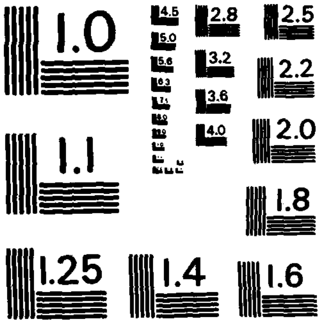
AD-A121 406 INTEGRATION OF A DETECTOR ARRAY WITH AN OPTICAL
WAVEGUIDE STRUCTURE(U) CINCINNATI UNIV OH DEPT OF
ELECTRICAL AND COMPUTER ENGINEERING J T BOYD 15 JUL 82
UNCLASSIFIED AFOSR-TR-82-0917 AFOSR-81-0130 F/G 20/6 NL


1.0
4.5
5.0
5.6
6.3
2.8
3.2
3.6
4.0
2.5
2.2
2.0
1.1
1.8
1.25
1.4
1.6

ADA121406

②

Unclassified
SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE	READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER **AFOSR-TR- 82-0917**	2. GOVT ACCESSION NO. AD-A121406
	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Integration of a Detector Array with an Optical Waveguide Structure	5. TYPE OF REPORT & PERIOD COVERED Interim Technical Report 15 March 1981 - 14 March 1982
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) J.T. Boyd	8. CONTRACT OR GRANT NUMBER(s) AFOSR-81-0130
9. PERFORMING ORGANIZATION NAME AND ADDRESS Department of Electrical & Computer Engineering University of Cincinnati Cincinnati, Ohio 45221	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 61102F 2305/B1
11. CONTROLLING OFFICE NAME AND ADDRESS Air Force Office of Scientific Research/NE Bolling Air Force Base, D.C. 20332	12. REPORT DATE July 15, 1982
	13. NUMBER OF PAGES
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	15. SECURITY CLASS. (of this report) Unclassified
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE None

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

DTIC
ELECTE
NOV 0 8 1982
S D
E

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Integrated optics, optical waveguide, laser annealing, laser recrystallization.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Laser annealing of planar optical waveguides has achieved significant reductions in scattering loss for Corning 7059 glass, ZnO, Si_3N_4, Ta_2O_5, and Nb_2O_5 thin-film waveguides deposited on thermally-oxidized silicon substrates. For two of these materials, ZnO and Corning 7059 glass, a loss of .01 dB/cm was achieved. This value is an order magnitude lower than any value previously reported for any planar thin-film waveguide. Rutherford backscattering experiments performed on Corning 7059 glass and ZnO indicate that the laser annealing is a solid phase annealing. Laser recrystallization

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

Unclassified
SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

of polycrystalline silicon has been investigated using both an argon ion laser and a CO_2 laser. Grain sizes larger than those reported in the literature have been achieved. The fabrication of photodetectors in such structures is underway. The use of laser annealing to improve the interface properties in metal-insulator-semiconductor devices having a deposited insulator is being investigated. Planar graded-index SiO_2 waveguides on silicon substrates having extremely low scattering loss have been demonstrated and are currently being characterized. A log-converting sensing element for charge-coupled device image arrays has been demonstrated.

AFOSR-TR- 82-0917

Interim Report

INTEGRATION OF A DETECTOR ARRAY WITH AN OPTICAL WAVEGUIDE STRUCTURE

J. T. Boyd

Solid State Electronics Laboratory
Department of Electrical and Computer Engineering
University of Cincinnati
Cincinnati, Ohio 45221

J. T. Boyd, Principal Investigator

Prepared for the:

Air Force Office of Scientific Research

Grant AFOSR-81-0130

July 15, 1982

Table of Contents

I. Introduction

~~We are currently performing~~ Current research under grant ~~AFOSR 81-0130 involving~~ involves integration of a detector array with an optical waveguide structure and applications to signal processing. This grant is continuing research initiated under grant AFOSR 76-3032; results from this earlier grant are described in the final report.[1] The present report summarizes progress achieved in Part I of this research program (March 15, 1981 - March 14, 1982). The main accomplishments resulting from research performed during this period include a number of accomplishments in the area of laser processing of semiconductors[2-5] and demonstration of graded index SiO_2 waveguides having very low scattering loss.[6] Significant progress was also made with regard to implementation of a log converting array sensor element for charge-coupled device (CCD) image arrays and demonstration of the advantages of edge detection of long wavelength radiation by silicon photodetectors. Results in each of these areas are discussed in the following sections.

