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Semi-Annual Status Report

NASA Grant No. NAG-1-177

INVESTIGATION OF SEMICONDUCTOR CLAD OPTICAL WAVEGUIDES

Submitted to:

National Aeronautics and Space Administration
Langley Research Center
Hampton, Virginia 23665

Submitted by:

T. E. Batchman
Associate Professor

G. M. McWright
Graduate Student Participant

Report No. UVA/528207/EE81/101

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SEMICONDUCTOR DEVICE LABORATORY
DEPARTMENT OF ELECTRICAL ENGINEERING
SCHOOL OF ENGINEERING AND APPLIED SCIENCES
UNIVERSITY OF VIRGINIA

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ABSTRACT

The objective of this research program is to investigate the unique properties of semiconductor-clad optical waveguides. Previous computer modeling studies on four-layer silicon-clad planar dielectric waveguides indicated that the attenuation and mode index should behave as exponentially damped sinusoids as the silicon thickness is decreased below one micrometer. This effect can be explained as a periodic coupling between the guided modes of the lossless structure and the lossy modes supported by the high refractive index silicon. The computer studies have also shown that both the attenuation and mode index of the propagating mode are significantly altered by conductivity charges in the silicon.

This report summerizes the research effort since the beginning of this grant. Silicon claddings have been RF sputtered onto $AgNO_3$-$NaNO_3$ ion exchanged waveguides and preliminary measurements of attenuation have been made. An expression has been developed which predicts the attenuation of the silicon clad waveguide from the attenuation and phase characteristics of a silicon waveguide. Several new applications of these clad waveguides are suggested in this report and methods for increasing the photo response of the RF sputtered silicon films are described.

I. INTRODUCTION

Although integrated optical devices were proposed as early as 1970, the development of practical circuits still awaits the invention of new devices and the improvement of existing devices. This lack of development in integrated optical circuits is certainly not due to a lack of application for such circuits. Optical memories, optical computers, optical data processors and wideband communication systems all await development of integrated optical circuits. It is the purpose of this research program to investigate the fundamental properties of semiconductor-clad optical waveguides based on glass substrates. During this study, devices such as direct optical modulators will be pursued to determine he potential for development of practical devices.

The second section of this report briefly discusses the underlying concepts of semiconductor-clad dielectric waveguides and describes the results of computer analysis of such structures. The third section explains the damped oscillatory behavior of the waveguide attenuation and phase characteristics in terms of coupling from the dielectric guide into the silicon layer. An equation has been developed which predicts the minimum attenuation values based on the attenuation of the silicon layer. The fourth section discusses the experimental sputtered silicon waveguides being fabricated and experimental results are presented showing the predicted oscillatory behavior. The final section of this report discusses the work proposed in the future as well as device applications for the effect.

II. THEORY AND NOTATION

The four-layer planar waveguide structure under consideration is shown in Fig. 1 where the guided light is propagating in the z-direction in the dielectric (N_3), and it is assumed that there is no variation in the y-direction. All materials are lossless except for the semiconductor (N_2). The dispersion relations for this structure are well known and two methods of solution for the complex mode propagation constant ($\alpha+j\beta$) have been described previously (1, 2).

The waveguide consists of a semi-infinite glass substrate, a dielectric core of thickness 1 μm, a semicondutor cladding varying from 0.01 to 10 μm in thickness, and a semi-infinite layer of air. A free-space wavelength of 632.8 nanometers was assumed and all material parameters shown in Fig. 1 are for this wavelength. Recall, that the permittivity of a lossy material is given by

$$\varepsilon_R = \varepsilon' - j\varepsilon'' = \varepsilon' - j\frac{\sigma}{\omega\varepsilon_o}$$

where σ is the conductivity of the metal at frequency ω. The permittivity can also be expressed in terms of the refractive index as

$$n = \varepsilon^{1/2} = n - jk$$

The three most common semiconductors, silicon, gallium arsenide, and germanium were used as the cladding layer, and relative permittivity values are summarized in Table I. Bulk values have been used where data was not available for thin films.

