Abstract | In the second of our ‘introduction to photolithography’ articles we take a look at imaging – a lithography system’s ability to consistently print the ever smaller features that keep the semiconductor industry moving forward.
The drive for more performance, functionality and cost efficiency in the semiconductor industry is intimately linked to the ability to print smaller and smaller IC features. That ability is governed by the imaging performance of the photolithography systems used.

A lithography system’s imaging performance is essentially determined by two key specifications: resolution (or critical dimension) and critical dimension uniformity (CDU). Resolution is the smallest feature size the system can print, while CDU is a measure of the spread in that smallest image size.

System resolution (CD) is determined by the Rayleigh equation:
\[
CD = \frac{k_1 \lambda}{NA}
\]
where \(\lambda\) is the wavelength of the light used, NA is the numerical aperture of the system’s lens and \(k_1\) is known as the resolution factor. This is determined by using shorter wavelengths of light, increasing the numerical aperture and/or reducing \(k_1\).

Looking towards the next wavelength jump, many customers have extreme ultraviolet (EUV) lithography on their production roadmaps. Research institutes are already involved in process R&D using 13.5-nm EUV systems and the most recent research data has shown the technology’s capability with 32-nm features. For more about recent EUV developments, see page 6.

### Lens Technology

Switching wavelengths presents numerous technical challenges that often require significant investment in time and engineering resources to resolve. For example, different wavelengths need new sources (e.g., lasers), resists and optics. So relying solely on wavelength jumps to improve resolution would slow down development due to the costs and technical challenges involved. However, continuous improvement in lens technology helps keep the industry moving forward by increasing the numerical aperture (NA). For example, in the mid 80s an NA of 0.4 was typical. Today, our XT:1400 systems offer a variable NA up to 0.93.

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### Refractive Index and Immersion

Mathematically speaking, NA = \(n \sin \alpha\) where \(n\) is the refractive index of the medium surrounding the lens and \(\alpha\) is the lens’s acceptance angle. So for a lens in air, NA has a theoretical maximum of 1 although in practice this is limited to 0.93 – a value achieved by our latest “dry” lithography systems.

However, immersing the lens in a medium with a higher refractive index gives the possibility of NA > 1 and hence better resolution – this is the basis of immersion lithography. Currently, water (with a refractive index of 1.43) is used as the immersion fluid because it has the best transmission and chemical properties. However, researchers are also looking at potential immersion fluids with even higher refractive indices.

### Lens Quality and CDU

While the lens’s numerical aperture plays a key role in determining the system’s resolution capabilities, lens quality plays a key role in determining the CDU performance of a system – as do other factors such as illumination uniformity and reticle quality. Together with our partner Carl Zeiss, ASML is continually striving to improve the quality of both immersion and non-immersion (dry) lenses by driving down aberration levels.

Thanks to these efforts, our systems offer best-in-class CDU performance. For example, the XT:1450G dry ArF tool has a CDU of 4 nm (at 65 nm resolution) and the XT:1900Gi has a CDU of 2 nm (at a resolution of 5 nm).

### Resolution Factor

The final part in Rayleigh’s equation is the resolution factor \(k_1\), which relates to the difficulty of the imaging process. It depends on several process variables such as the quality of the resist and the use of resolution enhancement techniques like off-axis illumination. The resolution factor \(k_1\) has a theoretical minimum value of 0.25 *, however values below 0.3 are considered difficult or expensive to achieve.

ASML works closely with our customers to reduce \(k_1\) to extend the capabilities and usage of current lithography technologies and ASML systems. Our Ultra-k1 portfolio of hardware, software and mask solutions...
enables the lowest $k$ values in the industry. It includes products such as:
- LithoCruiser for process and mask optimization
- NA/α Optimizer and Source-Mask Optimizer for designing illumination shapes
- CDU Predictor for realistic predicting CDU budget
- Customized Illumination for the ultimate in low-$k$, imaging
- ImageTuner for application-specific lens setup
- EFES for increased depth of focus (DoF) when printing contact holes
- DoseMapper for optimal CD control
- Polarization Control for an enhanced process window
- LithoGuide for precise imaging performance characterization

**Pushing resolution further**
ASML is at the forefront of wavelength, lens and $k$ developments. As a result, our systems offer industry leading imaging performance. We are also exploring processing techniques such as double patterning and double exposure to push resolutions even further without switching wavelengths. Current production typically uses ArF, KrF and i-line systems for critical, mid-critical and non-critical layers respectively. These techniques allow customers to extend manufacturing roadmaps with existing production lithography technology.

In the next issue, we’ll be looking at the second side of the lithography triangle – productivity.

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* Below this value of $k$, the first diffraction peak from the reticle does not pass through the projection lens.