The present research program has thus far investigated a number of integrated optical device configurations utilizing a silicon substrate. The motivation for investigating devices utilizing silicon is first, due to its potential use for such signal processing devices as the integrated optical spectrum analyzer,[7-10] second, its usefulness for performing waveguide detection in such signal processing devices formed on $LiNbO_3$, third, to provide integration of external components in fiber optic interferometric devices,[11] and fourth, to allow combination of integrated optical devices and integrated electronic circuits to form higher data rate systems. The recent demonstration in our laboratory of waveguide loss in thin film waveguides as low as .01 dB/cm after laser annealing implies that it may be worthwhile considering formation of the interferometer in an optical waveguide rather than a fiber.[11] Such a configuration would significantly reduce the size and allow total component integration on a silicon wafer substrate. This reduction in size and increase in component integration would be very desirable for application of guided wave interferometric sensors in military systems.

To support the overall goals of Air Force research, there has been significant interaction between personnel involved in the present and past AFOSR research program and those involved in military programs at the Air Force Avionics Laboratory, Rockwell International, McDonnell-Douglas, Battelle, Motorola, General Dynamics, Lockheed, Honeywell, and Oak Ridge National Laboratory. A number of papers have been co-authored by personnel from several of these institutions and from the Solid State Electronics Laboratory at the University of Cincinnati.

II. Laser Processing

A. Laser Annealing of Optical Waveguides

Success in using CO_2 laser annealing to significantly reduce scattering in Corning 7059 glass and ZnO waveguides has been extended to Si_3N_4, Nb_2O_5, and Ta_2O_5 waveguides. Conditions used for laser annealing and the technique used for measuring very low values of waveguide loss have been presented in last year's final report[1] and elsewhere,[3-5] so will not be repeated here. Table I summarizes the reduction of scattering losses obtained by laser annealing for the five materials mentioned above.

Table I

Waveguide loss resulting from laser annealing compared with previous results

Type of Waveguide	Annealing Power Density	Current Results		Lowest Loss Previously Reported
		Before Laser Annealing	After Laser Annealing	
ZnO	$2.3 \times 10^5 W/cm^2$	2.5 dB/cm	0.01 dB/cm	~1.0 dB/cm
Si_3N_4	$1.6 \times 10^5 W/cm^2$	6.0 dB/cm	0.1 dB/cm	~0.1 dB/cm
Nb_2O_5	$1.0 \times 10^5 W/cm^2$	7.4 dB/cm	0.6 dB/cm	~1.0 dB/cm
Ta_2O_5	$9.3 \times 10^2 W/cm^2$	1.3 dB/cm	0.4 dB/cm	~0.9 dB/cm
7059 glass	$3.5 \times 10^3 W/cm^2$	4.0 dB/cm	.05 dB/cm (.01 dB/cm)*	~1.0 dB/cm

*With surface coating applied.

It should be noted that the value of loss achieved for ZnO and Corning 7059 glass is an order of magnitude lower than the best value reported for any planar waveguide. Also, values of loss achieved by us for the other three materials are each the lowest value of loss ever reported for that material.

B. Rutherford Back Scattering Experiments

Rutherford backscattering (RBS) has been used to investigate effects of CO_2 laser annealing of Corning 7059 glass and ZnO thin-film optical waveguides. We have previously characterized these waveguides in a variety of ways, including careful measurements of optical attenuation or scattering loss before and after laser annealing.[3-5] The scattering loss in these waveguides decreases dramatically upon laser annealing, as discussed in the previous section. The experiments reported here were undertaken to help elucidate the mechanisms responsible for the reductions in scattering loss after laser annealing.

The thin-film optical waveguides were deposited by sputtering onto thermally oxidized silicon substrates. The Corning glass waveguides were deposited by rf sputtering to thicknesses of 1.566 μm (sample A and B) and 1.3603 μm (samples C and D). The ZnO was deposited to a thickness of 0.9 μm by dc triode sputtering. Each waveguide was implanted with 209 Bi at an energy of 150 keV and to a dose of $6 \times 10^{15}/cm^2$. The glass waveguides were laser annealed with a CO_2 laser at a wavelength of 10.6 μm, at a power density of 3×10^3 W/cm^2, a laser spot size of 900 μm, and a beam scan speed of 1 cm/sec. The power density used for 7059 glass corresponded to a value found previously to be successful in reducing scattering losses.[5] The ZnO waveguide was annealed with power densities of between $1.0 - 1.3 \times 10^5$ W/cm^2, a laser spot size of 150 μm, and a beam scan speed of 1 cm/sec. The power densities used for ZnO were much lower than the power densities of $2.0 - 2.3 \times 10^5$ W/cm^2 usually required for successful annealing of ZnO waveguides because the ion-implanted region had a relatively low damage threshold varying from 1.3×10^5 W/cm^2 to 1.6×10^5 W/cm^2.

