

Investigation on the Mechanism of the 193nm Resist Linewidth Reduction During the SEM Measurement

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ABSTRACT

Linewidth reduction (or line slimming) of resist features has been previously observed during routine scanning electron microscopy (SEM)⁽¹⁾. The impact of the linewidth reduction may result in measurement precision and accuracy errors and potential device reliability issues due to permanent feature deformation. The magnitude and the origin of these effects for various resist platforms are not well understood. In this study the measurement of the extent of slimming is performed on two 193nm single layer resist (SLR) platforms, including an acrylate based SLR and a polynorborene (poly-CO) based SLR. The maximum shrinkage is found to be approximately 15% and varies as a function of resist composition and electron beam landing energy and flux. Mechanisms for the resist shrinkage that impact both the physical (e.g., annealing or solvent loss) and chemical (e.g., bond scission, cross-linking, fragmentation, or deprotection) properties are evaluated. Potential methods for reducing the slimming effect are proposed in this paper.

Keywords: 193nm resist, line slimming, SEM, AFM, mechanism

1. INTRODUCTION

Variation of the resist line width during the SEM measurements has always posted a challenge to the lithography process control. Particularly the abrupt changes of the resist CD will create problems in, for example, measurement matching among different CD-SEMs. Even in the same given tool, the SEM induced CD variation will compromise the precision and accuracy of the measurements.

Several recent reports have drawn attention to a line slimming phenomenon associated with CD-SEM measurements of some 193nm photoresist systems. Among these studies it was demonstrated that the extent of line slimming depends not only on the choice of resist platforms, but also on the measurement conditions of the CD-SEM. For example, it was reported that the acrylate type of resists generally show more pronounced line slimming effect than the norborene- maleic anhydride (CO-MA) resists.^(2,3) It was also shown that, the line slimming can be reduced by reducing the landing voltage of e-beam, or its flux density during the CD-SEM measurement.⁽²⁻⁴⁾

In this study we first describe the occurrence of the 193nm resist line slimming in CD-SEM. Factors that affect the extent of slimming will be briefly discussed to connect with the prior literature. The main goal of this paper is to investigate the mechanism of the line slimming. A methodology that includes experimental designs to test several hypotheses will be reported. One key challenge in the study of the line slimming mechanism is the direct observation on the resist features that exposed to the e-beam from the CD-SEM measurement. The small field of view makes it extremely difficult to cleave wafers at the e-beam exposed area for the cross-section SEM analyses, which leaves the top down SEM the most available method for collecting information. Initial attempts to irradiate wafers in the e-beam flood exposure tools to simulate the CD-SEM environment also leads to totally different observations in the resist line width trend,⁽²⁾ suggesting different dominating mechanism in these tool conditions. In this study we will use Atomic Force Microscope (AFM) to directly probe the profiles of those resist features previously exposed to e-beam from CD-SEM measurements. Changes in the profiles of the SEM exposed resist as well as substrate (ARC) can be compared directly with the neighboring un-exposed region. We will also investigate two resist platforms, including an acrylate based SLR and a poly-CO based SLR, and report their linewidth stability in both CD-SEM and the e-beam curing tool. These two resist systems are evaluated under

different CD-SEM tool types and conditions as well. Finally, after the mechanism of the slimming being proposed, we will conclude this study with some recommendations to improve the resist line width stability.

2. EXPERIMENTAL

Both resists were exposed under the suppliers' recommended process conditions on a 193nm organic ARC. The exposure was done on a 193nm scanner. The CD measurements were performed on two types of CD-SEM tools, referred as SEM A and SEM B. In this study, we used SEM A to acquire resist line images for linewidth analyses, while in SEM B the linewidth was measured by analyzing the waveforms acquired through direct e-beam writing over resist features. The detailed SEM measured settings will be described later in the results section. The e-beam curing of the resist was performed on the ElectronCureTM-200M manufactured by Electron Vision Group. For the AFM study, the IBM SXM300 AFM in CD mode was used.

