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The role of plasmon scattering in the quantitative contrast analysis of high-resolution lattice images of GaAs

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ABSTRACT: We compare unfiltered, energy filtered zero loss and plasmon loss high-resolution lattice images from a cleaved GaAs wedge specimen. The filtered zero loss images exhibit lower lattice fringe amplitudes than the unfiltered images which can be explained only by the contributions of the plasmon images (whether coherently or incoherently) to the contrast being in phase with the filtered zero loss image contrast. The contrast maxima of the (200) lattice fringes occur at the same specimen thicknesses in the plasmon and zero-loss images, suggesting that the elastic and the plasmon scattering are coherently related at least for thicknesses up to 30nm.

1. INTRODUCTION

For a quantification of lattice images in high-resolution electron microscopy (HREM) a detailed understanding of the various scattering processes involved and their contribution to the image formation process is necessary. With the availability of energy filters for electron microscopy, it has become possible to investigate quantitatively the influence of plasmon scattering on both the image mean intensity and the image contrast. The approximation of simulating the effect of electrons which have undergone plasmon losses by adding to the image calculated for elastically scattered electrons incoherently a certain intensity with an overfocus corresponding to the less energetic plasmon electrons has been used for a while (Boothroyd and Stobbs 1988). Although lattice fringe contrast in plasmon loss images was experimentally observed by Hashimoto (1985), it seems not to be generally appreciated that its contribution can be significant to unfiltered lattice fringe contrast.

2. LATTICE FRINGE CONTRAST IN ENERGY FILTERED HREM

The experiments were performed using a JEOL 4000 FX electron microscope equipped with a specially designed objective lens system and a post-column GATAN energy filter system. It was operated at 387kV, the spherical aberration coefficient is 2.0 mm and the chromatic aberration constant 1.4 mm. A large selected area aperture was used to exclude stray electrons from outside the field of view, but no objective aperture because of a drift problem associated with the latter. A pair of images from the specimen edge was obtained without and with an objective aperture of 14.5 mrad semi angle in order to take account of electrons scattered through high angles which contribute a homogeneous background to the images. This contribution was then subtracted from the images taken without objective aperture. The beam convergence semi angle was 1.0 mrad. The energy filter slit width used was 10 eV, and a 3 mm EELS entrance aperture was necessary to exclude electrons hitting the drift tube of the filter from adding a spurious background. The energy loss was controlled with the filter's drift tube rather than by the alternative approach of varying the acceleration voltage. Images were acquired unfiltered, from the zero loss including phonon scattering contributions (0 eV), the first plasmon energy (16 eV) and the second plasmon energy (32 eV). The specimen was a GaAs wedge cleaved along {110} planes and tilted to the <100> zone axis. Exposure times were set to 1s for both unfiltered and filtered zero loss

images, 5s for the first and 10s for the second plasmon loss images. The sampling was 0.022 nm per pixel, and the images were corrected for the point spread function of the CCD camera and scaled for an incident intensity of unity.

