Optical lithography: Where will it end?

By John Bruning

Optical lithography is one of the most costly and highly leveraged technologies in the complex process of manufacturing integrated circuits (ICs). The leverage comes from the number of IC "chips" that fit on a silicon wafer and the density of circuit functions on the chip. The number of wafer processing steps is unchanged by the number of chips on the wafer. As IC features become smaller, device functionality and speed improve while power consumption decreases. These factors all improve value and reduce the cost per chip. The integrated circuit process is much like a multilayer circuit board, only more complex. Some of the more complex devices like dynamic memory or DRAM contain as many as 20-25 different layers. Any gains in performance or productivity at each layer are multiplied by the number of layers.

Optical lithography has been the major method used for printing IC patterns since the beginning of the IC over 25 years ago. Optical lithography started with contact printing on silicon wafers one inch in diameter at linewidths of 10-20 μm (which nearly matches linewidths on printed circuit boards today). As linewidths shrank and circuit complexity grew, it became necessary to move away from contact printing to projection printing to avoid the contamination introduced by contact. The movement to projection printing began 20 years ago with full-wafer projection imaging at unity magnification. The rapid progress of integrated circuit technology soon precluded imaging of the entire wafer, which was increasing in size while linewidths were decreasing. Step-and-repeat printing entered the picture in the mid-70s with lenses that reduced the mask by a 10:1 or 5:1 reduction ratio. This temporarily lessened the burden on the lens maker and the mask maker. The reduction lens projects the image of several chips at a time from the mask onto the wafer, steps to another area on the wafer, and repeats the process in a grid-like fashion. This process has been refined to uncanny levels of precision and sophistication in the last 15 years and shows no sign of resignation to more exotic lithographic technologies employing electrons, ions, or x-rays.

The "steppers" of today have become the "machine tool" of the semiconductor industry. Optical lithography continues to evolve to unexpectedly high levels of performance primarily through advances in metrology and precision engineering. This rapid growth rate, however, has made it nearly impossible for new lithographic technologies to industrialize to the maturity levels needed for high volume, high yield, and cost effective manufacturing. The levels of investment needed to keep up with the rapid and continual improvements in stepper technology, while high, are small compared to that needed to change to another lithographic technology altogether. The complexity of the IC process resists dramatic changes and seeks to extend technology and investment as long as possible.

First a precision metrology platform

Integrated circuits cannot be shrunk simply by printing smaller lines on a chip. Of equal importance to the size of the line is the accuracy of placement of the line within the circuit. A rule of thumb is that the printed line must be placed to within an accuracy of one fourth of the narrowest line. At today's technology of 0.6 - 0.8 μm linewidths, an image placement accuracy of 0.15 - 0.20 μm is required over the entire area of the wafer, now typically 150 - 200 mm in diameter. This is an all inclusive *overlay* error budget, between any layer, which represents contributions from the stepper platform, the wafer stage, and its metrology, as well as distortions in the mask and those introduced by the optical imaging system. The requirements for greater productivity and performance have led to a dramatic increase in the number of "pixels" that must be printed, as well as the placement accuracy of these pixels. Wafer sizes have grown from 25 mm in 1965 to 200 mm today at some manufacturing sites. Within five years it is speculated that wafer sizes may grow to 300 mm.

The requirements for improved accuracies over larger areas with smaller linewidths place great demands simultaneously on the stepper platform and the optical system. Improvements in the platform and the optical system can only take place with simultaneous improvements in metrology. The stepper platform must itself be a superb metrology tool, since it must locate and align to features on individual chips all over the wafer prior to printing the next layer. Alignment is done with another optical system designed specifically to acquire the alignment mark, along with a very precise stage metrology system that records the location of the wafer during the alignment mark "mapping" process. The wafer stage and motion control system achieve an accuracy of better than 100 nm with a repeatability that is significantly better.

