Quantum Noise Effects in e-Beam Lithography and Metrology

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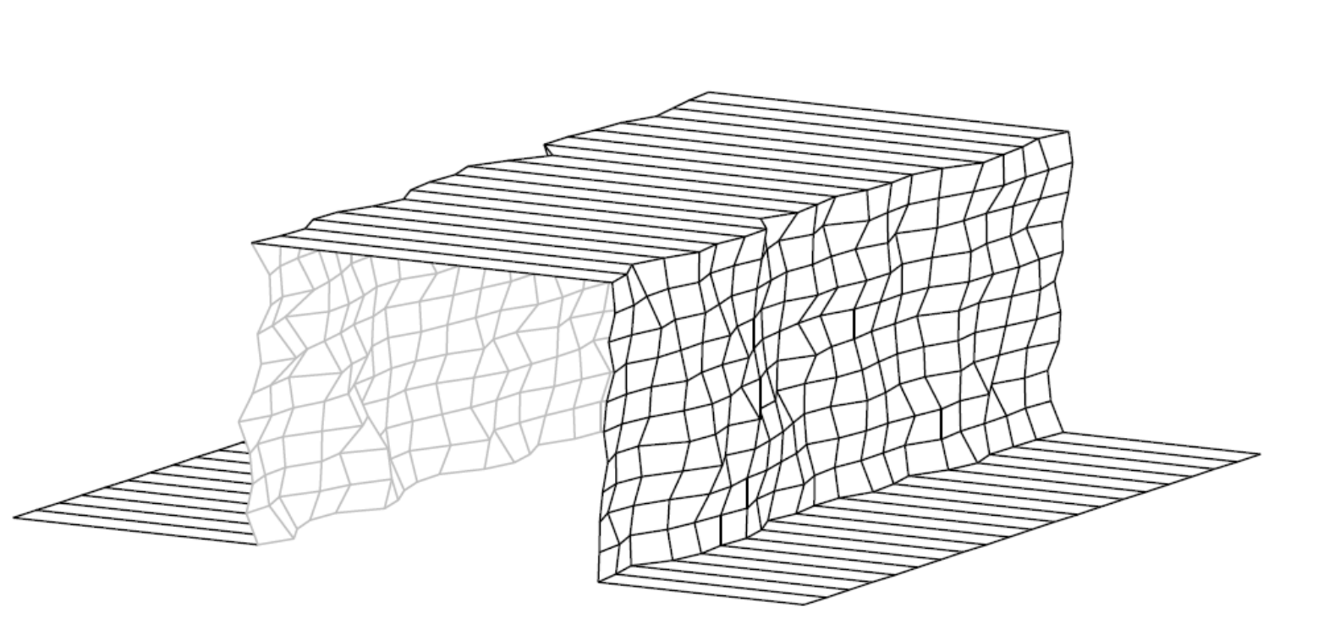
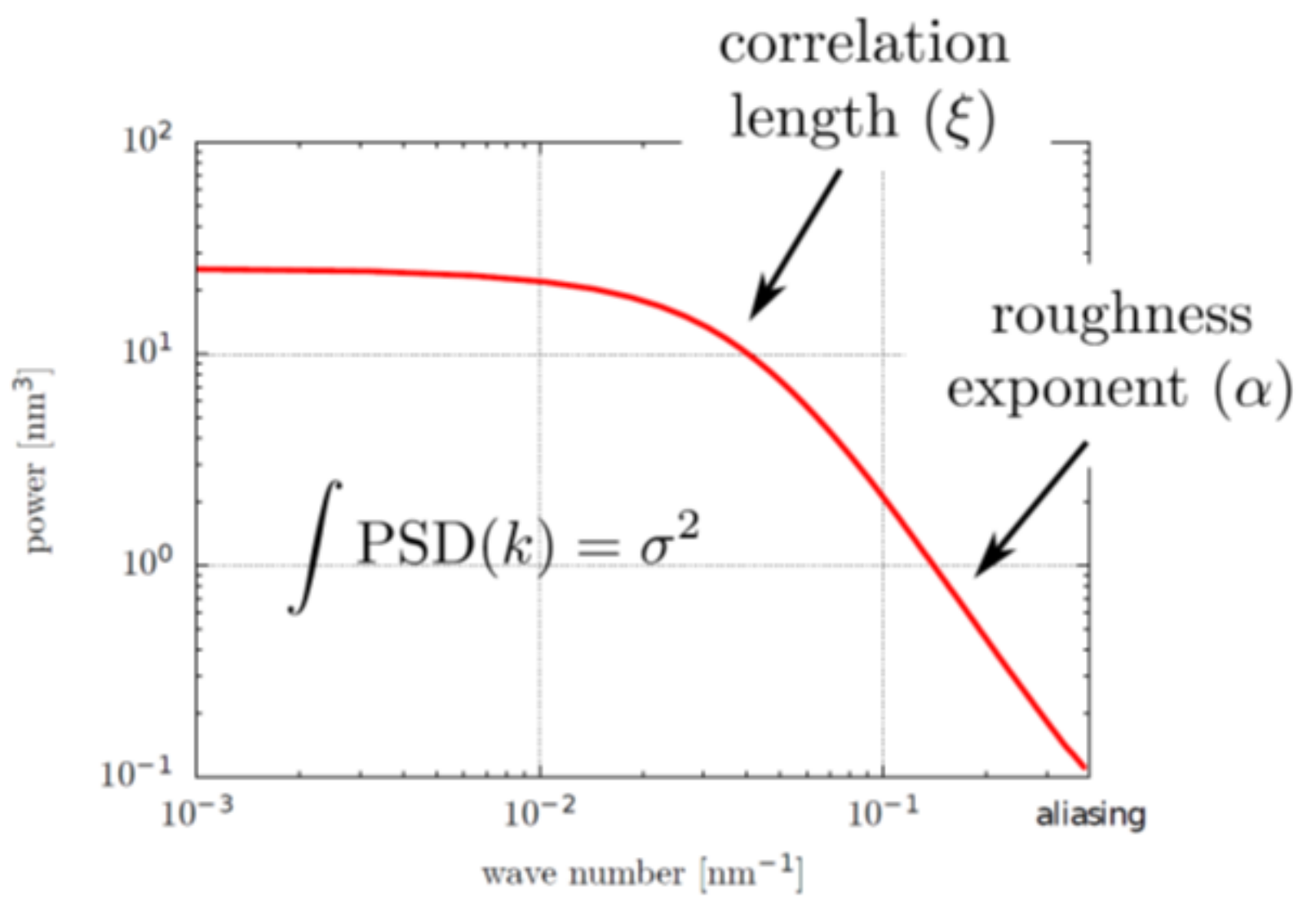
In lithography Line Edge Roughness (LER) and Critical Dimension (CD) determine the throughput through the resist sensitivity, and therefore tool investments - Three questions are addressed:

1.Does a CD-SEM measurement of LER really tell us what we want to know?

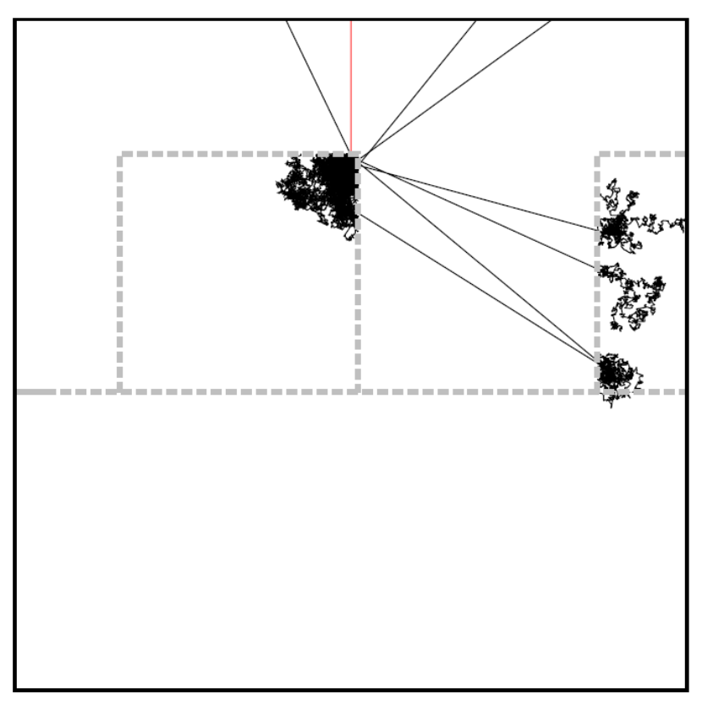
1. Construct PMMA lines on Si with rough sidewalls ….