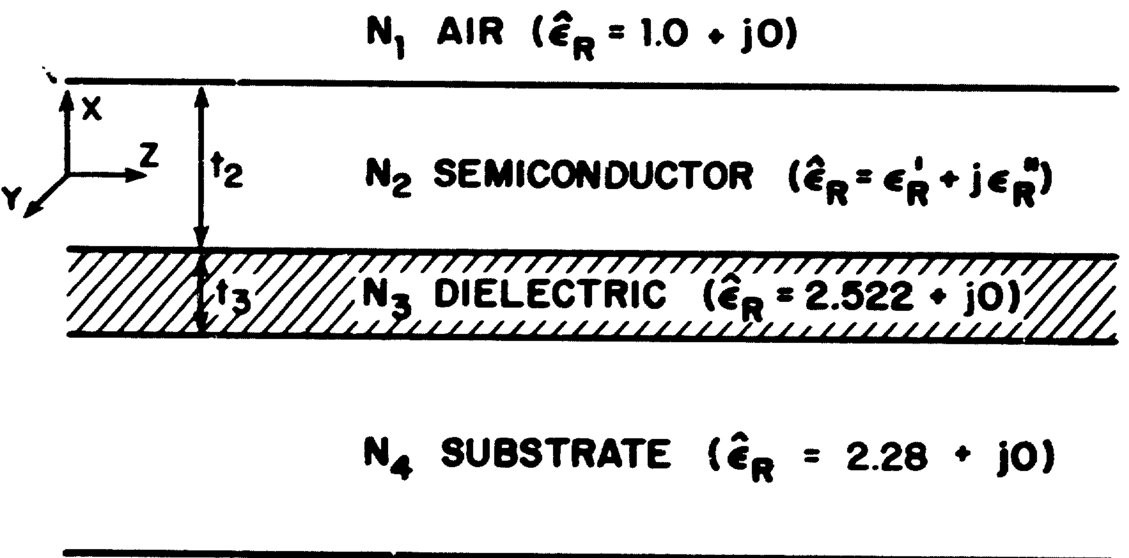

Figure 1. Four-layer planar waveguide structure

Table I

Semiconductor Parameters at $\lambda = 632.8$ nm

Material	Relative Permittivity ε_r'	ε_r''	Refractive Index n	k
Silicon*	16.76	1.75	4.1	0.213
Gallium Arsenide	14.3	1.21	3.79	0.16
Germanium*	14.43	19.54	4.4	2.22

*values for amorphous thin films

Silicon was selected as the first semiconductor cladding material to be investigated and Figs. 2 and 3 where generated by varying the cladding thickness from 0.01 to 10 μm. All other parameters were held constant in these calculations and results were confirmed by using both computer solution techniques. It was initially expected that decreasing the lossy cladding thickness to 0.01 μm would reduce the attenuation to zero in a well-behaved manner; however, the results were not as expected below a silicon thickness of 1.0 μm. The curves are similar to exponentially damped sinusoids with extreme values of the β/k curves corresponding to the median values (maximum slope) in the α curves. Extreme values of the α curve correspond to median values in the β/k curves and the oscillations in both curves approach the median value at 1.0 micrometer.

Since the period of these oscillations (0.08 to 0.09 μm) is not a fraction of the wavelength of light in the dielectric ($\lambda_d = 0.3985$ μm), it must be related to the waveguide structure or the properties of the semiconductor cladding. Gallium arsenide, which has a complex permittivity nearly the same as silicon, was used for the next series of calculations. The attenuation and phase characteristics are almost identical to those of silicon, and varying the dielectric waveguide thickness, t_3 to 0.8 μm, has little effect on the characteristics. The dielectric and glass layers were interchanged (i.e. glass substrate, GaAs, dielectric, air) and the rate of exponential decay increased, but the period remained constant.

As Table I indicates, the permittivity of germanium has a significantly larger imaginary part, and would thus be expected to have the largest effect on the observed characteristics. Calculations show that the larger conductivity of germanium nearly eliminates the damped oscillatory behavior in the thickness region of interest.

