Resolution

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In past editions of this column (Spring and Summer, 1995), we defined quite carefully what is meant by depth of focus (DOF): *the range of focus which keeps the resist profile of a given feature within all specifications (linewidth, sidewall angle, and resist loss) over a specified exposure range*. DOF was measured for a given feature using a focus-exposure matrix and a specific methodology was proposed for analyzing the focus-exposure data to obtain the most useful determination of the DOF. This careful attention to detail was needed to correct the vague and ambiguous way in which the term "depth of focus" is often used in the semiconductor industry. Surely no such ambiguities exist for a term so straightforward as resolution. Alas, clarity again alludes the industry.

Resolution is, quite simply, the smallest feature that you are able to print (with a given process, tool set, etc.). The confusion comes from what is meant by "able." For a researcher investigating a new process, "ability" might mean shooting a number of wafers, painstaking searching many spots on each wafer, and finding the one place where a small feature looks somewhat properly imaged. For a production engineer, the *manufacturable* resolution might be the smallest feature size which provides adequate yield for a device designed to work at that size. For most lithographers, the definition falls somewhere between these two extremes. Can we define resolution, similar to our definition of DOF, in such a way that it can meet all of these varied needs?

Producing an adequately resolved feature in a realistic working environment means printing the feature within specifications (linewidth, sidewall angle, and resist loss) over some expected range of process variations. As we have seen before, the two most common process variations are focus and exposure. Since our definition of depth of focus includes meeting all profile specifications over a set exposure range, a simple definition of resolution emerges: *the smallest feature of a given type which can be printed with a specified depth of focus*. This definition is perfectly general. If the exposure latitude specification used in the DOF definition is set to zero and the DOF specification in the resolution definition is set to zero, the "research" use of the term resolution is obtained (if it prints once, it is resolved). If the exposure latitude and DOF specifications are made sufficiently large to handle all normal process errors encountered in a manufacturing line, the "manufacturing" use of the term resolution is obtained. As with the definition of DOF, the choice of the specifications determines whether the resulting resolution is appropriate to a given application.

