Fabry–Perot Optical Intensity Modulator at 1.3 μm in Silicon

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***Abstract*—We report a new type of all silicon surface-normal optical intensity modulator at 1.3 μm, which can be easily butt-coupled with a cleaved single mode fiber. The device utilizes free carrier effects in silicon to achieve phase modulation, and a built-in Fabry–Perot cavity to convert the phase modulation into intensity modulation. We have demonstrated 10% modulation depth with driving current density as low as 6×10^3 A/cm^2, which is an order of magnitude smaller than the best result ever reported for silicon optical modulators. The measured 3 dB bandwidth is 40 MHz.**

INTRODUCTION

It is of great technological importance to be able to make active optoelectronic devices in silicon which can be used as interfaces between silicon electronic circuitry and fiber optics. For fiber-to-home and local area networks, robust and low cost components, which can be integrated with silicon electronic devices, are desirable at the user interface. A reflection type intensity modulator in silicon offers the possibility of such a realization. Because of its inversion symmetry, silicon does not have linear electrooptic effect, but free carriers can be used to modulate the index of refraction in silicon [1]. Hemenway *et al.* [2], [3] have demonstrated optical intensity modulation above 200 MHz with a silicon modulator. The current density needed in their device was above 5×10^4 A/cm^2 for 10% modulation. In this letter, we report a new all-silicon surface normal optical intensity modulator at 1.3 μm with an order of magnitude improvement in terms of driving current density.

A nonabsorption type optical intensity modulator usually consist of two functional components. One is an optical phase modulator, the other is a structure which provides a mechanism to convert phase modulation into intensity modulation. In an all silicon device, the free carriers injected in a p-i-n diode can be used to modulate the optical phase. The work then focuses on how to design a structure which can give higher intensity modulation for a given phase shift. The structure we used in this device is a Fabry–Perot (FP) cavity, which consists of two mirrors facing each other. Near resonance, reflection from the cavity is a very strong function of phase, allowing for high modulation depth with minimum phase change, therefore with a small current density.

DEVICE STRUCTURE AND FABRICATION

A schematic diagram of the device is shown in Fig. 1. The device consists essentially of a high-finesse Fabry–Perot resonant cavity formed by two silicon dioxide mirrors, and a p-i-n diode optical phase modulator placed inside the cavity. The 200 nm thick buried oxide, which has an reflectivity of 50% at 1.3 μm, functions as the bottom mirror, while the top mirror is formed by air–polysilicon–SiO$_2$–Si multilayer structure, which gives 82% reflection. The finesse of this Fabry–Perot cavity is about 7. The p-i-n diode makes up the free carrier optical phase modulator. Light incident on the Fabry–Perot cavity is partially reflected and partially transmitted. Forward biasing the p-i-n diode modulates the phase of the laser light inside the cavity and shifts the resonance of the FP cavity, converting the phase modulation to intensity modulation.

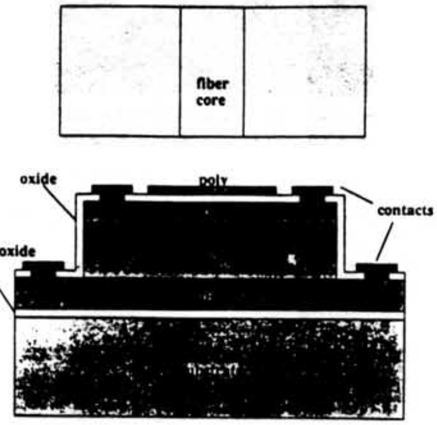

Fig. 1. Schematic diagram of the modulator diode. The optical fiber drawn at the top is for input and output coupling. Two silicon dioxide layers are about 0.2 μm thick and the top polysilicon layer 0.1 μm thick were chosen to maximize the cavity finesse.

The fabrication started with a silicon-on-insulator (SOI) wafer fabricated by the implantation of oxygen and annealing process (SIMOX). The oxygen dose was 1.0×10^{18}/cm^2, and after annealing the buried oxide layer was 0.2 μm thick. The oxide thickness was chosen to optimize the reflectance at 1.3 μm. On top of the SOI, a 2 μm heavily doped *n*-type epitaxial silicon layer was grown, followed by a 3.8 μm lightly doped n-type layer and a 0.9 μm heavily doped p-type layer. The doping levels of three layers were 1.1×10^{19}/cm^3, 1.0×10^{16}/cm^3, and 1.2×10^{20}/cm^3, respectively. The diode mesa was then defined using reactive ion etching. After growth of 0.22 μm thermal oxide, a 1000 Å thick silicon layer was evaporated and annealed to form a highly reflective surface for the high Q FP cavity. A second reactive ion etching step was used to define the polysilicon window. Finally, contact windows were opened, and aluminum metalization completed the process. Fig. 2 shows a top view of the fabricated device. Simulations show that this structure should produce a cavity with a free spectral range of 350 Å and passband of 50 Å (Fig. 3).

