Understanding EUV Shot Noise: Comparing Theory and Requirements to Experimental Evidence

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High resolution contact holes were printed with different EUV resists on an EUV microstepper exposure tool. Intrinsic critical dimension uniformity (corrected CDU) was separated statistically from other location effects. As expected, there was worse CDU for resists with lower dose to size. Comparison of corrected CDU to calculated shot noise showed a significant correlation. However the CDU of the fastest resists tested showed substantial variation, suggesting that different chemical approaches to making fast resists can give different CDU. Comparison of experimental results and of calculated shot noise to ITRS roadmap requirements for contact hole CDs suggests that some post processing that improves CDU will be needed in the future or that chip designs with tolerance to significant contact hole CDU will be needed.

Keyword: photoresist, EUV, contact holes, shot noise, CDU

1. Introduction

In 1921 Albert Einstein was awarded the Nobel Prize in physics. He received this prize not for his well-known theory of relativity, but for explaining the photoelectric effect. The photoelectric effect is the effect where emission of electrons from a substance is stimulated by illuminating it. The only way Einstein could explain the observed properties of the effect was to consider the light to be quantized, that is made up of particles, even though it obviously also had wave like properties. He didn't like this idea but was forced to this conclusion by the data. This conclusion was then built on by many great physicists and many phenomena can be explained by it. The further development of quantum mechanics showed that there is some intrinsic randomness in quantities one might think of as fixed, such as the momentum of a particle. But even today, the consequences of this concept are not always comfortable.

In lithography, there is already randomness

in the location of the polymer deprotection events in a chemically amplified resist. It has been shown that this deprotection randomness explains line edge and width roughness (LER and LWR) [1]. And simulation models incorporating a random (or "stochastic") nature of polymer deprotection have successfully predicted resist LER and LWR without any a priori assumption of line roughness [2]. Quantum mechanics and the particle nature of light says there will be a random variation in the actual dose that is received by a resist and that this variation should contribute to LER and LWR. For the ArF wavelength and for other wavelengths already in use for lithography, this variation is small because there are so many photons in an exposure. But for EUV exposures, there are many fewer photons in a typical exposure because of the much higher energy per photon, a factor of approximately fourteen. Just like early twentieth century physicists were uncomfortable with the thought that quantities

they intuitively thought were fixed are actually random, lithographers today may be uncomfortable with the thought that an exposure dose thought of as a fixed quantity is actually a random quantity and varies from spot to spot in an exposure field in a way that cannot be controlled. This paper describes work to look for evidence of this randomness in EUV exposure data from a variety of resists.

2. Mathematics of Shot Noise

The total dose of light irradiating a substrate is composed of photons and the arrival of a photon is an individual event occurring at a certain average rate where the rate is dependent on the light intensity. A distribution of events like this is described by the Poisson distribution, and the standard deviation of such a distribution is the square root of the number of events. The variation of the dose expressed as a percentage of the total dose is then the square root of the number of photons divided by the total number of photons, P_t , or 1 over the square root of the number of photons.

$$\sigma_{\text{dose}}/\text{Dose} = 1/(P_t)^{1/2} \quad (1)$$

This math is very simple, but one has to take into account the absorbance of the resist film. A typical resist film will absorb only a fraction of the impinging light. For EUV resist, the entire film thickness might absorb 25% of the light. It is useful to think about impingement and absorption as two separate processes. Absorption is a process where each individual photon has a fixed probability, p , of being absorbed. For a film with 25% absorbance, p is 0.25. This process is described mathematically by the binomial distribution. Then the standard deviation of the number of absorbed photons will be the square root of the product of the number of photons, the probability of absorption p and of $1-p$.

$$\sigma_{\text{total}} = (p*(1-p)*P_t)^{1/2} \quad (2)$$

If one wants the total variation in dose due to both variations in impinging photons and in absorbed photons, one has to take the geometric mean of the impinging photon standard deviation and the product of the

absorbed photon standard deviation times $1/p$. The factor of $1/p$ is needed because a change of one absorbed photon is equivalent to a change of $1/p$ impinging photons. For example, if 10,000 photons are impinging a film with 25% absorbance, then, on average, 2500 photons are absorbed. A random variation of one photon in the absorbance so that, say, 2501 photons are absorbed, is the equivalent of an impinging dose of 10,004 photons with exactly 25% absorption by the film. The 4 extra impinging photons compared to the one extra absorbed photon is a factor of 4 or $1/0.25$ which is $1/p$. This total variation in dose could be represented as shown.

$$\sigma_{\text{absorbance}} = (P_t + 1/p*(p*(1-p)*P_t))^{1/2} \quad (3)$$

But algebraic simplification gives the much simpler formula for shot noise below.

$$\sigma_{\text{total}}/P_t = (p*P_t)^{1/2}/(p*P_t) \quad (4)$$

Inspection of this formula shows that in practice one doesn't have to worry about absorption and impinging distributions. One can just calculate the expected number of absorbed photons and apply Poisson statistics to this number. However, dividing the variation into the variation in impingement and the variation in absorption is useful conceptually, because the absorption variation is a function of the resist film absorbance while the impingement variation is not.

