltage through a change in its polarization caused by voltage-induced birefringence in the GaAs. The system, using a picosecond pulse laser feedback stabilized to a microwave synthesizer (block diagram shown in Fig. 1), has a time resolution of 2 ps or a bandwidth greater than 100 GHz and a voltage sensitivity of 70 $\mu V/\sqrt{Hz}$. A microwave wafer probe station has been modified to allow for backside probing of IC's (see Fig. 2), allowing delivery of drive signals to frequencies of 40 GHz to the IC. The system can be used like a sampling oscilloscope to measure time waveforms, such as switching signals on digital IC's to determine propagation delays[3] and signal risetimes (Fig. 3), and distortion waveforms on analog IC's to measure saturation and clipping mechanisms, or the system can be used as a vector voltmeter to measure the small-signal frequency response of microwave IC's.[4]

Circuit measurements have been made on a number of IC test circuits, including MESFET and MODFET inverter chains, MESFET multiplexers, static and dynamic frequency dividers, heterojunction bipolar transistor comparators, and microwave distributed amplifiers.[5] Preliminary results on microwave test structures show that scattering parameters can be measured with the reference plane directly on the integrated circuit.

The charge sensing probe is related to the electrooptic sampling system described above. We shall now briefly describe the probe, some of the development it has undergone and some measurements we have made with it.

Our charge sensing optical probe[6-9] has an optical system that is similar to the electrooptic probe as can be seen from the schematic of Fig. 4. Fundamentally, of course, they are both optical interferomters. However, the charge probe relies on a different physical effect and operates by interferometrically detecting the phase change induced in an optical beam by the presence of free charge carriers in active semiconductor devices. Continuous linearly polarized 1.3μm laser light is split into two orthogonally polarized beams which diverge from each other by a small angle. The two beams are focussed through the backside of the circuit under test to two spots separated by about 30 microns. The probe beam passes through the active area of a device, where the phase of the beam is modulated by changes in sheet charge density. The reference beam passes through an inactive area, so its phase remains unmodulated. The beams reflect off surface metalizations and are recombined in the wedges. Polarizing beam splitters perform PM to AM conversion and the resultant intensity modulated beams are detected directly by wide bandwidth photodiode recievers. Initially we used a single birefringent wedge and either a narrow linewidth Nd:YAG laser[6] or a single-longitudinal mode InGaAsP laser[7], but these resulted in excessive phase noise. We developed a better system[8,9] which uses a commonly available multi-mode 1.3μm semiconductor lase and a phase-compensating Wollaston prism. This system, while still operating a laser-noise limit, achieved far higher signal to noise ratios and increased stability. Since then we have temperature-controlled the laser to stabilize it further and installed a Faraday rotation isolator which achieves about 50dB of optical feedback isolation with very little loss. It now operates much closer to the shot noise limit. The system has a noise floor of less than --127dBm in the range 10-200MHz operating at 1mA of

detected photocurrent. The system has a minimum detectable sheet charge density of $<1\times10^8$ electrons/cm^2/$\sqrt{Hz}$. The resolution of the probe is limited by the diameter of the optical spot which is about 3μm. Because photons at 1.3μm wavelength fall at an absorption minimum of silicon, the probe is highly noninvasive. To illustrate, we note that the equivalent electrical impedance of the probe is >100 megaohms. Also, because the free carrier/optical effect occurs in all semiconductors, the optical probe may be used in any semiconductor which transmits 1.3μm light. For example, we have measured sheet charge densities in GaAs and Silicon integrated diodes, transistors and capacitors.

Figure 5 demonstrates the kind of measurements made with the probe. In this case we observed the modulation of carriers through the base/emitter of a silicon npn biploar transistor. The device was driven with a square wave voltage. The observed waveform clearly shows evidence of the finite carrier lifetimes in this part of the device, which appear as a decay of the signal with times characteristic of the carrier type, device bias, geometry and doping level. This example also shows the high signal to noise ratios available and represents a signal with a peak-to-peak modulation index of 9.8%. We have also demonstrated the use of silicon in a broadband optical communications link. Using Manchester-encoded data as the input to the base of the transistor, we obtained an "eye-diagram" of the received signal (Fig. 6). Comparison of the input and recieved eye diagrams show high signal-to-noise ratio and good timing stability which is needed in a communication link. (The Manchester encoding removes the low frequency content of a broadcast signal to reduce sensitivity to thermal signals and 1/f noise.)

Evidence of the success of this JSEP program is seen in the fact that our work in the development of the

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charge sensing probe has expanded into three projects, one of which continues to be funded through JSEP. Our effort in the development of the silicon charge sensing probe will allow us to measure signals of ever-higher bandwidths and with greater physical resolution using a more sophisticated receiver design and improved imaging optics. Already, computer aided data acquisition and a piezo-electric-driven translation stage allow 3-D representation of received optical signal vs position. The data collected will be used to validate computer models of charge-carrying devices and second-order theoretical device models. A second direction seeks to develop the charge sensing probe into a charge sampling system of a type similar to the one used in the electrooptic system in order to observe carrier transport effects in Si and AlGaAs/GaAs devices with fempto-second resolution. Finally, our third effort, funded with the assistance of JSEP, seeks to design, model and fabricate a novel all-silicon optical modulator for use in a single-mode 1.3μm optical communications link. Immediate applications of such a device are envisioned in silicon chip-to-chip optical interconnects. Modulation indices of ten percent, observed in integrated silicon bipolar transistors, demonstrate that the carrier/optical effect is so efficient that useful optical devices made of silicon are feasible. Silicon has hetertofore not participated significantly even in short-distance optical communication links.

References

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2) K.J. Weingarten, M.J.W. Rodwell, and D.M. Bloom: "Picosecond optical sampling of GaAs integrated circuits," to be published in IEEE J. Quant. Elect., Feb., 1988.

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6) H. K. Heinrich, D. M. Bloom, and B. R. Hemenway, "Noninvasive Sheet Charge Density Probe for Integrated Silicon Devices," Appl. Phys. Lett. 48, (16), 1066-1068 (April 21, 1986)

7) H. K. Heinrich, B. R. Hemenway, K. A. McGroddy, and D. M. Bloom, "Measurement of Real Time Digital Signals in a Silicon Bipolar Junction Transistor Using a Noninvasive Optical Probe," Elect. Lett. 22, (12), 650-652 (June 5, 1986).

8) B. R. Hemenway, H. K. Heinrich, J. H. Goll, Z. Xu, and D. M. Bloom, "Optical Detection of Charge Modulation in Silicon Integrated Circuits Using a Multimode Laser Diode Probe," IEEE Electron Device Letters EDL-8, (8) (August 1987).

9) H. K. Heinrich, "A Noninvasive Optical Probe for Detecting Electrical Signals in Silicon Integrated Circuits," Dissertation, Stanford University, GL 4190 (April 1987).
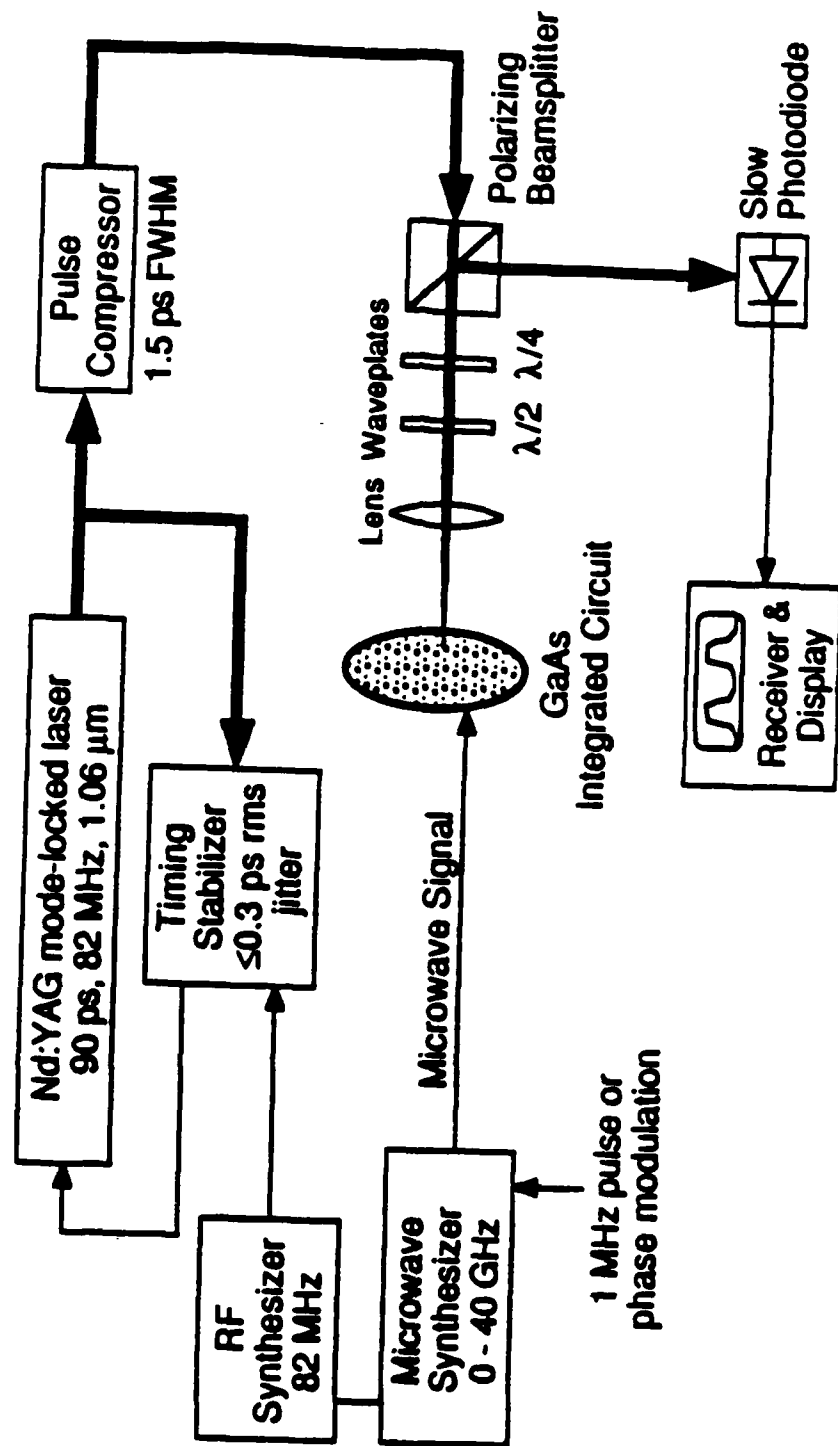
Fig. 1 Schematic Diagram Of Electrooptic Sampling System
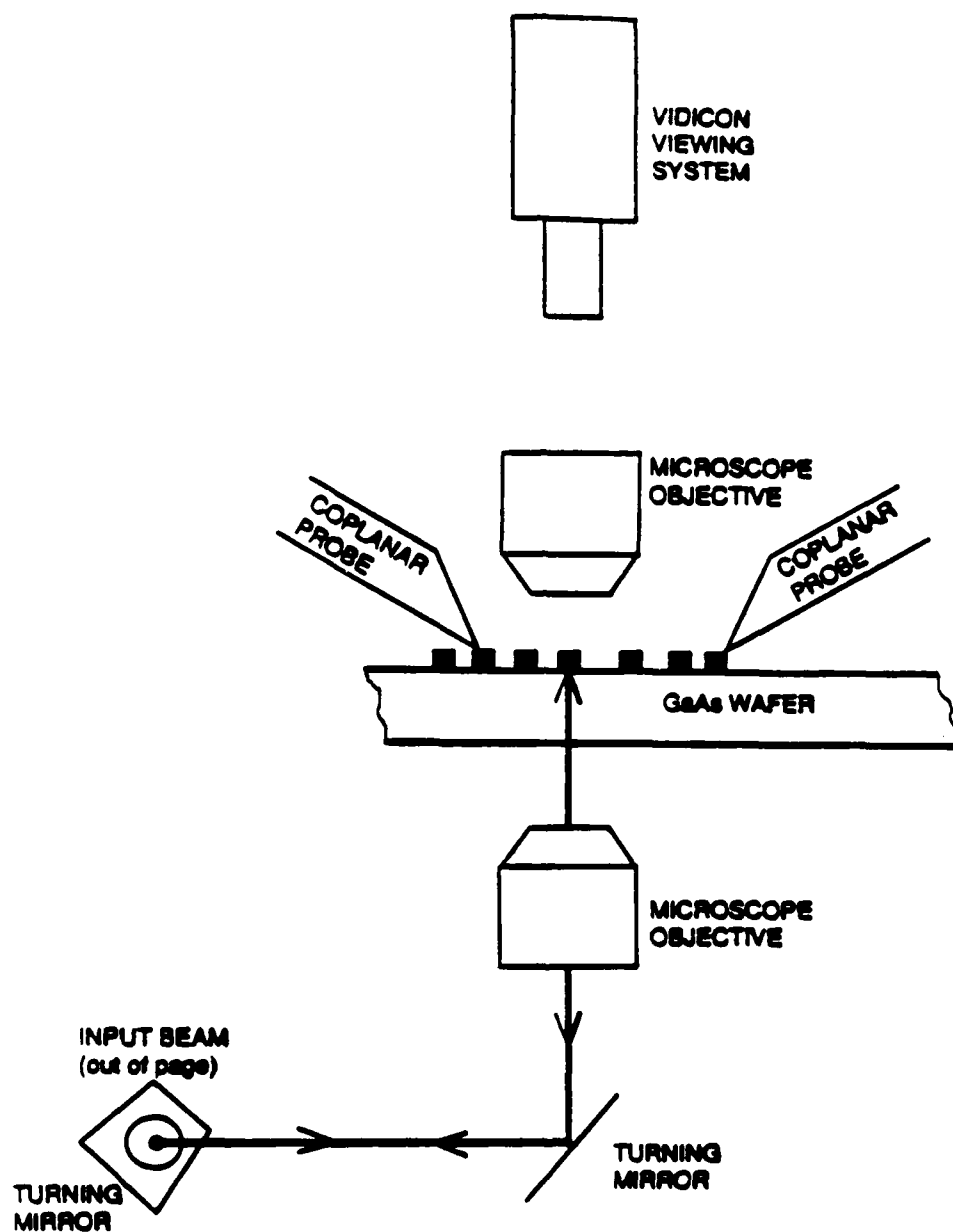
Fig. 2 Wafer Probe station showing optical and electrical access to wafers under test.