TEST RESULTS AND DISCUSSION

To test the device, a 1.3 μm diode laser was used as light source. A cleaved single-mode fiber pigtail was positioned directly above the device for both input and output coupling. The

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Fig. 2. Top view of the fabricated device. The inner most square is the polysilicon optical window, while the dark square indicates mesa edge.

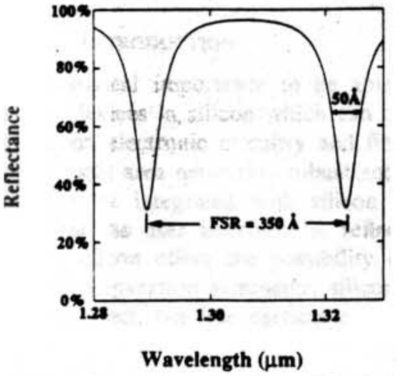

Fig. 3. Calculated wavelength response of the built-in Fabry-Perot cavity. Refractive index of silicon and silicon dioxide used in the calculation are 3.50 and 1.46, respectively.

reflected signal was separated from the incoming signal by a directional coupler, and fed into an optical receiver. An attenuator was placed between the laser diode and directional coupler to reduce feedback which might cause instability in the source laser. Both the driving signal for the silicon Fabry-Perot modulator and the output from the optical receiver were displayed on an oscilloscope. Fig. 4 shows the oscilloscope display for a testing frequency of 10 MHz. The measured modulation depth was 10%, and the peak current density was 6×10^3 A/cm^2.

For a maximum modulation depth, this device should be operated at a wavelength near the resonance of the FP cavity. Because of tuning limitation, the laser for testing in this experiment was not chosen at the optimum wavelength, nor was it a single wavelength laser. These two items have probably affected adversely the achievable modulation depth. Assuming an injected carrier density of $2 \times 10^{18}/\text{cm}^3$ (over a depth of 4 μm), and assuming a dependence of refractive index on carrier concentration of 1.5×10^{21} cm^3 [1], a modulation depth of 25% in our device should be possible. It should be noted, however, that the injected carrier density involves tradeoff between low power and high speed. (As lifetimes are reduced for high-speed operation, higher current levels are required to support the same injected carrier density.)

Since this is a nonabsorption modulator, this device can also be operated in transmission mode. The transmitted light intensity is simply the complement of reflected signal. To test the device, it is mounted on a glass slide, with a photodetector placed behind it. Modulation comparable to that of reflection mode is observed.

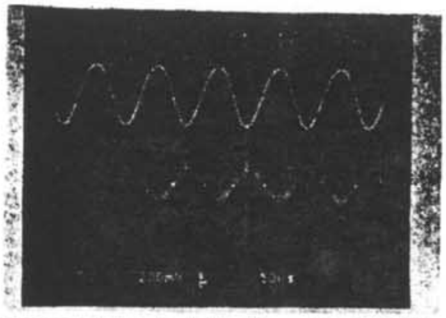

Fig. 4. Oscilloscope picture for testing frequency of 10 MHz. Upper trace is the driving signal, with a peak current density of 6×10^3 A/cm^2. Lower trace is the output from the optical receiver, with an modulation index of 10%.

High frequency measurements show that the device has a 3 dB cutoff frequency of 40 MHz. The device mesa size is 60 × 60 μm, and the peak driving current is about 200 mA. The core size of single mode fiber is only 8 μm in diameter, an optimum device requiring 3 mA of current can be designed by shrinking the area. The performance of this type of device can be further improved by using a Fabry-Perot cavity of higher finesse. The finesse of the FP cavity used in this device is about 7, and it is due to the low-reflectivity of the bottom mirror, which is formed by a single buried oxide layer. By employing a double buried oxide structure, finesse of 20 could be achieved, which means a factor of three reduction in current density, or increase in modulation index.

SUMMARY

We have fabricated a new type of optical intensity modulator at 1.3 μm with improved performance in silicon. Because it can be easily coupled with single-mode fiber, and at the same time it is compatible with silicon technology, this device can provide an interface between silicon electronic circuitry and fiber optics in applications such as the fiber-to-home return link where system cost is a deciding figure.

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