Available online at www.sciencedirect.com
SCIENCE DIRECT®
ELSEVIER
Microelectronic Engineering 83 (2006) 336–344
MICROELECTRONIC ENGINEERING
www.elsevier.com/locate/mee

Analysis of three-dimensional proximity effect in electron-beam lithography

S.-Y. Lee *, Kasi Anbumony

Department of Electrical and Computer Engineering, Auburn University, Broun Hall 304, Auburn, AL 36849, United States

Received 31 August 2005; received in revised form 24 September 2005; accepted 28 September 2005
Available online 25 October 2005

Abstract

In most of the proximity effect correction schemes, a two-dimensional model of proximity effect is employed by ignoring or averaging the variation of exposure along the depth dimension in the resist. However, as the feature size continues to decrease, the relative variation becomes significant so that it may need to be taken into account in proximity effect correction. In this study, the three-dimensional (3-D) proximity effect is analyzed in detail through computer simulation as a first step toward developing a 3-D proximity effect correction scheme. Effects of the parameters such as beam energy, resist thickness, feature size, developing threshold, etc., on the 3-D spatial distribution of exposure in the resist, in particular, depth-dependent proximity effect, are considered in the analysis. Results from the extensive simulation are presented in this paper.

Keywords: 3-D proximity effect; E-beam lithography; Exposure distribution; Iso-exposure contour

1. Introduction

The proximity effect due to electron scattering in the resist has been extensively investigated since it limits the spatial resolution of circuit features that can be fabricated by the E-beam lithographic process. The proximity effect blurs features and may even merge adjacent features in a circuit pattern. Various schemes for reducing such distortion in the written circuit pattern have been developed. In most of the schemes, the dose to be given to each feature or each region within a feature, or the shape of features, is controlled such that the *exposure* (energy deposited in the resist) distribution minimizing proximity effect is obtained. As the minimum feature size is reduced down to the scale of *nanometer*, the relative proximity effect becomes so significant that its correction is inevitable for most of circuit patterns.

All of the previous work on E-beam proximity effect, whether binary [1–3] or grayscale lithography [4,5], analysis or correction, are based on a two-dimensional (2-D) model, i.e., exposure variation along the resist depth dimension was not considered. Instead, the *point spread function* (PSF), or energy deposition profile when a point is exposed, was assumed to be 2-D. For example, the 2-D PSF is obtained by integrating (averaging) the corresponding 3-D PSF along the depth dimension. However, in general, the PSF and accordingly exposure can vary significantly along the depth dimension. For example, exposure distribution close to the resist surface is different from that at the bottom. Due to this variation, the sidewall of the remaining resist after development, which depends on an *iso-exposure* contour or surface, may not be what an application requires, e.g., undercut, overcut or vertically straight sidewall. In other words, proximity effect varies with depth in the resist in addition to location in a circuit pattern.

In this study, a 3-D model of PSF is employed in order to analyze proximity effect (exposure distribution) in the 3-D space of resist as a first step toward developing a 3-D proximity effect correction scheme. 3-D PSFs are generated using a Monte Carlo simulation method (SEEL [8]) which

* Corresponding author. Tel.: +1 334 844 1848; fax: +1 334 844 1809.
E-mail addresses: leesooy@eng.auburn.edu, sylee@eng.auburn.edu (S.-Y. Lee).

0167-9317/$ - see front matter © 2005 Published by Elsevier B.V.
doi:10.1016/j.mee.2005.09.009

accurately models 3-D electron energy deposition in the resist. Accuracy of such Monte Carlo methods was also verified in another study [9]. The shape of a 3-D PSF depends on parameters such as the beam energy, resist thickness, etc. Through extensive computer simulation, effects of the electron beam energy, resist thickness, feature size, and developing threshold on *3-D proximity effect* have been analyzed in detail. The main focus is not on the exposure level but on the spatial distribution of exposure.

This paper is organized as follows. In Section 2, the system and simulation models are described. In Section 3, 3-D proximity effect is discussed with a set of performance metrics introduced. In Section 4, the detailed analysis results obtained through simulation are discussed, followed by a summary in Section 5.

2. Model

The system model consists of a substrate and a certain type of resist as illustrated in Fig. 1. It is assumed that the substrate system is spatially homogeneous, i.e., the substrate composition and the resist thickness do not change with location. In [6,7], proximity effect correction for a heterogeneous substrate was considered, however, the exposure variation along the resist depth dimension was not taken into account, i.e., 2-D proximity effect correction.

