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The Fresnel effect of a defocused biprism on the fringes in inelastic holography

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Abstract

We present energy filtered holography experiments on a thin foil of Al. By propagating the reduced density matrix of the probe electron through the microscope, we quantitatively predict the fringe contrast as a function of energy loss. Fringe contrast simulations include the effect of Fresnel fringes created at the edges of the defocused biprism, the effect of partial coherence in combination with inelastic scattering, and the effect of a finite energy distribution of the incoming beam.

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1. Introduction

Although the study of partial coherence is a well developed field in optics, relatively few publications deal with its consequences for electron microscopy. This is remarkable since it is well known that a typical electron beam is far from fully coherent and it is expected that partial coherence must have a large influence on the images formed in an electron microscope. Usually its effect on TEM image formation is approximated by the coherent envelope function which dampens the high spatial frequencies of the microscope transfer function. This approach, however, fails completely to describe the outcome of experiments involving the direct measurement of coherence using an electron biprism [1,2]. Recently there have been several experiments, mostly based on holography, to test the effects of partial coherence in combination with inelastic scattering [3–8]. The outcome of these experiments has proven to be difficult to understand in simple terms of either coherent or incoherent imaging and it was shown that partial coherence has to be taken into account properly [9–22], to be able to understand the obtained contrast. Although the theory of partial coherence can be extremely difficult to solve for an arbitrary setup, we can usually use the symmetry of the system to make suitable simplifications. In this contribution, we show that it is currently possible to accurately simulate the outcome of holography experiments with inelastic scattering and partial coherence.

2. Experimental

A thin sample of pure Al was obtained by electropolishing a sheet of pure aluminum in a mixture of 10% perchloric acid and 90% ethanol. Experimental energy filtered holography images are acquired making use of a Philips CM30, 300 kV microscope with a GIF200 imaging filter. The energy selecting slit is chosen to be 3 eV. A biprism in the selected area aperture plane is used with a virtual diameter of 12 nm in the image plane. The specimen plane is shifted approximately $z = 5\,\mu m$ above the virtual biprism plane while keeping the specimen in focus on the viewing screen making use of free lens control. A positive

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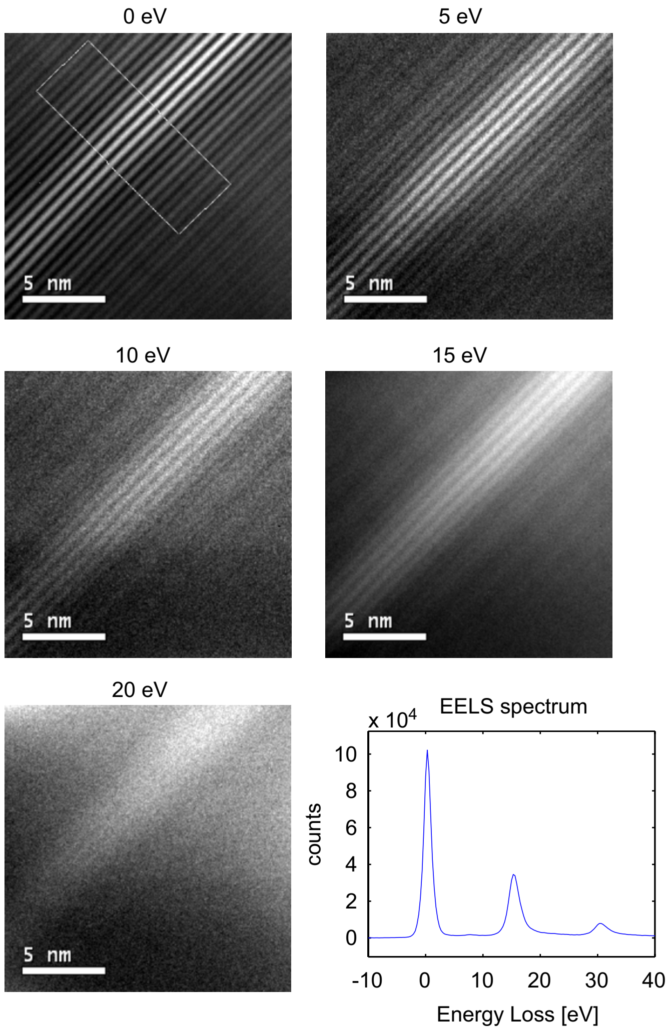

Fig. 1. Experimental holography images for different energy losses and an energy selecting slit of 3 eV. The shear is fixed at approximately 8 nm. In the right bottom corner the low loss EELS spectrum is shown. Line traces are taken perpendicular to the fringes in a region indicated on the first image in the top left corner.

