Nanometer Scale Patterning and Processing

Spring 2016

Lecture 21

E-Beam Lithography Process

Resolution enhancement process: ultrasonic development

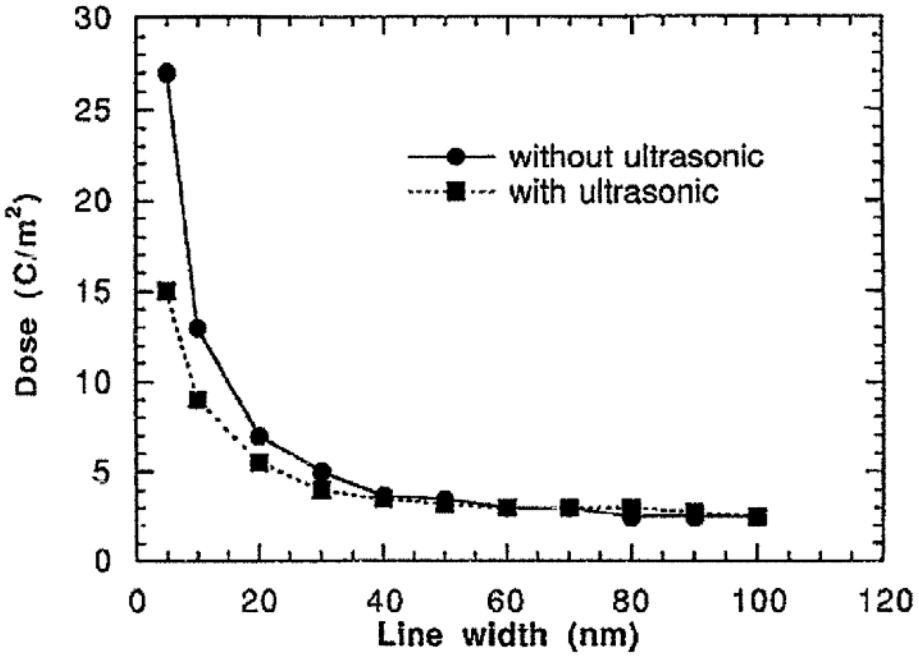
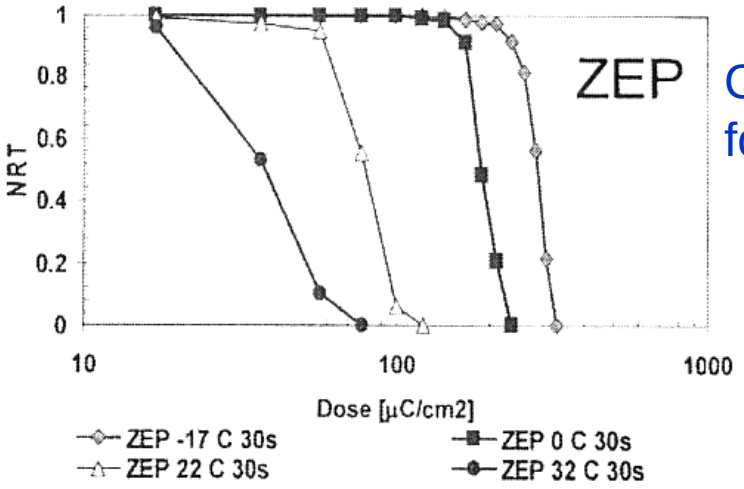


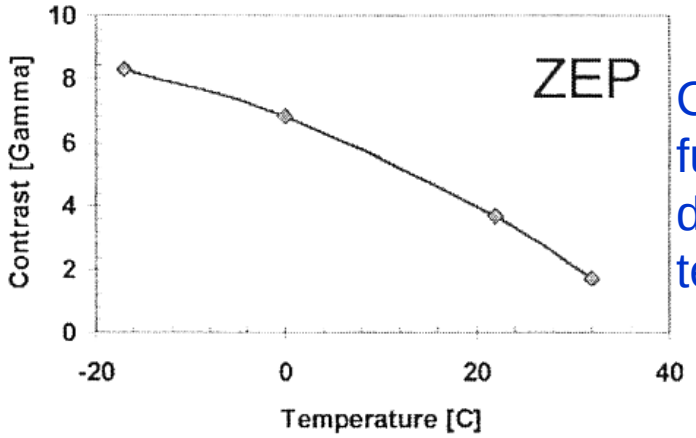
Fig. 3.30 Comparison of exposure dose required for PMMA development with and without ultrasonic assistance (Reprint from [60] with permission)

Ultrasonic helps to remove exposed resist (for positive tone) from inside narrow trenches.

Resolution enhancement process: low temperature development (ZEP)

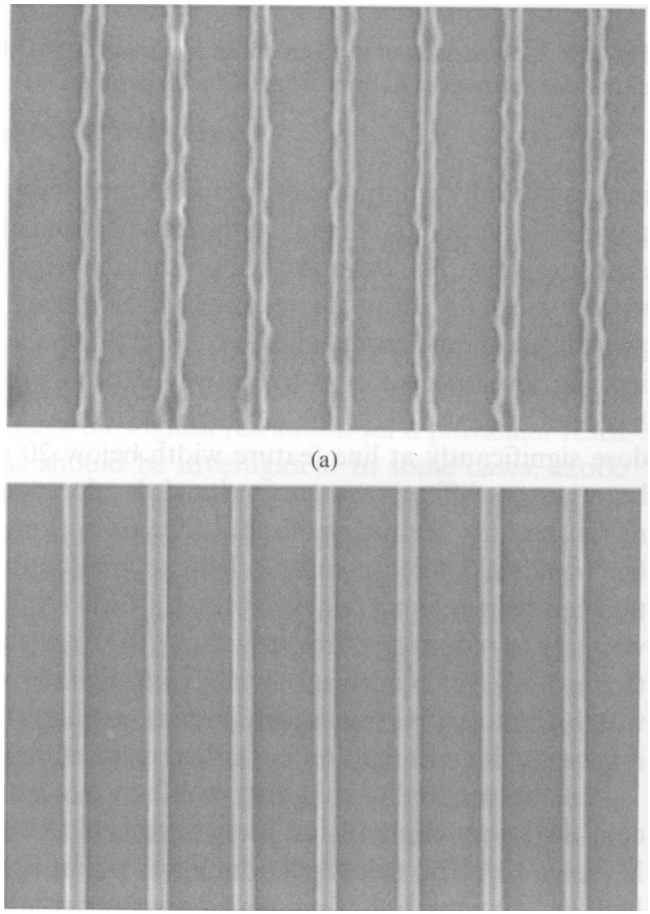


Contrast curve for ZEP-520



Contrast as a function of development temperature.

Low T development increases contrast, but decreases sensitivity



Comparison of edge roughness of ZEP-520 resist lines (40nm wide) developed at (top) room temperature; (bottom) -4°C.

