doi:10.1017/S143192761005871X
Microsc. Microanal. 16 (Suppl 2), 2010

Visualization of Antimony (Sb) Dopant Clusters in Silicon Specimen by Large Angle Convergent Beam HAADF-STEM

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Due to downsizing the scale of silicon-based transistor in integrated circuits, the concentration of charge carriers has been required to increase. Simply, it seems to be solved by increasing the concentration of impurity dopant atoms which are introduced into silicon crystal. But, the concentration of charge carriers has been reported not to increase in proportion to the concentration of dopant atoms in the high regime. Theoretically, it is said that in the high concentration regime, dopant clusters are formed and some of them become electrically inactive. Dopant clusters have been investigated by scanning transmission electron microscope (STEM) [1]. But, it was difficult to estimate the relative height of dopant atoms making up the cluster, because STEM image was two-dimensional information.

In this study, we observed antimony (Sb) dopant clusters in silicon crystal by our developed aberration corrected STEM (R005) [2]. Silicon wafer was doped with Sb ions implanted at 30 keV and annealed by rapid thermal treatment. The concentration was analyzed to be 6 x 10^{20} cm^{-3} around 30 nm depth from the surface, measured by secondary ion mass spectroscopy (SIMS). The STEM specimen was carefully prepared by mechanical polishing, dimpling and low angle ion milling. The probe has a current of 30 pA and the convergent semi-angle of 30 mrad. High-angle annular dark-field STEM (HAADF-STEM) images were obtained by detecting electrons from 39 to 104 mrad in semi-angle. The dwell time per pixel was 38 μsec. The specimen was observed from the [001] direction, because strong 111 diffractions are never excited. In viewing along the [001] direction, the multiple-scattering (channeling) effect must be suppressed, suggesting that information around the focal position would be enhanced using the spherical aberration corrected electron microscope [3].

During the observation, we fixed the probe current and also the parameters adjusting the contrast and brightness and measured the number of electrons at the detector for each pixel in the HAADF image. The thickness of the specimen was measured by electron energy loss spectroscopy. We found that the column intensity in the HAADF image is sensitive to the thickness for the thin specimen of below 20 nm, while it has a tendency to be saturated for the thick one. Therefore, the columns intensity is rather difficult to be interpreted for the thin specimen. In this study, we investigated the doped silicon of 20-30 nm in thickness.

Fig. 1 shows a typical HAADF image of Sb dopant area. Some brighter spots are Sb doped column which intensity ratio varies from 1 to 2.3 to the non-doped one. In Fig. 1, we observed 32 columns having higher intensities than 1.7 times the non-doped one. Multi-slice calculation shows that the column intensity depends on the relative position of Sb atom to the focal position. And, the columns having such higher intensities are estimated to contain a single Sb atom within 3 nm around the focal position. Taking into account that Sb concentration is 1 % in the specimen, the number of the doped columns containing a single Sb atom in the slice of 3 nm in depth is estimated to be 33 based on binomial distribution. The observation is in good agreement with the calculation. Therefore, we conclude that the columns, which have higher intensities than 1.7 times the non-doped one, contain a single Sb atom within 3 nm around the focal position.

Among 32 columns, some columns show positional correlation each other as indicated by white ellipses in Fig. 1. They suggest formation of dopant cluster. Figure 2 schematically shows our proposed model of Sb dopant cluster, which consists of two Sb atoms facing each other in six-membered ring. This model can be projected in two patterns when viewing from two different <001> directions as shown at the bottom of Fig 2. This was firstly observed by Oshima et al for As-doped Si, but not for Sb-doped Si [3]. And the electrical deactivation calculation of this Sb dopant cluster was reported [4].

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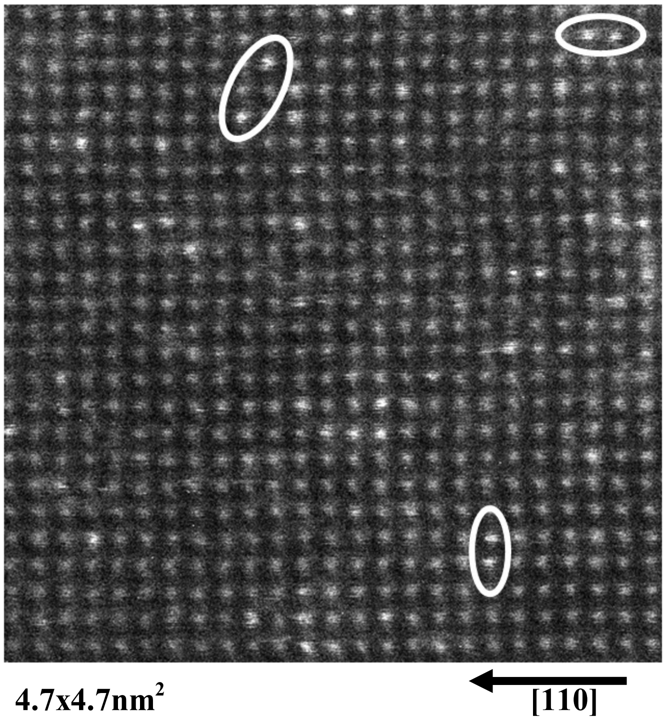

Fig. 1 A typical HAADF-STEM image of antimony (Sb) dopant atoms in silicon crystal. This image is taken at 300 keV, Cs=0, and the half-convergent beam of 30 mrad, and by collecting the electrons scattered at angles between approximately 39 and 104 mrad. The distance between two neighboring spots is 192 pm.

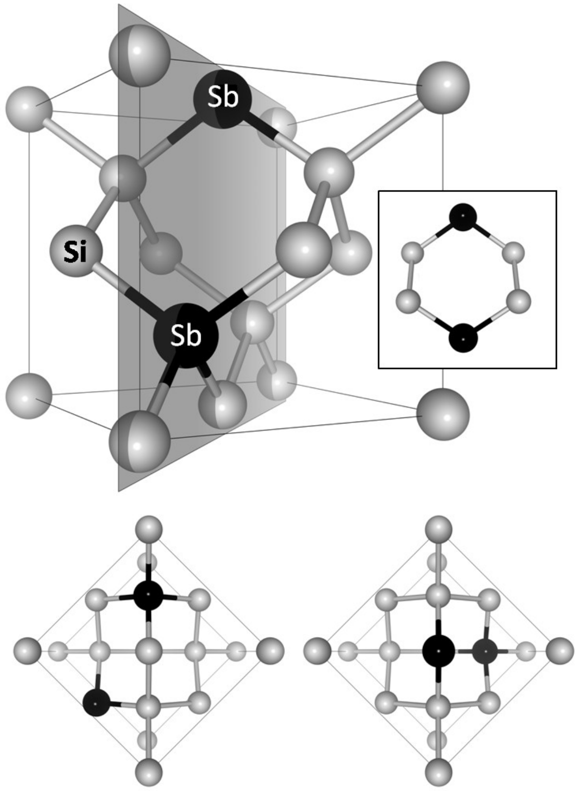

Fig. 2 Structural model of dopant cluster: Si (gray), Sb (dark). Two Sb atoms are facing each other in the six-membered ring as shown in the inset. Viewing from two different [100] directions, two patterns can be observed as shown in the bottom. These patterns were observed in the STEM image of Fig.1 (indicated by white ellipses).