MASSACHUSETTS INSTITUTE OF TECHNOLOGY

6.781/2.391J
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.

A. False- CARs are very sensitive to airborne contamination
B. True- FE Gun is a much smaller source (brighter)
C. False- It is used to make optical lithography masks and some products, such as diffractive optics for telecom systems.
D. False- e-beam lenses have NA around 10^-2 or 10^-3
E. True- PMMA is useful
F. False- the interferometer's resolution is given by the ability to resolve phase in an interference pattern, and that is not related to the depth of field
G. True- resolution is around 10 nm
H. False- ozone is useful for organics- metals are removed with piranha or other techniques
I. True- semiconductor companies use partially coherent illumination to balance the trade-off.
J. True- two-photon and multi-photon confocal microscopy
K. False- interference lithography can make smaller features with less distortion
L. True- with methods such as Spatial Phase Locking

(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 $\mu C/cm^2$, 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.

Question #32 Solutions Attached

(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?

Ans: Etch rate is a function of position on the substrate.

B) What is meant by microscopic nonuniformity?

Ans: Etch rate depends on pattern geometry, i.e., fine features etch at a different rate than coarse features.

C) What is the mean-free path of a Cl_2 gas molecule at 7 m torr assuming the ideal gas law?

Ans: Mean-free path, Λ, is given by

$$\Lambda = 1/\pi(1.414)(d^2)\, n$$

where d is the molecule diameter taken to be 0.5 nm for the case of Cl_2 , and n is the number density,

$$n@760\ \text{torr} = \frac{6.02 \times 10^{23}\ \text{molecular/mole}}{22.4 \times 10^{3}\ \text{cm}^3\ \text{/mole}}$$

$$= 2.69 \times 10^{19}\ \text{molecules/cm}^3$$

$$n@\ 7 \times 10^{-3}\ \text{torr} = 2.48 \times 10^{14}\ \text{molecular/cm}^3$$

$$\Lambda = 1/\pi\ (1.414)(5 \times 10^{-8}\text{cm})^2\ (2.48 \times 10^{14}\text{cm}^{-3})$$

$$\Lambda = 0.36\ \text{cm}$$

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?

Answer: We calculated above that the mean-free path for a neutral Cl_2 molecule with thermal velocity is 0.36 cm. Since the dark space is 7 mm across, the probability of a molecule colliding with another molecule in crossing the dark space is close to unity. For an ion such as Cl^+, whose effective cross-sectional area is smaller than the Cl_2 molecule, the probability of a collision is proportionally smaller, but also close to unity. However, multiple collisions are unlikely.

E) Is an ion likely to experience multiple collisions in crossing the dark space?

Answer: No, multiple collisions in crossing the dark space are of low probability.

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?

Answer: The dark space indicates that the excitation of atoms by electron bombardment is low, hence the electron density is low in the dark space.

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?

Answer: The mass, m, of a Cl atom is (35.5) (1.66 x 10^{-24} gms) = 5.89 x 10^{-23} gms

Boltzman's constant, k = 1.381 x 10^{-16} erg/K

Temperature, T = 300K

For a Cl ion before acceleration, thermal velocity is,

(1/2) m v^2 ~ kT, or $v_{thermal}$ ~ {2kT/m}$^{1/2}$

thus, $v_{thermal}$ ~ 375 m/sec

To calculate the velocity of the 25 eV ion, we set (1/2) m v^2 = 25 eV

25 eV = (25) (1.6x10^{-19}) Joules = (1/2) (5.9 x 10^{-26} kg) v^2

Therefore, v_{25eV} = {(50) (1.6x10^{-19})/ (5.9 x 10^{-26} kg)}$^{1/2}$ = 11,644 m/sec, considerably faster than the thermal velocity.

The velocity ratio is, (v_{25eV} / $v_{thermal}$) = 31

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?

Answer: Since the ions extracted from the body of the plasma acquire a velocity much higher than the thermal velocity, and since the accelerating field is perpendicular to the substrate, it is not surprising that the etching is highly vertical as long as the isotropic component of the etching is negligible compared to the etching stimulated by the ion bombardment. Even at a relatively low accelerating potential of 25 volts, the ratio of velocities is about 31, indicating that the ions arrive an at angle close to normal. It is difficult to estimate the effect of collisions on the angle of arrival but this is expected to be small. In any event it is outside the scope of this course.

