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# Proposal of a Silicon Optical Modulator Based on Inversion-Carrier Absorption

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## 1. Introduction

To overcome increased propagation delay of metal wiring in advanced sub-micron LSI's, on-chip optical interconnect has long been proposed these more than ten years. To meet the requirement, optical switches have to be integrated on silicon chip. Some candidate of Mach-Zehnder-type MOS transistor optical switch based on refractive index variation was proposed [1].

Prior to that work, the authors had proposed a silicon optical switch [2] based on free-carrier absorption. This report will describe successful results for the proposed device of which fundamental structure is shown in Fig. 1. Obtained performance of optical response of less than 1 % at this moment may not be large enough for practical use, free-carrier absorption mechanism should be made good use of.

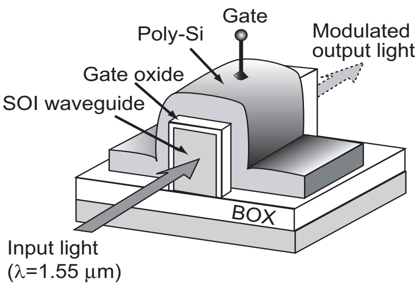


Fig. 1 A bird's eye view of the proposed silicon optical mudulator based on free-carrier absorption.

## 2. Experimental

A plan view of the proposed MOS capacitor structure is shown in Fig. 2. Wave-guide core which measures 50 μm in width and 1.5 μm in thickness is made of (110), 10 Ω-cm single-crystal silicon. The core is delineated with tetra-methyl-ammonium-hydroxide, TMAH. Polysilicon gate doped at $1x10^{17}cm^{-3}$ is 650-nm thick. Gate oxide thickness is 32 nm. The waveguide has a 90-degree bend [3], as shown in Fig. 3, in order to eliminate undersirable direct light noise. The popagation loss is 80 % at the bend.

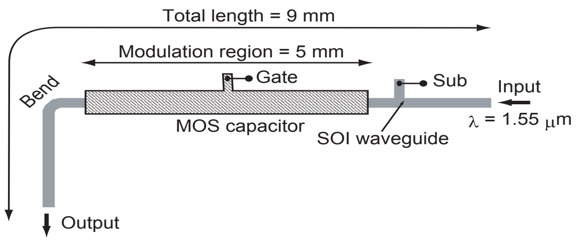


Fig. 2 A plan view of MOS-capacitor optical mudulator under test.

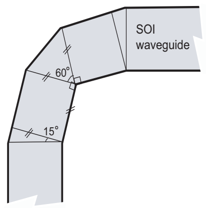


Fig. 3 Optical bend structure. Light propagation loss due to the bend is about 80%.

## 3. Results

### 1) *MOS capacitor characteristics*

Since channel implantation to control flat-band voltage, $V_{FB}$ is not carried out, thus the $V_{FB}$ is negative as shown in Fig. 4.

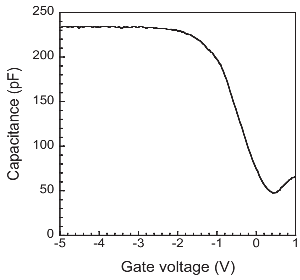


Fig. 4 C-V curve of the device under test Negative $V_{FB}$ is caused by no channel implantation to control the $V_{FB}$.

### 2) *Optical output*

Typical output light pattern taken by infrared microscope and video sytem is shown in Fig. 5. Since the silicon core of 31 μm in width in this device is very large in comparison with wavelength in silicon (approx. 0.44 μm), multi-mode propagation occurs resulting in multi-spots shown in the figure.

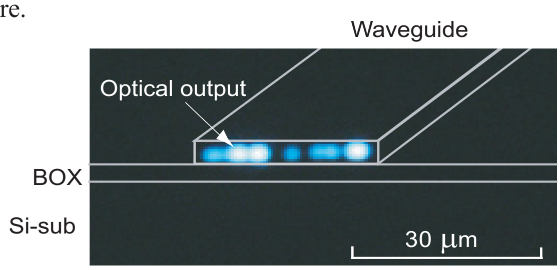


Fig. 5 Typical output light pattern for silicon core surrounded by doped polysilicon and buried-oxide (BOX).

### 3) *Modulation performance*

Typical optical response is shown in Fig. 6. As center value of this result is 2.5 μW, obtained optical response is ranging from 0.24 % at gate voltage of 11.5 V. Summary of the experimetally obtained optical responses are described in Fig. 7. Even if measured data show considerable scattering, there surely exist applied gate voltage dependence.

