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200Gb/s per lane Ge/Si waveguide avalanche photodiode

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Abstract *We demonstrate a waveguide-integrated Ge/Si APD with 3dB bandwidth of 52.2GHz at gain of 3.8 and 45.8GHz at gain of 6. This device also shows a large dynamic range with responsivity changes 1.6-3.5A/W. This high-performance device is suitable for various 200Gb/s per lane applications.*

Introduction

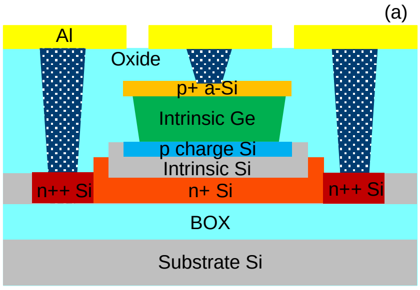
The optical fiber communication bandwidth increases significantly in last several years, which is driven by various high-speed demands such as cloud computing, online streaming, 5th generation (5G) wireless communications, etc. In nowadays, ethernet systems of 400G/800GBASE and beyond are essential to accommodate these fast-expending applications. However, higher bandwidth is unavoidable to bring larger shot noise and to degrade sensitivities of fiber communication systems. Furthermore, technologies like wavelength division multiplexing (WDM) and complex modulations (PAM, QAM, etc) are applied to maximize the efficiency of bandwidths. Those deployments also bring more demands on link budgets and limit operation distances. For instance, currently 4x100Gb/s photodiode (PD) receivers meet 10km reach applications, but the distance becomes 2km after data rate increasing to 200Gb/s per lane (200G/L) [1,2]. This degradation of sensitivity at higher baud rate limits the upgrade of fiber communications to next generation.

On the other hand, avalanche photodiode (APD) provides 5-10dB sensitivity margins compared to PD; moreover, APD receiver has similar size and close power consumptions as PD receiver, which is the ideal solution for high link budget scenarios such as 200Gb/s per lane communications. However, most of previous reported APD devices, under high gain operations, show 3dB bandwidth below 40GHz [3-5] and cannot meet bandwidth requirements of 200G/L receivers (3dB BW >45GHz) [1,6]. The fundamental limitation of APD 3dB bandwidth is gain-bandwidth product at linear mode [7], which is referred to APD operating at bias below breakdown voltage with low dark current and linear response of RF signals. Typically, III-V or pure-Ge APDs reported limited linear gain-bandwidth product ~150GHz, which can only have limited gain (such as <3) when APDs have 3dB bandwidth >45GHz. In contrast, germanium on silicon avalanche photodiode (Ge/Si APD) uses silicon as avalanching material with low ionization coefficient ratio and large linear gain-bandwidth product. These benefits provide the feasibility of Ge/Si APD operating at 200Gb/s per lane with high gains. In this paper, we report our latest progress of our Ge/Si APD for various 200G/L applications.

Device structure

Figure.1 (a) shows the cross-section of our 200Gb/s per lane WGAPD. This WGAPD, similar to our 106Gb/s design, adopts recess-type and separate-charge-absorption (SCAM) structure [8]. However, to further enhance device's bandwidth, we significantly redesigned device's film stack and more important, we completed a precisely control of electrical field distribution within device. Electrical field distribution plays an important role in APD RF characteristics because we need to have proper E-field (e.g. >7kV/cm) inside Ge absorber to make photon generated carrier to reach saturation velocity; and then we need to minimize E-field close to Ge/Si interface (like <150kV/cm) to avoid avalanching inside Ge. Moreover, we need to maintain a very high E-field (such as >400kV/cm) inside intrinsic silicon layer to keep multiplication process happening. All these need to have accurate control of thickness and doping profile of devices, especially at Ge/Si interface because of the existence of shallow level defect states and type-I heterojunction [9].

(a)



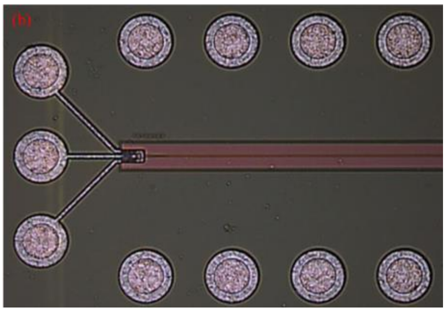


Fig. 1: (a) schematic diagram of cross-section of recess type WGAPD; (b) OM images of recess type WGAPD

Device characteristics

Figure 2 presents our IV and responsivity characteristics of our 200Gb/s per lane WGAPD at room temperature. The WGAPD breakdown voltage (V_{br}), defined as the bias at which dark current equals 100μA, is close to -14V. At operating bias equal to -12.6V (0.9Vbr), the APD dark current is only 1.4μA and the 1310nm responsivity is 3.5A/W (with input optical power equal to -17.8dBm) at room temperature. The punch-through voltage (V_{pt}) of this WGAPD is -10V, at this bias the entire device reaches smallest capacitance and APD gain is close to 2.8. The unity responsivity (at gain equal to 1) is 0.57A/W at 1310nm for both TE and TM modes which is extracted by using Ge/Si WGPD structure with the similar film thicknesses. The device's responsivity can be further improved by various reflector designs [10] because this APD is using one-side waveguide input shown as figure 1(b).