Resolution enhancement process: low temperature development (PMMA)

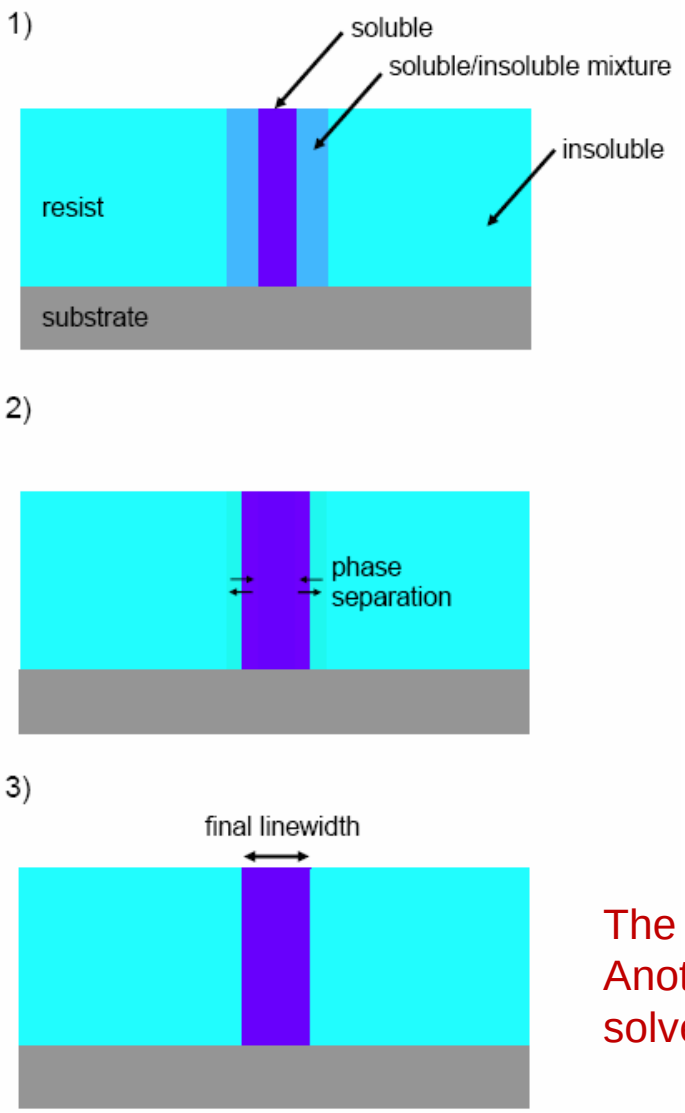


Figure 2-6: Schematic illustration of one possible explanation of resolution-enhancing mechanism of cold development.

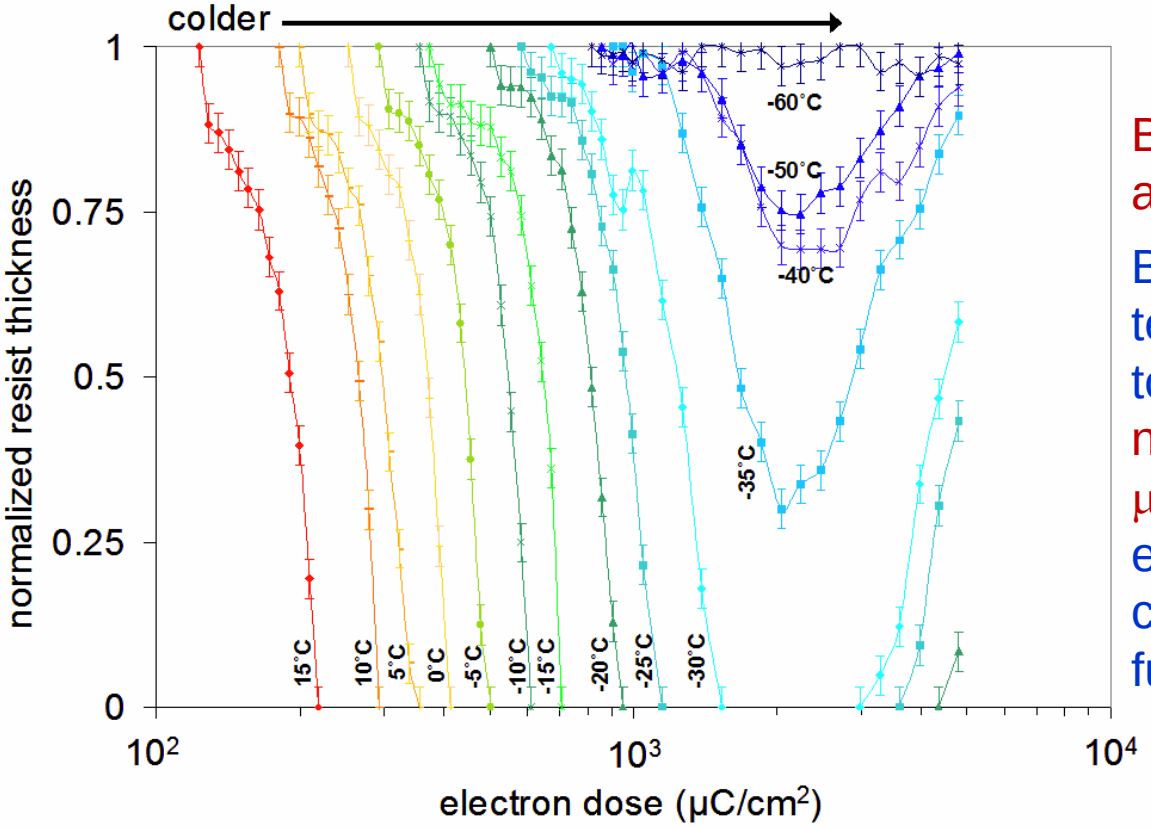
1) When a feature is exposed in PMMA, the soluble resist in the exposed region is surrounded by a boundary region of resist that, due to the initial polydispersity of the PMMA and random nature of chain scission, contains both soluble and insoluble polymer chains.
2) During development, this region phase-separates, with the soluble chains diffusing toward the soluble region and the insoluble chains diffusing toward the insoluble region.
3) The result is a region of soluble PMMA that is larger than the initial exposed feature, resulting in a degradation in resolution.

Cold development helps prevent this by limiting the diffusion that can occur in the boundary region, since diffusion is a thermally-dependent process.

The exact mechanism of cold development is still not clear. Another possible mechanism: colder developer is weaker solvent, so less attack to unexposed or partly exposed resists.

PhD thesis, Bryan M. Cord, MIT, June 2009

Cold development of PMMA



Best contrast (steepest slope) at -15°C.

Because, at even lower temperature, need higher dose to expose, but PMMA becomes negative at doses >~3000 μC/cm² (i.e. the already exposed PMMA with short chain begins to cross-link upon further exposure).

Figure 2-10: Measured contrast curves for PMMA developed in 3:1 IPA:MIBK at various temperatures. The initial resist film thickness was 160 nm and the development time was 60 seconds, except in the -40°C and -50°C cases (120 seconds) and the -60°C case (600 seconds), where longer development times were needed to show any measurable dissolution at all.

