Nano-scale Boron Mapping in Silicon Devices Using Cₜ-corrected STEM-EELS

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1. Introduction
Various kinds of elements are used in recent silicon ULSI chip fabrication. Among those elements, detection of boron at a transistor level has been one of the most challenging issues. Atom-Probe (AP) and scanning transmission electron microscope electron energy loss spectroscopy (STEM-EELS) are the expectative candidates of this issue [1, 2]. The study of AP for semiconductor devices is continuing due to difficulties in sample preparation and field evaporation of semiconductor materials, even though its spatial resolution and sensitivity is enough for detecting boron at nm-order. STEM-EELS seems to be suitable for detecting boron because no special sample preparations are needed if sample thickness is sufficiently thin. However, it is difficult to obtain boron mapping in silicon devices with STEM-EELS because the boron edge is blurred with the tail of the silicon edge [2]. Furthermore, EELS mapping is very sensitive to disturbance because it requires a long acquisition time.

Recently, spherical aberration (Cₜ) corrector for STEM was developed [2, 3]. This system ensures not only spatial resolution enhancement but also sensitivity improvement. Furthermore, several instruments are designed for eliminating disturbance because Cₜ-corrected microscope sensitivity to room environment becomes more noticeable [4]. From these viewpoints, we applied Cₜ-corrected STEM-EELS to nano-scale boron mapping in silicon devices.

2. Experiment

Samples
Figure 1 shows a schematic drawing of the test structure. A pair of trench type electrodes is used to connect the diffusion layer to the P+ layer (source). This structure is formed by deposition of boron doped amorphous silicon in the trench. Due to subsequent thermal treatments, the amorphous boron doped silicon changes into a poly crystalline state. This electrode is known as a boron doped poly-Si (BP) layer and used for power devices that need a vertical electrode. In this study, samples with different boron concentrations in the BP layer were prepared.

Instruments
STEM measurements were performed with FEI Titan³ 80-300 field-emission electron microscope equipped with Cₜ-corrector and covered with an environmental enclosure designed for eliminating disturbance. These devices suppress image and energy drifts. EELS spectra were collected using Gatan Model 863 GIF Tridiem.

3. Results and discussion

Figure 2(a) shows the relationship between boron concentration in the BP layers and Iₓdₜ leak. Idₜ leak current, which is caused by dislocations from the BP layer to drain area, decreases as boron concentration increases. Strain around the BP layers was measured with STEM convergent beam electron diffraction (STEM-CBED) (Fig. 2(b)). X and Z directions of strain in Fig. 2(b) are defined as shown in Fig. 1. Sample 1, which is a lower boron concentration sample, shows stronger strain than sample 2. STEM-CBED analysis had revealed that this strain, which is caused by volume shrinkage of the BP layer due to the epitaxial growth during crystallization, generates dislocations in sample 1 [5].

Figure 3 shows annular dark field (ADF) -STEM images of the BP layers. The BP layers of sample 2 show light and dark contrast while those of sample 1 show only light contrast. In this imaging mode, a light region corresponds to the epitaxial phase which consists of epitaxial growth Si and twins, and a dark region corresponds to the poly-Si phase [5]. These ADF-STEM images show that the BP layers of sample 1 consist of only the epitaxial phase and those of sample 2 consist of the epitaxial phase (circumference) and poly-Si phase (core).
Fig. 3 (a) and (b) ADF-STEM images of samples 1 and 2, respectively.

Figure 4(a) shows an enlarged image of the BP layer of sample 2 indicated by the square in Fig. 3(b). EELS spectra were acquired at P− layer (point 1) and the BP layer (point 2) and are shown in Figs. 4 (b) and (c). Background of B-K edge is indicated by red lines and B-K edge is shown as the filled area in both spectra. B-K edge clearly appears at point 2 while that of point 1 rarely appears. EELS mappings were obtained using B-K edge (Fig. 5). It should be noted that the high concentration boron region corresponds to the epitaxial/poly-Si phase boundaries in both samples. This shows that boron segregation occurs at the boundaries. The volume of boron segregation in sample 2 is larger than that of sample 1. This is consistent with the relationship of boron concentration in samples 1 and 2.

Fig. 4 (a) ADF-STEM image of BP layer of sample 2. (b) and (c) EELS spectra of point 1 and point 2, respectively.

Fig. 5 (a), (c) ADF-STEM image and boron mapping of sample 1, respectively. (b) and (d) ADF-STEM image and boron mapping of sample 2, respectively.

Crystalline microstructure analysis of the epitaxial/poly-Si phase boundary was carried out in order to examine the relationship between strain and boron segregation. Figure 6(a) shows high-resolution transmission electron microscope (HRTEM) image of sample 2 (indicated by the square in Figs. 5(b) and (d)). This area corresponds to the epitaxial/poly-Si phase boundary. Diffractograms, which are obtained from fast Fourier transform (FFT) of HRTEM image and correspond to diffraction pattern, were taken from the epitaxial phase, boundary and poly-Si phase (Figs. 6 (b)-(d)). The diffractogram of the epitaxial phase (Fig. 6 (b)) shows spots from P− single crystal Si layer and twins. In the poly-Si phase (Fig. 6 (d)), randomly rotated spots from poly-Si appear. It should be noted that the diffractogram of the boundary (Fig. 6 (c)) shows only a halo ring which comes from the amorphous state. This shows that the boron segregation region is an amorphous state of silicon having high concentration boron. This segregation results in strain relaxation by preventing the epitaxial growth in high boron concentration samples (sample 2). Thus, controlling boron concentration in the BP layers is one of the essential factors for suppressing generation of crystal defects.

Fig. 6 (a) HRTEM image of the epitaxial/poly Si boundary. (b)-(d) Diffractograms from the epitaxial phase, boundary and poly-Si phase, respectively.

4. Conclusions

Nano-scale boron mapping in silicon devices was achieved by using C-corrected STEM-EELS with an enclosure designed for eliminating disturbance. STEM-EELS mapping showed that boron segregation occurs at the epitaxial/poly-Si phase boundaries of the BP layer. Furthermore, HRTEM analysis revealed that this segregation region is an amorphous state. This amorphous state of boundary results in strain relaxation by preventing the epitaxial growth.

References