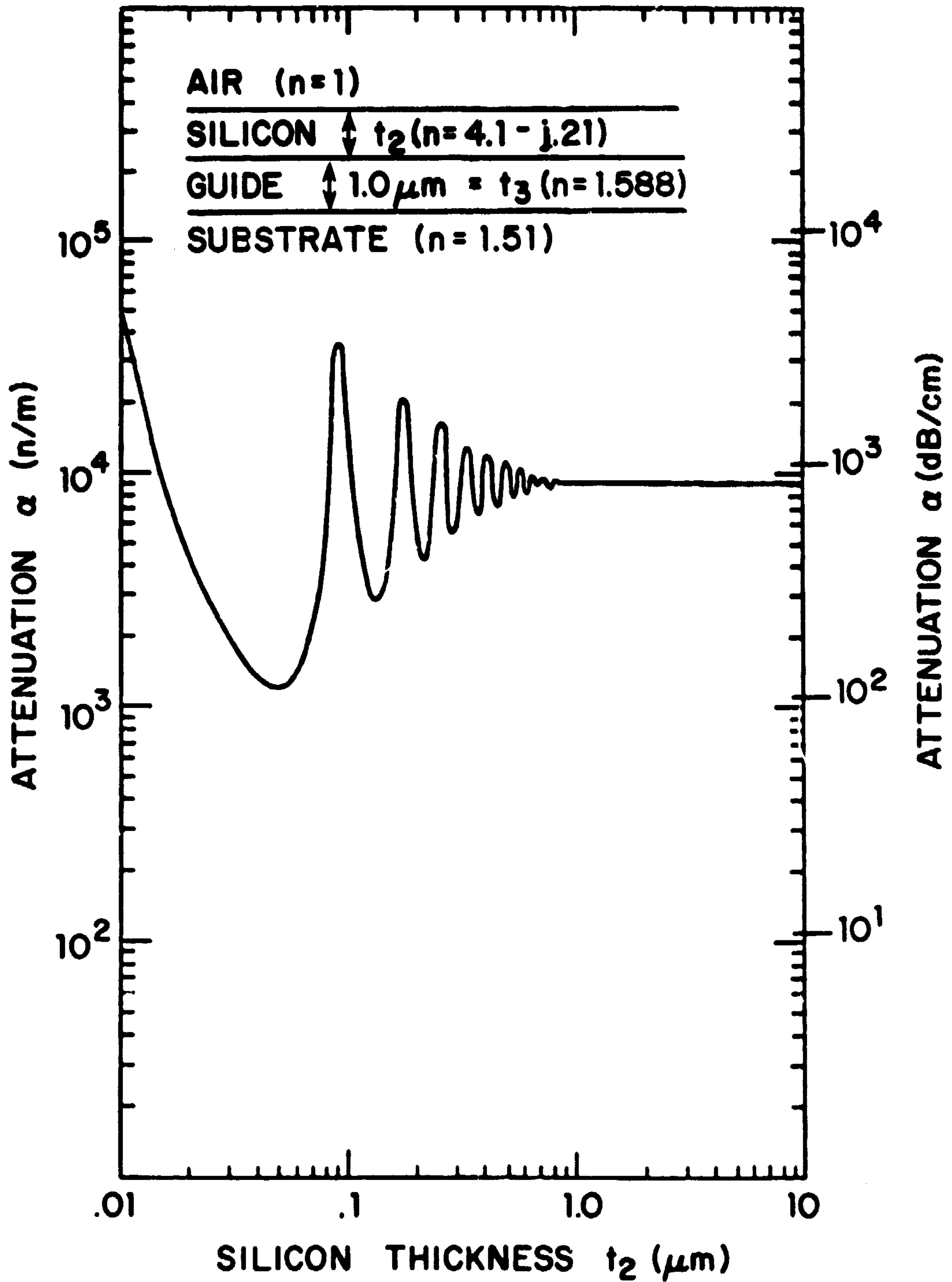

Figure 2. Attenuation characteristics of silicon-clad waveguide (TE_0 mode, normal conductivity).

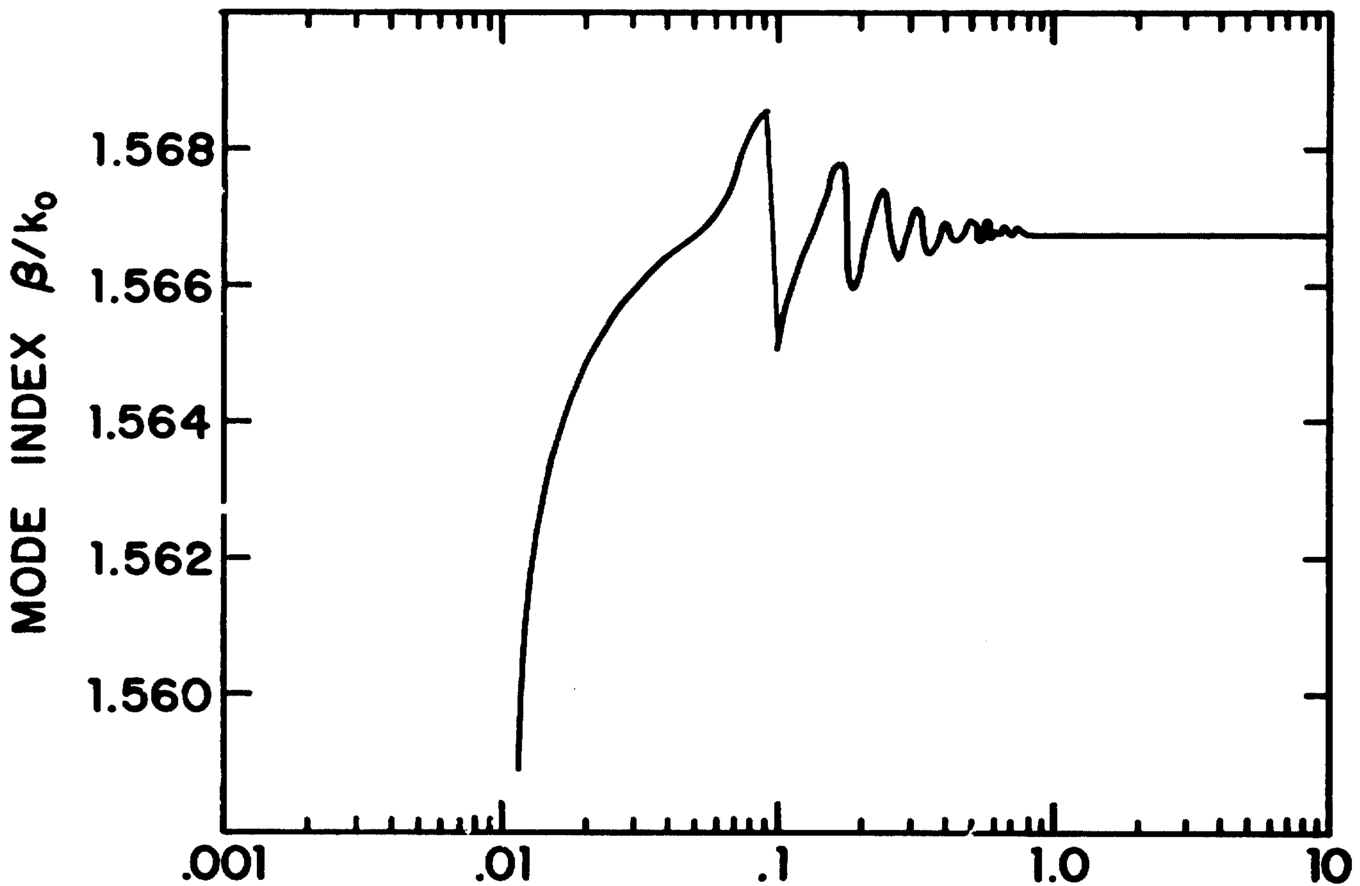

Figure 3. Mode index characteristics of silicon clad waveguide (TE_0 mode, normal conductivity).

We now consider the effect on the propagation characteristics of the light wave of photon-induced conductivity changes in the semiconductor cladding. Recall, that the imaginary portion of the relative permittivity of a semiconductor is a linear function of the conductivity and can thus be externally varied. For example, if light with energy greater than the semiconductor bandgap is incident on the semiconductor cladding, electron-hole pairs are created and the total conductivity becomes

$$\sigma = \sigma_o + e\Delta n|(\mu_e + \mu_n)$$

where Δn is the photon generated hole-electron pairs and μ_e and μ_n are the electron and hole mobilities, respectively. Previous computer-aided analysis has demonstrated that the attenuation and phase of the propagating light wave are altered by conductivity changes in the semiconductor cladding and that by proper choice of semiconductor cladding thickness, the effect may be maximized (Fig. 4). An amplitude modulator and phase modulator have been proposed using these results.