I) Calculate the arrival rate in number/cm^2 sec of neutral Cl_2 molecules at the surface of the substrate.

Ans: Arrival rate, F, is given by

$$F = P/\{2\,(1.414) m\,k\,T\}^{1/2}$$

$$M_{Cl2} = 2(35.5)\ (1.66 \times 10^{-24}\ gms)$$

$$= 1.18 \times 10^{-22}\ g$$

$$k = 1.381 \times 10^{-16}\ erg/K$$

$$T = 300K$$

$$P = (7 \times 10^{-3}\ torr)(133 Pa/torr)\ (10\ dynes/cm^2/1\ N/m^2)$$

$$= 9.3\ dynes/cm^2$$

$$F = 2.5 \times 10^{18}/cm^2 s$$

J) Assume that the substrate is cooled so that no spontaneous or isotropic etching occurs, that each arriving Cl_2 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 Cl_2 arrival rate does not limit the etching rate. If the etch rate is 10 nm/s, what is the ion current density.

Ans: An etch rate of 10 nm/s corresponds to the removal of 10^{-6} cm^3/s of Si per cm^2. The number density of Si is $5 \times 10^{22}/cm^3$. So, an etch rate of 10 nm/s corresponds to 5×10^{16} Si atoms/ cm^2 s. This, in turn, corresponds to an ion arrival rate of 2.5×10^{16} ions/ cm^2 s, or a current density of 4 mA/cm^2.

K) Is the assumption that the arrival of Cl_2 molecules on the surface is not rate limiting valid?

Ans: The arrival rate of Cl_2 molecules is given by

$F = 2.5 \times 10^{18}\ Cl_2/cm^2\ s$

If every pair of Cl^2 molecule that arrived resulted in one molecule of $SiCl_4$ being removed as a gaseous species then the removal rate of Si would be

$F/2 = 1.25 \times 10^{18}\ Si/cm^2\ s$

The corresponding etch rate would be:

etch rate $= (1.25 \times 10^{18}\ Si/cm^2 s)/(5 \times 10^{22}\ Si/cm^3)$
$= 2.5 \times 10^{-5}$ cm/s
= 250 nm/s.

Hence the actual rate of Si removal, 10 nm/s, is not limited by the arrival of Cl_2 but rather by the arrival of ions from the plasma.

(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 nm^3 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/nm^3

***ANSWER:* 5 eV/bond * 10 bonds/nm^3 = 50 eV/nm^3**

B) Calculate the number of quanta per nm^3 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

***ANSWER:* E_{photon} (eV)= $h\,c/(\lambda\,e)$ where e is the electron charge in Coulombs.**
Also $N = 50\ eV/nm^3/E_{photon} = \lambda\, e\ 50\ eV/nm^3/(h\,c) = 0.044\ \lambda(nm)$.

lambda	N
4	0.176
15	0.66
193	8.492
248	10.912

C) Assume that 100 quanta/nm^2 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.

***ANSWER:* Let the resist thickness be *r*, then the number of quanta for exposure of a parallelepiped with volume *r* x 1 nm x 1 nm is just 0.044 *r*(nm) λ(nm) > 100.**

D) Typical proposals for EUV lithography suggest that a resist with a sensitivity of 5 mJ/cm^2 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 photons/nm^2, and then eV/nm^3 and photons /nm^3.

***ANSWER*: 2 mJ/cm^2 corresponds to 125 eV/nm^2 ~ 1.5 photons/nm^2. This corresponds to 2.5 eV/nm^3 and 0.03 photons/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 mJ/cm^2 sensitivity).

