WAVEFRONT ENGINEERING FOR PHOTOLITHOGRAPHY

New optical techniques based on the application of fundamental physical principles to photomask design may bring about a revolution in the patterning of integrated circuits.

Marc D. Levenson

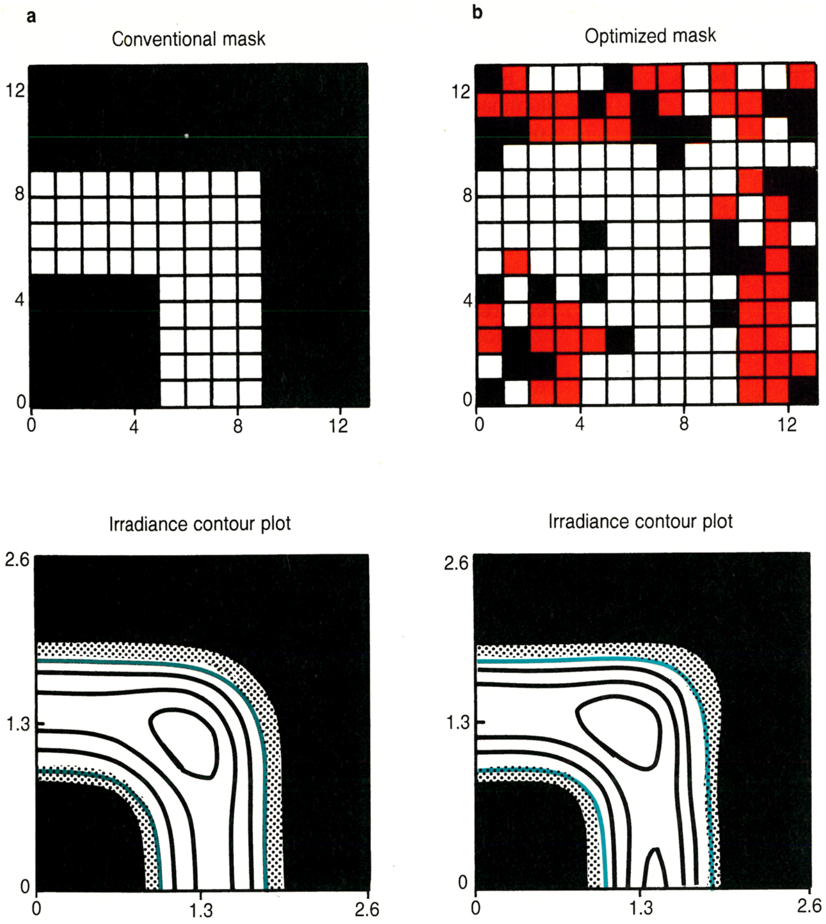
Physicists have always been fascinated by the very small.[1] These days, the inner structures of everyday items such as the personal computer fall into that size category and warrant our interest. The critical dimensions of individual features of state-of-the-art memory chips are now as small as 500 nanometers and are getting smaller. The microwave transistors in some satellite dish receivers require gates smaller than a quarter of a micron.

While complex deposition and implantation processes are used to control the vertical depths of such features, the lateral dimensions are defined by photolithography, a fascinating art whose underlying principles have not changed in almost a century. That remarkable period of intellectual stability is about to end, with profound consequences for our economy and even, perhaps, for a culture that has come to expect technical progress to be a commodity.

Photolithography is the technology of reproducing patterns using light. Developed originally for reproducing engravings and photographs, and later used to make printing plates, photolithography was found ideal in the 1960s for mass-producing integrated circuits.[2] That process begins with the design of the pattern to be produced. The patterns were originally handmade artwork, but since the early 1980s they have been more likely to be contained in a computer database. The pattern is then transferred to a photomask, which typically is a fused quartz plate coated with an opaque material such as chromium; transparent apertures mark the features of the design. The mask (sometimes also called the reticle), in turn, is used as a kind of magic-lantern slide in a high-technology projector (called a stepper), which exposes a photosensitive polymer layer (the resist) coated on a semiconductor "wafer." The resist is developed, exposing the underlying substrate in the pattern of the original design. One can then etch, implant ions on or deposit new material on the exposed substrate. The resist is then stripped off, the wafer processed and the process repeated, typically more than 20 times, to generate the complex layered structure of a modern integrated circuit.

Because all of the many millions of features of a typical semiconductor chip are printed simultaneously, photolithography is a remarkably efficient way of making complex devices. But it is hardly foolproof. Extraordinary care is necessary to avoid defects—especially on the masks, which are used to manufacture millions of chips. Overlay accuracy is of paramount importance, as each 500-nm feature on a 22×15-mm chip may require multiple process steps with different masks, and a misalignment of 150 nm anywhere can be fatal. Because there are many sources of error, and because a single six-standard-deviation error can destroy a chip with tens of millions of features, photomasks must be fabricated with a precision of 50 nm—even though the image at the wafer is demagnified by a factor of 5. (Compare the length scales of

Marc Levenson is a former research staff member at the IBM Almaden Research Center, in San Jose, California.



Comparison of conventional and optimized phase-shifting masks. **a:** Conventional mask pattern for a transparent elbow and the resulting irradiance contour plot. **b:** Phase-shifting mask optimized by simulated annealing to project a bright elbow and its resulting irradiance contour plot. The areas of the mask marked in red produce 180° phase shifts; the white regions, 0° transmission. The black areas are opaque. The 30%-intensity contour lines (blue) in the image produced by the optimized mask match the target function more closely than do those in the image produced by the conventional mask. Numbers indicate distances in microns. **Figure 1**

the masks and resulting irradiance plots in figure 1.) Mask metrology is clearly a challenge—one of many in the photolithographic manufacture of integrated circuits.

