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Growth-direction-dependent characteristics of Ge-on-insulator by Si–Ge mixing triggered melting growth

Y. Ohta, T. Tanaka, K. Toko, T. Sadoh *, M. Miyao

Department of Electronics, Kyushu University, 744 Motooka, Fukuoka 819-0395, Japan

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ABSTRACT

The lateral liquid-phase epitaxy of Ge-on-insulator (GOI) using Si seeds has been investigated as a function of the Si-seed orientation and the growth direction. Giant single-crystalline GOI structures with ~200 μm length are obtained using Si(1 0 0), (1 1 0), and (1 1 1) seeds. The very long growth is explained on the basis of the solidification temperature gradient due to Si–Ge mixing around the seeding area and the thermal gradient due to the latent heat around the solid/liquid interface at the growth front. In addition, growth with rotating crystal orientations is observed for samples with several growth directions. The rotating growth is explained on the basis of the bonding strength between lattice planes at the growth front. This rotating growth does not occur in any direction for (1 0 0) orientated seeds. Based on this finding the mesh-patterned GOI growth with a large area (250 μm × 500 μm) is demonstrated.

1. Introduction

The Ge-on-insulator (GOI) is a promising channel material for the advanced transistors with the very high-speed and low-power consumption [1–3]. In order to obtain GOI structures, various formation techniques, such as wafer bonding [4], oxidation-induced Ge condensation [5], and imprint-induced solid-phase crystallization [6], have been intensively developed. However, these techniques require complex processing or have difficulty in obtaining high-quality GOI structures.

Recently, lateral liquid-phase epitaxy (L-LPE) of Ge layers (length: ~40 μm) on insulator was reported by several research groups [7–10], where Si substrates were used as the crystal seeds for epitaxial growth of Ge layers. We previously succeeded in the giant (~200 μm) growth of GOI by optimizing sample structures and annealing conditions [11–13]. This growth length was one order larger than those reported in the previous works [7–10]. However, the detailed growth features, such as the crystal orientation dependence, have not been clarified. In the present paper, we investigate the effect of crystal orientation of Si seeds on the growth features, and discuss the rotating growth of GOI. In addition, we apply this technique to achieve a large area GOI by using a mesh-pattern.

2. Experimental procedure

In the experiments, Si(1 0 0), (1 1 0), and (1 1 1) substrates covered with thermally grown SiO_2 films (50 nm thickness) were used. The SiO_2 films on the substrates were selectively removed by wet etching to form seeding areas ($150 \times 30\ \mu m^2$). 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) at room temperature, and they were patterned into narrow stripe lines (200 μm length, 3–5 μm width). The sample structure is schematically shown in Fig. 1. Then capping SiO_2 layers (800 nm thickness) were deposited by RF magnetron sputtering. Finally, these samples were heat-treated by rapid thermal annealing (RTA) (1000 °C, 1 s) with heating and cooling rates of ~40 and ~10 °C/s, respectively, to induce liquid-phase epitaxial growth from the seeding areas.

The grown layers were characterized by Nomarski optical microscopy, electron backscattering diffraction (EBSD), and microprobe (spot size: ~1 μmϕ) Raman scattering spectroscopy. The capping SiO_2 layers were etched off before the EBSD measurements.

3. Results and discussions

The EBSD images of the samples grown on Si(1 0 0), (1 1 0), and (1 1 1) substrates are shown in Fig. 2, where the growth directions are shown in the figures. It is found that giant single-crystalline Ge stripes (length: 200 μm) with crystal orientations identical to those of Si seeds are realized on the SiO_2 layers using Si(1 0 0) and (1 1 0) seeding substrates. On the other hand, for the Si(1 1 1) substrate, the crystal orientation of the giant GOI structure grown along the ⟨0 1 1⟩ direction is (1 1 1), though that along the ⟨1 2 1⟩ direction gradually changes from (1 1 1) to (1 0 0). These results clearly show that crystal growth is initiated at Si seeding areas and propagates laterally over SiO_2 films for all samples.

* Corresponding author.
E-mail address: sadoh@ed.kyushu-u.ac.jp (T. Sadoh).

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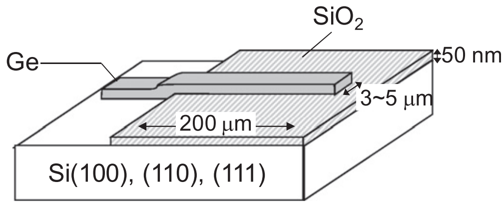

Fig. 1. Schematic sample structure before SiO_2 capping.