PhD thesis, Bryan M. Cord, MIT, June 2009

Forward scattering

α: forward scattering range, corresponds to standard deviation of electron distribution

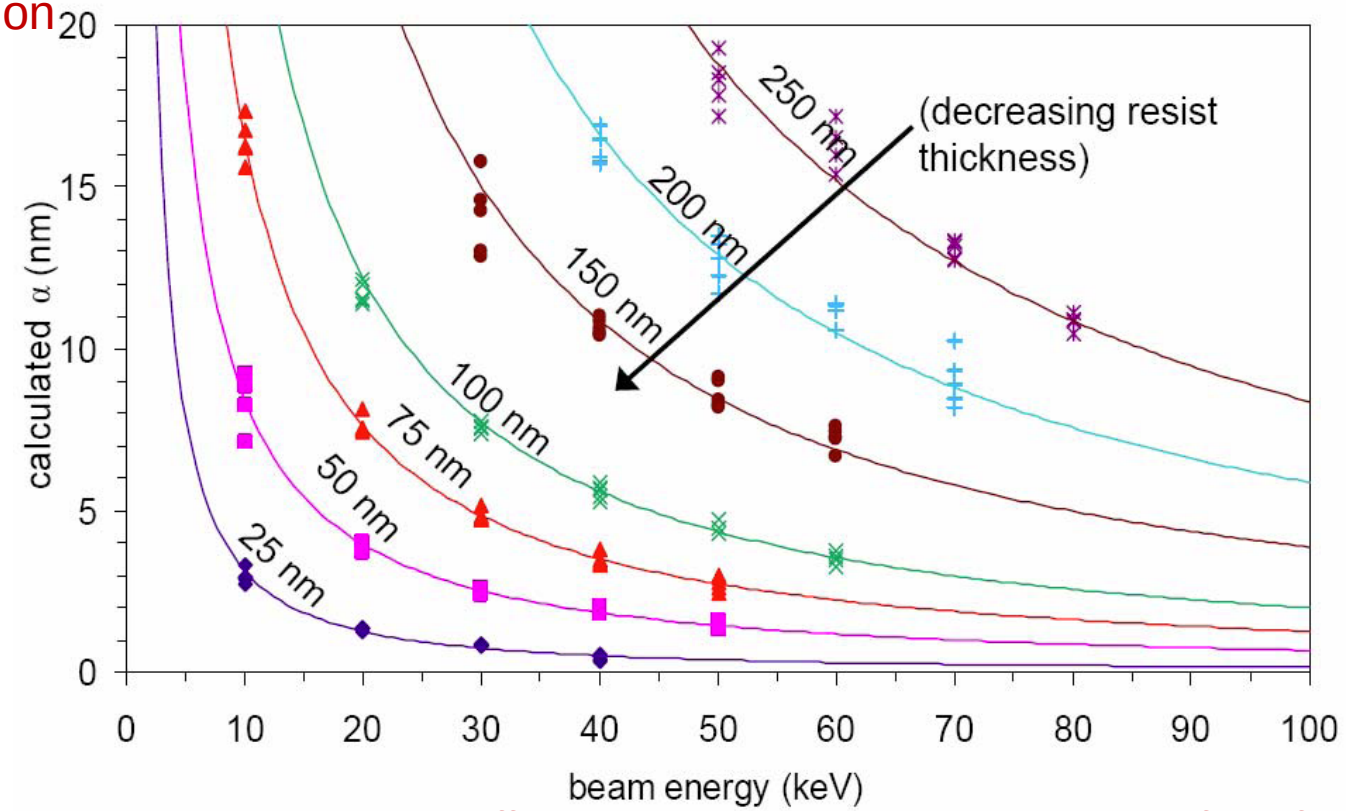


Figure 3-5: Forward scattering coefficients (α is the standard deviation of the final beam distribution) as a function of beam energy for various thicknesses of PMMA, calculated using CASINO, a free Monte Carlo modeling program. For simplicity, the initial beam profile was assumed to be a delta function (zero width) in this simulation. The scattering width decreases dramatically as the beam energy is increased, but using thicker resist results in more scattering.

PhD thesis, Bryan M. Cord, MIT, June 2009

Resolution limit: forward scattering and lateral diffusion

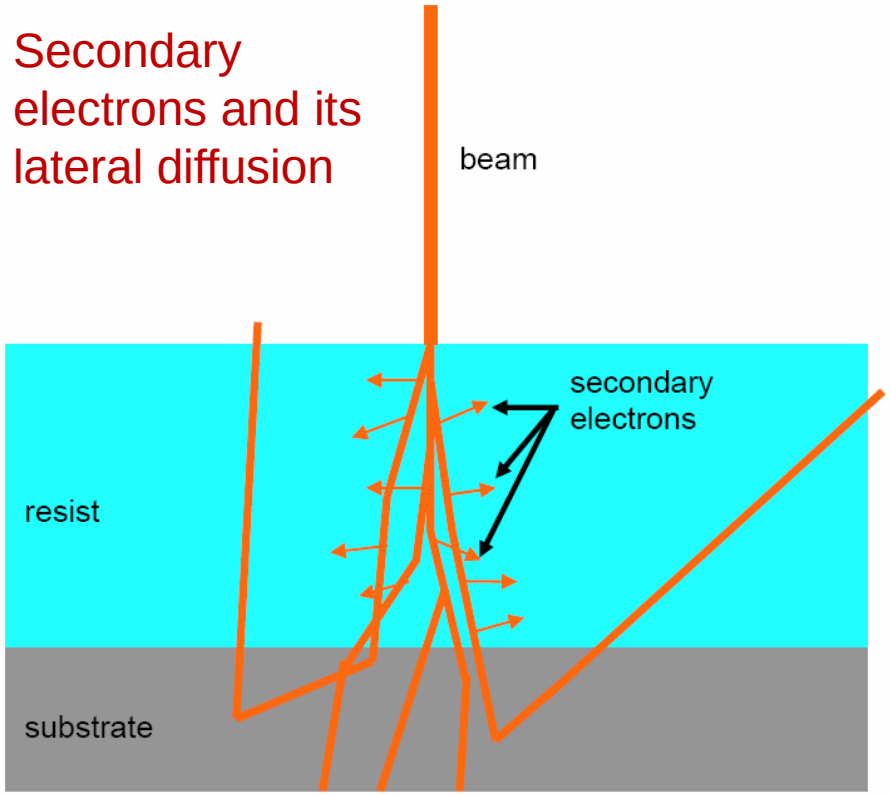


Figure 3-6: Schematic illustration of secondary electrons (SE), which typically travel/diffuse normal to the beam. (low energy SE is responsible for resist exposure)

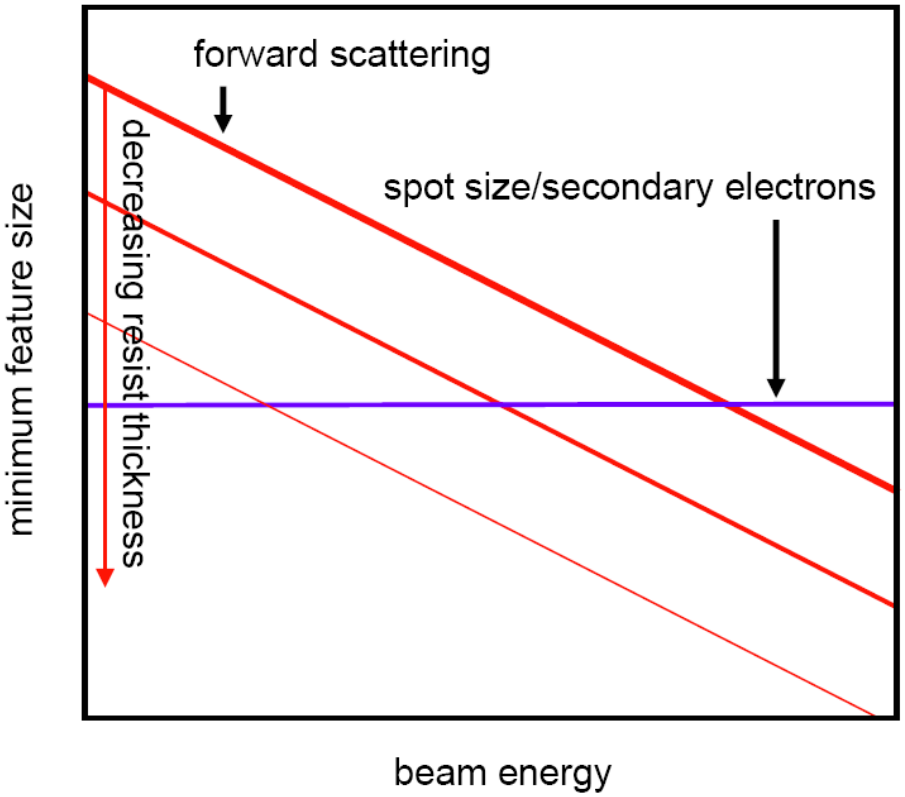


Figure 3-7: Schematic illustration of the effect of forward scattering, secondary electrons, and initial spot size on resolution. The weights of the red lines represent the relative thickness of the resist in each case. The minimum feature size at low beam energies is limited by forward scattering, while the spot size are the primary limiter at high energies.

