Unbiased Roughness Measurements: The Key to Better Etch Performance

Andrew Liang[a], Chris Mack[b], Stephen Sirard[a], Chen-wei Liang[a], Liu Yang[a], Justin Jiang[a], Nader Shamma[a], Rich Wise[a], Jengyi Yu[a], Diane Hymes[a]

[a]Lam Research Corp., 4650 Cushing Pkwy, Fremont, CA, 94538, USA,
[b]Fractilia, LLC, 1605 Watchhill Rd, Austin, TX, 78703, USA

ABSTRACT

Edge placement error (EPE) has become an increasingly critical metric to enable Moore's Law scaling. Stochastic variations, as characterized for lines by line width roughness (LWR) and line edge roughness (LER), are dominant factors in EPE and known to increase with the introduction of EUV lithography. However, despite recommendations from ITRS, NIST, and SEMI standards, the industry has not agreed upon a methodology to quantify these properties. Thus, differing methodologies applied to the same image often result in different roughness measurements and conclusions. To standardize LWR and LER measurements, Fractilia has developed an unbiased measurement that uses a raw unfiltered line scan to subtract out image noise and distortions. By using Fractilia's inverse linescan model (FILM) to guide development, we will highlight the key influences of roughness metrology on plasma-based resist smoothing processes.

Test wafers were deposited to represent a 5 nm node EUV logic stack. The patterning stack consists of a core Si target layer with spin-on carbon (SOC) as the hardmask and spin-on glass (SOG) as the cap. Next, these wafers were exposed through an ASML NXE 3350B EUV scanner with an advanced chemically amplified resist (CAR). Afterwards, these wafers were etched through a variety of plasma-based resist smoothing techniques using a Lam Kiyo® conductor etch system. Dense line and space patterns on the etched samples were imaged through advanced Hitachi CDSEMs and the LER and LWR were measured through both Fractilia and an industry standard roughness measurement software. By employing Fractilia to guide plasma-based etch development, we demonstrate that Fractilia produces accurate roughness measurements on resist in contrast to an industry standard measurement software. These results highlight the importance of subtracting out SEM image noise to obtain quicker developmental cycle times and lower target layer roughness.

1.0 INTRODUCTION

Throughout the years, continuous innovation in the industry has led to the pinnacle of semiconductor technology that is employed today. However, challenges such as edge placement error (EPE) have lately become increasingly critical in enabling Moore's Law. Stochastic variations, as characterized for lines by line width roughness (LWR) and line edge roughness (LER), are especially dominant factors in EPE and are known to increase with the introduction of EUV lithography.[1] Organizations, such as ITRS, NIST, and SEMI standards, have provided recommendations on the required LWR and LER to enable the next node technology.[2-5] However, despite this, the industry still has no agreed upon methodology to quantify these metrics.

Typically, to obtain roughness measurements, standard filters, such as Gaussian and box filters, are applied to scanning electron microscope (SEM) images to produce a measurable linescan.[6] These algorithms require user input for the number of pixels to smooth in the X and Y directions, which is highly subjective and leads to varying SEM noise smoothing. Consequently, as Mack shows in his study, the same image often results in vastly different roughness measurements and conclusions that depend on these user inputs.[6] Furthermore, even if these pixel parameters were standardized, the filters would still subtract out an unknown amount of image noise. The reason is that a fixed algorithm blurs high frequency roughness over the same frequency range.[7] Physical line structures have different correlation lengths and different amounts of image noise, so a single filter applied to a variety of images will invariably produce both overcompensated and undercompensated SEM noise subtractions. During analysis, engineers will not be able to distinguish between imaging and true process improvements and could potentially be misled to optimize their processes in the wrong direction.

An example is when plasma-based etch techniques are developed to reduce LWR and LER at the resist layer to achieve the desired roughness at the target layer.[8] Imaging roughness at the resist layer is particularly challenging due to lower image contrast, and thus higher SEM image noise, that is often observed at this layer. Optimizations using inaccurate process trends on resist can delay process development for days or months. Furthermore, if process trends at the resist and target layers do not match, the process optimizations will require experiments at the resist level be transferred all the way down to the target layer for every single experimental condition, which results in longer developmental cycle times.