Mapping a larger number of sites on the wafer improves metrology accuracy through improved statistics. Stage position is metered in x, y, and yaw with laser interferometers that have a resolution of a few nanometers. Pitch and roll are also metered and controlled to permit positioning of the exposure site on the wafer parallel to the image plane

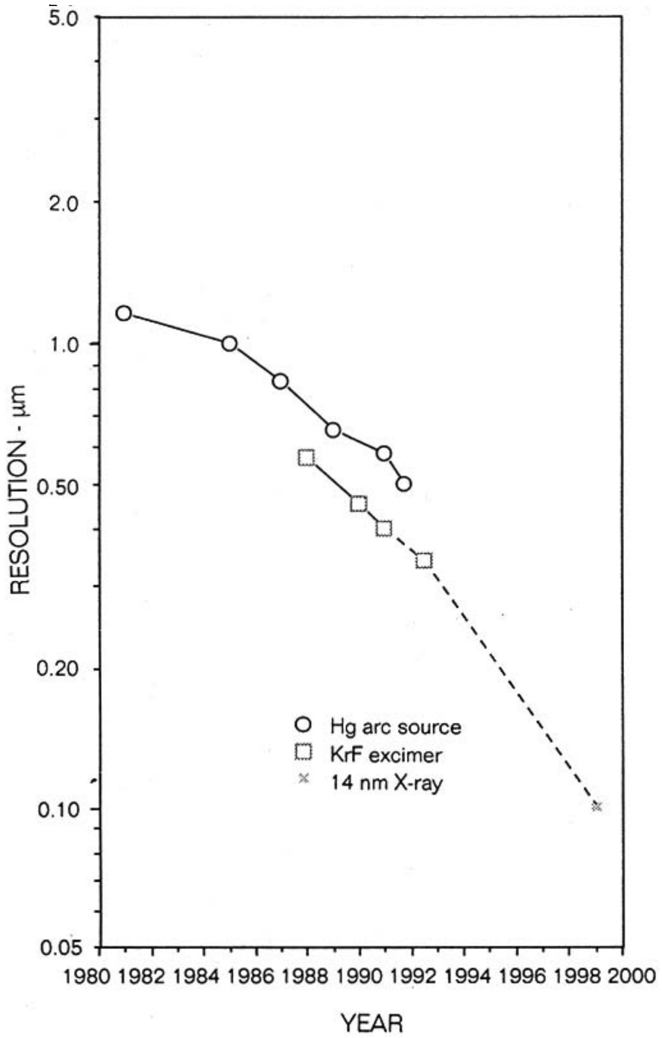

Figure 1. Resolution trend of reduction lenses for step-and-repeat optical lithography. Open circles represent lenses using mercury arc sources at either 436 or 365 nm wavelength. Open squares represent deep-UV lenses operating with the KrF excimer laser at 248 nm. The isolated point indicates when soft x-ray imaging at 14 nm might enter the scene with 0.1 µm resolution on chip sizes of 25 × 50 mm on a side.

of the lens to within a small fraction of the depth of focus range of the lens. Contamination under the wafer can aggravate the flatness of the exposure area enough to throw the image out of focus. Achieving high metrology accuracy is difficult to maintain without stringent control of the environment and a thorough understanding of all interactions of the machine with its environment.

Self calibration

Self calibration is key to measurement and position control to nanometer levels. Attainment of accuracy levels in this range requires the analysis of large amounts of data that must be acquired over a reasonably short period of time. The stepper metrology system provides a built-in capability to characterize the optical system in terms of the optimum plane of focus, the precise optical reduction ratio, and other controllable parameters in the optical column. Superb platform stability and performance can only be achieved through robust structural design, attention to kinematic principals, and a thorough understanding and management of the environment surrounding the platform. For example, the stage metrology air paths must be carefully controlled. There must be adequate air movement to promote temperature stabilization and eliminate stagnation, yet not so much as to create turbulence and introduce noise in the laser metrology path. Heat sources must be understood as to their location, intensity, and heat transfer mechanisms. Stage fine-motion should be frictionless and without hysteresis. The ability to completely characterize and calibrate the stepper *in-situ* is essential so that sets of steppers on a manufacturing line can be optimally matched in overlay characteristics. This is desirable in order to provide the manufacturing flexibility of exposing any circuit layer on any stepper.

