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Silicon Optical Modulator Based on Accumulation-Carrier Absorption of Metal-Oxide-Semiconductor Capacitor Waveguide

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1. Introduction

To overcome increased propagation delay of metal wiring in advanced submicron LSI's, on-chip optical interconnect has long been proposed. To meet the requirement, optical mudulators have to be integrated on a silicon chip. Some candidate of Mach-Zehnder-type MOS capacitor optical switch based on refractive index variation was proposed [1].

Prior to that work, authors had proposed a silicon optical switch [2] based on free-carrier absorption. First successful operation was reported [3] with inversion-carrier absorption resulting in an optical response of 0.23 %. Even though it is very small, it is validly analysed with a simple theory [4].

This report will describe much more improved optical response of greater than 13 % with metal-oxide-semiconductor (MOS) type waveguide, as shown in Fig. 1, based on accumulation-carrier absorption.

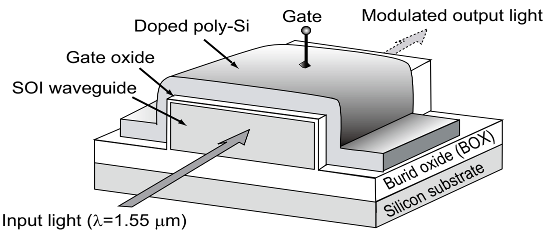

Fig. 1 Proposed optical silicon modulator of metal-oxide-semiconductor (MOS) capacitor waveguide.

2. Sample Preparation

A plan view of fabricated modulator structure is shown in Fig. 2. Waveguide core which measures 10-50 μm in width and 1.5 μm in thickness is made of (110), 10 Ω-cm, silicon-on-insulator (SOI) substrate. The core is delineated with tetra-methyl-ammonium-hydroxide, TMAH. Polysilicon gate doped with phosphorus at $1x10^{17}cm^{-3}$ is 150-nm thick.Gate oxide thickness is 39 nm and buried-oxide (BOX) thickness is 1.5 μm. An SEM cross-section of the modulator is shown in Fig. 3.

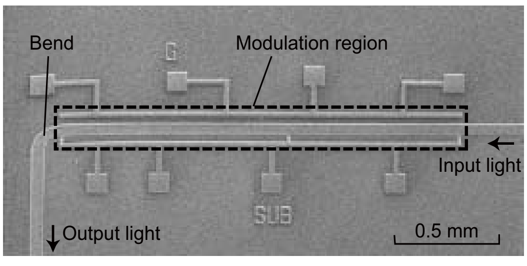

Fig. 2 A plan view of a fabricated MOS capacitor optical modulator.

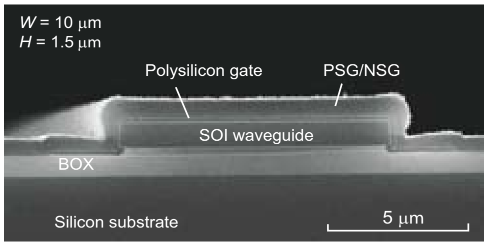

Fig. 3 SEM cross-section of the modulator.

The waveguide has a 90-degree bend, as shown in Fig. 4, in order to eliminate undersirable direct light noise. The popagation loss is about 80 % at the bend [5].

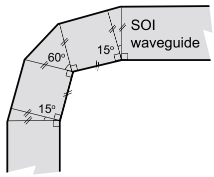

Fig. 4 Optical bend structure. Light propagation loss caused by the bend is about 80%.

3. Experimental Results

Even though, most of input light is absorbed inside the waveguide, as shown in Fig. 5, sufficiently detectable light comes out from the output end of the waveguide, as shown in Fig. 6. A capacitance-voltage (C-V) curve is measured, as shown in Fig. 7, to set applied voltage value. An obtained flat-band voltage (V_{FB}) is around - 5 V.

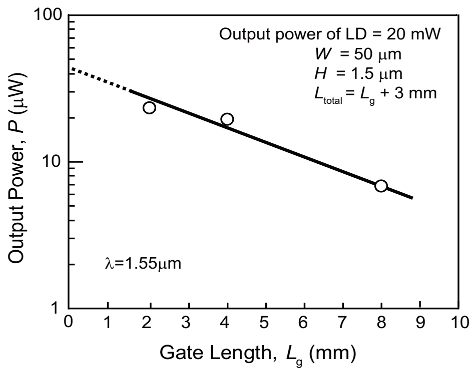

Fig. 5 Output light power dependence on the modulator length ranging from 2 to 8 mm. Total length of the device is the modulator length plus 3 mm. A power ratio of output light power to laser diode (LD) output power is less than 1 %.