To address these predicaments, Fractilia has developed an unbiased measurement that subtracts out image noise and distortions through Fractilia's inverse linescan model (FILM) without user input.[6] Given a set of beam conditions and feature geometries, FILM uses a physics-based model that detects edge locations from raw unfiltered line scans and results in robust roughness measurements even in the presence of high image noise.[6] By employing Fractilia to guide plasma-based etch development, we demonstrate here that Fractilia produces accurate roughness measurements in high SEM noise images in contrast to an industry standard measurement software that uses box filtering, resulting in quicker developmental cycle times and lower target layer roughness.

2.0 METHODOLOGY

Test wafers were deposited to represent a 5 nm node EUV logic stack. The patterning stack, seen in Figure 1 below, consists of a Si target layer with a spin-on carbon (SOC) layer as the hardmask and a spin-on glass (SOG) layer as the cap.

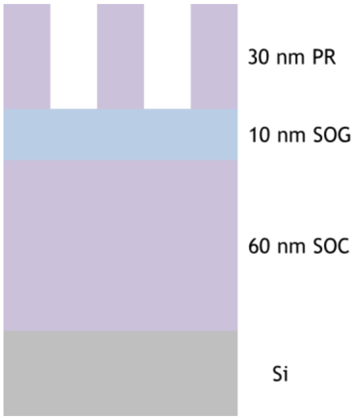


Figure 1: Patterning stack

These wafers were then exposed through an ASML NXE 3350B EUV scanner with advanced chemically amplified resists (CAR). Afterwards, they were etched through a variety of plasma-based resist smoothing techniques using a Lam Kiyo conductor etch system.[8] Plasma etch processes were chosen to produce after etch inspection (AEI) roughness trends at the resist and Si target layers and consists of two main etch steps: the photoresist (PR) treatment and the main etch. The resist treatment smoothed roughness at the resist layer while the main etch transferred the improvements down to the target layer. 56 nm pitch dense line and space patterns were imaged through advanced Hitachi CDSEMs and the LER and LWR were measured through both Fractilia's MetroLER software (v1.1) and a different industry standard roughness measurement software. The measurement parameters are highlighted in Table 1:

Table 1: Software measurement parameters

	Fractilia	Standard
X Pixel Filter Size	N/A	7
Y Pixel Filter Size	N/A	8
Threshold	50%	50%

X and Y pixel filter size parameters were determined qualitatively by minimizing the smoothed distance while maintaining robust measurements. In addition, Fractilia and standard software measurements were completed on the same set of images for a head-to-head comparison.

To begin the analysis of the two roughness measurement approaches, the fundamental relationship between measured roughness, metrology noise, and actual roughness was employed: [7]

$$\sigma^2_{measured} = \sigma^2_{metrology\ noise} + \sigma^2_{actual}\ (1)$$

Fractilia aims to eliminate the metrology component, reducing the equation to:

$$\sigma^2_{measured} = \sigma^2_{actual}\ (2)$$

If accomplished, Fractilia would always yield the correct process trend regardless of SEM imaging conditions. On the other hand, the standard software would yield either equation depending on the magnitude of the metrology noise after filtering. Intuitively for the standard software, high SEM image noise would comply with equation 1 while low SEM image noise would adhere closer to equation 2.

Trend data is crucial for etch process optimization, so looking at the improvement or change in measured roughness between one process and another becomes more practical than comparing absolute roughness. This then transforms equations 1 and 2 into the following:

$$\Delta\sigma^2_{measured} = \Delta\sigma^2_{metrology\ noise} + \Delta\sigma^2_{actual}\ (3)$$

$$\Delta\sigma^2_{measured} = \Delta\sigma^2_{actual}\ (4)$$

Once more, measured roughness trends of images with low SEM image noise would obey equation 4 regardless of measurement algorithm. However, with high SEM image noise, Fractilia becomes differentiated from the standard software. Specifically, trend measurements from Fractilia would continue to adhere to equation 4, but measurements from the standard software would comply with equation 3 instead. Then, if the change in metrology noise becomes opposite and greater than the change in actual roughness, measurements from the standard software would result in inaccurate trends.

