E-9-01 (Invited) Extended Abstracts of the 2020 International Conference on Solid State Devices and Materials, VIRTUAL conference, 2020, pp329-330

High-Speed Ge/Si Electro-Absorption Optical Modulator with C-band Wavelengths Operation at high Temperature up to 85℃

Junichi Fujikata[1], Masataka Noguchi[1], Kazuki Kawashita[3], Riku Katamawari[3], Hideki Ono[1,2], Daisuke Shimura[1,2], Yosuke Onawa[1,2], Hiroyuki Takahashi[1,2], Hiroki Yaegashi[1,2], Yasuhiko Ishikawa[3], and Takahiro Nakamura[1]
[1] Photonics Electronics Technology Research Association (PETRA), Tsukuba, Ibaraki 305-8569, Japan
[2] Oki Electric Industry Co., Ltd., 1-16-8, Chuo, Warabi, Saitama 335-8510, Japan
[3] Toyohashi University of Technology, Toyohashi, Aichi 441-8580, Japan
Phone: +81-29-868-6520 E-mail: j-fujikata@petra-jp.org

Abstract

We studied a high-speed Ge/Si electro-absorption optical modulator (EAM) evanescently coupled with a Si waveguide of a pn junction for high-bandwidth optical interconnect for a wide range of temperature from 25℃ to 85℃. We demonstrated C-band wavelength operation and 56 Gbps high-speed operation at high-temperature up to 85℃. From photoluminescence spectra, we confirmed bandgap energy dependence on temperature is relatively small, which is consistent with that of operation wavelengths with increasing temperature for a Ge/Si EAM.

1. Introduction

Silicon photonics has recently attracted much attention because it offers low cost, low power consumption, and high bandwidth for optoelectronic solutions for applications ranging from telecommunications to chip-to-chip interconnects [1]. To realize an effective photonics-electronics convergence system, it is very important to achieve a high-speed optical modulator to be integrated with a Si based optical circuit at a wide range of temperature.

In order to achieve a low power and high-density interconnect system, a very small capacitance of an optical modulator is required. A GeSi EAM is promising, because its electrical capacitance is about ten fF and device length is about dozens of micrometers [2-4]. It has been reported that a Ge layer on a Si substrate has a tensile strain as large as 0.2%, which reduces the direct band-gap energy to 0.77 eV, while the unstrained Ge layer has a 0.80 eV bandgap energy [5]. Therefore, it has been reported that it is necessary to apply the optimized composition of a GeSi layer to GeSi EAM to operate in the C band wavelength [1]. In addition, operation wavelengths of a Ge/Si EAM have been reported to shift to longer wavelengths at high temperature because direct bandgap energy decreases with temperature [3].

In this paper, we study a high-speed Ge/Si EAM evanescently coupled with a Si waveguide of a pn junction for high-bandwidth optical interconnect for a wide range of temperature from 25℃ to 85℃. We demonstrated C-band wavelength operation and 56 Gbps high-speed operation at high-temperature up to 85℃.

2. Experiment and Results

Figure 1 shows (a) schematic cross-section of a Ge/Si EAM on a Si rib waveguide with lateral pn junction and (b) a cross-sectional TEM (transmission electron microscope)

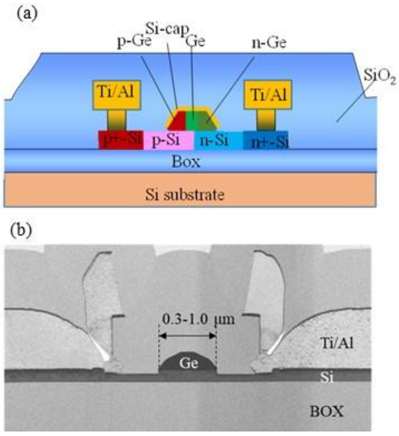

Fig. 1: (a) Schematic diagram of Ge/Si EAM. (b) Cross-sectional TEM image of Ge/Si EAM.