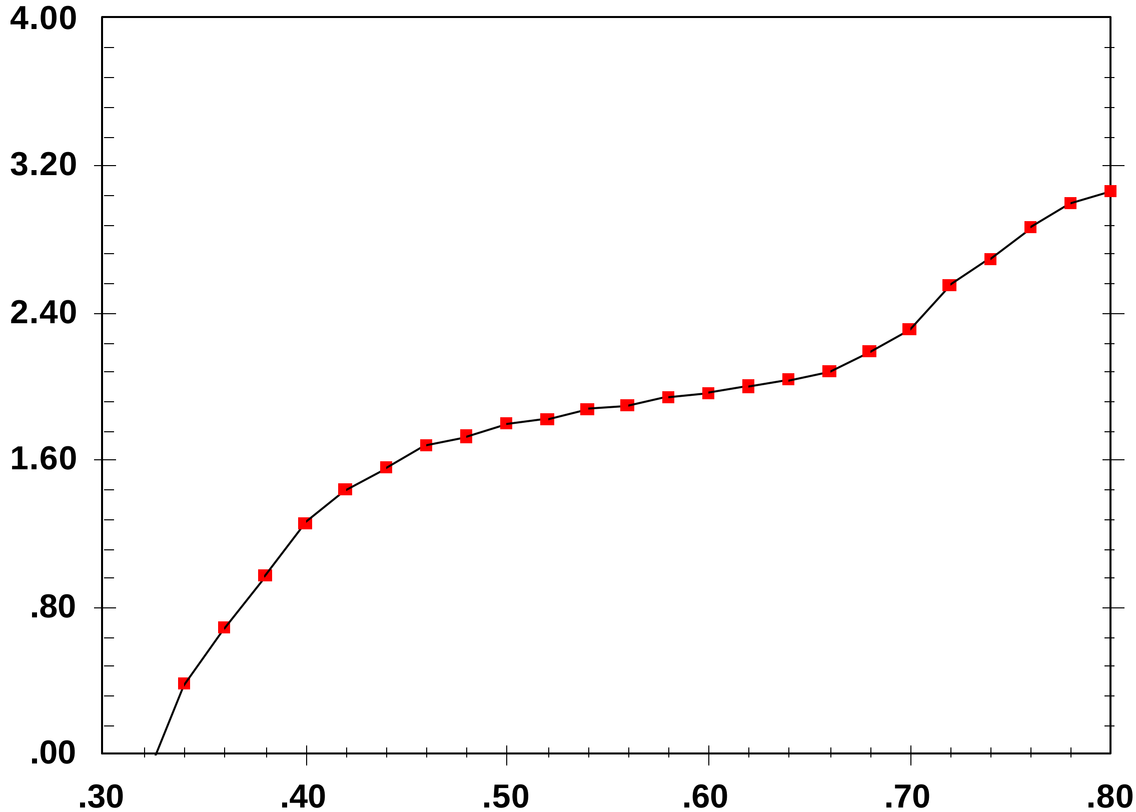
Figure 1 illustrates the concept of resolution. The depth of focus for a pattern of equal lines and spaces is shown as a function of feature size. (For this and subsequent figures, the DOF is based on profile specifications of CD ±10%, sidewall angle > 80°, resist loss < 10%, and an exposure latitude specification of 10%. All focus and exposure errors are assumed to be systematic. Each data point assumes that nominal exposure and focus were adjusted to give the best process window and thus the largest possible DOF. Mask linearity -- the ability to print different feature sizes at the same time -- is not considered here.) If zero depth of focus is required, the resolution for this process would be about 0.33 μm. A requirement of 1.0 μm DOF would increase the minimum printable feature size to 0.38 μm, and a requirement of 1.5 μm DOF would degrade the resolution further to 0.43 μm. Obviously, a simple statement of the resolution without clearly stating the DOF requirement (and thus the profile and exposure latitude requirements) would be of little use.

Figure 2 illustrates how a given process, tool set, etc., does not have a single resolution for all feature types. Obviously, the resolution of the isolated line shown here is greater than the other feature types. For typical DOF requirements, the contact hole shows the worst resolution under these conditions. Figure 3 illustrates how a careful definition of resolution can elucidate fundamental lithographic behavior, such as the role of numerical aperture. For larger features, lower NA gives more depth of focus. But for smaller features, the DOF falls off more quickly for the lower NA. This results in the well-known effect of an optimum NA to give the greatest DOF. But it also impacts resolution in an interesting way. If no DOF is required, the resolution (the point where each curve in Figure 3 hits the x-axis) follows the familiar trend of increased resolution with increased NA. If, however, a large DOF is required, the behavior of resolution with NA becomes more complicated.

Figure 4 expands on the results of Figure 3 and shows the resolution of equal line/space arrays as a function of numerical aperture for different DOF specifications. For example, with a required DOF of 1 μm, the resolution reaches an optimum (a minimum in the curve at a feature size of 0.37 μm) at a numerical aperture of 0.59. Larger numerical apertures actually reduce the resolution! As the required DOF is reduced, the NA which gives maximum resolution moves out to higher values. Also shown on the graph is the Rayleigh resolution criterion ($R = k_1 l/NA$) for comparison. Even if the required DOF is zero, the Rayleigh criterion overestimates the influence of numerical aperture on resolution (due to the 10% exposure latitude requirement still in the DOF = 0 definition). For larger required DOF, the Rayleigh criterion becomes less accurate at predicting the influence of NA on resolution.

Resolution is a fundamental measure of the capability of a lithography process. By applying the rigorous definition of resolution given here, resolution can be measured and used to quantify the impact of processes changes (such as changing the numerical aperture) or for comparing different processes. When scaling current capabilities to the future, the simple Rayleigh criterion may not be adequate.

Depth of Focus (mm)



Mask Width (mm)

Figure 1. Resolution can be defined as the smallest feature which meets a given DOF specification. Shown are results for equal lines and spaces, i-line, NA = 0.54, σ = 0.5, typical resist on bare silicon.

