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# Roughness Power Spectral Density as a Function of Aerial Image and Basic Process / Resist Parameters

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Linewidth Roughness (LWR) remains a difficult challenge for improvement in all resist materials. In previous work we focused on the impact of key components of LWR by analyzing the Power Spectral Density (PSD) curves which can be obtained using Fractilia's MetroLER computational software. By measuring the unbiased PSD (with SEM image noise removed), accurate assessment of PSD(0) (the low-frequency limit of the PSD) and correlation length (the length scale of the transition from white to correlated noise) is possible. We showed there was an important relationship between ArF resist frequency components and LWR through lithographic process (before and after a resist trim step) as a function of resist formulation. In this paper we will study how key frequency components such as PSD(0) and correlation length change as we vary basic resist properties such as diffusion. The impact of aerial image on LWR and its frequency components will also be studied with particular attention to how correlation length affects LWR as feature size decreases. We will also look at the impact of diffusion or resist blur on PSD(0) as a function of aerial image Normalized Image Log-Slope (NILS). Understanding the relationship between PSD(0) and correlation length and how to manipulate these variables to minimize LWR for different features is crucial for more rapid LWR improvement at different nodes.

**Keywords: Power Spectral Density, LWR, LER, linewidth roughness, line-edge roughness**

## 1. INTRODUCTION

Reducing linewidth roughness (LWR) continues to be a significant challenge in advanced lithography, especially with the scaling issues associated with decreasing feature size and trying to reduce line roughness. For many years the main CD-SEM output for LWR improvement experiments was commonly characterized through the use of a single averaged number value, a 3-sigma roughness measurement. With recent analytic advances in the ability to detect images without removing high frequency roughness and measuring unbiased LWR, we now have the ability to understand LWR in terms of how different spatial frequencies influence resist sidewall roughness.<sup>1</sup> Understanding how the spatial frequency of LWR impacts lithographic and etch processes can help us better design resists targeted towards their end application, and minimizes suboptimal optimization of resist materials and processes resulting from the common use of biased LWR measurements after the resist imaging step.

The spatial frequency of LWR is expressed by a power spectral density (PSD) curve and quantifies amplitude variance of the edge or linewidth per unit frequency. Graphically, it is typically represented on a log-log scale, as shown in Figure 1, where the y-axis is the power or variance of the line per unit frequency, and the x-axis is the frequency or the inverse of the length of the line over which the variance is measured. Low frequency roughness occurs over longer length scales and the high frequency region occurs over shorter length scales. The flat region of the graph in the low frequency region is termed PSD(0). This is the region or length scale where events that influence the PSD are considered "uncorrelated". This low frequency value of the PSD is an estimate of PSD(0), the value of PSD of an infinitely long line (zero frequency). In resist terms, PSD(0) comes from random independent events produced by mechanisms such as photon absorption, random fluctuations in film chemical concentration, or stochastic photon shot noise. The point at which the graph curves down is the length scale where the edge roughness becomes correlated. Such events are no longer independent but reflect the occurrence of a mechanism which is correlated, such as the path wise reaction-diffusion of an individual photoacid in a chemically amplified resist film. The inflection point is determined by the correlation length ( $\xi$ ) and at this point the power begins to fall at a frequency of  $1/2\pi\xi$ . The slope of the line is defined as  $2H+1$  where H is the roughness exponent (Hurst exponent). For the purpose of this work H is set to 0.5 for all analysis, which is the theoretical value expected when an ideal reaction-diffusion process is driving the correlation.<sup>2</sup> The variance (or  $1\sigma$  LWR squared) is defined as the area

under the curve and is a function of three PSD parameters, PSD(0) or the flat low frequency region, the correlation length (proportional to diffusion or resist blur), and the slope (H).

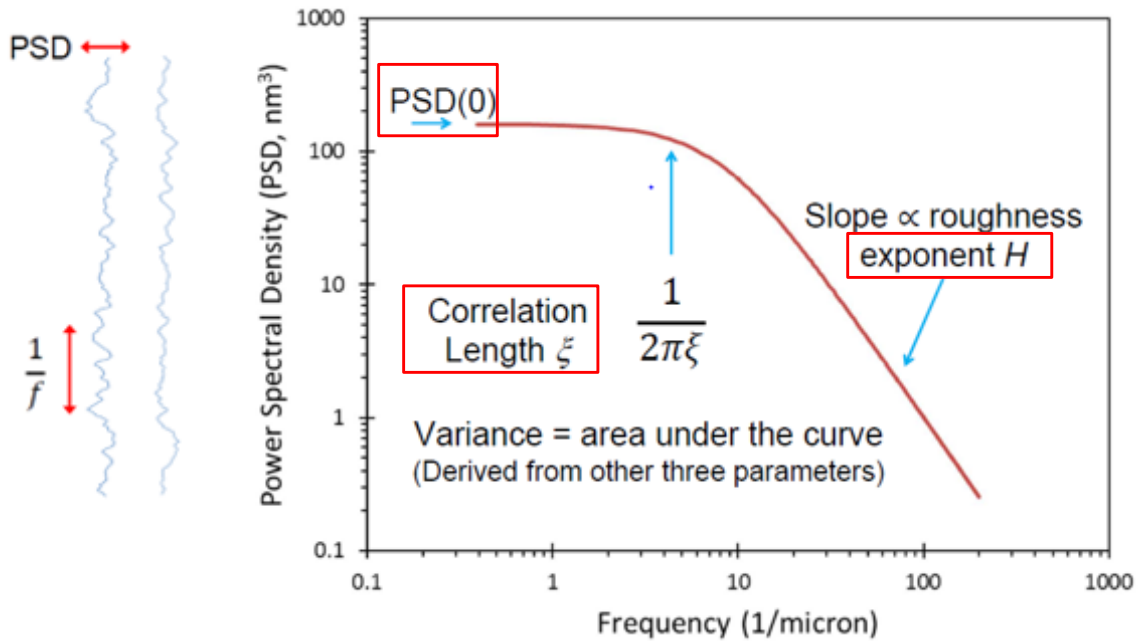


Figure 1: An example of how the roughness of a line edge relates to a PSD curve. A typical PSD can be described by three parameters: PSD(0), the PSD value in the flat low frequency region, the correlation length  $\xi$ , and the roughness exponent  $H$ . Line roughness (variance) is the area under the PSD curve. Figure from Ref. 3.

A primary goal for lithographic process optimization is reducing the area under the PSD graph. An approximation of the relationship between variance and the PSD parameters is:

$$\sigma^2 \approx \frac{PSD(0)}{(2H + 1)\xi} \quad (1)$$

Transforming the resist line into the PSD enables LWR to be expressed in terms of two independent variables [PSD(0) and  $\xi$ ] instead of a single dependent variable [i.e. the  $3\sigma$  LWR]. In practice, the three variables  $3\sigma$  LWR, PSD(0), and  $\xi$  will be used to fully characterize the roughness behavior of a feature.

With two independent variables governing the functional behavior, this allows the exploration of how both the roughness at high and low frequencies impact the overall LWR of a resist, and how these will be affected by process parameters such as subsequent etch or the aerial image quality. It has been proposed that in order to overcome the scaling issues associated with LWR and resist blur (which is related to correlation length), that resists should be developed which fundamentally display low PSD(0) and low correlation length properties, and then applying subsequent etch processes to improve the high frequency roughness by increasing the correlation length.<sup>3</sup> Based on this concept, experimental results were published showing that the correlation length of resist patterns can show correlation with LWR changes (which we will herewith call *LWR delta*, the  $3\sigma$  LWR after the process step minus the  $3\sigma$  LWR before the process step) through an etch trim process, and that smaller correlation lengths (i.e. more roughness in the high frequency length scales) yield larger *LWR delta*.<sup>4</sup> It was shown that the relationship between *LWR delta* through etch trim and correlation length is explained by the variance equation (eqn. 1) where *delta LWR* is proportional to the square root of  $1/\xi$  (Figure 2). Understanding frequency analysis was shown to offer insight into mechanisms, and the ability to predict which resists may yield lower LWR following etch

trim. This previous investigation found that unbiased PSD(0) was not affected by trim etch, whereas correlation length can increase by smoothing out high frequency roughness, thus ultimately reducing post-etch LWR.