Rutherford backscattering measurements were performed before and after laser annealing of each waveguide. The RBS analysis was accomplished using 2 MeV 4 He ions in backscattering. Typical RBS spectra are presented for both a Corning glass waveguide and a ZnO waveguide. For 7059 glass we observed a peak corresponding to not only the implanted Bi (1.9 MeV), but also one for Ba (1.8 MeV) which is a constituent of the Corning glass. We observed very close correspondence between data obtained before annealing and the data taken after annealing. Any redistribution of the implanted Bi was found to be restricted to less than 100 Angstoms after laser annealing. We thus concluded that no melting of the bulk 7059 glass material occurred and therefore the annealing occurred with the material in a solid phase.

In examining RBS data for ZnO, we found in addition to the Bi peak, peaks corresponding to the Zn in ZnO (1.6 MeV), the oxygen in ZnO (0.8 MeV), and the Si in SiO_2 (0.55 MeV). Again we observed close correspondence between the position of the implanted Bi before and after laser annealing. At least at the laser power densities used to anneal this ZnO waveguide, redistribution of the implanted Bi has not taken place, and thus no melting of the ZnO waveguide has occurred.

Thus in the case of Corning 7059 glass and ZnO thin-film waveguides, laser annealing improves their optical scattering loss characteristics dramatically without any evidence of melting. In the case of the Corning glass waveguides, the highest temperature during laser annealing is at the surface, just the region where the RBS technique is most sensitive. These RBS measurements support simple one-dimensional heat flow calculations[12] which suggest that laser annealing of these thin-film optical waveguides is a solid phase annealing.

C. Laser Recrystallization of Polycrystalline Silicon

We have created a new laser processing laboratory in which both high power argon ion and CO_2 lasers are supported on a low-vibration air-isolated table. The laboratory has been constructed so that the sample area can be evacuated, thus allowing experiments involving laser exposure in various gaseous environments to be carried out safely. Beam scanners and motorized stages which allow for sample heating currently exist, although we are currently awaiting delivery of a computer-controlled three dimensional motorized stage. The sample chamber which will allow laser exposure to occur in gaseous or vacuum environments is nearly completed.

As we are completing the laser processing laboratory, we now have a facility which will allow us to perform quite general experiments involving laser processing of semiconductors. We are beginning to perform experiments concerned with the laser-assisted growth of single crystal regions of silicon on amorphous substrates, particularly on SiO_2 layers pyrolytically-deposited onto $LiNbO_3$ substrates. Although considerable work has been carried out with regard to laser recrystallization of silicon by other investigators,[13-15] we expect to make significant contributions in the following areas: (1) Demonstration of laser annealing during deposition with the hope of increasing the crystalline grain size, (2) Laser recrystallization of polysilicon deposited at low temperatures of around 400°C, (3) Create larger recrystallized areas by scanning the laser in a spiral pattern, and (4) Use of laser heating to reduce interface state densities and leakage currents in MIS devices formed on regions of laser recrystallized silicon.

As noted above, one of our goals is to be able to recrystallize polysilicon having larger grain sizes than has been achieved by various laboratories up until now. We have been using both argon and CO_2 laser exposure. With CO_2 laser exposure we have achieved larger grain sizes than any yet reported in the literature. Fig. 1 illustrates a sample in which the surface has been etched to visually delineate the grain boundaries. Note that grains having dimensions 20 x 50 μm are present. The heating of the polysilicon by the CO_2 laser is accomplished by sandwiching the polysilicon between strongly-absorbing layers of SiO_2. The annealing used 2W of power focused down to a 120 μm diameter spot with a scanning speed of .3 cm/sec and a step increment of 50 μm between scan lines.

A major subject area to be explored in the present program is the laser-assisted growth of single crystal regions from polycrystalline silicon (polysilicon) deposited on $LiNbO_3$. Since $LiNbO_3$ undergoes a phase transition at about 700°C, it is necessary that the deposition of polysilicon occur at lower temperatures. However, polysilicon is normally deposited at higher temperatures (800°C - 1100°C). But polycrystalline films of silicon may be obtained by low temperature chemical vapor deposition, laser-induced chemical vapor deposition, and plasma deposition. The first two of these processes involve decomposition of a silicon-containing gas such as silane (SiH_4) near the surface of a substrate. The temperature of the substrate may vary from 0°C to 800°C. The deposition system generally operates at atmospheric pressure with continuous gas flow across the substrate surface. Silane comprises only a small portion of the total flow, most of which is composed of an inert carrier gas such as nitrogen. Since the deposition is carried out at low temperatures, thermal degradation of the substrate can be avoided.

