Comparison of Measurement Techniques for Linewidth Metrology on Advanced Photomasks

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***Abstract*—This paper compares electrical, optical, and atomic force microscope (AFM) measurements of critical dimension (CD) made on a chrome on quartz photomask. Test structures suitable for direct, on-mask electrical probing have been measured using the above three techniques. These include cross-bridge linewidth structures and pairs of Kelvin bridge resistors designed to investigate dimensional mismatch. Overall, the results show very good agreement between the electrical measurements and those made with a calibrated CD-AFM system, while the optical metrology system overestimates the measured width. The uncertainty in each of the measurements has been considered, and for the first time an attempt has been made to describe the levels and sources of uncertainty in the electrical measurement of CD on advanced binary photomasks.**

***Index Terms*—Advanced lithography, critical dimension (CD), electrical critical dimension (ECD), linewidth, metrology.**

I. Introduction

THE use of direct electrical measurement of critical dimension (CD) on advanced photomask plates has been presented in a number of previous publications [1]–[7]. These have described the design, fabrication, and testing of sheet resistance and electrical linewidth test structures capable of being electrically probed on-mask. Most recently, a set of electrical test structures based on optical metrology features was used to measure iso-dense proximity effects on binary photomasks with designed CDs as low as 480 nm (on-mask, 4X) [8]. This mask design also included, for the first time, test structures designed to investigate dimensional mismatch between closely spaced chrome features [9].

In addition to the on-mask electrical measurements, more traditional metrology techniques such as CD scanning electron microscopy (CD-SEM) and optical CD measurements have been evaluated [1], [3], [8]. The results have demonstrated that there are serious issues with the extraction of linewidth from SEM or optical images of photomask features. This is especially true for alternating aperture, phase shifting masks, and where optical proximity effects dominate imaging. Regardless of these results, persuading the mask-making community to integrate on-mask electrical measurements into their manufacturing process has proved to be difficult. One problem is the issue of probe needles coming into contact with the mask surface, even though the electrical structures would be located outside the exposure area, and the fact that delicate ICs are routinely probed during test. Another concern is the nonphysical nature of the electrical measurement, which could mean that effects observed do not transfer to dimensions of features on wafer. Finally, it should be noted that although a traceable standard for photomask linewidth is available from NIST [10] it is not employed throughout the industry and maskshops tend to still carry out individual correlation exercises with each customer.

In an attempt to demonstrate the strengths of on-mask electrical linewidth measurements, structures on the mask described in [8] and [9] have been measured using one of the few CD atomic force microscope (CD-AFM) tools in the world that is fully calibrated to a CD reference standard [11]. This paper presents a preliminary comparison of CD-AFM measurements with electrical and optical metrology results. In addition, an initial analysis of the uncertainties involved in the different measurement techniques is presented in order to aid comparison of the measurements. This analysis is based on the methods described in [12], which compared different metrology techniques used to measure submicrometre, single crystal silicon features.

II. Test Structures

A. Cross-Bridge Linewidth Structures

The mask used in the present work (MSN6659) was fabricated to the same design as mask MSN5757, which has been described in [8]. The test structures are based on an optical/SEM metrology feature set from Mentor Graphics who use it to in-

Manuscript received July 01, 2008; revised October 30, 2008. Current version published February 04, 2009. This work was supported in part by the Edinburgh Research Partnership in Engineering and Mathematics and the associated Institute for Integrated Systems, in part by Nikon Precision Europe GmbH, in part by Compugraphics International, Ltd., and in part by Mentor Graphics. Certain commercial equipment is identified in this paper to adequately describe the experimental procedure. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology nor does it imply that the equipment identified is necessarily the best available for the purpose. Official contribution of the National Institute of Standards and Technology.

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Digital Object Identifier 10.1109/TSM.2008.2010733

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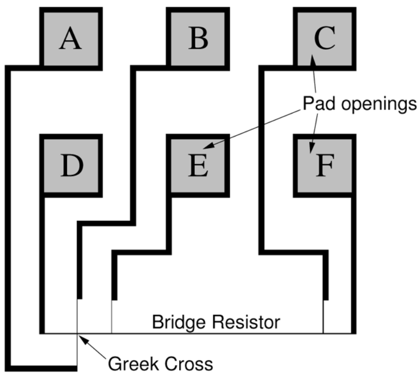

Fig. 1. Cross-bridge linewidth test structure.

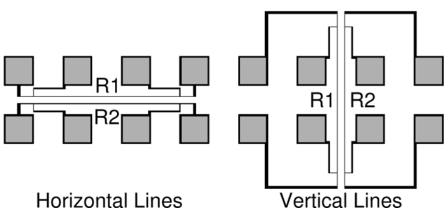

Fig. 2. Mismatch bridge resistor test structures.

vestigate iso-dense bias and other optical proximity effects in photolithography. The basic electrical linewidth test structure is the cross-bridge resistor [13]. This is made up of two parts, a Greek cross sheet resistance structure and a Kelvin connected bridge resistor. The layout of an isolated cross-bridge structure is shown in Fig. 1. The standard chrome on quartz photomask includes an anti-reflective coating (ARC) of insulating chromium oxynitride and so a second level of patterning is required to remove the ARC over the pads so that good electrical contacts can be made.

