SPIE 5th Meeting on Optical Technology for Microwave Applications
Orlando, FL, April 3-5, 1991

Data transmission at 1.3μm using silicon spatial light modulator

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ABSTRACT

We demonstrate and characterize a silicon Fabry-Perot spatial light modulator in a fiber optic data transmission system at 1.3μm wavelength. 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. The measured insertion loss is 3.5 dB, the modulation depth is 10%, and the bandwidth is 40 MHz.

1. 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-the-home and local area networks, robust 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]. Active devices based on free carrier effects have been successfully demonstrated in silicon [2,3,4]. In an earlier paper we reported a new type of silicon optical intensity modulator [5]. Here we present data transmission results using such a device in an all fiber system.

2. DEVICE STRUCTURE AND FABRICATION

A schematic diagram of the device is shown in Figure 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 a reflectivity of 50% at 1.3μm, functions as the bottom mirror, while the top mirror is formed by air/polysilicon/SiO_2/Si multilayer structure, which gives 82% reflection (from calculation). The finesse of this Fabry-Perot (FP) cavity is 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.

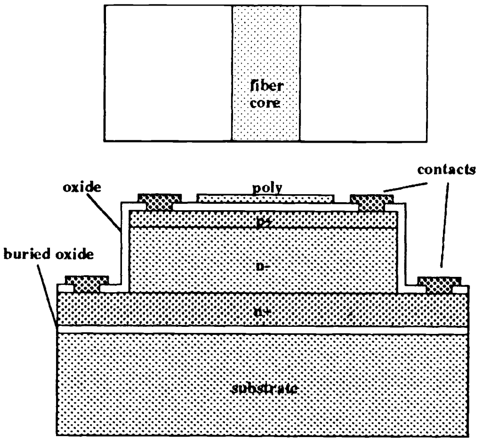

Fig. 1. Schematic diagram of the modulator diode. The optical fiber drawn at the top is for input and output coupling. Two silicon dioxide layers are about 0.2μm thick, and the top polysilicon layer 0.1μm thick were chosen to maximize the cavity finesse.

The fabrication started with a silicon-on-insulator (SOI) wafer fabricated by the implantation of oxygen and annealing process (SIMOX). The oxygen dose was $1.0\times10^{18}/cm^2$, and after annealing the buried oxide layer was 0.2μm thick. The oxide thickness was chosen to optimize the reflectance at 1.3μm. On top of the SOI, a 2μm heavily doped n-type epitaxial silicon layer was grown, followed by a 3.8μm lightly doped n-type layer and a 0.9μm heavily doped p-type layer. The doping levels of three layers were $1.1\times10^{19}/cm^3$, $1.0\times10^{16}/cm^3$, and $1.2\times10^{20}/cm^3$, respectively. The diode mesa was then defined using reactive ion etching. After growth of 0.22μm thermal

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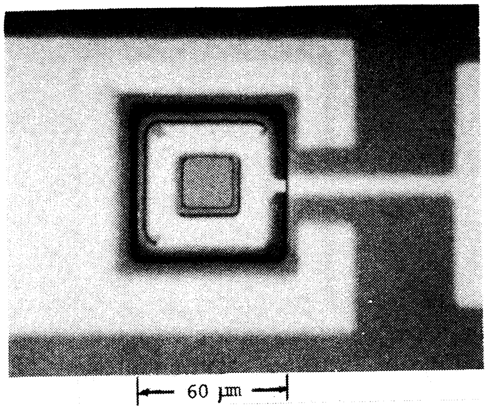


Fig. 2. Top view of the fabricated device. The inner most sqare is the polysilicon optical window, while the dark sqare indicates mesa edge.

oxide, a 1000Å 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. Figure 2 shows a top view of the fabricated device. Simulations show that this structure should produce a cavity with a free spectral range of 350Å and passband of 50Å .

3. TEST RESULTS AND DISCUSSION

For high frequency measurement, the fabricated device was wire bonded and mounted on a high speed header with a cleaved single-mode fiber pigtail positioned directly above the device for both input and output coupling. A 1.3μm semiconductor laser diode was used to provide a CW light source. A data signal from a word generator was amplified by a RF power amplifier, which drives the silicon spatial light modulator. CW light from the laser diode was partially reflected and partially transmitted by the device, with the intensities being modulated by the silicon device. The reflected signal was separated from the incoming signal by a directional coupler, and fed into an optical receiver where the data pattern was recovered. Both the data signal from the word generator and the output from the optical receiver were displayed on an oscilloscope. The fourth unused port of the directional coupler was properly terminated to eliminate reflection. A schematic diagram of the setup is shown in Figure 3.

In the data transmission experiment, a nonreturn-to-zero (NRZ) signal was used. For bit rate below 60 Mbit/s, a flat response was observed with a

