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Image Formation Mechanisms in Scanning Electron Microscopy of Carbon Nanofibers on Substrate

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Nanostructures fabricated on thick substrates (typically a silicon wafer) are building blocks for high-performance electronic devices. While detailed structural analysis using high-resolution electron microscopy usually requires a thinning process to obtain an electron transparent specimen, a non-destructive approach is also required to analyze the structure. A recent study showed that heat dissipation into the substrate from a nanotube device governs its electronic transport characteristics [1]. In such a system, structural analysis that can be performed without any sample modification is favorable since imaging can be performed before, after, and even during the electrical operation of devices to investigate structural change. In this paper, we present two kinds of imaging techniques using conventional scanning electron microscopy (SEM) developed for the characterization of carbon nanofiber (CNF) devices fabricated on a thick Si substrate without any sample modification.

Figure 1 shows SEM images of a CNF placed on the Si substrate, captured by a through-the-lens (TTL) secondary electron (SE) detector. With a 1 keV electron beam [Fig. 1(a)], the CNF shows uniform contrast along the fiber with a prominent edge peak at the periphery of the CNF. By using a 30 keV beam [Fig. 1(b)], however, a bright portion appears in the CNF. By tilting the substrate [Fig. 1(c)], it is found that the bright portion corresponds to an area where the CNF is not in contact with the substrate, thus suggesting a useful imaging technique to explore the CNF-substrate interface structure. This technique is important for considering the effect of heat dissipation via the substrate. This unique contrast comes from the fact that, by using the electron beam with sufficiently high energy to penetrate the CNF, SEs emitted from the substrate contribute to the image contrast only when there is a finite gap between the CNF and substrate as shown in Figs. 1(d) and (e) [2].

Figure 2 illustrates a scanning transmission electron microscopy (STEM) technique, using conventional SEM with a TTL detector, which provides the internal structure without specimen thinning. Here we use a constant beam energy of 30 keV, while capturing SEM images as a function of the substrate tilting. At moderate tilt angle of $\theta = 60^\circ$, a typical SEM image contrast with surface morphology is obtained as shown in Fig. 2(a). Bright contrast of Ni catalyst particle also indicates the contribution of the backscattered electrons as well as SEs generated at the substrate by the largely deflected electrons. At larger tilt angle of 88˚ [Fig. 2(b)], the internal structure of the CNF can be seen, thus a bright-field STEM image contrast is obtained using a conventional TTL detector of SEM without sample thinning or an additional detector below the specimen. The mechanism of this STEM contrast is described briefly in Figs. 2(c)-(e). At moderate to small tilt angles [Fig. 2(c)], the contrast is mainly formed by the SEs from the CNF

(SE1), providing the conventional SEM image contrast. Here, the contribution of SEs emitted from the substrate (SE2) is minor. At larger tilt angles [Fig. 2(d)], however, SE2 increases because of the large incident angle of the beam, thus dominating the overall detected signal. Moreover, the electrons deflected largely by the CNF [indicated as "A" in Fig. 2(e)] travel away from the substrate. Thus SE2s are mostly generated by the transmitted electrons that are only weakly scattered off the CNF ["B" in Fig. 2(e)], providing the bright-field contrast of the CNF. Detailed Monte Carlo simulation shows that the mean scattering angle of the incident beam is 5˚-7˚ and that the appearance of the bright-field STEM contrast requires the substrate tiled over 85˚ from the incident beam, consistent with our experiment.

These two imaging techniques are based on contrast formation mechanism enhanced by the existence of the underlying substrate below nanofibers, providing a novel structural analysis technique for nanostructures fabricated on thick substrates.

References

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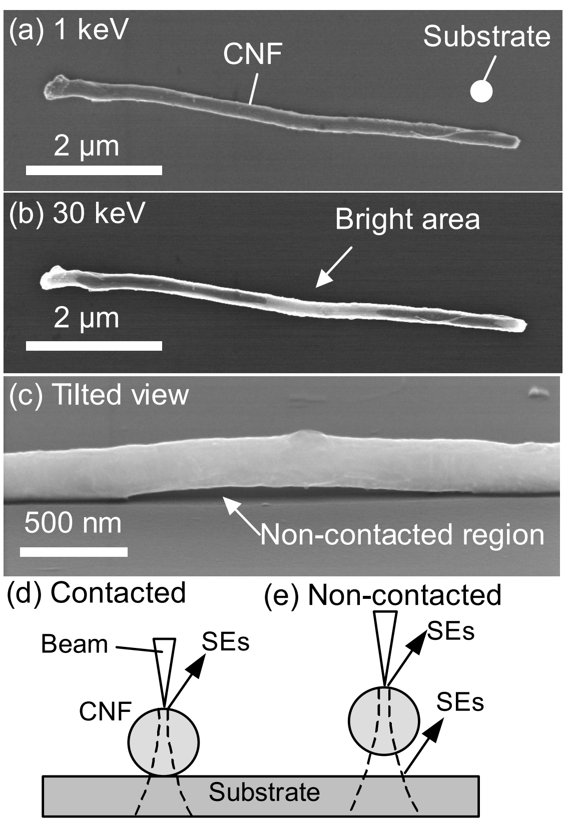

Figure 1. Top-view SEM image of CNF on Si substrate with the beam energy of (a) 1 keV and (b) 30 keV. (c) Tilted view of the bright portion shown in (b). Schematics of SE generation (d) without and (e) with a gap below CNF.

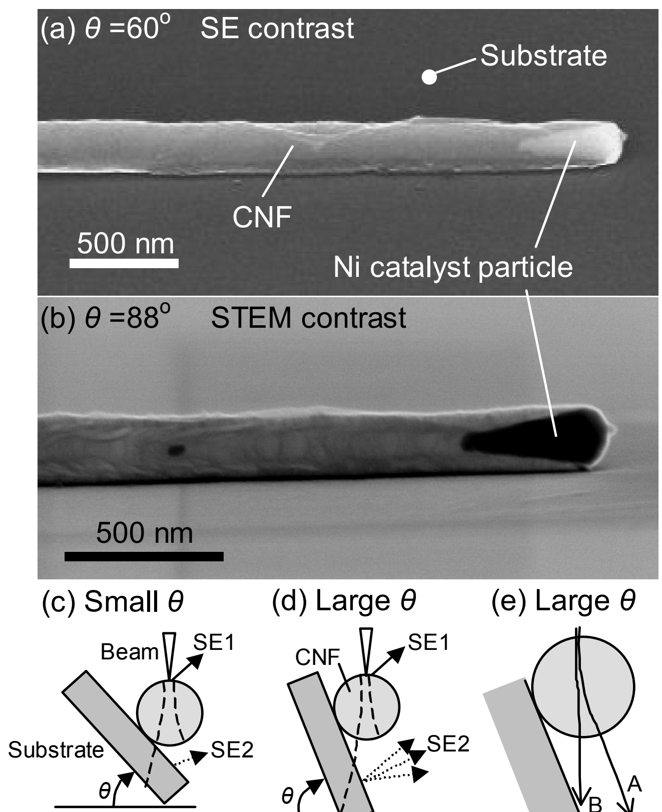

Figure 2. Tilted SEM image with (a) $\theta = 60^\circ$ and (b) $\theta = 88^\circ$. At a moderate tilt angle (c), SE1 dominates the observed contrast. At a large tilt angle [(d) and (e)], SE2 is enhanced due to substrate tilt only by the weakly scattered electrons (B), resulting in the bright field STEM contrast.