Spatial dose control for fabrication of saw-tooth structures

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(Received 21 July 2009; accepted 14 September 2009; published 1 December 2009)

Electron-beam (e-beam) lithography is often employed in the fabrication of three-dimensional structures, i.e., e-beam grayscale lithography where dose is spatially controlled such that the remaining resist profile is as close to the target structure as possible. The resist profile is determined by the developing rate distribution in the resist, which, in turn, depends on the exposure (energy deposited) distribution. In the past, a dose-to-depth relationship derived from experiments was referred to in determining a dose distribution for fabrication of a grayscale structure. However, the relationship is structure dependent since the exposure distribution depends on the dose distribution, i.e., exposure at each point is a function of doses at all points within the electron scattering range. Hence, a more general approach is to consider an exposure-to-depth relationship and dependency of the required exposure distribution on (the shape of) structure. In this study, such an approach has been investigated for saw-tooth structures with varying slope of tooth. Fabricated saw-tooth structures and analysis of slope dependency of the required exposure distribution are presented in this article. © *2009 American Vacuum Society.* [DOI: 10.1116/1.3245988]

I. INTRODUCTION

Three-dimensional (3D) structures are often used in various devices such as optical elements, microelectronmechanical systems, and nanoelectromechanical systems.[1–4] Their performance is known to be highly sensitive to their dimensional fidelity. Therefore, it is essential to control the feature size accurately in order to be able to fabricate such devices with the desired characteristics. One flexible approach to fabrication of such structures is to employ electron-beam (e-beam) grayscale lithography.[5,6] However, electron scattering in the resist and the isotropic process of resist development can make dimensions of the written features in a device substantially different from the target ones. Hence, spatial distribution of e-beam dose is to be controlled in order to achieve the exposure (energy deposited in the resist) distribution, which can lead to the target structure. This dose control becomes a challenging task for saw-tooth structures, widely used in blazed gratings, where the depth in a resist profile continuously varies in space. In such structures, the isotropic process of resist development coupled with the nonlinear relationship between exposure and developing rate makes it difficult to derive the optimal dose distribution for a target structure. Note that if there is no lateral development, derivation of the dose distribution would be easier since vertical columns of resist would be independent of each other during the developing process.

In the previous works,[2,3] blazed grating structures with a large period and/or a small aspect ratio were fabricated by deriving the dose distribution based on a dose-to-depth relationship. The remaining resist profile is determined by the spatial distribution of exposure, not point-by-point exposure, and exposure at each point depends on the dose distribution, not dose at the point. Therefore, a dose-to-depth relationship must be structure dependent. A more general approach is to consider exposure-to-depth relationship and the shape of a target structure in deriving a dose distribution for the fabrication of the structure. In our previous work,[7] the issue of deriving a dose distribution required to achieve a given target exposure distribution was investigated and it has been shown that the dose control scheme developed is able to greatly reduce the difference between the target and the actual exposure distributions. Also, in another study,[8] a five-step staircase structure with the step width of 1 μm was fabricated where the depth resolution of 20 nm was achieved. In a staircase structure, the depth in the remaining resist profile does not vary spatially, i.e., remains flat, within each step. There is no lateral development of resist at the center of each step and, therefore, an exposure-to-depth relationship may be referred to in determining the target exposure for each step.

One of our recent research efforts was on developing an effective and practical scheme for determining the spatial dose distribution for a structure where the remaining resist profile continuously varies in space, not piecewise constant or flat. In this article, the results obtained for periodic saw-tooth structures are presented. On the slope of each tooth, the depth varies linearly and the resist development process progresses laterally as well as vertically at each point. Therefore, a dose-to-depth or even an exposure-to-depth relationship only cannot be employed in determining a dose distribution. In this study, periodic saw-tooth structures with varying slopes were successfully fabricated and the dependency of dose distribution on the slope of tooth has been analyzed.