**Time, ns**

Relative Signal

120 ps
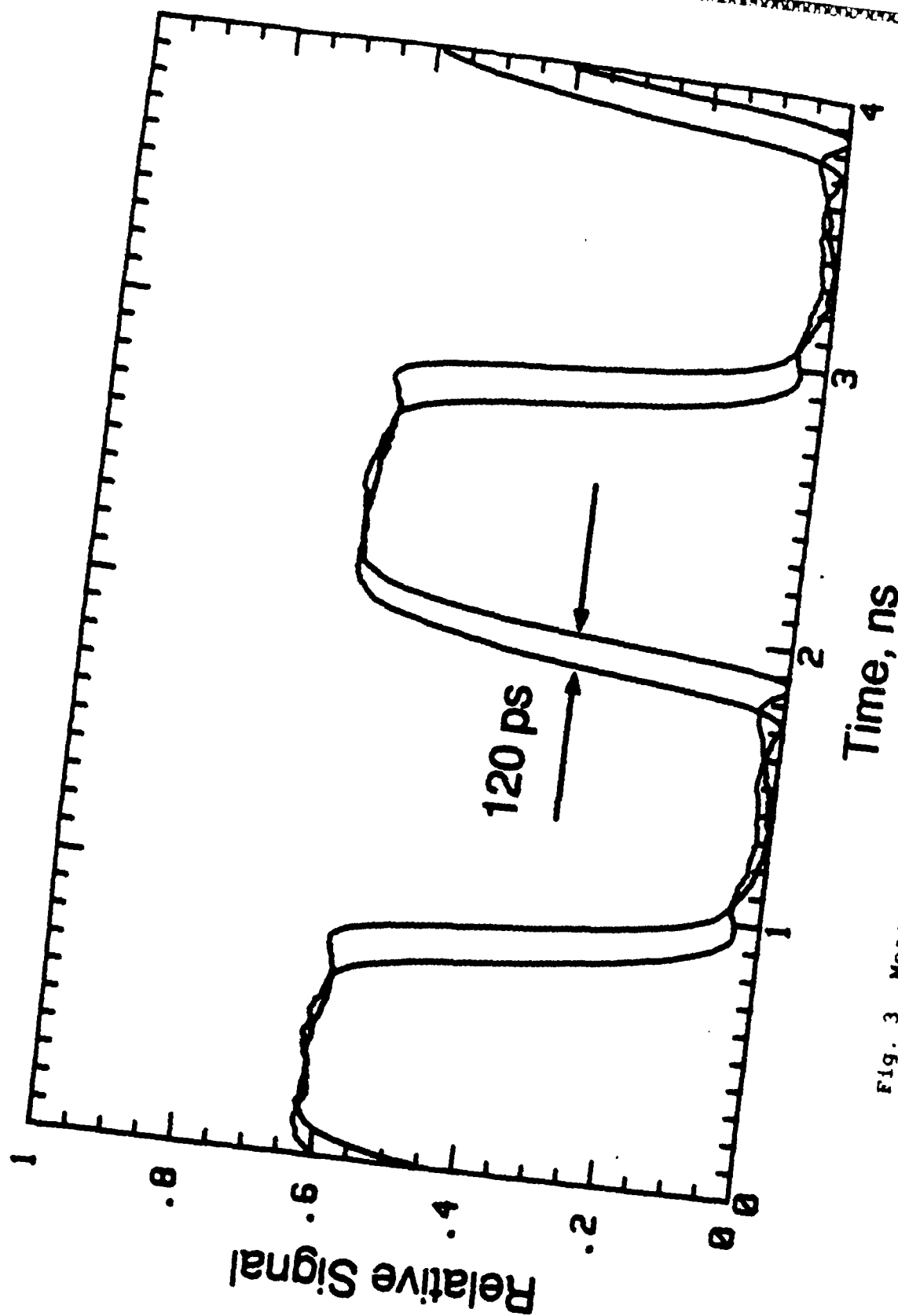
Fig. 3 Measurement of propagation delay through two inverters of an E/D MODFET inverter chain, with unity fan out.
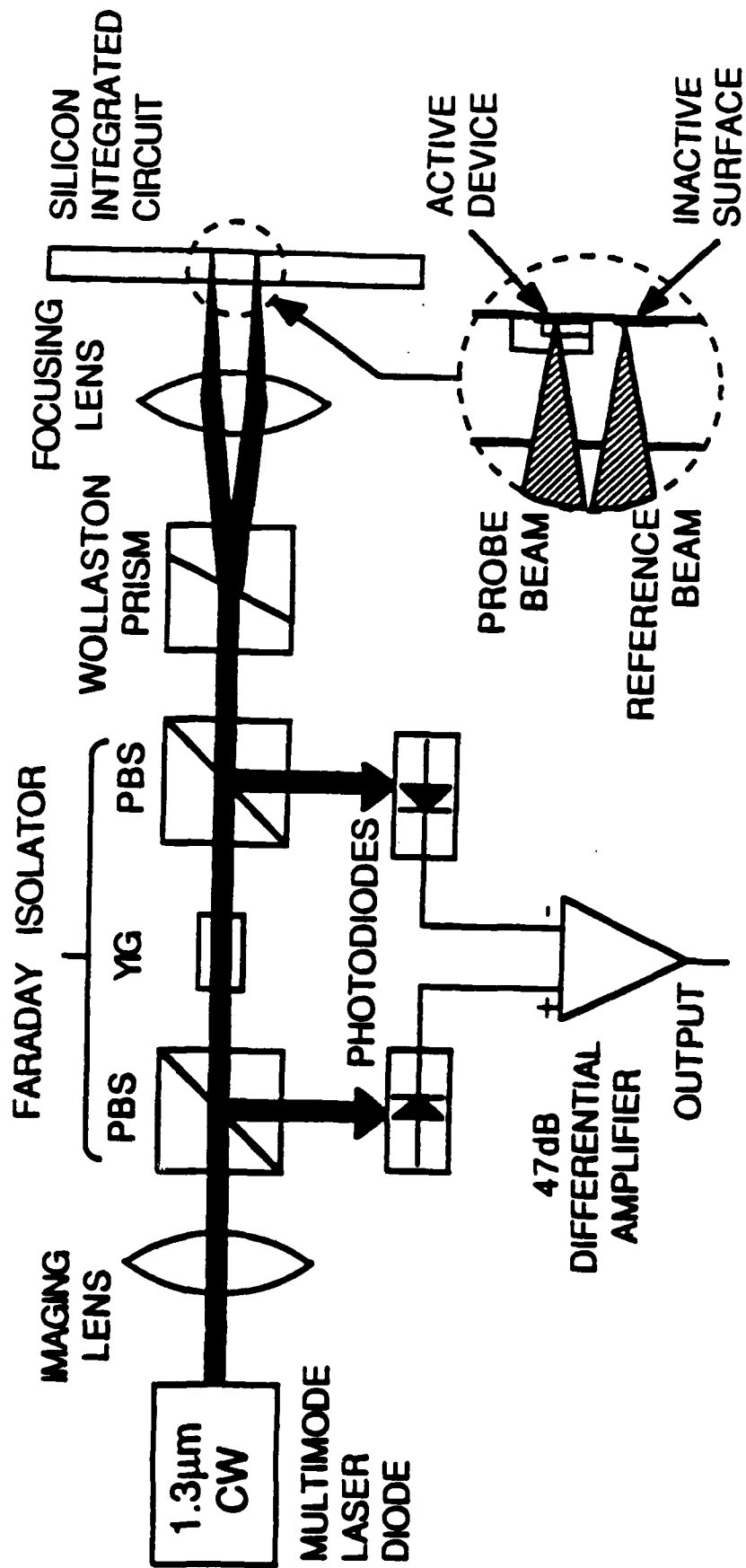
Fig. 4 Schematic diagram of optical charge sensing probe.

