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ABSTRACT

With the growing adoption of EUV lithography in both Logic and DRAM, the stochastics associated with EUV lithography has highlighted the need for accurate line roughness metrology. One of the approaches suggested to reduce stochastic effects is to transition to MOR (Metal Oxide Resist) from the traditional CAR resists. The CDSEM is the primary workhorse used today to measure line roughness in an inline environment. However, it is known that roughness reported by CD-SEM is dependent on the image acquisition conditions and the metrology algorithm settings.

On the other hand, SEM metrology for EUV now requires low landing energies to minimize resist damage and increase contrast on thin high NA EUV resists [3]. However, this combination of low-dose scanning and low landing energies significantly lowers the contrast of the SEM image leading to higher reported roughness values using traditional roughness metrology algorithms.

To understand and reduce the dependence of roughness on SEM image noise, we acquired images with different imaging conditions on a post-etch wafer and thin-resist EUV wafers with different stacks. The focus of this study is to demonstrate a novel roughness metrology algorithm that reduces the sensitivity of image SNR to roughness compared to traditional metrology methods.

In this paper, we provide comprehensive guidelines for measuring unbiased roughness on thin EUV resist wafers in terms of roughness metrology and scanning conditions. We hope this work can provide the basis for understanding the roughness transfer from litho to etch and better characterize EUV lithography.

Keywords: EUV, High NA, CD-SEM, Low Landing Energy

1. INTRODUCTION

Recently, the industry has moved towards extreme ultraviolet lithography (EUVL) technology for patterning dense features, avoiding multi-patterning. Increased Line edge roughness (LER) and Line width roughness (LWR) as a function of Line CD are one of the key challenges arising from EUV stochastic events [1]. As the industry looks ahead to high NA EUVL for further scaling, the challenges related to stochastics are rising due to the decreasing film thickness needed to overcome the impact on Depth of Focus by the high NA used. It is expected that a film thickness of 15nm and below is needed to maintain the aspect ratio with the feature size [2].

Roughness measurement on CD-SEM is a factor of both the imaging conditions and metrology algorithms used. The SEM scanning conditions of Landing Energy of the primary beam, the current, scan rate, pixel size, and anti-charge mechanisms, among others, can describe imaging conditions. It also depends on the wafer characteristics, such as electron yield and conductance. Two wafers with different stacks may yield images with entirely different SNR, even with the same imaging conditions, because of the difference in wafer characteristics. Metrology algorithms also affect the roughness measurements depending on the type of edge detection and finetuning method used in the algorithm.

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Typically, for EUV and resist layers in general, SEM scan conditions are optimized for best image contrast, SNR, shrink/damage reduction, and HVM considerations. In addition, recent work has shown the need for low-damage imaging enabled by low landing energy and low electron dose scanning regimes [3,4]. However, imaging under these conditions often yields lower contrast and higher noise than traditional imaging on After Etch Inspection (AEI) layers [2]. Another issue seen in such scanning conditions is imaging artifacts resulting from charging. Although there are always extensive ongoing efforts in different charge reduction techniques, depending on the resist stack used, it is not trivial to overcome these charging effects.

At the same time, metrology algorithms are usually optimized for CD sensitivity, precision, and matching. Metrology algorithms optimized for CD measurements use several image filtering techniques to improve edge detection and precision, but these also change the roughness measurements simultaneously. These algorithms were also developed for images with high SNR without much focus on current imaging challenges, as described above. Modifying these algorithms for better roughness measurements on EUV and high NA EUV thin resist layers may be detrimental to classical CD metrology and, at the same time, may not significantly improve current roughness characterization capabilities because of the contradicting requirements for each of these applications.

Any metrology algorithm has a few significant considerations: sensitivity to process changes, accuracy, repeatability, and matching. In this paper, we focus on the sensitivity of roughness measurements for thin resist EUV characterization on resist stacks using optimized SEM imaging conditions.