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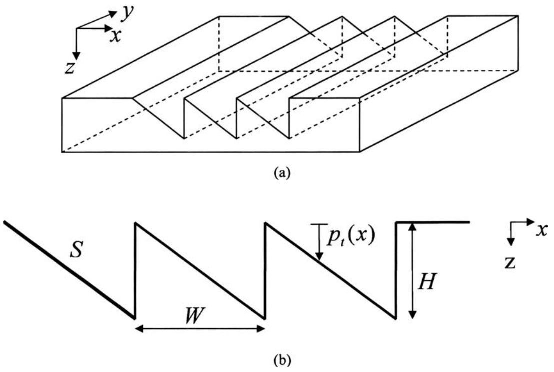


FIG. 1. Saw-tooth structure with teeth of width W and height H: (a) 3D coordinate systems and (b) cross section where $S=H/W$ is the tooth slope and $p_t(x)$ is the target depth distribution.

The rest of this article is organized as follows. In Sec. II, a saw-tooth structure model is introduced. In Sec. III, the exposure distribution required for a target tooth is derived. In Sec. IV, computation of the dose distribution required for a saw-tooth structure is discussed. In Sec. V, experimental results are analyzed, followed by a summary in Sec. VI.

II. MODEL OF SAW-TOOTH STRUCTURE

A periodic saw-tooth structure (saw-tooth structure hereafter) consists of N-teeth of the same shape as shown in Fig. 1. It is assumed that the saw-tooth structure is long enough that exposure or depth does not vary along the Y-dimension. Hence, it is sufficient to consider only the cross section of structure in the X-Z plane. The height (initial thickness of resist) and width of a tooth are denoted by H and W, respectively, and then the slope S of a tooth is represented by H/W. One of the main objectives of this study is to find out the dependency of dose distribution on the slope S or, equivalently, the width W of each tooth with all other parameters fixed. Therefore, as S is varied by changing W, the number of teeth N is set such that the total width of saw-tooth structure remains constant, i.e., $W_iN_i=W_jN_j$, where W_i, N_i, W_j, and N_j are the tooth width and the number of teeth of two different saw-tooth structures tested. Let *depth distribution* be the remaining resist profile in the cross-sectional plane, denoted by $P(x)$, i.e., the depth measured from the initial top surface of resist down as a function of x (refer to Fig. 1). Then, $\int P(x)dx$ is constant for all target saw-tooth structures tested in this study under the condition of $W_iN_i=W_jN_j$.

III. EXPOSURE AND DOSE DISTRIBUTIONS

Let $d(x)$, $e(x)$, $r(x)$, and $p(x)$ denote dose, exposure, developing rate, and depth distributions within a tooth, respectively. Isotropic development of resist may be modeled such that *effective* development at a point consists of vertical and lateral components. Depending on the relative magnitudes of the two components, the direction of effective development is determined. When the lateral component is zero as in the area where $e(x)$ is constant or flat, the effective development is entirely vertical. When the two components are of the same magnitude, the effective development is diagonal as illustrated in Fig. 2. The *target* depth distribution $p_t(x)$ may be expressed as $p_t(x)=Sx=Hx/W$, where $0\leqslant x\leqslant W$. Suppose that $p(x)$ is linearly proportional to $r(x)$, i.e., $p(x)=r(x)T$, where T is the developing time, ignoring the lateral development process. Then, $r(x)\propto Hx/W$. It is well known that the relationship between $e(x)$ and $r(x)$ is nonlinear, in particular, $r(x)\propto[e(x)]^{\alpha}+C$, where α is greater than 1.0. Ignoring the constant C, $e(x)\propto[r(x)]^{1/\alpha}$. In Fig. 3(a), $p_t(x)$ and $r(x)$ and $e(x)$ that are required for achieving $p_t(x)$ are illustrated. It is seen that the exposure distribution required for the linear depth profile follows a power function with the exponent less than 1.0.

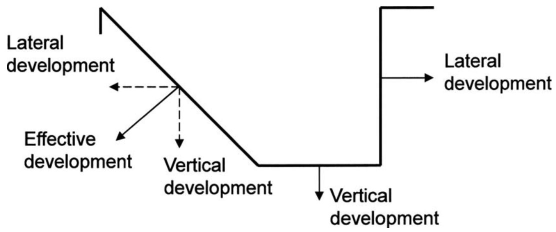


FIG. 2. Lateral, vertical, and effective developments.

