Optimizing Numerical Aperture and Partial Coherence

Chris A. Mack, *FINLE Technologies, Austin, Texas*

Exposure tools for optical lithography have historically provided some of the greatest challenges to the optics industry in terms of image resolution, field size and image quality. The result has been lens systems of immense complexity and cost. Yet despite their sophistication, these tools have until recently been fixed in their optical parameters, allowing no flexibility in how an image is formed. In the last three years, however, every major manufacturer of step-and-repeat projection lithography tools has introduced "flexible" steppers, models with variable numerical aperture and partial coherence. What is the reason for the sudden onslaught of configurable imaging systems? What should the average lithographer do with these two new knobs on their very expensive tools?

Six years ago, when the concept of varying numerical aperture (NA) and partial coherence (σ) was first introduced [1,2], there seemed little interest in the idea. At the time, numerical apertures of *i*-line steppers had reached 0.45 and were climbing steadily. It seemed that users would always need higher and higher numerical apertures. (Essentially, a variable numerical aperture means that the NA can be *reduced* from its maximum value. If the desired NA is higher than the current maximum, their is no need for a variable NA.) Since few people appreciated the role of partial coherence in image formation, their seemed little incentive to vary this parameter either. Why was there a change of heart in the industry? To answer this question, let's explore the fundamental reasons why a flexible stepper may be advantageous.

The role of numerical aperture in imaging is often described (and often misunderstood!) using the Rayleigh criterion for resolution (R) and depth-of-focus (DOF):

$$R = k_1 \frac{l}{NA}$$

$$DOF = k_2 \frac{l}{NA^2}$$

where λ is the wavelength of the light and k_1 and k_2 are described as "process dependent constants." Often, relying on the Rayleigh equations for guidance, lithographers conclude that higher numerical apertures result in better resolution but worse depth of focus. But is this claim correct?

In my experience a more appropriate term for a process dependent constant is an unknown variable. In fact, these two equations are simply scaling equations and k_1 and k_2 are simply dimensionless versions of the resolution and DOF, respectively. Furthermore, the DOF criterion applies only to a feature at the resolution limit of the imaging system. Thus, changing the wavelength or numerical aperture changes the DOF, but for a different feature size! If one were to ask the more appropriate question, for a given feature size how does NA and λ impact the DOF, the Rayleigh equations would be quite useless.

Fortunately, there is a better way. In the last two editions of the Lithography Tutor we defined the depth of focus in a very rigorous way: the range of focus which keeps the photoresist profile within specifications (linewidth, sidewall angle, and resist loss) over a given range of exposure (an exposure latitude specification). Using this definition, the role of numerical aperture can be investigated. Figure 1 shows an example where a given lithographic job (imaging 0.5μm lines and spaces with an *i*-line stepper, σ = 0.5) is performed and the numerical aperture is allowed to vary. The resulting DOF (based on ±10% linewidth variation, >80° sidewall angle, <10% resist loss and 20% exposure latitude) is plotted versus numerical aperture. From this graph comes a startling conclusion: there is one numerical aperture which gives the maximum depth of focus! Numerical apertures either higher or lower than this optimum value result in worse DOF. The Rayleigh criterion gives no hint that such an optimum could exist.

The reason for the peak DOF behavior with NA is the competition between two effects in imaging. For low NA, the imaging becomes *resolution limited*. The small numerical aperture does not capture enough of the diffraction pattern to provide a good quality image. Thus, higher numerical apertures give better images, and as a result improved DOF. However, as the numerical aperture increases, the imaging process becomes more sensitive to focus errors. In the high NA region, the process becomes *focus limited*, resulting in reduced DOF as NA is further increased. The competition between these two effects produces an optimum numerical aperture (in the case of Figure 1, at NA = 0.48).

The optimum NA is a strong function of feature size and type. Large features need lower numerical apertures while small features want higher numerical apertures. Given the fact that a single stepper must be capable of imaging different mask levels of different products with different minimum feature sizes and types, a one-NA-fits-all approach is not the best. For the case of printing the 0.5μm lines and spaces with an *i*-line stepper as shown in Figure 1, if the maximum numerical aperture of the stepper is greater than 0.48, the stepper would benefit from using a variable NA. In our current environment of very high NA state-of-the-art steppers, the need for variable NA capability has become quite pronounced.

Like numerical aperture, there is an optimum partial coherence to achieve the best DOF. If both NA and σ are allowed to vary, there will be one setting which gives the best out-of-focus performance. Figure 2 shows a typical result, where both NA and σ are allowed to vary and the depth of focus is determined at each setting. As is the case for all but the smallest of features, the optimum partial coherence is the lowest possible, and the optimum NA is also lower for the lower values of σ. For very small features (such as 0.35μm features printed with *i*-line), higher partial coherences become better.

