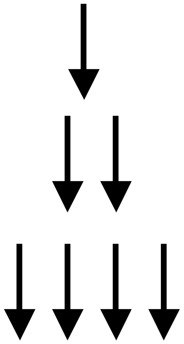
Shot Noise in Imaging

- Known problem for 100 years: photography, television, scanning electron microscopy
- Recognized in lithography >30 years ago

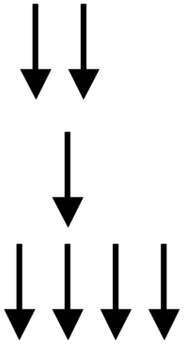
Goal of lithography: Put the resist edges in the right places (economically).

EXAMPLE: Raindrop lithography (Kruit and Hansen, 2007) :

Best possible case:
Each primary event gives rise to many secondary and tertiary events (e.g photomultiplier).



Worst possible case:
Each primary event gives rise, on average, to less than 1 secondary event (e.g. most SEM pictures)



AT BEST:

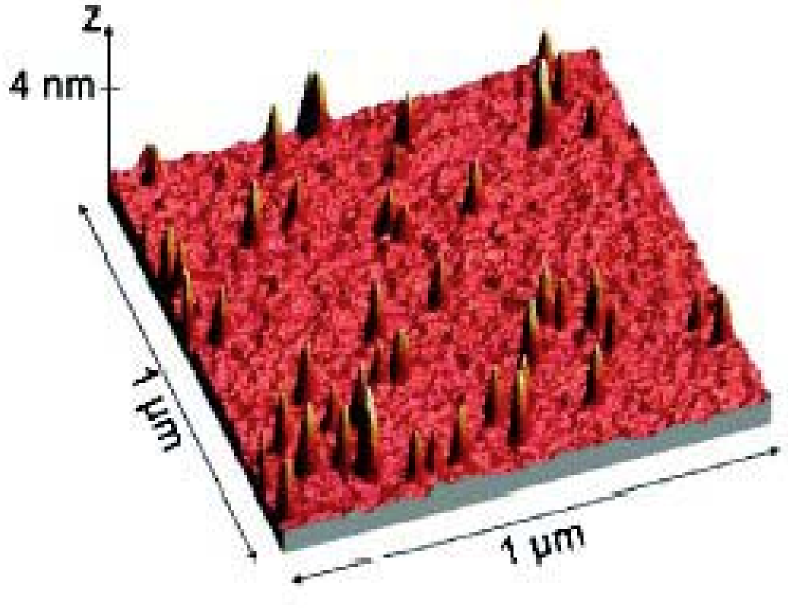
$$SNR \,\alpha\, \sqrt{\bar{n}}$$

mean rate of ocurrence of least frequent events

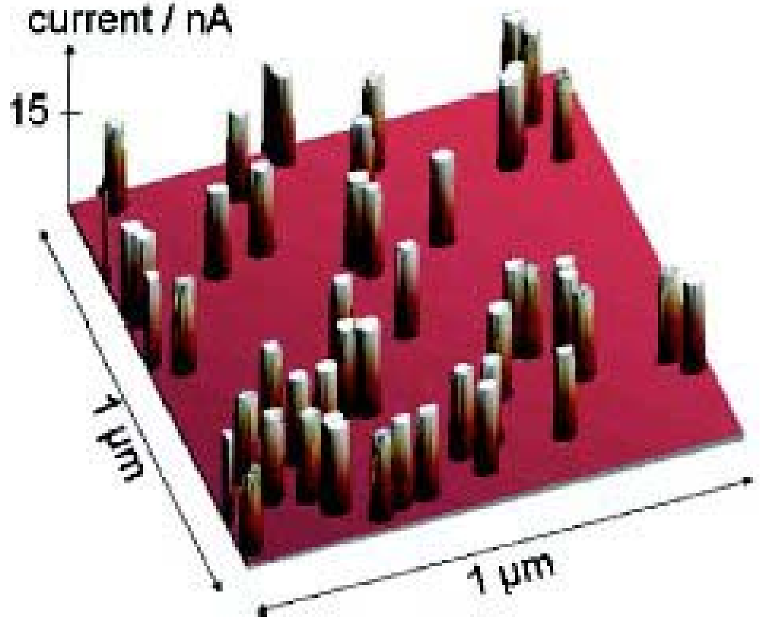
But even the varying number of tertiary events adds noise to the original noise in the exposing beam (classical shot noise). No amount of amplification can reduce it.

Now the SNR can be no better than that given by the Poisson distribution of the secondary events.

Direct observation of shot noise in patterning; ion tracks



Images of single ion impacts on diamond-like carbon..
Top: topographic contrast.
Lower: conductance contrast arising from the graphitization of the DLC by the ions.
Europhysics News (2004) Vol. 35 No. 5
Ion tracks – a new route to nanotechnology
Alois Weidinger, Hahn-Meitner Institute Berlin, Germany



No reports of ion tracks in developed polymeric resists (?)