3. RESULTS AND DISCUSSION

3.1 Initial observation of acrylate resist line slimming

In order to study the causes and dependencies of the resist line slimming, we put the resist samples through extensive e-beam exposure in the CD-SEM environment. Figure 1 shows the top down linewidth stability of the acrylate resist as a function of e-beam scanning time and landing voltage in SEM A. The SEM probe current was set at 2pA, and the resist feature (in this case, a semi-dense line at 360nm pitch) was under constant exposure of the e-beam flux at a 1.4 X 1.4 μm^2 field of view. Under this measurement condition, at the end of 5 minutes scanning period, the extent of line slimming was found to be 10%, 11%, and 12% at 300V, 500V, and 800V of e-beam, respectively. This landing voltage dependence is in good agreement with prior literatures on various resist platform and CD-SEM combinations.⁽²⁻⁴⁾

The effect of resist pattern density on the line slimming is demonstrated in Figure 2. Here the normalized linewidth of the acrylate resist was recorded through a 10 minutes continuous CD-SEM measurement as a function of resist pattern density. The SEM condition was the same setting as in Figure 1, with 800V landing voltage. While both the iso line and 1:2 L/S features showed 11% of slimming at the end of scan, slimming for dense line feature was significantly higher at 15%. This acrylate resist has vertical profile throughout the measurement features. Therefore, as reported by Pain et. al.,⁽³⁾ the observed proximity effect can be ascribed to the reflected e-beam experienced among the dense line features.

3.2 Possible mechanisms of line slimming

Before planning the investigation of slimming mechanisms, we had reviewed several possibilities that the resist may experience in the CD-SEM environment. The observation of the line slimming may be due to changes in resist physical properties from the e-beam induced local heating, e.g., solvent loss or annealing, that result in the reduction of the resist free volume. The impact of the SEM e-beam may also induce changes of the resist chemical properties, such as deprotection, bond scission, followed by fragmentation or cross-linking of the polymer platform, resulting in mass loss or shrinkage of the resist matrix.

3.3 Effect of soft bake temperature and acid catalyzed deprotection on line slimming

To test these above hypotheses, we prepared three acrylate resist wafers. Wafer A was prepared under the standard procedure, with both soft bake (SB) and post exposure bake (PEB) running at 130°C and 60 seconds. Wafer B had identical process condition as wafer A except that the SB condition was changed to 200°C and 90 seconds to anneal and dry out solvent from the resist film prior to the exposure. For wafer C, after patterning with procedures as in wafer A, we applied flood exposure (at three times of E_0) and PEB on the wafer to deprotect the imaged resist patterns. The result of linewidth stability of these wafers in CD-SEM is shown in Figure 3, where the SEM measurement conditions were the same as in Figure 2. In all three wafers we measured the same isolated line features with common process conditions (exposure and focus). The nominal linewidth at the beginning of the measurement was around 190nm, in the plot we normalize the initial

CD and report the percentage of slimming. It was readily noted that both wafers A and B follow very similar trend of line slimming to around 10% at the end of scan period, an indication that no significant role of either solvent loss or annealing in the slimming mechanisms. If the e-beam induced deprotection was the primary mechanism of the slimming in CD-SEM, we would have seen reduced and stable linewidth in a pre-deprotected resist feature (as in wafer C) through CD-SEM measurements. However, Figure 3 shows otherwise. In fact, substantial slimming was observed in wafer C with nearly 4% more at the end of scanning than in wafer A. This observation suggested that the deprotection of the resist platform is not a major mechanism for line slimming either. For wafer C, the initial acid catalyzed deprotection may have resulted in the admantyl leaving groups trapped in the resist matrix,⁽⁵⁾ hence in the early SEM scanning the trend behaves similarly to wafer A. The subsequent e-beam exposure in CD-SEM then triggered either the reduction of free volume created by the leaving groups, or the mass loss of the trapped leaving groups, hence results in more pronounced slimming than the baseline wafer A.

