Impact of Post-Growth Annealing for Thin-Film Ge Photodiodes on Si

Sho Nagatomo,1 Yuta Kawamata,1 Yusaku Izawa,2 Satohiko Hoshino,3 and Yasuhiro Ishikawa1

1Department of Materials Engineering, The University of Tokyo
7-3-1 Hongo, Bunkyo, Tokyo, 113-8656, Japan
Phone: +81-3-5841-7152 E-mail: y-ishikawa@material.t.u-tokyo.ac.jp
2Tokyo Electron Miyagi Limited
1 Techno Hills, Taiwa-cho, Kurokawa-gun, Miyagi 981-3629, Japan
3Technology Development Center, Tokyo Electron Limited
650 Mitsuzawa, Hosaka-cho, Nirasaki City, Yamanashi, 407-0192, Japan

Abstract
Effect of post-growth annealing is studied for thin-film (200 - 600 nm) Ge pin photodiodes on Si. High-temperature post-growth annealing in a furnace (≥ 800°C) can suppress the dark leakage current, while the detection efficiency for near-infrared light is degraded, resulting from the alloying of Ge film with Si. A laser annealing is demonstrated to prevent such a SiGe formation.

1. Introduction
Ge pin diodes on Si have been applied to near-infrared (NIR) photodetectors (PDs) in Si photonics [1]. One of the issues in Ge PDs on Si is the presence of threading dislocations in Ge with a high density, derived from the 4% lattice mismatch between Ge and Si. A post-growth annealing at high temperatures (< 937°C, melting point of Ge) is effective for the reduction of dislocations, leading to a suppressed dark current together with a high photodetection efficiency [2]. Previously, Ge films as thick as 1 µm were mainly used, while thinner films on the order of 100 nm are required for the operation frequency over ~50 GHz [3]. For such thin Ge films, however, the effect of post-growth annealing has not been examined sufficiently, and one of the concerns is that the alloying of Ge with Si would degrade the detection efficiency if most of the thin Ge is replaced to wider-gap SiGe alloy with a poor NIR absorption.

In this work, effect of post-growth annealing is studied for thin-film (200 - 600 nm) Ge PDs on Si. As a result, a post-growth annealing in a furnace leads to a reduction of dark leakage current, similar to the case for thicker films, while the photodetection efficiency is significantly degraded after the furnace annealing above 800°C due to the formation of SiGe alloy. A rapid NIR laser annealing is demonstrated to prevent the SiGe formation.

2. Experimental
Epitaxial films of Ge with the thickness of 200, 400, and 600 nm were grown on p+-Si (100) wafers by ultra-high vacuum chemical deposition with a two-step growth (370/600°C), followed by the growth of Si cap layer (50 nm). After the deposition of SiO2 layer, the samples were annealed in a furnace at high temperatures (700, 800, and 900°C) for 30 min in N2. A sample was also prepared, where an NIR laser (1.07 µm in wavelength, selectively absorbed in Ge) was exposed as a rapid post-growth annealing process (10 cycles of 12 msec exposure). In order to fabricate pin structures, phosphorous atoms were implanted for the top n-type contact. Al was deposited for the electrodes. Current-voltage (I-V) characteristics and free-space NIR responsivity spectra were measured at room temperature. Micro-Raman spectroscopy with a 457-nm laser excitation was used to examine the formation of SiGe alloy. The laser light fairly penetrates the Si cap layer (50 nm), but rapidly absorbed in Ge (~20 nm), being useful for the characterization around the Si cap/Ge interface.

Fig. 1 shows typical I-V characteristics for 200-nm-thick Ge PDs on Si with different post-growth annealing temperatures.

3. Results and Discussions
Figure 1 shows typical I-V characteristics for 200-nm-thick Ge PDs on Si (lateral size: 200 x 200 µm²) with different temperatures of post-growth
annealing in a furnace. The dark leakage current was found to be reduced by the post-growth annealing: at the reverse bias of 1 V, ~100 mA/cm² for as-grown (600°C) and 700°C, ~10 mA/cm² for 800°C, and ~2.5 mA/cm² for 900°C. This is ascribed to the reduction of dislocations in Ge, similar to the case for the thicker Ge (1 µm) [2]. However, as in Fig. 2, the furnace annealing at 800 and 900°C significantly degraded the responsivity.

Fig. 2. Responsivity spectra at reverse bias of 0.5 V for 200-nm-thick Ge PDs on Si with different post-growth annealing temperatures

The reduction of responsivity can be ascribed to the formation of wider-gap SiGe alloy. As in Fig. 3, the Raman scattering spectra revealed the formation of SiGe alloy, i.e., the Ge-Si peak at ~ 400 cm⁻¹ appeared for the furnace annealing at 800 and 900°C. Secondary ion mass spectroscopy analyses (not shown) also revealed the SiGe formation. Such a SiGe formation significantly reduces the thickness of absorptive Ge film, reducing the photodetection efficiency.

Based on these results, a careful annealing is found to be required for thin-film Ge on Si. As a novel post-growth annealing process, an NIR laser was exposed with the wavelength of 1.07 µm. At this wavelength, the laser light is selectively absorbed in Ge. Furthermore, the duration of laser exposure can be limited as short as 100 msec or below. This allows the rapid annealing, suppressing the inter-diffusion/alloying of Ge and Si. Using such a laser annealing, the dark current was found to be reduced as small as 20 mA/cm², which is almost the same as that annealed at 800°C in the furnace. The responsivity spectrum for 600-nm-thick Ge with the laser annealing is shown in Fig. 4(a). No degradation of the responsivity was seen in contrast to the furnace annealing, while a slight enhancement was observed in the wavelengths longer than ~1540 nm. It is important that the Raman spectra in Fig. 4(b) revealed that the formation of SiGe alloy is strongly suppressed for the laser annealing, being useful for the fabrication of thin-film Ge PDs on Si.

Fig. 3. Raman spectra for 200-nm-thick Ge PDs on Si with different post-growth annealing temperatures

Fig. 4. (a) Responsivity spectra at reverse bias of 0.5 V and (b) Raman spectra for PDs with 600-nm-thick Ge exposed to an NIR laser.

4. Conclusions

Effect of post-growth annealing was investigated for thin-film Ge pin PDs on Si. A post-growth annealing in a furnace reduced the dark leakage current, similar to the case for thicker films, while the photodetection efficiency was significantly degraded due to the formation of SiGe alloy. An NIR laser annealing was demonstrated to prevent the SiGe formation.

References