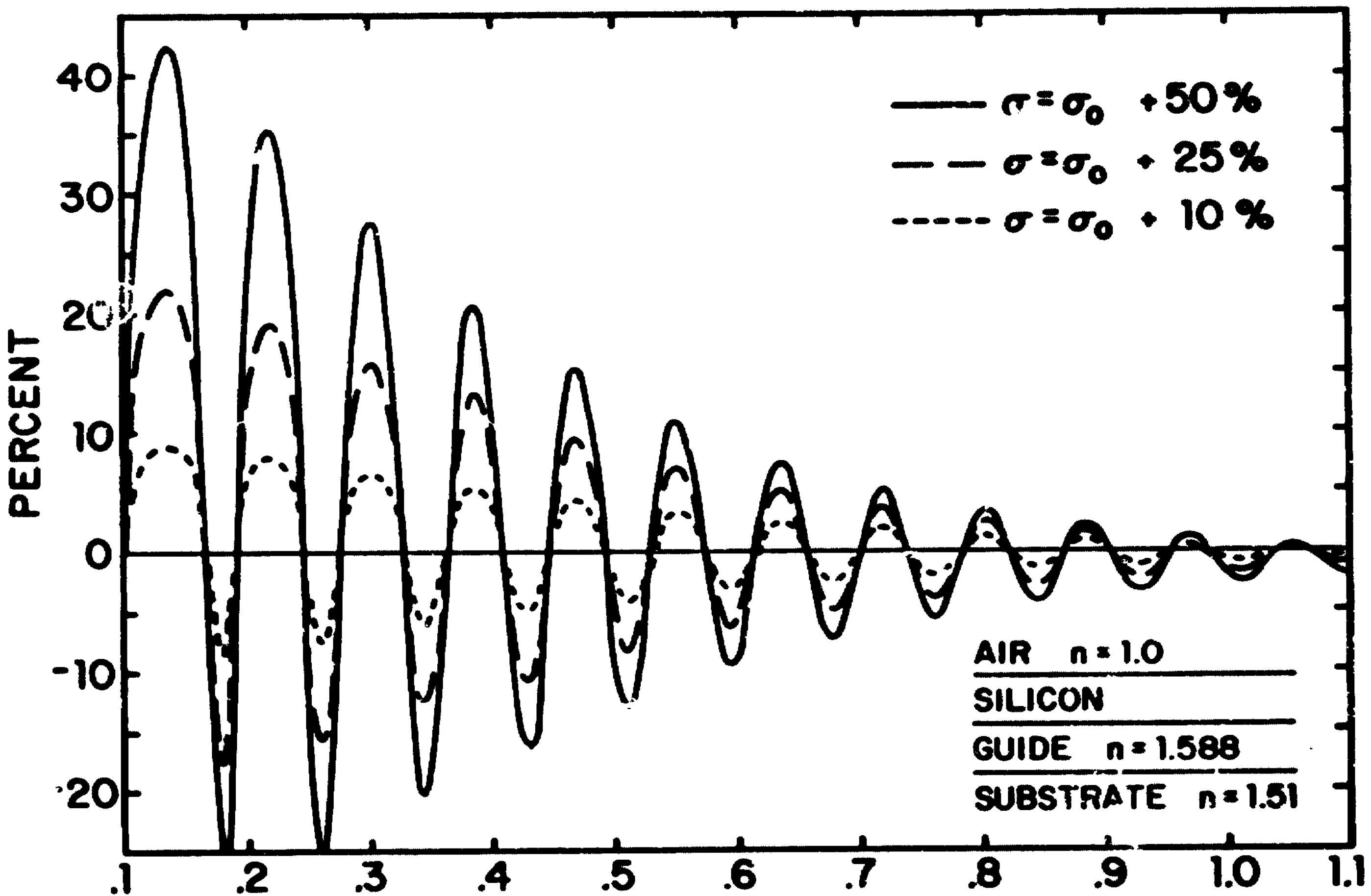

Figure 4. Percent change in attenuation with relative change in conductivity (σ_0).

III. FURTHER ANALYSIS OF COUPLING CHARACTERISTICS

Previous calculations have demonstrated that the local maximum/minimum points on the attenuation and mode index curves can be correlated with the electric field distributions at the appropriate thicknesses (1). Results indicated that the presence of a thin silicon film (<100Å) has little effect on the wave function profiles; the profiles are similar to those of the lossless three-layer structure (air-dielectric-substrate). For the thick silicon film structure, however, the lowest order mode of the lossless three-layer structure couples to the modes associated with the semiconductor film, as evidenced by oscillations of the field distribution in the semiconductor cladding. In this section, an analysis of the propagation characteristics of the partial structure (air-silicon waveguide-dielectric) is described which confirms that the coupling between the modes supported by the three-layer lossless structure and the high loss TE' modes of the silicon waveguide determines the attenuation and phase of the complete four-layer structure.