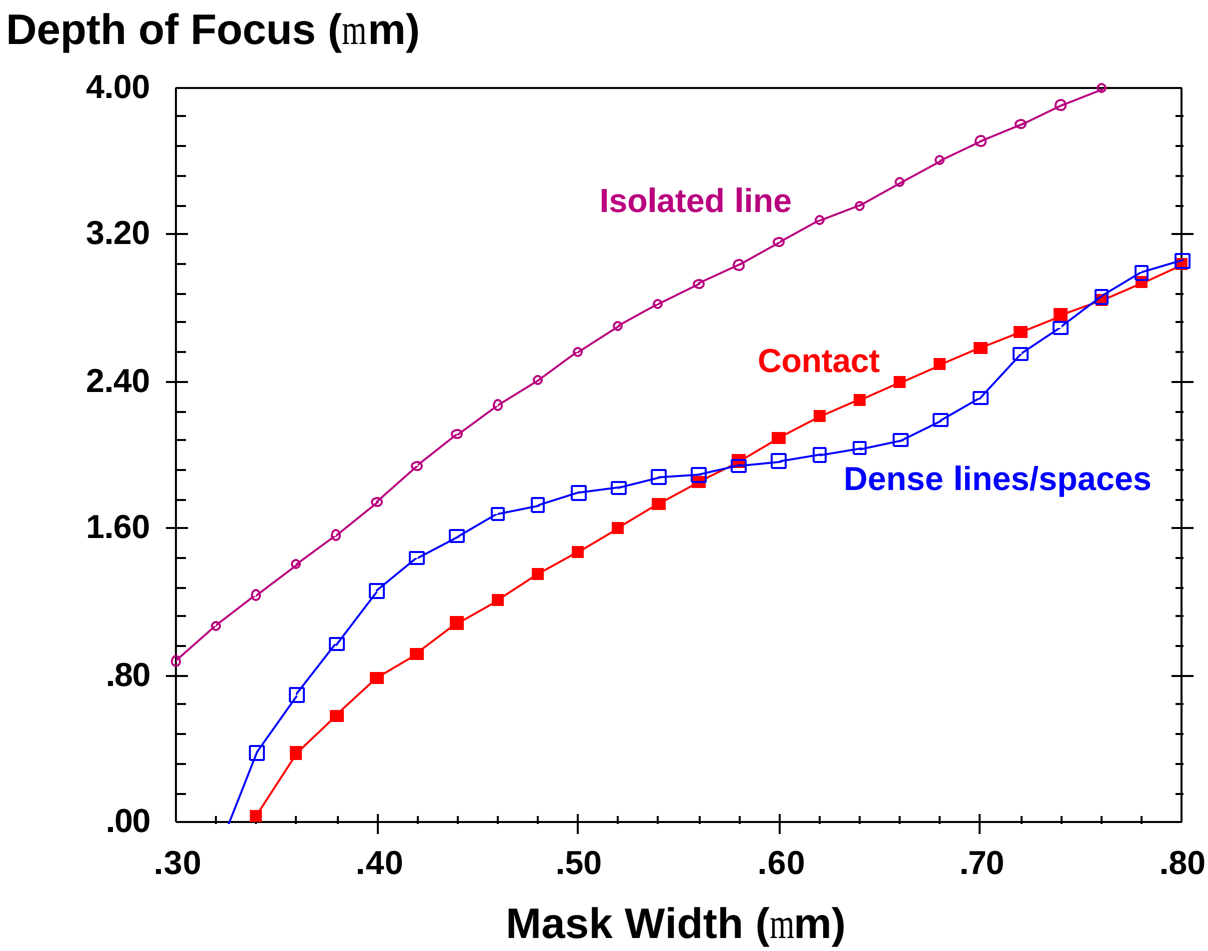


Figure 2. Comparison of the resolution for different feature types (i-line, NA = 0.54, σ = 0.5, typical resist on bare silicon).

