Experiment-based Estimation of Point Spread Function in Electron-beam Lithography

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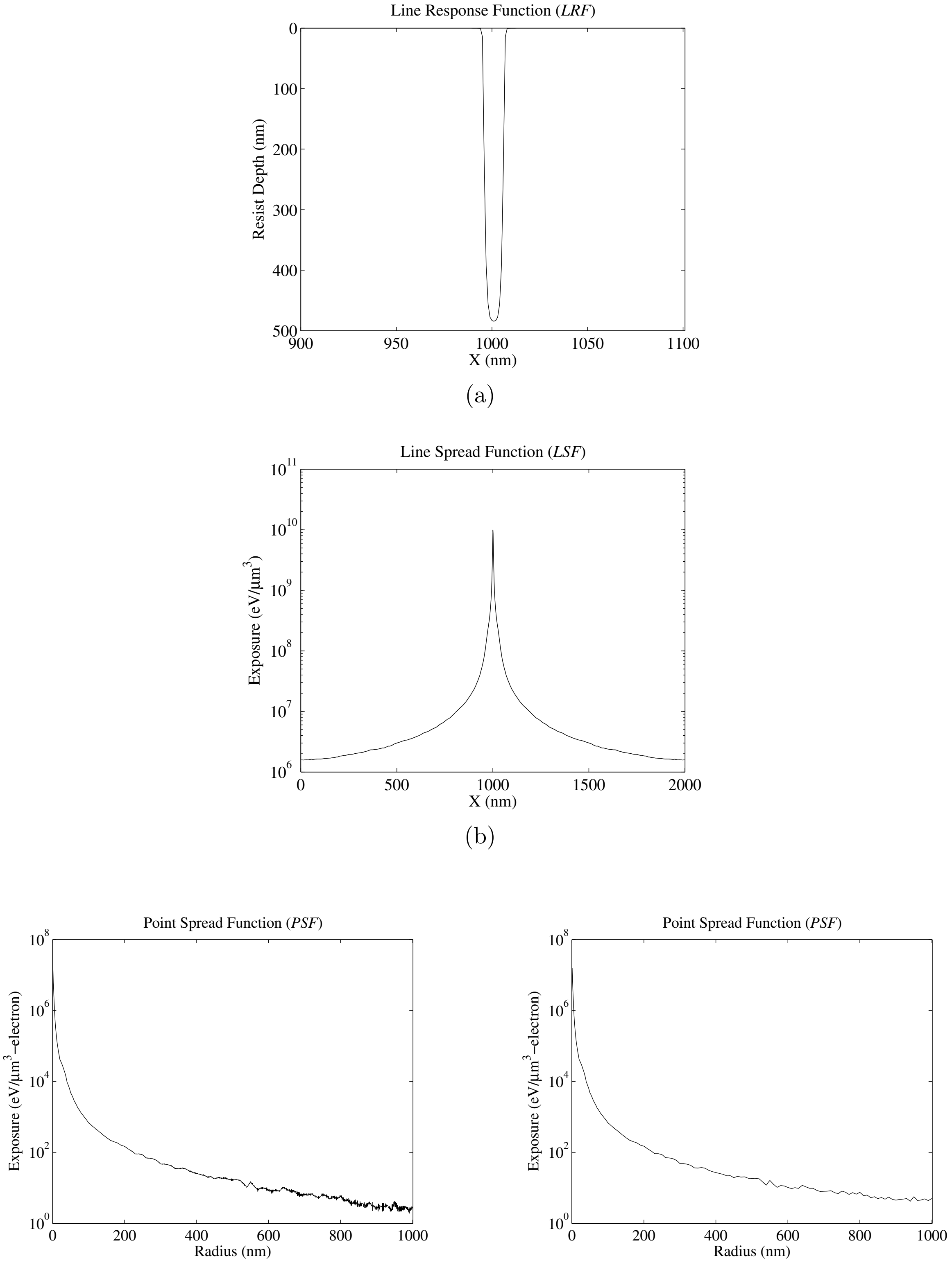
The electron-beam (e-beam) lithographic process consists of exposing a pattern in resist and subsequently developing the resist for pattern transfer. For applications such as proximity effect correction and estimation of the remaining resist profiles, both steps are often simulated. The exposure (energy deposited in the resist) distribution is computed by convolution between a circuit pattern and a point spread function (PSF) which quantitatively describes how the electron energy is deposited throughout the resist when a single point is exposed. Therefore, accuracy of a PSF greatly affects how realistic proximity effect correction or a remaining resist profile is.