However, lateral development cannot be ignored especially in saw-tooth structures where depth in the remaining resist profile continuously varies in space. Lateral development tends to make the effective developing rate larger compared to the case where the effective development is purely

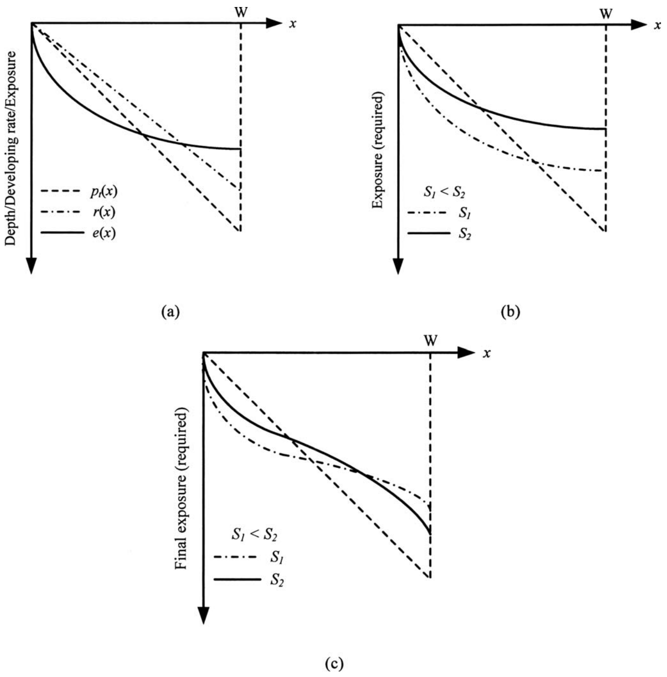


FIG. 3. Illustration of depth, developing rate, and exposure distributions for a tooth: (a) without consideration of the lateral development and inefficiency of development in a narrow space, (b) considering lateral development, and (c) considering both. $p_t(x)$, $r(x)$, and $e(x)$ are the target depth distribution and the developing rate and exposure distributions that are required to achieve $p_t(x)$. In (b) and (c), the widths W_1 and W_2 are normalized such that they become equal.

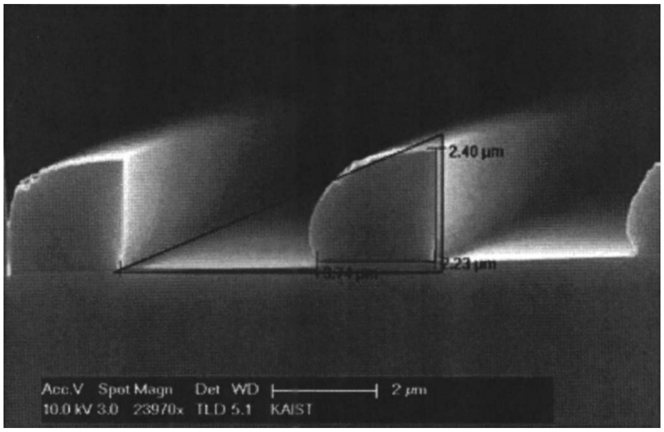


FIG. 4. Remaining resist profile when the spatial dose distribution is linear.

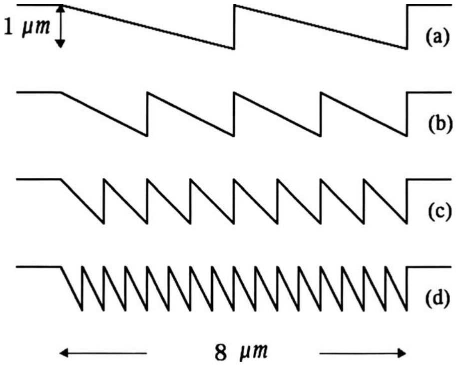


FIG. 5. Four target saw-tooth structures ($H=1$ μm): (a) $W=4$ μm, (b) $W=2$ μm, (c) $W=1$ μm, and (d) $W=0.5$.

vertical. The magnitude of lateral development increases as the slope S increases. Therefore, a lower exposure is required for a larger S, achieving the same depth in the remaining resist profile, as illustrated in Fig. 3(b). In a saw-tooth structure, the width of the developed area in a tooth becomes smaller as the depth increases. This smaller width makes developing process less effective, requiring a higher exposure for the same depth of development. The decrease in effectiveness of developing process is larger for a larger S, i.e., a sharper tooth. Hence, toward the bottom of the V-shaped trench between teeth, a higher exposure is required for the same depth of development when S is larger than when S is smaller [refer to Fig. 3(c)]. However, for the shallow part of the trench, a lower exposure is required for the same depth when S is larger.

