Recent Trends in Optical Lithography

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■ The fast-paced evolution of optical lithography has been a key enabler in the dramatic size reduction of semiconductor devices and circuits over the last three decades. Various methods have been devised to pattern at dimensions smaller than the wavelength used in the process. In addition, the patterning wavelength itself has been reduced and will continue to decrease in the future. As a result, it is expected that optical lithography will remain the technology of choice in lithography for at least another decade. Lincoln Laboratory has played a seminal role in the progress of optical lithography; it pioneered 193-nm lithography, which is used in advanced production, and 157-nm lithography, which is under active development. Lincoln Laboratory also initiated exploration of liquid-immersion lithography and studied the feasibility of 121-nm lithography. Many of the challenges related to practical implementation of short-wavelength optical lithography are materials-related, including engineering of new materials, improving on existing materials, and optimizing their photochemistry. This article examines the technical issues facing optical lithography and Lincoln Laboratory's contributions toward their resolution.

OPTICAL LITHOGRAPHY, THE TECHNOLOGY of patterning, has enabled semiconductor devices to progressively shrink since the inception of integrated circuits more than three decades ago. Throughout the 1980s and 1990s, the trend of miniaturization continued unabated and even accelerated. Current semiconductor devices are being mass produced with 130-nm dense features; by 2007 these devices will have 65-nm dense features. Optical lithography has been, and will remain for the foreseeable future, the critical technology that makes this trend possible. (To learn the fundamentals of optical lithography, see the sidebar entitled "Optical Lithography Primer.")

In 1993, a consortium of semiconductor manufacturers called SEMATECH (for Semiconductor Manufacturing Technology) began periodically publishing the *Technology Roadmap for Semiconductors,* which assesses and predicts semiconductor technology requirements [1]. Technological and market forces have resulted in critical dimensions for semiconductor chips that outpace the critical dimensions predicted by any editions of the *Technology Roadmap*.

Lincoln Laboratory has played a seminal role in the progress of optical lithography. In 1988, when most of the lithography community was solving difficulties in the nascent 248-nm lithography, Lincoln Laboratory started a systematic development of 193-nm lithography with argon fluoride (ArF) excimer lasers. A transition to the shorter wavelength required the solution of several material-science challenges, including improving on the transmission and durability of lens materials and coatings, and the development of transparent and etch-resistant photoresists. With

OPTICAL LITHOGRAPHY PRIMER

OPTICAL LITHOGRAPHY is a complex process used to mass-produce patterned silicon wafers in semiconductor manufacturing. Most integrated circuits are patterned with this technique.

Figure A illustrates a reduction projection lithography system commonly used in optical lithography. A laser shines ultraviolet light first through an illuminator, which expands, homogenizes, and conditions the beam, and then through a photomask, which contains the pattern to be imaged onto the wafer. The wafer is coated with a photosensitive material, the photoresist. A complex projection lens reduces the photomask pattern by a factor of four or five, and images it onto the photoresist.

Advanced lithography systems image the photomask pattern onto each wafer many times, in a two-step process called step and scan. In the scanning part, portions of the photomask are imaged onto the wafer in a continuous scanning motion, until the whole photomask pattern is transferred to the wafer. In the next stepping part, the wafer is moved to a new location, and the scanning is repeated. Because the wafer production rate, or throughput, significantly affects wafer costs, step-and-scan systems are designed to pattern a
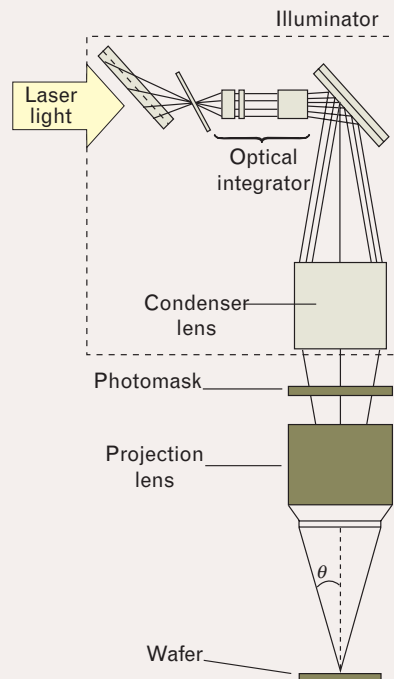

FIGURE A. Reduction projection lithography system.

full wafer in less than a minute.

The imaging (exposure) step is followed by the development step, where the exposed portions of the photoresist are removed, leaving behind the desired pattern, which is then transferred to the underlying wafer through an etch process. The sequence of coating the wafer with photoresist, exposing it with ultraviolet light, developing it, and etching it is repeated many times to complete the integrated circuit.

The performance of the projection system is ultimately determined by the laws governing the propagation of electromagnetic waves. In lithography, there are two key metrics: the resolution, or the ability of the system to distinguish between nearby features, and the depth of focus, which is a measure of the precision with which the surface of the wafer must be positioned. Both quantities depend on the patterning wavelength λ and the numerical aperture (NA), the latter being equal to $n\sin\theta$, where θ is the half-angle of the converging rays in the imaging system (see Figure A) and n is the index of refraction of the medium in contact with the photoresist. The expressions governing resolution and depth of focus are

