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In-depth analysis of high-quality Ge-on-insulator structure formed by rapid-melting growth

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ABSTRACT

High-quality Ge-on-insulator (GOI) structures are essential to realize next-generation large-scale integrated circuits, where GOI is employed as active layers of functional devices, as well as buffer layers for epitaxial growth of functional materials. In line with this, in-depth analysis of crystallinity of rapid-melting-grown GOI is performed. Structural and electrical measurements combined with a thinning technique reveal that the crystallinity of GOI (500 nm thickness) is very high and uniform in-depth direction, where high hole mobility (~1000 cm^2/V s) is achieved throughout the grown layers. These findings open up a possibility of application of rapid-melting-grown GOI to various advanced functional devices.

1. Introduction

For further improvement of large-scale integrated circuit (LSI) performance, various functional devices, such as ultrahigh-speed transistors, optical devices, and magnetic-nonvolatile memories, should be integrated on Si-platform [1–6]. Ge-on-insulator (GOI) structures are essential for this purpose, because they provide higher mobility channels, due to the higher electron and hole mobility compared with Si [1–4]. In addition, optical and thermoelectronic properties of Ge are attracting much attention [5,6]. Moreover, GOI is useful as epitaxial template of optical- and spintronic-materials, such as GaAs, AlGaAs, and Fe_3Si, due to good lattice matching [7,8]. Thus, formation techniques of high-quality GOI structures are becoming very important to realize next-generation LSIs.

In line with this, the oxidation-induced Ge condensation [9,10] and wafer bonding techniques [11] have been developed to achieve GOI structures on Si platform. Recently, rapid-melting-growth of Ge has been developed, which achieved the lateral-growth over insulating films [12–15]. Namely, our intensive efforts in this field significantly improved this technique [16–21], which achieved giant single crystalline Ge-on-insulator (GOI) stripe arrays of 1 cm length [20]. It is two orders of magnitude longer than those obtained by other groups [12–15]. Single-crystalline Ge network and hybrid-orientation GOI have been already demonstrated [18,19,21].

However, the in-depth crystallinity of such GOI has not been clarified. For application to active layers of various functional devices, high-quality GOI structures with uniform crystallinity in the depth direction are necessary. In the present study, we analyze in-depth crystallinity and electrical properties of rapid-melting-grown GOI. It is clarified that these GOI structures are high quality with high uniformity in the depth direction.

2. Experimental procedures

In the experiment, Si(100) substrates (600 µm thickness) covered with Si_3N_4 films (100 nm thickness) were used. These Si_3N_4 films were patterned by dry etching to form seeding areas (40×50 μm^2), where the Si_3N_4 films were locally removed. Edges of seeding areas were formed perpendicular to the [011] direction of Si(100) substrates. Then, a-Ge layers (100 and 500 nm thickness) were deposited by the molecular beam technique (base pressure: ~7×10^{-8} Pa), and they were patterned into narrow stripes (350 µm length, 5 µm width), as schematically shown in Fig. 1(a). The longitudinal direction of stripes was set to [011]. On the samples, SiO_2 capping layers (800 nm thickness) were deposited by RF magnetron sputtering. Finally, these samples were heat-treated by rapid thermal annealing (RTA) at 980 °C for 1 s to induce liquid-phase epitaxial growth from Si-seeding areas.

The surface morphologies and crystal quality of grown layers were characterized using Nomarski optical microscopy, electron backscattering diffraction (EBSD) of scanning electron microscopy (JEOL JSM-5510, operation voltage: 15 kV), and transmission electron microscopy (TEM) (Hitachi HF2200, operation voltage: 200 kV). Before EBSD and TEM observations, the capping SiO_2 layers were removed. The lateral distributions of Si atoms and strains were evaluated by micro-probe Raman spectroscopy (excitation-laser spot-diameter: ~1 µm, wavelength: 532 nm). The electrical properties were examined by the four-terminal method. To analyze in-depth crystal quality and electrical

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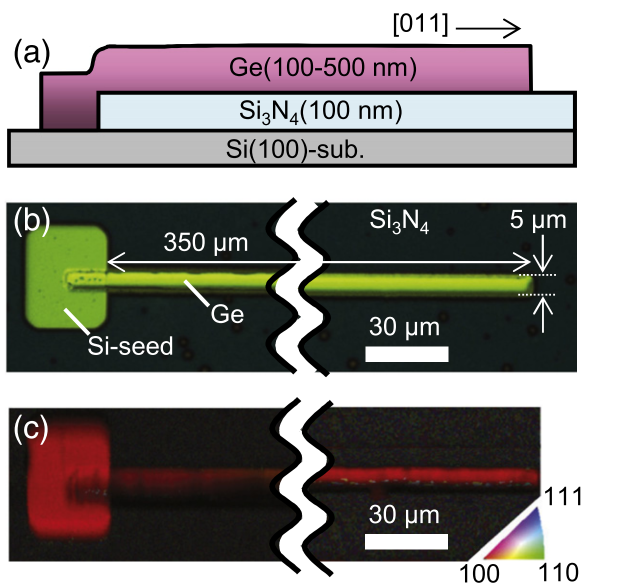

Fig. 1. Schematic sample structure (a), Nomarski micrograph (b), and EBSD image (c) of GOI (500 nm Ge thickness) after RTA (980 °C, 1 s).

