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Single Lane Beyond 400 Gbit/s Optical Direct Detection Based on a Sidewall-doped Ge-Si Photodetector

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Abstract *We present a photodetector in which the sloped sidewalls of germanium are carefully doped. The 3-dB bandwidth > 55 GHz and responsivity of 1 A/W are demonstrated. Single lane direct detection of record-high speed 290 Gbit/s PAM-4 and 408 Gbit/s PAM-8 optical signals are achieved. ©2022*

Introduction

Silicon photonics (SiPh) has been identified as a key enabling technology for high-speed data-center interconnects [1], optical I/O and co-packaged optics [2-4], and is also a potential solution for future applications in 800G and 1.6T to meet the ever-increasing data communication demands. One of the key building blocks of SiPh is photodetector (PD) that converts high-speed optical signals to electrical signals [5, 6]. An ideal PD should possess high quantum efficiency (QE), low dark current, and detect ultrahigh-speed optical signal >200 Gbit/s for single lane [7-9]. The germanium (Ge) material, possessing large absorption coefficients of up to 1550 nm and even 2000 nm by exploiting tensile-strained bandgap shrinkage, has exhibited excellent photodetection characteristics [10]. Various high-speed Ge-on-Si photodetection structures have been extensively investigated and demonstrated [11-14]. Remarkably, based on the novel biconcave germanium fin shape, the recorded 3-dB cut-off frequency up to 265 GHz has been reported [15], which is very impressive. Several hard-masks, lithography, dry etch and chemical mechanical polishing (CMP) processes are executed to form a lateral Si-Ge-Si p-i-n diode and define the actual width of the Ge region. And the QE and dark current need to be further improved. However, its research of optical large signal detection performances is insufficient. Additionally, the state-of-the-art Ge-Si high-speed optical detection capability also needs to be further investigated. In this scenario, a laudable goal would be to explore ultrahigh-speed, high responsivity, and low dark current PDs with easy fabrication processes, which is very helpful for realizing low-cost SiPh integrated on-chip optical interconnects.

In this paper, based on the commercial 90 nm SiPh available platform, we design and fabricate double sidewall doping Ge-Si PDs, which possess high electric field (>$1.1\times10^5 V/m$) in the Ge region. The responsivity is larger than 1 A/W at 1550 nm wavelength. With the aid of 8-inch wafer level test and analysis, the overall PDs have 3-dB opto-electrical (OE) bandwidth > 50 GHz and dark current less than 10 nA under -3 V bias. More importantly, we report, to the best of our knowledge, the first Ge-Si PD operating at > 400 Gbit/s for single lane in an intensity modulation direct-detection (IMDD) system. The 200, 256, and 290 Gbit/s four-level pulse amplitude modulation (PAM-4), and 300, 384, and 408 Gbit/s eight-level pulse amplitude modulation (PAM-8) clear openings of electrical eye diagrams are experimentally obtained without utilizing offline digital signal processing at the receiver side.

Design and Fabrication of the Ge-Si PD

Conventional Ge-Si waveguide PDs require P or N type heavily-doped germanium as well as a metal contact on germanium area to form the p-i-n junction. This will lead to the responsivity reducing because of the light absorption from metal contacts. For our designed PD structure, in order to improve the QE, the double sidewalls of Ge region are lightly doped with P and N types to build lateral p-i-n junction. Figure 1 (a) and (b) show three-dimensional (3D) schematic and cross-sectional view of the proposed sidewall doping Ge-Si PD with Si-contacted lateral p-i-n junction. The designed Ge-Si PDs are fabricated in commercial 90 nm silicon photonics platform with simple fabrication processes. The high-quality Ge film is epitaxial grown on the 0.22 μm-thick Si through a low-pressure chemical-vapor deposition (LPCVD) process with sloped sidewalls, which can be used for P and N doping.