$$\text{resolution} = \frac{k_1\lambda}{\text{NA}} \qquad (1)$$

and

$$\text{depth of focus} = \frac{k_2\lambda}{(\text{NA})^2} \cdot \quad (2)$$

The coefficients of proportionality k_1 and k_2 are measures of the difficulty in printing a given dimension with a given exposure system-photoresist combination. These values reflect several factors, including the effect of novel illumination modes and photomasks, and improved photoresist performance. In more advanced devices k_1 is 0.4 and k_2 is 0.7. When patterning equal lines
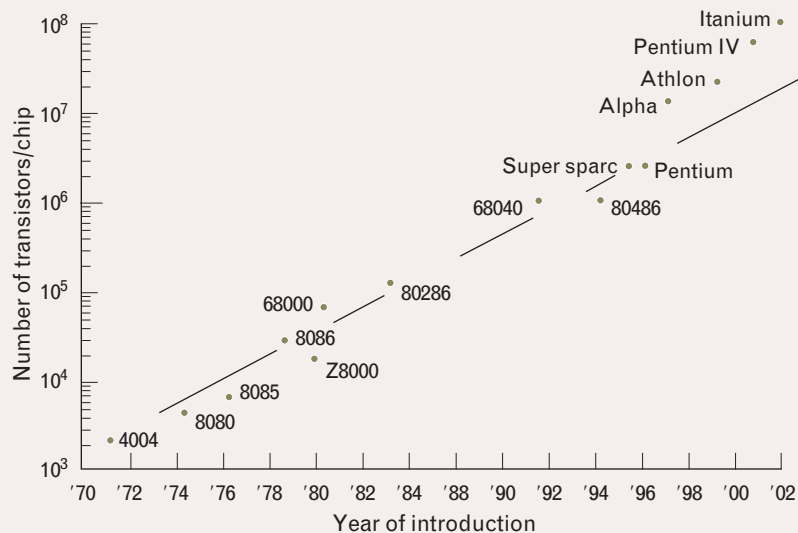
FIGURE B. Logarithmic plot showing how the number of transistors placed on a microprocessor chip increases according to Moore's law.

and spaces, the fundamental lower limit of k_1 is 0.25, determined by diffraction. For other geometries, k_1 can be smaller.

Equation 1 indicates that improved resolution can be obtained by reducing the wavelength λ of the laser and by increasing the NA of the imaging system. Continued improvements in optical lithography have enabled the printing of ever finer features, with the smallest size, or critical dimension, decreasing by

about 30% every two years. On average, the number of transistors in an integrated circuit has doubled every eighteen months. This trend, shown in Figure B, is known as Moore's law because it was recognized by Gordon Moore in 1965.

Keeping pace with Moore's law has been the main challenge of optical lithography. To this end, optical lithography has taken on the complex technological challenge of using deep ultraviolet lasers and fabricating optics with very high NAs and near-diffraction-limited performance, as discussed elsewhere in this article. An equally impressive effort is taking place in developing strategies to reduce k_1, without changing the wavelength or imaging optics. When the minimum feature size became less than the wavelength, k_1 became less than the NA and optical lithography entered the era of subwavelength imaging. This transition, which took place around 1996, is shown in Figure C as the intersection between the exposure-wavelength curve (orange) and the minimum-feature-size curve (green). The reduction in k_1 was facilitated by several factors, described in the companion article in this issue by Fritze et al., entitled "Subwavelength Optical Lithography with Phase-Shift Photomasks." These factors include modified illumination schemes and changes in the pattern on the photomask.
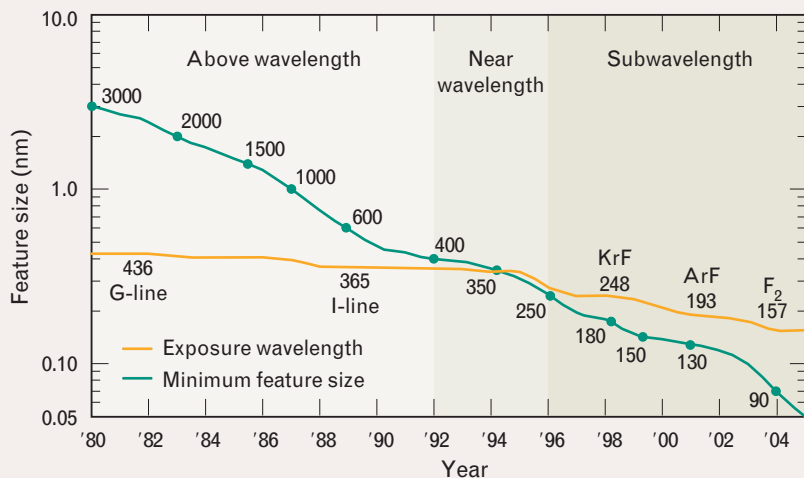

FIGURE C. Reduction in minimum feature size and exposure wavelength over time. Mercury arc lamps produce the G-line at 436 nm and the I-line at 365 nm. The krypton-fluoride (KrF) excimer laser operates at 248 nm, the argon-fluoride (ArF) laser operates at 193 nm, and the fluorine (F_2) excimer laser operates at 157 nm.

support from the Defense Advanced Research Projects Agency (DARPA), Lincoln Laboratory facilitated much of the development in these areas, largely through collaborations with suppliers and research laboratories [2]. It also had built and installed in its clean rooms the world's first 193-nm large-field projection lithography system [3], and fabricated the first devices at 193 nm [4].

By 1996, when it became apparent that 193-nm lithography would indeed become the next technology, we started studying the feasibility of 157-nm lithography, the wavelength of fluorine (F_2) excimer lasers [5]. (Although the actual wavelength used is 157.6 nm, the lithography community shortens this value to 157 nm.) Lithography at 193 nm was introduced into advanced manufacturing in 2001; 157-nm lithography is expected to follow in its path around 2005. In 2000, on the heels of these programs, we began exploring two new directions in optical lithography: increasing the numerical aperture (NA) beyond 1.0 by using immersion liquids [6], and shortening the wavelength further to 121 nm [7]. This article summarizes the current status of these technologies in which Lincoln Laboratory continues to play an important role—157-nm lithography, liquid-immersion lithography, and 121-nm lithography.

