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Giant growth of single crystalline Ge on insulator by seeding lateral liquid-phase epitaxy

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ABSTRACT

Giant growth (~400 μm length) of single crystalline Ge on insulator (GOI) with (100), (110), and (111) orientations is demonstrated by lateral liquid-phase epitaxy (L-LPE) using Si(100), (110), and (111) substrates, respectively, as the seeds. The micro-probe Raman measurements and transmission electron microscopy observations showed that the growth regions were of very high crystal quality and were defect free. In addition, lateral diffusion of Si atoms was observed only in the regions near the seeding edges (~100 μm). Based on these findings, the trigger for the giant growth of the high-quality GOI was discussed considering the solidification temperature gradient due to Si–Ge mixing and the thermal gradient due to the latent heat at the growth front.

1. Introduction

Single crystalline Ge is very attractive for high-performance complimentary metal-oxide-semiconductor field-effect transistors (CMOSFET) because of the high electron and hole mobilities compared with Si [1–3]. Developments of Ge-on-insulator (GOI) structures are strongly desired, because fully-depleted transistor structures will become essential in the next-generation ultra-large scale integrated circuits (ULSI). Consequently, many techniques, such as layer transfer [4] oxidation-induced Ge condensation [5] metal-induced lateral crystallization [6] and imprint-induced solid-phase crystallization [7] have been developed in recent ten years. However, some of them require complex processing, and others have difficulty in obtaining high-quality Ge crystals.

Recently, seeding lateral liquid-phase epitaxy (L-LPE) on insulator [8–11] similar to laser annealing [12] and/or micro zone-melting growth [13] were examined to obtain GOI structures, where Si substrates were used as the crystal seeds for the epitaxial growth. These efforts realized Ge stripes (20–40 μm length, 2–3 μm width) on Si substrates covered with SiO_2 or SiN. In our previous study, we significantly increased the growth length by optimizing RTA conditions and obtained giant single crystalline GOI (~400 μm length) [14]. However, the details of the crystallinity of the giant grown GOI structures have not been clarified.

In the present study, we investigate the details of the giant Ge stripes grown on SiO_2 layers using Si(100), (110), and (111) substrates as seeds, and crystallinity and Si incorporation of the Ge stripes were revealed. Based on the findings, the mechanism of the giant growth is discussed.

2. Experimental procedure

Si(100), Si(110), and Si(111) wafers (600 μm thickness) covered with SiO_2 films (50 nm thickness) were used as substrates. The SiO_2 films were patterned by wet etching to form seeding window areas ($150\times30\ \mu m^2$), where SiO_2 layers were locally removed. Edges of seeding areas were formed perpendicular to <011> direction for Si (100) and Si(111) substrates, and <001> direction for Si(110) substrates. Subsequently, amorphous-Ge (a-Ge) layers (100 nm thickness) were deposited using a solid-source molecular beam epitaxy (MBE) system (base pressure: 5×10^{-11} Torr), and they were patterned into narrow stripes (400 μm length, 2–15 μm width) by photolithography and wet etching, as shown in Fig. 1(a). Then SiO_2 capping-layers (800 nm thickness) were deposited by RF magnetron sputtering (Fig. 1(b)). Finally, these samples were heat-treated by rapid thermal annealing (RTA) at 1000 °C (1 s), to induce liquid-phase epitaxial growth from the seeding areas.

Morphology, crystal orientation, and crystal quality of the grown layers were characterized by Nomarski optical microscopy, electron backscattering diffraction (EBSD), and cross-sectional transmission electrical microscopy (TEM). The lateral distributions of Si atoms along the growth direction were measured by micro-probe Raman spectroscopy. To estimate the Si fraction (x), we used the following equation proposed by Mooney et al. [15]

$$\frac{I(Ge-Ge)}{I(Si-Ge)} = \frac{k(1-x)}{2x} \quad (1)$$

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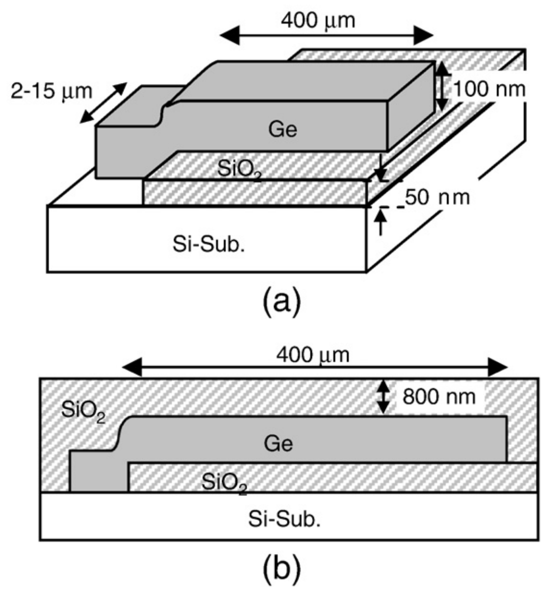

Fig. 1. (a) Bird's-eye view and (b) cross-sectional structure of the sample.

