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Low-Energy Electron Diffractive Imaging Based on a Single-Atom Electron Source

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Imaging of the atomic structures of two-dimensional materials and organic materials is a challenge for current electron microscopes because of low imaging contrast and high radiation damage for high-energy electrons. It has been a general trend to develop electron microscopy of lower energies. Thanks to the progress in aberration-correction techniques, transmission electron microscopes with voltages down to 15-40 kV have recently been demonstrated. However, it becomes very difficult to achieve atomic resolution when the electron energy is reduced below 10 keV. An alternative approach is phase retrieval imaging, which requires a sufficiently coherent source, detection of high-angle diffracted patterns with a sufficient resolution, and a sufficiently small detection area on the sample. There is no need to fabricate high-quality lenses with a large numerical aperture. In this work, we propose several experimental schemes of low-energy electron coherent diffractive imaging (CDI). A great advantage of low energy electrons over high-energy electrons and x-ray is that the cross-sections of interaction with the atomic potentials are very large, so that the diffraction pattern has good signal-to-noise ratios even at high scattering angles and thus high-resolution images can be reconstructed.

We plan to use noble-metal covered W(111) single-atom tips (SATs) as the electron sources for low-energy electron CDI. High brightness and fully spatial coherence of electron beams emitted from this type of SATs have been demonstrated [1-3]. This type of SATs can be reliably prepared and regenerated in vacuum [2,3]. Their pyramidal structures are thermally and chemically stable, ensuring their long operation lifetime.

To achieve a sufficiently small detection area on the sample, two types of schemes are proposed here. The first one is based on a lens-less imaging technique. Fig. 1 shows a schematic of an electron point projection microscope (PPM) with a MCP-screen mounted on a rail. The detector screen can be moved in a certain range behind the sample to record the transmission patterns at different positions. High-magnification images can be acquired when the detector screen is moved to the far end. High-angle diffraction patterns can be obtained when the detector is moved close to the sample. One example is shown in Fig. 2(a). The central pattern is the projection image or hologram of the sample, and six surrounding patterns are observed, which are related to diffraction of a single domain of monolayer graphene. The diffraction patterns are shown individually with enhanced contrast in Fig. 2(b). The central and diffracted patterns resemble the bright-field images and multiple dark-field images, respectively, in selected-area diffraction of TEM when the electron beam is defocused on the sample.

The lens-less scheme is simple and can achieve a high imaging contrast due to the use of low-energy electrons (20-500 eV). However, it can be applied to samples of thickness less than 1 nm. Thus, there is a need to develop a low-keV electron diffraction microscope with energies between 1 and 10 keV. Here we propose several imaging modes for a transmission-type low-keV EM (Fig. 3). A CDI scheme with a parallel beam to illuminate a sample is illustrated in Fig. 3(a). Fig. 3(b) illustrates a scheme with a slightly convergent beam to illuminate the sample. This scheme can reach a spot size fulfilling the oversampling requirement more easily than that in Fig. 3(a). Fig. 3(c) illustrates a scheme of in-line electron holography, same as the one originally proposed by Gabor [4]. In this case, an object is illuminated with a focused electron beam of a large converging angle in front of or behind the object.

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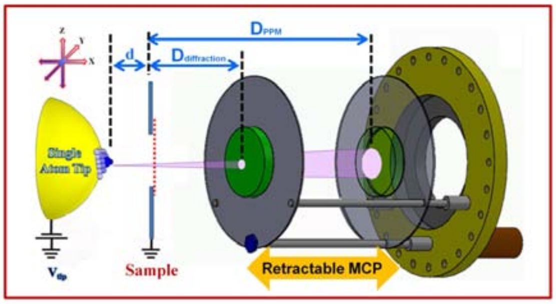

Figure 1. Schematic of a lens-less electron diffraction microscope with a retractable MCP.

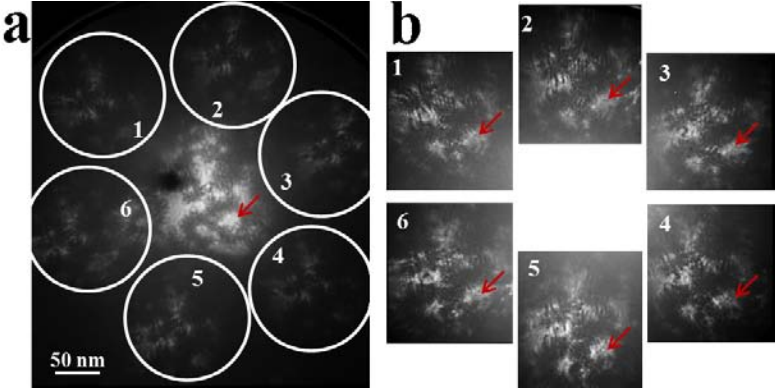

Figure 2. Transmission patterns recorded on a monolayer graphene with a lens-less electron diffraction microscope. (a) Diffraction patterns of a monolayer graphene sample. The electron energy is 270 eV. (b) Six dark-field patterns with enhanced contrast are shown.

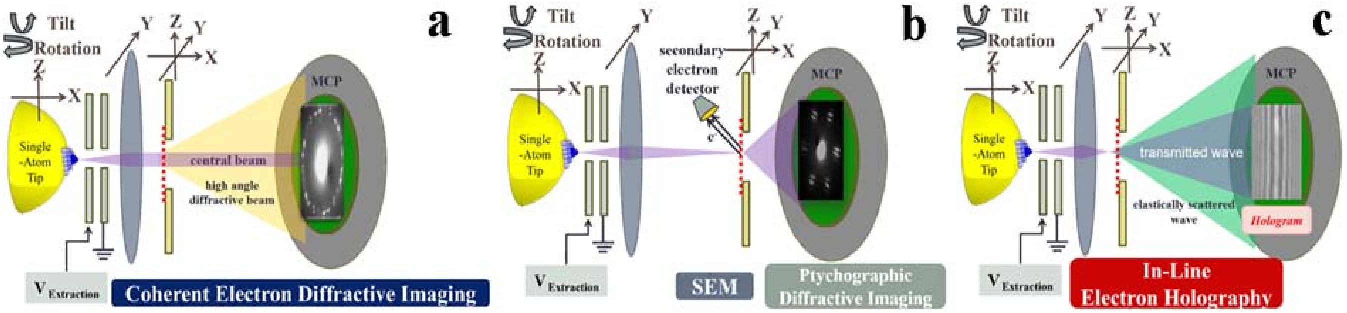

Figure 3. Proposed schemes of a low-keV electron microscope. (a) CDI with a parallel beam to illuminate the sample. (b) CDI with a slightly convergent beam to illuminate the sample. It also allows operation of scanning electron microscopy if the secondary electrons are collected by an electron detector. (c) In-line holography.