Superior Temperature Performance of Si-Ge Waveguide Avalanche Photodiodes at 64Gbps PAM4 Operation

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Abstract: We demonstrate a low voltage Si-Ge waveguide avalanche photodiode with extremely high temperature performance. It exhibits high temperature stability from 30 °C to 90 °C, and achieves excellent operation with 64 Gb/s PAM4 modulation.

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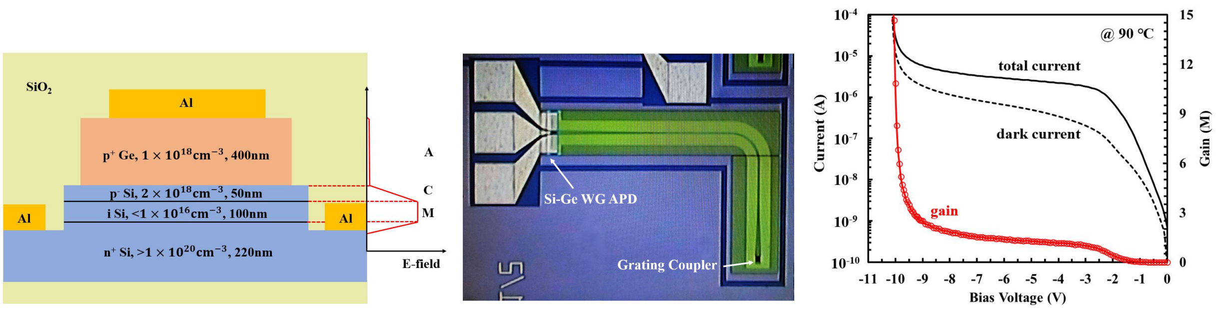
1. Introduction

Data transmission grows explosively due to the massive growth of data-based applications such as Internet of Things (IoT), machine learning and cloud computing. This requires that data centers and high-performance computers (HPCs) ultimately adopt high-bandwidth-density optical interconnects. Integrated silicon photonics with on-chip lasers and Si-Ge avalanche photodiodes (APDs) is a competitive solution due to its large scale integrability, low cost, and low energy consumption [1,2]. A low-voltage Si-Ge APD with internal multiplication gain and low excess noise has shown its advantages in reducing the power consumption and increasing the link budget in an optical link [3,4]. Currently data centers and HPCs consume 4.16×10^{11} W of power, and this number is continuously growing exponentially. Approximately 38% of the total consumed energy is for cooling in data centers. Meanwhile, one-degree-increase in the operation temperature of a data center can save approximately 4% energy consumption [5]. Hence, elevating the operation temperature of an optical link can bring a huge energy saving in data centers in potential. However, there were rarely researches about the high temperature performances for Si-Ge APDs. Here, we demonstrate a low-voltage, high-speed Si-Ge waveguide APD that shows superior high temperature performances with 100% internal quantum efficiency. It is extremely temperature insensitive in breakdown voltage, bandwidth and gain-bandwidth product (GBP). The excellent temperature characteristics of this Si-Ge APD enlightens its potential to be used in an optical link with high temperature operation to achieve energy efficient data centers and HPCs.

2. Device Structure

The Si-Ge waveguide APD was grown on a 220 nm silicon-on-insultaor (SOI) substrate and then buried by SiO_2 as passivation. It consists of a 400 nm p-type Ge absorber, a 50 nm p-type Si charger layer, a 100 nm UID Si multiplication layer, and a 220 nm n^+-type Si contact layer, as shown in Fig. 1(a). In order to improve the temperature insensitivity, the whole Germanium region is p-type doped that most of the electric field is restricted in the Si multiplication layer. All measurements in this work are taken from a 4 μm-width and 10 μm-length APD by coupling the light into the device through a grating coupler as shown in Fig. 1(b). The current versus voltage plot at 90 °C is shown in Fig. 1(c). This Si-Ge APD has a low breakdown voltage of -10 V. As expected, due to the increase of generation-recombination (G-R) at a higher temperature, the dark current is higher than operating at room temperature. However this type of device can still obtain a relatively high gain up to $\sim$ 15 at 90 °C.