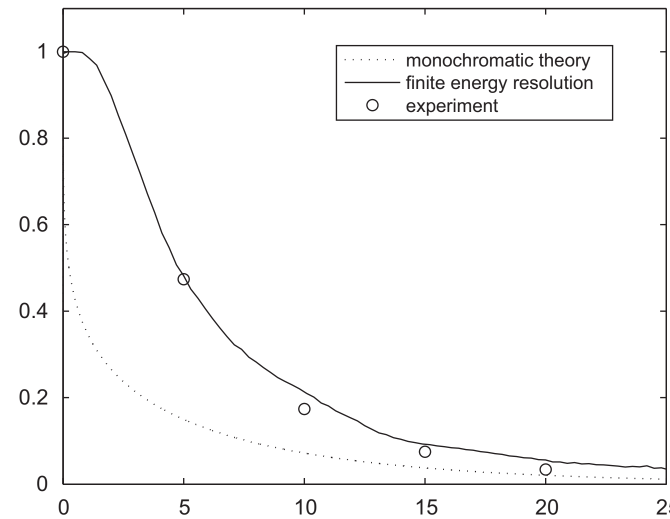

Fig. 2. Fringe contrast vs. energy loss for $s = 7.9$ nm. Simulated function takes into account the finite energy resolution and the experimental spectrum. An excellent agreement with experiment is obtained as opposed to the fringe contrast that is obtained from assuming a monochromatic beam.

voltage of 70 V is applied to the biprism to create a shear of approximately $s = 8$ nm. This creates an overlap between two electron paths, a distance s apart, that went both through the crystal[1] and both have an energy loss selected by the energy selecting slit. Numerical calculations are performed using the Matlab™ scripting language.

3. Results and discussion

The fringe patterns obtained at energy losses of 0, 5, 10, 15 and 20 eV are shown in Fig. 1. Fringes are clearly present at all energy losses, although their contrast reduces with energy loss. This effect has been described in detail in Ref. [16], and is basically due to the delocalised interaction of the fast electrons with the electrons in the specimen. In this paper we go one step further and describe the effect of the defocused biprism on the fringe pattern, an effect that becomes more important for small shear values as in the current experiment. The necessity for treating this effect properly is seen in the experimental images where Fresnel fringes around the biprism wire are present. They lead to the problem of unambiguously defining the fringe contrast, since the contrast changes depending on the position.

The image formation in case of partial coherence can be calculated making use of the reduced density matrix for the fast electrons [9–22]. The reduced density matrix is a quantum mechanical tool to properly describe the interaction between the fast electrons and the sample. Note that, because of this interaction, it is no longer possible to use a wave function as opposed to the situation of pure elastic scattering. If we describe the total system of fast particles and sample as non-interacting with the rest of the universe we can write the total wave function as [23]:

$$\Phi(x,y) = \sum_{i,j} a_{i,j}\psi_i(x)\Psi_j(y), \quad (1)$$

constructed from a complete orthonormal basis set of wave functions $\psi_i(x)$ and $\Psi_j(y)$ for the fast electrons and the sample, respectively. Performing the sum in i we get

$$\Phi(x,y) = \sum_{j} \phi_j(x)\Psi_j(y) \quad (2)$$

with

$$\phi_j(x) = \sum_{i} a_{i,j}\psi_i(x). \quad (3)$$

Note that the $\phi_j(x)$ are in general no longer orthogonal.

In the experiment we only measure the fast electrons which can be described by integrating out the non-observed

[1] As opposed to conventional elastic holography where a specimen wave is made to interfere with a vacuum wave.