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Ge/Si Waveguide Avalanche Photodiodes on SOI Substrates for High Speed Communication

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In this paper, we report the development and performances of two high-bandwidth Ge/Si waveguide avalanche photodiodes (APDs). They are either evanescent-coupled or directly butt-coupled with a multi-mode silicon-on-insulator waveguide. Both APDs demonstrate low dark current, high internal responsivity at long wavelength. The measured bandwidths are 23 GHz and 28.5 GHz at unity gain for evanescent- and butt-coupled APDs, respectively. Importantly, the corresponding receiver sensitivity is measured as -30.4 dBm at 10 Gb/s. This is already better than the current commercial available III-V based APD receivers.

Introduction

The traditional III-V APD receivers offer around 10 dB improvement in sensitivity up to 10 GB/s compared with PIN receivers. However, due to the multiplication noise and limited gain-bandwidth product of InP-based APDs, they become less attractive as the bit rate increases. In fact, the number of choices for the 40 GB/s APDs available on the market today is very limited. To make 40 GB/s transmission systems practical, low cost and power efficient, a new solution for highly sensitive receivers operating at 40 GB/s are in high demand.

Recently, the development of Ge/Si photodetectors and especially the first demonstration of high performance normal-incident Ge/Si avalanche photodiodes (APD) have been very successful (1). The experimental gain-bandwidth product (GBW) is as high as 340 GHz, more than doubled what the III-V compound counterparts provide. And the sensitivity is -28 dBm at 10 Gb/s for 1310 nm wavelength, which is comparable to that of III-V APD receivers. In order to outperform the III-V APDs at 10 Gb/s, or even 40 Gb/s, there are a few areas that Ge/Si APDs need to be improved, such as dark current, responsivity and bandwidth.

Due to its compact structure, waveguide structure can be the solution for all of the above-mentioned performance issues that normal-incident Ge/Si photodetecors suffer (2,3). Many Ge/Si waveguide PIN photodetectors have been demonstrated with high bandwidth and almost close-to-ideal internal responsivities moving from normal-incident structure to silicon-on-insulator (SOI) based waveguide structure (4-8). An additional benefit that makes waveguide structure attractive is the integration probability with other optical components, such as variable optical attenuators (VOAs), arrayed waveguide gratings (AWG) and so on.

In this paper, we design and demonstrate two types of Ge/Si waveguide APDs; both exhibit high performances for high-speed applications.

Overview of Ge/Si Waveguide APDs

Waveguide photodetectors have optical signals introduced either by direct coupling from the device edge or through a single-mode or multi-mode optical waveguide in the front of the device. In these photodetectors, the light travels parallel to the wafer surface, which is perpendicular to electric carrier transit path. In such way, the device quantum efficiency and transit-time bandwidth are no longer coupled with each other. By a proper waveguide structure design, high responsivity and high bandwidth can be achieved simultaneously.

Our previous normal-incident Ge/Si APDs indicated the device dark current increases linearly with the device active area, implying that it is dominated by bulk leakage current. Detailed analysis, discussed in reference (9), showed that the bulk leakage is originated in Ge absorption region at high bias. Moving to waveguide-based Ge/Si APDs would also allow for detectors with an area approximately ten to one hundred times smaller than the normal-incident devices, resulting in a corresponding reduction in the associated bulk-dominated dark current.

In this paper, we propose and demonstrate two types of the Ge/Si waveguide APDs. The light coupling schemes for these two are different in the way by which the APD is integrated with a SOI waveguide. The schematic device structures are shown in **Error! Reference source not found.** The evanescent-coupled device has a Ge absorber sitting on the top of a Si rib waveguide, so that as the light propagates into the Si waveguide underneath the Ge, it will gradually couple up into the Ge absorption layer. For the butt-coupled device, the Ge absorber is in direct contact with the Si rib output facet. As a result, part of the light will horizontally enter Ge, and the rest of the light can evanescently couple into Ge. Beam-propagation simulation shows better optical coupling efficiency from butt-coupling scheme than from evanescent-coupling with a given Ge absorber length. Therefore, the butt-coupled structure is expected to achieve high bandwidth without compromising device responsivity.

