

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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TAKE-HOME FINAL ASSIGNMENT, 2006

Handed out Thursday, April 27, 2006

Due no later than
5 PM on May 18, 2006

This is a take-home assignment. You may use any text, notes, etc. You may speak to Profs. Smith, Berggren, Barbastathis, or the TA's, either in class or outside of class, in order to clarify any of the problems. You may **not** consult with others on the solution of problems.

In the solutions to any of the problems, you may make simplifying assumptions, such as square pixels, square beams, etc. Assume that electrons, photons or gas molecules arrive on a surface independently and thus obey Poisson statistics (same assumption as we made in class and homework). Please be brief! Note that some superfluous information may be provided in some of the problems.

- (1) Please answer true/false and give a brief explanation for the following questions:
- A) True or false, chemically-amplified resists (CARs) are useful because they are very resistant to airborne contamination.
 - B) True or false, in a scanning-electron-beam system, such as an SEM, a field-emission source can be used to produce a finer focal spot than can be achieved with a thermionic source, assuming the current is the same in both cases.
 - C) True or false, the only current application of scanning-electron-beam lithography in industry is research and development.
 - D) True or false, a good electron beam lens system can have a numerical aperture (NA) up to 0.6.
 - E) True or false, Polymethyl methacrylate (PMMA) can be used as a resist in deep-UV, electron-beam, and x-ray lithography.

- F) True or false, the ability of a Linnik interferometer to resolve small steps on a surface is given by the optical system's depth of focus, λ/NA^2 .
- G) True or false, a typical atomic-force microscope (AFM) cannot resolve individual atoms.
- H) True or false, metal contaminants are usually removed from a sample by using ozone that oxidizes the metal.
- I) True or false, in optical-projection lithography (OPL), incoherent illumination can yield higher resolution than coherent illumination can, but the contrast is reduced for lower spatial frequencies.
- J) True or false, some optical microscopy methods can be used to resolve features much smaller than the wavelength of light
- K) True or false, contact lithography cannot yield as high a resolution as optical projection lithography (OPL) because there is additional demagnification in OPL.
- L) True or false, in optical and electron-beam lithography one can achieve alignment much better than the system resolution.

(2) Read the article "Robust Shadow-Mask Evaporation via Lithographically-Controlled Undercut," by B. Cord, C. Dames, K. K. Berggren, and J. Aumentado. *Microsystems Technology Research Report*, Massachusetts Institute of Technology (September 2006).

- A) Using the double-Gaussian point-spread function data in the paper, plot the cross-sectional, normalized dose profiles at the base of the PMMA layer and at the substrate for a grating of 250 nm period and 50 nm linewidth exposed in a PMGI/PMMA bilayer like the one in the paper. Assume that the length of the lines in the grating is much greater than their width and that the total width of the grating is 25 μm .
- B) Assuming perfect mass transfer during the development process and a nominal dose of 500 $\mu\text{C}/\text{cm}^2$, estimate how long it will take for lateral PMGI development to completely undercut the PMMA lines in the center of the grating in (A); i.e. approximately what development time will cause the entire grating structure to begin to

collapse?

- C) Repeat (B), this time taking into account the diffusion-limited nature of the development process.
 - D) Will increasing the grating period to 500 nm and the linewidth to 100 nm cause the lateral development rate to increase or decrease? Explain your answer.
 - E) Show that, in the structure described in (A), the proximity effect is negligible compared to mass transfer in determining the rate of undercut development.
- (3) Read the article: Giapis, Konstantinos, Geoffrey Scheller, Richard Gottscho, William Hobson, and Yong Lee. Microscopic and macroscopic uniformity control in plasma etching. *Appl. Phys. Letter* 57, no. 983 (1990).
- A) What is meant by macroscopic nonuniformity?
 - B) What is meant by microscopic nonuniformity?
 - C) What is the mean-free path of a Cl_2 gas molecule at 7 m torr assuming the ideal gas law?

Suppose we want to etch a lithographically patterned Si substrate using Cl_2 gas in a reactive-ion etching system operating at 7 m torr, 100 watts input power, a peak-to-peak voltage of 75 V, and a bias voltage of 25V.

