Gaining insight into effective metrology height through the use of a compact CDSEM model for lithography simulation

Chao Fang, Trey Graves, Alessandro Vaglio Pret\textsuperscript{b}, Stewart Robertson, Mark Smith
KLA-Tencor Texas, United States
\textsuperscript{b}KLA-Tencor/ICOS Belgium, Belgium

ABSTRACT

Computer simulation of lithographic performance, including resist CD, film thickness, sidewall angle and profile has been extensively studied during the past three decades. Lithography simulation has been widely adopted as an enabling technology for high-volume chip manufacturing. However, measurement artifacts arising from CD-SEM metrology are typically ignored in simulation, due to the difficulty of accurately modeling the effect of the CD-SEM at acceptable computational speed. In this paper, we demonstrate how CD measurements can be improved by including a fast, compact CD-SEM model. For example, the variation in effective resist metrology height along contour lines extracted from a simulated CD-SEM image is characterized for a range of structures through focus. We also demonstrate how SEM settings affect the shape of extracted SEM contour and metrology height at contour edge. The Edge Placement Error (EPE) caused by SEM artifact is carefully studied.

Keywords: CD-SEM Simulator, photolithography simulation, metrology height, EPE

1. Introduction

Scanning Electron Microscopy (SEM) is widely used to measure Critical Dimensions (CD) in semiconductor lithography processes [1]. In 7nm node and 5nm node, the metrology error from SEM could reach about 25% of the total measurement value [6]. Capability to predict the metrology results from a CD-SEM is highly desirable to reduce the uncertainty of metrology.

We have introduced a fast and compact CD-SEM simulator [7-9] and studied the SEM artifacts with this simulator. Our compact CD-SEM simulator is inspired by Monte-Carlo based simulators which are generally used to model the detailed image formation process of a CD-SEM [2- 5]. Due to the high computational cost of Monte-Carlo based CD-SEM simulations, 2D CD-SEM image simulation which is desired to be included in computational lithography is too expensive. The compact CD-SEM simulator simplified the details of electron tracking and use statistical method to average the signal strength. The basic process is shown in Fig 1. The results show good agreement with experimental data [8].

In this paper, we use a calibrated lithography and CD-SEM model to study the SEM contour locations and corresponding metrology height on resist. Accurate prediction of SEM contour location is critical to reduce the Edge Placement Error (EPE). Metrology height is a critical parameter in computational lithography tool when trying to obtain feature edge locations. Firstly, we study the variation in effective resist metrology height along contour lines extracted from a simulated CD-SEM image. Then, we demonstrate how SEM recipe settings affect the shape of extracted SEM contour and metrology height at contour edge. Next, we
study the impact of focus on effective metrology height. Finally, we characterize the edge placement error due to SEM metrology for 2D elbows contours.

Figure 1: Process to simulate SEM line scan with compact SEM simulator

2. CD-SEM Image Formation

A CD-SEM scans the sample surface using a focused electron beam, as shown in Figure 2. The typical landing energy of the incident beam for a CD-SEM is between 300 eV to 1.5 keV. The incident beam of electrons interact with the sample and undergo elastic and inelastic collisions resulting in an electron cloud inside the sample. Low energy secondary electrons (SE) are excited during this process and some of them are emitted from the sample surface. These emitted SEs may further interact with the sample surface or the SEM chamber. The SEs captured by SEM extraction field are collected by the SEM detector. The detector collects the SE and form the CD-SEM image according to the SE intensity. A typical Hitachi CD-SEM image consists of 512 by 512 to 2048 by 2048 pixels. Each pixel has a grey scale level from 0 to 255.

Figure 2: Incident electron beam enter sample surface at angle $\theta$. Secondary electrons are excited as incident electrons travel inside the sample.
3. SEM Edge Detection by Threshold Method

SEM image analysis techniques use threshold edge detection methods to determine the location of feature edges. The basic algorithm is [10]:

\[
I_{th}(T) = \frac{T}{100} \times (I_{max} - I_{min}) + I_{min}
\]

In this expression, \(I_{max}\) is the max level of signal and \(I_{min}\) is the minimum level of signal. Threshold method is a widely used the metrology method for CD-SEM.