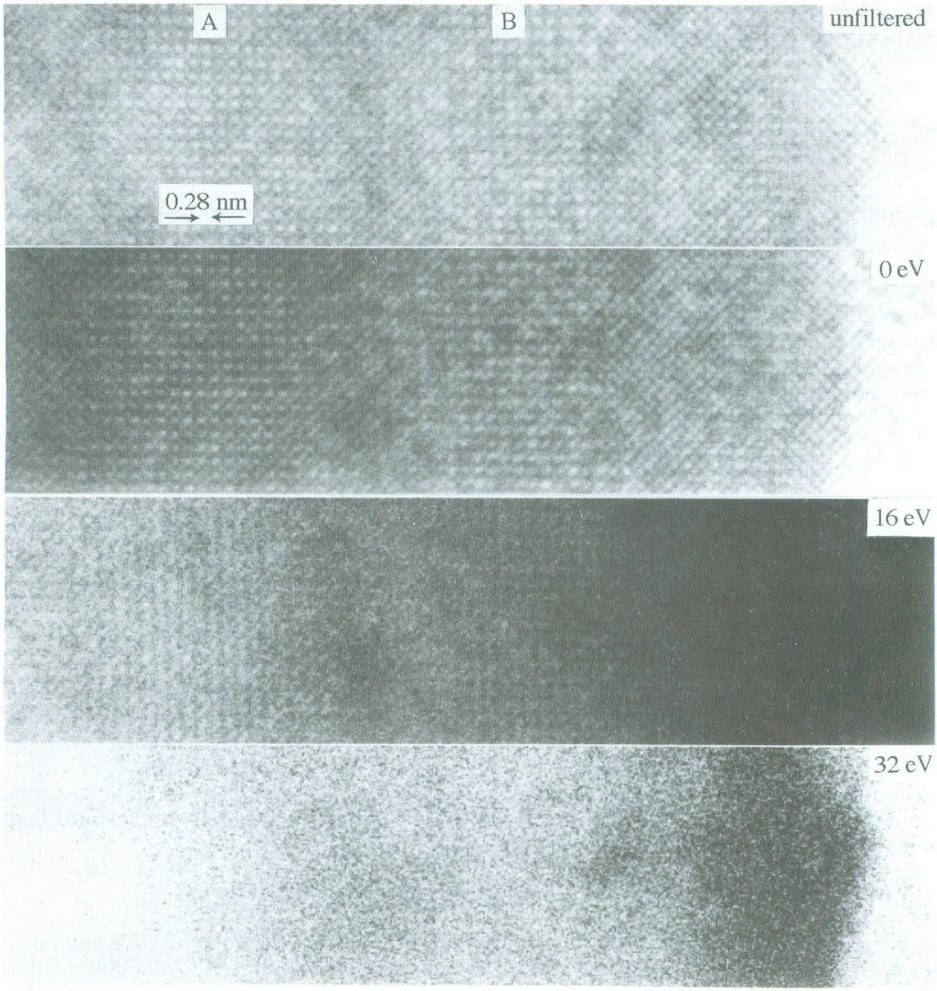

Fig. 1: Comparison of unfiltered, filtered zero loss, first and second plasmon loss images for a cleaved GaAs crystal; display contrast: black=0.3, white=1 (on a scale where the incident intensity is 1). The intensity is enhanced by a factor of 10 for the first and 50 for the second plasmon loss. The loss energies are indicated on the right.

intensity	unfiltered	filtered 0 eV loss	1st plasmon 16 eV loss	2nd plasmon 32 eV loss
mean at A	0.636	0.461	0.058	0.015
mean at B	0.651	0.520	0.044	0.013
rms at A	0.048	0.042	0.004	0.001
rms at B	0.050	0.044	0.004	0.001

Table 1: Intensity values from the regions of maximum (200) fringe visibility (A, B in Fig. 1). The rms values were obtained after low and high pass filtering (see text). All values have error bars of $<\pm$ 0.001.

Fig. 1 shows the unfiltered, zero loss filtered, first and second plasmon loss images obtained for an underfocus of around –75 nm. The right side of the images shows some of the amorphous surface layer, and the crystal thickness increases with the distance from the crystal edge towards the left. The most interesting feature of these images is the remarkable similarity of the plasmon loss image to the zero loss image. Not only does it show lattice fringes, demonstrating that inelastically scattered electrons do carry phase contrast, but the thicknesses at which the (200) fringes of 0.28 nm spacing dominate are the same. This leads to the conclusion that the plasmon loss image exhibits contrast characteristic of the full thickness of the crystal. Given that many of the electrons contributing to this plasmon loss image will have travelled through a significant part of the crystal before being scattered by the plasmon, contrast must be preserved on plasmon scattering. If the plasmon scattered electrons do add to the contrast coherently then they will do so, with a progressively varying phase, only for a distance of ≈ 20 nm giving a phase change of π on the basis of the 16 eV energy loss. Contributions for greater thicknesses should add incoherently.

