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Real-time imaging of atomic electrostatic potentials in 2D materials with 30 keV electrons

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Two-dimensional (2D) materials are of great scientific interest ever since the discovery of graphene. Characterization and manipulation of 2D materials at the atomic scale has been invaluable for the understanding of 2D materials, considering their profound structure-property relationship. Atomic resolution scanning transmission electron microscopy (STEM) has, for that reason, always been intimately linked to 2D materials research.

Yet, it has remained problematic to image the intrinsic atomic structure of 2D materials. Firstly, because energetic electrons readily cause radiation damage, even when the beam energy is reduced from 200 to 60 keV. Another major challenge is the observation of light atoms next to heavy ones, particularly when recording fast dynamical phenomena like phase transformation or the real-time tracking of single atoms. Such measurements require an imaging technique that is both sensitive and fast, which has not been demonstrated to date.

Here we show that 2D WS2 suffers from radiation damage during atomic resolution STEM imaging with an ultra-low electron beam energy of 30 keV (1). We follow the beam-induced formation of point defects, line defects and holes in 2D WS2 in real-time by direct atomic electrostatic potential imaging, and reveal the presence and motion of single sulfur atoms, that are invisible with the popular and most widespread adopted annular dark-field (ADF) STEM (Figure 1).

We achieved atomic electrostatic potential imaging with integrated differential phase contrast (iDPC) performed in an aberration corrected STEM, using a monochromated 30 keV electron beam. Currently, this is the only electrostatic potential imaging technique with highspeed and direct imaging performance, as it does not require time consuming post processing steps or complex reconstruction schemes. iDPC-STEM requires only several fast solid-state electron detectors, and not the 2-3 orders of magnitude slower electron cameras used for integrated center of mass (iCOM) STEM or electron ptychography. The minor compromise in accuracy offers a vast speed advantage that is beneficial for the observation of dynamical phenomena.

This approach can be directly applied to visualize light elements, like oxygen, carbon and nitrogen, in all 2D materials, and can be generalized to all other beam sensitive materials that require low electron dose and ultralow beam energies. Its direct compatibility with electron energy loss spectroscopy has the potential to solve challenging problems in materials science.

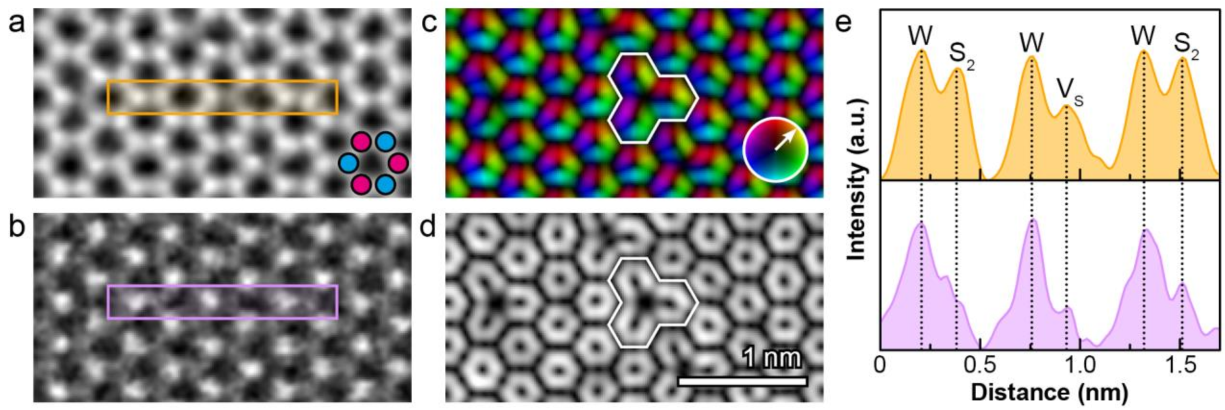

Figure 1. Atomic resolution 30 keV STEM images of 2D WS2 containing a single sulfur atom vacancy (VS). The position of the tungsten and two stacked sulfur atoms are indicated by, respectively, magenta and cyan dots in (a), and apply to all panels. Simultaneously acquired images of the (a) electrostatic potential with iDPC-STEM, (b) square of the electrostatic potential with ADF-STEM, (c) electric vector field with DPC-STEM and (d) magnitude of electric field with DPC-STEM. The distinct feature of the VS is outlined in the electric field images (c,d). Intensity line profiles from the colored rectangles in the iDPC-STEM and ADF-STEM (a,b) are plotted in (e).

References

(1) S. de Graaf, M. Ahmadi, I. Lazić, E.G.T. Bosch, B.J. Kooi. Real-time imaging of atomic potentials in 2D materials with 30 keV electrons. *arXiv:2102.12159 [cond-mat.mtrl-sci]* (2021)

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