Extended Abstracts of the 2017 International Conference on Solid State Devices and Materials, Sendai, 2017, pp855-856

PS-7-03

Low-optical-loss graphene-based phase modulator operating at mid-infrared wavelength

Yuki Yamaguchi, Shinichi Takagi, and Mitsuru Takenaka

Department of Electrical Engineering and Information Systems,
The University of Tokyo
7-3-1 Hongo, Boukyo-ku, Tokyo 113-8656, Japan
E-mail: yamaguchi@mosfet.t.u-tokyo.ac.jp

Abstract

We numerically analyzed a graphene optical modulator operating at mid-infrared wavelength. We found that the change in an operating wavelength from 1550 nm to 3000 nm enables a phase modulation with a significantly low optical loss by a realistic bias voltage.

1. Introduction

After the first success of exfoliation of single-layer graphene, its exceptional material properties such as zero-bandgap structure with Dirac cones enables various optoelectronic devices. Particularly, a graphene-based optical modulator has gained considerable attention for optical interconnections. Since the first demonstration of a graphene optical modulator on Si photonics platform [1], there has been many reports of graphene optical modulators relying on the change in its absorption coefficient through its chemical potential modulation by a gate voltage. On the other hand, a graphene-based optical phase modulator operating at the telecommunication wavelength has not been experimentally demonstrated yet because the phase shift accompanies a large optical loss within the realistic range of a gate voltage. A large gate voltage may reduce an optical loss, while, in practice, a breakdown in a gate dielectric makes it difficult to apply a large gate voltage [2]. In this work, we have proposed graphene-based optical phase modulators operating at a 3000 nm wavelength. Since the modulation of chemical potential required for π phase shift can be reduced by changing an wavelength from near-infrared (NIR) to mid-infrared (MIR) wavelength, the optical phase modulation with low optical loss is expected to be achieved within the realistic range of gate voltage.

2. Device structure

A cross-sectional schematic of a graphene optical modulator discussed in this paper is shown in Fig. 1. For a comparison, we analyzed the modulation characteristics operating at 1550 nm and 3000 nm wavelengths. For a single-mode operation at 1550 and 3000 nm, the thicknesses of the Si layer were designed to be 220 and 470 nm, respectively. The widths of the Si waveguides were 440 and 870 nm, respectively. A 7-nm-thick gate dielectric (Al_2O_3) was deposited on Si waveguide and inserted between both graphene layers. The distance between Au electrode and waveguide was assumed not to have no effect on the guided mode. We considered the fundamental TM mode as shown in Fig. 2. When a gate voltage V_g is applied between both graphene, the chemical potential of graphene is modulated, which leads changes in refractive index and absorption.

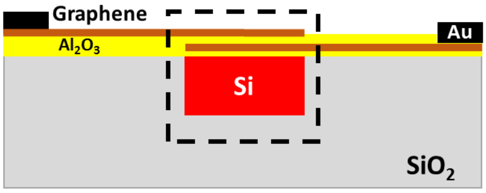

Fig.1 Schematic of graphene optical modulator.

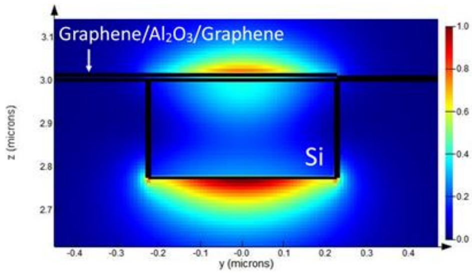

Fig. 2 Electrical field distribution of fundamental TM mode at 1550 nm (broken line in Fig. 1).

3. Result and discussion

In this study, we extracted effective refractive index and absorption of the TM mode by the finite-different eigenmode (FDE) solver in Lumerical software. An atomically thin graphene was modeled as a surface conductivity material model. We assumed the relationship between chemical potential (μ_c) and a gate voltage expressed by

$$\mu_c = \hbar v_F \sqrt{\eta\pi|V_g + V_0|}\ , \qquad (1)$$

where $\hbar$ is the reduced Plank constant, v_F is the Fermi velocity, V_0 is the voltage offset caused by natural doping (in this simulation we assumed there was no doping on graphene and $V_0 = 0$), and $\eta = 9\times10^{16}\ m^{-2}V^{-1}$, which was estimated using a parallel-plate capacitor model [1]. Figure 3 shows the phase shift and absorption of the TM mode at 1550 nm and 3000 nm as a function of a gate voltage. At both wavelengths, the chemical potential reaches 0.5 eV from the Dirac point when a gate voltage is 2.5 V, resulting in the surface carrier density of 2×10^{13} cm^{-2} in graphene [3]. It seems very difficult to accumulate more carriers in a metal-oxide-semiconductor structure because of the gate dielectric breakdown [2]. This means that the chemical potential of graphene must be less than 0.5 eV. Thus, the maximum applicable gate voltage was assumed to 2.5 V in this study.

There are two types of carrier transition in graphene, the in

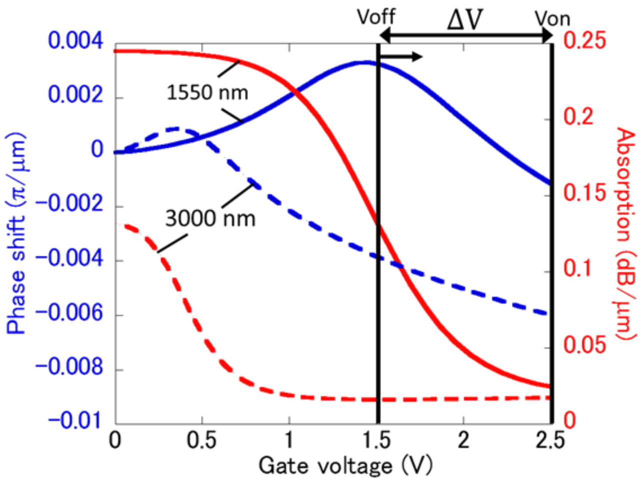

Fig. 3 Phase shift and absorption of the TM mode at wavelength of 1550 and 3000 nm as a function of a gate voltage. We fixed V_{on} at 2.5 V for 1550 nm and 2.0 V for 3000 nm, respectively, and V_{off} is changed to examine the modulation characteristics.