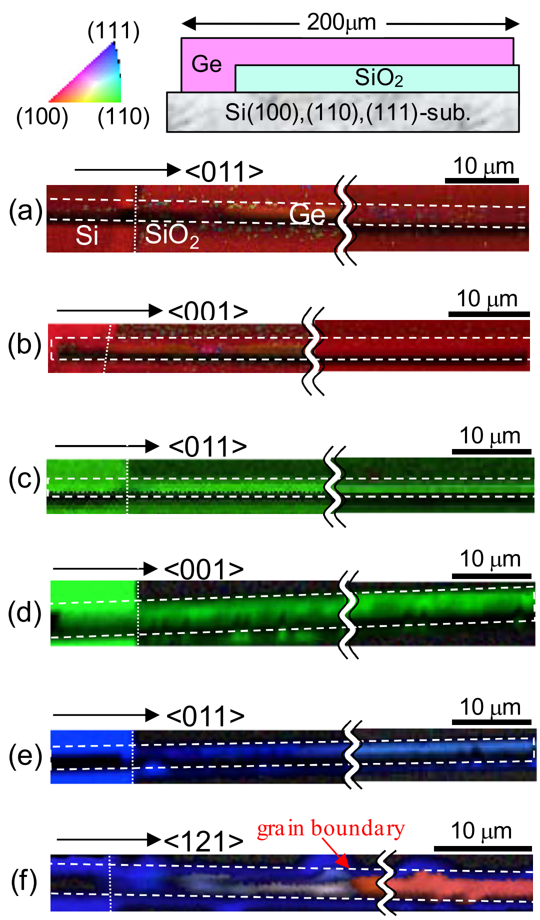

Fig. 2. EBSD images for samples grown with Si(1 0 0) (a,b), Si(1 1 0) (c,d), and Si(1 1 1) seeding substrates (e,f).

In order to evaluate the crystal quality and the Si fraction in laterally-grown regions, micro-probe Raman spectra were measured as a function of the distance from the seeding edges. The full-width at half maximum (FWHM) of the Raman peaks at 296.8 cm^{-1} due to Ge–Ge bonds for the sample with the Si(1 0 0) seeding substrate grown to the ⟨0 1 1⟩ direction, shown in Fig. 2a, is summarized in Fig. 3a, where FWHM obtained from a single-crystalline Ge bulk wafer is also shown for comparison. The FWHM values in the seeding area are about 4–5 cm^{-1}, which is wider than that of single-crystalline Ge (3.2 cm^{-1}). However, almost equal values ($\sim$3.3 cm^{-1}) to single-crystalline Ge are obtained from the L-LPE area, indicating the high crystal quality. The FWHM values obtained from the L-LPE areas of the samples shown in Fig. 2b-f were also $\sim$3.3 cm^{-1}. Although a grain boundary (GB) existed in the sample shown in Fig. 2f, the small FWHM was obtained, which was probably because the Raman peak was not broadened due to the very large grains with very high crystallinity.

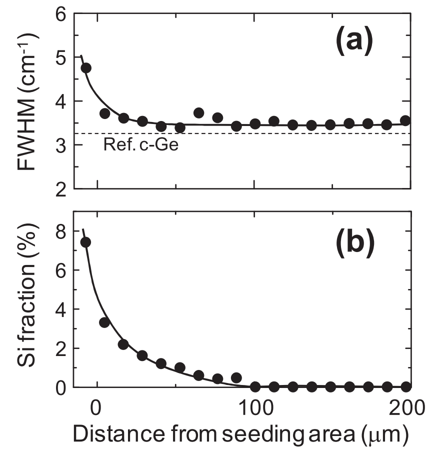

Fig. 3. FWHM of Raman peak due to Ge–Ge bonds (a), and Si fraction distribution in Ge layers (b).

The Si fractions in the grown layers were evaluated from the intensities of Raman peaks due to Ge–Ge (296.8 cm^{-1}) and Si–Ge bonds (380.9 cm^{-1}) [11,14]. The result is shown in Fig. 3b as a function of the distance from the seeding edge. It is found that the Si fractions in the seeding area and at the seeding edge on SiO_2 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 large region of 70–200 μm from the seeding edge.

The possible candidates of the driving force to initiate L-LPE of Ge on SiO_2 layers are the thermal flow from the liquid SiGe or Ge region to the Si substrate through seeding window or the increase in the solidification temperature due to Si–Ge mixing. However, the result of an additional experiment on quartz substrates employing poly-Si seeds, which suppresses thermal flow from the liquid SiGe or Ge regions to the substrates through seeding windows, indicated that Si–Ge mixing at seeding areas is the most important force to trigger the L-LPE [11].

In order to explain such a giant lateral growth of pure Ge obtained in the region far from the seeding area (>70 μm), another force should be considered, because the gradient of the Si fraction does not exist in this region. The latent heat of solidification at the solid–liquid interface is the important driving force to realize the giant growth. In the cooling process after RTA, the temperature of the solid-Ge rapidly falls with time. However, the molten-Ge tends to keep a constant melting-temperature due to latent heat. Consequently, a thermal gradient is automatically formed at the growth front, which realizes the continuous L-LPE [11]. The maximum growth length obtained in our experiments is limited by the sample structures, where a-Ge stripe patterns with 200 μm length are employed. Thus, we expect that very long lateral growth over 200 μm is possible by this L-LPE method.

From detailed analysis of the EBSD data, it was found that the crystal orientations of the growth directions in-plane to the sample surfaces did not change for all samples grown using Si(1 1 1) seeding substrates, though the crystal orientation of the surface of the Ge layer grown along to the ⟨1 2 1⟩ direction gradually changed, as shown in Fig. 2f. These results show that rotating growth occurs for the sample with the Si(1 1 1) seeding substrate grown along ⟨1 2 1>. On the other hand, such a rotating growth was not observed along ⟨0 1 1⟩ even though the use of the Si(1 1 1) seed, as shown in Fig. 2e.

In order to reveal the details of the rotating growth, the change in the crystal orientation perpendicular to the film plane was investigated as a function of the distance from the seeding edge. The results are summarized in Fig. 4a. It is found that the rotation