2. TECHNICAL APPROACH

Traditional LWR measurements on any SEM image are correlated to the noise present in the image. To overcome this effect, SEM images must be acquired at high frames to yield low-noise images. This imaging condition is usually not practical for many reasons, including throughput considerations. An unbiased roughness measurement algorithm was developed for high noise, low contrast imaging regimes typical of thin-resist scanning conditions. To validate the algorithm's performance, a reference 'ground truth' needed to be defined against which the algorithm's accuracy could be measured. An arbitrarily large number of frames was chosen to create a high SNR image in which the potential contribution of noise to roughness would be minimal. The roughness measurement at this SEM dose is the reference or target roughness to be achieved by the algorithm for a low number of frames.

3. EXPERIMENTAL

We used positive tone CAR resist and Negative tone MOR resist for our experiment, including different underlayers.
The resists were patterned in two modes, CDU and FEM, with a nominal pitch of 28nm.

3.1 Design of experiment

Table 1. Design of experiment

#	Resist Type	FT	UL	UL [nm]
D08	Spin on MOR	22	SoG	10
D09			Carbon	5
D10		12	SoG	10
D11			Carbon	5
D14	CAR	15	Carbon	5
D15			SoG	10
D17		30	SoG	10
D18			Carbon	5

3.2 Image acquisition and post-processing

All images were acquired on CD-SEM tool on two landing energies – 150eV and 500eV, 64 frames, image size of 500x500nm, and an anti-charge mechanism was used to achieve edge uniformity and charge control during imaging. The individual frames, which form the image when summed together, were also saved. Subsets of images can be created for the same site with a different number of frames per image but the same theoretical roughness. This technique eliminates any metrology noise introduced by process variation. The images were measured on software, which calculates roughness metrics like LER, LWR, and PSD information with biased and unbiased results. As the left and right edges' roughness are typically uncorrelated, LWR was chosen as the metric to represent overall roughness in addition to the PSD analysis.

4. RESULTS

4.1 SEM imaging

SEM imaging with different landing energies is shown in figure 1. Images acquired with 150eV show better surface morphology and lower underlayer signal, especially for thin resists.

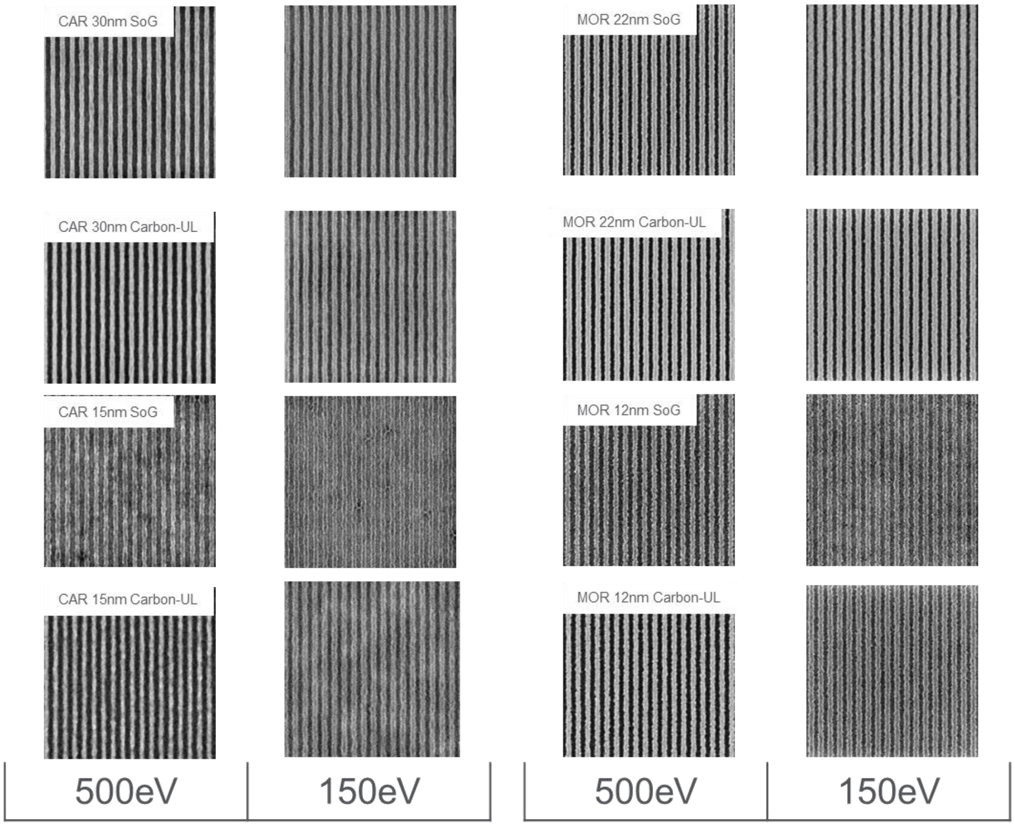
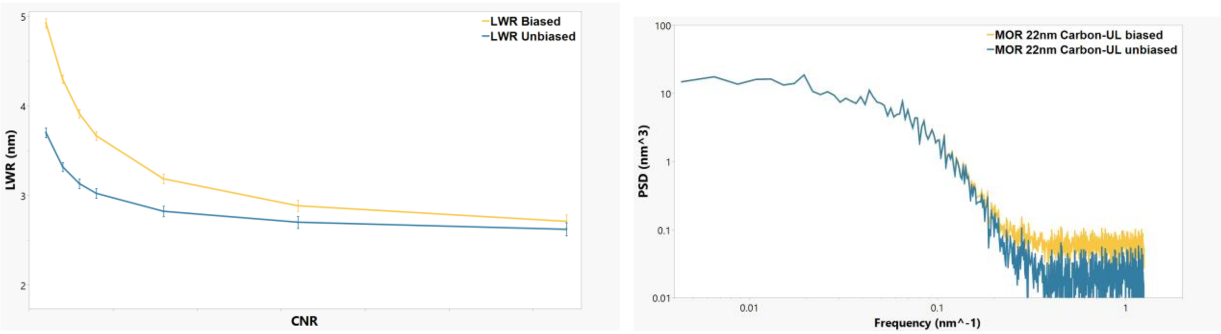


