Sub-5V Germanium Waveguide Avalanche Photodiode based 25 Gb/s 1310 nm Optical Receiver

H. T. Chen,[1,2,*] J. Verbist,[2,3] P. Verheyen,[1] P. De Heyn,[1] G. Lepage,[1] J. De Coster,[1] P.Absil,[1] B. Moeneclaey,[3] X. Yin,[3] J. Bauwelinck,[3] J. Van Campenhout,[1] and G. Roelkens[2]

[1] *Interuniversity Microelectronics Center (IMEC), Kapeldreef 75, 3000 Leuven, Belgium*
Hongtao.Chen@imec.be
[2] *Photonics Research Group, Department of Information Technology, Ghent University - imec, B-9000 Ghent, Belgium.*
[3] *Design Research Group, Department of Information Technology, Ghent University – iMinds – IMEC, B-9000 Ghent, Belgium.*

Abstract: We demonstrate low-voltage waveguide-coupled germanium avalanche photodetectors (APDs) with a gain×bandwidth product of 140 GHz at -5 V. An optical receiver based on such an APD operating up to 25 Gb/s is demonstrated.

OCIS codes: (040.1345) Avalanche photodiodes (APDs); (040.5160) Photodetectors; (200.4650) Optical interconnects.

1. Introduction

Integrated germanium avalanche photodetectors (APDs) offer great potential to improve the link budget of silicon-based optical interconnects. Low operation voltage is the key design target for the CMOS compatible Ge APDs. In [1,2], we demonstrate a 10Gb/s 1550nm silicon photonics optical receiver based on a Ge waveguide vertical p-i-n APD. A 5.8dB avalanche sensitivity improvement was obtained at a low APD bias voltage of -5.9V inferred from bit error ratio measurements. In this paper, by engineering the Ge APD design, a 10Gb/s 1310nm optical receiver is demonstrated showing 7dB sensitivity improvement at a low APD bias of -4.85V. A 20Gb/s 1310nm silicon photonics optical receiver based on such a Ge APD showing 6.2dB sensitivity improvement at -5.0V APD bias, and operation of the receiver up to 25Gb/s is demonstrated. The wafer-scale mean gain*bandwidth product value is 140GHz at -5V bias voltage (a 3dB bandwidth of 15.2GHz at the avalanche gain of 9).

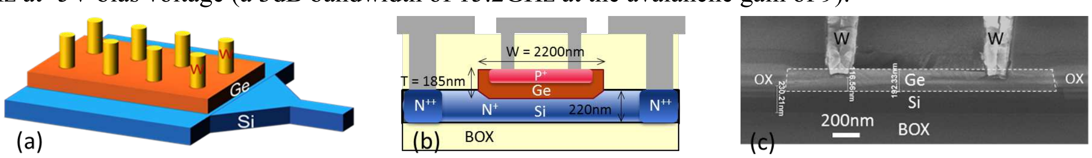

Fig. 1. (a) Schematic of the Ge waveguide APD. (b) Cross section of the Ge waveguide APD with Ge layer dimensions. (c) SEM cross-section image of the Ge waveguide APD.

2. Device Design and Fabrication

The Ge waveguide APDs, as shown in Fig. 1(a), were fabricated in imec's fully integrated Si Photonics platform going through a process flow described in [3]. The Ge layer dimensions and doping configuration are shown in Fig. 1(b). A vertical p-i-n structure (VPIN) is formed by implanting Si with phosphorous ions (before Ge growth) and by implanting the planarized Ge layer with boron ions. A 185nm thin Ge layer was adopted to lower the operation voltage of the Ge APDs. The simulated doping distribution is shown in Fig. 2(a). The heterogeneous Ge/Si VPIN configuration with the 185nm thin Ge layer results in a strongly non-uniform electric field at -3V bias voltage as shown in Fig. 2(b), mostly confined in the lower 100nm of the Ge layer. Fig. 2(c) shows the electric field profile along A-A' (in Fig. 2(b)) for a Ge layer of 185nm, 285nm and 385nm thick, respectively, at -3V bias voltage (assuming the same implant conditions). It can be seen that the thinner the Ge layer, the stronger the electric field is in the Ge layer. For the case of a 185nm-thick Ge layer, the electric field strength is calculated to be as high as 5.2×10^{5}V/cm at the Ge/Si interface at a bias voltage of -3V.