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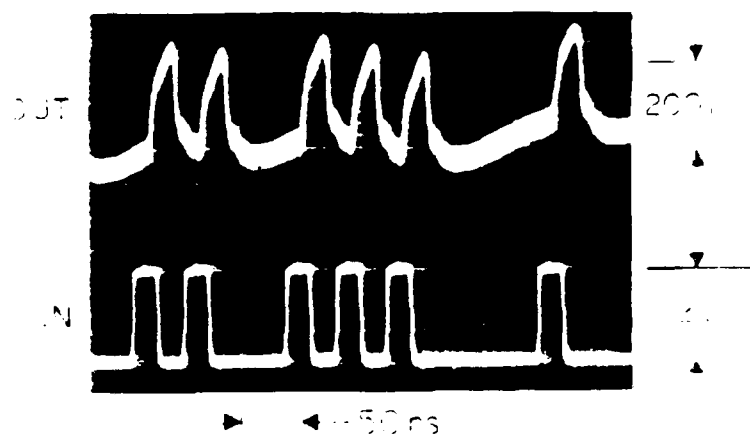
Fig. 5   Input electrical and observed optical charge
          sensing signals. Square wave applied to base of
          silicon npn bipolar transistor, emitter grounded.
          Probe beam was directed through the base/emitter
          junction.
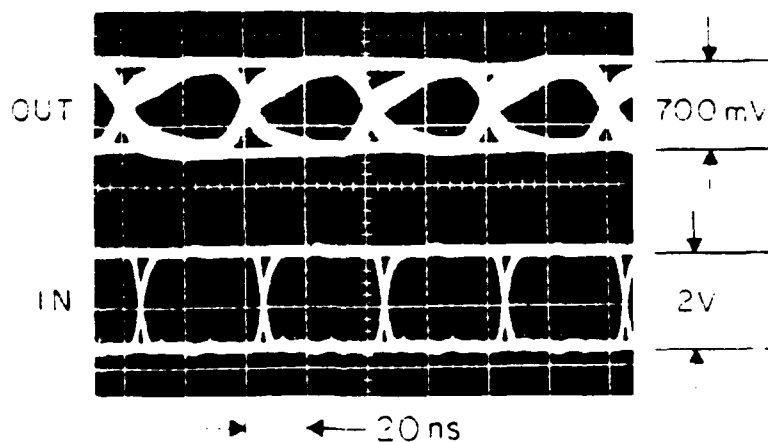
Fig. 6   Eye-diagrams of input electrical and received
          optical Manchester-encoded data input to base of
          transistor. Data rate is 25MBaud.

D. Publications, Invited Papers, Patents, and Honors

D.1 Publications supported or partially supported by JSEP

1) B. R. Hemenway, H. K. Heinrich, J. H. Goll, Z. Xu, and D. M. Bloom, "Optical Detection of Charge Modulation in Silicon Integrated Circuits Using a Multimode Laser Diode Probe," IEEE Electron Device Letters EDL-8, (8) (August 1987).

2) H. K. Heinrich, "A Noninvasive Optical Probe for Detecting Electrical Signals in Silicon Integrated Circuits," Dissertation, Stanford University, GL 4190 (April 1987).

3) H. K. Heinrich, B. R. Hemenway, K. A. McGroddy, and D. M. Bloom, "Measurement of Real Time Digital Signals in a Silicon Bipolar Junction Transistor Using a Noninvasive Optical Probe," Elect. Lett. 22, (12), 650-652 (June 5, 1986).

4) H. K. Heinrich, D. M. Bloom, and B. R. Hemenway, "Noninvasive Sheet Charge Density Probe for Integrated Silicon Devices," Appl. Phys. Lett. 48, (16), 1066-1068 (April 21, 1986).

D.2 Oral Disclosures

1) "Measurement of Charge Build Up in Resonant Tunneling Diodes," 1987 Ballistic Electrons for Transistors Conference, Santa Barbara, California, March 24, 1987. S. K. Diamond.

2) "Picosecond Sampling of Integrated Circuits," Second Topical Meeting on Picosecond Electronics and Optoelectronics, Incline Village, Nevada, January 13, 1987 (Invited Paper). D. M. Bloom.

3) "Noninvasive Testing of Very Fast VLSI Structures," 1986 IEEE Computer Elements Workshop, Mesa, Arizona, December 2, 1986. D. M. Bloom.

4) "Ultrafast Optical Electronics," Hughes Research Laboratories, Malibu, California, November 18, 1986. D. M. Bloom.

5) Ultrafast Optical Techniques for Charge and Voltage Measurements in Semiconductor Devices and Circuits," Bell Communications Research, Red Bank, New Jersey, September 28, 1986. D. M. Bloom.

6) "Noninvasive Optical Sheet Charge Density Probe for Silicon Integrated Circuits" Device Research Conference, University of Masschusetts, Amherst, Massachusetts, June 25, 1986. H. K. Heinrich.

7) Electrooptical Characterization of High Speed Devices" Device Research Conference, University of Massachusetts, Amherst, Massachusetts, June 23, 1986. D. M. Bloom.

8) "Electrooptic Sampling of Gallium Arsenide Integrated Circuits" 1986 Ultrafast Phenomena Conference, Snowmass, Colorado, June 16, 1986. K. J. Weingarten.

9) "Noninvasive Sheet Charge Density Probe for Integrated Silicon Devices " 1986 Conference on Lasers and Electro-Optics, San Francisco, California, June 7, 1986. H. K. Heinrich.

10) "Ultrafast Optical Electronics" LEOS Lecture Series, University of Maryland, Greenbelt, Maryland, June 3, 1986. D. M. Bloom.

11) "Internal Microwave Propagation and Distortion Characteristics of Travelling-Wave Amplifiers Studied by Electrooptic Sampling" MTT Conference, Baltimore, Maryland, June 2, 1986. M. J. W. Rodwell.

12) "Ultrafast Optical Electronics" University of Oregon, Eugene, Oregon, May 29, 1986. D. M. Bloom.

13) "Ultrafast Optical Electronics" OCATE Lecture Series, Tektronix Education Center, Portland, Oregon, May 28, 1986. D. M. Bloom.

14) "Ultrafast Optical Electronics" LEOS Lecture Series, Rockwell, Thousand Oaks, California, May 14, 1986. D. M. Bloom.

15) "Ultrafast Optical Electronics" University of New Mexico, Albuquerque, New Mexico, April 8, 1986. K. J. Weingarten.

16) "Ultrafast Optical Electronics", Los Alamos National Laboratory, Los Alamos, New Mexico, April 7, 1986. K. J. Weingarten.

D.3 Patents

H. K. Heinrich and D.M. Bloom, "Method and Means for
Optical Detection of Charge Density Modulation in
Silicon, March 1986.

D.4 Honors/Awards/Prizes

1986 Fellow of the Institute of Electrical and
Electronics Engineers (IEEE).

1985-86 Lasers And Electro-Optics Society (LEOS)
Traveling Lecturer, IEEE, Ultrafast Electronics.

Work Unit 85-2

Title: Optical and Nonlinear Optical Studies of Single-Crystal Fibers

Principal Investigator: R. L. Byer

Telephone: (415) 723-0226

A. Introduction

Single-crystal optical fibers are useful in devices which would either be impossible in glass fibers because of their amorphous structure, or which would take excessive lengths of glass fiber to implement. These applications can be divided into three classes. Passive devices include lightguides, polarizers, isolators and filters. Active devices are represented by fiber lasers and amplifiers. Finally, nonlinear devices, which take advantage of the sustained high field intensities possible in fiber waveguides to dramatically increase the efficiency of nonlinear interactions, include harmonic generators, Raman shifters and optical parametric oscillators.

This research program has concentrated on three materials which are applicable to such devices. Single-crystal sapphire (Al_2O_3) is transparent from 0.24 to 4.0 μm, is birefringent, and has a high melting point. It is useful for passive devices such as polarizers, filters and high-temperature light-guides. Because it is easy to grow, it has also been the crystal of choice for studies of single-crystal fiber growth. $Cr:Al_2O_3$, Nd:YAG and garnets doped with chromium can be used to make active devices. Lithium niobate ($LiNbO_3$) has been studied for applications to nonlinear devices. Magnesium doping has been shown to lessen the effects of photorefractive damage in $LiNbO_3$, and hence the magnesium-doped material is most often grown.

The overall objectives of this program are the growth, fabrication and characterization of single-crystal fibers. Growth studies aim to produce fibers with stable diameter and constant composition. Fiber fabrication includes all post-growth steps in the making of devices, such as end polishing, and annealing for improving mechanical strength and compositional uniformity. In addition, stoichiometry control via diffusion, poling of ferroelectric fibers to make them single-domain, and formation of diffused or coated claddings to protect the guiding interface or to reduce its diameter have been studied.

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Finally, characterization of the resulting fiber device during fabrication is necessary to determine the success of the processing steps and, after the device is completed, to measure its operating parameters and performance.

B. Summary of Principal Accomplishments

The principal accomplishments of this work unit were:

1) Construction of an apparatus for **laser-heated pedestal-growth** of single-crystal fibers. The system uses a real-time interferomentric diameter sensor and a digital control loop to grow fibers with **0.05% diameter variations** in Al_2O_3 and $LiNbO_3$

2) Growth of Al_2O_3 fibers with **0.08 dB/m losses**. These fibers have a transparency range from 240 nm to 4000 nm, a melting temperature of 2050° C, and a 5 mm bend radius, suitable for medical and industrial energy delivery applications.

3) Development of a **vapor transport equilibration** (VTE) technique to control the composition of $LiNbO_3$ crystals. This simple process has produced $LiNbO_3$ with the best compositional uniformity, the largest birefringence, the highest second harmonic (SHG) phasematching temperature at $1.06~\mu m$ (238°C), and the shortest wavelength phasematched SHG (954 nm) reported to date. The SHG of 954 nm produces **blue radiation** (477 nm), currently of great technological interest.

4) Development of a model based on the **thermoelectric effect** to explain the **ferroelectric domain structures** in $LiNbO_3$ fibers. This model explains previously misunderstood effects observed in bulk and planar samples, and is important in our efforts to produce **periodically-poled** crystals suitable for **quasiphasematching.**

C. Discussion

In this section, we summarize results in fiber growth, processing, and optical measurements.

Fiber Growth

Fibers useful for device applications must be oriented single crystals of good optical homogeneity, with diameter fluctuations on the order of 0.1%. The technique that we use to grow such fibers, laser-heated pedestal growth, involves melting the tip of a source rod with the focussed output of a CO_2 laser, dipping in a seed crystal, then pulling the seed

crystal and feeding in the source rod at different speeds, thereby effecting the growth of a fiber whose cross-section is smaller than that of the source rod by the ratio of the two speeds. Because of the extremely high radiation temperature of the laser source and the absence of crucible contamination problems, this process can be applied to essentially any crystal that melts before it decomposes. Two fiber growth apparatus are currently in operation at Stanford. One, in R. S. Feigelson's group at the Center for Materials Research, has been applied to the growth of more than 40 different materials in fiber form, while the apparatus in the Byer group has been appplied to the growth of device quality fibers of three materials, Al_2O_3, Nd:YAG, and $LiNbO_3$.

The basic growth apparatus, using a waveguide CO_2 laser and a reflaxicon-based reflective focussing system as a stable, symmetrical heat source, continuous-belt-drive feed and pull mechanisms for accurate speed control, a controlled atmosphere chamber to isolate the growth zone from environmental perturbations, and a real-time interferometric diameter measurement system to monitor the growth process, has been in operation for several years. The focussing optics and pulling mechanisms are shown in Fig. 1. This system has been used to grow over 600 fibers in various materials, in lengths up to 250 mm, and diameters ranging from 20 - 500 μm.

