DUV Optical Metrology for the 90nm Node, CD Linearity, Contacts and Corner Rounding

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ABSTRACT

Many techniques are used to reduce k1 for the 90nm node, including phase shift masks (PSM), assist features and optical proximity correction (OPC) features. Today, in addition to CD line widths, critical measurements of assist features, contact areas, and corner rounding, are now required to verify reticle integrity. New algorithms have been developed and implemented on the KMS100 DUV optical metrology tool to correct for iso/dense bias (optical proximity correction), assess corner rounding effects, and verify contact fidelity and printability. This paper presents new CD metrology studies for Chrome-on-Glass (COG) performed on a KMS100 DUV optical tool using these new metrology algorithms.

Keywords: CD metrology, photomask, optical proximity, optical metrology, contact area

1. INTRODUCTION

Photomask metrology systems have progressed over the years from visual filar systems to photo-multiplier scanning slit spectrometers, to high resolution CCD array camera imaging systems using sophisticated metrology algorithms. The most recent advance in photomask metrology has been the use of low voltage CD-SEM systems. These systems have the capability of measuring extremely fine features down to less than 180nm. Optical metrology systems were once thought not to be able to measure at this level of resolution nor with the linearity attributed to the CD-SEM. Through the use of novel measurement algorithms and incorporation of DUV optics and illumination systems, optical systems for measuring resolution enhancement technique (RET) photomasks have been developed with the capability of measuring features down to 200nm with an accuracy and linearity comparable to a CD-SEM.

Contact area measurements in addition to linear feature measurements are now required for the full characterization of photomasks. Previous methods of measuring contacts only used the linear value of one or both of the X or Y axis of the contact. This method is prone to inconsistencies in measured values due to the shape of the contact being measured. As the contact size approaches the imaging illumination wavelength, corner rounding becomes a greater factor in the quality of the linear measurement.

Optical steppers print square contacts as features with rounded corners on the wafer[1], thereby making it necessary to measure the corner rounding and missing area, to verify the photomask contact fidelity. Additionally, because the exposure energy necessary to clear the resist is proportional to the area of the contact[2], it becomes imperative that the area of mask contact image be measured through a method other than the product of the X and Y axis linear values.

The calculation for the pull back and subsequent corner rounding is readily achievable by comparing the product of the X and Y linear calculation for the area and the KMS100 measurement of the contact area. The variation of the wafer contact CD is impacted more by the area of the mask contact CD than the pull back associated with the lack of squareness of the mask contact[1]. But variation in the pull back of up to 20nm across the mask will contribute a 1% error to the overall feature uniformity on the wafer[2]. Therefore, having the pull back calculation will allow the user to fully characterize the photomask.

In this paper we present data to support the claim that the linearity of the KMS100 approaches low voltage CD-SEM metrology systems and describe an effective algorithm for measuring and verifying contact integrity using a DUV optical metrology tool. Details of the algorithms and results for Embedded Attenuated Phase Shift Masks (EAPSM) have been presented in previous publications[3,4].

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2. RESULTS AND DISCUSSION

We wish to ascertain the linearity of the algorithms for line width and area measurements. Comparison measurements with CD-SEM measurements have been performed and good agreement obtained with the fitting of a single parameter (a line factor). We have investigated the matching of line width and area measurements with different imaging lenses (0.75NA ELWD and 0.9NA). Even though these lenses give an imaging system with different coherence factors, excellent agreement for both line and contact measurements has been demonstrated.

2.1. Linewidth

Traditionally, in optical CD tools, a fixed threshold in the intensity profile of the line/space is used to define the edge position. This threshold algorithm gives excellent CD precision (3σ) and accurate pitch measurements. This high accuracy is due to the inherent linearity of the diffraction limited optics and because errors in the edge position cancel out as only one edge type (rising or falling) is used. Line width measurements are more problematic because of the difficulty in accurately determining the position of the edge with respect to the intensity profile. This is true especially in the presence of optical proximity effects. Theory[5] tells us that a threshold of 25% to 30% (depending on the coherence of the optical system and the transmissivity of the mask) gives accurate measurements for large isolated chrome-on-glass (COG) lines whereas a 50% threshold is typically used in practice to improve the measurement precision (3σ values). For large isolated lines, there is a constant distance between the measured and actual edge position that depends on the threshold, the optical system (objective lens and coherence factor) and the mask (especially the material, COG, MoSi etc.). A line factor (LF), which is added to clear and subtracted from dark line widths, is used to compensate for this error. By definition, the line factor is twice the error for the single edge. Every combination of mask type, objective lens and imaging mode requires a calibration to determine the best line factor. For small line widths, the linearity suffers due to the optical proximity effect (OPE) from the second edge[6], some metrologists vary the line factor for small lines to improve the linear range (multi-point calibration).

