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EUV scatterometry-based measurement method for the determination of phase roughness

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ABSTRACT

AFM-based roughness measurement reveals the topography of EUV masks, but is only sensitive to the top surface [1]. Scatterometry provides a more accurate approach to characterize the effective phase roughness of the multilayer, and it becomes important to determine the valid metrology for roughness characterization. In this work, the power spectral density calculated from scatterometry is compared to that from AFM for measurements before and after coating of substrates with a range of roughness levels. Results show noticeable discrepancies between AFM- and scatterometry-measured roughness, and indicates that when the physical surface roughness increases with deposition the EUV penetration into the multilayer tends to mitigate this effect. In this paper, we describe an EUV scatterometry-based measurement method for the determination of phase roughness with the goal of minimizing the amount of physical scattering data to be collected and rendering the method compatible with potential future standalone EUV reflectometer tools.

1. INTRODUCTION

It has been known that one of the contributors to the line edge roughness (LER) in resists is mask phase roughness [2]. At 13.5nm, small roughness on a reflective mask can induce significant phase modulation that affects the replication of the mask objects on the wafer [3]. Of highest concern is the correlated scattering coming from phase coherent roughness. This comes from roughness that propagates conformally through the multilayer directly mapping to random phase errors in the reflected field. This is referred to as replicated surface roughness (RSR) [4]. It is therefore important to determine a valid metrology to characterize the phase roughness of EUV masks.

Atomic Force Microscopy (AFM) measurement of EUV mask surface has been the method of record for characterizing mask roughness [5] [6] [7]. However, the AFM measures only the top surface of the mask, which is not necessarily indicative of the true roughness within the multilayer.

In this work, six test mask blanks with various roughness levels were prepared. The roughness on the mask substrates was distributed from 60 pm to 100 pm. The substrates were then coated using Ion Beam Deposition (IBD) at the SEMATECH Mask Blank Development Center. AFM measurements were performed on both the substrates and the multilayer blank. Scatterometry measurement was then performed on four of the six masks after multilayer coating and converted to power spectral density (PSD) for comparison.

2. TEST MASKS AND AFM DATA

Figure 1 shows the PSD calculated from the AFM measurements. Root mean square (RMS) values are noted on top of each PSD graph. The blue curves show the PSD of the substrate and green curves show the PSD of the top surface of the multilayer. At high frequencies ($\geq 3\times10^{-2}$ lines/nm) and low frequencies ($\leq 10^{-3}$ lines/nm), the deposition did not effectively increase the roughness. For the medium frequencies (10^{-3} lines/nm to 3×10^{-2} lines/nm) the IBD coating generally roughened the surface, as apparent from the increase in the RMS from Pre-deposition to Post-deposition. This change in roughness from substrate to the top surface suggests that the EUV scatterometry which depends on the overall roughness inside the multilayers may show an RMS level between that of the top and substrate. We note that this IBD data shows a different result than previously demonstrated with magnetron coating, where the top surface of the multilayers was consistently smoother than the substrate [4].

