How Secondary Electrons Worsen EUV Stochastics

Increasing dose not only faces diminishing returns, but lets electron noise dominate ove photon noise.

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The EUV lithography community should now be well aware that rather than EUV photons driving resist chemical response directly, they release photoelectrons, whi further release secondary electrons, that in turn cause the photon’s energy to be deposited over many molecules in the resist [1]. While this directly leads to a blurr effect which can be expressed as a quantifiable reduction of image contrast [2], this also leads to consequences for the well-known stochastic effects. The stochastic behavior in EUV lithography has often been attributed in large part to (absorbed) photon shot noise [3], but until now there has been no consideration of the direct contribution from the electrons themselves.

There is a randomness in the number of electrons released per absorbed EUV phot [4]. The upper limit of 9 can be taken to be the maximum number of lowest energy losses (~10 eV) from an absorbed 92 eV photon, while a lower limit of 5 can be estimated from considering Auger emission as well as the likely loss of an electron through the resist interface with the underlayer or the hydrogen plasma ambient above the resist. Intermediate values are also possible, e.g., two secondary electrons may precede an Auger emission, leading to 7 electrons total. Thus, unlike the class split or thinned Poisson distribution which characterizes photon absorption [5], a uniform distribution of integers from 5 to 9 as the probability mass function can b reasonably used, at least as a starting point. Let’s now take a closer look at the statistics from such a distribution.

Photoelectron and Secondary Electron Statistics: Mean and Variance

The probability distribution is characterized by a mean and a variance, whose squa root is the standard deviation. For a uniform distribution of integers from 5 to 9, tl expected mean is obviously 7. The variance is calculated as the expected value of th square of the electron number minus the square of the mean (49). The expected val of the square for the range [5,9] is given by $(5^2+6^2+7^2+8^2+9^2)/5 = 51$. Thus, the varian of the distribution is 51-49 = 2.

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The standard deviation of AB is therefore given by sqrt(51N+2N^2), and so the stand deviation divided by the average is sqrt(51N+2N^2)/(7N) = sqrt(2+51/N)/7.

The 3s/avg for classical photon shot noise shows a 3/sqrt(N) dependence on the mea number of photons per pixel (N). Thus as N goes to infinity, the 3s/avg noise should to zero. However, for the released electrons per pixel, 3s/avg is given by 3*sqrt(2+51/N)/7. This implies a high dose asymptotic limit (as N goes to infinity) of 3*sqrt(2)/7 ≈ 61%!

When we plot the two 3s/avg trends together, we find that at low doses, the 3s/avg i very high as expected for both cases (Figure 1). However, as dose increases, the pho shot noise trend decreases faster than the electron noise trend, so that the electron noise will dominate over the photon noise at higher doses. In fact, the electron nois 3s/avg is converging toward the 61% asymptotic limit. This means increasing dose w have diminishing returns for reducing stochastic behavior in EUV lithography.