The “dark space” between the main body of the plasma and the electrode on which the substrates are to be etched is about 7 mm thick. Assume that the molecules and ions within the main body of the plasma are at room temperature, and that ions acquire the full 25 eV as they are accelerated across the dark space.

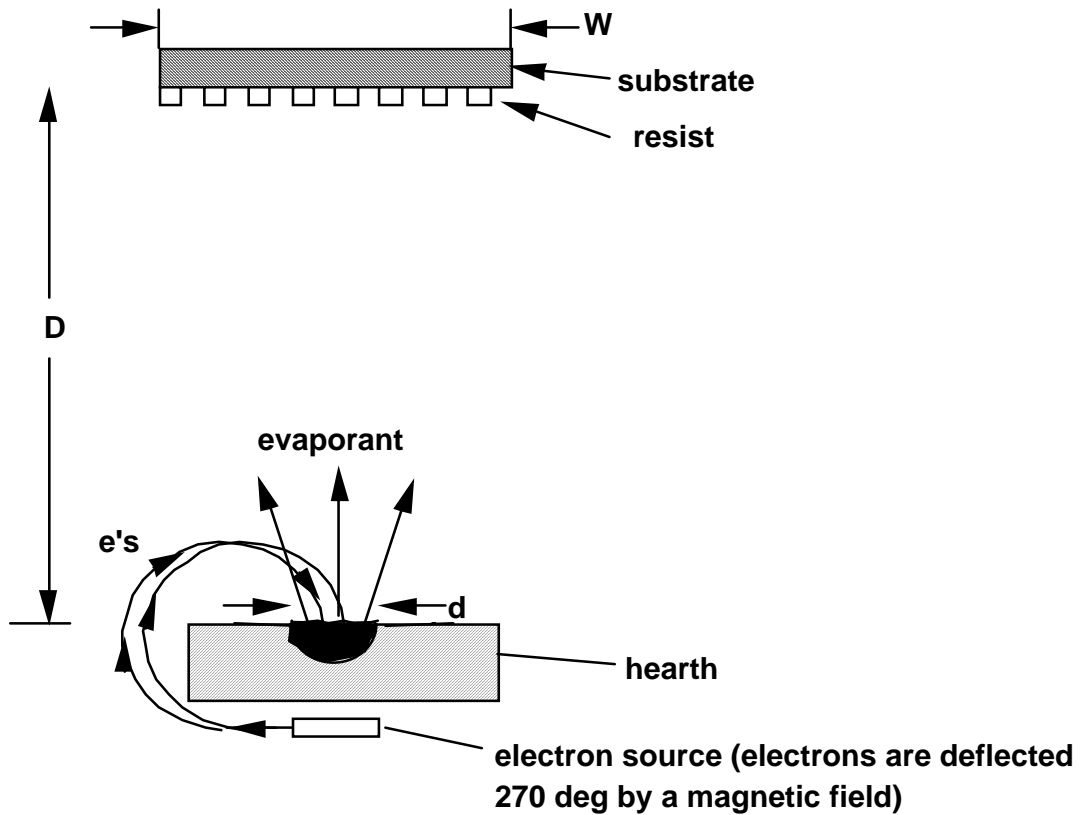
- D) Is an ion likely to experience a collision with a molecule in crossing the dark space?
- E) Is an ion likely to experience multiple collisions in crossing the dark space?
- F) Why do you think there is a dark space (very little emission of light) between the main body of the plasma and the powered electrode?