Thus, the goal of this analysis is then to produce different trends at the resist layer and similar trends at the Si layer. To accomplish this, one parameter of the PR treatment was varied to produce different roughness trends at the resist layer while one main etch was used to transfer those trends into the Si layer. As a result, the change in actual roughness equates to:

$$\Delta\sigma^2_{actual} = \Delta\sigma^2_{PR\ Treatment}\ (5)$$

after the resist treatment and:

$$\Delta\sigma^2_{actual} = \Delta\sigma^2_{PR\ Treatment} + \Delta\sigma^2_{Main\ Etch}\ (6)$$

after the resist treatment and main etch. Because the same main etch is used for all experiments, any change in roughness resulting from the main etch is approximated to be the same, so a constant *m* can be used instead, transforming equation 6 into:

$$\Delta\sigma^2_{actual} = \Delta\sigma^2_{PR\ Treatment} + m\ (7)$$

By substituting equations 3 and 4 with 5 and 7 for various conditions, the following equations are derived:

$$\Delta\sigma^2_{measured} = \Delta\sigma^2_{metrology\ noise} + \Delta\sigma^2_{PR\ Treatment}\ (8)$$

$$\Delta\sigma^2_{measured} = \Delta\sigma^2_{PR\ Treatment}\ (9)$$

$$\Delta\sigma^2_{measured} = \Delta\sigma^2_{PR\ Treatment} + m \ (10)$$

Through these three equations, the following flow chart for determining which algorithm is correct can be procured.

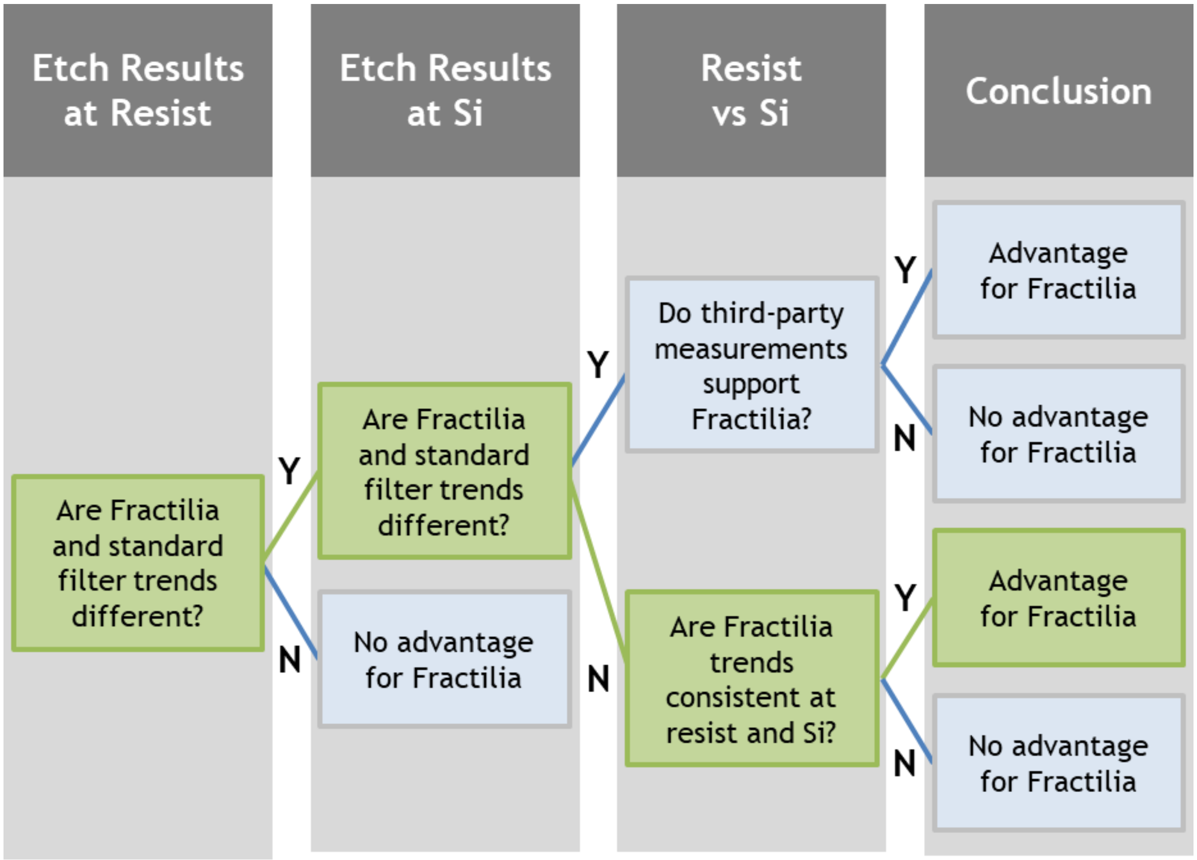
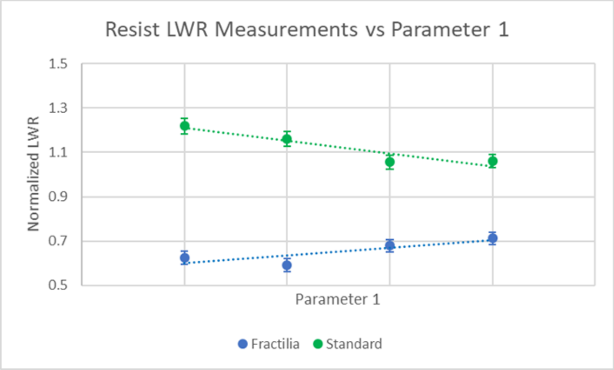