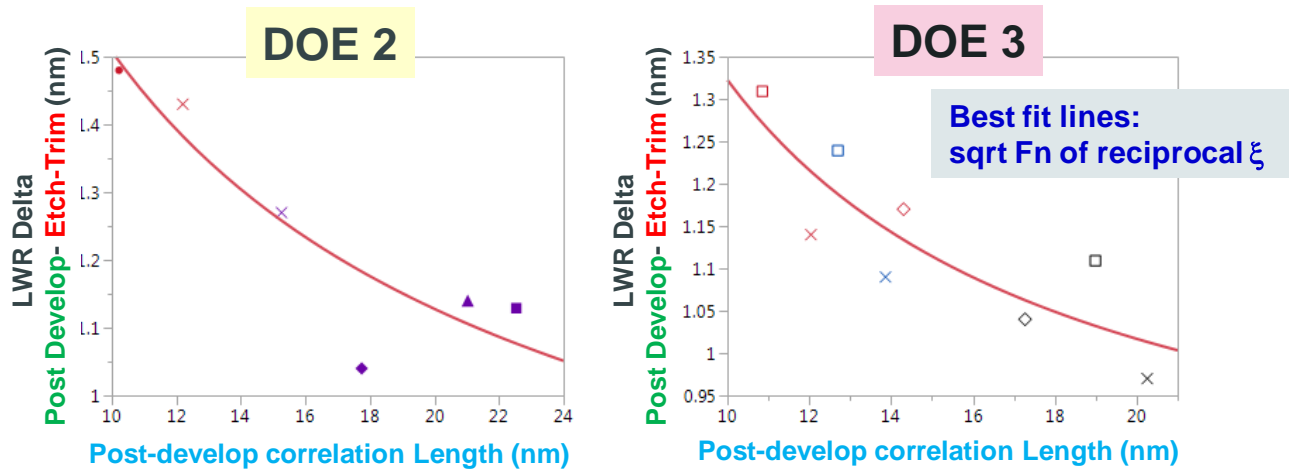


Figure 2. Etch-trim delta and unbiased correlation length for Design of Experiment (DOE 2 and 3), show a similar fit with reciprocal correlation length.

Previous work<sup>5</sup> also highlighted two different LWR frequency scenarios: 1) in one group of designed experiments (DOE's) the correlation length ran co-linear with PSD(0). When correlation length and PSD(0) were co-linear, the lowest correlation length resists corresponded to the lowest PSD(0). This scenario is found to be most common. 2) However, we also showed DOEs where correlation length and PSD(0) were not co-linear, in which the lowest PSD(0) and the lowest correlation length did not originate from the same resist in the DOE (Figure 3). Regardless of the relationship between PSD(0) and correlation length in a given DOE, the net LWR is made up of a combination of both factors, as shown in equation 1, and the LWR can most easily be estimated as proportional to  $\sqrt{PSD(0)/\xi}$ . For a given resist process, while a lower PSD(0) coupled with a higher correlation length yields a lower post-litho LWR, because of behavior in trim etch, it may not yield the desirable lower post-etch LWR. In a simplistic analysis, increasing the resist process correlation length often appears to be a good approach to reducing LWR in the resist features. However, it is very important to note that increasing correlation length also effectively increases resist blur which in turn has the detrimental effects of reducing the gradient of the latent image in the film, and hence reduces the effective image log slope (ILS) of the process and increases PSD(0).

With this understanding in mind, the logical next step towards reducing the net process LWR (through etch!) is to investigate how NILS and diffusion impact PSD(0) and correlation length. We will be describing our learnings on this in the current work below.

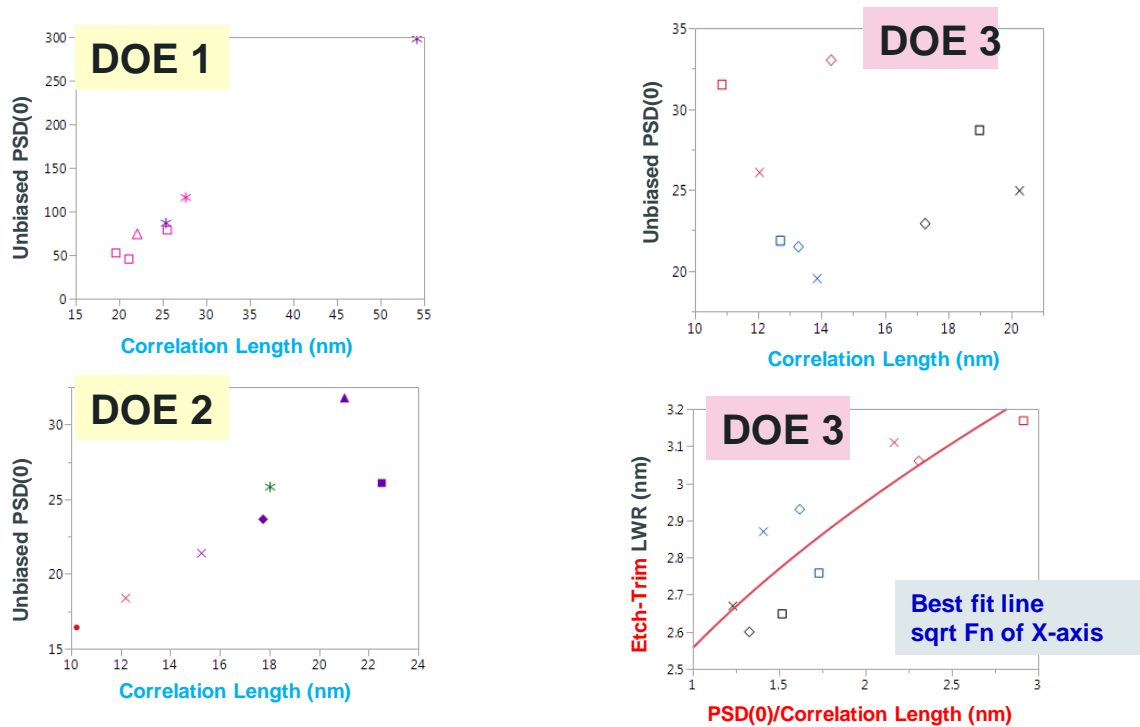


Figure 3. Both DOE 1 and DOE 2 show significant correlation between PSD(0) and correlation length. On the other hand, DOE3 shows no obvious correlation between PSD(0) and correlation length. Even when PSD(0) and correlation length are not correlated, the LWR measured after etch-trim can be described by both PSD functional components in the relationship defined by the variance equation 1. In this instance, PSD variables were measured after the lithography step at DuPont and compared with independently run etch-trim LWR measured at an external fab.

The current work investigates how unbiased PSD(0) and correlation length behave through variation in normalized image log (NILS), along with how the relationship between unbiased PSD(0) and correlation length changes with respect to diffusion. Three different DOEs were set up where nine wafers in each DOE corresponded to three different resists. Each of the resists were identical apart from the photoacid generators (PAG) used in the film: three different PAGs in three different resists. Each resist was subjected to three different post exposure bake (PEB) temperatures. Higher PEB temperature increases the photoacid diffusion length, and also increases the effectiveness of the photoacid catalyst in removing protecting groups from the polymer. Although correlation length and LWR have been investigated through PEB previously<sup>6</sup>, the prior work investigated the impact of PEB diffusion on correlation length and LWR for one feature. In this work, additional, unbiased PSD(0) and unbiased LWR through NILS is compared with  $\sqrt{PSD(0)/\xi}$ . We show trends that repeat through each independent DOE and some trends that are similar or different depending on the formulation.

## 2. EXPERIMENTAL

### Sample Preparation

The photoresists were formulated with 193nm photoresist polymer, PAG, quencher, and solvents. Due to the proprietary nature of these materials, the details of their composition are not disclosed. The solutions were filtered through 0.02 $\mu$ m PTFE filter prior to evaluation.

## Wafer Coating and Lithographic Evaluation

Thin films (900Å) were prepared by spin coating on an industry standard antireflective coating (ARC) on 300mm HMDS primed wafers using a TEL CLEAN TRACK LITHIUS i+. Films were exposed with an 193nm lithography immersion process using an ASML 1900i. CD-SEM metrology was carried out using a Hitachi CG4000. Images were captured using a square scan 1024X1024 pixels at 100K magnification and 500V. Pixel size was 1.32nm in both x and y. Post-lithographic LWR and PSD evaluation was carried out on positive tone 86nm pitch, 90nm pitch and 110nm pitch dense (1:1) lines/space patterns. These corresponded to NILS of 1.91, 2.35, and 3.01, respectively (Figure 4). All three features were imaged and processed on the same wafer.

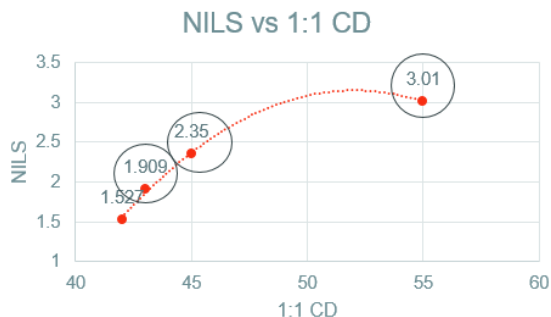


Figure 4. NILS vs CD during lithographic process

## Metrology and PSD Analysis

Unbiased image analysis plus Power Spectral Density analysis and unbiased LWR measurements were carried out using MetroLER v1.7 by Fractilia. All PSDs are averaged over 20 images and images were analyzed for systemic abnormalities and field distortions. PSD outputs were exported into excel from the DOE mode in MetroLER. Every LWR measurement is an averaged value from 20 images down a line to capture a more statistically significant representation of  $3\sigma$  LWR for each sample. In each SEM image the center 11 lines were analyzed, with a total of 220 lines for each sample.