Lithography at 157 nm

The transition from 193- to 157-nm lithography requires several important changes in the projection systems, the photomasks, and the photoresists. For the projection systems there are three new issues to consider. First, the lens material must be exclusively crystalline calcium fluoride, whereas at 193 nm many elements are fabricated of fused silica. Second, the optical coatings require new materials, mostly fluoride thin films. And third, the ambient must be high-purity nitrogen, with well-controlled levels of potential contaminants.

In general, issues encountered at 193 nm are more difficult to resolve at 157 nm because of the shorter wavelength. The change to optics made of calcium fluoride at 157 nm requires the growth of crystals of much higher quality than needed at 193 nm. The absorption coefficient must be less than 0.002 cm^{-1} at the new wavelength, which imposes stringent require-

ments on the impurity levels in the starting materials and in the final crystal. (Note that throughout this article, absorption coefficients are given in base 10, not base *e*.) The inhomogeneities in refractive index must be less than 1 part per million (ppm), and the residual stress-induced birefringence must be less than 1 nm/cm, both values implying near-perfect crystal growth.

Because of these requirements, the crystal-growing companies have made large investments in technology development and infrastructure. The optical lithography market has generated an explosive expansion in the fluoride-crystal-growth industry, driving a manifold increase in capacity and quality in just a few years. Still, the industry's current yield of near-perfect crystals is low at present. Unless there are significant improvements in the crystal-growth process, the demand for calcium fluoride crystals may not be met from 2005 to 2008, the ramp-up years of 157-nm lithography.

An added complication to the calcium-fluoride situation was the realization in early 2001 that calcium fluoride has an intrinsic birefringence that cannot be reduced by the crystal growth or annealing process [8]. This intrinsic birefringence is caused by the interaction between the laser electric field and the crystal lattice, and therefore it is both deterministic and dependent on the angle of propagation and crystalline orientation. Also, it is much larger at 157 nm than at 193 nm. To overcome this problem, it is necessary to employ lenses made of calcium fluoride with two different crystalline orientations. Again, crystal growers bear the burden of ensuring that high-yield processes are available to grow high-quality crystals, this time in both orientations.

Practically every optical element requires a thin-film coating for antireflective purposes. The most common coatings are antireflective. These consist of several layers of dielectric thin films, each having a thickness of approximately one quarter wavelength and alternating in their refractive index between high and low. Of course, these dielectric films must be highly transparent, and at 157 nm this requirement implies the use of metal fluorides. High-index materials are lanthanum fluoride or gadolinium fluoride; low-index materials are magnesium fluoride or alumi-

num fluoride. Oxide films used at longer wavelengths, such as silicon dioxide or hafnium oxide, are usually too absorptive at 157 nm. The near-universal use of fluoride thin films introduces a level of uncertainty because they must be qualified with respect to their antireflective properties as well as their durability upon long-term exposure to laser radiation.

Figure 1 shows a test chamber made of ultrahigh-vacuum-compatible materials, built at Lincoln Laboratory for the purpose of conducting long-term tests of such coatings. The chamber was purged continually with clean nitrogen, so that residual organic impurities were less than one half of one part per billion, and residual oxygen was kept below 0.5 ppm. We observed a remarkable phenomenon, shown in Figure 2, in which irradiating antireflective coatings with a 157-nm laser in the presence of several ppm of water vapor significantly increased the lifetime of the coatings. While the physical-chemical cause of this effect is still under investigation, we do know that it is a surface effect, enhanced by the affinity of water to surfaces. Supporting this assertion is an enhancement of the effect at higher water concentrations and when the outer dielectric layer is more porous. Because this effect appears to require the controlled introduction of a relatively high level of water in the vicinity of every optical element, it could have a significant impact on the design of projection systems.
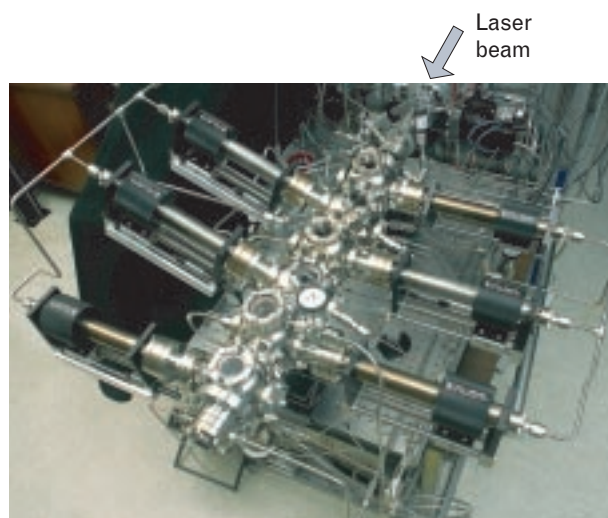

FIGURE 1. Photograph of the experimental setup for determining the durability of optical coatings. The system is ultrahigh-vacuum compatible, although it usually operates with nitrogen at one atmospheric pressure.