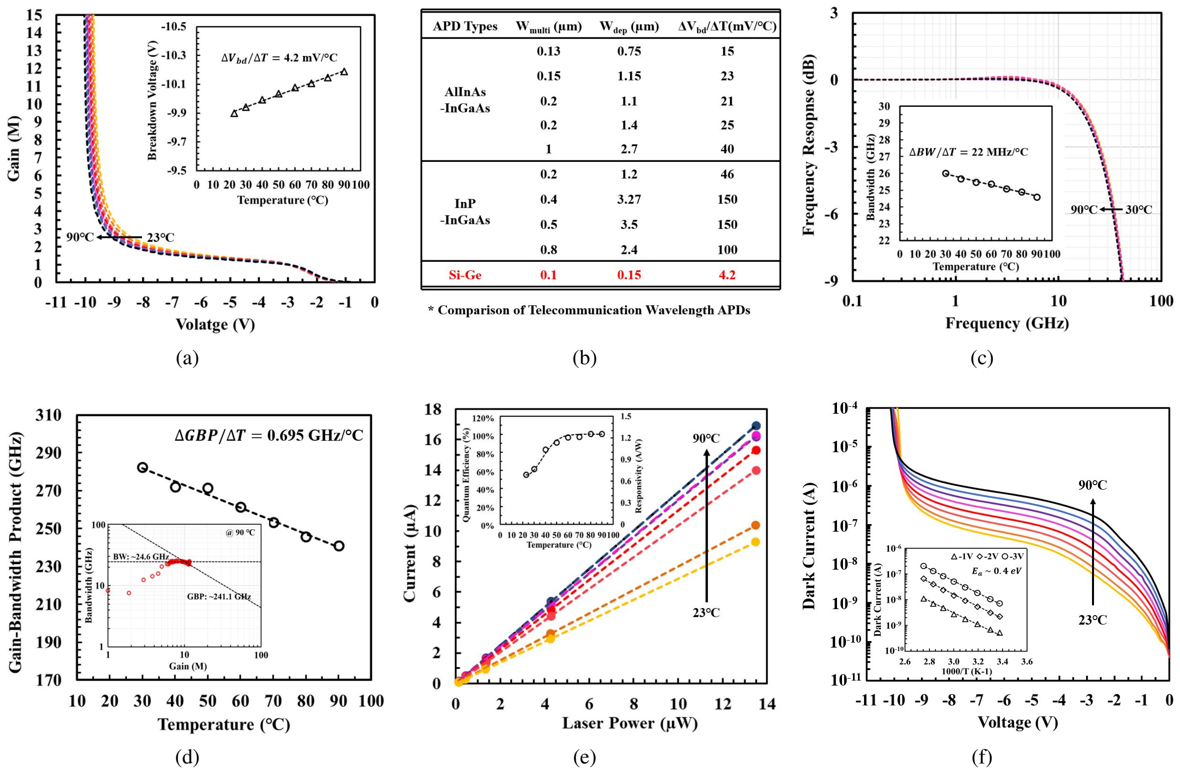
(a) (b) (c)

Fig. 1. (a) Device structure diagram; (b) schematic photo; (c) current versus voltage at 90 °C of $4\mu m\times10\mu m$ Si-Ge waveguide APDs.

