

110 Gbit/s NRZ and 160 Gbit/s PAM-4 GeSi Electro-Absorption Modulator

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Abstract: A pure Ge electro-absorption modulator operating at 1600 nm wavelength with electro-optic bandwidth beyond 67 GHz is reported. The 110 Gbit/s NRZ and 160 Gbit/s PAM-4 modulation clear openings of eye diagrams are demonstrated.

1. Introduction

Silicon photonics has been identified as a critical enabling technology for data centers, coherent communication, high-performance computer, and integrated artificial intelligence (AI) circuits applications because of its low cost, small footprint, low power consumption, high bandwidth, and complementary metal oxide semiconductor (CMOS) compatibility [1-2]. One of the key building blocks for silicon photonics is a modulator that convert the electrical signals to optical signals. Up to now, the silicon-based modulators are mainly realized by employing silicon (Si) free carrier plasma dispersion effect, Ge-Si or pure Ge Franz-Keldysh (FK) or quantum-confined Stark effect. The FK effect intrinsically possesses a sub-picosecond timescales electro-absorption response and enables 100 GHz optical modulation. Based on lateral/vertical or wraparound p-i-n structure of pure Ge and Ge-Si material, the clear open up to 60 Gbit/s non-return-to-zero (NRZ) and 56 Gbaud four-level pulse amplitude modulation (PAM-4) eye diagrams operating at O, C or L-band wavelengths have been demonstrated [3-7]. Furthermore, a single-lane of 160 Gbit/s PAM-4 generated by Ge-Si electro-absorption modulator (EAM) with 30 GHz bandwidth is demonstrated utilizing artificial neural network based nonlinear equalization [8]. These reported Ge-based EAMs might suffer from complex fabrication processes. The extra poly-Si tapers, or chemical-mechanical polish (CMP) of Ge, or several precise Ge or Si etchings are needed. In this scenario, a laudable goal would be to explore ultra-high-speed EAMs with easy fabrication processes, which is very helpful for realizing low-cost silicon photonic integrated on-chip optical interconnects.

In this paper, we report a pure Ge-EAM based on Si-doped lateral p-i-n structure operating at 1600 nm wavelength with 3 dB electro-optic bandwidth beyond 67 GHz. Additionally, the 80, 90, 100, and 110 Gbit/s NRZ and 128, 140, 150, and 160 Gbit/s PAM-4 modulation clear openings of eye diagrams are also demonstrated.

2. Design and fabrication of the pure Ge-EAM

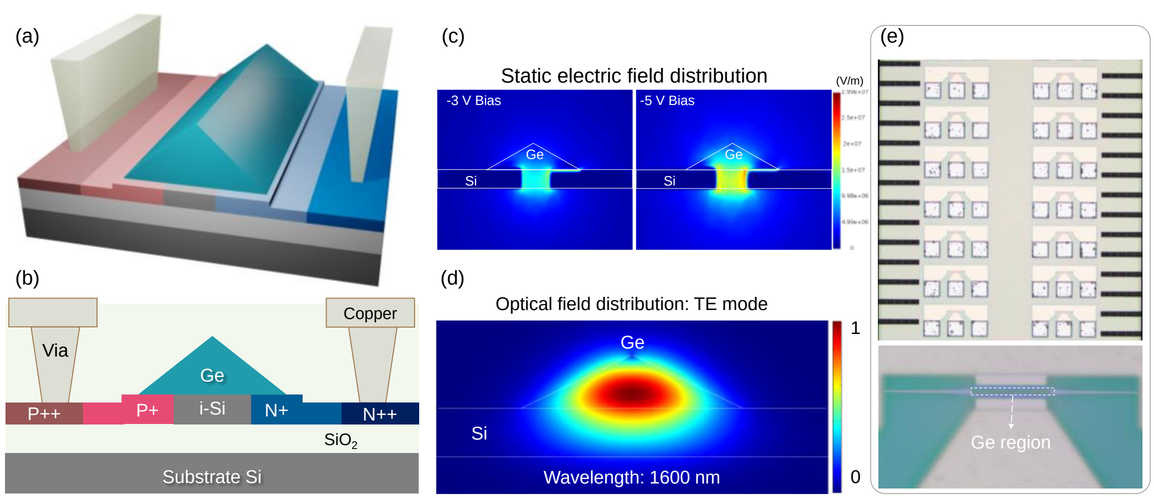

Fig. 1. (a) Three-dimensional (3D) schematic and (b) cross-sectional view of the proposed pure Ge-EAM. (c) Static electric field intensity distribution in the proposed pure Ge-EAM at -3 and -5 V bias conditions. (d) Transverse electric (TE) mode optical field distribution of the proposed pure Ge-EAM. (e) Optical micrograph of the proposed pure Ge-EAMs.