Biased image analysis was performed using the Hitachi CG4000 standard software package. Internal biased LWR measurements were obtained on the identical images as the unbiased LWR and PSD analysis. As with the unbiased LWR, each standard biased LWR measurement was averaged over the same number of images and lines. LWR generated from these standard screening images used Hitachi CD SEM software with a 50% threshold.

Table 1 outlines image dimensions and averaging used for LWR measurements for both the unbiased and biased analyses.

	STD Dow LWR Image	Square Image for STD LWR biased Measurement	Square Image for PSD analysis, unbiased LWR
<b>Measurement Software</b>	Hitachi CG4000	Hitachi CG4000	MetroLER 1.7
<b># Pixels per image</b>	512X512	1024X1024	1024X1024
<b>Magnification</b>	200k	100k	100k
<b>Line length</b>	645nm	1.35 $\mu$ m	1.35 $\mu$ m
<b>Images Averaged per sample</b>	20	20	20
<b>Lines averaged per sample for PSDs</b>	NA	200	200

Table 1: Dimension and magnification of images for LWR and PSD measurements

### 3. RESULTS AND DISCUSSION

During resist improvement studies, we observed that higher diffusion resist components could improve standard LWR with larger feature sizes (at high NILS), but LWR would dramatically increase at smaller feature sizes (lower NILS). The inverse of this was also observed, in which case resists with mediocre LWR at high NILS would yield the lowest relative LWR at low NILS. We hypothesized that the resultant LWR at different NILS was a function of the changes that were occurring among the LWR frequency components of PSD(0) and correlation length. Resists in the first example where LWR was low at high NILS but not at low NILS, were hypothesized to be “correlation length driven” resists (Resists 10 and 11 in Figure 5), where the ratio of PSD(0)/correlation length was low at high NILS based on the higher correlation length. In some cases these weren't the lowest PSD(0) resists. In these “correlation length driven” resists, the impact of diffusion to maximize high frequency smoothing and increase correlation length combined to reduce the overall roughness of the line. At high NILS, higher diffusion could be tolerated and utilized to reduce LWR. At low NILS we hypothesized that the high amount of resist blur reduced the gradient of the effective image log slope to the point where LWR increased significantly (Resists 10 and 11, Figure 5). The inverse example of a resist in which LWR was similar to others at high NILS, but displayed one of the lowest LWR at lower NILS, was also thought to be due to how LWR frequency components were affected through NILS. This type of resist was thought to be an example of both PSD(0) and correlation length being low, e.g. as demonstrated by Resists 12-14 in Figure 5. In this type of resist, the higher NILS LWR may be similar to others because the ratio of PSD(0)/correlation length can be high if the PSD(0) is not low enough to compensate for the increase in high frequency roughness associated with reduced correlation length. These resists were hypothesized to give relatively mediocre LWR at high NILS due to reduced amount of resist acid diffusion blur and lower initial correlation length, but displayed improved LWR at lower NILS again due to the reduced amount of resist blur and low PSD(0).

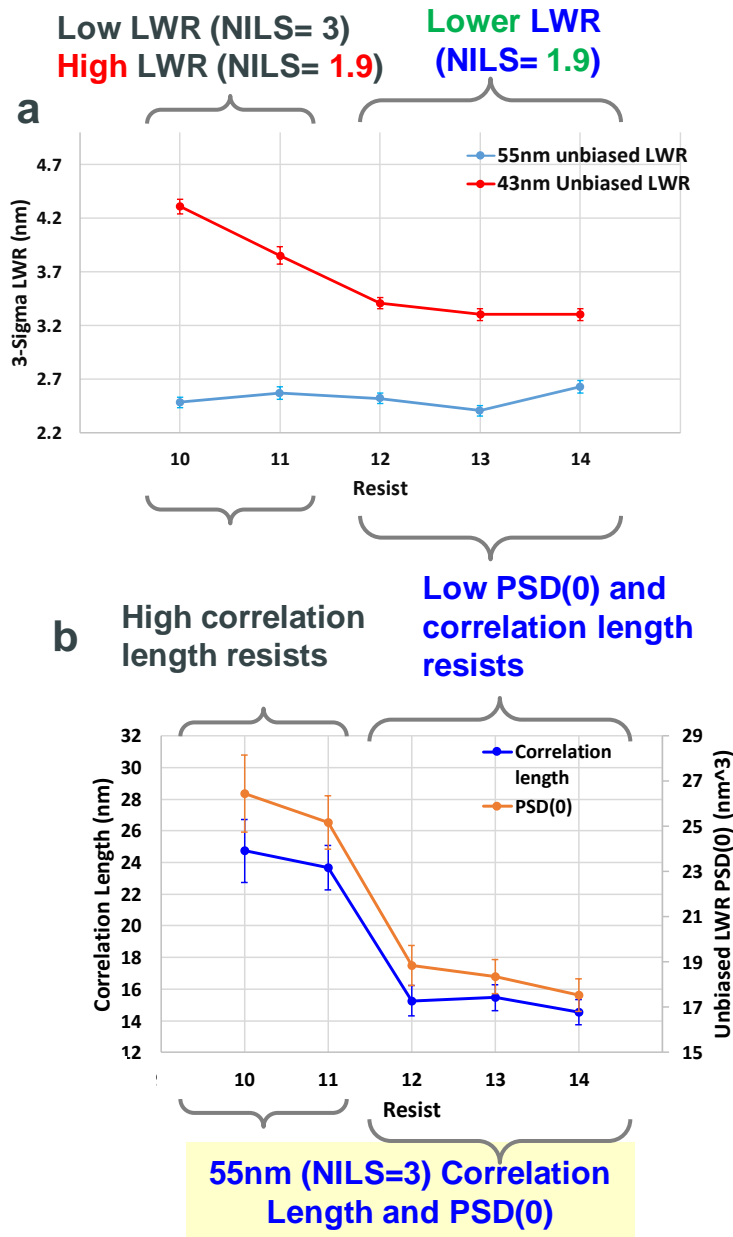


Figure 5. unbiased LWR of 5 resists at 55nm dense lines (NILS=3.01) and 43nm dense lines (NILS =1.9), corresponding with either high or low correlation length /PSD(0) frequency components measured on 55nm dense lines.

Changes observed in LWR through NILS, along with initial frequency analysis, motivated the desire to understand the impacts of diffusion and NILS on LWR frequency components. Simple resist DOEs were designed to study this further. The simplest way to increase diffusion within a photoresist apart from changing the PAG is increasing PEB temperature. Therefore, experiments were set up systematically varying both PAG molecular size and PEB temperature as shown in Table 2. The difference between PAG A, B and C is primarily the degree of photoacid diffusion. Films of each formulation were subjected to a post-exposure bake at three temperatures prior to the develop step. Three different feature sizes were then analyzed per wafer.



As a result, the experimental design effectively shows the impact of formulation and bake temperature through NILS. In Table 2, the positive tone 55nm dense L/S feature has a high NILS of 3.01, whereas the 45nm dense pattern imaged under the same conditions has a NILS value of 2.35, and the 43nm image has a NILS value of 1.9.

	Formulation	PEB	CD (dense L/S)/ NILS
1	PAG A	Low	55nm, 45nm,43nm  NILs = 3.01,2.35,1.9
2	PAG A	Medium	
3	PAG A	High	
4	PAG B	Low	
5	PAG B	Medium	
6	PAG B	High	
7	PAG C	Low	
8	PAG C	Medium	
9	PAG C	High	

Table 2. Each DOE contains 9 wafers, 3 formulations baked at 3 temperatures. All 9 wafers were analyzed at 3 different dense features to allow for thorough evaluation.

Three DOEs were constructed and analyzed in this way to ensure the trends and methodology were repeatable. As shown in Table 3, DOE 1 contains more resist formulation differences than the resist formulation changes investigated in DOE’s 2 and 3. All three DOE’s were run at three PEBs through NILS as shown in Table 2.

DOE	Formulation	Comment
DOE 1	PAG A, B, C	
DOE 2	PAG D, E, F	Similar formulations. Loading variations
DOE 3	PAG D, E, F	

Table 3. Outline of the formulation changes made in the resists investigated in these three DOEs.