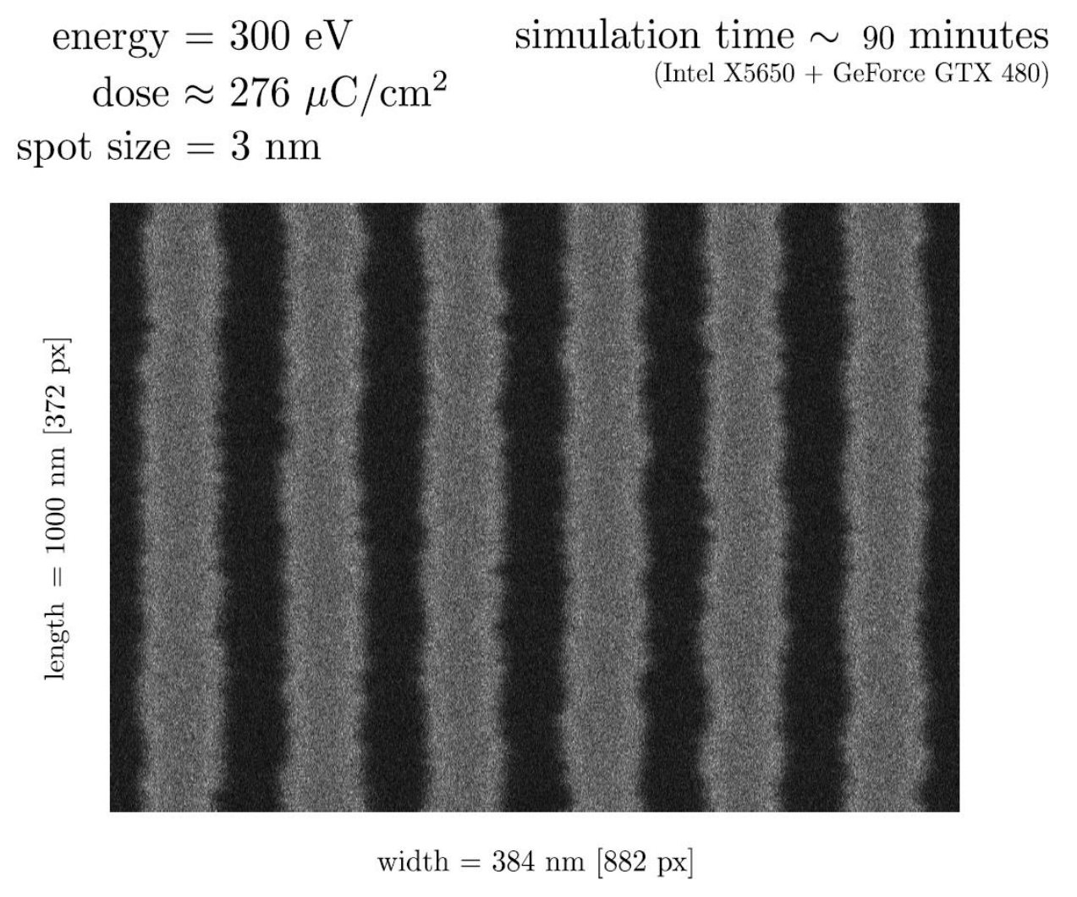
…. using a roughness model



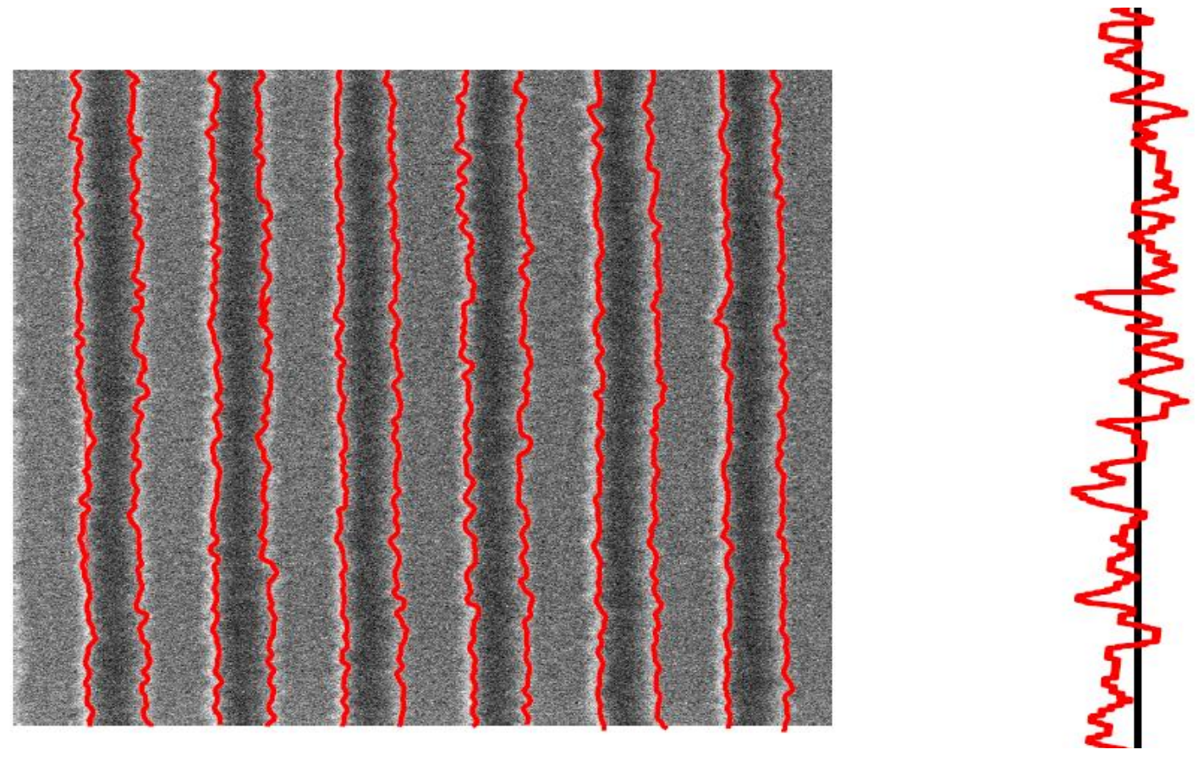
2. Use electron-scattering Monte Carlo simulations ….



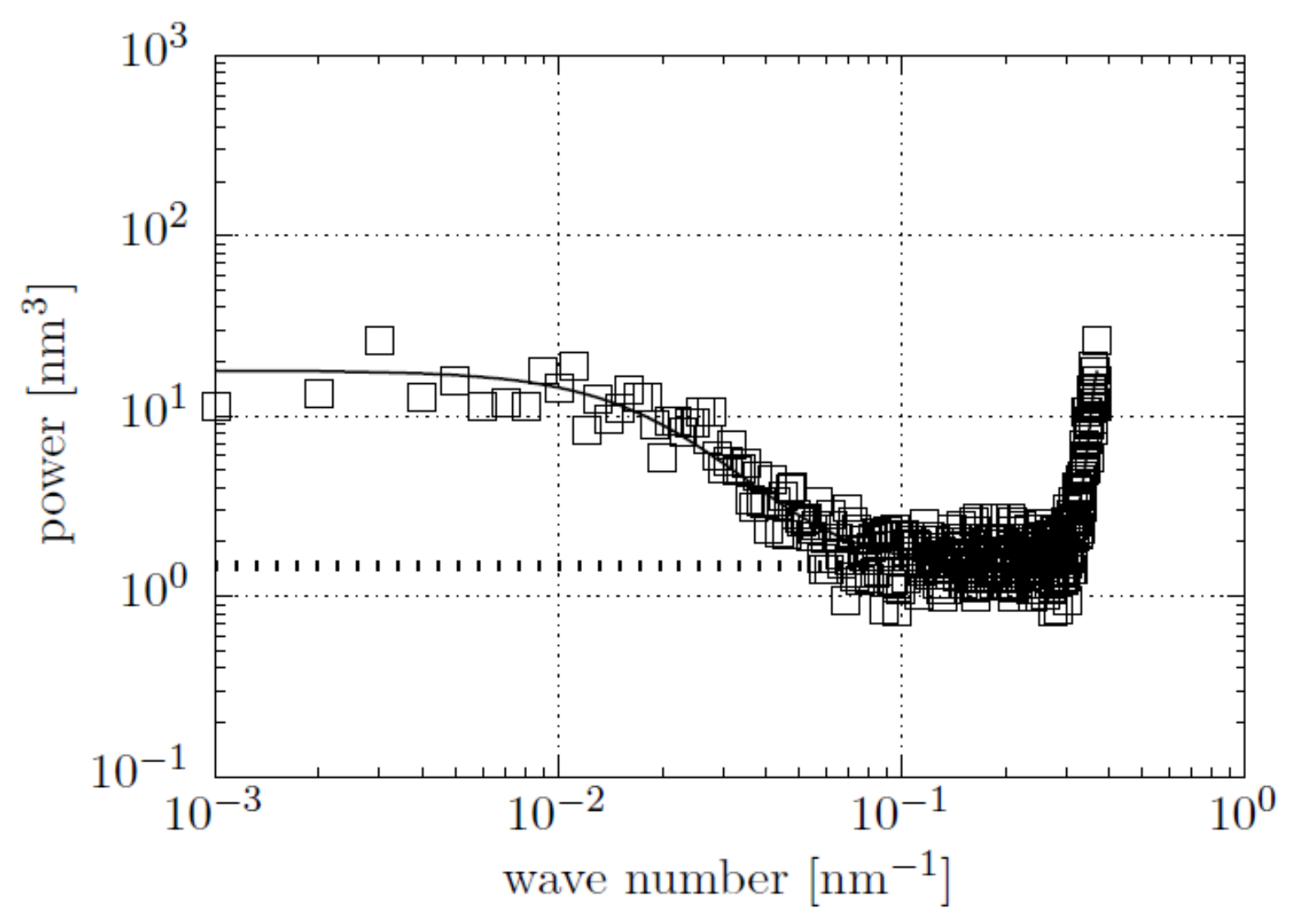
…. to simulate SEM images and add Poisson noise