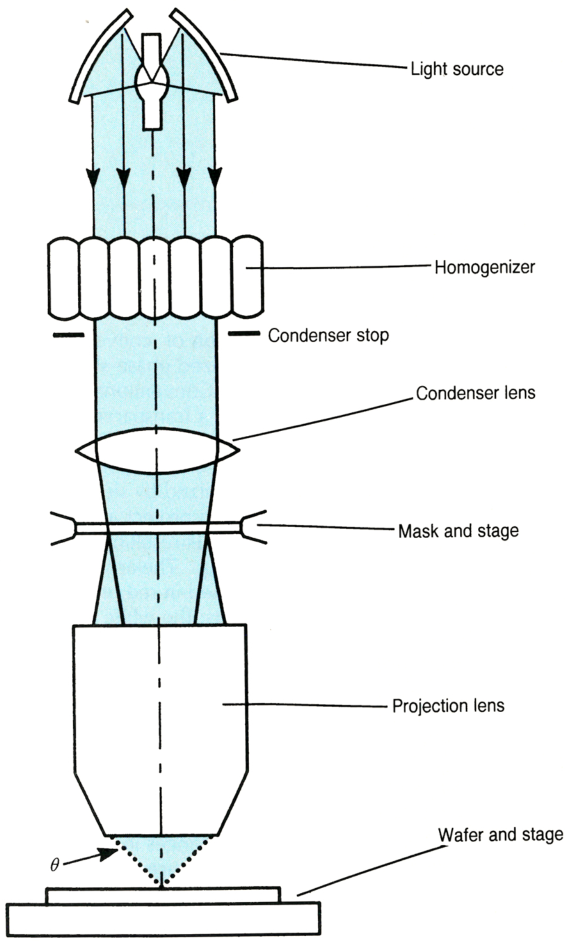
Nevertheless the process has worked brilliantly for a quarter-century. Photolithographic optics increased in sophistication through the 1970s and 1980s. Every three or four years, scientists and engineers found a way to squeeze four times as many devices onto a typical integrated circuit chip. Computers have gotten more and more powerful as their circuit features have gotten smaller and more numerous. New applications for microelectronics have become commonplace. A typical automobile today has more data processing capability than the Apollo spacecraft had in 1969. And yet the real cost of building these technological wonders has fallen consistently, putting game-playing computers in the pockets of schoolchildren.

Physical limits

For at least a decade, skeptics have warned of various physical limits to this continuing evolution toward smaller circuit elements. Such skeptics once thought that photolithographic techniques could not be used for features smaller than 1 micron; however, one can now buy memory chips with millions of such features for as little as $5. Lens designers, resist chemists and instrumentation engineers have overcome barriers again and again. Today chips with 500-nm features are in full production, and manufacturers are delivering optical lithography systems capable of 350-nm resolution. Furthermore, in spite of enormous investments, new patterning technologies employing electrons, x rays and ions have not proved economically viable.

And yet there *are* real physical limits to photolithography. The shortest wavelength of light commonly used is 365 nm, the so-called i line of mercury. Can innovative optical techniques such as the one illustrated in figure 1 really be used to pattern chips with 250-nm or 100-nm features? Or must some other method be found to produce those devices before long?

Figure 2 shows the design of a typical stepper. This exposure tool gets its name from the fact that each chip on the semiconductor wafer is sequentially stepped through the exposure region. The system consists of a light source, a homogenizer–condenser, a stage at the object plane for the mask, a highly corrected projection lens and a stage for the wafer.[2] At each point on the wafer, light converges with a cone of half-angle θ. The numerical aperture of the imaging lens is defined as $\mathrm{NA} = \sin\theta$. According to the 19th-century laws of optics, the smallest feature that such a system can project is $0.6\lambda/\mathrm{NA}$, the size (full width at one-third maximum) of the Airy disc. Lenses capable of imaging a full chip are available with $\mathrm{NA} = 0.5$, which implies a resolution limit of 440 nm for 365-nm light. A more serious limitation is that the depth of focus for such a diffraction-limited image is about $0.5\lambda/(\mathrm{NA})^2 = \pm 730$ nm. (The depth of focus is the range over which the image remains in adequate focus.) Because the photoresist layer is typically 1000 nm thick and the chip itself is not flat, this focal depth may seem infeasibly small. However, the photoresist material's index of refraction and complex



Photolithographic 'stepper.' This diagram shows only the essential elements of this device for exposing semiconductor wafers. The homogenizer insures that the mask is illuminated uniformly. The condenser stop controls the angular content of the illumination. The numerical aperture of the projection lens is defined by the cone angle θ. Today's 8-inch-diameter wafers typically contain 200 semiconductor chips. **Figure 2**

dissolution dynamics compensate somewhat for defocusing. The shortening of the depth of focus with increased resolution is nevertheless the most serious limitation for optical lithography and may set a practical limit on the numerical aperture.

Reducing the wavelength permits one to project features of the same size with lower values of the numerical aperture and thus with a larger depth of focus. The most convenient wavelengths shorter than 365 nm are 248 nm (from the KrF laser) and about 257 nm (from a high-pressure mercury arc). Collectively, wavelengths in this range are called deep ultraviolet, or duv, in lithography. With duv, printing 440-nm features requires a numerical aperture of 0.34, which produces a depth of focus of ± 1080 nm. Thus both i-line and duv lithography are adequate (at least optically) for producing the present generation of circuits with 500-nm features.

Exposure tools designed for wavelengths of both sorts are available today, but what comes next?[3] Shorter wavelengths are available, such as 193 nm from an ArF excimer laser. Prototype steppers with numerical apertures as large as 0.7 have been built, but a continuation of the shorter-wavelength, larger-NA strategy encounters tremendous difficulties, not the least of which is the paucity of optical materials and photoresists transparent to wavelengths shorter than 200 nm.

Twenty years of effort and hundreds of millions of dollars have been devoted to technologies promising revolutionary changes. The most developed of these requires a synchrotron and an electron storage ring to produce x rays. New mask technology, new stepper alignment systems and new resists must all be proven reliable enough and economical enough for production[4] within the next year or so to allow mass production of a 256-megabit dynamic random-access memory by 1996.

The semiconductor industry would prefer some evolutionary solution to the quandary of what comes next, and several options to improve optical lithography do exist. However, they require some sacrifices, and all of the new ideas produce images that differ in significant ways from the patterns on the mask. Thus engineering a mask design to produce the desired resist structure may soon become nontrivial.

