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High-Speed Ge/Si Electro-Absorption Optical Modulator for High-Bandwidth Optical Interconnect

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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. With decrease in Ge/Si layer width, we demonstrated C-band wavelength operation and 25 Gbps with relatively low applied voltage of 1.0 V_{pp}. From photoluminescence spectra, we confirmed bandgap energy increase in case of submicron width of a Ge/Si layer, which is consistent with C-band wavelengths operation of 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.

In order to achieve a low power and high-density interconnect system, a very small capacitance of an optical modulator is required. GeSi EAM is promising, because its electrical capacitance is about ten fF and device length is about several tens micrometers [2,3]. In addition, GeSi EAM structure is also applicable to photodetector, which has advantage for fabricating the integrated optical circuit. It has been reported that s 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 [4]. 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 this paper, we study a high speed stacked Ge/Si layers of an EAM which evanescently coupled with a Si waveguide of a pn junction for high-bandwidth optical interconnect. With decrease in Ge/Si stack width, we demonstrated C-band wavelength operation and high speed of more than 25 Gbps with relatively low applied voltage of 1.0 V_{pp}. From photoluminescence spectra, we confirmed bandgap energy increased in case of submicron width of a Ge/Si stacked layer, which is consistent with C-band wavelengths operation of a Ge/Si EAM.

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) image of a Ge/Si EAM. The fabrication process started from a 300 mm-diameter SOI (silicon-on-insulator) wafer,

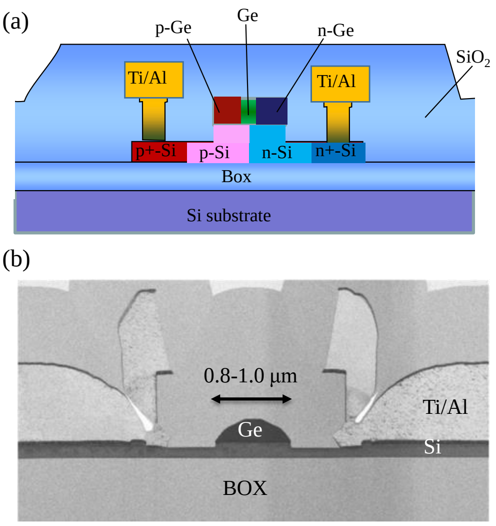

Fig. 1: (a) Schematic diagram of Ge/Si EAM. (b) Cross-sectional TEM image of Ge/Si EAM.

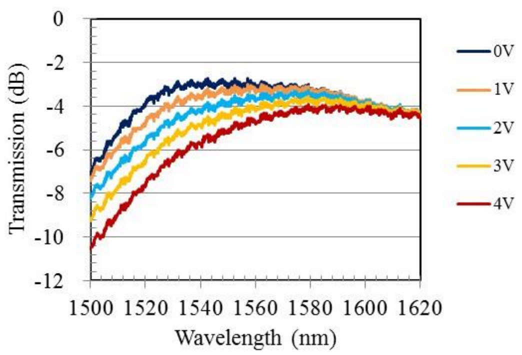

Fig. 2: Experimental result of optical transmission dependence on applied bias voltage.

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 and the wafers were annealed to form a lateral pn junction in an SOI layer. Subsequently, a 500 nm-thick epitaxial germanium mesa were selectively grown on the Si pedestal 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 implanted to a Ge layer and the wafers were annealed to form a lateral p-i-n junction in the 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 experimental result of optical transmission dependence on applied bias voltage for a 0.8 μm-wide and 20 μm-long Ge/Si EAM. With increase in reverse bias voltage, optical transmission power decreased around 3 dB to 4 dB at around 1500-1560 nm wavelength, which would originate from band-gap shrinkage of Franz-Keldysh effect. On the other hand, a 1.4μm-wide Ge/Si EAM operated at around 1600 nm wavelength, which is consistent with tensile-strained Ge band-gap energy on a Si [4]. Therefore, operation wavelength band for a Ge/Si stacked layer of an EAM could be controlled by changing a stacked Ge/Si layer width. Insertion optical loss was 3 to 5 dB for 20 μm length, which would be improved by optical coupling structure and Ge/Si interface crystalline quality. From I-V characteristics, leakage current of the Ge/Si EAM is about several nA, which would not affect the optical transmission loss.

