Examining the Sensitivity of Electron Holography for Two-Dimensional p-n Junction Mapping

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The shrinkage of the process geometry in the semiconductor industry requires a technique to obtain two-/three-dimensional (2D/3D) dopant profiles, with high spatial resolution and wide dynamic sensitivity, to understand device performance. Off-axis electron holography (EH) based on transmission electron microscopy (TEM) has been demonstrated to be capable of mapping and characterizing 2D electrostatic potential distributions, and hence, the doping profiles in devices with nanometer resolution [1]. However, very little is known about the sensitivity of electron holography in dopant profiling. To develop the EH technique for practical use, it is necessary to systematically examine the sensitivity.

Recently, it has been reported that a Si/Si p-n junction implanted in a lower level (10^{15} cm^{-3}) p-wafer was successfully mapped and characterized by EH [2]. In current work, a Si/Si p-n junction serial with different n+-doping levels on highly doped p-wafers was fabricated for EH examination. The p-wafer is $\sim 10^{19}$ cm^{-3} boron (B)-doped Si (100) (sub-Si). After epitaxially growing a 50nm intrinsic Si layer (EPI) on the sub-Si, a 50nm silicon oxide (SiO_2) layer was deposited. Phosphorus (P) ions were then implanted into SiO_2 layer at 40 keV with four different doses: 1×10^{14}, 1×10^{13}, 1×10^{12} and 1×10^{11} cm^{-2}. The n-type surface layers with different doping levels were formed on the sub-Si by rapid thermal annealing (RTP) at 850ºC for 10 seconds. Secondary-ion mass spectrometry (SIMS) was used to obtain depth profiles and concentrations of the dopants in the samples. Fig. 1(a) gives depth distributions of P and B for the sample with the implanting dose of 1×10^{13} cm^{-2}. The P depth profiles in all four samples are shown in Fig. 1(b), which indicates that concentrations of P around the EPI/sub-Si interface are $\sim 4\times10^{18}$, 4×10^{17} and 4×10^{16} cm^{-3}, respectively, for the samples with implanting doses of 1×10^{14}, 1×10^{13} and 1×10^{12} cm^{-2}. For the sample with implanting dose of 1×10^{11} cm^{-2}, the P concentration around the EPI/sub-Si interface is lower than the detection limit ($\sim 1\times10^{16}$ cm^{-3}) of the SIMS.

Cross-sectional TEM samples were prepared by focus ion beam (FIB) operating at 30 keV. EH experiments were performed on a JEOL 2010F TEM equipped with an electron biprism. To get a proper field of view, a Gatan Image Filter (GIF) was used to obtain extra magnification and better signal-to-noise ratio. Digital holograms were reconstructed using the Holoworks plug-in for Gatan DigitalMicrograph software. In Fig. 2, holograms (a), (c), and (e) are taken from three samples with lower implanting doses: 1×10^{11}, 1×10^{12} and 1×10^{13} cm^{-2}, respectively. The reconstructed phase images corresponding to the holograms are shown in Figs. 2(b), 2(d) and 2(f). In the phase images, there is an apparent phase jump in the SiO_2/Si interface. In the Si region, the n-type surface layer is distinguished clearly from the p-region by brighter contrast, even for the sample with the lowest doping level (1×10^{16} cm^{-3} or less). This work demonstrates that electron holography has not only high spatial resolution but also high sensitivity for 2D dopant profiling.

References
[1] W.D. Rau et al., Phys. Rev. Letts. **82** (1999) 2614.
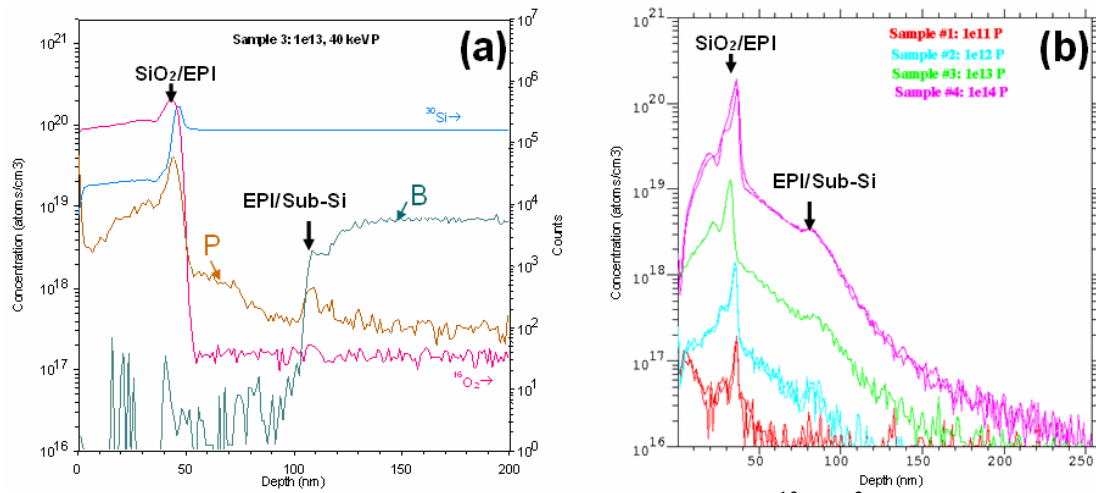[2] Z. Wang et al., Appl. Phys. Lett. **81** (2002) 478.

