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Improving Optical Properties of Ge Layers Fabricated by Epitaxial Growth Combined with Ge Condensation

Katsuya Oda[1, 2, 3], Kazuki Tani[1, 2, 3], Shin-ichi Saito[1, 2, 3], Tadashi Okumura[3], and Tatemi Ido[1, 2, 3]

[1] Photonics Electronics Technology Research Association,
[2] Institute for Photonics-Electronics Convergence System Technology,
[3] Central Research Laboratory, Hitachi, Ltd.
1-280 Higashi-Koigakubo, Kokubunji, Tokyo 185-8601, Japan
Phone: +81-42-323-1111, E-mail: Katsuya.Oda.cb@hitachi.com

1. Introduction

Silicon photonics are attracting attention as a key technology for achieving high-speed optical interconnection to overcome signal delay and power consumption of metal lines in large-scale integrated circuits. There are some approaches to realize on-chip light sources that can be fabricated with CMOS logic circuits [1][2], germanium laser is the most promising device due to a compatibility with Si processes and low cost [3]. However, since lattice constants are quite different between Si and Ge, improving crystallinity of Ge layers grown on Si substrate is a serious issue. Therefore, process technologies for reducing dislocation density in the Ge layers must be developed to improve the performance of Ge light-emitting devices. We fabricated high-quality Ge layers by Ge condensation and epitaxial growth, and investigated crystallographic and optical properties of Ge layers.

2. Experimental

An eight-inch silicon-on-insulator (SOI) wafer was used as a substrate. First, a SiGe layer was epitaxially grown by ultra-high-vacuum chemical vapor deposition (CVD) with disilane (Si_2H_6) and germane (GeH_4), then it was oxidized at 850°C with wet ambient to selectively oxidize Si atoms. Next, the Ge layer was epitaxially grown by low-pressure CVD with GeH_4 and H_2 carrier gas. To suppress indirect transition by filling electrons into the L-valley in the conduction band [4], in-situ n-type doping was also carried out by supplying phosphine (PH_3). Carrier concentration in the n-Ge layers was 1.4×10^{19} cm^{-3}, which was derived using Hall measurements. To improve the surface morphology of the Ge layers, growth temperature was reduced to 420°C at the first step then additional Ge layers were grown at higher temperature. The optimum growth temperature was 700°C for the 2nd growth step to achieve good crystallinity of Ge layers [5]. Figure 1(a) shows a cross-sectional scanning electron microscopy (SEM) image of Ge/condensed SiGe layers, which is notably uniform, formed on the buried oxide (BOX) layer. Moreover, the Ge layer can be selectively grown only on the condensed SiGe layers, as shown in Fig. 1(b). Figure 2 shows atomic force microscopy (AFM) images of Ge layers grown on the Si substrate and condensed SiGe layer. The surface morphology of the Ge layer grown on the condensed SiGe layer was quite good, and the root mean square roughness was 0.38 nm for an area of 2 × 2 μm.

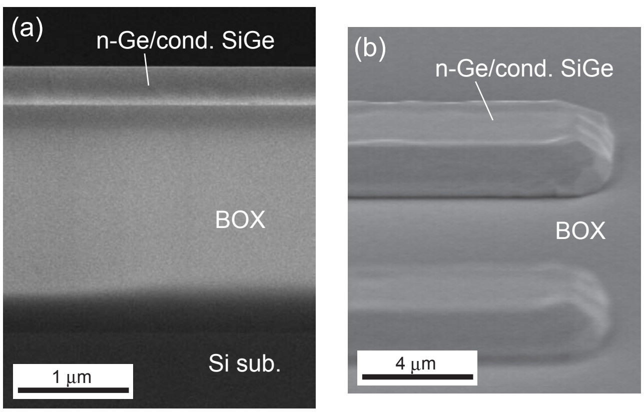

Fig. 1 SEM images of n-Ge / condensed (cond.) SiGe / BOX structure; (a) cross-sectional view, (b) bird's-eye view.

3. Results

3.1 Crystallinity and lattice strain

To evaluate the crystallinity and lattice strain of the Ge layers, high-resolution X-ray diffraction (XRD) was carried out. Since a reciprocal space mapping technique is difficult to apply to the Ge layers formed on the BOX layer, symmetrical (004) and asymmetrical (-1-13) diffractions from the Ge layers were measured. Figure 3 shows rocking curves of (-1-13) diffractions from the Ge layers grown on the Si substrate and the condensed SiGe layer. A curve from an n-Ge bulk substrate is also plotted as a reference. Although the thickness of the Ge layers was less than 500 nm, diffraction peaks corresponding to the Ge layers were clearly observed, this means that single crystalline Ge layers were successfully obtained. Moreover, the diffraction angle of the epitaxially grown Ge layers was smaller than that of the Ge substrate. The diffraction angle of the Ge layers in the (004) rocking curves was larger than that of the Ge substrate indicating that the Ge layers contain tensile strain in the <110> direction. The lattice strain was also measured using Raman spectroscopy, as shown in Fig. 4. The Raman shift of the epitaxially grown Ge layers is smaller than that of n-Ge bulk substrate. The figure also shows that

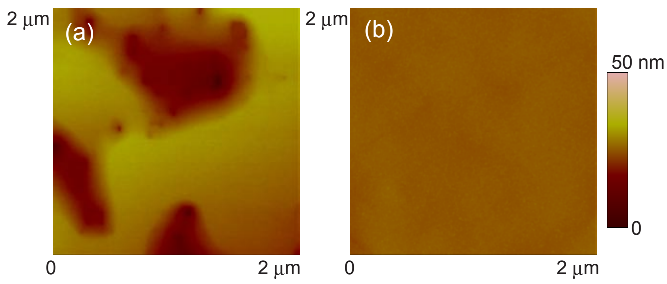

Fig. 2 AFM images of n-Ge layers grown on (a) Si substrate, (b) condensed SiGe layer.

the Ge layers have in-plane tensile strain. Although the tensile strain originated from the difference in thermal expansion coefficients between Si and Ge [6], we found that the Ge layer grown on the condensed SiGe layer has larger tensile strain than that corresponding to the Si substrate.