The results can be described as a periodic coupling between the guided mode (TE_0) in the dielectric and the lossy TE' modes of the same guide. The coupling determines the attenuation and phase characteristics of the complete four-layer structure. Since the field plots indicate successive coupling to higher order modes in the silicon layer, a partial structure consisting of a silicon guiding region surrounded by semi-infinite layers of air and dielectric was analyzed. The attenuation and mode index are shown in Figs. 5 and 6. All modes are very lossy and the attenuation increases for higher order modes. In Fig. 6, note that a phase match condition between the TE' modes of the partial structure (air-silicon guide-dielectric) and the TE_0 mode

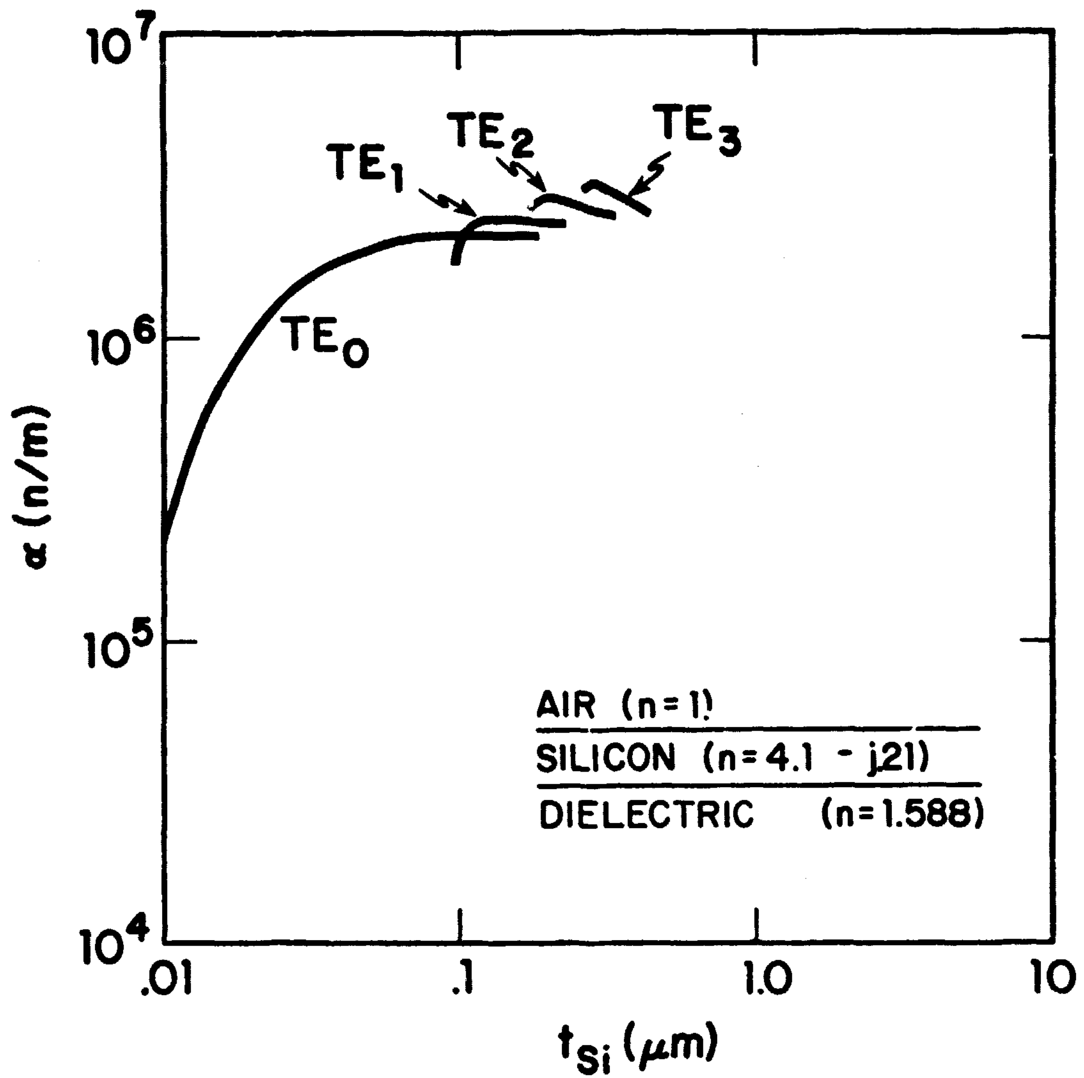

Figure 5. Attenuation characteristics of silicon waveguide.

