Effects of Residual Aberrations on Line-end Shortening in 193 nm Lithography

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ABSTRACT
This paper extends and further validates the methodology for calibrating 193nm chemically amplified resist models and applying the models to line-end shortening simulation in the presence of image imperfections [1]. SPLAT, an imaging simulator, is used to simulate the light intensity at the bottom of resist film and predict the resulted wafer patterns in the presence of lens aberrations. The mask critical dimensions (CD) were measured to exclude the mask CD error effects. The experiments were conducted at Texas Instruments on a 193nm scanner. The mask CD errors proved a major contribution to isolated-dense line CD bias on the wafer. The lens aberrations were shown to be critical to the choice of optimal imaging location and the through-focus CD variation. By finding the optimal image location and threshold photoacid concentration, this model can predict line CD through focus, pitch and feature size, with a RMS error of 5nm. However, this model is not adequate in predicting the narrow space between line ends due to the poor resist response in very low contrast areas. A variable threshold model based on trajectory dissolution rate assumption is proposed to predict the wafer CD in low contrast areas, which resulted in a RMS error of 24nm. Considering the large SEM measurement noise on 193nm resists, this error is reasonable and sufficient for OPC applications.

Key word: 193nm lithography, resist, lens aberrations, model calibration, variable threshold model

1. INTRODUCTION
Pattern dimensions, tool quality and resist response all play important roles in lithographic performance. Many characteristics of wafer patterns, such as line-end shortening, corner rounding and space scuming, can not be correctly captured without the aid of resist models. In addition, two-dimensional features are more sensitive to lens aberrations than line CDs. The across-chip line CD variation (ACLV) and tool-to-tool wafer CD variation can not be ignored and can be attributed mostly to residual aberrations in lenses. Thus a combination of resist modeling and lens aberration simulation is needed to adequately predict the wafer images through focus/dose, across chip and from tool-to-tool. Furthermore, the extensive use of Resolution Enhancement Technique (RET) greatly boosts the need of a fast, predictive and scalable model to ensure that the RET designs reach CD targets and have enough process latitude. Current production-oriented modeling work of 193nm lithography usually focuses on one particular dose and best focus and tries to predict the CDs of different patterns through rapid numerical models including diffused aerial image model [2][3], variable threshold resist model (VTR) [4][5], etc. A detailed review of VTR models can be found in [11]. This methodology can ensure line CD control within 5% variation but may fail in capturing the 2-dimensional pattern distortions that result in unwanted scum or bridging [6]. Furthermore, the simulation errors can be magnified by the dose/defocus bias brought forth by non-uniform wafer planarity or tool-dependent lens aberrations. Thus the process latitude may be unexpectedly poor when using reticles corrected by this methodology [7]. On the other hand, lithography engineers have been using physical-model-based simulators such as PROLITH and SOLID-C to evaluate the feasibility of process setup and predict the though-dose, though-focus printing results of mask patterns. Although the simulators capture the trends of printing results as process or reticle varies, they generally are not used to predict pattern CDs if certain accuracy is required due to the large number of model parameters to be calibrated and the time-consuming simulation process. To provide a solid base for characterizing the major process factors in 193nm lithography and predicting the pattern transfer quality, a predictive, scalable and fast model is needed which should be easily calibrated on production tools.

Based on the enormous amount of experimental data and SEM pictures obtained at Texas Instruments, a systematic divide-and-conquer strategy is presented and the modeling methodology is developed in this paper. The main factors affecting printing quality include mask accuracy, choice of imaging imaging focal plane, lens aberrations, resist post exposure bake (PEB) process and resist dissolution mechanism. First, the actual mask CDs were measured and used in all simulations, which excluded the mask error effect. Then by inspecting the CD vs. defocus curves of isolated and
dense lines, the location of focal plane in the resist was determined. When adding lens aberrations and simulating CD vs. defocus curves of lines, it was found that the actual focal plane location was 0.1µm lower than calculated under the assumption of aberration-free lens. Using the measured mask CDs, lens aberrations and the imaging location found above, the light intensity in resist of lines at different defocus, different pitch and 9.5mJ/cm² dose are simulated. A threshold light intensity model was used to determine the line CDs. Then the calibrated single-threshold resist imaging model was further used to simulate 2-dimensional patterns. A trajectory dissolution rate model is developed to simulate the wafer patterns in low contrast area. In this model, the dissolvability of resist at a certain location is enhanced by the maximum acid concentration in its neighborhood.

