X-Rays and Extreme Ultraviolet Radiation: Principles and Applications

Chapter 11. X-ray & EUV Imaging Homework Problems

11.1 Why is the coherent cutoff, σ = 0, so sharp in Figure 11.3? Why are the partial coherence curves gradual and why do they reach to higher spatial frequencies, albeit it lower modulation? What are the coordinates and what is the significance of the blue dot?

11.2 Why is there overshoot for σ = 0.2 in Figure 11.4? How is that reduced for other values, such as σ = 0.9? Why is this important? Are there examples where a value closer to 0.2 might be useful?

11.3 What is the advantage of tomography? Why does it provide clearer views of thick, complex structures? What price does one pay for this extra information and clarity?

11.4 Why is fluorescence imaging so sensitive and efficient, as in nanoprobes and microprobes? What are some scientific and technical examples where this technique provides powerful insights?

11.5 (a) What are the advantages of full field zone plate microscopy? (b) What scientific issues are being addressed with zone plate based transmission x-ray microscopy (nanoscopy)? (c) What limits spatial resolution in nanoscale x-ray zone plate tomography? (d) How might this be overcome? Consult the websites at BESSY II, ALS, and ALBA regarding scientific pursuits and recent achievements.

11.6 (a) What are the advantages of zone plate based scanning transmission x-ray microscopy (STXM)? (b) What are some of the important requirements for achieving high spatial resolution? (c) What is the down side? (d) What are some important scientific applications that benefit from nanoscale STXM? (f) How are STXM and ptychography related? Consult websites at the ALS and the Canadian Light Source (CLS).

11.7 (a) What are the advantages of x-ray coherent diffraction imaging (CDI)? (b) Why has CDI only recently become a popular technique? What are examples of scientific pursuits using CDI? What is a limitation of CDI? Why is CDI pursued in some cases with x-ray free electron lasers (FELs)?

11.8 (a) Describe ptychography? (b) How does it differ from STXM and CDI? (c) What is its major advantage? (d) What is a significant disadvantage? (e) How might this be overcome with new facility developments? (f) What are some current scientific pursuits being pursued with ptychography? (g) Why is it less attractive for use at x-ray FELs?

11.9 Compare x-ray, visible light and electron microscopies.

11.10 Surface height variations of mirror substrates can affect EUVL image formation, through achievable resolution, flare, and throughput. If surface height variations are plotted as a spectrum of spatial frequencies, which portions of the spectrum are associated with spatial resolution, which with flare (scattering within the image), and which with throughput (loss of radiation due to scattering out of the image field. (a) Explain each separately. (b) Draw a diagram of a surface showing surface height variations of various lateral scale lengths (spatial frequencies) and their effect on incident radiation. (c) Sketch a power spectral density curve which has an ordinate the energy density of surface height variations $(\Delta s)^2$ per unit area in *k*-space (k^2), presented in units of $(\text{nm})^4$, versus an abscissa of surface height spatial frequencies (k) in units of $(\text{nm})^{-1}$. In your sketch give numerical estimates of the spatial frequency ranges relevant to figure error, flare, and throughput, for a typical EUV optic. Consult Figure 11.10HW below.