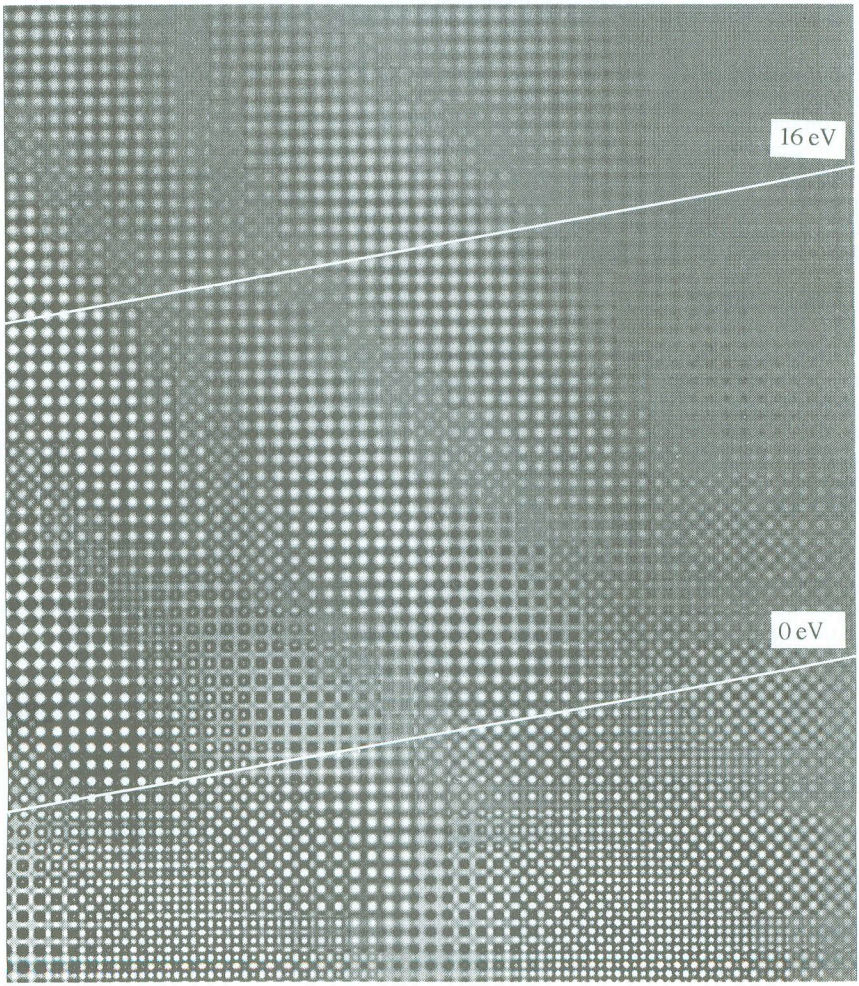

Fig. 2 : Patchwork of image simulations for a GaAs crystal with the imaging parameters given in the text. The thickness increases from 2nm on the right to 50 nm on the left and the defocus from –120 nm at the bottom to +20 nm at the top. The white lines indicate the approximate images expected for zero loss and plasmon loss image.

Values of the mean intensity and the fringe amplitude (defined as the rms value after low pass noise filtering by convolution with a Gaussian mask with one pixel standard deviation and high pass filtering to reduce dark contamination spots) as derived from Fig. 1 are given in Table 1. The rms values of the intensities indicate that the (200) fringe amplitude in the filtered image is about 88%, and in the plasmon image about 9%, of that for the unfiltered image, independent of the thickness. The only way to explain the increased (200) fringe amplitude in the unfiltered image if the zero loss and plasmon loss image *intensities* are to be added is if the bright fringes in the plasmon image coincide with the bright fringes in the zero loss image. If the fringes in the plasmon loss image are reversed with respect to the zero loss image then we expect the unfiltered image to have less contrast than the filtered one *if the unfiltered image is formed incoherently*. For a GaAs plasmon of 16 eV energy we calculate a focus change of 72 nm overfocus and should thus be able to determine the expected relative position of the bright (200) fringes in the filtered zero loss and plasmon loss image from the image simulations shown in Fig. 2. The two white lines indicate the expected thickness profile for a GaAs wedge for the zero loss and the plasmon loss image (at 72 nm overfocus from the zero loss). The focus at the crystal edge is $\approx$–75 nm and the additional underfocus at increased specimen thickness caused by the exit surface of the cleaved crystal being at 45° to the electron beam direction leads to the inclination of the white lines in Fig. 2. Although the observed zero loss and the plasmon loss image contrast are approximately reproduced, they are π out of phase for the thicknesses with strong (200) fringe contrast in each image. The relative phase depends sensitively on the precise distance between the bands of strong (200) contrast running approximately along the picture diagonal but if, as we believe, the vertical separation of the lines is exact then the simulations, coupled with the contrast data, suggest coherent amplitude additions might be important.

3. CONCLUSION

From our measurements of the amplitudes of the lattice fringes in the unfiltered, filtered zero loss and plasmon loss images (which are consistent over three sets of images obtained with similar defoci) we can say that because the unfiltered lattice fringe amplitude is greater than the filtered amplitude, the plasmon image must be adding (whether coherently or incoherently) in phase with the filtered image. Our simulations suggest that if the addition were purely incoherent, at some thicknesses the plasmon image should add in phase and at others out of phase. However, the simulations, whilst reproducing the trend of pattern changes with thickness, yield a phase difference of π for the absolute specimen thickness at which the strong (200) lattice fringes occur in the experimental images. For these thicknesses, given incoherent scattering, the plasmon image should then reduce the lattice fringe amplitude of the unfiltered image. There are uncertainties in the parameters used for the simulations but we have confidence that the chromatic aberration constant is not in error by the 30% or so which would be required to explain an incoherent plasmon contribution *increasing* the contrast of an unfiltered image. Furthermore, the period of the strong (200) fringe contrast in the plasmon loss image is the same as in the filtered zero loss image and this is difficult to explain for solely incoherent addition.

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