There is one other aspect of this variation that needs to be considered. An exposure dose is a dose per area, so one has to pick an area of exposure to calculate the total number of photons in that area and then calculate shot noise. For lines and spaces, this would require selecting a particular length of line and then the noise calculation would reflect dose variation on that length scale. For contact holes the calculation is simpler. Contact holes of leading edge dimensions are small enough that any spatial variation within the dimension of one contact hole in the dose at the reticle plane has a high enough spatial frequency that the variation does not make it through the lens. So the change in dose for a single hole results in a simple change in the

diameter of the hole. One might argue that the in an array of, say, 25 contact holes or a five by five array, the total dose for the 25 holes is what matters for calculating the shot noise. But the statistical properties of adding variations demonstrate that this makes no difference. The expected variation of the sum of individual random doses for 25 contact holes is one fifth the expected variation of each hole. This is exactly the same variation you would get calculating the variation of the total dose rather than adding variations of the individual doses. So even though the variation for the whole dose of contact array looks smaller as a percentage of the dose, when you split it up into pieces the variations of those individual pieces will be the same as if each piece was calculated separately.

3. Experimental Procedures

We chose to study contact holes because counting photons is easier for holes than for lines and space as described above. In order to measure random variation of the size of an exposed feature, one has to eliminate other variations as much as possible. Some of the potentially significant variations in CH size are mask induced variation from contact hole to contact hole, exposure variations across the exposure field of the exposure tool, apply, bake and development inhomogeneities across the wafer, resist type, and stochastic variations in resist deprotection and development. We chose to study the same five by five array of 26nm dense contact holes for every resist tested. This is expected to eliminate or minimize variations due to position in the exposure field. However we didn't have measurements for the size of each contact hole on the mask and could not obtain them. So we chose to measure same array and the same contact holes for many resists and then use statistical analysis as described below to eliminate the effect of contact hole location. We measured the same array four times using a two by two matrix of dose and focus centered around best focus and dose to size. Exposure were done on the Berkeley EUV microexposure tool (BMET) using a 20% positive bias to the reticle contact hole size and using quadrupole illumination.

Measuring particular locations in arrays small of contact holes by top down SEM is

difficult because a large magnification is needed and it's hard to select a unique array out of the whole array. So rather than programming the top down SEM to measure a particular contact hole, we programmed it to photograph a particular array of holes and then used SuMMIT image processing software to measure the area of each particular hole. Thirteen different EUV contact hole resists were tested this way. For one resist, SEM data for one of the four exposure fields was not available, so the data from the other twelve resists were used to do an analysis of variance and determine if contact hole position was a statistically significant influence on hole size. It was found to be significant, so the data from these twelve resists was then used to calculate average contact hole sizes for each of the 25 holes measured.

A correction factor for contact hole position was then calculated for each individual position by dividing the average size for that position by the average size of all the contact holes. The data for all thirteen resists was then corrected for contact hole position by dividing the data for each point by the contact hole position correction factor for that position. A standard deviation was calculated individually for each five by five array that was measured. This gave four standard deviations for twelve resists and three standard deviations for one of the resists. The standard deviations for each resist were pooled to get a CDU corrected for hole position for each resist. This was compared to a CDU calculated similarly but uncorrected for hole position. Comparing the uncorrected and corrected CDU gave a CDU for contact hole position alone. This matched the contact hole size CDU calculated separately by pooling the CDUs calculated for each array of 25 contact holes.

This procedure includes the effects of stepper field position and mask variables in the CDU for contact hole position. Systematic dose and focus variations within the 25 hole array are expected to be small because the array is so small in dimension. Variations from exposure field to exposure field are captured in the field to field variation which is separated statistically from the variation from hole to hole. So the

corrected CDUs for each resist should not include significant variation from these factors.