3.2 Optical properties

Figure 5 shows photoluminescence (PL) spectra from the Ge layers grown on the Si substrate and the condensed SiGe layer. Although a small peak originating from the condensed SiGe layer was observed at the wave length of 1490 nm, the main peak from the Ge layer grown on the condensed SiGe layer was very steep, and its intensity was about 3 times higher than that corresponding to the Si substrate. This might be due to the improvement in crystallinity with the Ge condensation technique and carrier confinement improved by isolation between the Ge layer and the Si substrate. Furthermore, obvious red-shifts of the PL peaks from the epitaxially grown Ge layers were observed. The peak wave length of PL spectra from the n-Ge layers as a function of lattice mismatch in <110> crystal orientation is the inset of Fig. 5. The lattice mismatch was derived from the symmetrical (004) and asymmetrical (-1-13) rocking curves of XRD. This result suggests that the direct bandgap energy at Γ point was reduced, which is consistent with the presence of the in-plane tensile strain. The PL intensity from Ge stripe structures as a function of pumping power is shown in Fig. 6. The width of the Ge stripes was 10 μm. The PL intensity steeply increases with pumping power which is due to increasing carrier recombinations at Γ point in the isolated Ge layer, and sufficient crystallinity of the Ge stripes fabricated by a combination of Ge condensation and epitaxial growth.

4. Summary

Single crystal Ge layers were successfully fabricated on a BOX layer by a combination of Ge condensation and epitaxial growth. A steep PL spectrum with higher peak intensity was obtained from Ge stripes by improving crystallinity and carrier confinement. These results indicate that this combination technique efficiently improves the performance of Ge light-emitting devices.

Acknowledgements

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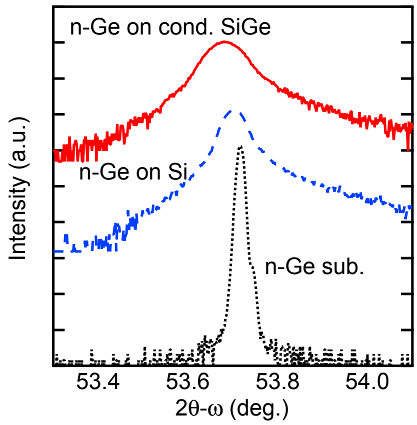

Fig. 3 (-1-13) rocking curve of XRD from n-Ge layers grown on Si substrate and condensed SiGe layer.

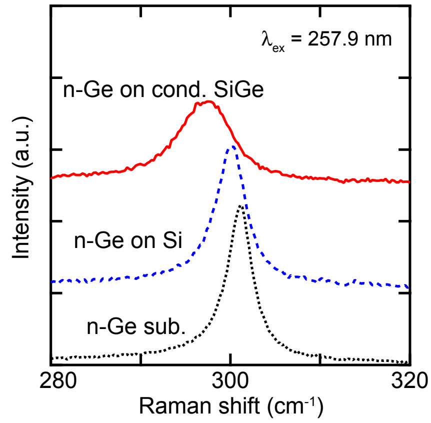

Fig. 4 Raman spectra from n-Ge layers grown on Si substrate and condensed SiGe layer.

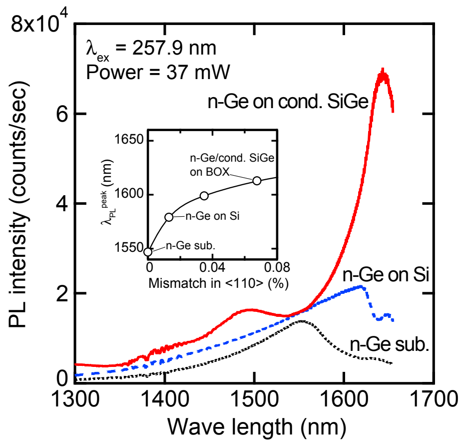

Fig. 5 PL spectra from n-Ge layers grown on Si substrate and condensed SiGe layer. Peak wave length as function of lattice mismatch in <110> is shown in inset.

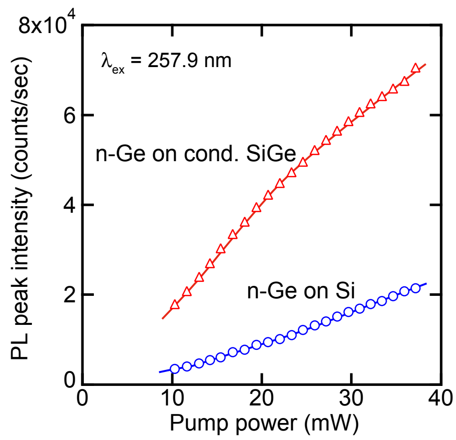

Fig. 6 Pumping power dependence of PL peak intensity from 10 μm-wide Ge stripes.