### DOE 1: Correlation Length

The correlation length is the point on the PSD curve where the amplitude of sidewall roughness is affected by events on a length scale that are becoming correlated due to correlated deprotection reactions and concomitant impacts on resist development pathways. Lower correlation lengths are often associated with greater high frequency roughness, whereas longer correlation lengths are associated with resist smoothing at higher frequencies. In general, correlation length is proportional to resist diffusion, so an increase in correlation length is expected with increasing PEB temperature or increasing photoacid diffusion<sup>2</sup>. Figure 6 shows correlation length increasing through bake temperature and decreasing with each set of formulations, especially for 55nm features. This trend shows the influence of both process and formulation on correlation length. As the NILS decreases the correlation length difference between formulations also decreases as the slope of the aerial image begins to dominate.

Less expected were the changes in correlation length magnitude that are observed through feature size (varying NILS). For both PAG B and C correlation length increases as the NILS decreases. The question of whether diffusion itself increases or the influence of diffusion increases as the slope of the aerial image is reduced will be discussed in a later section. At high NILS (55nm) PAG A shows a similar trend through PEB as in the less diffusive formulations (PAG B and PAG C). However, at lower NILS the trend through PEB breaks down for the high diffusion PAG. This may indicate a threshold.

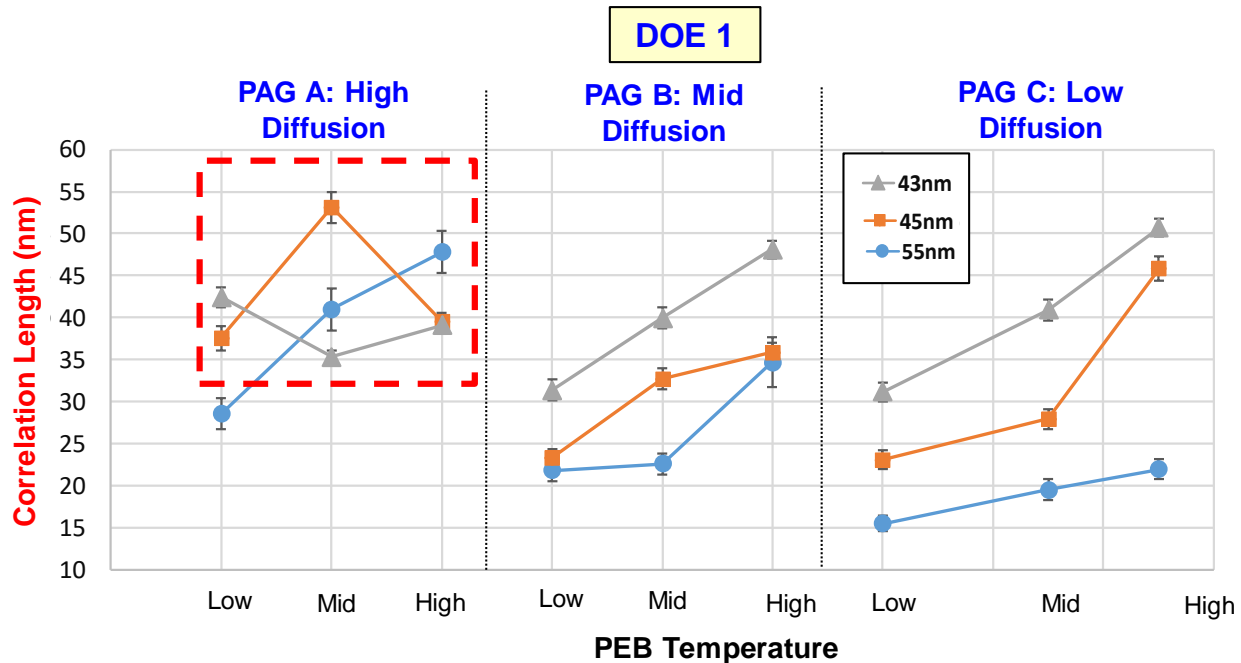


Figure 6. DOE 1 correlation length as a function of increased PEB temperature (“Low”, “Mid”, “High”), change in PAG and NILS. Error bars are 2 \* standard error (SE) and are equivalent to 95% confidence intervals.

### DOE 1 Unbiased PSD(0)

We next address the impact of increasing correlation length through diffusion and NILS on PSD(0) and uncorrelated roughness. In previous work we have shown that PSD(0) and correlation length are often correlated, but occasionally they are not.<sup>4,5</sup> Figure 7 shows that PSD(0) does not increase in the same way as correlation length does through PEB temperature. For low diffusion resists, there is a point where increasing correlation length does not increase PSD(0). For PAG C formulations at high NILS, PSD(0) does not change through bake temperature. For PAG B, PSD(0) doesn’t start to increase until the highest bake temperature. For PAG C formulations, NILS decreases for the 45nm lines, PSD(0) does not start to increase until the mid PEB temperature, at which point PSD(0) begins to increase significantly. Selecting a PEB temperature where correlation length increases but it has not yet increased PSD(0) likely demonstrates evidence of an optimum diffusion behavior for that feature size.

While the concept that one can find a photoacid diffusion optimum to yield improved LWR at a given feature is not new, here we show the power of unbiased frequency analysis to understand how resist formulation components, process conditions and aerial image quality interact. Ideally, one seeks to find a condition in which correlation length increases and PSD(0) stays unchanged (or decreases) at the diffusion optimum. If PSD(0) is proportional to noise (in the image)/gradient, at high NILS the gradient is steeper and can tolerate increased correlation length (resist blur). As the correlation length increases so does resist blur, and the gradient of the effective aerial image is degraded to point where PSD(0) increases significantly as seen at high bakes with 45nm and 43nm lines.

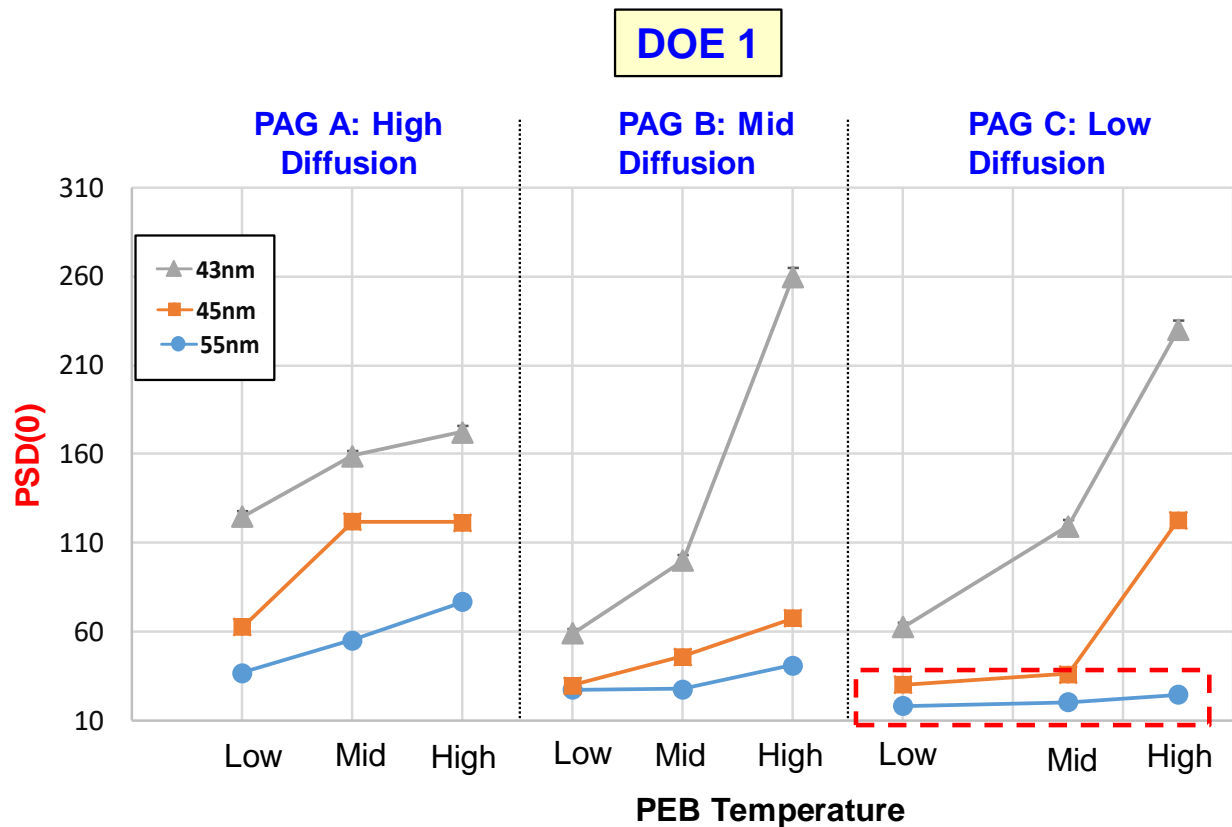


Figure 7. DOE 1 PSD(0) as a function of increased PEB temperature (“Low”, “Mid”, “High”), change in PAG and NILS. Error bars are 2 \* SE and are equivalent to 95% confidence intervals.

