Electron Beam Metrology of 193 nm Resists at Ultra Low Voltage

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Abstract

Resist slimming under electron beam exposure introduces significant measurement uncertainty in the metrology of 193 nm resists. Total critical dimension (CD) uncertainty of up to 10 nm can arise from line slimming through a combination of the line slimming during the initial measurement pass and the variation of line slimming across the wafer. For a 100 nm process, the entire CD error budget, can be consumed by line slimming. This research examines the uncertainty that results from the use of offset techniques to account for resist slimming in the process control of 193 nm resist CDs. The uncertainty associated with such offset techniques can be as great as 10 nm, depending upon the 193 nm resist and landing energy evaluated. Data are presented to demonstrate that 193 nm resist CD features experience line slimming greater than 5 nm at 500 eV landing energy during the initial measurement pass. Further, subsequent measurements demonstrate greatly reduced slimming and as a result are not indicative of the true magnitude of line slimming. Experiments conducted using CD-AFM pre- and post-analysis, demonstrate that ultra low landing energies significantly decrease the line slimming, reducing it to 1 nm or less.

Introduction

In-line critical dimension (CD) measurement capability is utilized to ensure that the lithography and etch processes are running under control and at a target value that is correct for proper device yield and performance. For sub 100 nm process technologies and especially the advanced logic devices manufactured therein, the transistor performance is the most critical attribute. In fact, transistor speed, which is a direct function of the poly gate CD, determines the value of microprocessor devices. For state of the art microprocessor devices at the 100 nm node each nanometer of CD control is worth more than $20 per device.[1,2] It is in this context that 193 nm resist slimming must be viewed and understood for its impact on sub-100 nm manufacturing.

The issue of resist slimming under electron beam exposure has existed for some time. During the early development of 248 nm resist systems, line slimming of 5 – 10 % of the CD was observed. As these resist systems matured, various additives were used to fortify the resist against susceptibility to exposure from energetic electrons which are encountered during plasma etch. These additives also served to improve the behavior of the resist with respect to critical dimension scanning electron microscope (CD-SEM) beam exposure: line slimming during CD measurement was minimized. The 248 nm resist line slimming behavior has become the benchmark by which the 193 nm resist systems are gauged.[3,4] State-of-the-art 193 nm resists exhibit significant line slimming relative to this benchmark. Several factors further exacerbate the impact of resist line slimming in the sub-100 nm regime. First is the 90 nm and smaller target linewidths for this generation of technology. At a 10 % Precision-to-Tolerance (P/T) ratio, the CD process control window for this generation is less than 9 nm; in fact, for high performance logic applications, the window is actually much less than this.[5] The situation is further complicated by the emergence of line edge roughness (LER) as a device performance limiter[6]. Unfortunately, many of the resist additives that demonstrate improved line slimming and etch resistance, have also resulted in significant LER[7] and may be unacceptable for device performance reasons. Given these competing factors, it may not be possible to eliminate 193 nm resist slimming through re-formulation. Consequently, the onus must be placed upon the metrologist and the CD SEM equipment suppliers to minimize the impact of line slimming on the measurement result.

A number of studies have been performed to characterize this problem.[8,9,10,11] Several potential solutions have been proposed, including reformulation of resist to withstand electron beam exposure[9] and pre-dosing samples until the trending levels off.[8] Vasconi, et al. found that "Electron landing energy is the key parameter to minimize the resist CD variation amplitude".[10] This result, confirmed by analysis of data from several other studies[12], shows that an effective way to mitigate resist slimming is to reduce landing energy on the CD SEM. These previous studies have also shown that slimming rates are greatest during initial exposure, regardless of SEM imaging conditions.

It is instructive to analyze the behavior of these resist systems during electron beam exposure. Kudo and co-workers[4] performed the original observations and modeling of this generic behavior. Habermas and co-workers[11] performed more detailed physical modeling of resist slimming and attempted to develop analytical models which related SEM parameters to observed slimming. Figure 1 depicts the response of a specific 193 nm resist system to electron beam exposure. The data have been collected on the Yosemite CD SEM[†] under identical static measurement conditions; only landing energy has been varied. This behavior is, in general, typical of 193 nm resist systems. Observation of the trends evident in Figure 1 shows that the resist response begins with a region of rapid line slimming, followed by a slower rate and finally by a near asymptotically slow decay. Kudo fit this behavior for a methacrylate resist, and found that a good fit was obtained using the following triple exponential rate model:

$$CD = a_1 e^{-\frac{\ln 2}{t_1}t} + a_2 e^{-\frac{\ln 2}{t_2}t} + a_3 e^{-\frac{\ln 2}{t_3}t}$$

The half-life (τ) periods of the three regions of distinct linewidth slimming behavior can be obtained by a fit of the equation above to the data of Figure 1. As can be seen from the figure excellent agreement of the model with the data has been obtained. Table 1 summarizes the relevant statistics for each of the landing energy conditions.

