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Dynamic Scattering Theory for Dark-Field Electron Holography of 3D Strain Fields

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Dark-field electron holography (DFEH) is a TEM technique aiming at measuring strain fields in crystals with high precision, nanometer spatial resolution and large fields of view.[1] DFEH extracts geometric phase information ϕ_G in diffracted beams (denoted by reciprocal lattice vector $\boldsymbol{G}$) by holographically interfering diffracted beams from strained and unstrained regions of the crystal lattice. Two-beam conditions are utilized to maximize the intensity and thus the signal-to-noise ratio in the diffracted beam.

The current assumption when using DFEH, is that either the strain is uniform, or that the measured strain corresponds to the average strain over the thickness of the foil. The latter corresponds to strain fields varying in the viewing (z-)direction which is a ubiquitous feature of thinned TEM specimen and modern 3D microelectronic devices (e.g. FinFETs) or quantum dots. Whilst z-dependent strain fields in combination with dynamical scattering are well known to produce complicated deviations from the above average assumption in case of strain studies by means of convergent beam electron diffraction, high-resolution TEM or nano-beam electron diffraction, a systematic investigation of this effect in DFEH was missing so far.

Here we are filling that gap. We show that within 2-beam scattering conditions analytic solutions can be derived within a perturbation approach. The analytic solution consists of introducing a weighting kernel f_u^G to the former average approach which depends on the extinction length ξ_G of the diffracted beam and the thickness t of the sample:

$$\varphi_G = -2\pi \int f_u^G(z)\,\mathbf{G}\cdot\mathbf{u}(z)\,\mathrm{d}z \qquad \text{with} \qquad f_u^G(z) = \frac{\pi \sin\left(\pi\xi_G^{-1}(t-2z)\right)}{\xi_G \sin\left(\pi\xi_G^{-1}t\right)}$$

Here $\boldsymbol{u}$ denotes the displacement field yielding the strain tensor components after derivation. This weighting formalism facilitates a straightforward yet sufficiently accurate discussion of z-dependent strain influence (see Figure 1): For instance, because $\int_0^t f_u^G(z)\,\mathrm{d}z = 1$, a z-independent displacement field $\boldsymbol{u}$ yields a reconstructed geometric phase corresponding exactly to $\boldsymbol{G}\cdot\boldsymbol{u}$. Furthermore $f_u^G(z)$ is symmetric with respect to the middle of the specimen, and hence antisymmetric strain fields are not measured by DFEH (and are found in the bright field phase instead). Since the weighting kernel is G-dependent, different diffracted waves measure differently projected parts of the strain, which is important for reconstructing 2D strain fields from linearly independent diffracted beams. We furthermore remark that the weighting kernel formalism is an important prerequisite towards tomographic reconstruction of strain fields because it provides the link to the projection transformations used in that context. A comprehensive discussion including the important influence of the excitation error (i.e., experimentally unavoidable deviations from exact Bragg conditions) can be found in Ref. [2].

References:

[1] M.J. Hÿtch, F. Houdellier, F. Hüe, and E. Snoeck, *Nature* 453 (**2008**) 1086.
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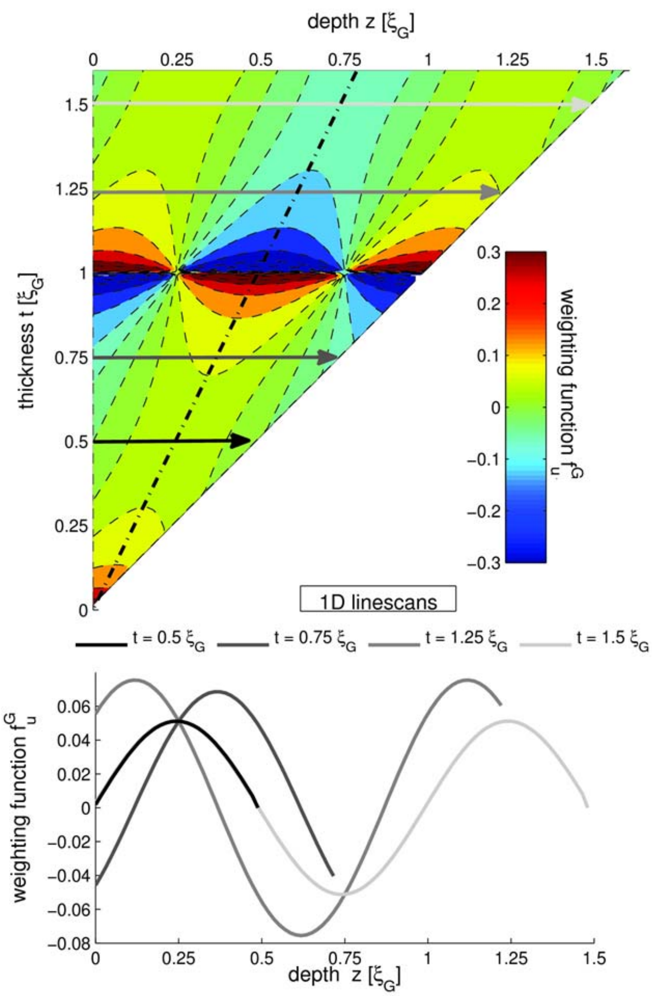

Figure 1. *Weighting function* $f_u^G(z/\xi_G, t/\xi_G)$ *with 4 1D-cuts at special thicknesses t=0.5, 0.75, 1.25, 1.5* ξ_G*. The black dashed-dotted line indicates the point of symmetry at z=t/2.*