Recently, a feedback control was developed and installed to stabilize the output power of the CO_2-laser used to melt the source-rod. Before this system was implemented, the power was very sensitive to temperature variations in cooling water and the ambient temperature. Drifts of laser power of up to 10% were observed, resulting in fiber diameter fluctuations. The stabilized laser has power variations of less than 0.2%. The feedback control loop also has the capacity to modulate the power. The maximum modulation frequency is 1kHz with a modulation depth of 20%.

A computer has been installed and interfaced to the fiber growth machine. It allows the parameters of growth to be monitored in real time. The values from the diameter measurement system are digitally processed with a suitable control function and fed back to the fiber puller during the growth process. A digital PID control loop has been implemented and the diameter stability for fibers improved. With this system, diameter control as good as 0.05% rms has been obtained, more than adequate for our device applications. Figure 2 shows the diameter variations on a 170 μm diameter Al_2O_3 fiber.

To our knowledge, this is the smoothest crystal fiber ever grown. Optimization of the control function could result in further improvement of the diameter variations.

A second feature of the computer interface is that data taken during fiber growth can be recorded on a mass storage medium for analysis. The spectrum of the diameter variations gives information about the dynamics of the growth process, which can be compared to the theoretical model which we have developed for this meniscus-controlled growth process. Preliminary data is in reasonable accord with theoretical predictions. In addition, the stored data can be used to model coupling between guided modes in the resulting fiber. Software was developed to modulate the diameter of the fiber as it is grown using the feedback control. The resolution of the diameter measurement along the axis of the fiber is approximately 6 μm. Thus, any function may be used for the modulation which has only spatial components with a period of greater than ~ 20 μm. Modulation with a period of less than 20 μm can be obtained in an open loop configuration if desired.

This patented growth technology has been licensed to Lasergenics, a start-up company interested in commercializing the crystal fiber technology for medical and optical markets.

Processing of LiNbO$_3$

Several steps are necessary to prepare as-grown LiNbO$_3$ fibers for device applications: composition control, cladding and poling. We have made significant progress in all these areas. In the course of these studies, we have discovered techniques that will have an impact on bulk and planar LiNbO$_3$ technologies, as will be seen in the following discussion.

LiNbO$_3$ exists as a solid solution over a range of Li/Nb ratios of 0.42 to 0.5. The Curie temperature and birefringence of this material depend strongly on the composition. Since nonlinear optical interactions depend on the homogeneity of the birefringence, it is then essential that the composition of the crystals be uniform. It is possible to grow homogeneous crystals only of the congruently melting composition, Li/Nb = 0.486/0.514, so that it has not been possible to take advantage of the range of birefringence (and therefore the range of phasematching wavelengths) made possible by the variable composition. It is known from work by Holman that Li can be made to diffuse in or out of a LiNbO$_3$ crystal when heated in the presence of a powder of known Li/Nb ratio. We have used this **vapor transport equilibration** (VTE) process to equilibrate

fibers to the stoichiometric phase boundary. This simple process has produced LiNbO$_3$ with the best compositional uniformity, the largest birefringence, the highest second harmonic (SHG) phasematching temperature at 1.06 μm (238°C), and the shortest wavelength phasematched SHG (954 nm fundamental) reported to date. Figure 3 shows the second harmonic output power as a function of temperature for two samples of different length. The width of the curve is inversely proportional to the length of the crystal up to the longest piece we have investigated, 5 cm, indicating the excellent homogeneity of VTE processed LiNbO$_3$. VTE is now a standard procedure for preparing our fibers for further processing. We are also applying VTE to thin bulk samples for use in resonant harmonic generation and parametric oscillator applications. VTE may also be a valuable preprocessing step for planar LiNbO$_3$ substrates for integrated optics, to eliminate the sample-to-sample variations in optical properties that presently result in poor yields.

For low-loss waveguides, it is important to form a layer of reduced index of refraction ("**cladding**") around the core. In studies carried out together with John Shaw's group, we have investigated several means for forming such cladding layers, including extruded glass on the surface of Nd:YAG fibers, and H$^+$, Ta, and Mg indiffusion in LiNbO$_3$. Of the indiffused claddings, Mg seems the best, as it diffuses rapidly and reduces both the ordinary and the extraordinary indices of refraction. Both polarizations must be guided for efficient birefringently phasematched nonlinear interactions. A plot of the parabolic index of refraction profile formed by MgO indiffusion into a 50 μm diameter c-axis LiNbO$_3$ fiber is shown in Figure 4. It was possible to **propagate the fundamental mode** at 633 nm in this fiber. The radius of the mode was 7 μm, in accord with theoretical predictions. We are now extending this result to a-axis fibers, which are necessary for birefringent phasematching of nonlinear interactions.

LiNbO$_3$, as a ferroelectric crystal, has domains of spontaneous electric polarization. Because the odd-rank material tensors change sign on crossing a domain wall, it is necessary that the material be in single domain form ("poled") for device applications. In studying the domain distributions in as-grown fibers, we concluded that the domain distributions are governed by the thermoelectric fields generated by the strong temperature gradients present in the vicinity of the molten zone. Thus, by controlling the temperature gradients, we can create substantially single domain fibers, or periodically poled fibers, as

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shown in Figure 5. Periodically poled fibers are of interest for device applications, because the array of domains creates a sign grating in the nonlinear susceptibility. If the period of this grating is equal to the coherence length of a nonlinear interaction, then the sign changes in the susceptibility compensate for the velocity mismatch of the interacting waves. Such an interaction is said to be "quasiphasematched". The advantage of quasiphasematching is the elimination of the constraints imposed by birefringent phasematching, allowing any interaction within the transparency range of the material, and allowing the use of the d_{33} coefficient instead of d_{31}, which leads to an order of magnitude increase in efficiency. We are currently studying means for reducing the variations in the domain spacing of the periodically poled fibers, as these are currently too large for device applications.

Optical Measurements

The simplest optical devices that we investigated use Al_2O_3 as a passive lightguide. Al_2O_3 is attractive in these applications because of its broad transmission window (240 nm - 4 μm), high melting point (2050°C), and resistance to chemical or mechanical damage. A plot of the scatter loss measured with an integrating sphere as a function of wavelength for two Al_2O_3 fibers is shown in Figure 6. The loss in the 2 - 3 μm range, where silica glass fibers are opaque, is on the order of 0.1 dB/m, more than adequate for short range delivery of high power laser radiation for medical or industrial applications. The losses in fibers grown with the recently improved control loop have not yet been measured, but we expect even better results. Absorption measurements by vacuum calorimetry indicate losses comparable to the scatter losses. These fibers have aroused considerable interest in the medical and sensor communities, leading to the previously discussed effort at commercialization by Lasergenics, and many requests for samples by outside groups.

Al_2O_3 fibers are also useful in sensor applications. We have built an all optical temperature sensor by doping the tip of a fiber with metal ions to create a small, integral blackbody. The radiation emitted by the blackbody tip and guided down the fiber can be monitored with a photodiode. Such a temperature sensor is chemically and mechanically rugged, resistant to high temperatures, immune to electrical noise, and can have good performance. With relatively crude electronic processing, we obtained 10 mK resolution

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in a 1 Hz bandwidth at 1500° C, using a Ni/Cr doped 170 μm diameter Al_2O_3 fiber. Other sensors could be built using the dependence of the fluorescence of appropriate dopants on various parameters, e.g. the pressure dependence of Cr^{3+} emission wavelength in ruby.

Fiber lasers and superfluorescent sources have been built in conjunction with John Shaw's group. Monolithic oscillators have been built in both $Cr:Al_2O_3$ and $Nd:YAG$. The most interesting device is a Nd:YAG laser in a 50 μm diameter fiber clad with a high index of refraction glass. The threshold (300 μW) and the slope efficiency (50%) are among the best reported for any Nd laser.

Application of the VTE $LiNbO_3$ to efficient guided wave nonlinear optical devices awaits successful extension to a-axis fibers of the cladding technology already demonstrated in c-axis fibers. Encouraging preliminary results have been obtained for SHG of 1.06 μm radiation, where conversion efficiency comparable to that of a bulk interaction was obtained, despite considerable intermodal scattering. As the cladding of a-axis fibers improves, efficient SHG will be demonstrated. The knowledge gained from this work will be combined with the monolithic resonator technology developed for the fiber Nd:YAG lasers to fabricate guided wave parametric oscillators.

In addition to device work, new materials for tunable laser sources have been studied in conjunction with Feigelson and a visiting scholar, Günter Huber. Fiber growth is a convenient method to obtain spectroscopic samples to investigate the influence of the host on the fluorescence wavelength. The materials are chromium-doped scandium oxide, yttrium oxide, lutetium oxide and mixtures of scandium oxide with the two other compounds. The preliminary measurements on lifetime and intensity of the fluorescence indicate that tunable solid state lasers that emit radiation in the near infrared are possible.

D. Publications, Invited Papers, Patents, and Honors (April 1, 1986 - March 31, 1987)

1) Publications supported or partially supported by JSEP

1. G. A. Magel, D. Jundt, M. M. Fejer, and R. L. Byer, "Low-loss Single Crystal Sapphire Optical Fibers," Proc. SPIE **618**, Infrared Optical Fibers and Materials II (1986).

2. Robert L. Byer and J. Nightingale, "Monolithic Nd:YAG Fiber Laser," Optics Lett. **11**, pp. 437-439 (July 1986).

2) Other Related Publications

1. M. M. Fejer, M. J. F. Digonnet, and R. L. Byer, "Generation of 22 mW of 532 nm Radiation by Frequency Doubling in a Ti:MgO:LiNbO$_3$ Waveguide," Opt. Lett. **13**, 230 (1986).

2. Y. S. Luh, R. S. Feigelson, M. M. Fejer, and R. L. Byer, "Ferroelectric Domains in Single-Crystal LiNbO$_3$ Fibers," J. Cryst. Growth, **78**, 135 (1986).

3. M. M. Fejer, "Single-Crystal Fibers: Growth Dynamics and Nonlinear Optical Interactions," Ginzton Lab Report No. 4235, Ph.D. dissertation, Stanford University (September 1986).

3) Oral Disclosures

(invited)

1. M. M. Fejer and R. L. Byer, "Nonlinear Optics in Single Crystal Fibers," CLEO '86, San Francisco, CA, June 1986.

2. R. L. Byer, "Growth and Applications of Single Crystal Fibers," Nippon Telegraph and Telephone Company, Ibaraki electrical Communications Labs., Tokyo, Japan, September, 1986.

(contributed)

3. Y. S. Luh, M. M. Fejer, R. L. Byer, and R. S. Feigelson, "Stoichiometric Lithium Niobate for Nonlinear Optical Applications" CLEO '87, Baltimore, April 1987.

4) Patents

1. J. L. Nightingale, M. M. Fejer, R. L. Byer, "Apparatus for Translating Crystal Fibers," patent number 4,607,776, issued Aug. 26,1986.

2. M. M. Fejer, G. A. Magel, and R. L. Byer, "Method and Means for High-Resolution Measurement of Fiber Diameter," patent number 4,650,322, issued March 17, 1987.

3. Y. S. Luh, M. M. Fejer, R. L. Byer, and R. S. Feigelson, "Tailored Properties of Lithium Niobate for Nonlinear Optical Applications by Vapor Transport Equilibration," pending.

