Fabrication and evaluation of GeSn photodiodes with metal-interlayer-semiconductor-metal structure formed at an ultra-low temperature (200 °C)

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1. Introduction

Germanium tin (GeSn) alloys are promising for CMOS-compatible near-infrared photodetectors (PDs) because of their tunable narrow bandgap. However, the reduced bandgap of GeSn results in an increased dark current density. Furthermore, the low thermal stability of Sn leads to precipitation at high temperatures, imposing strict limits on the processing conditions. Consequently, low-temperature fabrication techniques are desired for GeSn PDs.

To suppress the dark current density, a metal-insulator-semiconductor (MIS) structure with an ultra-thin TiO_x interlayer can be employed because TiO_x offers a negligible conduction band offset and a relatively large valence band offset to Ge, allowing efficient photoelectron collection while suppressing the dark current of hole injection [1]. Moreover, a $TiGe_yO_z$ interlayer between metal and Ge also can alleviate Fermi-level pinning [2], further reducing dark current as shown in Fig. 1.

To apply these technologies to GeSn PDs, a low-temperature fabrication process should be developed. In this study, we fabricated GeSn photodiodes with metal-interlayer ($TiO_x/TiGe_yO_z$)-semiconductor-metal (MISM) structure at an ultra-low temperature (200 °C) and investigated the effect of Ge cap layer on the performance of GeSn PDs.

2. Experiment details

A 200 nm-thick undoped $Ge_{0.97}Sn_{0.03}$ layer capped by a 5 nm-thick undoped Ge cap layer was grown at 150 °C by molecular beam epitaxy method on a low-doped bulk p-Ge (100) substrate. After that, the wafer was cut into two parts, and the Ge cap layer was etched for one of the two parts. These two parts are referred to as GeSn and Ge-capped GeSn substrates, respectively. After surface cleaning, a 1.6 nm-thick Ti film was deposited at room temperature by RF magnetron sputtering. The Ti layer was subsequently thermally oxidized in an electric furnace at 200 °C for 15 min, which formed a TiO_x layer with a thickness of approximately 3 nm. According to our previous study, a $TiGe_yO_z$ layer should be also formed under the TiO_x layer [3]. After the $TiO_x/TiGe_yO_z$ layer was patterned by lithography technique, Al electrodes were deposited by thermal evaporation and patterned using the liftoff technique. The PD structures are shown in Fig. 2. The responsivity was measured under the irradiation of a continuous waved laser with a wavelength of 1.55 µm.

3.Result and Discussion

Figure 3 shows electrical and optical characteristics of the GeSn and Ge-capped GeSn PDs. The undoped GeSn layers are p-type according to current-voltage (I-V) characteristics shown in Fig. 3 (a) and Fig. 3 (b). Although the on/off ratio is only 4 for the GeSn PD, it increased to 160 when the Ge cap layer remained. We believe that Sn oxidation occurred at the interface between GeSn and TiO_x layer, formed $TiGe_\alpha Sn_\beta O_\gamma$ interlayer, and this $TiGe_\alpha Sn_\beta O_\gamma$ interlayer cannot effectively alleviate Fermi-level pinning. Moreover, the Sn oxidation can also degrade the film quality of TiO_x layer, caused decrease in effect barrier height for holes. The details of chemical bond formation will be investigated and reported at the conference. Nevertheless, typical PD behaviors were observed for both samples. The GeSn PD showed a good responsivity of 0.22 A/W despite its high dark current density, implying good crystalline quality of the GeSn layer (Fig. 3(c)). The responsivity was improved to 0.31 A/W for the sample with Ge cap layer (Fig. 3(d)). This is reasonable because the Ge cap layer can not only passivate the GeSn surface but also prevent Sn oxidation, so that the photo carriers have relatively longer lifetime in the Ge-caped GeSn PDs. These results will be compared with Ge PDs fabricated using the same process and the effects of Ge cap layer on GeSn PD performance will be discussed in detail and reported in the conference.