2. EXPERIMENTAL SETUP

The experiments were done at Texas Instruments on a 193nm scanner, NA 0.6, σ 0.75. The resist Sumitomo PAR710 was used, soft bake 130°C, 60sec, and post exposure bake 130°C, 60sec. After soft bake, the resist thickness is 350nm. Along with the resist, the Bottom Anti-Reflective Coating (BARC) AZ-20 was also used with thickness 82nm. A full through dose and through defocus matrix was exposed. The dose used was from 9 to 10.5mJ/cm² in step of 0.5mJ/cm². The defocus was from –0.2 to 0.2µm in step of 0.1µm. After development, the SEM pictures of the patterns were taken. All SEM pictures had the same magnification of 150K. The resist parameters were provided by International SEMATECH. The optical constants of PAR710 are n=1.699, A=0, B=1.114, C=0.05mJ⁻¹. The BARC AZ-20 has refractive index n=1.706174, k=0.40784.

The lens aberrations were measured through Litel in-situ technology and the Strehl ratio was 0.926. Before the exposure experiments, the mask was measured. In all the simulations, the measured mask CDs were used to exclude the mask error effects.

3. SIMULATION SETUP

Ref. [8] [9] show that the Aerial Image Model, even including aberrations, is not sufficient to capture the through-focus behavior of lines. On the other hand, the imaging in resist model which was presented in [1] is shown to be capable of capturing the essential through-focus variation of lines. Thus the imaging in resist model is used as a base model in this paper. It first simulates the image intensity on a plane which is in the resist film and parallel to the resist surface, and then uses (1) to convert image intensity to photoacid concentration:

\[ C_o(x,y) = 1 - e^{-C.Dose.I(x,y)} \] (1)

Where \( I(x,y) \) is the normalized image intensity in the resist, and \( Dose \) is the exposure dose in mJ/cm², \( C \) is the Dill’s C parameter in cm²/mJ. The conversion of image to acid is for simulating the effects of different doses. In this paper, the imaging plane is assumed to be the bottom of the resist, because that was where CD were measured. Finally a threshold detector is used to determine the simulated CD, which assumes the resist is developed where the photoacid concentration is above a given threshold.

It is worthy of mentioning the importance of using the measured mask CDs instead of the designed values in the simulation. Fig. 1 (a) and (b) plots the mask and wafer line widths vs. pitch, respectively. It can be seen that the wafer CDs almost exactly follow the variation of mask CDs. When the pitches are less than 400nm, the mask CD errors are magnified by the Mask Error Factor (MEF) that can be up to 2 for lines if the pitch is small. Therefore the isolated-dense bias is mostly due to the mask CD variation.

4. IDENTIFYING IMAGING LOCATION AND THRESHOLD PHOTOACID CONCENTRATION

In gate printing process, line width control is the first priority. A plot of line widths of 100-140nm lines at pitch 350nm, exposure dose 9.5mJ/cm², and at defocus –0.2 to 0.2 µm is shown in Fig. 2. Note that there were no patterns of the 100nm line on the wafer when the defocus was less than 0µm. This could be due to processing error.

The actual position of the focal plane and the threshold acid concentration were obtained by minimizing the Root Mean Square (RMS) error of the simulated line widths. The simulation set includes 100, 120, 130 and 140nm lines, at 350nm pitch, exposed at defocused from –0.2 to 0.2µm. Fig. 3 shows the simulated line widths vs. defocus when the focal plane is 0.20, 0.25 and 0.30µm below resist top surface. The corresponding RMS errors are 9.94, 4.99 and 2.79 nm, respectively. It can be seen that the best focal plane is 0.30µm below the resist surface.
Although the Strehl ratio of the lens has only minor impact on aerial images, it significantly affects the imaging in resist. Assuming the lens is aberration-free, the best focal plane was found to be 0.2µm below the resist top surface. It can be seen that lens aberrations are critical to the choice of best focus and to the through-focus variation of CDs.

