Ultrafast 67 GHz Waveguide-Coupled Silicon-Germanium Avalanche Photodiode

Yang Shi, Mingjie Zou, Zuhang Li, Xinliang Zhang & Yu Yu*
Wuhan National Laboratory for Optoelectronics & School of Optical and Electronic Information,
Huazhong University of Science and Technology, Wuhan, 430074, China.
*[*yuyu@mail.hust.edu.cn](mailto:yuyu@mail.hust.edu.cn)*

Abstract: We demonstrate a silicon-germanium avalanche photodiode with record-high bandwidth of 67 GHz under a modest gain of 6.6, by levering the gain and bandwidth through comprehensively manipulating photocurrent density and electric field in multiplication region.

1. Introduction

The explosive growth of global data traffic has been going on for several years, driven by applications such as datacenter, high-performance computing and mobile internet. Optical interconnects have gradually replaced traditional electrical interconnects as new broadband enablers in these scenarios. As a crucial building block in optical link, the reception of high-speed optical signals is mainly performed through large-bandwidth positive-intrinsic-negative (PIN) or avalanche photodiodes (APDs). Typically, the APDs can provide 5-10 dB higher sensitivity thanks to the significant internal gain. Therefore, they are often considered canonical optical receivers for scenarios such as long-distance optical communications and passive optical networks. Compared with indium phosphide (InP)-based counterparts, silicon-germanium (Si-Ge) APDs have gradually obtained attention, owing to excellent multiplication property of silicon material and low-cost complementary metal-oxide-semiconductor (CMOS)-compatible fabrication. The waveguide-coupled structure is used to achieve simultaneous high responsivity and large bandwidth, compared with the normal-incidence APDs. Furthermore, the separate-absorption-charge-multiplication (SACM) structure is very popular as it prevents the multiplication of the Ge material by providing a weak electric field in the Ge region, potentially providing higher gain-bandwidth products (GBPs) and lower excess noise. In conventional APDs, the GBP is usually a constant and a high gain can be obtained by increasing the bias voltage, degrading the bandwidth inevitably. This is unfavorable for high-speed signal reception where a larger bandwidth is prioritized. On the other hand, for high-speed applications, a modest gain is usually preferred to enable high-sensitivity data reception when considering the multiplication noise [1].

Here, we demonstrate a waveguide-coupled SACM APD with a record-high bandwidth of 67 GHz operating at 1550 nm, by manipulating photocurrent density and electric field in the multiplication region. Being different from conventional APDs, the gain of the proposed device first increases and then decreases at high bias voltage, resulting in a significant bandwidth improvement under a fixed GBP. The reduced gain under high bias voltage is attributed to the electric field shielding in the multiplication region, known as the space charge effect (SCE) [2], weakening the impact ionization. This phenomenon can be elaborately regulated by controlling the photocurrent density (i.e., electron-hole density) through tailoring the device volume, as well as optimizing the electric field in the multiplication region. Under -10.6 V bias, the measured bandwidth is as high as 67 GHz with a gain of 6.6, corresponding a GBP of 442 GHz. Open eye diagrams for 64 Gb/s on-off keying (OOK) are obtained. Thanks to the CMOS-compatible fabrication and high bandwidth, this work is promising for low-cost and ultra-fast photodetection.

2. Device Structure

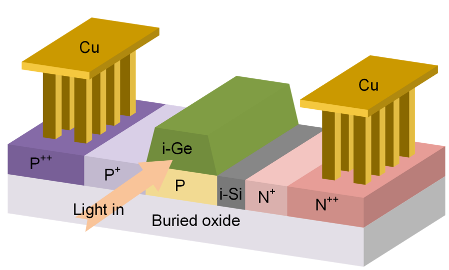

Fig. 1. The structure of the waveguide-coupled SACM APD.

Figure 1 shows the structure of the proposed SACM APD with a lateral p^+-i-p-i-n^+ junction, fabricated on a silicon-on-insulator (SOI) platform. The waveguide-coupled structure is utilized to decouple the optical absorption and carrier transit path, enabling a simultaneous high responsivity and large bandwidth. The intrinsic Ge (i-Ge) and intrinsic Si (i-Si) serve as optical absorption layer and electron multiplication layer, respectively. The i-Ge region of 14-µm length guarantees sufficient optical absorption at 1550 nm. A 100-nm multiplication width is adopted for a large bandwidth and a low breakdown voltage. In addition, the small-volume i-Ge and i-Si regions are beneficial to increasing the photocurrent density under high bias voltages, which helps to shield the electric filed in the multiplication region and enlarge the bandwidth. The P-doped charge layer with a concentration of 1×10^{18} cm^{-3} keeps the electric field in the Ge region lower than 2×10^{7} V/m, preventing the Ge multiplication. It is of equal width with the Ge region to make the Ge region contact with the Si multiplication region, thereby minimizing the carrier transit time and ensuring the high-speed operation.

3. Static Performance

Firstly, the static performance of the fabricated APD is measured. Figure 2(a) shows the measured dark current and photocurrent when operating at 1550 nm with different optical powers varying from -10 to -25 dBm. The optical power is the power fed into the active region by deducting the coupling loss. The breakdown voltage is determined to be -8.4 V, defined as the applied voltage when the dark current reaches 100 µA. The low breakdown voltage provides low power consumption and the potential compatibility of the integrated electrical circuit. The measured dark current is 20 µA at -7.6 V (90% of the breakdown voltage).