***ANSWER:* 100 photons per pixel requires a resist sensitivity of 100 *hc*/(λ) /nm^2 = 134 mJ/cm^2. This will results in production ~ 25 times slower than planned. The result will be an unacceptable cost-of-ownership.**

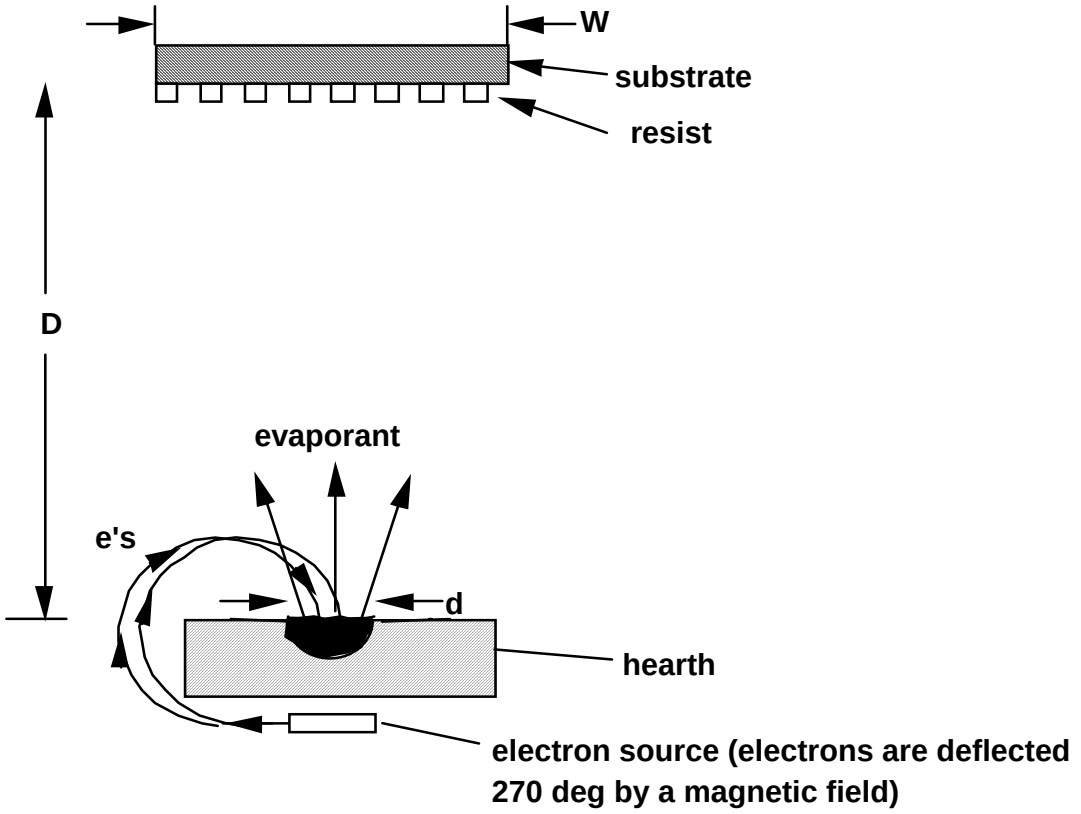
F) If a resist sensitivity of 5 mJ/cm^2 is to be achieved, what is the minimum pixel size that can be used and still maintain acceptable shot-noise performance?

***ANSWER:* By increasing the pixel area by ~ 25 times (to 5-nm x 5-nm) the sensitivity can be decreased correspondingly to 5 mJ/cm^2. 5 nm line-edge roughness is totally unacceptable for manufacturing at the 25-nm node.**

(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

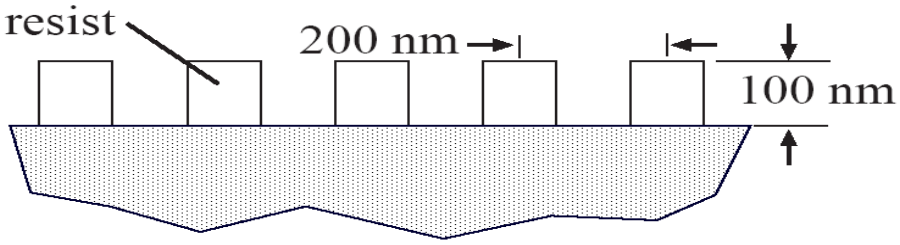
nanoimprint lithography and liftoff" by Z. Yu, et al, J. Vac. Sci. Technol. B, vol 21, pp2874-2877 (2003). In particular, look at Figure 2.