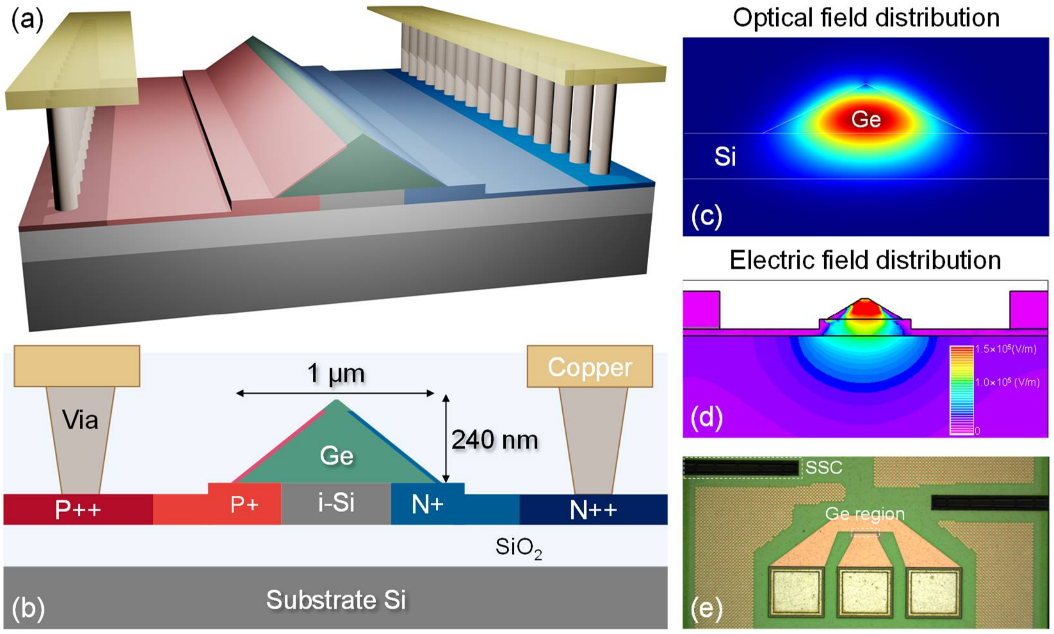

Fig. 1: (a) Three-dimensional (3D) schematic and (b) cross-sectional view of the proposed sidewall doping Ge-Si photodetector. (c) and (d) Simulated static optical field and electric field distribution in the Ge region. The bias voltage is -3 V. (d) Optical micrograph of the Ge-Si PD. SSC: spot size convert.

The bottom width of Ge film is designed to be about 1 μm to balance the high yield quality and bandwidth. The thickness of Ge is about 240 nm. The length of Ge active region is 50 μm to achieve high QE. The Ge double sidewalls and 220 nm Si waveguide are doped to form the P+ and N+ regions. Approximately 90 nm depth of shallow sidewall doping on Ge was used to minimize the free carrier absorption loss and photo-generated carries loss in the doped regions. This doping depth would unintentionally help to reduce the intrinsic of Ge, which is beneficial to decrease the carrier transit time. For Ge sidewall doping region, the concentrations of N+ and P+ are optimized to be around $1\times10^{18}cm^{-3}$. For 220 nm Si slab doping region, the concentrations of N+ and P+ are about $2.0\times10^{18}cm^{-3}$. Figure 1 (c) and (d) show the simulated static optical field and electric field distribution in Ge region. The overall electric field intensity of Ge intrinsic region is larger than $1.1\times10^{5}V/m$, which is benefit from the well-designed sidewall doping. And the overlaps of optical field and electric field are very high. The optical micrograph of the proposed Ge-Si PD is shown in Fig. 1(e). The light was coupled in via Si edge-coupler based on suspended spot size convert (SSC) structure with -3.0 dB/facet coupling loss.

Experimental Setup and Results

The chips are fabricated on an 8-inch Si wafer with 26 reticles. The wavelength dependence of responsivity in the C+L bands are shown in Fig. 2(a) at -3V bias. At 1550 nm, the responsivity is

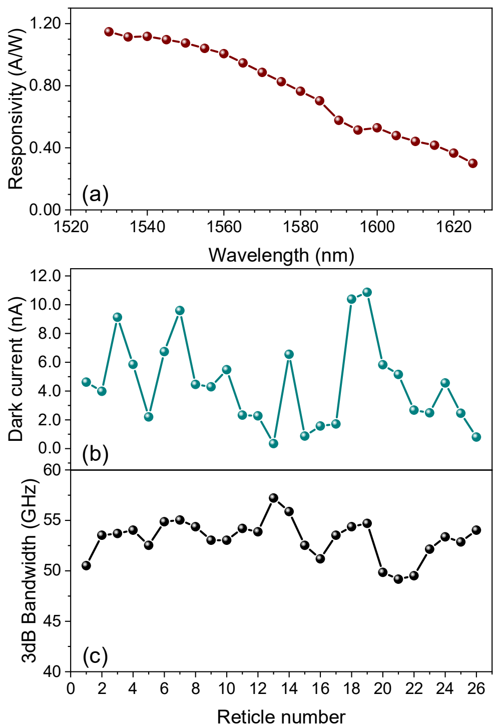

Fig. 2: (a) The responsivity as a function of wavelengths. The dark current (b) and 3-dB bandwidth (c) distribution of the PD chips at different reticle sites under -3 V bias.

large than 1A/W. In the L-band, the responsivity drop is mainly due to the decrease of the Ge absorption coefficient at longer wavelength. The measurements of dark current and 3-dB bandwidth were performed at wafer level with DC~67 GHz Keysight Lightwave Component Analyzer and Keithley source meter [7, 8], as shown in Fig. 2 (b) and (c). Very low dark currents in the range of 1-10 nA at -3 V are achieved. The