The 3-D point spread function is denoted by $\mathrm{PSF}(x,y,z)$ which describes the exposure distribution in the resist when a point on the X–Y plane is exposed (refer to Fig. 1). The resist depth is along the Z-axis. Let $f(x,y,0)$ represent the dose to be given to each point $(x,y,0)$ on the resist surface for writing a circuit pattern. For example, when each circuit feature is exposed with a constant dose D, then $f(x,y,0)=D$ if $(x,y,0)$ is within a feature ($f(x,y,0)=0$ otherwise). Let us denote the exposure distribution in the resist by $e(x,y,z)$. Assuming that the E-beam lithographic process is linear and space-invariant, $e(x,y,z)$ can be expressed by the following convolution:

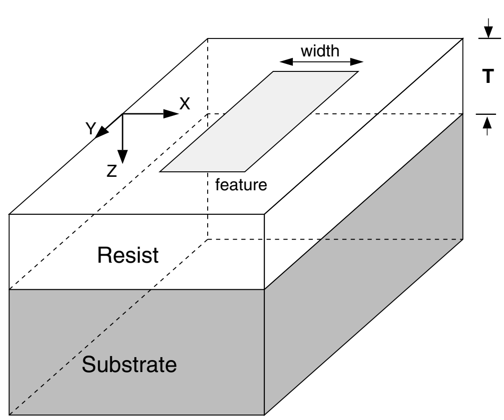

Fig. 1. A 3-D model, where the Z-axis represents the resist depth.

$$\begin{aligned} e(x,y,z) &= \int_{x'}\int_{y'}\int_{z'} \mathrm{PSF}(x-x',y-y',z-z')f(x',y',0)\mathrm{d}x'\,\mathrm{d}y'\,\mathrm{d}z' \\ &= \int_{x'}\int_{y'}\int_{z'} \mathrm{PSF}(x-x',y-y',z-z')f(x',y')\delta(z')\mathrm{d}x'\,\mathrm{d}y'\,\mathrm{d}z' \\ &= \int_{x'}\int_{y'} \mathrm{PSF}(x-x',y-y',z)f(x',y')\mathrm{d}x'\,\mathrm{d}y' \qquad (1) \end{aligned}$$

From Eq. (1) it is seen that the exposure distribution at a certain depth (z_0) can be computed by the 2-D convolution between $\mathrm{PSF}(x,y,z_0)$ and $f(x,y,0)$ in the corresponding plane, $z=z_0$. That is, $e(x,y,z)$ may be estimated layer by layer.

Since the PSF is radially symmetric, $\mathrm{PSF}(x,y,z)$ may be expressed as $\mathrm{PSF}(\sqrt{x^2+y^2},z)=\mathrm{PSF}(r,z)$, where $r=\sqrt{x^2+y^2}$. In Fig. 2, $\mathrm{PSF}(r,z)$ is plotted for the substrate system of 500-nm thick PMMA on S_i. The PSF shows a narrow high-amplitude distribution of exposure in the top layer while a wide low-amplitude distribution in the bottom layer. This depth-dependent energy spread in the resist leads to the 3-D proximity effect which refers to variation of performance metrics with the resist depth. In this study, the 3-D proximity effect is analyzed based on the spatial exposure distribution in the resist. The profile of remaining resist after development is mainly determined by the spatial distribution of exposure though the developing process can also affect the profile.

3. 3-D proximity effect

In proximity effect correction using a 2-D model, variation of the exposure distribution, $e(x,y,z)$, along the Z-axis is not considered. Instead, in most cases, a 3-D $\mathrm{PSF}(x,y,z)$ is averaged over z to get a 2-D point spread function $\mathrm{PSF}(x,y)$, i.e., $\mathrm{PSF}(x,y)=\int_0^T \mathrm{PSF}(x,y,z)\mathrm{d}z$, where T is the thickness of resist. Then, the 2-D exposure distribution $e(x,y)$ is estimated for proximity effect correction, i.e., $e(x,y)=\int_{x'}\int_{y'}\mathrm{PSF}(x-x',y-y')f(x',y')\mathrm{d}x'\,\mathrm{d}y'$. However, the actual profile of remaining resist can vary with z significantly due to the depth-dependent exposure distribution as illustrated in Fig. 3. Therefore, proximity correction with a 2-D model would not lead to an accurate result especially when a certain shape of sidewall of the remaining resist is desired. In this section, the 3-D *intra* and *inter* proximity effects are quantified.

3.1. Intra-proximity effect

In order to quantify the 3-D intra-proximity effect, the two metrics, *width variation* and *exposure contrast*, are introduced.

3.1.1. Width variation

The width of a line feature may vary with the resist depth after development as illustrated in Fig. 3. The line feature is long enough in the Y-direction that its width can be assumed not to vary with y. Let $W(z)$ denote the width of the line feature, where z is the depth in the resist. $W(z)$ is approximated, in this simulation study, by the