The optical column

The optical stepper is a stunning example of the marriage of the highest precision disciplines in optics, mechanics, metrology, and manufacturing. These interrelated disciplines are all at the state-of-the-art and tend to continually "bootstrap" one another. The specifications and performance levels for today's lithographic lenses are at levels that only a few years ago were viewed unlikely or unmanufacturable, yet the complexity level in the last few years has increased more than at any other time. This has been driven largely by the demand for DRAM, the density of which has nearly doubled every two years for the last 20 years. There has been an unrelenting quest in the electronics industry to sustain this phenomenal rate of progress. This has been achieved by increases in chip size, greater cleverness in circuit design, exploitation of the vertical dimension on the wafer to increase density, and increasing density by decreasing device dimensions with higher resolution lithography.

The level of difficulty has increased because of the simultaneous need to increase resolution and field size of the lens while reducing all distortions in the lens. Improvements in alignment and stage precision, along with reduced lens distortion, led to improvements in overlay capability of the stepper. While perhaps contrary to intuition, as the size of the printed features gets smaller, the lens must get larger. A state-of-the-art lithographic lens weighs more than 200 kilograms! Achieving improvement in all characteristics in a larger physical structure taxes all aspects of precision engineering and the design sciences. Nonetheless, great progress has been made and the opportunity for further improvement remains. Figures 1 and 2 summarize the progress in lenses over the last 10 years and extrapolate current trends for the next decade. The dramatic increase in performance of optical systems in the last few years is evident. This has been achieved primarily by improvements in optical design,[1] metrology, precision engineering practice, new manufacturing methods, and tooling.

Resolution is defined by the simple equation $W_{min} = k\lambda/NA$, where k is a factor that ranges from 0.5 to 1.0, depending on the device manufacturing application and process characteristics, λ is the wavelength of operation of the lens and illumination system, and NA is the numerical aperture of the lens on the image side. Higher resolution is achieved with a smaller wavelength, a higher NA, or both. The total range of sharp focus for such lenses is approximately λ/NA^2. From this, it is clear that focal depth is lost more quickly when resolution is improved by increasing NA than by reducing the wavelength. In practice, however, new lens designs are moving toward both shorter wavelength and higher numerical apertures. The total focus budget available in production applications ranges from 1 - 2 µm. This budget is so tight that there are strong development efforts to evolve production processes that operate effectively at smaller k-factors so that the lowest NA lens consistent with the resolution requirements can be used.

State-of-the-art lenses for lithography today have NAs of 0.45 - 0.55 and operate at wavelengths of the mercury g-line (436 nm), i-line (365 nm), or the KrF excimer laser wavelength of 248 nm.[2,3] Mercury arc illuminated lenses are corrected for color aberrations over a bandwidth of 5-10 nm, the natural bandwidth of the spectral lines of the arc lamp. These color corrected lenses use a variety of different glasses to achieve the appropriate color correction. The choice of glasses for the g-line is quite broad, but very restrictive for the i-line, due to higher absorption. The 248 nm lenses are not color corrected, principally because there is only one suitable glass that has adequate transmission at that wavelength. These lenses are made entirely of fused silica and are monochromats. To avoid chromatic aberrations, the bandwidth of the laser source must be restricted to no more than a few picometers! This requires narrowing the free-running bandwidth of the laser source without a detrimental loss of illumination intensity. These systems have been in use for some time now for 0.5 µm imagery and will likely be the dominant method used for production in the 0.25 µm regime within the next five years.

Productivity and reliability are expected to increase and technical specifications will improve. Productivity rates of 25-50 wafers per hour are a common requirement that has been maintained in recent years in spite of increasing wafer sizes. Reliability requirements approaching 1000 hour mean-time-between-failure are anticipated.

