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Studies of Ge Quantum Dots on Slightly Oxidized Si(001) Surfaces by C_s-corrected TEM/STEM

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The recent successful implementation of a spherical aberration (C_S) corrector has demonstrated the achievement of an electron probe less than 0.1nm in high-angle annular dark field scanning transmission electron microscopy (HAADF-STEM) and point-to-point resolution less than 0.1 nm in TEM. The smaller and brighter probe allows Z-contrast imaging of atoms in complex structures (1). Shklyaev et al. reported that germanium (Ge) quantum dots with a typical size of ~7 nm and ultrahigh density ~1 x 10^{12}/cm^2 were formed on Si surfaces with an ultrathin SiO_2 coverage, which are nice candidates of semiconductor quantum dots (2,3). They considered that the key point enabling their results was existence of the ultrathin SiO_2 film as a mask. In the above studies, however, the existence of the ultrathin SiO_2 films was proved through the experiments in reciprocal-space by a reflection high-energy electron diffraction and an X-ray absorption near-edge study, but not through the real-space observation. In the present study we tried observation and analysis of Ge nanodots on the Si(001) surfaces and their interfaces using a conventional and C_S-corrected STEM/TEMs.

In the present experiment Ge nanodots were prepared by deposition at 450 °C onto Si(001) surfaces with ultrathin SiO_2 films in an ultra-high vacuum chamber evacuated by a turbo molecular pump and an ion pump into 1 x 10^{-10} Torr (4). The TEM/STEM observations were performed with an ordinary 200 kV TEM (JEM-2010F) and a newly developed C_S corrected 200 kV STEM/TEM (JEM-2100F) equipped with a thermal field emission gun (5). The C_S-correction was performed by two hexapole lenses and two transfer lenses developed by Haider and Rose (6). The point-to-point resolution of STEM was less than 0.09 nm after the C_S-correction. The elemental analysis in the STEM mode was also carried our by energy-dispersive X-ray analysis and electron energy loss spectroscopy.

FIG. 1(a) shows a typical bright field cross-sectional TEM image of an interface housing Ge nanodots between a Si(001) substrate and a capping polycrystalline Si layer overdeposited. The interface layer and the capping layer with many stacking faults are detected in the TEM image contrast. The width of the interface layer is less than 5 nm. However, the existence of the Ge nanodots is not clearly observed due to their weak contrast. FIG. 1(b) shows an HADF-STEM image of the same sample obtained with the C_S-corrected STEM. From the image, one can easily detect existence of Ge nanodots in the interface area from their bright contrast. It is also easily determined that the lateral size and height of the dots are 5-8 nm and 4 nm, respectively. The clear bright contrast against the dark background of silicon areas comes from so-called Z-contrast characteristic of the HADF-STEM, which is relative to approximately square of atomic number (Z^2), such as $(32)^2$ for Ge(Z_{Ge}=32) and $(14)^2$ for Si(Z_{Si}=14)(4). A higher resolution HAADF-STEM image obtained with the C_S-corrected STEM shows clearly the existence of a Ge-rich crystalline layer and its geometry against the oxide layer from the Z-contrast image as shown in FIG. 2(a). Judging from these kinds of observation, we can propose a new model of Ge nanodots grown on Si(001) surfaces with an ultrathin SiO_2 coverage (4). Also strain state of the interface of Ge/Si was analyzed from Cs-corrected HRTEM images using the geometric phase method. Finally, C_S-corrected STEM/TEMs are very much useful for analysis of interface structures composed of various kinds of semiconductors due to the Z-contract image and elemental analysis capabilities using a smaller and higher electron density probe.