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



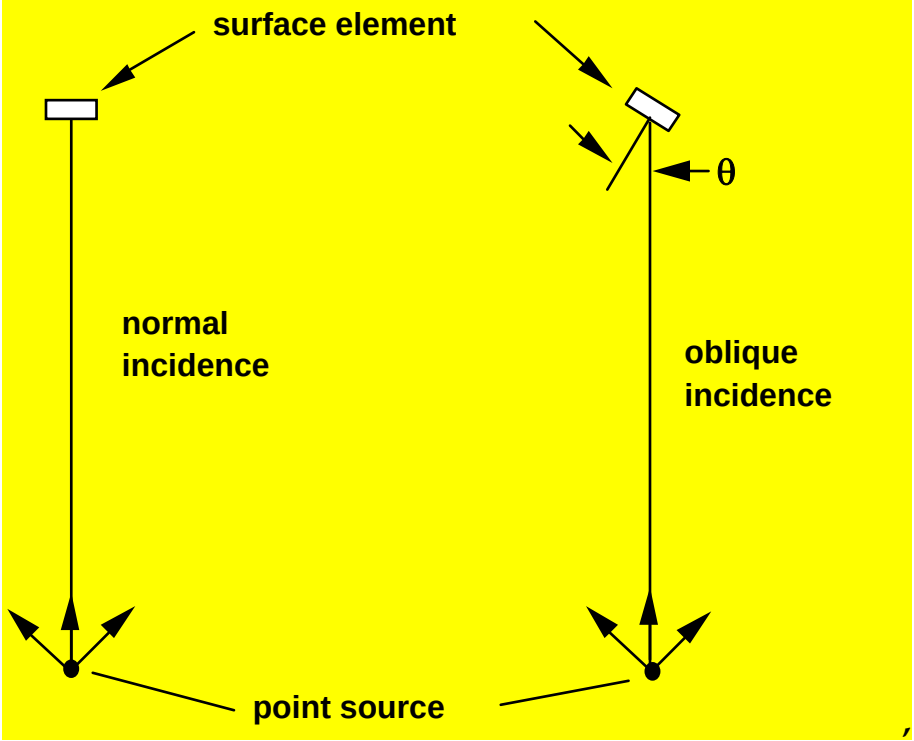
The source diameter, d, is 1.0 mm, the source-to-substrate distance, D, is 500 mm, and the pattern area on the substrate has a diameter, W, of 2.0 cm. A line-of-sight from the center of the source to the center of the substrate is perpendicular to the substrate.

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.

Ans. Consider first an elementary point source that emits evaporant equally in all directions, i.e., isotropic emission. In order to calculate the amount of sidewall coating, consider two infinitesimally small surface areas, one normal to the line-of-sight from the point source and one oblique to the line-of-sight:



The deposit thickness, t_O, on the oblique surface is related to the deposit thickness on the normal surface, t_n, by

$$t_O = t_n \cos\theta$$

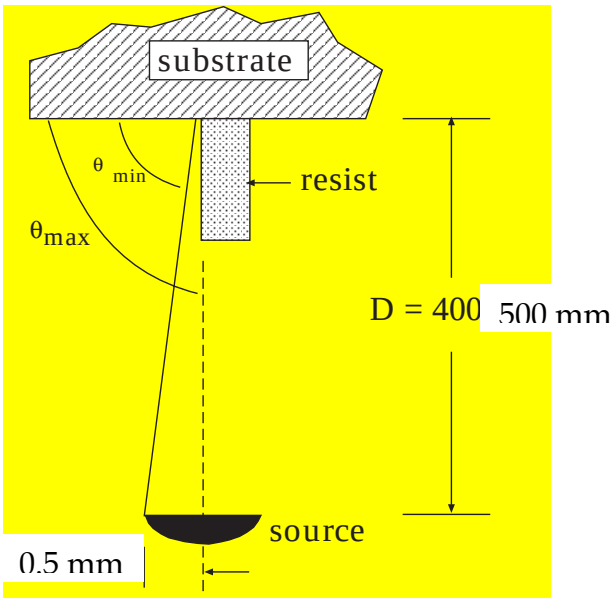
For an extended source we can calculate the deposit thickness on any oblique surface as follows:

$$t_O = \int_{\theta_{min}}^{\theta_{max}} t_n \cos\theta \, d\theta$$

$$= \frac{t_n}{(\theta_{max} - \theta_{min})} \int_{\theta_{min}}^{\theta_{max}} \cos\theta \, d\theta$$

In effect, we are assuming that the extended source can be considered a continuous distribution of equivalent point sources.