![Cross-sectional feature diagram](image)

Figure 3: Threshold method for CD-SEM edge location extraction [10]

4. SEM Edge Projection Study

The edges extracted from the SEM threshold method only vaguely contain the height information [10]. To better define the measurement height at the edge location, we use a projection method. In a simple investigation of the edge measurement height on the resist target, the following edge projection process was created:

1. Obtain 3D target resist profile (trench) via lithography simulation
2. Simulate top-down CD-SEM image of the target and extract edges using a 60% threshold
3. Project the edge extracted from SEM image back onto 3D target profile then determine the height at the intersection. The process is shown in Fig. 4.
4.1 SEM Edge Measurement Height: Continuum vs Stochastic Resist Model

Using the edge projection method, we first studied the SEM edge measurement height on a continuum resist simulation. The target feature is a 100nm trench on a 400nm pitch printed in resist on organic BARC, exposed using 193nm ArF immersion lithography. The resist thickness after development was 85nm. Figure 5 (left) shows the simulated SEM image and Figure 5 (right) shows the corresponding resist profile with SEM edges projected. It can be seen that the projected SEM edge is at a constant height.
While continuum resist model captures the resist profile in an average sense, it ignores the stochastic nature of the resist and exposing light which strongly affect resist profile and edge roughness [11, 12]. Figure 6 shows the SEM edge locations on a stochastic resist profile target. The effective metrology height clearly varies significantly along the trench. The extracted SEM edge in general is a 2D compression of a 3D surface.
4.2 Metrology Height Variation with SEM Threshold Setting
Experimentally, we know that changing the SEM threshold leads to different metrology CD results. Picking the proper threshold on SEM is crucial to get meaningful metrology result. Using the edge projection method, one can directly study the impact of threshold setting on metrology and also be able to gauge the proper threshold for desired metrology.

As an example, we study the 100 nm trench in 400 nm pitch case. For a trench feature, at low threshold the CD-SEM tends to measure near the bottom of the trench while at high threshold, the CD-SEM measures nearer the top. With the edge projection method, we can study this threshold effect on metrology in 3D. We extract SEM edge at two thresholds, 60% and 90%. Then the edges are projected on the target. Fig 6 shows the projected edges and metrology results. Fig 6 (left) shows the 60% threshold case; the minimum metrology height is at bottom of the trench and maximum metrology height is at 30 nm, with an average of around 12nm. Fig 6 (right) shows the 90% threshold case; the minimum metrology height is around 33nm and maximum metrology height is around 51nm, with the mean metrology height around 43nm.

![Projected SEM edge on 3D target at 60% SEM threshold (left) and Projected SEM edge on 3D target at 90% SEM threshold (right)](image)

5. Calibration of an ArF Immersion Photoresist with SEM Simulator
The following resist calibration was performed on dense to iso trenches at multiple pitches in stochastic mode [8]. Top-down CD-SEM images and cross sections were courtesy collected by imec. Exposures were performed with a NXT:1900 ArF immersion system with NA=1.35, XY polarization, and custom illumination. A comparison between a calibrated resist model and the cross-section SEM is shown in Figure 5 for multiple pitches. Top images are experimental CD-SEMs, while the bottom images are synthetic SEM images.

![Table of metrology results at different thresholds](table)
Figure 8: Comparison between top-down CD-SEM experimental results (top) and simulated SEM results (bottom) through pitch.

PROLITH™ (KLA-Tencor, Milpitas, CA, USA) was calibrated using SEM images to mimic top-down CD-SEM metrology and cross-section resist profile [8]. CD and LWR calibration results through pitch, exposure dose and foci gave a global RMS error value below 2nm. Such low value was mainly because experimental vs. simulation metrology match due to the SEM emulator.

6. **Metrology Height Variation across Focus for Isolated and Dense Trenches**

Using the calibrated ArF immersion photoresist model, the impact of scanner focus on effective metrology height was studied for two types of features. The first case is an isolated feature, 85nm trench in 400nm pitch. The virtual lithography is carried out for four focus settings ranging from -0.06um to 0.075um. The SEM threshold setting was 60%. The trench CD is shown in Fig.9 which varies from 76nm to 89nm. The more interesting results are the changes in effective metrology height which are shown in Fig. 10. This varies from 22nm to 5nm with a mean height of 13nm. The span of metrology height across focus conditions is large for this feature.