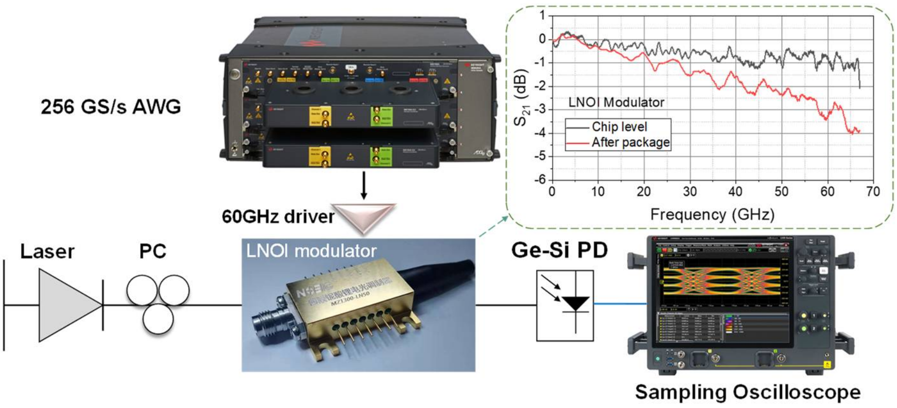

Fig. 3: Schematic of the experimental setup for the measurement of high-speed PAM-4 eye diagrams. PD, photodetector; AWG, arbitrary waveform generator; PC, polarization controller; LNOI, thin film lithium niobite on insulator.

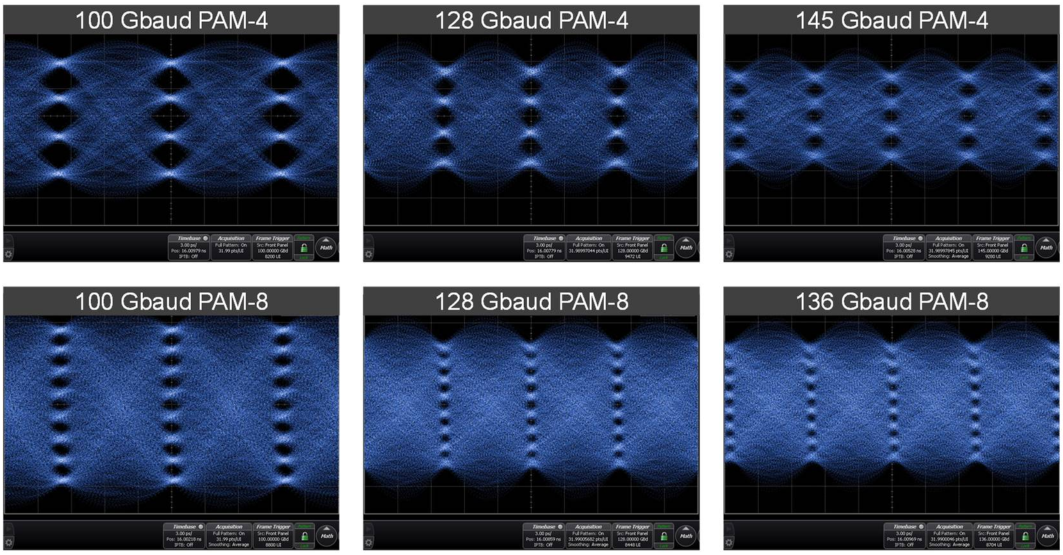

Fig. 4: Measured 100, 128, and 145 Gbaud PAM-4, and 100, 128, and 136 Gbaud PAM-8 eye diagrams under a −3 V bias voltage with about 0.8 mA DC current. The horizontal scale is 3 ps/Div.

bandwidths beyond 50 GHz are achieved for the 26 reticles site. The bandwidth is limited by the transit time, which might be further optimized by sidewall doping conditions.

The setup of high-speed PAM-4 and PAM-8 eye diagrams measurement is illustrated in Fig. 3. The high-speed RF signal with word length of $2^{15}-1$ is generated by a 256 GS/s arbitrary wave generator. After amplified by 60 GHz driver, the RF signal is sent to the thin film lithium niobite on insulator (TFLNOI) modulator, which has a 3-dB bandwidth of 64 GHz after packaging, as shown in the inset of Fig. 3. A -3 V was applied to the Ge-on-Si PD with 55 GHz bandwidth. The output electrical data was measured with oscilloscope without using a transimpedance amplifier (TIA). Clear opening eye diagrams up to 100, 128, and 145 Gbaud PAM-4, and 100, 128, and 136 Gbaud PAM-8 are obtained, as shown in Fig. 4. To the best of our knowledge, we report, for the first time, the SiPh photodetector operating at >400 Gbit/s per lane in an IMDD system. We believe that the proposed sidewall doping PD devices possess the great potential to achieve low-cost >400 Gbit/s data reception per lane for future 800G/1.6T data center transceivers.

Conclusions

We have proposed a sidewall-doped PD, which can directly detect the record-high speed of 290 Gbit/s PAM-4 and 408 Gbit/s PAM-8 optical signals. The responsivity is larger than 1 A/W at 1550 nm wavelength. With the aid of wafer level test, the PDs have 3-dB bandwidth beyond 50 GHz, and dark current less than 10 nA under -3 V. The demonstration of single lane beyond 400 Gbit/s detection illustrates the great potential of Ge-Si PDs, which is very helpful for realizing low-cost SiPh integrated on-chip optical interconnects in the future.

Acknowledgements

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