

Predicting critical dimension uniformity in advanced electron-beam projection lithography masks

Eric P. Cotte, Andrew R. Mikkelsen, Oscar Matesanz, Roxann L. Engelstad,^{a)}
Edward G. Lovell, and Phillip L. Reu
Computational Mechanics Center, University of Wisconsin, Madison, Wisconsin 53706

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Meeting the stringent budgets for both overlay errors and critical dimensions (CDs) for the insertion of next-generation lithographies requires that the sources of mask-related distortions be identified and minimized. Such sources include the mask fabrication process, electron-beam patterning, and exposure conditions. This article describes numerical simulations to characterize CD nonuniformities for the stencil format of the electron-beam projection lithography PREVAIL mask. Finite element (FE) submodeling and equivalent modeling techniques were used to investigate CD uniformity for a worst-case scenario. Whereas a global model is sufficient to predict mask overlay errors, submodeling and statistical analyses are necessary to characterize mask CD errors. The FE simulations illustrate that CD nonuniformities (from mask fabrication) can be limited to 1.0 nm, if the maximum membrane prestress is monitored and controlled. Such results comply with the CD error budgets set for the sub-65-nm lithography nodes. © 2003 American Vacuum Society. [DOI: 10.1116/1.1614251]

I. INTRODUCTION

Critical dimension (CD) control is a major requirement for advanced lithographic technologies including electron-beam projection lithography (EPL). In particular, stencil masks, such as the PREVAIL design shown in Fig. 1(a),¹ are inherently prone to fabrication distortions resulting from perforating stressed membranes. The specialized applications proposed, e.g., contact layers, are typically characterized by uniform isotropic patterns. However, to assess CD uniformity for a worst-case scenario, an orthotropic layout was studied. In addition, the effects of nonuniform pattern density distributions were also examined. The fabrication process flow of the PREVAIL mask was simulated, as depicted in Fig. 1(b),¹ and an orthotropic static random access memory (SRAM) pattern (based on the IBM Falcon layout) was used as a test case.² Material properties, thicknesses, and layer stresses are listed in Table I. Equivalent material properties were determined for this pattern via techniques developed at the University of Wisconsin Computational Mechanics Center.^{3,4} Submodels and sub-submodels were created to determine the critical dimension variations of the 400 nm SRAM features in relation to the displacements of the global model. While the global model represents one quarter of a PREVAIL mask, submodels focused on single 1.1 mm×1.1 mm membrane windows delimited by silicon struts within the mask. In turn, sub-submodels represent a specified array of unit cells, containing the SRAM features. Combinations of pattern densities were also considered, with fully patterned windows next to half-patterned horizontal or half-patterned vertical windows. CD uniformity was analyzed across an entire mask, within a window, and for a single feature. The effects of membrane stress and gravity were taken into account.

II. FINITE ELEMENT MODEL VERIFICATION

Finite element (FE) models were developed and benchmarked against a relevant theoretical solution. This corresponds to the deflection of a slit in an infinite prestressed membrane, as shown in Fig. 2(a), and was first calculated by Westergaard.⁵ The maximum in-plane distortion, δ , was re-

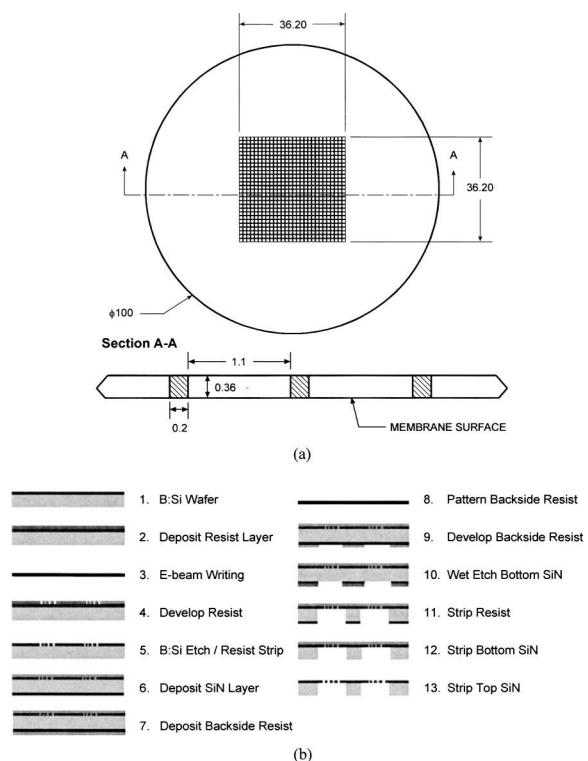


FIG. 1. (a) Schematic of IBM's 100 mm EPL prototype stencil mask (all dimensions in millimeters) and (b) a typical EPL mask fabrication process flow (see Ref. 1).