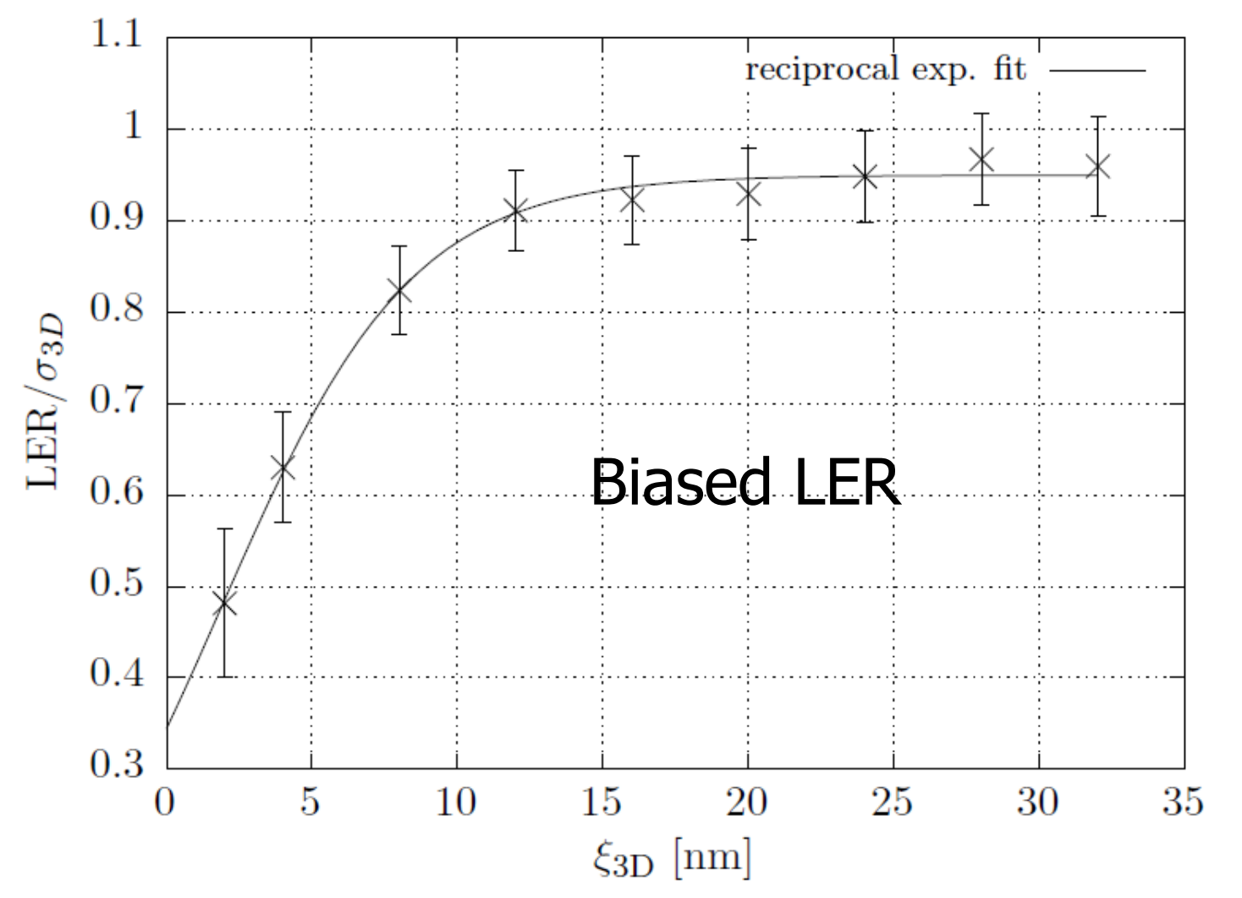
3. Determine LER, as a function of the parameters, from these top-down SEM images ….



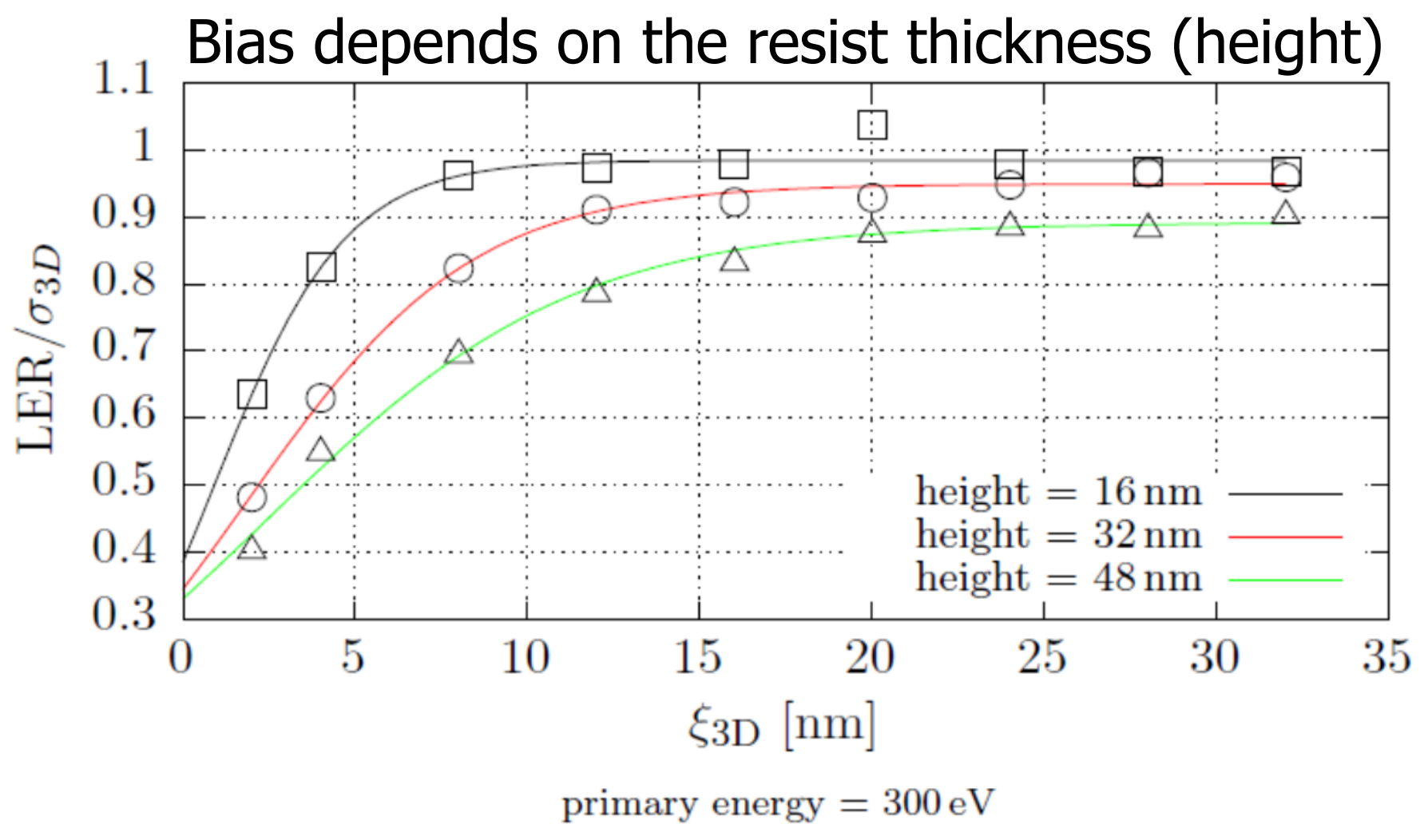
…. using a power spectral density analysis