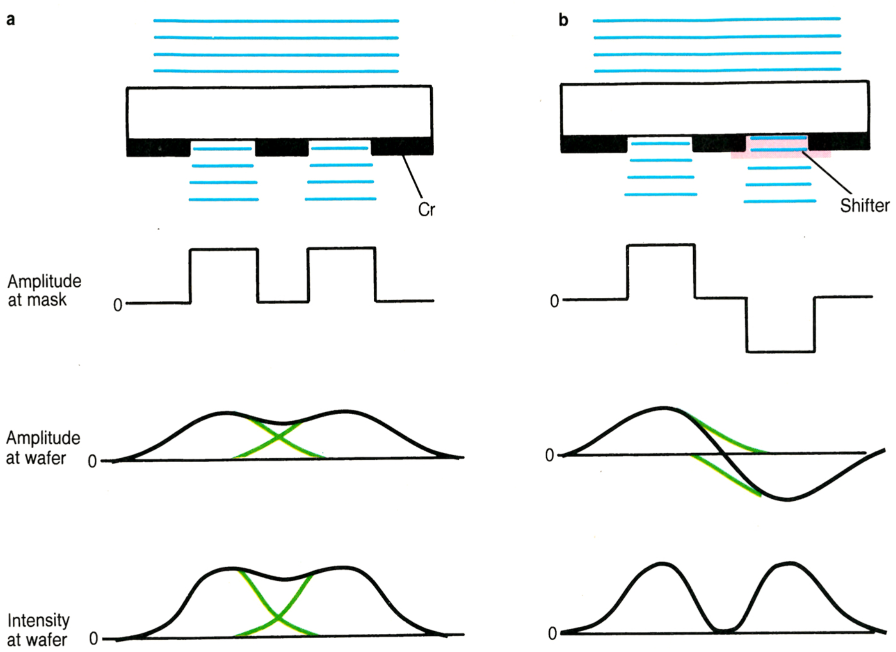
The phase-shifting mask

Although it has a long history, the optical image formation process is quite complex in detail. Light is an electromagnetic wave with frequency, phase and amplitude. The light used in photolithography is partially coherent and partially incoherent, which makes the image transfer process nonlinear, both in amplitude and in irradiance (intensity). The resist's behavior is also complex, nonlocal and nonlinear. New techniques take advantage of these nonlinearities.

One way to improve resolution dramatically without reducing the depth of focus is to employ destructive interference to enhance contrast. Special photomasks known as phase-shifting masks are needed to create the necessary interference pattern in the image.[5]

Figure 3 compares the working of a conventional transmission mask with a simple phase-shifting mask. In each case the light passing through the photomask is represented as an electric field amplitude. In a transmission mask (figure 3a) the electric field has the same phase at each aperture. As the light propagates through the optical system, diffraction and spatial filtering eliminate the higher-spatial-frequency components, broadening the amplitude profiles. At the wafer, the electric field profiles partly overlap and, because the light remains somewhat coherent, interfere constructively. The resist is sensitive to the irradiance of the light, which goes as the square of the total amplitude, not as the amplitude itself. Constructive interference causes the irradiance at the center of the dark line between two bright features (termed "spaces") to be larger than the sum of the irradiances from the individual apertures. This unwanted brightness degrades the resolution, causing the images of neighboring apertures (and the resulting resist features) to blend together.

In the "alternating aperture" phase-shifting mask depicted in figure 3b, also called a Levenson–Shibuya mask, one of every pair of apertures is covered by a transparent medium that shifts the light's phase by 180°. The result is that the amplitudes alternate between positive and negative. As the light propagates through the optical system, the amplitude profiles broaden as before, but they remain positive on one side of each dark line and negative on the other. At the wafer, destructive interfer-



Mask optics. **a:** Conventional transmission mask. **b:** Alternating-aperture phase-shifting mask. The opaque chromium features are labeled "Cr." The transparent phase-shifting medium is also indicated. The shifter thickness is sufficient to introduce a half-wave of phase shift into light passing through it compared with light passing through an uncoated aperture. This has the effect of reversing the amplitude at one aperture at the mask and converting constructive interference to destructive interference at the wafer. **Figure 3**

ence insures that the electric field reaches zero at some point within every dark line. Since the irradiance is proportional to the square of the field, it must also be zero at a dark line. Interference effects enhance the resolution rather than reduce it. The enhancement factor depends on the "partial coherence" of the illumination system, but typically it is between 1.4 and 3.

As the oppositely phased apertures come closer together on a phase-shifting mask, more and more of the negative contribution to the total amplitude overlaps the positive, producing more and more regions of zero irradiance. This is termed the "checkbook effect" from a well-known financial analog. Thus one reaches the limit of phase-shifting mask resolution when the entire image becomes dark. In comparison, a transmission mask produces a uniform illumination level when used to project patterns that are too fine for the optical system.

Because the physics of destructive interference does not require a perfectly focused image, the depth of focus also is significantly enhanced for images produced in this way. The actual enhancement depends again on the partial coherence of the illumination, but an infinite depth of focus is possible for dark lines at perfect coherence. Such a narrow, completely dark line appears in the center of a laser beam in the transverse electromagnetic 01 mode.

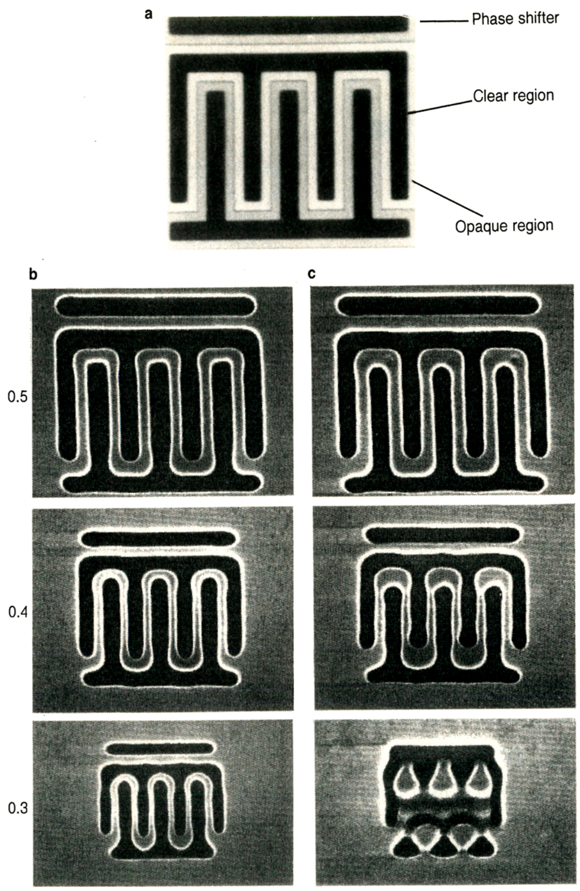
Photomasks with gratings of dark lines and bright spaces are used as test patterns to judge the resolution of an exposure system. The alternating-aperture mask described above typically provides a 50% enhancement in the maximum useful resolution over that of a transmission mask. For the same fine line pattern the contrast of the phase-shifted image is better: The bright spaces are brighter, and the dark lines are darker. Figure 4 compares the image-producing performance of transmission and phase-shifting mask patterns for various feature sizes.[6]

In a mask pattern where every dark line requires a phase shift, a change in phase at one place on the mask can alter the correct choice of phase everywhere else. Other circuit features—such as opaque T shapes—automatically produce phase conflicts. Solving these problems resembles the task of finding the ground state of a spin glass as well as some other problems familiar to physicists. So far, no generally useful algorithms for designing such masks exist.

