Application of Critical Shape Analyses to Two Dimensional Patterns

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Abstract

Two–dimensional optical proximity correction is a requirement for feature patterning at 0.18 μm and below lithography process nodes. These corrections to semiconductor designs are intended to address the non-linearities of pattern transfer between mask making, lithography, and etch. Traditionally, IC patterns from design through etch have been characterized using critical dimension (CD) measurements. Semiconductor devices, however, are not simply made up of one-dimensional structures such as long lines and spaces. In many cases CD measurements alone are insufficient metrics of imaging performance. The fidelity of two-dimensional printed features is as important as the CD. This paper will examine the pattern fidelity of arbitrarily shaped two-dimensional patterns. Metrics such as pattern area, corner rounding, line end shorting, and the critical shape difference will be used as characterize the process. Both experimental and simulated data will be used to explore the importance of two–dimensional critical shape verses two–dimensional area on feature transfer.

Keywords: SEM Image Analysis, Critical Shape, Critical Shape Difference, ProDATA, SIAM

1. Introduction

The semiconductor industry has entered sub-wavelength process nodes where feature sizes are smaller than the wavelength of light used to produce them. Previous process generations met lithography challenges through unique hardware solutions that allowed feature sizes above wavelength. These lithography techniques will not meet current device technology roadmaps. Optical extension technologies offer the bridge to sub-wavelength optical lithography. One challenge to the semiconductor industry is the identification and implementation of production worthy optical proximity correction (OPC) designs that maintain or improve product yields. The result of this requirement has been an explosion of technology development activity by design, photomask, and fab operations to augment their products and take advantage of sub-wavelength extensions to optical lithography.

The main challenge to the implementation of low k1 ($CD*NA/\lambda < 0.5$) lithography is that the pattern transfer is non-linear. These non-linearities lead to proximity effects and line end shortening. To minimize these effects, corrections must be designed to cover the non-linearity associated with mask making, lithography, and etch on pattern transfer. Understanding and managing the pattern transfer process of advanced lithographic processes means that using linewidth measurements by themselves is inadequate to gauge lithographic performance. The area and shape of the printed features are as significant as the critical dimension (CD) in quantifying pattern transfer and fidelity.

Our paper will examine the process transformation of two-dimensional critical shapes from design to reticle to wafer (Figure 1). We have chosen to examine pattern transfer behavior using contact features and a 193 nm exposure tool and process. Metrics such as area, critical shape difference, and corner rounding will be used to characterize behavior.

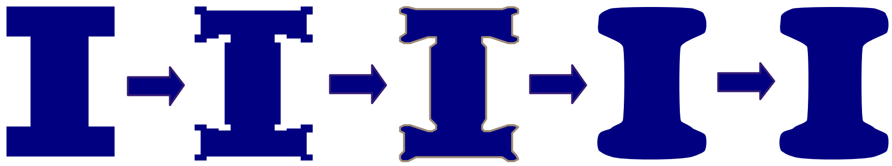


Figure 1. The pattern transfer process from design to final wafer pattern

The goal of this work is to demonstrate the importance of shape and area as well as the development of characterization metrics lithographers will use to quantify pattern transfer.

2. Experimental

To investigate the pattern transfer process, contact test reticles were produced by Photronics, Inc. with a vector e-beam wet etch process and an ALTA3500 laser pattern generator using their NanoRangeIID dry etch process. The masks were exposed at IMEC on an ASML PAS5500/950 193nm scanner using Sumitomo PAR710 on Shipley AR19 BARC resist process. Photomask and wafer CD measurements and images were collected on a KLA-Tencor 8100XP-R. Analyses of the images were performed using Klarity ProDATA SEM Image Analysis Module (SIAM™) software, which has been described elsewhere[1]. Simulation of reticles designs was investigated using PROLITH v7.

3. Results And Discussions

3.1 Design to Reticle

The primary function of a photomask is to modulate electromagnetic radiation in a manner that allows a two-dimensional pattern to be transferred to a wafer. The two-dimensional pattern consists of features that are usually not perfect in size or location. The non-linear transfer of features from mask to wafer and the implementation of OPC must be considered as coupled.

Mask making technologies are sensitive to OPC selection as documented by Lucas[2]. Laser mask making technology is particularly sensitive to design biasing of darkfield OPC features. Small OPC features can be reduced by process induced biasing such that they fall below the resolution limit of the tool as shown in Figure 2.

