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Authors

Naulleau, P
Anderson, C
Chao, W
et al.

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Studying Resist Stochastics with the Multivariate Poisson Propagation Model

Patrick Naulleau[1], Christopher Anderson[1], Weilun Chao[1], Suchit Bhattarai[2], Andrew Neureuther[2]

1.Introduction

With delays in the manufacturing insertion of extreme ultraviolet (EUV) lithography, the pressure on EUV resist performance has significantly increased. Much progress is still needed in order to support an insertion half pitch of 16-nm. The concern is further exacerbated by the fact that progress in ultimate performance has slowed considerably in recent years. Figure 1 shows a plot of the ultimate resolution of EUV resist over the past decade include both chemically amplified (black bars) and non-chemically amplified (gray bars) resists. All results were obtained using the SEMATECH Berkeley MET [1,2]. For the cases below 20-nm half pitch, the pseudo phase shift mask method was used [3].

Although we do see several materials achieving 16-nm half pitch resolution, sensitivity and line-width roughness (LWR) performance are far from the goals set forth in the International Technology Roadmap for Semiconductors (ITRS) [4] for 17-nm half pitch in 2019. The ITRS calls for a resist sensitivity of 15 mJ/cm^2 and LWR of 1.4 nm.

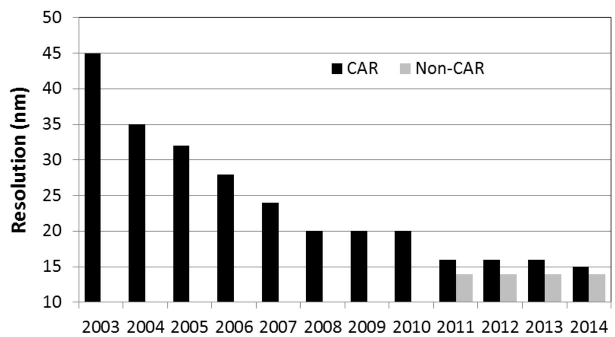

Figure 1. Progress in EUV resists, both chemically amplified (CAR) shown in black bars and non-CAR shown in gray bars as a function of year.

The observed slow down in progress suggests that resists may be nearing stochastic limits. Here we compare leading resist performance to stochastic modeling using the Multivariate Poisson Propagation Model (MPPM) [5-7]. The results show that with current chemically amplified resist parameters, we are approaching stochastic limits both in terms of photon statistics as well as materials statistics.

2. Z-factor performance

The composite performance of a resist in terms of resolution, sensitivity, and LWR can be quantified by a single metric referred to the Z-factor [8] which is derived from the analytic description of the stochastic photon limited performance of a resist in terms of resist diffusion and absorbed photon count [9]. The Z-factor is defined as

$$Z \propto R^3 L^2 S, \quad (1)$$

where R represents the resolution, L the LWR, and S the sensitivity. We note that the Z-factor is most conveniently used when normalized against the target performance. In this form it is known as the nano-Z-factor [10].

In Table 1 we show the performance for four leading resist with better than 17-nm half-pitch resolution. Three of the resists are chemically amplified and the fourth is not. The nano-Z-factor is computed relative to the 2019 ITRS requirements described above yielding a reference Z-factor of 1.44×10^5 $nm^5 mJ/cm^2$. The data shows that the best chemically amplified (CA) resist is still nearly an order of magnitude short of target in terms of the nano-Z-factor. The shortfall is due almost exclusive to the LWR performance. For non-CA materials, a nano-Z-factor of 3.7 has been achieved, with the shortfall here being mostly due to the poor sensitivity. Despite the non-CA resist being by far the slowest, it is also by far the closest to the overall performance target as represented by the nano-Z-factor.

Table 1. Leading resolution EUV resist performance (CA = chemically amplified, NCA = non-chemically amplified).