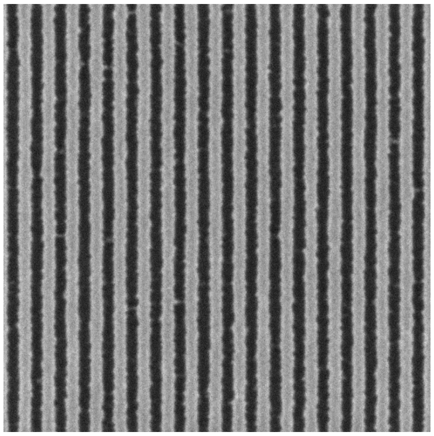
Figure 1. SEM imaging on the DOE using 150eV and 500eV

4.2 Effect of roughness measurement on SEM image noise

To understand the dependence of roughness of a high NA EUV resist stack on the SEM dose used in imaging, we chose a stack with low shrink and charging during imaging to partition the effect of dose, shrink, and charging. The selected stack was MOR resist of 22nm thickness and Carbon underlayer, and imaging was done with 500eV landing energy. Roughness data from 20 sites were averaged to remove the effect of metrology noise. In the PSD, the high frequency noise floor is lowered for both low and high numbers of frames during the unbiasing indicating the reduction of SEM noise from the roughness measurements. Since the SEM noise is already minimal in a high number of frames, the absolute reduction in LWR is not significant for high frames, while it is significant for low number of frames. This fact allows the unbiased LWR to converge to the reference roughness much faster than the biased LWR. The LWR convergence plot for low and high frames and PSD for a single site is shown in figure 2.