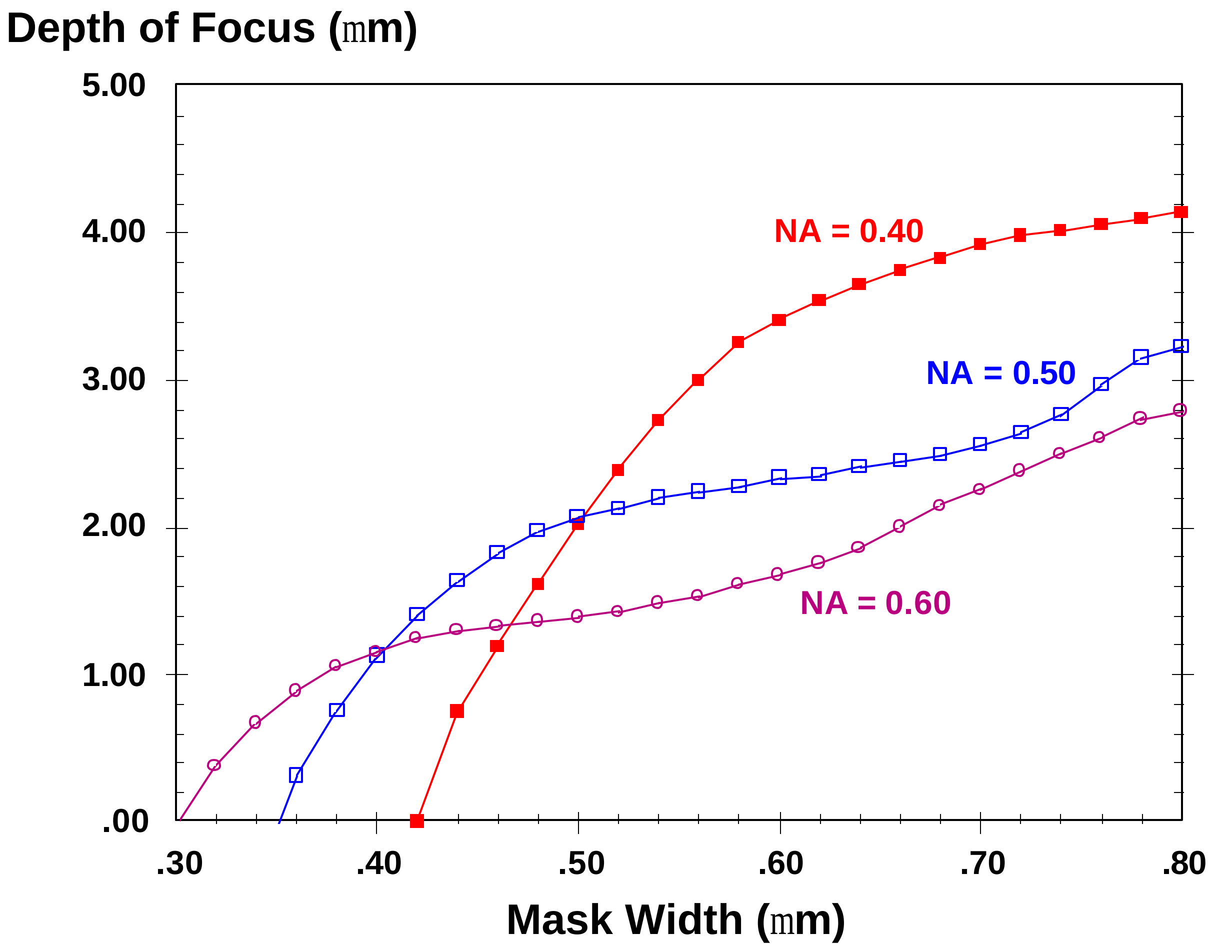


Figure 3. The definition of resolution can be used to study fundamental lithographic trends, such as the impact of numerical aperture (NA) on resolution.