The second case is a dense feature, 46nm trench in 90nm pitch. The focus conditions also varies from -0.06um to 0.075um. Again, a SEM threshold setting of 60% was used. The trench CD results are shown in Fig.11. The variation of CD across pitch is from 40nm to 43nm, much less variation compare to the isolated feature. The metrology height also varies less compared to isolated feature. The range of metrology height is 23nm to 27nm with mean at 25nm as shown in Fig. 12.
Figure 9: Projected SEM edge on 85nm trench in 400nm pitch across focus. Projected SEM edge on target at -0.06um focus (top left), Projected SEM edge on target at -0.015 um focus (top right), Projected SEM edge on target at 0.075um focus (bottom left), Projected SEM edge on target at 0.03um focus (bottom right).

Figure 10: Metrology height varies across focus conditions for 100nm trench in 400nm pitch feature.
Figure 11: Projected SEM edge on 46nm trench in 90 nm pitch across focus. Projected SEM edge on target at -0.06 um focus (top left), Projected SEM edge on target at -0.015 um focus (top right), Projected SEM edge on target at 0.075 um focus (bottom left), Projected SEM edge on target at 0.03 um focus (bottom right).

Figure 12: Metrology height varies across focus conditions for 46nm trench in 90nm pitch feature

Comparing these results, we see that the dense structure has an effective measurement height of 25nm and is relatively insensitive to focus setting, whilst the isolated structure has a mean metrology height of around half of that of the dense structure (13 nm) and it changes by ±9nm through the focus range under study.

This information can be used to estimate the errors incurred by the common computational lithography assumption that edge positions extracted from CD-SEM data can be predicted by slicing the resist simulation space at a single fixed metrology height.
We compare the CD measurement of a trench by slicing a simulated resist profile polygon at certain metrology height with the threshold derived value from the simulated SEM image. In Fig 13, the green curve is the fixed metrology height polygon CD, the orange curve is the simulated SEM CD and the blue curve is the delta. In Fig 13 (left), the CD measured from polygon is extracted at 13 nm metrology height (which was obtained from previous step shown in Fig 10). The error is overall small over the center focus range but quickly increases to around 10 nm in the negative side of focus. Fig 13 (middle) shows that data for the 46nm trench in 90nm pitch feature. The CD measured from the polygon is extracted at a 25 nm metrology height (obtained from the analysis shown in Fig 12). The matching between SEM CD and Polygon CD is very good in this case. However, if the polygon CD is instead extracted at 13nm (i.e. matching metrology height for the 400nm pitch), a large error is observed (see Fig 13 (right)). In summary, the effective metrology height of resist appears to be strongly pitch dependent and in some cases focus dependent also.

![Graphs showing CD measurement comparison](image)

Figure 13: Comparison of CD measurement at certain metrology height with SEM measurements across focus for 85nm trench in 400nm pitch at 13nm metrology height (left), for 46nm trench in 90nm pitch at 25nm metrology height (middle), for 46nm trench in 90nm pitch at 12nm metrology height.

7. **Metrology Dependent Edge Placement Error (EPE)**

Finally, we investigate the metrology height variation of a SEM edge contour extracted from a more complicated 2D elbow mask pattern. The pattern consists of three elbow features. Using the SEM simulator, we extract the SEM contour and project that contour back onto the resist profile, as shown in Fig 14. The projected edge shows a lower metrology height on the external edges of the pattern and a higher metrology height on the internal edges. A possible explanation is the visibility reduction in the trench push the edge higher.

This metrology height variation introduces what we call edge placement error (EPE), due to the metrology artifacts. Fig 15 compares the edge from SEM image (red) with the contour extracted from the simulated resist profile at a 13nm metrology height. At the external edges of the pattern, the contours from the SEM and polygon overlap well. However, the internal edges show non-negligible edge placement error. In this example EPE values of up to 4nm are observed (resulting in CD errors of up to 8nm). These type of errors may be a significant contributor to reported mismatches between lithography simulation results and experimental results.

![Graphs showing EPE](image)
Figure 14: Simulate SEM image of elbow feature (left) and SEM edge contour projected on 3D profile (right)

Figure 15: SEM edge contour (red) vs polygon edge contour (blue)
8. Summary and Conclusions

We have shown that by projecting edges determined from a synthetic CD-SEM image onto the corresponding simulated lithography profile, an understanding of SEM metrology artifacts can be gained. Firstly, the height on the resist profile where the SEM has placed the “edge” can be determined. We see that the effective metrology height has sensitivity not only to the threshold value employed but also the feature geometry and the exposure focus setting. Finally, we show that using single metrology height to extract polygons from a lithography simulation introduces significant edge placement errors when compared to a contour extracted from a top down CD SEM image.

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References