PSF's are usually obtained by theoretical modeling such as using a double-Gaussian function or a Monte Carlo simulation. While such modeling is widely used, it has some practical limitations. The PSF's generated in such a way may not be accurate or realistic since not all effects and parameters involved in the physical process of electron energy being deposited in the resist can be considered. This would lead to simulation results, such as estimation of exposure distribution, which do not match well the actual ones. Also, for certain substrate compositions, such theoretical modeling may not be straightforward.

In order to avoid the above-mentioned limitations, a new approach is proposed to estimate PSF's using experimental results without simulation. The idea is to adopt the concept of line response function (LRF) and utilize it in estimating PSF's. The LRF is the remaining resist profile or depth distribution when a (single-pixel wide) line is exposed. It is experimentally obtained, therefore, realistically reflects the exposing (and developing) condition. Assuming that the line is oriented parallel with the Y-axis, only the cross-section of resist perpendicular to the Y-axis is considered. Let $d(x)$ and $r(x)$ denote the LRF (see Fig. 1(a)) and developing rate distribution in the cross-section, respectively. The resist developing process is isotropic. Therefore, for a given point x_0 on the X-axis, $d(x_0)$ depends on not only $r(x_0)$ but also $r(x)$ in the adjacent region. Based on this observation, $d(x)$ can be modeled as a combination of vertical component $d_V(x)$, i.e., the depth due to vertical development, and lateral component $d_L(x)$ i.e., the depth due to lateral development. Note that lateral development is non-existent or negligible where the depth profile is flat. Hence, estimation of the developing rate distribution can start from the center point x_c where the slope of $d(x)$ is zero and therefore $r(x_c)$ can be computed directly from $d(x_c)$ without considering lateral development. Through a recursive procedure, the developing rates of the previous points are used in computing the developing rate of the current point. The exposure distribution $e(x)$ is derived point-by-point through a nonlinear conversion from $r(x)$. Note that the exposure distribution for a line, $e(x)$, is the line spread function (LSF: see Fig. 1(b)). Let $p(x)$ denote PSF. Then, the relationship between LSF and PSF can be expressed by $e = A \times p$ in the discrete domain, where A is a square matrix which represents the 2-D convolution. Finally, PSF can be computed by $p = A^{-1} \times e$. The size of matrix A can be controlled by using nonuniform sampling and interpolation on LSF such that the computation of inversion is efficient.

The proposed experiment-based approach to PSF estimation has been implemented and its performance has been analyzed through simulation. A set of typical results is provided in Fig. 1. The substrate system employed in the simulation is composed of 500 nm PMMA on Si. The beam energy is 50 KeV with the beam diameter of 5 nm. Fig. 1(a) depicts the depth profile (LRF) obtained through simulation of resist development. The corresponding exposure distribution (i.e., LSF) derived from the LRF is shown in Fig. 1(b). The PSF estimated from the LSF is shown in Fig. 1(c), which is well matched with the PSF by the Monte-Carlo simulation in Fig. 1(d). The future study includes verification of the proposed method through experiment.



(a)

(b)

(c)

(d)

Figure 1: Simulation results for the substrate of 500nm PMMA on Si, the beam energy of 50 keV, and the beam diameter of 5nm: (a) line response function, (b) line spread function, (c) estimated point spread function, and (d) point spread function from Monte Carlo simulation.