For the part of the substrate that is on axis, the following sketch (not drawn to scale) applies:



$\theta_{max} = 90\,\text{deg} = \pi/2 = 1.571\,rad$

$\theta_{min} = 1.571\,rad - (0.5\ \ mm/500mm) = 1.571 - 1\times10^{-3} = 1.570\,rad = 89.95\,\text{deg}$

Therefore, $t_o = [100\,nm/(1.571-1.570)]\int_{1.570}^{1.571}\cos\theta\,d\theta$

Because the range of the integral is so small we can approximate it:

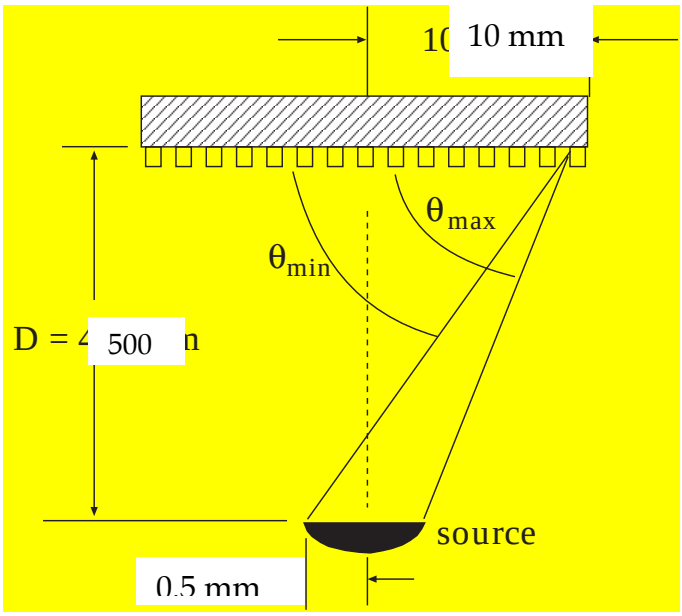
t_O = 100 nm [cos(1.5705)] = 0.03 nm

t_O = 0.03 nm!

This thickness would not be a monolayer on a perfectly smooth surface. However the sidewall of a resist structure is far from smooth, having a roughness of about 5nm. Hence, the film on the sidewall will certainly not be continuous.

B) Calculate the thickness of sidewall coating for regions at the edge of the substrate.

Ans. For the off-axis part of the problem, the following sketch (not drawn to scale) applies:



θ_{min} = 1.571 rad - (10.5 mm/ 500 mm) = 1.550 rad = 88.8 deg

θ_{max} = 1.571 rad - (9.5 mm/ 500 mm) = 1.571 – 1.90×10^{-2} = 1.552 rad = 88.9deg

The thickness of deposit on the sidewall is calculated as follows

$$t_o = [100 \text{ nm}/(1.552 - 1.550)] \int_{1.550}^{1.552} \cos\theta \, d\theta$$

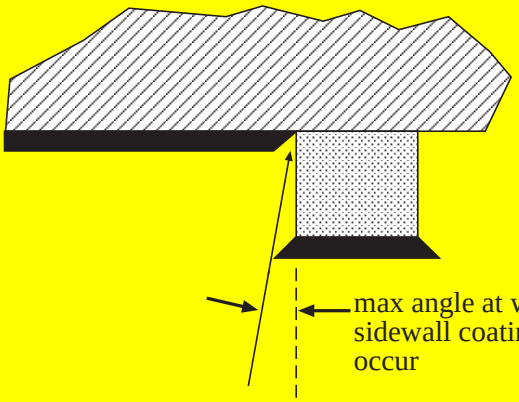
$$t_o = 100 \text{ nm } [\cos(1.551)] = 2 \text{ nm}$$

This may be thick enough to form a continuous film on a smooth surface. However, the surface of a resist sidewall is rough on the scale of 5 nm and hence the 2 nm deposit would not be continuous.