The optical responsivity under unity gain is 0.77 A/W at -4.8 V, obtained by comparing the responsivity with the reference p-i-i-n photodiode without the charge layer on the same chip. The gains under different voltages and optical powers are shown in Fig. 2(b). To be noted, the gain reaches the maximum value at -9.5 V for different optical power, and it decreases under higher voltages due to the high photocurrent density inside the multiplication region and the resulting SCE, as shown in the dashed box in Fig. 2(b).

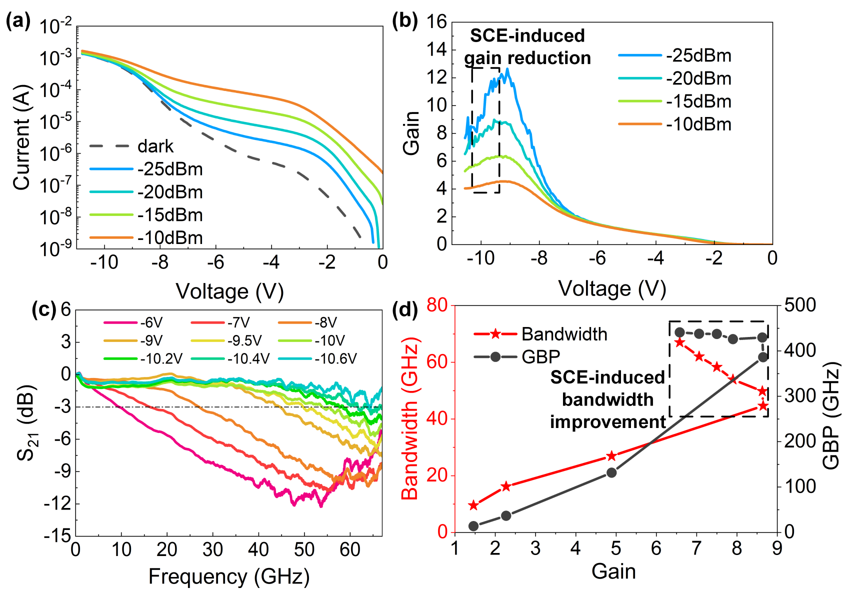

Fig. 2. (a) The measured current-voltage characteristic in dark state and under different optical power. (b) The measured gains under different voltages and optical power. (c) The measured S_{21} frequency response from -6 to -10.6 V. (d) The measured bandwidth and GBP under different gains.

4. Dynamic Performance

In order to characterize the optoelectric bandwidth, the S_{21} frequency response of the APD is measured from 10 MHz to 67 GHz. Figure 2(c) shows the normalized S_{21} frequency response under voltages from -6 to -10.6 V, under an inputting optical power of -20 dBm. It can be seen that, from -6 to -9.5 V, the bandwidth increases from 9.5 to 49.8 GHz, benefitting from the Ge region depletion and the decreased carrier transit time and junction capacitance. In conventional APDs, if the voltage continues to increase, the bandwidth will decrease, as the gain increases with the voltage (the GBP is unchanged). However, in this device, when the voltage rises beyond -9.5 V, the bandwidth improves abnormally from 49.8 to 67 GHz thanks to the SCE-induced gain reduction.

The bandwidth and GBP under different gains are shown in Fig. 2(d), with identical inputting power of -20 dBm. As shown in Fig. 2(b), the gain first increases and then decreases with the voltage increasement, and thus a fold-back occurs near the maximum gain of 8.6 in Fig. 2(d). The largest GBP is measured to be 442 GHz, and it is almost constant though the gain decreases. In other words, the bandwidth increases under a fixed GBP. Figure 3 shows the reported state-of-the-art APDs with high bandwidths [3-8]. To the best of our knowledge, this work demonstrates a record-high bandwidth and exhibits the first bandwidth exceeding 60 GHz among all reported APDs.

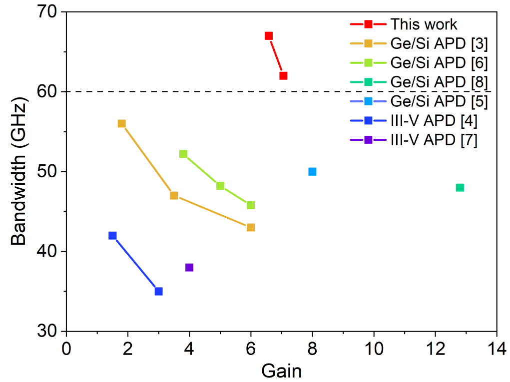

Fig. 3. The literature overview of the APDs with high bandwidths.

The eye diagrams of the APD are measured at -10.6 V. The post-compensation and offline digital signal process are carried out to deduct the distortion from the cables and the transmitter. As shown in Fig. 4, we record the eye diagrams for 50 and 64 Gb/s OOK signals by setting the inputting optical power as -14 dBm and the signal-to-noise ratios (SNRs) are measured to be 17.8 and 13.2 dB, respectively.

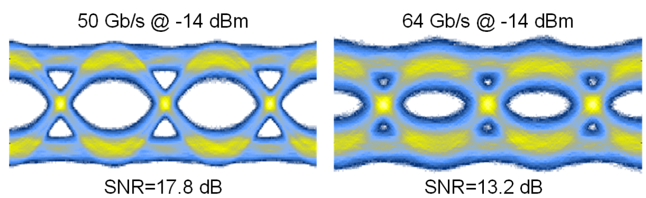

Fig. 4. The measured eye diagrams of 50, 64 Gb/s OOK signals.

5. Conclusion

In conclusion, we have demonstrated a waveguide-integrated APD with a bandwidth of 67 GHz and a high GBP of 442 GHz, adopting a simple CMOS-compatible fabrication. It potentially enables low-cost and ultra-fast on-chip photodetection. This work is expected to open up a new way for next-generation optical interconnects.

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