# Impact of Mask Roughness on Wafer Line-Edge Roughness

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The influence of line-edge roughness (LER) of an optical photomask on the resulting printed wafer LER is investigated. The LER Transfer function (LTF) proposed by Naulleau and Gallatin, and later corrected by Tanabe, is shown to be a very useful tool for evaluating the low-pass filtering behavior of the imaging tool and its impact on the transfer of mask LER to the wafer. High-frequency mask LER can also impact wafer LER by lowering the normalized image log-slope (NILS) of the image, though it would take a large amount of mask LER before this affect would be noticeable. Low-frequency mask LER, most likely due to mask writer errors such as shot placement or rotation errors, will produce wafer LER that may be significant in magnitude. Further work characterizing the magnitude and frequency content of mask LER over many different masks and processes is needed.

**Keywords**: Line-edge roughness, LER, mask roughness, photomask roughness, LER Transfer Function, LTF

## 1. Introduction

Masks are typically specified based on mean and uniformity of critical dimensions over a range of feature types of nominal sizes. Thanks to growing values of the mask error enhancement factor (MEEF), CD specifications on the mask have been shrinking at a faster rate than the nominal wafer CD.[1] Lately, another important lithographic metric has begun to affect the way mask specifications are being approached: wafer line-edge roughness (LER). As the importance of LER to wafer lithography grows, concern about the transfer of roughness from the mask to the wafer has also grown. Early experimental studies[2] showed that the frequency filtering affect of projection imaging significantly attenuated the impact of mask roughness. A theoretical study[3] defined the LER transfer function (LTF) from mask to wafer in the frequency domain. The relationship between the LTF and the MEEF has also been discussed.[4] However, the combination of shrinking specifications, increased resolving capability of lithographic imaging tools, and increased importance of wafer LER has meant that mask roughness can no longer be thought of as an insignificant contributor to wafer LER.

Wafer LER (and the related concept, linewidth roughness, LWR) is a growing problem for a simple reason: the magnitude of the wafer LER has not been shrinking at the same rate that feature sizes on the wafer have been shrinking. In fact, it might be argued that LER magnitude has remained about constant ever since its recognition as a potential problem. The industry has no approach to shrink LER in lock-step with shrinking feature sizes, leading to an inevitable collision when LER becomes the limiter to lithographic resolution in manufacturing. If shrinking the magnitude of wafer LER (over the right frequency range) will ever be possible, it will first require a thorough understanding of the various mechanisms that contribute to wafer LER. This is the motivation for this work.

## 2. Background and the LTF

How does the mask contribute to feature roughness on the wafer for projection optical lithography? An obvious answer is that rough features on the mask will print as rough features on the wafer, mediated by the low-pass filtering effect of the imaging lens. This mechanism for roughness transfer will be addressed in some detail below. Another mechanism at work in Extreme Ultraviolet (EUV) masks is the roughness of the multilayer reflector of the mask blank giving rise to phase variation in the nominally 'clear' regions of the mask. This mechanism seems to dominate for EUV masks[5,6], but is not significant for 193-nm imaging. Since this paper will focus on 193-nm lithography, phase roughness of the mask blank will not be addressed here. A third mechanism – the impact of mask roughness on the image log-slope – will be introduced in a subsequent section.

The main mechanism by which a mask impacts wafer LER is the transfer of mask feature-edge roughness directly to the wafer through the process of imaging.[3,4] To characterize the frequency filtering effect of the imaging process, the LER transfer function (LTF) will be used. Consider a long feature edge oriented in the *y*-direction. Let $\Delta_{mask}(y)$ represent the deviation of the mask feature edge from its nominal position (that is, the roughness of the edge), with the wafer roughness given by $\Delta_{wafer}(y)$. The LTF is then defined as[3]

$$LTF(f) = \frac{\mathcal{F}\{\Delta_{wafer}\}}{\mathcal{F}\{\Delta_{mask}\}} \qquad (1)$$

where $\mathcal{F}\{\}$ is the Fourier transform, transforming spatial position *y* into spatial frequency *f*.

The behavior of the LTF as $f \rightarrow 0$ is significant. At zero spatial frequency, $\Delta$ becomes simply an edge placement error (or critical dimension error), as does the magnitude of its Fourier transform. Thus, in the limit of small $\Delta$, LTF(0) is just the mask error enhancement factor (MEEF), defined as the change in wafer dimension resulting from a small change in mask dimension. When Naulleau and Gallatin derived their LTF, they normalized it so that LTF(0) = 1.[3] This error was corrected by Tanabe et al. [4], and it is the Tanabe correction to the Naulleau and Gallatin equation that will be presented below.