Whether it is forward scattering or beam spot size that limits the minimum line-width, the effect of SE diffusion is to further broaden the line.

Resolution limit: forward scattering and beam diameter

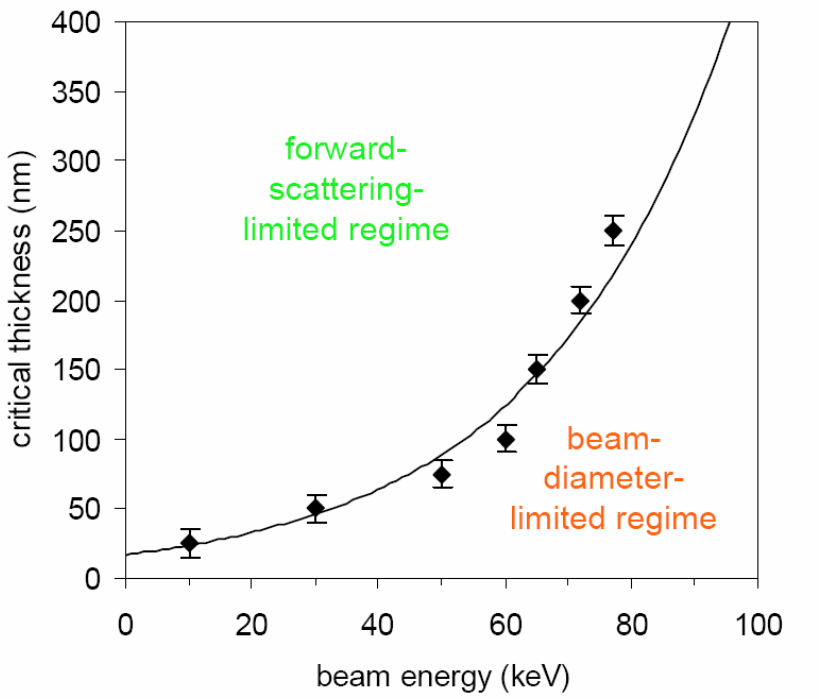


Figure 3-11: "Critical thickness" of resist as a function of beam energy. At resist thicknesses above critical thickness, forward scattering limits resolution, whereas below the critical thickness the only resolution limiter is the beam diameter, which is at least *theoretically* energy-independent.

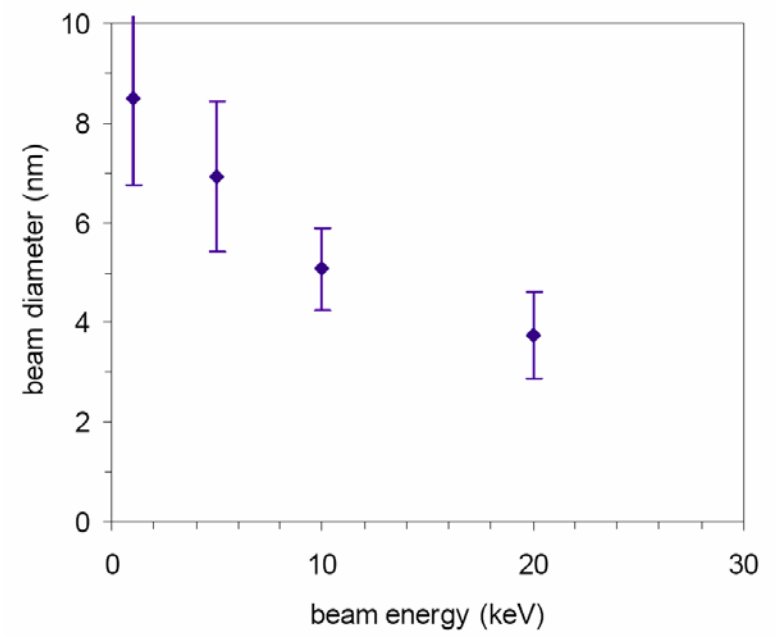


Figure 3-19: Beam diameter as a function of beam energy as measured in the MIT Raith-150 system. While beam diameter is inexplicably large at voltages below 10kV, it seems to be reasonably close to its 3-4 nm specification at 20kV and only slightly larger at 10kV, suggesting that beam diameter is not the limiting factor in our resolution.

A third limiting factor is resist swelling by developer. PhD thesis, Bryan M. Cord, MIT, June 2009