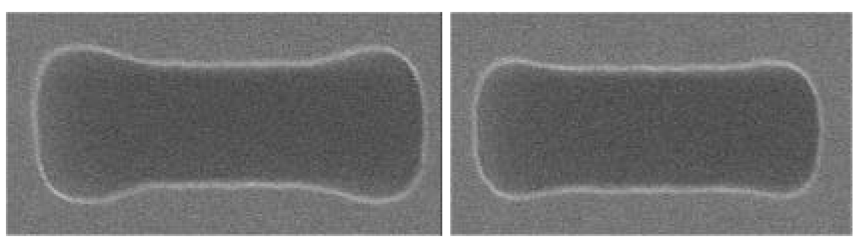
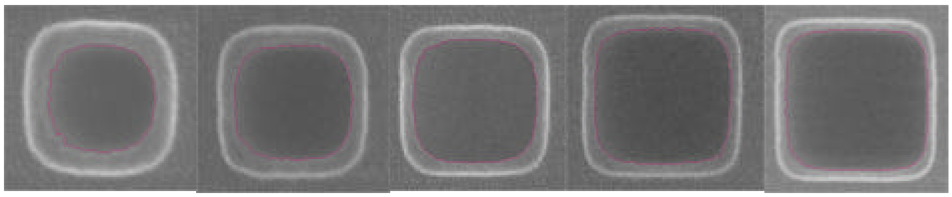


Figure 2. OPC degradation as design data biasing drops below the write tool resolution limit.

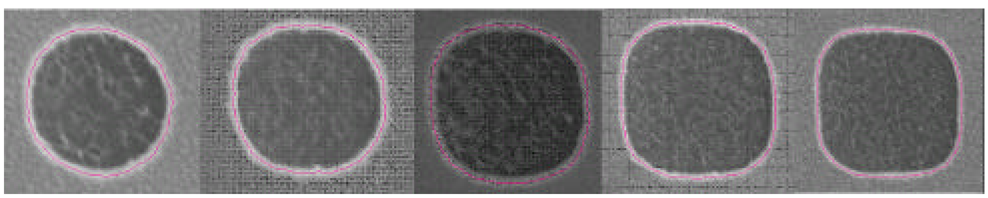
In our study we concentrated on the non-OPC contacts present on the test masks to develop a baseline for later OPC characterization. Feature fidelity variations between e-beam and laser write tools are examined using ProDATA SIAM to capture, analyze and compare the critical shapes. Critical shape is an extension of the one-dimensional critical dimension to two-dimensional features; the critical shape is the polygon that defines the top down (in the plane of the substrate) shape of a feature.

Figures 3 and 4 show SEM images from the contact test masks following extraction of the critical shape using ProDATA SIAM. Location of the critical shape edge within the edge width of the SEM image was done through calibration against linescan measurements made by the CD SEM and were in all cases within 1 nm of the linescan.



500nm 600nm 700nm 800nm 1000nm

Figure 3. Vector e-beam reticle contacts (various sizes) with SIAM critical shape outlines superimposed on the SEM images.



500nm 600nm 700nm 800nm 1000nm

Figure 4. Laser reticle contacts (various sizes) with SIAM critical shape outlines superimposed on the SEM images.

Contact critical shapes measured with SIAM are expressed as an effective CD ($=\sqrt{area}$) equivalent to a square contact having the same area. These data show that while the nominal CD specifications were met, the area linearity falloff for the e-beam reticle behavior was somewhat more precipitous (Figure 5).

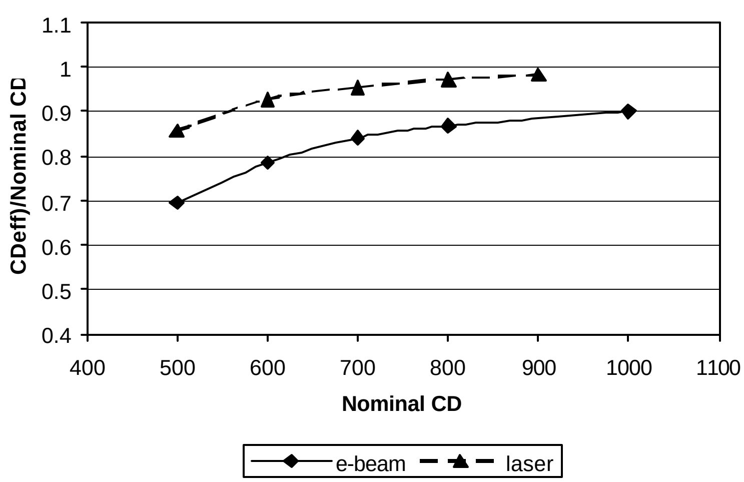


Figure 5. Area linearity response for e-beam and laser reticle contact features.