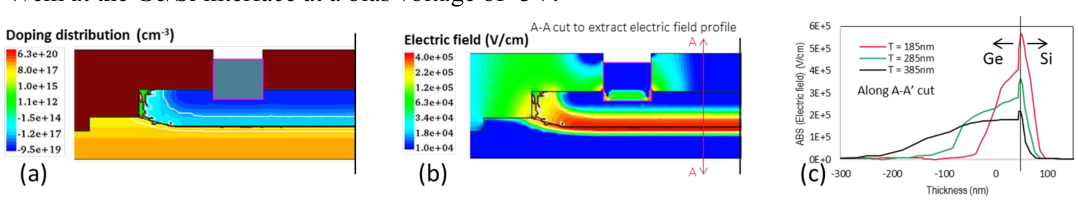

Fig. 2. (a) Simulated doping distribution in the Ge APD. Boron ion implantation in the Ge layer is generated from Monte-Carlo simulation. Only half of the structure is shown for clarity. (b) Simulated electric field distribution in the Ge layer at -3V bias. (c) Electric field profiles along A-A' cut in the Ge APD at -3V bias.

3. Standalone APD Characteristics

Static current-voltage characteristics of a 10µm long VPIN Ge APD device are shown in Fig. 3(a). The device has a low dark current of ~10nA at -1V. The light current was measured at 1310nm wavelength under an waveguide referred input optical power of -19.8dBm, -14.8dBm, -9.8dBm and -4.8dBm, respectively. The measured primary responsivity is 0.3A/W at -1V. The light current increases rapidly as the bias voltage surpasses -3V. The avalanche gain extracted from static measurements is consistent for the various input optical powers, as shown in Fig. 3(b). It goes up to ~10 at -5V.

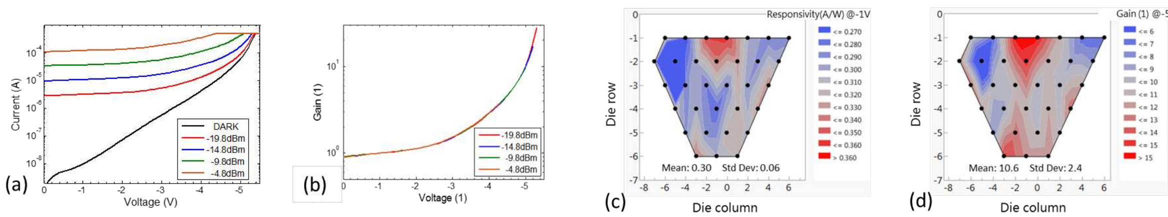

Fig. 3. (a) I-V characteristics of a 10µm long APD device. (b) Avalanche gain extracted from static measurements. (c) wafer-scale primary responsivity data at -1V. (d) Wafer-scale avalanche gain data at -5V.

Wafer-scale measurements of the static device performance were carried out to verify the manufacturability of the Ge APDs. Wafer-scale primary responsivity data (in the bottom half wafer) of the Ge APD at -1V under an input optical power of -19.8dBm are shown in Fig. 3(c). The mean primary responsivity value is 0.3A/W with a standard deviation of 0.06A/W. Fig. 3(d) shows wafer-scale avalanche gain data extracted from static measurements at -5V under an input optical power of -19.8dBm. The mean avalanche gain value is 10.6 with a standard deviation of 2.4.

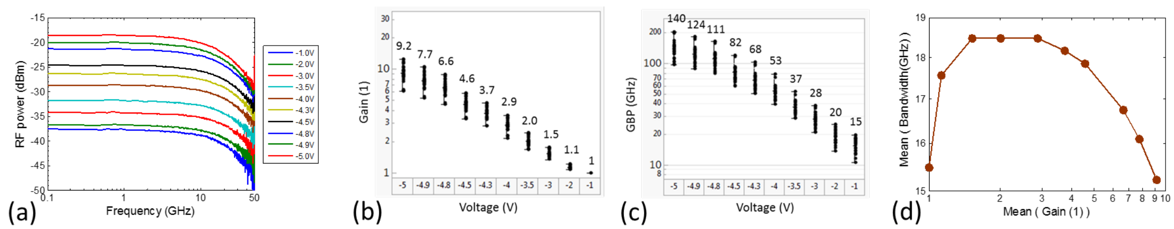

Fig. 4. (a). Small-signal RF measurements of the S_{21} parameter at 1310nm wavelength. (b) wafer-scale avalanche gain data. (c) Wafer-scale gain×bandwidth product data. (d) The mean value of measured 3dB O/E bandwidth data versus the mean value of avalanche gain data.