It is possible that the particular exposure field that was at the dose to size was at a different position on the wafer for different resists. However, the dose matrix was set knowing the dose to clear for each resist and the wafers themselves were 4" wafers, so it is expected that this variation will be small. There are, of course, going to be small random variations in time in the actual exposure dose by the exposure tool, but since we are comparing variations within small field of holes exposed all at the same time, this should not be an effect here. The remaining variation included in the corrected CDU should then be due to shot noise and to stochastic variation in resist deprotection.

4. Results and Discussion

The analysis of variance results are shown in Figure 1. The main effects are Fields, CH location and Resist. There are three two way interactions and one three way interaction. Since the same resist wasn't ever tested twice there is no pure measure of error. However, the three way interaction is small compared to the main effects and was used as an estimate of error for doing F tests. Fields has the largest effect, which is not surprising. Given that the four fields tested for each resist have difference doses and focuses, one would expect a significant change in CD from field to field. Resist is also a significant effect on CD size. This is also not surprising because there was some variation in how closely the measured fields hit the target CD and so there will be some CD variation from resist to resist because of this. Also, the resists had different measured exposure latitudes, which would also be expected to have a significant effect on CD size measured across two doses. The interaction of field and resist was also statistically significant, probably reflecting different exposure latitudes of the different resists. Finally CH location was clearly significant, meaning that some of the measured CDU was due to consistent variation from contact hole position to contact hole position.

Given that CH location was significant, a calculation of contact hole local CDU due to

Table 1: ANOVA results on contact hole data from 12 resists

	SS	DF	MS	F	P
SS Total:	6,710.4				
SS Fields:	572.5	3	190.83	69.49	less than 0.01
SS CH location:	507.4	24	21.14	7.70	less than 0.01
SS Resist:	1,130.8	11	102.80	37.44	less than 0.01
SS Fields x CH Location:	193.1	72	2.68	0.98	
SS Fields x Resist:	1,557.2	33	47.19	17.18	less than 0.01
SS CH Location x Resist:	574.6	264	2.18	0.79	
SS Location x Resist x Field:	2,174.8	792	2.75		

specific contact variation is meaningful. This calculation showed a three sigma CDU due to contact hole position of 2.00nm or about 8% of the CD. This is clearly a significant amount but much less than the residual CDU pooled from all resists of 8.2nm three sigma. On average, only 16% of the observed variance in printed CH size position was due to specific contact hole position. The rest of the variation, the "corrected CDU" must be due to shot noise and stochastic effects in the deprotection of the resist. Figure 1 shows the residual CDU for each of the resists graphed against the dose to size for each resist. There was a large variation in this corrected CDU as a function of resist.

Figure 1: Local CDU for each resist after removal of field and CH position effects

There is the expected effect of better CDU for resists with a higher dose to size. Resists with a dose to size of 30mJ/cm² or more had three sigma local CDUs of 4nm or less. Resist with a photospeed faster than 30mJ/cm² showed a wide variation in local CDU. This variation probably reflects different chemical approaches to making a fast EUV contact hole resists. It was of interest to compare expected shot noise with observed corrected local CDU. The nominal CD, mask bias [3] and exposure dose were used to calculate the number of impinging photons for exposing each resist to the target size of 26nm. The companies that supplied

the resists were asked for the absorbance of the resist. They all used the atomic composition of the resist and an assumed density to calculate the absorbance of the resist film via standard EUV absorbance calculations [4]. Various assumption of film density were used by different suppliers, but the results were all corrected to an assumed density of 1.2g/cm^3 based on experimental measurement of an EUV resist [5]. Using these absorbances an expected shot noise for each resist could be calculated. Figure 2 shows the correlation of corrected CDU with the calculated values of shot noise (expressed as a percentage of the exposure dose to size) for each resist.

Shot noise versus corrected CDU

Figure 2: Corrected CDU for each resist versus calculated shot noise

With the exception of one data point, the correlation is good. Larger shot noise gives larger CDU. In order to determine how much of the corrected CDU is due to the shot noise itself, the shot noise needs to be expressed in the same units as the CDU. The calculated shot noise was converted into nm by using the calculated percentage variation in dose and the observed exposure latitude for each resist. Figure 3 shows the correlation of three sigma shot noise in nm to three sigma corrected CDU. The values of shot noise expressed in nm range from 0.79nm to 1.48nm, while the values of corrected CDU range from 2.74nm to 8.21nm.

