64Gbps PAM4 Modulation for a Low Energy Si-Ge Waveguide APD with Distributed Bragg Reflectors

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Abstract: We demonstrate a low-voltage waveguide Si-Ge APD that integrates a distributed Bragg reflector (DBR). Quantum efficiency has been improved from 60% to 90% at 1550nm while still achieving a 25GHz bandwidth. The device under 64Gbps PAM4 modulation showed 30% increase in OMA, which enables 1.2dB improvement in receiver sensitivity.

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1. Introduction

Power consumption and bandwidth-density are emerging as two of the central constraints for data center and high performance computers (HPC) [1, 2]. The Exascale supercomputing needs a thousand-fold increase in computing efficiency compared to the current petascale computing system while still maintaining a similar power consumption as the petascale systems at 20-50 MW scale [3]. Silicon photonics has the capability to provide a power efficient solution to move data in HPCs and data centers by integrating with high speed and energy efficient components. Among the key components, a low-voltage, high-speed Si-Ge avalanche photodiode with internal multiplication gain can improve optical receiver sensitivity by several dB in a power efficient way [4, 5]. More importantly, the adoption of APD in an optical link can reduce the power needed from lasers, hence reducing the power consumption for the whole link by multiple folds. Having a high data rate in each individual channel is cost effective to increase the system bandwidth-density, as it would require less channels to achieve the same capacity. To achieve high speed, a waveguide APD is often designed with a small size but its internal the quantum efficiency is usually sacrificed. Obtaining a design to recycle input optical power to increase quantum efficiency can improve system sensitivity and optical link budget without consuming additional energy. Here we demonstrate a high-speed, low-voltage avalanche photodiode that integrate a distributed bragg reflector and achieve over 40% improvement in quantum efficiency and be able to improve the optical system sensitivity by 1.2dB. This type of device can be fabricated without additional processing steps, hence it provides a cost-effective solution to improve the energy efficiency for a silicon photonic optical link.

2. Device Structure

The schematic of this SiGe waveguide APD with DBR is shown in Fig.1(a). This device is designed using a separate absorption-charge-multiplication (SACM) structure to confine a high electric field in the silicon multiplication region. The APD is fabricated on a 220 nm silicon-on-insulator (SOI) substrate and consists of a p-type Ge absorber, a p-type Si charger layer, and a Si multiplication layer which are epitaxially grown on the SOI. The DBR is fabricated in the same flow as a regular waveguide SiGe APDs during a waveguide etching step, and no additional fabrication process is needed [5, 6]. Since this waveguide APD couples light through a TM mode grating coupler centered at 1550nm, the DBRs are designed to optimize TM mode only. However due to the broadband nature of DBR and waveguide photodetectors, this design can be implemented in devices in a wide range of spectrum. We have included two DBR designs in this experiment where DBR2 uses a first order grating, and DBR1 uses a second order grating design. The second order grating in DBR1 are expected to have a higher scattering loss and lower reflectivity. However this design can be implemented in a dimension as large as 250 nm, which reliefs photo-lithography and fabrication constrains. For comparison, each type of DBR includes a split of 2-, 4- and 6-period of gratins on the chip. A FDTD simulation is conducted on the DBR structures and Fig.1(b) show the photo generation profile at 1550nm along the cross-section of a 4μm x 50μm device. Since germanium has a higher refractive index than silicon, in this structure, light propagates through a Si waveguide and evanescently couples from Si to Germanium and oscillates between these two materials until being fully absorbed. Consistent with measurement, at 1550nm, only 60% of the light is absorbed when traveling at 10μm-long distance. Fig.1(c)-(e) show the top views of the 4μm x 10μm-long devices with and without DBRs. The existence of the DBR reflects light back to the absorption region, being re-absorbed and generating photo carriers.

3. Measurement Results

The calculated reflectivities for the two DBR designs are shown in Fig. 1(f). Six periods of grating can achieve reflectivity upto 85% and 95% for DBR1 and DBR2, respectively. Due to a smaller scattering loss for the first order gratings in DBR2 and a slight off-shift of peak in DBR1 design, DBR2 in this work has 10% higher reflectivity than DBR1. The inset of Fig.1(f) shows the calculated reflectivity vs. wavelength over a broad range spectrum for the two DBR designs with 2, 4, and 6 periods, respectively. With 6 periods of gratings, the reflectivity has a 1dB-bandwidth over 200nm and 500nm for DBR1 and DBR2, respectively, making one design can fit for devices in a wide range of spectrum. Fig.1(g) shows a typical IV for a low voltage SiGe APD with DBR2 measured at 0, -5, -10dBm optical power, respectively. Similar to the low-voltage SiGe waveguide APDs that we have designed previously [5, 6], the low-voltage operation of APD at only 10V allows it to be compatible with computer power rails and reduce energy consumption for an optical link.