3.4 Effect of e-beam curing on the acrylate resist SEM stability

With e-beam induced bond scission and its subsequent fragmentation or cross-linking in the resist platform as the only untested hypotheses so far, we moved on to the e-beam curing tool trying to simulate the conditions that resists experienced in the CD-SEM environments. The e-beam flood exposure used in this experiment was carried out on the ElectronCure™-200M, with operation setting at 25kV and 3mA. A set of acrylate resist wafers was prepared under the same exposure condition. One wafer was reserved for baseline comparison, and the others went through e-beam flood exposure with dose varying from 100uC, 1000uC, to 2000uC. We then measured the common isolated lines, at the best focus condition, of these wafers in CD-SEM. Figure 4 shows the trends of the acrylate resist line slimming as a function of e-beam flux dosage. Both wafers with 100uC and 1000uC flood exposure showed more pronounced slimming than the reference wafer. For the wafer treated with 2000uC e-beam flux, a 3.5% of CD reduction was initially observed but the linewidth remained more stable than the reference wafer throughout the CD-SEM measurement. IR spectra of the blanket acrylate wafers showed that the carbonyl peaks from both acrylate and lactone groups diminished with the increasing e-beam flood exposure dose, and those peaks vanished in the wafer with 2000uC treatment. Same observation was reported earlier by Neisser et. al. in a COMA/acrylate based resist system.⁽²⁾ These IR results, along with the fact that the linewidth of the extensively e-beam cured resist remains more stable in the CD-SEM environment suggests that the initial bond scission at the carbonyl group moiety was what first occurred to the resist matrix during the SEM measurements. The decarbonylation itself represents mass loss of the polymer platform that might account for at least part of the slimming. Cross-section SEM of the resist features before and after 2000uC e-beam flood exposure also indicated slight film thickness loss (around 5%) that associated with the line slimming, as shown in Figure 5a and 5b. What remains to be answered at this stage is the fate of reactive species (radicals) resulting from the initial bond scission at the carbonyl groups. Do they undergo further fragmentation or cross-linking? In the case of e-beam flood exposure, Figure 5c shows that the resist pattern reflows after being treated with 2000uC of e-beam followed by a 130°C- 60 seconds post e-beam bake process. This ruled out the possibility of cross-linking for this acrylate resist system during the e-beam curing process. The extent of the glass transition temperature (Tg) reduction, from above 180°C to below 130°C, may also indicate a polymer main chain scission process during the e-beam flood exposure, a close resemblance to the PMMA e-beam resist system.⁽³⁾

The difference in line slimming of this acrylate resist between the CD-SEM and the e-beam curing system may be ascribed to the local heating in the SEM environments. We believe that the initial chain scission occurred upon e-beam bombardment in both systems. However, the subsequent local heating in the CD-SEM, due to high e-beam flux density, would either stimulate more radical initiated fragmentation, or induce the shrinkage of the free volume within the resist matrix.

3.5 Effect of resist system on line slimming

The poly-CO resist was then introduced for comparison. Figure 6 shows the CD trend of the isolated lines in two resist platforms- acrylate and poly-CO, observed by SEM A. The measurement condition was 800V, 2pA, 1.4x 1.4 um² FOV, under continuous scan mode. The data shows the linewidth of poly-CO resist dropped non-linearly by 7.5% in 5 minutes. Larger drops were observed for the acrylate resists at 11%.

3.6 Measurement tool dependence

The linewidth stability was also studied in SEM B, using the direct beam writing mode. Figure 7 shows SEM B measurements of these two resist systems at two landing voltage settings, 500V and 1000V. The probe current was 10pA and the FOV was at $1 \times 1 \text{ } \mu\text{m}^2$. Under our experimental setting, the total e-beam flux experienced by the resist features during each measurement scan in SEM B was equivalent to two seconds of continuous scan in SEM A. The measured resist features are isolated lines with nominal CD around 140nm. The acrylate resist, under 1000V, shows more moderate slimming that leveled off at around 3.5%, while the poly-CO resist shows less than 1% of slimming. Lower the landing voltage of e-beam also reduced the extent of slimming substantially. In fact, under 500V the acrylate resist linewidth started to increase after five measurements and the poly-CO resist CD was growing almost from the beginning! The scale and the trend of the linewidth variation, either reduction or growth, in this SEM B study are very similar to those reported in certain 248nm resist systems.^(1,6) In those studies, contribution from resist charging and carbonization were proposed to be comparable, if not larger, to the resist mass loss during the SEM measurements. The CD trend can therefore be adjusted by carefully controlling the measurement environments.

As mentioned earlier, we used SEM A to acquire resist line images for linewidth analyses. Under the SEM A experimental setting, the CD measurements were performed with the resist features under constant e-beam exposure. The SEM B setting, with the direct beam writing mode, allowed the e-beam to quickly scan across resist and turning off between measurements. We could therefore expect a more moderate local heating for the resist features measured in SEM B. Nevertheless, in either environment the poly-CO resist showed less tendencies of line slimming compared to the acrylate resist.

