Absolute sensitivity calibration of extreme ultraviolet photoresists

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Abstract: One of the major challenges facing the commercialization of extreme ultraviolet (EUV) lithography remains simultaneously achieving resist sensitivity, line-edge roughness, and resolution requirement. Sensitivity is of particular concern owing to its direct impact on source power requirements. Most current EUV exposure tools have been calibrated against a resist standard with the actual calibration of the standard resist dating back to EUV exposures at Sandia National Laboratories in the mid 1990s. Here we report on an independent sensitivity calibration of two baseline resists from the SEMATECH Berkeley MET tool performed at the Advanced Light Source Calibrations and Standards beamline. The results show the baseline resists to be approximately 1.9 times faster than previously thought based on calibration against the long standing resist standard.

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1. Introduction

Extreme ultraviolet (EUV) lithography [1-3] is a leading candidate for the high volume manufacturing of nanoelectronics at feature sizes of 32 nm and smaller. One of the major challenges facing the commercialization of EUV lithography is simultaneously achieving resolution, line-edge roughness, and sensitivity requirements for resists. Noting that the source is widely viewed as the largest single challenge facing EUV, resist sensitivity is of particular concern due to its direct coupling to EUV source power requirements. Although, in principle, resist sensitivity measurements are straightforward, the accuracy of the measurement depends on well calibrated detectors and detailed knowledge of the illumination beam size and uniformity. In practice, thus, it is often preferable to use a reference resist of a known sensitivity to calibrate exposure tool dose sensors. In fact, this reference resist method was originally used to calibrate the SEMATECH Berkeley microfield exposure tool (MET) [4] which serves as one of the world's most productive resist testing centers. The reference resist used was Rohm and Hass *EUV-2D* with a reported sensitivity of 6.8 mJ/cm^2 for equal line-space printing of 100-nm lines. The reported sensitivity value was determined based on EUV exposures performed at Sandia National Laboratories in the mid to late 1990s [5]. It is also our understanding that the majority of other EUV exposure tools available today were either calibrated off this same reference resist or from some secondary reference derived from exposures at the SEMATECH Berkeley MET.

Owing to the importance of the of the resist sensitivity issue to the commercialization of EUV lithography, the non-traceable sensitivity reference standard used in the calibration of the latest EUV tools has raised concerns. To address this issue we have performed independent absolute sensitivity measurements of two new industry baseline resists using the Advanced Light Source Calibration and Standards Beamline [6].

2. Previous calibration procedure

Printing operations using the SEMATECH Berkeley MET started in early 2004 at which point the tool was calibrated against a dose to size (E_{size}) for 100-nm equal lines and spaces in Rohm and Hass *EUV-2D* resist of 6.8 mJ/cm^2. As mentioned above, the reference resist sensitivity value was derived from exposures performed on the Sandia EUV 10× tool and thus is only as accurate as the calibration of the now decommissioned exposure tool. A reference resist was used instead of the integrated MET wafer dose sensor due to poor illumination uniformity available at the time as well as the fact that there was no means to remove the photodiode dose sensor for independent calibration verification. The illumination uniformity concerns also led to the use of E_{size} instead of dose to clear (E_0) for transferring the resist standard to the tool.

Even assuming perfect dose calibration from the 10× tool, we note that one would expect some level of error in the procedure described above attributable simply to the fact that the imaging properties of the 10× and MET tools would be expected to be different. No attempt was made to compensate for this effect given inadequate knowledge of the actual imaging conditions in the 10× including wavefront aberrations and pupil fill. Nevertheless, it is instructive to consider the potential magnitude of such an error through modeling. Figure 1 shows *Prolith* [7] resist modeling results for printed feature size as a function of dose for both an idealized 10× system and the SEMATECH Berkeley MET. The assumed illumination was 0.4 σ Gaussian and 0.35-0.55 annular for the 10× and MET tools, respectively. The resist model was developed by Rohm and Hass and reported in the literature [8]. From these results we see that imaging characteristics differences between the 10× and MET tools could readily lead to calibration transfer errors as large as 30%, not to mention potential initial calibration errors in the reported 10× tool dose numbers.