Figure 1 shows (a) three-dimensional (3D) schematic and (b) cross-sectional view of the proposed pure Ge-EAM with Si-doped lateral p-i-n junction, which is similar to the demonstrated structure by Liow et al [9]. Here, the epitaxial Ge base width is designed to 1.0 µm, the height of the Ge is estimated to be 0.24 µm. The length of Ge is 25 µm to obtain high operation speed and appropriate extinction ratio (ER) with low insertion losses. The device exhibits a small active region of 1.0×25 µm^2. The pure Ge-EAM is implemented in commercial 90 nm silicon photonics platform with simple fabrication processes. The 220-nm-thick Si rib waveguide is implanted by N+ and P+ with 350 nm intrinsic region (i-Si) to build fringing electric field with applied drive voltage. The 150-nm-thick Si slab is implanted by P++ and N++ for ohmic contact. The doping concentration of N+ and P+ regions are estimated to be $2.5\times10^{18}cm^{-3}$ and $2\times10^{18}cm^{-3}$. The high-quality Ge film is epitaxial grown on the 0.22 µm-thick Si through a low-pressure chemical-vapor deposition (LPCVD) process. Figure 1(c) shows the static electric field intensity distribution in the proposed pure Ge-EAM at -3 and -5 V bias conditions. The center of Ge region has an electric field up to 1.1 kV/cm at -5 V bias. Figure 1(d) shows the transverse electric (TE) mode optical field distribution of the proposed pure Ge-EAM at wavelength of 1600 nm. The optical micrograph of the proposed pure Ge-EAMs is shown in Fig. 1(e). The light was coupled in and out of the pure Ge-EAM via Si edge-coupler based on suspended spot size convert (SSC) structure with -3.5 dB/facet coupling loss.

3. The static and dynamic performances of the pure Ge-EAM

The working principle of pure Ge-EAM is based on FK effect, according to which the material absorption coefficient is changed by an applied electric field. The optical transmission spectra of Ge-EAM when the reverse bias voltage changes from 1 to 14 V with 1 V step were shown in Fig. 2(a). Here, the coupling loss of two SSC-based edge-couplers were subtracted. The 1 V reverse bias voltage is set as the “0” state of EAM with minimum loss. Figure 2(b) shows the extracted ER as a function of wavelength under various bias voltages. The bias voltages increase from 1 to 13 V. The whole peaks of the ER curve appeared around 1600 nm. It matches well with the FK effect of Ge. For the wavelength of 1600 nm, the ERs of pure Ge-EAM are about 3.85 and 5.8 dB under 3 and 5 V swing, respectively. The maximum ER can reach to 12.6 dB with 13 V swing. So, the overall modulation efficiency is approximate to 1 dB/V. The insertion loss is less than 6.9 dB for the wavelength changing from 1605 to 1630 nm.

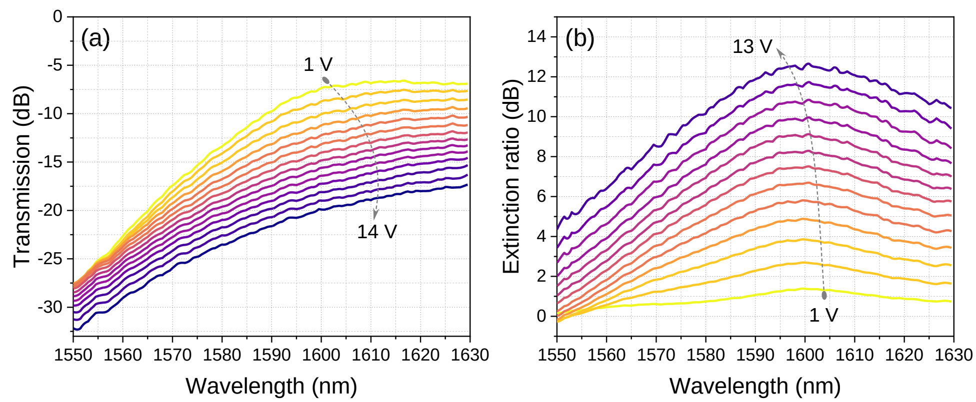

Fig. 2. (a) The optical transmission loss and (b) extinction ratio of the proposed pure Ge-EAM under different bias voltages. The bias voltage variation step was 1 V. The coupling loss of two SSC-based edge-couplers were subtracted.

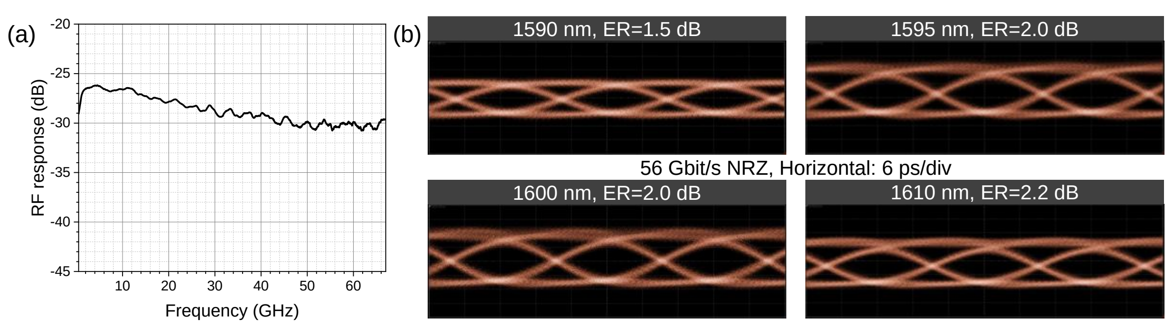

Fig. 3. (a) The RF S21 response of the pure Ge-EAM at -2.5 V bias. (b) Measured 56 Gbit/s NRZ eye diagrams for wavelength of 1590, 1595, 1600, and 1610 nm under -3.1 V bias condition.