4. Results



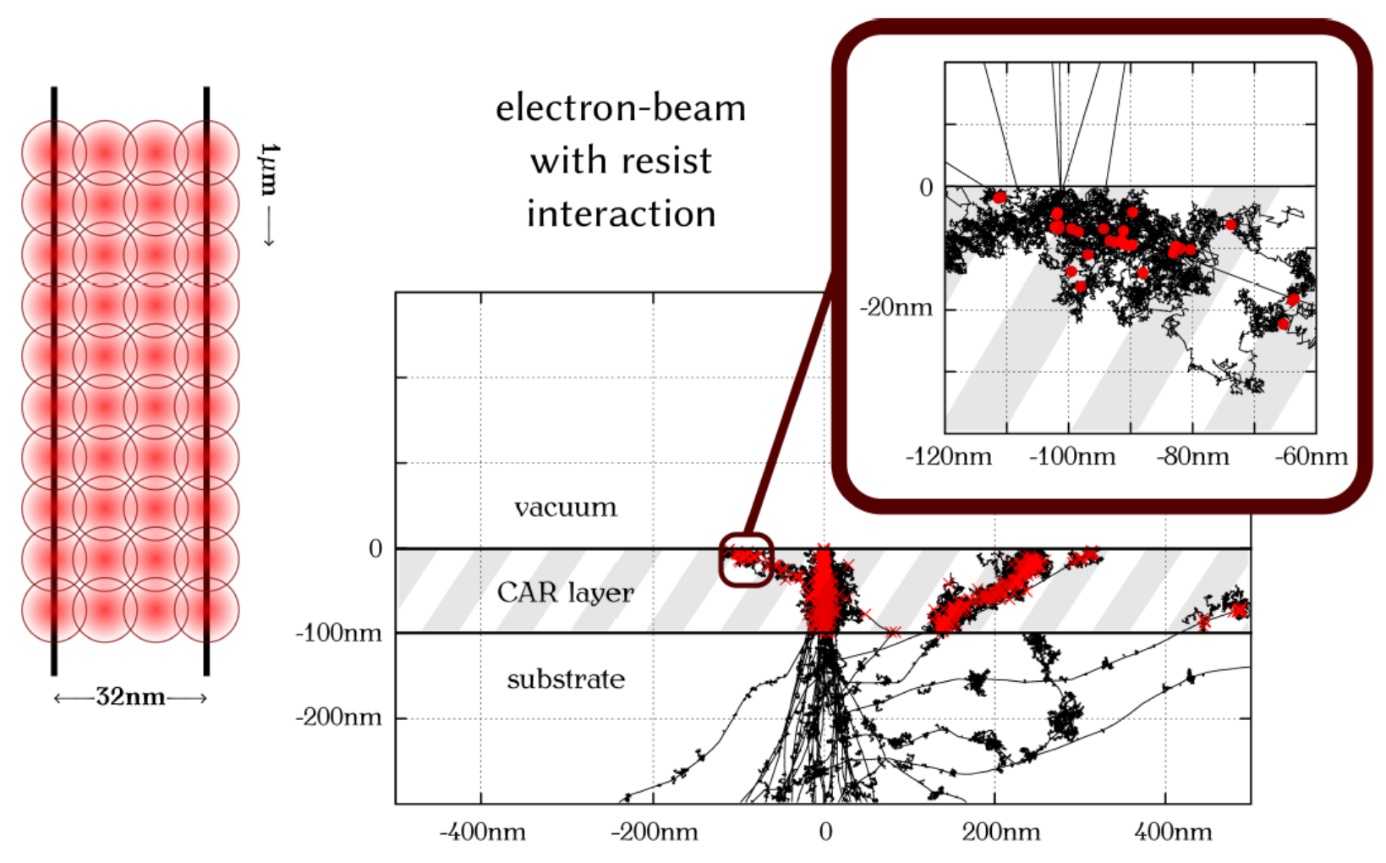
Bias depends on the resist thickness (height)



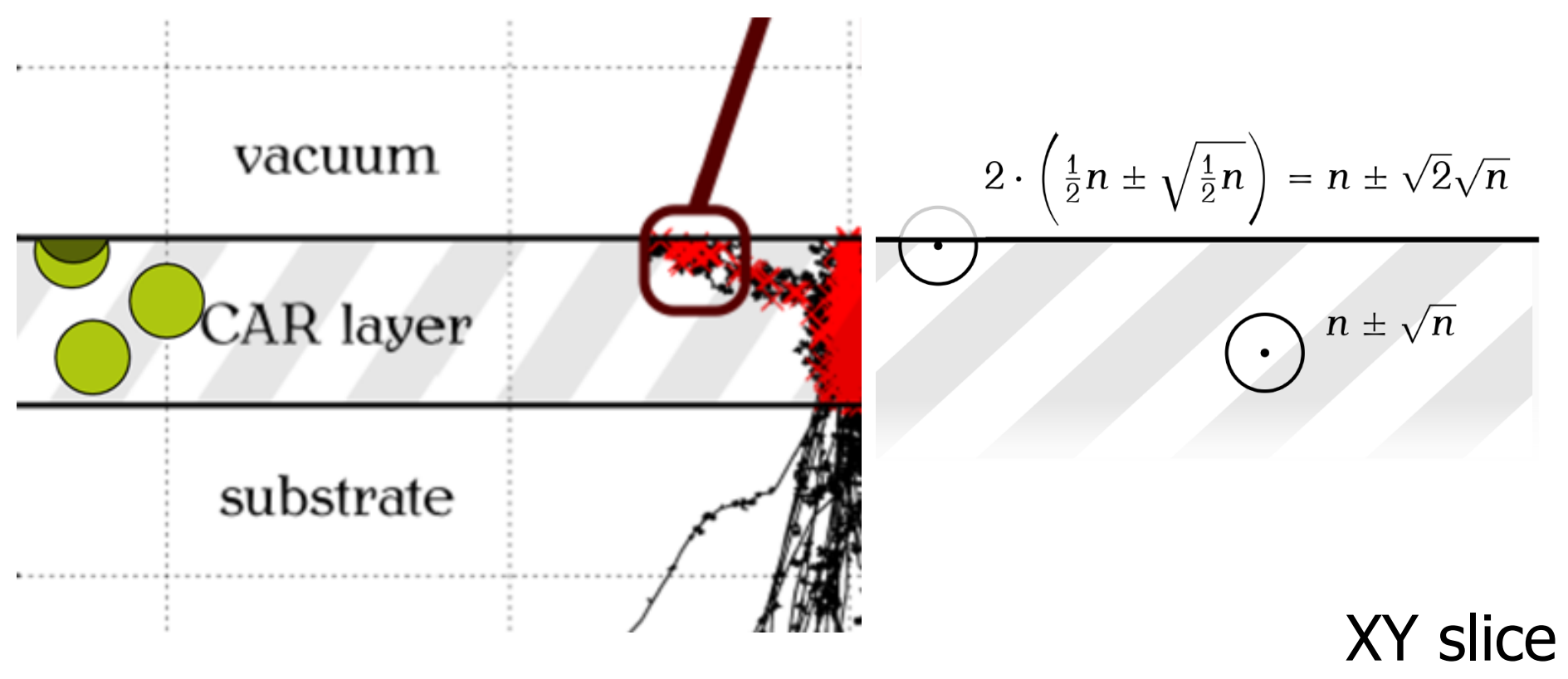
LER is biased: be careful to base throughput (resist sensitivity) on LER measurements