- One test pattern:

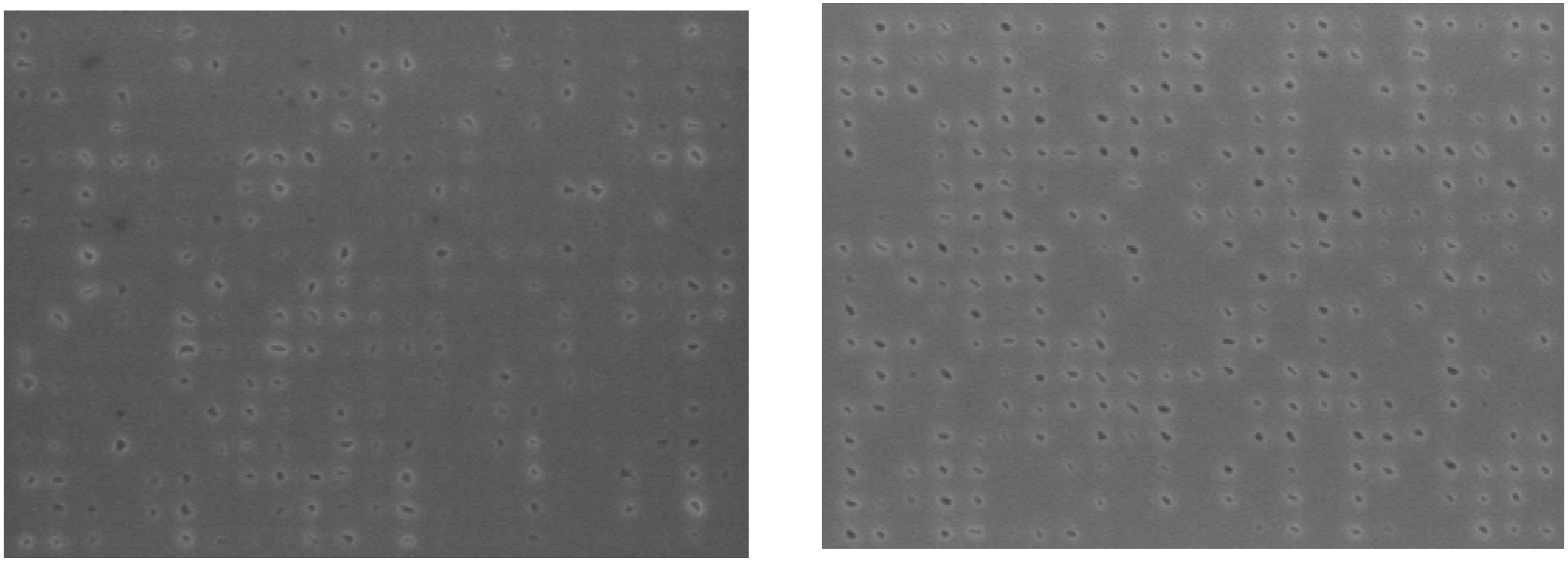
Array of minimum features.

Measure area of each and compile a histogram. Tedious.