(a) (b)

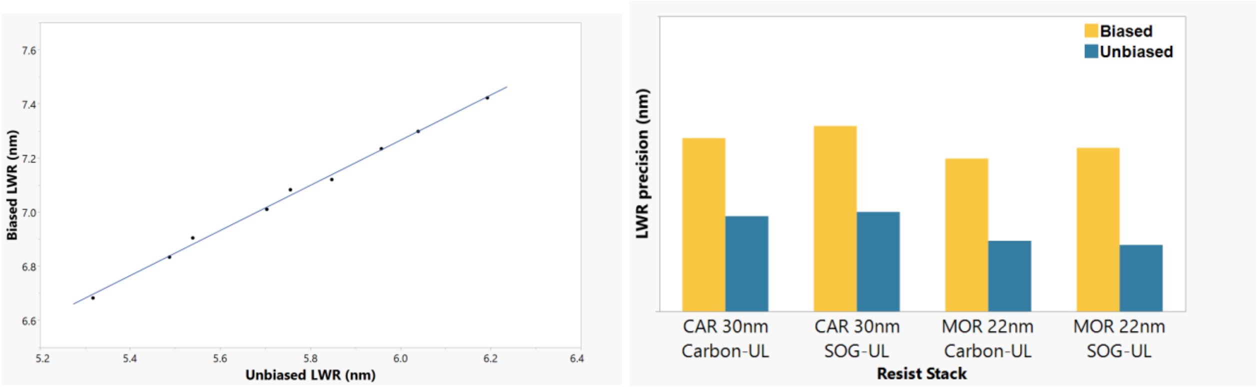


(c)

Figure 2. a) Shows the dependency of LWR on the number frames for biased and unbiased measurements. b) Shows the PSD before and after the unbiasing c) Shows the SEM image used for the PSD plot

4.3 Sensitivity of roughness measurement to unbiasing

While performing unbiasing to roughness, it is essential to validate that sensitivity to roughness variations is not altered. For a given scan condition on a single wafer, the SEM noise across sites should be similar; therefore, any roughness variation on a wafer should come from the process and not from the SEM tool. The biased and unbiased LWR were measured on CAR resist with 15nm film thickness and Carbon underlayer of 5nm thickness. The wafer was printed under FEM conditions which induced roughness changes across the wafer. The roughness was measured from the left to right of the wafer in the direction of focus change. The biased and unbiased LWR are well correlated, with a constant offset in the measured roughness from the unbiasing process. The precision of the LWR measurement was calculated with ten times dynamic loading and unloading of the wafer, and an improvement in LWR precision of almost 50% was observed. A possible explanation is that if SEM noise significantly contributes to the measured LWR repeatability, removing this noise improves the precision.



(a) (b)

Figure 3. a) Demonstrates the correlation between biased and unbiased LWR measurements. b) indicates the precision improvement of unbiased LWR measurements

4.4 Effect of roughness measurement by resist shrink during SEM imaging

One of the significant concerns regarding the accuracy of roughness measurements is the impact on measured LWR while the resist is shrinking during image acquisition. The frames saved during image acquisition were binned into three images to perform this analysis. The first image consists of frames 1 to 8, the second image consists of frames 9 to 16, and the third image is from frames 17 to 24. This binning was repeated for twenty images for higher statistics. Two imaging modes, one with 500V and the other with 150V, were chosen to have a high shrink and low shrink imaging condition on a CAR resist stack with 30nm film thickness. As expected, the 500eV condition showed higher initial shrink, with both conditions showing total shrink of more than 10% of line CD; however, the measured LWR change was less than 5% on both the high and low shrink conditions. The shrink and CD vs. frame trends are shown in figure 4.