2. New calibration procedure

For the reasons described above, there is considerable interest in the development of a more accurate tool dose calibration procedure for the SEMATECH Berkeley MET tool. To address this concern we have used the Advanced Light Source Calibrations and Standards Beamline to perform absolute E_0 measurements in two MET baseline resists: TOK EUVR-P1123 and Rohm and Hass XP-4502D (MET-1K). The E_0 measurements are then transferred to the MET which is now possible due to the recent upgrades in the illuminator yielding much improved illumination uniformity [9]. Again, the accuracy of this method relies on the accuracy of the calibrating tool which in this case Calibrations and Standards Beamline. This accuracy depends both on knowledge of the total flux impinging on the wafer plane (i.e. the accuracy of the photodiode used to measure the flux) as well as accurate knowledge of the beam profile. The beam profile is determined using a scanning pinhole technique and detector is calibrated using two independent techniques: cross calibration to a standard and self calibration. The photodiode used is an IRD AXUV-100 diode and cross calibration standard was a NIST calibrated SXUV-100 diode. The self calibration method [10] involves measuring the generated photocurrent as a function of photon energy at two different incident angles. The diode front surface oxide thickness is then determined from the ratio of the energy response. Figure 2 shows the self calibration data yielding a measured oxide thickness of 7 nm. Using this measured oxide thickness and the known average pair creation energy [11] we can determine the diode responsivity. For further verification, the self-calibration responsivity is also checked against a reference standard for which we use a NIST calibrated SXUV-100 diode. Figure 3 shows a plot of the self-calibrated responsivity compared to the reference standard. We see that both methods yield essentially the same results. The responsivity at our wavelength of interest (13.5 nm) is 0.255 A/W.

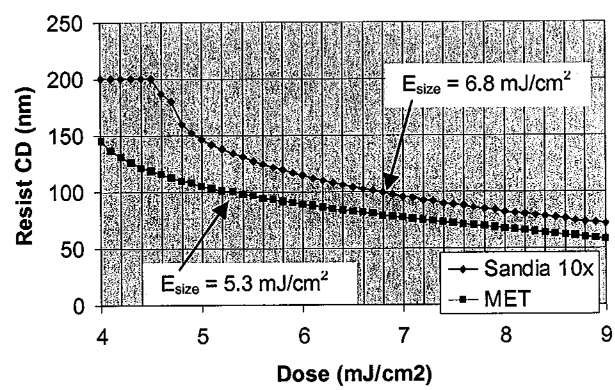

Fig. 1. Resist modeling results for printed feature size (CD) as a function of dose for both an idealized 10× system and the SEMATECH Berkeley MET. The assumed illumination was 0.4 σ Gaussian and 0.35-0.55 annular for the 10× and MET tools, respectively.

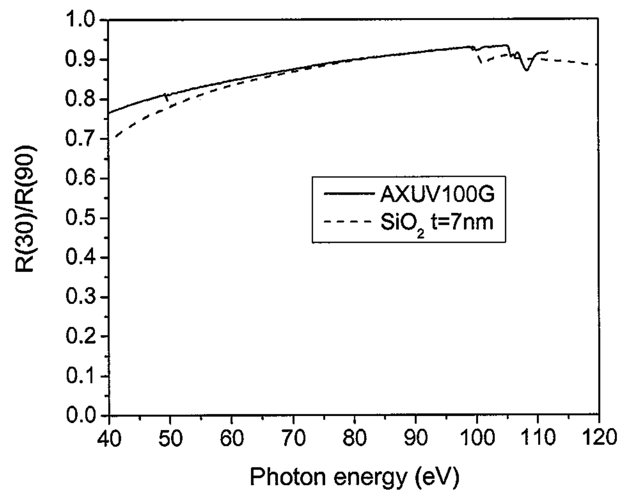

Fig. 2. Self calibration data for the IRD AXUV-100 diode used in the results presented here. The ratio of the photo-current as a function of photon energy at two different incidence angles is used to determine the thickness of the diode front surface oxide.

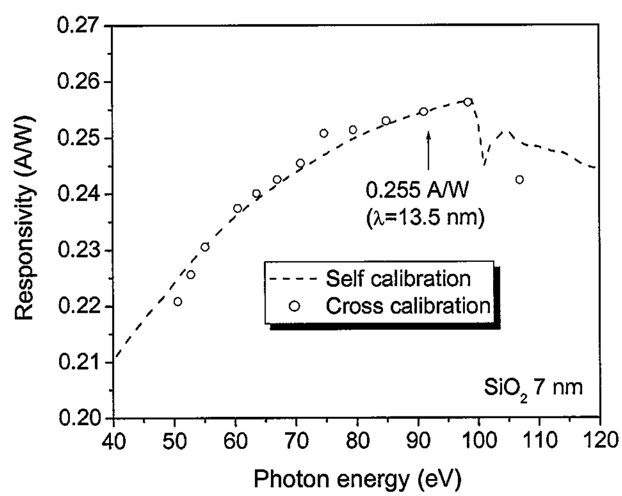

Fig. 3. Direct comparison of self and cross calibration methods. The diode responsivity at 13.5 nm is 0.255 A/W.