An OPE algorithm, based on a model of the imaging system, was implemented on the KMS-100 to improve the measurements of dense line arrays and to improve the linear range. A description of the OPE algorithm and results have been presented previously[3,4]. The OPE algorithm is based on comparison of the measured profile with a stored profile, so the accuracy and linearity will depend on how well the stored profiles accurately represent the optical imaging system. To generate the stored profiles, we have developed a simple modulation transfer function (MTF) model where the MTF is determined by analyzing a rising and a falling edge profile. Different models are used for the 0.75NA and 0.9NA lenses and for different mask types. For a COG mask, this simple model gives the same edge position as the 50% threshold, so a line factor is again used to correct the CDs. Recent papers[7] suggest that a line factor should also be used for CD-SEM metrology.

Figure 1 shows a set of measurements of isolated clear lines for a COG mask taken on the KMS-100 using the 0.75NA ELWD and 0.9NA lenses and on a CD-SEM. The deltas from the nominal values are plotted, where the nominal values are assumed to have a constant offset from the tape values. The line factors for the 0.75NA and 0.9NA lenses were determined by minimizing the overall error compared with the CD-SEM, see table 1. Figure 2 shows similar results for dark lines, no CD-SEM data was available. The same LFs are used for both sets of measurements; figure 3 shows the comparison between the 0.75NA and 0.9NA lenses for the clear and dark lines on a more appropriate scale.

The agreement between the CDSEM and the KMS-100 for both the 0.75NA ELWD and 0.9NA lenses is excellent, figure 1, with a maximum difference of about 10nm and no obvious linearity error between the KMS-100 and the CD-SEM. The scatter in the measurements between the CD-SEM and KMS are probably due to line edge roughness and the difficulty in ensuring that the same region of the line is being measured on the two tools. A larger box was used on the CD-SEM to improve the static precision to about 2 or 3nm. In these experiments, moving the measurement window gives a measurement difference of several nm. Care was taken to ensure that the measurements taken with the 0.75NA ELWD and 0.9NA lenses were at the same position on the lines, a one micron box was used in both cases. Agreement between the lenses on the KMS is excellent for lines above about 0.5μ, where the difference is well within the 1 - 1.5nm 3σ precision of the system. Over the full range of clear and dark lines, the maximum difference is only 6nm. Line factors of 81 and 75 nm were used for the 0.75 and 0.9NA lenses (multipoint calibration was not used).

It is tempting to conclude that the result for the 0.9NA lens is more linear than the 0.75NA ELWD lens but this is not necessarily the case. The linearity for the small features is determined, in part, by how well the MTF model matches the actual intensity profiles. The MTF model assumes incoherent imaging and this matches the 0.75NA lens better than the 0.9NA, so it is very possible that the 0.75NA measurements are more linear. Unfortunately these differences are within the precision of the CD-SEM measurements and it is not possible, using the CD-SEM results, to determine which lens is giving better linearity performance. The evidence presented here supports a system linearity of better than 10nm over the full range of measurements made. We expect future improvements in the model to improve the matching between the lenses.

2.2. Contacts

Various techniques have been employed for measuring contacts. In this paper, we have used both the KMS100 standard line width tool to measure the horizontal and vertical dimensions of the contacts and a new threshold based area tool. The new area tool uses a threshold algorithm similar to the line width threshold algorithm. We plan to extend the OPE algorithm to area measurements in the future. Measurements of clear, nominally square, isolated contacts are summarized in figure 4 for different lenses and thresholds.

One method of calibrating the area tool is to measure a segment of a line, see figure 5. The product of the box height and known line width should match the area measurement. The area measurements change with the threshold as is obvious from figure 6. As with the line width threshold algorithm, there is an error between the measured and actual position of the edge when the threshold is set to something other than the ideal value. We find that a threshold of 26% gives good agreement for the 0.9NA lens, table 1, which is very close to the theoretically expected value of 25% - 30%.

If the wrong threshold is used, it is clear from figure 6 that an area is lost (or gained) and that this “lost area” will be proportional to the perimeter and hence proportional to the linear dimension. In figure 4 we can see that there is a linear error between the nominal and measured values when a 50% threshold is used. We can use an area line factor (ALF) analogous to the line factor used to correct the line width measurements.

The correction for a square contact is:

$$\mathrm{A'} = \left(\sqrt{\mathrm{A}} \pm \mathrm{ALF}\right)^2 \tag{1}$$

where A is the measured area, A’ is the corrected value and ALF is the area line factor which is added for clear features and subtracted for dark features. For square contacts, we would expect the ALF to be equal the to the line factor. Equation 1 will hold for contacts of any constant shape, although the value of the ALF will depend on the shape (a different ALF will be needed for squares or circles, for example).