Mask designs

The difficulty of designing and fabricating alternating-aperture masks has stimulated efforts to find easier methods of using destructive interference in imaging. The result has been a variety of mask designs, many of which offer only marginal improvements over conventional transmission masks. Figure 5 shows some of these mask structures along with the resulting amplitude patterns at the mask plane. The "strong" phase-shifting mask designs—the alternating-aperture design in figure 5b and the "chromeless phase-edge" design in figure 5c—offer the most resolution improvement but produce the worst practical difficulties. Figure 5b shows the structure employed by Du Pont Photomasks, in which the mask substrate itself is etched to a depth of $0.5\lambda/(n-1)$, where n is the index of refraction of the substrate, to produce a 180° phase shift.[7] The optics of the small pits in the substrate are somewhat complex, and the transmission values of the shifted and unshifted apertures are not exactly the same. The chromeless design in figure 5c requires only a single patterning step, but to produce large opaque regions by destructive interference, such a mask must contain complex and defect-prone grating or checkerboard patterns.

The "weak" phase-shifting designs more closely resemble a conventional mask (figure 5a) in design, fabrication and performance.[8] Figure 5d shows a a "shifter–shutter" mask, where two phase edges are placed so close together that only a single dark line results. For dark lines slightly smaller than the Airy spot, this design gives the smallest change in image linewidth with variations in exposure and focus. The "rimshifter" mask in figure 5e uses phase-shifted light to enhance the drop in amplitude at the edges of opaque lines, thus narrowing the transition region between light and dark. The "attenuated phase-shift," or "leaky chrome," mask in figure 5f replaces the opaque material with partially transmitting regions that also produce a 180° phase shift. Such a design enhances the transition between light and dark at the expense of partially exposing all dark



Resolution improvement achieved with a phase-shifting mask. **a:** The general mask structure. **b:** Resist pattern produced with phase shift. **c:** Resist pattern produced without phase shift. Each resist pattern is labeled with the expected minimum line and space width. The quality of the phase-shifted image at 0.3 microns is clearly better than that of the unshifted image at 0.4 microns. (From ref. 6; courtesy of Tsuneo Terasawa, Hitachi Central Research Laboratory.) **Figure 4**

regions. Ideally, one can use a single material for both attenuation and phase shifting in this design. It happens that all common attenuating materials for x-ray masks function in both ways, and thus all x-ray lithography necessarily employs phase-shift masks.[9]

Circuit patterns, however, are not composed solely of single dark lines and line–space patterns. The image of an isolated bright space can be enhanced with a different kind of phase-shifting mask, first employed by Tsuneo Terasawa and his coworkers at Hitachi. In the pattern shown in figure 6a, each bright space is accompanied by two phase-shifted "outriggers" that are too narrow to print by themselves in photoresist. The outriggers cancel part of the diffraction pattern of the central aperture, narrowing it and increasing the peak brightness.[6]

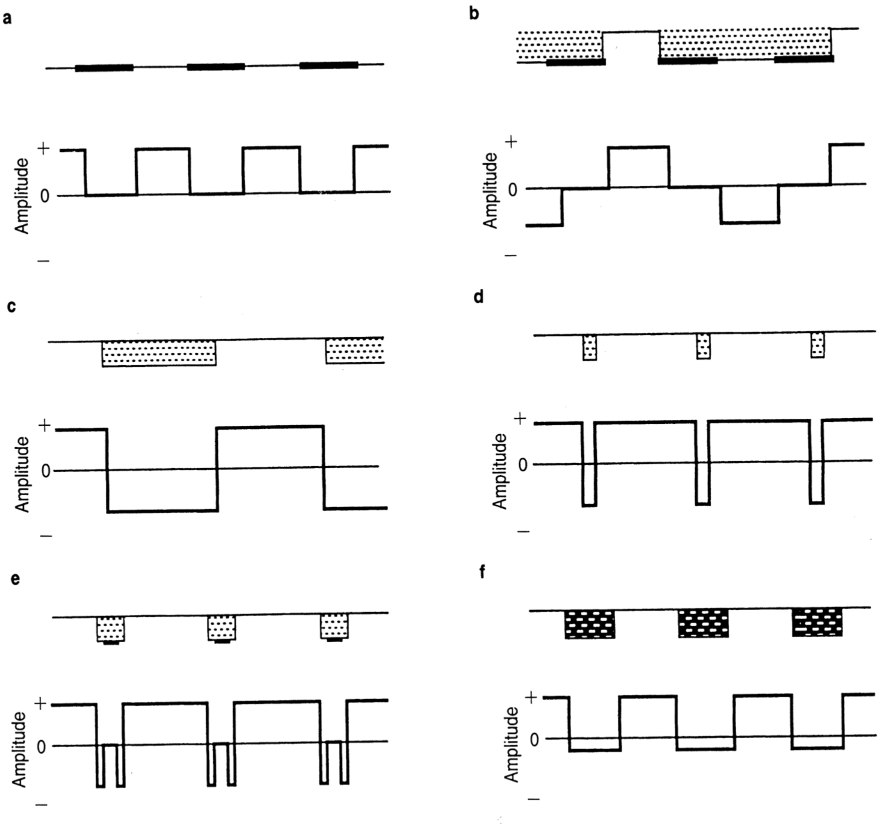
Contact holes are another type of feature typically found on integrated circuits. They are ordinarily patterned by square apertures in the mask that project as circular bright spots slightly larger than the Airy disc. The depth of focus of such spots is particularly small because the light is diffracted in two dimensions. However, James Durnin and Joseph H. Eberly at the University of Rochester have described how to produce a "nondiffracting" beam of light by surrounding such a spot with phase-shifted rings.[10] The ideal contact-hole mask would project an amplitude pattern proportional to the Bessel function of zero order $-J_0(ar)$. Two-dimensional outrigger patterns similar to the one in figure 6a can approximate this ideal case, as can the rimshifter contact-hole pattern shown in figure 6b. Such patterns improve the practical resolution by perhaps 50% while doubling the depth of focus.[11]