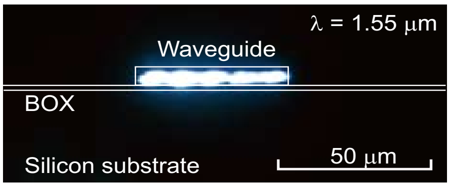

Fig. 6 Output light pattern in a case of 50-μm-wide wave guide. Multi-mode propargation is clearly observed.

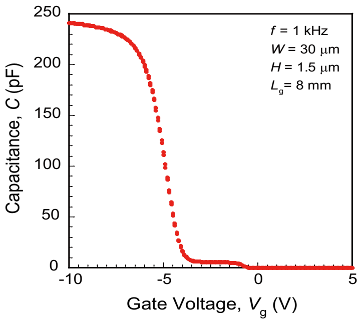

Fig. 7 Capacitance-voltage (C-V)curve obtained for 8-mm long, 30-μm-wide modulator.

Figure 8 shows modulated optical output pattern for 8-mm long, 30-μm-wide modulator. Optical response is defined as,

$$\text{Optical response} = (P_{max} - P_{min})/P_{max}, \qquad (1)$$

where P_{max} and P_{min} are optical output power at applied voltages of 0 V and -30V, respectively. Optical response of 100% means P_{min} of 0.

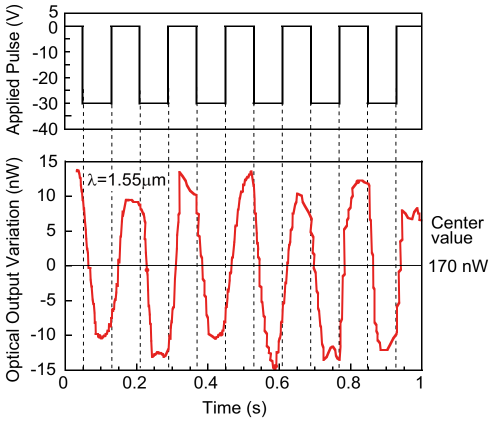

Fig. 8 Obtained optical output modulation for a device of 30 μm in width and 8 mm in length.

Summarized optical response and extinction ratio are shown in Fig. 9. Optical response of greater than 13% at V_g of -30 V is realized. As compared to the previous result [3], more than 50-times increase in optical response is obtained.

4. Discussion

To analyze the modulation behavior, a simple multi-reflection approximation method [4] is applied taking into consideration of light hole and neglecting accumulated majority carriers inside polysilicon gate. Results are shown in Fig. 10. Even if the concidence looks good, much more precise investigation is needed for quantitative analysis.

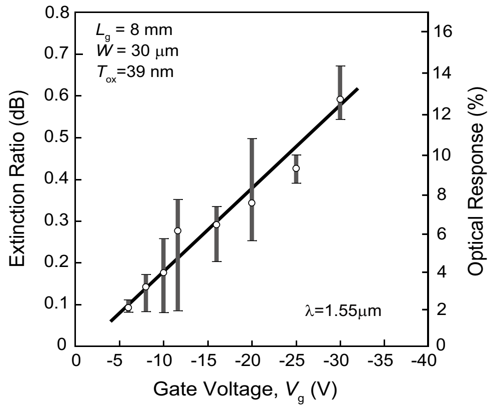

Fig. 9 Dependences of extinction ratio and optical response on applied gate voltage. Optical response of greater than 13% is realized at gate voltage of -30 V.

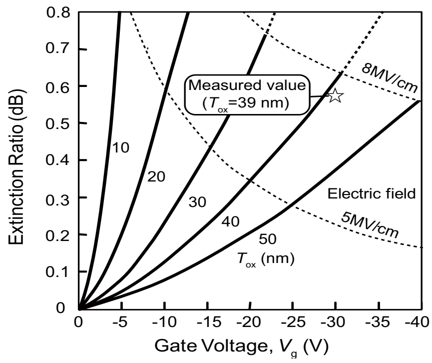

Fig. 10 Calculated extinction ratios assuming refractive indices of 3.29+0.000571i and 3.46 for phosphorus-doped polysilicon gate clad and 10 Ω-cm single-silicon core, respectively. Effective mass of hole is defined as $0.16m_0$.

5. Conclusion

A novel metal-oxide-semiconductor (MOS)-type silicon optical modulator based on accumulation carrier absorption is proposed and successfully realized at 1.55-μm wavelength regime. With a 8-mm-long modulator, optical response of greater than 13% is realized at gate voltage of -30 V.

As compared to previous Mach-Zehnder-type MOS capacitor optical switch, the proposed modulator has potential advantages superior to Mach-Zehnder type modulator such as modulator-length insensitivity, ability of simultaneous multi-wavelength modulation, and accelerated modulation performance in deeper infrared wavelength regime .

References

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