Small-signal radio-frequency (RF) measurements were carried out at 1310nm wavelength using an average input optical power of -14.2dBm. As shown in Fig. 4(a), with increasing bias voltage, the generated low-frequency RF power increases substantially. The wafer-scale avalanche gain data extracted from these small-signal measurements is shown in Fig. 4(b). It reaches a mean value of 9.2 at -5V. The wafer-scale gain×bandwidth product (GBP) data is shown in Fig. 4(c). The mean value is 140GHz at -5V. Fig. 4(d) shows the mean value of the 3dB bandwidth data (at a given reverse bias) as a function of the mean value of avalanche gain data (at that same reverse bias).

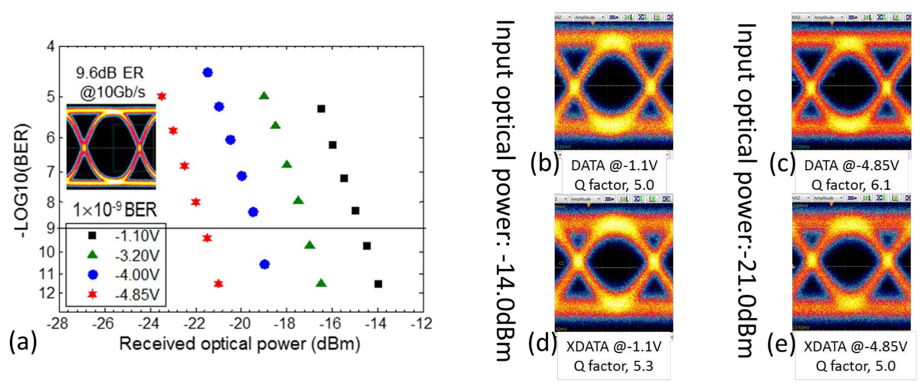

Fig. 5. (a) Measured BER at 10Gb/s as a function of input optical power. 10Gb/s eye diagram of the electrical signal with a BER of 3×10^{-12} (b) from TIA DATA port at -1.1V APD bias under -14.0dBm input optical power (c) from TIA DATA port at -4.85V APD bias under -21.0dBm input optical power (d) from TIA XDATA port at -1.1V APD bias under -14.0dBm input optical power (e) from TIA XDATA port at -4.85V APD bias under -21.0dBm input optical power, respectively.

4. APD based Optical Receiver Characteristics

4.1. APD based 10Gb/s 1310nm Optical Receiver

A 10Gb/s optical receiver was constructed by wire-bonding an APD device to a 10Gbps trans-impedance amplifier (TIA) to assess the receiver sensitivity. The 0.13μm SiGe BiCMOS TIA has an input referred root-mean-square (RMS) noise current lower than 1.2μA. A (2^{31}-1) long 1310nm optical NRZ PRBS data pattern at 10Gb/s (as shown in the inset of Fig. 5(a)) was launched into the wire-bonded APD receiver. The measured bit error ratio (BER) as a function of average input optical power for various bias voltages is shown in Fig. 5(a). For a BER of 1×10^{-9}, the waveguide-referred primary sensitivity is -14.7dBm average optical power at -1.1V APD bias. A 7dB sensitivity improvement is obtained at -4.85V APD bias, yielding an absolute receiver sensitivity of -21.7dBm for a 1×10^{-9} BER. The avalanche gain, extracted from small-signal measurements, is ~7 at -4.85V APD bias. 10Gb/s eye diagrams of the electrical signals from the TIA at a BER of 3×10^{-12} at both -1.1V and -4.85V bias voltage from both the DATA and XDATA port were recorded by a high-speed oscilloscope, as shown in Fig. 5(b) ~Fig. 5(e).