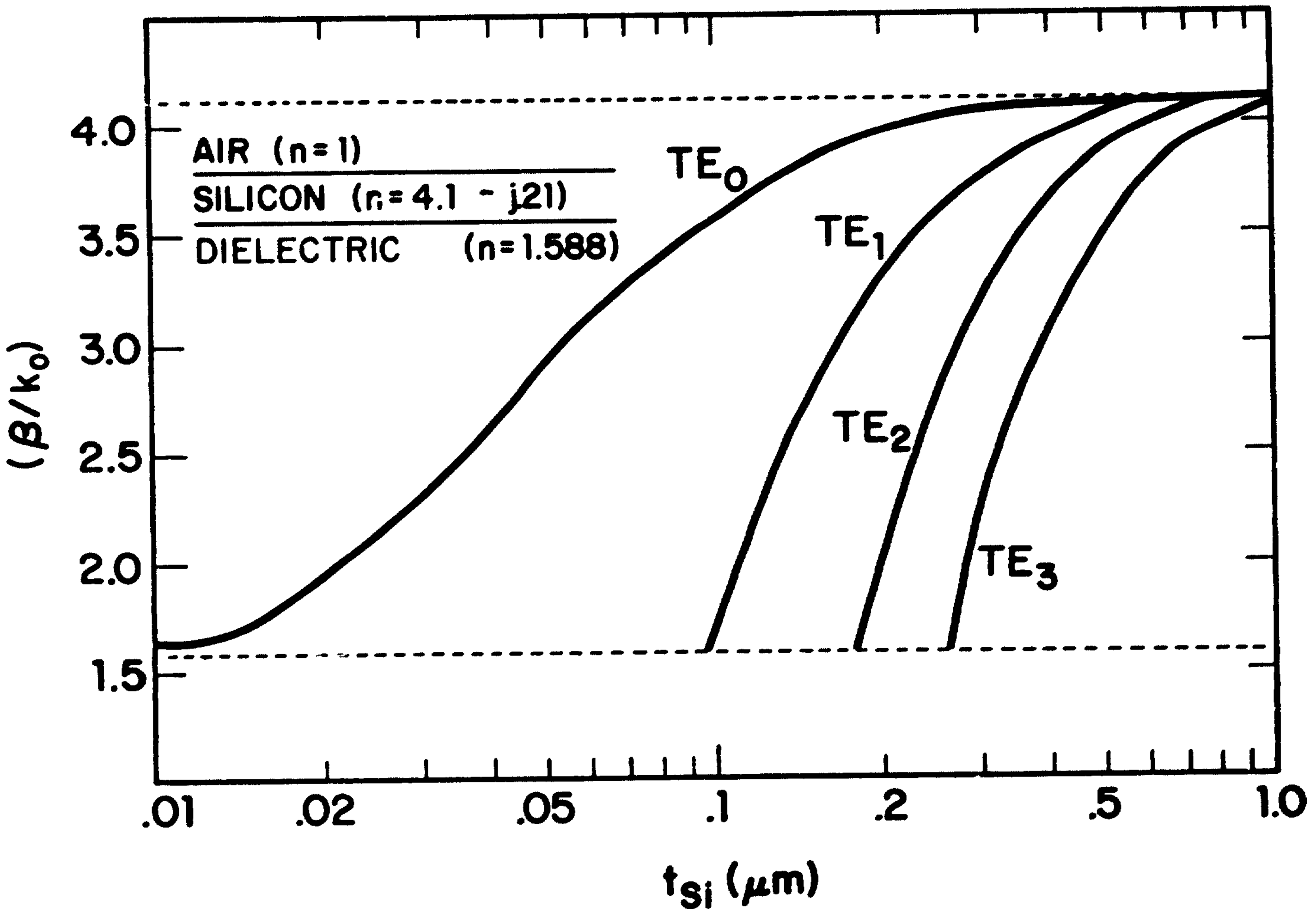

Figure 6. Mode index characteristics of silicon waveguide.

of the complete waveguide (Fig. 3) occurs at the cutoff thicknesses for successively higher order modes of the partial structure. The sharp peaks on the attenuation curve for the four-layer structure (Fig. 2) occur whenever the guided wave mode index matches that of one of the high loss TE' modes of the partial structure. The sharp nulls in the attenuation curve, indicating very low coupling efficiency, occur at thicknesses midway between the cutoff value of two adjacent lossy TE' modes. These results are similar to power transfer calculations for linearly tapered directional couplers (3, 4). Furthermore, the abrupt transistions on the mode index curve of the complete structure (Fig. 3) occur when the phase match condition is satisfied and the guided wave couples into successively higher order modes of the partial structure.

Close examination of Fig. 2 indicates that the attenuation in the region of an oscillation minima is governed by an equation of the form

$$\alpha = K(1 - e^{-\alpha_i t_{2_i}} \cos \omega t_{2_i})$$

where K = semi-infinite attenuation of the four-layer waveguide (i.e. when $t_2 \to \infty$

α_i = attenuation (n/m) of the three-layer silicon waveguide at thickness t_{2_i}

t_{2_i} = thickness of the silicon at any point near a local minma (i) in the range $0.1 < t_2 < 1.0$ μm

ω = period of the oscillation determined by the cutoff thickness of each TE' mode

For the silicon clad waveguide in Fig. 2, this equation becomes

$$\alpha = 9.1 \times 103[1 - e^{-\alpha_i t_{2_i}} \cos (\frac{2\pi \times 10^6}{0.085} t_{2_i})] \text{ n/m}$$

The field plots and the analysis of the partial structure indicate, then, that the attenuation and mode index of the four-layer structure may be explained as a coupling between the basic TE_0 mode of the dielectric waveguide and the high

loss TE' modes of the semiconductor guide. As more TE' modes are excited, the effect on the TE_0 mode becomes negligible and the waveguide characteristics exponentially approach those of the three-layer structures where the semiconductor layer is considered semi-infinite.

IV. FABRICATION OF EXPERIMENTAL DEVICES

Since a RF sputtering systems is available in the Semiconductor Device Laboratory, a silicon target has been purchased and films are being sputtered on ion exchanged waveguides. It was decided that a large number of waveguides would be sputtered with uniform silicon films 1 mm wide and extending across the waveguide. The film thickness will be varied from 0.04 μm to 0.40μm by steps in order to confirm the damped oscillatory behavior of the four-layer silicon-clad structure.

Unfortunately, sputtered amorphous silicon is permeated with dangling bonds which render Si photoelectrically and photoconductively dead-certainly less than ideal characteristics for a semiconductor film which relies on photon-induced conductivity changes. These dangling bonds lie between the conduction and valence band and act as fast, non-radiative recombination sites (11, 12, 13). One solution, however, is to sputter in hydrogen which effectively passivates the dangling bonds, thereby revealing the interesting properties of silicon. Unfortunately, the available system only allows RF sputtering in argon. It was decided, however, that since the predicted characteristics (damped oscillatious of the attenuation curve) are purely bulk effects, they should be apparent in even unpassivated silicon-clad waveguides. A holder was designed which would allow the deposition of a silicon film 1 mm wide and 20 mm long on the waveguide surface.

