Direct Electric Field Imaging by Differential Phase-Contrast in the Scanning Transmission Electron Microscope

Dr. Gabriel Sánchez Santolino

Chalmers University of Technology, Sweden

Understanding the properties of materials and devices at the atomic-scale is essential to control their functional properties. Recent advances in aberration-corrected scanning transmission electron microscopy (STEM) have made possible to directly characterize both the structure and chemistry of localized structures in materials. However, at these small scales, functionality is ultimately governed by strong confined electromagnetic fields, such as the built-in electric field at p-n junction devices. It is then a must, in order to harness the physical properties of materials and devices, to directly characterize highly-confined electric and magnetic fields in materials with high resolutions.

Differential phase contrast (DPC) imaging in the STEM enables the study of such fields by exploring novel segmented detector geometries. Electrons, as charged particles, are deflected by the interactions with the electromagnetic fields present inside materials. As waves, the phase of the incident electron wave-function is shifted proportionally to the strength of the field. Therefore, if we divide the detector plane using a segmented detector, the shift of the beam and therefore the fields inside the sample can be measured by taking the difference between the signals reaching diametrically opposed segments. It is possible then to visualize local electric fields in materials, even with atomic resolution. Figure 1 shows simultaneous high angle annular dark field (HAADF) image, (b) electric field vector colour map and (c) electric field strength map or SrTiO$_3$ along the [001] zone axis. The electric field vector and strength maps are reconstructed from quantitative DPC-STEM images. Furthermore, converting such local electric fields to charge densities it is possible to obtain the internal atomic charge density distributions, mapping the spatial distribution of both the positive nuclear and the negative electronic charges in real space. Current status of atomic-resolution DPC-STEM developments and future directions will be discussed.
Figure 1. Atomic resolution DPC-STEM images of SrTiO3 observed from the [001] direction. (a) HAADF image. (b) Electric field vector color map and (c) electric field strength map. The inset color wheel in (b) denotes the electric field direction and strength.

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