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Proposal of Ge/Si hybrid MOS optical modulator operating at mid-infrared wavelengths

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Abstract

We present Ge/Si hybrid MOS optical modulator for mid-infrared photonics. We numerically analyze the accumulation in Ge/Si MOS capacitor formed on Si waveguide and its optical modulation efficiency which relies on the hole-induced absorption in Ge. The modulation efficiency is predicted to be 15 dB/mm with 2 V bias, showing the feasibility of the intensity optical modulation based on the free-carrier absorption.

1. Introduction

Optical fiber communication has developed at the near-infrared (NIR) wavelength ranges from 1.3 μm to 1.6 μm. However, the strong demand for communication capacity requires further extension of available wavelengths toward the mid-infrared (MIR) spectrum. In particular, the 2-μm wavelength band is emerging for optical fiber communication because of the developments in photonic crystal fibers and Tm-doped fiber amplifiers. In addition, the MIR wavelengths are expected to be useful for sensing gases and biological molecules [1]. For the EO conversion in communication and the lock-in detection in sensing, an optical modulator operating at MIR wavelengths is indispensable. However, a MIR optical modulator has not been intensively explored yet.

In this paper, we propose an optical modulator for MIR wavelengths based on a Si hybrid metal-oxide-semiconductor (MOS) capacitor which has been originally demonstrated in III-V/Si hybrid MOS optical modulator for NIR wavelength, where a III-V compound semiconductor layer is bonded upon Si waveguide with a gate dielectric [2]. Instead of a III-V layer, we propose to bond a Ge layer on a Si waveguide to form a Ge/Si hybrid MOS capacitor.

Since the hole-induced absorption in Ge is predicted to be 10 times greater that in Si [4], the free carrier absorption in Ge with hybrid MOS structure enables optical intensity modulation over a wide MIR spectrum. We report numerical analysis of the characteristics of the Ge/Si hybrid MOS optical modulator.

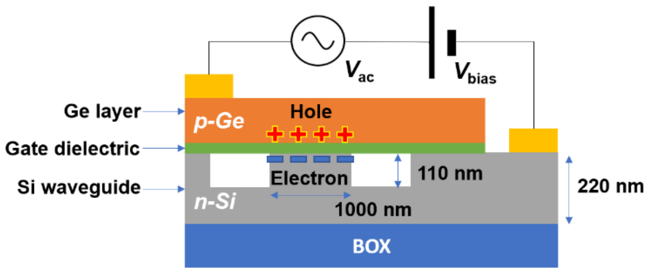

Fig. 1 Schematic of Ge/Si hybrid MOS optical modulator.

2. Device structure and analysis method

The device structure of the Ge/Si hybrid optical modulator is shown in Fig. 1. A p-type Ge thin layer is bonded on a n-type Si rib waveguide with a gate dielectric. For a 2 μm wavelength, the total thickness of the Si layer is designed to be 220 nm. The height and width of the Si rib waveguide are also 110 nm and 1000 nm, respectively. Applying a gate voltage between the Ge layer and Si layer induces hole accumulation at the Ge MOS interface, which yields optical intensity modulation based on the carrier absorption.

To maximize the modulation efficiency, accumulated holes must interact with a waveguide mode as much as possible. Fig. 2 shows the relative intensity of the fundamental transverse electric (TE) mode at the MOS interface as a function of the Ge thickness at a 2μm wavelength. When the Ge thickness is 100 nm, we can achieve the maximum modulation efficiency at a 2 μm wavelength. In the following discussion, we assume a 100-nm-thick Ge layer for a 2 μm wavelength.

For numerical analysis, we use commercially available TCAD (Sentaurus) to calculate the distributions of electron and hole in the MOS structure with varied voltages. The calculated distributions of holes and electrons are shown in Fig. 3. When a gate voltage (V_g) of 2 V is applied from the flat-band voltage (V_{fb}), holes and electrons accumulate at the Ge and Si interface, respectively. Note that the surface quantization of the MOS interfaces is considered in the simulation. Then, the changes in refractive index and absorption associated with the free-carrier effects in Ge and Si [3][4], we calculate the effective refractive index and absorption coefficient of the fundamental TE mode of the Ge/Si hybrid waveguide. The effective oxide thickness (EOT) is assumed to be 3 nm.

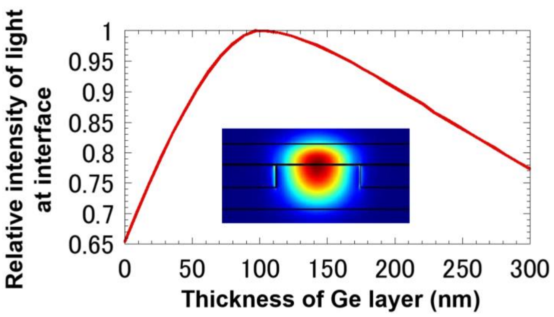

Fig. 2 Relative optical intensity at the MOS interface as a function of Ge thickness at a 2 μm wavelength.