In a chemically amplified resist there is random variation in how many acids are generated per absorbed photon and further variation in how many deprotection events happen per acid molecule

generated. The relationship in variation in deprotection events per photon is quite complicated because there is a strong spatial dependence in the ratio and also a dependence on resist chemistry [6], but it is clear from simulations that the chemistry of chemically amplified resist can amplify the effect of shot noise variation [7]. In this work the ratio of observe ratio of corrected CDU to shot noise CDU ranges from 2.9 to 6.0. The variations of calculated absorbances and the measured exposure latitudes of the tested resists were quite small compared to this variation. There is considerable variation in the dose to size for the resists tested, but this does not explain this large ratio range either since the biggest variation in this ratio is for resists with doses in the range from 20mJ/cm^2 to 30mJ/cm^2 . Clearly it would be of benefit to resist formulators to understand the chemical causes of the change in ratio of observed CDU to shot noise CDU.

Shot noise versus CDU

Figure 3: Corrected CDU for each resist versus CDU calculated due solely to shot noise

5. Shot noise and the ITRS Roadmap

Given the observed level of local CDU observed in this study and in others [8], it is worthwhile comparing observed and expected levels of shot noise to expected future requirements of the industry. The 2012 ITRS lithography roadmap [9] shows expected printed contact hole sizes for years up to 2026. However, it doesn't show CDU requirements for these contact holes because the requirement is design dependent. So we chose to compare the observed and expected shot noise to a local CDU requirement of 5% of the ITRS contact hole size and to a requirement of 10% of the ITRS contact hole size. Best current performance as tested by

SEMATECH for contact hole local CDU is 3nm three sigma for 26nm dense contact holes at 20mJ/cm² exposure dose [10] This three sigma value corresponds to a variance of 9nm². In Figures 4 and 5 this variance is shown as “Status” and is compared to a variance corresponding to a 5% and 10% of ITRS target CH size three sigma LCDUs, respectively. One can see that current status is reasonable compared to the 10% target, but needs substantial improvement to meet the 5% target.

One can calculate the expected shot noise in nm for the contact holes sizes in the ITRS roadmap. We did so by assuming a dose of 15mJ/cm², an exposure latitude of 12%, a resist film absorbance of 25% and a mask bias of 20%. This standard deviation was converted into a variance so that it could be divided into impinging or dose shot noise and absorbance shot noise. The sum of these two values is the expected total shot noise. In figures 6 and 7, this shot noise variance is compared to the 5% and 10% LCDU targets. The blue bar is the dose or impinging photon shot noise, the red bar is the absorbance shot noise and the green bar is what is left for resist stochastic, mask LCDU and any other contributors to local CDU. When the expected shot noise LCDU exceeds the target CDU the green bar goes negative, implying that the resist process or some post processing, such as etch, that improves LCDU will be needed to meet the target, even assuming no addition to the LCDU from resist stochastic.

Figure 4: Current contact hole LCDU variance compared to 5% 3 sigma LCDU of ITRS CH roadmap

Examining Figures 6 and 7 it is evident that the absorbance shot noise is the larger part of the shot noise. Reducing this noise would require more absorbance in the resist films

Figure 5: Current contact hole LCDU variance compared to 10% 3 sigma LCDU of ITRS CH roadmap

Figure 6: Expected shot noise variance compared to 5% 3 sigma LCDU of ITRS CH roadmap

Figure 7: Expected shot noise variance compared to 10% 3 sigma LCDU of ITRS CH roadmap

and could have a significant beneficial effect, but resist developers would have to find ways to increase the absorbance above 25% without creating too many undesirable side effects, such as side wall slope. It's also clear that eventually some sort of smoothing or contact hole rectification will be necessary to give acceptable LCDUs. Some work showing the potential of such methods had already been done¹ and more progress improving contact hole LCDU is likely to be made in the future.

6. Summary

The inherent variation in 26nm contact hole CD was assessed by eliminating CH position effects for multiple resists. Some CDU was found that was due to hole position, but most of the CDU was due to the shot noise and resist stochastics. This remaining variation, “corrected CDU”, should be mostly or all due to shot noise and resist stochastics. There was a wide variation in the corrected CDU among the resists tested with most of that variation being in the resists with fast photospeed. This variation was not due to differences in resist absorbance or exposure latitude. It seemed to be mostly due to differences in the amount of stochastic variation in polymer deprotection between the different resists. It would clearly be helpful for resist developers to understand why this variation occurs.

Comparison of expected shot noise to 5% and 10% of projected industry contact holes sizes shows that chip designs that can accommodate some local CDU would be helpful and that long term ways to improve CDU by post processing or other methods would be helpful.

References

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