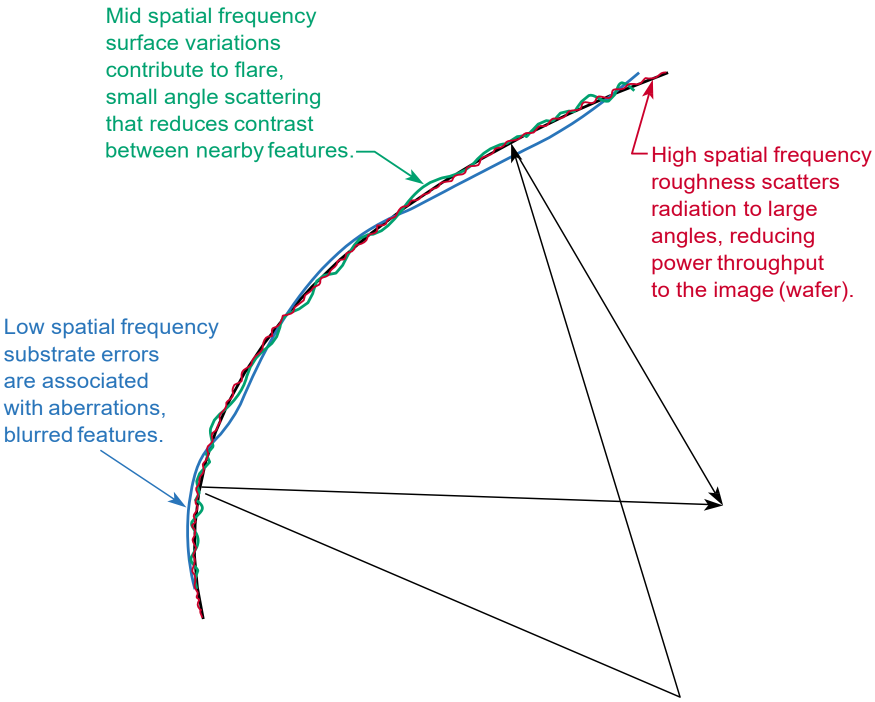

Figure 11.10HW A curved surface showing surface height variations characterized as low spatial frequency "figure errors", mid-spatial frequencies associated with scattering which contributes to "flare", and high spatial frequencies which scatter radiation outside the image plane.

11.11 To minimize wavefront errors in EUVL imaging optics it is important that multilayer coatings not add significantly to the surface height variations, Δs, of the optical substrate. Indeed, to some degree high spatial frequency surface height variations of the substrate can be smoothed by use of a proper multilayer coating technique. For low spatial frequency variations of the multilayer *d-* spacing, measured from a specified ideal which accounts for varying angles of incidence, a successful approach is to limit variation, Δh, of the multilayer coating thickness (h = Nd) to an rms value equal to half that of the substrate, Δs. For an imaging system consisting of N_S optical surfaces, assuming random surface height errors which then add in quadrature, show that a total wavefront error of λ/25 requires an rms coating thickness variation of

$$\Delta h = \frac{1}{2\sqrt{5}\sqrt{N_S}} \cdot \frac{\lambda}{25}$$

corresponding to a normalized d-space variation (Δh= N Δd) of

$$\frac{\Delta d}{d} = \frac{1}{25\sqrt{5}N\sqrt{N_s}}$$

where, N is the number of multilayer pairs, N_S is the number of mirrors in the imaging system, and λ is the EUV wavelength. What is the allowable d-space variation, Δd/d, for a system of 6 mirrors and 40 layer pairs? Consult Figure 11.11HW below.