2. Can we simulate the relation between the actual shape of the resist line and the CD measurement?

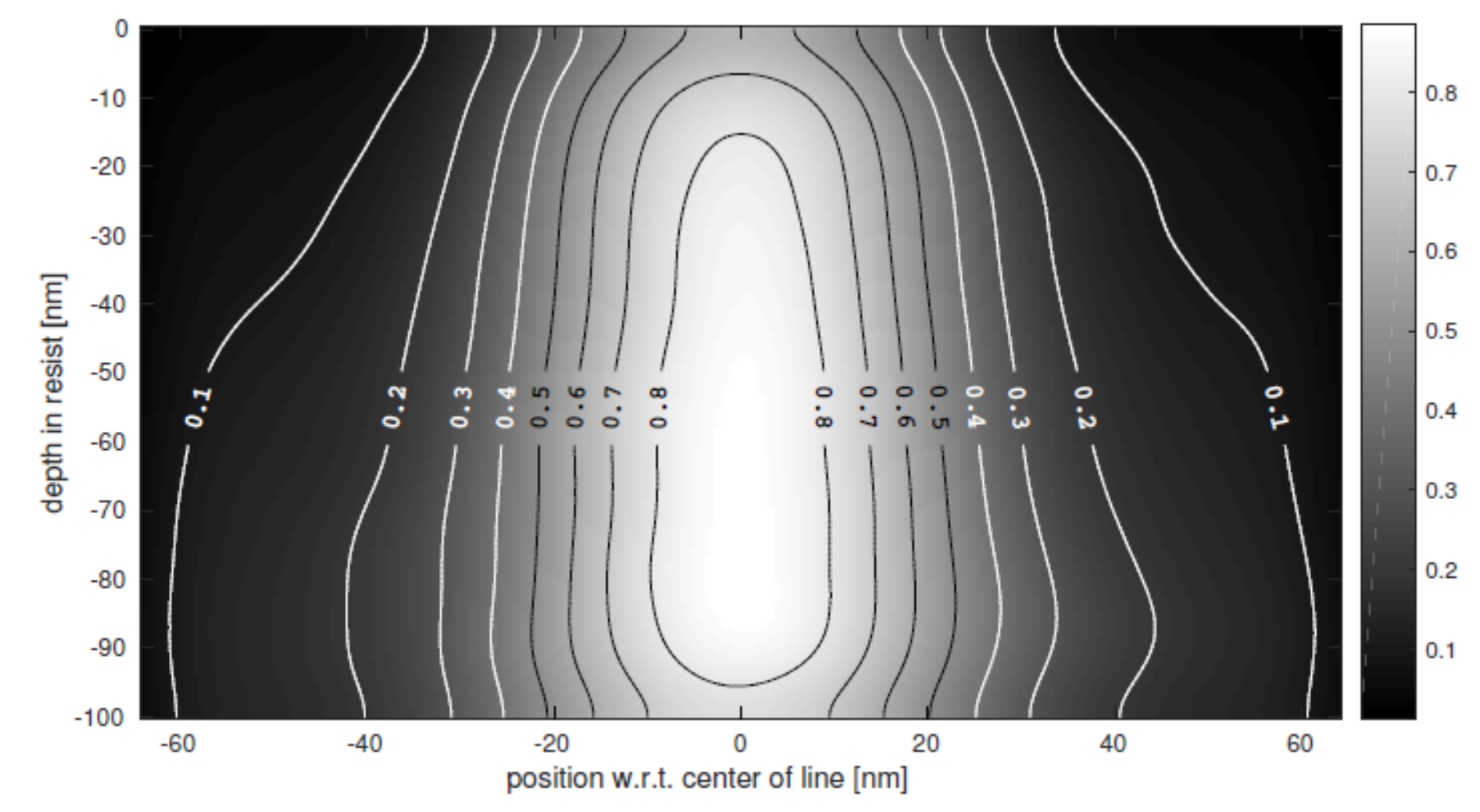
1. Acid generation at every inelastic interaction, no stochastics from PAG distribution, no roughness from molecular size distribution (only possible on GPU: 2.000 primary electrons in parallel; 100.000 scattered electrons in parallel)



2. Simulate acid diffusion during post exposure bake, substitute each acid by a 3D Gaussian distribution, mirror acid diffusion at the resist surfaces

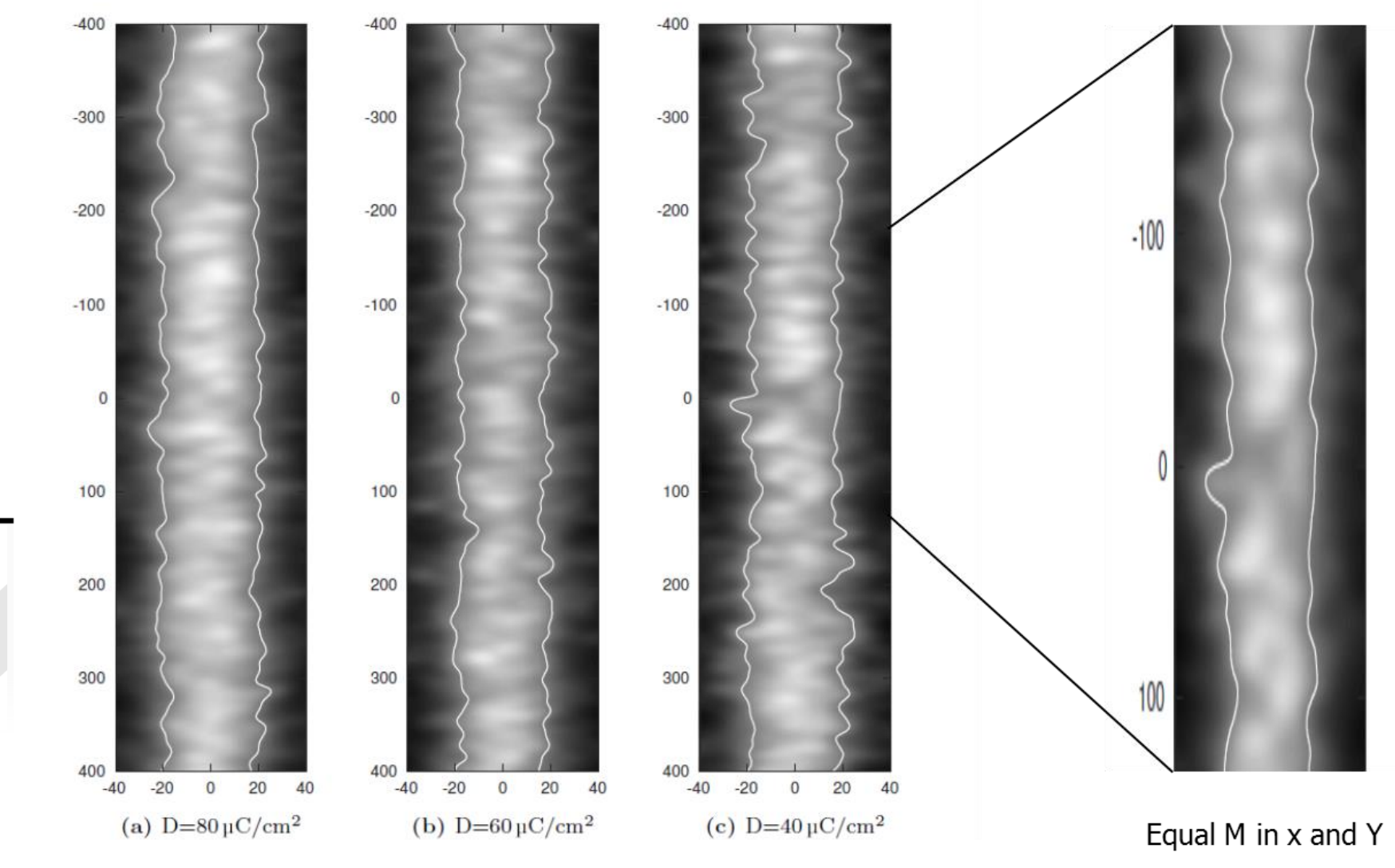


3. Determine equal solubility surfaces



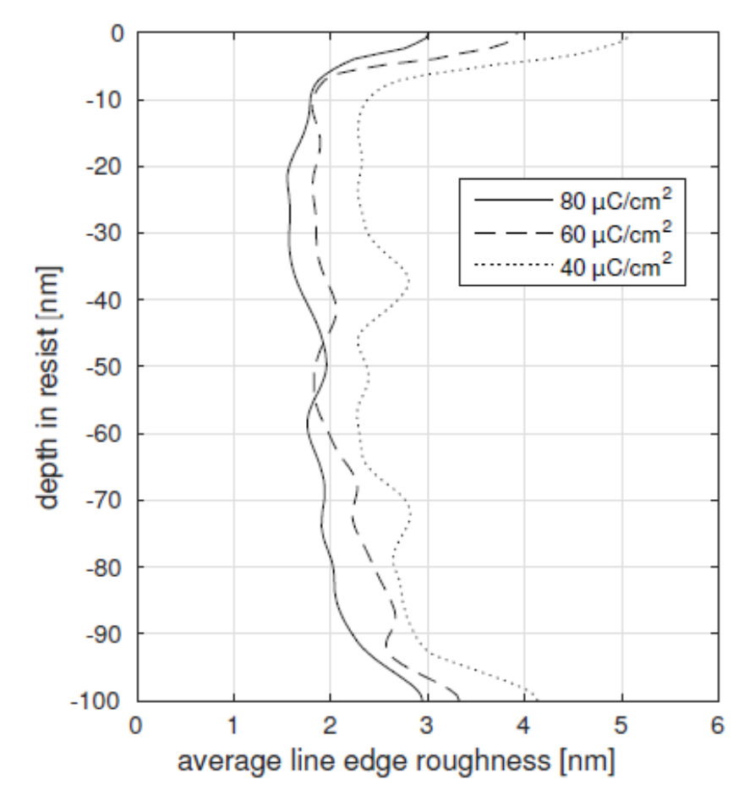
20 kV electrons; spotsize FW50%=10.5 nm, exposure 32nm x 1 μm; $\sigma_{\mathrm{diffusion}}$ =5 nm

