Comparison of Measurement Techniques for Linewidth Metrology on Advanced Photomasks

Stewart Smith, Member, IEEE, Andreas Tsiamis, Student Member, IEEE, Martin McCallum, Andrew C. Hourd, J. T. M. Stevenson, Anthony J. Walton, Member, IEEE, Ronald G. Dixon, Richard A. Allen, Senior Member, IEEE, James E. Potzick, Michael W. Cresswell, Life Fellow, IEEE, and Ndubuisi G. Orji

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.

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.

S. Smith, A. Tsiamis, J. T. M. Stevenson, and A. J. Walton are with the Institute for Integrated Micro and Nano Systems, School of Engineering and Electronics, Scottish Microelectronics Centre, University of Edinburgh, Edinburgh EH9 3JF, U.K. (e-mail: Stewart.Smith@ed.ac.uk).

M. McCallum is with Nikon Precision Europe GmbH, West Lothian EH54 7EZ, U.K.

A. C. Hourd was with Compugraphics International, Ltd., Fife KY7 4NT, U.K.

R. G. Dixon, R. A. Allen, J. E. Potzick, M. W. Cresswell, and N. G. Orji are with the National Institute of Standards and Technology, Gaithersburg, MD 20899–8120 USA.

Digital Object Identifier 10.1109/TSM.2008.2010733

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

$$R_S = \frac{\pi R_{avg}}{\ln 2}. \quad (1)$$

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 mΩ/μm for an average sheet resistance of 22.47 mΩ/μm. The overall variability for that set of the measurements ($\sigma_S$) was 22 mΩ/μm 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

$$W_B = \frac{R_SL_B}{R_B}. \quad (2)$$

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 ~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 mΩ/μm 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 figure) 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 (M5K) 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 $\sim700$ 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 $\mu$m 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 $\mu$m 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.

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 ($1 \mu$m) length of the bridge while the electrical results give the average width of a 400-$\mu$m 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

<table>
<thead>
<tr>
<th>Distance ((\mu m))</th>
<th>Width (nm)</th>
<th>Std. Dev. (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>404.92</td>
<td>7.95</td>
</tr>
<tr>
<td>130</td>
<td>402.15</td>
<td>5.92</td>
</tr>
<tr>
<td>200</td>
<td>403.51</td>
<td>7.88</td>
</tr>
<tr>
<td>270</td>
<td>400.55</td>
<td>7.22</td>
</tr>
<tr>
<td>340</td>
<td>400.28</td>
<td>4.96</td>
</tr>
</tbody>
</table>
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 \( \mu \text{A} \) is \( \pm 2 \mu \text{A} \), which is equivalent to a possible systematic offset of up to \( \pm 1.6 \text{ nm} \) 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 \( 50 \text{ nA} \) taken over 500 measurements at 500 \( \mu \text{A} \). 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 \( \mu \text{A} \). The accuracy of the meter in this range is \( \pm 3.75 \mu \text{V} \), which is equivalent to a change in linewidth of about \( \pm 0.6 \text{ nm} \). The measured voltage for the 480 nm bridge structures at 500 \( \mu \text{A} \) is around 11 V \( (R_D \approx 22.1 \text{ k}\Omega) \) with an accuracy of \( \pm 0.4 \text{ mV} \), which is equivalent to a change in linewidth of less than \( \pm 0.02 \text{ nm} \). 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 \( \mu \text{V} \), 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
derived from this analysis is $\sqrt{\sum \sigma_i^2} = 0.23$ nm with a possible systematic offset of $\pm 0.62$ 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 (3$\sigma$) which, for a bridge with a nominal length of 400 $\mu$m, 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 x 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 leveling 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 $\mu$A is around 250 $\mu$V and at that level the accuracy of the voltmeter is $\pm 3.7$ $\mu$V. This could result in a measured sheet resistance of up to $23\Omega/square$, 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 $\mu$A 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-$\Omega$ 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 $\mu$A 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
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 ±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 ~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


Stewart Smith (M 05) received the B.Eng. (honors) degree in electronics and electrical engineering, in 1997, and the Ph.D. degree, in 2003, from the University of Edinburgh, Scotland, UK. His Ph.D. thesis was entitled “Sheet Resistance and Electrical Linewidth Test structures for Semiconductor Process Characterisation”. He is an RCUK Academic Fellow with the School of Engineering and Electronics at the University of Edinburgh. His current research interests include the design and fabrication of biomedical Microsystems, test structures for MEMS and the electrical characterization of advanced photomasks.

Andreas Tsiamis (S 06) received the B.Eng. (honors) degree in electronics and electrical engineering and the B.Sc. degree in computer science from the University of Edinburgh, U.K., in 2005. He is presently working toward the Ph.D. degree from the Institute of Integrated Micro and Nano Systems at the University of Edinburgh. His research interests include the electrical characterization of advanced photomasks.

