Simulation of Asymmetric Energy Deposition Profiles in E-beam Lithography on Curved Substrates

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There is a growing interest in patterning non-flat surfaces using electron beam lithography (EBL) in various applications[1]. Multiple challenges arise in patterning non-flat surfaces, one of which is the asymmetric interaction volume, resulting from the electron beam hitting the substrate under an angle. The point spread function (PSF), defined here as the spatial distribution of the deposited energy, is no longer radially symmetric. Therefore an adjustment is required to the proximity effect correction (PEC) that is standardly used in EBL.

The proximity effect in EBL is caused by electrons backscattered from the substrate, exposing the resist over a relatively large area around the incident beam. This effectively leads to a layout density dependent background dose and consequently to a varying critical dimension. In PEC, a correction is applied to the deposited dose, such that the features are exposed as intended.

To determine the non-radially symmetric PSF for EBL on curved surfaces requires a full 3D Monte-Carlo simulation. Current high performance PEC algorithms accordingly need to be adapted for the use of such non-symmetric PSF's. The angle of incidence in EBL on curved surfaces may be as large as 45°. Figure 1 shows a dot exposure for perpendicular (0° with surface normal) and 45° incidence angle. To validate these results, we use a GPU accelerated full 3D Monte Carlo electron scattering simulator, developed by Verduin et al.[2]. The simulation results clearly show that the energy deposition profile is not radially symmetric for non-perpendicular incidence (see Figure 2).

We will present simulation data for various beam incidence angles and we will discuss the shape of the resulting energy deposition profiles. We will show experimental exposure results of lines that are corrected and uncorrected for this asymmetry effect, by using simulations. Additionally we will adapt the existing PEC algorithm to correct for a non-symmetric point spread function and present the results.

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[1] Daniel W. Wilson, et. al. "Recent advances in blazed grating fabrication by electron-beam lithography", Proc. SPIE 5173, (November 3, 2003); doi:10.1117/12.510204.

[2] T. Verduin et. al. " GPU accelerated Monte-Carlo simulation of SEM images for metrology ", Proc. SPIE 9778, (April 21, 2016); doi:10.1117/12.2219160.

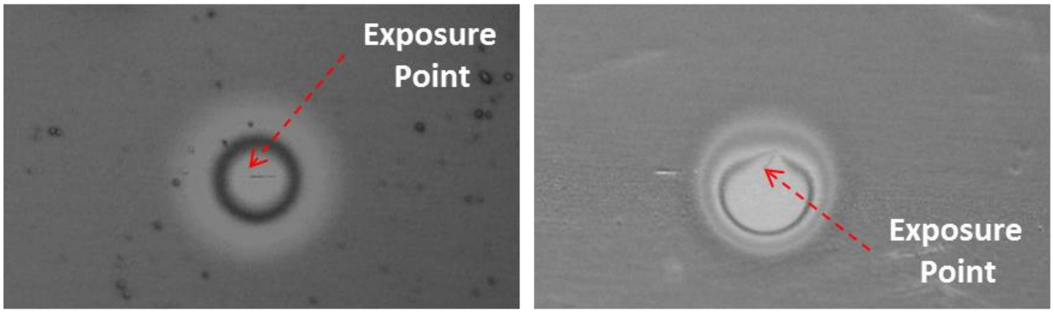

Figure 1 – On the left hand side, a flat surface has been exposed at a perpendicular incidence angle (0° with the surface normal). On the right hand side, a non-flat surface has been exposed at an incidence angle of 45°. The sample consists of a 1 μm thick PMMA resist layer on top of a Silicon substrate. Beam energy: 50 keV; beam current: 10 nA; exposure time: 2 seconds. Images were taken with an optical microscope.

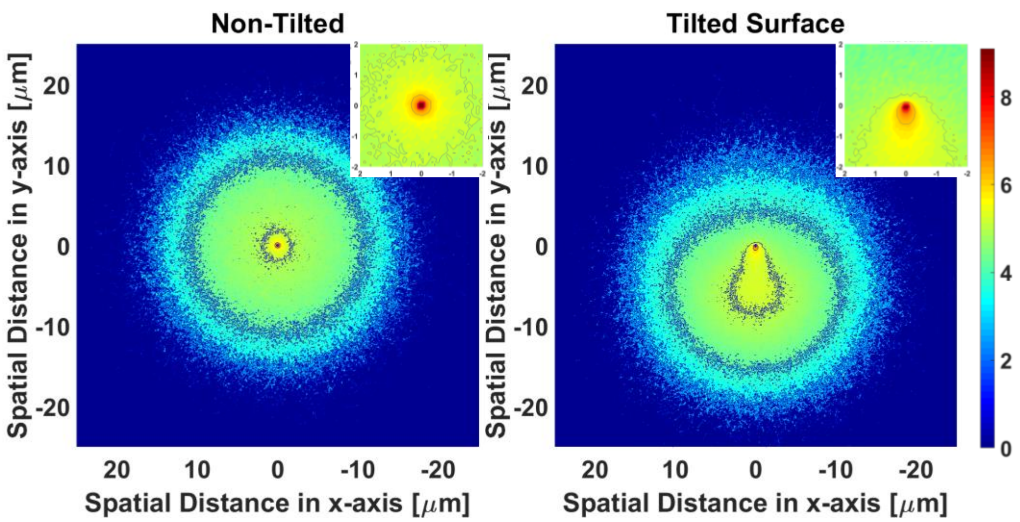

Figure 2 – Spatial distribution of the energy losses occurring during inelastic scattering in the uppermost resist layer of 100 nm thickness, simulated using a GPU-accelerated full 3D Monte Carlo program; Left: the incident beam is perpendicular to the resist surface; Right: the incident beam is at 45° (approximately) to the surface normal. The inserts are enlargement around the point of incidence.