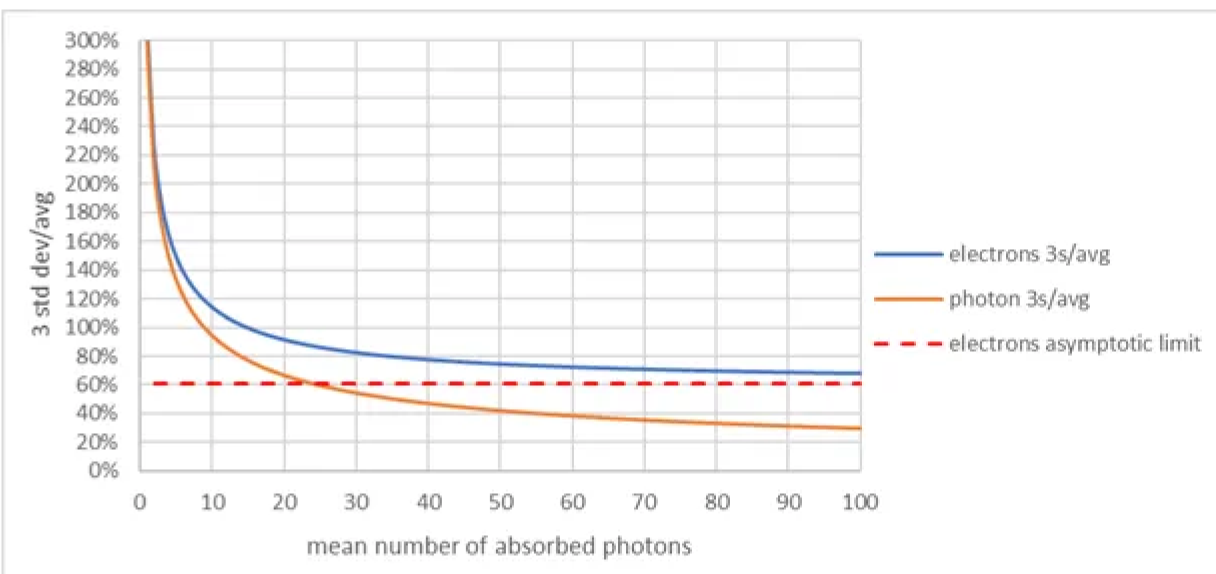

Figure 1. 3s/avg for photon shot noise and electron noise as a function of mean absorbed photon number per pixel.

For reference, an absorbed dose of 20 mJ/cm^2 corresponds to 54 absorbed photons 2 nm x 2 nm pixel or 14 absorbed photons in a 1 nm x 1 nm pixel. The pixel size should scale with the pitch, so at the same absorbed dose, the 3s/avg noise will be higher. However, smaller pitch usually uses thinner resist, which lowers the absorb photon number further, worsening the noise.

Figure 2 shows how the electron noise looks like along a 20 nm half-pitch feature edge. The variation approaches 50% easily.

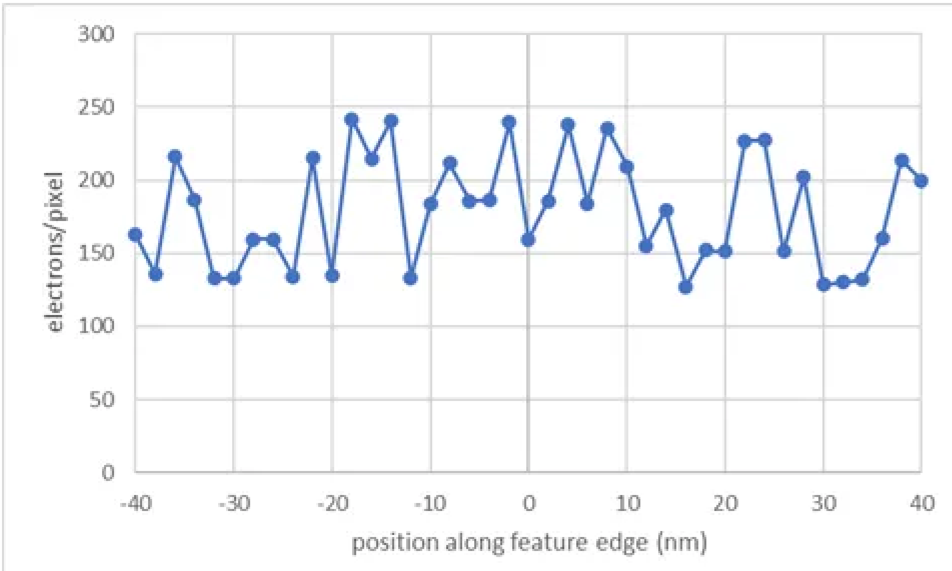

Figure 2. An example of electron noise along 20 nm half-pitch edge. The absorbed photo dose is 11 mJ/cm2 and the pixel size is 2 nm x 2 nm.

The Effect of Electron Blur

The electron scattering results in an effective blurring mechanism which replaces noisy photon absorption profile with a smoothed out profile characterized by the b scale parameters. However, it is important to realize that this only presents the pro for the **mean** electron number per pixel. The variance of AB calculated above show that there are local fluctuations in electron density which are significant deviation from the mean. This is illustrated in Figure 3.

