Antiresonant reflecting optical waveguides in SiO_2-Si multilayer structures

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A new type of optical waveguide utilizing an antiresonant reflector is described. Implementation in the SiO_2-Si system gave losses as low as 0.4 dB/cm for the TE mode. The TM mode loss is > 60 dB/cm, making the device an excellent planar technology integrated optic polarizer.

Over the past decade there has been sustained interest in building low-loss optical waveguides on planar substrates. This research has been driven by numerous device applications such as directional couplers, filters, switches, and possibly optical interconnections for electronic circuits.

Some recent work[1,2] has been directed at constructing optical waveguides on silicon wafers, which provide a medium with excellent mechanical integrity and readily lend themselves to integration with silicon electronic circuits. Additional incentive is given by the high level of sophistication in materials and processing technology. A common approach[1] has been to grow a layer of thermal silicon dioxide (SiO_2) by thermal oxidation of the silicon substrate, and then to deposit on top of this a layer of SiO_2 doped with elements that produce a small increase in the index of refraction. Another approach has been to deposit on the thermal SiO_2 another dielectric layer such as silicon nitride (Si_3N_4, Ref. 2) or silicon titanium dioxide ($Si_{1-x}Ti_xO_2$, Ref. 3), which both have a substantially higher index of refraction than that of SiO_2.

One potential problem with these approaches is that the doped SiO_2 or the deposited dielectrics may be more lossy than pure SiO_2. Additional complications arise in optimizing the optical confinement. Since the evanescent field becomes a propagating wave at the high index Si substrate ($n = 3.5$ at $1.3\,\mu m$), with weakly guiding doped SiO_2 or thin deposited dielectrics, substantial thicknesses of SiO_2 are required to minimize radiation losses into the substrate. For deposited dielectrics with a larger index change available, this can be eliminated with thicker deposited core layers, but this leads either to an overmoded guide or to a small mode poorly matched to optical fibers. Another approach for waveguides on high index substrates has been the fabrication of a periodic Bragg reflecting medium on the substrate, which can be understood as providing an evanescent tail by propagation within the stop band of the periodic medium.[4,5] This entails a complicated multilayer growth.

In this letter we describe a simple waveguiding structure which utilizes pure SiO_2 as the core layer, and which features a dramatically reduced radiative loss into the high index substrate without using total internal reflection. In addition, large modes appear possible with a good degree of higher order mode filtering through loss discrimination. One implementation of the waveguide is shown in Fig. 1. A layer of polycrystalline silicon about $0.1\,\mu m$ thick is deposited by chemical vapor deposition (CVD) on top of a 2-μm-thick layer of thermal SiO_2. The core of the waveguide is a 4-μm-thick layer of undoped SiO_2 deposited by low-pressure CVD. Light propagating in the top core SiO_2 layer undergoes total internal reflection at the air-SiO_2 interface, and very high reflection from the set of Si-SiO_2 interfaces.

This very high reflectivity, on the order of 99.96%, arises from the antiresonant character of the lower layers of the structure relative to the component of propagation normal to the layers. When the core SiO_2 thickness d_1 is large enough, $d_1 \gg \lambda/2n$, the fundamental mode will propagate with a glancing incident angle from the core SiO_2 into the thin Si layer, and this index discontinuity and glancing angle provide a large reflection. Since reciprocity guarantees an equal reflection regardless of the direction of propagation, a large and equal reflection occurs at each interface of the lower layer structure in the waveguide.

If we consider the thin Si layer, it then acquires the transmission characteristics of a Fabry–Perot resonator, and high reflection occurs at the antiresonant wavelengths of this Fabry–Perot. In a similar fashion, the lower SiO_2 layer is also another Fabry–Perot cavity in series which also operates at its antiresonant wavelengths with proper design to provide even larger reflection. Since low-loss operation of the waveguide relies on properly phased reflections from all the interfaces, one might conclude that the device only works over a narrow band of wavelengths and has strict fabrication tolerances. This is not the case, as can be inferred from the Fabry–Perot analogy. While the resonances of a Fabry–Perot occur over a narrow band of wavelengths, the antiresonances are spectrally broad. This behavior can be seen in the theoretical loss calculation of the waveguide shown in Fig. 2. Also note that while the TE loss is low, the TM loss is very high since TM reflections are always lower by the same phenomenon which gives rise to the Brewster angle. The degree to which the TM loss is higher depends in detail on the proximity of the propagation angle in the core relative to the Brewster angle. For a given device this in turn depends on the relative indices of the core and reflecting layers, and on the core layer thickness.