The raw (unfitted) statistics demonstrate the impact of line slimming on measurement performance. For the 500 eV condition, nearly 25% of the total measured line slimming occurs as a result of the first measurement. The comparable figure for the 175 eV case is less than 10%. The 500 eV condition has a three sigma precision term which is ~25% higher than that observed for the 175 eV condition. The fitted statistics demonstrate the Yosemite CD SEMs sub-nanometer precision capability at both 500 eV and 175 eV.

	CD Delta 1st – 2nd Measurement	Total Slimming	Perceived 3 Sigma variation	Perceived 3 Sigma variation (trend removed)
175 eV	0.9 nm	12.6 nm	8.62 nm	0.64 nm
500 eV	4.2 nm	18.3 nm	10.33 nm	0.57 nm

Table 1: Relevant statistics for line slimming data in Figure 1

The three line-slimming processes described by this model have different significance for the metrologist. The first process occurs rapidly (in seconds) and is the most problematic from a CD metrology perspective since it occurs during a typical single measurement interval. The second process occurs at a rate that is not relevant for typical CD metrology in a production environment. It is of interest, however, because this process, as Kudo,et al.[4] demonstrated, has a similar half-life for all resist types, including 248 nm formulations. This leads one to assume that identical physical processes (e.g. solvent loss) could be responsible for the behavior observed in this region. The third process is very slow, and is not significant for CD metrology. It is worth re-emphasizing that the initial rapid line slimming is not observed for 248 nm resists and accounts for the relative stability of these systems with respect to electron beam irradiation

Figure 2 depicts the triple exponential model broken down into the three model components. As is readily observed from the figure, the second and third exponential components show little difference in slimming behavior comparing 500 eV to 175 eV. This is not the case for the first component where a factor of 3-5 difference in slimming magnitude is observed. The susceptibility of the ArF resist systems to electron beam exposure would be expected to correlate inversely with the etch resistance of these materials