3.7 Effect of e-beam curing on the poly-CO resist SEM stability

The e-beam curing experiment report earlier in this paper was also applied to the poly-CO resist system. Figure 8a and 8b show the cross-section SEM of the poly-CO resist features before and after 2000uC of e-beam curing, respectively. A substantial amount of thickness and CD shrinkage was observed on the cured resist pattern. Like the acrylate resist, IR spectra of the cured poly-CO resist also indicated complete loss of two carbonyl peaks in the polymer side chain. Figure 9 shows the results of the Figure 8a and 8b features in SEM A, under the same measurement setting as in Figure 4 for acrylate resist. It was shown that the CD of the cured resist (8b) has shrunk 8% initially and remained unchanged throughout the measurements. This observation along with the IR result again suggests that the initial bond scission at the carbonyl group moiety was what first occurred to the resist matrix during the SEM measurements. Unlike the acrylate resist, however, the cured feature did survive the PEB condition without reflowing, as shown in Figure 8c.

3.8 Proposed mechanism for line shrinkage

From the observation in this study, we believe the difference between the two resist systems in the e-beam curing can be ascribed to the degree of dissolution protection in the polymer platforms. Losses of the carbonyl groups from e-beam flood exposure also indicated initial side chain scission in both resist systems, which should also be part of the mechanisms in the CD-SEM environment. The extent of shrinkage from e-beam curing should depend on the free volume and rigidity (T_g) of the original resist matrix, as well as the size and volatility of the side chain fragments. In the CD-SEM environment, on the other hand, the situation is more complicate due to the local heating factor on the resist features. More experiments are still needed to confirm the subsequent reactions of the reactive radicals generated from the chain scission at the carbonyl groups under the SEM environments. Our observations do suggest that in SEM A, the local heating may promote radical induced main chain scission, and prompt the relaxation of resist free volume. By combining this mechanism with the acid catalyzed thermal deprotection, as wafer C in Figure 3, we could observe a worse case of linewidth slimming. For the poly-CO resist, along with the CO-MA resist systems, the polymer main chains are more stable and therefore the line slimming should depend more on the volatility of the side chain fragments. In the CD-SEM B environment, the resists can be more chemically stable through better control of the temperature on the measurement sites. As shown in Figure 8, both resists could behave similarly to the 248nm resists in certain SEM B conditions.

3.9 Direct observation of the resist shrinkage by AFM

The actual CD-SEM induced resist profile change was manifested by the AFM study as shown in Figure 10. Figure 10a and 10b describe the acrylate resist profiles recorded by AFM before and after four measurement iterations in SEM B. The measurement conditions were set at 10pA probe current, 1x 1 μm^2 FOV, and 1000V landing voltage. The extent of line slimming in Figure 10b compared to 10a was at 4%. It was shown by AFM results that the line slimming was also accompanied by 9nm or 2.5% of film thickness shrinkage. Smaller extent of shrinkage was observed on the poly-CO resist under the same measurement conditions, a trend that agrees with the SEM measurement data. Figure 10b also shows that in the CD-SEM scanned area there was also film shrinkage observed in the ARC layer. In this example, nearly 20% of ARC thickness reduction was recorded from only four measurement iterations! This observation agrees well with the chain scission hypothesis since this ARC was designed with a platform containing e-beam active methacrylate moiety.

4. CONCLUSIONS

Through extensive study on an acrylate resist system we have tested several hypotheses of the origins of resist line slimming. Depending on the experimental condition, we have found the maximum of non-linear line slimming to be near 15%. Our study in this paper has shown that the e-beam induced chain scission is most likely the initial cause for both resist systems. However, the extent of shrinkage was determined by the nature of resist systems and the measurement environment. After all, the observed line slimming was a result of either mass loss or free volume reduction in the resist matrix. Since the e-beam induced chain scission is inevitable in both 193nm resist systems, designing resist systems with less volatile side chain or less free volume should be one direction to address the SEM stability issue.

As several reports referenced earlier in this paper, we have also shown that the slimming can be controlled by the CD-SEM measurement condition. By optimizing the tool condition to control flux and penetration of e-beam into the resist, and provide adequate cooling time between SEM measurements, the current 193nm resists should have CD-SEM behavior comparable to the 248nm resists.

In this paper the use of AFM provides a solution for direct and quantitative observation of the CD-SEM measured resist profiles. It was confirmed that the linewidth slimming was actually a reflection of resist profile shrinkage, in both CD and thickness, but not just an artifact of the measurement algorithm on a deformed profile. The AFM also recorded an organic ARC film shrinkage caused by the CD-SEM, at nearly 20% after only four measurement iterations. This observation reminds us again the impact of the SEM measurements on the resist/ ARC features.

