Electron beam broadening in thin samples in a scanning electron microscope

Milena, H.[1], Müller, E.[2] and Gerthsen, D.[2]

[1] Laboratory for Electron Microscopy, Karlsruhe Institute of Technology, Germany, [2] Laboratory for Electron Microscopy, Karlsruhe Institute of Technology, Germany

Lately there has been a growing interest in scanning transmission electron microscopy (STEM) at low primary electron energies $E \leq 30$ keV. The advantages of low-kV STEM are high material contrast for materials with low atomic numbers and reduced knock-on-damage compared to higher electron energies. Moreover, it can easily be performed in a standard scanning electron microscope, using an annular STEM-Detector positioned below the sample. However, the mean free path length decreases with lower energies and therefore more scattering events take place. This leads to plural and multiple scattering even for small sample thicknesses and beam broadening worsens the lateral resolution. The behaviour of the beam in the sample cannot be directly measured. However, Drees et al. [1] recently proposed a new technique to measure beam broadening. In the present study, we use this approach to analyze beam broadening in materials with atomic numbers Z between 10 and 32 for thicknesses up to 800 nm with wedge-shaped samples prepared by focused-ion-beam milling.

A semiconductor STEM detector in a Thermo Fisher DualBeam Strata 400S was used for measuring the transmitted intensity. The STEM detector comprises a circular bright-field segment, four annular dark-field and a high-angle annular dark-field (HAADF) segment (Fig. 1). The segments are separately controllable and correspond to specific scattering angle ranges. The measured STEM intensity is corrected by subtraction of the back-level intensity (intensity with blanked electron beam) and normalized with the intensity of the incident electrons.

The samples were simultaneously imaged with the distinct detector segments for different sample thicknesses t. This leads to curves of the normalized intensity $I(t)$ integrated up to specific angles defined by the number of used detector segments (Fig. 2). The radial intensity of an electron probe can be described in a first assumption by a Gaussian distribution. We define the beam diameter b as the diameter which contains 68 % of the total probe intensity (1σ of a Gaussian distribution). This beam diameter corresponds to the beam broadening if the primary beam diameter is small and can be neglected. A dashed horizontal line in Fig. 2 indicates the thickness where the measured intensity corresponds to 68%. Beam broadening is calculated by $b(t)=t \tan \theta$ with the scattering angle q assuming that the electrons are scattered on the average at $t/2$ as schematically indicated in Fig. 3. By fitting curves of the form $b = a_1 \frac{Z}{E} \left(\frac{\rho}{A}\right)^{1/2} t^{a_2}$ the measured beam broadening is compared with the prediction by Goldstein [2, 3] with a_1=0.11, a_2=1.5, the material density ρ and the atomic mass A of the material. Fig. 4 shows an increase of beam broadening with increasing material density for different samples as expected for decreasing mean free path lengths. Beam broadening was also simulated using the electron transport equations. Fig. 5 comprises beam broadening for different primary electron energies E and shows good agreement for the product $b \times E$ for measured, simulated data and the theoretical calculations for Si.

References

[1] H. Drees, E. Müller, M. Dries, D. Gerthsen, Ultramicroscopy, 185:65-71, 2017.

[2] J.I. Goldstein, J.L. Costley, G.W. Lorimer, S.J. Reed, Scanning Electron Microscopy 1 (1977) 24.

[3] R. Gauvin, S. Rudinsky, Ultramicroscopy 167:21-30, 2016.

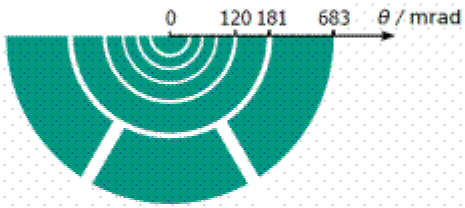

Figure 1: Scheme of the segments of the STEM-detector with corresponding outer scattering angles (HAADF not to scale)

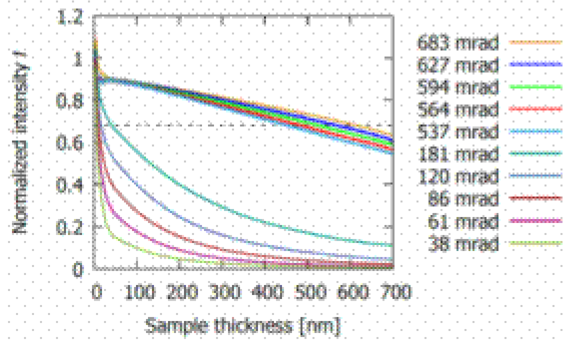

Figure 2: Normalized intensity as a function of the thickness. The intensity is integrated for the different curves up to the angles indicated in the legend.

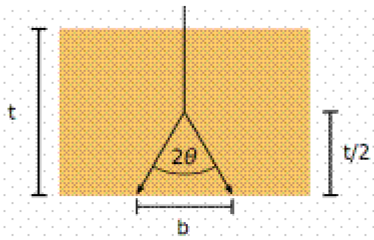

Figure 3: Illustration of the concept for the determination of beam broadening *b* in a sample of thickness *t*

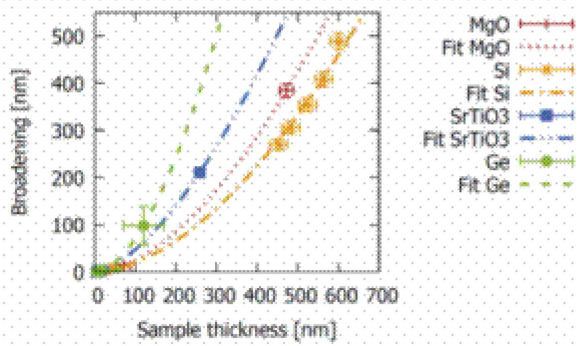

Figure 4: Measured beam broadening for *E*=25 keV for different materials

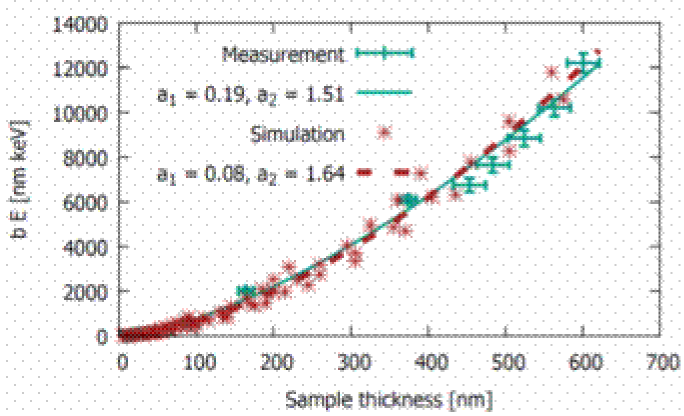

Figure 5: Measurement and calculated product of beam diameter and electron energy *bE* as a function of sample thickness for Si