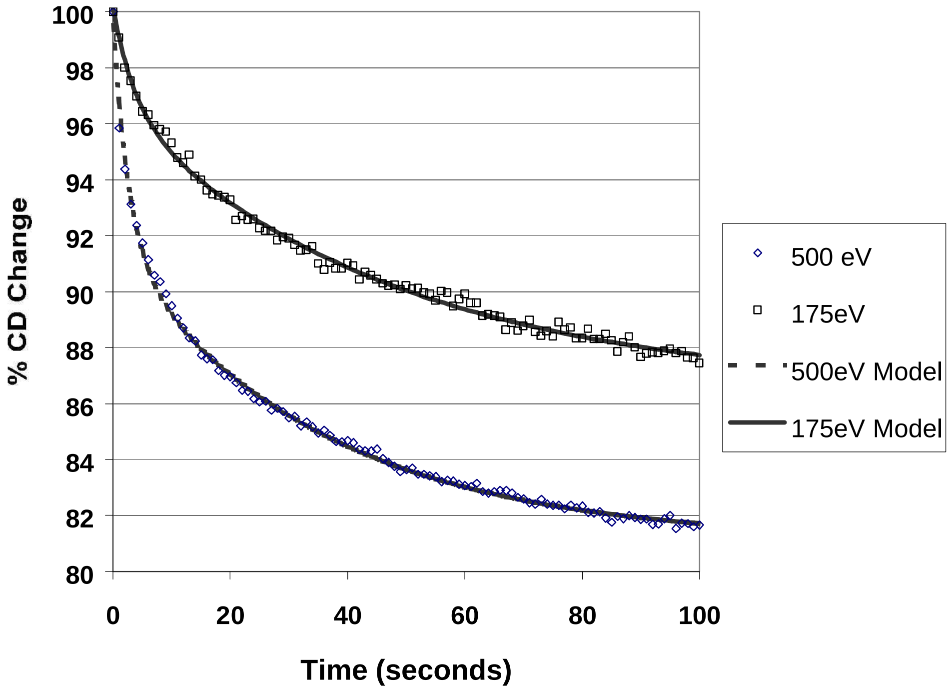


Figure 1: 193 nm resist line width slimming trend

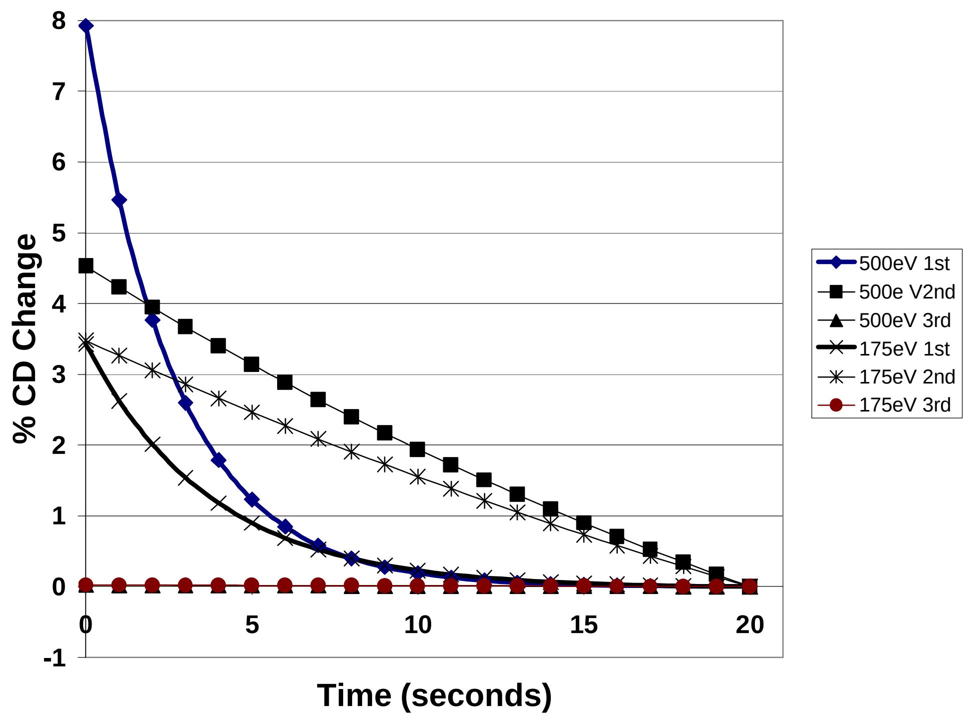


Figure 2: Analysis of the effects of the three components of the triple exponential model for CD measurements using 500 eV and 175 eV landing energies.

However, many studies conducted to improve the etch resistance of the ArF systems either through resist additives or post processing (thermal, flash DUV exposure, & etc.) have demonstrated little or no impact on the initial region[4] of rapid line slimming. Only electron beam cure has demonstrated improvement in line slimming behavior, by, effectively, pre-dosing the entire sample to bring it down into the third region of small and near constant slimming behavior.

Focussing on the initial region of line slimming, the model can be used to estimate the impact of a CD SEM measurement on the size of a feature relative to its initial (unmeasured) state. The change from the initial state due to the first measurement sequence represents the most rapid change during the entire observation as is evident from Figure 2 and the model itself. Thus, this represents the most problematic region for model prediction, since slight error in model parameter estimation can lead to extremely large extrapolated error. This paper will describe a method to experimentally determine this initial line slimming as a function of landing energies and will present the results.

In what follows, we describe the behavior of a Sumitomo† ArF 193 nm resist system during initial exposure to electron beam of varying energies. The purpose of analysis being to identify a landing energy for which measurement uncertainty due to line slimming is less than 1 nm. This was accomplished through the use of critical dimension atomic force microscope (CD-AFM) metrology, to determine the initial and final states of the sample.