B. *Mismatch Test Structures*

The mismatch test structures on mask MSN6659 are pairs of Kelvin connected bridge resistors, 600 μm long, 0.5 μm wide, and separated by 30 μm. There are two different arrangements with lines running either vertically or horizontally as shown in Fig. 2.

The mask features an array of 54 sets of mismatch test structures, placed around and between the blocks of cross-bridge linewidth test structures.

III. MEASUREMENTS

A. *Electrical Measurements*

1) Cross-Bridge Structures: The sheet resistance R_S of the chrome layer of the mask is measured using the Greek cross structure and the method described in [14]. Current is forced between two adjacent arms of the cross (pads A and D in Fig. 1) and the voltage is measured between the other arms (pads B and E). This measurement is then repeated with the current reversed in order to remove voltage offsets, caused for example by thermoelectric effects, from the measurement. In order to determine and remove the effects of any geometric asymmetries in the structure the measurements are then performed with the

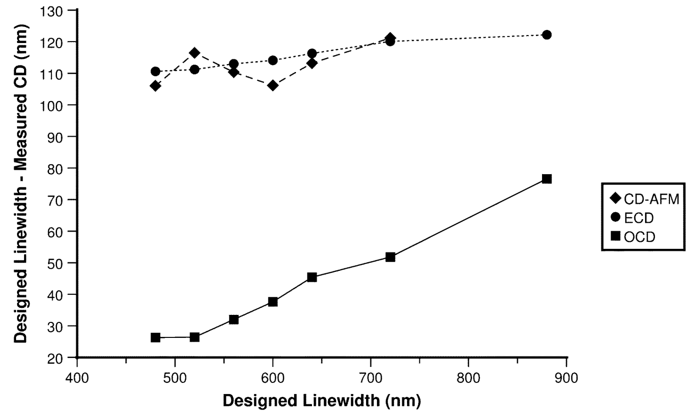

Fig. 3. Comparison of optical, electrical, and AFM metrology.

connections rotated through 90° ($I_{\mathrm{DB}}, V_{\mathrm{EA}}$ etc.). The results of the four Kelvin V/I measurements are averaged (R_{avg}) and the sheet resistance is calculated using

$$R_S = \frac{\pi R_{\mathrm{avg}}}{\ln 2}. \tag{1}$$

The sheet resistance is measured five times with a force current of 500 μA and the results averaged. The average standard deviation over the five measurements was determined from a set of 200 measurements with a 10 minute delay between each group of five. This was found to be about 2.8 m$\Omega/\square$ for an average sheet resistance of 22.47$\Omega/\square$. The overall variability for that set of the measurements (3σ) was 22 m$\Omega/\square$ or about 0.1%.

The resistance R_B of the bridge resistor section is then measured by forcing a current between pads D and F and measuring the voltage drop between pads E and C. As with the sheet resistance measurement, the current is then reversed to remove any voltage offsets. The average electrical linewidth (ECD) of the bridge section can then be calculated using

$$W_B = \frac{R_S L_B}{R_B} \tag{2}$$

where L_B is the length of the bridge section (400 μm). A similar set of 200 measurements of the bridge resistor showed a 3σ variability of $\sim$2.6 Ω for an average resistance of 22 102 Ω ($I = 500$ μA). These repeatability figures for sheet resistance and bridge resistance measurements translate into linewidth uncertainties of 0.4 and 0.05 nm, respectively, for an average ECD of 406.7 nm (nominal CD 480 nm).

It should be noted that the measurements of repeatability were performed on mask MSN5757 as MSN6659 was not available for electrical testing at this time. Both masks have essentially the same test structures and have been fabricated from similar mask blanks but the linewidths are slightly different due to the GHOST processing on MSN6659 [15].

2) Mismatch Test Structures: The resistance of each Kelvin bridge resistor in the mismatch test block is measured in a similar way to the bridge section of the cross-bridge structure. The approximate linewidth is then calculated using an average value of sheet resistance extracted from the many Greek cross structures on the mask. This is 22.45 $\Omega/\square$ with a variation of about 1% across the mask. The estimated electrical CDs are then used to calculate the dimensional mismatch, $\Delta W/W(\%)$, in X (from the vertical lines) and Y (from the horizontal lines). As this is a relative figure, the results are unaffected by small errors in the sheet resistance used to calculate the electrical linewidth.

B. Optical Measurements

Optical CD (OCD) measurements have been made using a MueTec $\langle \mathrm{M5K} \rangle$ mask metrology system with 248-nm ultraviolet illumination. This captures an image of features on the mask, always in transmission at 248 nm, and determines the CD [16]. The system extracts an intensity profile from the image and applies a threshold in order to determine the position of the feature edges. This is a subjective measurement requiring careful calibration and it has been demonstrated in previous publications that this technique has problems when measuring phase-shifted masks [7] or isolated features below ~700 nm [8], as a consequence of the calibration methodology used in these references.