We can calculate the ALF by measuring a section of a line as shown in figure 5 using the equation:

$$\mathrm{ALF} = \pm\left(\mathrm{w} - \mathrm{A/h}\right) \tag{2}$$

where A is the measured area with no ALF, h is the height of the measure window, w is the width of the line and where the plus sign is used for clear features. For the 0.9NA lens we get an ALF of 63nm, which is fairly close to the LF of 73.5nm for the line width tool with 50% threshold. This difference between the LF and ALF will be due to the differences in the implementation of the width and area algorithms.

In figure 4, we plot the corrected area for different line factors. There is still a slight discrepancy between the 26% threshold and the corrected 50% threshold values. The best ALF values for the 0.9 and 0.75NA lenses were determined by the matching the measurements to the 26% threshold data. This gives an ALF of 60nm for the 0.9NA lens, compared with 63nm for the line width calculation. This 3nm difference in the ALF gives rise to an error in the area measurement which is proportional to the linear dimension and accounts for a difference of about $0.02\mu^2$ at 3μ. As the error due to an incorrect ALF is proportional to the linear dimension, one should use the largest convenient line width for determining the ALF; measuring a 3μ line would probably have given the correct ALF of 60nm.

Figure 7 shows the delta between the nominal and measured contact area values in more detail for the 26% threshold and the best corrected 50% threshold contact areas. We observe an average offset of $0.054\mu^2$ between the measured and nominal values. This can be explained as a constant "missing area" due to corner rounding. The missing area is related to the corner-rounding radius by:

$$\text{MissingArea} = 4\left[r^2 - \frac{1}{4}\pi r^2\right] \tag{3}$$

which gives an average corner rounding radius is 0.25μ.

The ALF is only correct for a specific feature shape although it would be possible to calculate the new ALF if the feature shape was known in advance. For example, one could find the ALF for square features by measuring a line segment and then calculate a new ALF for circular contacts. It is also straightforward to calculate the effect of using a given ALF on different shapes, for a typical value of 60nm for the ALF for square 0.5μ contacts, we get an error of 2% for a circular contact and –2.3% for a 1.5μ x 0.5μ rectangle. These percentage errors will be proportional to the feature size. This small error for circles explains the good agreement observed between the corrected 50% and 26% values even where the corner rounding becomes significant.

The linear dimensions of the contacts (CDx and CDy) were measured over the central 1/3rd of the contact (with a minimum of 3 pixels) and their product is also plotted in figure 4. Here the area follows the nominal values with no offset for sizes between about 0.5μ and 2μ. This is expected because the measurements are of the central region of the contact and do not include the effects of the corners. Below about 0.5μ, the 0.25μ corner rounding starts to play a roll in the linear measurements and the product, CDx.CDy, falls accordingly. Above 2μ it appears that we have a linear error, possibly in the x or y line factors. Figure 8 shows CDx and CDy compared with the square root of the area measurements, here the falloff in the CDx and CDy below 0.5μ is more apparent.

Static repeatability values were measured to determine the relative precision for the different area measurement algorithms. We would expect the 3σ of the area measurements to depend on the feature size:

$$\begin{aligned} & A + n_A = (CDx + n_x)(CDy + n_y) \\ \Rightarrow \quad & n_A = CDx.n_y + CDy.n_x + n_x.n_y \end{aligned} \tag{4}$$

where n_x, n_y are the noise in the CDx and CDy measurements n_A the noise in the resulting area measurement. The term $n_x.n_y$ can be ignored. For linear measurements, the 3σ is largely independent of feature size for features above about 300nm[4], so one would expect the 3σ for area measurements to be proportional to the linear dimension.

We calculate the 3σ of the square root of the areas and, almost equivalently, the 3σ of the areas normalized by 2x the square root of the average area, see figure 9. The average values are 1.3nm, 1.0nm and 2.2nm for the normalized 3σ calculations for the 0.75NA ELWD 50%, 0.9NA 50% and 0.90NA 26% respectively and 1.3nm for both CDx and CDy. Figure 9 shows that the normalized values are fairly constant, increasing for features below about 0.3 to 0.4μ. Obviously this crude test does not give us the long-term precision for area measurements but is useful for demonstrating the relative performance of the different algorithms.

3. CONCLUSIONS

1. Excellent linearity for isolated clear lines on a COG mask has been demonstrated for both the 0.75NA ELWD and 0.9NA lenses using the OPE algorithm. Agreement between the CD-SEM and the optical tool is better than 10nm over the full range of features measured.
2. Agreement between line width measurements using the 0.75NA and 0.9NA lenses is excellent, within the precision for lines above 0.5μ and within 6nm over the full range.
3. Area measurements on COG using a 26% threshold give very good linear results.
4. Area measurements with a 50% threshold show excellent precision, comparable to the line width tool and 2x better than the 26% threshold.
5. An area line factor (ALF) can be used to give good linearity for the 50% threshold for isolated square contacts.
6. The ALF can be determined by measuring the area of a line segment and calculating the ALF based on the measured area.

