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Zero biased Ge-on-Si photodetector with a bandwidth of 4.72 GHz at 1550 nm*

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High quality Ge was epitaxially grown on Si using ultrahigh vacuum/chemical vapor deposition (UHV/CVD). This paper demonstrates efficient germanium-on-silicon p-i-n photodetectors with 0.8 μm Ge, with responsivities as high as 0.38 and 0.21 A/W at 1.31 and 1.55 μm, respectively. The dark current density is 0.37 mA/cm^2 and 29.4 mA/cm^2 at 0 V and a reverse bias of 0.5 V. The detector with a diameter of 30 μm, a 3 dB-bandwidth of 4.72 GHz at an incident wavelength of 1550 nm and zero external bias has been measured. At a reverse bias of 3 V, the bandwidth is 6.28 GHz.

Keywords: Si-based, Ge, epitaxy, photodetector
PACC: 7340L, 4280S, 4282, 2940P

1. Introduction

Silicon-based photonic devices have been generating growing interest in recent years due to the advantages of low cost, dependability, integration and intelligence. In recent years, more and more researchers have attempted to use SiGe to develop near-infrared photodetectors operating at the telecommunication wavelengths of 1.3 and 1.55 μm.[1−3] Unfortunately, as an indirect bandgap material, SiGe has a low absorption coefficient. This makes it difficult to achieve high responsive speed and appropriate responsivity simultaneously. So Ge becomes the optimal material candidate due to its compatibility to the Si CMOS process and high absorption coefficient at the NIR (1300–1500 nm) region.[4−6]

In our work, a Ge layer with a pitting surface was obtained when the growth temperature was lowered to 290 °C. On the buffer layer with pits, the high quality Ge layer with a threading dislocation density of $\sim 1 \times 10^5$ cm^{-2} was grown at 600 °C. The root-mean-square (RMS) surface roughness of the Ge film was 0.33 nm. Then the Ge p-i-n photodetector was fabricated successfully, with responsivities as high as 0.38 and 0.21 A/W at 1.31 and 1.55 μm, respectively. The dark current density was 0.37 mA/cm^2 and 29.4 mA/cm^2 at 0 V and reverse bias of 0.5 V. The 3 dB-bandwidths of the detector, which were measured at a wavelength of 1550 nm, were 4.72 GHz, 5.38 GHz and 6.28 GHz at reverse bias of 0 V, 1 V and 3 V, respectively.

2. Material growth and devices fabrication

The schematic cross section of the Ge p-i-n photodetector is shown in Fig.1.

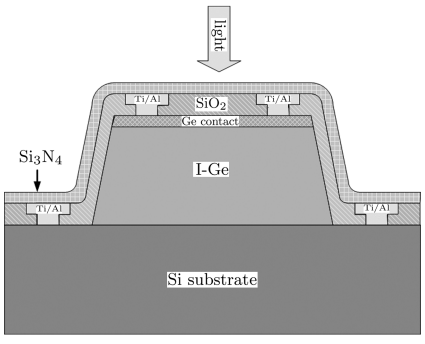


Fig.1. Schematic cross section of the Ge p-i-n photodetector.

A cold wall UHV (ultrahigh vacuum)/CVD (chemical vapor deposition) starts on N$^+$-doped

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Si(100) with a resistivity of 0.02 $\Omega \cdot$cm. Before growing, the substrate was degassed at 300 °C in the pretreatment chamber and deoxided in the growth chamber by heating to 930 °C for 5 minutes. The heteroepitaxy of Ge on Si was initiated at 290 °C with a flow of 8 sccm of pure GeH_4. Following that the 30–50 nm of the low temperature Ge buffer was deposited on Si, the substrate temperature was elevated to 600 °C, and about 800 nm thick Ge was grown on the buffer layer. The top of the Ge layer was implanted with BF_2^+ at a dose of 4×10^{15} cm^{-2} and energy of 40 keV. The thickness of the formed P-doped layer was 200 nm. Circular mesas with diameters ranging from 15 μm to 150 μm were then fabricated by dry-etching patterned films down to the Si substrate using an inductively coupled plasma etcher. After a 640 nm thick SiO_2 film was deposited, metal contacts on Si and Ge were formed with a 50 nm titanium adhesion layer and a 1 μm thick aluminum layer. As a passivation layer, a 490 nm thick Si_3N_4 film was deposited finally. The SiO_2 and Si_3N_4 were optimized in terms of thickness in order to form an anti-reflection layer with the transmission rate of 90% and achieve a high responsive characteristic. The micrograph of the photodetector is shown in Fig.2. For achieving a good high frequency characteristic, the pad electrode was designed to match the high frequency characteristic.

