Low-voltage TEM for quantitative analysis of low-dimensional materials on the atomic level

Kaiser, U.[1]

[1] University of Ulm, Germany

Nowadays the term *"low-voltage"* in transmission electron microscopy refers to accelerating voltages equal or below 80kV, often 60kV down to 40 and 20kV. The ultimate goal of low-voltage atomic-resolution analytical electron microscopy is the acquisition of quantitative data about the atomic structure, the chemical composition, and the local electronic states of thin electron-beam-sensitive objects including organic molecules. The latter aim goes back to the late sixties and early seventies of the last century primarily due to the pioneering work of Otto Scherzer [1] and Albert Crewe [2]. The aim of preventing radiation damage at that time created important discussions about how low should we go in the accelerating voltage [3] and how to calculate and understand the interactions [4]. Today, about 50 years later, the TEM community utilizes the realization of aberration correction in STEM and TEM by reducing the chromatic (Cc) aberration by means of monochromators [5, 6]. or by compensating it by Cc correction and by eliminating the spherical aberration of the objective lens as recently achieved in the SALVE (Sub-Angstroem Low-Voltage Electron microscopy) instrument [7-11] by means of a novel case-designed spherical and chromatic aberration corrector.
In this presentation the performance of the SALVE microscope operating at electron energies in the range between 80 and 20keV [7-9] will be presented. The application of such low voltages increases the contrast and avoids (a) knock-on damage even in the case of low-Z materials and (b) prevents an appreciable reduction of resolution at lower electron energies. We will demonstrate this behaviour by showing that sub-Å resolution is achieved down to 40keV and 1.3Å resolution at 20keV in a wide field of view of 4000x4000 pixels, making the tool predestined for in-situ studies of dynamic effects in low-dimensional materials at the atomic level [8]. The correction of both spherical and chromatic aberration allows the use of most elastically and inelastic scattered electrons for image formation, without the loss of beam intensity resulting from monochromation. In combination with an imaging energy filter it is possible to form atomic-resolution EFTEM images using plasmon-loss or core-energy-loss electrons. For atomic- resolution energy-filtered TEM not only correction of the chromatic aberration of the objective lens is required but also the performance of the imaging energy filter must satisfy several conditions. Primarily chromatic distortions and non-isochromaticity must be kept very small. First EFTEM images obtained with the low-voltage Gatan imaging filter attached to the SALVE instrument will be presented.
The interaction of the incident electrons with low-dimensional materials often results in changes of the atomic structure due to ionisation effects, which may prevent the imaging of the pristine state of the material but can also be utilized for manipulating the structure on the level of the single atom. Especially non-conducting materials suffer from ionization effects, which usually increase at lower voltages [12]. Sophisticated sample preparation methods are then needed to reduce these effects. Promising means are the production of clean surfaces [13] and sandwiching the radiation-sensitive material between two single sheets of graphene [14]. First results in HRTEM imaging using these procedures will be presented [15-17].

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