Making the mask

Combining these features into masks to produce a working circuit can be a challenge, especially for complex and irregular logic circuits. Basic topology leads to one major pitfall for strong phase-shifting masks: Each 180° region must have a boundary, and the transition between regions of 0° and 180° phase always prints as a narrow dark line, whether or not it corresponds to a desired opaque region. Figure 6c shows a pair of opaque lines "bridged" by 0–180° phase steps that would result in short circuits or other malfunctions. One way of eliminating these unwanted features is to expose the resist twice, once with the high-resolution phase-shifting mask and once with a special "block out" mask that protects the desired circuit but erases the unwanted bridges.[12] Simple circuits are being manufactured using that technique, but doubling the number of masks and exposure steps is impractical for complex devices. To eliminate the bridges while using only one mask, one must introduce additional phase levels—either 90° or 60° and 120°. The transition region between 0° and 180° then must be designed and a more complex multilevel mask fabricated. Figure 6d shows a typical multilevel phase-transition design. The 60° phase steps produce dim lines in the image that tend to narrow the range of acceptable exposures, especially if the wafer is slightly out of the focal plane.[13]

While much of the original research on phase-shifting masks was done in the US in the early 1980s, almost all of the serious development and application of these ideas has taken place in Japan. Test circuits with features as small as 0.17 microns were reported[14] in 1990. The Oki Electric catalog includes a GaAs high-electron-mobility transistor fabricated with the two-mask technique. Fujitsu has announced a 16-megabit static random-access memory made using phase-shifting masks. About half of the Japanese electronics industry plans to manufacture the next generation of 64-Mb DRAMs using 365-nm-wavelength steppers and phase-shift masks rather than duv.[15] Figure 7 shows a cell of a prototype 256-Mb DRAM fabricated by Hitachi. Phase-shifting masks were used with 365-nm light to fabricate the critical 250-nm word-line level shown in figure 7b, data lines and other interconnects.[16] Because of the early industrial interest, Japan has developed the infrastructure necessary to fabricate and test phase-shifting masks well ahead of the US. Sematech, the US semiconductor manufacturers' consortium, is attempting to catch up, but it cannot compete with the wide enthusiasm in Japan.

A photomask used in production must be entirely free of printable defects. Great care is taken to inspect and repair the patterns on today's transmission masks. To repair transparent defects on a transmission mask one can locally deposit carbon or some other opaque material using a focused ion beam or laser beam and a reactive atmosphere. To remove opaque defects one can ablate them with a pulsed laser. No one really knows yet how to find and identify phase-shifting defects or how to repair



Mask structures and the corresponding electric field patterns at the mask plane. The mask in **a** is of the conventional transmission type, while those in **b–f** are phase-shifting masks. **b:** Alternating-aperture mask. **c:** Chromeless phase-edge mask, which produces dark lines in the image solely through destructive interference at the phase transitions. **d:** Shifter–shutter mask. **e:** Rimshifter mask. **f:** Attenuated phase-shift mask. The masks in **d**, **e** and **f** improve on the conventional design by substituting negative amplitudes for zero over an appropriate region. Thick black regions represent opaque material; dashed regions represent 180° phase shift; and the "brick-like" shading in **f** represents partially transmitting material with a 180° phase shift. **Figure 5**

them. The local deposition or removal of a well-controlled layer of transparent material—leaving behind an optically flat surface—seems beyond the current state of the art. One current research topic concerns methods to eliminate defects on special mask plates by etching bad regions down to a buried "etch-stop" layer.[17] Electromagnetic modeling suggests that the 360° phase steps that sometimes occur in this technique may not themselves print as defects.

Phase-shifting masks must be fabricated today by elaborate techniques expected to produce no printable defects in the shifter layers. In one process the phase-shift pattern is written three times by the electron beam, with the shifter material etched to an additional third of the desired depth each time.[7] If the defects introduced in each writing and etching step are independent, then it is unlikely that any defect larger than 60° will appear on the final mask. A few such defects should not affect performance. For DRAMs and other chips produced in large quantity, such a complex mask fabrication process is worth the cost. Other methods to enhance the performance of optical lithography may prove more suitable for microprocessor chips and application-specific integrated circuits made in smaller quantities.

Illumination refinement

Another area ripe for revolution is the homogenizer–condenser system that illuminates the mask. The potential of the illumination system for enhancing the resolution and the process window (the range of acceptable focuses and exposures) in semiconductor production has not been sufficiently appreciated, in spite of the analogous improvements demonstrated in microscopy long ago.

The criterion for judging the performance of a stepper illumination system has been the uniformity of the light level at the mask. Generally 2% or better is required. To insure that this uniform illumination is transmitted through the imaging lens after diffraction from the mask pattern, the aperture (or "stop") of the condenser system is designed to be smaller than that of the projection lens by a factor σ, which is typically 50–70%. Thus at the projection-lens pupil of a conventional stepper, the illumination forms a disc in the center, occupying a fraction σ of the aperture diameter.

When a mask is placed in the object plane, diffraction produces additional beams of light in the lens pupil. Figure 8a shows the behavior of a transmission mask with a fine line–space pattern in a stepper. The zeroth order of diffraction—the undiffracted beam—reproduces the illumination disc of radius σNA. The $+n$th and $-n$th diffraction orders produce similar discs displaced from the origin at angles $\pm n(\lambda/p)$, where p is the pitch of the mask diffraction grating. At least the 0 and ± 1 diffraction orders must be transmitted through the pupil and imaged on the wafer. However, when $p \sim M\lambda/\mathrm{NA}$, where M is the magnification of the projection lens, substantial fractions of the ± 1 orders are lost from the lens pupil pattern, and the image quality projected by a transmission mask declines. At the wafer, the minimum feasible pitch is $p/M \sim \lambda/\mathrm{NA}$.