9nm pitch grating

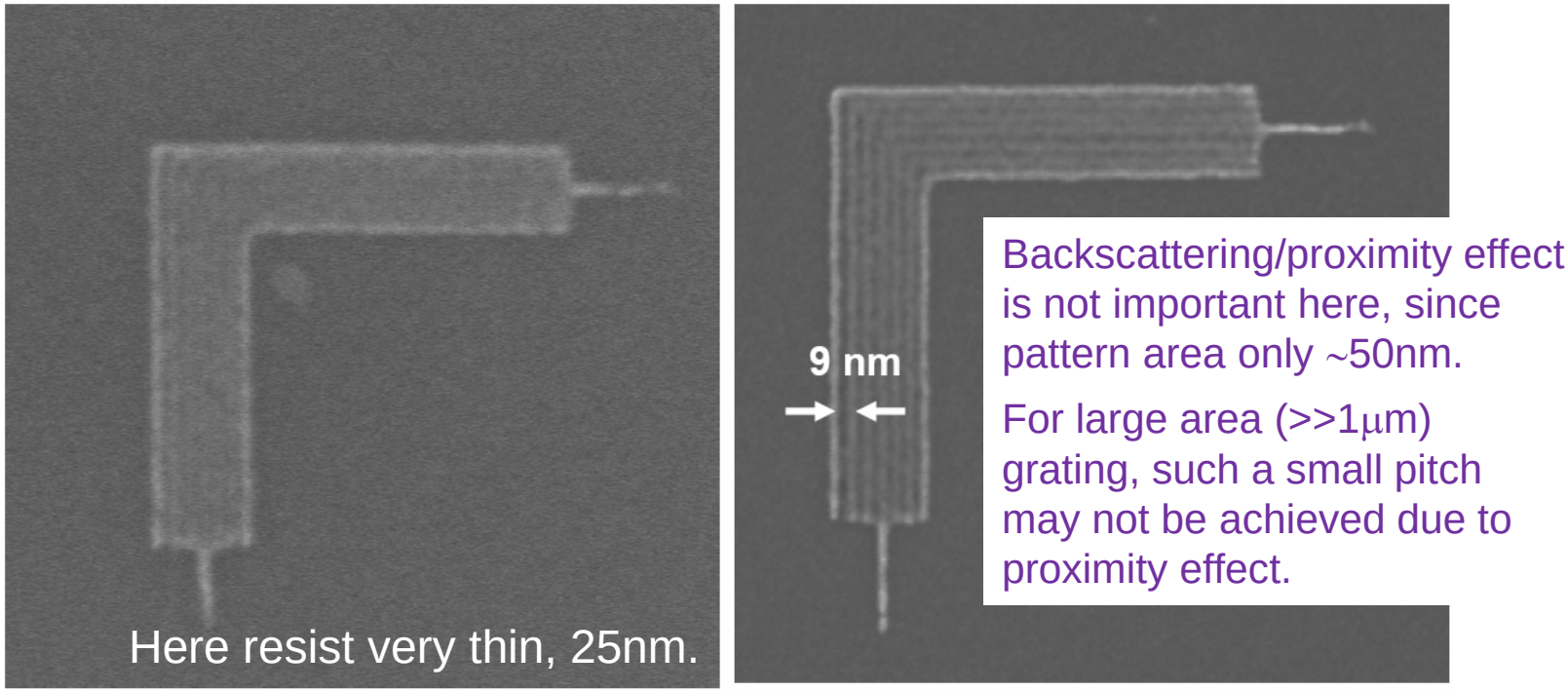


Figure 3-20: 9-nm-pitch nested-L structure fabricated in HSQ on Si and imaged in the MIT Raith-150 system (left) and on the Raith-150^{TWO} prototype tool. The left image shows minimal to nonexistent modulation, while the discrete lines of the structure are clearly visible in the right image. Since the 150^{TWO}'s environment has much better vibration isolation and control than the MIT facility, it seems likely that low-frequency vibrations are a significant source of imaging resolution degradation on the MIT tool.

PMMA should have similar resolution, but difficult to image (too soft, whereas exposed HSQ is SiO_2, rigid and not deformed during imaging), PMMA doesn't stick to substrate well (may be lifted off during development), and lines may fall due to capillary force during drying after development.

PhD thesis, Bryan M. Cord, MIT, June 2009

Delay effect on HSQ

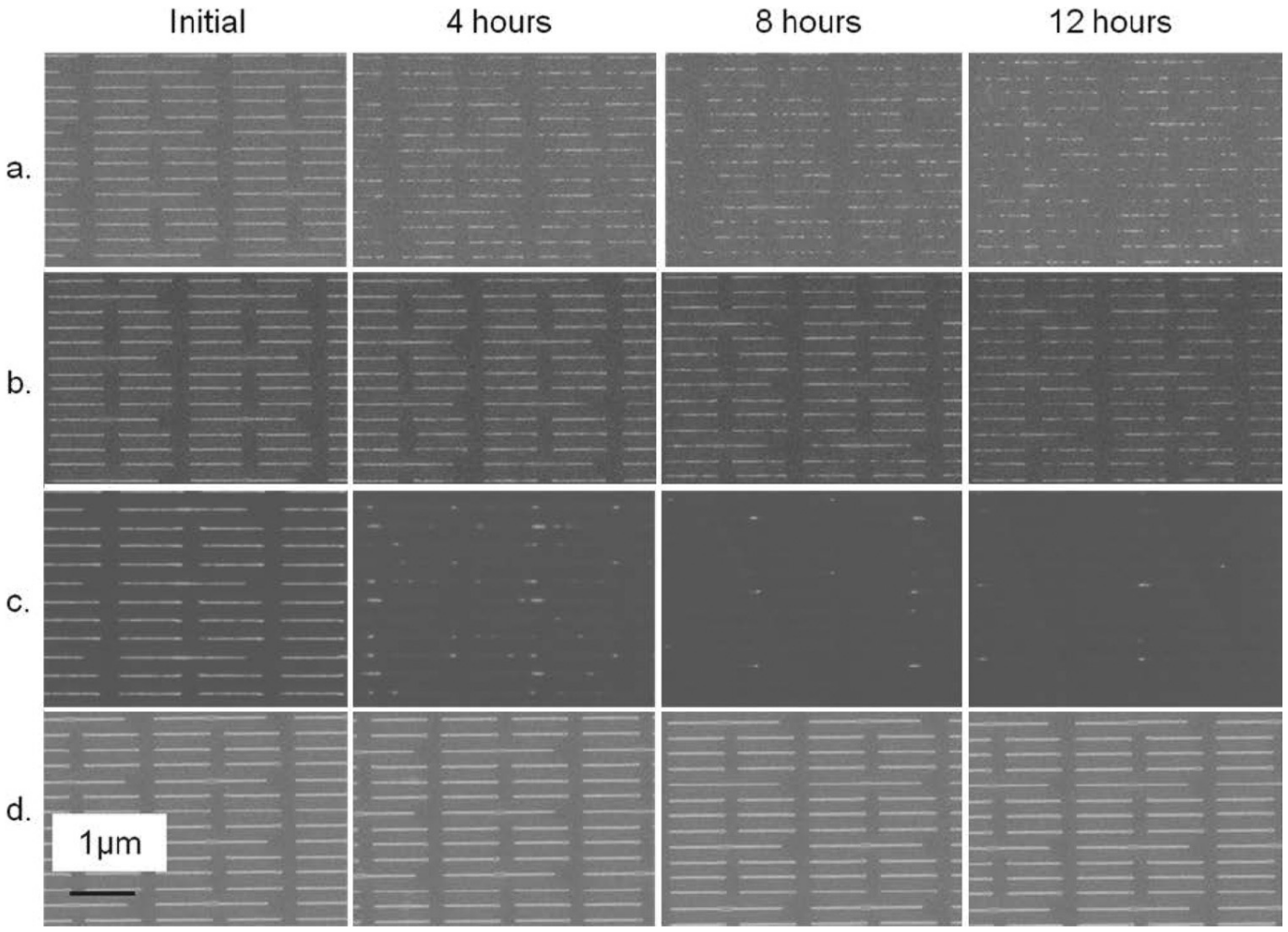
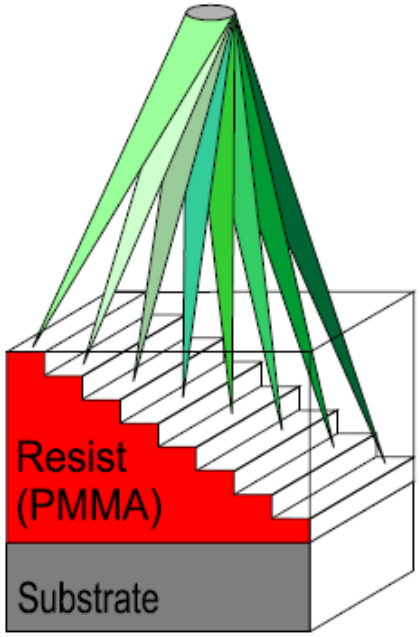


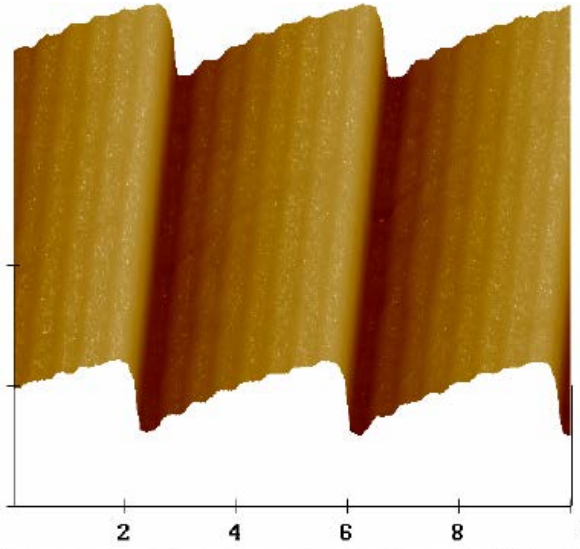
FIG. 2. SEM micrographs that reveal the delay effect for HSQ over a period of 12 h for (a) uncoated HSQ on bare silicon, (b) coated with Espacer 300Z on bare silicon, (c) uncoated HSQ on AR3 bottom layer, and (d) S_Enhancer on HSQ on bare silicon.