Consider the simple but important case of an isolated edge imaged by conventional illumination (a disk-shaped source of radius $\sigma$ in partial coherence space). For small $\Delta_{mask}$ these edge deviations can be treated as a linear perturbation to the imaging, allowing the derivation of the LTF: [3]

$$LTF(\tilde{f}) = MEEF \frac{\int_{\tilde{f}-1}^{\sigma} ds \sqrt{\left(\sigma^2 - s^2\right)\left(1 - \left[s - \tilde{f}\right]^2\right)}}{\int_{-\sigma}^{\sigma} ds \sqrt{\left(\sigma^2 - s^2\right)\left(1 - s^2\right)}}, \qquad \tilde{f} \le 1 + \sigma$$

$$LTF(\tilde{f}) = 0, \qquad \tilde{f} > 1 + \sigma \tag{2}$$

where the normalized spatial frequency is given by $\tilde{f} = f\lambda / NA$, $\lambda$ is the imaging wavelength, and *NA* is the numerical aperture. While derived only for an isolated edge, this equation in fact will be applicable to any practical feature, since the interaction of the nominal edges is captured by the MEEF, and since it will be reasonable to assume that the imaging of the roughness of one edge will not be influenced by the roughness present on nearby edges. Equation (2) is plotted in Figure 1 for various values of $\sigma$.

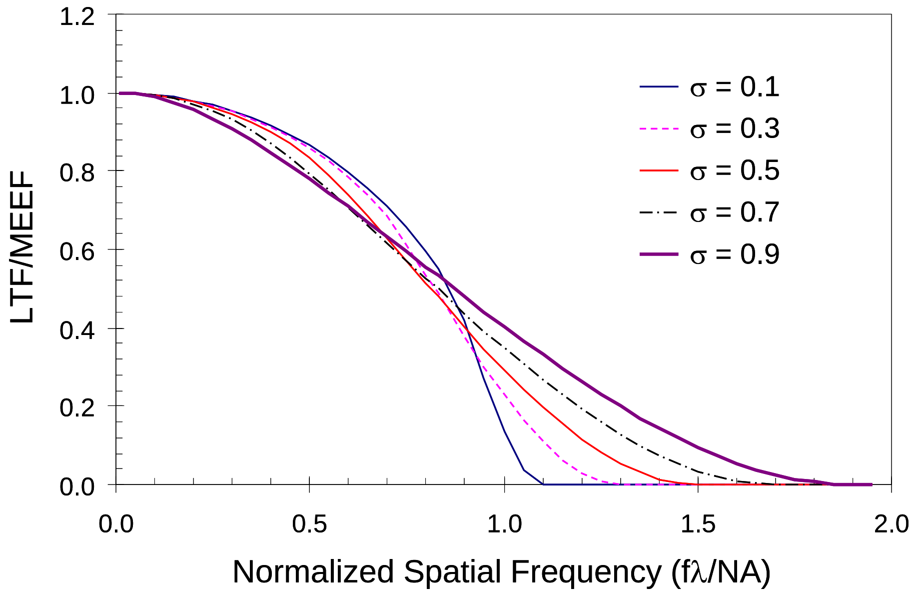


Figure 1. Plot of the LER transfer function (LTF) for conventional illumination for different values of the partial coherence factor, $\sigma$.

A simplified version of the LTF can be obtained by empirically fitting results of equation (2) to an appropriate algebraic function. The following function was found to match the true LTF reasonably well for all values of $\sigma$,

$$\frac{LTF(\tilde{f})}{MEEF} \approx \frac{1+k}{1+k\left(\frac{\tilde{f}_{\max}}{\tilde{f}_{\max}-\tilde{f}}\right)^n}, \qquad \tilde{f} \le \tilde{f}_{\max} = 1+\sigma \tag{3}$$

when $k$ = 0.07 and $n = 4.2\tilde{f}_{\max} - 2.75$. This simplified and approximate form of the LTF may prove useful in some applications.