Method

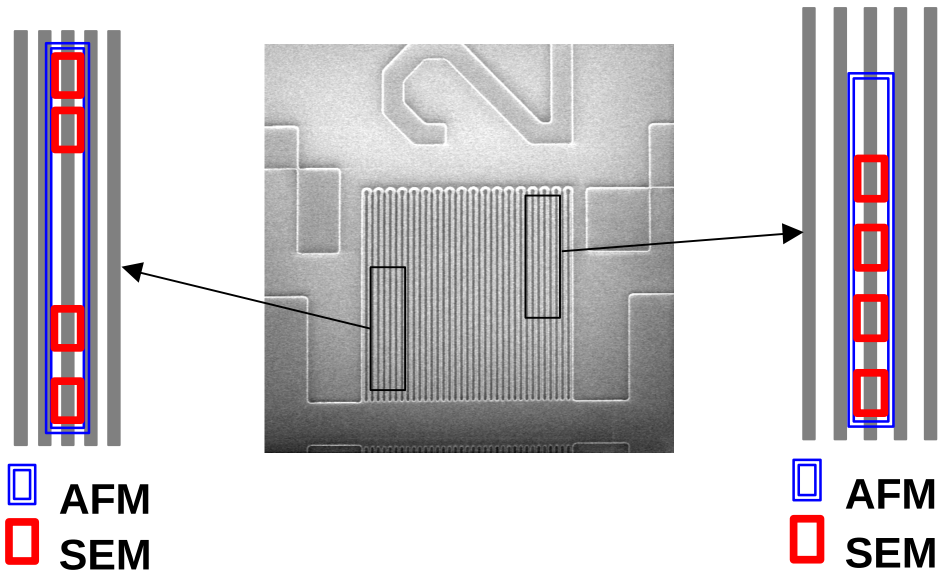
The experiment was designed to determine the impact of a single CD SEM measurement pass, at various accelerating voltages, by using an atomic force microscope (AFM) to characterize the sample prior to and immediately following the CD SEM measurements. The use of the CD AFM as a complimentary technique also minimizes contamination and avoids the effects of charging from the analysis of CD SEM induced resist line slimming.

For this test we used 260 nm of Sumitomo PAR810† 193 resist on bottom anti-reflective coating (BARC). The lithography process targeted a 90 nm nominal CD. All wafer processing was conducted at the ATDF line at International SEMATECH (ISMT). Measurements at ISMT were made using a Veeco SXM320. † The SXM320† differs significantly from a conventional AFM being based on technology that was developed by Martin and Wickramasinghe in the early 90's.[13] The most notable differences are that force sensing in the SXM320† occurs along two axes (one vertical and one lateral) and that the tool uses flared tips that allow imaging of vertical sidewalls. The tool can also be operated with conical tips in a one-dimensional mode that more closely resembles conventional AFM. However, even in this mode, the operation of the SXM320† differs from a conventional AFM in that it uses a heterodyne interferometer to detect changes in the cantilever vibration, whereas a conventional AFM uses an optical lever arrangement. In some circumstances, these different detection schemes could lead to differences in sensitivity and signal to noise.

CD SEM metrology was performed on the wafers with a Yosemite† CD SEM. This CD SEM has the ability to measure wafers at ultra-low landing energies such as the 95 eV and 175 eV settings used for these studies. The low landing energies are achieved by an electron optical design that includes high energy electron transport down the column and retarding fields above the wafer surface. The electron optics are optimized to maintain image resolution at these ultra-low landing energies, thereby enabling metrology from ultra-low to high landing energies, as may be required for sensitive materials such as 193 nm resist.

Two complete experimental runs were conducted. For the first run, the sampling plan did not adequately consider the requirements of the AFM. The second run sampling plan was designed to better accommodate the use of the AFM. The first experimental sample plan consisted of five fields measured at 4 sites each. The experimental sequence called for AFM pre-measurement, one pass SEM measurement on a fresh site at 95 eV, 175 eV, 300 eV and 500 eV at each die, followed by AFM post measurement. The measurements are depicted schematically in Figure 3. Care was taken to ensure that the measurement sites were not exposed to the electron beam at any time other than that required for acquisition of the measurement image.

As undesirable AFM tip-sample interactions were observed during the first experimental run, an attempt to minimize the effects of AFM tip contamination was undertaken with the second experimental design. This included reducing the total size of the AFM scan area, more frequent checks of tip width, and a different choice of feature for pattern recognition. In the first run, the intersection of the target lines with the cross-bar was used for navigation. Although this was suitable



First run AFM measurement Second run AFM measurement

Figure 3: Site measurement locations

for the SEM navigation, it was not an ideal choice for the AFM because it involves scanning over a feature with a significant topographic change along a lateral axis that does not have feedback. Consequently, the chance of tip contamination while scanning this feature is increased. Therefore, the line end was used for navigation in the second run experiment.

Results

The slimming behavior of the Sumitomo resist, tested over 5 repeated CD SEM measurements at both 100 eV and 500 eV landing energy, is shown in Figure 4. The SEM image acquisition conditions (probe current, number of frames summed, focus, pattern recognition, etc.) were held fixed so that only the effect of landing energy on line slimming could be observed.