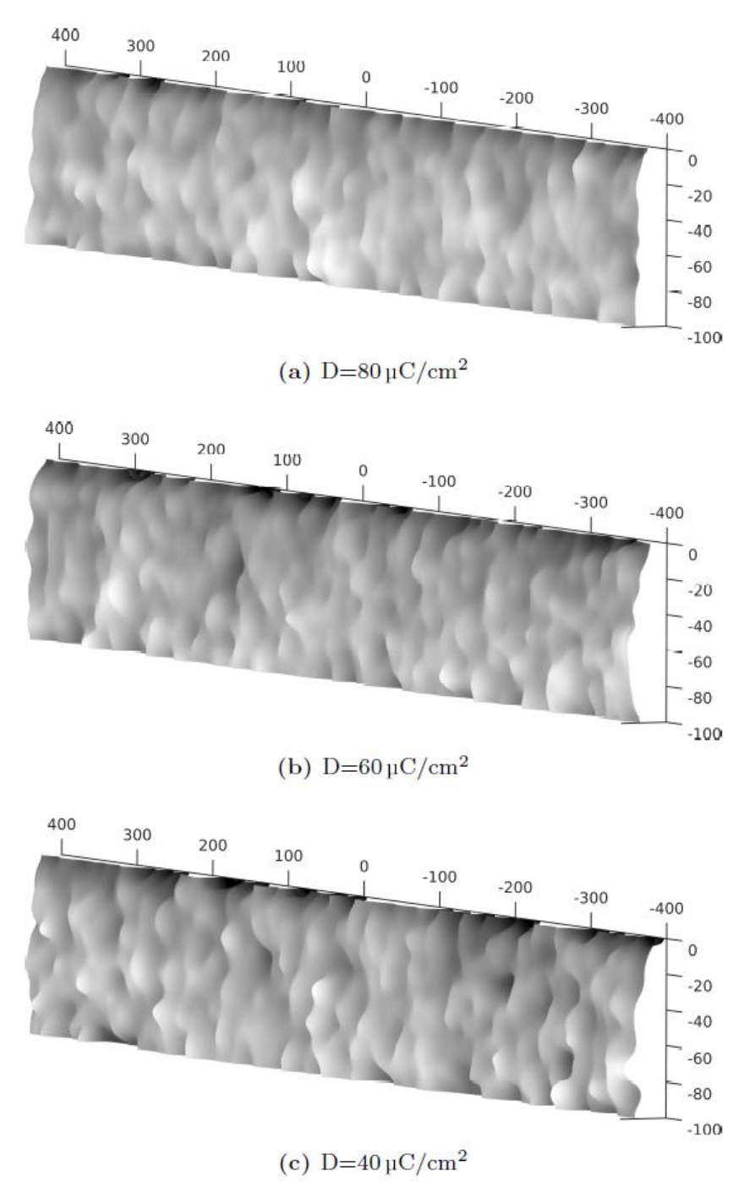
Narrower at the top because SE's escape, at the bottom because fewer SE's are created in Si than in PMMA