Table 1 shows the rate of degradation (percent change in transmission per incident laser dose in MJ/cm^2) of antireflective coatings for two different porosities upon irradiation by a 157-nm laser in an ambient containing varying concentrations of water vapor. The table also lists the enhancement ratio, which indicates how the presence of water hinders the degradation rate.
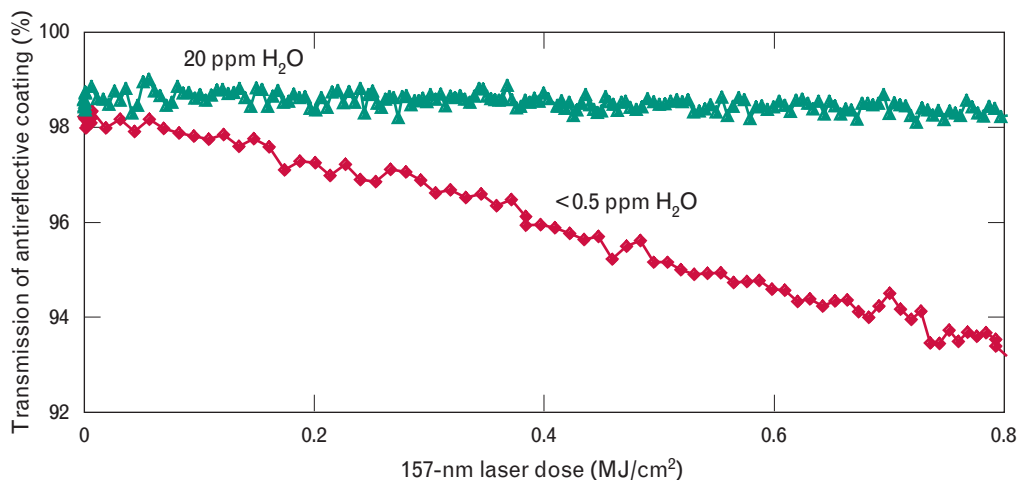

FIGURE 2. Effect of water vapor on the durability of an antireflective coating under 157-nm laser irradiation. We see that the transmission of the antireflective coating is stable for a higher water concentration of 20 parts per million (ppm).

**Table 1. Degradation Rate
of Antireflective Coatings***

	1.5 ppm	3 ppm	6 ppm
Low porosity	10	2	2
High porosity	13.3	1.6	0.3
Enhancement ratio (low/high porosity)	0.8	1.3	6.7

*percent change in transmission per 157-nm laser dose in MJ/cm^2

The cleanliness of the purge gas is also of paramount importance at 157 nm. Photoinduced contamination of optics due to trace contaminants in the purge gas has already been observed at 248 and 193 nm, and the shorter wavelength of 157 nm only exacerbates this effect. Furthermore, scattered 157-nm radiation is more effective at decomposing organic materials, thereby liberating volatile contaminants, which in turn may form photoinduced deposits on optical surfaces. Over the past four years we have used a sensitive gas-chromatograph mass spectrometer to test over one hundred materials for such photoinduced outgassing. Tested materials include optical adhesives, tubing for purge gases, and photoresists [9]. The concern over detrimental effects of photo-outgassing is not unique to lithography. In fact, the phenomenon is akin to similar effects in space optics programs, where our gas-chromatograph mass-spectrometer system has been useful in identifying photoinduced contamination reactions.

We used the results of the outgassing studies to determine the magnitude of photo-contamination of optics and its dependence on laser operating conditions. We constructed a special test bed, where controlled amounts of vapor contaminants were introduced into a chamber, and changes in transmission with increasing laser doses were monitored in situ. In addition, laser-cleaning experiments were also carried out, when oxygen replaced the contaminant. Figure 3 shows how the transmission changed in the presence

of 3 ppm of toluene and various concentrations of oxygen. From these kinds of plots, we extracted information on the forward and reverse photoinduced processes (i.e., the contamination and cleaning) that take place simultaneously as long as the hydrocarbon contaminant and the oxygen are both present. The steady-state surface coverage was calculated for various conditions and chemistries. Also, we observed that not every residue is removable with oxygen. As a result, we established a set of conditions, described in Table 2, that determines the stringent purity requirements on the purge gas.

Photomasks at 157 nm encounter materials issues as well. The photomask substrate at longer wavelengths is made of fused silica with up to 1000 ppm of hydroxyl (OH) groups; at 157 nm the photomask substrate is made of modified fused silica doped with fluorine at concentrations of a few percent. This fused silica does not contain hydroxyls, which absorb strongly at 157 nm. Fluorine-containing fused silica has been shown to be transparent enough to serve as a
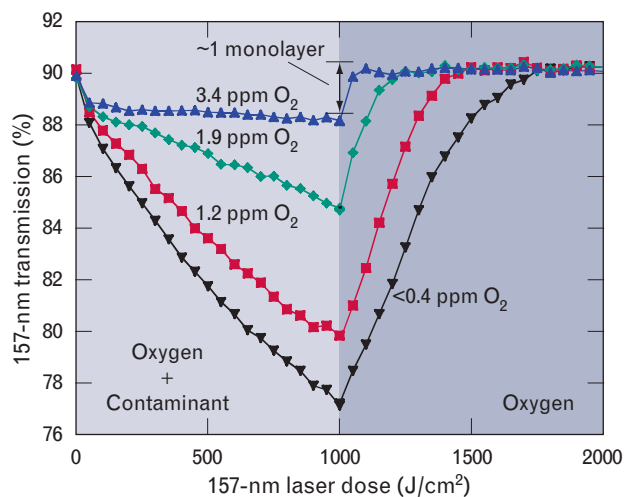

FIGURE 3. The change in transmission of a calcium-fluoride substrate in the presence of 3 ppm of toluene, and varying concentrations of oxygen (O_2). The reduction in transmission at any given oxygen concentration is due to photoinduced contamination; the increase in transmission at these same oxygen levels is evidence for photoinduced cleaning of the contamination layer. Note that the 157-nm transmission is sensitive to hydrocarbon contamination; even the presence of one monolayer of hydrocarbon causes the transmission at 157 nm to drop by almost 2%.

Table 2. Effects of 157-nm Photoinduced Contamination of Optical Surfaces Caused by Contaminants in the Ambient		
	Low Levels	*High Levels*
Hydrocarbons	Reversible	Irreversible
	Parts-per-billion levels limit surface losses to < 0.1% in sub-ppm levels of oxygen.	Brief exposure ($< 1 \text{ kJ/cm}^2$) to ppm levels can lead to permanent degradation.
Organosilicons	Irreversible	Irreversible
	Parts-per-trillion levels are necessary to limit growth of SiO_2 over lifetime of tool.	
Fluorocarbons	No contamination	No contamination at > 10 ppm

photomask substrate, and it is also resistant to laser-induced damage [10].

