euspen's 25th International Conference & Exhibition, Zaragoza, ES, June 2025
www.euspen.eu

Multi-scale optical interferometry analysis of polished copper thin films for noise characterization

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Abstract

The precise assessment of surface quality, particularly roughness, is critical in semiconductor manufacturing. Polished copper thin films, with roughness values often approaching measurement noise levels, require highly accurate characterization to optimize manufacturing processes and ensure device reliability.

Our study focused on characterising and reducing the noise inherent in roughness measurements of thin copper films using a Bruker Contour-GT interferometer. A multi-scale approach was implemented through 64 repeated measurements at observation scales of 5X, 20X, 50X, and 115X, providing a comprehensive surface characterization. Statistical processing significantly reduced measurement noise, as demonstrated by spectral power density (PSD) curves, and enabled the extraction of precise roughness parameters, including Sq (root mean square height), Sdq (root mean square gradient), Sdr (developed interfacial surface ratio), Sal (autocorrelation length), and Str (texture aspect ratio).

Using this statistical protocol, we carried out repeated measurements at 37 different points on a wafer, revealing small variations in surface quality. Analysis of this data, using an 64 images-averaging per measurement point, enabled us to reduce noise considerably and obtain more accurate roughness parameters. Our study reveals a significant correlation between roughness parameters and the magnification used when analysing polished copper surfaces. By increasing the magnification, we observed a progressive increase in Sdq, indicating a higher density of asperities at finer scales. At the same time, Sal decreased, revealing smaller average asperity sizes. These results are consistent with the hierarchical nature of the surfaces, where asperities of different sizes coexist. Str, on the other hand, remained relatively stable, suggesting that the general shape of the asperities is independent of the scale of observation. This study highlights the importance of multi-scale characterisation for an in-depth understanding of surface roughness and its implications for device performance.

Optical interferometry, surface analysis, noise reduction, multiscale characterization

1. Introduction

The ongoing miniaturization of integrated circuits necessitates high-speed, reliable interconnects. Copper is a choice material role due to its high electrical conductivity. However, the quality of the copper surface plays a critical role in determining the reliability and longevity of these interconnects [1]. Chemical Mechanical Planarization (CMP), a polishing technique widely used in the semiconductor industry, produces ultra-smooth copper surfaces with roughness values typically in the sub-nanometer range [2]. Highly polished films pose significant measurement challenges, as their low roughness values often match or exceed the noise levels inherent in conventional techniques such as White Light Interference (WLI). Distinguishing genuine surface deviations from random fluctuations presents challenges, often resulting in inaccurate roughness parameter quantification. This ambiguity can compromise both process control and device reliability. Therefore, it is imperative to develop robust measurement protocols that effectively separate genuine surface variations from noise-induced artifacts. This separation ensures that any real changes in roughness across different regions of a wafer can be accurately detected and monitored, thereby maintaining uniformity and consistency in the manufacturing process.

This study focuses on the development of a robust methodology for the characterization of the surface roughness of polished copper films. White light interferometry (WLI) [3] offers a fast, non-destructive and highly sensitive approach to accurately measure the low amplitudes of roughness typical of polished copper films. We have implemented a rigorous experimental approach aimed at reducing measurement artefacts and obtaining high quality data, enabling us to detect small variations in surface parameters across the wafer surface.

2. Methodology

In this work we characterized surface of copper thin film deposited on 200 mm wafers and polished by CMP process.

In order to achieve comprehensive multi-scale characterization of surface parameters, a Bruker Contour-GT White-Light Interferometer (WLI) was employed, as detailed in Table 1. We acquired 640x480 pixels images working in PSI (Phase-Shift Interferometry) Mode.

Measurement noise, theoretically independent of surface characteristics, was addressed by extending a previously developed noise bias reduction method for profile measurements to 2.5D measurements [4], [5].

