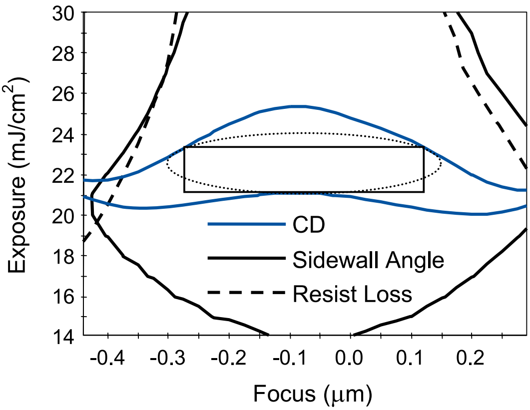
Depth of Focus

To measure the size of a **focus-exposure process window**, the first step is to graphically represent errors in focus and exposure as a rectangle on the same plot as the process window. The width of the rectangle represents the built-in focus errors of the processes, and the height represents the built-in dose errors. The problem then becomes one of finding the maximum rectangle that fits inside the process window. However, there is no one answer to this question. There are many possible rectangles of different widths and heights that are "maximum," i.e., they cannot be made larger in either direction without extending beyond the process window. The result is a very important trade-off between **exposure latitude** and **depth of focus (DOF)**.

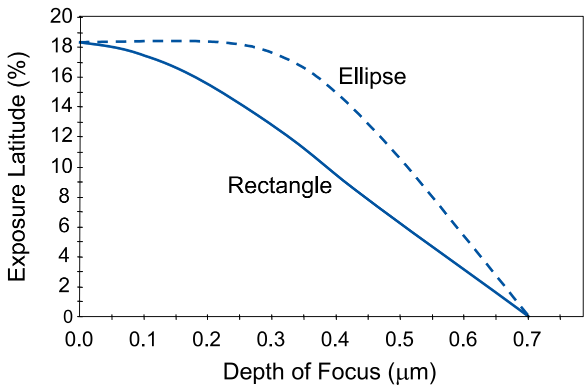


If all focus and exposure errors were systematic, then the proper graphical representation of those errors would be a rectangle. If, however, the errors were randomly distributed, then a surface of constant probability of occurrence is an ellipse.

Using either a rectangle for systematic errors or an ellipse for random errors, the size of the errors that can be tolerated for a given process window can be determined. Taking the rectangle as an example, one can find the maximum rectangle that will fit inside the processes window. Every maximum rectangle is determined and its height

Depth of Focus (cont'd)

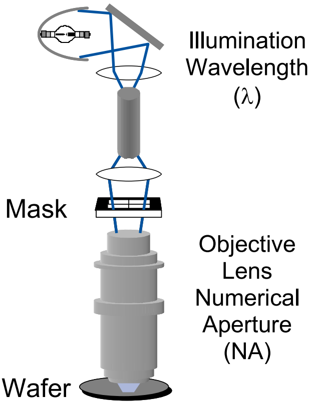
(the exposure latitude) is plotted versus its width (depth of focus, DOF). Likewise, assuming random errors in focus and exposure, every maximum ellipse that fits inside the processes window can be determined. The horizontal width of the ellipse would represent a 3σ error in focus, while the vertical height of the ellipse would give a 3σ error in exposure. A plot of the height versus the width of this family of maximal error shapes gives the exposure latitude versus DOF curve.



The exposure latitude versus DOF curve provides the most concise representation of the coupled effects of focus and exposure on the lithography process. Each point on the exposure latitude vs. DOF curve is one possible operating point for the process. The user must decide how to balance the trade-off between DOF and exposure latitude. One approach is to define a minimum acceptable exposure latitude and then operate at this point. This has the effect of maximizing the DOF of the process. In fact, this approach allows for the definition of a single value for the DOF of a given feature for a given process. The **depth of focus** of a feature can be defined as the range of focus that keeps the resist profile of a given feature within all specifications (linewidth, sidewall angle, and resist loss) over a specified exposure range.

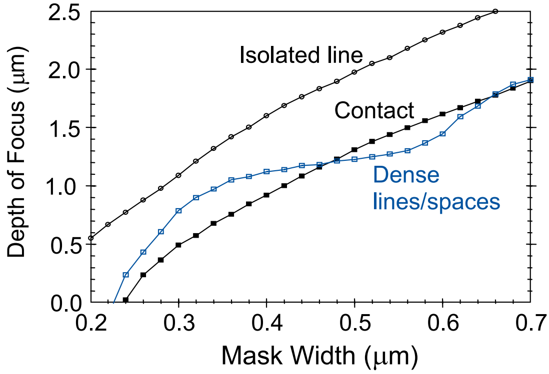
Resolution

Resolution is the smallest feature that you are able to print (with a given process, tool set, etc.) with sufficient quality. For a production engineer, the manufacturable resolution is the smallest feature size that provides adequate yield for a device designed to work at that size.

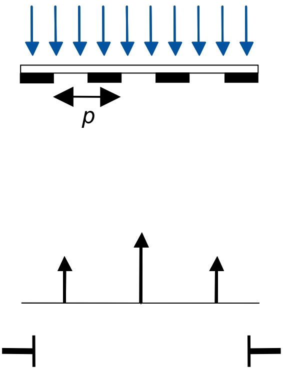


In practice, process variations limit resolution since smaller features have inherently less process latitude. It is common to use focus and exposure dose as representative process variables, so that resolution is defined as the smallest feature of a given type that can be printed with a specified **depth of focus**.

For contact holes, the **point spread function** of the lens forms a good measure of resolution. For dense lines and spaces, the smallest pitch is limited by how many **diffraction orders** can pass through the lens (and thus is limited by λ/NA). For an isolated feature, there is no hard resolution cut-off. Instead, linewidth control is the limiter.



