Orientation dependence of linewidth variation in sub-50-nm Gaussian e-beam lithography and its correction

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The width of tilted line patterns, such as are needed when drawing circular structures, is found to vary with the oblique angle when it falls into the sub-50-nm scale in Gaussian e-beam lithography. The authors’ analysis shows that this orientation dependence of linewidth variation originates from the nonuniformity of discrete primitive filling in Cartesian coordinates. Two correction schemes based on pattern segmentation are proposed. Test exposures of high resolution zone plate patterns show that both two schemes work well; a double-insert scheme is superior in terms of dose distribution uniformity. © 2006 American Vacuum Society. [DOI: 10.1116/1.2393292]

I. INTRODUCTION

Traditional vector scanning Gaussian beam–e-beam lithography tools are designed and optimized for microelectronics applications, in which most edges of the patterns are parallel to the axes of Cartesian coordinates. Patterns for other applications such as diffractive optics fabrication require accurate, curved structures. Several obstacles to pattern curved structures with regular rectangular e-beam tools have been noted,1 resulting in significant efforts to reduce the size of the pattern files and improve the degree of their fidelity. While custom-built pattern generators have been used on modified e-beam writers2–7 and have achieved great success, such solutions are not routinely available for general purpose electron beam lithography laboratories. Polygonizing the complicated structures and segmenting them into machine supported primitives is still the most widely used approach. While much attention has been focused on file size reduction without sacrificing (and even improving) the pattern accuracy at layer-out level,8,9 our experience with high resolution zone plate fabrication shows that even for an accurately segmented ring pattern, the fidelity of its exposure could be degraded to an unacceptable level due to the exposure strategy. In this article, we describe the solution we have arrived at to overcome the orientation dependence of linewidth variation (ODLWV) effect, which is attributed to the primitive filling strategy of the lithography tools, and we demonstrate our solution in the case of patterning Fresnel zone plates as x-ray optics.

Binary zone plates are important diffractive optics for extreme ultraviolet and x-ray focusing.10 From the point of view of a lithographer, a zone plate is just a chirped circular grating with a local period equal to the inverse of the radius from the center of the pattern. When working as an x-ray lens, its focusing resolution is proportional to the outermost zone width. Therefore, a high resolution (sub-50-nm) x-ray zone plate is composed of a large number of concentric rings, whose width typically ranges from 20 to 60 nm.

Patterning high resolution zone plates is very demanding for e-beam lithography, because the regularity of the structures makes them very sensitive to astigmatism and angular dose variation. This is especially important at higher beam voltages such as the 100 keV accelerating potential employed in the present work, where a reduced proximity effect11 in thin-film exposures means that there is less “blurring” of any unevenness in the exposure pattern. For this reason, high voltage zone plate patterns can serve as sensitive check for any orientation-dependent variation of exposure.

II. ORIENTATION DEPENDENCE OF LINEWIDTH VARIATION EFFECT

Our zone plates are patterned using a JEOL JBX-9300FS e-beam lithography system12 at Lucent Technologies, Bell Laboratories, which operates at 100 keV and delivers a 4 nm Gaussian beam when the current is less than 1 nA. The address grid of the deflectors is $1 \times 1 \text{nm}^2$ in a $500 \times 500 \mu\text{m}^2$ field. The machine-level pattern files are generated directly by an updated version of custom software described earlier.13 Each ring is segmented into 500–800 parallelograms, depending on its radius, to ensure an accuracy better than 1 nm. The shot rank steps are assigned to the parallelograms as a function of the radii to modulate the doses for proximity effect correction11 (Fig. 1).

The exposure time is determined by the upper limit of the deflection rate (fixed), the current (variable), the resist sensi-
tivity (fixed), and the shot pitch (variable). To shorten the exposure time it is desirable to raise the current which requires increasing the shot pitch. When the shot pitch is larger than 2 nm, however, we found that all the zone plate exposures show a square pattern, as shown in Fig. 2. High magnification scanning electron microscopy (SEM) micrograph shows that it is a collective angular linewidth/dose variation. This kind of variation can also be found in the zone plate patterns generated by the software provided by the tool vendor and third party fracturing software. In all the cases the variation worsened as the shot pitch was increased.

A pattern layout with circular symmetry results in an asymmetric exposure. Our analysis shows that the asymmetry comes from the primitive filling algorithm of the JBX-9300FS system associated with its Cartesian coordinates and would likely occur in most rectilinear exposure systems.

Figure 3(a) shows the filling scheme of a parallelogram (or trapezoid, in JEOL’s term). When the width of the parallelogram is not an exact multiple of the shot pitch, the scanning start position of each row will shift to the boundaries to avoid a misalignment [Fig. 3(b)]. In this case the areas surrounded by boundaries ABGH and CDEF have a lower dose density and will be underdosed compared with the central area surrounded by boundary BCFG. As a result, the parallelogram will be thinner than was intended. The linewidth \( \Delta w \) of this underdosed part [say, ABGH, for the pattern in Fig. 3(b)] can be deduced as

\[
\Delta w = \left( \frac{w}{\cos \theta \mod p} \right) \cos \theta,
\]

where \( w \) is the linewidth of the parallelogram, \( p \) is the shot pitch, and \( \theta \) is the oblique angle.

