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Characterization of Strain Relaxation Process during Ge Condensation by Synchrotron Microbeam X-ray Diffraction

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1. Introduction

The performance of metal-oxide-semiconductor field-effect transistors (MOSFETs) has been improved by scaling down the size of the devices. However, the scaling is approaching a limit, so technologies independent of scaling are needed for achieving further improvements. Use of strained Si or Ge at the channel region enhances carrier mobility in MOSFETs, so these technologies have been extensively studied [1].

The Ge condensation method is expected to be used for fabricating SiGe-on-insulator (SGOI) and Ge-on-insulator (GOI) substrates because these substrates allow the devices with a strained Si or Ge channel [2,3]. This Ge condensation method is considered to produce a relaxed and thin SiGe layer with a high Ge fraction and low dislocation density. This occurs because the Ge concentration in the initial SiGe layer is sufficiently low to suppress dislocation and slippage at the BOX layer interface, which occur during condensation [4].

However, the crystalline quality of SGOI or GOI substrates fabricated to date is not sufficient. We, therefore, characterize the strain relaxation process during Ge condensation by synchrotron microbeam X-ray diffraction. The use of the focused X-ray microbeam enables us to obtain microscopic structural information during the relaxation process.

2. Experimental Procedures

A $Si_{1-x}Ge_x$ (x = 0.2) layer with a 70-nm thickness was epitaxially grown on a bonded SOI wafer with a 60-nm top Si and 143-nm buried oxide (BOX) layers by chemical vapor deposition (CVD). Ge condensation was started by thermal oxidation in dry O_2 at 1050°C. After a 4-hour oxidation, an oxidation at 900°C was carried out for 1 hour to obtain the GOI structure.

For comparison, a SiO_2 capped layer with a 100-nm thickness was deposited on the SiGe layer grown on the SOI wafer by the sputtering method. The sample was annealed in an Ar atmosphere at 1100°C for 3 hours.

The Ge fraction and the lattice relaxation rate of the SiGe layer were estimated by the center position of the SiGe diffraction peak observed in an X-ray reciprocal space map (RSM) obtained using a conventional X-ray source. The crystalline quality was characterized by microbeam X-ray diffraction. The experiments were carried out at BL13XU of SPring-8. The beam size of X-rays focused by a Fresnel zone plate was 0.7×1.1 μm^2. The divergence of the microbeam was estimated to be 0.05 deg from the width of the 004 reflection of a Si wafer [5].

3. Results and Discussion

The RSM around the 224 Bragg reflection of the sample after the 5-hour oxidation together with the trajectory of the SiGe peak position during the condensation are shown in Fig. 1. Before the condensation, the peak of the SOI layer was located at (H,K,L) = (2,2,4) apart from the substrate peak because of an unintentional crystallographic misorientation between the SOI layer and the substrate. From the trajectory we see that the Ge fraction increased and reached 100%, while the lattice strain remained.

The Ge fraction and the lattice relaxation rate estimated from the RSMs are shown in Fig. 2. The Ge fraction increased with the oxidation time, while the lattice relaxation rate decreased after the 3-hour oxidation. We can see from the trajectory in Fig. 1 that the lattice spacing of the SiGe layer gradually increased with the oxidation time. Therefore, the decrease in the lattice relaxation rate indicates that the increase of the Ge fraction was more enhanced than the increase of the lattice spacing after the 3-hour oxidation.

The variations of the rocking curve of the 004 Bragg reflection depending on the measurement position were obtained by using microbeam X-ray diffraction for these samples. Results of the sample oxidization for 1 hour are shown in Fig. 3. The center position and FWHM of the rocking curve change significantly depending on the position of the SiGe layer and that of the SOI layer. Furthermore, the rocking curves of the substrate also fluctuated. These results indicate that the lattice planes of the SiGe layer are undulated even after the 1-hour oxidation, and the distortion propagates to the substrate through the SOI and BOX layer.

The result obtained from the GOI samples is shown in Fig. 4. The FWHM of the rocking curves is much larger than that shown in Fig. 3. The FWHM of the SiGe peak averaged over the measurement positions during the Ge condensation is shown in Fig. 2. It increases with the oxidation time.

In the RSM of the sample annealed in Ar, the SiGe

peak was observed at the position of (H,K,L) = (2,2,3.975), indicating the SiGe layer is completely strained and Ge atoms are fully diffused into the SOI layer. The variation of the rocking curve of this sample is shown in Fig. 5. The FWHM is much smaller than that of the sample oxidized for 1 hour, but the fluctuation in the intensity is still observed. This means that even during the diffusion process without the lattice relaxation, the microscopic nonuniformity of the crystalline quality of the SiGe layer occurs.