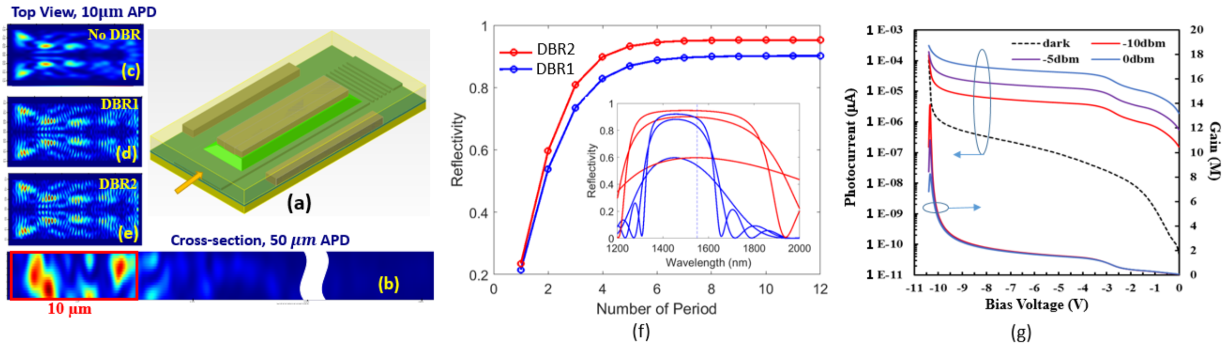

Fig. 1. (a) Schematics of SiGe waveguide APDs integrated with DBR; (b)-(e): FDTD simulated photo generation profiles: (b) Cross-section for a 4μm x 50μm device without DBR, (c) Topview for a 4μm x 10μm without DBR, (d) with DBR1, (e) with DBR2; (f) Calculated reflectivity vs number of period for the DBRs. The inset shows the calcuated reflectivity vs wavelength; (g) Dark and photo current vs voltage for a APD integrated with DBR2, measured at optical power of 0,-5,-10dBm, respectively.

Fig. 2(a) show the measured photocurrent vs. optical power for the three types of APDs with 4μm x 10μm dimension. The devices with 6-period gratings using DBR1 and DBR2 designs have consistently shown 30% and 40% higher photocurrent than no-DBR designs. The measured responsivity and quantum efficiency vs. device lengths in Fig.2(b) have shown a similar trend, where DBR1- and DBR2- devices with 6 grating periods have 30%-40% higher quantum efficiencies than a nominal APD without DBRs. Specifically on our chip where the 4μm x 30μm APDs consistently show the highest responsivites due to better mode coupling, the 4μm x 30μm APDs with 6-periods of gratings has a quantum efficiency as high as 95%.

The speed of APDs for both types of DBR designs are measured by an impulse response method as illustrated in [5, 6]. Fig.2(b) shows the measured impulse response for a 4μm x 10μm APD with DBR2 design. FWHMs of 14.5ps which correspond to a 3dB bandwidth of 25GHz is achieved. A similar bandwidth is also achieved from the DBR1 APDs. These bandwidths are in the same range as a nominal waveguide APDs without DBR given the same dimension, and indicates the integration of DBR can significantly increase waveguide APD responsivity without degrading its high speed performances.

The 32 Gbps NRZ and 64 Gbps PAM4 eye diagrams of Si-Ge APDs are measured by using $2^9 - 1$ pseudo random binary sequence (PRBS9) signal generated by a 96 GSa/s arbitrary waveform generator (AWG). Figure 3(a) and (c) show the measured eye diagrams measured at -8V with 32 Gbps NRZ and 64 Gbps PAM4 modulation for devices without DBR, with DBR1, and with DBR2, respectively. The post measurement analysis showed that the optical modulation amplitude has increased 30% for the APDs with DBRs. We expect receiver sensitivities can improve 1.2dB by integrating DBR designs in waveguide APD receivers.

4. Conclusion

High speed and energy efficient optical links are becoming essentially important for data centers and high performance computers (HPC). In this paper, we have demonstrated a low-voltage waveguide Si-Ge APD that integrates a distributed Bragg reflector (DBR) in its waveguide. The internal quantum efficiency has been improved from 60% to 90% at 1550nm for a waveguide APD with DBR while still achieving a 25GHz 3dB bandwidth. The APDs with DBR under 32Gbps NRZ and 64Gbps PAM4 modulation showed 30% increase in optical modulation amplitude (OMA) comparing to devices without DBR, which enables a 1.2dB improvement for APD receiver sensitivities by incorporat-