C. CD-AFM Measurements

CD-AFM measurements were performed using a Veeco SXM320 at the National Institute of Standards and Technology (NIST). This tool is effectively a three-dimensional AFM where the deflection of the tip can be measured in-plane as well as out of plane. The tip itself does not come to a point like a standard AFM tip but instead is wider at the bottom, which enables it to directly measure the shape of features with vertical or re-entrant sidewalls. The tip width of this instrument is calibrated using a single crystal, critical dimension reference material (SCCDRM), which was developed at NIST. This calibration enables the CD-AFM tool to perform linewidth measurements with expanded uncertainties as low as 1.5 nm $(k = 2)$ [11], [17]. The AFM measurements were obtained near the center of the bridge resistor on both types of test structures. However, this positioning is only approximate due to the length of the structures and the absence of nearby navigation markers. Twenty AFM scan lines are taken over a 1 μm length of track and the average width is calculated. The typical standard deviation of the 20 measurements is 5–7 nm. The expanded uncertainties of the values as measured by the AFM ranged between 1.7 and 3.8 nm, with tip wear driving the larger uncertainties. However, it should be noted that these estimates do not include the uncertainty resulting from linewidth roughness (LWR). In order to investigate any longer range changes in linewidth one of the structures was remeasured at five different positions, about 70 μm apart, along the length of the bridge.

IV. Results

A. Cross Bridge Structures

Due to the length of time required for CD-AFM measurements these initial results only cover the smallest of the isolated linewidth structures. There are also difficulties with the measurement of dense features using the CD-AFM due to the shape of the tip. As a result, there are measurements from six isolated cross bridge structures with designed linewidths between 480 and 720 nm. These results are plotted along with ECD and OCD results in Fig. 3. It should be noted that this graph shows the measured CD subtracted from the designed linewidth.

TABLE I
CD-AFM Measurements Made at Five Different Positions

Distance (μm)	Width (nm)	Std. Dev. (nm)
60	404.92	7.95
130	402.15	5.92
200	403.51	7.88
270	400.55	7.22
340	400.28	4.96

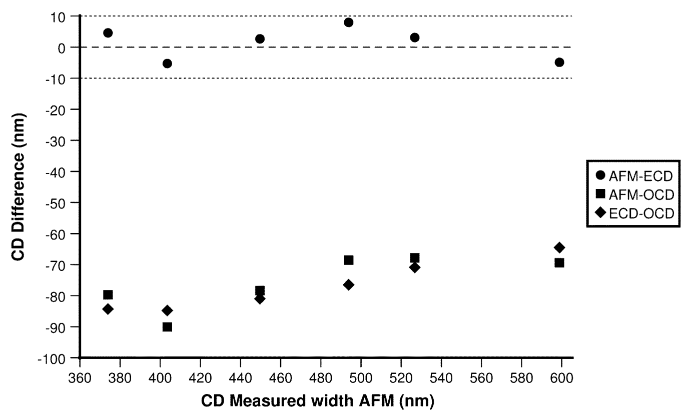

Fig. 4. Measurement offsets for isolated linewidth structures.

These results show excellent agreement between the CD-AFM and ECD measurements, but a significant offset between them and the optical CD metrology results. The level of agreement between the electrical and standards calibrated CD-AFM results is surprisingly good. It is expected that there would be a systematic offset between any two measurement techniques, associated with the type of measurement used [18]. The variation of the AFM results away from the smooth trend of the ECD measurement can be explained by noting that the AFM measurement is looking at a relatively short (1 μm) length of the bridge while the electrical results give the average width of a 400-μm line.

In order to investigate this, further measurements were made at five different positions along a bridge structure with a nominal width of 520 nm. This is the second point for the CD-AFM in Fig. 3 with a measured width of 403.5 nm. These measurements were made using an AFM tip with significant wear so they should be considered as indicative of the variation of width along the line rather than of absolute CD. The results have been normalized to the value for the center of the line given above (i.e., 403.5 nm) and are presented in Table I, along with the standard deviation of the twenty individual measurements made at each position. Note that the "Distance" column gives the approximate position of the AFM measurement along the measured line. These results suggest that the variation of linewidth at this long range is very small and is of a similar scale to the standard deviation of the individual measurements at each point.

Fig. 4 is a more direct comparison of the three different measurement methods. It shows the differences between the measurement results plotted against the CD measured with the NIST CD-AFM. The offset between the ECD and AFM results is less

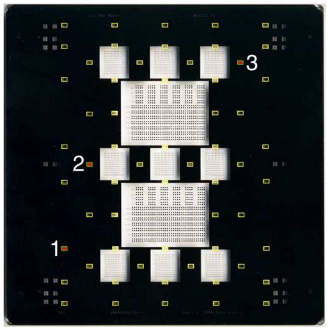

Fig. 5. Scanned image of photomask with measurement sites highlighted.