With the focal plane and threshold obtained above, Fig. 4 compares the experimental and simulated CDs vs. defocus at 350nm and 1750nm pitch, exposure dose 9.5mJ/cm². The RMS error for the four different lines at 5 defocuses and 4 different pitches (320, 350, 500 and 1750nm) is 5.28 nm. That is, the RMS error over 80 line CD measurements is 5.28 nm, or 5.3% of the smallest line width (100nm mask CD).

Generally, the CD control in gate printing process requires ±5% CD variation. SEM measurement error is more than 10nm due to resist slimming and line-edge roughness (LER) [6]. Thus this simple resist imaging model, aided by lens aberrations, is capable of predicting line CD with RMS error less than 5% of the current 130nm node. It is sufficient for optical proximity correction (OPC) applications.

5. ANALYSIS OF EXPERIMENTAL AND SIMULATED 2D PATTERNS

With the defocus setup and the threshold obtained in Section 4, the pattern shown in Figure 5 was simulated with dose 9.0, 9.5, 10.0 and 10.5 mJ/cm², defocus –0.2 to 0.2µm. Then the simulated images were compared with the monochromatic representations of the corresponding experimental SEM pictures. Note that there was noticeable amount of bias on mask. The designed space between the two line ends is 120nm, while the actual space on mask is equivalent to 134nm. For this pattern, the CD is the spacing between the two line ends. Fig. 6 plots the through-dose, through-focus space of this pattern.

The overlay of the simulated images with the monochromatic representations of experimental pictures is shown in Fig. 7. The simulations agree with experimental images in black areas in Fig. 7, and do not agree in gray areas. In Fig. 7, from (a) to (d) correspond to exposure dose 9.0, 9.5, 10.0 and 10.5 mJ/cm², respectively. Only the overlay of simulations at 0µm defocus is shown. Figure 8 plots the corresponding spacing predicted by the imaging model.

Fig. 7 show that this resist imaging model fits through-dose, through-focus experimental SEM pictures very well, even though the threshold photoacid concentration was obtained by fitting line widths at the dose of 9.5mJ/cm² only. However, the space CD predicted by this resist imaging model is significantly and consistently larger than the experimental data. The RMS error of prediction is 43.6nm, which indicates the chemical effects other than optical effects must be taken into account. There could be two mechanisms contributing to this line-end gap shrinkage phenomenon. First is the post exposure bake (PEB) process. Along the edge of lines the light intensity is high and the image slope is steep. In the neighborhood of line-end space, however, the image intensity is low (typically less than 0.7).

Thus it is expected that larger amount of photoacid can diffuse into the line than into the space. The other mechanism is the dissolution process. The neighborhood of lines has very high dissolution rate and thus is dissolved instantly at the beginning of developing. Then the sidewalls of lines are attacked by developer, which effectively increases the dissolution of lines. In contrast, the neighbor of line-ends is dark and the dissolution rate is relatively low. Thus it takes more time to open the space and therefore leaves less time for the developer to attack resist line ends. As a consequence, the space is developed for less time and may show more roughness and scum than the line edges do.

The reason that the resist imaging model succeeds in predicting line widths but fails in predicting line-end gap is further explained by Fig. 9. Fig. 9 shows that the lines have much steeper and higher peak light intensity than the gaps, which justifies the above argument that spaces are developed for less time and the advancing of developer is relatively slow. Also, note that the lens aberrations have bigger impact on spaces than on lines. The light intensity across spaces is not symmetric or sharp whereas that of lines is almost as symmetric and sharp as without aberrations.

To determine the impact of dissolution on printing the line-end spaces, a trajectory dissolution rate model is presented in next sections.

