Cryogenic Ge-on-Si avalanche photodiodes operating at 1550 nm wavelength

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Abstract: We report the first demonstration of Ge-on-Si APD for 1550 nm wavelength photodetection at the cryogenic temperature down to 11 K, with I_{dark}=0.369 µA, R=4.84 A/W and G=1840 at V_{bias} = −20.8 V. © 2024 The Author(s)

1. Introduction

Photodetectors operated at cryogenic temperatures (less than 120 K) have been widely used for a variety of applications, e.g. infrared imaging, quantum communication and computing [1,2]. Among the photodetectors, the avalanche photodiode (APD) outstands for its exceptional sensitivity at low-light condition, resulting from its internal avalanche multiplication process. With the advancement of the silicon photonics technology, germanium-on-silicon (Ge-on-Si) APD has attracted great attentions in recent years [3-7]. This device combines the superb avalanche multiplication properties of Si and the relatively large light absorption coefficients of Ge at λ = 1550 nm. Traditionally, the investigations of 1550 nm wavelength Ge-on-Si APDs are carried out only at temperature T ≥ 100 K [4,8]. One concern is that Ge is no longer an efficient 1550 nm light absorber due to the bandgap broadening at very low temperature. This significantly hinders the potential applications of Ge-on-Si APDs in cryogenic systems below 100 K temperature.

In this work, we report the first demonstration of a Ge-on-Si APD operated at T < 100 K for 1550 nm light detection. The photo-response performances of the device are characterized at T ranging from 11 to 300 K. It is found that the APD works well at T = 11 K, with a dark current I_{dark} = 0.369 µA, a responsivity R = 4.84 A/W and an avalanche gain G = 1840 when biased at V_{bias} = −20.8 V.

2. Design and fabrication

The vertical-illuminated Ge-on-Si APD is based on a separate-absorption-charge-multiplication (SACM) structure. Figures 1(a) and 1(b) show the three-dimensional (3D) and the cross-sectional schematics of the device, respectively. The optical microscopy image of the fabricated SACM Ge-on-Si APD with a mesa diameter D = 15 µm is shown in Fig. 1(c). To realize the SACM structure, the p^+-Ge contact layer, i-Ge absorption layer, p^--Si charge layer, i-Si multiplication layer and n^+-Si contact layer are formed on a Si (100) substrate by multiple epitaxy and ion-implantation steps. The circular mesa of the APD is formed by UV photolithography and fluorine-based dry etching. After that, the exposed mesa is passivated with an 800 nm thick silicon oxide (SiO_2) film by plasma enhanced chemical vapor deposition (PECVD). The SiO_2 layer also serves as an anti-reflection coating of the incident light. Finally, contact vias are etched and aluminum (Al) ground-signal-ground (GSG) electrodes are formed by magnetron sputtering and chlorine-based dry etching.

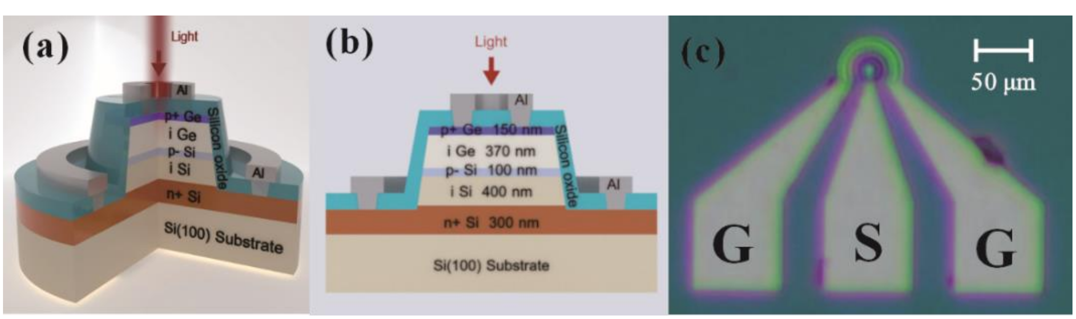

Fig. 1. (a) The 3D schematic of a normal-incident SACM Ge-on-Si APD. (b) The cross-section of the Ge-on-Si APD. (c) The optical microscopy image of the fabricated Ge-on-Si APD with D = 15 µm.