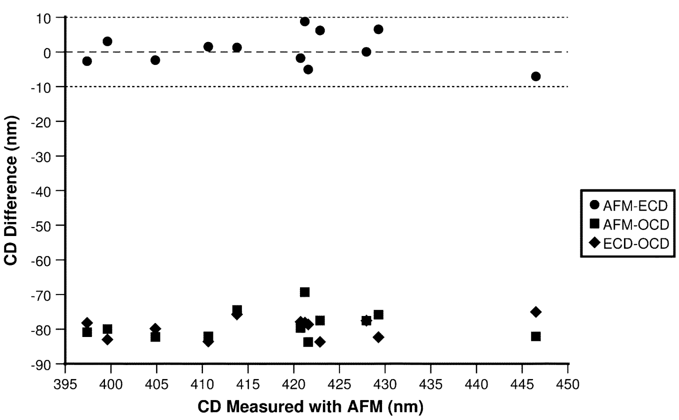

Fig. 6. Measurement offsets for mismatch test structures.

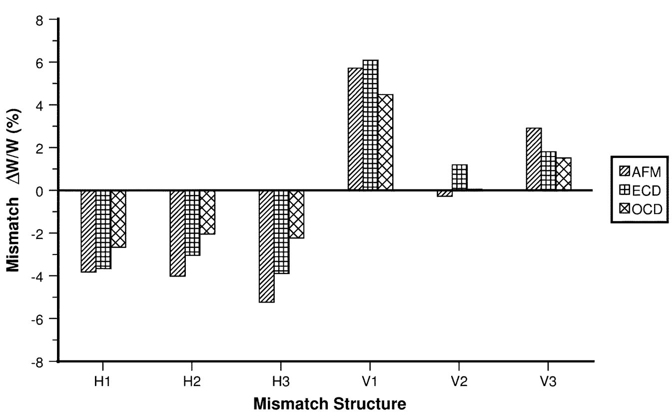

Fig. 7. Comparison of percentage mismatch ΔW/W extracted using different metrology techniques.

than 10 nm for each of the test structures and does not display an obvious dependence on the width. This is not the case for the optical results where the offset is significantly larger and also seems to reduce as the dimensions increase.

B. *Mismatch Test Structures*

Three blocks of mismatch structures from MSN6659 have been measured with the NIST CD-AFM. Each block has four individual Kelvin bridge resistors and so this provides measurements of 12 features with a nominal width of 500 nm. The structures were chosen on the basis of the initial electrical measurements, which either showed larger or smaller offsets in the vertical or horizontal directions than the average. Fig. 5 shows the positions of the three blocks of structures that were measured while Fig. 6 presents the offsets between each of the different measurement methods for these structures.

As with the isolated cross-bridge structures, there is good agreement between the electrical and CD-AFM measurements where the difference is always less than 10 nm. The optical results show a significant difference when compared to the other measurement techniques, probably due to calibration issues, but there is no significant trend with width unlike the results in Fig. 4. This is probably due to the much smaller range of dimensions in this data set.

Values for the dimensional mismatch between each pair of lines have also been calculated for each measurement technique and the results are shown in Fig. 7. The results from the electrical measurements are closer to those obtained with the CD-AFM for every set of structures except for the vertical lines in block 2. In this structure the offset is close to zero and the observed result may be explained as an artefact of the AFM measurement variability.

V. Analysis of Measurement Uncertainties

A. *Electrical Measurements*

Electrical linewidth repeatability measurements of structures on mask MSN5757 were made using an HP4062UX. This is a production semiconductor characterization system consisting of an HP4142B modular source monitor tool, an HP4280A capacitance meter, and an HP4085B switching matrix. The system is programmed and controlled from an HP745i workstation running HP-UX and HP-BASIC. The current source for the resistance measurement is an HP41421B source monitor unit, while the voltage is measured with an HP3457A digital multimeter, which has been added to the 4062UX system. The current through the structure is measured with another HP41421B SMU, in voltage source mode, which is set to 0 V. The current measurement accuracy at 500 μA is ± 2 μA, which is equivalent to a possible systematic offset of up to $\pm$ 1.6 nm in both the Greek cross and the bridge measurements. However, these are likely to be in the same direction for both measurements and as such will cancel out. The standard deviation of the current measurement is $\sim$50 nA taken over 500 measurements at 500 μA. This is equivalent to a change in linewidth of less than 0.05 nm when applied to the Greek cross measurements and 0.09 nm for the bridge resistance measurements.