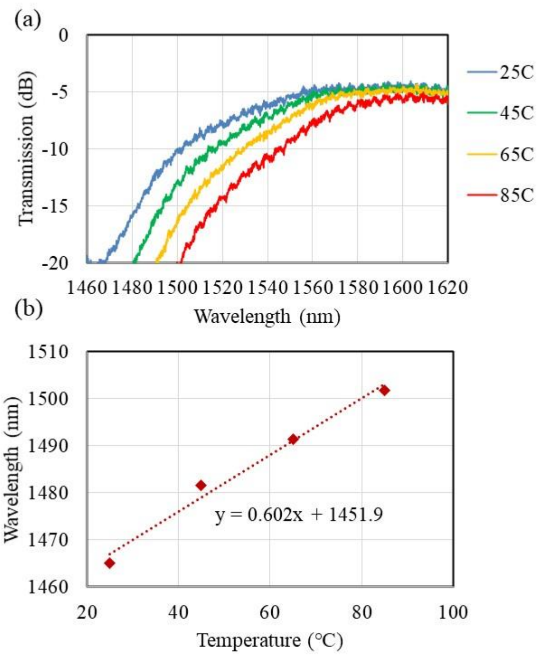

Fig. 2: (a) Experimental result of optical transmission spectrum dependence on temperature and (b) measured wavelength at -20 dB transmission for different temperature for a GeSi EAM.

image of a Ge/Si EAM. The fabrication process started from a 300 mm-diameter SOI (silicon-on-insulator) wafer, of which SOI thickness was 200 nm. A Si pedestal was patterned by immersion ArF lithography and dry etching.

Then, boron (B) and phosphorus (P) ions were implanted by ultra-high-vacuum chemical vapor deposition (UHV-CVD) method. A 20 nm-thick Si-capping layer was also deposited on a Ge layer to passivate the Ge surface. Next, B and P ions were doped to a Ge layer. Then a SiO_2 upper-clad layer was deposited, and contact-holes were formed by UV lithography and dry-etching process. Finally, metal electrodes of Ti/TiN/Al layers were deposited and patterned.

Figure 2 shows (a) experimental result of optical transmission spectrum dependence on temperature and (b) measured wavelength at -20 dB transmission for different temperature for a GeSi EAM. In this study, absorption edge wavelength was defined as that of optical transmission at -20 dB. With increase in temperature, optical absorption edge wavelength shifts to longer wavelength, because direct bandgap energy decreases with temperature [6]. From the slope of absorption edge wavelength dependence on temperature was 0.60, which is smaller value than the previously reported GeSi modulator [2]. From the theoretical analysis, increase of Si composition in GeSi alloy decreases the direct band gap energy and its temperature dependence a little [6]. Therefore, GeSi alloying at the Ge/Si interface would affect the temperature dependence of optical absorption-edge wavelength.

Figure 3 shows photoluminescence (PL) spectrum-peak wavelength dependence on temperature for a bulk Ge layer, a strained Ge layer on Si, and a 0.6μm-width Ge/Si EAM. As for a bulk Ge layer, the slope of PL spectrum peak wavelength vs. temperature was 0.7643, which is comparable with the theoretical value [6]. On the other hand, 0.6μm-width of a Ge/Si EAM shows smaller dependence of PL spectrum peak wavelength dependence on temperature. The slope of PL spectrum-peak wavelength dependence is 0.535, which is smaller than theoretical value for $Ge_{0.915}Si_{0.085}$. Therefore, GeSi alloying with various GeSi composition would contribute to smaller temperature dependence of bandgap energy, that is operation wavelength dependence on temperature for a Ge/Si EAM.