In Fig. 4, the remaining resist profile obtained when $d(x) \propto p_t(x)$, i.e., the dose distribution simply follows the linear slope of a tooth [$p_t(x)$], is shown. When $d(x)$ is linear, $e(x)$ is also (approximately) linear except at both ends of the tooth since $e(x)$ is a linear convolution of $d(x)$ with a point spread function, which describes the exposure distribution when only a single point is exposed. It is seen that $p(x) \propto [e(x)]^{\alpha} \propto x^{\alpha}$ as discussed earlier, where α is greater than 1. Note that $p(x)$ is measured from the initial top surface of the resist down. That is, when the exposure distribution is linear in space, the corresponding depth distribution is not linear.

IV. DOSE DISTRIBUTION

The dose, exposure, developing rate, and depth distributions of saw-tooth structure (not a tooth) are denoted by $D(x)$, $E(x)$, $R(x)$, and $P(x)$, respectively. After the exposure distribution $e(x)$ required for a tooth of saw-tooth structure is determined from $p_t(x)$, a dose distribution $D(x)$, which leads to the exposure distribution $E(x)$ for the structure, needs to be found. In a periodic saw-tooth structure, the developing process of a tooth can be considered to be independent of those of others. Therefore, $e(x)$ may be replicated N times to obtain the exposure distribution $E(x)$ for a N-tooth structure, i.e., $E(x)=\sum_{i=0}^{N-1} e(x-iW)$. Deriving $D(x)$ from $E(x)$ requires correction of proximity effect within each tooth and among teeth. An efficient scheme for proximity effect correction in e-beam grayscale lithography was developed in the PYRAMID project.[3] The PYRAMID software is employed to compute $D(x)$ given $E(x)$. The area of each tooth in the X-Y plane is partitioned along the Y-dimension into thin rectangular regions. A dose for each region is determined through the iterative procedure of proximity effect correction implemented in the PYRAMID software.

V. ANALYSIS OF THE RESULTS

In this study, saw-tooth structures with $N=2$, 4, 8, and 16, i.e., $W=4$, 2, 1, and 0.5 μm, respectively, have been fabricated with $H=1$ μm, as shown in Fig. 5. Note that the total

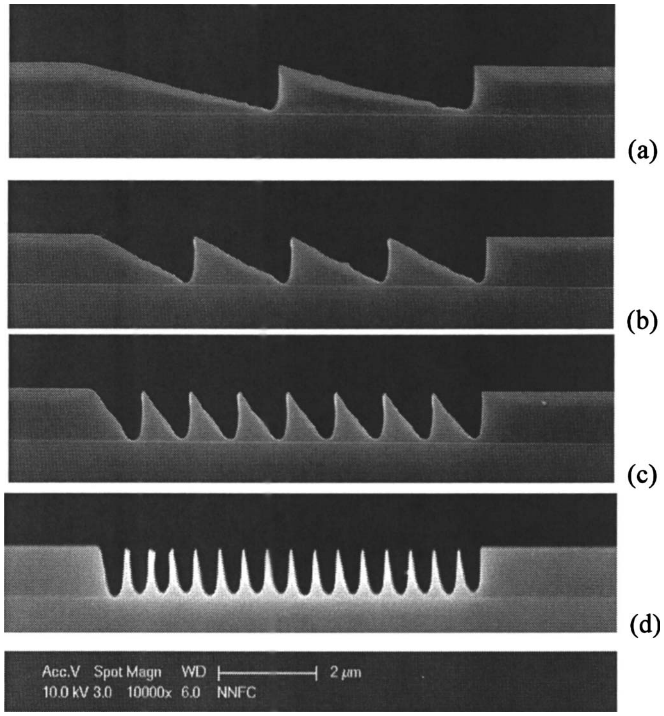
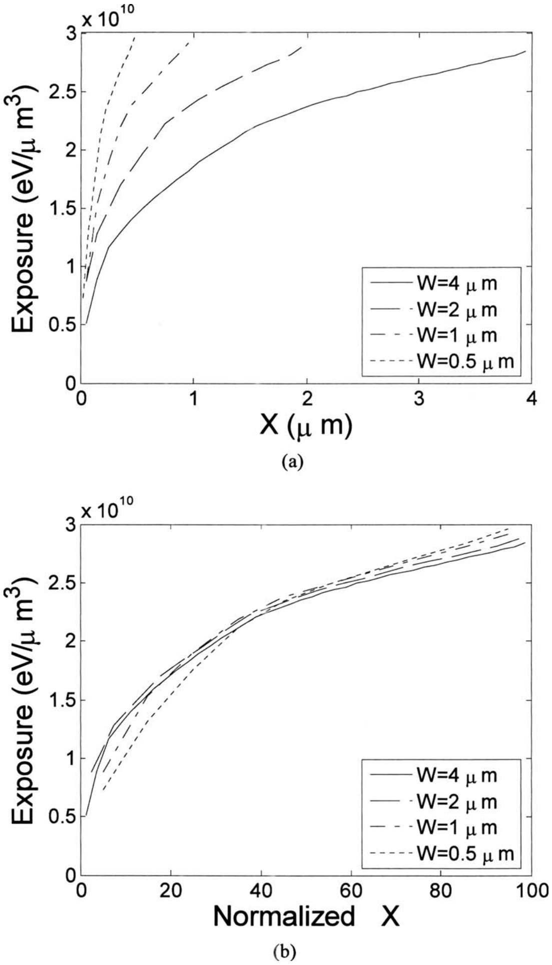


