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Critical dimension sensitivity to post-exposure bake temperature variation in EUV photoresists

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ABSTRACT

Chemically amplified resists depend upon the post-exposure bake (PEB) process to drive the deprotection reactions (in positive resists) that lead to proper resist development. For this reason they often exhibit critical dimension (CD) sensitivity to PEB temperature variation. In this work the effects of variation in different aspects of the PEB step on post-develop CD are studied for two extreme ultraviolet (EUV) photoresists. The spatial and temporal temperature uniformity of the PEB plate is measured using a wireless sensor wafer. Programmed variations in the bake plate temperature set point are then used to measure the CD sensitivity to steady state temperature variation. In addition, the initial temperature ramp time is modified using a thin sheet of polyimide film between the wafer and the bake plate. This allows for measurement of the CD sensitivity to transient temperature variation. Finally, the bake time is adjusted to measure the CD sensitivity to this parameter.

Keywords: Extreme ultraviolet (EUV) lithography, micro-exposure tool (MET) optic, synchrotron, photoresist, post-exposure bake (PEB)

1. INTRODUCTION

Although great progress has been made in extreme ultraviolet (EUV) lithography development over the past few years, significant challenges remain. One such challenge is the development of suitable photoresists. The relatively low power available from EUV sources combined with the loss of roughly 30% per optical element due to absorption means that the power seen at the wafer is small. Therefore, techniques such as chemical amplification are necessary in order to make photoresists sensitive enough to achieve wafer throughput goals for manufacturing. In most chemically amplified resists, the chemical amplification process is driven by a post-exposure bake (PEB) step. Therefore, the post-develop resist pattern may be highly sensitive to PEB parameters. In order to meet the critical dimension (CD) control requirements of the 32-nm technology node, the International Technology Roadmap for Semiconductors (ITRS)[1] mandates a CD sensitivity to PEB temperature variations of 1 nm/°C, well below the current state-of-the-art for deep ultraviolet (DUV) resists. Additional challenges are sure to emerge from the (as yet unmeasured and unspecified) photoresist sensitivity to the transient aspects of the PEB step, although recent experiments have shown that post-develop CD is particularly sensitive to this component of the PEB process.[2]

In this work we present the results of experiments performed using the static Microfield Exposure Tool (MET) printing system at the Advanced Light Source at Lawrence Berkeley National Laboratory.[3-5] This system uses synchrotron radiation at a wavelength of 13.5 nm and the optic has a numerical aperture (NA) of 0.3 and a field size of 600 μm × 200 μm at the wafer. Wireless sensor wafers[6] were used to characterize the across-wafer temperature variation of the PEB plate used for wafer processing. Measurements of CD sensitivity to steady state PEB temperature variation are presented in Section 2, while sensitivity to transient temperature variation is discussed in Section 3. The sensitivity to PEB duration is addressed in Section 4. Finally, conclusions are presented in Section 5.

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2. STEADY STATE TEMPERATURE SENSITIVITY

In order to observe the effect of steady-state temperature variation on resist CD, the target temperature of the PEB bake plate was changed in small increments, and the resulting effect on CD was observed. Rohm and Haas EUV-2D resist was used, with a nominal PEB temperature of 130°C and temperature increments of 2°C on either side of the nominal.

The temperature uniformity of the bake plate was measured using a wireless temperature sensor wafer for each temperature set-point, and the results are shown in Figure 1, Figure 2, and Figure 3 after the wafer had reached its ``steady-state" temperature near the end of the bake cycle. Clearly, the poor temperature uniformity of this bake plate would be unacceptable for use in a production environment. However, in this case the exposed area of the wafer is only approximately 1 cm^2, meaning that good temperature uniformity is not required across the entire 4" wafer.