Microscope slides were initially sputtered with silicon in order to determine a consistent deposition rate. It was discovered, though, that the silicon thickness versus sputtering time curve was highly non-linear; that is, sputtering for twice the length of time did not yield twice the thickness of silicon, even when power coupled into the system and reflected power were

carefully monitored. Furthermore, it was discovered that the majority of the deposition was accomplished in the final several minutes of sputtering. The first thirty minutes only yielded approximately 100 Å of silicon while the final five minutes yielded over 500 Å. Also, the deposition rate varied depending on the sputtering run. The last few runs of each session always yielded thicker films, presumably because of system heating.

It was also noted that the silicon film, was not completely uniform along the intended direction of light propagation, probably because of distortions in the applied electric field by the metallic waveguide mask. Dektac measurements along with a qualitative color comparison indicated that the films were, indeed, uniform over the middle 50% of the 1 mm wide silicon strip, but a tapered effect was obtained along the edges. Fortunately, detailed analysis indicated no significant mode coupling would occur along this tapered region - that is, all coupling (or lack, thereof) should be dependent on the silicon thickness in the middle 50% of the film (3, 4).

Silicon strips varying in thickness from 300 Å to 1200 Å intervals were sputtered on ion-exchange waveguides to determine sputtering times and film thicknesses. Dektac measurements confirmed the film thickness and uniformity along the central 50% of the silicon strip.

In all sputtering runs attempted thus far, argon has been the gas of interest. As previously mentioned, sputtering in a hydrogen/argon mixture passivates the silicon, thereby revealing its interesting photoconductive properties. A careful literature search was performed to determine the optimum hydrogen/argon mixture. Unfortunately, the optimum ratio is a complex function of individual sputtering system parameters (power coupled in, reflected power, total gas pressure, target to substrate spacing, etc.), and references (6), (7), (8) sputtered in mixtures from .1% H_2 to 20% H_2;

however, reference (6) obtained sputtered silicon films with properties most closely associated with those of a glow-discharge system (high resistivity, good photoconductivity, etc.) in a 3% H_2 - Ar mixture. Using this as a basis for our experiments, a 1% H_2 - Ar gas mixture has been purchased and will be used for future films.

Qualitative confirmation of the damped oscillatory behavior of the attenuation vs. silicon thickness curve has been successful, as Fig. 7 indicates. Light is coupled into the silicon-clad guide via a prism coupler. Uninterrupted propagation occurs until the beam encounters the 1 mm wide silicon cladding. For a silicon film 200 Å thick (Fig. 7a) the beam is clearly attenuated, as computer calculations predict. For a film 500 Å thick (a predicted minimum on the attenuation-thickness curve 1) nearly uninterrupted propagation occurs (Fig. 7b), and for a film 1100 Å thick (a predicted region of high attenuation), the beam is again attenuated (Fig. 7c) The photographs confirm, then, the predicted attenuation variation.