### DOE 1 Unbiased LWR

Figure 8 shows how changes in correlation length and PSD(0) translate to unbiased LWR values. It is important to remember that unbiased LWR is measured independently of the PSD analysis although both are carried out on the same sets of lines. For the least diffusive PAG C, at the 55nm lines, LWR stays the same through varying PEB; while at the 45 nm lines LWR decreases from low to mid PEB; and at the 43 nm lines LWR increases over the same bake. LWR also decreases slightly at 55nm for PAG B before it increases at high PEB temperatures. As with PSD(0), the LWR increases significantly after a certain amount of diffusion. This is an example of unbiased LWR being a function of frequency analysis parameters as shown in Figure 9.

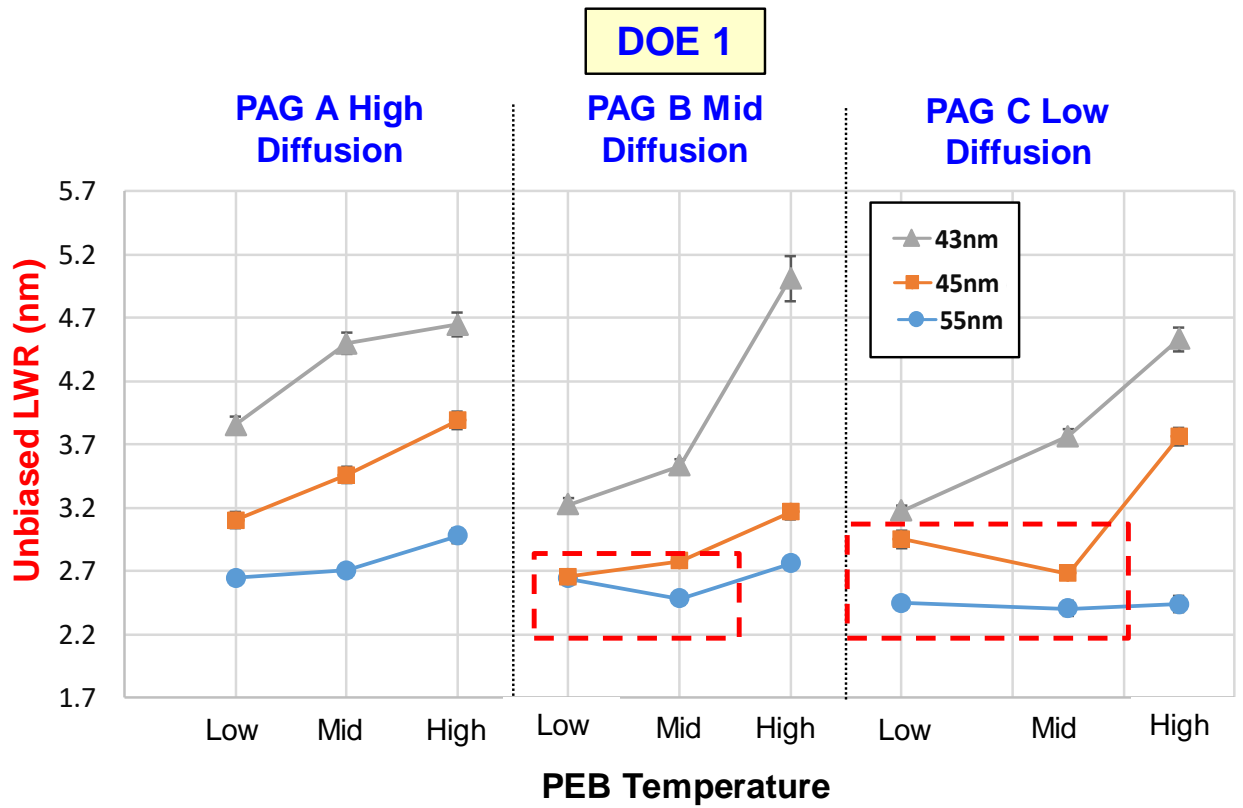


Figure 8. DOE 1 unbiased LWR as a function of increased PEB temperature (“Low”, “Mid”, “High”), change in PAG and NILS. Error bars are 2 \* SE and are equivalent to 95% confidence intervals.

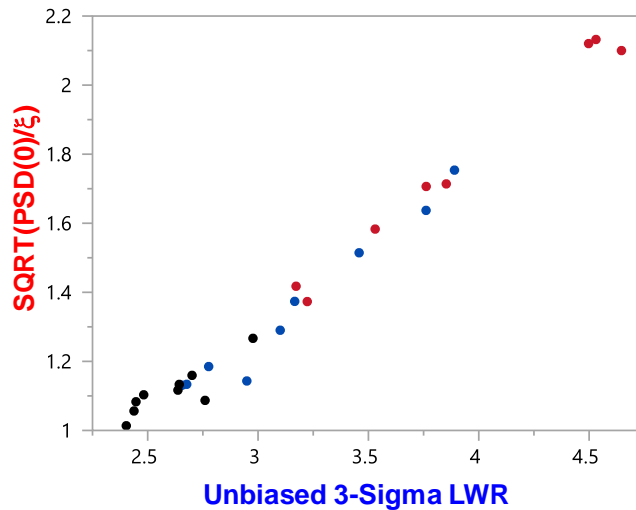


Figure 9. DOE 1 unbiased LWR vs SQRT[PSD(0)/correlation length ( $\xi$ ): 9 wafers 3 feature sizes.

## DOE 2 and 3 Correlation Length

To test whether the trends seen in DOE 1 are reproducible and to further improve our understanding based on formulation, two different DOEs were prepared and tested independently. The PAGs used in these DOEs are different from DOE 1 but again vary from high diffusion PAG D to low diffusion PAG F. DOE 3 varies from DOE 2 only in the ratios of resist components. Figure 10 shows the observed changes in correlation length with respect to varying PEB temperature, formulation, diffusion, and feature size (NILS) for both DOE 2 and DOE 3. Although the trends in correlation length for all three DOEs are very similar despite the differences in formulation, the trends are more pronounced in DOEs 2 and 3. PAG D (higher diffusion photoacid) in both DOE 2 and 3 shows similar trends in correlation length at low NILS (43nm) where correlation length no longer increases with high bake temperature, and correlation length even starts to decrease. A similar change in trend with the high photoacid diffusion formulations was also seen in DOE 1. DOE 3 shows a slight decrease in correlation length at high PEB at low NILS (43nm) for all the formulations; this will be discussed later.

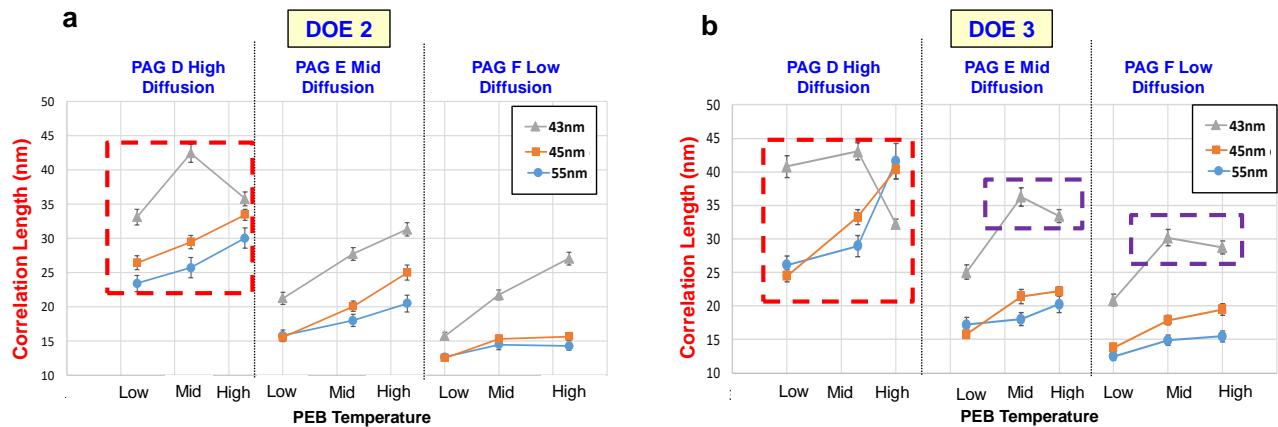


Figure 10. DOE 2 and DOE 3 correlation length as a function of increased PEB temperature (“Low”, “Mid”, “High”), change in PAG and NILS. Error bars are  $2 * SE$  and are equivalent to 95% confidence intervals.