Examination of the temperature uniformity data shows a similar signature for all three cases: a relatively uniform area near the center of the bake plate, then a rapid drop-off in temperature towards the edges. Therefore, care was taken in all PEB experiments to ensure that the exposed area of the wafer was placed at the center of the bake plate. In addition, the temperature data from the sensor in the center of the sensor wafer was used as the effective PEB temperature for data analysis. The temperature trajectory for the center sensor is shown for all three steady-state temperature settings in Figure 4. Note that the sensor wafer was set to begin data acquisition on a certain temperature change, and therefore some of the initial temperature ramp-up was not captured by this measurement. However, as the goal of this experiment is to determine the effect of steady-state PEB temperature on CD, this was not deemed important.

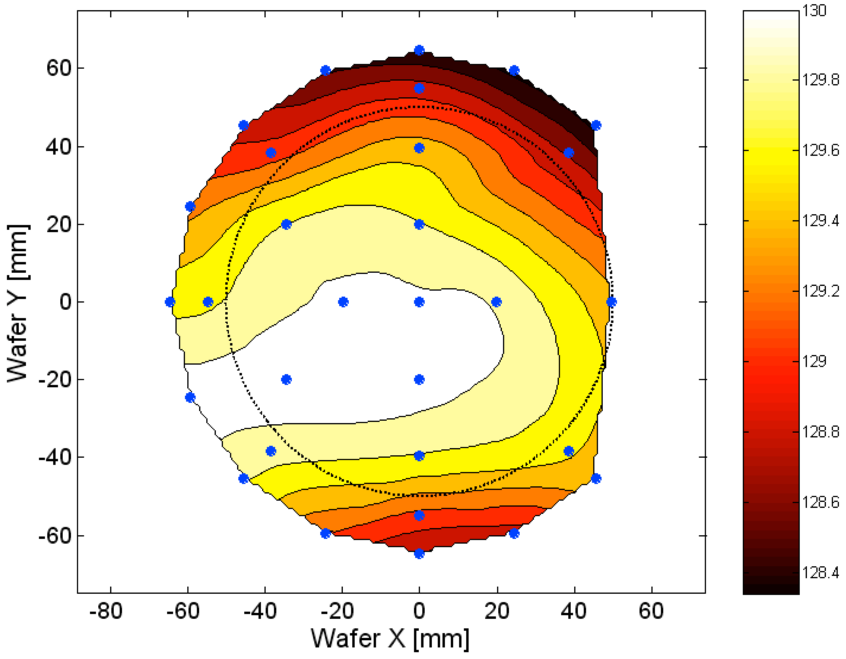

Figure 1. PEB temperature uniformity measured using wireless temperature sensor wafer with bake plate center targeted for the baseline temperature of 130°C. The dotted outline represents the diameter of a 4" wafer, while the points show the temperature sensor locations.

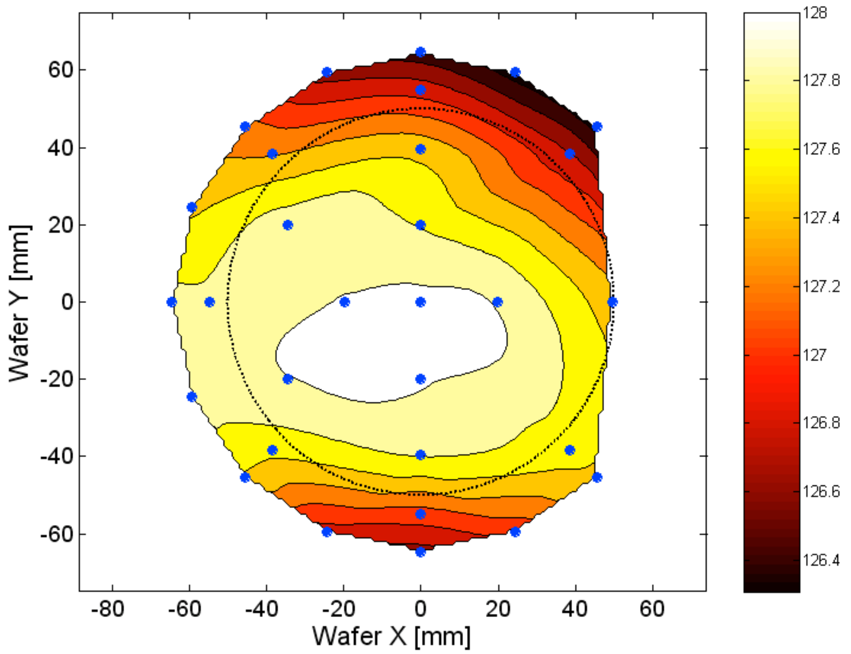

Figure 2. PEB temperature uniformity measured using wireless temperature sensor wafer with bake plate center targeted for 128°C. The dotted outline represents the diameter of a 4" wafer, while the points show the temperature sensor locations.