The line slimming data for the 500 eV landing energy condition was extrapolated using the exponential model as well as polynomial, power and linear fit models, in order to estimate the initial CD. The extrapolated CD value has been proposed as a means to correct measured CD values in a manufacturing environment. Depending upon the model chosen, the predicted line slimming due to the first measurement varies from 0.9 nm to 3.3 nm.

Such extrapolations, using models with little or no physical basis, can result in significant errors in the estimated CD. Figure 5 shows representative Yosemite CD SEM[†] images taken at 1 um and 0.75 um Field of View (FOV). Figure 6 shows representative SXM CD AFM[†] linescans from both runs.

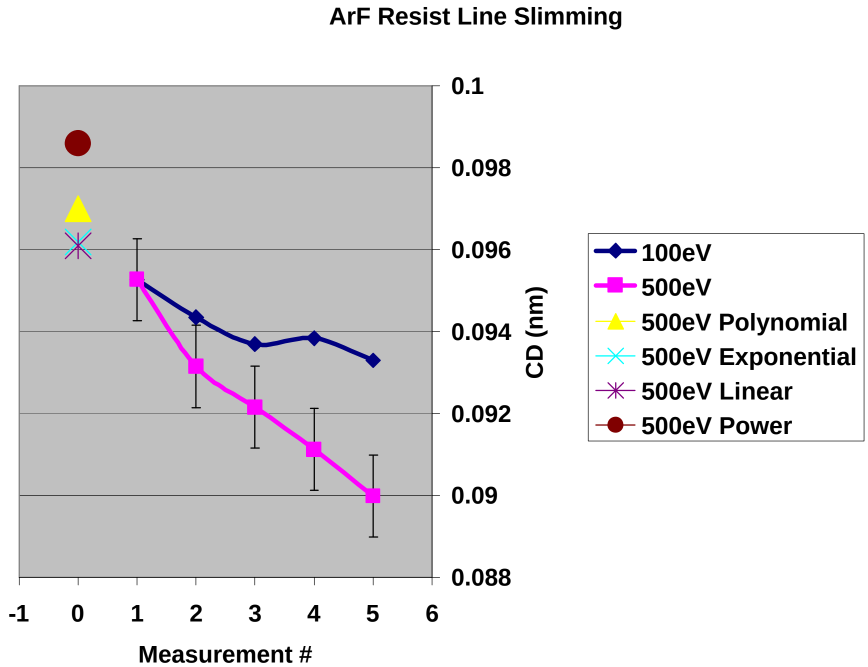
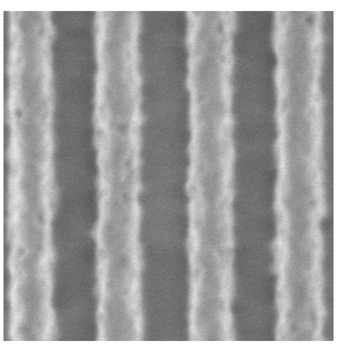
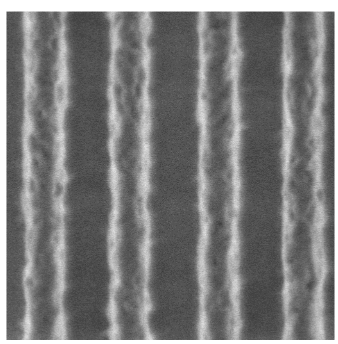


