Surface-Illuminated Near-Infrared Ge Photodetector on Si-on-Quartz Substrate with Extended Operating Wavelength

Ryoya Ogura,[1] Koji Abe,[1] Yuki Yoshino,[1] Naoki Hamada,[1] Jose A. Piedra-Lorenzana,[1] Takeshi Hizawa,[1] Toshimasa Umezawa,[2] Naokatsu Yamamoto,[2] Kouichi Akahane,[2] and Yasuhiko Ishikawa[1]
[1]Department of Electrical and Electronic Information Engineering, Toyohashi University of Technology, 1-1 Hibarigaoka, Tempaku, Toyohashi, Aichi 441-8580, Japan
[2]National Institute of Information and Communications Technology, 4-2-1 Nukui-Kitamachi, Koganei, Tokyo 184-8795, Japan
ogura.ryoya.oz@tut.jp, ishikawa@ee.tut.ac.jp

Abstract: *Surface-illuminated near-infrared photodetectors of a strain-enhanced Ge thin film on a Si-on-quartz wafer exhibit a high responsivity of >0.1 A/W not only in the C band but also in the L band.*
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I. INTRODUCTION

Near-infrared (NIR) photodetectors (PDs) using an optical absorption layer of Ge epitaxial film on Si have been applied to waveguide-integrated PDs in Si photonics. The PDs have exhibited high responsivity in the major communication bands of the O (1260–1360 nm) and C (1530–1565 nm) bands, with an operating frequency as high as 50 GHz or higher [1-4]. Arrayed structures of surface-illuminated PDs are of growing interest not only in optical communications such as multi-core fiber communication but also in NIR sensing and imaging including time-of-flight LiDAR (light detection and ranging). However, surface-illuminated PDs of a Ge thin film on Si suffer from low responsivity because the Ge thickness limits the optical absorption in contrast to the waveguide PDs, where the absorption is dominated by the in-plane Ge length. In the C band, the optical absorption coefficient of Ge on Si is about 4000 cm^{-1} [5]. This corresponds to the optical penetration length of about 2.5 μm, i.e., an efficient surface-illuminated photodetection requires a Ge film as thick as a few microns. Such a film is much thicker than that (< ~1 μm) for the waveguide PDs, degrading the response frequency to less than 10 GHz as a tradeoff. In the longer wavelength range of the L (1565–1625 nm) and U (1625–1675 nm) bands, the responsivity is further degraded because of the low absorption coefficient [5].

In this study, a surface-illuminated PD of a strain-enhanced Ge thin film (500 nm in thickness) grown on a Si-on-quartz (SOQ) wafer is reported, which exhibit a high responsivity of >0.2 A/W in the C band and >0.1 A/W even in the L band.

II. APPROACH TO ENHANCE RESPONSIVITY IN THIS STUDY

There are several approaches to enhance the responsivity while keeping a thin film for the optical absorption. One of the approaches is to use a multilayered resonator structure, but the enhancement is limited at the resonance wavelengths. GeSn alloys are the candidates due to the narrower direct gap than 0.80 eV for Ge, enhancing the optical absorption in the C band and extending the absorption edge towards the longer wavelength. However, the solid solubility of Sn in Ge is <1% at the thermal equilibrium, whereas the Sn content should be as high as several % for the reasonable enhancement.

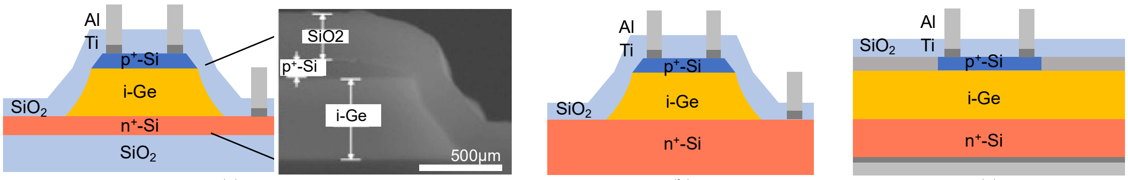
As an alternative method, the authors have proposed the use of an elemental Ge film grown on a SOQ wafer [6,7]. It is known that a tensile lattice strain narrows the direct gap of Ge [5,8], extending the optical absorption edge. In a Ge film epitaxially grown on an ordinary Si (SOI) wafer, an in-plane tensile strain of about 0.2% is generated by the thermal expansion mismatch during the cooling from the growth temperature (c.f., the compressive strain due to the 4% lattice mismatch is relaxed in the initial stage of the growth) [5]. The direct bandgap of Ge is narrowed to 0.77 eV, extending the optical absorption edge from 1550 to 1610 nm. Replacing the substrate to SOQ with the base substrate of fused quartz, the in-plane tensile strain is enhanced to >0.3% due to an increased thermal expansion mismatch [6,7]. The direct gap is narrowed to about 0.75 eV, extending the absorption edge to about 1650 nm.