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Figure 1. CD stability of the acrylate based SLR in SEM A as a function of e-beam scan time and landing voltage.

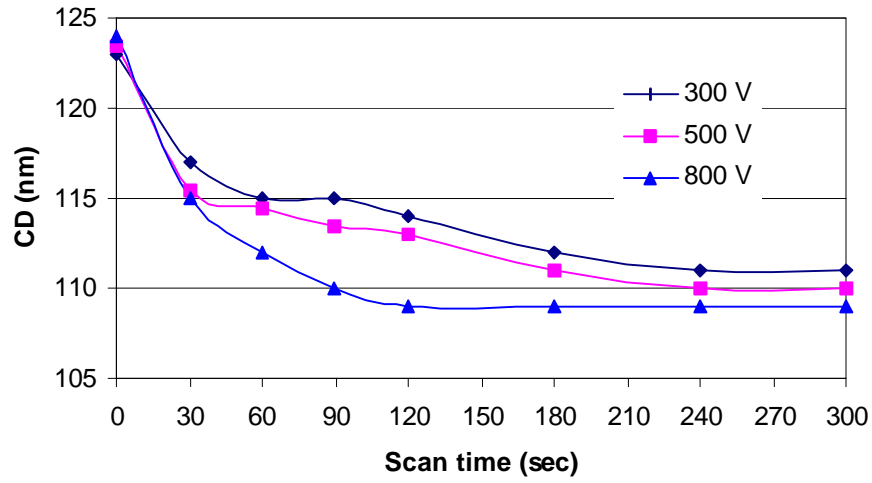


Figure 2. Effect of resist pattern density on line slimming.

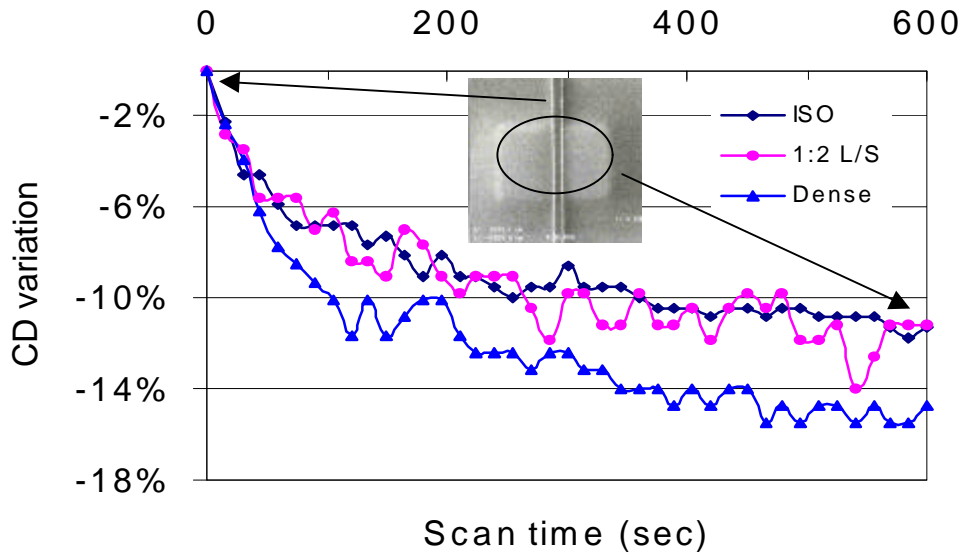


Figure 3. Effect of resist process conditions on the line slimming.

