

## Energy Selected Secondary Electron Image Revealing Surface Potential by High Accelerating Voltage Scanning Electron Microscope

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SEM (scanning electron microscope) has been widely used for microstructure analysis of materials. A variety of detectors such as BSI (back scattered image) and SEI (secondary electron image) can be attached to a SEM column, and we are able to obtain a variety of scanning images using these detectors. In the BSI, image contrasts are caused from variations of mass density and atomic number of a sample. On the other hand, SEI is sensitive for surface potential of samples. As an observation example, the contrast of a p-n junction in the semiconductor has been visualized and reported [1]. A report [2] suggested that the SEI image contrast has a correlation with the surface potential, due to the carrier density at the junction. Thus, the SEI is a method that makes it possible to visualize the distribution of dopant, whose concentration and atomic species determine the potential gaps of the junctions such as p-n and Schottky.

In general, scanning/transmission electron microscope (S/TEM) has higher spatial resolution than SEM, because higher accelerating voltage is used. It is well known that S/TEM is used for structure analysis by high resolution imaging and diffractometries, and chemical and electronic state analyses by EDS (energy dispersive spectroscopy) and EELS (electron energy loss spectroscopy). Moreover, several researchers reported the visualization of dopant distribution in semiconductor by electron holography, Lorentz microscopy, angle segmented STEM detectors and etc. We conducted experiments on the SEI using a field emission (FE) STEM, which has high resolution imaging and analysis capabilities.

For our experiments, we used an FE S/TEM (JEOL, JEM-2800) equipped with an Everhart-Thornley type SEI detector above the upper pole of the objective lens. Figure 1 shows schematic relationship between the SEI detector and two electrodes (E1 and E2). These electrodes are used to separate the energy of the SEI. The E1 selects to detect the fast SEs whose potential  $> -E1$ , on contrary, the E2 limits the fastest SEs, whose potential  $< -E2$ . We prepare a sample, which has known concentration of a dopant, to clarify the relation between SEI contrast and the potential distribution due to dopant concentration. The dopants for the sample Si wafers were boron (B) and arsenic (As), whose concentrations along depth direction was pre-observed by secondary ion mass spectrometer (SIMS). Cross sectional samples were prepared by Ar<sup>+</sup> ion milling instrument (Ion Slicer, JEOL EM09100IS). The SEIs in this paper were observed at 200 kV.

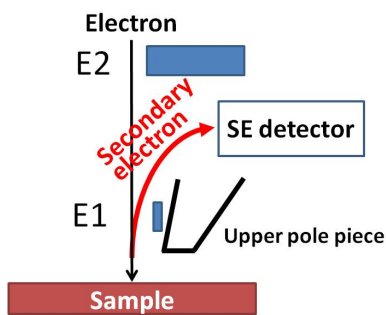
Figure 2 shows a SEI when  $E1 = 0$  eV and  $E2 = -10$  eV. The image is composed of slow SEs, whose energy is  $< 10$  eV. The left end is the vacuum region, and the light gray rectangle near the vacuum region is thought to be the SiO<sub>2</sub> layer existing on the wafer surface. Under this observation condition, it is understood that the contrast is dark from the interface of SiO<sub>2</sub> and Si to the depth of approximately 400 nm, which is thought to be B diffused region. Thus, with slow SEs, p-type Si shows dark contrast in image. Figures 3(a) and (b) show the cross section of As doped wafer. Figure 4 shows the intensity profiles from Figs 3 (a) (violet) and (b) (green), and As concentration by SIMS (red), which is shown as a reference. In Fig. 4, the intensity profile (green line) from Figs. 3 (b), which is composed of slow SEs ( $< 10$  eV), monotonously decreases from the surface of the sample toward the p-type region, and becomes constant at approximately depth of 300 nm, which is thought to be n-type region. Therefore, with slow SEs, the n-type region is imaged with bright contrast. This tendency is similar to As concentration profile by SIMS shown by red line. The contrast of the SEI catches even low doped region, whose concentration is close to the detection limit of SIMS (0.1 ppm). That is, it seems

that the energy-sorted SEI responds its contrast very sensitively, reflecting the change of surface potential of Si, due to the dopant concentration, even if it is as low as 0.1 ppm. This concentration sensitivity is enough for semiconductor characterization. Another profile from Fig. 3(a) (violet line) shows different behavior to one from Fig. 3(b). The n-type doped region shows dark contrast with faster SEs, whose potential is > 5.4 eV. And we can observe small dip at the beginning of depletion layer. The contrast of the image in Fig. 3(a) suggests that the energy selected SEI may have capability to image the specific characters of semiconducting materials such as depletion layer.

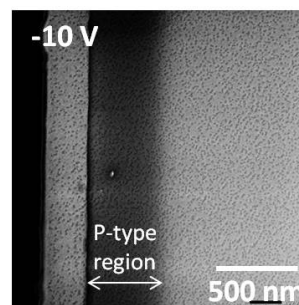
Finally, we can conclude the SEI imaging performed at the higher accelerating voltages, such as 200 kV, can realize simultaneous acquisition of high resolution imaging and high resolution elemental analysis and highly sensitive contrast of dopant concentration. This capability is clearly sought after for the characterization of semiconducting materials and devices.

References:

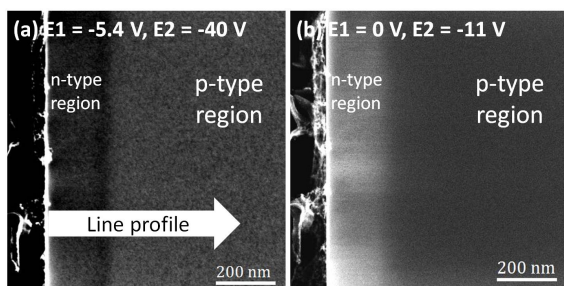
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 [2] D Venables and DM Maher, J. Vac. Sci. Technol. B **14** (1996), p. 421.  
 [3] H Sasaki *et al*, Microscopy **63** (2014), p. 235.



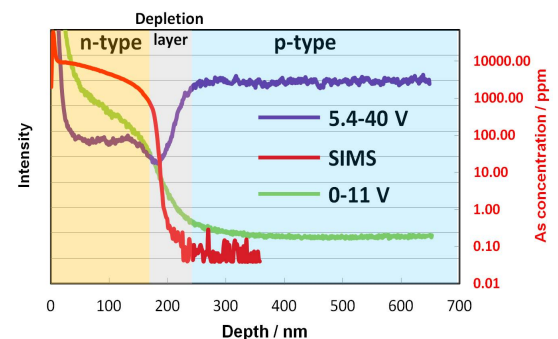
**Figure 1.** Schematic relation of a SE detector and electrodes for energy selection of SEs.



**Figure 2.** SEI of the cross sectional B doped Si wafer at  $E1 = 0\text{ V}$ ,  $E2 = -10\text{ V}$ . p-type Si shows darker contrast than non-doped Si



**Figure 3.** SEIs of cross sectional As doped Si wafer at (a)  $E1 = -5.4\text{ V}$ ,  $E2 = -40\text{ V}$  and (b)  $E1 = 0\text{ V}$ ,  $E2 = -11\text{ V}$ . Contrast of n-type region is reversed in (a) and (b).



**Figure 4.** Intensity profiles of SEIs shown in Figs 3(a) and (b). The concentration profile of As by SIMS is also shown in this figure.