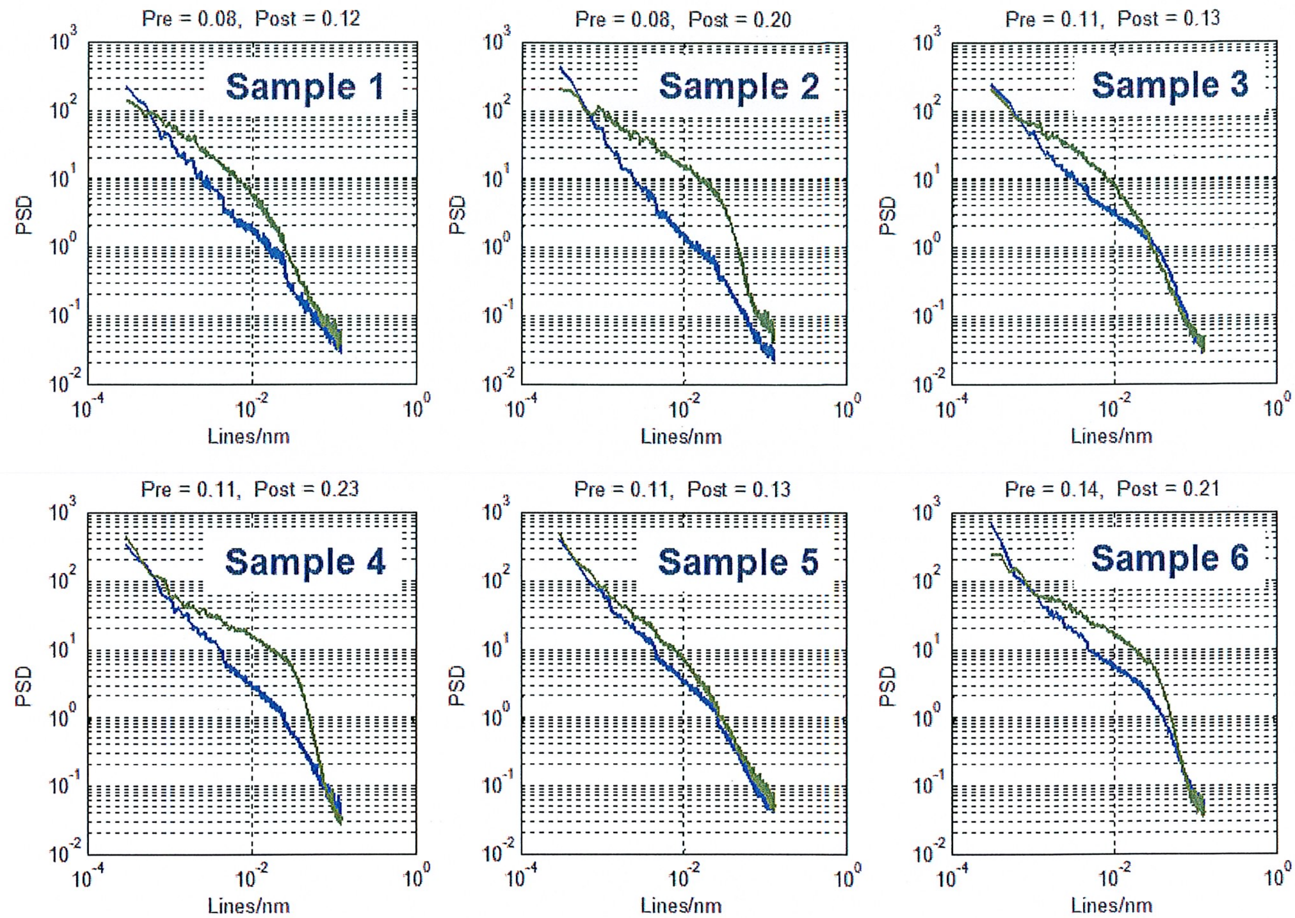

Figure 1. PSD of the six test masks as a function of frequency. Blue curves represented the PSD before coating and green curves represented that after coating. The RMS values were noted on top of the graphs and in the unit of nm.

3. SCATTEROMETRY MEASUREMENT

Scatterometry measurements were performed using the synchrotron-based reflectometer at the Calibrations and Standards Beamline 6.3.2 at the Advanced Light Source (ALS), Lawrence Berkeley National Laboratory (LBNL). The beamline has a high spectral purity of 99.98%, wavelength precision of 0.007%, and a reflectance precision of 0.08% [8].

3.1 In-Plane Measurement

In-Plane measurement refers to the set up where the detector is placed in the plane of incidence. The angle of incidence was set at 6 degrees. The detector was set on the specular reflection side and scanned from 1 degree beyond specular to 31 degrees beyond specular. Assuming the roughness to be conformally replicated, the PSD can be calculated by [9]

$$\frac{1}{P_o}\frac{dP}{d\Omega} = \frac{16\pi^2}{\lambda^4}\cos^3\theta_i \cdot R \cdot PSD(f)$$

where P_0 is the incident power, dP is the scattered power into the solid angle $d\Omega$, the frequency f is related to scattered angle θ_s (from normal) by

$$f \cdot \lambda = \sin(\theta_s) - \sin(\theta_i)$$

and the incidence angle θ_i= 6 degrees.