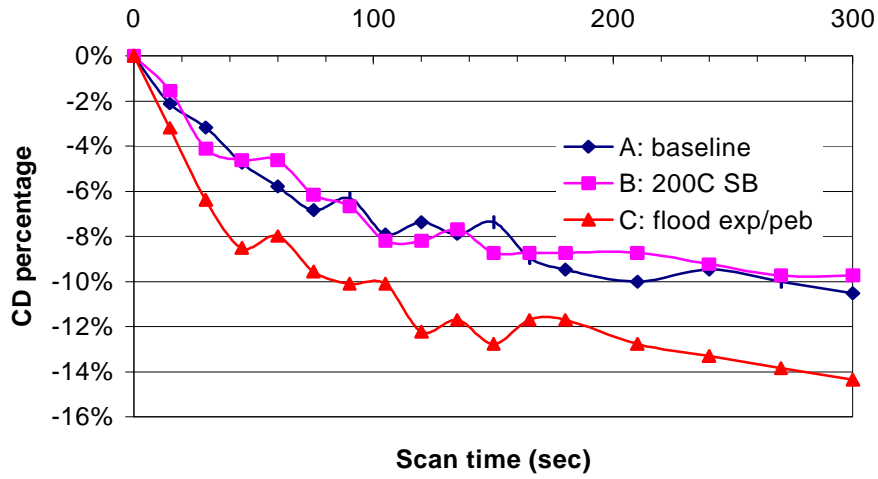


Figure 4. Effect of e-beam flux on the resist line slimming

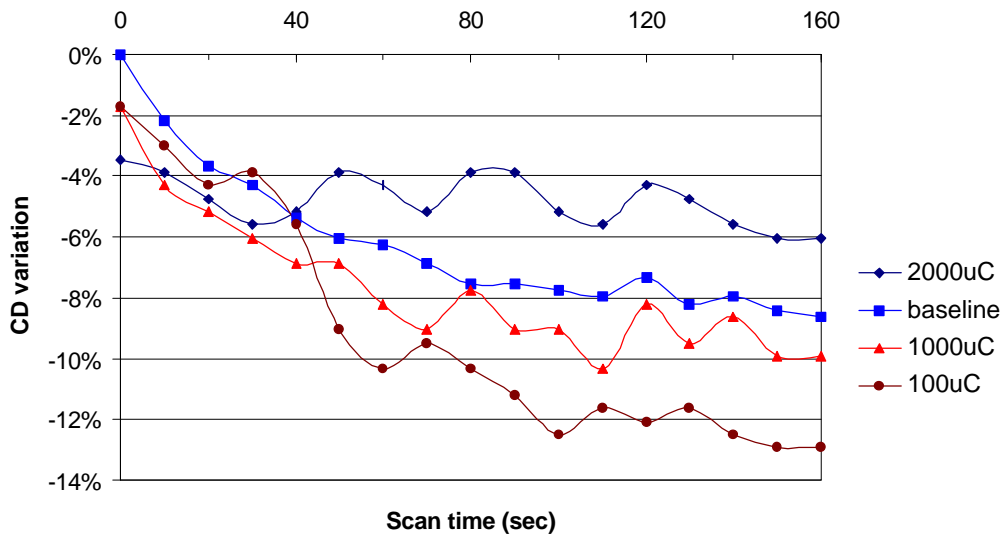


Figure 5. Effect of e-beam flood exposure on the acrylate resist profiles: (a) post development, and the same features after (b) post 2000uC e-beam flood exposure, and (c) post 2000uC e-beam and 130°C bake.

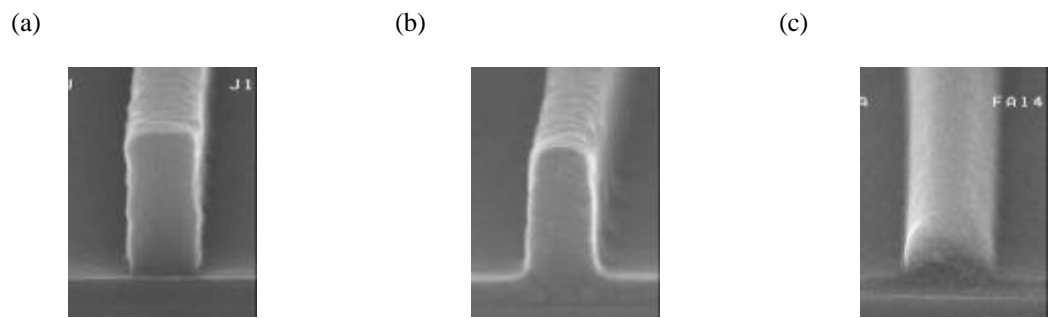


Figure 6. CD stability of resist systems in SEM A measurements.