XY slice at 50 nm from top surface. White line is threshold at 0.5

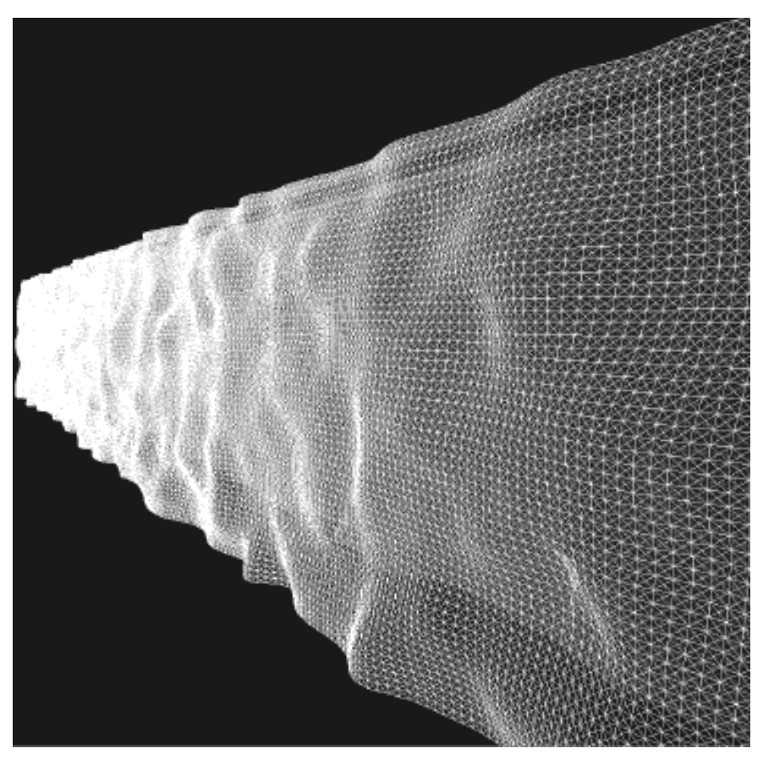
4. Determine LER as a function of depth



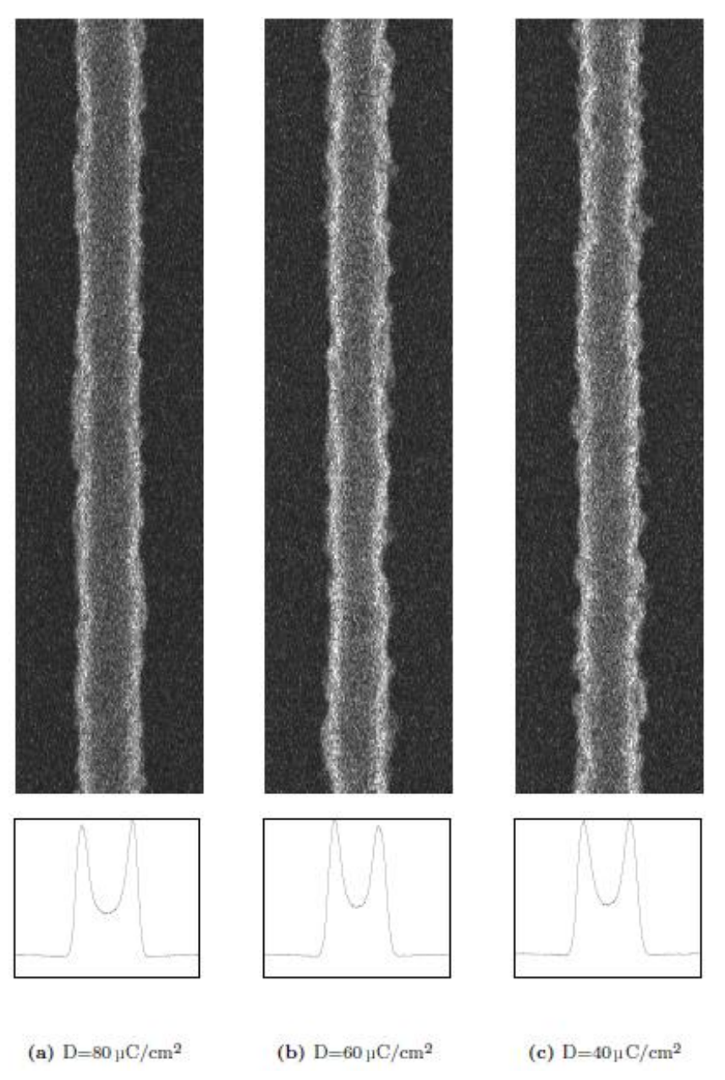


3D-view of the solubility surfaces; threshold at 0.5

5. Triangulate the solubility surfaces, ….



… simulate top-down SEM images and determine the LER

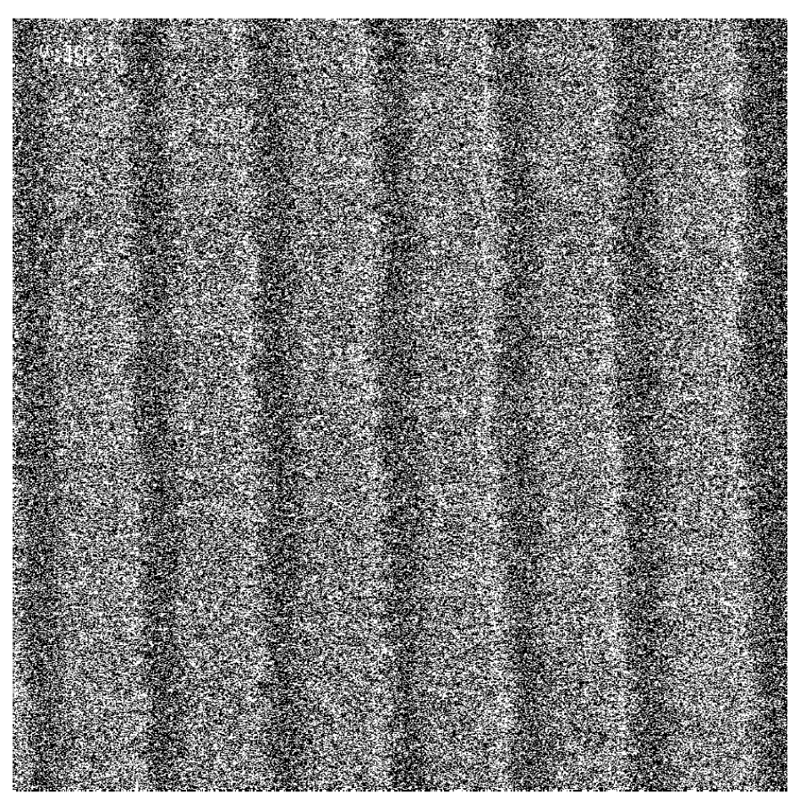


exposure dose [μC/cm^2]	imaging energy [keV]	LER [nm]
80	0.5	1.32 ± 0.13
80	1.0	1.24 ± 0.12
80	5.0	0.98 ± 0.10
60	0.5	1.63 ± 0.16
60	1.0	1.56 ± 0.16
60	5.0	1.24 ± 0.12
40	0.5	1.72 ± 0.17
40	1.0	1.56 ± 0.16
40	5.0	1.32 ± 0.13

LER increases at lower dose (shot noise)
LER decreases with imaging energy

3. Is a CD SEM LER measurement reproducible?

1. Exposure in the CD SEM brings about changes in the resist. Therefore we try to measure at minimum dose

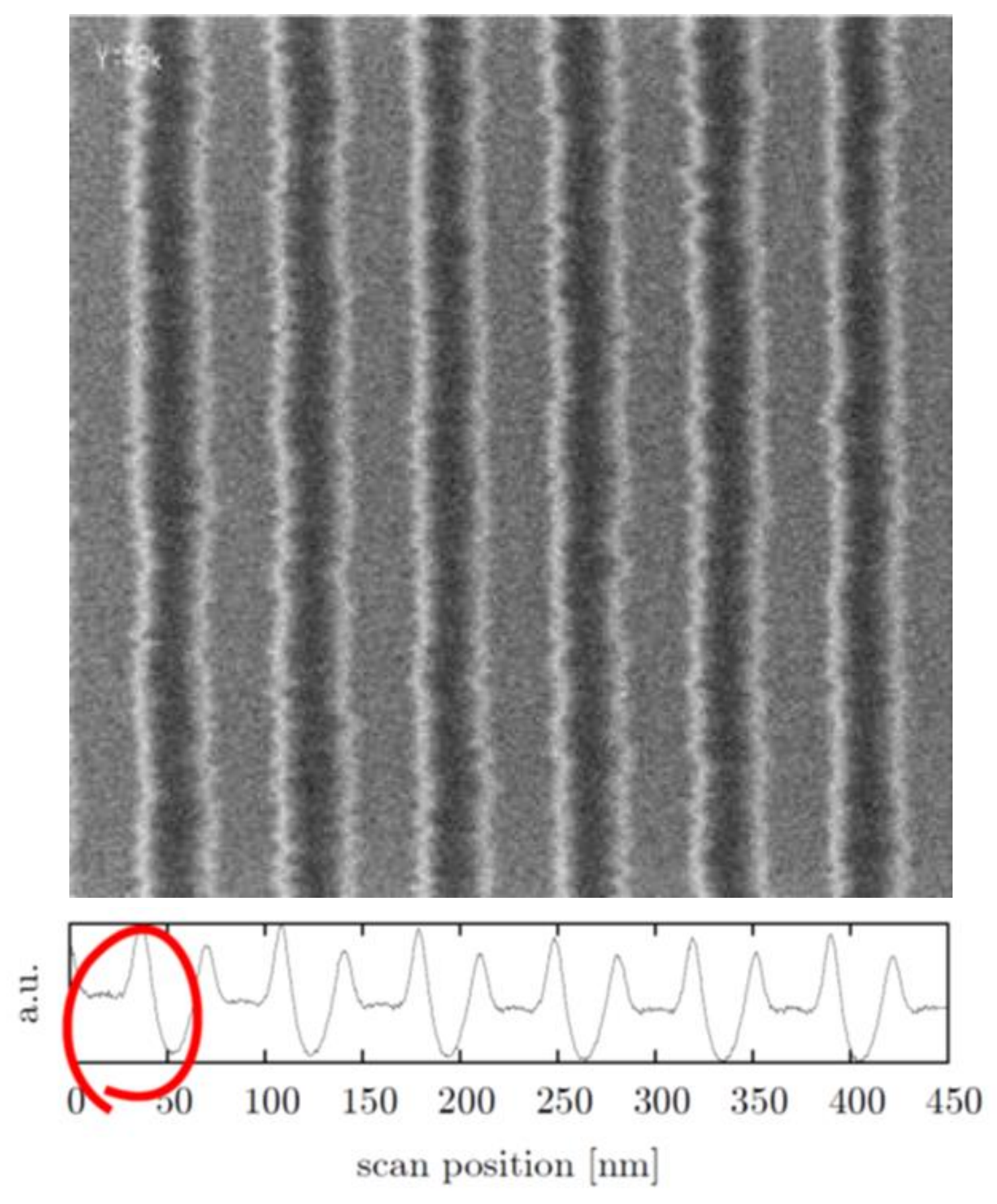


Images acquired at lowest possible dose of a Hitachi CG4000 CD SEM by I.Servin of CNRS-LTM/CEA-LETI