Figure 2 also shows loss measurements which were made on samples for a variety of silicon layer thicknesses, all with $d_1 = 4.0\,\mu m$ and $d_2 = 2.0\,\mu m$. Waveguide loss was determined by successively cleaving waveguides to various lengths and measuring the insertion loss as a function of the guide length, with the slope yielding the waveguide loss per unit length. The broad minimum, in agreement with the theoretical calculation, confirms that fabrication tolerances are not strict. Calculations show a similar noncriticality for

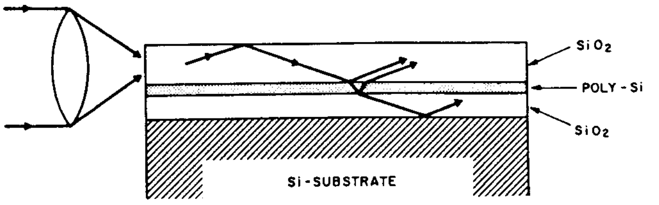

FIG. 1. Waveguide structure using antiresonant reflection on silicon wafer.

the bottom SiO_2 layer thickness. From this we can also infer that there is a reasonably broad range of wavelengths over which the loss will remain low.

If the core layer is thick enough, the fundamental mode has a negligible evanescent tail in the air, and the glancing incident angle shown in Fig. 1 can be approximated by

$$\sin \phi \simeq \lambda / 2 n_1 d_1 . \tag{1}$$

Using Snell's law to obtain the angle in the silicon layer, one can easily find that the antiresonance of the thin silicon layer is obtained with a thickness t approximated by

$$t \simeq \frac{\lambda}{4n_2}(2N+1)\left(1-\frac{n_1^2}{n_2^2}+\frac{\lambda^2}{4n_2^2\, d_1^2}\right)^{-1/2} \quad N=0,1,2,\ldots, \tag{2}$$

where λ is the wavelength, n_1 is the refractive index of the top and bottom SiO_2 layers, n_2 is that of the silicon layer, and d_1 and d_2 are the upper and lower SiO_2 layer thicknesses shown in Fig. 1. Since n_2 is significantly larger than n_1, t does not deviate too much from an odd multiple of $\lambda / 4n_2$. Similarly, the antiresonant condition of the bottom SiO_2 thickness d_2 is approximated by

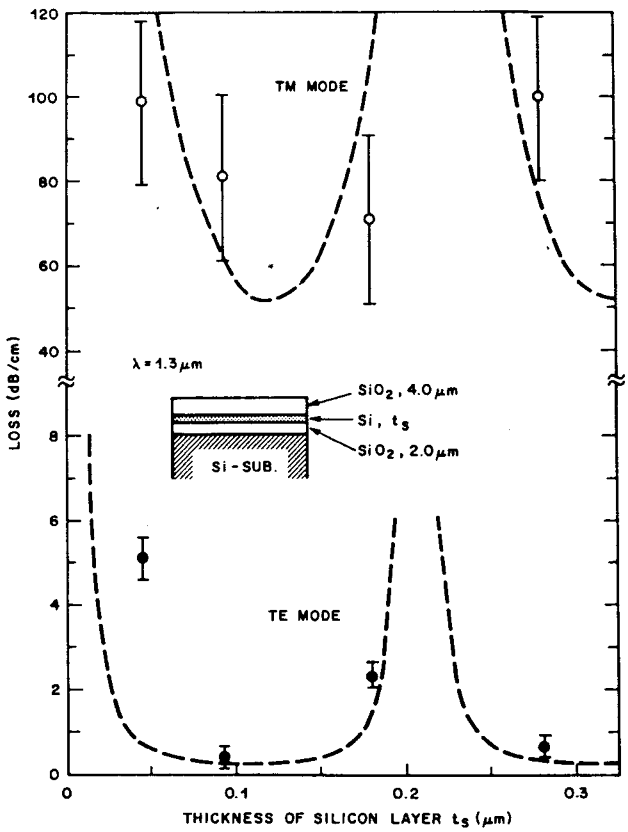

FIG. 2. Waveguide loss measurement as a function of the thickness of the polycrystalline silicon layer. Dotted line is the theoretical calculation.