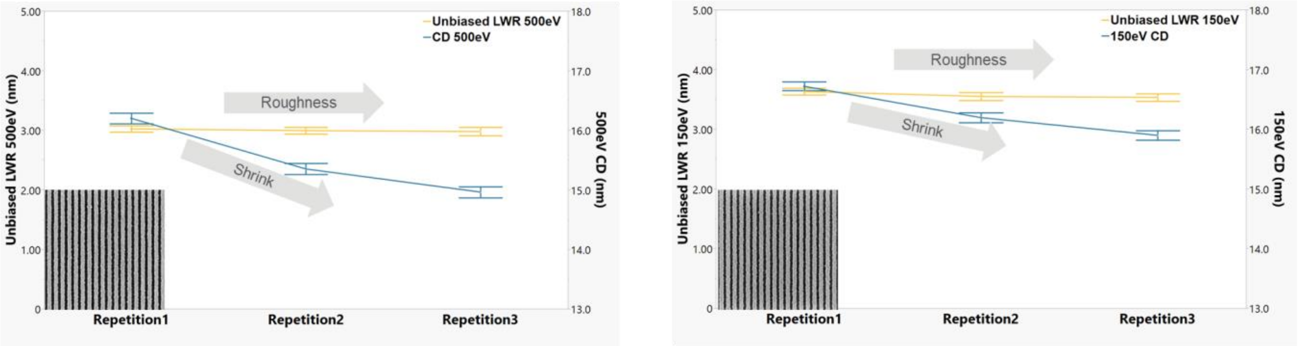
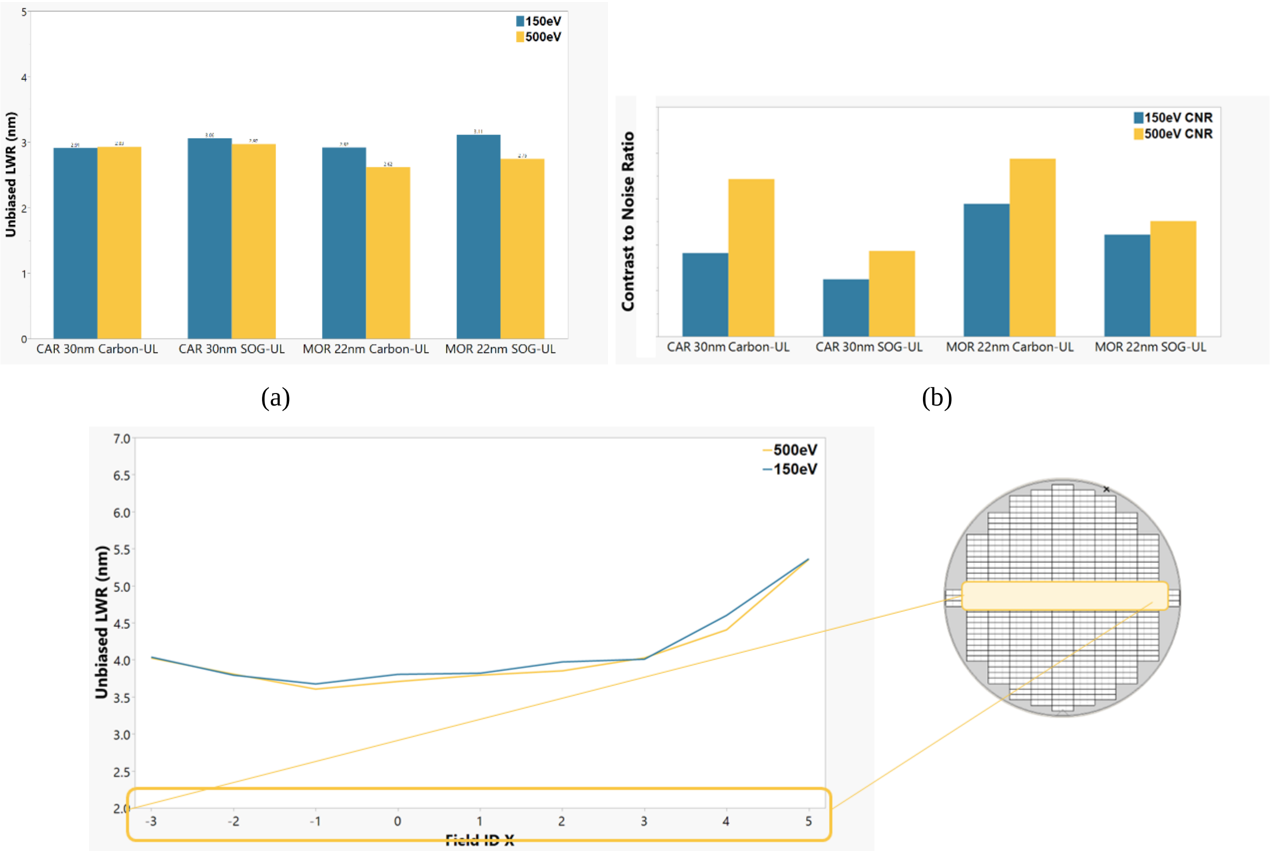