III. SAMPLE PREPARATION

Mesa-shaped Ge PDs on SOQ, schematically shown in Fig. 1(a), were fabricated as follows. As the stating substrate, a 4-inch bonded SOQ wafer (Shin-Etsu Chemical Co. Ltd.) was used. The top Si(001) layer was 200 nm in thickness, which was highly n-type doped by a P-ion implantation. First, an undoped Ge epitaxial layer of 500 nm in thickness was grown at 600°C by chemical vapor deposition using a source gas of GeH_4. Subsequently, a Si cap layer of 120 nm in thickness was grown on Ge using a source gas of Si_2H_6. A post-growth annealing was performed at 800°C for 10 min in N_2 to reduce the threading dislocation density in Ge. Next, to form a vertical pin junction, an implantation of B ions for the p-type doping was performed in the Si cap layer and top region of the Ge layer. To define the area of PDs, the Ge and Si cap layers were patterned by reactive-ion etching in a square-shaped mesa structure with the width ranging from 10 to

500 µm. Then, the mesa structure was embedded by a SiO_2 passivation layer of 280 nm in thickness, which simultaneously acts as an anti-reflection coating. Finally, Al/Ti electrodes were formed.

As a reference, a PD of Ge on bulk n^+-Si(001) wafer was prepared, as schematically shown in Fig. 1(b). A non-mesa planar structure in Fig. 1(c) was also prepared to examine the effect of mesa patterning on the dark leakage current. In our previous work, a relatively large peripheral leakage was observed for the planar PDs [8].



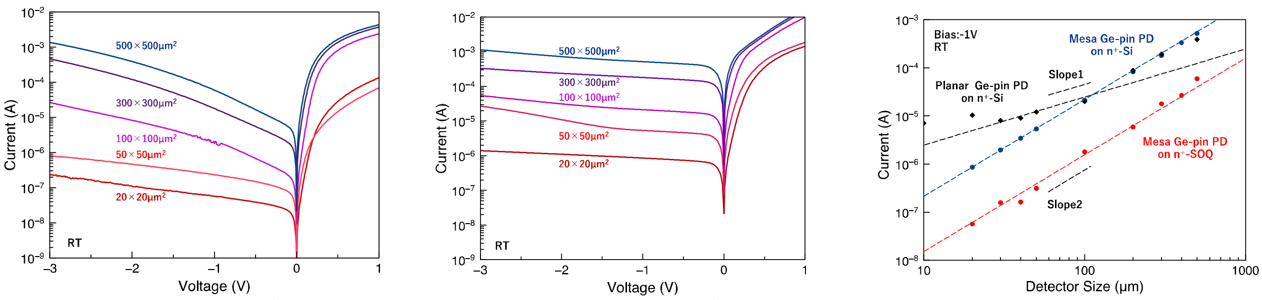
(a) (b) (c)

Fig. 1. Cross-sectional structures of the fabricated Ge pin PDs. (a) Mesa-shaped PD on n^+-SOQ together with a typical scanning electron microscope image, (b) mesa-shaped PD on bulk n^+-Si, and (c) planar PD on n^+-Si.

IV. Results and Discussion

A. Dark Leakage Current

Figs. 2(a) and 2(b) show typical current-voltage (*I-V*) characteristics of the mesa-shaped Ge PDs at room temperature under dark. Both of the PDs on n^+-SOQ and bulk n^+-Si exhibited rectifying diode properties, and the reverse current decreased reasonably with decreasing the PD size. Fig. 2(c) shows the dark leakage current at the 1-V reverse bias as a function of the PD width. In the logarithmic plot of Fig. 2(c), both of the mesa-shaped PDs on n^+-SOQ and bulk n^+-Si revealed the dependence with the slope of 2. This indicates that the leakage current is dominated by the area of the PD (pin junction). The leakage current was smaller for the PDs on n^+-SOQ; the areal leakage current density is as low as 10 mA/cm^2 for the Ge PDs on SOQ, which is lower than 100 mA/cm^2 for those on bulk Si. This indicates that the crystalline quality is higher for the Ge layer on SOQ despite the mechanism to be clarified. Compared to the non-mesa planar PDs, the mesa-shaped PDs showed lower leakage currents for the PD width of 100 µm or smaller. It is important that the planar PDs revealed the slope of 1 in this width range, corresponding to the leakage current dominated by the peripheral length. This indicates that the mesa patterning is effective for reducing the peripheral leakage current. It should be mentioned that there is a trend of the forward current decreasing with decreasing the PD size. This is probably attributed to an increase in the contact resistance between the Al/Ti electrode and top p-type region, resulting from the decrease in the contact area. As discussed later, the contact resistance as a parasitic resistance should be reduced for increasing the response frequency.



