Communication

The Superior Responsivity Enhancement of Thin-Film Ge Photodetectors by AuNP Coatings

Juin Jie Liou 1, Hao-Tse Hsiao 2, I-Cheng Yao 2, Jia-Syun Jheng 2 and Chu-Hsuan Lin 2,*

1 School of Information Engineering, Zhengzhou University, Zhengzhou 450000, China; juin.liou@hotmail.com
2 Department of Opto-Electronic Engineering, National Dong Hwa University, Hualien 974301, Taiwan; a3747@livemail.tw (H.-T.H.); gampeter@yahoo.com.tw (I-C.Y.); 410325003@gms.ndhu.edu.tw (J.-S.J.)

* Correspondence: chlin0109@gms.ndhu.edu.tw; Tel.: +886-3-8634188

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Abstract: We have tried to improve the responsivity of germanium-based thin-film photodetectors. It has been shown that applying a mechanical strain to the detector led to a 46.6% enhancement on the 1550 nm detection. This improvement is better than the 1310 nm case, because the bandgap shrinkage is more beneficial to the small-energy photon detection. The AuNP coating is even more attractive for responsivity enhancement of thin-film germanium (Ge) detectors. The responsivity enhancement due to the AuNP deposition is as high as 89% and 47%, for the 1310 nm and 1550 nm detections, respectively. To the best of our knowledge, this is the best responsivity enhancement for the thin-film Ge detectors reported to date.

Keywords: thin-film germanium; responsivity; smart-cut; AuNP

1. Introduction

Germanium (Ge) is a promising material for fabricating near-infrared optical sensors due to its high absorption coefficient and easy integration with complementary metal-oxide-semiconductor technology [1–3]. The main issue with incorporating Ge photodetectors in Si-based photonics is the relatively high cost of Ge, and, hence, Ge thin films are used to reduce the expense. However, the film thickness can affect the responsivity (quantum efficiency), and various methods were proposed to improve the responsivity of thin-film Ge detectors [4–6]. Ge thin film could be transferred onto the insulator by the technique of smart cut. This method results in a high-quality Ge film without suffering from threading dislocation due to lattice mismatch between Ge and Si layers [7]. It has been proven that a thicker active layer can give rise to a higher responsivity [8]. Nonetheless, a thick film possesses the disadvantages of higher cost, more recombination centers, and lower speed. This trade-off exists even for the high-absorption-coefficient III–V material operating at the optical-communication wavelengths [9]. In this paper, we will illustrate methods to effectively boost the Ge-based photodetector’s responsivity without having to increase the thickness of the Ge thin film.

2. Experiments

An n-type Ge substrate was prepared as a “host” substrate with a resistivity of 1–30 Ω·cm. The H+ ions were implanted into this host substrate to form a weakened layer. Before bonding, the host substrate was hydrophilically cleaned in the KOH aqueous solution (KOH:H2O = 1:2). On the other hand, a glass or Si substrate with a thick (~100 nm) thermal oxide layer was taken as the “handle” substrate. The handle substrate was hydrophilically cleaned in the SC1 solution (NH4OH:H2O2:H2O = 1:2:8). The two substrates were bonded at the room temperature and annealed to induce layer transfer along the weakened layer. Different H+ implantation leads to different annealing parameters to get the optimized thin-film transfer. Take the thin Ge for AuNP study for example, the temperature profile
was first increased to 100 °C, keeping it at 100 °C for one hour, 250 °C for 2 h, 300 °C for 2 h, and finally 500 °C for half an hour. The rough surface was then smoothed by the SC1 solution for 2 s. The thickness of the transferred Ge layer was ~1 µm. A thin insulator, such as GeO₂ from native oxidation or SiO₂ from chemical deposition, could then be formed on the transferred Ge layer. Finally, a metal gate and surrounding large-area ohmic contact were deposited to form a metal-insulator-semiconductor (MIS) diode. The MIS structure is widely adopted due to the advantages of simple processing and low dark current [10]. Figure 1 shows the schematic structure of such thin-film Ge photodetectors.