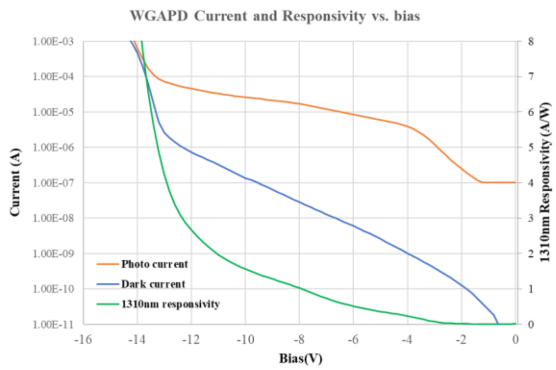


Fig. 2: WGAPD dark/photo currents and responsivity characteristics.

Figure 3 presents WGAPD room temperature S21 curves under different gains. All S-parameters' measurements are conducted by Keysight 67GHz LCA (N4373E) with 50Ω load and input optical power ~-17dBm. The optical power is close to sensitivity specifications in most 400GbE or 800GbE standards. What's more, the low input optical power causes less photon-generated carriers and as a result, no space-charge effect happens then it has no impact during device's gain and bandwidth measurements. Under this operating condition, our 200Gb/s per lane WGAPD's 3dB bandwidths reach 52.2GHz at gain of 3.8, 48.2GHz at gain of 5 and 45.8GHz at gain of 6, respectively. Besides high 3dB bandwidths, all measured S21 curves present flat response at low frequency range (DC-20GHz), which proves this APD device is not operating under high bias range (e.g. > V_{br}) with negative differential resistance (NDR) effect to boost bandwidths [9]. This high-performance linear APD device satisfies complex modulations adopted by various 200G/L systems including 112Gbaud PAM4 and 128Gbaud QAM16.

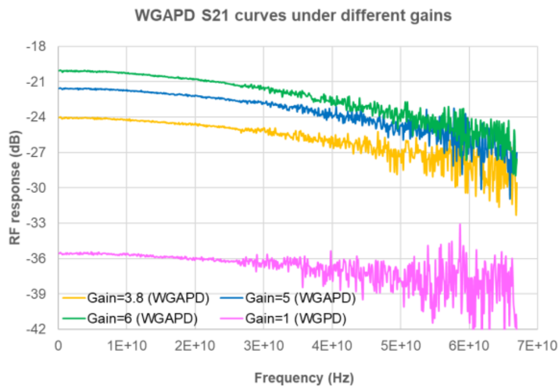


Fig. 3: S21 curves of WGAPD under high gain and WGPD at gain=1 (with the same input optical power)

Moreover, we conducted RF fittings of S22 curve to study this device's junction characteristics, parasitic parameters, and transit time bandwidth under operating bias. Figure 4(a) is the circuit model applied to extract parameters and figure 4(b) presents the measured and fitting results of S22 curve on Smith chart.

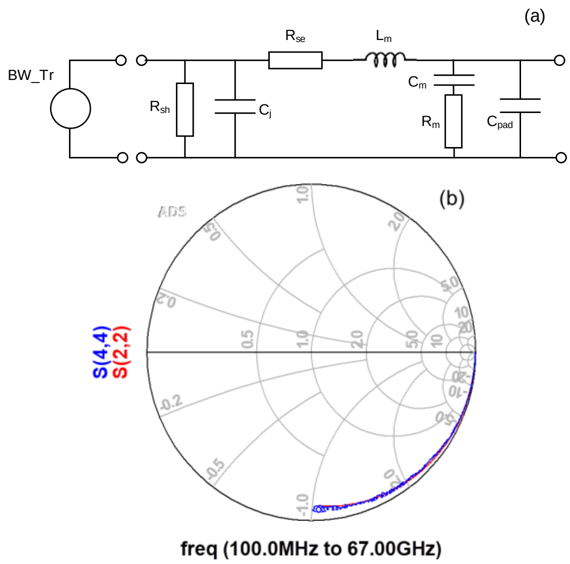


Fig. 4: (a) WGAPD circuit model, (b) measured and fitting results of WGAPD S22

Table 1 shows all parameters extracted from circuit model. Our APD device has small junction capacitance of 23.1fF and series resistance of 7.6Ω, which has a large RC-limited bandwidth (>100GHz). Therefore, this APD's 3dB bandwidth is mainly dominated by transit-time limited bandwidth especially at high gains.

