Venturing Down the Voltage Scale in Electron Microscopy – Successes and Challenges

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Historically, higher TEM voltages were favoured since they reduce the effects of spherical and chromatic aberration; however, with the development and commercial introduction of spherical aberration correctors, electron monochromation and Cc-correction have now allowed atomic resolution at much lower accelerating voltages. Low-voltage High-Resolution Electron Microscopy has several significant advantages, including increased cross-sections for inelastic and elastic scattering, increased contrast per electron and improved spectroscopy efficiency, decreased delocalization effects and reduced radiation knock-on damage. Together, these often improve the contrast to damage ratio obtained on a large class of samples. Third-order aberration correction now allows us to operate the TEM at low energies while retaining atomic resolution, which was previously impossible.

The improvement in contrast for inorganic materials, biological samples and especially nano-biological samples in low-voltage TEM while retaining atomic resolution cannot be understated. For example our group has shown spherical aberration corrector in conjunction with electron monochromator at 40 keV takes the user surprisingly close to the lower bound imposed by fifth-order spherical aberration, and enables imaging with an information limit better than 1 Å, and a workable resolution of better than 1.4 Å [1].

One direct application of low-voltage Electron Microscopy is examining Quantum Materials [2]. Quantum materials are atomically layered materials such as graphene or hexagonal boron nitride (h-BN). Their properties differ strongly from the properties of their three dimensional bulk state. Depending on the composition, quantum materials may act as conductors, insulators, semiconductors or even as superconductors. Especially combinations of different quantum materials are of high interest to explore new phenomena and to build the foundation for future electronic devices at the nanometer scale. Our research on quantum materials is widely spread, reaching from defect formation in graphene to the characterization of hybrid quantum materials. We use a Cs corrected Zeiss Libra TEM to investigate chemical vapor deposition (CVD) graphene with added copper and mercury defects. With TEM we address the question, where the Hg and Co atoms are placed on the graphene. At the same time, we observe the effect of the copper and mercury on the pi electrons in graphene with Raman spectroscopy. Furthermore, we are interested in graphene based hybrid structures, such as graphene oxide embedded in a vanadium pentoxide nanofiber matrix (Fig. 2). The graphene sheets and the nanofibers have approximately the same thickness, leading to a material with enhanced mechanical performance in comparison to pure vanadium pentoxide and pure graphene oxide sheets. Application of Low-Voltage Electron Microscopy and its development and future directions will be presented.

[1] David C. Bell, Chris J. Russo and Dmitry Kolmykov, “40 keV Atomic Resolution TEM”, Ultramicroscopy. 114, pp 31-37 (2012)
[2] David C. Bell, Estelle Kalfon-Cohen and Robert M. Westervelt, “New Microscopy the Imaging of Quantum Materials”, Microscopy and Microanalysis 20 (S3), 1086-1087, (2014).

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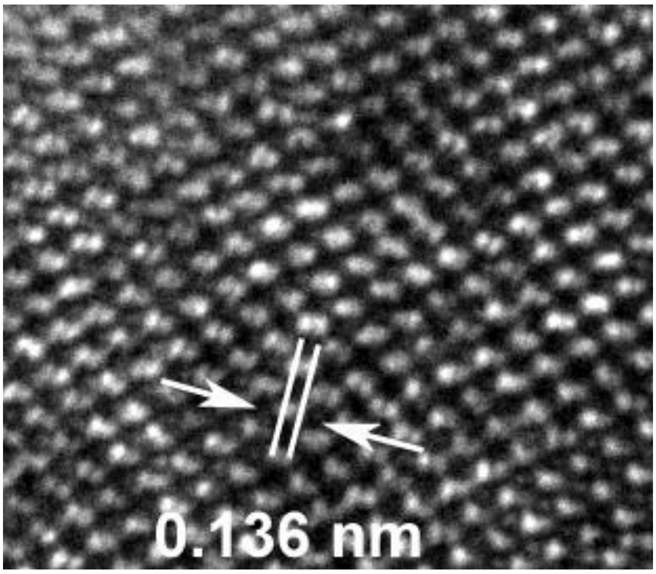

Figure 1.
40 keV Imaging of Si (110) indicating the 0.136 nm lattice spacing.
Use of a spherical aberration corrector in conjunction with electron monochromator [1].

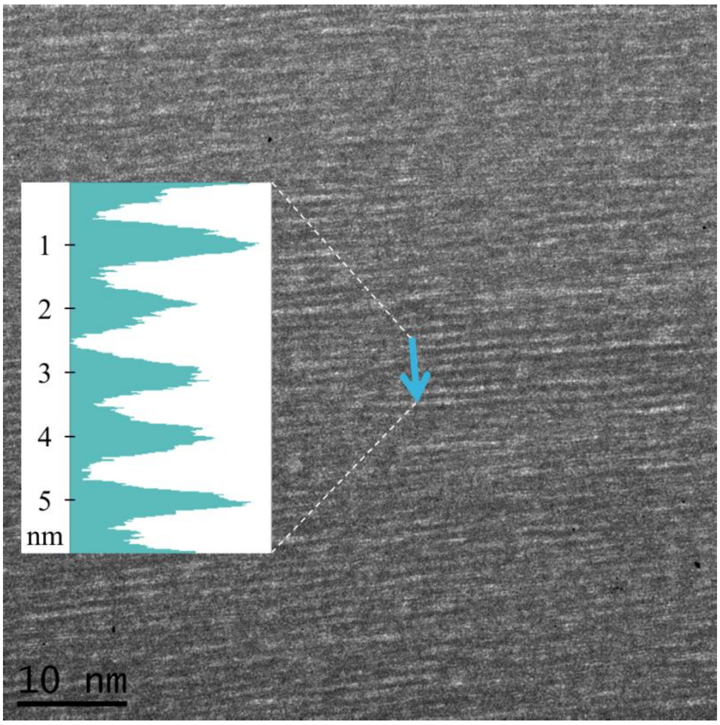

Figure 2.
The image shows the structure of a free-standing thin-film composed of vanadium pentoxide nanofibers and graphene oxide nanosheets. Fibres and sheets both have an average thickness of 1 nm and oxygen-containing functional groups which promote the interaction between both components, leading to a material with enhanced mechanical performance in comparison to pure vanadium pentoxide and pure graphene oxide sheets. (Sample courtesy of Max Planck Institute for Condensed Matter Science, Stuttgart)