4. M. M. Fejer and R. L. Byer, "Nonlinear Optical Processes in Electric-Field-Biased Quantum Wells," pending.

5) Honors/Awards/Prizes

Robert L. Byer was made a fellow of the National Academy of Engineering in 1987.
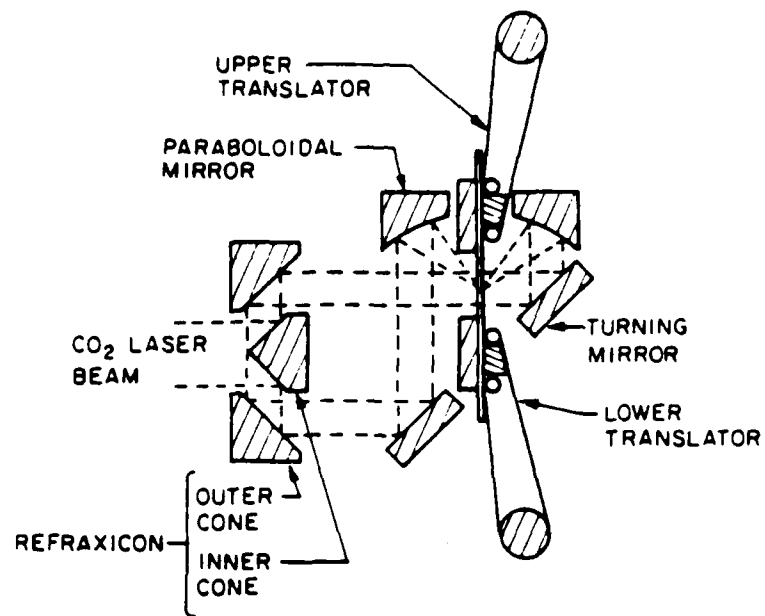
Figure 1. Detail of the focussing optics and pulling mechanisms employed in the laser-heated pedestal growth apparatus for producing single-crystal optical fibers.
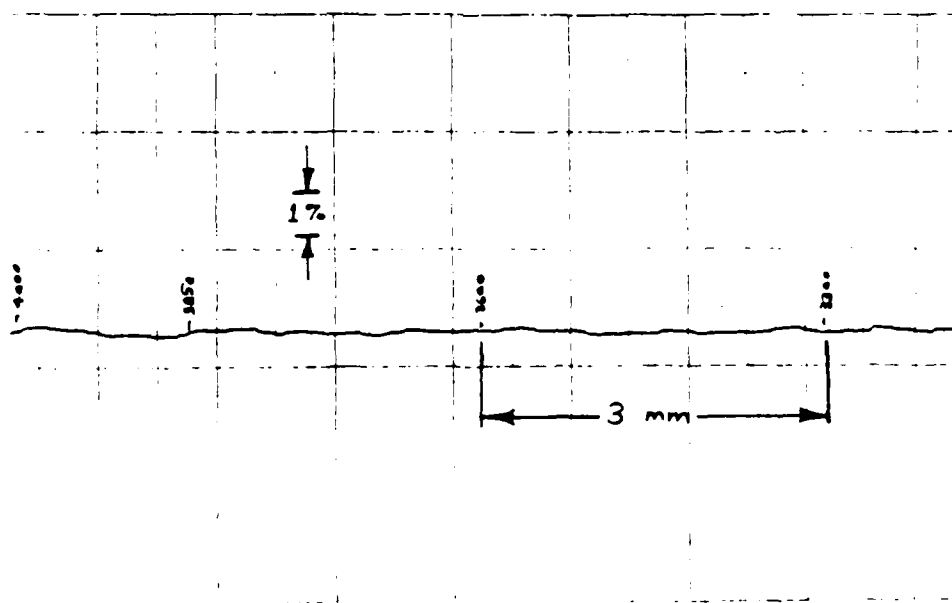

Figure 2. Diameter vs. length plot of a single-crystal sapphire fiber 170 μm in diameter, exhibiting diameter variations during feedback control of under 0.05% rms.
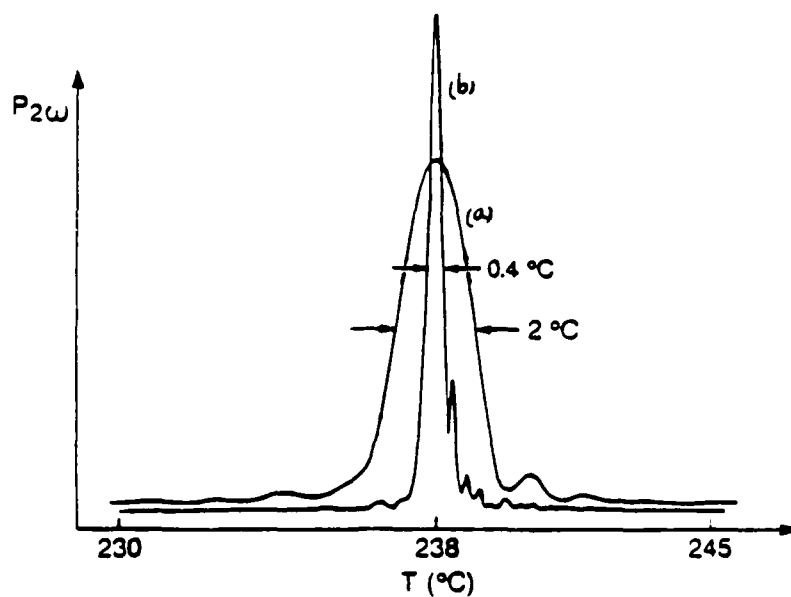
Figure 3. Second harmonic power vs. temperature curves for VTE processed LiNbO₃, showing excellent homogeneity of samples: (a) 4 mm long; (b) 20 mm long.
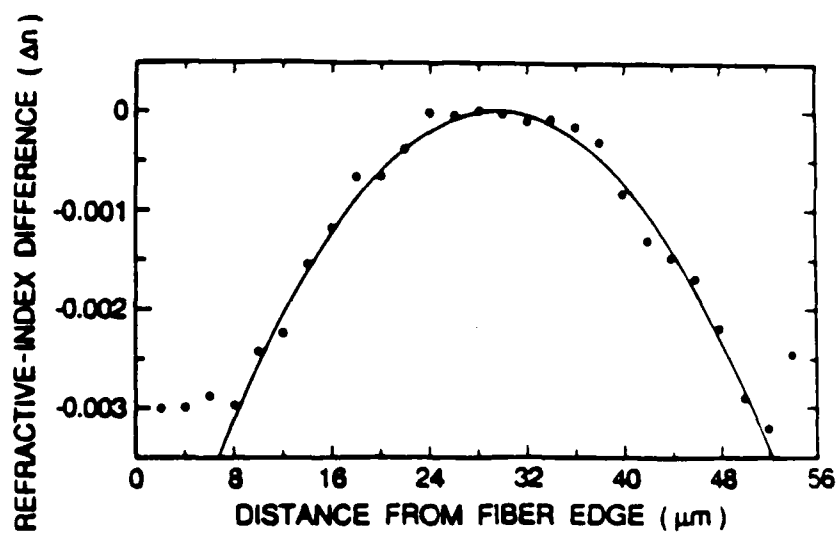
Figure 4. Parabolic refractive index profile of 56 μm diameter c-axis lithium niobate fiber with magnesium in-diffused cladding.
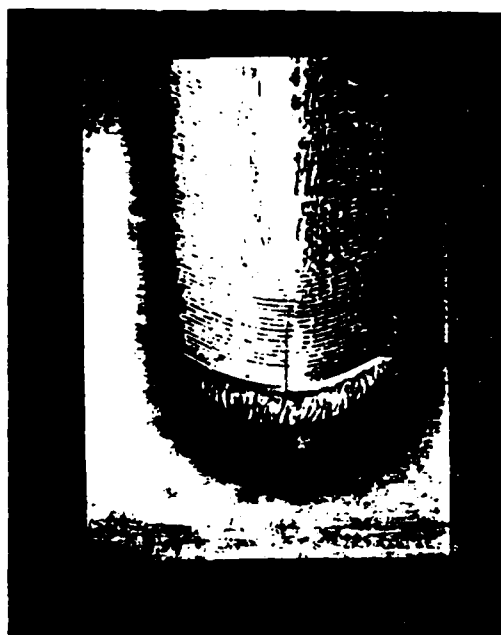
Figure 5. Etched cross-section of a 600 μm diameter a-axis LiNbO₃ fiber rotated during growth with asymmetric heating. Periodic domains spaced at ~10 μm are visible
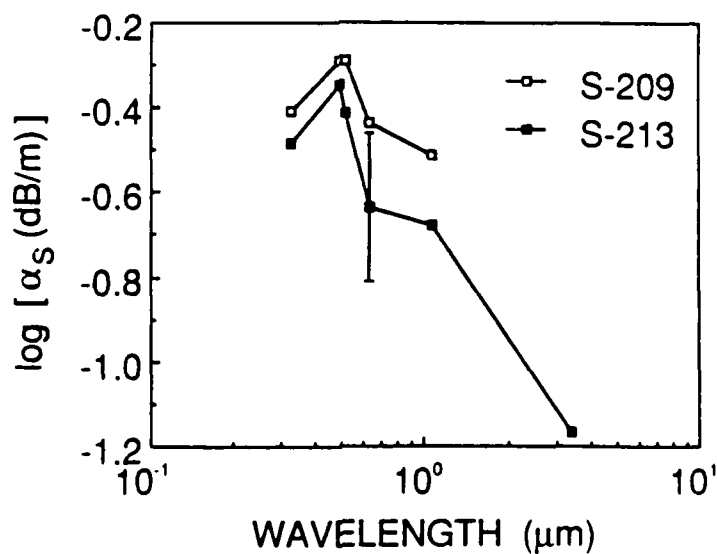

Figure 6. Scattering losses vs. wavelength for two 150 μm sapphire fibers. UV to near-IR losses cluster around 0.3 dB/m; 3.39 μm scattering loss is less than 0.07 dB/m.

Work Unit 85-3

Title: Scanning Optical Microscope

Principal Investigator: G. S. Kino

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A.   Introduction

A.1. Very-High-Frequency Signal Processing Techniques

The first year and a half of this program was devoted to research on acousto-optic techniques for tapping single-mode optical fibers. With this system, it was possible to use the acoustic wave excited by the transducer to Bragg scatter light out of the fiber. The device operated at a center frequency of 3.5 GHz with a bandwidth of approximately 1 GHz , and had an efficiency of about 2%/watt .

The work has been transferred to an NSA contract, administered by ONR, and is continuing on an extended scale.

A.2. The Scanning Optical Microscope

The standard optical microscope has an inadequate transverse resolution for use with submicron integrated circuits. Furthermore the glare from layers below or above the region being examined in a transparent material makes it impossible to make quantitative measurements with good transverse resolution of depth or thickness of a thin transparent film. To do this with an SEM, a cross-section must be cut from the material.

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Recently, we have constructed a new and very simple real-time scanning optical confocal microscope. With it, we obtain images with a transverse definition of the order of 200 nm , and a depth resolution between 3 dB points of 500 nm . The 5000-line, 700-frame/sec images can be observed directly by eye or with a video system or camera. The system is easy to align and construct, and we believe that it is the forerunner of a range of real-time high-definition microscopes with vastly enhanced capabilities over what is presently available.