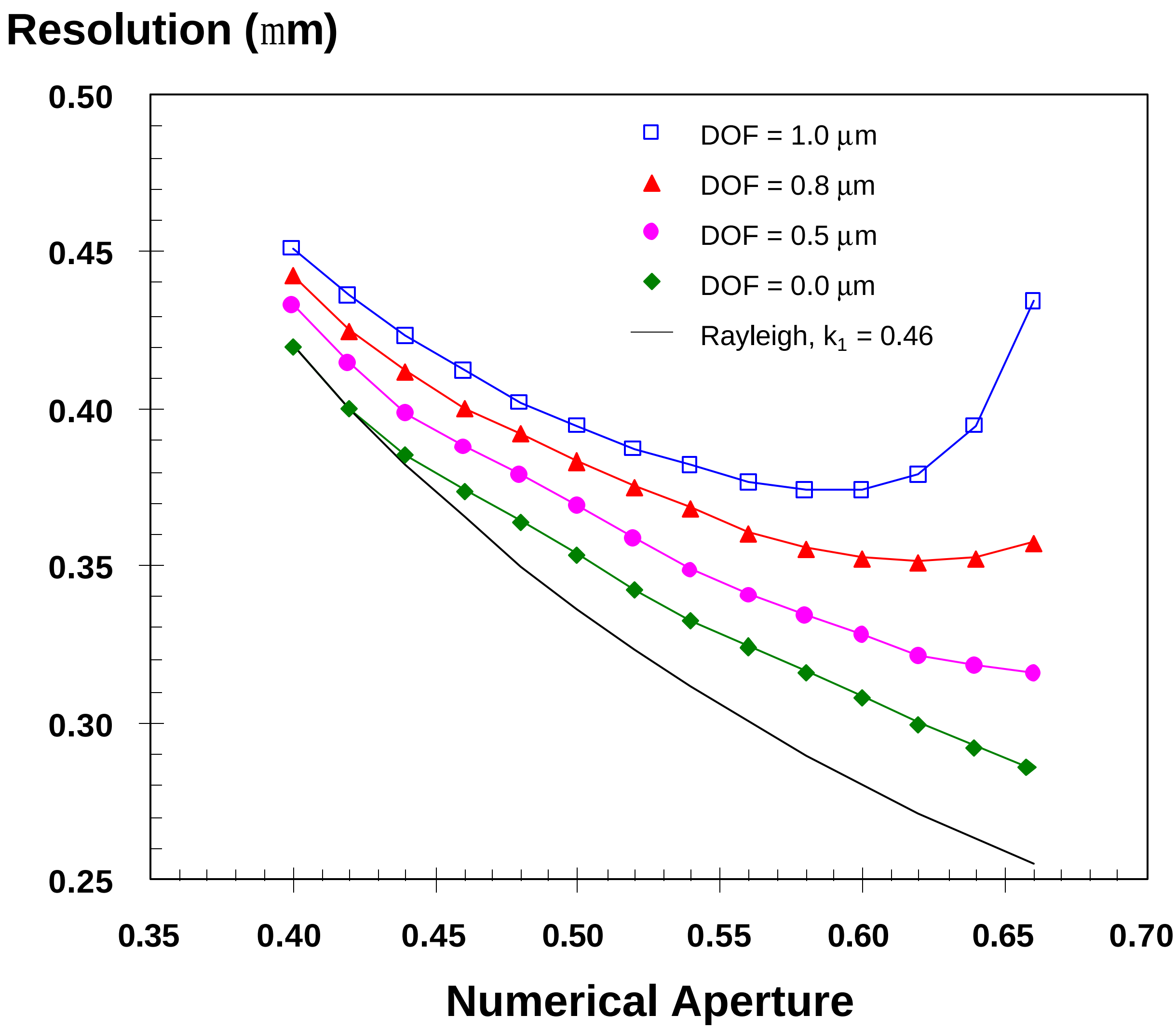


Figure 4. Resolution as a function of numerical aperture is more complicated than Rayleigh's criterion would imply.