Fig. 1 (a) SIMS results from the sample implanted at dose 1×10^{13} cm^{-2}; (b) P doping profiles for all four samples implanted at different doses.
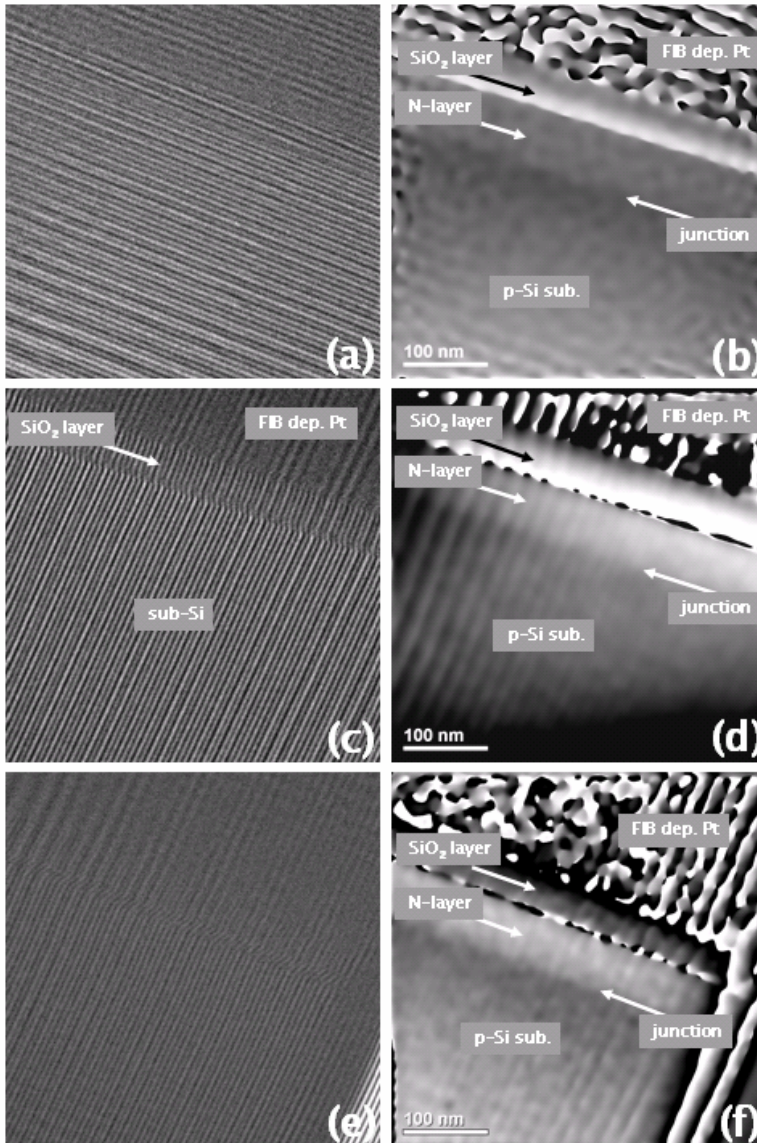

Fig. 2 Electron holograms (a), (c), and (e) and corresponding reconstructed phase images (b), (d), and (f), respectively, for samples implanted at different doses: (a) and (b) -- 1×10^{11} cm^{-2}; (c) and (d) -- 1×10^{12} cm^{-2}; (e) and (f) -- 1×10^{13} cm^{-2}. In the phase images, p-n junction contrast is clearly visible.