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Direct Sub-Angstrom Imaging of a Crystal Lattice

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Achieving sub-angstrom imaging has been a long-standing goal for electron microscopy. Improved resolution allows not only a wider range of materials to be imaged, but also allows each material to be imaged in several possible orientations. It provides much improved sensitivity to atomic arrangements at defects and interfaces, down to the single-atom level for the first time in some instances. Sub-angstrom information transfer can be accomplished in an uncorrected transmission electron microscope (TEM) with tilted illumination (*1*), but the information in the images becomes extremely delocalized and the increased information transfer is only in the direction of the tilt. Underfocusing the main imaging lens can also partially compensate for the existence of spherical aberration (*2*), but the images recorded are similarly highly delocalized and contain low signal strength. Postprocessing of focal-series data can overcome some of these limitations (*3*, *4*). However, this is not direct imaging because it requires the collection of many images, and extensive processing of image data increases the risk of the introduction of image artifacts. Previous evidence of a sub-angstrom point spread function from a scanning TEM (STEM), with apparent spots in a Fourier transform and an intensity profile of a single atom (*5*), is not unambiguous because such measurements are sensitive to errors due to noise, instabilities in the microscope, and incorrect adjustment of the detector black level.

An indisputable test for demonstrating sub-angstrom resolution is a Si crystal observed in the [112] orientation, because it contains pairs of Si columns 78 pm apart. Figure 1, A and B, shows an image recorded with a VG Microscopes HB603U 300-kV STEM fitted with a Nion aberration corrector. It was recorded in the annular dark-field (ADF) imaging mode. In a STEM, electron optics focus a beam of electrons into a narrow spot, or probe, which is scanned over the sample in a raster. The ADF detector's collects electrons scattered by the sample to angles greater than the detector inner radius, which in this case was 0.0009 Gray (90 mrad). Such high-angle scattering is largely incoherent thermal diffuse scattering, which means that the resolution observed in the image is determined by the intensity distribution of the illuminating probe (*2*). Before correction, without a large defocus, the optimum (Scherzer) resolution limit for ADF imaging on this microscope was 0.13 nm. The addition of the corrector allows the probe-forming aperture to be opened up to give an expected probe size in the range of 60 pm. In Fig. 1, A and B, pairs of atomic columns can be resolved with a spacing of 78 pm. The Fourier transform of this image (Fig. 1C) shows clear information transfer to 71 pm, and there is apparent lattice information at 61 pm. We expect this spot to be weak, because at such a high spatial resolution, the physical width of the atoms is substantial and reduces the contrast between closely spaced columns. There is no evidence that the high-frequency spots are due to incorrect background level or distortions (*6*), and the simulated image profile compares well with the experimental data (Fig. 1D).

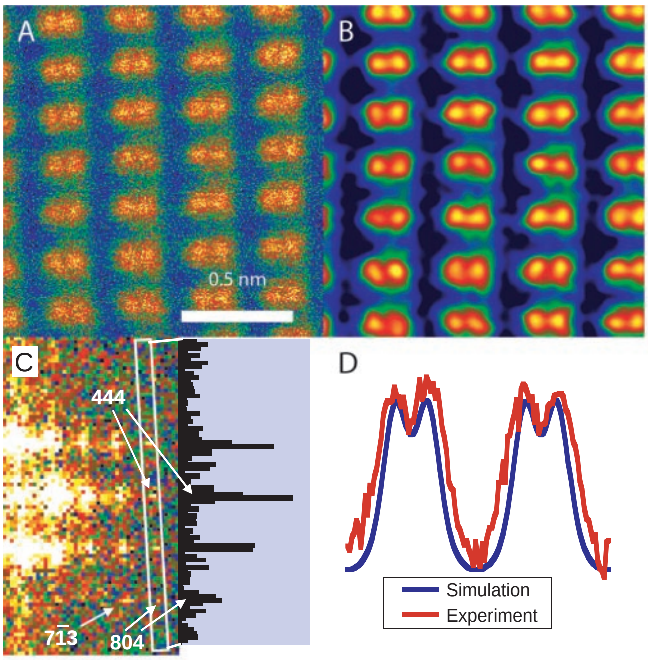

Fig. 1. (**A** and **B**) ADF images of Si[112] recorded with an aberration-corrected STEM. The image in (B) has been low-pass filtered to reduce the noise, and the small effects of image drift during the scan have been unwarped. (**C**) The modulus of the Fourier transform of the image data and a profile through the spots enclosed by the box. The 444 spacing (78 pm) corresponds to the smallest atomic column spacing, and there is information transfer to the 713 (71-pm) spacing and weak transfer at the (804) 61-pm spacing. (**D**) An intensity profile through two column pairs in (A), formed by summing over a width of 10 pixels. A simulated profile (*6*) is shown for comparison.

In summary, we have demonstrated direct sub-angstrom resolution with an aberration-corrected STEM, an advance that allows materials and nanostructures to be imaged with a new level of sensitivity. We expect light columns to be visible in the presence of adjacent heavy columns and individual dopant or impurity atoms to be detectable within materials, at defects and interfaces, and on their surfaces. Such capability should enable a new understanding of the atomic-scale origins of properties with applications in the materials, chemical, and nanosciences.

References and Notes

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6. Materials and Methods are available as supporting material on *Science* online.
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Materials and Methods
Figs. S1 and S2

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