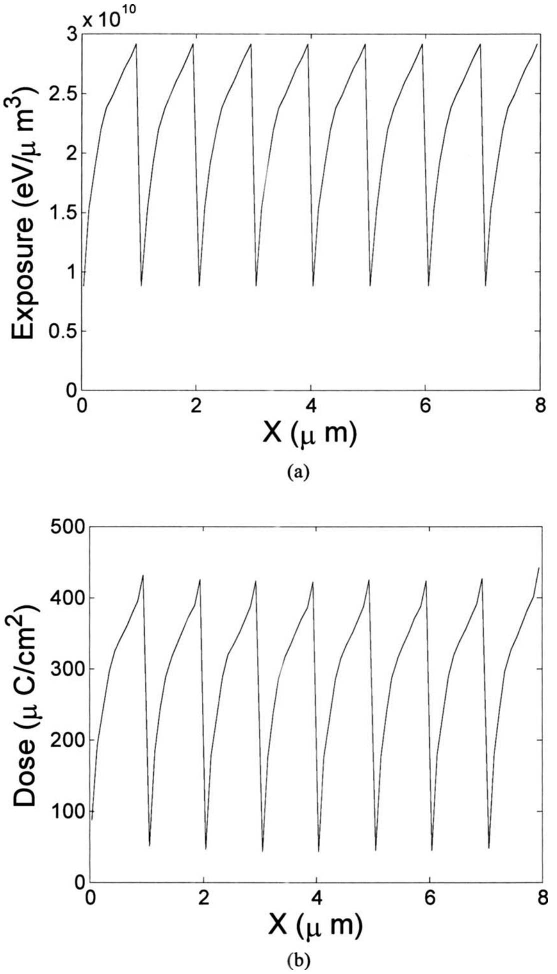
FIG. 6. SEM images of cross sections of the fabricated saw-tooth structures ($H=1$ μm): (a) $W=4$ μm, (b) $W=2$ μm, (c) $W=1$ μm, and (d) $W=0.5$ μm.



(a)

(b)

FIG. 7. Exposure distribution, $e(x)$, within each tooth in the saw-tooth structures shown in Fig. 6: (a) the X-axis is in the real scale and (b) the X-axis is in the normalized scale.



(a)

(b)

FIG. 8. (a) Exposure distribution and (b) dose distribution for the saw-tooth structure with $W=1$ μm and $N=8$.

area exposed is the same for all the saw-tooth structures fabricated. The substrate system was prepared by spin-coating Si wafer with 1000 nm polymethyl methacrylate and soft baked at 160 °C for 1 min. The structure was written using ELIONIX ELS-7000 e-beam tool with the acceleration voltage of 50 keV and a beam current of 100 pA. The sample was developed in MIBK:IPA=1:1 for 30 s at the room temperature of 23 °C. The remaining resist was coated with 10 nm Pt before the cross section was imaged by FEI FE-SEM (Sirion).