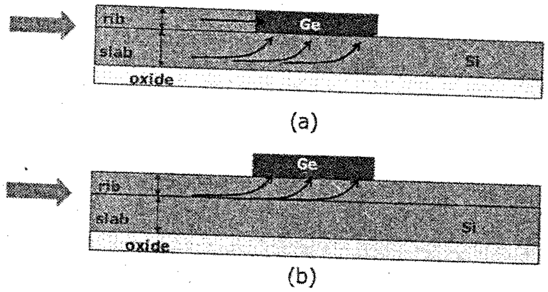

Figure 1. Schematic diagrams of butt-coupled (a) and evanescent-coupled Ge/Si waveguide APDs.

The device layer structure is a conventional Separate Absorption, Charge and Multiplication (SACM) APD structure in which light absorption and carrier multiplication take place inside Ge and Si, respectively. The schematic layer structure shown in Figure 2 (a) consists of 0.4μm-thick intrinsic Ge absorption layer, 100nm-thick p-type Si charge layer and 0.4μm-thick intrinsic Si multiplication layer. Device top view is shown in Figure 2 (b). A coplanar waveguide (CPW) transmission line with characteristic impedance of 50Ω was fabricated with device for high-speed measurement probing.

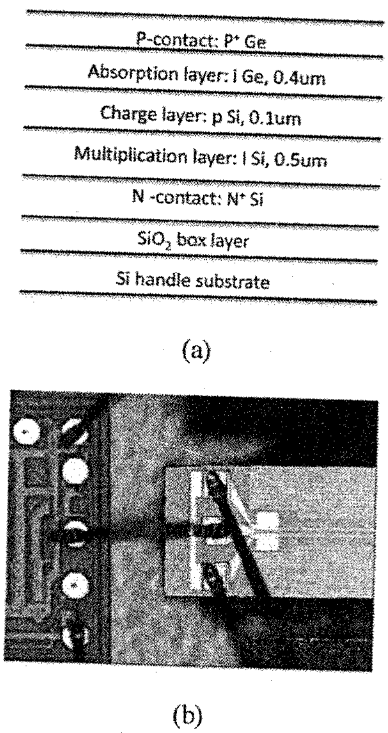

Figure 2. Schematic (a) and top view (b) of a Ge/Si waveguide APD.

As all the waveguide devices are integrated with approximately 2 mm-long multi-mode Si rib waveguides, the waveguide transmission loss and the optical coupling loss between the lens fiber and the Si waveguide were evaluated using the cutback method on a series of stand-alone passive waveguides. The coupling loss and transmission loss combined is approximately 3.3 to 3.9 dB (i.e. ~53% to ~60% power loss) at both 1310 nm and 1550 nm. This number was used to extract device internal responsivity (or quantum efficiency) from the experimental external responsivity.

Experimental Results of Evanescent-coupled Waveguide APDs

The room temperature dark current and photocurrent of a typical 5×70 μm evanescent-coupled APD are shown in Figure 3. The breakdown voltage, defined here at dark current of 10 μA, is -24.45V. The dark current is 52 nA at -10V and increases to 1.45 μA when biased at 90% of breakdown voltage. Device primary responsivity, corresponding to the intrinsic responsivity at unity gain, was obtained from the Ge/Si P-I-I-N waveguide devices on the same wafer that the APD devices were fabricated. The extracted internal primary responsivities for a 70μm-long device are 0.9 A/W and 0.7 A/W at 1310 nm and 1550 nm wavelength, respectively. The device current multiplication gain, also plotted in Figure 3, was calculated by normalizing responsivity at any given bias to the primary responsivity.

