Soft X-Rays and Extreme Ultraviolet Radiation: Principles and Applications

Chapter 10 Homework Problems

10.1 The Semiconductor Industry Association's (SIA) roadmap is a timeline for the introduction of new manufacturing capabilities relevant to electronic devices. Discreet entry points, referred to as "nodes", describe the year in which a new technology is to achieve volume production. For lithography the nodes are defined in terms of the half-period, in nanometers (nm), which optical reduction cameras ("steppers") are expected to be capable of printing. For example, in 2002, it is expected that a stepper will be able to project to the wafer (actually to be the resist on the wafer) a periodic pattern of dense 130 nm lines and 130 nm spaces. This capability will certainly include optimized partially coherent illumination (σ), and may also include other optical enhancements such as phase masks and shaped illumination. The ability to print narrower isolated lines, for use in defining microprocessor gates, is made possible by materials processing techniques involving carefully controlled recording and pattern transfer thresholds. For example, the 130 nm node calls for 90 nm isolated lines in the latest roadmap. The roadmap itself is a constantly evolving document, now known as the International Technology Roadmap for Semiconductors (ITRS), and can be followed on the Internet at the websites http://public.itrs.net/Files/2001ITRS/Home.htm and http://www.sematech.org. For this assignment go to the websites and update the roadmap given in the text as Table 10.1, page 403. Note in particular changes in the nodes for years 2002, 2005, 2008, 2011 and 2014. Be aware that this is an ever-evolving document, with yearly reconsideration. For example, there is much discussion with regard to "pulling in the schedule", that is moving from a 3-year schedule of new nodes, to a 2-year cycle. For the latest version of the ITRS roadmap, as found at the above websites, what are the updated values for isolated line widths for microprocessor gate widths ("MPU/physical gate lengths"), what are the anticipated chip sizes for high volume microprocessors ("logic devices"), and how many transistors are expected for each of these high volume ("cost performance") chips? What are the anticipated "across-chip" clock speeds for all nodes?

10.2 Deep ultraviolet (DUV) steppers currently operate at wavelengths of 248 nm, are evolving to 193 nm for leading edge technology, and are expected to advance to 157 nm at a future manufacturing node. For a DUV stepper operating at 193 nm, with a 0.75 NA, what k_1 value is required to print 90 nm isolated lines in resist at the wafer? For $k_2 = 0.5$ (as defined in the text), what is the depth of focus ($\pm$)? How does your required value of k_1 (above) relate qualitatively to the degree of partial coherence, σ? How does this value of k_1 relate to the cutoff period for coherent imaging ($\sigma = 0$, cutoff period = $\lambda / 2NA$) and for incoherent imaging ($\sigma = \infty$, cutoff period = $\lambda / 4NA$)? How is it possible to fabricate electronic devices with gate widths of 90 nm or less, in this case where the optical transfer is limited to a period of 260 nm (2×130 nm)? For further insights to these issues consult the literature, for example the book by H.J. Levinson *Principles of Lithography* (SPIE, Bellingham, WA, 2001), chapters 8 and 10.

10.3 Specifications for a pre-production "beta-tool" are now being set. Consider a "Beta-tool" which includes nine Mo/Si multilayer mirrors. The nine includes two for the condenser/mask illumination system, one for the mask, and six for the imaging (mask to wafer) optics. Calculate the reflectivity at an incident angle of 85° of a single Mo/Si mirror as a function of wavelength, from 12.0 to 15.0 nm, assuming 40 layer pairs, a d-spacing of 6.89 nm, an asymmetry parameter $\Gamma = 0.44$, and an effective interface parameter, $\sigma = 0.5$ nm rms. Use the multilayer reflectivity code at the website http://www-cxro.lbl.gov/ optical_constants/multi2.html. What is the peak reflectivity of a single mirror, at what wavelength, and what is the relative spectral bandpass

(FWHM / wavelength of peak reflectivity)? Assuming the nine mirrors to be perfectly matched (same d-spacing, etc.), what is the combined peak reflectivity, R^N , and relative spectral bandpass for nine mirrors? The optical system also includes two additional glancing incidence condenser optics, each of 85% reflectivity, and a UV/visible suppressing spectral purity filter having a 50% transmission at EUV wavelengths of interest. What will be the net throughput for the full optical system (nine multilayer mirrors, two glancing incidence mirrors, and one transmission filter), and what will be the relative spectral bandpass?