Martin McCallum is currently Programme Manager for Advanced Lithography Development at Nikon Precision Europe, West Lothian, U.K. He is responsible for Nikon optical and NGL lithography development projects in Europe. Prior to this, he was a Project Manager in the Optical Extension program at International SEMATECH.
Andrew C. Hourd received the B.S. degree in physics from the University of Leicester, U.K., and the Ph.D. degree in 1988. He was the Research and Development Manager at Compugraphics International Ltd., Glenrothes, Scotland, from November 1995 until July 2008, during which time he was responsible for internal and collaborative projects for the advancement of photomask manufacture. In the four years prior to joining Compugraphics, he held the position of Research Fellow at the University of Dundee, Scotland. He moved to the University of Dundee, in 1983, to work in the field of thin film amorphous semiconductors, concentrating on their preparation and device processing using plasmas, and has recently returned to this research group.

J. T. M. Stevenson received the B.Sc. degree in physics in 1967, the M.Sc. degree in instrument design from the University of Aberdeen, U.K., in 1969, and the Ph.D. degree from the University of Edinburgh, U.K., in 1988. He spent five years at Ferranti Ltd., Dalkeith, as a Development Engineer on moire measuring systems. In 1974, he joined the Wolfson Microelectronics Institute to work on the design of a pattern generator for the production of integrated circuits. In 1980, he was appointed to a research fellowship in the Edinburgh Microfabrication Facility, University of Edinburgh. His main research interests are in optical lithography and optical measurement techniques.

Anthony J. Walton received the B.S. and the Ph.D. degrees in physics from Yale University, New Haven, CT. He has been a Staff Scientist in the Manufacturing Engineering Laboratory, National Institute of Standards and Technology (NIST), Gaithersburg, MD, since 1994. He works primarily on atomic force microscope dimensional metrology and standards development at NIST—including the NIST calibrated atomic force microscope project. Between 2001 and 2004, he spent three years as the first NIST Guest Scientist at SEMATECH where he developed a CD-AFM based reference measurement system and utilized this system for the 2004 release of single crystal critical dimension reference materials to SEMATECH member companies. He now continues to work on furthering CD-AFM metrology at NIST and has research interests in calibration methods, traceability, and uncertainty analysis in AFM dimensional metrology. Dr. Dixon is a member of SPIE and the American Physical Society (APS).

Ronald G. Dixon received the Ph.D. degree in physics from Yale University, New Haven, CT. He has been a Staff Scientist in the Manufacturing Engineering Laboratory, National Institute of Standards and Technology (NIST), Gaithersburg, MD, since 1994. He works primarily on atomic force microscope dimensional metrology and standards development at NIST—including the NIST calibrated atomic force microscope project. Between 2001 and 2004, he spent three years as the first NIST Guest Scientist at SEMATECH where he developed a CD-AFM based reference measurement system and utilized this system for the 2004 release of single crystal critical dimension reference materials to SEMATECH member companies. He now continues to work on furthering CD-AFM metrology at NIST and has research interests in calibration methods, traceability, and uncertainty analysis in AFM dimensional metrology. Dr. Dixon is a member of SPIE and the American Physical Society (APS).

Richard A. Allen received the B.S. and the M.S. degrees, both in physics, from Rensselaer Polytechnic Institute, Troy, NY, in 1982 and 1984, respectively, and the M.B.A. degree from Columbia Union College, in 2007. He has worked at the Jet Propulsion Laboratory in Pasadena, CA, where he developed test structures for in situ monitoring space radiation effects in the VLSI Technology Group and at College Park Software in Altadena, CA, where he worked on the development of LISP-based expert systems tools. Since June 1990, he has been with the Semiconductor Electronics Division, National Institute of Standards and Technology, Gaithersburg, MD. His present interests include developing metrology test structures for microfluidics, MEMS, and microelectronics applications. Mr. Allen is a Member of the American Physical Society.

James E. Potzick is a Physicist at the National Institute of Standards and Technology, Gaithersburg, MD. He has been involved in the accurate measurement of various physical quantities at that institution for over 20 years. He is currently Project Leader for Optical Photomask Metrology in the Nano-Scale Metrology group. Prior to this, he developed improved methods for measuring the mass flowrate of gases, gas temperature, humidity, and dynamic forces. He is the Author of numerous technical publications in the fields of fluids, mechanics, electronics, acoustics, dimensional metrology, and theory of measurement. He holds three patents. Dr. Potzick is a member of SPIE and BACUS.

Michael W. Cresswell received the B.S. and the M.S. degrees, both in physics, from Rensselaer Polytechnic Institute, Troy, NY, in 1982 and 1984, respectively, and the M.B.A. degree from Columbia Union College, in 2007. He has worked at the Jet Propulsion Laboratory in Pasadena, CA, where he developed test structures for in situ monitoring space radiation effects in the VLSI Technology Group and at College Park Software in Altadena, CA, where he worked on the development of LISP-based expert systems tools. Since June 1990, he has been with the Semiconductor Electronics Division, National Institute of Standards and Technology, Gaithersburg, MD. His present interests include developing metrology test structures for microfluidics, MEMS, and microelectronics applications. Mr. Allen is a Member of the American Physical Society.

Ndubuisi G. Orji received the Ph.D. degree in mechanical engineering from the University of North Carolina, Charlotte. He is a member of the technical staff of the National Institute of Standards and Technology, Gaithersburg, MD. He works on applications of scanning probe microscopy techniques in semiconductor manufacturing. His research interests are in nanoscale dimensional metrology, optical metrology, reference measurement systems, uncertainty analysis, and standards development. Dr. Orji is a member of SPIE and the American Society for Precision Engineering.