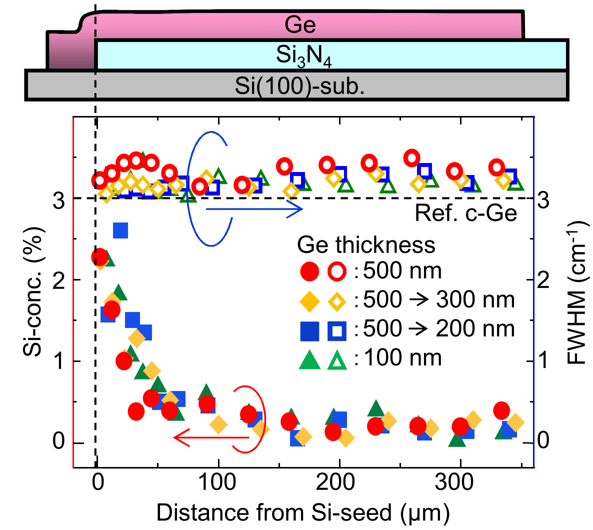

Fig. 2. Lateral profiles of Si concentration and FWHM of Ge–Ge peak obtained by microprobe Raman spectroscopy for grown GOI (100 and 500 nm Ge thickness). The data of samples after thinning Ge layer from 500 to 300 and 200 nm are also shown.

properties of GOI (500 nm thickness), these measurements were repeated after thinning of the samples by wet etching with H_2O_2 [22].

3. Results and discussion

A typical Nomarski optical micrograph of grown GOI (500 nm thickness) is shown in Fig. 1(b). It is found that there is no agglomeration or breaking of Ge stripe, and a uniform and flat Ge stripe with 350 μm length is obtained even for the very thick Ge layer. Crystal orientation of the GOI structures was investigated with EBSD after removing the capping layers. The EBSD image of GOI (500 nm thickness) is shown in Fig. 1(c). It is found that the entire region of the long Ge stripe is orientated to (100), which is identical to the orientation of the seeding Si(100) substrate. This clearly indicates that crystallization was initiated at the seeding area and propagated laterally over the Si_3N_4 film. These results well agree with our previous study of GOI (100 nm thickness) [14,16–18].

Si concentration and crystallinity of grown GOI (100 and 500 nm thickness) were investigated by micro-probe Raman spectroscopy. Here, the laser penetration depth is about 15 nm in SiGe (Si concentration ≤ 10%) [23]. The Si concentration was evaluated from the intensities of Raman peaks due to Ge–Ge and Si–Ge bonding, using the equation proposed by Mooney et al. [24] The Si concentration and full width at half maximum (FWHM) of the Ge–Ge peaks in GOI (100–500 nm thickness) are summarized as a function of the distance from the Si-seed in Fig. 2. In the figure, the data of samples after thinning from 500 to 300 and 200 nm by wet etching with H_2O_2 are also shown. For all samples, Si concentration is ~3% near the seeding areas and decreases to 0% around 100 μm away from the seeding areas. It is found that Si diffusion from the seeding areas does not depend on neither the thickness nor the depth of Ge layers. This is because the diffusion length of Si atoms is much larger compared with the thickness (100–500 nm) of GOI. On the other hand, the values of FWHM are 3.0–3.5 cm^{-1} for all samples, which are almost the same as that for c-Ge shown by the broken line in Fig. 2. This indicates that the crystal quality of the grown layers is very high for the thick sample (500 nm thickness) as well as thin samples (100 nm thickness), and uniform in the depth direction.

The crystal structures were investigated by TEM measurements. A cross-sectional TEM image of the thick GOI (500 nm thickness), observed at around 300 μm from the Si-seed, is shown in Fig. 3(a). It clearly indicates that the top- and bottom-interfaces of the Ge layer are very flat. Figs. 3(b) and (c) show the lattice images obtained at positions #1 (inner part of Ge layer) and #2 (bottom interface between Ge and Si_3N_4), respectively. No crystal defects such as dislocation or stacking fault are detected in the grown layers. The depth profile of Ge concentrations obtained by energy-dispersive X-ray spectroscopy along the arrow indicated in Fig. 3(a) is shown in Fig. 3(d). It is found that a pure Ge layer is formed, which supports the result of Raman spectroscopy

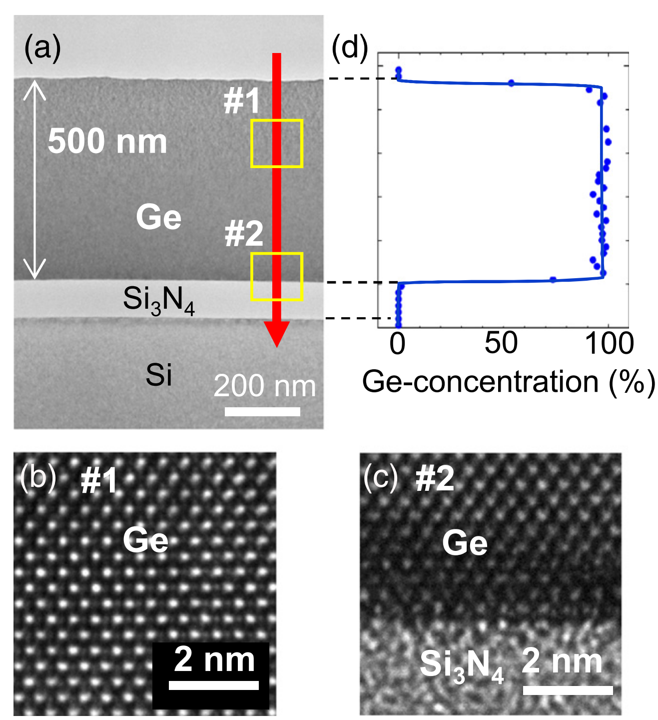

Fig. 3. Cross-sectional TEM image of GOI (500 nm Ge thickness) away from Si-seed by ~300 μm (a), lattice images [(b),(c)], and Ge concentration profile (d). The Ge concentration profile (d) was obtained along the arrow in (a).