In Fig. 6, the cross-sectional SEM images of the four saw-tooth structures fabricated are provided, which correspond to the target structures in Fig. 5. It is seen that the remaining resist profiles achieved are very close to the target ones. The tooth slopes are mostly linear and there exists good uniformity among the teeth as designed. One deviation from the target saw-tooth structures is the rounding at the bottom of the trench, especially when S is large. In the current dose control for the saw-tooth structures, each tooth area (X-Y plane) is partitioned into a set of 100 nm wide regions for dose control when $W=4$, 2, and 1 μm and a set of 50 nm wide regions when $W=0.5$ μm. This rounding deformation may be reduced by a finer dose control at the bottom of the trench.

In Fig. 7, the actual exposure distributions, $e(x)$, for each tooth used to achieve the results in Fig. 6 are plotted in the real [Fig. 7(a)] and normalized [Fig. 7(b)] scales of X-dimension. As discussed in Sec. III, the exposure distribution, $e(x)$, required for a tooth with a linear slope is in the shape of $x^{1/\alpha}$, where α is greater than 1, as can be seen in Fig. 7(a). Also, the required exposure is higher for a smaller S when the depth is small since the lateral development is less. However, this relationship is reversed toward the bottom of the trench where the inefficiency of developing process due to the narrow space outweighs the effect of lateral development [see Fig. 7(b)]. That is, for the same height of teeth, a larger exposure range is required for a narrower tooth or, equivalently, a tooth with a larger slope. In Fig. 8, the dose distribution, $D(x)$, for the saw-tooth structure with eight teeth ($W=1$ μm) which achieves $E(x)=\Sigma_{i=0}^{7}e(x-iW)$ is provided. Though $e(x)$ is identical for all teeth, $d(x)$ is different for a different tooth. $D(x)$, which consists of $d(x)$ of all teeth, is higher toward both ends of the saw-tooth structure in order to compensate for the proximity effect.

VI. SUMMARY

Saw-tooth structures with varying linear slope have been fabricated using e-beam grayscale lithography. The exposure and dose distributions required for the fabrication of the target saw-tooth structures have been derived and the dependency of exposure distribution on the slope of tooth has been analyzed. It is shown that saw-tooth structures can be fabricated with high dimensional fidelity by controlling the spatial exposure distribution. The dose distribution, which leads to the required exposure distribution, was computed by the PYRAMID software. For a saw-tooth structure with a larger tooth slope, a larger range of exposure distribution is needed for the same tooth height due to the lateral development in the shallow region and the inefficiency of developing process at the bottom of the V-shaped trench. It might be possible that the effect of rounding at the bottom of the trench in the saw-tooth structure with a large tooth slope is reduced by controlling the spatial dose distribution more finely in that region.

ACKNOWLEDGMENT

This work was supported by a research grant from National NanoFab Center.

[1] P. Naulleau, E. Anderson, E. Gullikson, and J. Bokor, Opt. Commun. **200**, 27 (2001).
[2] C.-H. Chang *et al.*, J. Vac. Sci. Technol. B **21**, 2755 (2003).
[3] B. Morgan, C. Waits, J. Krizmanic, and R. Ghodssi, J. Microelectromech. Syst. **13**, 113 (2004).
[4] T. Bourouina, T. Masuzawa, and H. Fujita, J. Microelectromech. Syst. **13**, 190 (2004).
[5] Raghunath Murali, Devin Brown, Kevin Martin, and James Meindl, J. Vac. Sci. Technol. B **24**, 2936 (2006).
[6] K. Mohamed, M. M. Alkaisi, and R. J. Blaikie, J. Vac. Sci. Technol. B **25**, 2357 (2007).
[7] F. Hu and S.-Y. Lee, J. Vac. Sci. Technol. B **21**, 2672 (2003).
[8] J. Kim, D. C. Joy, and S.-Y. Lee, Microelectron. Eng. **84**, 2859 (2007).