6. ANALYSIS OF DISSOLUTION MODEL

To illustrate the impact of dissolution, a one-dimensional dissolution model was developed to predict CDs. Suppose the dissolution rate along a line is \( r(x) \), and the maximum dissolution rate is at \( x=0 \). Assume the dissolution rate at other points is so low that the vertical dissolution of the resist at that point can be neglected. Only the point at the \( x=0 \) can be developed vertically. This assumption is valid if the resist contrast is high enough. After the resist at \( x=0 \) is developed, its neighboring resist can be and can only be dissolved by the developer filling \( x=0 \). This assumption is approximately true given the fact that the sidewall area is much larger than the resist surface area. Then the time for developer to dissolve the resist at \( x \) with length \( dx \) is

\[
\frac{dt}{dx} = \frac{1}{r(x)} \]

(2)
Then the developer advances to dissolve the resist at \(x+dx\). Thus the resist being developed during time \(T\) is determined by

\[
\int_0^T dx = T - \frac{h}{r(0)}
\]

(3)

Where \(L\) is the length of the resist having been developed, \(h\) is the resist thickness and \(h/r(0)\) is the time needed to develop the resist at \(x=0\).

The dissolution rate is a function of activated site concentration, which is usually described by enhanced Mack Model \[10\]:

\[
r(s) = \frac{1+K_{enh}s^n}{1+K_{inh}(1-s)^l}
\]

(4)

Where \(s\) is the normalized activated site concentration, \(K_{enh}\) is the enhanced dissolution constant, \(K_{inh}\) is the inhibition dissolution rate, \(R_{resin}\) is the resin dissolution rate.

The parameters given by International SEMATECH are: \(R_{resin}=550\text{nm/s}, R_{min}=0.05\text{nm/s}, R_{max}=568\text{nm/s}, n=14, l=12\). If the photoacid diffusion in PEB is ignored, the activated site concentration is given by

\[
s = 1 - e^{-K_{i}c_{t}}
\]

(5)

Where \(K_{i}\) is the reaction rate, \(C_{p}\) is the photoacid concentration and \(t\) is PEB time.

To simplify the dissolution modeling, assume that acid diffusion is negligible and thus dissolution rate is directly a function of acid concentration. Furthermore, \(r(s)\) is approximated as three line segments. In other words, the dissolution rate as a function of acid concentration is given by

\[
r(c) = \begin{cases} 0 & c < c_0 \\ R_{max} \cdot \frac{c - c_0}{c_1 - c_0} & c_0 \leq c \leq c_1 \\ R_{max} & c > c_1 \end{cases}
\]

(6)

Where \(c\) is acid concentration, \(c_0\) and \(c_1\) are cutoff photoacid concentrations and \(R_{max}\) is the maximum dissolution rate.

Furthermore, assume the acid concentration is a linear function of position \(x\), which is approximately true in the region where light intensity transits from high to low. Then the dissolution rate as a function of position \(x\) is

\[
r(x) = \begin{cases} r_0 - \frac{\beta x}{\beta} & x \leq \frac{r_0}{\beta} \\ 0 & x > \frac{r_0}{\beta} \end{cases}
\]

(7)

Substituting (3) to (7), the advancing length of resist is given by

\[
L = \frac{r_0}{\beta} (1-e^{-B(\frac{T}{r_0})})
\]

(8)

To make this model easy to use, an equivalent threshold photoacid concentration is derived which is the photoacid concentration at \(x=L\). This equivalent threshold can be directly put into resist imaging model to calculate CD. The threshold is given by

\[
T_c = c_{max}, \exp\left(-kt + k, \frac{h}{c_{max}}\right)
\]

(9)

Where \(c_{max}\) is the maximum acid concentration along the line, \(k\) is the slope of acid concentration along this line, \(t\) and \(h\) are constants to be determined.