10.4 Surface height variations of mirror substrates can affect 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 $(nm)^4$, versus an abscissa of surface height spatial frequencies (k) in units of $(nm)^{-1}$. In your sketch give numerical estimates of the spatial frequency ranges relevant to figure error, flare, and throughput, for a typical EUV optic. Consult the diagram below.

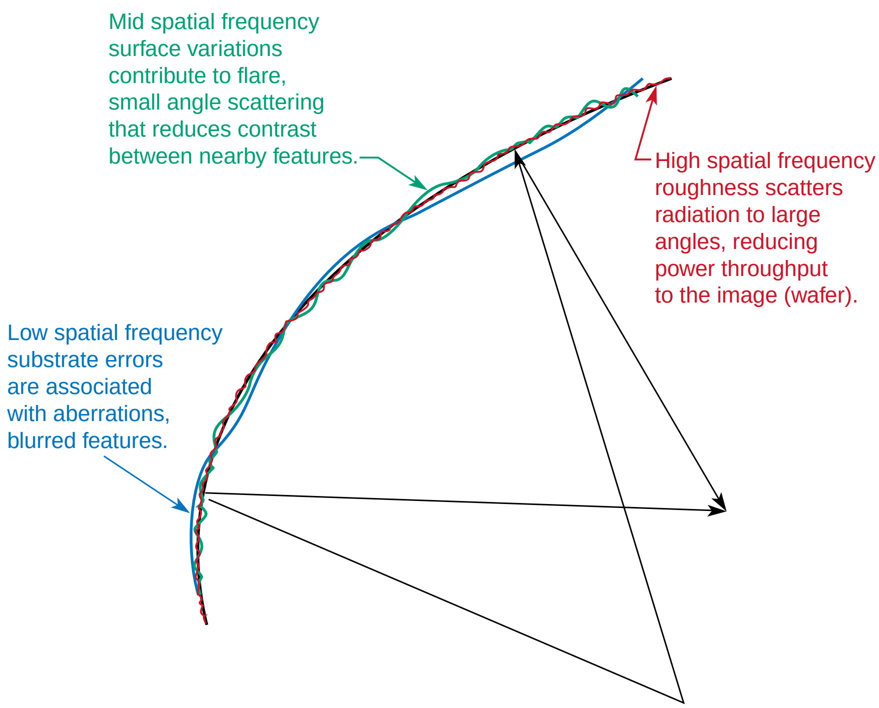

Figure 10.4 A curved surface showing surface height variations characterized as low spatial frequency "figure errors", mid-spatial frequencies associated with scattering which contributes to "flare", and high spatial frequencies which scatter radiation outside the image plane.

10.5 To minimize wavefront errors in EUV 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 ($\Delta h = N\,\Delta d$) of

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

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, $\Delta d/d$, for a system of 4 mirrors and 40 layer pairs? What is $\Delta d/d$ for a 6-mirror system with the same number of multilayer pairs?