3. Temperature-Dependent Characteristics

Figure 2(a)-2(f) illustrate the temperature-dependent gain, bandwidth, GBP, internal quantum efficiency (QE), and dark cureent from 23 °C to 90 °C, respectively. As a result of phonon scattering, carriers require higher electric field to maintain the same gain, hence the gain curve of a APD usually shifts to higher bias as the temperature increases. Fig. 2(a) shows the breakdown voltage increases only $\sim$ 4.2 mV/°C, which is much lower than other AlInAs-InGaAs and InP-InGaAs SACM APDs at telecommunication wavelength [6–8]. Due to the special structure design, we expect the temperature performances of this design also exceeds the SACM Si-Ge APDs with higher breakdown voltages. The detailed comparison of breakdown voltage changes, $\Delta V_{bd}/\Delta T$, are shown in Fig. 2(b). This remarkably low temperature-dependent breakdown voltage is due to the ultra-thin multiplication width, $W_{multi} = 0.1\mu m$, and depletion width, $W_{dep} = 0.15\mu m$; and the intentially doped Germanium absorption region. It also exhibits a stable bandwidth and GBP, the temperature-dependent frequency responses were demonstrated in Fig. 2(c), 2(d). The results were achieved by doing fast Fourier transform (FFT) of impulse responses. To perform the impulse-response measurement, a Calmar femtosecond fiber pulsed laser was coupled into the APD as the impulse light source and the response was observed on a 65 GHz DCA sampling scope after a 25 GHz bias tee. 3-dB bandwidth reduces from 26.0 GHz at 30 °C to 24.6 GHz at 90 °C which only has a $\sim$ 22 MHz/°C degradation. The GBP reduces from 282.4 GHz at 30 °C to 241.1 GHz at 90 °C, with a $\sim$ 0.695 GHz/°C gradient.

In addition to low temperature variation in both bandwdith and GBP, another bonus of operating such a Si-Ge APD at an elevated temperature is the increased internal QE. Figure 2(e) displays the photocurrent versus laser power, where QE equals to the slope of the fitted linear lines. The internal QE increases from 56% at 23 °C to nearly 100% at > 80 °C owing to the increased absorption coefficient of Ge absorber [9]. Moreover, the dark current shows a uniform increase with temperature from 23 °C to 90 °C as shown in Fig. 2(f). By fitting the dark current at -1 V, -2 V, and -3 V, the activation energy of the Si-Ge APD, $E_a = 0.4\ eV$, is extrected which is the half bandgap of Ge Γ 1 point, $E_{\Gamma 1} = 0.8\ eV$. Therefore, the main source of dark current at low bias comes from G-R process in the Ge absorber.



APD Types	W_{multi} (μm)	W_{dep} (μm)	$\Delta V_{bd}/\Delta T$(mV/°C)
AlInAs -InGaAs	0.13	0.75	15
	0.15	1.15	23
	0.2	1.1	21
	0.2	1.4	25
	1	2.7	40
InP -InGaAs	0.2	1.2	46
	0.4	3.27	150
	0.5	3.5	150
	0.8	2.4	100
Si-Ge	0.1	0.15	4.2

* Comparison of Telecommunication Wavelength APDs

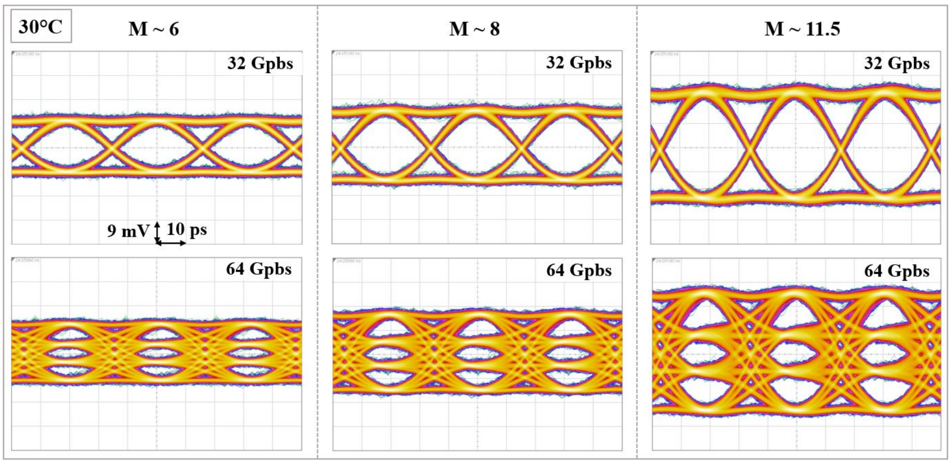
Fig. 2. Temperature-dependent characteristics of (a) gain ; (b) different telecommunication wavelength SACM APDs; (c) bandwidth; (d) gain-bandwidth product; (e) internal quantum efficiency; and (f) dark current for Si-Ge waveguide APDs.

