High-Resolution STEM analysis of Si/HfO₂/SiO₂/Si gate dielectric interfaces

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The distribution of single dopant atoms can dramatically alter the properties of semiconductors and catalysts, which are arguably the two most important classes of modern materials. The detectability and lateral localization of such single atoms has been greatly improved by the recent development of aberration correction in scanning transmission electron microscopy (STEM) [1], which enables the formation of electron probes with diameters that can be as small as 0.06-0.08 nm [2]. We take advantage of a previously unappreciated effect of aberration correction, the increase in depth resolution. By consecutively focusing the electron probe into different planes of the specimen, a slice-by-slice image of the three-dimensional structure is available, which is realized by recording through-focal series. The recorded image stacks can then be used for 3-D reconstructions.

We show how the improved vertical resolution along with sub-Ångstrom lateral resolution enables the direct and unequivocal three-dimensional location of single Hf atoms inside a semiconductor device structure. The Hf atoms are visible in a narrow SiO₂ layer located between a single-crystalline Si wafer and a polycrystalline HfO₂ dielectric film, but are not in contact with the Si substrate. All individual Hf atoms remain at least 0.3 nm away from the Si/SiO₂ interface.

Recently, we added parallel electron energy-loss spectrometers to both the 100kV and the 300kV aberration-corrected VG STEM. We used spectrum imaging techniques to acquire high-resolution electron energy-loss spectroscopy data across the HfO₂/SiO₂/Si interface structure to investigate local electronic structures. Core-loss ionization edges were used to identify and analyze the local unoccupied densities of states, which are compared to DOS calculations. Low energy-loss spectrum line-scans are analysed to investigate inter- and intraband transitions and to determine the local complex dielectric functions.

References