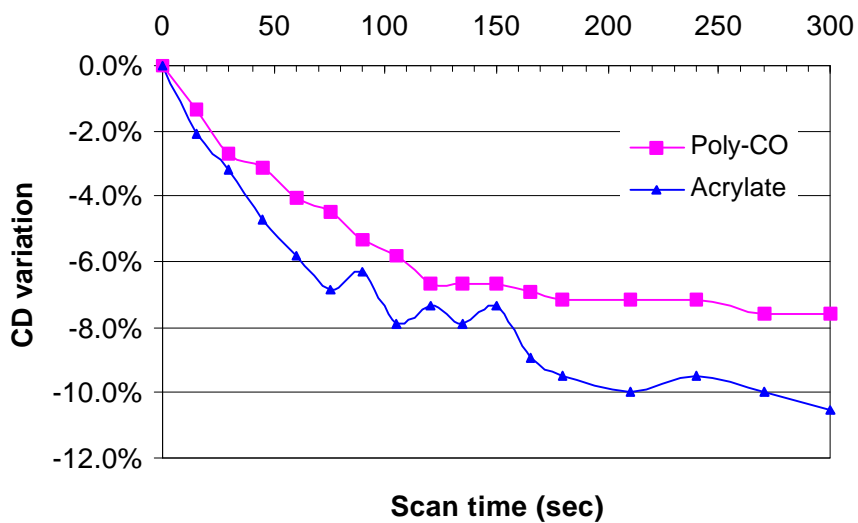


Figure 7. CD stability of resist systems in SEM B measurements.

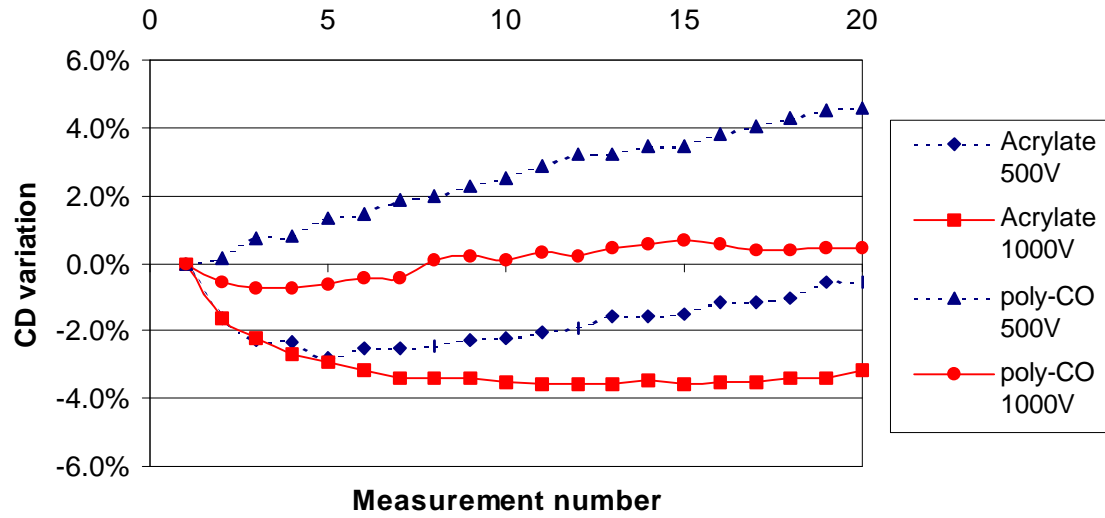


Figure 8. Effect of e-beam flood exposure on the poly-CO resist profiles: (a) post development, and the same features after (b) post 2000uC e-beam flood exposure, and (c) post 2000uC e-beam and 150°C bake.