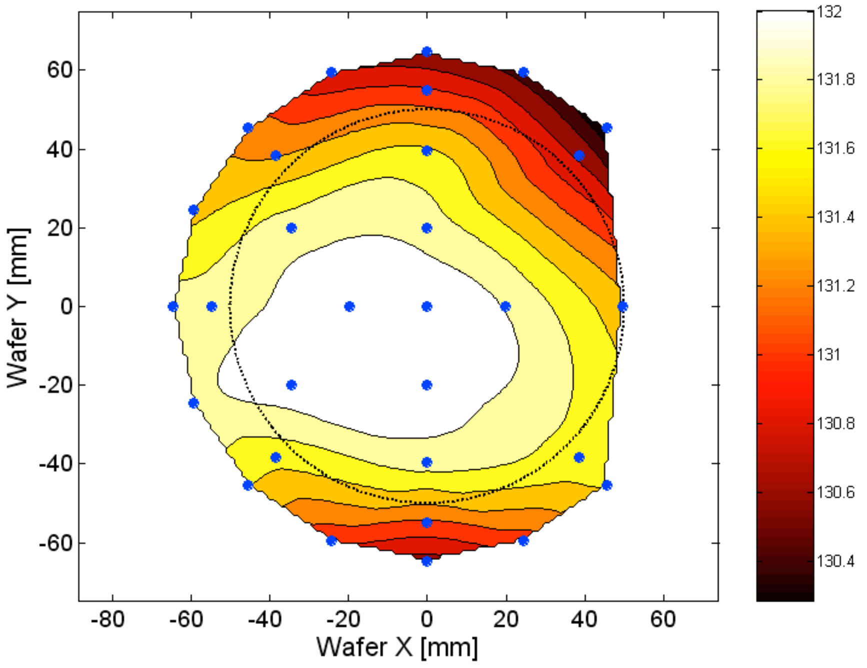

Figure 3. PEB temperature uniformity measured using wireless temperature sensor wafer with bake plate center targeted for 132°C. The dotted outline represents the diameter of a 4" wafer, while the points show the temperature sensor locations.

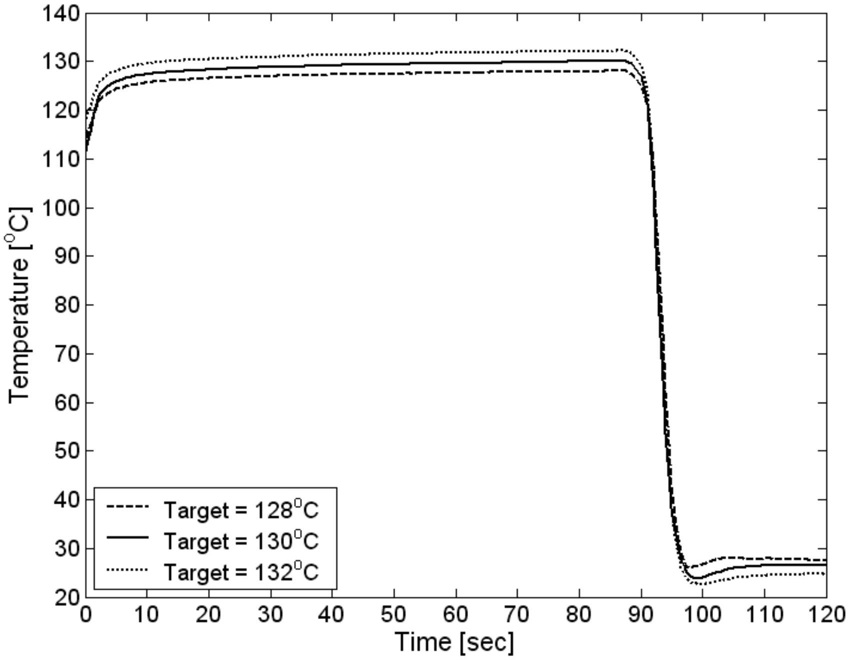

Figure 4. PEB temperature trajectories for steady-state CD sensitivity experiment measured using temperature sensor wafer.