The value of $\tilde{f}_{\max}$ is significant since LTF = 0 (meaning no roughness is transferred) for all frequencies greater than $\tilde{f}_{\max}$. The relationship between this normalized cut-off frequency and source parameters for various standard source shapes is given below:

Conventional: $\tilde{f}_{\max} = 1+\sigma$

Annular: $\tilde{f}_{\max} = 1+\sigma_{outer}$

Quadrupole: $\tilde{f}_{\max} = \sqrt{(1+\sigma_{radius})^2 - 0.5\sigma_{center}^2} + \frac{\sigma_{center}}{\sqrt{2}}$

Dipole: $\tilde{f}_{\max} = \sqrt{(1+\sigma_{radius})^2 - \sigma_{center}^2}$

For conventional, annular, and quadrupole illumination, this $\tilde{f}_{\max}$ corresponds to the standard pitch resolution limit of the imaging tool. For dipole, however, $\tilde{f}_{\max}$ corresponds to the resolution in the poor imaging direction. Roughness along a properly oriented line can be thought of as a pattern oriented in the perpendicular direction. Since dipole has very poor resolution in this direction, the roughness is poorly imaged, corresponding to an even greater frequency filtering effect. Consider a typical case of $\sigma_{center}$ = 0.8 and $\sigma_{radius}$ = 0.1. For properly oriented lines, the spatial frequency limit is 1 + $\sigma_{center}$ + $\sigma_{radius}$ = 1.9. For the roughness, the spatial frequency cut-off is 0.755, which is 2.5 times lower. Thus, not only does dipole provide the maximum resolution for properly oriented lines and spaces, it also provides the maximum attenuation of mask LER.

## 3. Impact of Mask LER on NILS

To first order, wafer LER is inversely proportional to the normalized image log-slope (NILS) of the image for that feature. Lower NILS makes the feature more sensitive to the stochastic variations that cause LER. Consider mask roughness at a frequency above $\tilde{f}_{\max}$. According to the LTF, this roughness won't be transferred to the wafer. However, this roughness will cause a decrease in NILS and thus indirectly will cause an increase in wafer LER.

To evaluate the magnitude of this effect, consider an idealized rough mask as shown in Figure 2. The mask edge is made up of a square wave of absorber with a 50% duty cycle, a total width of the rough region of $w_r$ (corresponding to the peak-to-valley amplitude of the roughness), and a period smaller than $1/\tilde{f}_{\max}$. Since the frequency of the roughness is above the LTF cut-off, the roughness itself cannot be imaged. Thus, its only impact will be to create an effectively gray region at the mask edge with 50% transmittance and width equal to $w_r$. Thus, a mask with this high-frequency roughness can be modeled as a mask with a gray boundary layer (as shown in Figure 2). Note that the nominal feature edge will be at the center of the gray boundary region.

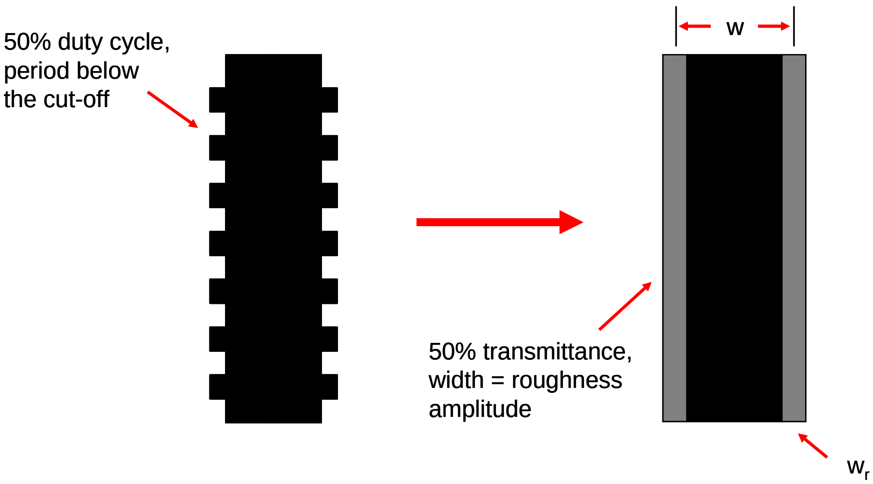


Figure 2. A model rough mask with 50% duty cycle is transformed into a mask with a 50% transmitting boundary layer of width equal to the peak-to-valley amplitude of the roughness.

The impact of this gray boundary region on NILS can easily be calculated. For the case of equal lines and spaces of nominal width *w* imaged with coherent illumination, the NILS of the image can be calculated analytically.

$$NILS = NILS_0 \cos\left(\frac{\pi w_r}{2w}\right) \tag{3}$$

where it is assumed that only the 0 and ±1 diffraction orders are used to form the image and $NILS_0$ is the NILS when there is no roughness ($w_r = 0$). Assuming $w_r << w$, the cosine can be expanded using the first terms of its Taylor series:

$$NILS \approx NILS_0\left[1-\left(\frac{w_r}{0.9w}\right)^2\right] = NILS_0\left[1-\left(\frac{w_r}{k\,w}\right)^2\right] \quad where\ k = 0.9 \tag{4}$$

Thus, NILS falls off approximately quadratically as the amplitude of the high-frequency mask roughness increases.