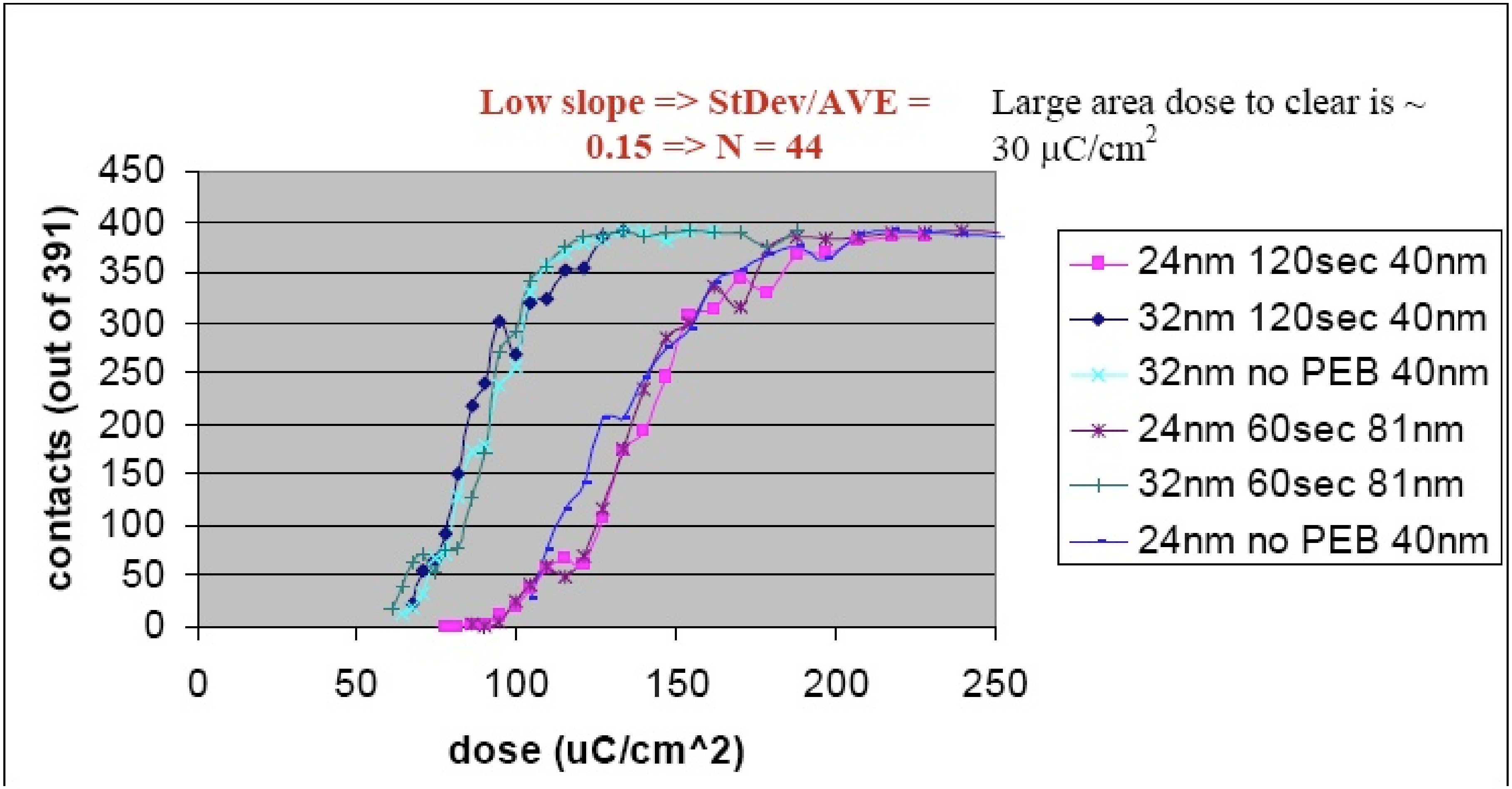
- Alternative:

observe clearing of minimum features (vias) as a function of dose.

One Attempt to observe effect of shot noise in developed resist; count the number of cleared vias as a function of dose



Examples of exposed and developed features on 100nm centers. Note the different appearance of cleared and uncleared features (Courtesy A. Neureuther, J. Alex Liddle and Marshall Miller).



Low slope => StDev/AVE = 0.15 => N = 44

Large area dose to clear is ~ 30 $\mu C/cm^2$

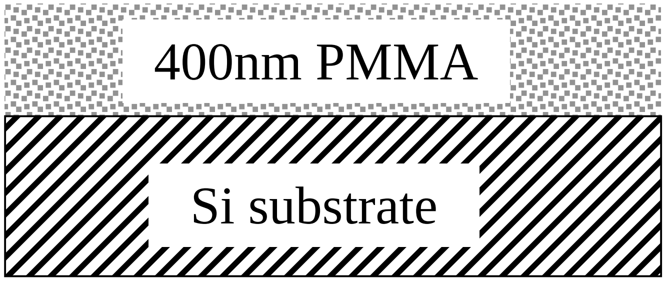
Fig. 4b Printed Contacts versus Exposure Dose. Note the higher dose required at smaller features such that number of electrons to clear 50% is about the same for 24 and 32 nm features. No significant difference was found with PEB time or resist thickness

Low slope of curve suggests that factors other than classical shot noise dominate.
Need 0.25mC/cm2 to be 'sure' of clearing 24nm via; 10,000 electrons/via.(40KeV)

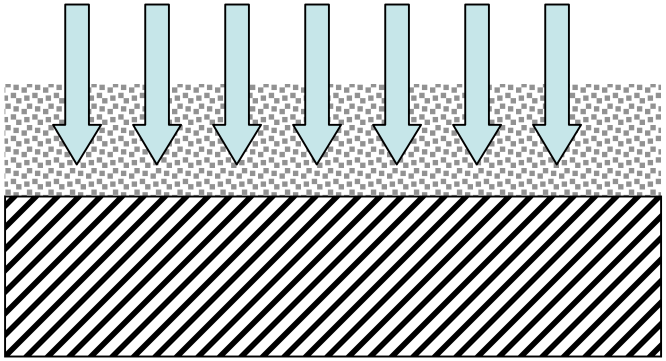
Avoid the exposure tool problems:
Measure roughness of development front of flood exposed resist