^{a)}Electronic mail: engelsta@engr.wisc.edu

TABLE I. Material properties, thicknesses, and stress values for typical PRE-VAIL mask components (see Ref. 1).

Material	Elastic modulus (GPa)	Poisson's ratio	CTE ^a (ppm/°C)	Thickness (nm)	Stress (MPa)
B:Si	160.0	0.21	10	1500	5.0
Photoresist	3.1	0.35	30	300	15
SiN	160.0	0.12	10	50	100

^aCoefficient of thermal expansion.

lated to the slit length, far-field mean stress perpendicular to the slit, and material properties of the infinite membrane through the following equation:

$$\delta = \frac{\ell(1-\nu^2)\sigma_m}{E}, \quad (1)$$

where ℓ =slit length, ν =Poisson's ratio of the membrane, σ_m =applied uniaxial mean stress, and E =elastic modulus of the membrane.

Equation (1) can be used to estimate CD errors and validate FE models of rectangular pattern perforations. For such a slit with no width, in a membrane large enough to be considered infinite, the FE model results compare well with the Westergaard solution, as shown in Table II. But the results also illustrate that this analytical solution is not applicable

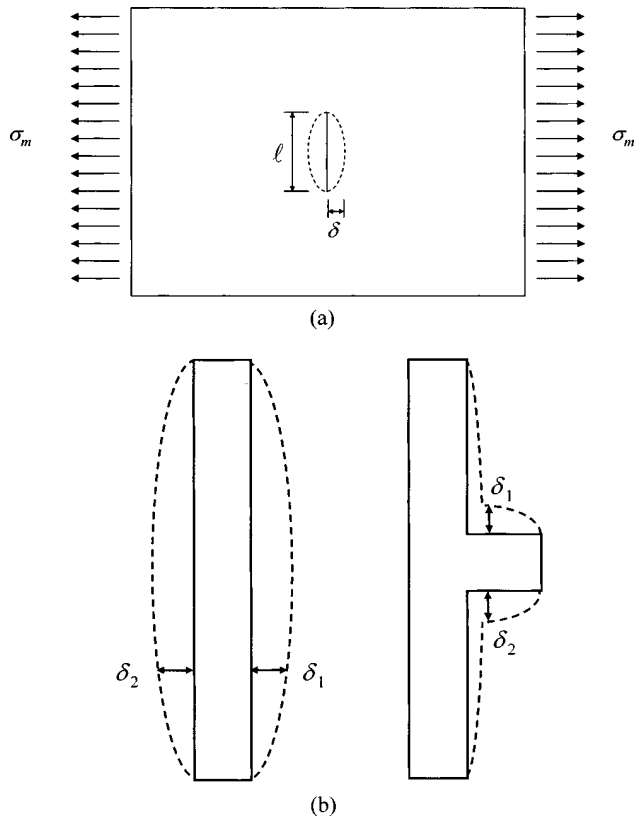


FIG. 2. Schematics illustrating (a) a slit of length ℓ in an infinite membrane under uniaxial stress σ_m , with maximum in-plane distortion, δ and (b) CD errors defined as $\delta = \delta_1 + \delta_2$ for two features. The unstressed slit or feature is shown as a solid line. The shape of the slit or feature under stress is shown as a dashed line.