Figure 2: Flow to analyze Fractilia and standard measurements

By producing opposing trends at the resist and similar trends at the Si layer, the underlying theory of roughness measurements discussed above and Fractilia measurements can be analyzed and verified.

3.0 RESULTS AND DISCUSSION

First, AEI trends at the resist layer were processed and measured and shown in Figures 3 and 4 below:



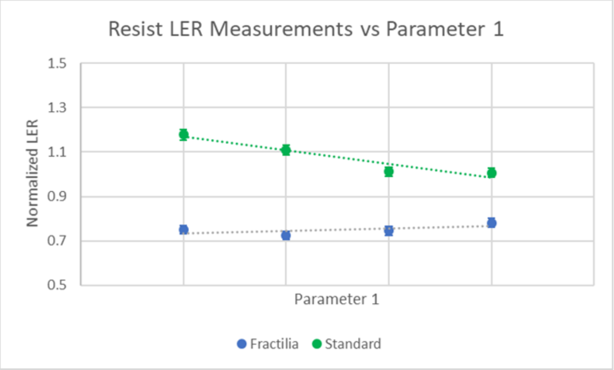


Figure 3 (left): LWR trends after PR treatment
Figure 4 (right): LER trends after PR treatment

The resulting data is consistent with the prediction that Fractilia can produce a different trend than the standard software, especially when there is appreciable SEM image noise. Fractilia shows that as parameter 1 is increased, the LWR and LER degrades. Through power spectral density (PSD) analyses seen below, the image noise is indeed subtracted out for both LWR and LER for Fractilia.