Although depth of focus is one of the more important metrics to judge the quality of a lithographic process, it is not the only one. Another critical effect, at least on some mask layers, is the print bias between dense and isolated lines. As Figure 3 shows, lower partial coherence results in a larger difference between the linewidth of a line in an array of equal lines and spaces and the linewidth of an isolated line. This "bias" between dense and isolated lines, in this case, begins to decrease for $\sigma > 0.35$. Thus, there is a trade-off between the reduced dense-isolated bias and the reduced DOF at higher partial coherence factors.

In the next column, we'll look more closely at this bias, one example of an *optical proximity effect*. (Editor's note: beginning with the next issue of *MLW*, the Lithography Tutor will become the Lithography Expert, delving more deeply into the problems and solutions of optical lithography.)

References

1. C. A. Mack, "Optimum Stepper Performance Through Image Manipulation," *KTI Microelectronics Seminar, Proc.*, (1989) pp. 209-215.

2. C. A. Mack, "Algorithm for Optimizing Stepper Performance Through Image Manipulation," *Optical/Laser Microlithography III, Proc.*, SPIE Vol. 1264 (1990) pp. 71-82.

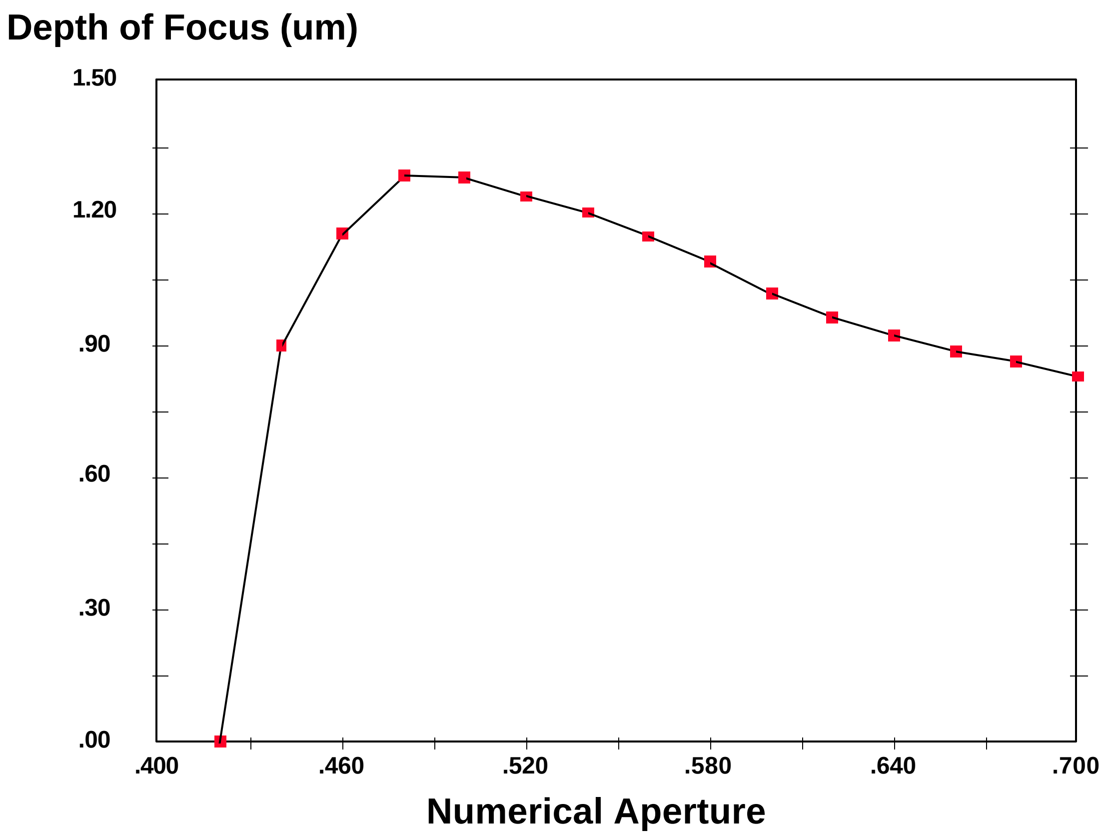

Figure 1. There is an optimum numerical aperture which balances the trade-off between the resolution limited (low NA) and focus limited (high NA) performance regions to give the maximum depth of focus.