The voltmeter typically measures around 2.5 mV for the Greek cross with a force current of 500 μA. The accuracy of the meter in this range is ± 3.75 μV, which is equivalent to a change in linewidth of about ± 0.6 nm. The measured voltage for the 480 nm bridge structures at 500 μA is around 11 V ($R_B \approx$ 22.1 kΩ) with an accuracy of ± 0.4 mV, which is equivalent to a change in linewidth of less than ± 0.02 nm. These will not cancel out in the same way as the effects of any inaccuracy in the current measurement and so there is the possibility of a systematic linewidth offset due to the voltage measurement. The repeatability of the voltage measurements on the Greek cross is less than 0.5 μV, which equates to a linewidth uncertainty of 0.08 nm. Similarly for the bridge, the voltage repeatability for 500 measurements is about 0.1 mV or less than 0.005 nm. The combined statistical uncertainty

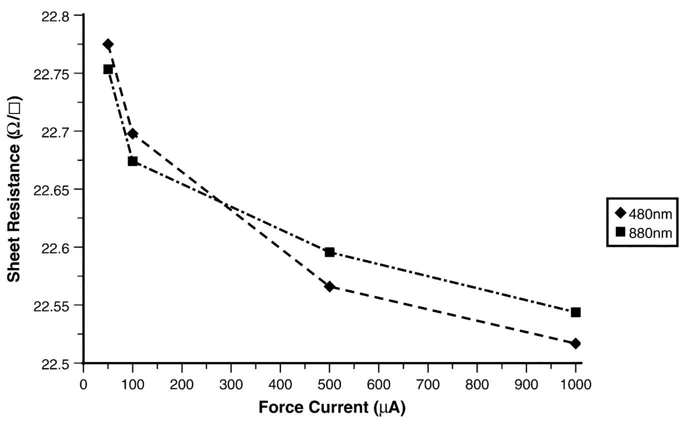

Fig. 8. Sheet resistance plotted against force current for two different Greek crosses. This shows a variation of around 1% over the range of currents used.

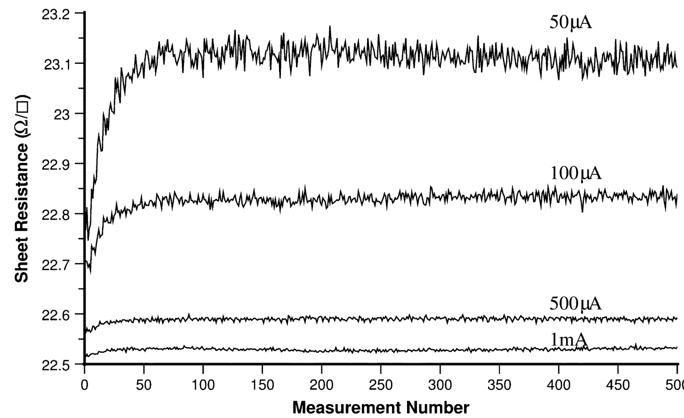

Fig. 9. Sheet resistance variation over 500 measurements for different measurement currents.

derived from this analysis is $\sqrt{\Sigma\sigma_i^2} = 0.23$ nm with a possible systematic offset of ± 0.62 nm if the effects of inaccuracies in the voltage measurements are additive.

The analysis of electrical linewidth metrology described in [12] suggests a number of possible sources of uncertainty. For example, any uncertainty in the length of the bridge resistor will affect the calculation of the ECD. The estimate of the possible misplacement of the voltage taps is 60 nm (3σ) which, for a bridge with a nominal length of 400 μm, is equivalent to an uncertainty of about 0.06 nm in linewidth. The uncertainty caused by the tap shortening effect is difficult to determine for these test structures but it is likely to be extremely small as the bridge length is approximately 800 $\times$ the tap width. There are a number of factors, such as line edge roughness, sidewall angle, and oxidation, which might be expected to cause a systematic offset in the electrical measurement of linewidth. It is not clear how much of a contribution to the measurement uncertainty these will cause; oxidation is likely to be less of a problem than for the silicon structures in [12] but the contributions from roughness and sidewall angle could well be larger. Another assumption is that the sheet resistance measured at a certain measurement current is relevant to the bridge measurement. Fig. 8 shows the extracted sheet resistance from Greek crosses with two different nominal widths. This indicates the extracted sheet resistance is a function of the level of the force current with both structures showing a similar dependence.

The results in Fig. 8 are averages of the first five results from a set of 500 measurements, as this best reflects the protocol used for the ECD measurements of mask MSN6659 that have been compared with the other metrology techniques. The full sheet resistance results from a Greek cross with a nominal arm width of 480 nm can be seen in Fig. 9. It shows that the apparent sheet resistance changes more for the low current measurements. This effect is caused by changes in the measured voltage as the current does not vary significantly with measurement number. The fact that this has a larger effect on the low current measurements, where the measured voltage is small, suggests that it is caused by a voltage offset that is not corrected for by reversing the measurement current and furthermore has a thermoelectric component, which accounts for the initial increase before levelling off in thermal equilibrium. If this was caused by Joule heating of the device under test it might be expected that the effect on resistance would be greater for the higher measurement currents, which is not the case. The measured voltage at a current of 50 μA is around 250 μV and at that level the accuracy of the voltmeter is ± 3.7 μV. This could result in a measured sheet resistance of up to $23\Omega/\Box$, which is near to what is observed in Fig. 9.