References

(1) P. D. Nellist et al., *Science,* 305 (2004) 1741.
(2) A. A. Shklyaev et al., *Phys. Rev.,* B62 (2000) 1540.
(3) A. A. Shklyaev and M. Ichikawa, *Phys. Rev.,* B65 (2002) 045307.
(4) N. Tanaka et al., *Appl. Sur. Sci,.* (2008) in print.
(5) S.- P. Cho et al., *Proc. IMC16* (Sapporo, 2006) p.1344.
(6) M. Haider et al., *J. Electron Microsc.,* 47 (1998) 353.
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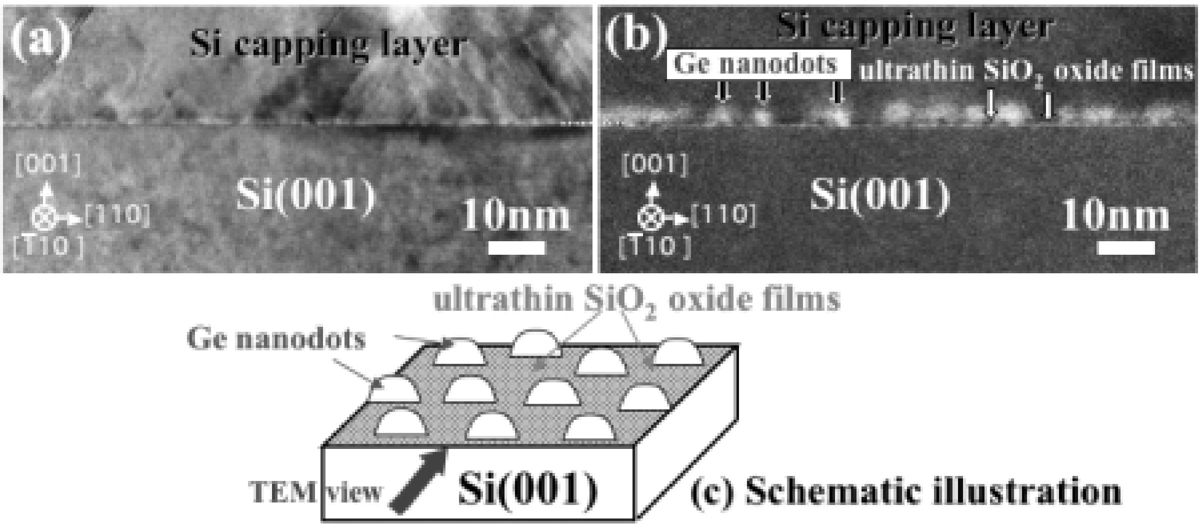

FIG. 1: (a) Conventional TEM image, (b) C_S-corrected HADF-STEM image of poly-Si cap layer/Ge-nanodots/silicon-oxide films/Si(001), and (c) bird-view illustration.

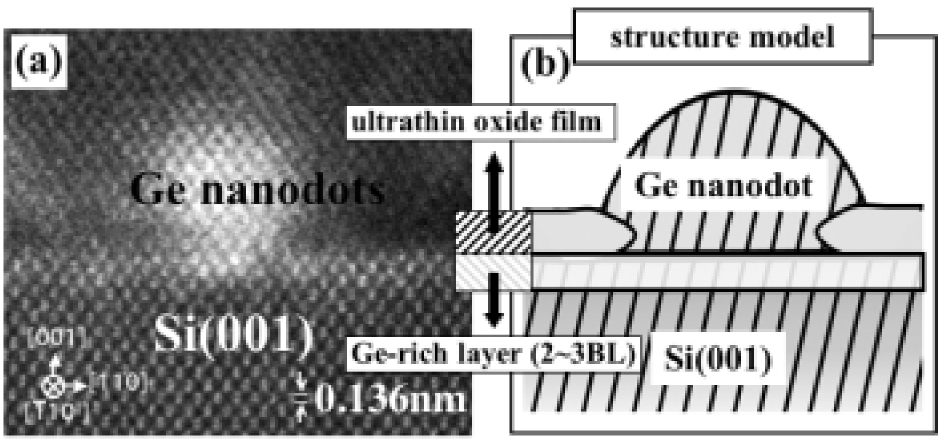

FIG. 2: (a) C_S-corrected high-resolution HAADF-STEM image revealing the details of the interface structures, (b) a newly proposed structure model of Ge nanodots grown on slightly oxidized Si surfaces.