(Karen Tedesco), Bing Dai

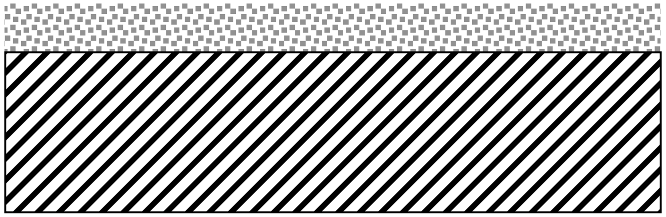
Starting sample:



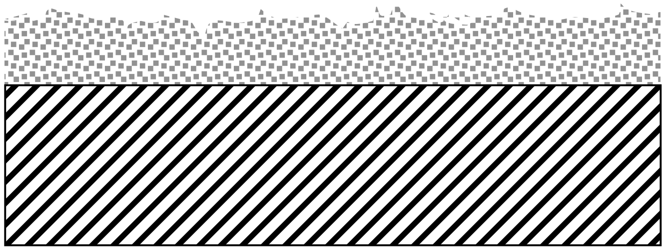
Expose uniformly:



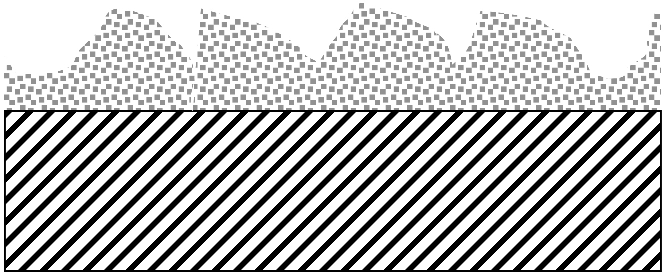
Partially develop and examine in AFM.
If we are shot noise limited, we expect to see the profiles below:



Light
$\sim 10^{4}$quanta.nm^{-2}



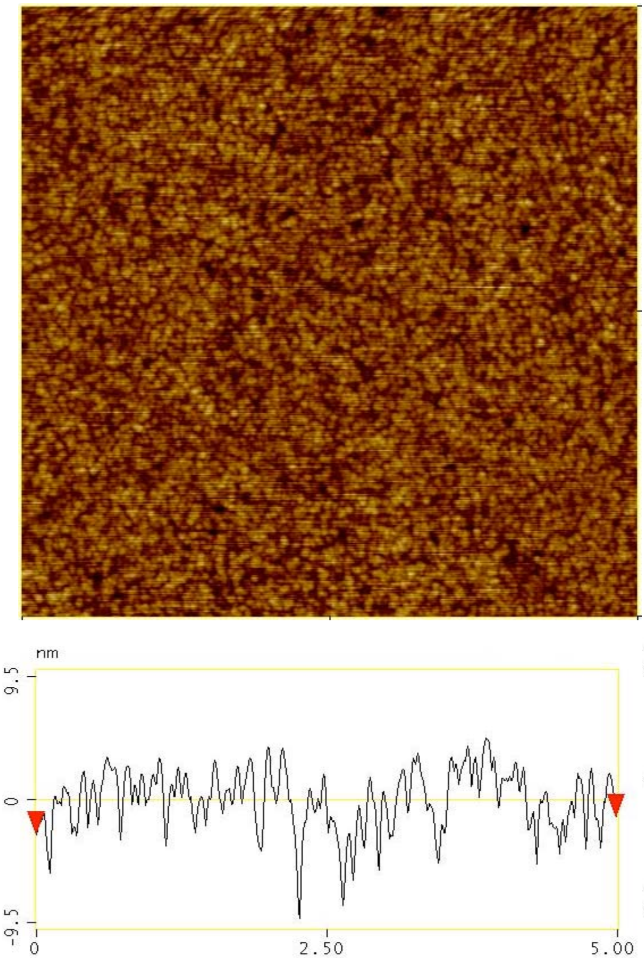
Electrons
~10quanta.nm^{-2}



Ions
<<1quanta.nm^{-2}

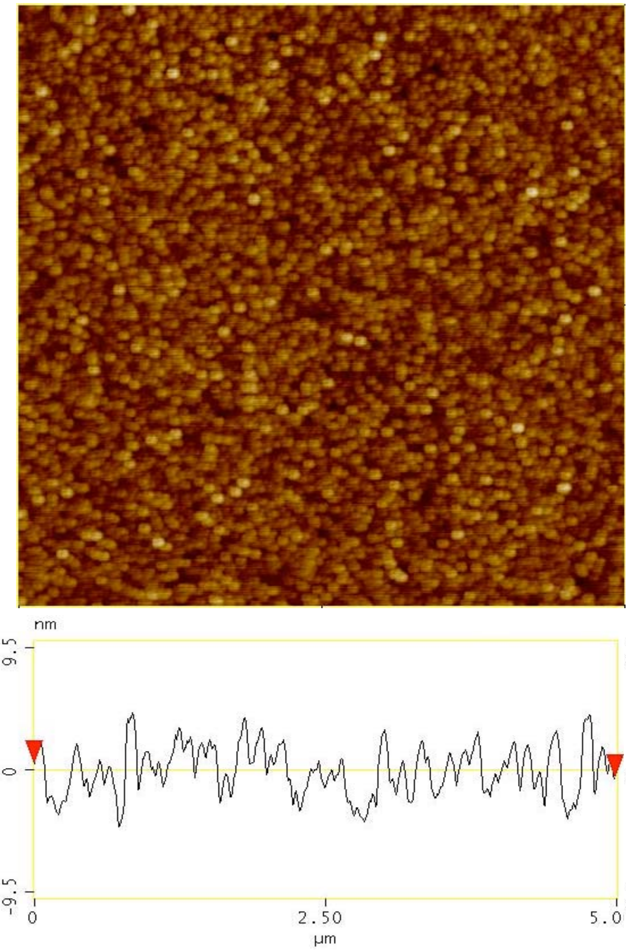
Experimental Results

Ar$^+$ ions at 200keV



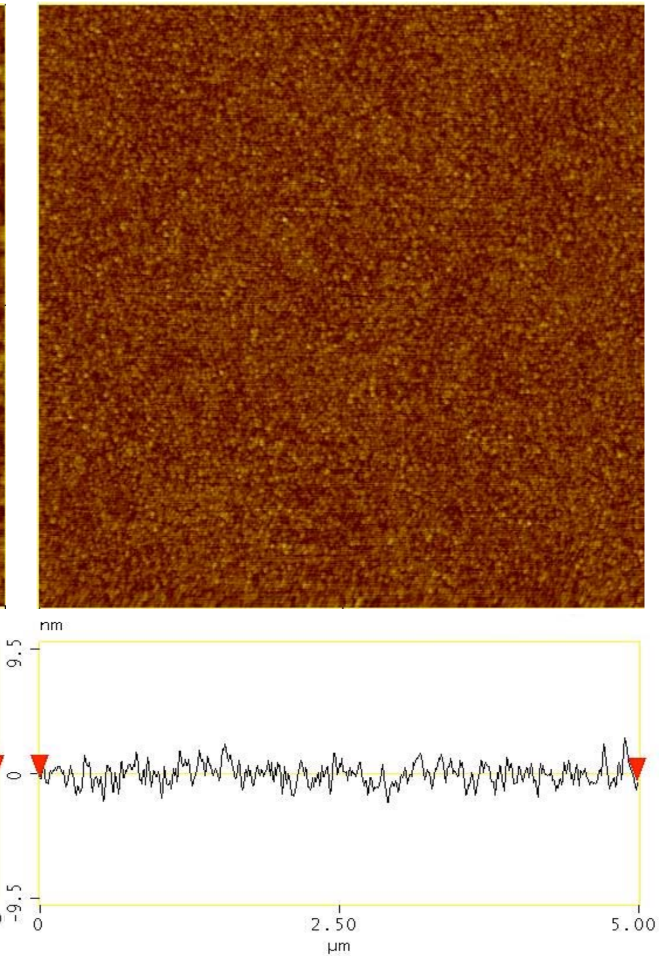
Dose: **0.015 ions.nm^{-2}**
Stepheight: **13.2nm**
Develop time: **1min**
Roughness: 2.3nm

Electrons at 25keV



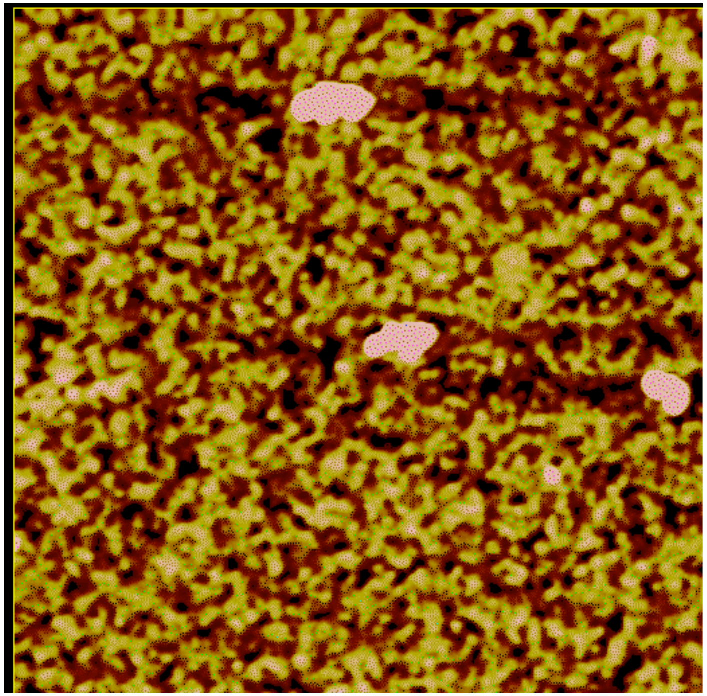
Dose: **8 electrons.nm^{-2}**
Stepheight: **18nm**
Develop time: **7s**
Roughness: 1.9nm