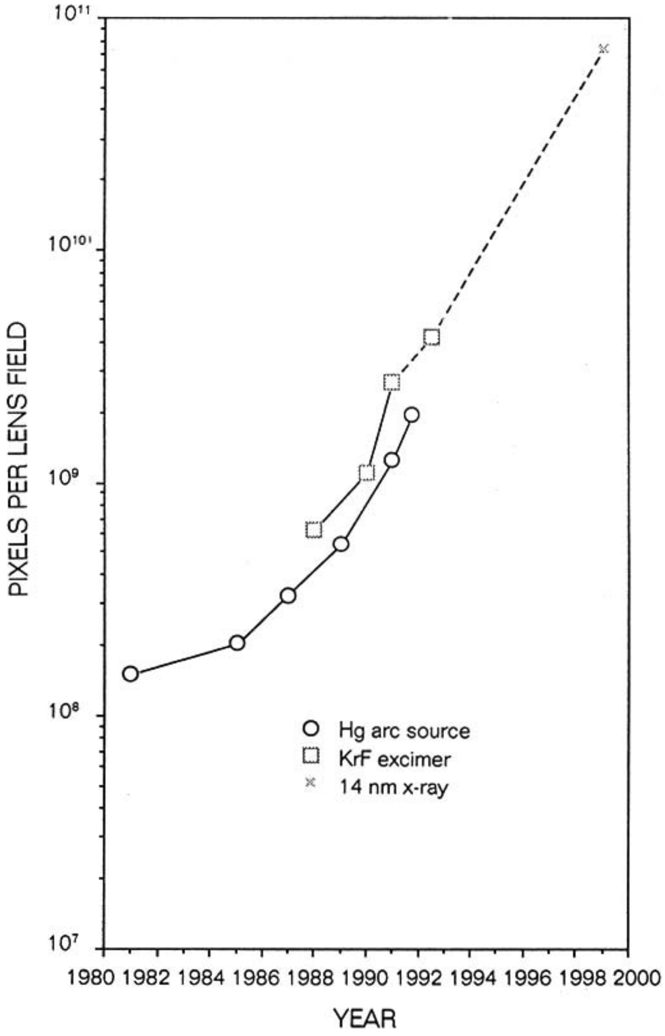

Figure 2. Lens capability trend for reduction lithography lenses measured in pixels corresponding to the resolution in Figure 1. This represents the number of pixels that can be imaged by the lens field either in a step-and-repeat or scan-and-step mode. The latter mode will likely to be required for soft x-ray imaging.

The weather matters

The high performance of lithographic lenses today is achieved only as a result of a very delicate balance of residual design aberrations, the use of many individual elements, and strict adherence to tight tolerances on element surfaces during fabrication and assembly. A change in the temperature of the lens of many degrees would adversely alter performance, but that is of little consequence since the lens and stepper operate in the controlled environment of a chamber that maintains temperature constant to within 0.1° C. The environmental chamber, however, does not control barometric pressure. Weather-induced pressure variations alter the refractive index of the air between the elements enough to change focus and reduction ratio of the lens. If not compensated for, barometric pressure changes would introduce out of tolerance conditions for this exacting imagery.

Managing the aerial image

A traditional criterion for design of a lithographic lens used to be that geometrical lens aberrations had to be reduced to less than 0.25 λ. Under these conditions, the lens satisfies the Rayleigh criterion and is considered to be *diffraction limited*, meaning that further improvements in imagery were limited by diffraction, not geometrical aberrations. In the realm of large NA, large field size, and super-low distortion, this criterion is no longer adequate. Residual distortion in the design of the lens (attributable to imperfections in imaging a perfect grid) must be held to less than 10 nm everywhere in the image field. There must be no *sweet spot* in the lens and there must be no significant variation of the residual aberrations over the image field that would create changes in linewidth at the image. Astigmatism and field flatness should be held to levels less than a few hundred nanometers at any point in the field.