## DOE 2 and 3 Unbiased PSD(0)

The unbiased PSD(0)'s as a function of formulation, photoacid diffusion, PEB temperature, and NILS are shown in Figure 11 for both DOE's 2 and 3. Unbiased PSD(0) systematically reduces from PAG D (higher photoacid diffusion) to PAG F (lower photoacid diffusion). For the high NILS features (55nm), PSD(0) reduces or stays constant through low to mid PEB temperatures for all the tested formulations. For formulations with less photoacid diffusion, the PSD(0) does not increase within this PEB temperature range even for 45nm feature sizes (NILS 2.35). As discussed in DOE 1, the frequency analysis demonstrates what is changing in the resist development response as each reaches a diffusion optimum. For “correlation length driven” resists, LWR improves due to the increase in correlation length and because the area under the PSD curve is reduced. High photoacid diffusion PAG D behaves differently at low NILS as was seen in DOE 1 with PAG A.

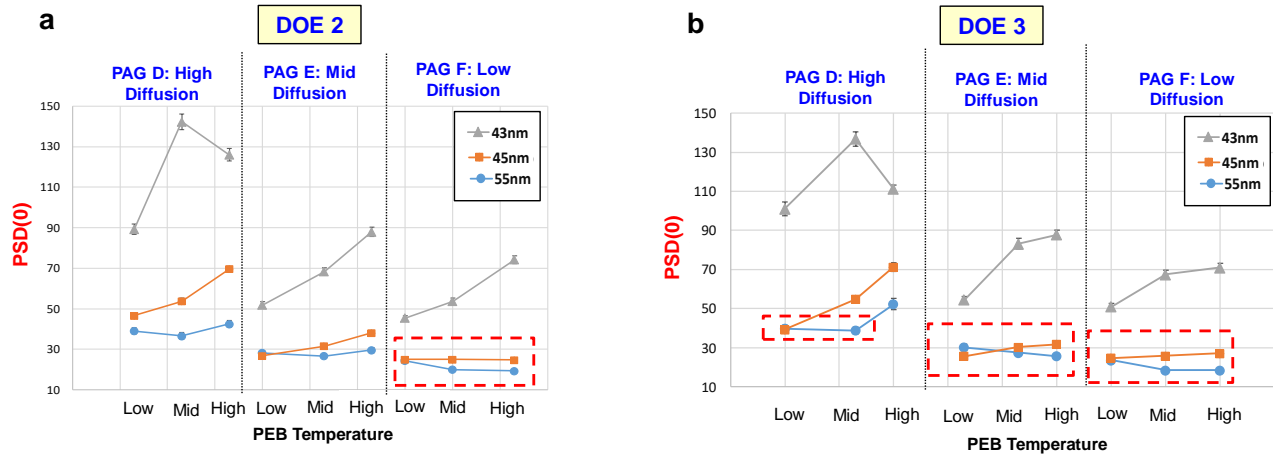


Figure 11. DOE 2 and DOE 3 PSD(0) as a function of increased PEB temperature (“Low”, “Mid”, “High”), change in PAG and NILS. Error bars are 2 \* SE and are equivalent to 95% confidence intervals.

### DOE 2 and 3 Unbiased LWR

Changes in measured unbiased LWR become more pronounced as correlation length and PSD(0) start to change in opposite directions. An example of this is seen in Figure 12 for both 55nm and 45nm images, where the LWR reduces for low diffusion formulations (PAG F) as the PEB temperature increases. Figure 13 illustrates how the changes in unbiased LWR can be explained and verified by changes occurring with LWR frequency components. In this graph, DOE 3, the unbiased LWR on the y-axis is replaced with the  $\sqrt{\text{PSD}(0)/\text{correlation length}}$ . Expressing LWR as a function of correlation length and PSD(0) combined shows the same trends through PEB, NILS and formulation, as observed in the measured unbiased LWR (Figure 13b). This confirms that the trends we observed are likely not measurement artifact but a real function of the resist response to varying NILS and PEB at different frequencies down the line.

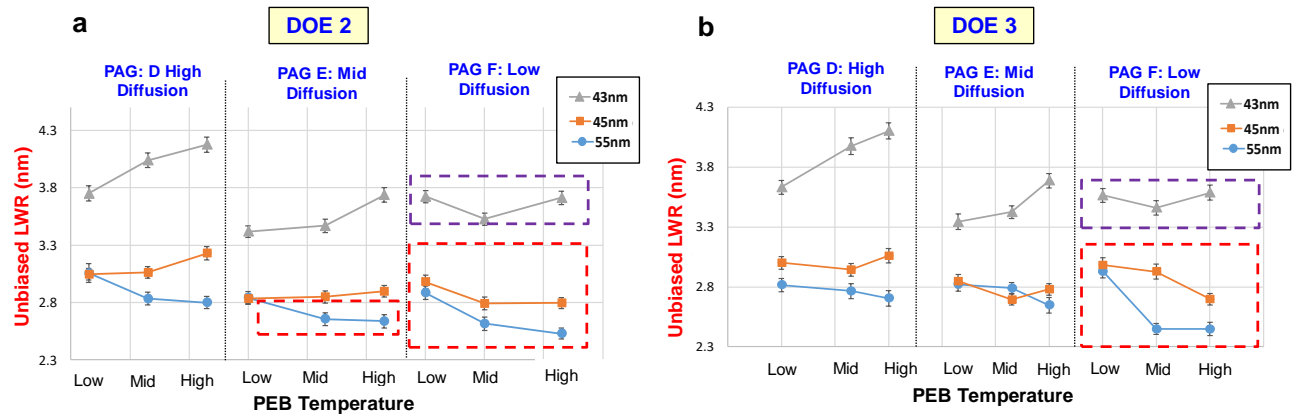


Figure 12. DOE 2 and DOE 3: unbiased LWR as a function of increased PEB temperature (“Low”, “Mid”, “High”), change in PAG and NILS. Error bars are 2 \* SE and are equivalent to 95% confidence intervals.

## DOE 3: SQRT(PSD(0)/correlation length)

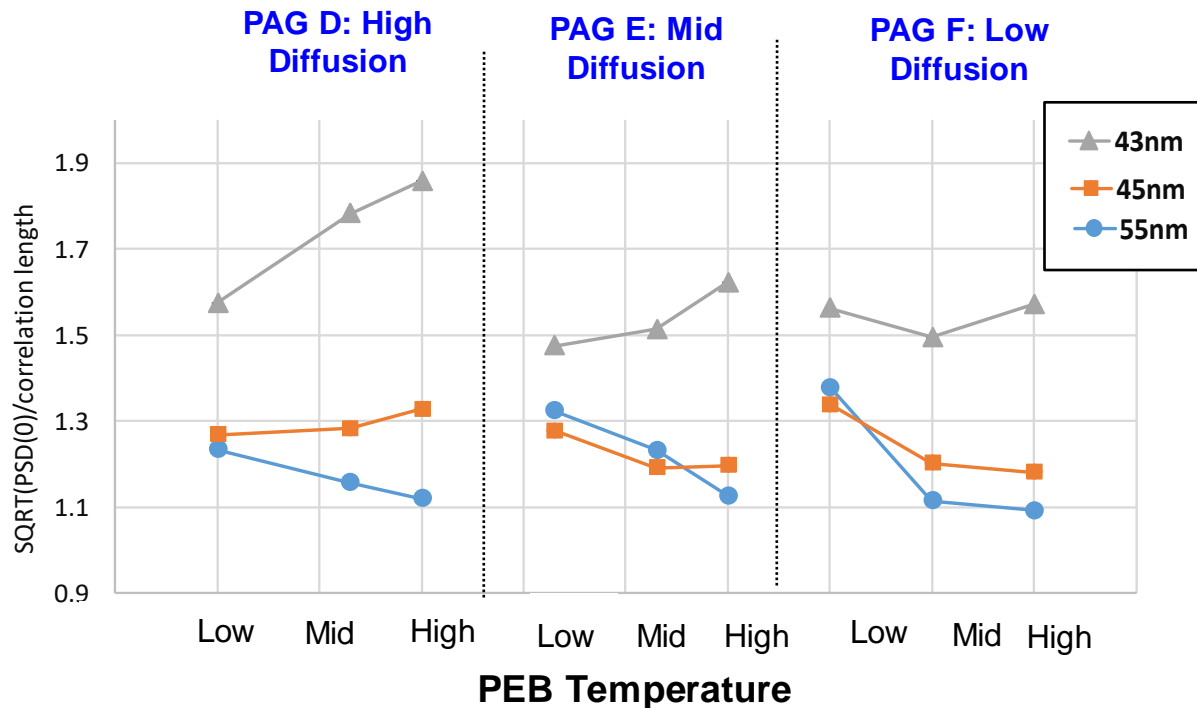


Figure 13. DOE 3: unbiased LWR as a function of increased PEB temperature (“Low”, “Mid”, “High”), change in PAG and NILS. Error bars are 2 \* SE and are equivalent to 95% confidence intervals.

### Correlation length and PSD(0) as a function of NILS

It is well known that LWR increases as a function of 1/NILS, but how does correlation length and PSD(0) change as a function of NILS? While there seems to be some dependence of PSD(0) on both NILS and correlation length, what happens to correlation length itself? Figure 14 shows the increase in correlation length in all three DOEs as a function of NILS and formulation photoacid diffusion, where PEB temperature is kept low. DOE 2 and 3 show no significant change in correlation length between NILS values of 3.01 and 2.35 but show notable increases at lower NILS. DOE 1 shows more change in correlation length through the range of tested NILS.