The bandwidth test experiments were accomplished by collecting the radio frequency (RF) response as a function of frequency. The pure Ge-EAM have a 3 dB electro-optic bandwidth of beyond 67 GHz as shown in Fig. 3(a). It might benefit from the small RC constant. The feasibility analysis of Ge-EAM was further carried out by measuring the large-signal eye-diagrams. As shown in Fig. 3(b), clear and open eye diagrams at 56 Gbit/s were observed at wavelength of 1590, 1595, 1600, and 1610 nm with a dynamic ER of 1.5, 2.0, 2.0, and 2.2 dB respectively. From Fig. 4, we can see that clear opening of the eye diagrams are obtained for 80, 90, 100, and 110 Gbit/s optical modulation signal with -3.1 V bias. Additionally, the clear opening of the eye diagrams up to 128, 140, 150, and 160 Gbit/s PAM-4 are also achieved without utilizing any digital signal processing, as shown in Fig. 5.

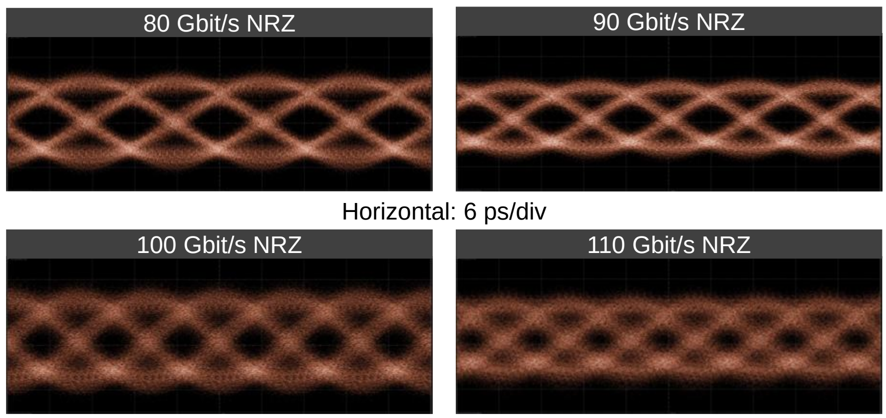

Fig. 4. Measured 80, 90, 100, and 110 Gbit/s NRZ eye diagrams under -3.1 V bias condition.

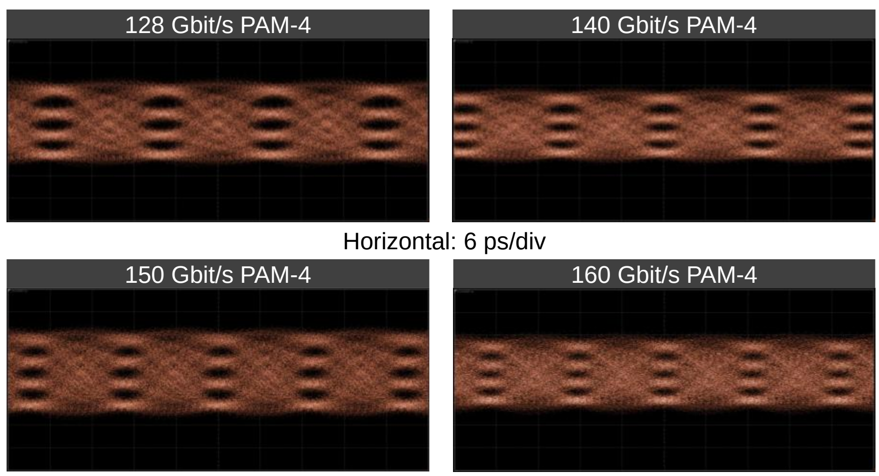

Fig. 5. Measured 128, 140, 150, and 160 Gbit/s PAM-4 eye diagrams under -3.1 V bias condition.

4. Conclusion

We have demonstrated 110 Gbit/s NRZ and 160 Gbit/s PAM-4 modulation clear openings of eye diagrams based on pure Ge-EAM at 1600 nm. The device possesses a 3 dB bandwidth beyond 67 GHz, which might benefit from the compact active region of $1.0\times25\ \mu m^2$ with small RC constant. The dynamic ER up to 2.2 dB are obtained for 56 Gbit/s NRZ modulated signals. The high performances pure Ge-EAM is fabricated in commercial 90 nm silicon photonics platform with simple fabrication processes, which is very helpful for realizing low-cost silicon photonic integrated on-chip optical interconnects.

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6. References

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