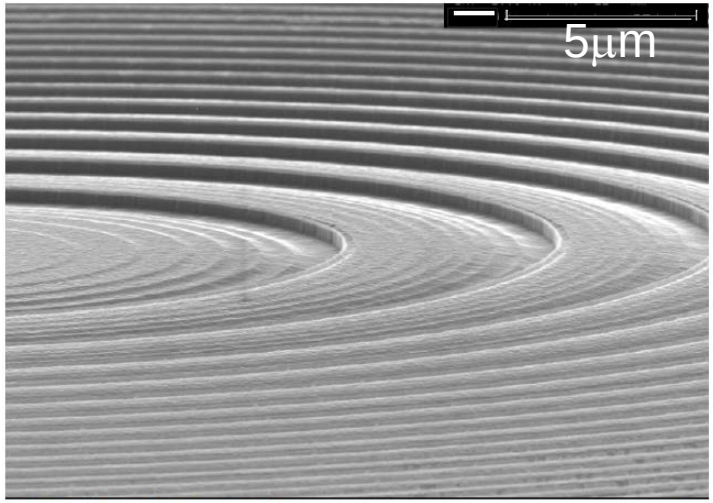
Gray-scale electron beam lithography

E-beam with variable beam stepping frequencies (i.e. variable doses)

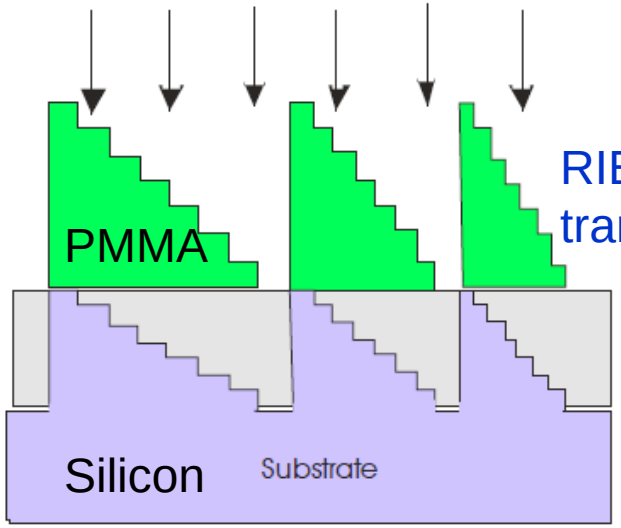


AFM of a blazed grating in resist





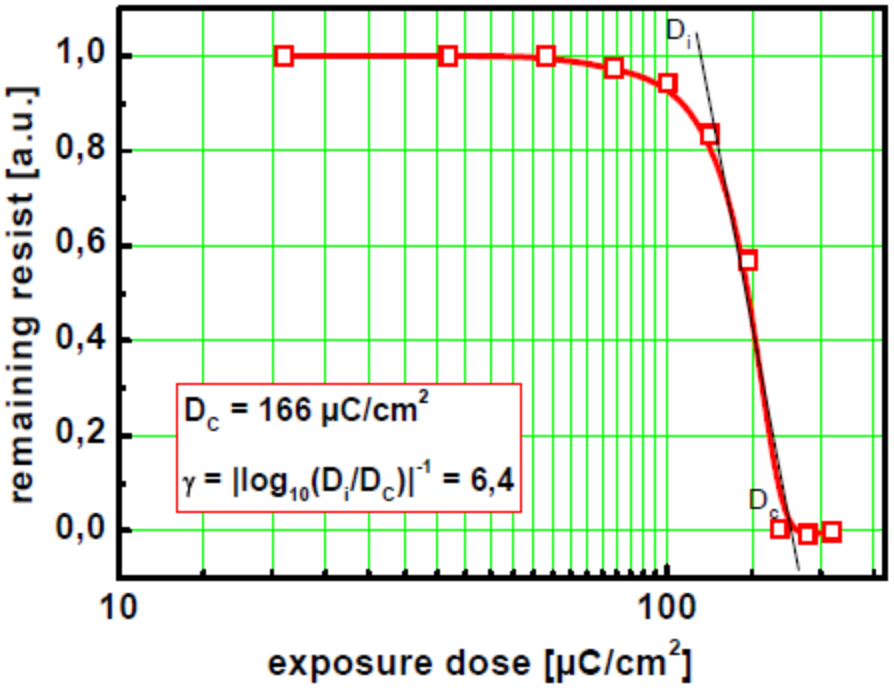
SEM of an 8-level FZL transfered into Si by analog RIE
focal length f= 62 μm @ 1,55 μm; d = 610 nm



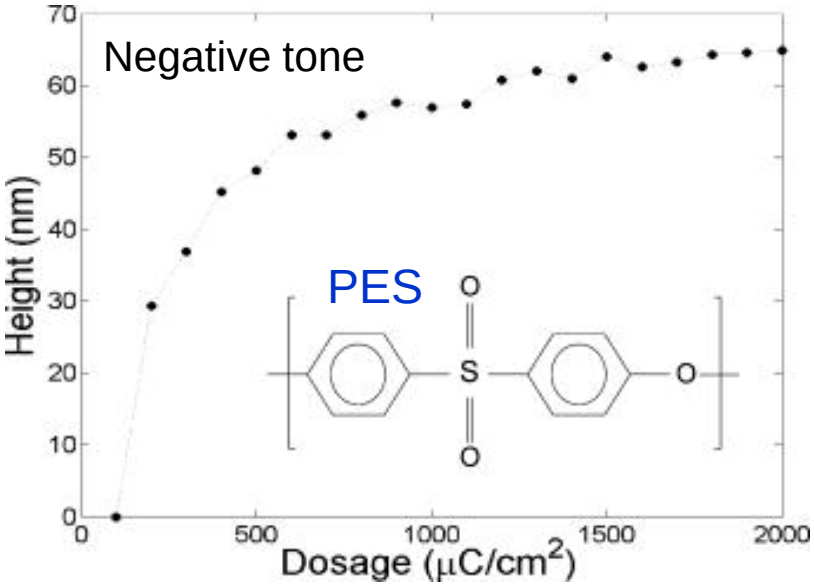
RIE pattern transfer into Si

Fresnel zone lens (plate) in silicon

Which resist is best for gray-scale EBL?