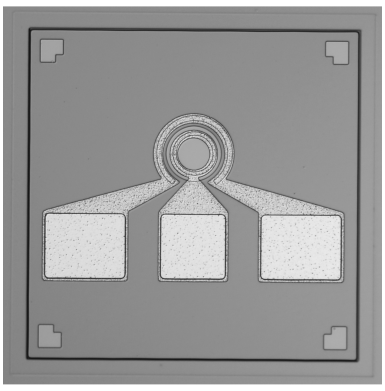


Fig.2. Micrograph of the photodetector.

3. Results and discussion

Figure 3 shows the measured dark current and photocurrent of the photodetector with a diameter of 30 μm. The dark current of the device was 2.59 nA, 0.21 μA and 0.33 μA at 0 V, reverse bias of 0.5 V and 1 V, respectively. The corresponding dark current density was 0.37 mA/cm^2, 29.4 mA/cm^2 and 46.6 mA/cm^2. These measured dark currents, which were low, show further that the Ge epitaxial layer has a good characteristic.

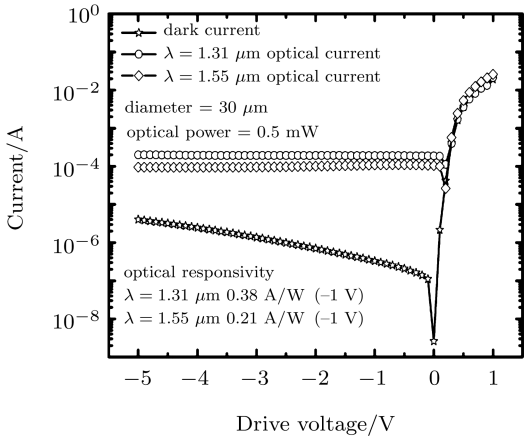


Fig.3. Current-voltage characteristics at darkness and with illumination by 1310 nm and 1550 nm light of the 30 μm diameter detector.

The device has responsivities as high as 0.38 A/W and 0.21 A/W at 1.31 μm and 1.55 μm, which can be seen in Fig.3. Noticeably, the curve of the opticcurrent is smooth enough. The results of the test demonstrate that the photodetector can operate at zero external bias with low dark current and high responsivity.

Figure 4 shows the normalized frequency responses at 1550 nm for the detector with diameters 30 μm. The measure system includes a laser of 1.55 μm, the N5230A network analyzer of Agilent with the test range from 300 kHz to 20 GHz, a JDSU high speed modulator and a radio frequency GSG probe of 40 GHz. The 3 dB-bandwidths of the detector with a diameter of 30 μm are 4.72 GHz, 5.38 GHz and 6.28 GHz at 0 V, –1 V and –3 V, respectively. Operation at a speed of 5 Gb/s can be accomplished because the 3 dB-bandwidth of the 30 μm-diameter detector exceeds 3.5 GHz at the zero external bias.

The 3 dB-bandwidths of our device were not high enough due to the doped-Si substrate of the Ge photodetector. The capacitance between pads and the Si substrate is the most important restrictive factor in achieving the high 3 dB-bandwidths. In future work, we will consider reducing the capacitance by using Si-on-insulator material or a deep-doped Si substrate. Maybe adding an isolated layer will be feasible, too.

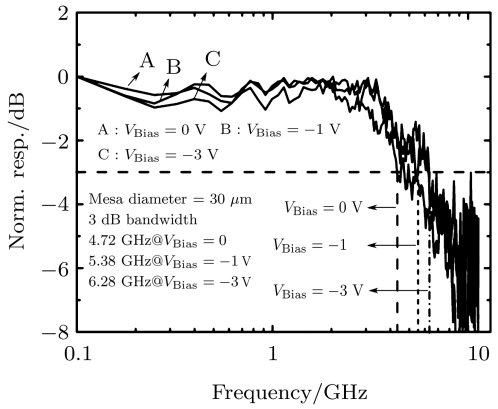


Fig.4. Normalized frequency responses at 1550 nm of the detector with diameters 30 μm.

4. Conclusion

A Ge layer on a Si substrate was obtained by a ultra-low-temperature Ge buffer layer using cold-wall UHV/CVD. The Ge film has a threading dislocation density of $\sim 1\times10^5$ cm^{-2} and an RMS surface roughness of 0.33 nm. We designed and fabricated high speed Ge p-i-n photodetectors, then obtained low dark current densities of 0.14 and 29.4 mA/cm^2 at the 0 V and –0.5 V, respectively. The 3 dB-bandwidth of detector was 4.72 GHz at zero bias and 1550 nm.

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