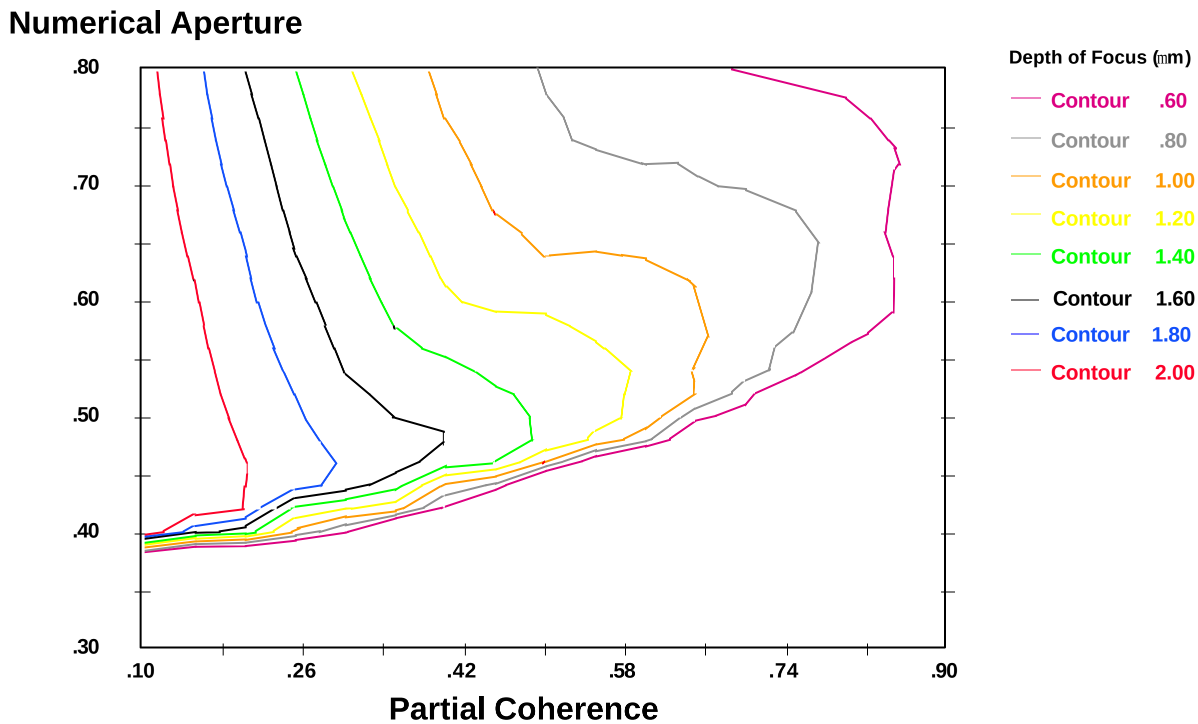

Figure 2. Contours of constant depth of focus as the numerical aperture and partial coherence of the stepper are changed (*i*-line imaging of 0.5µm lines and spaces).

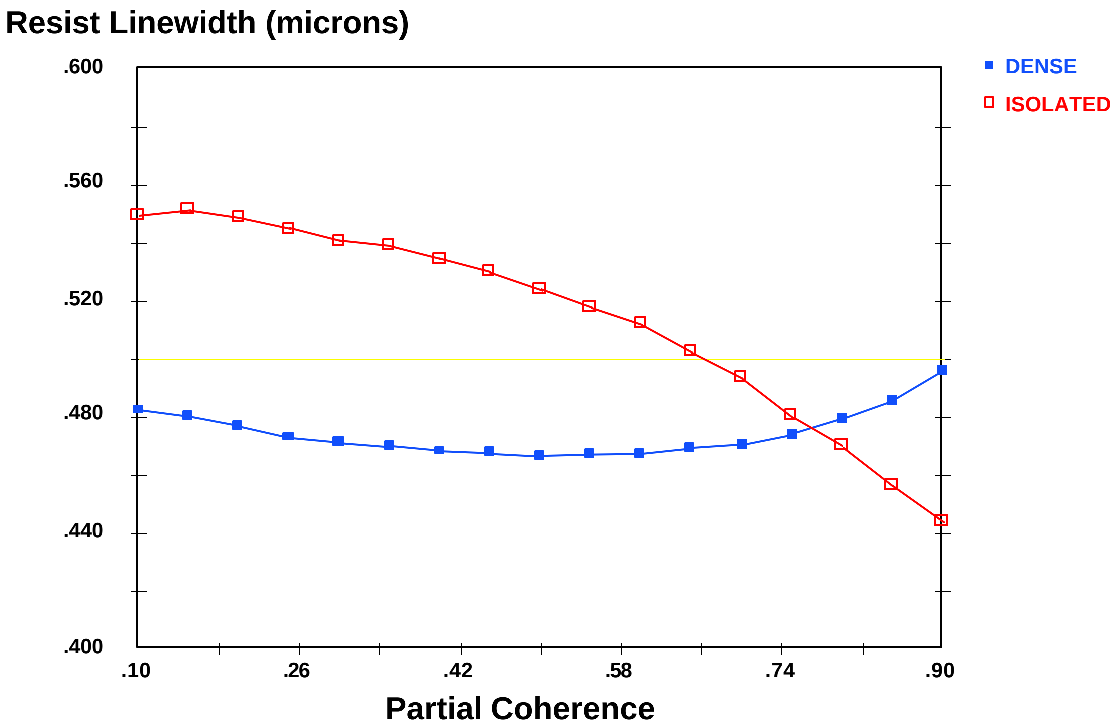

Figure 3. The dense to isolated print bias is a strong function of the partial coherence (in this case, *i*-line exposure with NA = 0.48 was used).