The electrical linewidth results derived from the sheet resistance measurements in Fig. 8 are shown in Fig. 10. The variation of the linewidth is dominated by the sheet resistance measurements. For the 480-nm nominal lines the range is about 2 nm, while it is larger at nearly 5 nm for the wider lines. The effect is greater for the wider lines because when calculating the electrical CD the sheet resistance is divided by the bridge resistance (2). Therefore, the effects of sheet resistance errors are exaggerated for wider lines, which have a lower resistance. It is possible to explain some of this variation of linewidth with current by referring to the accuracy of the voltage measurements, but it seems likely from the variation with time that there is an additional voltage offset that is affected by heating when measurements are repeated. However, it does suggest that the measurements made at higher currents, where small voltage offsets are swamped, are more reliable.

The overall uncertainty of the electrical linewidth measurements, made at a current of 500 μA for both the Greek cross and bridge resistors, is less than 0.5 nm $(k = 2)$ but there is the possibility of larger systematic errors due to the voltage measurement accuracy and the choice of force current used, perhaps as much as 1% of the measured linewidth or $\sim$5 nm for the narrowest structure. It may be that it was simply fortuitous that the measured ECDs are so close to the AFM results with no apparent systematic offset. On the other hand, the analysis predicts larger systematic errors for wider features but no divergence between the ECD and AFM results can be observed in Fig. 4 over the range of dimensions measured.

Measurements of a 10-Ω resistor in an Agilent 16346 B Calibration Module suggest that the analysis above is correct as they show an overestimation of the resistance at low current values due to an offset in the voltage measurement. A current of 500 μA or above was required in order to achieve resistance measurements that are within the quoted uncertainty $(\pm 0.07\%)$ of the resistor calibration. These measurements were performed with

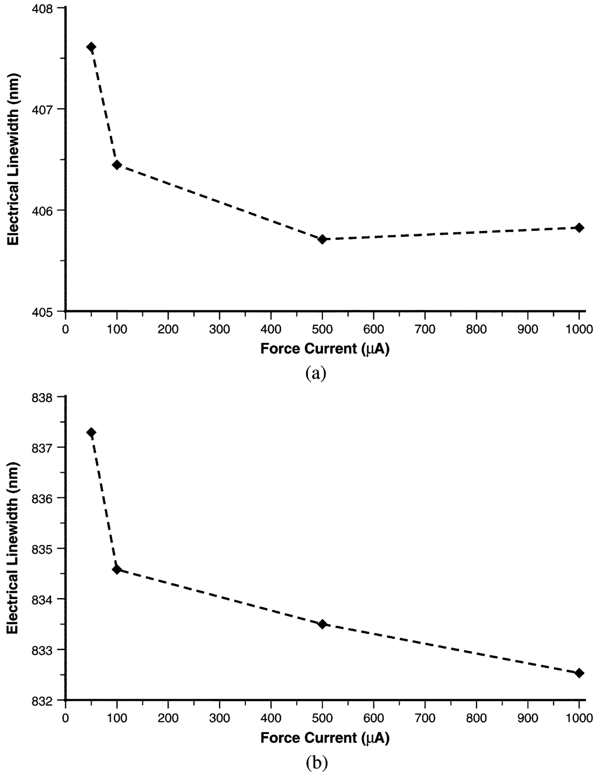

Fig. 10. Electrical linewidth plotted against force current for two different test structures. (a) Nominal CD $= 480$ nm. (b) Nominal CD $= 880$ nm.

a protocol that is as close as possible to that used for the sheet resistance extraction from the on-mask test structures.

B. Optical Measurements

The repeatability performance of the MueTec $\langle \mathrm{M5k} \rangle$ has been rigorously evaluated via a formal Equipment Assessment activity [16] to verify the suitability of the tool to support the 90-nm manufacturing node of the 2001 International Technology Roadmap for Semiconductors (ITRS) within a typical production environment. A methodology was developed to characterize the tool performance that consisted of measuring a range of clear and opaque feature sizes (200–1000 nm) sequentially over 30 loops each day for three consecutive days.

This study showed that, for isolated Cr lines, the tool was able to sustain a short-term measurement repeatability (i.e., precision) of $\leq$0.5 nm (3σ) against a target tool specification of 1.0 nm (3σ). In fact, the three-day long-term repeatability, which represented accuracy against the calibration that the tool was using, could be sustained at a similar level against a specification of 1.5 nm (3σ). Full details of similar measurements made on isolated spaces and dense lines and spaces can be found in [16].

C. CD-AFM Measurements

The CD-AFM measurements were performed using a Veeco SXM320 with tip calibration being performed before each measurement [11]. A detailed description of the methodology and the analysis used to determine the uncertainty of the CD-AFM measurements made on photomasks can be found in [19]. In summary, the major contributions to the uncertainty of the CD-AFM measurement are from the tip shape calibration, around 1 nm using the SCCDRM, and tip wear, which is more difficult to assess. Other contributions come from the repeatability of the measurement, which can be strongly affected by the linewidth roughness of the feature being measured. The standard deviation over the 1-μm measurement length is typically around 6 nm, as mentioned previously.

