Accurate Control of Remaining Resist Depth in E-beam Grayscale Lithography

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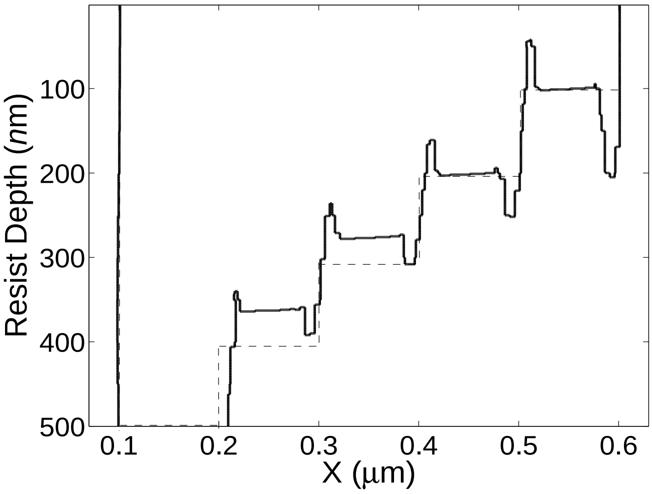
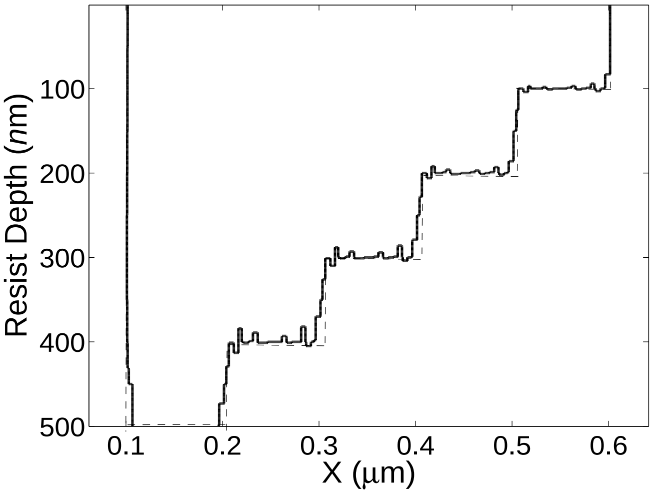
In E-beam grayscale lithography, a three-dimensional (3-D) structure is transferred onto the substrate using the remaining resist layer after development as a grayscale mask. The remaining resist profile which resembles the 3-D structure is obtained by the electron-beam (e-beam) lithographic process and the substrate is etched through the remaining resist. Therefore, it is essential to achieve the remaining resist profile required for accurate transfer of the 3-D structure. In most cases, an empirical approach to e-beam lithographic and resist developing processes was taken with a two-dimensional (2-D) model for the resist layer, i.e., the relationship between the e-beam dose and remaining resist thickness, which is experimentally determined, is employed in controlling the remaining resist profile. Such approaches do not take the following facts into account: (*i*) the exposure (energy deposited) is not the same as the dose (energy injected), (*ii*) the exposure varies with the resist depth, and (*iii*) the resist developing rate is not linearly proportional to the exposure. In order to have an accurate control of the remaining resist profile, an analytic model which is more universally applicable is desired.

In this study, 3-D exposure and resist developing models are employed for an analytic approach to controlling the remaining resist profile in e-beam grayscale lithography, in particular, the thickness of remaining resist. Let $d(x, y)$, $e(x, y, z)$, and $r(x, y, z)$ represent the e-beam dose for the point (x, y, H) on the surface of resist, the exposure at the point (x, y, z) in the resist, and the developing rate of resist at the point (x, y, z), respectively, where H denotes the initial thickness of resist. The exposure distribution $E(x, y)$ in a 2-D model may be expressed by $\int_{z=0}^{H} e(x, y, z)dz$, i.e., the 3-D exposure distribution is averaged along the resist depth dimension, and due to the electron scattering, $E(x, y) \neq d(x, y)$. Let the non-linear relationship between exposure and developing rate be expressed by the mapping $F[\,]$. Then, $r(x, y, z) = F[e(x, y, z)]$ and $R(x, y) = F[E(x, y)]$. Now, the development depth at (x, y) obtained for a development time of T and measured from the original surface of resist is represented by $p(x, y)$. With the 2-D model, $p(x, y)$ may be estimated to be $R(x, y)T$ (which is denoted by $p_{2D}(x, y)$) since the resist developing rate is assumed to be $R(x, y)$ independent of z in this model. However, when the 3-D model is adopted, $p(x, y)$ is estimated such that $\int_0^{p_{3D}(x,y)} \frac{dz}{r(x,y,z)} = T$. It is clear that $p_{2D}(x, y) \neq p_{3D}(x, y)$ unless $r(x, y, z) = R(x, y)$ for all z $(0 \leq z \leq H)$. In Figure 1, the remaining resist profiles obtained with the 2-D and 3-D models through computer simulation are provided, where one can observe that the 2-D model is not able to control the resist depth accurately and leads to significant errors at the transition regions between feature steps (Figure 1-(a)) while the 3-D model allows one to achieve the profile very close to the target profile (Figure 1-(b)).

In this paper, a 3-D analytic model of the e-beam grayscale lithographic process will be described and compared with the conventional 2-D model in order to show the inaccuracy of the 2-D model. Also, how the proposed 3-D model can be utilized in controlling the dose distribution given a target 3-D structure will be explained. In addition, the potential performance improvement by the analytic 3-D model over the empirical 2-D model in terms of resist depth control will be examined through an extensive computer simulation.



(a)



(b)

Figure 1: Remaining resist profiles obtained by (a) 2-D dose control and (b) 3-D dose control for beam energy of 50 keV and the substrate system of 500 nm PMMA on Si. The target profile is shown by the dashed line.