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.

If the deposited material is mobile and forms an overhang, depicted in the sketch as a 45 degree buildup, the sidewall coating will be reduced below what we calculated above. Let's consider when the deposit will be cut off, first for the on-axis case with material arriving from the furthest extreme of the 1.0 mm-diameter source.

On-axis case (not drawn to scale)



In this case the maximum angle of incidence is given by

$$0.5 \text{ mm} / 500 \text{ mm}) = 1 \times 10^{-3} \text{ rad}$$

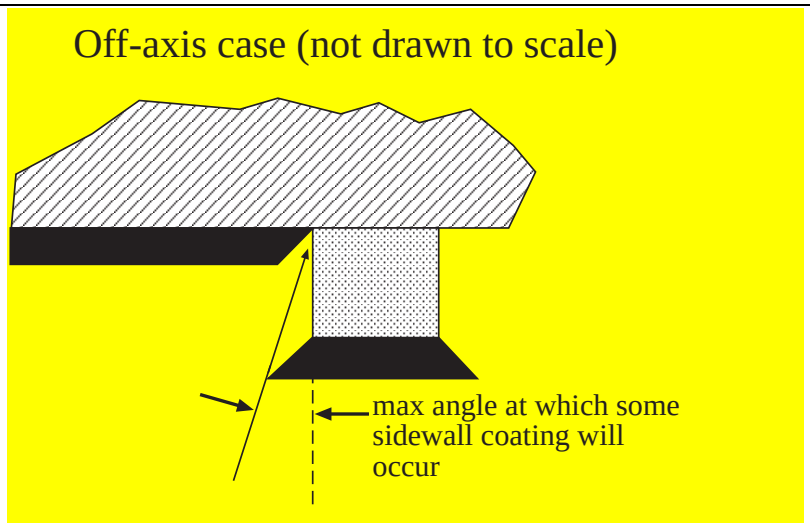
Therefore, deposition on the sidewall will be fully cut off when the overhang extends out a distance given by

$$100\text{nm X } 1.0 \times 10^{-3} = 0.1 \text{ nm}$$

This will occur after only 0.1 nm out of the total of 100 nm has been deposited. In this case the amount of material deposited on the sidewall is given by

$$(0.03 \text{ nm}) (0.1 / 100) = 0.00003 \text{ nm;}$$ **which is clearly negligible!**

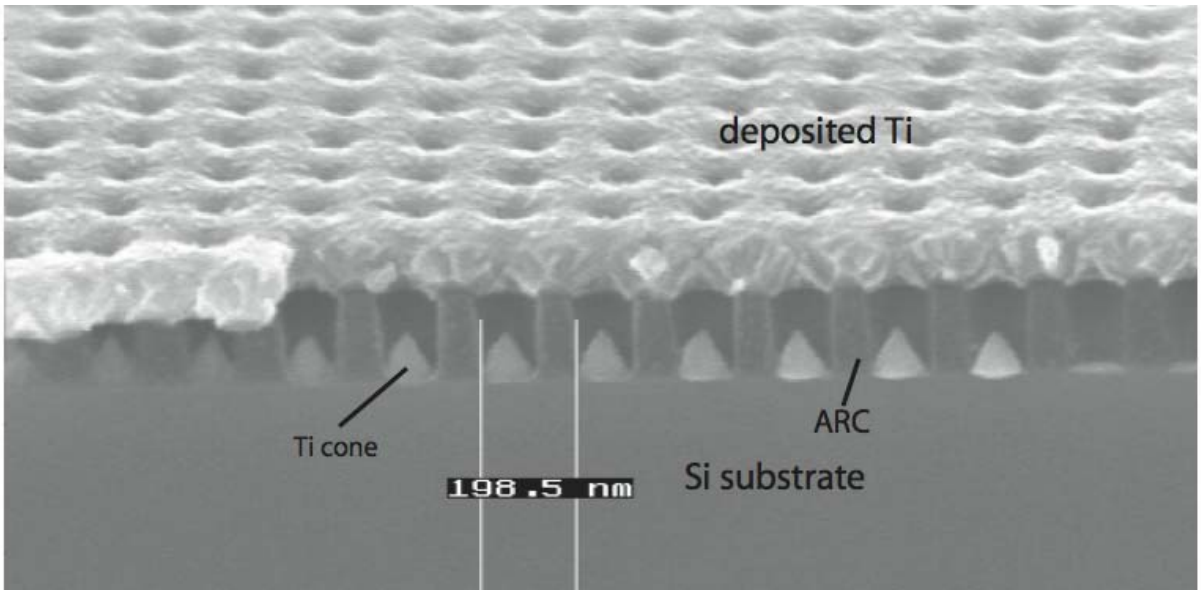
Next, consider the off-axis case and the maximum angle of deposition.