4. Eye Diagrams Results

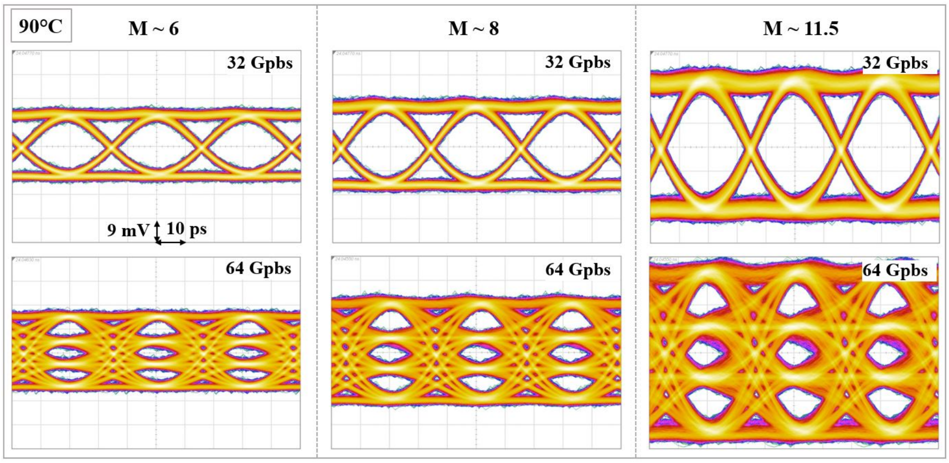
Eye diagrams of Si-Ge APDs were measured by using a 96 GSa/s arbitrary waveform generator (AWG) which produces a $2^9 - 1$ pseudo random binary sequence (PRBS9) signal. The signal distortion from Mach-Zehnder modulator (MZM), transimpedance amplifier (TIA), and electrical cables was calibrated by the AWG internal functions before the test. An erbium-doped fiber amplifier (EDFA) and a band-pass filter were used to compensate the optical loss from MZM and the grating coupler [10]. Figures 3(a), 3(b) show the measured eye diagrams at 32 Gbps NRZ and 64 Gbps PAM4 modulation with gain of M $\sim$ 6, 8, and 11.5 at 30 °C and 90 °C respectively. The Si-Ge waveguide APD exhibit clear open eye diagrams with both 32 Gbps NRZ and 64 Gbps PAM4 modulation, and the optical modulation amplitude increases with the multiplication gain. In addation, the Si-Ge APD has a wider open eye diagrams at 90 °C due to the increased quantum efficiency in Fig. 2(e).

5. Conclusion

The Si-Ge waveguide APD exhibits an extremely high temperature performance. At 90 °C, it has low breakdown voltage about -10 V, high gain value up to 15, high 3-dB bandwidth about 24.6 GHz, high GBP higher than 240 GHz, high



(a)



(b)

Fig. 3. 32 Gbps NRZ and 64 Gpbs PAM4 eye diagrams of Si-Ge waveguide APDs with M $\sim$ 6, 8, and 11.5 at (a) 30 °C and (b) 90 °C.

internal QE up to 100%, and clear open eye diagrams with 32 Gbps NRZ and 64 Gbps PAM4 operation up to M $\sim$ 11.5. It also exhibits a superior high temperature stability, which the breakdown voltage increases $\sim$ 4.2 mV/°C; the bandwidth reduces $\sim$ 0.09%/°C; GBP reduces $\sim$ 0.24%/°C. The advantages of this low-voltage high speed Si-Ge APD with high temperature stability opens an opportunity to explore a high-bandwidth-density optical link operating at an elevated temperatures for energy efficient data centers and HPCs.

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