We also plan to investigate an alternate method of laser-assisted growth which will allow growth of larger area regions of a single crystal silicon. This proposed method involves introducing laser annealing <u>during</u> polysilicon

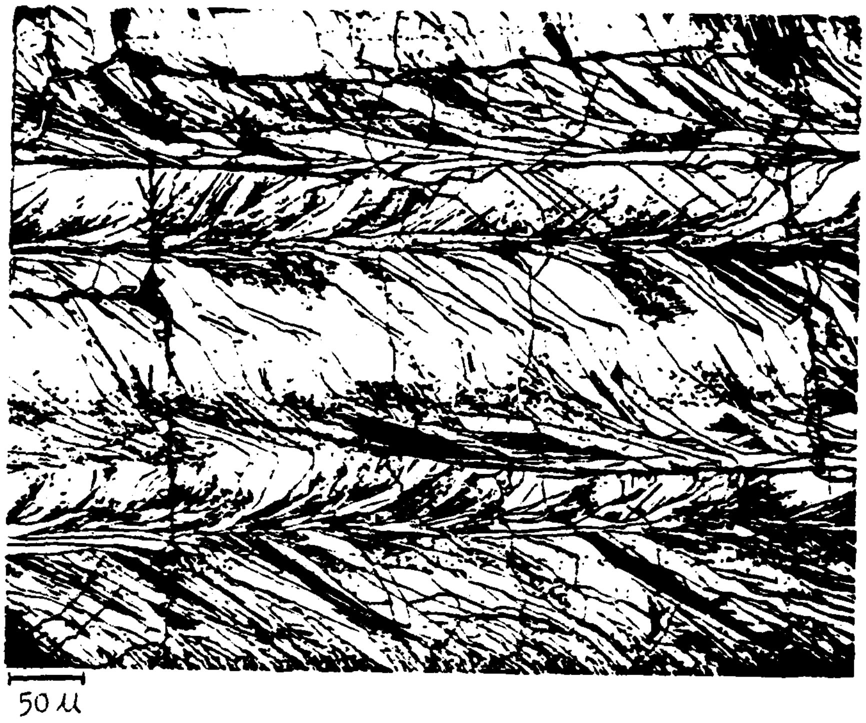


Fig. 1 Sample of polycrystalline silicon which has been etched to delineate grain boundaries. Note that some grains have dimensions on the order of 50 μm.

deposition. We anticipate that such an approach will cause polysilicon to become single crystal silicon just as it is deposited. Because of this, it should be possible to form larger areas of single crystal regions.

D. Photodetectors Fabricated on $LiNbO_3$

Once silicon is laser recrystallized on $LiNbO_3$, we plan to fabricate photodetectors in the silicon and demonstrate integrated waveguide detection. Fig. 2 illustrates the configuration to be considered. Because $LiNbO_3$ is sensitive to high temperatures, photodetector fabrication will utilize either low temperature processes or localized heating i.e., ion implantation, laser annealing, laser-assisted doping, and laser microphotochemical deposition. The thin sputtered layer of Si_3N_4 shown in Figure 2 between the polysilicon and $LiNbO_3$ shall provide some thermal insulation and be of an appropriate thickness to maximize reflection of the annealing laser back into the polysilicon. In these two ways the Si_3N_4 layer will reduce heat flow into the $LiNbO_3$ substrate. The thickness of Si_3N_4 will still be small enough, however, so that efficient evanescent coupling of light propagating in the waveguide into the silicon detector can still occur. This method of waveguide detector coupling utilizes illumination along the surface of the photodiode detector element rather than normal incidence. Such illumination has been shown by the principal investigator to yield a combined coupling and detector quantum efficency of over 80% and to accomplish coupling with no observable excess scattering. The high quantum efficiency obtainable with incidence along a photodiode is important in integrated optical systems utilizing a semiconductor laser, since the absorption of silicon at these wavelengths is not particularly strong. The performance of the photodetectors fabricated on the silicon layers on $LiNbO_3$ will be experimentally evaluated both electrically and optically.