(a) Ge PD on n^+-SOQ (b) Ge PD on bulk n^+-Si (c) Dark current at 1-V reverse bias

Fig. 2. Typical *I-V* characteristics of (a) mesa-shaped Ge PD on n^+-SOQ, (b) mesa-shaped Ge PD on bulk n^+-Si, and (c) dark leakage current at the 1-V reverse bias as a function of the PD width for the mesa-shaped Ge PDs on n^+-SOQ and bulk n^+-Si together with the planar PDs on bulk n^+-Si.

B. Spectral Responsivity

Typical responsivity spectra are shown in Fig. 3 for the mesa-shaped Ge PDs on n^+-SOQ and bulk n^+-Si in the wavelength range from 1455 to 1640 nm at the reverse bias of 1 V. The responsivity was higher for the Ge PDs on n^+-SOQ in whole the wavelength range. This is attributed to the tensile lattice strain enhanced in the Ge film on SOQ [6,7], which narrows the direct bandgap and extending the optical absorption wavelength. Despite the thin Ge absorption layer of 500 nm in thickness, a high responsivity of about 0.25 A/W was obtained in the C band of 1530–1565 nm, which is significantly higher than <0.20 A/W for the Ge PDs on bulk n^+-Si. The enhanced responsivity is more obvious in the longer wavelength range of the L band, 1565–1625 nm. The Ge PD on n^+-SOQ revealed the responsivity more than 0.1 A/W, which is several times higher than that for the Ge PD on bulk n^+-Si.

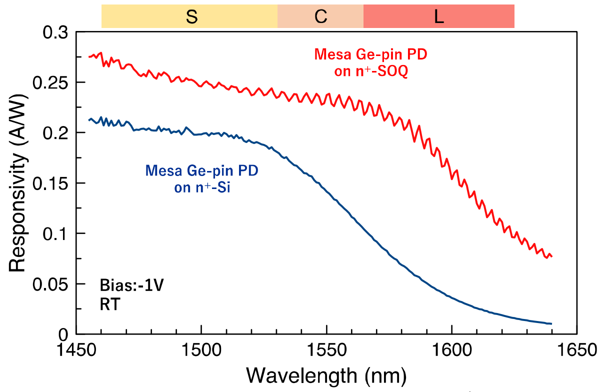


Fig. 3. Typical responsivity spectra of mesa-shaped Ge PDs on n^+-SOQ and bulk n^+-Si.

C. Frequency Response

Fig. 4 shows typical frequency response for the mesa-shaped Ge PDs on n^+-SOQ and bulk n^+-Si for the PD width of 20 µm at the reverse bias of 1 V and wavelength of 1550 nm. The 3-dB cutoff frequencies were obtained as approximately 0.5 and 0.8 GHz for the Ge PDs on n^+-SOQ and bulk n^+-Si, respectively, which are more than one order of magnitude lower than the theoretical one of about 20 GHz. The parasitic contact resistance mentioned above, together with the parasitic capacitance, should be responsible for the observed low response frequency in terms of the RC delay, and the reduction should be necessary for increasing the 3-dB cutoff frequency.

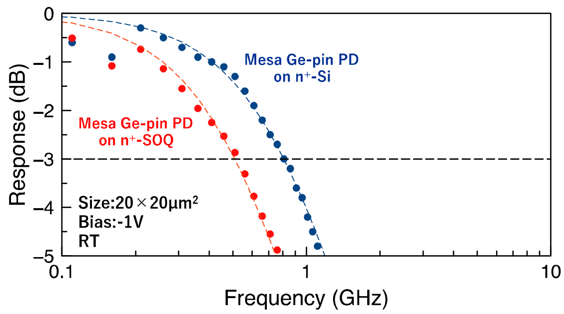


Fig. 4. Typical frequency responses for mesa-shaped Ge PDs on n^+-SOQ and bulk n^+-Si.

V. Conclusion

Surface-illuminated PDs of a strain-enhanced Ge thin film on SOQ wafer was reported. The mesa patterning was effective for reducing the dark leakage current. The PDs exhibited a high responsivity of >0.2 A/W in the C band and >0.1 A/W even in the L band. The response frequency was below 1 GHz, which should be improved by reducing the parasitic resistance and capacitance.

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