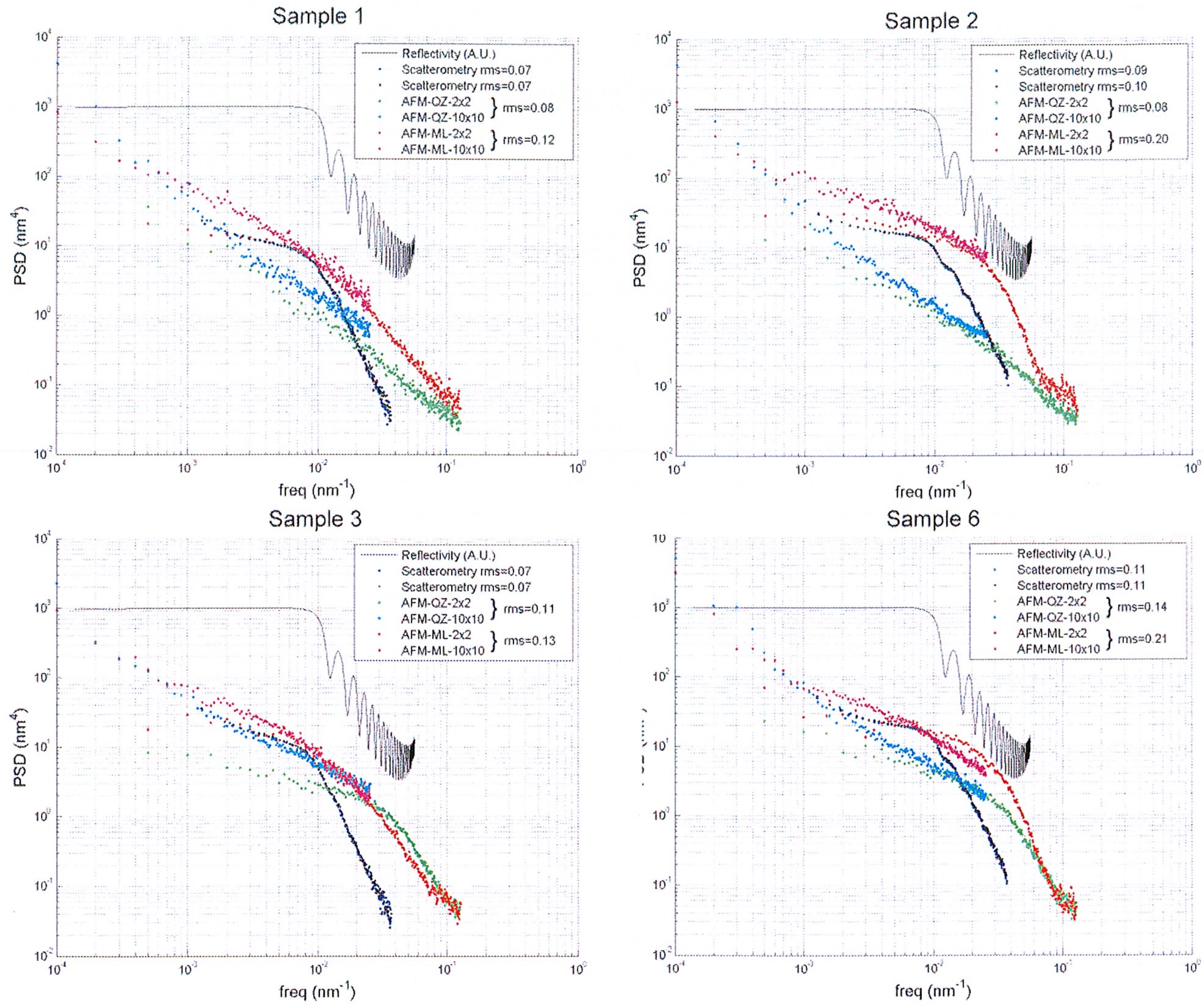

Figure 2. PSD of the four selected test masks calculated from AFM and scatterometry as a function of frequency.

Figure 2 shows the PSD calculated from scatterometry measurement compared with that from the AFM measurements. Dark blue and black dots are duplicates of the same measurement with slightly shifted angles for each measured point. Green and light blue dots (AFM-QZ) are the AFM measurements on the mask substrate within a region of 2μm by 2μm and 10μm by 10μm, respectively. Red and purple dots (AFM-ML) are AFM measurements on the mask blank within a region of 2μm by 2μm and 10μm by 10μm, respectively. The black curve is the theoretical reflectivity in arbitrary units as a function of reflected angle. Interestingly, its roll-off is consistent with the change in slope of the scatterometry curve and its ripples are reproduced in the measured scattering data. In the mid spatial frequency roughness regime (approximately 10^{-3} to 10^{-2} nm^{-1}) the scatterometry PSD is dropping below the AFM PSD. In 3 of the 4 cases it is 1.5 times lower and in the case where IBD increased the top surface AFM the most the scaterrometry PSD is 2.5 times lower. In fact, the EUV scatterometry PSD at 5 x 10^{-3} nm^{-1} appears to roughly reverse the increase in AFM PSD as measured by its RMS value in going from substrate to multilayer coating top surface. Thus EUV penetration into the multilayer is reducing the impact in the physical growth of surface roughness.

4. DISCUSSION

The comparison of AFM and scatterometry measured data given by Figure 2 showed that the typical AFM method to measure surface roughness on the multilayer overestimated the phase roughness obtained by scatterometry.

Scatterometry measured roughness appears to match the substrate roughness at low spatial frequencies and approach the multilayer roughness before it is limited by the multilayer angular bandwidth. From the four masks we measured here, AFM on mask blank overestimated the RMS value by ~70% to ~100%. This was also obvious throughout medium and high frequencies, where the overestimation took place. Possibly due to a significant decrease in mask blank reflectivity, at high frequencies ($f > 3\times10^{-2}$ nm^{-1}), the roughness given by scattering light was even below that of the mask substrate. The effect of reflectivity is also evident from the ripples in the scatterometry data.

The implication here is that AFM is not sufficiently accurate to provide a quantitative description of the true EUV phase roughness as required to assess the masks imaging performance from the perspective of induced wafer plane LER.

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