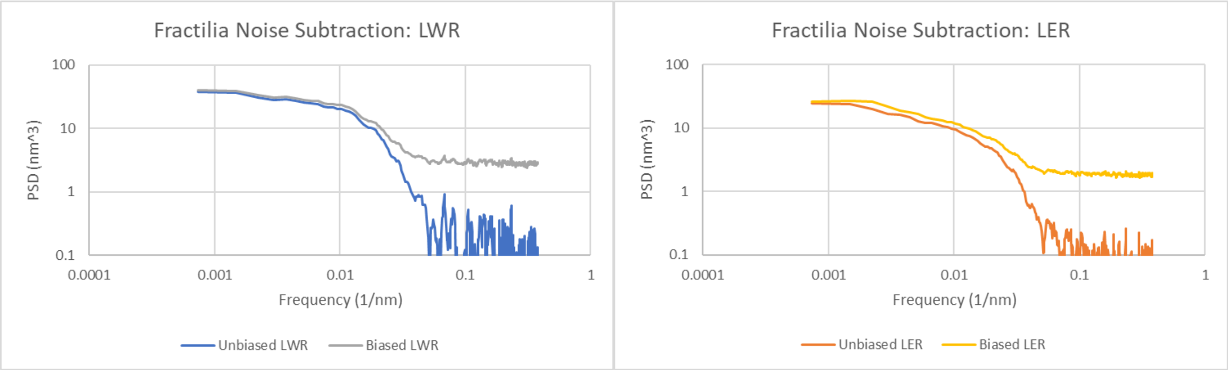


Figure 5a (left) and 5b (right): Post PR treatment PSDs for LWR and LER using Fractilia

Thus, through equation 9, the degradation seen in the measured roughness is purely due to the PR treatment process. It is expected that after the main etch, the same trends will remain. On the other hand, through equation 8, the improvement in LWR and LER for the standard software is surmised to be due to an improvement in image noise. Through visual inspections of the SEM images shown in Figures 6a and 6b below, this is indeed the case. Increasing parameter 1 yields clearer images, which reduce the contribution of SEM image noise to roughness.

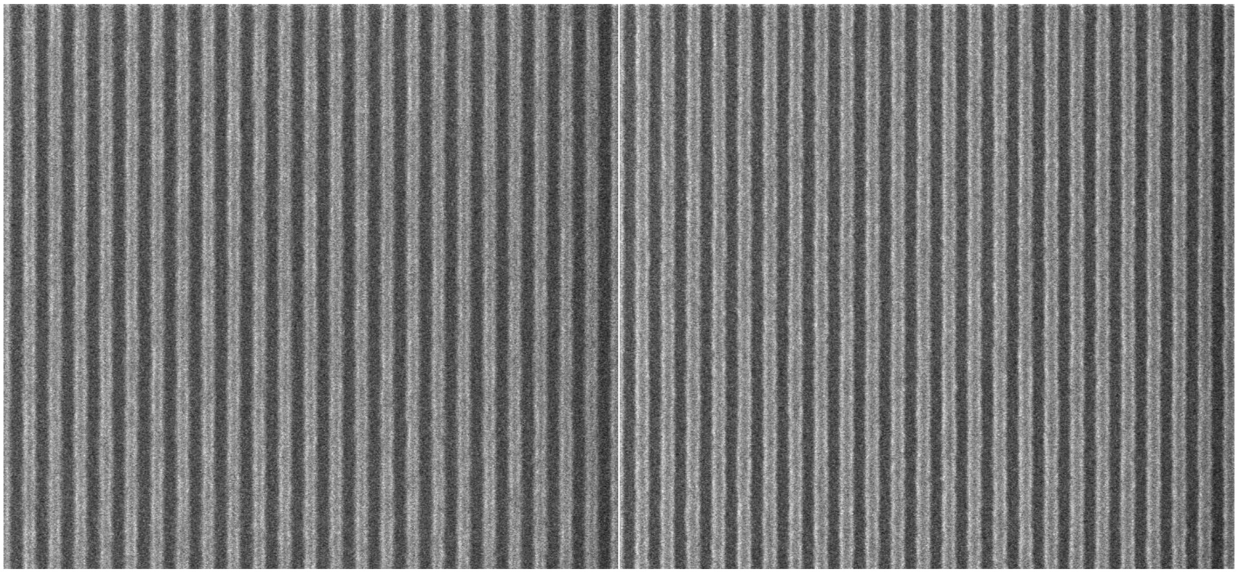
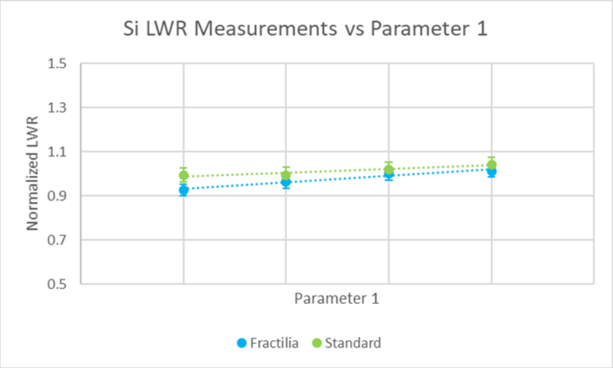