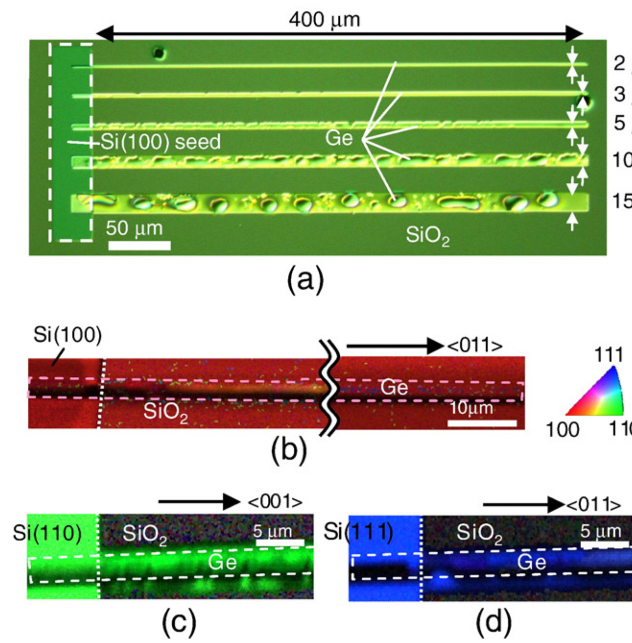

Fig. 2. (a) Nomarski optical micrograph of the sample on Si (100) after RTA (1000 °C, 1 s). EBSD images of GOI grown on (b) Si (100), (c) Si (110), and (d) Si (111) substrates. Seeding Si regions and directions of Ge stripes, i.e., growth directions, are shown in the EBSD images.

where *I*(Ge–Ge) and *I*(Si–Ge) are the peak intensities of Raman signals originating from Ge–Ge and Si–Ge vibration modes, respectively, and *k* is a constant. We determined *k* as 1.6 by measuring Raman spectra for single crystalline Si_xGe_{1-x} ($x = 0.11$, 0.21, 0.43, and 0.51) samples epitaxially grown on Si substrates. The strain ratios (ε) in the grown Ge layers were evaluated from the Raman peak position due to the Ge–Ge vibration mode (ω_{Ge-Ge} in cm^{-1}) and Si fraction (x) by using the following equation [16].

$$\omega_{Ge-Ge} = 282.5 + 16(1-x) - 385\epsilon \quad (2)$$

3. Results and discussion

A typical Nomarski optical micrograph of the sample (substrate: Si (100)) after RTA is shown in Fig. 2(a). Agglomeration of Ge is clearly observed in wide stripe patterns (width > 10 μm), which is attributed to the high interface energy between the liquid Ge region and the SiO_2 underlayer. However, such a phenomenon is significantly controlled by reducing the stripe width. As a result, flat Ge stripes with 400 μm length are obtained for the narrow stripe patterns (width < 3 μm).

The EBSD images of the samples (stripe width: 3 μm) grown on S (100), (110), and (111) substrates are shown in Fig. 2(b), (c), and (d), respectively, where the capping SiO_2 layers were etched off before the observation. It is found that the grown Ge regions show identical colors to those of the Si substrates, which indicates that single crystalline Ge with the crystal orientations identical to those of the Si substrates are grown on SiO_2 layers for all samples. In addition, dark lines are observed along the grown regions, which are due to the shadowing of the electron beams, because the normal direction of the samples was inclined with 70° from the electron beams in the EBSD measurements. This clearly means that crystal growth is initiated at the Si seeding areas and propagates laterally over SiO_2 films. Interestingly, the whole a-Ge regions are single-crystallized even though the giant lateral growth reaches to 400 μm. The length of this giant growth is one order longer than those reported in the previous works [8–10]. The maximum growth length obtained in our experiments is limited by the sample structures, where a-Ge stripe patterns with 400 μm length are employed. We expect that huge lateral growth over 400 μm is possible by this L-LPE method. Further experiments using a-Ge stripe patterns with mm to cm lengths are now underway.

To evaluate the Si fraction and the crystal quality in laterally-grown regions, micro-probe Raman spectroscopy measurements (spot size: ~1 μmϕ) were performed as a function of the distance from the seeding areas. The typical Raman spectra obtained from different positions in the sample shown in Fig. 2(b) (substrate: Si(100), growth direction: <011>) are shown in Fig. 3(a). Two peaks are observed at frequencies of 296.8 and 380.9 cm^{-1} in the spectra. The main peaks (296.8 cm^{-1}) originating from the vibration modes for Ge–Ge bonds are observed in all spectra. On the other hand, the sub-peaks (380.9 cm^{-1}) originating from the vibration modes for Si–Ge bonds are observed in the region near the seeding area (distance < 50 μm), however it cannot be detected in the region far from the seeding area (distance > 70 μm), as shown in Fig. 3(a). This indicates that Si–Ge mixing at the Ge/Si interface in the seeding areas causes Si diffusion into the Ge region on SiO_2, however, the diffusion length is limited below 70 μm. The lateral distribution of the Si fraction evaluated from the Raman spectra using Eq. (1) is summarized in Fig. 3(b). These results indicate that the Si fraction in the seeding area and the seeding edge are 8 and 4%, respectively. It gradually decreases along the growth direction and reaches to zero, where lateral growth length exceeds 70 μm. Consequently, pure single crystalline Ge is obtained in the long region between 70 μm and 400 μm from the seeding edge.

Fig. 3(c) summarizes the full-widths at half maximum (FWHM) of the main peaks and the strain ratio in the grown Ge evaluated from the Raman shift using Eq. (2) by the closed circles and the open circles, respectively. The FWHM value obtained from a single crystalline Ge bulk wafer is also shown in Fig. 3(c) for comparison. The FWHM values in the seeding area are about 4–5 cm^{-1}, which is wider than that of the single crystalline Ge (3.2 cm^{-1}). However, almost equal values (~3.3 cm^{-1}) to that of single crystalline Ge are obtained from the L-LPE region, indicating very high crystal quality of the grown region. In addition, Raman peak positions due to the Ge–Ge vibration mode of grown Ge are about 297.1 cm^{-1}, which is lower than that of strain free bulk-Ge (peak position: 298.5 cm^{-1}). This shift of Raman