	Resist CA-A	Resist CA-B	Resist CA-C	Resist NCA-A
Resolution (nm)	16	16	15	15
LWR (nm)	3.1	4.8	3.8	1.5
Sensitivity (mJ/cm^2)	30	20	22	70
Nano- Z-factor	8.2	13.1	7.4	3.7

We note that the resist labels A, B, C represent the chronological order of the introduction of the resist, each being approximately 1 year apart and resist A being introduced in 2011. This indicates that we have not seen significant improvement in the nano-Z-factor since 2011. Figure 2 shows the resist images from the materials with the two lowest nano-z-factors.

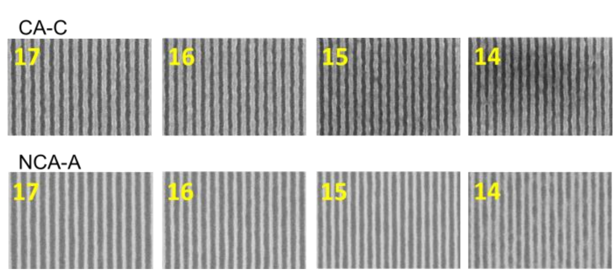

Figure 2. Resist images from the materials with the two lowest nano-z-factors in Table 1. Labels represent the line-space half pitch.

3. Stochastic limits

The stagnation in nano-Z-factor improvement shown above raises the question of stochastic limits. To study this problem we use the MPPM [5-7]. The MPPM allows individual variables to be switched between stochastic and deterministic allowing the relative importance of the various terms to be studied. We begin by considering only the photon stochastics. The key parameters in this case are: resist absorptivity which is approximately 4.2 μm^{-1} for the CA resists and 19 μm^{-1} for the NCA resist; film thickness which is 30 nm for the CA resists and 20 nm for the NCA resist; and deprotection blur which we determine from the measured LWR correlation length [5].

Figure 3 illustrates the determination of the deprotection blur from the LWR correlation length measurement. The correlation length is computed from the LWR power spectral density (PSD) through a fit to a fractal model of the line roughness plus measurement noise. The measurement is performance using a commercially available software package [7]. Figure 3(a) shows the results for resist CA-A, Fig. 3(b) is for resist CA-C, and Fig. 3(c) is for resist NCA-A.