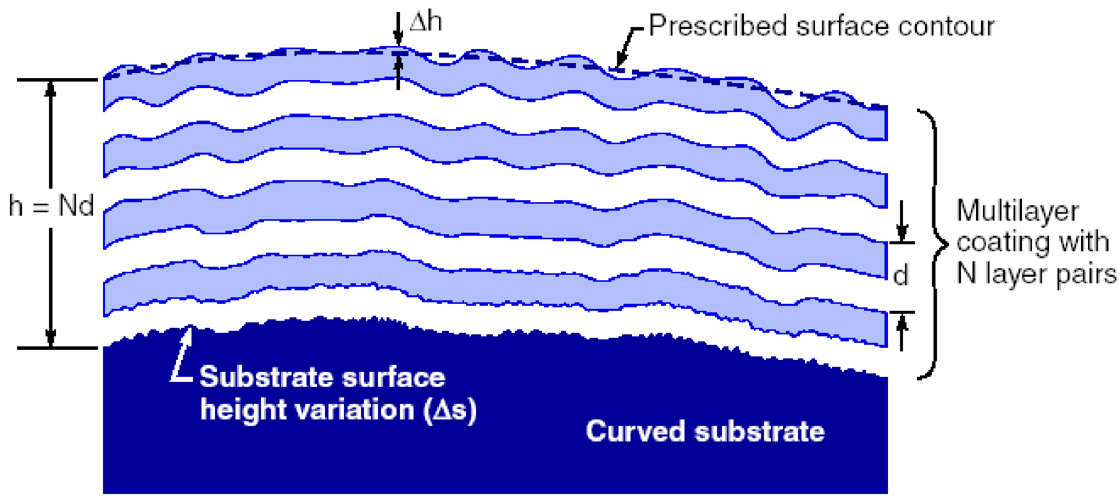

Figure 10.5 Multilayer uniformity, or smoothness, is critical for maintaining wavefront quality in EUV projection (imaging optics). Wavefront errors can be introduced in part by the optical substrate, and by the multilayer coating. In some cases high spatial frequency surface roughness can be smoothed 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 Δ*h* is the rms surface height variation, measured from an ideal surface (dashed line) specified for the particular optic.

10.6 For the 45 nm and 32 nm nodes, 25 nm and 18 nm isolated lines are expected to be printed, respectively. In order to print these isolated lines, what k_1 values are required for a 0.25 NA at a wavelength of 13.4 nm? What are the corresponding values for DOF (±) at $k_2 = 0.5$? For more information on the International Technology Roadmap for Semiconductors (ITRS), go to http://public.itrs.net/Files/2001ITRS/Home.htm.

10.7 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 13.4 nm wavelength, assuming a simple normal incidence, double pass (once in, once out) transmission model, neglecting diffractive effects. 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".

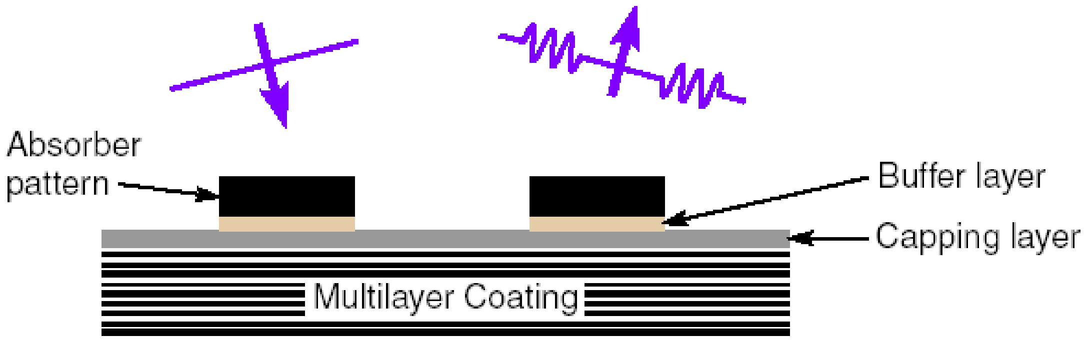

Figure 10.7 A mask for EUV lithography consisting of a highly absorbent patterning layer, a buffer layer to enable mask patterning and repair, a capping layer to control oxidation on the multilayer, and the multilayer mirror itself.

10.8 For a laser plasma source of 1% conversion efficiency (2π sterad, spectrally in-band), what time-averaged laser power in kW is required to drive a throughput of 80 wafers/hour, assuming a resist sensitivity of 5 mJ/cm^2 at 13.4 nm wavelength, nine Mo/Si multilayer mirrors (6+2+1) at 70% reflectivity (see homework problem #10.3), and a collection solid angle equal to 60% of a hemisphere ($0.6 \times 2\pi$). The optical train includes two additional glancing incidence condenser optics at 85% reflectivity each, and a visible/UV suppressing spectral purity filter that transmits 50% at 13.4 nm. Each 300 mm diameter wafer will contain 116 fields, each 22 mm wide by 26 mm (scan) length. Include a contingency factor of 2 that accounts for gas absorption and geometrical alignment factors in the optical system. Include an additional factor of 2 for wafer scanning factors such as step, settle, acceleration, and wafer loading time. What is the EUV in-band power reaching the first optic, reaching the mask, and reaching the wafer? Although the contingency factor is actually distributed throughout the entire optical system, here, for convenience, it is arbitrarily included in the power reaching the mask expression. Also, the factor of 2 that accounts for wafer handling does not effect the in-band power calculations. For a comparison with the literature, consult the papers by J. Benschop *et al.*, "EUCLIDES: First Phase Completed", SPIE 3997, 34 (2000), and by V. Banine and R Moors, "Extreme Ultraviolet Sources for Lithography Applications", SPIE 4343, 203 (2001).