Rayleigh Criteria: Resolution



The easiest (though not the only) way to derive the **Rayleigh resolution criterion** is with the imaging of equal lines and spaces. For a pitch p, the diffraction pattern will be discrete diffraction orders at **spatial frequencies** that are multiples of $1/p$. The lens allows a portion of the diffraction pattern to pass through and be used to form the image. The largest spatial frequency that can make it through the lens is NA/λ.

In order to form an image, at least two diffraction orders must go through the lens. Assuming coherent illumination, this means the zero order and the two first orders must go through the lens. The smallest pitch that allows this to happen would put the first diffraction orders exactly at the edge of the lens:

$$\frac{1}{p_{\min}} = \frac{NA}{\lambda}$$

For equal lines and spaces, the resolution is one half of this minimum pitch:

$$R = \frac{p_{\min}}{2} = 0.5\frac{\lambda}{NA}$$

Since the above criterion for resolution is fairly specific (equal lines and spaces with coherent illumination), it is common in lithography applications to generalize somewhat and simply say that resolution is directly proportional to λ/NA, using k_1 as the proportionality factor:

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

Rayleigh Criteria: Depth of Focus

Defocusing of a wafer is equivalent to causing an aberration—an error in curvature of the actual wavefront relative to the desired wavefront. The distance from the desired to the "defocused" wavefront is called the **optical path difference (OPD)**. Describing the position within the exit pupil by an angle θ, the optical path difference is

$$OPD = \delta(1 - \cos\theta) = \frac{1}{2}\delta\left(\sin^2\theta + \frac{\sin^4\theta}{4} + \frac{\sin^6\theta}{8} + \cdots\right)$$

The diffraction pattern of an array of small lines and spaces is a set of discrete diffraction orders, points of light entering the lens spaced regularly depending only on the wavelength of the light λ and the pitch p of the mask pattern. The angle of the first diffracted order is $\sin\theta = \lambda/p$.

For small lens numerical apertures, the largest angles going through the lens are also quite small and the higher-order terms in the Taylor series for *OPD* can be ignored.

$$OPD \approx \frac{1}{2}\delta\sin^2\theta$$

If the *OPD* were set to a quarter of the wavelength, the zero and first diffracted orders would be exactly 90° out of phase with each other. At this much *OPD*, the zero order would not interfere with the first orders and no pattern would be formed. The true amount of tolerable *OPD* must be less than this amount (as indicated by the factor k_2).

$$OPD_{\max} = k_2\frac{\lambda}{4}, \quad \text{where } k_2 < 1. \text{ Thus,}$$

$$DOF = 2\delta_{\max} = k_2\frac{\lambda}{\sin^2\theta} = k_2\frac{\lambda}{NA^2}$$

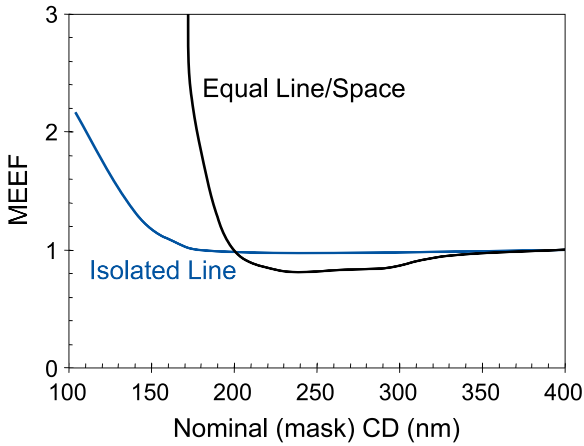
where the last expression on the right applies only at the resolution limit, so that the first diffracted orders are at the edge of the lens. Note that this **Rayleigh DOF criterion** applies only to low numerical apertures when imaging dense patterns at the resolution limit.

Mask Error Enhancement Factor (MEEF)

For "linear" imaging, mask critical dimension (CD) errors translate directly into wafer CD errors (taking into account the reduction factor of the imaging tool). If, however, the features of interest are near the edge of the linear resolution limit, the assumption of linear imaging falls apart. Near the resolution limit, small errors in the mask dimension can cause large errors in the final resist CD. This amplification of mask errors is characterized by the **mask error enhancement factor (MEEF)**. The MEEF is defined as the change in resist CD per unit change in mask CD:

$$\mathrm{MEEF} = \frac{\partial CD_{resist}}{\partial CD_{mask}}$$

where again the mask CD is in wafer dimensions. Regions where the MEEF is significantly greater than 1 are regions where mask error may come to dominate CD control on the wafer.

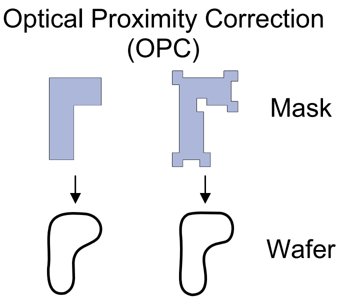


Optical proximity correction techniques allow us to lower the linear resolution, but without improving the MEEF.

Resolution Enhancement Technologies

Attempts to improve the process window by optical means (sometimes called optical "tricks") include:

- Optimization of the mask pattern shape (optical proximity correction, OPC)
- Optimization of the angles of light illuminating the mask (off-axis illumination, OAI)
- Adding phase information to the mask (phase-shift masks, PSM)
- Control of the polarization of the illumination



Collectively, these optical approaches are known as **resolution enhancement technologies** (RETs). While some techniques improve feature resolution at the expense of pitch resolution, many of the RET approaches can improve pitch resolution and increase the process window simultaneously. However, the most promising RETs (especially the best PSMs techniques) require a revolution in chip layout design that has yet to occur.