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Planar Silicon Optical Waveguide Light Modulators

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Abstract

The results of an experimental investigation of a new type of optical waveguide based on planar technology in which the light guiding and modulation are achieved by exploiting free carrier effects in silicon are presented. Light is guided between the n+ substrate and two p+ regions, which also serve as carrier injectors for controlling absorption. Light confinement of single mode devices is good, giving spot sizes of 9 µm FWHM. Insertion loss measurements indicate that the absorption losses for these waveguides are extremely low, less 1 dB/cm. Estimates of the switching speed indicate that values in the nanosecond region should be possible, however, the measured values are high, 20 microseconds, due to the large area of the injector junctions, $1x\ 10^{-2}\ cm^2$, and the limitations imposed by the detection circuit. The modulating properties of these devices are impressive, measurements indicating that modulation depth can approach 100 % (≈ 30 dB).

1. Introduction

Along with its unique electrical and mechanical properties, silicon has optical properties that make it, among other things, an attractive material for application in the fabrication of optical waveguides for the wavelength range between 1000 and 6000 nm. In this wavelength region absorption is very low ($\alpha < 1\ cm^{-1}$), but by introducing free electrons or holes it is possible to increase absorption by four or five orders of magnitude (1). Of course, accompanying the increase in absorption is a corresponding decrease in the refractive index (1,2). By exploiting these properties and the very advanced silicon technology that is available to us today, new types of optoelectronic devices and systems can be made.

The approach of the work reported here is different from that of other researchers in that the devices are planar silicon waveguides and, thus, have the inherent advantage of much lower scattering losses due to the very smooth waveguide walls achieveable. In addition, better confinement of the light, as well as, injection and extraction of carriers is obtained due to the novel double p+ region geometry employed, which both improves guidance and modulation of the light.

Waveguide Device Fabrication

The geometry of the planar silicon optical wavegude is shown in Figure 1. Light propagates in the region between the two p+ regions just above the n+ substrate. The devices made for this study were fabricated using standard planar silicon technology. The p+ regions shown in Figure 1. were formed by diffusion of boron into lowly doped (3 x 10^{13} cm^{-3}) highly perfect epitaxial layers grown on n+ silicon wafers having a donor concentration of 1 x 10^{18} cm^{-3}. The effective width of the waveguides, which is determined by these diffusions, was varied from 4 to 46 μm photolithographically. Contacts to the waveguides were made via 5 mm long aluminium stripes 250 μm wide on either side of the waveguide and via an aluminium layer covering the entire backside of the chip. After fabrication the wafers were cut into 10 x 10 mm chips. Since the coupling of light into the waveguide is critically dependent on quality of the ends of the waveguide, these were then carefully polished to an optical finish after the dicing operation. The finished waveguides were either 7 or 9 mm long.

Electrical and Optical Measurements

Measurements at a wavelength of 1550 nm showed that waveguides up to 16 μm in width were single mode and that those 16 to 28 μm in width could support two modes, while those from 28 to 46 microns in width permitted three modes to propagate. This behaviour is indicated in Figure 2. Note that the fundamental first order mode can be made to propagate in any of the waveguides, no matter what the width. Typically, the first order mode has a full width half maximum (FWHM) of 9 to 14 μm depending on the width of the waveguide, as can be seen in Figure 2. It was also found that a single mode can not only be sustained in any of the guides tested, but could also be steered spatially, either by adjusting the point of excitation or by the injection of carriers. Depending on the conditions, the light propagates on different sides of the waveguide. This same effect can be produced by changing the bias applied to the p+ regions.