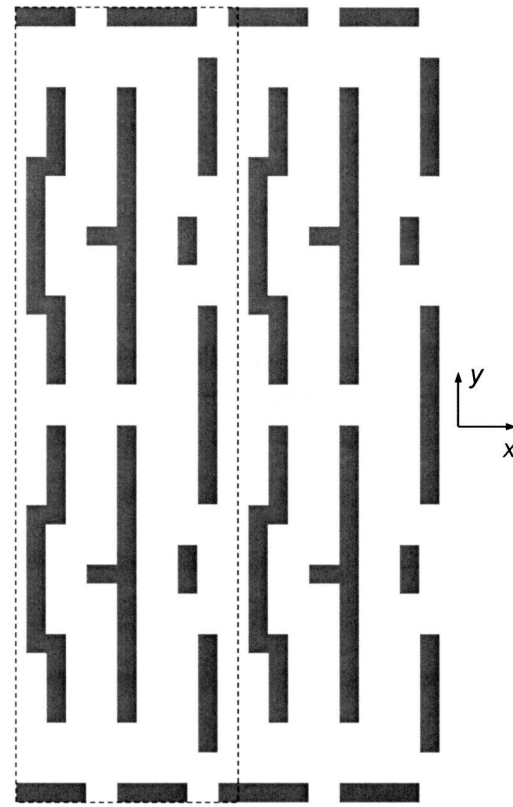


FIG. 3. Schematic representing the SRAM pattern modeled. The dashed line indicates the perimeter of the unit cell. Critical feature size is 400 nm (see Ref. 2).

for a slit of finite width (400 nm in the example considered). Figure 2(b) illustrates CD error for two different features with finite widths. The CD variation at specific locations on the features is defined as $\delta = \delta_1 + \delta_2$, i.e., the total lateral deformation. After validation, the FE models can be applied to these and more realistic patterns, which lack analytical solutions.

III. FINITE ELEMENT MODELING TECHNIQUES

Equivalent modeling is the first technique required to facilitate FE simulation using patterns such as the orthotropic SRAM layout, consisting of the repeated unit cell shown in Fig. 3.²⁻⁴ This procedure replaces a patterned (i.e., perforated) membrane with an equivalent uniform solid membrane in which the material properties are changed to account for the type of feature coverage. The equivalent elastic modulus values of the SRAM pattern were found to be

$$E_x^* = 0.1487 \times E, \quad E_y^* = 0.4525 \times E, \quad (2)$$

where E is the actual elastic modulus of the membrane material.

The second technique needed to make the simulations less computationally intensive is submodeling. It consists of using the displacements of a global model (representing the entire structure studied) as boundary conditions in a sub-model (simulating only a portion of the global model) representing the geometry of the structure in finer details. For the