The alternating-aperture mask behaves as shown in figure 8b. The zeroth order is entirely suppressed in the lens pupil, and the ± 1 orders are displaced from the origin by $\pm \lambda/2p$. Full transmission and full contrast are achieved down to a mask pitch of $p \sim M\lambda/\mathrm{NA}(2-\sigma)$, which is typically 50% better than the limit for a transmission mask.[5] Clearly, reducing the fraction σ improves the performance of phase-shifting masks. Condenser systems with $0.2 < \sigma < 0.5$ are being designed.

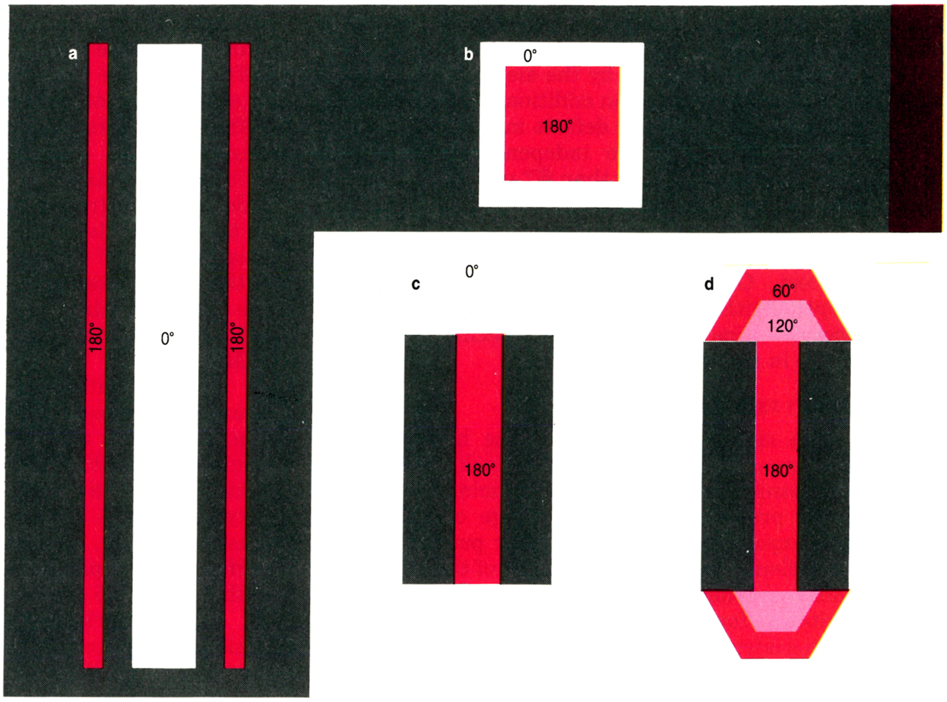
More remarkably, properly optimized off-axis illumination with conventional masks can realize some of the resolution and depth-of-focus advantage of alternating-aperture masks. Figure 8c shows the most promising form of off-axis illumination, called SHRINC by Nikon and QUEST by Canon.[18] In this system the condenser projects four discs of illumination centered at angles $(\theta_x, \theta_y) = (\pm C, \pm C)$ into the projection-lens pupil. A line-space pattern oriented in the x or y direction projects a zero diffraction order into each illumination disc and ± 1 orders displaced from the zeroth order along the y or x axis. As the pitch of the grating shrinks, one of the first diffraction orders is soon lost outside the lens aperture; however, the other first order continues to be transmitted until the mask pitch reaches $p \sim M\lambda/(C + \sqrt{\mathrm{NA}^2 - C^2})$. The zeroth and remaining first-order components interfere at the wafer plane to produce an image with a pitch of p/M in a manner analogous to the operation of the alternating-aperture mask.

While SHRINC and QUEST improve the performance of x and y geometries on conventional masks, they pose puzzles for mask designers. Mask features oriented at 45° have poorer resolution with these techniques than with conventional illumination. Mask designers must thus avoid fine features in these forbidden orientations, as well as isolated small lines and large features that might produce distorted images. Because the zeroth-order beam is stronger than the first-order beam, perfect destructive interference and 100% contrast are not possible with SHRINC–QUEST and transmission masks. The reduced zeroth-order components of the "weak" phase-shifting masks in figures 5d–f improve the performance of SHRINC–QUEST. While a strategy employing both SHRINC–QUEST and phase shifting may seem overly elaborate, the mask designs required do not suffer from the phase topology problem.

Optimized predistortion

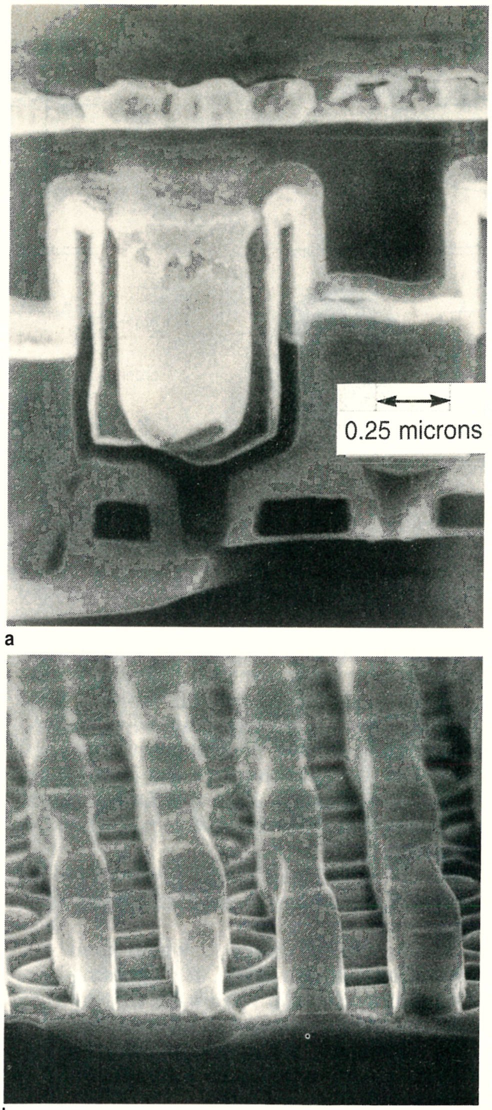
Whatever the imaging technology, photomask design promises to be a complex undertaking when the circuit features are no larger than a wavelength. The mask pattern may have to be predistorted in some way to yield the desired image pattern. Process engineers have long used informal "biasing" formulas to print better resist patterns, often without the knowledge of circuit designers or management. Formal optimization procedures may give better results than intuitive engineering.