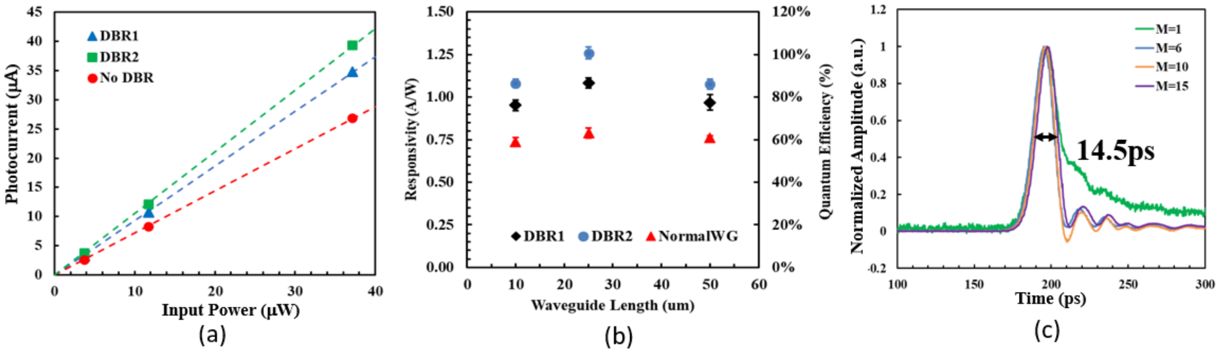

Fig. 2. (a) Phtocurrent vs input optical power for APDs with and without DBR designs. (b) Responsivity for devices at various lengths with and without DBR designs. (c)Impulse response of an APD integrated with DBR2 at various multiplication gains.

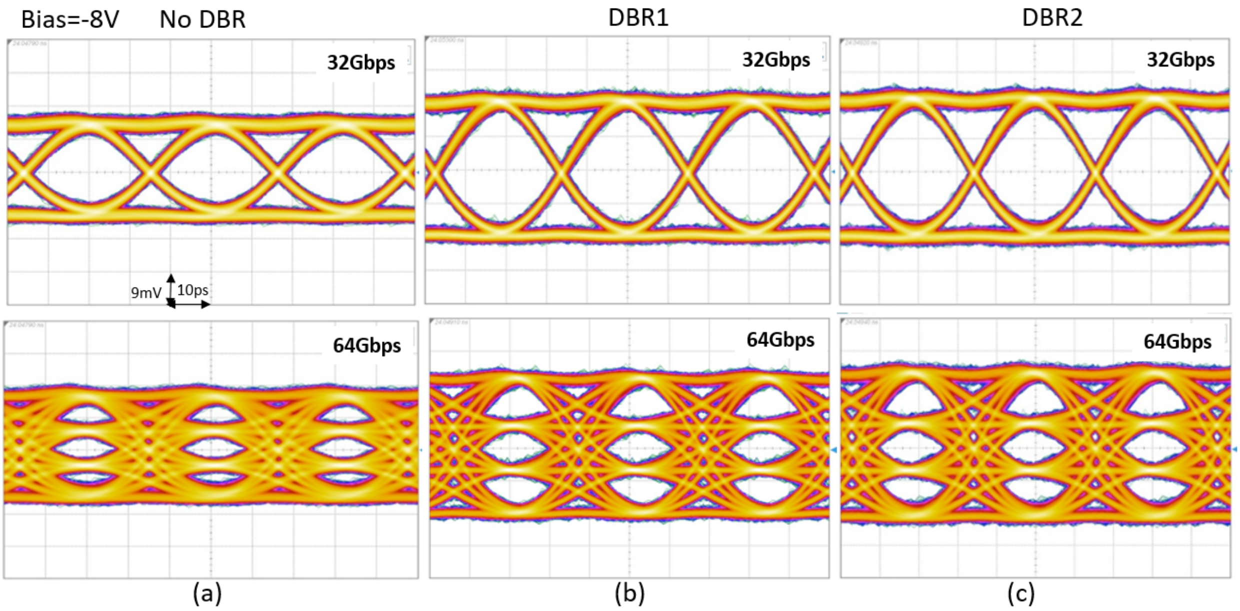

Fig. 3. Measured 32 Gbps NRZ and 64 Gpbs PAM4 eye diagrams for SiGe waveguide APDs measured at 8V with (a) No DBR, (b) DBR1, (c)DBR2.

ing DBR designs. This design can improve the optical link budget and reduces the energy consumption in an optical system without additional cost.

References

1. D. Thomson, *et al.* ”Roadmap on silicon photonics.” Journal of Optics, 18(7):073003, 2016.
2. Q. Cheng, *et al.* ”Recent advances in optical technologies for data centers: a review,” Optica 5, 1354-1370 (2018).
3. S. Rumley, *et al.*, ”Silicon photonics for exascale systems,” Journal of Lightwave Technology, 33(3):547–562, 2015.
4. J. C. Campbell. ”Recent Advances in Avalanche Photodiodes,” IEEE J. Lightwave Tech. 34, 278-285 (2016).
5. Z. Huang, *et al.* ”25 Gbps low-voltage waveguide Si-Ge avalanche photodiode,” Optica 3, 793-798 (2016).
6. B. Wang, *et al.* ”50 Gb/s PAM4 Low-Voltage Si-Ge Avalanche Photodiode,” CLEO: Science and Innovations, SM4J-7 (2019).