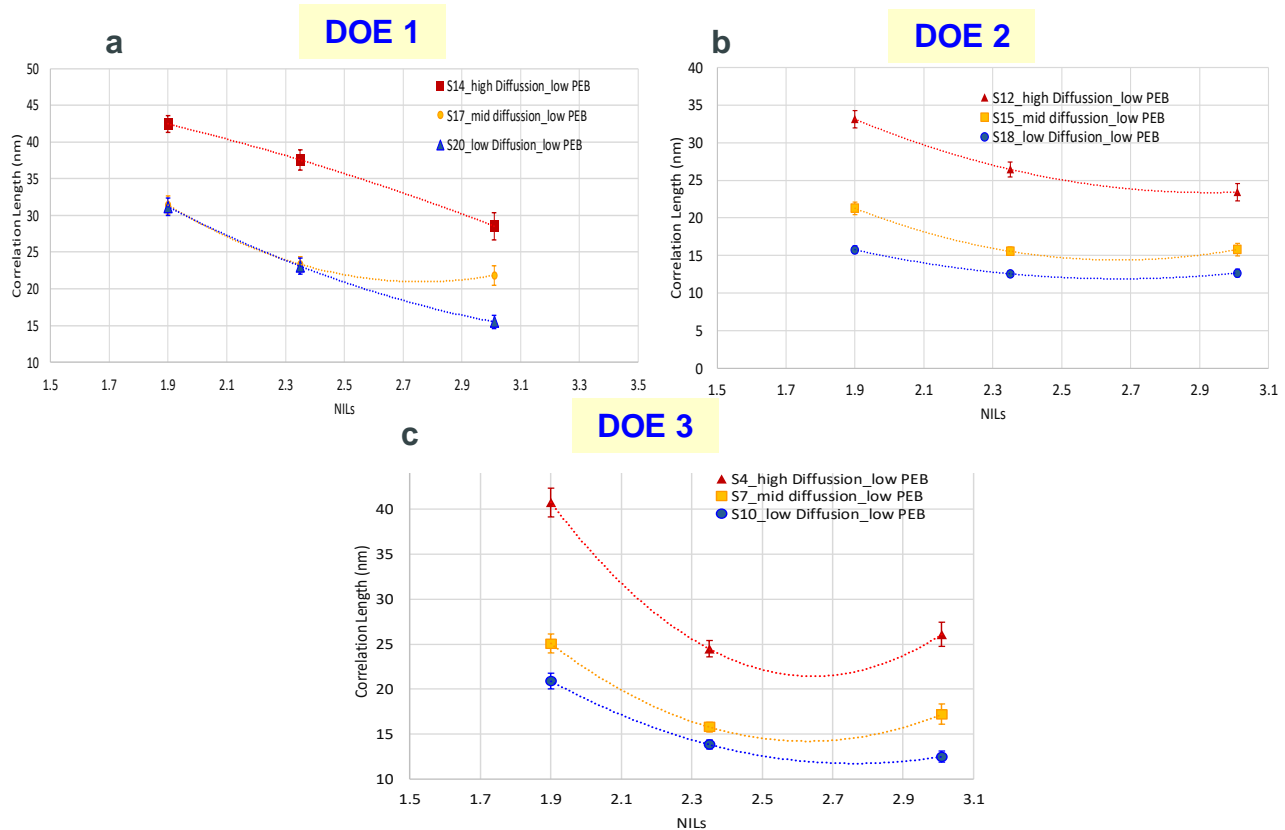


Figure 14. DOE 1, 2 and 3. The red lines are high diffusion formulations (PAG A and D), yellow are medium diffusion (PAG B and E) and blue are low diffusion formulations (PAG C and F). Correlation lengths plotted through NILs while keeping PEB temperature low and seeing the impact of formulation diffusion.

Figure 15 shows the change in correlation length through PEB and NILS with different photoacids. Figures 14 and 15 clearly show that correlation length is increasing as NILS decreases. It was expected that correlation length or resist blur may not increase through NILS as shown in Figure 16 by Gallatin.<sup>7</sup> The diagram on the left shows the impact of resist blur on an image with a low image slope (poor resolution) and the image on the right shows the effect of the same resist blur on a steeper image slope (improved resolution). The impact of the resist blur at low NILS is much larger on the LWR than at high NILS; however the blur itself is not changing. In this case, are we observing the increase of an “effective correlation length”? If an increase in resist photoacid diffusion reduces the effective image log slope, it seems that reducing the image log slope yields a behavior similar to an increase in resist blur or correlation length. From a chemistry perspective, the dose to size increases at lower NILS which largely compensates for the lower image log slope in terms of level of photoacid generation, but the production or influence of each photoacid is a lot more spatially separated, due to diffraction.



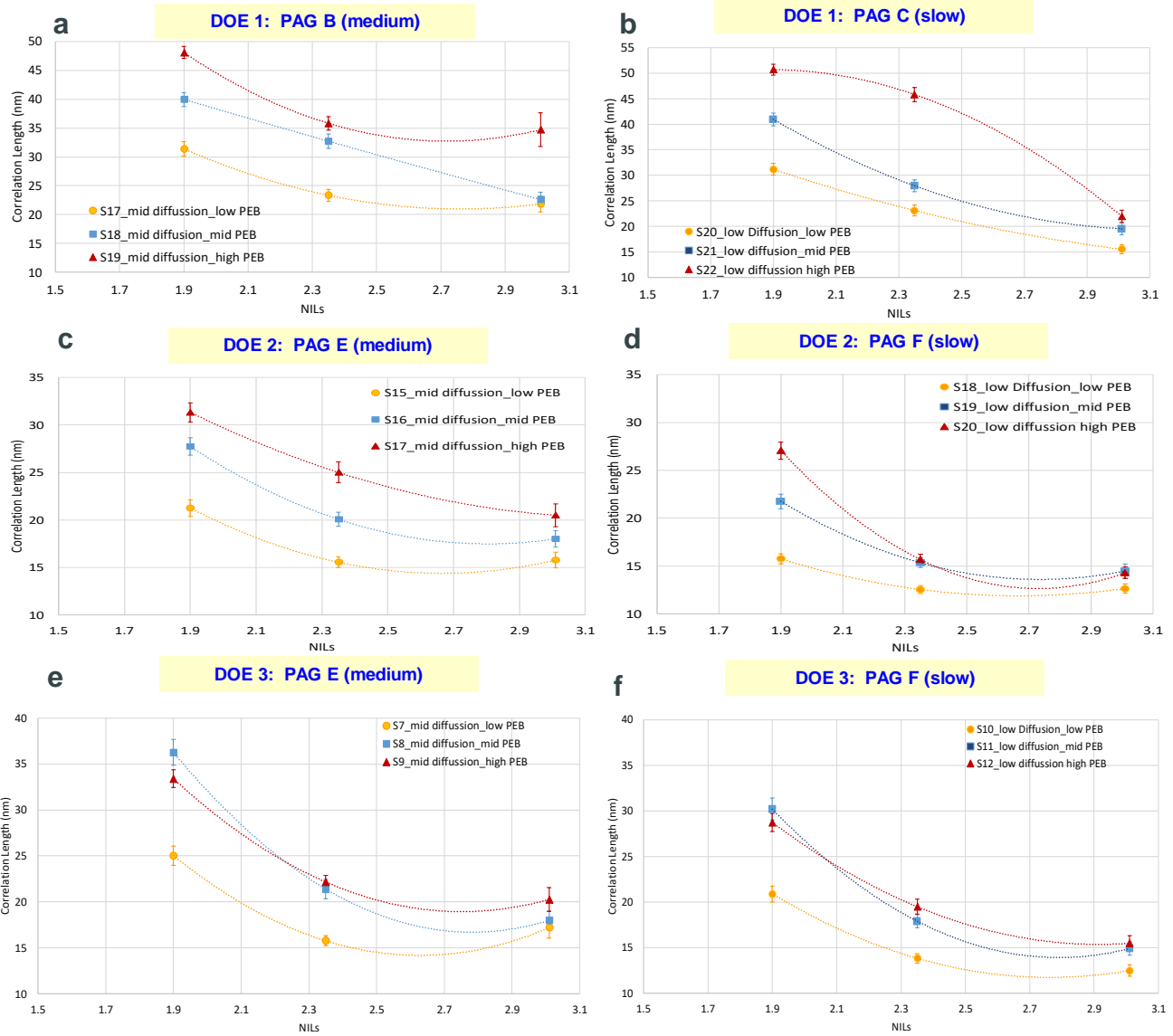
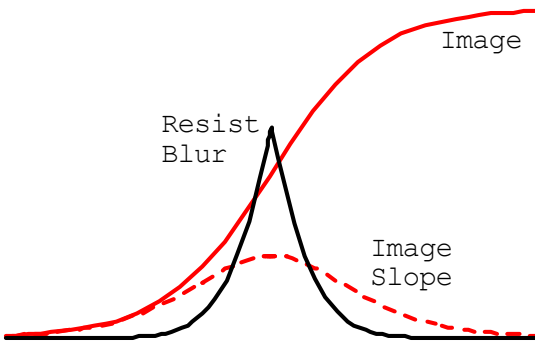


Figure 15. DOE 1, 2 and 3: Medium or slow photoacid diffusion formulations show the impact of PEB temperature through NILs on correlation length.