As shown in Fig. 4, the linewidth of the underdosed part varies with the linewidth of the parallelogram and its oblique angle. This results in an ODLWV effect. Applying the data in Fig. 4 to a zone plate pattern, the result shows that the square pattern is exactly the result of the ODLWV effect. The locations of the “square pattern” boundaries shown in the simulation match the experimental results very well (see Fig. 5).

For high contrast exposures, the ODLWV effect is universal. Only when the linewidth of the parallelogram is small does the ODLWV effect become significant, since the under-

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Fig. 1. Primitive arrangements in the first quadrant of a zone plate pattern generated by custom software.

Fig. 2. (a) Square pattern of dose variation as viewed in a SEM micrograph of a zone plate exposure. (b) A high magnification SEM micrograph shows the square patterns are collective angular dose/linewidth variations. (c) and (d) Differential interference contrast (DIC) micrographs of the zone plates exposed with the patterns generated by (c) custom software and (d) JEOL software.

Fig. 3. (a) Trapezoid filling scheme of the JBX-9300FS. (b) Linewidth variation is due to the nonuniform filling near the primitive boundaries. (c) Correction of ODLWV effect by segmenting a parallelogram into three parts. The outer parts, whose widths are multiple of the shot pitch, are exposed at regular dose. The insert is exposed at a corrected dose which accounts for the missing spots. (d) Double-insert correction scheme, which is especially good for exposure of very thin lines. The dose for the two inserts (areas in boundaries BCFG with shadowed shots and JKLL with bold shots) is corrected by counting the excess shot spot area.
dosed parts then make up a non-negligible portion of the whole figure. In our resist/substrate structure, the square pattern does not look very clear in the inner area of the zone plate pattern, whose linewidth is larger than 50 nm.

It is necessary to note here that another kind of angular dose variation effect in single-pass-line exposure was mentioned by King et al., which is a result of the projection effect. It is much more significant compared with the ODLWV effect reported here but seems to be easier to correct.

III. CORRECTIONS

The ODLWV effect results in an inconsistency in the dose requirement for the exposure of the parallelogram. It is especially harmful for the exposure of the high resolution dense patterns, such as zone plates and circular gratings because the tolerance of the “right” dose is very small for these patterns and the variation introduced by the ODLWV effect sets a bar for the minimal ring width achievable. Therefore, an effective correction method was pursued.

A. Angular dose modulation based scheme

Angular dose modulation is a straightforward correction scheme since the ODLWV effect is a result of the nonuniformity of the shot dose distribution. However, it is less practical to realize as a correction scheme, especially for dense patterns. First, the areas near the boundaries of the parallelogram are underdosed, no matter whether the total dose in the boundary is corrected or not. This occurs because the placement of the individual pixels is slightly different at the edge, as shown in Fig. 3. Therefore, the total dose must be greater than a “standard” dose so that the scattered electrons from the inner area can make up for the missing dose in the outer area. As a result, an ideal correction needs information on the data of electron beam distribution and of short range electron scattering, neither of which are easily measured with high accuracy. Second, when the total dose in a parallelogram increases, its contribution to the proximity effect also increases. Thus, extra proximity effect correction (PEC) work will be needed. In the case of zone plates, the original one-dimensional PEC will be replaced by a two-dimensional PEC, dramatically increasing the complexity. Third, even after a perfect dose modulation rank list is obtained, the tremendous number of linewidth/angle combinations will lead to a huge number of correction dose rank steps. Although a great number of overlapped doses can be merged, the required sorting will still be time consuming. Fourth, the zigzag profile of the parallelogram contributes a lot to the line edge roughness (LER), and this will not be eliminated by a correction based on angular dose modulation. For these reasons, we believe that angular dose modulation is not the most satisfactory solution.

B. Segmentation based schemes

1. Basic ideas

As illustrated in Figs. 3(c) and 3(d), and as described in more detail elsewhere, the basic points of segmentation based schemes can be described as follows:

(1) As shown in Fig. 3(c), a parallelogram, whose width is not an exact multiple of the shot pitch, will be segmented into three parts. The width of the two outer parts is designated as the maximal multiple of the shot pitch allowed so that they can be exposed at the original dose. The central part, which we call the “insert”, needs a dose adjustment. Since its real width is only one shot pitch, the exposure dose will be corrected to \( D = \frac{p}{g} \), where \( D \) is the regular original dose, \( p \) is the shot pitch, and \( g \) is defined as \( g = \frac{p}{k} \), where \( k \) is defined as \( k = \frac{p}{g} \) with \( g \) representing the grid unit. Thus the total number of the correction dose rank steps is only a multiple of \( (2k-2) \) of the original dose rank number. For an exposure with ten original dose rank steps exposed at 4 nm shot pitch on a 1 nm grid, 60 more dose ranks will be needed in total. This is a sufficiently small number for most advanced e-beam lithography systems, making it not necessary to sort and merge the overlapped dose ranks.
To improve the uniformity of the dose distribution of the insert and further reduce its potential contribution to the LER, the above single-insert correction scheme can evolve into a double-insert scheme by replacing the zigzag insert with two well-defined straight inserts and cutting the dose in half, as illustrated in Fig. 3(d). This scheme needs \((k-1)/2\) new dose ranks, which is still an acceptably small number.

2. Test method

We tested the above scheme with two groups of zone plate patterns. Group A is for a zone plate with 160 \(\mu m\) diameter, 30 nm half pitch for the outermost zones, and a “pull-in” of 8 nm on all exposed zones (meaning that the exposed width of the outermost zones is 22 nm). Group B is for a zone plate with 80 \(\mu m\) diameter, 20 nm half pitch for the outermost zones, and no pull-in. Both groups were composed of zone plate patterns exposed with no correction, with the single-insert and double-insert scheme corrections. The corrected patterns were all exposed with a 4 nm shot pitch, while uncorrected patterns were exposed with both 2 and 4 nm shot pitch. A trilevel resist structure\(^1\) was adopted for high resolution patterning by employing a thin imaging layer atop of a thicker lower layer. The trilevel structure used here was composed of 50 nm ZEP520 e-beam resist at top, 10 nm germanium hard mask, 200 nm hard baked photoresist buffer layer, and silicon substrate. After exposure, the resist was developed in hexyl acetate\(^2\) for 90 s and rinsed in isopropanol alcohol for 45 s, followed by a short CF\(_3\)Br reactive ion etch to transfer the pattern to the germanium layer to enhance the imaging contrast for later inspection.

Limited by the 1 nm address grid precision, many adjacent rings on the test pattern are of the same widths and behave similarly. A couple of wide belts will form when the underdose or overdose occurs collectively among the rings with the same widths. For the patterns in group A, the ring width changes by about 30 nm over a 40 \(\mu m\) change in radius, so the minimal belt width is about 1 \(\mu m\) which falls into the resolution range of a high quality optical microscope. Therefore, all the test patterns were inspected and imaged with a Nikon Eclipse L200D optical microscope under differential interference contrast (DIC) mode.

IV. RESULTS AND DISCUSSION

From the results shown in Fig. 6, we can see that the single-insert scheme corrected the variation in most of the area. However, some thin square frames remain. These square frames are much darker in the thin ring (outer) area than in the thick ring (inner) area. After checking the pattern file, it was found that the square frames are around the boundaries, where the insert width experiences a dramatic change from \((2k-1)g\) to 0. It seems that when the line is thin, the outer trapezoids may not be able to smooth out the dose variation introduced by the heavily dosed insert. Such kind of square frames are not found in the patterns corrected with the double-insert scheme, which look perfect in terms of angular uniformity. Double-insert correction patterns even surpass the uncorrected patterns exposed with a 2 nm shot pitch, which is otherwise routinely recommended.

The segmentation based correction scheme involves a trade-off of several factors. After correction, the pattern file size is tripled, its minimal dose drops to \(1/k\) of original value, and the pattern file generation is no longer independent of the exposure parameters (shot pitch, beam current, etc.). To increase the minimal dose, a substitute segmentation scheme can be employed. As illustrated in Fig. 7, by replacing the narrow insert (whose width is less than one-fourth of the shot pitch) with an insert which is two-shot-pitch wider, the minimal dose doubles. The minimal dose can be further increased up to the uncorrected value in the same way. The drawback is that the outer parallelograms get thinner, and as a result they are less effective in isolating the dose variation from the outer area.

The segmentation based correction schemes make full use of the address precision, but the shots are less dense compared with an exposure with minimal shot pitch. Therefore a
corrected pattern cannot be of the same quality in principle, and its ultimate performance is limited by the address grid size.

V. CONCLUSION

The ODLWV effect was observed in high resolution vector scanning Gaussian beam–electron beam lithography. It is considered to be the result of the nonuniformity of the discrete primitive filling in Cartesian coordinates. Two correction schemes based on primitive segmentation were proposed and tested. Both schemes work well. The double-insert scheme is especially good in terms of dose uniformity. A trade-off of several factors, segmentation based correction schemes take full advantage of the machine addressing capability when the shot pitch is limited by the minimal dose and deflection frequency. Therefore, they are effective solutions for nonrectangular structure patterning when the deflection rate hardware upgrade is not viable.

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15The possible insert widths are \( g, 2g, \ldots, (k-1)g, (k+1)g, \ldots, (2k-1)g \).