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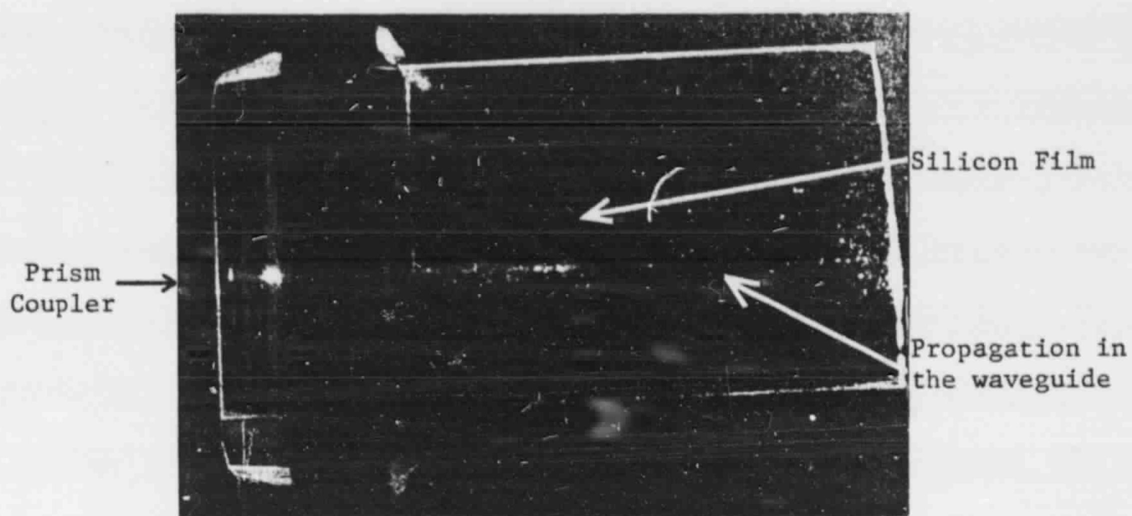
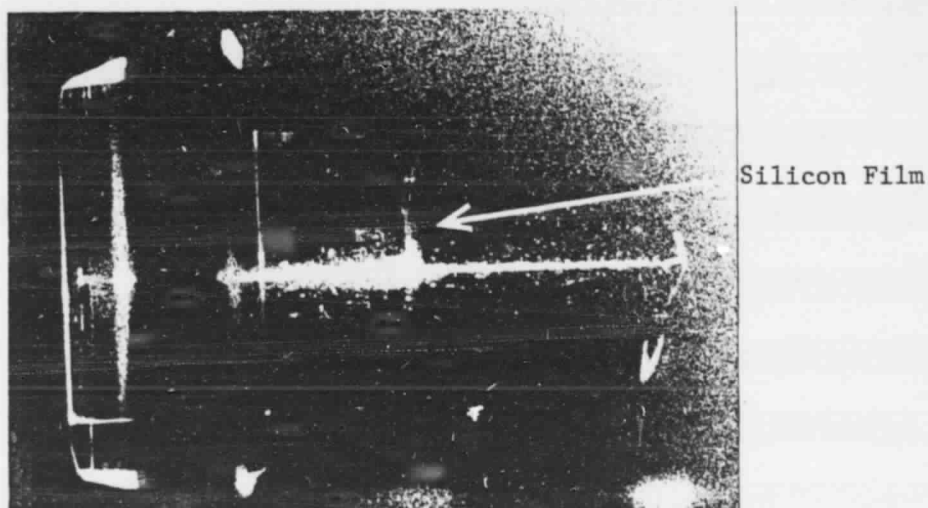
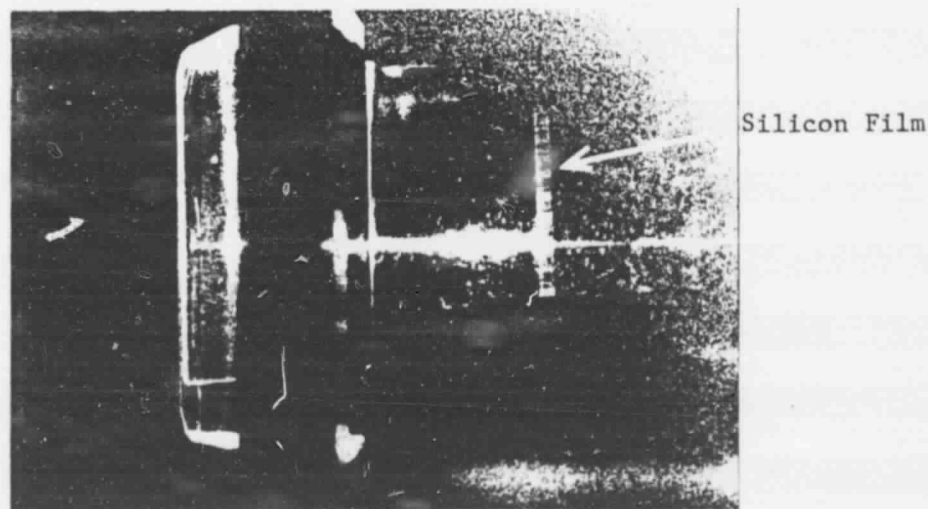


(a) Silicon film ~200 A° thick



(b) Silicon film ~500 A° thick



(c) Silicon film 1100 A° thick

Figure 7. Experimental measurements of waveguide attenuation. All photographic exposures are 1 sec, f2, ASA 400 film. (Top view of waveguide)

CONCLUSIONS AND FUTURE DIRECTIONS

The qualitative confirmation of the damped sinusoidal behavior of the silicon-clad waveguides must now be supplemented with quantitative measurements to confirm the predicted attenuation levels. This will require the development of a measurement technique which allows measurement of very high attenuation levels or the attenuation must reduced. There are two techniques which can be used to reduce the attenuation. The first is to measure the loss of a very short section of silicon. This has the disadvantage that the measurement is subject to errors due to losses at the discontinuity between the silicon clad region and the air clad region. A better method is to introduce a buffer layer between the silicon and the waveguide and thus reduce the attenuation. Both methods require the coupling of light from the waveguide to a detector, in order to make attenuation measurements.

The fluid-coupler method uses a high refractive index liquid to couple light from the guide to a photodetector. Most of the light couples from the guide as well as scattered light due to propagation losses into the liquid and hopefully into the detector. This method would be good for making attenuation measurement over a relatively long (~ 1 cm) propagation path. Unfortunately it suffers from the requirement of having an accurately controlled detector to waveguide distance and a reasonable uniform high-refractive-index drop size. A more sensitive technique uses a fiber optic probe incorporated into a scanning photometric microscope to sample the light as a function of distance along the propagation axis. Attenuation measurements from 0.02 dB/cm to 4.6 dB/cm have been reported (9).

The prism coupling technique can also be used for the measurements since it eliminates the need for the index-matching liquid. It makes use of a second prism to couple light into the detector. This method introduces measurement variations due to prism coupling efficiency which are a function of prism pressure, waveguide flatness and waveguide cleanliness. The fluid-coupler will be used on the majority of the attenuation measurements since it is the simplest and provides the best results for high attenuation levels.

Experiments are currently underway to improve the photo response of the amorphous silicon films by passivation with hydrogen. By introducing a controlled amount of hydrogen into the sputtering chamber with argon the silicon will be passivated and the photo response is greatly improved. Based on several reported experiments (11, 12, 13) a mixture of 1% H_2 in argon has been selected for our first experiments.

Several devices, other than the amplitude and phase modulators previous suggested, have been postulated and will be explored in some detail during the remainder of this study. One such device would replace the silicon layer with a GaAs layer (single crystal) which could then be biased so as to operate in the Gunn Mode of oscillation. This would then modulate the guided light wave with the natural Gunn frequency. Other devices such as variable waveguide couplers, mixers and directional couplers are conceptually possible but need to be explored in greater depth.

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