The absorber in binary photomasks is the traditional chromium-based stack of thin films. Several absorptive materials have been proposed for attenuating phase-shift photomasks, and it appears that practical options may become available [11]. The largest uncertainty with the photomask at 157 nm is not related to the photomask itself, but to the means required to protect it from particle contamination. There is essentially zero tolerance to particles landing on the photomask, because of the severe yield implications of even one particle in the wrong place. Therefore, the accepted method of protecting the photomask has been to use a very thin membrane, the pellicle, which is placed several millimeters away from the photomask. Because of the standoff, particles on the pellicle are out of focus, and a high process yield can be maintained. The pellicles at 193 and 248 nm are submicrometer-thick fluoropolymers, chosen for their mechanical properties as well as for their transmission and their laser durability [12].

At 157 nm, the situation is much more complex. Several pellicle candidates meet the mechanical and transmission requirements, but to date all materials have exhibited rapid degradation in 157-nm transmission when irradiated with a 157-nm laser. A common benchmark used to asses the durability of pellicle materials is the 10% lifetime, which is the laser dose that changes the transmission of the pellicle by 10%. For practical use in industry, this value must be at least 100 J/cm^2, and probably 1 kJ/cm^2. Figure 4
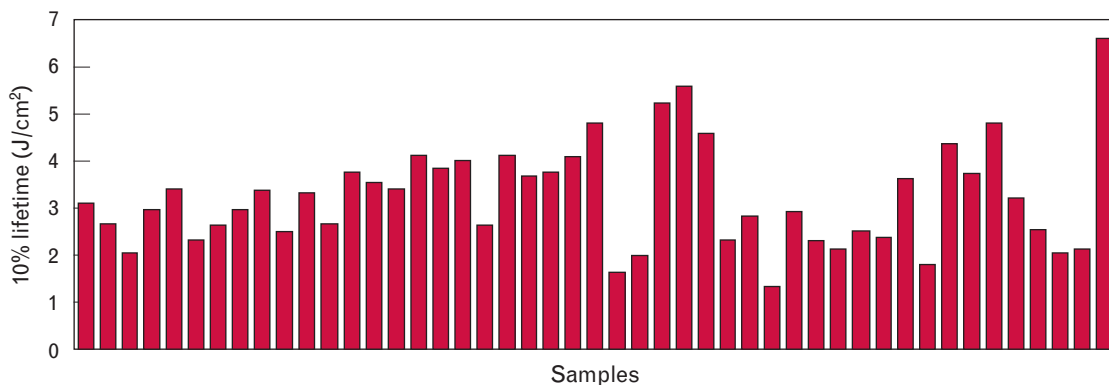
FIGURE 4. 10% lifetime of pellicle material samples tested. The 10% lifetime is defined as the incident laser dose that produces a 10% change in the transmission of the pellicle material with a thickness of 0.8 μm.

shows that the 10% lifetime of all pellicle materials tested at 157 nm is less than 7 J/cm^2, which is at least one and probably two orders of magnitude less than what is needed, given the number of wafers that are exposed for each photomask. The failure mode of the pellicles is loss of transmission, a process named photochemical darkening. The underlying photochemistry is complex, but it is probably initiated by photogenerated free radicals, which then form a range of unsaturated bonds.

While active research is ongoing to reduce photochemical darkening, an alternative approach has been engineered that uses thin inorganic plates as hard pellicles. The hard pellicles are made of the fluorinated fused-silica material used in photomask blanks. Because of manufacturing limitations, they are about 800 μm thick, not as thin as soft pellicles. They must be viewed as an additional optical element in the projection system, which means that they must meet stringent requirements of flatness and uniformity, and even their mounting is critical. Nevertheless, at present hard pellicles are more promising than soft pellicles, because of the uncertainty of controlling photochemical darkening.

Photoresists at 157 nm have encountered a different set of challenges. The thickness of photoresists is determined by two opposing considerations. In order to maintain a good photoresist profile after development, it has been customary to set an upper limit on the absorption of photoresists. An optical density of 0.4 is an accepted value for this upper limit, and this value translates into a lower limit of transmission of about 40%. The optical density is the product of absorption coefficient and thickness; therefore, the more transparent the photoresist, the thicker it can be. Traditional hydrocarbon polymers have 157-nm absorption coefficients of approximately 6 μm^{-1}, implying that the maximum photoresist thickness is less than 70 nm. While the absorption coefficient determines the upper limit of the photoresist thickness, processing considerations set a lower limit of approximately 200 nm (for the 65-nm node). Thus the absorption coefficient of 157-nm photoresists must be reduced to approximately 2 μm^{-1}, or maybe even less.