In order to measure the effect of the steady-state PEB temperature on critical dimension, focus-exposure matrix (FEM) wafers were exposed and baked at each of the different temperatures. Rohm and Haas EUV-2D resist was used with a post-application bake temperature of 130°C. The wafers were exposed using a dark field resolution pattern. The post-exposure bake step was performed immediately after exposure to minimize any environmental contamination effects. Each FEM took approximately 45 minutes to expose, which is long compared to the exposure time for a single field (less than one second). However, because the wafer was under vacuum it is expected that contamination effects are unlikely. In addition, at the exposure temperature (20°C) little acid diffusion is expected and acid evaporation should be negligible.

The temperature data discussed previously was collected immediately before the PEB of the corresponding wafers in order to minimize the effect any potential temperature drift between the time of measurement and the actual PEB. Each row in the FEM was replicated three times, meaning that each focus-exposure combination had three instances on the wafer. The dose-to-size (E_{size}) for the relevant feature sizes was then determined for the baseline PEB temperature (130°C), and CD data collected for each replication at E_{size} and best focus. Next wafers were exposed at 128°C and 132°C using the same FEM recipe as the baseline wafer. In each case the CD was measured at the dose corresponding to E_{size} of the baseline wafer and best focus for each replication.

The CD data for 100 nm and 60 nm features is shown in Figure 5 and Figure 6, respectively. In each case, a line is fit to the data using linear regression. The slope of the line gives a measure of the CD sensitivity to PEB temperature variation. In this case, the CD sensitivity is -1.46 nm/°C for 100 nm features and -1.82 nm/°C for 60 nm features. The CD variation seen within each temperature group is most likely due to random dose variation within the FEM. This is particularly problematic for smaller features, as they are more sensitive to dose variation. We note that independent measurements have demonstrated the exposure-to-exposure random dose variation to be approximately 1.5%, which is consistent with the scatter observed here.

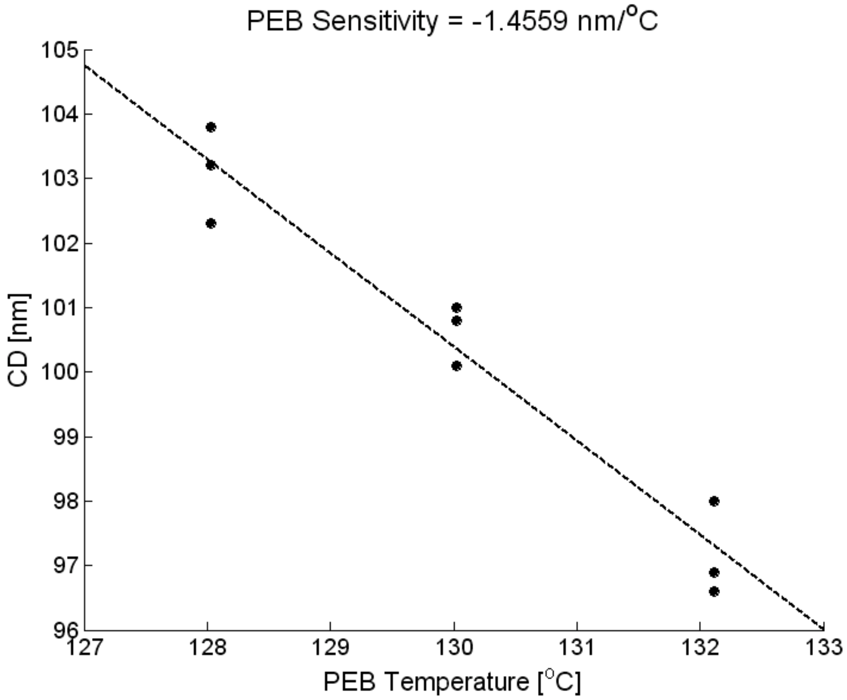

Figure 5. CD sensitivity to steady-state PEB temperature for 100 nm features.