Contrast curve of PMMA

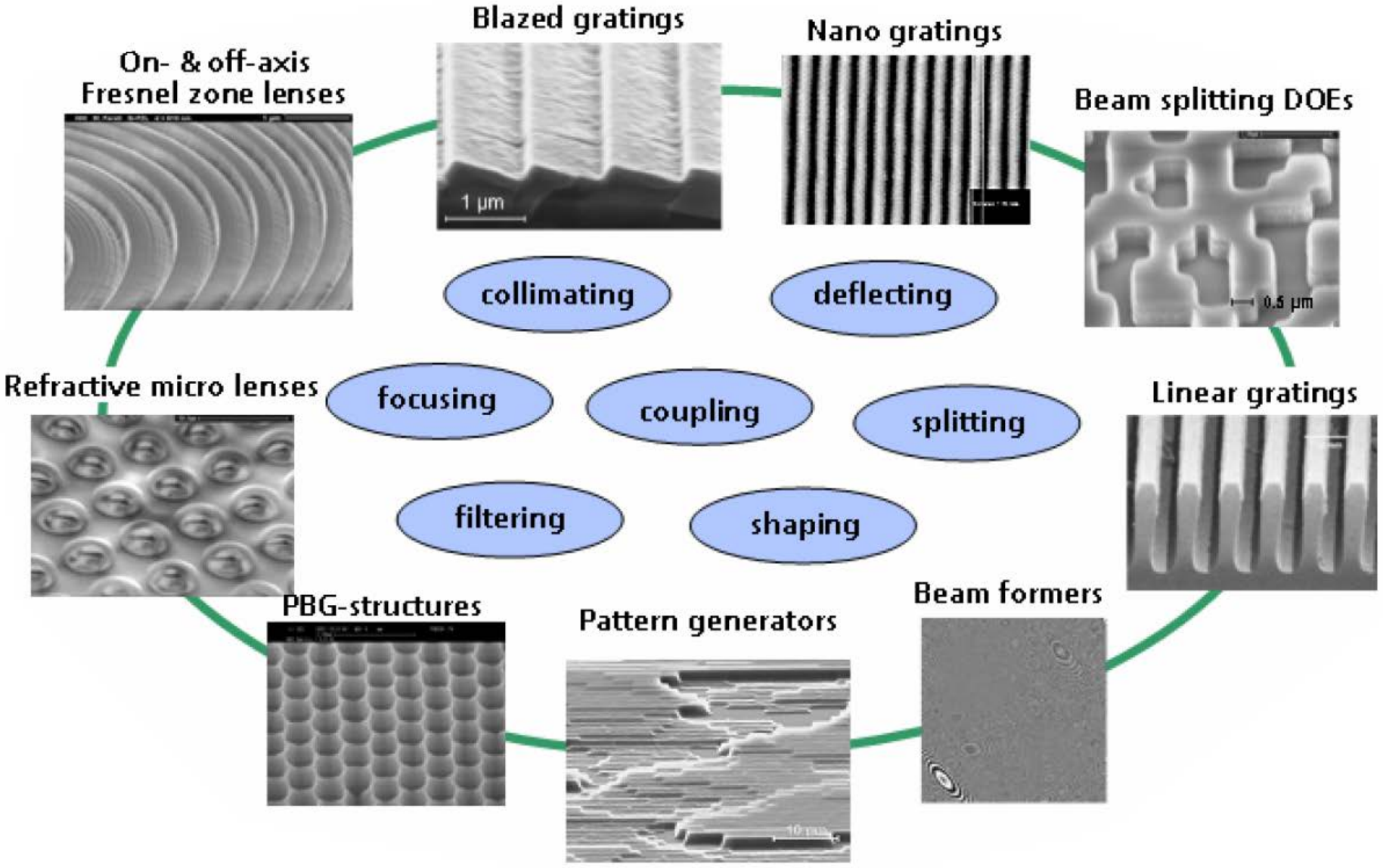


Exposure response of PES on Si wafer to 10keV electron beam. The sensitivity was found to be ~200μC/cm², with contrast only γ~0.8.

- Ideal resist has positive tone with very low contrast (ideally $\gamma<1$) and high sensitivity.
- High contrast leads to very narrow process/dose window (tiny dose change → large depth change).
- When using negative resist, make sure that the electron can reach resist bottom (otherwise, resist at bottom will be dissolved by developer, lifting off all the resist above).

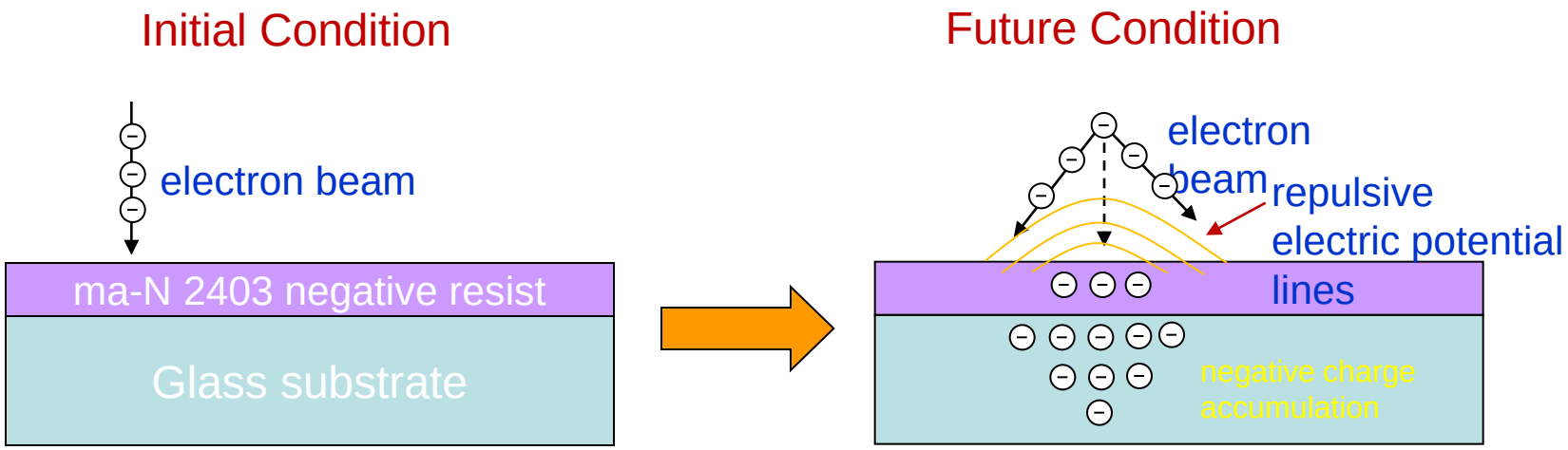
Bryce, "Poly(ether sulfone) as a negative resist for electron beam lithography", APL, 90, 203110 (2007).

Micro and nano optical elements in silicon and silica by gray scale e-beam lithography



Charging during e-beam writing

- Even though most resists are insulating, charging is not an issue for typical resist thickness of <500nm, because most electrons penetrate deep into the conducting substrate at 30kV. (more serious charging for lower kV)
- When electron beam lithography must be performed on insulating substrates (quartz, SiO_2/Si…), negative charge buildup can occur on substrate surface, causing beam deflection, and thus pattern distortion.



Anti-charging technique: coat conducting layer

- To eliminate charging effect, one can coat a conducting layer on top of or beneath the resist.
- Typically 10nm metal is enough, such as Al, Ti, Cr or Au; conducting polymer may also work.
- Lighter metal (Al) causes less (forward) scattering of electron beam than the heavier one (Au), so is preferred.
- Al and Ti can be removed easily by diluted HF (1:100 diluted).
- Some resist (such as SU-8) is sensitive to UV light generated during *e-beam* evaporation (thermal evaporation or sputtering is OK).

GOOD
(no charging)
Coat metal

BAD
(moderate charging)
ESpacer > 24 hours
(a conducting polymer?)