3. Characterization

The total current *vs.* bias voltage (I_{total}-V_{bias}) characteristics of the Ge-on-Si APD are measured using a Keithley 4200A-SCS parameter analyzer and a high-precision optical alignment stage. The APD is illuminated by a lensed fiber which is connected to a tunable laser with λ = 1475 to 1650 nm. Figure 2(a) shows the room-temperature I_{total}-V_{bias} characteristics of the APD illuminated with different optical power (P_{in}) at 1550 nm wavelength. The black dashed line is the I_{dark} of the device. The breakdown voltage V_{br} is defined as the voltage at which the current exceeds 100 µA. The V_{br} is −23.05 V at room temperature, and the I_{dark} =1.219 µA at 0.95 V_{br}. Figure 2(b) shows the responsivity and gain of the device at various P_{in} and the inset shows the zoomed-in view of the plots near the V_{br}. Due to the space charge effect [9], it can be observed that G and R increase with decreasing P_{in}. When P_{in} = −28.5 dBm, the R and the G at V_{bias} = 0.95 V_{br} are measured to be 3.51 A/W and 5.1, respectively. In addition, the Ge-on-Si APD is demonstrated to cover a wavelength range from 1475 to 1650 nm at room-temperature, as shown in Fig. 2(c). The P_{in} is fixed at −28.5 dBm. Figure 2(d) shows the R and G of the device at the fiber-optic communication bands from S to U. When the V_{bias} = −22 V, the APD exhibits R = 0.981 A/W at λ = 1650 nm.

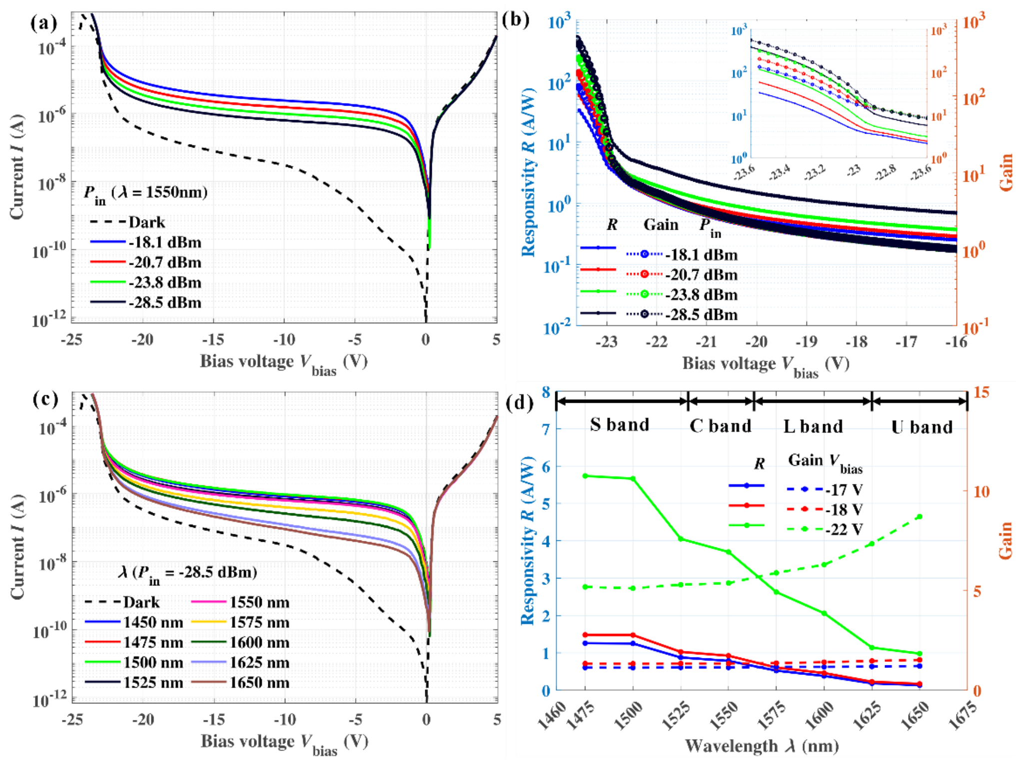

Fig. 2. Photo-response characteristics of the Ge-on-Si APD at room-temperature. (a) The I_{dark} and I_{total} of Ge-on-Si APD as the V_{bias} varies. (b) The R and G as the V_{bias} varies. (c) The I_{total}-V_{bias} curves as the λ varies. (d) The R and G of the APD at different V_{bias}.