Tab. 1: parameters extracted from WGAPD S22 curve

Parameter	Symbol	Value
Shunt Resistance	R_{sh}	4.4 MΩ
Junction Capacitance	C_j	23.1 fF
Series Resistance	R_{se}	7.6 Ω
Metal Inductance	L_m	85 pH
Pad Capacitance	C_{pad}	10.5 fF
Metal/Sub Capacitance	C_m	25.5 fF
Metal/Sub Resistance	R_m	19 kΩ

Besides high gains, we also analyse our device's bandwidth performance at unity gain. However, the operating bias, at gain equal to 1, is smaller than V_{pt}. That causes E-field mainly existing in Si layer but Ge layer is not completely depleted, so photon generated carriers cannot reach saturation velocities when WGAPD device is biased at gain of 1. Therefore, we can only extract 3dB bandwidth at unity gain by using Ge/Si WGPD with the same film thickness as WGAPD. This Ge/Si WGPD 3dB bandwidth reaches 64GHz as shown in figure 3 and 5.

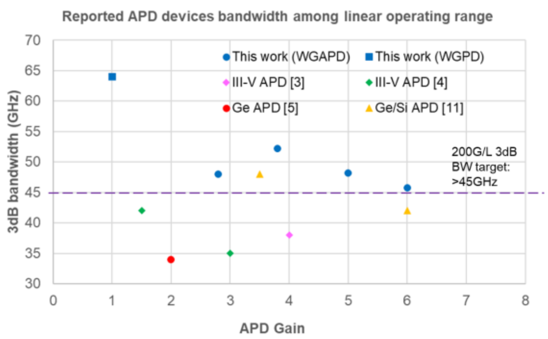


Fig. 5: Reported APD devices operating in linear gain-bandwidth product range

Figure 5 lists various reported APD devices' 3dB bandwidth operating at linear mode. To our best knowledge, our APD demonstrates the best 3dB bandwidths at high gains among all published results. Moreover, our APD 3dB bandwidth meets 200G per lane requirements (>45GHz) within a large dynamic range: APD responsivity changes from 1.6A/W to 3.5A/W (gain 2.8-6). Thus, this APD receiver meets the operation requirements for both high-sensitivity and overload, which benefits a variety of 200Gb/s per lane optical fiber communications systems.

Conclusions

We successfully developed a recess-type Ge/Si WGAPD with record high bandwidth and responsivity, which pave the road of large-scale implementations for various 200Gb/s lane optical fiber communications systems with high link budget requirements.

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References

[1] R. Nagarajan, I. Lyubomirsky, "Next-Gen Data Center Interconnects: The Race to 800G", *COBO Webcast*, 2021

[2] Y. Tian, et al, '800Gb/s-FR4 specification and interoperability analysis', *Optical Fiber Communications Conference and Exhibition*, paper W7F6, 2021

[3] M. Nada, et al, "A 42-GHz Bandwidth Avalanche Photodiodes Based on III-V Compounds for 106-Gbit/s PAM4 Applications" *Journal of Lightwave Technology*, Volume: 37, Issue: 2, 2019

[4] T. Okimoto, et al, "106-Gb/s Waveguide AlInAs/GaInAs Avalanche Photodiode with Butt-joint Coupling Structure", *Optical Fiber Communications Conference and Exhibition*, paper W3D.2, 2022

[5] S. Assefa, et al, "Reinventing germanium avalanche photodetector for nanophotonic on-chip optical interconnects", *Nature*, vol. 464, pp. 81-84, 2010

[6] B. Welch, "Modulation proposal for 200G/L solutions for 500m and 2km reaches", *IEEE P802.3df 200 Gb/s, 400 Gb/s, 800 Gb/s, and 1.6 Tb/s Ethernet Task Force,* Feb 2022

[7] J. Campbell, "Recent Advances in Avalanche Photodiodes", *Optical Fiber Communications Conference and Exhibition*, paper M3C.1, 2015

[8] M. Huang, et al, 'Recess-type waveguide integrated germanium on silicon avalanche photodiode', *Optical Fiber Communication Conference*, paper F2C.3, 2021

[9] M. Huang, et al, 'Germanium on silicon avalanche photodiode for high-speed fiber communication', *Book chapter of "Photodetectors - Recent Advances, New Perspectives and Applications,"* edited by Dr. Kuan Chee, University of Cambridge, 2022 (Invited)

[10] Y. Yuan, et al, "High Responsivity Si-Ge Waveguide Avalanche Photodiodes Enhanced by Loop Reflector", *IEEE Journal of Selected Topics in Quantum Electronics,* Vol. 28, No. 2, 2022

[11] M. Huang, et al, '56GHz Waveguide Ge/Si Avalanche Photodiode', *Optical Fiber Communication Conference*, W4D.6, 2018