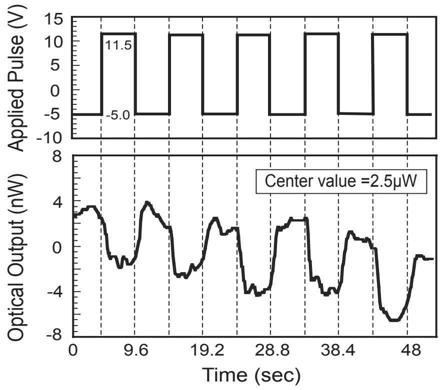

Fig. 6 Optical response of the device at λ=1.55 μm. Applied gate voltage is -5 V and 11.5 V in this case.

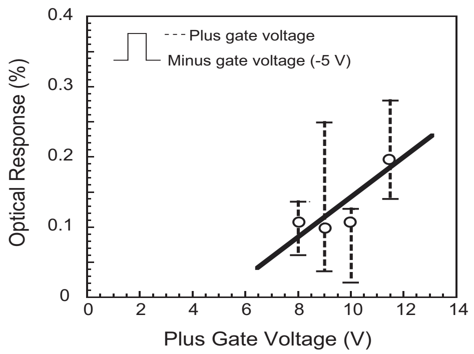

Fig. 7 Summary of optical responses of the device at λ=1.55 μm.

## 4. Discussion

Fundamental propagation characteristics are simulated in this optical waveguide system based on conventional propagation mechanism with Marcatili approximation. As shown in Fig. 8, it is simulated that light propagation meanders only inside SOI. Reflection at the SOI-polysilicon interface occurs for 187 times for 5-mm long waveguide.

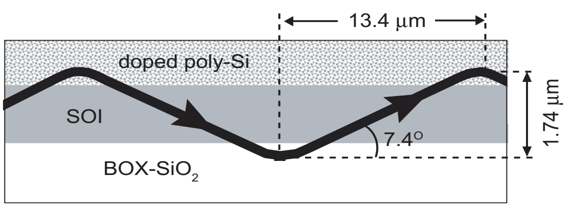

Fig. 8 Simulated light propagation inside the SOI core.

As is obtained in Fig. 9, doped polysilicon clad absorbs all light propagated inside the polysilicon, it is validly assumed that the light only propagates inside the SOI core.

In addition to the simulated structure cited above, interaction between inversion layer and light is simulated provided that the simplified structure shown in Fig. 10. Refractive indices of SOI ($N_A$=1x10$^{15}$cm$^{-3}$) and doped polysilicon ($N_A$=1x0$^{17}$cm$^{-3}$) are evaluated to be 3.46 and 3.09+0.00301i, respectively. And the inversion layer is evaluated to be 3.24+0.00416i based on Drude's theory. Reflectivity with and without inversion layer is evaluated to

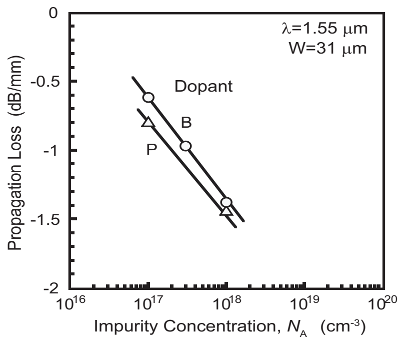

Fig. 9 Propagation loss of doped polysilicon at λ=1.55 μm.

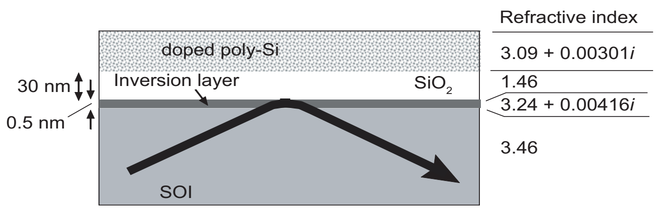

Fig. 10 Simulated MOS capacitor structure associated with the one described in Fig. 8.

be 0.998597 and 0.998581, respectively, based on the Drude's theory.

Thus, the simulated result show that optical response is 0.23% at gate voltage of 11.5 V. While the experimental valuse is around 0.2 % as shown in Fig. 7. The coincidence between the experimental and the simulated is excellent even if simplified propagation simulation is carried out.

## 4. Conclusion

A novel silicon optical modulator based on inversion carrier absorption is proposed and successfully realized at 1.55-μm wavelength regime. With a 5-mm long modulator, optical response is 0.15-0.3 % at gate voltage of 8 V to 11.5 V. While, the simulated response is estimated to be 0.23 %.

Even though the response is very small, the coincidence between the experimental and the simulated results is excellent leading to confirmation of free-carrier absorption mechanism in this device.

Since doped polysilicon clad absorbs light propagating inside the polysilicon, improved device structures without the doped polysilicon issue should be provided in future.


**Achnowledgement**

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**References**


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