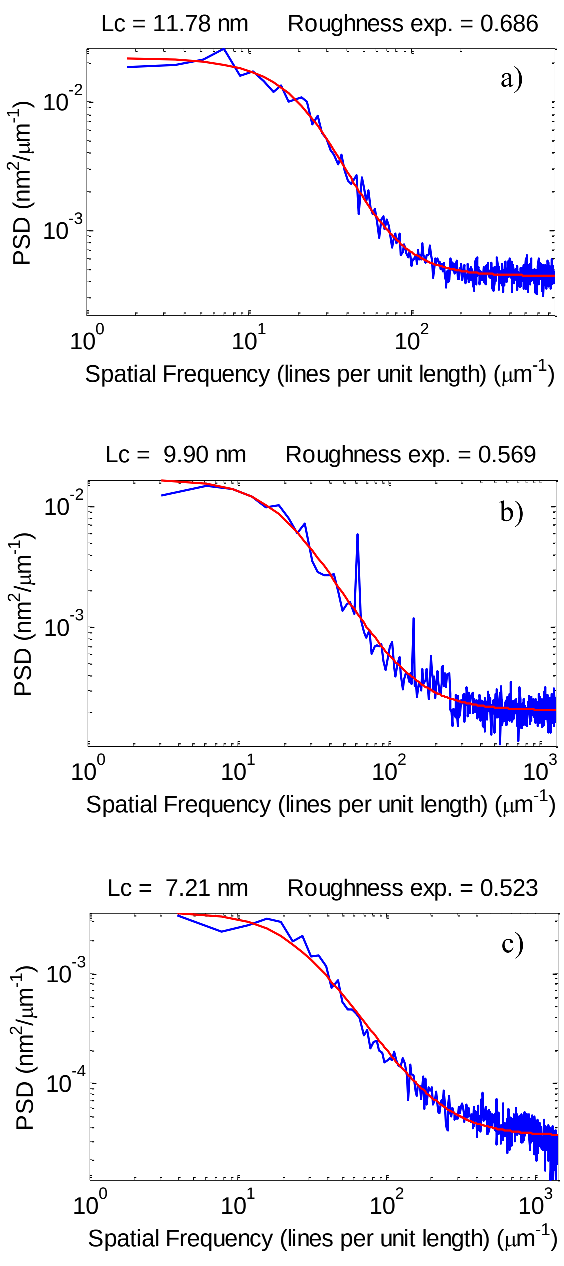

Figure 3. Measured LWR power spectral density and extracted correlation length (Lc) for resists (a) CA-A, (b) CA-C, and (c) NCA-A. Also reported is the roughness exponent which is related to the slope of the PSD in the cut-off region.

As expected, we see decreasing correlation length (deprotection blur) with improving resolution. We note also that the spikes observed in the PSD in Fig. 3(b) are scanning electron microscope noise artifacts and have no appreciable impact on the measured LWR or correlation length.

We now have all the parameters required to compute the photon limited LWR which is shown in row 1 of Table 2. In most cases, there remains significant margin between the photon limit and the measure LWR. Assuming the photon-limited LWR to be uncorrelated from material and processing limited LWR terms, we can estimate the material-limited LWR by subtracting the modeled photon limited LWR from the measured LWR (row 3 in Table 2). In all cases the estimated material-limited LWR is larger than the photon-limited contribution.

Table 2. Predicted stochastic limited LWR performance compared to measured resist performance.

	Resist CA-A	Resist CA-B	Resist CA-C	Resist NCA-A
Measured LWR (nm)	3.1	4.8	3.8	1.5
Photon limited LWR (nm)	2.1	2.7	2.5	1.0
Estimated material LWR (nm)	2.3	4.0	2.9	1.1
Modeled material LWR (nm)	2.4	2.4	2.4	1.1

Although typically described in the context of photon noise, the concept of stochastic modeling is not limited to photon noise. Rather, the Poisson model readily applies to counting experiments in general. Noting that resist material non-uniformity can also be viewed as a counting problem, the stochastic model above can be extended to materials effects. For example, we may be concerned with the number of photo acid generators (PAGs), quencher, molecules, protecting groups, or cross-linking groups in a given volume of resist, or in the number of acids generated or bonds broken per absorbed EUV photon. All these items can be treated as random variables and propagated through the resist model to generate the dependent random variables of final acid count and/or deprotection or cross-linking. This multivariate approach allows a variety of stochastic terms to be studied in combination as well as individually.

Using this approach, we next we compare the estimated material limit to the modeled material limit where the MPPM for the CA resists includes random variables for PAG concentration, quencher concentration, acid generation, and protecting group concentration. In the non-CA case, the material components included in the MPPM include random variables for bond breaking (which in the model can be seen as equivalent to acid generation) and relevant bond concentration (which in the model can be seen as equivalent to PAG concentration).

The fourth row of Table 2 shows the predicted material-limited LWR. The model input values are based on estimates provided by the resist suppliers. For the CA resist where very little variation was observed in the supplier provided estimates, we take the average values and apply them to all three CA resists leading to the same predicted stochastic material-limited LWR for all three.

In the case of resists CA-A and NCA-A, the predicted material limited LWR is very close to the estimated experimental material limit shown in row 3. Note that the MPPM as currently implemented model and described above does not necessarily capture all stochastic material effects nor does it capture development stochastics. In the cases where the model closely matches this measurement, the expectation is that the MPPM is capturing the dominant experimental terms.

4. Summary

Stochastic modeling has been used to show that the recent slow down in RLS progress is consistent with approaching stochastic limits. The modeling suggests that further improvements require improvements in both photon and materials stochastics.

6. Acknowledgements

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