At the University of California at Berkeley, Avideh Zakhor and Yong Liu have combined lithography simulation with such optimization procedures as simulated annealing to find the mask patterns that project an image that best matches a given target function.[19] Figure 1 compares the results of such an optimization with a hand-designed mask. The optimized mask pattern is much more complex, with many subresolution "serifs" disconnected from the main body of the feature. The 30% intensity contour (blue line) of the resulting image more closely matches the desired shape than does the same contour in the conventionally produced image. Using the optimization procedure one can arrange the three-dimensional target function to maximize the depth of focus or to shift the plane of optimum focus so as to account for chip topography. Often several different mask patterns will



Phase-shifting mask patterns. Shown are typical patterns for an isolated bright line (**a**), a contact hole (**b**) and a multiphase solution (**d**) to the topological puzzle of terminating a 180° phase shift sharply (**c**). **Figure 6**

Cell from a 256-megabit dynamic random-access memory, as seen in a scanning electron microscope. **a:** The completed cell. **b:** The gate layer that was patterned using mercury i-line light and phase-shift techniques. The minimum feature patterned photolithographically is 250 nm. (From ref. 16; courtesy of Shinji Okazaki, Hitachi Central Research Laboratory.) **Figure 7**



have nearly identical deviations from the target pattern. A fabrication cost function can automatically choose the most feasible among them.

To be effective, optimization programs require fast and accurate simulation subroutines. Current optics and resist simulation packages run far too slowly when the area being simulated is larger than a few square microns. That situation is changing as new programs are written and existing packages such as SAMPLE from the University of California are optimized for new computer platforms. However, the results obtained are only as accurate as the tool and resist parameters used as input. In particular, residual lens aberrations, the exact illuminator geometry and the resist development parameters need to be correct. Obtaining accurate values for these somewhat variable quantities in a timely manner is essential but at present almost impossible.

As we approach the ultimate limits of optical lithography, the entire process, from design to the manufacture of circuits, must be optimized as a system. Everyone involved must be able to access and use all the relevant information. Because of the complexity of the many nonlinear interactions in mask fabrication, partially coherent imaging, resist development and circuit operation, "expert" computer systems may be needed to guide circuit designers through the maze of constraints and opportunities.

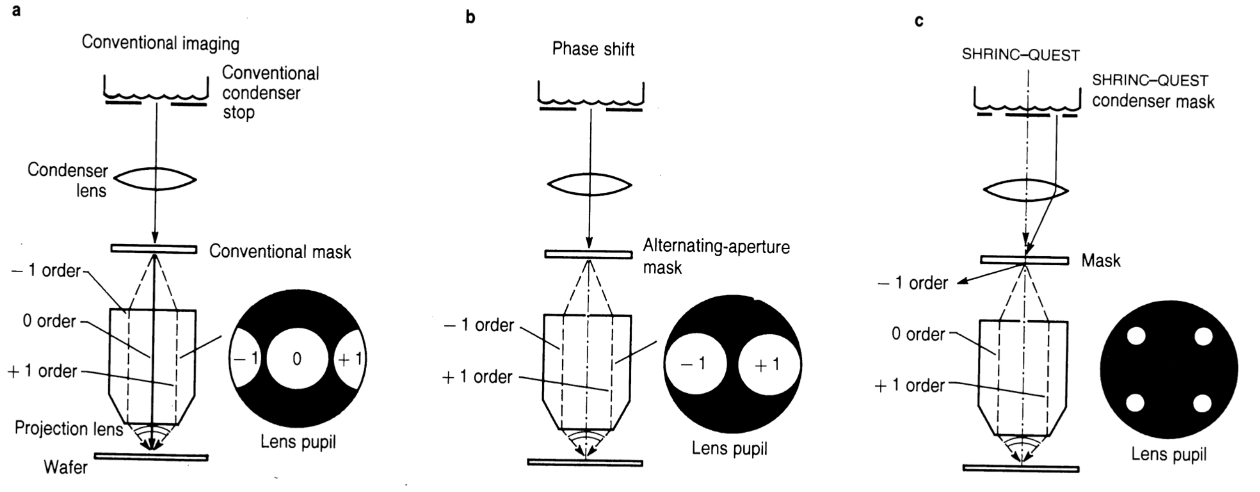
The ultimate optical exposure tool

Perhaps the ultimate photolithography exposure tool already exists in prototype form at Stanford. The Markle–Dyson imaging system relays images of a reflective mask onto a resist-coated wafer with an aberration-free lens that has both reflecting and refracting elements.[20] The numerical aperture can be as large as 0.7 at duv and shorter wavelengths. This unity-magnification projection system produces resist patterns with dimensions down to 0.25 microns using conventional masks and mercury lamp illumination. With an alternating-aperture mask, the system has already achieved a resolution of 0.13 microns. One key innovation of this system is the use of the reflective mask, which allows the illumination to pass through the partially reflective main imaging mirror while a large semiconductor wafer is stepped from one chip to another directly behind the opaque part of the mask plate. Of course, reflective photomasks are yet another new technology, which presents new materials and fabrication issues. The Markle–Dyson system is compatible with SHRINC–QUEST illumination, and a full-scale device could simultaneously image an entire 35×20-mm chip. The technical challenge is to fabricate the duv optics to the required accuracy and to pattern the necessary 1× optical masks with a precision of better than 10 nm—essentially the same precision required by 1× x-ray masks.

With proper masks and 193-nm illumination, the Markle–Dyson system should be capable of patterning a 1-gigabit memory chip, which probably will go into production early in the next century. The smallest feature of that chip is expected to be about 0.14 microns, not that much smaller than features on today's developmental chips. The difference is that more than a billion such features must be functional on the gigabit chip, which will sell for less than $100. To go beyond the 1-Gb chip, lithographers may well need to introduce some dramatically new technology, such as soft-x-ray projection printing.