4.2. APD based 25Gb/s 1310nm Optical Receiver

A higher data-rate optical receiver is built by wire-bonding another APD device to a 40Gbps TIA. The 0.13μm SiGe BiCMOS TIA has an input referred (RMS) noise current of ~2μA for 25Gb/s settings [4]. Fig. 6(a) shows the measured BER at 20Gb/s as a function of input optical power at 1310nm wavelength ((2^{31}-1) long NRZ PRBS data pattern). The waveguide-referred primary sensitivity is -11.2dBm average optical power at -1.1V APD bias for a BER of 1×10^{-9}. A 6.2dB sensitivity improvement is obtained at -5.0V APD bias, yielding an absolute receiver sensitivity of -17.4dBm for a 1×10^{-9} BER. The avalanche gain, extracted from small-signal measurements, is ~9 at -5.0V APD bias. The 20 Gb/s eye diagrams of the electrical signal from the TIA with a BER of 2×10^{-9} at both -1.1V and -5.0V bias voltages are shown in Fig. 6(b) and Fig. 6(c).

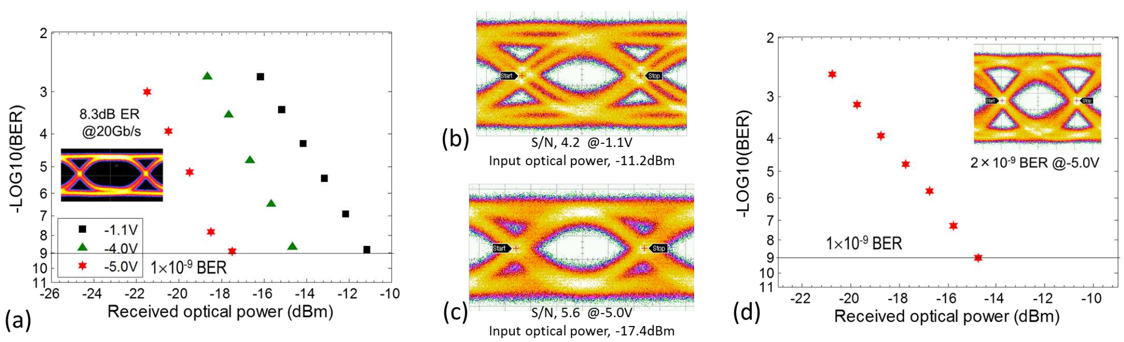

Fig. 6. (a) Measured BER at 20Gb/s as a function of input optical power. (b) 20Gb/s electrical eye at -1.1V APD bias (with a BER of 2×10^{-9}). (c) 20Gb/s electrical eye at -5.0V APD bias (with a BER of 2×10^{-9}). (d) Measured BER at 25Gb/s as a function of input optical power.

Operation of the receiver at 25Gb/s was also evaluated using a (2^{31}-1) long 1310nm optical NRZ PRBS data pattern. The obtained BER at -5V APD bias at 25Gb/s is shown in Fig. 6(d). The absolute sensitivity is -14.8dBm for a 1×10^{-9} BER. The 2.6dB power penalty for a 1×10^{-9} BER at 25Gb/s compared to that at 20Gb/s can be largely attributed to the bandwidth limitation (15.2 GHz) of the APD at -5.0V bias voltage, which can be observed from the 25Gb/s electrical signal eye from the TIA (inset of Fig. 6(d)).

This work was partially sponsored by imec's industry-affiliation program on Optical I/O. We acknowledge the process line in imec for manufacturing the Ge APD devices. The TIA development was supported by the EU-funded FP7 ICT projects Mirage, Phoxtrot and Discus. We also thank Danny Frederickx and Ludo Viaene for the wire bonding of the Ge APDs to TIAs.

References

[1] H. T. Chen, et al, "Low-voltage Ge avalanche photodetector for highly sensitive 10Gb/s Si photonic receivers," Proc. 11th International Conference on Group IV Photonics, 106–107 (2014).
[2] H. T. Chen, et al., "High sensitivity 10Gb/s Si photonic receiver based on a low-voltage waveguide-coupled Ge avalanche photodetector," Opt. Express 23, 815-822 (2015).
[3] P. Verheyen, et al., "Highly uniform 25 Gb/s Si photonics platform for high-density, low-power WDM optical interconnects," in Advanced Photonics for Communications,OSA Technical Digest (online) (Optical Society of America, 2014), paper IW3A.4.
[4] B. Moeneclaey, et al, "A 40 Gb/s transimpedance amplifier for optical links", IEEE Photon. Technol. Lett. 27(13), 1375-1378 (2015).