ProDATA SIAM software permits the overlap and evaluation of differences between critical shapes. The critical shape of the contacts were overlapped with the design providing additional information showing the threshold for linearity falloff begins when the area loss exceeds 10%.

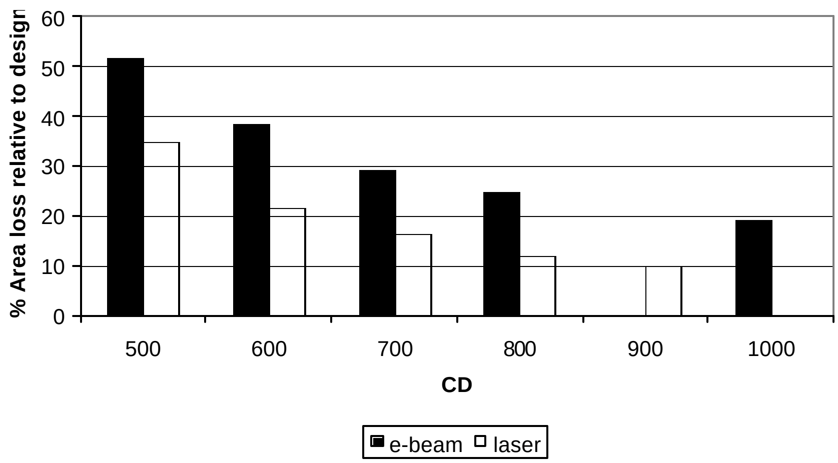


Figure 6. Reticle area loss expressed as percent loss relative to design for e-beam and laser contacts.

Besides area loss (Figure 6), another major differentiation in the mask making methods is the amount of corner asymmetry present. In order to measure asymmetry, metrics are needed to characterize the change of a critical shape in reference to some target shape. The critical shape difference (CSD), previously referred to as the critical shape error[4], can be used for this characterization.

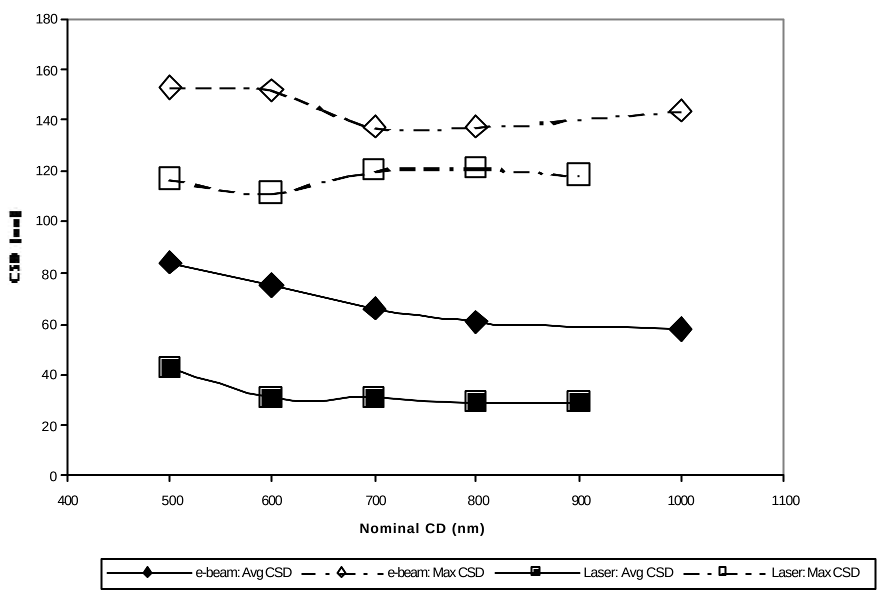


Figure 7. Mask feature fidelity of contact holes using CSD_{avg} and CSD_{max} for both laser and e-beam mask writers.

CSD is defined as the point-by-point difference between the critical shape of interest and a reference critical shape. The result is a frequency distribution of absolute error vectors. Once the distribution is measured it can be characterized to describe the overall shape difference. As an example, one can chose to examine the average CSD, maximum CSD, or a "percentile" CSD (the value of the CSD such that the given percentile of vector lengths are smaller than this value). Figure 7 shows the CSD response for design to reticle critical shape overlap of contacts where the design assumes perfectly square corners.

