Minimization of Line Edge Roughness and CD Error in Electron-beam Lithography

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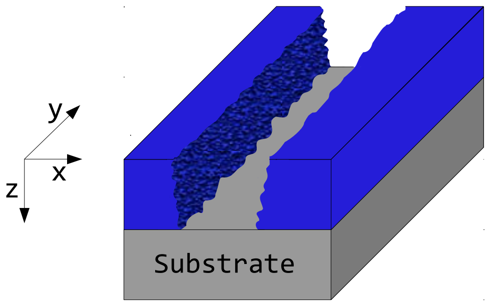
Electron-beam (e-beam) lithography, one of the widely-used tools in nanofabrication, is capable of writing patterns with high resolution in the resist. As the minimum feature size decreases well below 50 nm, line edge roughness (LER) has become a critical issue to be addressed. The LER is caused by a number of statistically fluctuating effects such as shot noise (electron influx variation), stochastic energy deposition of electrons, statistical distributions of chemical species in the resist (such as photoacid generator), the random-walk nature of resist development process, etc. Since the LER dose not scale with the feature size, it can significantly limit the minimum feature size and the maximum circuit density. Most of the efforts to decrease the LER so far are of empirical or trial-and-error. There has been no development of a systematic method to reduce the LER. In this study, a computational approach is taken in developing an effective method to minimize the LER, taking the CD error due to the proximity effect also into account. The LER and CD error vary with the resist-depth dimension and therefore a 3-D model (Fig. 1(a)) is employed instead of a 2-D model used in most of the previous work.

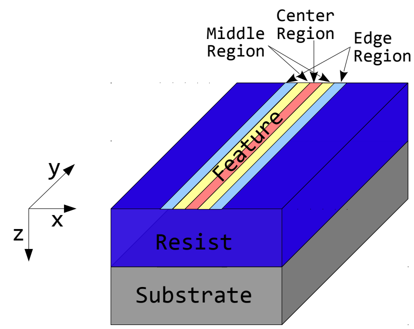
In our previous work, it was observed that the LER is high inside a feature, rapidly decreases over the feature edge, and then mostly stays low or slightly increases outside the feature. This is mainly due to the fact that the exposure (energy deposited in the resist) level quickly drops down from the exposed area (inside the feature) to the unexposed area (outside the feature) and the absolute stochastic fluctuation of exposure is smaller outside the feature, i..e, in the unexposed area. This suggests that it might be possible to reduce the LER by shrinking the area of a feature to be exposed, from the feature boundary inward. Another important result from our previous study is that the dose given to a different part of feature has a different effect on the level and stochastic fluctuation of exposure at a different layer and location in the resist. It indicates that further reduction of the LER may be possible by controlling the spatial distribution of dose within a feature. Note that this spatial dose control is a commonly-used technique also in the proximity effect correction, i.e., reducing the CD error.

Our method developed for minimizing the LER and CD error starts with determining how much a feature area is to be shrunk. Since a sophisticated procedure for optimizing the spatial distribution of dose is employed in a later step of the method, the minimum, instead of optimal, amount of shrinking is determined in this step. Then, the feature area to be exposed is partitioned into regions along the length dimension of feature for spatial control of dose (Fig. 1(b)). The doses for the regions are derived through an iterative procedure. In each iteration, the LER and CD error at each layer of resist are computed through simulation of resist development, and the dose of each region is adjusted, considering its effect on the exposure distribution (level and stochastic fluctuation), such that a certain cost function consisting of LER and CD error is reduced. An example of cost function is $max\{max_i\{LER(i)\}, max_i\{CD\_error(i)\}\}$ where i is the index of resist layer.

In Fig. 2, a set of typical results is provided where the width of line feature employed is 20 nm. The substrate system is composed of a 300 nm CAR (chemically amplified resist) on Si and the e-beam energy is 50 keV. The same average dose level of 20 $\mu C\ cm^2$ is used in both cases. It is clearly seen that a significant improvement in both LER and CD error has been achieved by the proposed method. In this particular case, the maximum and average (among resist layers) LER's are reduced from 5.12 nm and 2.98 nm to 2.01 nm and 1.56 nm, respectively. The maximum and average CD errors are decreased from 5.95 nm and 3.79 nm to 1.37 nm and 0.81 nm, respectively. In this paper, the complete description of the model and method, and a more comprehensive set of results will be presented.

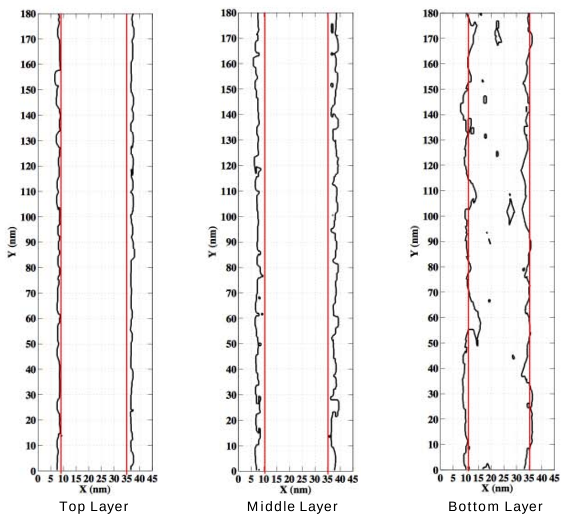


(a) 3-D model of substrate system

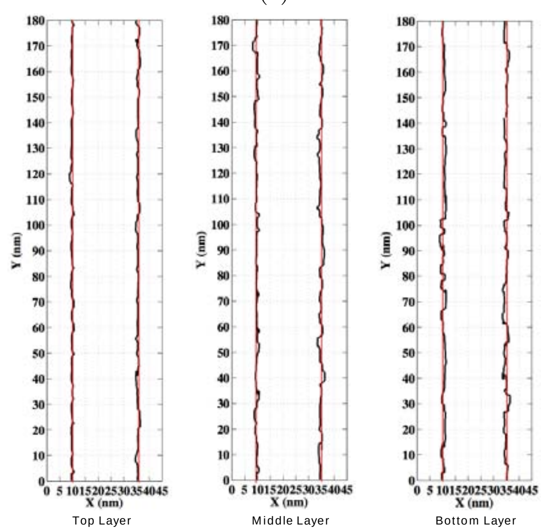


(b) Feature partitioning for spatial dose control

Figure 1: Simulation Model



(a)



(b)

Figure 2: The boundaries of developed line feature at different layers: (a) by using uniform dose and exposing the whole feature and (b) by the proposed method.