7. A second method of calculating the ALF is to calibrate against an area obtained using the 26% threshold.
8. Different ALFs could be used for features with different aspect ratios or shapes, however the linear correction seems to work well over a reasonable range of feature shapes.
9. For large features (where CDx and CDy are valid), it is possible to estimate the corner radius by calculating the missing area.

Based on the superior precision of the 50% threshold area tool and item 3 above it would seem that this would be the best solution for measuring contacts below about 1µ. For shapes other than squares, a different ALF calculation should be used although the error is small for typical contact shapes. For arbitrary shapes, or where it is difficult to determine the ALF, a setting of 26% should be used. The accuracy of the 26% threshold has been demonstrated for COG and will probably hold for high contrast images on attenuated phase shift masks (such as MoSi designed for 248nm) but more work needs to be done. Long-term precision results will be required to validate these conclusions.

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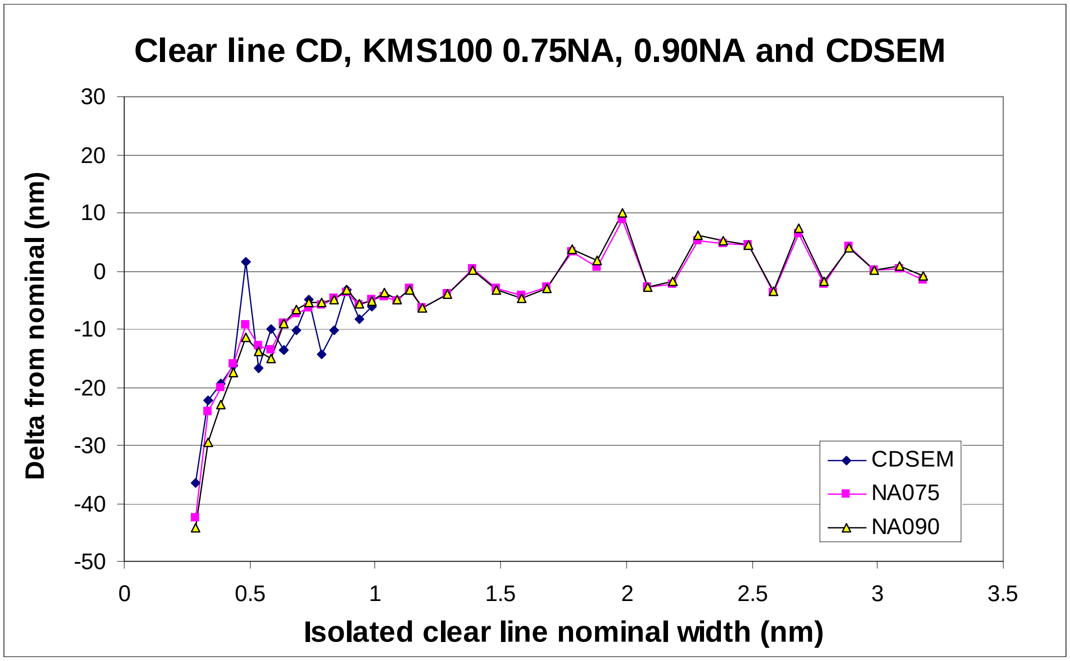

Figure 1. KMS-100 linearity for clear lines. The graph is the difference between the nominal and measured values for the CD-SEM and KMS-100 with the 0.75NA ELWD and the 0.90NA lenses. Note the excellent agreement between all three measurement sets. There appears to be non-linear process error below about 1μ