BAD
(severe charging)
no anti-charging layer

Anti-charging technique: variable pressure (VP) EBL

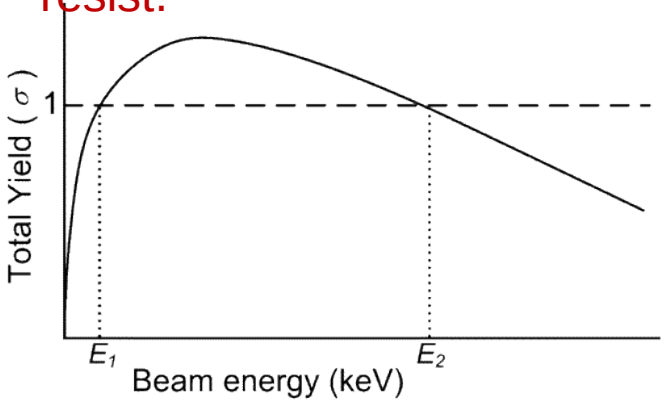
- It is the same idea as VP-SEM, i.e. introducing gas (H_2O, N_2, Ar, He) into the chamber.
- Gas molecules ionized by electron impact, these positive gas ions migrate to negatively charged surface and balance surface charge.
- Primary electron beam will be scattered to some extent by collision with gas molecules, forming a beam "skirt" around the focused primary beam at sample surface.
- Higher energy e-beam has less "skirt"; it is shown that "skirt" didn't reduce resolution.
- (For SEM only) Gas also amplifies secondary electron (SE) signal by "gas cascade" effect.

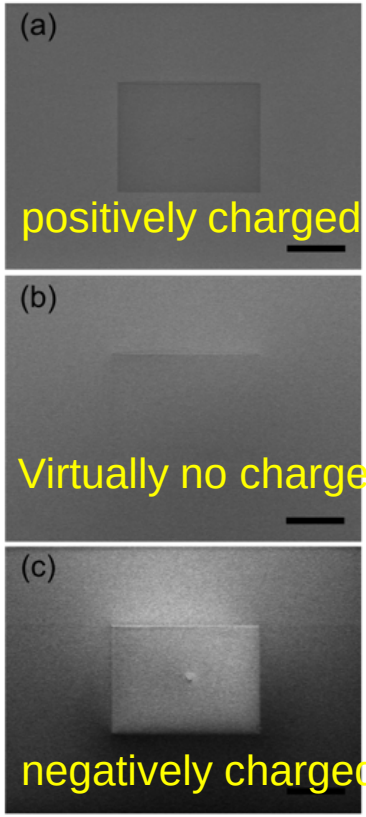
VP-SEM images of 15nm Au/Pd film patterned on a glass substrate with a 30keV primary beam energy under
a) high vacuum
b) 0.4 Torr (water vapor pressure)
c) 1 Torr
The dashed red line indicates the pattern dimensions as written.
The pattern exposed with 1Torr pressure shows no significant distortion or displacement.

"Variable pressure electron beam lithography (vp-ebl): A new tool for direct patterning of nanometer-scale features on substrates with low electrical conductivity", Nano Lett. 6(5), 963-968(2006).

Anti-charging technique: critical energy EBL

Total electron yield (σ) vs beam energy for a typical resist.





How to find E_2?

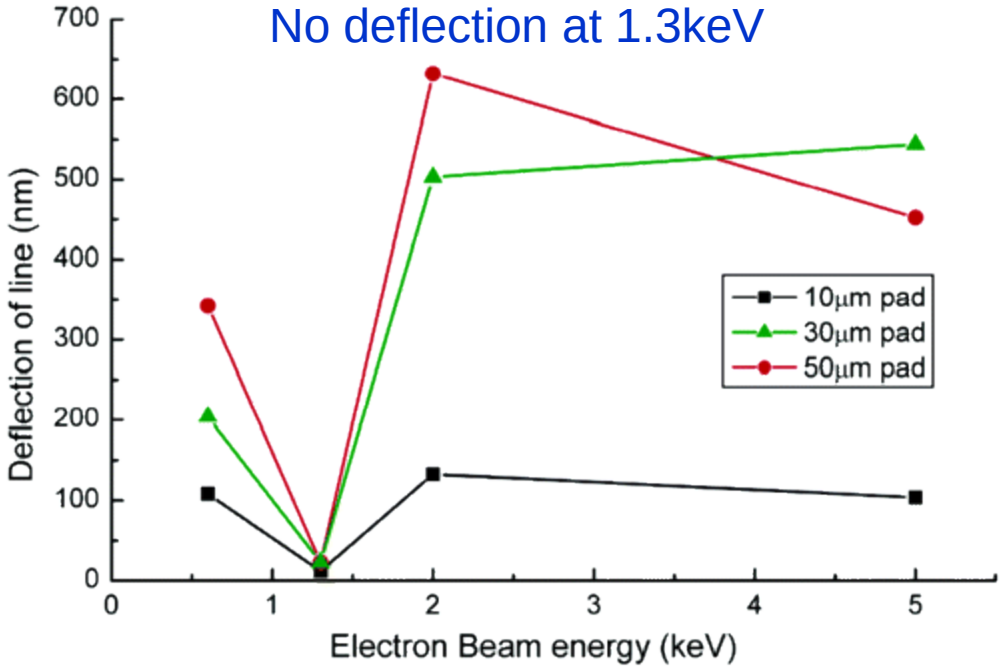
"Scan square" or variable magnification SEM images after dropping the magnification from ×500 to ×200.

a) 0.5keV
b) 1.3 keV
c) 2.0 keV

- Bulk insulating material is positive charged when σ > 1 and negatively charged when σ < 1. Charge buildup is zero at critical energy/crossover voltage (E_1, E_2), where σ is unity.
- In between, σ>1, so >1 electron (including SE and BSE) ejected for each incident electron.
- E_1 is too small, E_2 depends on resist thickness and substrate material.
- For 65nm PMMA on glass, E_2=1.3keV. Such low kV can penetrate such thin resist.

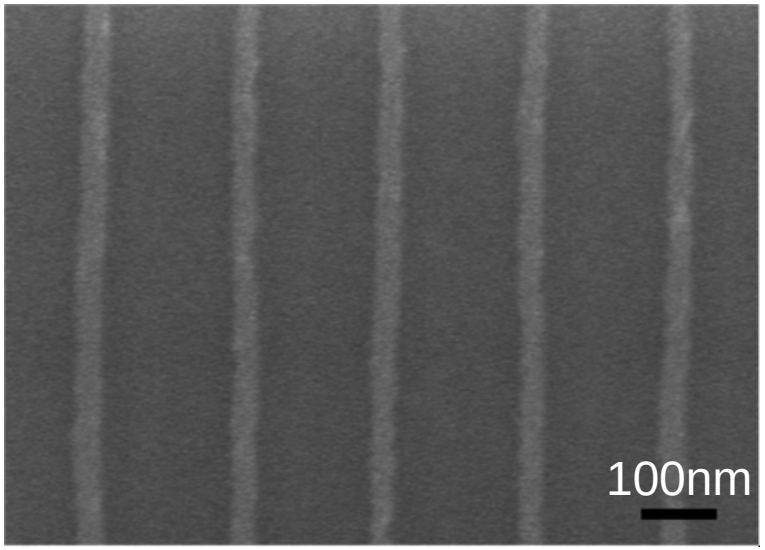
"Nanoscale Patterning on Insulating Substrates by Critical Energy Electron Beam Lithography", Nano Lett. 6(9), 2021-2025 (2006).

Anti-charging technique: critical energy EBL



Line deflection determined by SEM measurement at various voltages based on methods reported by Craighead.
(Two parallel single-pass reference lines were first patterned with a 1μm gap, followed by charge pads written at 30μC/cm^2. Finally, a third single-pass line was patterned between the pad and the reference line)

Result of EBL writing



SEM images of 5nm thick Au after lift-off. The minimum feature size was 60nm with an area dose 10μC/cm^2.