3. Calibration results

Two independent measurements of E_0 in P1123 and MET-1K were performed with 1 month separation in time. The beamline conditions were also changed between the two independent measurements resulting in a factor of 10 flux difference between the two measurements. As shown in Table 1, despite the significant time gap and changes in beam conditions, very similar results are obtained in the two measurements. The processing conditions for MET-1K were, post-application bake temperature of 130 °C for 60 seconds, a post-exposure bake temperature of 120 °C for 90 seconds, and a develop time of 45 seconds. For the EUVR-P1123 resist the processing conditions were, post-application bake temperature of 120 °C for 90 seconds, a post-exposure bake temperature of 100 °C for 90 seconds, and a develop time of 60 seconds.

Table 1. Absolute dose to clear measurement results in MET baseline resists.

	9/07	10/07	Average
Synchrotron ring current (mA)	20	250	NA
MET-1K E_0 (mJ/cm^2)	7.6	7.3	7.45
EUVR-P1123 (mJ/cm^2)	5.6	6.0	5.8

Next the same resist formulations from the same bottles and identically processed were used to calibrate E_0 in the MET and determine E_{size} for comparison to previously assumed results based on the original tool calibration. Table 2 shows the resulting E_{size}/E_0 measurement results where in this case E_{size} is measured for 50-nm equal lines and spaces reflecting the improved resolution of the MET baseline resists compared to EUV-2D. Two different measurement methods were used in the determination of the ratio, with the first being separate exposures of a clear field on the mask as well as a line-space field. In order to mitigate any concerns related to potential mask reflectivity differences between the two field due to, for example, contamination differences, the measurement was also performed using a hybrid field on the mask that included large clear areas with embedded line space features allowing both E_{size} and E_0 to be measured from one area on the mask.

Table 2. Absolute dose to clear measurement results in MET baseline resists.

	Separate fields	Single field	Average
MET-1K E_{size}/E_0	1.84	1.80	1.82
EUVR-P1123 E_{size}/E_0	1.82	1.70	1.76

From the ratios in Table 2 and the absolute E_0 numbers in Table 1, we can find the calibrated E_{size} values for the MET baseline resists and compare them to previous values based our old calibration (Table 3). The results show an average difference of a factor of 1.9 with the new calibration showing that the resists are in fact faster than previously thought.

Table 3. Comparison of dose to size measurements for MET baseline resists for old versus new calibration.

	New calibration	Old calibration	Ratio
MET-1K E_{size} (mJ/cm^2)	13.6	25	1.84
EUVR-P1123 E_{size} (mJ/cm^2)	10.2	20	1.96

4. Discussion

The factor of 1.9 sensitivity improvement shown above depends both on the accuracy of the E_0 measurement as well the determined E_{size}/E_0 ratio. While justification has been presented above for the accuracy of the E_0 values, one might ask if the ratio measurement is indeed accurate (i.e. nonlinearity in MET dose control). Given that MET dose control is achieved through shutter timing and that the Advanced Light Source synchrotron facility runs at a repetition rate of 1 MHz and that the source is extremely stable, we have no reason to suspect the presence of non-linearity. Nevertheless, we have verified the E_{size}/E_0 ratio measurement by comparing measured and modeled results for EUV-2D resist. Figure 4 shows the modeling results yielding a E_{size}/E_0 ratio of 1.83 which compares well with the measured value of 1.88.

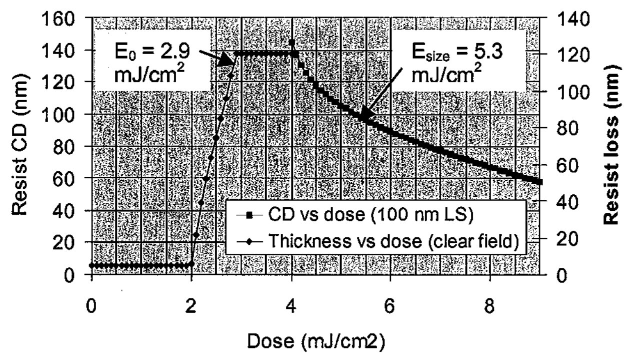

Fig. 4. Resist modeling results for the E_{size}/E_0 ratio in Rohm and Hass EUV-2D resist.

5. Summary

Absolute sensitivity calibration of two MET baseline resists have been performed using the Advanced Light Source Calibrations and Standards Beamline. The resulting calibrations have been transferred to the SEMATECH Berkeley MET and compared to previous tool calibration values showing that the MET calibration had been in error by a factor of 1.9 with resists now being faster than previously thought. We note that we believe this result to be far reaching given that several other EUV tools had either been calibrated using the same standard previously used by the MET or have been calibrated against the MET.

6. Acknowledgements

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