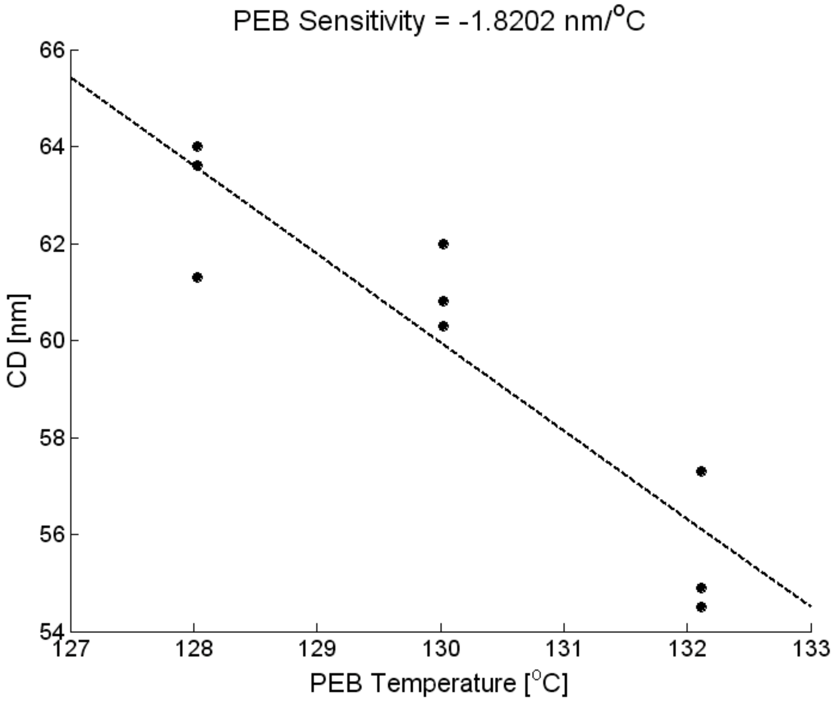

Figure 6. CD sensitivity to steady-state PEB temperature for 60 nm features.

An effort was also made to measure the steady state temperature sensitivity of another EUV photoresist, Rohm and Haas MET-1K (XP 3454C). This resist has higher resolution and lower sensitivity when compared with EUV-2D. The same experimental procedure described above was followed, however, no clear trend was observed in the CD vs. PEB temperature data. The experiment was then repeated with a wider temperature range (varying PEB temperature by ±5°C about the nominal) with a similar outcome, *i.e.*, no trend was seen in the data. Given the relatively low temperature sensitivity seen in EUV-2D (less than 2 nm/°C) and the fact that MET-1K is roughly three times slower than EUV-2D in terms of sensitivity, it seems reasonable to assume that the steady state PEB temperature sensitivity for MET-1K could be lower than that of EUV-2D. Therefore, one explanation for the experimental results for MET-1K may simply be that the temperature sensitivity for this resist is low enough that the CD variation observed is dominated by other effects in the system, most probably the random dose variation discussed above.

3. TRANSIENT TEMPERATURE SENSITIVITY

Modifying the temperature trajectory in the transient phase is more difficult than the steady-state. This is accomplished by inserting a thin sheet of Kapton polyimide film (0.005" thick) between the wafer and the bake plate. This has the effect of slowing the temperature ``ramp-up" at the beginning of the PEB step. The measured effect on the Kapton film on the initial temperature transient is shown in Figure 7. The ramp time (from 24°C to 110°C) without the Kapton film was 3.1 seconds, while the ramp time with the Kapton film was 30.5 seconds.

