High-resolution X-ray microdiffraction from a locally strained SOI with a width of 150 nm

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Abstract. A 150-nm-wide region in a locally strained silicon on insulator (SOI) was studied using high-resolution X-ray microdiffraction technique. Synchrotron radiation X-rays with energies of 10 keV were focused on the sample by a zone plate. The focused beam size was approximately 0.8 x 0.4 µm². The sample was a model of a gate of metal-oxide semiconductor field-effect-transistors (MOSFETs); a 30-nm-thick SOI plate with an 80-nm-thick silicon nitride capping film with tensile inner stress. The capping film was removed in a stripe pattern by etching with a width of 150 nm. The width of the gap where the film is removed corresponds to the gate length of MOSFETs. Using thin SOI as a sample, we could observe only thin surface area even by X-ray diffraction that has deep penetration depth. Reciprocal space maps (RSMs) of symmetrical SOI 004 were measured around the 150-nm-gap of the film. RSMs showed that the SOI lattice was tilted along the stripe pattern up-to 0.1 deg at both sides of the gap. The tilting spreads more than 1 µm distant from the center of the gap.

1. Introduction

Strained silicon is a promising technology to enhance carrier mobilities of metal-oxide semiconductor field-effect-transistors (MOSFETs). The technology improves performance of MOSFETs without further size reduction of transistors. In order to achieve the maximum performance, designed strain should be added in a specific position. Therefore, techniques to detect strain in high-spatial-resolution are highly required. The strain and its distribution have been measured by using various methods, for example, convergent beam electron diffraction (CBED), micro-Raman spectroscopy [1] and microbeam X-ray diffraction [2]. Each of these methods has advantages and disadvantages. CBED has the highest-spatial-resolution. However, samples need to be thinned for transmission electron microscope investigation, that causes relaxation of the stress. Micro-Raman spectroscopy has relatively high-spatial-resolution and relatively high-sensitivity to the strain. The most important strain is the strain in a few nm thick surface that is related to carrier mobilities. For this reason, UV-Raman spectroscopy is adopted to measure strain in the surface because the penetration depth of 364 nm UV light for silicon crystals is 5 nm.[3] However, it is difficult for micro-Raman spectroscopy to obtain strains if directions of the stress are complicated. Because, strains are calculated from Raman shifts based on an assumption of directions of the stress. That is, one cannot get strain if the directions of the stress are unknown. On the other hand, X-ray diffraction directly gives both angles of the lattice tilt and lattice spacing. Synchrotron radiation X-ray microdiffraction is one of the most powerful tools to investigate the local strain on surfaces or interfaces of...
semiconductor materials. Using SOI as a sample one can measure strain in the surface area by X-ray that has large penetration length. In addition, high intense synchrotron X-ray enables out-of-plane diffraction by a few nm thick samples, whereas conventional X-ray is used with in-plane diffraction that cause broadening of X-ray footprint on the sample resulting in worse spatial resolution. Furthermore, by limiting the angular divergence perpendicular to the scattering plane, both high-spatial- and high-angular-resolution have been achieved.\[4\] Besides, the X-ray microdiffraction technique gives structural information of a region that is smaller than the beam size in some cases. This is achieved by virtue of the simultaneous measurement of the lattice tilting and the lattice spacing. For example, from a reciprocal space map measured by the X-ray microdiffraction, size of domains that are one order smaller than the beam size can be estimated.\[5\]

2. Experiment

Figure 1 shows the schematic of the sample. The sample is a model of a gate of MOSFET. The thickness of buried-oxide is 200 nm and SOI is 30 nm. The SOI is covered by 80-nm-thick silicon nitride capping film, that has inner stress of 2 GPa. The capping film is removed by etching in a line shape with a width of 150 nm. The 150-nm-wide area, the gap, where the film is removed corresponds to the gate width of MOSFET. Tensile strain along [110] is introduced to the gap by the film.\[6\] The tensile strain increases carrier mobilities in n-type MOSFETs, so that performance of transistors increase. UV-Raman spectroscopy revealed that compressive strain exists at edges of the gap and tensile strain exists at the center of the gap.\[6,7\] We have applied the synchrotron X-ray microdiffraction technique to the same sample to evaluate lattice tilting around the gap.

The microdiffraction experiment was performed at BL13XU SPring-8. Synchrotron X-rays with energy of 10 keV were focused on the sample by a zone plate. The beam size at the focal point was approximately 0.8 × 0.4 μm². Detail about the high-resolution microdiffraction system is described in references 8 and 9.

In order to locate the center of the gap, the incident angles of the X-ray were set at lower and higher half maximum positions of the rocking curve of the substrate silicon 004, then the sample was translated in [110] direction by monitoring the diffraction intensities.

There is a difference in orientations between the silicon substrate and the SOI, so that only the diffraction from the SOI can be measured.\[10\] Reciprocal space maps (RSMs) of symmetric SOI 004 around the 150-nm-wide gap were measured by changing the sample position in [110] direction (56 positions by 0.1 μm step). X-rays were incident on the sample from [110] direction.
Figure 2. Intensity variation of the substrate silicon 004 diffraction around the 150-nm-gap along [110]. Incident angles of the X-ray to the sample were set at lower angle (open circle) that gives half maximum and higher angle (cross mark) that gives half maximum of the 004 rocking curve.

Figure 3. RSMs measured at sample positions at the center of the gap (a), 0.5 μm (b) and 2.4 μm (c) distant from the center of the gap. Spots are splitted in (a) and (b), whereas spot is single in (c).

and the sample was rotate around [110]. Therefore, lattice tilt in 2D RSMs is the rotation around [110]. A RSM was measured by rotating the sample by 0.04 deg step and observing diffraction images using a CCD detector. Exposure time for a single image was 1 s. Time spent for getting a single RSM was 6.5 min.

3. Results

Figure 2 shows diffraction intensities obtained with X-ray incident angles set at lower and higher sides of half maximum positions of the rocking curve. Open circles make a peak at the center of the gap. On the other hand, cross marks make double peaks beside the gap. We regard the center of these curves as the center of the gap.

Typical RSMs measured around the gap are shown in figure 3. Figure 3 (a), (b) and (c) are RSMs taken at positions: 0, 0.5 and 2.4 μm denoted in the horizontal axis of figure 2, respectively. Lengths are distances from the center of the gap in [110] direction. The RSM measured at the position of 2.4 μm (figure 3 (c)) has a single peak. In contrast, the other RSMs has two peaks (figure 3(a) and (b)). The distribution of the lattice tilt was extracted from 56 RSMs by integrating RSMs in 2θ direction. The distribution is shown in figure 4. There is 0.13 deg tilted element at the position of -0.8 μm. Most part of SOI between positions from 0.2 to 0.7 μm is tilted up-to 0.1 deg. If the distance from the center of the gap becomes larger than 2 μm, no splittings are seen. That is, the gap affect to the lattice tilt as far as 2 μm from the center.
of the gap in [110] direction. The reason of lattice tilts around [110] is still unclear because the gap is uniform in [110] direction. We need more experiments to understand these phenomena.

4. Conclusion
We have revealed the SOI lattice tilting distribution around the 150-nm-wide gap of the silicon nitride capping film on the SOI by high-resolution X-ray microdiffraction technique. The tilting was along [110] direction. The maximum tilt was 0.13 deg. The tilted region spread more than 1 μm distant from the center of the gap.

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