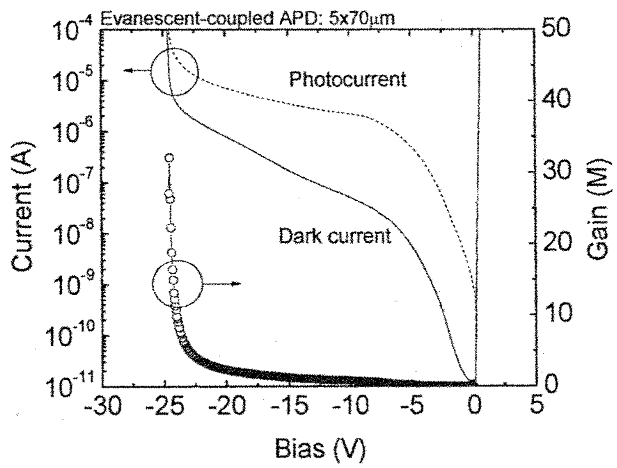

Figure 3. Typical current vs. voltage characteristics measured from a 5×70 μm evanescent-coupled waveguide APD for 1550nm wavelength at room temperature.

The frequency response of the evanescent-coupled waveguide Ge/Si APDs was measured using heterodyne technique at 1550 nm. At low bias voltages, the bandwidth of a 70μm-long device is 23GHz, as shown in Figure 4, which agrees with our theoretical expectation based on RC-time and transit-time constants. At high bias voltages, the avalanche build-up time increases and the 3dB bandwidth drops to 8GHz. The resulting gain-bandwidth product was measured in the range between 200GHz to 300 GHz.

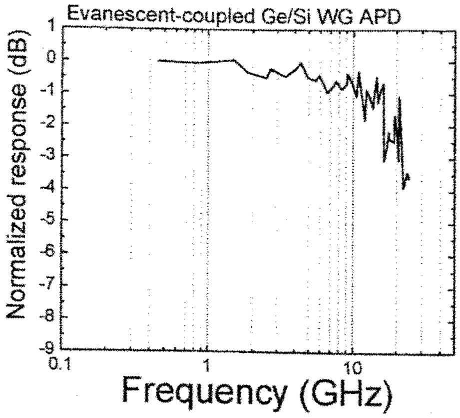

Figure 4. Measured frequency response for a 70 μm-long evanescent-coupled Ge/Si APD device.

The receiver sensitivity of evanescent-coupled waveguide APDs was measured after packaging the devices with transimpedance amplifiers (TIAs). The top view picture is shown in Figure 2 (b). Bit error rate (BER) testing yielded -30.4 dBm sensitivity at 1×10^{-12} BER for 10Gb/s with word length of 2^{31}-1 PRBS, as plotted in Figure 5. It demonstrates sensitivity performance better than that of the current state-of-the-art InP-based 10Gb/s waveguide APD receivers (10-11).

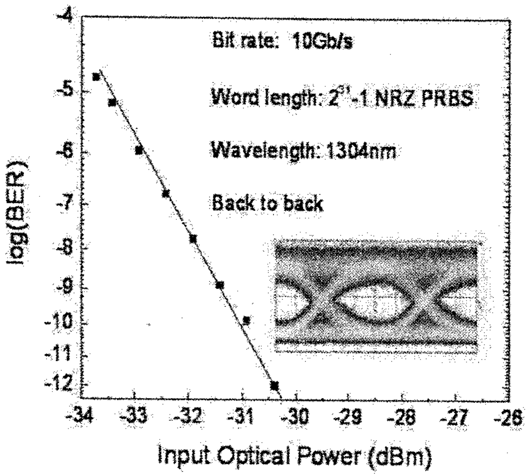

Figure 5. Measured BER performance with respect of various input optical power at 10Gb/s, 1304 nm, PRBS 2^{31}-1 and room temperature.

Experimental Results of Butt-coupled Waveguide APDs

The room temperature dark current and photocurrent of a typical 4×50 μm butt-coupled APD are shown in Figure 6. The breakdown voltage, defined here at dark current of 10 μA, is -23.2V. The dark current is 74nA at -10V and increases to 1.1μA when biased at 90% of breakdown voltage.