3.2 Reticle to Wafer Image Fidelity Transfer

Loss of area of a contact hole has a major impact in the amount of energy that is ultimately transmitted through the reticle and therefore influences feature resolution. For contacts with dimensions such that k1 < 0.5 the shape of the image ceases to vary because the diffraction pattern of the contact is spread enough that it fills the pupil. Therefore, the image intensity can be described by an Airy disk function

$$I(r) = I_0 \left[\frac{J_1\left(2p \dfrac{NA}{l} r\right)}{\left(p \dfrac{NA}{l} r\right)} \right]^2 \qquad (1)$$

Where I_o is the intensity at r=0 and J_1 is the Bessel function of the first order. Born and Wolf[3] have shown that I(r) has radial shape related to the image optical properties, NA and λ, that is independent of the mask size except through the maximum intensity, I_0, given by

$$I_0 = Ep\left(\frac{NA}{l}\right)^2 \qquad (2)$$

E is related to the energy passed by the contact and proportional to the area.

$$E \propto AREA \qquad (3)$$

Defining $I_{threshold}$ as the intensity value of the image at a radial distance from the center of $CD_{wafer}/2$, we arrive at the small contact imaging equation

$$I_{threshold} = C \cdot AREAp\left(\frac{NA}{l}\right)^2 \left[\frac{J_1\left(2p \dfrac{NA}{l} \dfrac{CD_{wafer}}{2}\right)}{\left(p \dfrac{NA}{l} \dfrac{CD_{wafer}}{2}\right)} \right]^2 \qquad (4)$$

where the value C is a proportionality constant.

Using equation 4 and PROLITH 7 one can determine the effects of area variation on the theoretical contact linearity. First PROLITH simulates the imaging process using an ideal mask. Simulation returns an image CD for a set image threshold ($I_{threshold} = 0.3$) and equation 4 is then solved to determine the constant C. Once C is known, equation 4 and the area measured from the SEM images can be employed to determine ultimate resolution based on linearity.

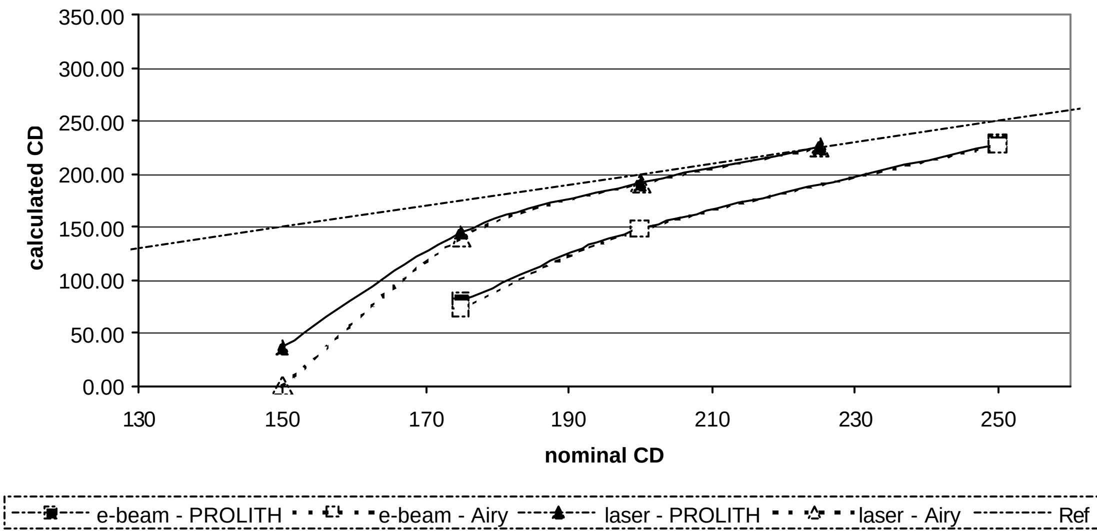


Figure 8. PROLITH vs. Contact Imaging Equation

The shape is as important as the area with respect to the final printed feature. Therefore, the critical shape variation of the test reticle contacts as a function of mask making method was investigated. In order to accomplish this, the SIAM extracted SEM image critical shapes were converted to polygons and imported as mask files for PROLITH simulation. CSD is a PROLITH output allowing for comparison of the mask to wafer features. The simulation conditions were selected to reflect the exposure conditions of the actual reticles.