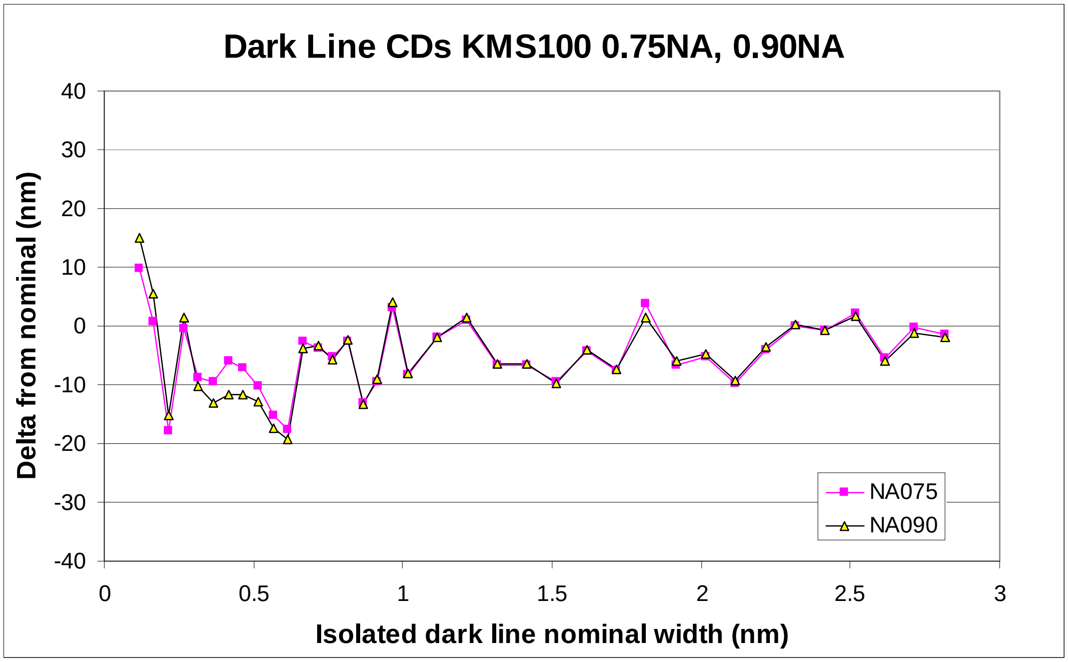

Figure 2. KMS-100 linearity for dark lines. Delta between nominal and measured dark lines for the 0.75NA ELWD and 0.9NA lenses.

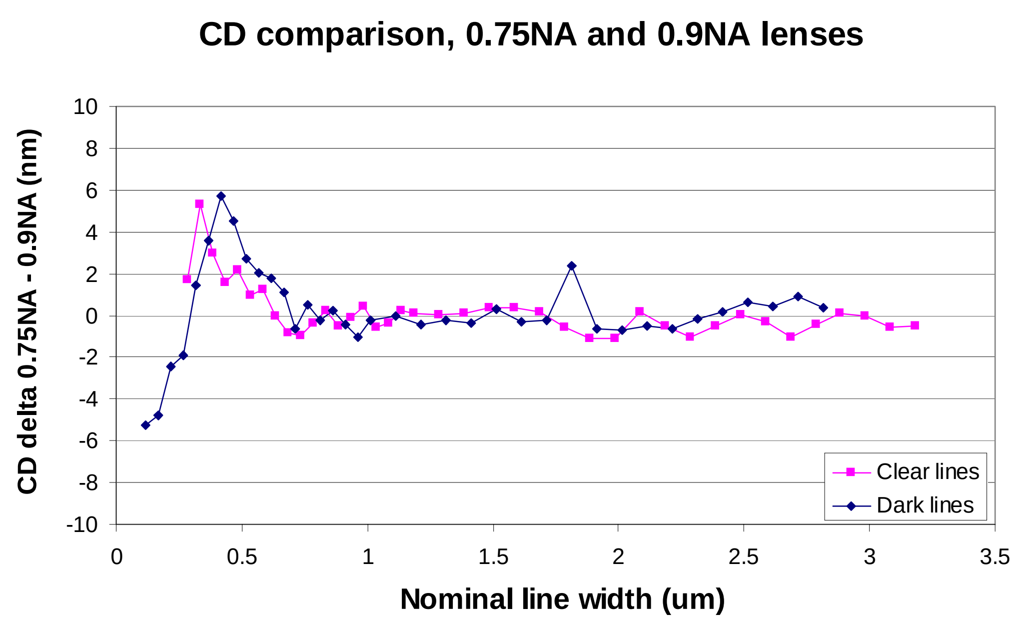

Figure 3. Difference between line width measurements taken with the 0.75NA ELWD and 0.9NA lenses. Above about 0.6µ the difference less than 1 nm and is largely due to the measurement precision. The maximum error over the full range is about +/-6nm.