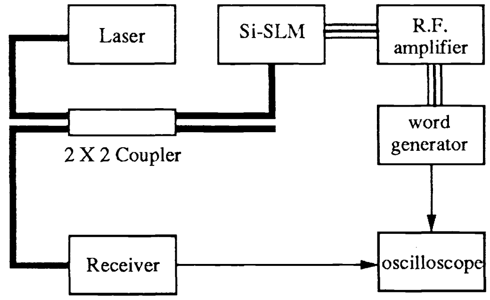
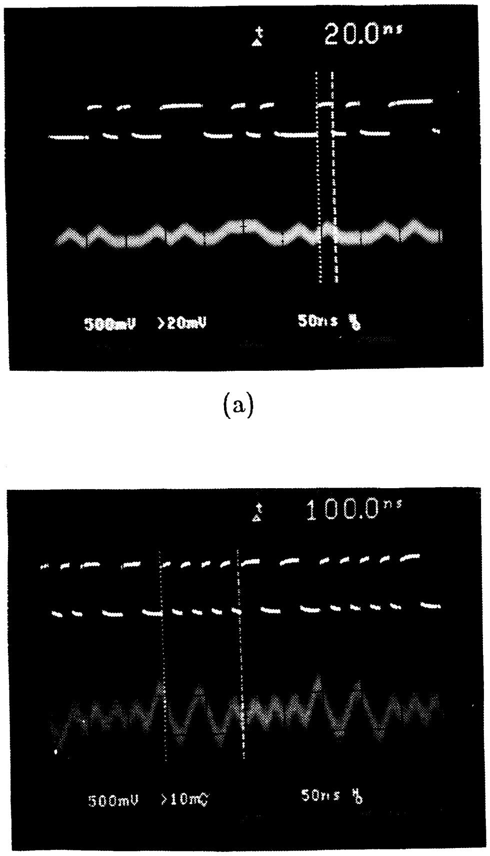


Fig. 3. Schematic diagram of the test setup.



(a)

(b)

Fig. 4. Oscilloscope picture for bit rate of (a) 50 Mbit/s, (b) 80 Mbit/s. Upper trace is the transmitted bit pattern. The lower trace is the output from the optical receiver.

modulation depth of 10%. Figure 4(a) shows an oscilloscope picture for a bit rate of 50 Mbit/s. The upper trace is the bit pattern being transmitted, and the lower one shows the output from the optical receiver. It is clear that the data is fully recovered. The ~70ns delay is due to RF amplifier which drives the modulator. As the bit rate approaches the bandwidth of the silicon modulator, the output from the optical receiver gradually degrades. Shown in Figure 4(b) is an oscilloscope picture for a bit rate of 80 Mbit/s. Even though the received high frequency signal has a reduced amplitude, the bit pattern can still be recognized. The 3 dB bandwidth of the device was found to be 40 MHz with a 50Ω source impedance. This speed is primarily determined by the carrier lifetime. Higher bandwidth could be achieved by reducing the carrier lifetime, but higher power would then be required.

Insertion loss is another important figure of merit for an optical modulator. Because it is a surface normal device in which input/output coupling fiber can be brought in contact with the top mirror of the FP cavity of the device, lower insertion loss is expected as compared to other type of devices in which light has to travel through a thick substrate. Another advantage of front surface coupling is simplified packaging process, which is very important in a production environment. The measured insertion loss of this device is 3.5 dB fiber-to-fiber, i.e. 44% of the light incident upon the device is reflected back into the coupling fiber. The insertion loss can be further reduced by using a FP cavity with higher finesse.

The measured modulation depth is 10% for a peak current of 200 mA, which corresponds to current density of 6×10^3A/cm^2. This is lower than the 24% reported for a non-Fabry-Perot silicon diode structure [4], but the peak current density in our experiments were 1/20 of those used in their experiments. Higher modulation depth could be achieved with an increased current density. Second, for a maximum modulation depth, this device should be operated at a wavelength near the resonance of the FP cavity. However, because of laser tuning limitations, the wavelength used was not optimized. Furthermore, the laser was not a single wavelength laser, but has three additional satellite modes with a mode spacing of 1 nm.

Scaling the device to smaller dimensions would improve the device performance. The core size of single mode fiber is 9μm in diameter, while the size of current device is $60\times60\mu$m. By shrinking the device to comparable size, reduced driving current for same modulation depth or higher modulation depth for same current can be achieved. Higher modulation bandwidth would also be expected due to increased device input impedance. The performance of this type of device could also be further improved by using a Fabry-Perot cavity of higher finesse. The finesse of the FP cavity used in this device was 7, and was limited by the low reflectivity of the bottom mirror (50%), which was formed by a single buried oxide layer. By employing a double buried oxide structure, a finesse of 20 could be achieved which would yield a factor of three reduction in current density, or increase in modulation index, along with lower insertion loss.

4. SUMMARY

We have fabricated a new type of silicon spatial light modulator and characterized it in a fiber optical transmission system at 1.3μm. The measured bandwidth is 40 MHz with insertion loss of 3.5 dB and modulation depth of 10% at a driving current density of 6×10^3A/cm^2. Because it can be easily coupled with single-mode fiber and 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-the-home return link.

5. ACKNOWLEDGEMENTS

The authors would like to thank National Science Foundation and the Princeton Opto-Electronic Materials Center (POEM) for supporting this project, and R. Sundaresan of Texas Instruments, Inc. for supplying the SIMOX wafer used in this study.

6. REFERENCES

[1] R. A. Soref and B. R. Bennet, "Electrooptical effects in silicon," IEEE J. Quantum Electro., vol. QE-23, p. 123, Jan. 1987.

[2] B. R. Hemenway, O. Solgaard, D. M. Bloom, "All-Silicon integrated optical modulator for 1.3μm fiber-optic interconnects", Appl. Phys. Lett., vol. 55, no. 4, July 24, 1989.

[3] B. R. Hemenway, O. Solgaard, A. A. Godil, and D. M. Bloom, "A polarization-independent silicon light intensity modulator for 1.3μm fiber optics," IEEE Photon. Tech. Lett., vol. 2, p. 262, Apr. 1990.
[4] O. Solgaard, A. A. Godil, B. R. Hemenway, D. M. Bloom, "Pigtailed Single-Mode Fiber Optic Light Modulator in Silicon," IEEE Photon. Tech. Lett. vol. 2, no. 9, p. 640, Sept. 1990.
[5] X. Xiao, J. C. Sturm, K. K. Goel and P. V. Schwartz, "Fabry-Perot optical intensity modulator at 1.3μm in silicon," IEEE Photon. Tech. Lett., March 1991(to be published).