Figure 4. a) Effect of shrink and measured unbiased LWR for SEM imaging using 500eV landing energy b) Effect of shrink and measured unbiased LWR for SEM imaging using 150eV landing energy

4.5 Effect of landing energy on LWR sensitivity

Although the benefit of moving to lower landing energy for reducing resist shrink is well studied [3,4], its effect on measured LWR is unknown. As the image contrast to noise ratio (CNR) is reduced while acquiring images with lower landing energies, there is a possibility that the measured LWR may change. To understand the effect of landing energy of the SEM and CNR on LWR sensitivity, images were acquired on resist stacks of CAR with resist thickness of 30nm and SOG underlayer printed with FEM conditions with different landing energies, and unbiased LWR was measured. We also measured the unbiased LWR roughness on CAR and MOR resist stacks printed under POR conditions. While there is a slight offset of measured LWR specifically on the MOR resist (figure 5a), the LWR sensitivity does not change between 500V and 150V landing energies as seen in figure 5c. To understand the reason the offset in measured unbiased LWR is due to the difference in CNR, we measured the CNR for these images (figure 5b). We found that its uncorrelated to the measured unbiased LWR. We can speculate that the difference in measured unbiased roughness is due to the fact that the SEM electron interaction volume is different in CAR vs MOR, leading to a difference in collected electron signal from the surface. Further studies are needed to validate this phenomena.



(a) (b)

(c)

Figure 5. a) Shows the unbiased LWR comparison for different resist stacks for 150eV vs. 500sV imaging conditions b) Shows the CNR difference for the same images. c) shows the sensitivity of roughness variation in FEM wafer for 150eV vs. 500eV SEM imaging

4.6 Effect of resist thickness on roughness

Imaging of MOR and CAR resists with different resist thickness and underlayer were performed. The unbiased LWR was compared for different thicknesses but the same underlayer. It is observed that the unbiased LWR roughness increases as the resist thickness decreases as shown in figure 6. This is because the lower resist thickness increases the resist stochastics, degrading the roughness.

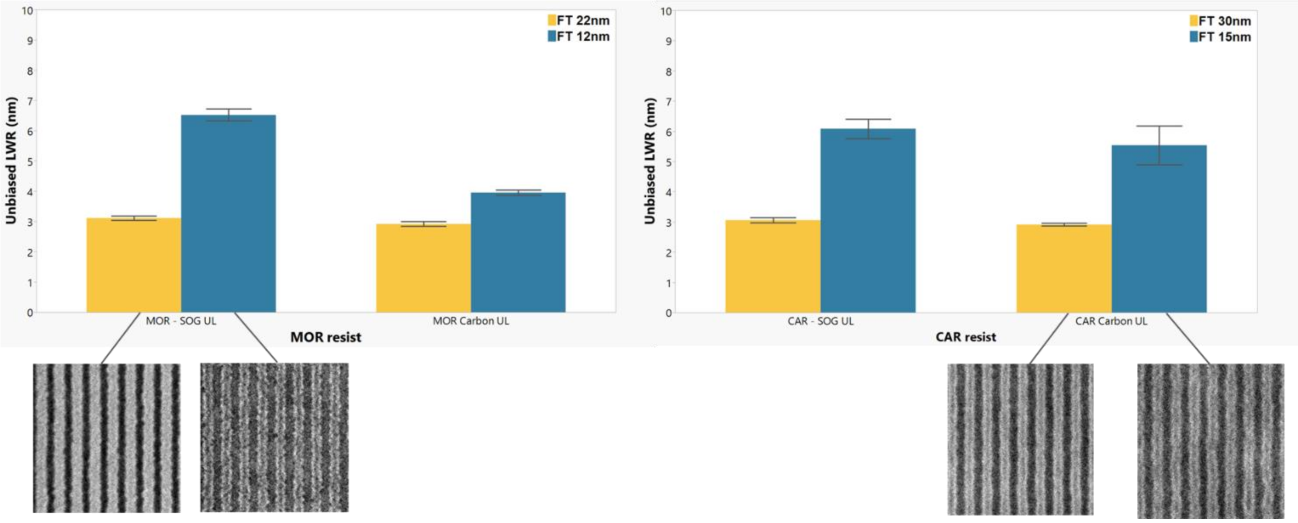


Figure 6. Indicates the degradation of unbiased LWR with decreasing film thickness