4.Conclusion

The results demonstrate the feasibility of ultra-low temperature (200 °C) formation of asymmetric MISM structure with $TiO_x/TiGe_yO_z$ interlayer for GeSn PD fabrication. A good responsivity of 0.22 A/W was achieved for MISM GeSn PDs. A Ge cap layer effectively passivates the GeSn surface, suppressing dark current while improving responsivity to 0.31 A/W (0.62 A/W if exclude electrode shading), which is comparable with asymmetric MSM Ge-PDs [4,5], where the metal shading is also considered when calculating responsivity. The highest temperature for GeSn PD fabrication is only 200 °C, preventing Sn precipitation and ensuring low-temperature compatibility, which has considerable potential for future GeSn devices with higher Sn fraction.

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Reference

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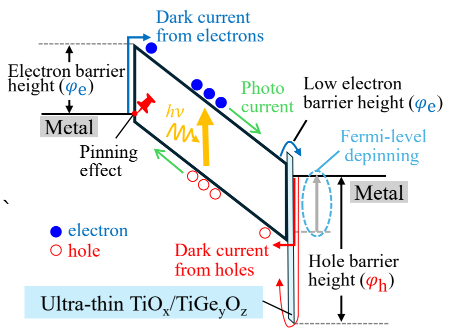

Fig. 1. A $TiO_x/TiGe_yO_z$ layer enables efficient photoelectron collection while suppressing the dark hole current.

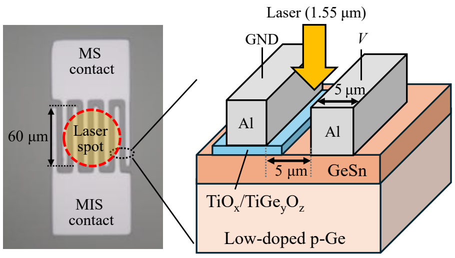

Fig. 2. Top view and cross-sectional schematic of MISM PD.

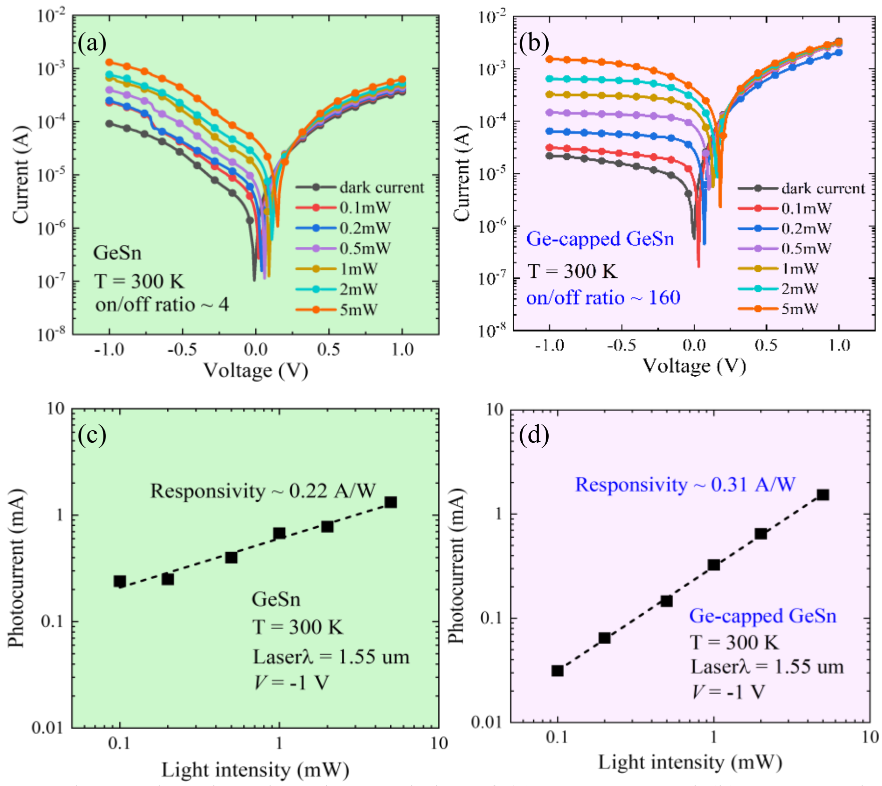

Fig. 3. Photodetection characteristics of (a) GeSn PD and (b) Ge-capped GeSn PD under dark and various laser power (λ = 1.55 μm); Responsivity of (c) GeSn PD and (d) Ge-capped GeSn PD.