Photons at 248nm



Dose: **3.10^4 photons.nm^{-2}**
Stepheight: **22nm**
Develop time: **4min**
Roughness: 0.9nm

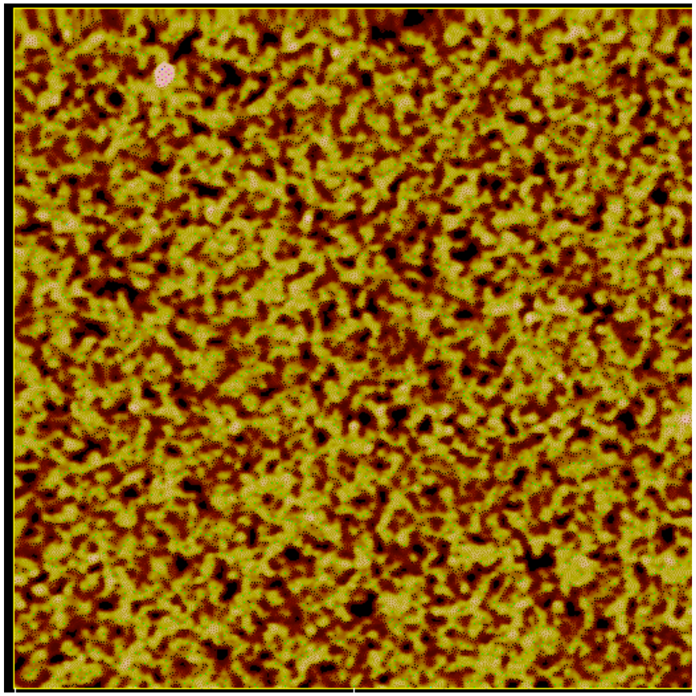
The effect of cold development, ZEP 520



R. T. develop, 10 sec.

Stepheight = 9.9 nm

Roughness = 6.58 nm



Cold develop (0^{o}C), 3 min.

Stepheight = 9.6 nm

Roughness = 3.43 nm

260 nm thick ZEP520 exposed by 200KeV Ar+ dose 0.1uC/cm^2 or 1ion/(12nm)^2

Scan area is (2um)^2.