The present device is capable of carrying out "optical cross sectioning" of transparent samples, i.e., observing individual thin layers without glare from other layers obscuring the image. We are thus beginning to extend the research to investigate fluorescent imaging, imaging of biological samples, and to carry out imaging of deep, narrow trenches in silicon with near infrared light.

B. Summary of Principal Accomplishments

The principal accomplishments of this work unit were:

(1) the development of a very-high-frequency acousto-optic tap for optical fibers with a bandwidth of 1 GHz ;

(2) the development of techniques for deposition of zinc oxide directly on optical fibers, and for photolithography of interdigital transducers on optical fibers;

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(3) the demonstration of a real-time scanning optical confocal microscope with submicron definition and very good depth resolution; and

(4) the invention of simple, inexpensive techniques which eliminate most of the alignment problems and complexity of the confocal optical and tandem scanning microscopes.

C. Discussion

C.1. Very-High-Frequency Signal Processing Techniques

The aim of this program was to develop a technology for very-high-frequency modulation of optical fibers and to use Bragg diffraction as a technique for tapping an optical fiber.

In our initial work, we used a D-shaped fiber that was placed in contact with a quartz wedge. The bottom surface of the wedge had a radius of approximately 50 cm, with the plane of a circle parallel to the axis of the fiber. When this wedge was pushed against the fiber, it formed a Hertzian contact. It was previously shown, in work on this program, that we could transmit acoustic waves efficiently through such a contact at frequencies up to 8 GHz. With this present device, we operated at a center frequency of 3 GHz, using a ZnO transducer deposited on the sloping face of the wedge. The acoustic wave was transmitted through the wedge into the fiber. This acoustic wave Bragg diffracted light

out of the fiber into the wedge and light was emitted through the third side of the triangle formed by the wedge.

With this device, we demonstrated a bandwidth of the order of 1 GHz at a center frequency of 3.2 GHz with fairly low efficiency. This experiment demonstrated the basic principles of operation.

We then decided to work with a different, more efficient, configuration. The basic idea was to deposit ZnO directly on the fiber to form a convergent acoustic beam along the axis of the fiber. Thus, the efficiency would be better because of the improvement in intensity; furthermore the alignment problems would be far simpler.

The system was constructed as shown in Fig. 1. A gold film was deposited on the fiber and then a thin ZnO film was sputter deposited on the surface of the gold. This was followed by an interdigital transducer which was formed by projection lithographic techniques. The interdigital transducer had an 8 micrometer period, and produced two beams which could cause Bragg scattering of the light out of the bottom surface of the fiber. Using this system, and operating at a center frequency of 3.5 GHz , we obtained a bandwidth of approximately 1 GHz and an efficiency of approximately 2%/watt .

We are now continuing related work on an NSA contract. We are interested in single-sideband modulators, amplitude modulators, and taps using the ZnO technology. We are also

developing a contacting technology, a gallium film between a cylindrical hole and the fiber which just fits into the hole.

C.2. The Scanning Optical Microscope

We have investigated a number of concepts for real-time scanning optical confocal microscopes which would give enhanced resolution compared to a standard microscope, and would at the same time give very good depth resolution The first involved the use of a Bragg cell for scanning the optical beam; it was capable of measuring optical phase (and hence depth) with great precision, as well as yielding a transverse resolution a factor of approximately two better than that of a standard microscope. However, it proved to be excessively complicated to construct and align.

 In this project we have made use of a much simpler principle for real-time scanning. The objective lens of the microscope is illuminated through a pinhole. This illuminates a spot on the object; the light reflected from the object then passes back through the objective lens and the pinhole to a detector. If the object is moved out of focus, the reflected light at the pinhole is defocused and does not pass through it. Therefore, the microscope has an extremely short depth-of-focus with no glare from objects in front of or behind the surface of interest. Furthermore, since the objective lens is used both on transmission and reception, the point spread function of the system is the square of that

of a normal microscope. The spatial frequencies in the image are doubled, thus making it possible to observe objects half the size of those that can be seen with a normal microscope using the same objective.

A simple technique for forming an image is to raster scan the object mechanically, using a single detector, and form a video display of the image. We worked with various forms of such a system during the first part of this project, and investigated electro-optic techniques for producing phase contrast and differential phase images with far better contrast and quantitative measurement characteristics than the standard Zernike and Nomarski microscope systems. These techniques will be applied, eventually, in our real-time scanning optical microscope described below.

Recently, in a major breakthrough, we have constructed the real-time scanning optical confocal microscope shown in Fig. 2. In this microscope 200,000 pinholes of 20 µm diameter, approximately 200 µm apart, are photolithographically etched into a circular glass plate made from a black emulsion photomask. The pinholes are placed along spiral paths to form a Nipkow disk. A beam from a mercury vapor discharge source, or from an argon laser, illuminates an area approximately 1.4 cm in diameter, or about 2000 holes at a time, and the light passes through an objective lens to illuminate 2000 spots on the object. The light reflected from the object passes through the pinholes which are

observed through a microscope eyepiece. Alternatively a video or photographic camera can be used. To fill in the gaps between the sampling points, the disk is rotated at 2500 rpm . This forms a high-quality 5000-line image at a rate of 700 frames/sec .

For good contrast, the reflected light from the disk must be eliminated. In an earlier system by Petran et al,[1] this was done by bringing the light back through a conjugate set of pinholes. This makes the optical system extremely complicated and mechanical alignment prohibitively difficult. In our much simpler system, we use the polarizer and analyzer shown in the diagram, along with a beam stop at the focal point of the reflected light from the disk passing through the transfer lens to the eyepiece. The reflectivity of the disk is 4% , but only 1% of the incident light passes through the disk. The measured discrimination against reflected light from the disk is about 35-40 dBs compared to that of a perfectly reflecting object. This is adequate for good reflectors like integrated circuits, but barely adequate for poor reflectors like some biological samples. The difficulty in obtaining better discrimination against unwanted light is due to the use of a beam splitter in the beam path, which causes a small rotation of the plane of polarization of

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[1]M. Petran. M. Hadravsky, M. D. Egger, and R. Galambos, "Tandem-Scanning Reflected-Light Microscope," J. Opt. Soc. Amer. 58, 661-664 (1968).

the light from the partially-collimated mercury vapor dis-
charge source.

Four images of an integrated circuit are shown in Fig.
2. It will be seen that, as the object is moved down by ap-
proximately 0.5 μm steps, different layers of the inte-
grated circuit are observed, while others disappear. This
result should be contrasted with that which would be obtained
with a conventional microscope, where the out-of-focus beam
becomes blurred and light reaches the observer from layers
above and below those at the focal plane.

We have developed a theory for the variation $V(z)$ of
the amplitude of the signal with a distance z from the fo-
cus. This leads to the approximate formula for the distance
$d_z(3\ dB)$ between 3 dB points of $V(z)$:

$$d_z = 0.45\lambda/(1 - \cos\theta_0)$$

where θ_0 is the angular aperture of the lens and λ is the
wavelength. For $\lambda = 540\ nm$ and an aperture correponding to
$\sin\theta_0 = 0.9$, the theory predicts $d_z = 500\ nm$. The mea-
sured value of d_z is 600 nm. We believe that this is
probably due to the use of an imperfect lens and a somewhat
larger pinhole size than the optimum value; this is to allow
more light to pass through the disk.

The transverse resolution of the microscope is also
better than that obtained with a conventional microscope with
the same objective lens. With this microscope, we have been
able to observe gratings in which there are strips only

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200 nm wide (period 400 nanometers). This is close to the Abbé theoretical resolution of the system, which is half that of a conventional microscope.

We have obtained far better range resolution than with a conventional optical microscope, as well as an improvement in transverse resolution between a factor of 0.5 to 0.7. This development opens up the possibility of new types of phase contrast imaging systems, optical cross sectioning of biological samples, and new types of fluorescent and luminescent imaging systems with extremely good discrimination against glare from regions out of focus. In all cases it is possible to work with an imaging system with low submicron resolution.

D. Publications, Invited Papers, Patents, and Honors

D.1. Publications Supported or Partially Supported by JSEP

(1) B. L. Heffner, W. P. Risk, B. T. Khuri-Yakub, and G. S. Kino, "Deposition of Piezoelectric Films on Single-Mode Fibers and Applications to Fiber Modulators," Proc. IEEE Ultrasonics Symp. 709-713 (1986).

(2) B. L. Heffner and G. S. Kino, "Switchable Fiber-Optic Tap Using Acoustic Transducers Deposited Upon the Fiber Surface," Opt. Lett. 12, 208 (March 1987).

(3) B. L. Heffner, "Switchable Optical Fiber Taps Using the Acousto-Optic Bragg Interaction," Ph.D. Dissertation, Stanford University, Stanford, CA (August 1986).

D.2. Other Related Publications

None.

D.3. Oral Disclosures

(1) G. Q. Xiao and G. S. Kino, "A Real-Time Confocal Scanning Optical Microscope," Presented at the 4th International Symposium on Optical and Opto-electronic Applied Science and Engineering, March 30-April 3, 1987, The Hague, The Netherlands.

(2) G. S. Kino, T. R. Corle, P. C. D. Hobbs, and G. Q. Xiao, "Optical Sensors for Range and Depth Measurements," Presented at ICALEO, Arlington, VA (November 1986)

D.4. Patents

(1) G. Q. Xiao and G. S. Kino, Ultrafast Confocal Scanning Optical Microscope, U.S. Patent Application.

### D.5. Honors/Awards/Prizes

None.

Fig. 1.