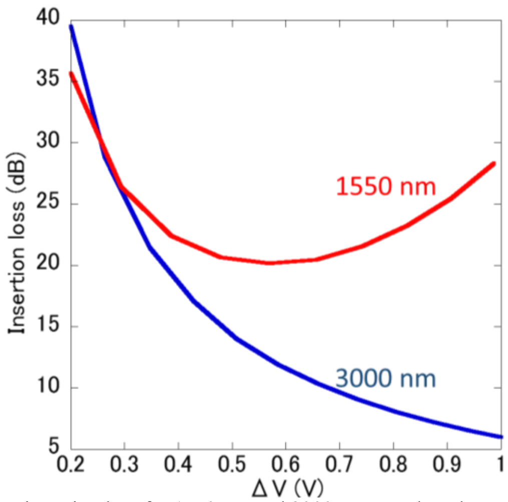

Fig. 4 An insertion loss for 1550 nm and 3000 nm wavelength as a function of ΔV.

traband transition and the interband transition. Both mechanisms depend on chemical potential of graphene [4]. When a wavelength was 1550 nm, the absorption caused by the interband transition remains even with a gate voltage of 2.5 V, meaning that a large optical loss is unavoidable for phase modulation. In contrast, at 3000 nm, the absorption caused by the interband transition can be suppressed at a gate voltage of 1.5 V, then the absorption increases gradually because of the intraband transtion. Therefore, the phase shift with a low optical loss is achievable with a voltage range from 1.5 V to 2.5 V.

At a 1550 nm wavelength, we assumed that an on voltage (V_{on}) was fixed to be 2.5 V to maximize the phase shift. We calculated the modulation characteristics by changing an off voltage (V_{off}) from 1.5 V to 2.5 V. At a 3000 nm, V_{on} was fixed to be 2.0 V, and V_{off} was swept from 1.0 V to 2.0 V. In this range, the phase shift is larger than one in the range of 1.5 V to 2.5 V with almost unchanged absorption. For each voltage swing (ΔV) defined by $V_{on} - V_{off}$, we calculated a phase shifter length for π phase shift, then calculated an insertion loss as

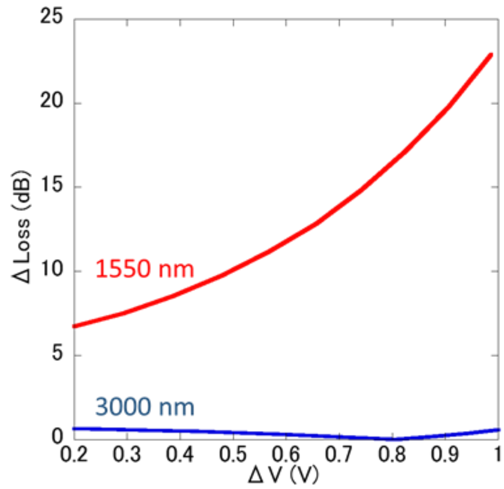

Fig. 5 Change in optical loss for p phase shift at 1550 nm and 3000 nm wavelengths as function of ΔV.

shown in Fig. 4. In the case of 1550 nm, the insertion is greater than 20 dB, making a realistic phase modulator difficult. On the other hand, in the case of 3000 nm, the insertion loss decreases as ΔV gets increased. When ΔV is 1 V, the insertion loss is approximately 5 dB, which is more realistic loss as compared with that at 1550 nm. We also calculate a change in optical loss when a phase is modulated from 0 to π (ΔLoss), which affects an extinction ratio for modulation. Figure 5 shows ΔLoss as a function of ΔV. As compared with 1550 nm, we can achieve quite small ΔLoss at 3000 nm. Thus, graphene is more suitable for optical phase modulation at a MIR wavelength.

4. Conclusion

We have numerically analyzed graphene optical modulators operating at wavelengths of 1550 and 3000 nm. At 1550 nm, an insertion loss and attenuation change for π shift are too large for realistic phase modulation. In contrast, we have revealed that a graphene phase modulator gives much less insertion loss and attenuation change at the wavelength of 3000 nm. Thus, we have shown the feasibility of optical phase modulation based on graphene operating at MIR wavelength.

Acknowledgements

This work partly supported by NEDO Integrated Photonics-Electronics Convergence System Technology (PECST) project and a Grant-in-Aid for Scientific Research (S) from MEXT.

References

[1] Ming Liu *et al*., "A graphene-based broadband optical modulator", *Nature*, **474**, 64-67(2011).

[2] T. Kayoda, J. Han, M. Takenaka and S. Takagi, "Evaluation of Chemical potential for graphene optical modulators based on the semiconductor-metal transition," *International Conference on Group IV Photonics*, ThD5 (2013).

[3] G. W. Hanson, "Dyadic Green's functions and guided surface waves for a surface conductivity model of graphene" *Journal of Appl. Phys.*, 103, no. 6, 064302 (2008).

[4] S. A. Mikhailov and K. Ziegler, "New Electromagnetic Mode in Graphene", *Phys. Rev. Lett*., **99**, 016803 (2007).