Table 1: Bruker Contour GT-X WLI specifications

Magnification	5X	20X	50X	115X
Numerical Aperture	0.12	0.4	0.55	0.8
Vertical Resolution [µm]	<0.1	<0.1	<0.1	<0.1
Field of View [µm]	1300 x 1000	300 x 200	130 x 100	60 x 40
Sampling [µm]	1.98	0.9	0.2	0.09
Optical Resolution [µm]	2.2	0.7	0.5	0.2

The noise bias effect is reduced by calculating the limit value of the Sq parameter using the following approach:

$$Sq = \sqrt{\frac{1}{A}\iint_A z^2\,(x,y)dxdy} \qquad (1)$$

$$Sq^2_{measured} = Sq^2_{object} + Sq^2_{noise} \qquad (2)$$

With the number of measurements increasing, the noise contribution diminishes and Sq^2_{mean} approaches Sq^2_{object}:

$$Sq^2_{mean} = Sq^2_{object} + \frac{Sq^2_{noise}}{N} \qquad (3)$$

Combining the two previous equations allows unbiased estimation of the object's roughness parameter:

$$Sq^2_{object} = \frac{N \cdot Sq^2_{mean} - \overline{Sq^2_{measurements}}}{N-1} \qquad (4)$$

$$Sq^2_{noise} = \frac{\overline{Sq^2_{measurements}} - Sq^2_{mean}}{1-N^{-1}} \qquad (5)$$

Sixty-four repeated measurements at magnifications of 5X, 20X, 50X, and 115X were conducted to capture detailed surface characteristics across multiple length scales. This multiscale approach mitigates measurement noise by averaging multiple data points, thereby enhancing the accuracy of roughness parameter estimation.

Our methodology involves measuring polished copper thin films at 37 different locations on a wafer, with each location sampled using 64 averaged images. To further validate the significance of any detected roughness variations across different wafer locations, we use statistical methods such as bootstrapping. The bootstrap method employed in this analysis involves resampling with replacement from the full dataset (37×640×480 pixels, obtained by concatenation of the 37 images), drawing 10,000 samples of the same size as the original data . This technique allows for robust estimation of population parameters without making assumptions about the underlying distribution. Each bootstrap sample is used to estimate mean and Sq values. The process generates a distribution of these statistics, from which confidence intervals and standard errors are derived. This approach is particularly valuable for spatially distributed data, as it captures the inherent variability and potential heterogeneity across different sampling locations [6].

We also estimated mean and confidence intervals for individual measurements by extracting 37 individual samples from 10,000 boostrapped dataset. Finally, we extracted main surface parameters Sq (Root Mean Square Height), Sal (autocorrelation length), Str, Sdr (Developed Interfacial Area Ratio), Sdq (Root Mean Square Gradient), from the 37 original measured images and then apply bootstrapping 10,000 times over these 37 values for each parameter. For data treatment and analysis we used Python libraries[7], [8], [9], [10]. Finally, a Bruker AFM Dimension Icon® was used to verify surface roughness values.

3. Results

3.1 Noise reduction

Figure 1 (left) illustrates the power spectral density (PSD) curves for averaged roughness measurements at varying magnifications.