VI. Conclusion

Three different techniques, electrical, optical and CD-AFM, have been used to measure the linewidths of metal features on a standard chrome on quartz photomask. ECD measurements are made by direct probing onto the mask, while optical measurements are made using a mask metrology and verification tool. The CD-AFM measurements are made using a state-of-the-art system, which is calibrated using a traceable reference standard and has an uncertainty of less than 4 nm.

Measurements of isolated cross-bridge linewidth structures with nominal widths between 0.48 and 0.72 μm show good agreement between ECD and CD-AFM measurements. The offset is less than $\pm$10 nm and shows no obvious dependence upon nominal size over the range of dimensions measured. This is not the case for the optical measurements which are offset by 60 to 90 nm from the electrical and AFM measurements. The optical results also show a dependence on the nominal width with the offset reducing as dimensions increase. The AFM measurement is taken over a very short (1 μm) distance while the ECD is an average over the length of a 400 μm line (600 μm for mismatch structures). For this reason, further AFM measurements were taken at $\sim$70 μm steps along a bridge structure. These demonstrated a surprisingly small variation in width of less than 5 nm.

In addition to the cross-bridge structures, a number of Kelvin resistors designed for use as dimensional mismatch structures were also measured with the three different techniques. These 12 structures are all isolated metal features with a nominal width of 0.5 μm, but the measured dimensions varied by as much as 50 nm. As with the cross-bridge structures, the AFM and ECD measurements are within 10 nm of each other while the offset of the optical measurements is between 70 and 85 nm. Analysis of the uncertainties in the electrical measurements suggest that they are significantly less than 10 nm at the current levels used, and as such are within the observed variation between the ECD and AFM results.

Overall, the ECD and CD-AFM measurements show very good agreement with no obvious systematic offset while the optical measurements overestimate the width of these narrow isolated features by as much as 90 nm. These results demonstrate the capability of the on-mask electrical measurement technique, especially when compared to the optical tool. However, it should be recognized that the accuracy performance of the optical tool is governed by the calibration artefact used to establish the calibration within the manufacturing environment, and this artefact is not traceable to the NIST standards.

The closeness between the independent electrical measurements and calibrated CD-AFM measurements does show that we are approaching a situation where an absolute linewidth standard for binary photomasks may be definable, as we are now directly probing the physical material that composes the measurement feature. This, in turn, will provide feedback to help create better calibration artefacts for the large number of optical metrology tools that are already in place supporting photomask manufacture.

ACKNOWLEDGMENT

The authors would like to acknowledge the support of the Edinburgh Research Partnership in Engineering and Mathematics and the associated Institute for Integrated Systems, Nikon Precision Europe GmbH, Compugraphics International, Ltd., and Mentor Graphics. The NIST authors acknowledge support from the NIST Office of Microelectronics Programs, the NIST Advanced Technology Program, and the Nanomanufacturing Program of the Manufacturing Engineering Laboratory.

REFERENCES

[1] S. Smith, M. McCallum, A. J. Walton, and J. T. M. Stevenson, "Electrical CD characterisation of binary and alternating aperture phase shifting masks," in *Proc. IEEE Int. Conf. Microelectronic Test Structures*, Cork, U.K., Apr. 2002, pp. 7–12.

[2] S. Smith, M. McCallum, A. J. Walton, J. T. M. Stevenson, and A. Lissimore, "Comparison of electrical and SEM CD measurements on binary and alternating aperture phase-shifting masks," *IEEE Trans. Semicond. Manuf.*, vol. 16, no. 2, pp. 266–272, May 2003.

[3] S. Smith, M. McCallum, A. J. Walton, J. T. M. Stevenson, P. D. Harris, A. W. S. Ross, A. C. Hourd, and L. Jiang, "Test structures for CD and overlay metrology on alternating aperture phase-shifting masks," in *Proc. IEEE Int. Conf. Microelectronic Test Structures*, Japan, Mar. 2004, pp. 29–34.

[4] M. McCallum, S. Smith, A. C. Hourd, A. J. Walton, and J. T. M. Stevenson, "Cost effective overlay and CD metrology of phase-shifting masks," in *Proc. SPIE, 24th Annu. BACUS Symp. Photomask Technology*, 2004, vol. 5567, pp. 596–603.

[5] S. Smith, M. McCallum, A. J. Walton, J. T. M. Stevenson, P. D. Harris, A. W. S. Ross, and L. Jiang, "On-mask CD and overlay test structures for alternating aperture phase shift lithography," *IEEE Trans. Semicond. Manuf.*, vol. 18, no. 2, pp. 238–245, May 2005.