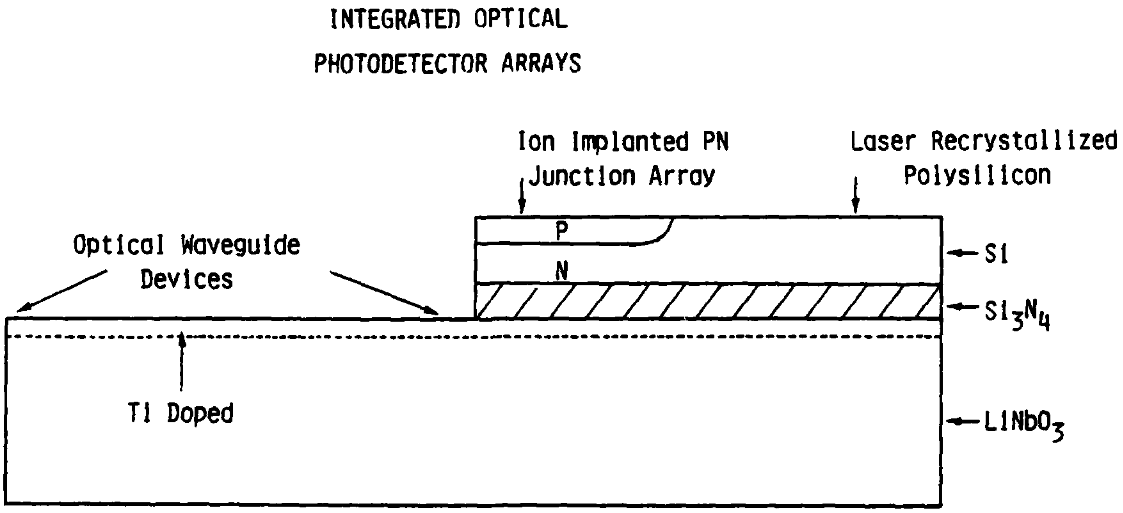


Fig. 2 Photodectector formed in laser recrystallized silicon film on a $LiNbO_3$ substrate.

III. Graded Index SiO_2 Waveguides

Planar optical waveguides consisting of a graded SiO_2 layer have been fabricated on silicon substrates. The expectation is that such planar waveguides would have many of the advantages of graded-index fibers, including low scattering loss. We have demonstrated such waveguides having low loss. These waveguides were formed by oxidizing silicon wafers continuously at 1100°C for a period of several weeks. The graded index results from some unknown combination of impurity, density, and stress distributions.

Thermally-grown layers of SiO_2 on a silicon substrate have provided an excellent surface for thin-film waveguide deposition. The smooth SiO_2 surface associated with thermal growth has helped to reduce waveguide scattering, as is evident from the very low losses achieved using this substrate. The low refractive index of SiO_2 ($n=1.46$) has allowed formation of waveguides having strong field confinement so that thin oxide layers (1 micron or less) are sufficient to prevent any significant coupling of light propagating in waveguide modes to the silicon substrate.

One potential problem which exists in the planar graded-index structure is the presence of the silicon substrate characterized by its high refractive index and strong absorption for wavelengths less than 1.1 microns. Because the actual refractive index change causing waveguiding associated with graded-index structures is usually small, the resulting field confinement is considerably weaker than for deposited waveguides. As a result, significant coupling of light from the waveguide to the substrate can occur unless the isolating portion of the SiO_2 layer is sufficiently thick. The isolating portion of the SiO_2 layer is that portion of SiO_2 between the SiO_2/Si interface and the waveguiding portion of the SiO_2 layer. The isolation region thickness required to cause substrate coupling to be negligible depends on details of the refractive index profile. In considering a variety of situations quantitatively we are able to conclude that planar graded-index SiO_2 waveguiding structures with negligible substrate coupling can be fabricated. Figure 3 shows a plot of waveguide attenuation resulting from substrate absorption as a function of SiO_2 layer thickness for several values of maximum refractive index difference, assuming a linearly-graded index profile. Figure 3 clearly shows that there are values of SiO_2 thickness and refractive index difference which yield very low values of attenuation and are within the range of fabrication.

Figure 4 is a photograph of the streak of light characteristic of laser propagation in a planar waveguide. The photograph was taken using 3000 ASA film with a 1 hour exposure and a F/8 aperture. The output from a HeNe laser having an output of 5mW was coupled into the waveguide with a prism coupler, a typical coupling efficiency being at least 10%. There is thus quite a bit of laser power associated with the field propagating in the waveguide. This fact along with the extremely long exposure and only the hint of a streak in Figure 4 indicates extremely low scattering. Because of the low amount of scattered light, we have had trouble actually measuring waveguide attenuation using the precise method we previously developed. However, we are currently implementing a three-prism measurement and expect results very soon.