**Resist resolution is better than  
Image resolution Low NILS**



**Image resolution is better than  
Resist resolution high NILS**

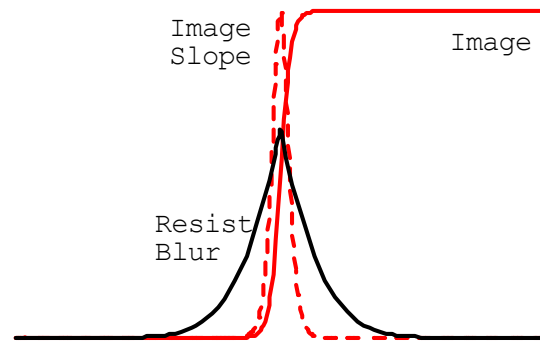


Figure 16. There are two different resolution regimes relevant for discussing LWR. On the left the image has lower resolution than the resist (low NILS). On the right, this is reversed and the resist has lower resolution than the image (high NILS). In both cases the resist blur is considered the same. [7] Reprinted with permission from SPIE

Another possible explanation for why correlation length is increasing through NILS is illustrated in Figure 17. The left diagram illustrates the steep gradient and high concentration photoacid protons (red dots) at the exposed sides of the mask edge at high NILS. We hypothesize that with a higher gradient and photoacid proton concentration in the exposed area, that more diffusion pathways would overlap, thus reducing the actual correlation length due to the interferences between adjacent overlapped pathways, the result of which is that photoacid diffusion then becomes uncorrelated. The right diagram proposes that a lower NILS creates a state with a lower photoacid gradient, and as a result, the concentration of photoacid protons at the mask edge is spread out more. The greater average distance between photoacid protons at lower NILS reduces the overlap of diffusion deprotection reaction pathways during PEB, thus effectively increasing correlation length. The real correlation length is effectively the same at each NILS condition as in Figure 16, but what we see experimentally could be different due to interactions. In Figure 11 DOE 3, the correlation length starts to reduce at high bake temperatures even in the low NILS (43nm) images. Despite the reduced dose at higher bake temperatures, could this decrease in correlation length indicate a point where diffusion spheres are starting to overlap again?

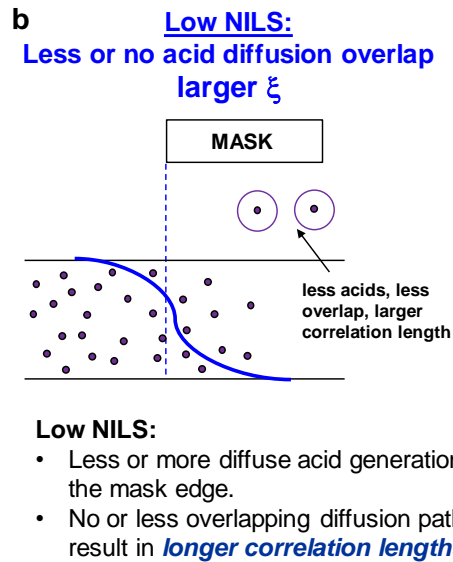
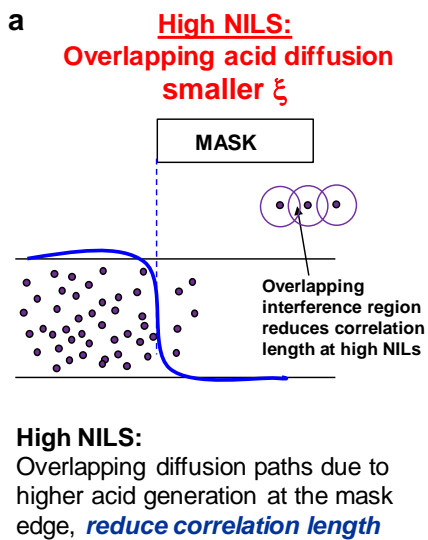


Figure 17a-b. 17a shows protons (red dots) at a high NILS mask edge where diffusion reaction pathways could overlap. 17b illustrates the results of a lower concentration of protons at the mask edge due to lower NILS.

It has been shown that LWR reduces as a function of increasing correlation length and decreasing PSD(0) for a given feature. However, as NILS for a given image decreases the correlation length and resist blur increase to the point where PSD(0) and resolution are impacted and LWR increases. Understanding how correlation length changes through NILS can highlight which resists will be impacted by decreasing feature size. As seen in Figure 5, three resists showed improved LWR at lower NILs and two resists did not. Figure 18 supports the hypothesis that lower correlation length and PSD(0) resists at higher NILs are more likely to show improved LWR at lower NILs.

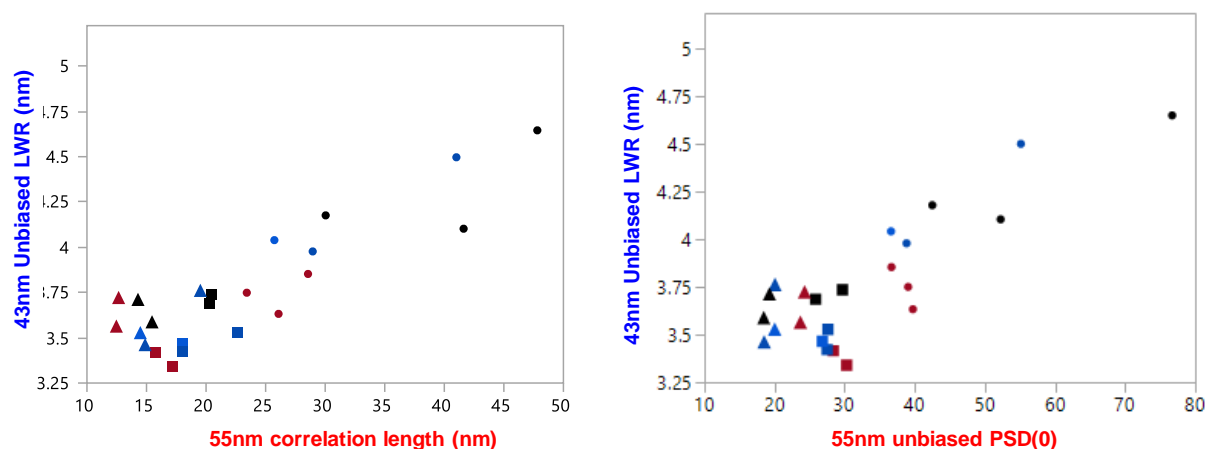


Figure 18. Decreasing 55nm feature correlation length and PSD(0) show improved LWR at 43nm features. Circles are high PAG diffusion, squares are mid PAG diffusion and triangles are low PAG diffusion.

#### 4. CONCLUSIONS

In this paper, we show the benefits of understanding frequency analysis with respect to understanding the impact of photoacid diffusion and NILS on LWR. Our data shows that as photoacid diffusion increases, so does correlation length. The impact of photoacid diffusion and correlation length on PSD(0) was shown to be different in that up to a certain photoacid diffusion limit PSD(0) either stayed constant or decreased. The optimal photoacid diffusion occurs when PSD(0) decreases or remains constant while correlation length increases. When the two parameters are co-optimized, the LWR is minimized. As photoacid diffusion increases further, both correlation length and PSD(0) increase significantly and thus significantly increase the resultant LWR. The concept of a photoacid diffusion optimum and an increase in correlation length with increased diffusion is not new, but here we show how the dual combination of PSD(0)/correlation length experimentally influences unbiased LWR. When we break down LWR into its frequency components we find as expected that PSD(0) also increased with decreasing NILS. We also find that correlation length increases through increasing NILS. The increase in correlation length can impact an image in two ways: it can decrease LWR if PSD(0) has not increased significantly (typically a higher NILS or lower photoacid diffusion case), or it can significantly increase LWR if PSD(0) also significantly increases as the PSD(0) plays a dominant role in defining the total area under the PSD curve. The resolution or NILS has a significant impact on which regime takes effect. A hypothesis is proposed linking NILS and photoacid reaction diffusion to observed LWR. Future work will include further defining the relationships between both correlation length and PSD(0) through NILS and improving our understanding of what governs the observed increase in correlation length.

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