These requirements put limits on geometric aberrations that are far more stringent than the Rayleigh criterion. In the final design stages of these lenses, the aerial image must be modeled with features and shapes typical of customer applications at all positions in the field and through focus under partial coherent illumination to more accurately simulate conditions of use. Modern simulation tools model the transfer of the aerial image into the exposed and developed photoresist materials used in manufacturing.[4,5]

Tolerances employed during the fabrication and final assembly of elements are also modeled to simulate the lens manufacturing process. The tolerance in radius, thickness, refractive index, and surface figure required for all elements (sometimes 20 or more) to go together without adjustment would be impossibly tight. To achieve final performance targets and assure that all lenses of the same type match each other and can be used interchangeably, the assembly process must be fine tuned for each lens. Present day tolerances on optical surfaces are at the 10 nm level in form and at the 1 nm level for roughness. Centering and spacing requirements for elements are at the more "relaxed" tolerance level of 1 μm.

What's next?

The enormous progress in precision engineering and metrology has led to lithographic lenses of unprecedented quality and performance. Billion pixel lenses are being used in the early stages of development of the 64 Mb DRAM. How much farther can the technology be pushed? It seems fairly certain that the 256 Mb and perhaps even the 1 Gb DRAM will be manufacturable with optical lithography using reduction lenses operating in the deep-UV region. Getting there will require cleverness and exploitation of novel processing techniques that can tolerate the use of smaller k-factors. In addition, alteration of the aerial image has recently shown promise through the use of "phase shift" mask techniques.[6,7] This promising new technique gives a new degree of freedom to the lithographer by allowing control of the *phase* in the mask plane in addition to the amplitude. This could improve resolution up to 30 or 40% under ideal conditions.

The use of wavelengths shorter than 248 nm awaits the development of more robust and highly transparent optical materials. Work is ongoing here and abroad. There are no known materials that are simultaneously transparent, homogeneous, and isotropic that refract light at wavelengths much below 200 nm. Diffraction-limited imaging for lithography in the extreme ultraviolet or soft x-ray region has not been seriously considered to date because of inadequate materials for refractive systems or poor reflectivities in reflective systems. Reflectivity in the extreme ultraviolet and soft x-ray wavelength region has improved through the use of new multilayer techniques and holds great promise for extending optical lithography to very high resolutions.[8]

Diffraction-limited imaging in the soft x-ray region at 14 nm has been demonstrated recently using a precisely fabricated Schwarzschild mirror design with multilayer coated mirror surfaces.[9,10] This demonstration has shown basic feasibility of reduction imaging at the 0.1 μm resolution level. The scaling of soft x-ray optical systems to practical sizes needed for lithography will be very challenging and is under study. The metrology and precision engineering technologies developed for optical steppers will play a vital role in extending optical lithography into this exciting new area.

References

1. J. Bruning, "Lithographic lenses for microcircuit fabrication", Opt. News, **14:6**, 1988, 23-24.
2. V. Pol *et al.*, "Excimer laser-based lithography: A deep ultraviolet wafer stepper," Proc. SPIE **633**, 1986, 6-16.
3. R. McCleary, *et al.*, "Performance of a KrF excimer laser stepper," Proc. SPIE, **922**, 1988, 396.
4. W.G. Oldham, *et al.*, "A general simulator for VLSI lithography and etching processes," IEEE Transactions of Electron Devices, **ED-26**, No. 4, 1979, 717-722.
5. C.A. Mack, "PROLITH: A comprehensive optical lithography model," Proc. SPIE **538**, 1985, 207-220.
6. M.D. Levinson, *et al.*,"Improving resolution in photolithography with a phase-shifting mask," IEEE Transactions on Electronic Devices, **ED-29** No. 12, 1982, 1828-1836.

7. H. Fukuda, *et al.*, "Phase-shifting mask and flex method for advanced photolithography," Proc. SPIE, **1264**, 1990, 14-25. 8. A. Hawryluk and L. Seppala, J. Vac. Science and Tech., B 6, 1988, 2162.
9. J.E. Bjorkholm, *et al.*, "Reduction imaging at 14 nm using multilayer-coated optics: printing of features smaller than 0.1 mm." J. Vac. Science and Tech., **B 8(6)**, 1990, 150-159.
10. Bell Lab Soft X-ray Projection Lithography Group, "Soft x-ray projection lithography", Opt. & Phot. News, **2:5** 1991, 27-29.