300eV, 10pA corresponding to 1 electron/nm ^{2}, or 16 μC/cm^2

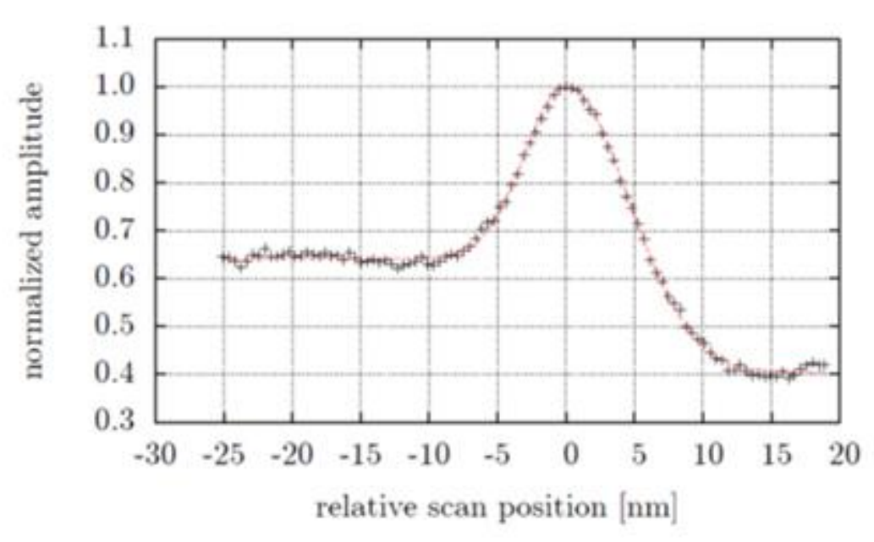
Pitch = 72 nm

2. We integrate the line pattern along the line-direction



Integrated line profiles

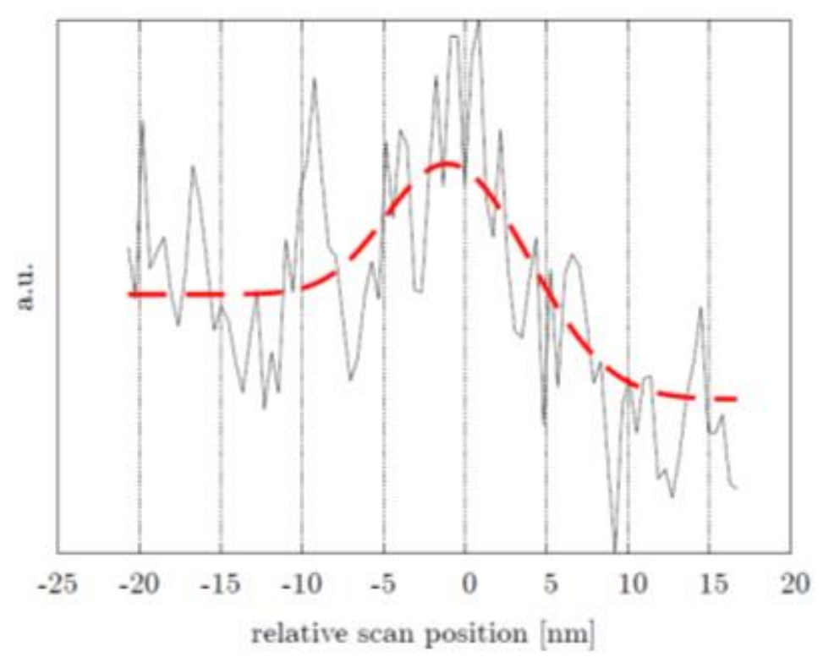
3. Fit the integrated line profile to a model which contains the x-position …



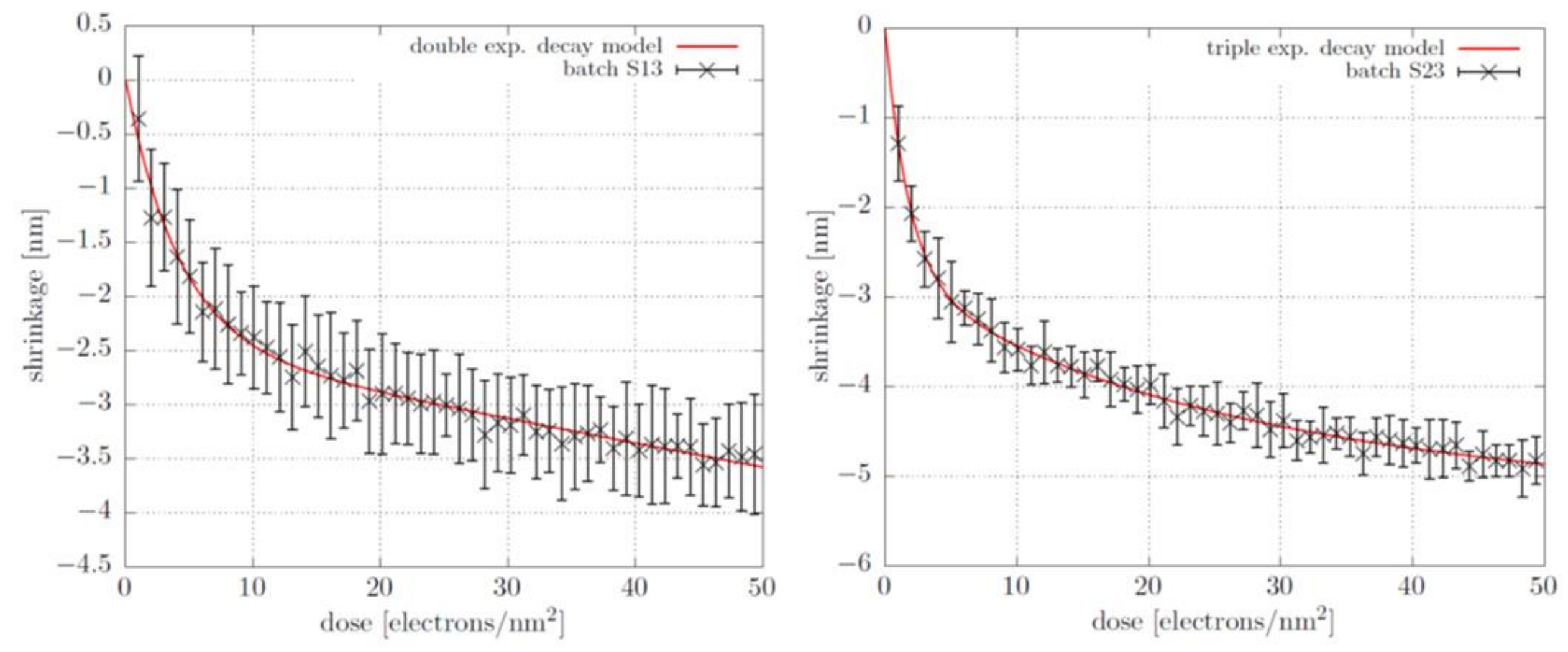
Introduce a model based on two merged Gaussians :

$$P(x) = \begin{cases} b_L + (1-b_L)\exp\left(-\frac{1}{2}\frac{(x-\mu)^2}{\sigma_L^2}\right) & x < \mu \\ b_R + (1-b_R)\exp\left(-\frac{1}{2}\frac{(x-\mu)^2}{\sigma_R^2}\right) & x \geq \mu \end{cases}$$

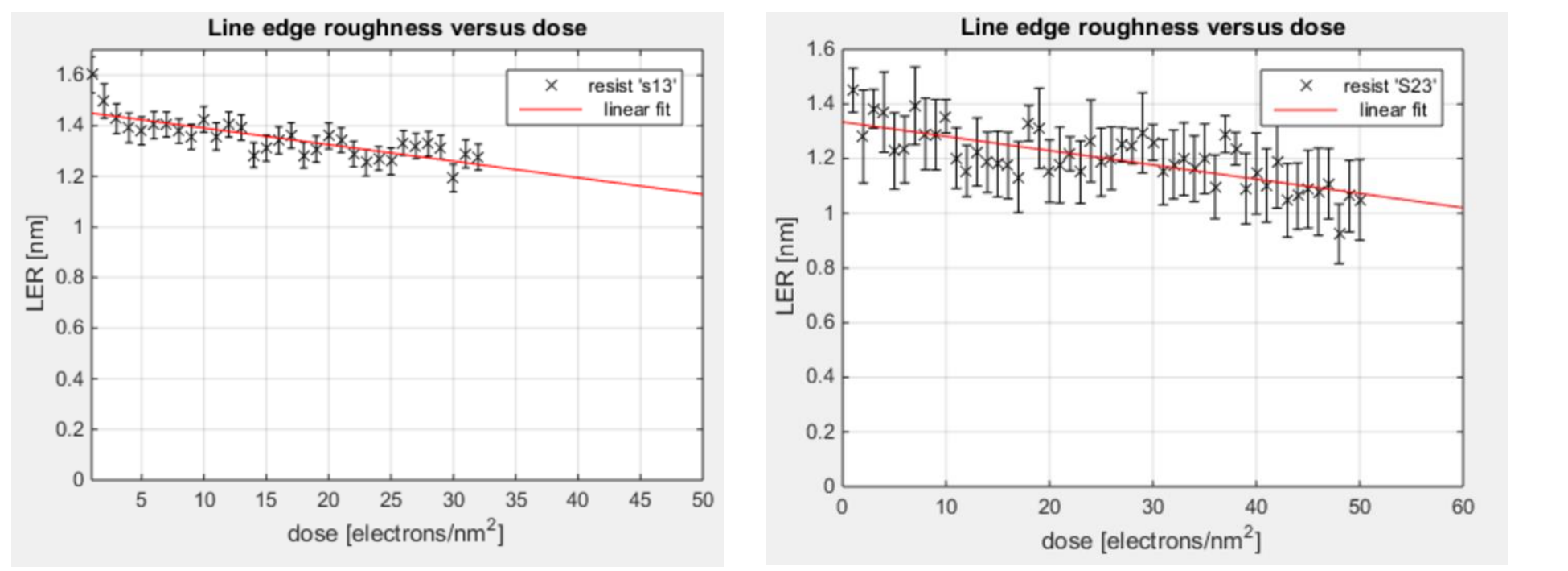
… to find the position of the edge at every z position



4. Results. Severe resist shrinkage within what is a normal acquisition dose (10 electrons/nm^2 = 160 μC/cm^2)



Some LER reduction at higher dose



Severe resist shrinkage in the very first few frames of CD SEM imaging

References:

- T. Verduin, P. Kruit, C.W. Hagen, J. Micro/Nanolith. MEMS MOEMS **13** (2014) 033009
- T. Verduin, S. R. Lokhorst, P. Kruit, C.W. Hagen, Proc. of SPIE **9424** (2015) 942405-1
- T. Verduin, S. R. Lokhorst, C.W. Hagen, P. Kruit, Proc. of SPIE **9778** (2016) 97781Z-1

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