We analyzed the Ge/Si EAM by Raman spectroscopy with excitation laser wavelength of 457nm to investigate the crystalline strain and GeSi alloying of the Ge/Si EAM. The Raman spectrum peak of Ge-Ge bonding was around

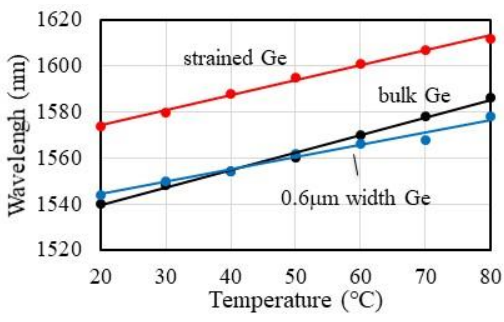

Fig. 3: Photoluminescence-spectrum-peak wavelength dependence on temperature for a bulk Ge layer, a strained Ge layer on Si, and a 0.6μm-width Ge/Si EAM.

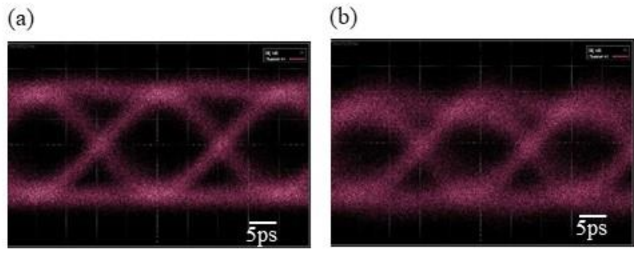

Fig. 4: Output waveforms at 56 Gbps with 2^{31}-1 PRBS at 1.55 μm wavelength at (a) 25℃ and (b) 85℃ of Ge/Si EAM.

298 cm^{-1}, which is consistent with that of a tensile-strained Ge layer. In addition, a small broader peak originated from GeSi mixed crystalline was observed. Therefore, GeSi mixed crystalline layer was formed by Ge epitaxial growth process, and this contributes to the shorter wavelength operation and smaller temperature dependence of operation wavelengths.

Figure 4 shows output waveforms at 56 Gbps with 2^{31}-1 PRBS (pseudo-random bit sequence) at 1.55 μm wavelength at 2.0 V_{dc} for a 40μm-long Ge/Si EAM. Clear eye opening was obtained and extinction ratio was 3.0 dB at 25℃ and about 2 dB at 85℃. At 85℃ optical coupling between a lensed fiber and a Si waveguide for a Ge/Si EAM is unstable in the measurement system, which increased the optical intensity jitter in the output waveform. Frequency bandwidth was more than 30 GHz for 40μm length of a Ge/Si EAM. The electrical capacitance is estimated to be about 50 fF in case of 40μm length. Therefore, the Ge/Si EAM is promising for low power and high-bandwidth optical interconnect by improving the insertion optical loss.

4. Conclusions

We studied a high-speed Ge/Si EAM evanescently coupled with a Si waveguide of a pn junction for high-bandwidth optical interconnect for a wide range of temperature from 25℃ to 85℃. We demonstrated C-band wavelength operation and 56 Gbps high-speed operation at high-temperature up to 85℃. From PL spectra, we confirmed bandgap energy dependence on temperature is relatively small, which is consistent with that of operation wavelengths with increasing temperature for a Ge/Si EAM.

Acknowledgements

This paper is based on results obtained from a project (JPNP13004) commissioned by the New Energy and Industrial Technology Development Organization (NEDO). The authors thank SCR members of AIST for their cooperation in the device fabrication.

References

[1] J. Liu et al., Nat. Photonics **2**(7), 433 (2008).
[2] D. Feng, *et al*., IEEE J. Sel. Topics Quantum Electron. **19**(6), 64 (2013).
[3] S. A. Srinivasan et al., J. Lightwave Tech. **34**(2), 419 (2016).
[4] J. Fujikata et al., OFC2020, Th3C4 (2020).
[5] Y. Ishikawa et al., J. Appl. Phys. **98**, 013501 (2005).
[6] L. Wu, et al., Optics Express **28** (5), 7585 (2020).