John Bruning *is president of GCA Tropel in Fairport, N.Y., and executive vice president and chief technical officer of GCA.*

Soft x-ray projection lithography

By the Bell Lab Soft X-ray Projection Lithography Group*

As the VLSI (very large scale integration) industry demands cameras that can produce images of ever greater resolution, lithographic technology has responded by developing lenses capable of diffraction limited imaging. When the need arose for sub-half micron features, the industry sought higher resolution by using shorter wavelengths, the near UV in the mercury i-line at 365 nm, and soon the deep UV using excimer lasers at 248 nm and, eventually, perhaps even 193 nm. However, as we increase resolution we decrease the depth of focus, and patterns produced by poorly focused imaging is a major source of defects in the final circuits. The relationships for resolution, Res, and depth of focus, DOF, are given by the well known formulae:

$$\text{Res} = K_1 \frac{\lambda}{\text{NA}} \qquad \text{DOF} = \pm K_2 \frac{\lambda}{\text{NA}^2} \qquad (1)$$

where λ is the wavelength, NA is the numerical aperture of the projection lens—usually between 0.4 and 0.5—and K_1 is a constant determined by practical considerations like resist contrast and processing details, and may range from 0.8 to 0.6 when using conventional masks that have opaque patterns and 0.5 or less when using phase masks. The value of K_2 also depends on processing details, but is typically equal to 0.5 and somewhat greater.

It is impossible to push the wavelength of ordinary lenses to much shorter wavelengths. Quartz becomes opaque at wavelengths in the 150 nm range. To achieve greater resolution by increasing the numerical aperture reduces the depth of focus. For high resolution, the DOF becomes so small that it is necessary to planarize the surfaces, an expensive operation.

To achieve projection lithography with a tenth micron resolution, and using $K_1 = 0.8$ and $K_2 = 0.5$, we must go to much shorter wavelengths. Figure 1 plots regions of sub tenth micron resolution and DOF greater than ± 0.5 μm vs. the numerical aperture and the wavelength. The cross-hatched regions are where both conditions are satisfied.

To make a tenth micron projection system with a sizeable DOF, we are compelled to make a camera that works in the soft x-ray region below several tens of nm in wavelength. Since we ultimately want to make a printer that is production worthy, we must choose a wavelength with which we can produce a large quantity of quality product. Wavelength will be determined by factors like resist sensitivity, camera losses, and x-ray source power. As we will see later, the best compromise between these factors is in the 10-15 nm range, with 13-14 nm being the current favorite because of our ability to make mirrors that have high reflectivity in that region.

Experiments

Experiments to test feasibility of x-ray projection lithography at 14 nm have been done by our group at Bell Labs.[1] One of

---

*The Bell Lab Soft X-ray Projection Lithography Group comes from the research and the development areas bringing together experience in optical lithography, laser physics, electron microscopy, thin films, lens design, etc. The purpose of their project is to determine, by theoretical and experimental studies, if soft x-ray projection is a practical solution for the needs of the VLSI industry when, near the end of the decade, it is anticipated that a tenth micron lithography will required. The background of most of the team is that of an individual scientific investigator and this is their first experience as part of a large group effort.

J.E. Bjorkholm, J. Bokor, L. Eichner, R.R. Freeman, W.M. Mansfield, L. Szeto, D.W. Taylor, D.M. Tennant, O. R. Wood II—*AT&T Bell Laboratories, Crawfords Corner Road, Holmdel, N.J. 07733.* T.E. Jewell, D. L. White, W.K. Waskiewicz, D. L. Windt—*AT&T Bell Laboratories, 600 Mountain Avenue, Murray Hill, N.J. 07974.* A.A. MacDowell—*AT&T Bell Laboratories, 510 E. Brookhaven Lab, Upton, N.Y. 11973.*