- G) Calculate the velocity of a 25 eV Cl ion and compare this to the molecule's thermal velocity. What is the ratio of the two velocities?
- H) From the ratio of velocities can you **estimate** the deviation from 90 deg of the angle of incidence of the ions on the substrate? Do you believe this is connected with the highly directional etching obtained in RIE when the isotropic component of etching is absent or very small?
- I) Calculate the arrival rate in number/cm² sec of neutral Cl₂ molecules at the surface of the substrate.
- J) Assume that the substrate is cooled so that no spontaneous or isotropic etching occurs, that each arriving Cl₂ molecule sticks and dissociates, and that each bombarding ion gives rise to the removal of 2 Si atom, and that there is always sufficient Cl adsorbed on the surface, i.e., that the Cl₂ arrival rate does not limit the etching rate. If the etch rate is 10 nm/s, what is the ion current density.
- K) Is the assumption that the arrival of Cl₂ molecules on the surface is not rate limiting valid?
- (4) Assume a bond in a resist takes 5 eV to break, and that the absorbed photon energy in its entirety goes into bond breaking. Assume that in every 1 nm³ of material there are 10 bonds that must be broken in order for a material to develop. Assume that the vertical absorption profile of the incident radiation in the resist is uniform (i.e. no z-dependence to the absorption),
- A) Calculate the sensitivity of the resist in units of eV/nm³
- B) Calculate the number of quanta per nm³ required to achieve this sensitivity as a function of wavelength for photons ranging from 4 nm to 400 nm. Make a chart of this function
- C) Assume that 100 quanta/nm² are required for relatively noise-free exposures. Make a chart of resist thickness vs. photon wavelength and indicate the region on this graph where shot noise is low enough to permit ~ 1nm line-edge roughness in the film.
- D) Typical proposals for EUV lithography suggest that a resist with a sensitivity of 5 mJ/cm² will be used. Suppose a 50-nm-thick film

will be used. The EUV wavelength is 13.4 nm. First convert the resist sensitivity to eV/nm^2 , then $\text{photons}/\text{nm}^2$, and then eV/nm^3 and $\text{photons}/\text{nm}^3$.

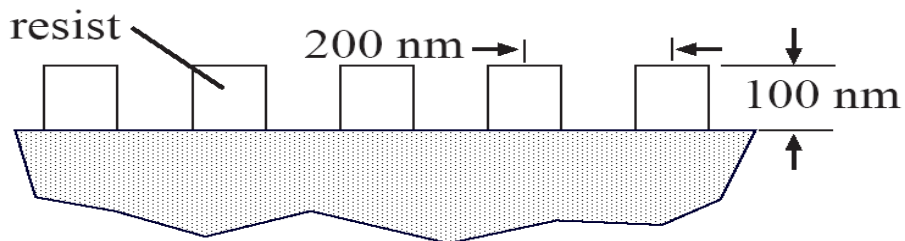
- E) What resist sensitivity (in mJ/cm^2) is required to achieve 1 nm line-edge roughness based on shot noise? Typically EUV systems are limited in the source power that they can provide. What would be the consequences of this result on the manufacturing throughput of EUV systems (relative to the planned $5 \text{ mJ}/\text{cm}^2$ sensitivity).
- F) If a resist sensitivity of $5 \text{ mJ}/\text{cm}^2$ is to be achieved, what is the minimum pixel size that can be used and still maintain acceptable shot-noise performance?
- (5) This is a problem dealing with the liftoff process. As a preliminary to solving this problem, you should look at the article, "Fabrication of large area subwavelength antireflection structures on Si using trilayer resist nanoimprint lithography and liftoff" by Z. Yu, et al, J. Vac. Sci. Technol. B, vol 21, pp2874-2877 (2003). In particular, look at Figure 2.

A refractory material such as Ti is evaporated onto a relief structure in resist, as depicted schematically below:

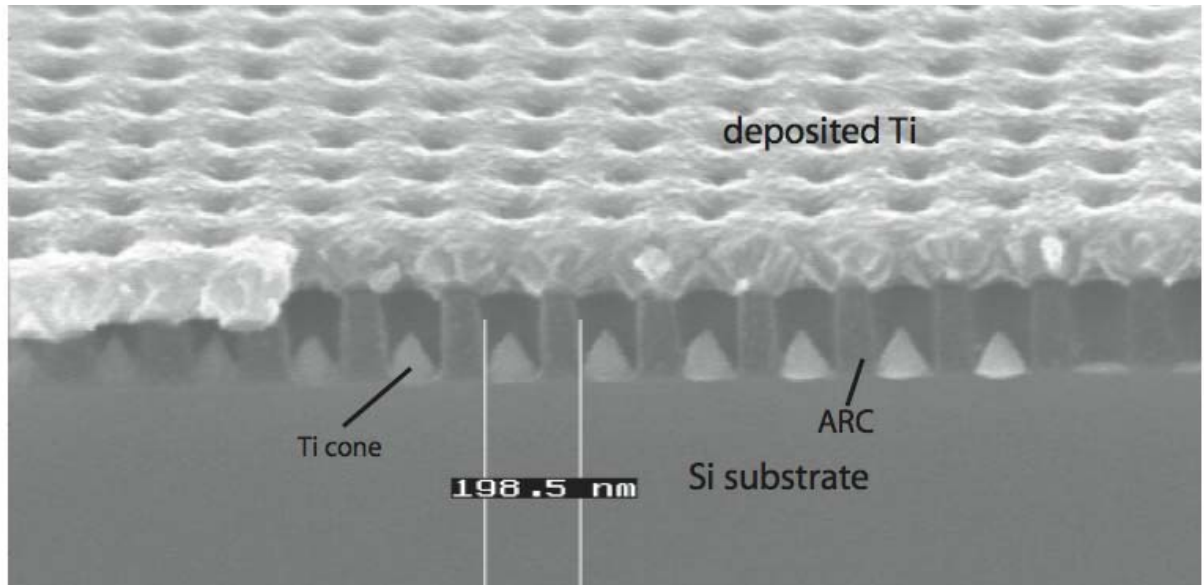


The source diameter, d , is 1.0 mm, the source-to-substrate distance, D , is 500 mm, and the pattern area on the substrate has a diameter, W , of 2.0 cm. A line-of-sight from the center of the source to the center of the substrate is perpendicular to the substrate.

The resist profile is as sketched:



- A) Assuming atoms stick where they land (i.e., there is no surface migration) calculate, for regions in the center of the substrate, the thickness of material on the resist sidewalls after deposition of 100 nm on the substrate.
- B) Calculate the thickness of sidewall coating for regions at the edge of the substrate.
- C) Calculate the sidewall coating if the deposited material does exhibit surface migration such that the opening at the top of the resist is gradually pinched off as the deposited material accumulates. This phenomenon is depicted in the following graphic. Hint: make simplifying assumptions about how the material builds up and pinches off the opening.



- (6) Read the article, "Immersion zone-plate-array lithography," by D. Chao, A. Patel, T. Barwicz, H. I. Smith and R. Menon, *J. Vac. Sci. Technol. B* 23(6) pp2657-2661 (2005).
- A) What is the reason for wanting to obtain a π phase shift through the zones? Explain your answer.
- B) Why was Aquasave used on top of the PMMA? What is Aquasave?

- C) After patterning the zone plate, the Ni was removed. Why did they bother to remove the Ni?
 - D) Why was chrome deposited?
 - E) What did the Fulton-Dolan process accomplish?
 - F) Given that the zone plates have a numerical aperture of 1.14 in water, calculate the spatial period of the outermost zones, and compare this with the finest spatial period achieved in the lithography.
 - G) Given that the zone plates designed for the 400 nm exposing wavelength and those designed for the HeNe wavelength (632.8 nm) were made in the same material and located on the same surface, what was the approximate phase shift for the HeNe radiation?
 - H) Calculate the spatial period of the outermost zones of the zone plates designed for operation at the HeNe wavelength (632.8).
 - I) Explain in a few words how the point-spread function of the zone plate was measured experimentally.
- (7) Read the article "Hybrid optical maskless lithography: scaling beyond the 45 nm node" by M. Fritze et al, J. Vac. Sci. Technol. B 23(6):2743, Nov/Dec 2005, and then answer the following questions:
- A) According to this article, what is the main argument in favor of combining interference lithography and projection lithography? What are the limitations in terms of applying this technology to nanolithography markets?
 - B) In page 2744, first paragraph, the authors state about interference lithography that "Depth of focus, in principle infinite, can be quite large in practice, and is limited mainly by the coherence length of the laser source." Justify this statement using basic Optics, and name at least one additional reason that limits the depth of focus of a real-life interference lithography system.
 - C) According to Figure 3(b), process latitude is more relaxed for immersion systems than "dry" systems. Explain qualitatively why.