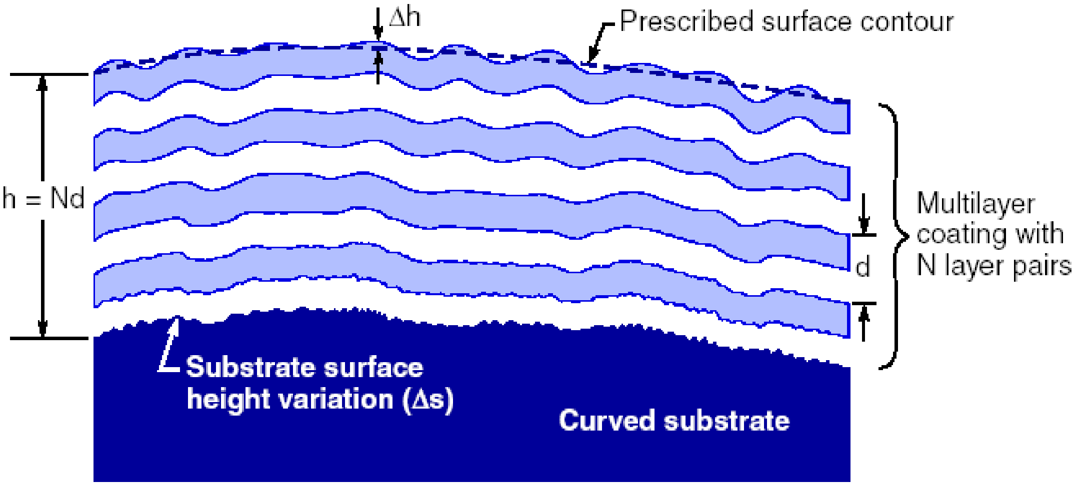

Figure 11.11HW Multilayer uniformity, or smoothness, is critical for maintaining wavefront quality in EUV projection (imaging optics). Wavefront errors can be introduced in part by the optical substrate, and by the multilayer coating. In some cases high spatial frequency surface roughness can be smoothed by the multilayer coating. A goal in the coating process is to have the added wavefront error due to the coating be smaller than that due to the substrate. In the figure above h is the coating thickness, *d* is the multilayer period, N is the number of periods, and Δh is the rms surface height variation, measured from

11.12 Masks for EUV lithography consist of a thick, low thermal expansion glass substrate, a multilayer coating matched to that of the optical system, and an absorber pattern which defines the circuit features to be replicated. Between the high reflectivity multilayer coating and the absorber pattern there are thin films for various practical reasons: a thin capping layer to stabilize oxidation of the multilayer during absorber patterning and a buffer layer for use during potential mask patterning and repair. In this model, the capping layer also acts as an etch stop. Leading candidate materials for the absorber material are Cr and TaN. For each of these four candidate absorber materials calculate the thickness required for 99% absorption at 13.5 nm wavelength, assuming a simple normal incidence, double pass (once in, once out) transmission model, neglecting diffractive effects. See Figure 11.12HW below. Use the website http://www.cxro.lbl.gov/optical_constants to obtain the required values of the complex refractive index. Compare your results with those in the literature, for example, with S. P. Vernon, S. Hector *et al.*, "Masks for extreme ultraviolet lithography", BACUS Symposium on Photomask Technology and Management, *SPIE* **3546**, 184(1998); and with P. Mangat *et al.*, "EUV Mask Fabrication with Cr Absorber"

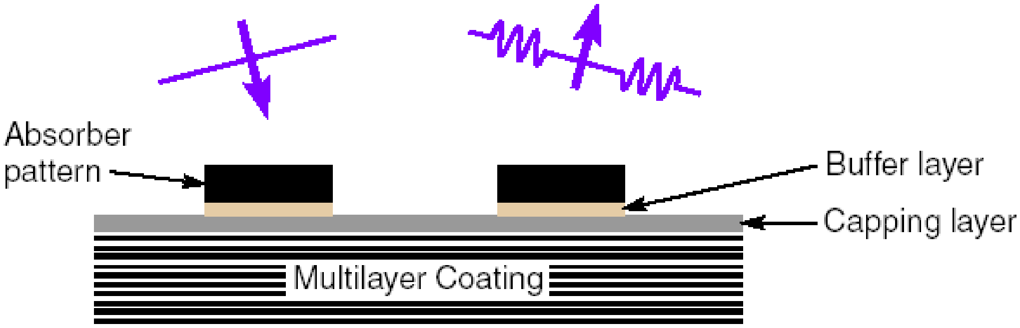

Figure 11.12HW A mask for EUV lithography consisting of a highly absorbent patterning layer, a buffer layer to enable mask patterning and repair, a capping layer to control oxidation on the multilayer, and the multilayer mirror itself.

11.13 Why is it anticipated that “at-wavelength” metrologies, that is at 13.5 nm, will be required for mask defect inspections?