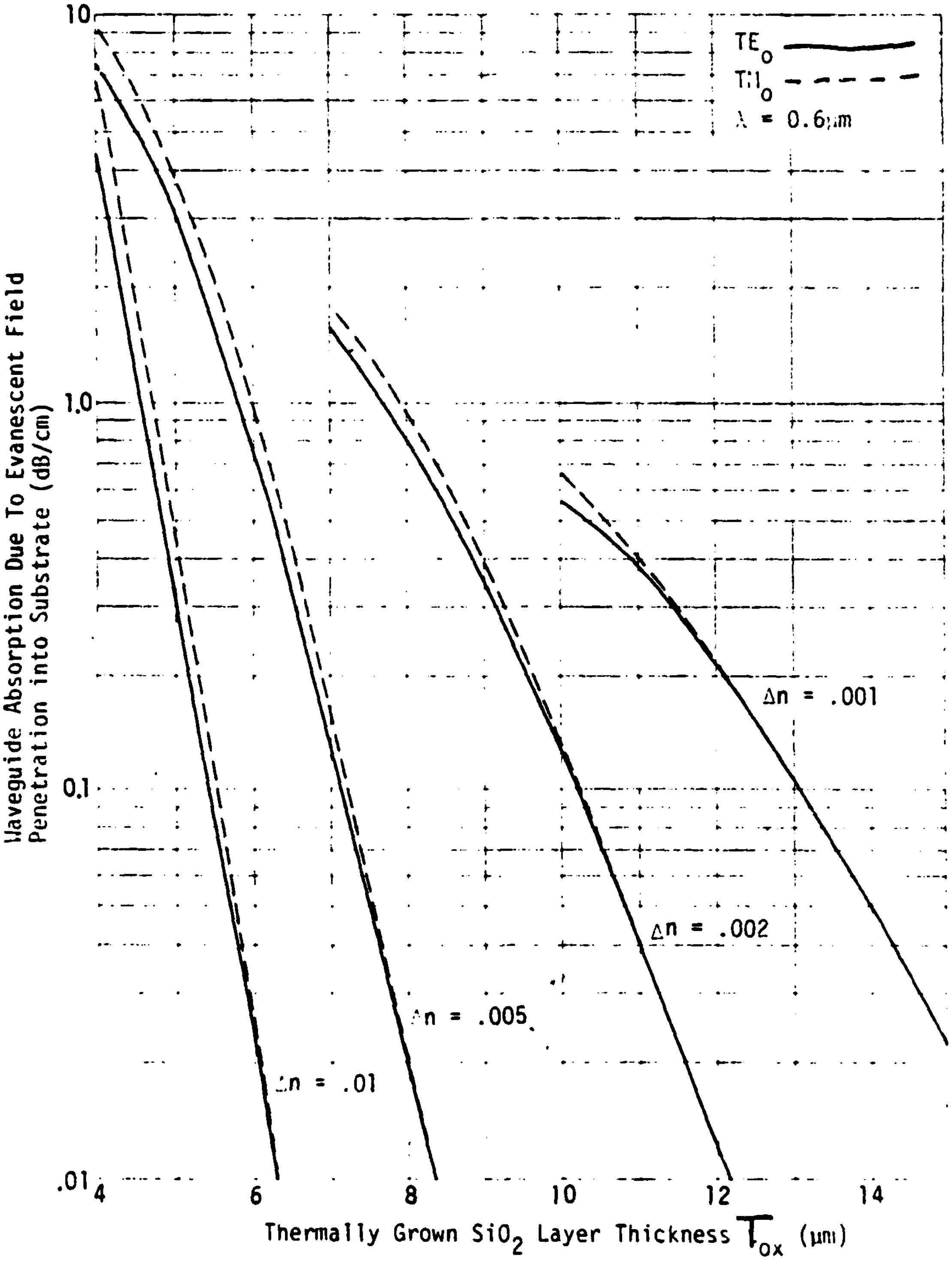


Figure 3 Waveguide attenuation due to substrate coupling and absorption as a Function of SiO_2 Thickness for Linearly Graded Refractive Index Profiles for λ = 0.63μm for Both TE_0 and TM_0 Modes.

Figure 4 Photograph of HeNe laser light propagating in a graded-index SiO_2 waveguide. Film used had ASA3000, aperture used was F/8 and exposure time was 1 hour.

IV. Research in Other Areas

The main accomplishment besides the areas discussed in the previous two sections is in the area of a log-converting sensor element for a CCD image array. This device is expected to be useful in situations where very large variations in the light level to be sensed occur. The log-converting sensor element is implemented by creating an injection circuit such that the charge injected into the CCD is proportional to the photodiode voltage, and thus to the logarithm of the incident light intensity. Double level polysilicon gate technology has been used to fabricate devices which are operational. Testing of these devices is underway and is expected to be completed shortly.