D) Propose a technique that would improve the process latitude even further than Figure 3(b) suggests.

- (8) In this problem, we will examine the effects of numerical aperture and process latitude on the quality of patterns produced by optical projection lithography. To perform the simulations, you need to download *all* the Matlab files (the MIT server) into the same directory in your computer. The code should work with Matlab in any platform, such as Windows, Linux, Macintosh, etc.

The main function is `demo_nested.m`, which performs the following: (1) defines a pattern of “nested L’s” to be printed on a substrate [the nested L’s are often used in tests of new lithographic tools]; (2) simulates the effect of diffraction due to the limited aperture of two optical systems, one with high NA=0.85 and the other with low NA=0.2, using both coherent and incoherent illumination; (3) simulates the “clipping” effect of the photoresist on the pattern that is actually exposed on the wafer.

You can modify the numerical aperture by changing the first argument of the `circ()` function call in lines 34-35 of `demo_nested.m`. The photoresist effect is simulated in lines 50-54. The given function `photores2.m` represents a low-threshold high-contrast resist. You can also change the photoresist exposure function by replacing `photores2.m` with `photores.m`, `photores3.m` or you can make up your own photoresist functions.

- A) Comment as thoroughly as you can on the difference between the four patterns that are generated by the function `demo_nested.m` as given.
- B) Which form of illumination, coherent or incoherent, would require more serifs to be corrected?
- C) Which form of illumination, coherent or incoherent, has the lowest contrast? Justify your observation from basic optical principles.
- D) Repeat the simulation with even lower NA=0.1, and notice that the difference with NA=0.2 is rather drastic for both coherent and incoherent illumination. Justify your observation from basic optical principles.

- E) Is the performance of `photores3.m` better or worse than `photores2.m` with the low NA system? Why, and how could you make it even better? What is the tradeoff that you face as you try to tune the photoresist response for low NA?
- (9) Read the papers M. D. Austin, H. Ge, W. Wu, M. Li, Z. Yu, D. Wasserman, S. A. Lyon, and S. Y. Chou, "Fabrication of 5 nm linewidth and 14 nm pitch features by nanoimprint lithography," *Appl. Phys. Lett.*, vol. 84, pp. 5299-301, 2004. and:
- A) Provide an overview of the basic fabrication method – use sketches and short text descriptions.
- B) What are the various factors that contribute to limit the ultimate resolution of this technique?
- C) Now read the paper [F. Hua, Y. G. Sun, A. Gaur, M. A. Meitl, L. Bilhaut, L. Rotkina, J. F. Wang, P. Geil, M. Shim, J. A. Rogers, and A. Shim, "Polymer imprint lithography with molecular-scale resolution," *Nano Lett*, vol. 4, pp. 2467-2471, 2004]. Express in your own words (you may use sketches) the basic idea of their fabrication method.
- D) Estimate the width of the features in figure 2a-d. Is this consistent with a CNT dimension? Would you expect it to be? Why?
- E) Hypothesize the origin of the difference in widths between the figures. Suggest an experiment to test your hypothesis.
- F) Now look at figure 3 b and c. How did they decorate the image to improve the contrast? Draw a sketch that clarifies what exactly is on the substrate during the imaging process. How does the imaged linewidth relate to the dimensions of the CNT and its replica? Explain the observed asymmetry in the linewidth profile (darker on one side of the feature than the other). What additional information would it have been good to know about the decoration method?
- G) Sketch an idealized figure of the profile (the insets in the figure 3b and 3c) and indicate on it the best dimension to use to indicate the width of the CNT. If instead of TEM, we assume these images are annular-dark-field STEM images, how does that change the interpretation of the image?

H) Compare these two papers: which of the techniques is likely to be of greater practical utility in the long run? Why?