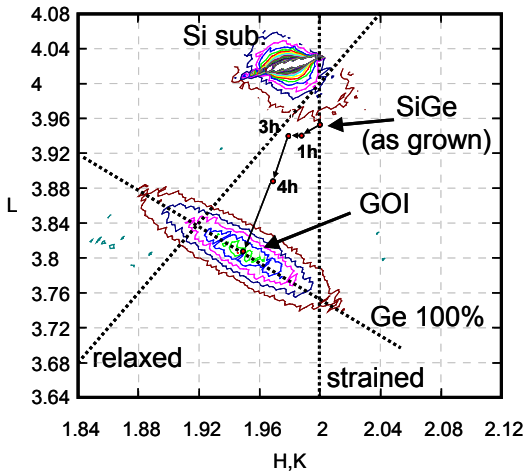

Fig. 1. Reciprocal space map around 224 Bragg reflections of GOI sample. Lines denoted by "relaxed", "strained", and "Ge 100%" indicate expected peak positions of fully relaxed, completely strained SiGe layers, and Ge layer, respectively.

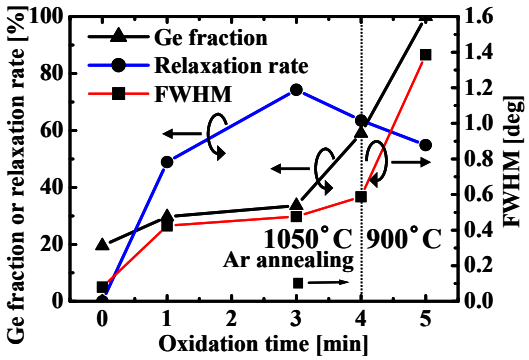

Fig. 2. Ge fraction, lattice relaxation rate and the FWHM of the SiGe layer during the Ge condensation. The FWHM was obtained by synchrotron microbeam X-ray diffraction.

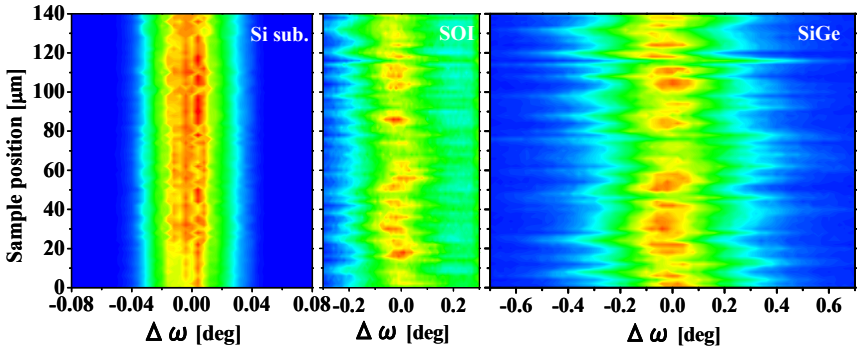

Fig. 3. The variations of the rocking curve of the 004 Bragg reflection depending on the measurement position for the sample oxidized for 1 hour.

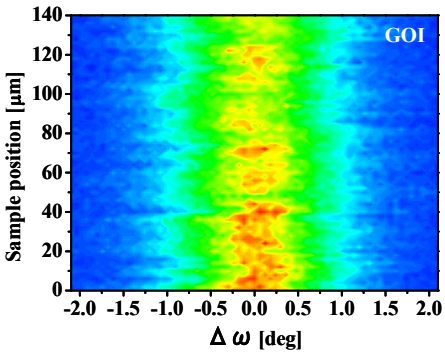

Fig. 4. The variations of the rocking curve of the 004 Bragg reflection of the Ge layer depending on the measurement position for the GOI sample.

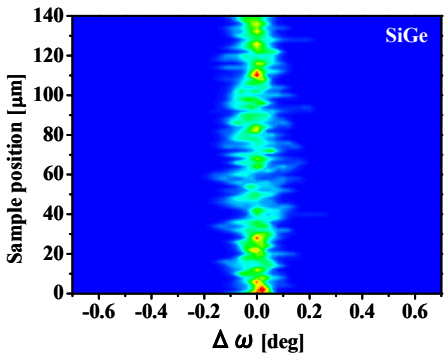

Fig. 5. The variations of the rocking curve of the 004 Bragg reflection of the SiGe layer depending on the measurement position for the sample annealed in Ar at 1100°C for 3 hours.

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