The I_{total}-V_{bias} characteristics of the APD at different temperatures are measured on a helium-cooling probe station with DC and fiber ports. Figure 3(a) shows the I_{total}-V_{bias} characteristics with T ranges from 11 K to 350 K at λ = 1550 nm. The P_{in} is fixed at −18.1 dBm. An obvious photo-response can be observed for the fabricated Ge-on-Si APD at λ = 1550 nm, T = 11 K. In addition, the I_{dark} increase as the T increase and meanwhile V_{br} becomes larger. The temperature-dependent V_{br} shifts to 23 V at T = 300 K, which consistent with the room temperature result mentioned above. The shifting of V_{br} at higher T is due to the enhancement of phonon scattering. Thus, a larger reverse V_{bias} is needed to trigger the avalanche multiplication process [10].

To better understand the APD performance at low T, the I_{dark} and I_{total} versus V_{bias} at T = 11 K is plotted in Fig. 3(b). It is worth noting that when V_{bias} = −20.8 V, a decent photo-to-dark current ratio, which is defined as (I_{total}−I_{dark})/I_{dark}, of larger than 200 is achieved. It is at the same V_{bias} that a dark current of 0.369 µA, a responsivity of 4.841 A/W and a gain of 1840 are achieved. The comparison between the R and G characteristics of the APD near breakdown voltage at different T is shown in Fig. 3(c). It should be noted that although the 1550 nm responsivity of the APD without gain is only around 0.0026 A/W at T = 11 K, a large responsivity could still be achieved due to the much larger avalanche gain of the device as compared to those operated at room temperature.

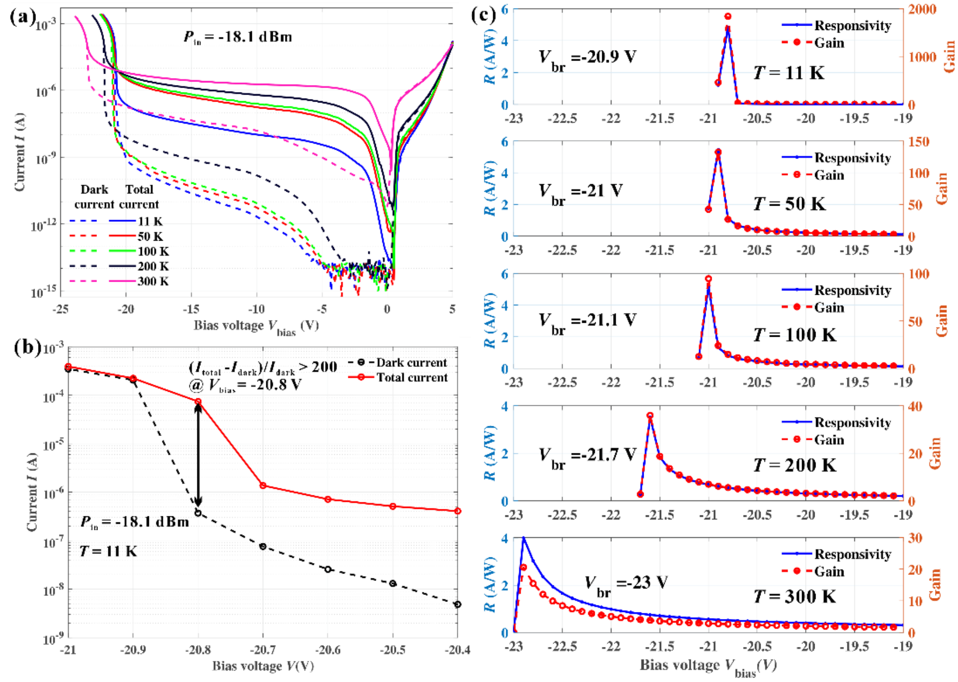

Fig. 3. (a) The I_{dark} and I_{total} of Ge-on-Si APD as the T ranges from 11 to 300 K at λ = 1550 nm. (b) The I_{total} and I_{dark} of the APD at T = 11 K. A photo-to-dark current ratio over 200 is realized at V_{bias} = −20.8 V. (c) The R and G of the device at different T.

4. Conclusion

In summary, a Ge-on-Si APD operated at T < 100 K for 1550 nm light detection is demonstrated for the first time. The APD works well at T = 11 K, with I_{dark} = 0.369, R = 4.84 A/W and G = 1840 at V_{bias} = −20.8 V. This work paves the way for large-scale photonic integrate circuits at cryogenic temperatures for a variety of emerging applications.

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5. References

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