Figure 6a (left): SEM image of decreased parameter 1
Figure 6b (right): SEM image of increased parameter 1

As Fractilia is confirmed to provide a differentiated solution, the samples are etched down into the target layer, where SEM image noise plays a negligible role, to confirm Fractilia's measurement accuracy. The AEI roughness results from the Si layer are shown below:



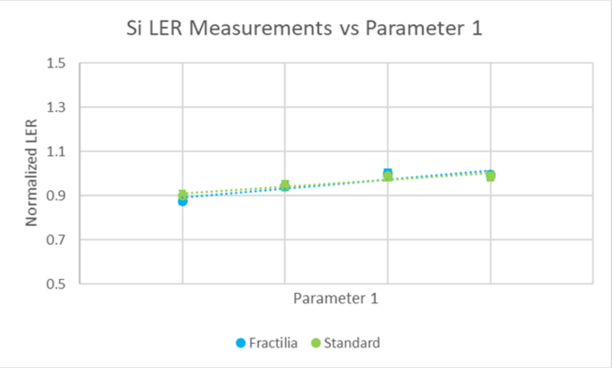
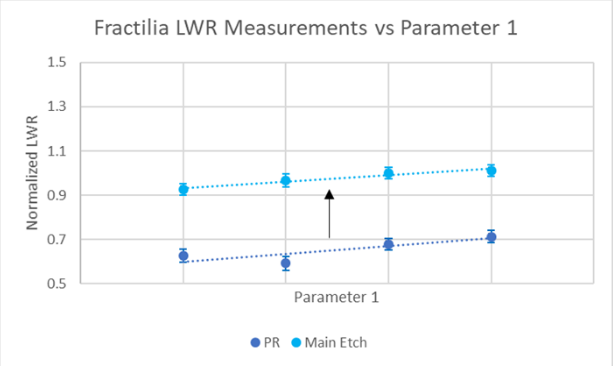


Figure 7 (left): LWR trends after Si main etch
Figure 8 (right): LER trends after Si main etch

Again, the resulting data is consistent with the theoretical predictions. That is, SEM images in Si have low metrology noise and produces identical trends between Fractilia and software using standard image filters. The low noise is demonstrated from the overlapping measurement points between Fractilia and standard filters, which occurs when the contribution from metrology noise is negligible compared to the contribution from actual line roughness. Consequently, the similar trends between Fractilia and the standard software can then be explained through equation 10.

To show the change in trends from the resist to the Si layer for Fractilia and the standard filters, the following figures and tables were produced:



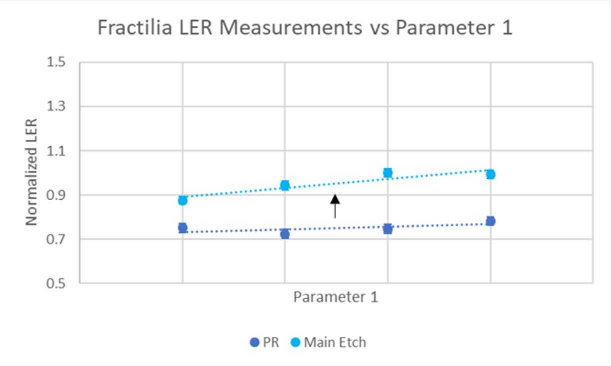
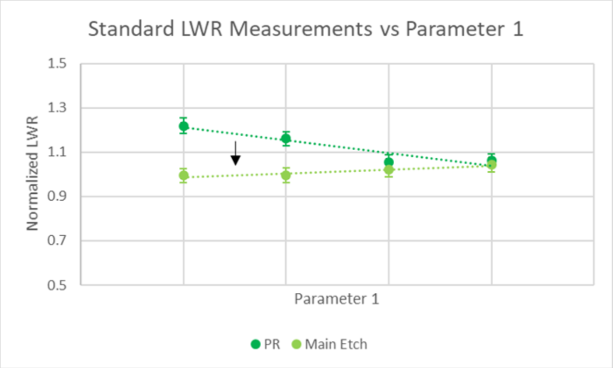


Figure 9 (left): Resist and Si LWR trends for Fractilia
Figure 10 (right): Resist and Si LER trends for Fractilia



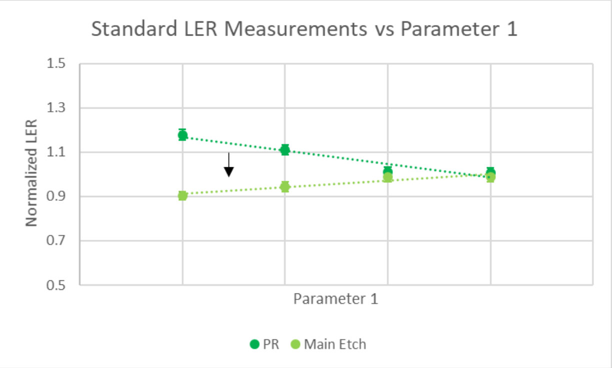


Figure 11 (left): Resist and Si LWR trends for standard filter
Figure 12 (right): Resist and Si LER trends for standard filter

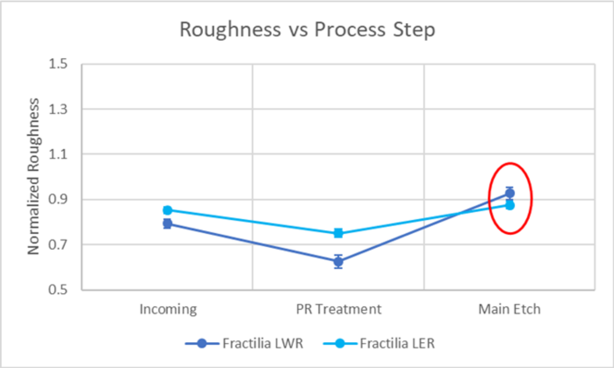
Table 2: LWR trend slopes

LWR	Fractilia	Standard
Resist	0.0007	-0.0011
Si	0.0006	0.0003

Table 3: LER trend slopes

LER	Fractilia	Standard
Resist	0.0002	-0.0012
Si	0.0008	0.0006

When comparing resist and Si layers, Fractilia maintains the same positively sloped trends for both LWR and LER, which confirms Fractilia's measurement accuracy. It is of note that for LWR, the magnitudes of the slopes are roughly the same, but for LER, the slope at the resist is much less than that at Si. This is thought to be due to some physical interaction between the resist treatment and the main etch, which suggests that these particular etch processes affect LWR and LER independently. On the other hand, the standard software measurements flip the LWR and LER trends from negatively sloped to positively sloped and offer no other additional analysis from the magnitude of the slopes. By using the standard software, it is possible to optimize etch processes in the wrong direction. Even more, it is entirely possible to spend resources optimizing the wrong process, as highlighted in Figures 13 and 14.