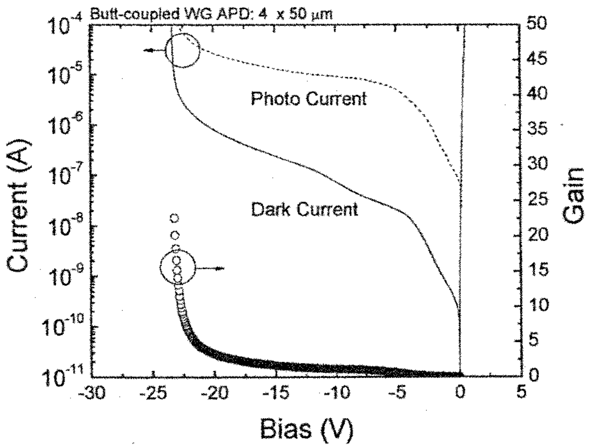

Figure 6. Typical current vs. voltage characteristics measured from a 4×50 μm butt-coupled waveguide APD for 1550nm wavelength at room temperature.

The internal responsivity at 1550 nm is shown in Figure 7 for the butt-coupled and evanescent-coupled APDs with Ge waveguide length of 10 to 100 μm. Given the optical loss before the device, the internal responsivity is 0.81A/W and 0.59A/W at 1550 nm for a butt-coupled and evanescent-coupled device with 50um long Ge absorber, respectively. From the discussion in the overview section, it is confirmed that butt-coupled waveguide device structure has higher light coupling efficiency than evanescent-coupled structure. Thus, if shorter device is needed, high bandwidth application as an example, butt-coupled device is a better candidate for the task.

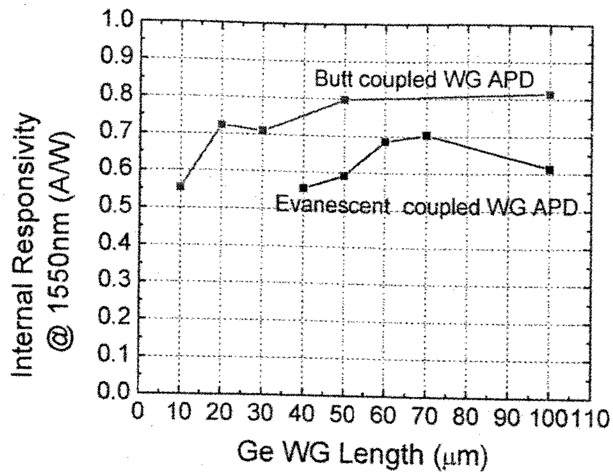

Figure 7. Internal responsivity at 1550 nm as a function of Ge waveguide length for evanescent-coupled and butt-coupled APDs.

The -3dB bandwidth results of these types of devices are shown in Figure 8. For a 30 μm-long butt-coupled device, due to its shorter RC-time constant, the bandwidth achieved 29.5GHz at unity-gain.

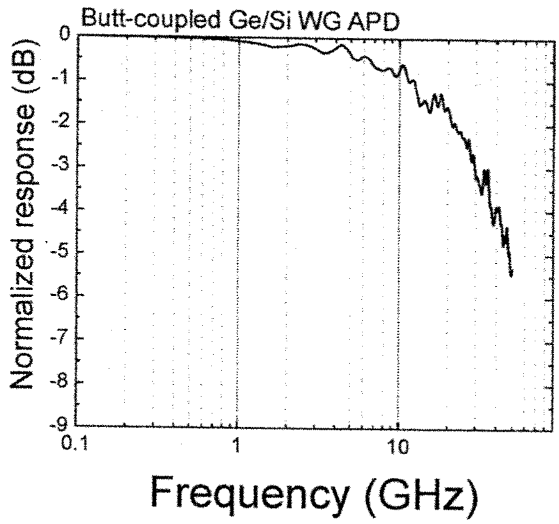

Figure 8. Measured frequency response for a 30 μm-long butt-coupled Ge/Si APD device.

Summary

We demonstrate two types of Ge/Si waveguide APDs for high-speed communication applications. Bandwidth of 23 and 29.5GHz were achieved for the evanescent-coupled and butt-coupled APD, respectively. The 10Gb/s optical receiver built on Ge/Si evanescent-coupled waveguide APD demonstrates -30.4 dBm sensitivity at bit error rate of 1×10^{-12}. Once again, this shows the competence of the Ge/Si APD technology for high-speed, long-wavelength optical communication.

Acknowledgments

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