Exploratory research toward that particular end is already under way at AT&T Bell Laboratories, Sandia National Laboratories, Lawrence Livermore National Laboratory, the Center for Research in Electro-optics and Lasers at the University of Central Florida, Orlando, and other centers.[21] The proposed all-reflective projection systems look remarkably familiar to an optical physicist. A modest numerical aperture of about 0.1 and wavelengths near 13 nm should permit patterning of sub-0.1-micron circuit elements with a relatively robust 1-micron depth of focus. Materials scientists and device physicists, however, may need to invent entirely new concepts to achieve a practical yield of billions of devices, each less than 0.1 microns in extent.

There seems to be adequate funding for such long-



Diffraction optics. **a:** Conventional stepper imaging. **b:** Effect of using an alternating-aperture mask. **c:** Off-axis illumination with a conventional mask. The dark circles show the diffraction patterns from the mask in the pupil of the projection lens. In SHRINC–QUEST illumination the first-order diffracted beam due to light from one condenser mask aperture overlays the zeroth-order beam from another. **Figure 8**

term research programs as soft-x-ray projection lithography. Support does not seem nearly so generous for innovations in optics expected to pay off sooner. The mask-making industry certainly cannot afford to underwrite the effort necessary for the development of phase-shift mask technology. Insiders compare the photomask industry to the airline industry—high technology, high reliability, high service, but with the profits controlled by the dumbest competitor.

As Alec Broers of Cambridge University concluded in his recent memoir of the past two decades of controversy about lithography:[4]

> In retrospect the correct strategy . . . would have been to develop optical projection for exposing wafers and scanning electron beams for writing the masks and not to have worked on alternatives such as x rays. [However,] the spoils are likely to go to those who invest enough in their choice [now] to prove it was the right one.

The US optical lithography industry does not fall in that category of investors. If current trends continue, there will very likely be no surviving domestic lithography suppliers and ultimately no purely domestic manufacturers of commodity semiconductors. The American high-technology community will have lost key markets and key capabilities. Without the revenue to support development costs, revolutionary concepts invented in America will enrich others or, even worse, never be brought to fruition at all.

In a revolution, there are always losers and only occasionally winners.

References

1. R. P. Feynman, J. Micromechanical Syst. **1**, 60 (1992).
2. W. M. Moreau, *Semiconductor Lithography: Principles, Practices and Materials*, Plenum, New York (1988), ch. 8.
3. D. W. Johnson, C. W. Mack, Proc. SPIE **1674**, 486 (1992).
4. A. Broers, New Scientist, 18 April 1992, p. 23.
5. M. D. Levenson, N. S. Viswanathan, R. A. Simpson, IEEE Trans. Electron. Devices **29**, 1828 (1982). M. Shibuya, Japanese patent number Showa 62-50811 (1980). A fabrication technology for a very similar mask with applications in optical data storage and character recognition was patented in the German Democratic Republic in 1976 by Hartmut Hänsel and Wulf Polack of VEB Carl Zeiss, Jena; patent number DD 126 361.
6. T. Terasawa, N. Hasegawa, T. Tanaka, S. Katagiri, T. Kurosaki, J. Vac. Sci. Technol. B **8**, 1300 (1990).
7. J. Nistler, G. Hughes, A. Muray, J. Wiley, Proc. SPIE **1604**, 236 (1991).
8. M. D. Levenson, Microlithography World, September–October 1992, p. 7.
9. Y.-C. Ku, E. H. Anderson, M. L. Shattenburg, H. I. Smith, J. Vac. Sci. Technol. B **6**, 150 (1988).
10. J. Durnin, J. J. Micelli Jr, J. H. Eberly, Phys. Rev. Lett. **58**, 1499 (1987).
11. M. D. Levenson, F. M. Schellenberg, Microlithography World, May–June 1992, p. 7.
12. K. Inokuchi, T. Saito, H. Jinbo, Y. Yamashita, Y. Sano, Jpn. J. Appl. Phys. **30**, 3318 (1991).
13. H. Watanabe, Y. Todokoro, Y. Hirai, M. Inoue, Proc. SPIE **1463**, 101 (1991).
14. T. Yamanaka, N. Hasegawa, T. Tanaka, K. Ishibashi, T. Hashimoto, A. Shimizu, N. Hashimoto, K. Sasaki, T. Nishida, E. Takeda, "A 5.9 μm^2 Super-Low-Power SRAM Cell Using a New Phase-Shift Lithography," *International Electron Devices Meeting-90 Technical Digest* (1990), p. 477.
15. H. Asakura, Y. Funaki, Nikkei Microdevices, April 1992, p. 23 (in Japanese; translation available from Japanese Technical Translators, Sunnyvale, Calif.).
16. K. Sagara, T. Kure, S. Shukuri, J. Yugami, N. Hasegawa, H. Shinriki, H. Goto, H. Yamashita, E. Takeda, in *1992 Symp. on VLSI Technology (Seattle): Digest of Technical Papers*, IEEE, New York (1992), p. 10.
17. N. Hasegawa, T. Tanaka, A. Imai, H. Fukuda, in *Abstr. 51st Annu. Mtg. Jpn. Soc. Appl. Phys.*, vol. 2, paper 27P-ZG-10 (1990), p. 493 (in English).
18. N. Shiraishi, S. Hirokawa, Y. Takeuchi, N. Magome, Proc. SPIE **1674**, 741 (1992). M. Noguchi, M. Muraki, Y. Iwasai, A. Suzuki, Proc. SPIE **1674**, 92 (1992).
19. Y. Liu, A. Zakhor, IEEE Trans. Semicond. Mfg. **5**, 138 (1992).
20. A. Grenville, R. L. Hsieh, R. von Bunau, Y. H. Lee, D. A. Markle, G. Owen, R. F. W. Pease, J. Vac. Sci. Technol. B **9**, 3108 (1991). R. L. Hsieh, A. Grenville, G. Owen, R. F. Pease, J. Vac. Sci. Technol. B **10**, 3042 (1992).
21. J. E. Bjorkholm, J. Bokor, L. Eichner, R. R. Freeman, J. Gregus, T. E. Jewell, W. M. Mansfield, A. A. MacDowell, E. L. Raab, W. T. Silvast, L. H. Szeto, D. M. Tennant, W. K. Waskiewicz, D. L. White, O. R. Wood, J. H. Bruning, J. Vac. Sci. Technol. B **8**, 1509 (1990). ■