The last several years have witnessed a continuous reduction in the absorption coefficient of 157-nm
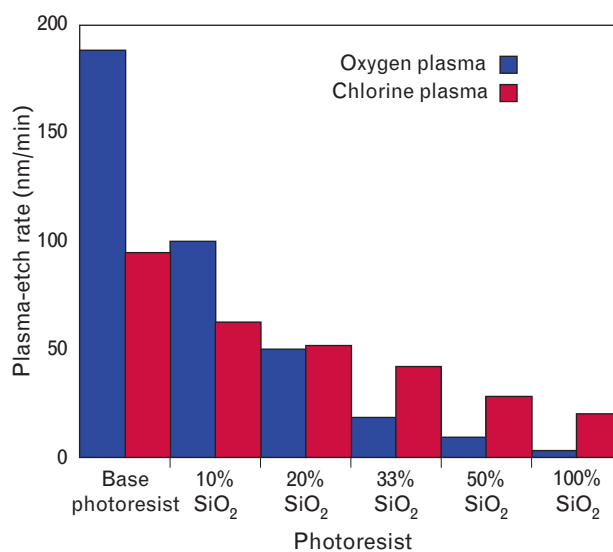

FIGURE 5. Plasma-etch rates of photoresists incorporating varying amounts of inorganic nanoparticles, in different reactive ion-etching chemistries (chlorine and oxygen). The base photoresist contains no silicon dioxide (SiO$_2$). Reductions of an order of magnitude in the plasma-etch rate can be achieved with about 30% to 50% content of nanoparticles.

photoresists, accomplished primarily by the incorporation of C-F bonds and the elimination of C-H, unsaturated, and aromatic bonds along with carbonyl groups in the polymer. Of course, the new materials must retain all the excellent photo-imaging properties of the more established photoresists, as well as their plasma-etch resistance. Fortunately, the basic chemical amplification scheme that works so effectively at 248 and 193 nm can still be used at 157 nm [13]. The specific chemistry and formulation of the photoresist entails various trade-offs. Still, resolution of 50 nm has been shown with photoresists having a thickness of 120 nm [14]. Absorption coefficients of even less than 1 μm^{-1} have been reported recently [15]. Another promising approach to the development of 157-nm photoresists is the incorporation of transparent inorganic nanoparticles in the polymer [16]. This approach accomplishes two goals simultaneously—increased transparency and enhanced plasma-etch resistance (lower etch rate), thus enabling a smaller thickness. Figure 5 shows plasma-etch rates of a commercially available photoresist modified with varying amounts of silicon dioxide nanoparticles.

In the aggregate, the various subsystems required for a successful implementation of 157-nm lithography are in place. Lincoln Laboratory has performed pioneering research in many of these areas and continues to be a significant technology contributor.

Liquid-Immersion Lithography

Liquid-immersion lithography achieves higher patterning resolutions not by reducing the patterning wavelength λ in Equation 1 in the sidebar, but by increasing the NA beyond 1.0 through the use of immersion liquids. Equation 1 shows that, in addition to reducing λ and k_1, increasing the refractive index of the imaging medium results in higher resolution. If instead of air or nitrogen, we employ a liquid with a refractive index n of about 1.4, then the maximum NA approaches 1.4, and a resolution enhancement proportional to n is achieved without changing wavelength, lasers, photomasks, and other established components of the technology base.

The physics underlying this resolution enhancement is as follows: adding a liquid between the last optical element and the photoresist enables the coupling of rays that propagate at steep angles and that would otherwise be reflected through total internal reflection at the optics-air interface. This phenomenon is the basis of oil-immersion microscopy, which has been used for over a century, and the newly engineered liquid-immersion lithography.

The differences between oil-immersion microscopy and liquid-immersion lithography are more practical than fundamental. One difference is the wavelength. To be useful, liquid-immersion lithography must be implemented at the deep ultraviolet (UV) wavelengths of 193 and 157 nm. At such short wavelengths there are few transparent liquids. Furthermore, even small residual absorption can lead to detrimental photochemical reactions, which could degrade the liquid, the optical element in contact with the liquid, or the photoresist in contact with the liquid. Another difference is that the field of view must be much larger in lithography than in microscopy. The design of diffraction-limited imaging optics is therefore more complex in lithography. The third difference relates to the optical-mechanical specifications of the liquid. To be useful in lithography, any spatial or temporal variations of the index should be kept to a minimum, and no bubbles should be present during imaging. Finally, since lithographic projection systems are used in a step-and-scan mode, the engineering of handling the liquid in a high-speed scanning environment is critical.

In 2000, Lincoln Laboratory started an analysis of liquid-immersion lithography to determine the practical feasibility of this concept. Many of the issues listed above were examined closely [6, 17], and at first pass none proved to be insurmountable. Key to liquid-immersion lithography is the availability of transparent liquids. Figure 6 shows the absorption coefficient of deionized water and other transparent liquids considered for 193-nm immersion lithography. Deionized water is the best candidate, with an absorp-
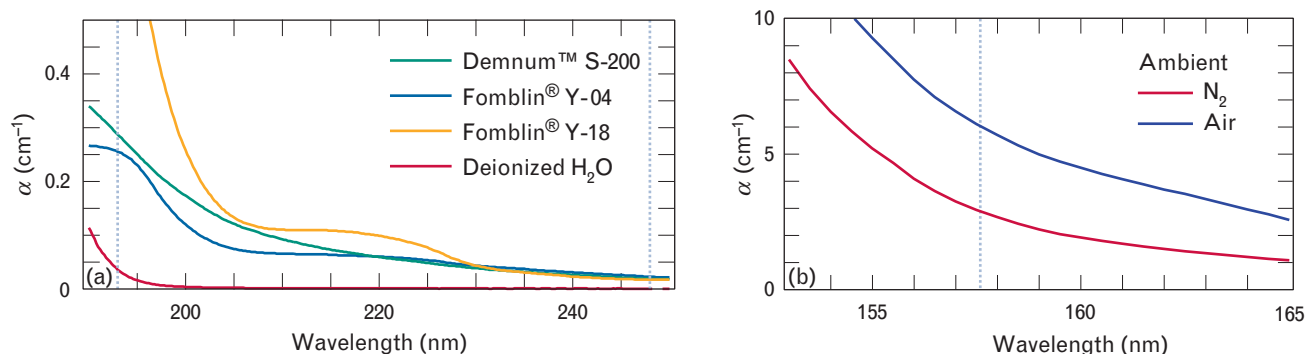