Figure 4: Comparison of line slimming at 100 eV and 500 eV landing energies


175eV, 1um FOV


500eV, 1um FOV

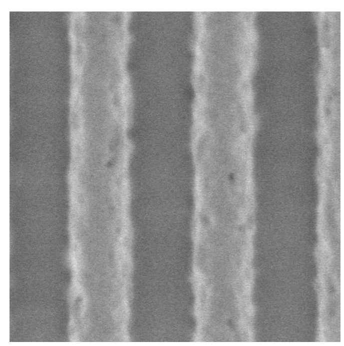
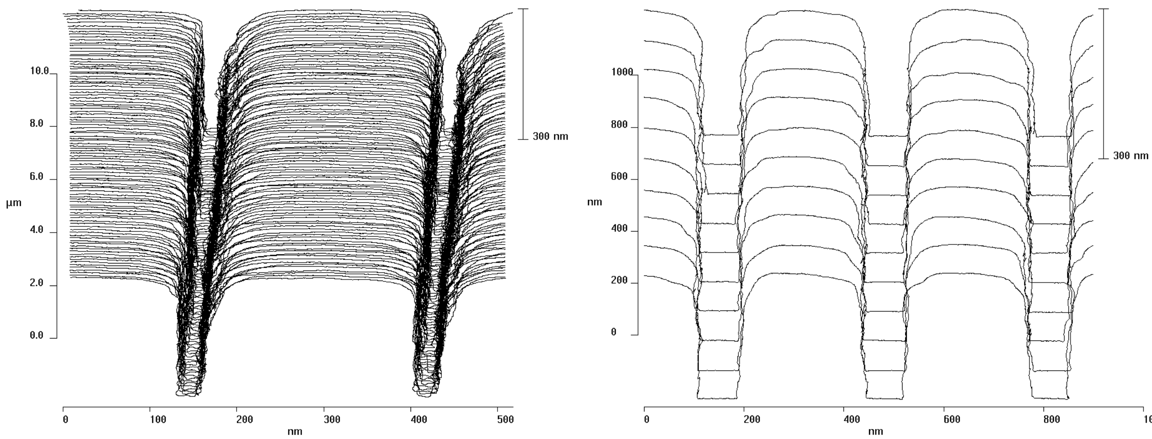

175eV, 0.75um FOV

Figure 5: Sample SEM images

As was discussed in an earlier description of the first run results[14], the correlation of the CD AFM results to the CD SEM results was good. For all of the data, taken at all landing energies and locations on the wafer following CD SEM measurement, the agreement of the AFM bottom CD data with the maximum gradient-based algorithm chosen on the CD SEM was within 5 nm. The agreement of the AFM 50 % threshold results was even better, at less than 1 nm. The data for the first AFM experimental run has been plotted against a simple model for line slimming[11] based on a Grün range estimate for the electron range in resist. This is shown in Figure 7. Excellent agreement between the measured resist response to the landing energy and the Grün range model is shown. The line slimming values for 95 eV and 175 eV are quite low and not distinguishable from the statistical uncertainty whereas the 300 eV is larger in magnitude and nearly significant. For the 500 eV case the line slimming is 4.9 nm in magnitude and statistically significant at 95 % confidence. The relatively high uncertainty observed in the AFM results is believed to be due to undesired tip-sample



First Pass AFM Data **Second Pass AFM Data**

Figure 6: Sample AFM scans. (Note difference in pitch between first and second pass)

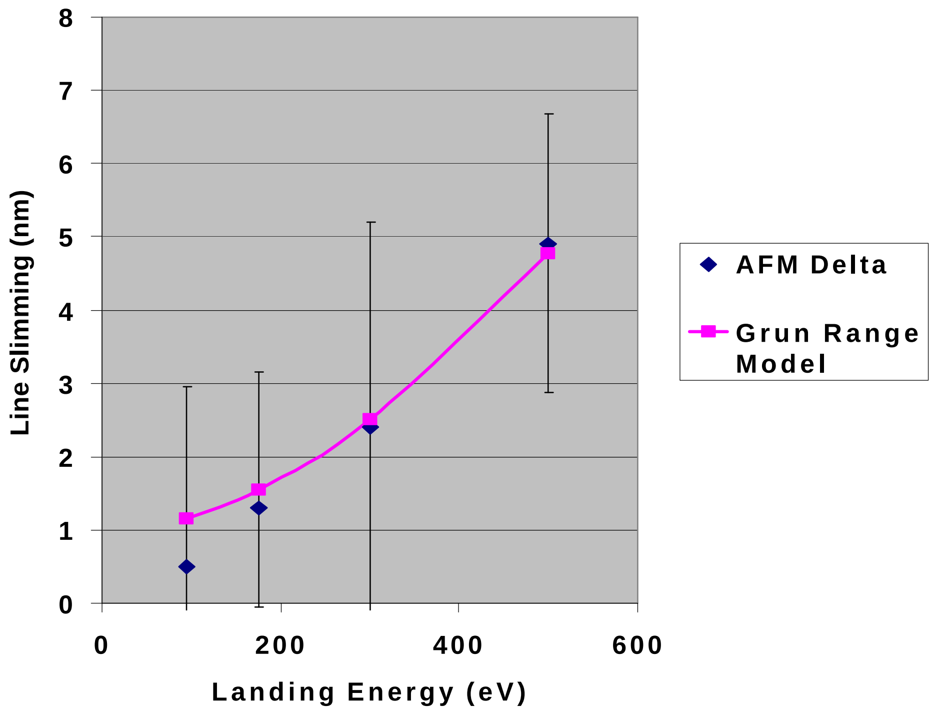


Figure 7. Run 1 CD AFM experimental results.

interaction. Detailed observations of the results showed an increase in AFM tip width through the course of the data collection. This is a strong indication that the tip was being contaminated, or accumulating material, during the data acquisition. After examining the experimental design and results of the first run, we concluded that the scanned area was too large, the features were too close for the tip size used, and the pattern recognition target was not well suited for AFM scanning. As a result, a new sample scheme was designed to address these issues. This is shown schematically in the right hand side of Figure 3.