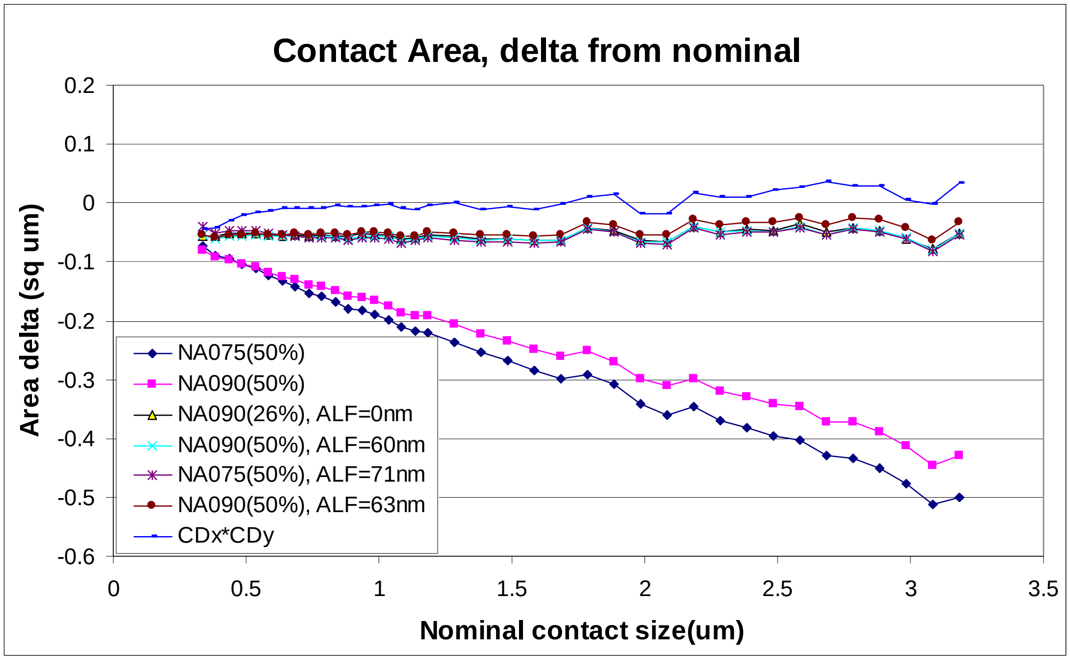

Figure 4. Summary of contact measurements using different lenses, algorithms and Area Line Factors (ALFs). Graphs are the delta from the nominal values.

	Raw CD (μm)	CD+LF (μm)	Static 3σ (nm) [1]	LF (nm)	ALF (nm)
Tape	0.80				
Nominal = Tape + process error	0.985				
CD-SEM	0.9788		2 – 3		
0.75 NA OPE	0.899	0.980	1	81	
0.9 NA OPE	0.905	0.980	1	75	
0.9 NA 50% threshold	0.908	0.980	0.8	72	
0.9 NA 26% threshold	0.9792		2	0	
0.9 NA Area 26% threshold	0.9806		2.2		0
0.9 NA Area 50% threshold	0.917	0.980	1		63
0.9 NA Area 50% threshold			1		60[2]
0.75 NA Area 50% threshold			1.3		71[2]

Table 1. Summary of line factors (LF) and area line factors (ALF) used for calibrating the line width and contact area tools. [1] Preliminary. [2] Determined by the best match to the area 26% threshold data.

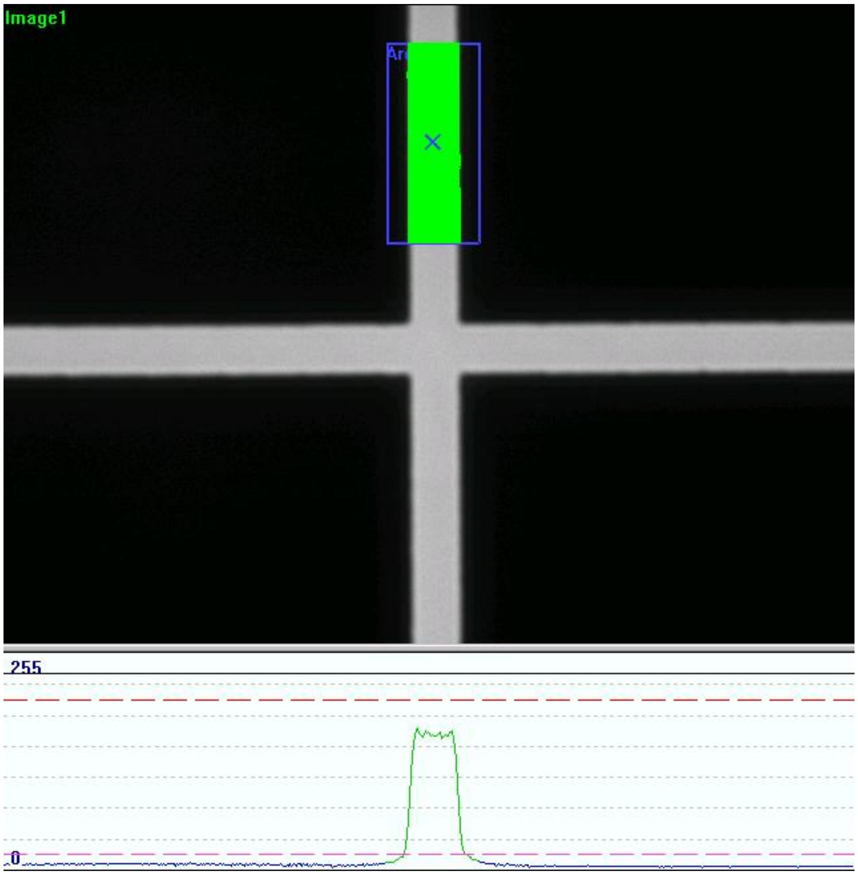

Figure 5. Area tool calibration. The measured area of a line segment should match the product of the box height (3μ in the image above) and the line width. The area tool threshold can be adjusted to give a good match or the ALF can be calculated.

