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MASK ROUGHNESS INDUCED LER: a rule of thumb

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An issue requiring some attention

The ITRS requires < 1.2nm line-edge roughness (LER) for the 22nm half-pitch node. Currently, we can consistently achieve only about 3nm LER. Further progress requires understanding the principle causes of LER.

Much work has already been done on how both the resist and LER on the mask effect the final printed LER. What is poorly understood, however, is the extent to which system-level effects such as mask surface roughness, illumination conditions, and defocus couple to speckle at the image plane, and factor into LER limits.

A typical lithography system, Kohler Illumination.

Presently, mask-roughness induced LER is studied via full 2D aerial image modeling and subsequent analysis of the resulting image. This method is time consuming and cumbersome.

It is, therefore, the goal of this research to develop a useful "rule-of-thumb" analytic model for mask roughness induced LER to expedite learning and understanding.

Mask Roughness LER: Random or Predictable Effect?

When coherently illuminated, roughness on the mask couples to speckle in the aerial image. By specifying illumination conditions (coherence, σ), optical conditions, and mask roughness characteristics (replicated surface roughness (RSR) and correlation length), the resulting speckle statistics are largely determined.

$$\text{Speckle} = \partial I$$

Intensity variations, specified by illumination conditions and mask roughness parameters

Greater height variations (RSR) and lesser self-similarity across the mask (correlation length) mean that the mask is "rougher" in a statistical sense.

So...Can't we push a few terms around and rearrange?

$$\text{LER} = 3\sigma = 3 \cdot \text{Speckle} \frac{1}{\text{Intensity} \cdot \text{ILS}}$$

An Analytic Solution

Given the rms speckle (intensity variation), the resulting LER can be expressed in terms of the aerial image log slope (ILS). In practice, the ILS can be quickly determined using 1D aerial image simulations. To determine the illumination- and mask-specific clear-field rms speckle, a one-time 2D aerial image simulation can be performed. From these two values, the full parameter space can be reached by this analytic extension.

Image-log-slope (ILS) measures the aerial image intensity transition across an edge when features are present on a mask; e.g. from line to space.

ILS is typically used as a metric of imaging quality, and can be applied to determine the coupling between intensity variations (speckle) to line-edge movement (LER).

$$\text{ILS} = \frac{\partial \ln I}{\partial x} = \frac{1}{I} \frac{\partial I}{\partial x}$$

small change in intensity
movement of line-edge

Larger ILS means that a given intensity variation would change line-edge position less than a smaller ILS would.

Verification

To verify the validity of this approach, we compared the analytic LER to the LER resulting from the full 2D aerial image simulations (extracted using SUMMIT).

Our first attempt was a poor match. A direct comparison between the clear-field speckle and feature-specific speckle at the line-edge and in the middle of the space shows great disparity. It is apparent that the presence of features affects speckle in a complex way. The simplification to clear-field speckle is thus not accurate. Another simplification is possible, however, under the long correlation limit where image plane mixing of uncorrelated elements of the mask does not occur.

Simulated = Analytic?

For large RSR and long correlation lengths under highly coherent illumination, the LER enters a "geometric regime", whereby it is proportional to the mask slope error as it propagates through focus.

To confirm, we convolved the PSF of our optical system with the clear-field rough mask, took the slope, and propagated through focus appropriately.

Our second attempt using line-edge speckle (rather than the clear-field) and the geometric model gives an excellent match.

a rule-of-thumb

An analytic solution exists for mask roughness induced LER. For the case that line-edge speckle matches closely with clear-field speckle in the limit of long correlation lengths, it provides a powerful, fast method to obtain LER. Otherwise, this method provides a clean proof-of-principle.

The patent disparity between clear-field and line-edge speckle provokes future research into the effect features have on coherence, as seen through speckle.

In the course of data accumulated here, simulations show that in all cases LER peaks for mid-spatial frequency roughnesses (32nm, wafer dim.), about the resolution of our optic. Simulations will be extended to higher NA to see if this is coincidental.