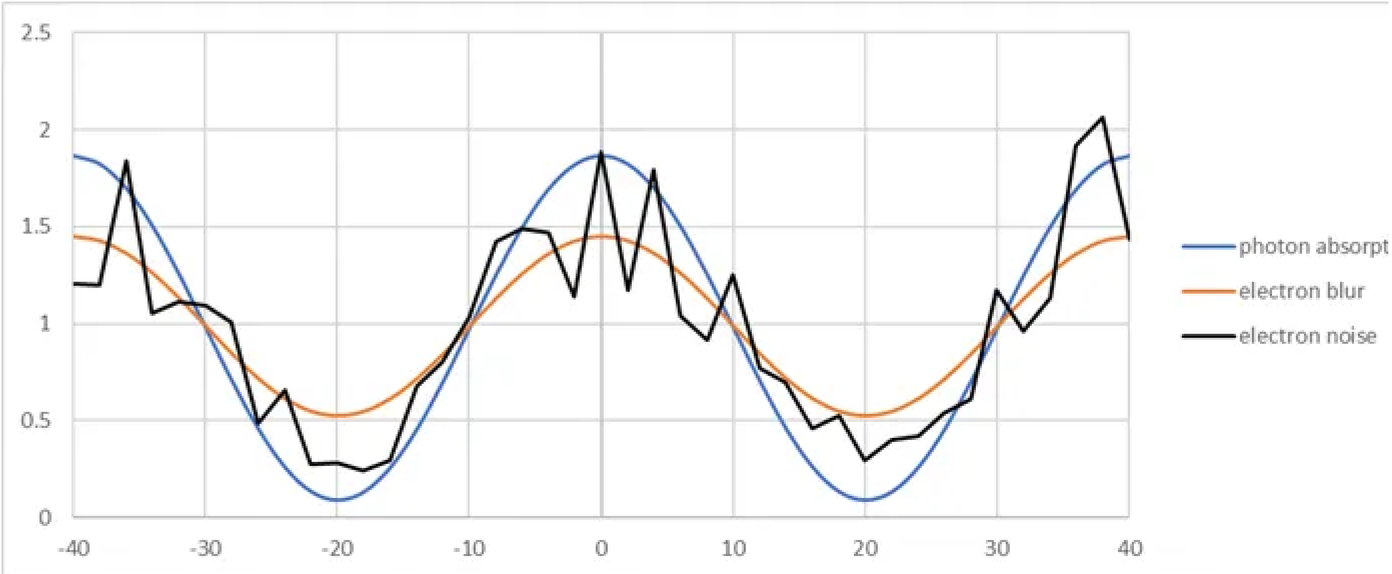

Figure 3. Electron noise superimposed on top of target absorbed photon profile and projected electron blur profile.

Predicting Stochastic Edge Defect Probabilities

The blur reduces the profile contrast (max-min)/avg, making fluctuations more like to cross the printing threshold, which is now closer to the profile maximum or minimum. While the probability of a given pixel crossing the threshold when it shouldn't can in fact be non-negligible, for a printed defect to actually emerge, we should expect a cluster of adjacent pixels to all wrongly cross or fail to cross the threshold, becoming defective. Therefore, the probability of the defect occurring should be the product of the probabilities of all the pixels in the cluster becoming defective.

To get these probabilities, we need to compute the cumulative distribution functio (CDF) for the AB distribution described above. In fact, we can treat this using five independent Poisson distributions corresponding to the cases of 5 electrons/photo electrons/photon, etc., all the way to 9 electrons/photon, each case equally weighte The CDF for the Poisson distribution is commonly described in terms of the gamn function [6], and is basically the sum (for j=0 to k, the test absorbed photon or

photoelectron number) of exp(-N)*N^j/j!, with N being the expected absorbed photo
photoelectron number.

The computation of the CDF for the released electrons per pixel can be carried ou with a Python code which can be generated by AI, for example. It is applied to the following case: 20 nm half-pitch, 11 mJ/cm^2 absorbed dose (40 nm thick resist), 2 n 2 nm pixel, electron blur probability density function: 0.5*(1/5nm*exp(-r/5nm)-0.08/0.4nm*exp(-r/0.4nm)). For an 8 nm x 6 nm below-threshold defect at th edge, the per-pixel probabilities of failing to cross threshold are shown in Figure 4 The nearer the pixel to the edge, the higher the probability of the electron number fluctuations being on the wrong side of the printing threshold.

Figure 4. Per-pixel probabilities near the edge of a 20 nm half-pitch feature (2 nm x 2 nm pixel size). The dose and blur conditions are provided in the text.

Multiplying the 12 per-pixel probabilities gives 3.7e-6 as the probability for the 8 r x 6 nm defect. While the failure of exposure is considered limited to this region at edge, the narrowed exposed region adjacent to it could also possibly fail to develop fully, due to the effectively higher aspect ratio, which could cause less flow at the trench bottom or more localized buildup of dissolved photoresist [7]. Thus, this co be a possible microbridging mechanism.

Going to 10 nm half-pitch, for example, we would scale the pixel size to 1 nm x 1 n so that even doubling the absorbed dose would still halve the absorbed photons pe pixel, leading to both increased photon and electron noise, as shown in Figure 1. T relatively larger standard deviation at smaller pitches means the CDF will lead to larger probabilities of forming defects, as has also been observed in a recent EUV stochastic defect study [8].

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