FIGURE 6. (a) The absorption coefficient α of deionized water and other transparent liquids considered for 193-nm immersion lithography. Dashed lines indicate the 193-nm and 248-nm wavelengths. (b) The absorption coefficient of a perfluoro-polyether when exposed to air and when exposed to nitrogen (N_2). The dashed line indicates the 157.6-nm wavelength. Dissolved oxygen can increase the apparent 157-nm absorption coefficient of the liquid by approximately 3 cm^{-1}.

tion coefficient of 0.036 cm^{-1}, which enables a sufficient working distance of several millimeters for the optical and mechanical designers of projection systems. Note that for practical reasons, the working distance must be at least approximately 1 mm. At 157 nm, the most transparent liquids found to date have an absorption coefficient of approximately 3 cm^{-1}, requiring a working distance of less than 0.1 mm. To achieve a larger working distance, we must reduce the absorption coefficient proportionally.

The transparent liquids under consideration belong to the class of perfluoro-polyethers (PFPEs). These liquids, which are currently used as lubricants and heat-transfer fluids, and their optical properties, such as transmission at 157 nm, have not been the subject of optimization. For instance, hydrocarbon impurities at the level of 10 ppm may be sufficient to account for most of the observed absorption at 157 nm. Lincoln Laboratory has an active program to identify the causes of the 157-nm absorption in these liquids, and ultimately engineer a liquid transparent enough for immersion lithography. Indeed, we have recently demonstrated the highest transparency of any liquid at 157 nm, with an absorption coefficient of 0.5 cm^{-1}. This value is within striking distance of the target needed in practical implementation.

Preliminary experiments at Lincoln Laboratory have focused on the possible photoinduced changes at the liquid-optics interface and at the liquid-photoresist interface. A 157-nm antireflective optical coating exposed to flowing PFPE under laser irradiation has shown no degradation in transmission, up to at least a 15-kJ/cm^2 dose. Similarly, fused silica exposed to deionized water and 193-nm laser irradiation has not shown changes in transmission. Furthermore, angle-resolved forward scattering at 157 nm has not revealed the existence of bubbles due to flowing PFPE, up to flow rates of at least 30 cm/min.

Interactions between the immersion liquid and the photoresist may lead to subtle changes in photoresist performance. Again, our initial experiments involving contrast curves of 157-nm photoresists with and without PFPE during exposure indicate that no major changes take place. Figure 7 shows contrast curves of three 157-nm photoresists exposed in semitransparent liquid, compared to their respective curves
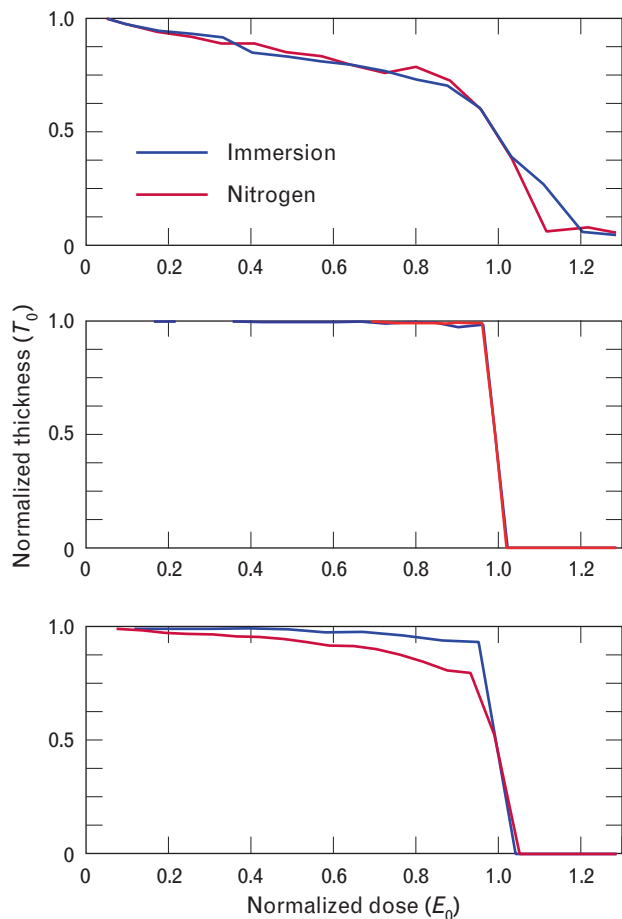

FIGURE 7. Contrast curves of three 157-nm photoresists exposed in semitransparent liquid (immersion), compared to their respective curves when exposed in nitrogen. The upper and middle photoresists show no change, while the bottom photoresist exhibits behavior that can be attributed to the formation of a surface-inhibition layer.

when exposed in nitrogen; there is indication that in one photoresist a liquid-induced inhibition layer is formed, but this result must still be confirmed. Thinning of 193-nm photoresists by the liquid in the absence of laser irradiation has been measured to be less than 0.5 nm, well within acceptable limits.

While many of these initial experiments are being refined and expanded, they nevertheless have shown that no major roadblocks are expected in implementing liquid-immersion lithography. Largely as a result of this work performed at Lincoln Laboratory, liquid-immersion lithography has emerged during the last year as a serious candidate for extending optical lithography. In 2002 and 2003 SEMATECH orga-

nized formal workshops on this topic; one of their outcomes was an accelerated set of feasibility studies, several of which are being carried out at Lincoln Laboratory. If these studies are successful, liquid-immersion lithography at 193 nm would be used to print 45-nm devices, and at 157 nm it would be employed in patterning 32-nm features. These dimensions are projected to be mass produced in the year 2007 or later.