Table I.

Simulation Conditions
λ = 193 nm
NA = 0.63
σ = 0.55
Conventional Illumination

The image threshold was used to evaluate the aerial image quality through the calculation of an image based critical shape difference. In this approach, the image threshold has the same function as exposure dose for CD characterization. The selection of the optimum threshold means finding a CSD value that minimizes variation of the critical shape difference through focus. This is the two-dimensional shape equivalent to a Bossung curve as shown in Figure 9. Therefore, a process window contour can be computed for CSD and expressed through focus and image threshold.

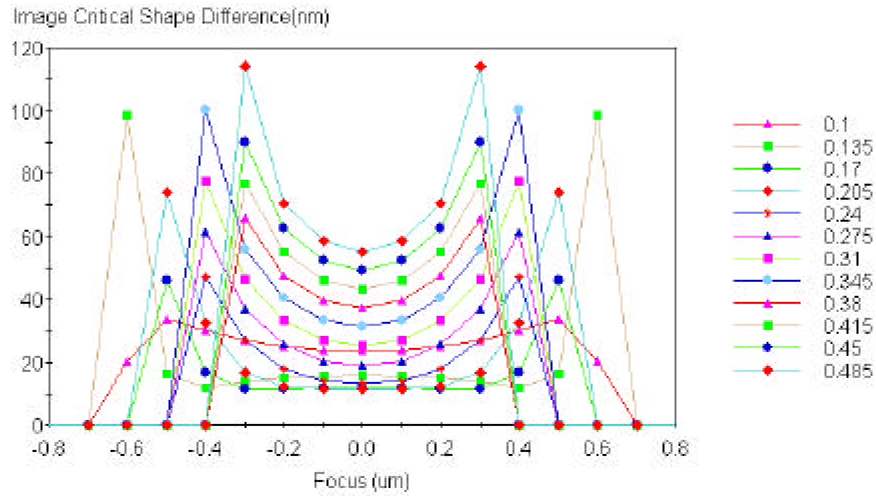
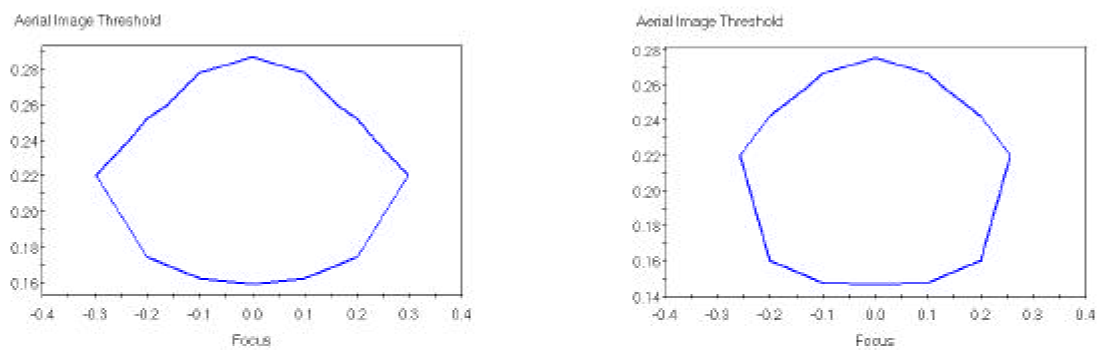


Figure 9. 2D equivalent to the CD Bossung plot

Figure 10 below shows the CSD process windows for 800nm contacts where the CSD_{avg} upper bound is set to 20 nm.



(a) (b)

Figure 10. The aerial image CSD process window results for (a) 800nm laser reticle contact (b) 800nm e-beam reticle contacts.

The laser contact window has slightly larger width (focus latitude) compared to the e-beam contact while the height (exposure latitude) between the two is comparable. CSD can also be applied to actual resist profiles to explore the resist process response contribution to the two-dimensional process window.

4. Conclusions

The application of increasingly complex mask making and wafer lithography processes requires measurement of two-dimensional parameters of mask and wafer features (line shortening, corner rounding, etc.). In this paper we have presented metrics and software tools to evaluate manufacturing challenges to pattern transfer and in particular OPC implementation. Pattern fidelity of dry etch processed laser reticle contacts was competitive with e-beam wet etch. The key was controlling area loss. CSD can be used to judge the process window in the transfer process. Our future work will extend to Area MEEF characterization and include an investigation through pitch and with varying contact OPC.

5.0 Acknowledgements

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6.0 References

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