[6] S. Smith, A. Walton, M. McCallum, A. C. Hourd, J. T. M. Stevenson, A. W. S. Ross, and L. Jiang, "Improved test structures for the electrical measurement of feature size on an alternating aperture phase-shifting mask," in *Proc. IEEE Int. Conf. Microelectronic Test Structures*, Leuven, Belgium, Apr. 2005, pp. 17–22.

[7] S. Smith, A. Tsiamis, M. McCallum, A. C. Hourd, J. T. M. Stevenson, and A. Walton, "Comparison of optical and electrical measurement techniques for CD metrology on alternating aperture phase-shifting masks," in *Proc. IEEE Int. Conf. Microelectronic Test Structures*, Austin, TX, Mar. 2006, pp. 119–123.

[8] A. Tsiamis, S. Smith, M. McCallum, A. C. Hourd, O. Toublan, J. T. M. Stevenson, and A. J. Walton, "Development of electrical on-mask CD test structures based on optical metrology features," in *Proc. IEEE Int. Conf. Microelectronic Test Structures*, Tokyo, Japan, Mar. 2007, pp. 171–176.

[9] S. Smith, A. Tsiamis, M. McCallum, A. C. Hourd, J. T. M. Stevenson, and A. J. Walton, "Electrical measurement of on-mask mismatch resistor structures," in *Proc. IEEE Int. Conf. Microelectronic Test Structures*, Tokyo, Japan, Mar. 2007, pp. 3–8.

[10] J. E. Potzick, J. M. Pedulla, M. T. Stocker, and D. J. Herr, "Updated NIST photomask linewidth standard," in *Proc. SPIE Metrology, Inspection, and Process Control for Microlithography XVII*, , 2003, vol. 5038, pp. 338–349.

[11] R. G. Dixson, R. A. Allen, W. F. Guthrie, and M. W. Cresswell, "Traceable calibration of critical-dimension atomic force microscope linewidth measurements with nanometer uncertainty," *J. Vacuum Sci. Technol.*, vol. B 23, no. 6, pp. 3028–3032, 2005.

[12] J. S. Villarrubia, R. G. Dixson, S. N. Jones, J. R. Lowney, J. Michael, T. Postek, R. A. Allen, and M. W. Cresswell, "Intercomparison of SEM, AFM, and electrical linewidths," in *Proc. SPIE, Vol. 3677: Metrology, Inspection, and Process Control for Microlithography XIII*, 1999, pp. 587–598.

[13] M. G. Buehler, S. D. Grant, and W. R. Thurber, "Bridge and van der Pauw sheet resistors for characterizing the line width of conducting layers," *J. Electrochemical Soc. Solid State Technol.*, vol. 125, no. 4, pp. 650–654, Apr. 1978.

[14] M. G. Buehler and W. R. Thurber, "An experimental study of various cross sheet resistor test structures," *J. Electrochemical Soc. Solid State Technol.*, vol. 125, no. 4, pp. 645–650, Apr. 1978.

[15] A. Tsiamis, S. Smith, M. McCallum, A. C. Hourd, O. Toublan, J. T. M. Stevenson, and A. J. Walton, "Investigation of electrical and optical CD measurement techniques for the characterisation of on-mask GHOST proximity corrected features," in *Proc. IEEE Int. Conf. Microelectronic Test Structures (ICMTS08)*, Edinburgh, U.K., Mar. 2008, pp. 29–34.

[16] A. C. Hourd, A. Grimshaw, G. Scheuring, C. Gittinger, S. Döbereiner, F. Hillman, H.-J. Brück, S.-B. Chen, P. Chen, R. Jonckheere, V. Philipsen, H. Hartmann, V. Ordynskyy, K. Peter, T. Schätz, and K. Sommer, "Reliable sub-nanometer repeatability for CD metrology in a reticle production environment," in *Proc. SPIE, Vol. 4889: 22nd Annu.BACUS Symp. Photomask Technology*, 2002, pp. 319–327.

[17] M. W. Cresswell, W. F. Guthrie, R. G. Dixson, R. A. Allen, C. E. Murabito, and J. V. Martinez De Pinillos, "RM 8111: Development of a prototype linewidth standard," *J. Res. Nat. Inst. Standards Technol.*, vol. 111, no. 3, pp. 187–203, May–June 2006.

[18] R. A. Allen, P. Troccolo, J. C. Owen, J. E. Potzick, and L. W. Linholm, "Comparisons of measured linewidths of sub-micrometer lines using optical, electrical, and SEM metrologies," *Proc. SPIE*, vol. 1926, pp. 34–43, 1993.

[19] R. G. Dixson, N. G. Orji, J. E. Potzick, J. Fu, R. A. Allen, M. W. Cresswell, S. Smith, A. J. Walton, and A. Tsiamis, "Photomask applications of traceable atomic force microscope dimensional metrology at NIST," *Photomask Technology 2007, Vol. 6730: Proc. SPIE*, pp. 6370D–1, Sept. 2007.

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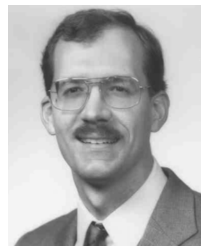

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