4.7 Effect of underlayer on roughness

Imaging was carried out on MOR and CAR resists with different resist thicknesses and underlayers. The LWR was compared for the same thicknesses but different underlayer. In the EUV resist with a relatively thicker stack, the underlayer had little effect on the measured unbiased LWR. In contrast, for the thinner resist, unbiased LWR depended on the choice of the underlayer used, as shown in figure 7

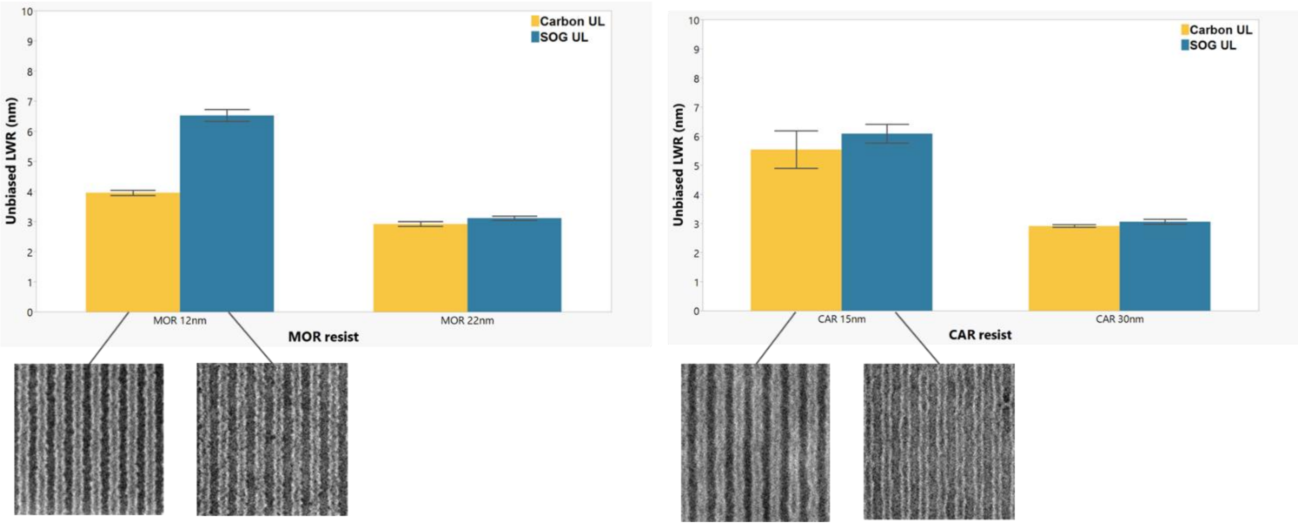


Figure 7. Shows the effect of underlayer choice on unbiased LWR for thin resists. The thicker resists are less sensitive to the choice of underlayer for unbiased LWR.

5. SUMMARY

Minimizing roughness is a critical challenge in the development of thin resists. Therefore, roughness characterization on imaging conditions optimized for thin resists is a key developmental milestone. Optimized imaging conditions for EUV resists have converged to low landing energy with low electron dose. However, these imaging conditions generate SEM imaging issues like low contrast, low SNR and shrinkage. For roughness measurements in this environment, it is essential to unbias the roughness while being sensitive to roughness variations and overcoming these imaging issues. An unbiased roughness measurement algorithm that answers these challenges was developed and was used to characterize a DOE of thin-resist EUV wafers. It is observed that there is a strong dependence of roughness to the resist thickness decrease, which the increased stochastics can explain. Furthermore, the choice of the underlayer used affects the roughness of thin EUV resists, unlike thicker resist stacks which show an insensitivity of roughness to the underlayer stack.

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