Cold development reduces the surface roughness for the same step height

Factors other than shot noise dominate roughness of developing front

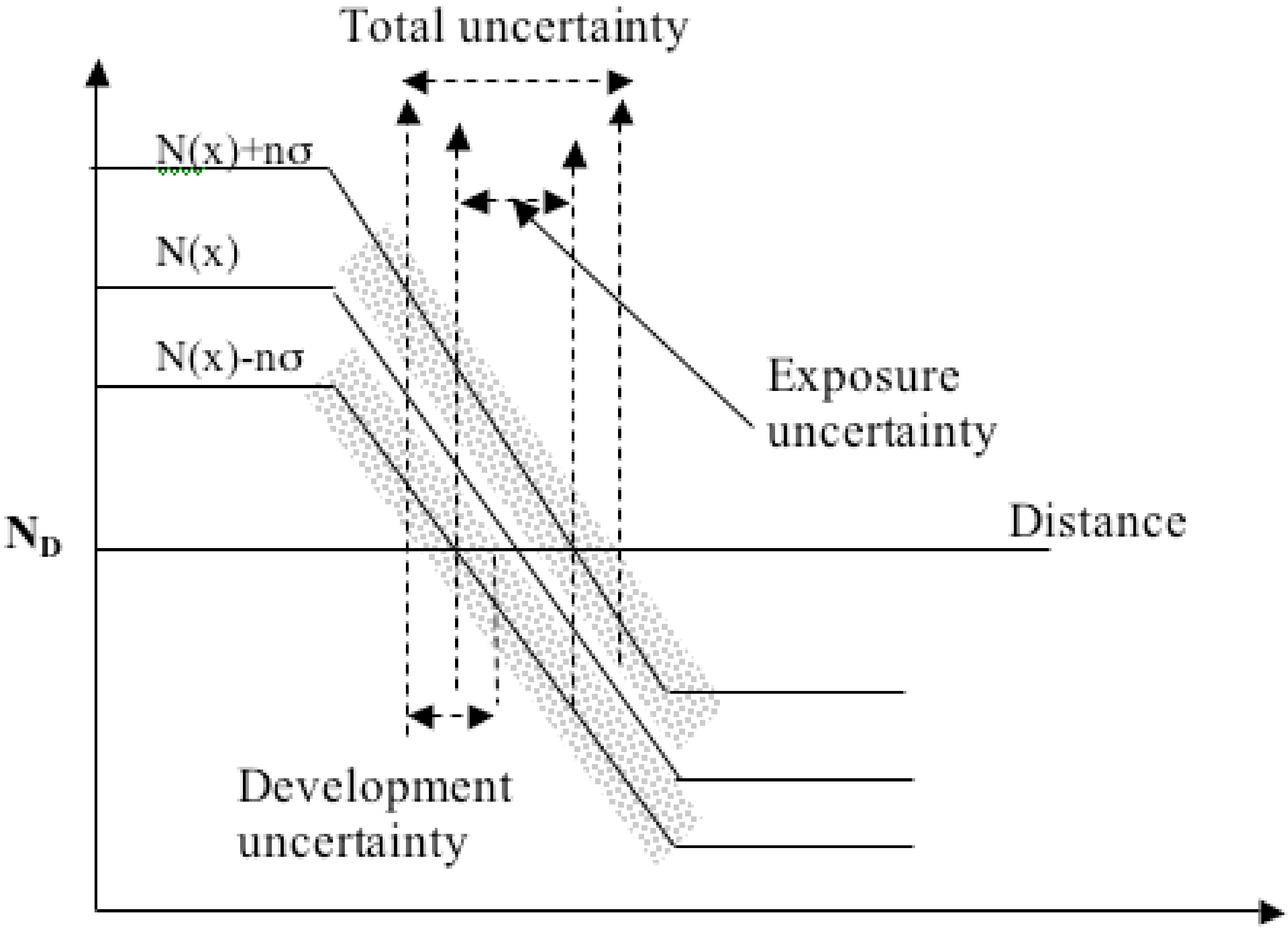


Illustration of uncertainly of position of feature edge as a result of fluctuations in mean exposure level N and in response to given developer (modified from H. I. Smith, JVST, B4, 148 (1986)).
See also Ming Yu, Allan Sagle and Benny Buller, SPIE5751, p687 (2005)

So why haven't we seen shot noise effects?

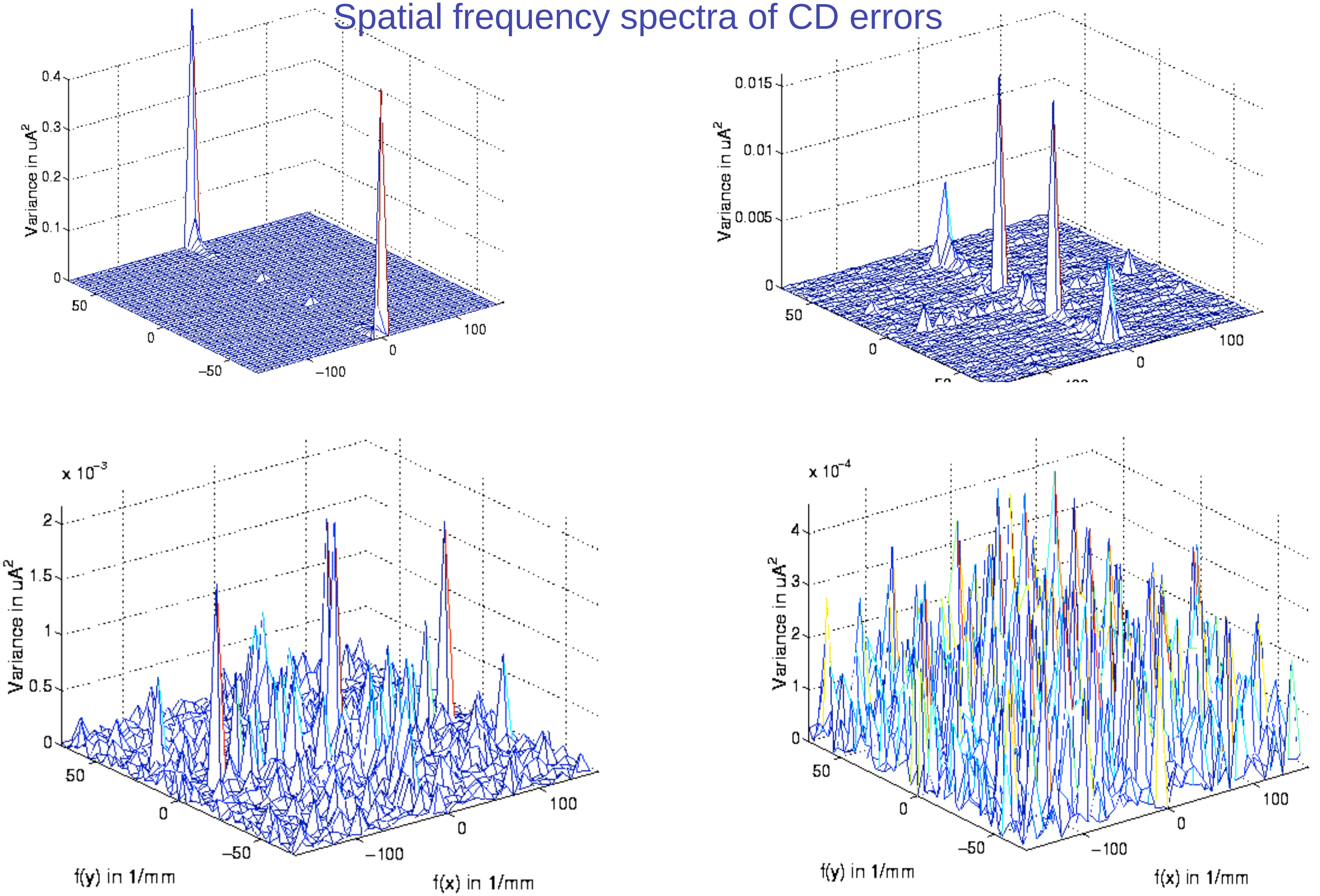
They've been hidden by other factors:

- Exposure tool vagaries, Development uneveness,
- Resist structure
- Spatial frequency filtering

Shot noise is 'white' but observed edge placement errors are not

(Ouyang, Berglund, Deeter and Pease, 1999)

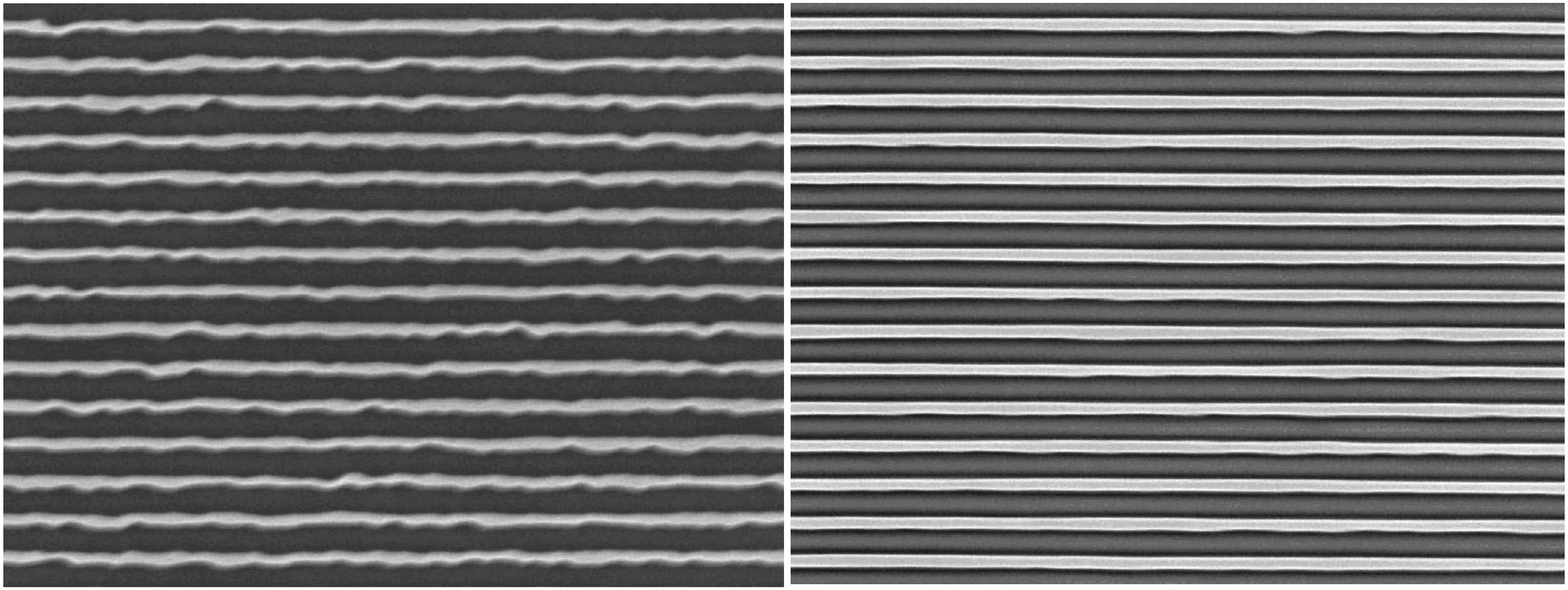
Spatial frequency spectra of CD errors



Example of low pass spatial frequency filtering

- 'lithographic perfection' (S. Y. Chou)

1-D smoothing of edges by controlled transient heat treatment in presence of top electrode.



Conclusions

- Shot noise can't go away
- Often masked by exposure imperfections and uneveness in developing.
- Can often be confined to spatial frequencies of interest. e.g. grating pattern when smooth edges are needed (reduced noise bandwidth)
- Room for improved resist technology
- 10mJ/cm2 is about 3000 primary quanta/ 25nm2 features. This is marginal just on grounds of primary shot noise.