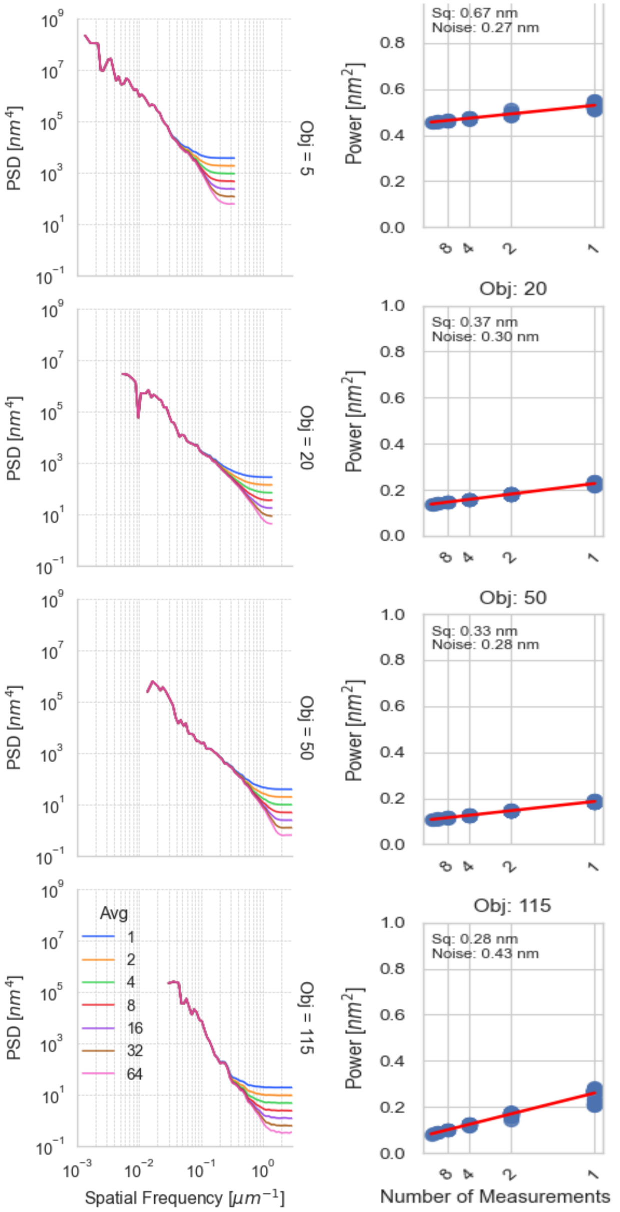

Figure 1. Left side: noise reduction by measurement averaging shown by PSD curves; right-side: unbiased estimation of surface Sq with determination of the noise

The magnitude of white noise is evident in the high-frequency region of the spectra, particularly for the 115X objective, which is highly sensitive to measurement parameters.

In the right side of Figure 1 we plotted the power in the signal of roughness measurements as a function of the number of repeated measurements of which the average is taken. From the slope and the intercept we can obtain the estimated unbiased Sq roughness and the noise of the measurements, which are plotted in Figure 2. We easily remark the importance of noise amplitude in the measures, with increasing values with the magnification, becoming more important than estimated Sq values.

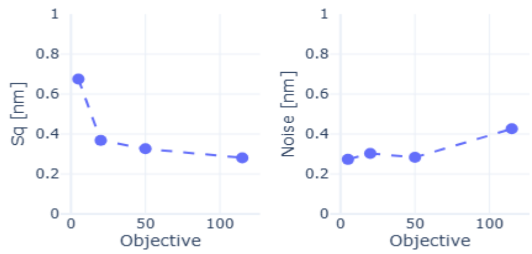

Figure 2: Unbiased Sq roughness and noise estimation based on averaging method

For comparison, the Sq roughness values obtained by AFM are shown in Table 2.

Table 2: Sq roughness values obtained by AFM

Scanned Area	1x1 µm	60x40µm
N° pixels	512x512	640x480
AFM Sq	0.475 nm	0.495 nm

3.2 Data Boostrapping

In the Figure 3 are plotted bootstrap analysis results of the Sq for different magnifications used in this study. The spread of data points indicates significant deviations of individual measurements from the bootstrap mean and confidence intervals (red), exceeding expectations based on measurement noise alone. This suggests true spatial heterogeneity in the Sq values across sampling points.

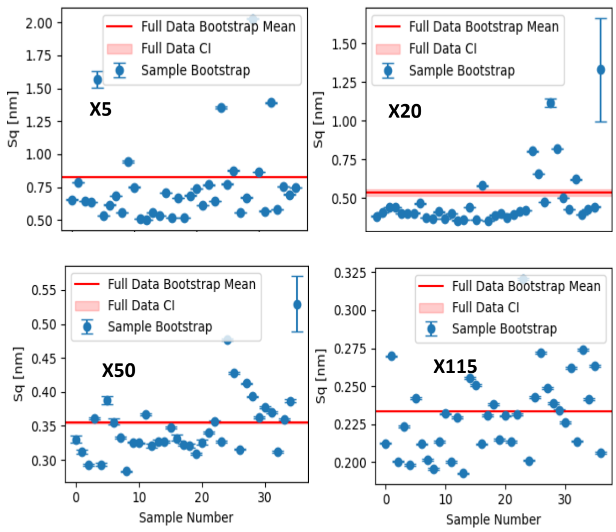

Figure 3: Bootstrap analysis of surface roughness (Sq) measurements across multiple spatial locations