z = 0.0 μm

z = 0.4 μm

z = 0.96 μm

z = 1.77 μm
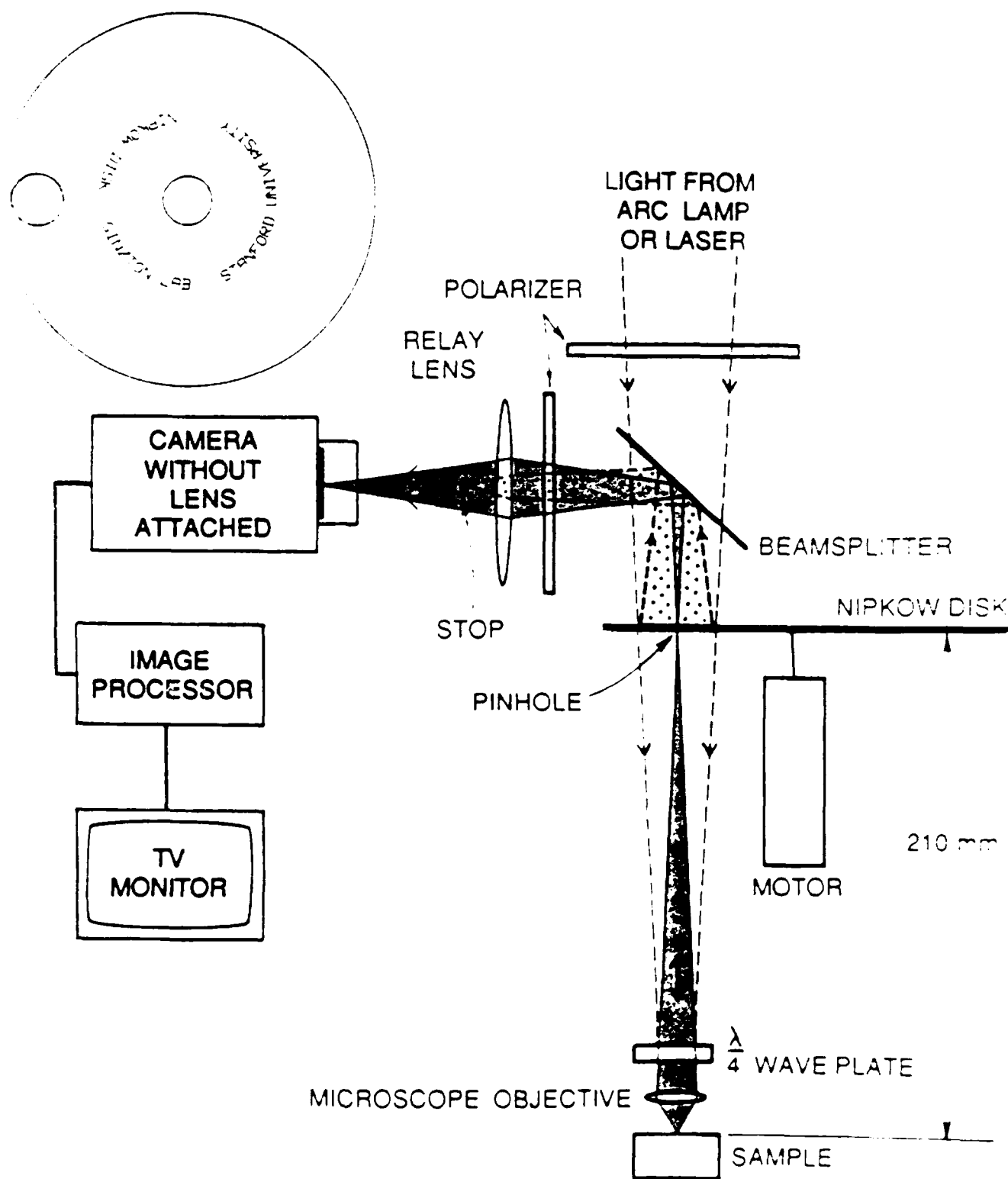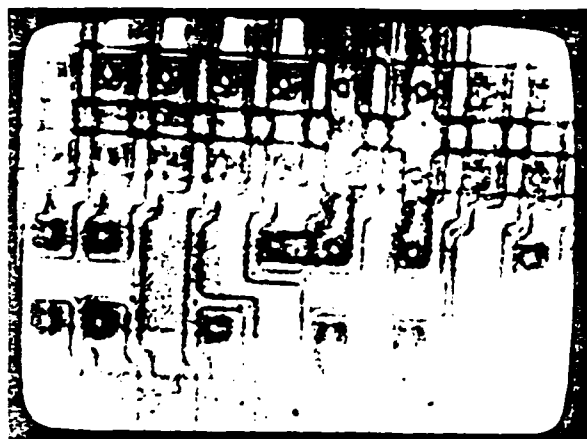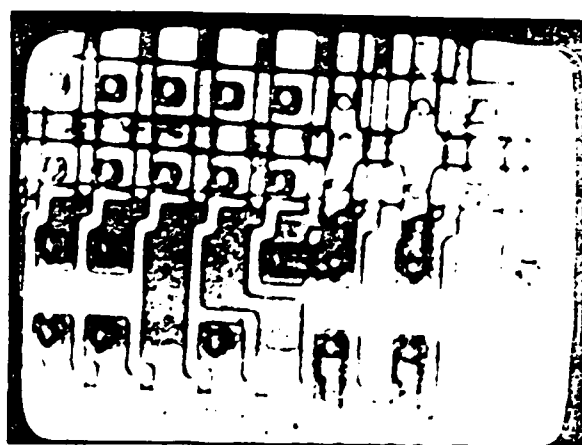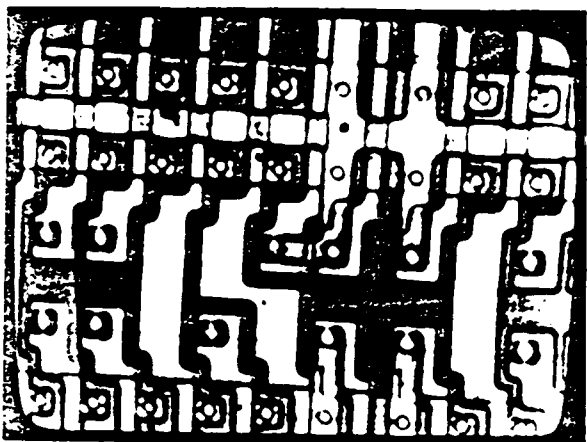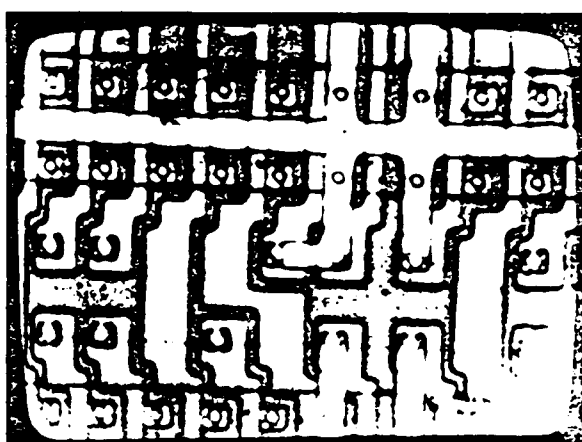
⊢⊣ ⊢—10 μm

Fig. 2.

Work Unit 85-4

Title: "Metal-Vacuum-Metal Tunneling or Scanned Tunneling Microscopy"

Principal Investigator: Calvin F. Quate

Telephone: (415) 723-0213

A. Introduction

In this work we will explore the new technology that surrounds the Tunneling Microscope. Vacuum tunneling offers us a method for exploring surfaces on the atomic scale. We can examine details at this level in exquisite manner not heretofore available. It is a technology that deserves a great deal of attention. The technology was introduced in the form of vacuum tunneling but this term is now a misnomer since tunneling can be observed, not only in vacuum but in air, in liquids, and in various insulating oils. Furthermore, the Force Microscope which is an outgrowth of the STM does not require tunneling electrons.

The technology associated with the Scanning Tunneling Microscope has demonstrated that it is relatively easy to fabricate a scanning tip that has a single atom at the extremity. This discovery was used in the microscope to image conducting surfaces with atomic resolution. In the Force Microscope we use the force between the atomic size tip and the substrate to examine insulators. It has also been used with a tip of magnetic material to image magnetic surfaces. This versatility suggests that further exploration of this technology may in fact allow us to exploit new phenomena on the atomic, or

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molecular, scale. It is our purpose in this program to explore and examine some of these possibilities.

We have found that our ability to examine atomic structures and image adsorbed molecules either individually or as monolayers has attracted an extraordinary amount of attention from researchers in a wide variety of fields. Chemists working with catalysis want information on molecules, their structure and the adsorbed sites. Those working with IC's ask numerous questions about the details of metal atoms deposited on semiconductors and thin dielectric films. And biologists show intense interest in our images of organic molecules.

B. Summary of Principal Accomplishments

The principal accomplishments of this work unit were:

(1) Operation of the STM in air at ambient pressure with high scanning speeds.

(2) Imaging of organic molecules both as LB monomolecular films, and as single molecules.

(3) Demonstration of the Atomic Force Microscope with the first recording of the atomic structure of insulators.

(4) Measurement of the wide energy gap in high temperature superconductors.

C. Discussion

The STM and the AFM form the backbone of the work on this program. They enable us to work at the molecular level. Not only can we "see" what we are doing with this form of direct imaging of atoms and molecules, but we should be able to go beyond that and manipulate the molecular entities with great precision.

The state-of-the-art has advanced during the interval covered by this report. Whereas at the beginning it was necessary to operate in UHV at room temperature, it is now possible to operate in air at ambient pressure and in liquids over the temperature range from 4 K to 300 K. We can now image organic molecules either in the form of LB monomolecular films or as single entities. We can use the tunneling electrons as a spectroscopic tool to probe the vibrational modes of these molecules as a function of the spatial position. We have been successful in measuring the band gap of the new high temperature superconductors and show that the band gap is much wider than predicted by conventional theories.

We will now describe these events in more detail. Thin dielectric films on semiconducting surfaces have been studied at some length. The system we used was Silicon Oxide and Silicon Nitride on Silicon. When these films are less than 20 Angstroms in thickness it is possible for electrons to tunnel through the insulating barrier into the vacuum barrier and reach the scanning tip. We have determined in this work that the tunneling current depends in a critical way on the thickness of the dielectric layer. It, therefore, gives us information on the interface between the semiconductor and the dielectric film. We have shown that this interface is quite rough, a conclusion that has been verified with concurrent studies with the TEM. This result has important implications in that it indicates that the STM can be used in some instances to examine "buried interfaces". Such interfaces are of great importance in semiconductor technology.

There are other instances where the interface beneath the actual surface can be examined. We believe that it will be possible to pass electrons through thin metallic layers as "hot electrons". This would allow us to examine these films by scanning the tip over the films and monitor the current that tunnels from the tip through the vacuum gap through the

metal overlayer to a semiconducting substrate.

In still another instance, with monomolecular films of organic material (such as LB films), the electrons can easily tunnel through films to the tip. Thus as shown in our work the structure of these films can be analyzed on a scale that is measured in molecular dimensions. And, finally, the work in our laboratory (and in other labs) has shown that we can determine with great precision the position of metal atoms as deposited on Silicon (111). We measure the position of the first layer by comparing it with the atomic arrangement of the clean silicon surface. In principle we can follow this same procedure as we increase the coverage and determine the atomic positions of the second and third layers of metal. This may be sufficient as far as the characteristics of the overlayer are concerned since it is known from x-ray data that after three, perhaps four layers of atoms, the material properties are close to the properties of the bulk.

We have been able with these instruments to examine monolayers of LB films as deposited on the surface of graphite. The individual molecular chains appear in these images with a detail that has not been available before. We believe that it is now feasible to study a variety of such films including PMMA and CaF2.

We have also shown that it is feasible to image individual molecules as adsorbed on graphite. We have gone beyond imaging to study the spectroscopic properties of these molecules. This is done by monitoring the conductance of the tunneling system while we vary the voltage on the tip. When the energy of the electrons corresponds to the energy of a vibrational mode of the adsorbed molecule we find a strong peak in the conductance curve. Since this can be done as a function of the spatial position of the tip we can map out the various vibrational modes and characterize the nature of the films. It is important to realize that we are dealing with single layers of molecular films. This is in contrast to much

of the work on LB films for electronic devices since that involves many layers atop each other. This study suggests that we may soon be in a position to manipulate these films in a way that suits our purpose.

The Atomic Force Microscope (AFM) was conceived by G. Binnig while he was on Sabbatical leave in our laboratory and developed by our graduate students. It has now been advanced to the point where it can be used to examine atomic features of insulators. Boron Nitride is the example where it is most easily done. This instrument which uses a tip mounted on a fine cantilever monitors the force between atoms on the tip and atoms in the substrate. Not only does the AFM allow us to probe insulators, it complements the STM when we examine conductors. A prime example is graphite. This layered material has both A atoms and B atoms in the layer. The A atoms have a corresponding atom beneath it in the next lower layer. The B atoms do not because of the displacement of the alternate layers in this structure. The STM measures the position of the B atoms whereas it is believed that the AFM measures the position of the A atoms. Therefore, with a tunneling tip mounted on a cantilever we could simultaneously monitor the deflection of the cantilever and the magnitude of the tunneling current. The cantilever deflection would reveal information on the A atoms and the tunneling current would provide information on the B atoms. In a second example we could use this combination to study the thin dielectrics referred to above. Here as we know the tunneling current gives us information on the interface between the insulator and the semiconductor whereas the cantilever deflection would provide information on the surface topography of the insulating film. Again the two techniques are used to complement each other.