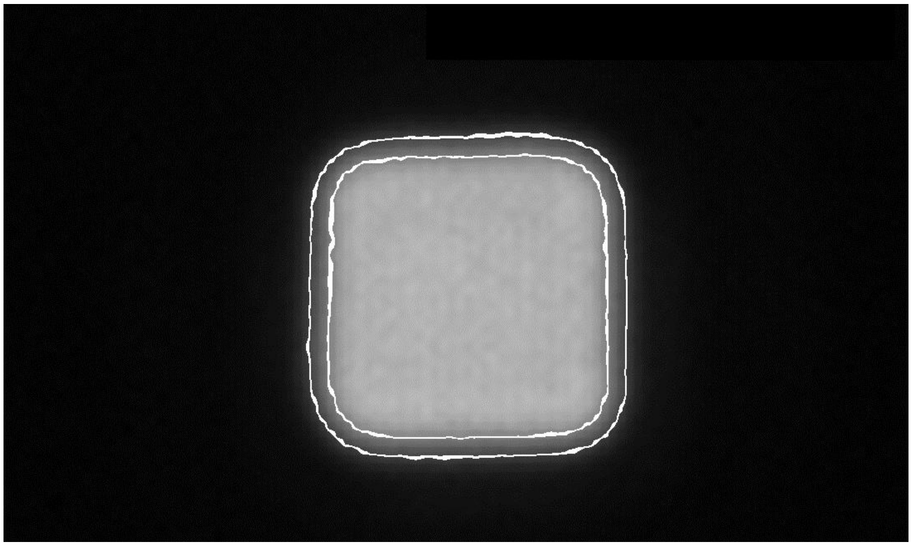

Figure 6. Area measurement versus the threshold for a 1µ contact imaged with the 0.9NA lens. The contour lines for a 26% and a 50% threshold are shown in white. The difference in area for the two thresholds is approximately proportional to the perimeter; this explains the linear error in the 50% threshold measurements in figure 4.

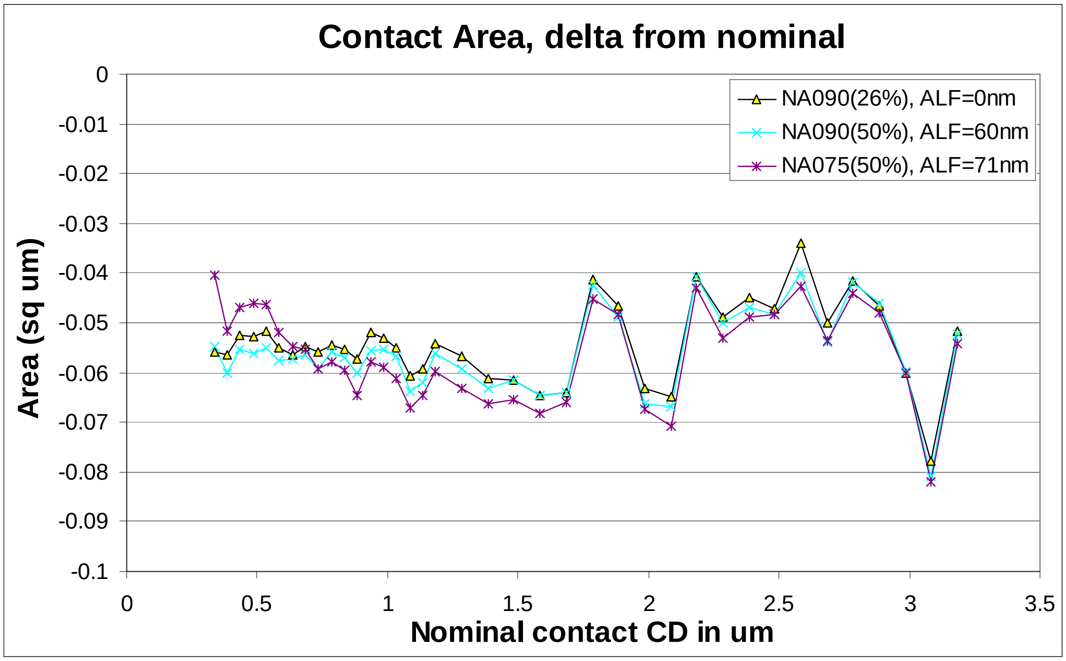

Figure 7. Contact area measurements, delta from nominal comparison of 26% threshold and 50% threshold with ALF correction. The average offset of 0.054µ^2 between the nominal and measured areas is probably due to a corner rounding radius of about 0.25µ.