The data therefore indicates that the variations in measurements across different spatial locations likely represent true differences in the underlying phenomenon being measured, rather than measurement uncertainty or noise.

3.3 Process uniformity estimation

Surface parameters such as Sal, Sdq, Sdr, and Str play a crucial role in characterizing surface topography, providing insights into geometric and textural properties that are essential in various scientific and industrial applications. These parameters evolve with changes in magnification and lateral resolution, offering a comprehensive understanding of surface features at different scales.

Figure 4 plots the calculated Sq, Sal, Str, Sdr and Sdq values as measured in 37 different locations of the wafer, with different objectives. As magnification increases, the focus shifts to smaller areas, potentially missing larger wavelength features. This leads to a decrease of height parameters as Sq [11]. The hybrid parameters (Sdq, Sdr) increase wlith magnification should be attributed to the detection of finer surface details, allowing steeper local slopes and more complex surface topography quantification. Meanwhile, the relationship between Sdq and Sdr remains consistent across magnifications, forming a topological map that characterizes different surface types, as showed in reference [12]. Now, concerning spatial surface parameters, we see the autocorrelation length Sal decreases while increasing the lateral resolution: this indicates that finer, high-frequency features become more prominent, leading to faster decay of the autocorrelation function.

On the other hand, quite surprisingly, the texture aspect ratio, Str, remains quite stable over increasing magnification, as demonstrated by ANOVA analysis conducted over different magnifications conditions (see p_value obtained on graph). This stability of Str in this context suggests that while the surface directional characteristics remain consistent across different scales of observation, suggesting that the CMP process used is consistent and well-controlled, producing uniform effects at various scales.

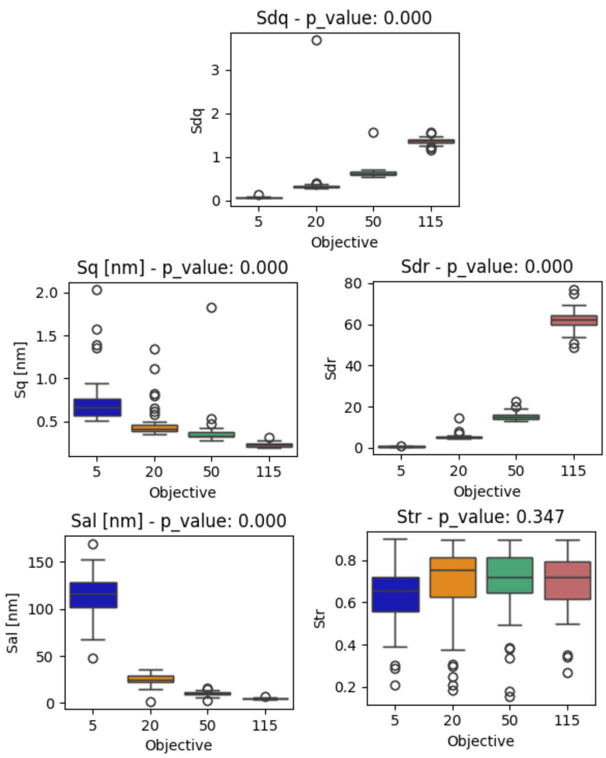

Figure 4: Variations in surface roughness parameters (Sq, Sal, Str, Sdq, and Sdr) at different magnifications, illustrating scale-dependent surface characteristics

For a more in-depth view of surface characteristics let's take a look to

Figure 5, which shows averaged PSD curves for for different magnifications. One can remark the parallel nature of the curves in the mid-frequency range showing that the relative power distribution across different frequencies remains consistent across the magnifications: supports the observed Str stability across magnifications, as the relative directional properties remain consistent across scales. Meanwhile, the decreasing power with increasing frequency correlates with the reduction in Sal at higher magnifications, reflecting the reduced contribution of shorter wavelength features to the overall surface roughness.