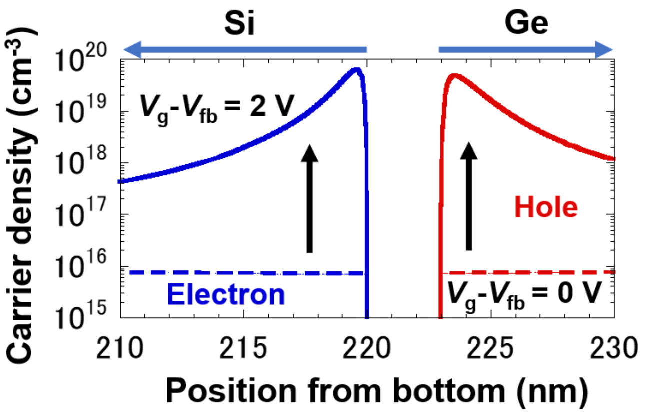

Fig. 3 Distributions of hole and electron near MOS interface.

3. Results and Discussion

The relationship between the absorption modulation efficiency at a 2 μm wavelength and V_g is shown in Fig. 4. To eliminate the effect of a threshold voltage, we plot the result with respect to a gate overdrive, $V_g - V_{fb}$. It is shown that the absorption increases almost linearly to the gate voltage because of carrier accumulation at the MOS interface. The absorption modulation efficiency is found to be 13.5 dB/mm when Vg is modulated with an amplitude of 2 V at a bias voltage of 1.5 V. The device length required for 3-dB extinction ratio (ER) is approximately 210 μm. Thus, thanks to the large free-carrier absorption in Ge, the Ge/Si hybrid MOS capacitor is promising for intensity modulation.

In contrast to the electroabsorption modulation such as Franz-Keldysh effect, the free-carrier absorption is effective for a wide range spectrum, which makes the proposed Ge/Si hybrid MOS modulator more attractive. The wavelength dependence of the absorption modulation efficiency is shown in Fig. 5. Since the intervalence-band absorption decreases at a wavelength greater than 3 μm, the absorption modulation efficiency decreases up to 5 μm. However, as an operating wavelength increases from 5 μm, the absorption modulation efficiency starts to increase because of the intra-band free-carrier absorption. Although the efficiency is not constant, the proposed modulator can be used over the wide range of the MIR wavelengths.

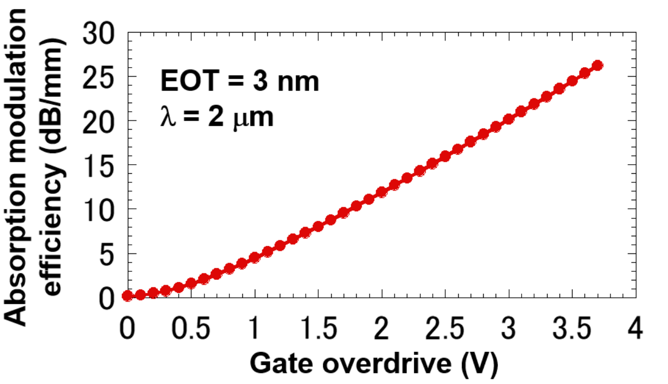

Fig. 4 Absorption modulation efficiency at a 2 μm wavelength as a function of gate overdrive.

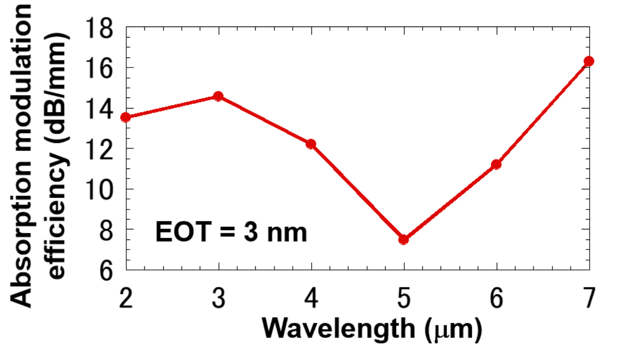

Fig. 5 Wavelength dependence of absorption modulation efficiency.

The required length of device for a given gate voltage amplitude is shown in Fig. 6, comparing between proposed Ge/Si hybrid MOS absorption modulator and a MZI modulator with a Si/Si MOS optical phase shifter. We design the Ge/Si MOS modulator and MZI modulator to have same optical modulation amplitude (OMA) with 3-dB ER. The device length of the proposed device is comparable to the MZI modulator for achieving same performance, while the proposed device has a simpler device structure.

Thus, the Ge/Si hybrid MOS optical absorption modulator using free carrier effect is attractive for mid-infrared photonics applications.

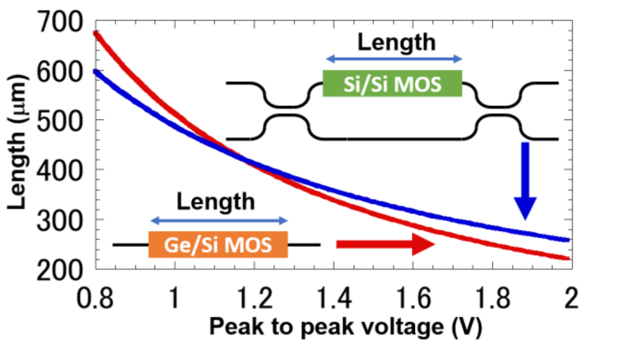

Fig. 6 Benchmark between Ge/Si hybrid MOS absorption modulator and MZI modulator with Si/Si MOS optical phase shifter.

4. Conclusions

We have numerically analyzed the modulation characteristics of the Ge/Si hybrid MOS optical modulator. The large hole-induced absorption in Ge makes an optical absorption modulator feasible over the wide range of mid-infrared wavelengths for optical communication and sensing.

Acknowledgements

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