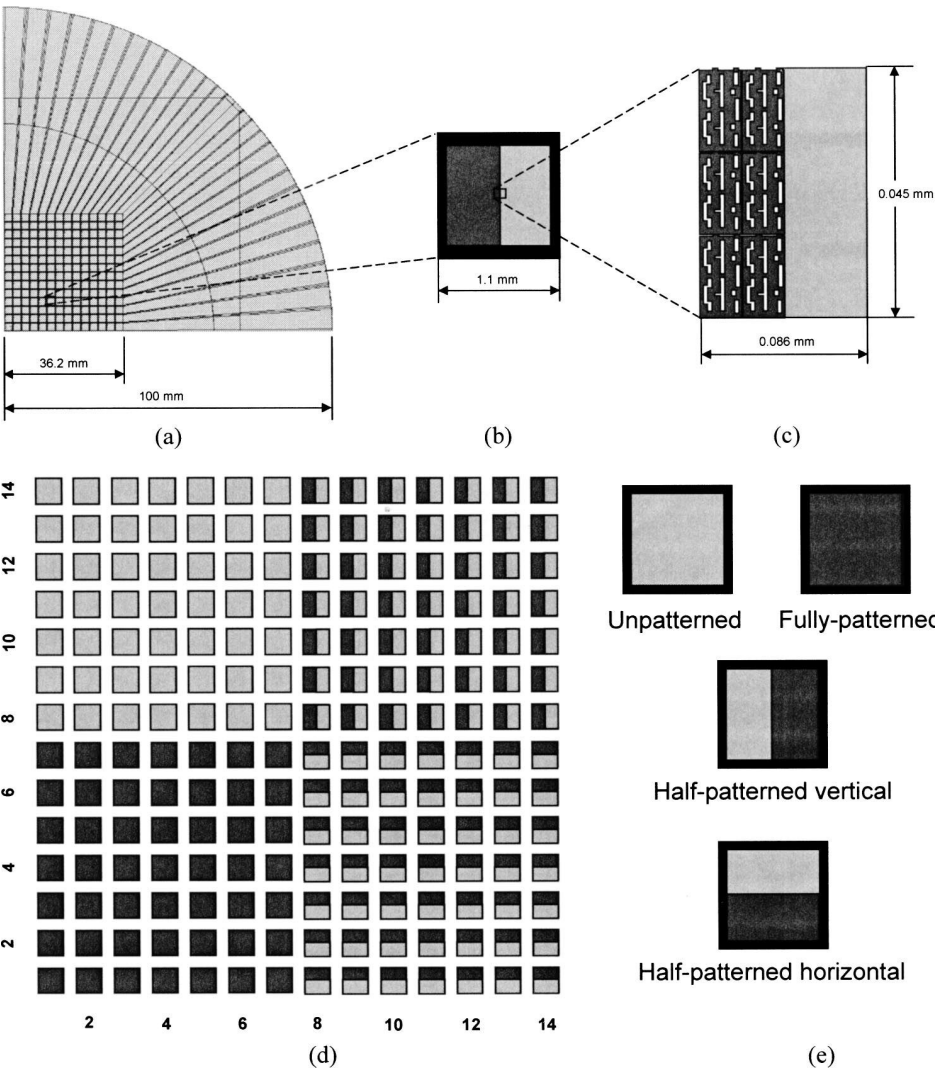


FIG. 4. Schematic of the FE submodeling technique illustrating the (a) quarter-symmetry global model, (b) submodel, (c) sub-submodel, (d) location of the different types of windows over the patterned quadrant shown in (a), and (e) the various window types. Window locations are identified by (row, column) numbers.

case at hand, submodeling was used twice, as shown in Figs. 4(a), 4(b), and 4(c). First, the fabrication process steps of the EPL mask are simulated using a quarter-symmetry FE model, as shown in Fig. 4(a). This model contains a relatively coarse mesh within the 1.1 mm×1.1 mm membrane windows. The displacements at the perimeter of the indi-

vidual windows (as calculated with the global model) are then used as input for the submodels of each window across the EPL mask [see Fig. 4(b)]. These submodels are generated with a relatively fine mesh. Finally, to simulate the fabrication of the actual SRAM features, displacement results from the submodels are used as inputs into the sub-

TABLE II. FE results for a Westergaard-like problem and percent difference between analytical and numerical distortion results. Feature sizes are 3.9 μm ×400 nm, far-field uniaxial stress is 5.0 MPa, elastic modulus is 160 GPa, and Poisson's ratio is 0.21.

Case	Slit in infinite membrane	Feature in infinite membrane	Feature in finite membrane	Off-center feature in finite membrane
Schematic				
Maximum δ	0.12 nm	0.13 nm	0.14 nm	0.15 nm
Difference	1.8 %	12.7 %	24.1 %	28.9 %

TABLE III. CD uniformity data within an EPL mask. Window locations are noted in parentheses and correspond to the schematic in Fig. 4(d).

Window coverage	CD average, μ (nm)	CD standard deviation, σ (nm)	CD maximum, $\mu+3\sigma$ (nm)
Fully-patterned (1,1) (1,7) (7,1) (7,7), and (4,4)	0.05	0.05	0.19
Half-patterned horizontal (1,8) (7,8) (7,14), (1,14), and (4,11)	0.08	0.07	0.30
Half-patterned vertical (8,8), (8,14), (14,8) (14,14), and (11,11)	0.17	0.13	0.55

submodels, as shown in Fig. 4(c). The sub-submodels are constructed with extremely dense meshing to identify the distortions down to the level of the features, i.e., to study CD variations.

IV. CD UNIFORMITY RESULTS FOR THE VARIOUS WINDOW TYPES

Average values for CD error, as well as CD standard deviation and maximum CD (3σ), can be reported for a particular feature, the features within a window, or the features across a mask. First, in Table III, CD is reported across an EPL mask patterned with the layout shown in Fig. 4(d), which represents the type of coverage in each window for the quarter-symmetry model. Pattern coverage varies from 0% (unpatterned) to the SRAM pattern studied in the previous section (fully-patterned), with some windows half-patterned either vertically or horizontally, as illustrated in Fig. 4(e). CD uniformity results are listed for particular windows representing fully-patterned, half-patterned vertical, and half-patterned horizontal layouts, for a membrane biaxial prestress of 5.0 MPa. (It should be noted that CD error varies linearly with membrane stress.) The results illustrated that windows of a specific type behave similarly, regardless of their location in the quadrant shown in Fig. 4(d). Half-patterned vertical windows have the highest CD variation, with a maximum (3σ) of 0.55 nm. Next, it is of interest to focus on this particular type of window and to investigate CD errors with respect to feature type.

