Experimental observation of roughness of resist induced by shot noise and other effects

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The limit on the control of feature size set by shot noise has been debated for thirty years or more[1,2]. However there has been little direct observation of the effect although certain pattern infidelities have been described, primarily unopened contact windows[3] and line-edge roughness. But such measurements suffer from contributions from small variations in the performance of the exposure tool. To avoid such contributions we designed and performed a series of experiments (fig. 1) in which films of a simple, high-resolution, well-characterized resist are exposed with flood or scanned defocused beams with different numbers of particles and are partially developed. Those films exposed with few particles of high energy (e.g. 200KeV Ar^+ ions at << $1/nm^2$) would be expected to show a rougher surface than those exposed with many low energy particles (e.g.193nm photons at >>$1/nm^2$).

In a preliminary set of experiments we prepared samples PMMA (450K MW) 400nm thick on oxidized (200nm) Si wafers. Following pre-bake some wafers were exposed to electrons (10 to 25KeV), some were exposed to 30KeV Ga^+ ions in a focused ion beam system, some were exposed to 200KeVAr^+ ions and some to 248nm photons. Following exposure and development the partially developed regions were examined in an atomic force microscope. Although the original intent was to expose with a defocused beam (to eliminate roughness due to resolved lines) it turned out that those exposed with a focused beam also yielded useful information.

From the results of those exposed with defocused beams (figs. 2) we can see that although those films exposed with ions are indeed rougher than those exposed with electrons (about 1/nm2) and photons (>>1/nm2) the difference is far less marked than expected. All showed roughness that appeared to be primarily the effect of development.

Those exposed with focused beams of electrons showed the exposing line structure for shallow development. On further development there is a stage where the lines coalesce and for development depths >100nm the resulting structure becomes rougher with no sign of the original line structure. Initially we suspected a problem with the AFM but the experiment was repeated and the results confirmed. Fine line structure was also evident in those films exposed with the Ga^+ focused beam but the depth of penetration was insufficient to see the effect of deeper development.

In summary if shot noise dominates other effects we expect:

Really rough surface with ions (far fewer than $1nm^{-2}$)
Less rough with electrons (about $1nm^{-2}$)
Very smooth surface with photons (>> $1nm^{-2}$)

But we saw no significant increase on surface roughness between photon, electron and ion exposure; only from 0.9 to 2.3nm rms.

The main cause of the surface roughness is the appearance of grains, increasing from 30 to 100nm in diameter during development. So, at least for our experiments, the contribution of the shot noise to surface roughness was small compared with the effects of resist chemistry and of development. There have been previous reports of such coagulation[4].

Future work includes a wider set of experimental conditions, a more carefully controlled development process and exposure with 193nm photons instead of 248nm.

[1]See, for example H. I. Smith, J. Vac. Sci. Inst. **4B**,148 (Jan/Feb. 1986).
[2] M. Yu et al. SPIE2005 paper 5751-150
[3] A. R. Neureuther et al. J. Vac. Sci. Inst. 2**4B,** 3025 (2006).
[4] T. Tamaguchi et al. ,Jap. J.Appl. Phys. **42**, 3765, (2003).

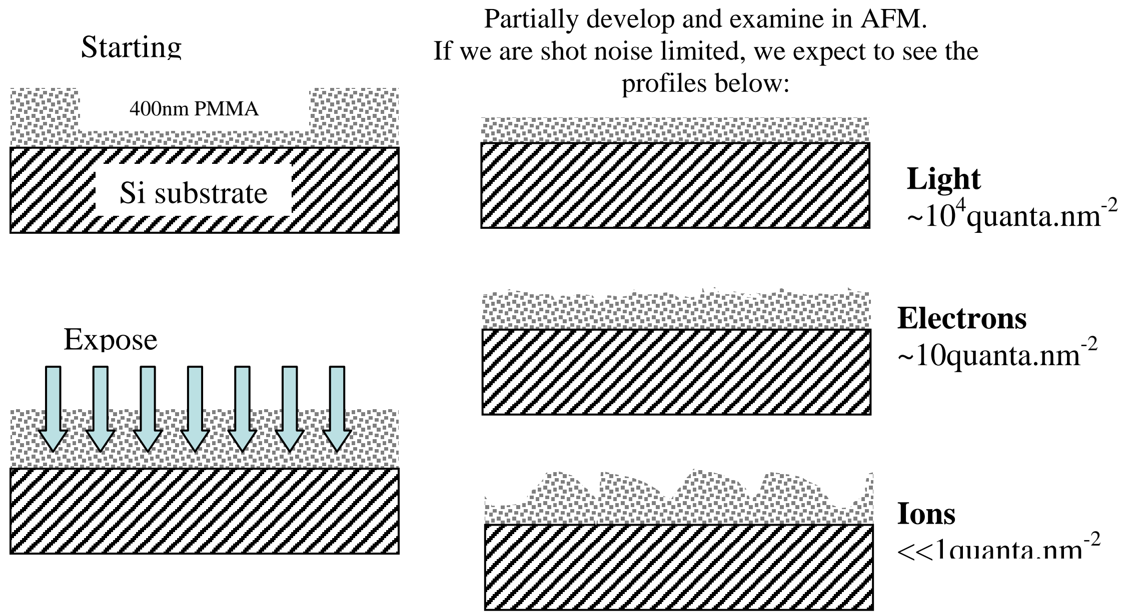

Fig. 1 Schematic of experiment to identify roughness due to shot noise. The depth of development was approximately determined by observing the step height between the exposed and unexposed regions.

Fig. 2(below). AFM images and traces showing only a slight increase in roughness in going from photon expose to ion exposure.