In order to determine the effect of the change in temperature ramp-up time on CD, wafers were coated with a 125 nm layer of Rohm and Haas MET-1K (XP 3454C) photoresist. The wafers were exposed using a dark field resolution pattern, and the post-exposure bake step was performed immediately after. Post-application bake temperature was 120°C, and the nominal post-exposure bake temperature was 120°C. However, with the Kapton film in place the temperature sensor wafer recorded a temperature of only 118°C at the end of the PEB cycle, so the bake plate set point was adjusted between wafers to achieve a steady-state temperature of 118°C without the Kapton film for the control wafer.

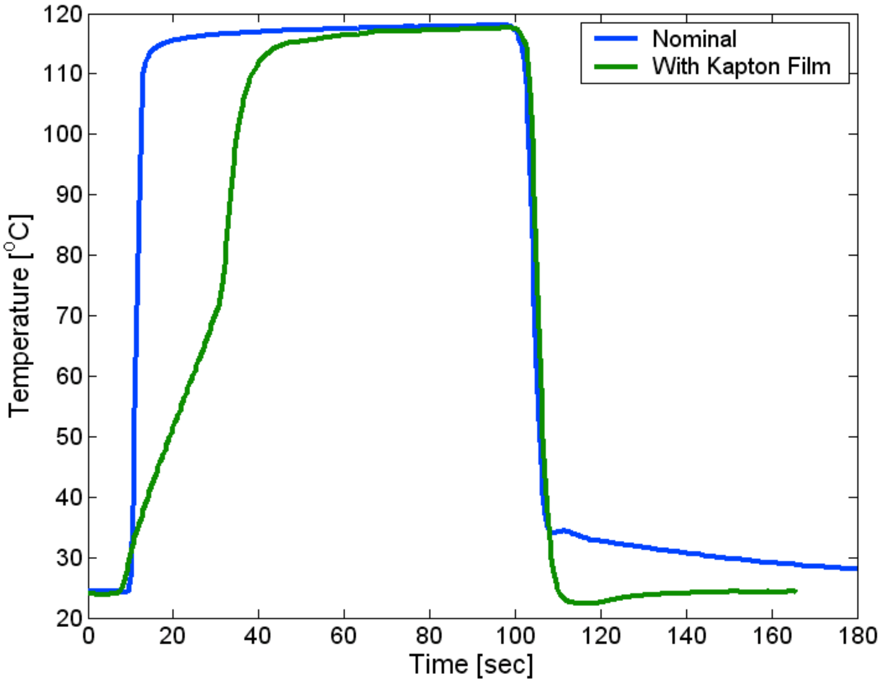

Figure 7. Post exposure bake temperature trajectories with and without 0.005" Kapton polyimide film between the wafer and the bake plate as measured with a commercial wireless temperature sensor wafer.

The CD was then measured for three different feature sizes (50 nm, 60 nm, and 100 nm, equal lines and spaces) in the center of the field using a SEM and the SuMMIT software package[7] with default parameters. The results are shown in Figure 8 and Table 1.

4. PEB TIME SENSITIVITY

Variations in the duration of the PEB step can also affect the resulting critical dimension by changing the amount of time in which the chemical reactions responsible for changing the solubility of the exposed resist can occur. In order to characterize this effect for a sample EUV photoresist, an experiment was performed in which the PEB time was varied and the resulting CD measured.

The experimental setup was very similar to that described in Section 3. Wafers were coated with a 125 nm layer of Rohm and Haas MET-1K (XP 3454C) photoresist and exposed using the same dark field resolution pattern. The post-exposure bake step was performed immediately after exposure. Post-application bake and post-exposure bake temperatures were both 120°C. One wafer was baked for the nominal PEB time of 90 seconds, while a second wafer was baked for 100 seconds. The CD was then measured for three different feature sizes (50 nm, 60 nm, and 100 nm, equal lines and spaces) in the center of the field using a SEM and the SuMMIT software package with default parameters. The results are shown in Table 2.