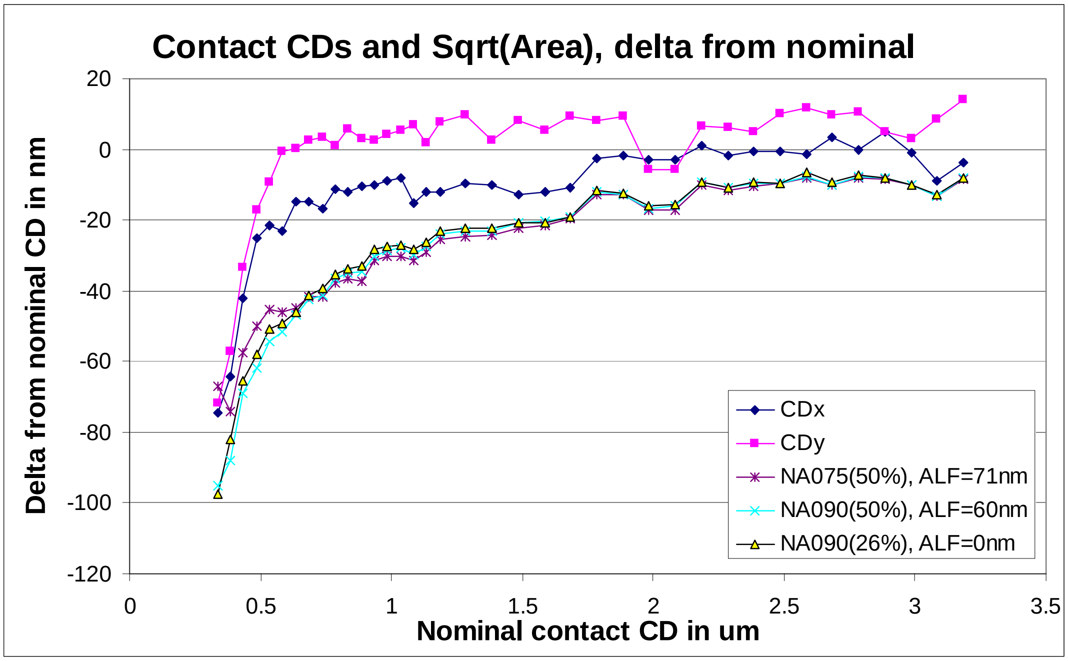

Figure 8. Contact measurements, delta from nominal. Width and height compared to the square root of the area. Note the fall off in the linear measurements below 0.5µ due to corner rounding.

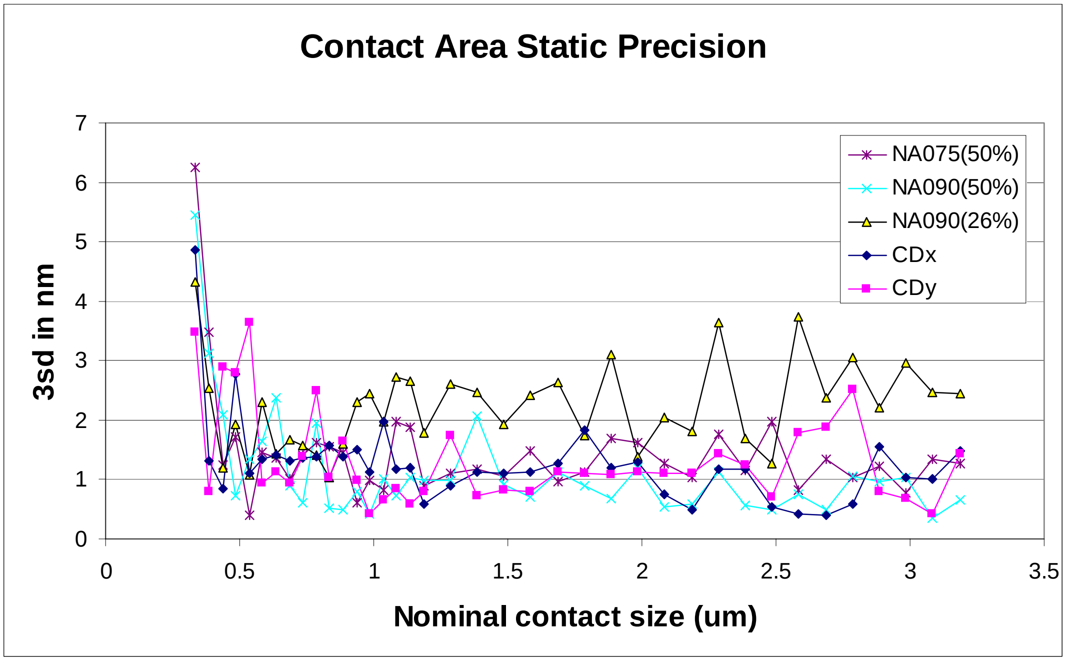

Figure 9. Contact area precision compared with the precision for the width and height measurements. For the area precision, the 3σs of the square root of the area measurements are plotted. The average values are 1.3, 1.0 and 2.2 for the normalized area for the 0.75NA ELWD 50%, 0.9NA 50% and 0.90 26% respectively and 1.3nm for both CDx and CDy.