The maximum angle indicated is now given by (10.5 mm / 500 mm) = 0.02.
Deposition will be cut off when the overhang extends out a distance of

(100nm) (0.02) = 2.1 nm

That is, after only 2.1 has been deposited. Thus, as illustrated in the micrograph, there is no sidewall coating.



(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 Pi phase shift through the zones? Explain your answer.

The purpose of the pi phase shift is to maximize the focusing efficiency, i.e., maximize the number of photons into the first-order focus. By having the phase of the transmitted light differ by pi radians in alternate zones, one eliminates the zero order transmission and the energy that would otherwise go into the zero order goes into the other orders, increasing the efficiency of first order focusing from 10% (the value for an amplitude zone plate) to about 40% (the value for a pi-phase zone plate).

B) Why was Aquasave used on top of the PMMA? What is Aquasave?

Aquasave is a conducting polymer that is water soluble. Its purpose is to carry away the charge put in by the electron beam. If there is no such conducting layer, or insufficient conduction, the sample will charge up and deflect the electron beam from where it is supposed to be.

C) After patterning the zone plate, the Ni was removed. Why did they bother to remove the Ni?

The purpose of the Ni was to serve as a hard mask for the etching. Once this function is performed one should remove it. If the Ni were left in place we'd have an amplitude zone plate (10% efficiency) rather than a pi-phase zone plate (40% efficient).

D) Why was chrome deposited?

The function of the chromium is to block all light that is not incident on the zone plates, e.g., the light incident on the spaces in between the circular zone plates.

E) What did the Fulton-Dolan process accomplish?

The Fulton-Dolan process enables one to remove by electrochemical means the chromium that is not electrically continuous with that on the periphery of the substrate. That is, all the chromium within the circular zone plates is etched away while that in between the zone plates is retained.

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.

We know from lecture 2 that for normal-incidence illumination

$$p = \lambda / NA = 400 \text{ nm} / 1.14 = 351 \text{ nm}.$$

The finest period achieved with the lithography was 2 x 1.15nm = 230 nm. It is not surprising that we can achieve a finer period in lithography than is present in the zone plate. In fact, the **theoretical** limit for the finest period would be p/2, or 175 nm. However, this would be at **zero** contrast and hence it is not really achievable. The contrast in the image that produced the 230 nm period was very low; it represented the **practical** limit.

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?

If we assume that the refractive index is the same at 400 nm and at 632.8 nm then the phase shift, $\delta\phi$, for the 632.8 nm light would be

$\delta\phi = (180\text{deg})\,(400\text{nm}/632.8\text{ nm}) = 114\text{deg}.$

H) Calculate the spatial period of the outermost zones of the zone plates designed for operation at the HeNe wavelength (632.8).

Actually, this is an ill posed or trick question; we're given the focal length and the wavelength, but no other information. We would need to be given additional information to answer it. For example, we could be given the diameter of the zone plate. For a fixed focal length, the spatial period of the outermost zones would get finer as the diameter is increased.

I) Explain in a few words how the point-spread function of the zone plate was measured experimentally.

For a fixed development time, we measure the diameter of the spot developed in the resist as a function of exposure time. We then plot the reciprocal of exposure time versus the spot diameter. This is equivalently the experimental point spread function.

(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?