V. CD UNIFORMITY RESULTS WITHIN AN EPL MASK WINDOW

Figure 5(a) identifies the different features used for CD monitoring in this study. Table IV illustrates CD variations for each type of feature located in the half-patterned vertical window (11,11), where the maximum error for all features lies. *T* features do not distort laterally as much as *I* features, in spite of their length; but their “stems,” identified as *Ty* features, experience relatively large CD nonuniformities. A maximum (3σ) CD error of 0.68 nm occurs for *U* features. Figure 5(b) illustrates CD nonuniformities across a *U* feature, with a maximum of 0.6 nm (smaller than the maximum of 0.68 nm calculated statistically), as well as distortion plots

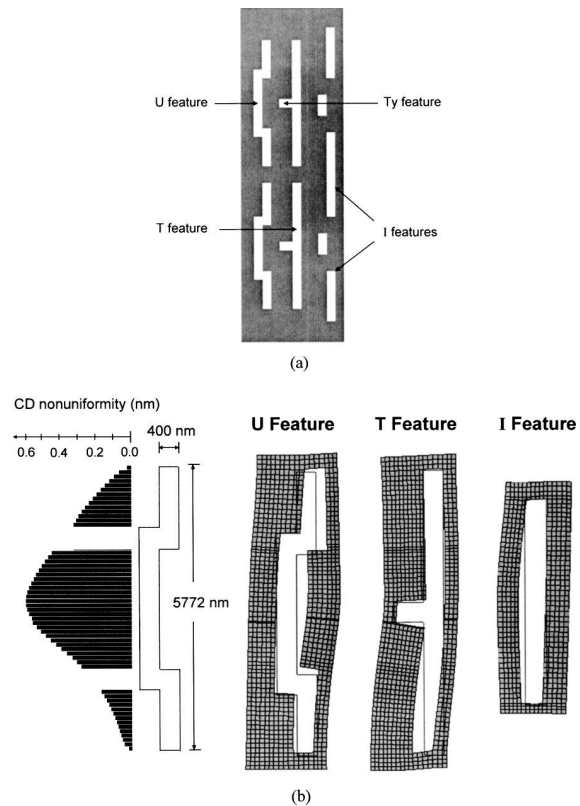


FIG. 5. (a) Schematic of a unit cell identifying the different types of features and their labeling conventions, and (b) CD nonuniformity across a *U* feature and distortion plots for all features. Maximum CD error is 0.6 nm for the *U* feature.

illustrating CD variations for other features within the bottom of the half-patterned vertical window (11,11).

VI. SUMMARY AND CONCLUSIONS

To accurately determine stencil mask pattern distortions, finite element models were created and validated with Westergaard's analytical solution for a slit in an infinite membrane under uniform stress. Equivalent modeling and sub-modeling techniques were developed to focus on CD uniformity for an entire PREVAIL mask, a 1.1 mm×1.1 mm window, and actual 400 nm wide features. Half-patterned vertical windows yielded the largest CD nonuniformities. All features were studied separately, and U-shaped features were found to yield the largest CD nonuniformities, with a maximum value (3σ) of 0.68 nm. Since CD error is proportional to stress, the maximum value would remain lower than 1.0

TABLE IV. CD uniformity data within EPL mask window (11,11), corresponding to the schematic in Fig. 4(d).

Feature type	CD average, μ (nm)	CD standard deviation, σ (nm)	CD maximum, $\mu+3\sigma$ (nm)
<i>I</i>	0.18	0.12	0.54
<i>T</i>	0.10	0.07	0.30
<i>Ty</i>	0.22	0.09	0.50
<i>U</i>	0.23	0.15	0.68

nm for the pattern considered if the membrane stress was kept below 7.35 MPa. The results of this study are in compliance with the CD error budgets for sub-65-nm EPL masks.

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