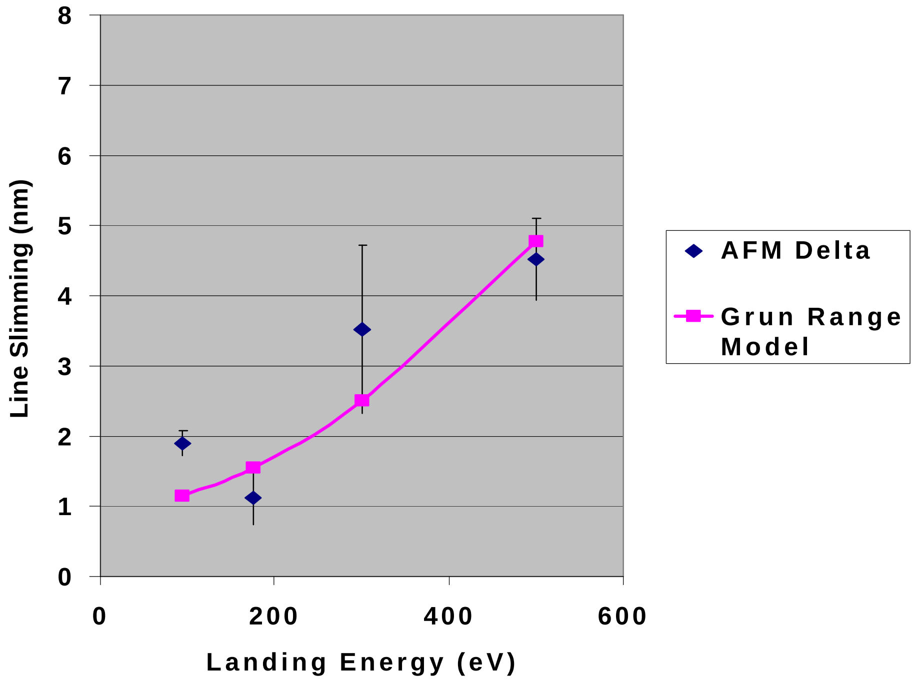


Figure 8: Run 2 CD AFM experimental results

When the initial AFM measurements for the second run were performed, the observations indicated that tip contamination problems were significantly reduced relative to the first experimental pass. However, tip contamination remained an issue during the post SEM AFM measurements. Consequently, the entire series of post-SEM AFM measurements was repeated, and two sets of results are available. The average of these runs are shown in Figure 8. Interestingly, the general trends are the same - even though tip contamination was still a problem. This suggests that the analysis methodology we used is effective at removing the effects of tip contamination on the results. Basically, the method consists of using an AFM "monitor" site which is measured before and after each target site. This provides an indication of the contamination and provides a measure of the relative tip width for each target site. This relative measure is correlated to a tip measurement conducted on a tip size calibration structure to ensure that the tip is changing and not the wafer monitor site.

The results from the second experimental run indicate basically the same trend and magnitude as the results of the first pass. However, there is still a considerable amount of variation or experimental "noise" on top of the observed trend. We believe that this is partly the result of the considerable LER of these structures. The high LER increases sensitivity to the relative positioning of the SEM and AFM measurement windows. We used windows that extended 1 µm along the length of the features, and believe that the relative placement of the windows was consistent to approximately the 50 nm level. However, due to the LER, this level of overlap may not be sufficient to achieve consistency in width measurements at the level of ~1 nm.

Analysis

The AFM results also demonstrated the significant benefit of low landing energy operation. The 95 eV and 175 eV cases showed a small magnitude of linewidth slimming approaching 1 nm at 175 eV. The 300 eV case demonstrated a greater magnitude of slimming, nearly 3 nm. The 500 eV case showed the largest degree of line slimming at nearly 5 nm. For advanced logic processes 5 nm consumes the entire process tolerance. Using this AFM data to describe the dependence of resist slimming on landing energy, as Habermas[11] has done for long term (many repeats) data, results in observed behavior which is much closer to the $V^{1.75}$ landing energy dependence predicted by the Grün range expression. This may suggest that the conceptual view of line slimming as arising from separate mechanisms (as depicted in the triple exponential model), has significant merit.