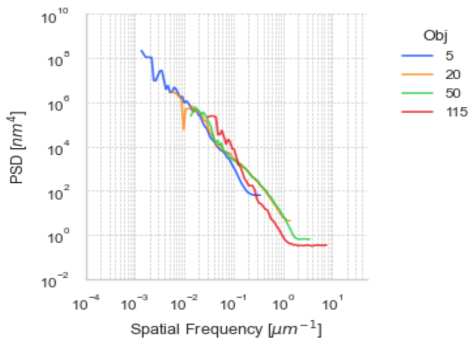

Figure 5: PSD curves obtained from averaged measures with different magnifications

The aim of our protocol is to reduce the measurement noise in order to obtain values for the surface parameters that are as close as possible to reality, allowing us to capture the slight fluctuations as a function of position on the wafer and, in this way, to trace the non-uniformities of the CMP process, so that they can be corrected.

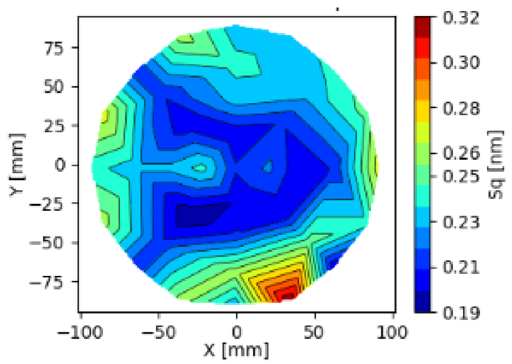

Figure 6: Sq contour map for 115X magnification, showing process uniformity

Based on these verified results, we can plot contourmaps for the different surface parameters which allows us to have an in-depth view of CMP process performance uniformity, as shown in

Figure 6, illustrating the Sq values distribution accros wafer positions. From this kind of colormap we can estimate manufacturing process performance and uniformity : surface roughness values are below 0.5 nm RMS (as also confirmed by AFM), in agreement with sepcifications cited in [13].

4. Conclusion

This study presents a comprehensive investigation into noise characterization and reduction in surface roughness measurements of polished copper thin films. By employing multi-scale white-light interferometry and advanced statistical methods, our study significantly reduced measurement noise, enabling accurate extraction of roughness parameters.

White-light interferometry enabled multi-scale characterization of polished copper thin films. Sixty-four repeated measurements across four magnifications (5X, 20X, 50X, and 115X) were averaged to significantly reduce noise, as validated by power spectral density (PSD) analysis. Statistical methods, including bootstrapping, were applied for robust data analysis. This noise reduction technique proved particularly crucial at higher magnifications, where noise became more pronounced than the estimated Sq values. In order to adress process uniformity, 37 different locations on a wafer were measured, providing a broad spatial perspective.

Surface parameters exhibited interesting trends across different magnifications. The Sq (Root Mean Square Height) parameter demonstrated a decrease with increasing magnification, suggesting a shift in focus to smaller surface areas. Conversely, Sdq (Root Mean Square Gradient) and Sdr (Developed Interfacial Area Ratio) increased with magnification, indicating the detection of finer surface details and more complex topography. The Sal (autocorrelation length) parameter decreased with increasing lateral resolution, confirming the prominence of finer, high-frequency features.

The stability of the Str (texture aspect ratio) parameter across magnifications suggests that the CMP process produces surfaces with consistent directional characteristics across scales. The stability of Str parameter was further supported by the parallel nature of PSD curves in the mid-frequency range across different magnifications.

Acknowledgements

The authors would like to thank Denis Mariolle for AFM measurements and usefull discussion.

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