On the other hand, \(T_c\) must be greater than \(c_0\). Thus the threshold acid concentration is

\[
T_c = \max\{c_0, c_{max}, \exp\left(-kt + k, \frac{h}{c_{max}}\right)\}
\]

(10)
The resist imaging model was modified to include this dissolution effects. After obtaining the photoacid concentration of the patterns, the line at which the CD is to be measured is extracted, the peak and slope of photoacid concentration are calculated. Then threshold acid concentration is calculated through (10). The threshold is thereafter used to find out the CD. The parameters in this dissolution model, \( t \) and \( h \), were extracted by fitting CDs with the space at 9.5 and 10.5mJ/cm\(^2\). The simulations are compared with experiments in Fig. 10. The RMS error is reduced to 24nm, half that of the imaging model. Note that the SEM measurement error is much larger at the line ends than at the line edges, due to severe line-edge roughness (LER) and residual scum. Plus the space CD control is not of main concern for printing gate. Thus the prediction of spaces is adequate for OPC and process verification.

7. CONCLUSIONS

In this chapter, first the resist imaging model was implemented to predict the line CDs. With two parameter, the focal plane and threshold photoacid concentration, fitted at one dose 9.5mJ/cm\(^2\), the model predicts the line widths through focus, through pitch and through line-width with RMS error of 5.28nm. The SEM measurements were noisy due to the resist LER and slimming phenomena, and the measurement error is believed to be more than 10nm. Meanwhile, the process variation, if well controlled, is about 5% of the nominal CD, i.e., 6.5nm. Thus the error is less than measurement or process errors, which makes it sufficient for the purpose of OPC and process verification. By comparing experiments with simulations, it is shown that the lens aberrations are critical to the choice of best focus and through-focus CD variation. The focal plane should be shifted to compensate for the lens aberrations. On the other hand, the mask CD errors are the main factors that determine the wafer CD errors. The unexpected isolated-dense bias is mostly due to mask CD bias.

Then the model was applied to simulate 2D resist patterns. The simulation fits well with the experimental SEM pictures through dose and through focus, even though the parameter was only trained at one dose. However, the model failed in predicting the space between line ends. The experimental spaces are much larger than predicted, which is believed to be due to chemical effects such as PEB or develop. Note that at the line ends, the LER is particularly severe and the resist, due to its small bulk, is more sensitive to SEM. Thus the measurement error is believed to be much larger than along lines. Further improvement of simulation performance was achieved by incorporating a 1D trajectory-dissolution-rate model to describe the low-contrast of 193nm resists. The dissolution model reduced the RMS error of predicting gaps down to 24nm, a 50% improvement on imaging model. A resist imaging model, combined with PEB and 2D/3D dissolution model, is expected to solve the prediction problem. Since line ends are very sensitive to resist processing while line widths are not, the PEB/dissolution model should be trained at the line-end spaces.

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Fig. 1 Mask and wafer CD vs. pitch, (a) plots mask CDs, the designed line widths are from 100 to 140nm, (b) plots the corresponding wafer CDs, exposed at 0 defocus, dose 9.5mJ/cm²
Fig. 2 Line widths vs. defocus at 350nm pitch, the designed line widths are 100, 120, 130 and 140nm wide, respectively. Note that the wafer CDs of the 100nm line at –0.2 and –0.1μm defocus are 0, which means there were no patterns on the wafer.
Fig. 3 Simulated line width vs. defocus at 350nm pitch, lens aberrations included. From (a) to (d) the focal plane are 0.20, 0.25 and 0.30μm below the resist surface, respectively.
Fig. 4  Experimental and simulated line width vs. defocus at 350nm and 1750nm pitch, lens aberrations included. Here (a) and (b) are experimental CDs at 350 and 1750nm pitch, respectively. (c) and (d) are corresponding simulated CDs.
Fig. 5  the mask pattern used for calibrating simulation models, note that the mask is 4X

Fig. 6  the experimental line-end spacing, the legend refers to dose
Fig. 7 Overlay of simulated and experimental images, the simulations overlap with experiments in the black area, while they do not agree in the gray area.

Fig. 8 simulated line-end spacing of the 2D pattern, the legend refers to dose.
Fig. 9 Light intensity across lines and line-end spaces, exposed at 9.5mJ/cm². The line is 140nm wide, isolated. The space is 134nm on mask. The legends refer to defocus.

Fig. 10 comparing experimental and simulated CDs of the space between the two line ends. In the legend, “Gap” means simulated CD, “Exp” means experimental CD. Dissolution model was used.