An investigation of whether any benefit could be achieved by using laser annealing of the insulator-semiconductor interface in metal-insulator-semiconductor (MIS) devices has been undertaken. Of particular interest are deposited insulators on silicon, as success here could allow creation of a viable low temperature process for MIS integrated circuits. We have evaluated the quality of the interface by performing surface state density measurements using a computer-controlled capacitance-voltage measurement system having interactive graphics capability. Insulator leakage and breakdown have also been measured. So far no significant improvement upon laser annealing has been observed, although further testing is currently in progress.

V. Outlook - Progress with Regard to Objectives

Significant progress towards several of the objectives of the portion of the AFOSR research program for which this interim report applies has been accomplished. Significant progress continued to occur in the area of laser annealing of optical waveguides where lower values of loss were obtained and Rutherford backscattering measurements were performed in cooperation with Oak Ridge National Laboratory. In the area of laser recrystallization of polysilicon, larger grain sizes than any previously reported in the literature were obtained. The creation of a planar graded-index SiO_2 waveguide having very low scattering has been achieved, but the actual waveguide propagation loss needs to be measured. We expect to do this in the next month. Although not yet complete, significant progress in the areas of a log-converting sensing element and the creation of photodetectors on laser recrystallized regions of silicon have been made. We expect to successfully complete work on the log-converting sensing element in the next few months and to make considerable progress on photodetectors in laser recrystallized silicon in the next six months.

At the present time research in this program is continuing, as described in our most recent proposal.

VI. List of Program Publications

S. Dutta, H.E. Jackson, J.T. Boyd, and C.W. White, "Rutheford Back Scattering (RBS) Evidence for Solid Phase Laser Annealing of Corning 7059 Glass and ZnO Thin Films," to be published.

S. Dutta, H.E. Jackson, and J.T. Boyd, "Use of Laser Annealing to Achieve Low Loss in Corning 7059 Glass, ZnO, Si_3N_4, Nb_2O_5, and Ta_2O_5 Optical Thin-Film Waveguides," Optical Engineering, to be published.

J.T. Boyd, "Past Progress and Future Directions of Research on Optical Waveguide Structures Formed on Silicon Substrates," presented at and published in the Proceedings of the 1982 National Science Foundation Grantee-User Meeting on Optical Communications, Berkeley, June, 1982.

S. Dutta, J.T. Boyd, and H.E. Jackson, "Laser Annealing of ZnO Optical Waveguides," presented at the Meeting of the American Physical Society, Dallas, March, 1982.

S. Dutta, H.E. Jackson, and J.T. Boyd, "Use of Laser Annealing to Achieve Low Loss in Corning 7059 Glass, ZnO, Si_3N_4, Nb_2O_5, and Ta_2O_5 Optical Thin-Film Waveguides", presented at and published in the Proceedings of the Society of Photoinstrumentation Engineers Meeting, Los Angeles, January, 1982.

S. Dutta, H.E. Jackson, J.T. Boyd, R.L. Davis, and F.S. Hickernell, "CO_2 Laser Annealing of Si_3N_4, Nb_2O_5, and Ta_2O_5 Thin Film Waveguides to Reduce Optical Scattering," IEEE Journal of Quantum Electronics, Vol. QE-18, pp 800-806, April, 1982, Joint Special Issue on Optical Guided Wave Technology, also published in IEEE Transactions on Microwave Theory and Techniques, Vol. MTT-30, April, 1982.

J.T. Boyd, S. Dutta, H.E. Jackson, and A. Naumaan, "Reduction of the Effects of Scattering by Laser Annealing of Optical Waveguides and by Use of Integrated Waveguide Detection," Optical Engineering, Vol. 21, pp. 293-295,1982.

F.K. Hopkins, H.E. Jackson, and J.T. Boyd, "In-Plane Scattering Measurements in a Planar Optical Waveguide by an Integrated Technique," Applied Optics, Vol. 20, pp. 2761-2763, Aug. 15, 1981.

S. Dutta, "Reduction of Scattering in Thin-Film Optical Waveguides by Carbon Dioxide Laser Annealing," Ph.D. Dissertation, University of Cincinnati, 1981.

S. Dutta, H.E. Jackson, J.T. Boyd, F.S. Hickernell and R.L. Davis, "Scattering Loss Reduction in ZnO Optical Waveguides by Laser Annealing," Applied Physics Letters, Vol. 39, pp. 206-208, Aug. 1, 1981.

A. Naumaan, D. Zelmon, and J.T. Boyd, "A thick SiO_2 Graded-Index Planar Waveguide," presented at and published in the Proceedings of the 31st Electronic Components Conference, Atlanta, May 11-13, 1981.

F.S. Hickernell, R.L. Davis, S. Dutta, J.T. Boyd and H.E. Jackson, "Optical Waveguide Loss Reduction in Zinc Oxide Films by Laser Annealing," presented at and published in the Proceedings of the AIME Electronic Materials Conference, Santa Barbara, June 24-26, 1981.