When an infrared light (produced from the laser diode and coupled to a fiber tip) irradiates at the edge of the gate electrode (Figure 1), excess electron-hole pairs can be generated in Ge and give rise to the photocurrent. Figure 2 shows the dark and photo currents of the above-mentioned thin-film MIS Ge photodetector (i.e., control sample). The insulator in this structure is a native GeO₂ and carriers can easily tunnel through the thin insulator. Dividing the difference between the photocurrent and the dark current by the input power of infrared (1.3 mW for 1310 nm infrared and 1 mW for 1550 nm infrared) yields the responsivity. In this case, the ~2 V responsivities at the wavelengths of 1310 and 1550 nm are 149 and 49 mA/W, respectively.

**Figure 1.** The schematic structure of a thin-film Ge photodetector. The inset shows the top-view of a photograph of a Ge-on-glass photodetector. The infrared output from fiber irradiates the edge of the gate electrode.

**Figure 2.** The current–voltage (IV) characteristics of the thin-film Ge photodetector (i.e., control sample). The power coupled to the edge of the gate electrode is 1.3 and 1 mW, respectively, for the 1310 and 1550 nm infrared lights.
The absorption depths of Ge at the wavelengths of 1310 and 1550 nm are 1 and 10 µm, respectively [11]. The transferred thickness of Ge is much smaller than the absorption depth at the wavelength of 1550 nm, and the insufficient absorption results in the obviously smaller responsivity at the wavelength of 1550 nm than that of 1310 nm.

3. Adequate Responsivity Enhancement by Strain

Although a thicker Ge film may lead to a higher responsivity, the Ge thickness is in fact limited by the material cost and technology constraint. It has been shown that the responsivity of the Ge-on-insulator MIS detector can be improved by applying a mechanical strain [8]. In the study by Lin et al. [8], the strain effects on the 850 and 1310 nm detections were investigated. With a 0.13% biaxial strain, 9% of 850 nm infrared photocurrent enhancement on the 0.8-µm-thick Ge detector and 11% of 1310 nm infrared photocurrent enhancement on the 1.3-µm-thick Ge detector were demonstrated. In fact, the responsivity enhancement should be a more meaningful index than the photocurrent enhancement reported in [8], since the dark-current component can be excluded from the responsivity.

In this paper, the strain effect on the responsivity of the Ge thin-film detector for the 1310 and 1550 nm wavelengths is shown. The setup to apply a mechanical strain is schematically drawn in the inset of Figure 3. The Ge detector was put on a hemisphere base and covered with a steel board. The center of this steel board is open for electrical measurements. The four corners of this steel board were pressed with screws to apply strain on the detector. The magnitude of strain could be adjusted by the rotation of screws and the strain level could be quantified by the Raman spectroscopy [12]. The responsivity enhancement at 1310 and 1550 nm is shown in Figure 3. With a 0.13% biaxial strain, the responsivity at 1550 nm achieves a 46.6% enhancement, which is much higher than the 14.1% enhancement for the 1310 nm case. This is due to the fact that the shrinkage of the bandgap of Ge resulting from the tensile strain can help to increase the absorption coefficient of Ge [13]. Since the photon energy of 1550 nm infrared is smaller than that of its 1310 nm counterpart, the effect of bandgap shrinkage due to strain would be more beneficial to the 1550 nm detection. Therefore, the responsivity enhancement at 1550 nm is more pronounced than at 1310 nm, as shown in Figure 3.

![Graph](image.png)

**Figure 3.** The responsivity ($R$) enhancement versus degree of mechanical strain applied on the thin-film Ge detector. The responsivity is calculated from the $-2$ V data. The inset shows the schematic set-up to apply mechanical strain.