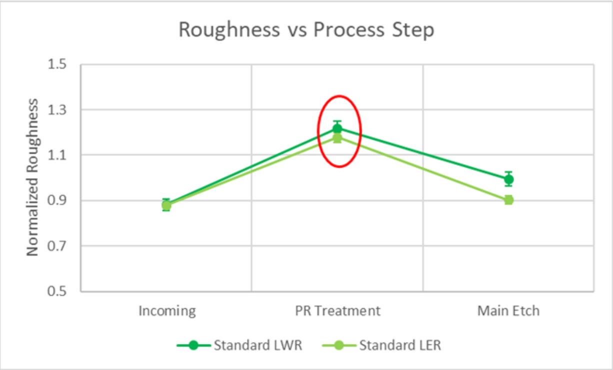
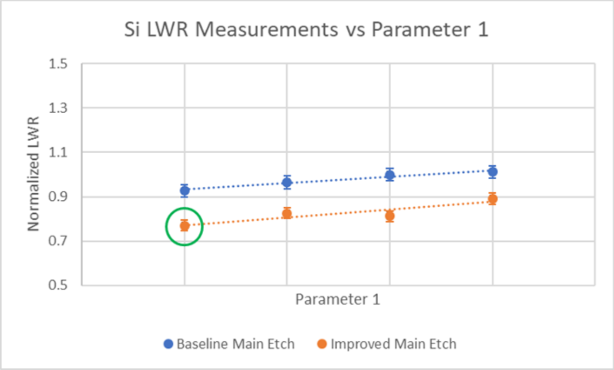


Figure 13 (left): Fractilia LWR and LER as a function of process step
Figure 14 (right): Standard LWR and LER as a function of process step

Fractilia identifies the main etch as a process step that needs to be improved while the standard software identifies the PR treatment instead. If the standard software was used, time and resources may have been spent on optimizing the PR treatment with possibly minimal gain. Conversely, quick tuning of the main etch, as suggested by Fractilia measurements, leads to improvement in LWR and LER as shown in Figures 15 and 16 below:



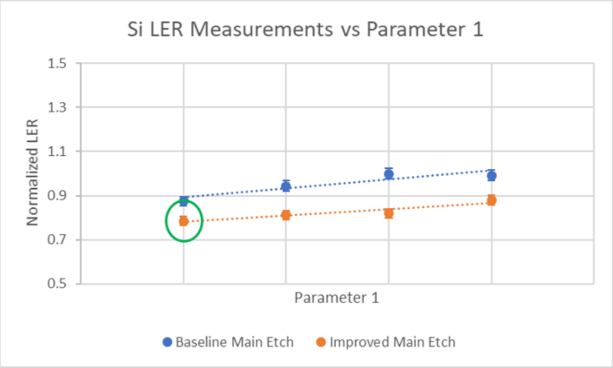


Figure 15 (left): LWR reduction from improving the main etch
Figure 16 (right): LER reduction from improving the main etch

By expanding the scope of the process development to include optimization in the main etch, the standard software would still have led to the same conclusion as Fractilia. However, time and money would be lost compared to Fractilia. With this, the differentiated trends at the resist layer as well as the identical trends at the Si layer have been demonstrated and the trends produced by Fractilia have been determined to be correct from theory to experimentations.

4.0 CONCLUSION

Quantifying roughness consistently throughout the industry has been a continuous challenge. Fractilia aims to standardize roughness measurements through two key innovations: a robust physics-based inverse linescan model and automatic image noise subtractions. We discussed the theory behind roughness measurements and validated the value brought by Fractilia experimentally through comparisons of roughness trends measured by Fractilia and an industry standard software at the resist and Si layers. We observed that roughness trends between Fractilia and the industry standard software did not agree at the resist level, but did agree at the Si layer after main etch. We found that roughness trends measured by Fractilia were consistent between the resist and Si layer but roughness trends measured by the industry standard software were not. The aggregate of these trends demonstrated the accuracy of the Fractilia measurements in low contrast and high SEM image noise relative to the box filtered measurements. These results further showed that Fractilia's methodology can lead to improved productivity in process development by accurately identifying process steps that require improvements. Ultimately, Fractilia's methodology shows clear advantages over standard industry practices and is the key to better roughness measurements and faster etch development cycles.

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