

## Effects of Fresnel Fringes on TEM Images of Interfaces in X-Ray Multilayers

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Cross-sectional High-Resolution Transmission Electron Microscopy (HRTEM) has been widely used to examine the structure and morphology at multilayer interfaces at an atomic scale. Assessment of the interfacial structures quantitatively from these TEM images however is difficult due to the Fresnel fringe effects, which produce different apparent structures with defocus values in the images. These fringes result from the electrons experiencing an abrupt change in the scattering potential parallel to the electron beam path. Imaging of multilayers in cross-section, in which the electrons travel parallel to the interfaces between the two layer materials, always results in such fringes. X-ray multilayers having alternating layers of very different atomic numbers or scattering powers are more prone to these fringes than the heterostructures having less contrast layers. The visibility of the fringes increases with increasing defocus away from minimum contrast, while optimum resolution in bright-field imaging is obtained at the Scherzer defocus, which is about 100 nm from the minimum contrast for most high resolution microscopes. Fresnel fringes are thus present when imaging at optimum defocus. The effects of these fringes have been commonly overlooked in efforts of making quantitative interpretation of interfacial profiles. They however have also been employed to characterize the structures and compositional roughness at interfaces.<sup>1-3</sup> In this report, we present the observations of the Fresnel fringes in nanometer period Mo/Si, W/C, and WC/C multilayers in through-focus-series TEM images. Calculation of the Fresnel fringes of a Mo/Si multilayer using charge density approximation is used to illustrate the characteristics of the fringes from different interfacial structures.

Fresnel fringes are observed in many TEM through-focus-series images of W/C, WC/C, Ru/C, and Mo/Si, multilayers.<sup>4</sup> The visibility of these fringes depends on the thickness of the specimen, and on the defocus value. The contrast of the fringes is higher with increasing defocus

both positive and negative values from the minimum contrast condition. The fringes in the W/C and Mo/Si appear symmetrical on the two interfaces of the W-rich and Mo-rich layers signifying similar structures at interfaces of the high-Z on low-Z and of the low-Z on high-Z materials. The fringes in the WC/C multilayers however show different characteristics at the two interfaces of the WC-rich layers, which likely indicates different shapes of the potentials and hence of the chemistry or the composition at the two interfaces. Micro-densitometry traces of the multilayers across the layers and interfaces of through-focus-series images show similar behaviors are those observed from the images. These traces can be used for quantitative comparison with calculation to determine the interfacial profiles.

Simulated Fresnel fringes of a 9 nm period Mo/Si multilayer is generated using charge density approximation method. The calculation produces line tracings of the a multilayer period, similar to the micro-densitometry traces of the experimental TEM images. The potentials of the Mo and Si layer are assumed to be uniform, and the transition layers have a finite linear slope at the interfaces. Comparison of structures of different potential difference ( $\Delta P$ ), transition layer thickness ( $d_{tr}$ ) and slope ( $m_{tr}$ ), and their combinations, are used to study the characteristics of the fringes. Similar to the experimental results, the fringes have higher contrast at higher defocus values, and change in sign from positive to negative defocus. The contrast or intensity is higher for larger potential difference between the layers. Changes in  $\Delta P$  with constant transition layer thickness, and hence change in the slope or abruptness in change of composition does not result in significant difference in the spacing of the fringes. The profile however varies for different  $\Delta P$  with the same slope from positive to negative defocus. For the same potential difference, the contrast increases with higher slope and shorter  $d_{tr}$ , while the spacing increases with lower  $m_{tr}$  and longer  $d_{tr}$ . Comparison of the fringe intensities and spacings of two different transition layer thicknesses with the same slope and hence of two different  $\Delta P$ , reveals that the difference in the intensity is significantly higher for the shorter  $d_{tr}$  and higher  $\Delta P$ , while the spacing is much wider in the longer  $d_{tr}$  and lower  $\Delta P$ . This observation indicates that the potential difference and the abruptness of the interfacial composition change are a strong function of the fringe contrast, while the fringes spacing depends more strongly on the thickness of the transition or interfacial layer.

This work was supported by the Director, Office of Energy Research, Office of Basic Energy Sciences, Material Sciences Division, of the U.S. Department of Energy, under contract No. DE-AC03-76SF00098 and by the Air Force Office of Scientific Research, of the U.S. Department of Defense under Contract No. SF49620-87-K-0001.

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