Figure 3 shows photoluminescence (PL) spectra of a Ge/Si EAM device and a blanket Ge layer on the same SOI wafer. As for a blanket Ge layer, the peak wavelength in the PL spectra was observed at around 1580 nm, which shows a bandgap shrinkage was induced due to about 0.2% tensile strain in the blanket Ge layer on the SOI. On the other hand, the PL spectrum peak shifted to around 1500nm in case of a 0.8 μm-wide Ge/Si EAM device.

We analyzed the Ge/Si EAM device by Raman spectroscopy with excitation laser wavelength of 457nm to 633nm to investigate the crystalline strain of the Ge/Si EAM. The Raman spectrum peak of Ge-Ge bonding was around 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 would be formed by annealing process, and this contribute to the shorter wavelength operation than the tensile-strained Ge EAM. From T-CAD simulation, electric field intensity is larger at the interface between a Ge layer and Si pn junction in case of low applied voltage around 1.0 V. Therefore, the GeSi mixed crystalline layer would be mainly formed in the Ge/Si interface region.

In the EAM structure, the distance between p and n-type electrodes in a Ge layer affects the optical absorption coefficient in the Ge layer and also electrical capacitance in the simulation. By optimizing the widths of p and n-type Ge

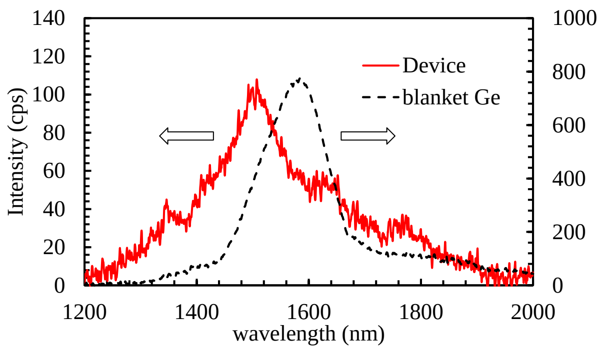

Fig. 3: Photoluminescence spectra of Ge EAM device and blanket Ge layer on the same wafer.

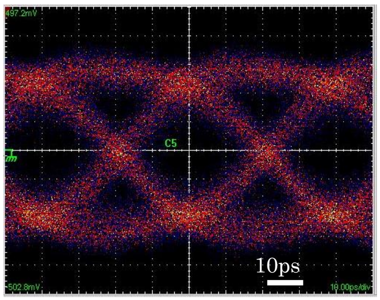

Fig. 4: Output waveform at 25 Gbps with 2^{31}-1 PRBS at 1.52 μm wavelength from Ge EAM device.

electrodes, over 30 GHz bandwidth could be obtained from T-CAD simulation.

Figure 4 shows an output waveform at 25 Gbps with 2^{31}-1 PRBS (pseudo-random bit sequence) at 1.52 μm wavelength at 1.0 V_{dc} for a 40μm-long Ge/Si EAM. Clear eye opening was obtained and extinction ratio was about 3 dB, which would contribute to the efficient optical interconnect. Frequency bandwidth was 15 to 20 GHz for 40μm length of a Ge/Si EAM and 25-40 GHz for 20 μm length. 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 optical interconnection. With decrease in Ge/Si stack width, we demonstrated C-band wavelength operation and 25 Gbps with relatively low applied voltage of 1.0 V_{pp}. From photoluminescence spectra, we confirmed bandgap energy increased in case of submicron width of a Ge/Si layer, which is consistent with C-band wavelengths operation of a Ge/Si EAM.

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