$$d_2 = (d_1/2)(2M+1), \quad M=0,1,2\ldots . \tag{3}$$

Figure 3 shows the intensity profile in the guided mode when the above conditions are satisfied, with the mode profile obtained from a rigorous numerical evaluation of the complex propagation constant of the leaky mode. The antiresonant character of the field in the lower two layers is evident from the placement of the nodes and antinodes which can be seen in the 100× vertical expansion of the region including the lower reflecting layers. Also evident is the low confinement of the silicon layer, which is desirable since polycrystalline Si can have substantial loss even at wavelengths normally beyond the single crystal Si absorption cutoff. In fact these waveguides have been operated at 6328 Å with losses of only several dB/cm, even though polycrystalline Si has an absorption of about 4000 μm^{-1} at that wavelength.

Lateral guiding can be easily achieved by etching shallow channels (several thousand angstroms is adequate) in the upper SiO_2 layer to provide a ridge loading, and other techniques such as pre-etching the lower substrate prior to deposition should also be possible.

A final point to make is that this guide structure gives very large loss discrimination against higher order modes. Simple leaky guides in general have a loss which increases roughly quadratically with mode number,[5] but the structure studied here is much more discriminating than this. For the structure shown in Fig. 3 the fundamental mode loss is calculated to be 0.255 dB/cm, while the second mode has a loss of 99.2 dB/cm, and the third mode has a loss of 21.64 dB/cm. This behavior is expected since the second mode is actually resonant in the lower SiO_2 layer which enhances transmission into the substrate, with the third mode again acquiring the desired antiresonant structure but with large incidence angles on the high reflecting lower structure, and more bounces per unit length as well.

From the device utility viewpoint, mode matching considerations are the same as in conventional guides. Any portion of the input field distribution which does not match the fundamental mode will couple to lossy higher order modes. These are actually radiation modes, as they are in a conven-

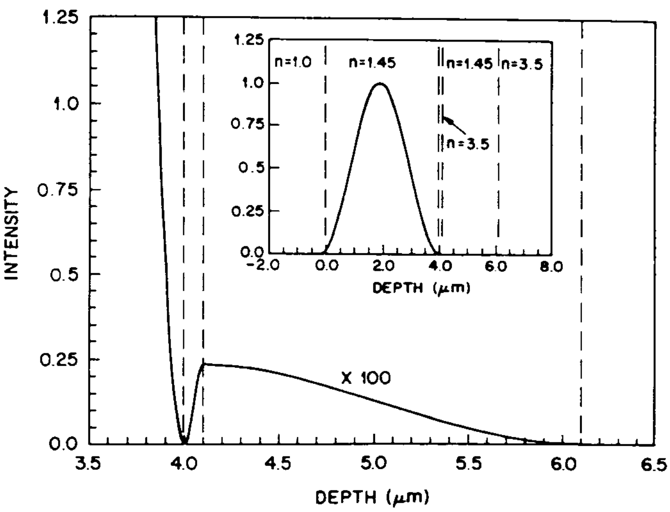

FIG. 3. Light intensity of TE mode as a function of distance into the substrate. The part from 3.5 to 6.5 μm is shown under 100× magnification to show the intensity profile in the polycrystalline silicon film.

tional strictly fundamental mode guide, so that the coupling loss considerations are the same as in conventional guides.

In closing, we have demonstrated a new waveguide which utilizes antiresonant reflecting layers to produce low-loss propagation on a high index substrate. The device makes an excellent integrated optic polarizer, and yields large fiber compatible modes with a reduced overmoding problem. The fabrication techniques employed here are already in a refined state from silicon electronics technology, but we also point out that the structure should be possible in many other materials systems. Even when total internal reflection is employed in a more conventional waveguide, it may prove desirable to supplement the reduction of the evanescent tail by using an antiresonant reflector as described here.

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