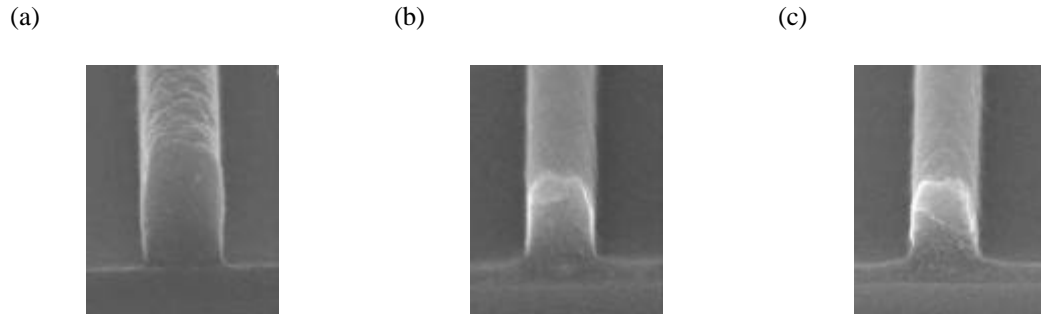


Figure 9. Effect of e-beam cure on the poly-CO resist SEM stability

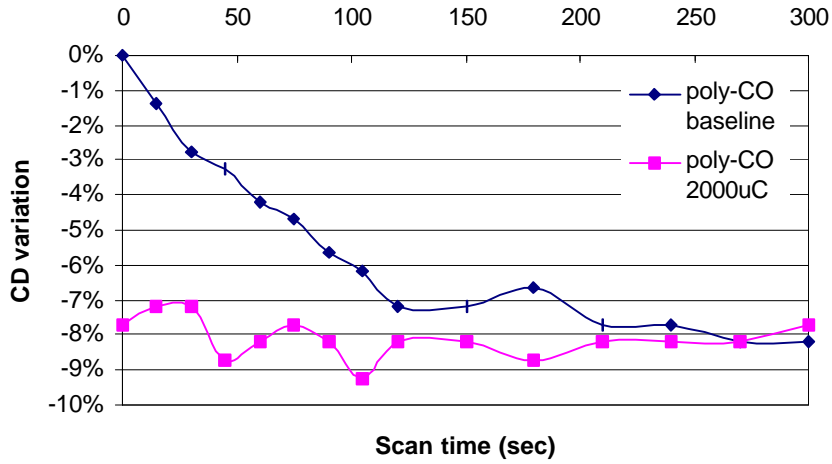
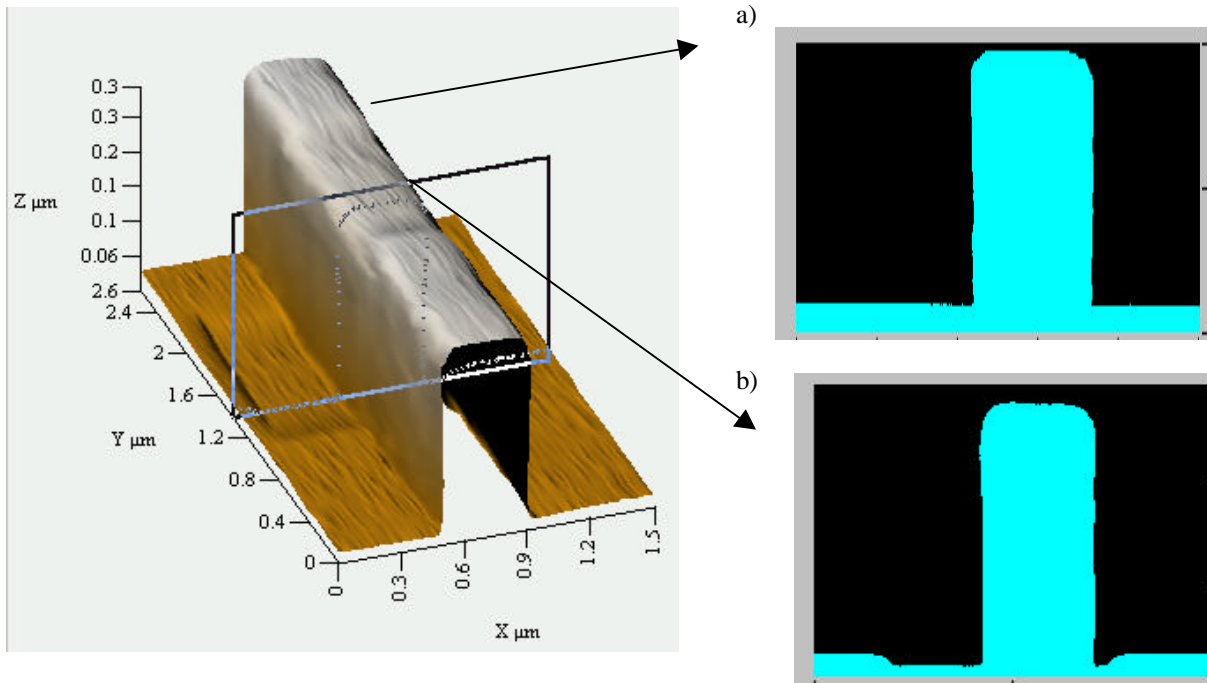


Figure 10. AFM linescans* of the acrylate resist profiles a) before, and b) after SEM B inspection.



* Note, there has been no attempt to correct the images for the size of the AFM tip (hence the lines are fatter by the width of the tip and the footprint in the arc is narrower by the width of the tip).