VII. Acknowledgments

The author would like to acknowledge the contributions of S. Dutta, D. Zelmon, H. Lu, H. A. Timlin, C. L. Fan, and A. Naumaan to the research described here. The help of C. W. White of Oak Ridge National Laboratory with the RBS experiments is appreciated. The work of H. E. Jackson on most of the projects described has greatly contributed to the degree of success achieved and is appreciated. The author also wishes to acknowledge the skillful work of our microelectronics technicians, J. T. Garrett and R. Kirschner.

VIII. References

1. J. T. Boyd, D.A. Ramey, C. L. Chen, A. Naumaan, S. Dutta, and S. H. Chang, "Integration of a Detector Array With An Optical Waveguide Structure and Applications to Signal Processing," Final Report, AFOSR-76-3032, Aug. 7, 1981.

2. S. Dutta, H.E. Jackson, J.T. Boyd, and C.W. White, "Rutheford Back Scattering (RBS) Evidence for Solid Phase Laser Annealing of Corning 7059 Glass and ZnO Thin Films," to be published.

3. S. Dutta, H.E. Jackson, J.T. Boyd, R.L. Davis, and F.S. Hickernell, "CO_2 Laser Annealing of Si_3N_4, Nb_2O_5, and Ta_2O_5 Thin Film Waveguides to Reduce Optical Scattering," IEEE Journal of Quantum Electronics, Vol. QE-18, pp 800-806, April, 1982, Joint Special Issue on Optical Guided Wave Technology, also published in IEEE Transactions on Microwave Theory and Techniques, Vol. MTT-30, April, 1982.

4. S. Dutta, H.E. Jackson, J.T. Boyd, F.S. Hickernell and R.L. Davis, "Scattering Loss Reduction in ZnO Optical Waveguides by Laser Annealing," Applied Physics Letters, Vol. 39, pp. 206-208, Aug. 1, 1981.

5. S. Dutta, H.E. Jackson, and J.T. Boyd, "Extremely Low-Loss Glass Thin Film Optical Waveguides Utilizing Surface Coating and Laser Annealing," Journal of Applied Physics, Vol. 52, pp. 3873-3875, June 1981.

6. A. Naumaan, D. Zelmon, and J.T. Boyd, "A thick SiO_2 Graded-Index Planar Waveguide," presented at and published in the Proceedings of the 31st Electronic Components Conference, Atlanta, May 11-13, 1981.

7. M.C. Hamilton, D.A. Wille, and W.J. Miceli, "An Integrated Optical RF Spectrum Analyzer," Optical Engineering 16, 475 (1977).

8. D.B. Anderson, J.T. Boyd, M.C. Hamilton, and R.R. August, "Integrated Optics Approach to the Fourier Transform," IEEE Journal of Quantum Electronics, Vol. QE-13, pp 268-275, April 1977, Special Issue on Integrated Optics.

9. M.K. Barnoski, B.V. Chen, T.R. Joseph, J.Y.M. Lee, and O.G. Ramer, "Integrated-Optic Spectrum Analyzer," IEEE Trans. on Circuits and Systems CAS-26, 1113 (1979).

10. D. Mergerian, E.C. Malarkey, R.P. Pautienus, J.C. Bradley, G.E. Marx, L.D. Hutcheson, and A.L. Kellner, "Operational Integrated Optical RF Spectrum Analyzer," Appl. Opt. 19, pp 3033-3034, 1980.

11. T.G. Giallorenzi, J.A. Bucaro, A. Dandridge, G.H. Sigel, Jr., J.H. Cole, S.C. Rashleigh, and R.G. Priest, "Optical Fiber Sensor Technology," IEEE Journal of Quantum Electronics, Vol. QE-18, p. 626, 1982.

12. S. Dutta, "Reduction of Scattering in Thin-Film Optical Waveguides by Carbon Dioxide Laser Annealing, Ph.D. Dissertation, University of Cincinnati, 1981.

13. J.C.C. Fan and H.J. Zeiger, "Crystallization of Amorphous Silicon Films by Nd: YAG Laser Heating," Appl. Phys. Lett. 27, 224, (1975).

14. J.F. Gibbons and K.F. Lee, "CW Laser Recrystallization of (100) Si on Amorphous Substrates," Appl. Phys. Lett. 34, 831 (1979).

15. A. Gat, L. Gerzberg, J.F. Gibbons, T.J. Magee, J. Peng, and J.D. Hong, "CW Laser Anneal of Polycrystalline Silicon: Crystalline Structure, Electrical Properties," Appl. Phys. Lett. 33, 775 (1978).