Lithography at 121 nm

The shortest UV wavelength to be used in optical lithography may possibly be 121.6 nm, the wavelength of the Lyman-α line of atomic hydrogen. If feasible, lithography at 121 nm would enable extension of projection dry lithography in a direct path extending from 248 to 193 to 157 nm, and then to 121 nm. As with any new lithographic wavelength, many issues must be examined and then overcome before this patterning wavelength can be introduced into manufacturing. Lincoln Laboratory has explored the various subsystems at 121 nm [7]. Some appear to require relatively minor engineering changes, but others may be more difficult to solve.

One advantage of 121-nm lithography over alternatives such as extreme ultraviolet (EUV) at 13-nm or electron-beam lithography is that vacuum-based systems are not necessary. In fact, the absorption coefficient at 121 nm of most common purge gases and atmospheric constituents is similar to, and even lower than, that at 157 nm. Therefore, lithographic systems can be engineered by using best practices similar to those used at 157 nm.

The main deviation from 157-nm lithography would be the use of pulsed discharge sources at 121 nm instead of lasers. Because convenient lasers have not been demonstrated at 121 nm, we would resort to hydrogen-containing plasmas. This approach is not novel. Mercury plasmas have been used in lithography at 436 and 365 nm, and even in the early phases of 248 nm. They are also being engineered for future EUV lithography. Indeed, in an initial experiment we employed a focused plasma system optimized for EUV and showed that approximately 6%, or about 0.5 J/pulse, of the stored capacitor energy can be generated at 121 nm. This efficiency was one order of

magnitude higher than that at EUV, holding the prospect of powerful 121-nm plasma sources for lithography even in the absence of lasers.

The biggest challenge to date in 121-nm lithography is the lack of suitably transparent optical materials. Projection systems at 121 nm would have to use high NAs over 0.75, which almost certainly demands optical designs that require lenses, either all refractive (using only lenses) or catadioptric (a combination of lenses and mirrors). Therefore, highly transparent lens materials are essential. Because of the short wavelength, it appears that only a few crystalline fluorides have the requisite high band gap. The primary candidate is lithium fluoride (LiF), which is often used as window material for detecting Lyman-α radiation. However, the absorption coefficient required in lithography applications would be about five times lower than that of the most transparent LiF that we have identified, i.e., approximately 0.02 cm^{-1} compared to the lowest measured 0.09 cm^{-1}. The cause of the relatively high absorption coefficient has not yet been determined, but it is probably related to the presence of lithium oxide or hydroxide in the crystal. Therefore, it should be possible to grow truly low-absorption LiF under the appropriate ambient and annealing conditions. Such a demonstration must still be performed.

The next critical issue of any new lithographic wavelength is that of a suitable photoresist. Our studies indicate that the basic photochemistry of polymers and additives is not qualitatively different at 121 nm than at 157 or 193 nm. Therefore, the widely accepted scheme of chemical amplification via photolytically generated acids applies at 121 nm, and the required incident doses presented in Figure 8 are quite low, about 1 mJ/cm^2. The main difficulty in engineering photoresists at 121 nm is the universally high absorption coefficient of organic polymers. This implies the use of very thin layers of photoresist, approximately 25 to 35 nm thick. These thicknesses are at least three times lower than those of the thinnest photoresists used at 157 or 193 nm, and they may not be compatible with pattern transfer processing steps such as reactive ion etching.

Photolithography at 121 nm is still a possibility, but to a large extent its success will be determined by

timely solutions to the severe materials-related issues summarized above.

Summary

Optical lithography, which has been the foundation for much of the semiconductor industry's success in the last two decades, will continue to evolve and meet the new challenges imposed by a *Technology Roadmap* that expects continuous shrinking in printed dimensions. This evolution follows several technical paths, including a reduction of the lithographic wavelength to 157 nm, insertion of a transparent liquid in the optics-wafer gap, and a possible further reduction in wavelength to 121 nm. Each option faces difficult technical challenges, but very few of these challenges appear to be insurmountable. To the practitioners of photolithography these options may appear as disruptive technologies. Still, to a large extent, they are evolutionary steps compared to the alternatives being considered, such as extreme ultraviolet or electron-beam lithography. Precisely because these alternatives are in the gray zone between traditional and radically different, they have the best chance of successfully sustaining the vigor of the semiconductor industry to at least the end of this decade. Lincoln Laboratory has been at the vanguard of developing these next-generation optical lithographies, and we expect to continue to do so in the future.
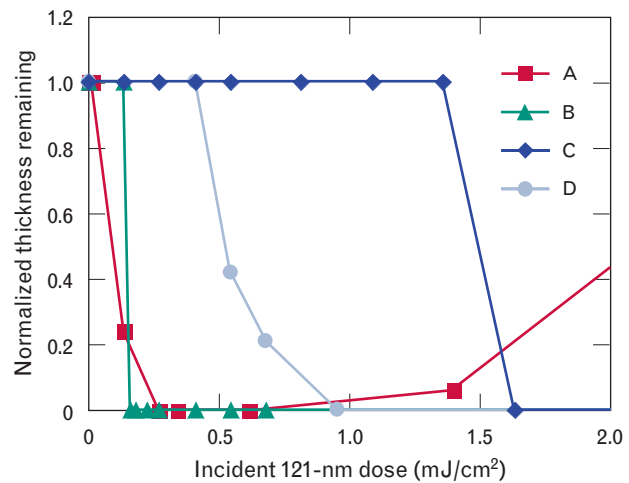
Acknowledgments

FIGURE 8. Contrast curves of four photoresists developed for 193 and 248 nm use, when exposed at 121 nm. The contrast is high, and the required dose is low, approximately 1 mJ/cm^2 and below. The curve for photoresist A shows negative-tone behavior, which means that as the dose of incident 121-nm radiation increases beyond 0.6 mJ/cm^2, the amount of photoresist material remaining increases.

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