Interference lithography can provide a regular grid with small features (limited to λ/2NA) without distortions and need to RET and other complex correction techniques. Subsequently, optical projection lithography of larger features is used to remove parts of the previously written regular grid, finally resulting in the desired pattern. The assumption is that the second step will only require large features, and therefore the need for corrections will be minimal. The obvious disadvantage is that, with this method, writing is limited to regular "Manhattan" geometries, which are reliably found only in electronics.

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.

In an ideal, monochromatic (temporally coherent) interference lithography system, interference fringes of perfect contrast are obtained throughout the region of overlap of the interfering beams, which can in principle be infinite. In actuality, all light sources, including lasers, have limited temporal coherence (i.e., they are not perfectly monochromatic.) Interference occurs only within a range equal to the coherence length of the source. Outside that region, the interference contrast gradually drops and so writing becomes impossible. Typical coherence lengths for 193nm lasers are in the range of a few hundred micrometers to millimeters, so the "depth of focus" specified by coherence is much longer than the depth of focus of a high-NA imaging lens (typically a few micrometers.)

C) According to Figure 3(b), process latitude is more relaxed for immersion systems than "dry" systems. Explain qualitatively why.

The exposure latitude requirement originates from the narrowing of interference lines adjacent to a trimmed feature due to the diffraction broadening (this is explained in Figure 2.) High-NA systems, especially using immersion, are subject to less severe diffraction artifacts; therefore, the process latitude is better.

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

Resolution Enhancement Techniques, e.g. serifs, could be used to improve the process latitude. This is because the edges of the trimmed features result in narrowing of neighboring lines; therefore, by proper shaping of the edges of the trimmed features the narrowing can be eliminated or reduced. However, the use of RET would annul the whole purpose of using HOMA, which is to avoid excessively complicated RET by combining interference lithography and projection lithography.

(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 from 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.

Coherent exposure has more ringing; incoherent has lower contrast. These observations are even more obvious at lower NA.

B) Which form of illumination, coherent or incoherent, would require more serifs to be corrected?

Incoherent.

C) Which form of illumination, coherent or incoherent, has the lowest contrast? Justify your observation from basic optical principles.

Incoherent, because of the MTF rolloff towards higher frequencies.

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.

You observe that the nested Ls almost merge with strong ringing in the coherent case, and merge totally in the incoherent case. The drastic difference wrt the previous case is because the line spacing 0.8μm

works out to be below the Rayleigh resolution 1.22λ/(NA) of the system for NA=0.1, whereas it is just above for NA=0.2

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?

The threshold is higher in `photores3.m` than `photores2.m`, and so the former rejects better the high intensities near the line boundaries. However, `photores3.m` is not perfect either because it has lower contrast than `photores2.m`. Ideally, we should aim for the highest threshold possible and the highest sharpness, but then we would be giving up process latitude.

(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?

Answer: (1) accuracy in growth (atomic level); (2) stretching and distortion of imprint polymer; (3) intermolecular bonding length scales in polymer; (4) interatomic bonding lengths in polymer.

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?

ANSWER: 2a: 17 nm, 2b: 33 nm, 2c: 50 nm, 2d: 50 nm. This is not consistent with a CNT dimension. But we don't expect it to be because the image is convolved with the AFM tip dimension.

E) Hypothesize the origin of the difference in widths between the figures. Suggest an experiment to test your hypothesis.

ANSWER: presumably the tip was either wearing out or being damaged as the experiments went on. The difference is too large to be explained by any other effect (expecially given the TEM data). They could have gone back to measure the first sample again at the end of the experiment.

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?

ANSWER: roughly yes, it is consistent with a CNT. They use shadow evaporation of metal to decorate the image. The imaged linewidth depends on the angle of evaporation, which we are not told, therefore we don't know the right scaling factor to use. The asymmetry comes form the fact that we are looking at the feature (Which is presumably absorbing more electrons) and its shadow (which is presumably transmitting more electrons). We are told illumination is with TEM, so the shadow should be the bright part, the feature should be the dark part. If illumination were STEM, the shadow would appear dark in the image (no scatterers present) while the CNT would appear bright.

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?

Answer: any well-reasoned answer is acceptable. But what I had in mind is that the Austin paper actually demonstrates pattern transfer into underlying material, while the Hua paper is limited to relief structures in PolyUrethane.

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