Although equations (3) and (4) were derived for coherent illumination, a number of simulations (using PROLITH v12.0) were performed for conventional, annular, quadrupole and dipole illumination. All of these simulations produced results that matched the quadratic fall-off of equation (4) with *k* in the range of 0.9 – 1.1. Thus, *k* = 1 can be used to estimate the basic trends involved.

How much high-frequency roughness on the mask can be tolerated? Consider allowing a drop of NILS of just 1% (a very small amount). The NILS can be kept within this level of NILS reduction so long as $w_r < 0.1w$. In other words, a high-frequency mask roughness equal to 10% of the nominal CD would result in only a 1% reduction in NILS. So long as mask roughness is kept below this amount, the impact of mask roughness on NILS can be safely ignored. Note that $w_r$ is about equal to the $3\sigma_{rms}$ value of the roughness.

## 4. Discussion

In general, high-frequency roughness on the mask will be process-induced during mask making. The stochastic nature of electron beam exposure, chemically amplified reaction-diffusion, and etching produce mostly roughness with length scales on the order of or less than 100 nm. After reduction by 4X in the imaging tool, this roughness will be of frequencies greater than the cut-off frequency of the LTF. Thus, so long as the amplitude of the process-induced roughness is kept at a manageable level (less than 10% of the minimum resolvable feature size), process-induced mask LER can usually be safely ignored from the perspective of wafer LER needs. It is possible that some small amount of process-induced LER will be at frequencies low enough to pass through the imaging tool to the wafer. Since there has been very little published data on the frequency characteristics of mask LER, it is hard to make a more definitive statement at present.

Mask writer-induced LER, on the other hand, occurs at frequencies low enough to pass through to the wafer. For example, Stokowski and Alles showed that systematic shot placement errors from an e-beam writer produced errors that appeared as low-frequency roughness on the mask.[7] For one particular mask, a 1-μm period roughness was observed with a peak-to-valley amplitude of 1.5 nm, thought to be due to the exposure shots rotated by 1.5 mrad. An 8-μm period roughness with a peak-to-valley amplitude of 3.5 nm was also found, thought to be due to a 0.4 mrad rotation of the shot deflection system. The 4X mask used in their study was chrome on glass and had features down 65-nm half pitch.

To see how such a mask might affect wafer LER, consider an imaging tool with $\lambda$ = 193 nm and $NA$ = 1.2. The 1-μm period and 8-μm period mask edge errors would produce normalized frequencies at the wafer of 0.64 and 0.08, respectively. If the imaging used conventional illumination with $\sigma$ = 0.5, the resulting LTF would be

1-μm period roughness on mask: $LTF\left(\tilde{f} = 0.64\right) \approx 0.68 MEEF$
8-μm period roughness on mask: $LTF\left(\tilde{f} = 0.08\right) \approx 0.99 MEEF$

If, for example, the feature in question had a MEEF of 3, 1-μm period mask roughness would transfer with an LTF of 2, so that its 1.5 nm amplitude on the mask would produce a 3σ wafer roughness of about 0.8 nm. The 8-μm period mask roughness would transfer with an LTF of 3, so that its 3.5 nm amplitude on the mask would produce a 3σ wafer roughness of about 2.6 nm. Since these errors would be systematic, they would add directly to the wafer LER coming from other sources. Obviously, the magnitude of these errors are significant.

Interestingly, for small-dimension mask features these mask writer shot placement errors will produce roughness that is correlated across the two edges of the feature. Since most other errors produce wafer LER that is uncorrelated edge to edge, an examination of such edge LER correlations on the wafer could be a useful tool for accessing the magnitude of the mask's contribution to wafer LER. Note, however, that the long periods involved (up to 2 μm on the wafer for the example given above) mean that a very long measurement window on the wafer will be required.

## Conclusions

Mask LER is likely an important contributor to wafer LER. The LER Transfer function (LTF) proposed by Naulleau and Gallatin[3], and later corrected by Tanabe et al.[4], is a very useful tool for evaluating the low-pass filtering behavior of the imaging tool and its impact on the transfer of mask LER to the wafer. High-frequency mask LER can also impact wafer LER by lowering the NILS of the image, though it would take a large amount of mask LER (3σ LER more than 10% of the minimum feature size) before this effect would be noticeable. Low-frequency mask LER, most likely due to mask writer errors such as shot placement or rotation errors, will produce wafer LER that may be significant in magnitude in high MEEF regions of the image. Further work characterizing the magnitude and frequency content of mask LER over many different masks and processes is sorely needed.

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