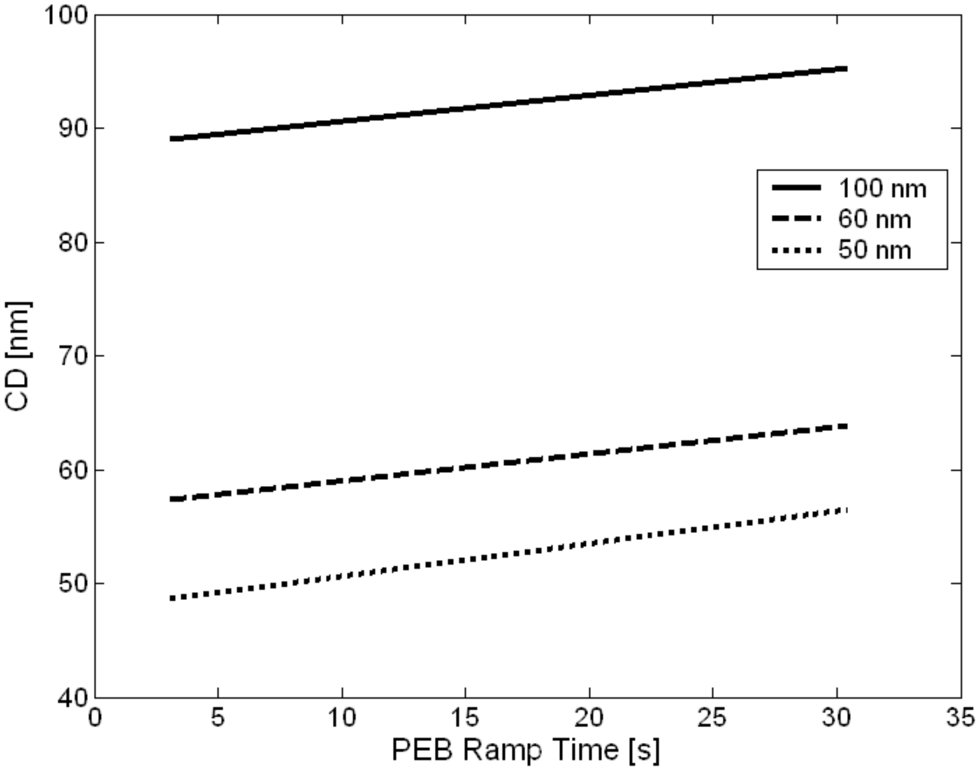

Figure 8. CD sensitivity to PEB temperature ramp time for Rohm and Haas MET-1K resist.

Table 1. Effect of PEB temperature ramp time on CD for Rohm and Haas MET-1K (XP 3454C).

Nominal CD	CD (no Kapton)	CD (with Kapton)	CD Ramp Time Sensitivity
50 nm	48.6 nm	56.5 nm	0.29 nm/sec
60 nm	57.4 nm	63.9 nm	0.24 nm/sec
100 nm	89.0 nm	95.3 nm	0.23 nm/sec

Table 2. Effect of PEB time on CD for Rohm and Haas MET-1K (XP 3454C).

Nominal CD	CD (PEB = 90s)	CD (PEB = 100s)	PEB Time Sensitivity
50 nm	52.6 nm	48.4 nm	0.42 nm/sec
60 nm	61.1 nm	56.9 nm	0.42 nm/sec
100 nm	90.5 nm	87.6 nm	0.29 nm/sec

5. CONCLUSIONS

The effect of variation in key PEB parameters on post-develop CD was studied for EUV photoresists. The effect of steady-state PEB temperature was measured for Rohm and Haas EUV-2D and found to be less than 2 nm/°C. In addition, the effect of initial temperature ramp time was measured for Rohm and Haas MET-1K and found to be on the order of 0.3 nm/sec ramp time. Finally, the effect of PEB time variation on CD was measured to be around 0.4 nm/sec for MET-1K. While the requirements for sensitivity to steady state PEB temperature variation are specified in publications such as the ITRS (1 nm/°C for the 32-nm node), it seems that more attention should be given to either specifying tight limitations on PEB temperature ramp time or on methods for mitigating sensitivity to variation in this parameter. The results presented here may serve as a basis for comparison in the future development of EUV photoresists.

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