In this time period we have started to investigate magnetic fields with these instruments. Our initial approach is the study of "spin dependent" tunneling where the

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tunneling probability can depend on the alignment between a ferromagnetic domain in the tip (iron for example) and the domain in the ferromagnetic substrate. This suggestion has been put forward by R. Meservey at MIT. For this purpose we have formed a collaboration with D. Rugar at IBM-Almaden. Rugar will furnish thin films of magnetic material that they are using in magneto-optic devices. These materials contain magnetic domains that are easily aligned in a controlled manner.

Finally, we are fortunate in having nearby a strong group working with the high temperature superconductors. We are participating in this effort since the advent of superconductors operating at liquid nitrogen temperatures may well have an important impact on the future of electronic devices. We would like to participate in this event. The point contact that comes in a natural way with the STM can be used to monitor the energy gap in a unique way.

D. Publications, Invited Papers, Patents, and Honors

(1) Publications supported or partially supported by JSEP

S.A. Elrod, A. Bryant, A.L. de Lozanne, S. Park, D. Smith and C.F. Quate, "Tunneling Microscopy from 300 to 4.2 K," IBM J. Res. Develop. **30**, pp. 387-395 (1986) - partially supported by IBM Corporation, the Defense Advanced Research Projects Agency and the Office of Naval Research.

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(2) Other Related Publications

G. Binnig and D.P.E. Smith, "Single-tube Three-dimensional Scanner for Scanning Tunneling Microscopy," Rev. Sci. Instrum. **57**, pp. 1688-1689 (1986)

C.F. Quate, "Vacuum Tunneling: a New Technique for Microscopy," Physics Today, **39**, pp. 26-33 (1986)

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(3) Oral Disclosures

C.F. Quate, "Scanning Tunneling Microscope," Whitney Symposium on Science and Technology VII, General Electric, Schenectady, New York, June 10-13, 1986 - (Invited)

C.F. Quate, "Telescopes and Microscopes - New Instruments to Extend our Vision," University Seminar Series, Stanford University, September 13, 1986 - (Invited)

C.F. Quate, "Experimental Observations on a   Graphite Substrate with the Scanning Tunneling Microscope," American Vacuum Society, Greater New York . Chapter, Yorktown Heights, New York, November 12, 1986 - (Invited)

C.F. Quate, "The Scanning Tunneling Microscope," Microengineering Colloquium Series, University of Utah, Salt Lake City, Utah, January 29, 1987 - (Invited).

(4) Patents

None

(5) Honors/Awards/Prizes

Leland T. Edwards Professor of Engineering,   Stanford University (first recipient) - July 1986

Achievement Award, IEEE Society on Ultrasonics, Ferroelectric and Frequency Control - November 1986.

T.R. Albrecht and C.F. Quate, "Atomic Resolution with the Atomic Force Microscope," Proceedings of the STM '87, Second International Conference on Scanning Tunneling Microscopy, (September 1987), (To be published in the J. Vacuum Science and Technology A, March/April 1988).

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Appendix

Biography of Principle Investigators

1. David M. Bloom

David M. Bloom was born on 10 October 1948 in Brooklyn, NY. He received the B.S. degree in electrical engineering from the University of California at Santa Barbara in 1970 and the M.S. and the Ph.D. degrees in electrical engineering from Stanford University in 1972 and 1975, respectively.

From 1975 to 1977 he was employed by Stanford University as a Research Associate. During this period he was awarded the IBM Postdoctoral Fellowship. From 1977 to 1979 he was employed by Bell Telephone Laboratories, Holmdel, NJ., where he conducted research on optical phase conjugation, ultrafast optical pulse propagation in fibers, and tunable color-center lasers. From 1979 to 1983 he served on the staff and later as a Project Manager at Hewlett-Packard Laboratories, Palo Alto, CA. While there he conducted and managed research on fiber optical devices, high-speed photodetectors, and picosecond electronic measurement techniques. In late 1983 he joined the Edward L. Ginzton Laboratory, W. W. Hansen Laboratories of Physics, Stanford University, where he is currently an Associate Professor of Electrical Engineering. His current research interests are ultrafast optics and electronics.

He was awarded the 1980 Adolph Lomb Medal of the Optical Society of America for his pioneering work on the use of nonlinear optical processes to achieve real time conjugate wavefront generation. In 1981 he was elected a Fellow of the Optical Society of America in recognition of his distinguished service in the advancement of optics. He was the 1985 EEE LEOS traveling lecturer. In 1986 he was elected a Fellow of the Institute of Electrical and Electronics Engineers for contributions to nonlinear optics and ultrafast optoelectronics.

2. Robert L. Byer

Professor Byer received his Ph.D. in 1969 in Applied Physics at Stanford University. His early work led to the first observation of optical parametric fluorescence and to the first demonstration of CW optical parametric oscillation in $LiNbO_3$.

After joining the Applied Physics Department in 1969, Professor Byer initiated research in remote sensing using tunable laser sources. Research in that area led to the development of the unstable resonator Nd:YAG laser and to high power tunable infrared generation in $LiNbO_3$ parametric tuners.

In 1974 Professor Byer and his colleagues initiated research in Coherent Anti-Stokes Raman Spectroscopy (CARS), named the effect, and continued research on high resolution Raman spectroscopy in pulsed and supersonic nozzle expansions.

In 1976 Professor Byer suggested the use of stimulated Raman scattering in hydrogen gas to generate $16\mu m$ radiation from a CO_2 laser source. Research at Stanford University confirmed the expected simplicity and efficiency of the approach.

In 1930 research on slab geometry solid state lasers was begun. The program led to the successful theoretical and experimental development of high peak and average power solid state laser sources. Research in advanced solid state laser sources is continuing with emphasis on laser-plasma produced soft X-ray radiation for application to X-ray microscopy and X-ray lithography.

Current research interests include the study of laser diode pumped miniature solid state laser sources, the growth and application of single crystal fibers, and the synthesis of advanced nonlinear materials.

Professor Byer is a Fellow of the Optical Society of America, a Fellow of the Institute of Electrical and Electronics Engineers, a Member of the American Physical Society and the American Association for the Advancement of Science. In

1985 Professor Byer was President of the IEEE Lasers and Electro-optics Society. He was Chairman of the Applied Physics Department from 1981 to 1984 and was appointed Associate Dean of Humanities and Sciences in 1985. In 1987 he was appointed Vice Provost and Dean of Research.

He has worked in industry at Spectra Physics, (1964–65), and has consulted for numerous companies including Chromatix, Molectron, Westinghouse, General Motors, Newport and Hoya. He was co-founder of Quanta Ray Inc. in 1975, and of Lightwave Electronics Corp. in 1984.

Professor Byer has published more than 150 scientific papers and holds 15 patents in the field of nonlinear optics and laser devices.

3. Gordon S. Kino

Gordon S. Kino was born in Melbourne, Australia on June 15, 1928. He is Professor of Electrical Engineering and Professor by Courtesy of the Applied Physics Department at Stanford University. He received his B.Sc. and M.Sc. in mathematics at London University, England, and his Ph.D. in electrical engineering at Stanford University.

He has worked in microwave tubes, electron guns, plasmas, the Gunn effect, and microwave, acoustic, and fiber-optic techniques for medical instrumentation. His current interests are in acoustic and optical techniques for nondestructive testing, and signal processing. He has published over 300 papers in these fields.

Professor Kino was a Guggenheim Fellow in 1967, and is a Fellow of the IEEE, the American Physical Society and AAAS, and a member of the National Academy of Engineering.

4. Calvin F. Quate

Calvin Quate is a Professor of Applied Physics and Electrical Engineering at Stanford University, and since July 1984 has been a Senior Research Fellow at Xerox Palo Alto Research Center. He received his B.S. in 1944 from the University of Utah, and his Ph.D. in 1950 from Stanford University. He worked at Bell Laboratories during 1949–58, and at Sandia Corporation, during 1959–61. He was a Guggenheim Fellow and Fulbright Scholar at Faculte des Sciences, Montpellier, France, 1968–69. He has been at Stanford University since 1961, where he was Chairman of the Department of Applied Physics, 1969–72, 1978–81. He acted as Associate Dean, School of Humanities and Sciences, 1972–74, 1982–83. Professor Quate was the first recipient of the Leland T. Edwards Chair, 1986.

Professor Quate is a member of: National Academy of Engineering; National Academy of Sciences; American Physical Society; Institute of Electrical and Electronics Engineers (Fellow); American Academy of Arts and Sciences (Fellow); Acoustical Society (Fellow); Royal Microscopical Society (Honorary Fellow). He was awarded the IEEE Morris N. Liebmann Award, 1981; IEEE Achievement Award, Ultrasonics, Ferroelectrics and Frequency Control Society, 1986; Rank Prize for Opto-electronics, 1982.

Research interests include linear and nonlinear properties of acoustic waves in the microwave region. Imaging, scanning microscopy and new concepts for data storage, including both acoustic waves and vacuum tunneling.

5. Stephen E. Harris

Stephen E. Harris was born in November 1936 in Brooklyn, New York. He received the B.S. degree in electrical engineering from Rensselaer Polytechnic Institute in 1959. After one year at Bell Telephone Laboratories, he attended Stanford University where he received the M.S. and Ph.D. degrees in electrical engineering in 1961 and 1963, respectively.

Since 1963 he has been on the faculty of Stanford University where he is now a Professor of Electrical Engineering and of Applied Physics and Director of the Edward L. Ginzton Laboratory. His research work has been in the fields of lasers, quantum electronics, nonlinear optics, acousto-optics, and atomic physics. Some of his research contributions include the first observation of optical parametric spontaneous emission, the invention of the tunable acousto-optic filter, the invention and demonstration of generation of ultraviolet light by phasematched third harmonic generation in metallic vapors and inert gases and the first observation of laser-induced inelastic collisions. His present interests are in the development of new techniques for generating extreme ultraviolet and soft x-ray radiation.

Professor Harris was one of the founders of Chromatix, Inc. in 1968, and has consulted for Sylvania Electronic Systems, Spectra-Physics, Westinghouse Electric Corporation, and for several government agencies. With the support of a Guggenheim Fellowship he spent the 1976-77 academic year with the Physics Department at Dartmouth College.

He has received the 1965 Alfred Noble Prize of the American Society of Civil Engineers, the 1973 Curtis McGraw Research Award of the American Society for Engineering Education, the 1978 David Sarnoff Award of the IEEE, the 1984 Davies Medal for Engineering Achievement awarded by Rensselaer Polytechnic Institute, and the 1985 Charles Hard Townes Award of the OSA.

Dr. Harris is a Fellow of the IEEE, the Optical Society of America, and the American Physical Society. In 1977 he was elected to the National Academy of Engineering, and in 1981 he was elected to the National Academy of Sciences.

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