It seems clear from the foregoing experimental results as well as from work performed by other researchers,[8,9,10,11,12] that for the preponderance of 193 nm resist formulations, control over landing energy is essential to minimize the resist slimming effect. The results indicate that the linewidth slimming effect is dependent upon the landing energy, which is directly related to the penetration depth of the incident electrons. The dominance of landing energy as a determinant of line slimming as demonstrated in the aforementioned research suggests that the slimming is not thermally driven[15]. Line slimming, induced by a thermal process, would require a strong dependence on the electron current. This does not appear to be the case, rather line slimming is driven by the surface changes which result from the electron penetration depth.

Examination of the beam-sample interaction is required to further understand the mechanisms involved in linewidth slimming. To improve on the Grün range estimates Monte Carlo simulation, using Metrologia[†] software, was used to calculate the penetration depth of electrons for the landing energies used in the experiments. It was found that the electron interaction volume is contained to a region within 20 nm of the resist surface for 500 eV electrons and within 5 nm for 200 eV electrons. It will be assumed that all of the physical and chemical changes, which result in the observed line slimming, occur in this thin layer of resist. Reactions expected to result from the interaction of the electrons with the resist sample include: chain scission, photo-acid generator (PAG) decomposition and crosslinking[4]. Based upon an understanding of these chemical reactions, it is expected that the effects of the 193-nm resist samples' exposure to the electron beam should initially proceed rapidly. Thus, they are probably responsible for the linewidth slimming that occurs in the first region of the triple exponential decay model. It is these reactions that are of most importance to the metrologist since this is the timeframe during which inline metrology will take place. Kudo, et al.[4] discuss these reactions for the well-studied case of poly methyl methacrylate (PMMA) resist. For PMMA, continuous e-beam exposure results in chemical changes to the polymer that make it impervious to further mass loss. The 193 nm resists, which are susceptible to chain scission, lose mass and only slowly generate a chemically inert outer layer. In contrast, poly hydroxyl styrene (PHS)-based DUV resist crosslinks quickly and forms a stabilizing outer coat which may serve to protect the structure from further damage due to e-beam exposure. Kudo, et al. also report that the additives that were studied to improve resist slimming either reduce the depth of penetration of the electron beams or assist in the formation of the inert layer.

Discussion

This research has demonstrated that significant errors can arise from line slimming. These errors, and the resulting uncertainties directly affect 193 nm process control. CD test features experience the largest slimming during the initial measurement pass and subsequent measurements are not indicative of the true impact of line slimming on process control.

This work has shown that an effective method to reduce the error and uncertainty due to resist line slimming is to choose ultra low landing energies – at or below 200 eV. It has also been discussed that these 193 nm resist systems pose some added difficulty for accurate AFM measurements due to tip contamination. This is indicated by the tip monitoring data that were taken as well as the observed variation in the results. The CD-AFM results for repeated sites typically had a factor of three larger standard deviation than did the SEM results (with the line-slimming trend removed – refer to Figure 1 and Table 1).

The nature of the physical relationship between landing energy and line slimming has been qualitatively addressed during this work. Plausibility arguments relating e-beam penetration depth and magnitude of line slimming have been put forward. Results obtained from the CD AFM experiments indicate that a better agreement[11] with the predicted Grün range ($V^{1.75}$) may be obtained using the initial measurement line slimming. If this is the case, then perhaps there is a change of density in the outer 20 nm of the resist structure due to the e-beam interaction. This assumption will be tested in future experimental work.

To quote from Kudo, et al.[4] "In summary, the investigated changes in the resist formulation were only partly successful in reducing LWS [Line Width Slimming], or, in the case of a low-boiling solvent, are impractical for manufacturing use. The differences between the polymer backbones available for 193 nm lithography are also insufficient to lead to substantial improvements. A solution to the LWS problem must therefore come through a modification of the CD SEM measurement hardware and/or software." The only available, long term solution for the 193 nm resist line slimming issues is to be found within the operation of the CD SEM. As has been shown in this work, decreasing landing energy to values below 200 eV, can significantly reduce the effect of line slimming to levels which are below the level of statistical significance required for advanced process control.

Acknowledgements

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[†]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.

Footnotes:

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