It should be noted that the variations of dark currents under different levels of strain are relatively small (smaller than 2%). The dark current is dominated by the defect density, and the strain does not have a strong influence on the defect density. Hence, the mechanical strain can be used as a method to improve the responsivity of a thin-film Ge detector.
4. Superior Responsivity Enhancement by Gold Nanoparticles

Although the mechanical strain has already shown a responsivity enhancement, further enhancement is desired in order to overcome the limited responsivity of thin-film Ge. In 2018, it has been reported that ultra-high responsivity could be achieved on bulk Ge detectors with assistance of gold nanoparticles (AuNPs) [14]. The work-function difference between AuNPs and Al gate results in the accumulation of photogenerated holes, which leads to the depletion shrinkage and extra tunneling current. Here, we would like to explore the benefit of implementing AuNPs on the thin-film Ge detectors.

The procedures to coat AuNPs on thin-film Ge are similar to those in [14], and the remaining procedures for contact formation have been introduced in the previous paragraph. The GeO$_2$ in the sample of Figure 4 is native GeO$_2$. According to the transmission electron microscopy (TEM) photograph in Ref. [14], the thickness of the native GeO$_2$ layer is ~4 nm. The current–voltage (IV) relation has been measured, and the corresponding responsivities of the thin-film Ge detector with AuNPs (labeled as w/AuNP) and control detector without AuNPs (labeled as w/o AuNP) are shown in Figure 4. Applying AuNPs leads to 89% and 47% responsivity enhancements on the 1310 and 1550 nm detection, respectively. The enhancement for the 1310 nm case is higher, because the more absorption of 1310 nm infrared produces a stronger photogenerated hole accumulation, leading to a higher tunneling current. The IV curve of AuNP detector (inset of Figure 4) has also displayed a notable increasing photocurrent with increasing negative bias, a phenomenon that differs from the saturated behaviors of photocurrent seen in the control samples (Figure 2). To the best of our knowledge, this is the best responsivity enhancement of the thin-film Ge detector demonstrated to date, although it is still inferior to that of bulk Ge detectors reported in [14] (gain of 10.9). There may be two reasons for the lower responsivity enhancement for thin-film case. One is due to the lower absorption in the Ge thin film than in Ge bulk, and, consequently, a lower accumulation of photogenerated holes, in the thin-film than the bulk material. The other reason is that the surface of thin-film Ge is rough (Figure 5), with a root mean square (RMS) roughness of ~12 nm. This can result in a nonuniform distribution of AuNPs, and there would be less temporary accumulation of holes. The size of each nanoparticle is ~30 nm (Figure 6), which is much smaller than the hill structures of the rough surface of thin-film Ge. The rough surface of Ge can indeed reduce the reflection of incident light just like the texture of solar cells, but the difference is usually smaller than 20%. The responsivity enhancement of AuNP thin-film Ge detectors reaching 89% indicates that the main contribution comes from AuNPs. Of course, further study with AuNPs on smooth thin-film Ge detectors is desired.

![Figure 4](image_url)

**Figure 4.** The ratio of responsivity ($R$) enhancement with AuNPs added. The inset shows the IV behaviors of the thin-film Ge detectors with AuNPs coated.
Figure 5. The atomic force microscopy (AFM) images of the surface of thin-film Ge. The surface is rough due to the smart-cut process.

Figure 6. AuNPs on the flat Si surface. As AuNPs are much smaller than the hill structure of the rough surface of thin-film Ge, a flat surface is used to display the shape and size of the AuNP.

5. Conclusions

Using the tensile mechanical strain could lead to a 46.6% responsivity enhancement in the 1550 nm detection, which is much more pronounced than the case for 1310 nm detection. In order to further increase the responsivity, AuNPs are coated on thin-film Ge photodetectors. AuNPs lead to 89% and 47% responsivity enhancements on the 1310 and 1550 nm detection, respectively. This is the best responsivity enhancement for the thin-film Ge detector reported to date.

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