Insertion loss measurements confirmed our estimates of the importance of the different factors that play a role in determining the optical losses of the silicon planar optical waveguide in the wavelength range of 1550 nm. It was found that the insertion losses of planar waveguides can be quite large in spite of the fact that absorption and scattering losses are expected to be very low in these devices. The absorption in silicon is very small and as a consequence the contribution to the insertion loss is less than 1 dB/cm when the scattering losses are negligible. Since the index of refraction of silicon is approximately 3.48 the transmittance of a single interface is 0.7, resulting in a contribution to the insertion loss of 0.49 (≈ 3 dB). The coupling efficiency can be made nearly 1.0 if the mode size of the incoming beam can be made to match the waveguide's and the numerical apertures (NA) are the same, but this is difficult in practice, in spite of the fact that for these devices NA ≈ 0.6. Thus, the measured total insertion losses were in the range 10 - 15 dB, in spite of the fact that the absorption and scattering losses were approximately 1 dB/cm.

The modulation speed of these devices is determined by the speed with which carriers can be injected and extracted from the waveguiding region, i.e. by the switching time of the diode injector structures. Employing the simplest of models and noting that the base width is much less than the diffusion length in these structures, one finds the switching time can be approximately 2 nanoseconds. Actual measurements of the light modulating properties of this device revealed a much slower switching speed. Measurements show it clearly takes approximately 20 microseconds to turn-on and another 20 microseconds to turn-off the modulator. However, it must be remembered that the area of this device is extremely large ($1x10^{-2}$ cm^2). Although not shown here, it was found possible to completely extinguish the light beam eminating from end of the waveguide, at least down to the detection sensitvity of our system. This implies that it is possible to achieve a modulation depth of nearly 100% (≈ 30 dB) in these devices.

Conclusions

In this work we have demonstrated that it is possible to fabricate low loss planar silicon optical waveguides for the near infrared wavelength region around 1550 nm having good confinement. Spot diameters of the first order mode were 9 - 14 μm FWHM dependent on the width of the waveguide. Optical losses are so low that it is possible to maintain single mode operation even in waveguides nearly 50 μm wide. In addition, it was possible to modulate the light beam by approximately 30 dB, which is truely impressive. On the other hand, due to the large areas of the p-n injector junctions, the measured switching speed of the devices fabricated was disappointingly long, 20 microseconds. However, it should be possible to reduce this significantly by employing the correct design.

References:

1. R.A. SOREF and B.R. BENNETT, 'Electrooptical Effects in Silicon', IEEE J. of Quantum Elect. **QE-23**, No.1, pp 123-129,(1987)

2. R.A. SOREF and J.P. LORENZO, '1.3 μm Electro-Optic Silicon Switch' App. Phys. Lett., **Vol. 51** No. 1, pp 6-8, (1987)

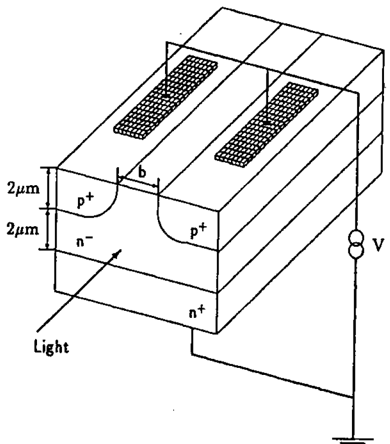

Figure 1. A perspective view of the planar p+n-n+ waveguide structure employed in this work. Note that the optical beam is confined to the region between the two p+ regions on top and the n+ substrate beneath.

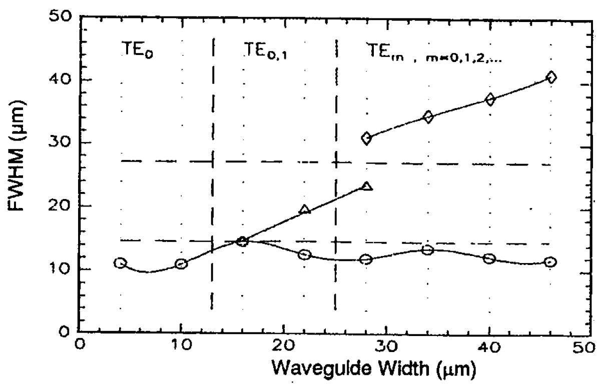

Figure 2. The measured spot size versus width of typical planar silicon optical waveguides made during the course of this work. Note that the first, second, and third order modes are observable in waveguides having widths around 28 μm.