# Photolithography at 193 nm

Mordechai Rothschild, Mark W. Horn, Craig L. Keast, Roderick R. Kunz, Vladimir Liberman, Susan C. Palmateer, Scott P. Doran, Anthony R. Forte, Russell B. Goodman, Jan H.C. Sedlacek, Raymond S. Uttaro, Dan Corliss, and Andrew Grenville

**For the last two decades photolithography has been the principal technology for patterning the progressively smaller and denser features required in microelectronic devices and circuits. In recent years, the increasing sophistication of photolithographic techniques using radiation at wavelengths comparable to the feature size has enabled the mass production of circuits in which critical dimensions are 0.25 $\mu$m. The drive to smaller dimensions is expected to continue in the future to critical dimensions of 0.18, 0.13, and even 0.07 $\mu$m, which necessitates a shift to radiation at shorter wavelengths. Lincoln Laboratory has been at the forefront of the development of next-generation photolithographic technology, namely, the use of 193-nm laser radiation. This article presents the rationale behind the transition to this new wavelength, and reviews the status of critical issues encountered in its implementation as a manufacturing process. These issues concern the suitability of optical materials and coatings for lens fabrication, the use of photoresists and wafer processing for device fabrication, and the outlook for extending the usefulness of 193-nm lithography to printing at critical dimensions approaching 0.1 $\mu$m.**

The tremendous growth in the functionality of microelectronic chips over the past two decades has been a fundamental reason for the explosive utilization of this technology in so many aspects of modern life. The driving force behind the greater utilization of microchips has been the continued miniaturization of these devices, which enables an increase in the complexity and speed of circuits without a corresponding increase in cost, size, and power consumption. To illustrate this progress in miniaturization and the increase in functionality, we note that 256-kbit dynamic random access memory (DRAM) microchips, with minimum feature sizes of 1.5 $\mu$m, were introduced in 1983. In 1997, only fourteen years later, 256-Mbit DRAM chips (with one thousand times the capacity of the 1983 chips) were introduced with minimum feature sizes of 0.25 $\mu$m.

The trend in microchip development is clear. A new generation of DRAM chips has been introduced every three years, with four times the capacity of the previous generation and 0.7 times the feature size. This trend is expected to accelerate in the next few years. We thus expect that 1-Gbit DRAM chips with 0.18-$\mu$m printed dimensions will go into advanced manufacturing in the year 1999, followed by 4-Gbit DRAM chips with 0.13-$\mu$m printed dimensions in 2003 and 16-Gbit DRAM chips with 0.10-$\mu$m printed dimensions in 2006. Chips with 0.07-$\mu$m features are already being contemplated for mass production in 2009. These dimensions are found in memory chips with high-density patterns such as DRAMs. The semiconductor industry projects that the development of microprocessor chips, where the device architecture requires a lesser density of structures (transistor gates) at minimum feature size, will experience a similar shrinking trend, only at an even more aggressive pace, namely, 0.14 $\mu$m in 1999 and 0.10 $\mu$m in 2003.

## Trends in Photolithography

The ongoing and seemingly inexorable trend in microchip development has been fueled by the continu-

ous advances in lithography, and in particular in its main branch, projection photolithography. Conceptually, projection photolithography is similar to traditional optical photography: the "flashbulb" is a high-power lamp (and recently a laser), the camera "lens" is near-perfect projection optics, the "scenery" is a set of carefully designed patterns on a mask or reticle, the photographic "emulsion" is a high-resolution photoresist, and the "film" is a wafer (usually silicon).

The conceptual simplicity of projection photolithography belies its great complexity. In particular, the camera, while abiding by the laws of optics, must reproducibly provide a sharp aerial image of very small features with a comfortable process margin. Reproducibility is largely determined by the process margin, or the allowable error, of each step of the process. The most critical process margin in photolithography is the depth of focus (DOF), which must be larger than any variations in the flatness of the photoresist surface. Such variations in flatness, which are unavoidable, are caused by the surface deviations of the wafer and by the topography added to it through the deposition and etching of various thin films in the course of fabricating a device.

The laws of optics that govern the sharpness of the aerial image can be distilled into two rules. In the first rule, the smallest feature size that can be printed—the linewidth $W$—is determined by the wavelength $\lambda$ and the numerical aperture NA of the projection optics:

$$W = k_1 \frac{\lambda}{\mathrm{NA}}, \tag{1}$$

where the parameter $k_1 \geq 0.25$. The processing conditions of the wafer determine the exact value of $k_1$, which at present is larger than approximately 0.5. In the second rule, the DOF is also determined by $\lambda$ and the numerical aperture NA:

$$\mathrm{DOF} = k_2 \frac{\lambda}{(\mathrm{NA})^2}, \tag{2}$$

where the parameter $k_2$ may also depend on the value of $k_1$. The value of the parameter $k_2$ must be large enough to enable a minimum DOF of no less than 0.5 $\mu$m (although until recently a minimum DOF of 1.0 $\mu$m was considered necessary for an acceptably high yield in manufacturing).

Equations 1 and 2 indicate the direction in which photolithography should evolve if it is to print smaller and smaller linewidths; these equations also point out the challenges to be expected on the way. Specifically, in order to decrease the linewidth we might attempt to reduce the parameter $k_1$, reduce the wavelength $\lambda$, or increase the numerical aperture NA. Reducing the value of $k_1$ alone, however, may cause a decreased process yield (and $k_1$ has an absolute lower limit of 0.25), and reducing the other two values causes an unwanted reduction in DOF. The remarkable success of photolithography in the past several years can be attributed to pursuing all three of these approaches to decrease linewidth, while at the same time learning to sustain a high yield despite a gradually shrinking DOF.

In the choice between reducing the wavelength $\lambda$ and increasing the numerical aperture NA, Equations 1 and 2 indicate that reducing $\lambda$ causes less of a decrease in DOF and therefore should be preferable. The microchip fabrication industry has successfully made the transition from a wavelength of 436 nm (the so-called G-line of mercury arc lamps) to 365 nm (the I-line of mercury arc lamps), and is now in the process of making a transition to 248 nm (the krypton-fluoride excimer laser). This article reviews the status of the next expected transition to a wavelength of 193 nm (the argon-fluoride laser), which is currently under active development throughout the world, and in which Lincoln Laboratory has played, and continues to play, a pivotal role. Indeed, the DARPA-funded program at Lincoln Laboratory, started in 1988, has provided the seminal results upon which the present worldwide activities in this field are based.

The shift to a new wavelength of 193 nm in photolithography has centered on the development of three key components: a new light source (the argon-fluoride laser, which has been available commercially since the late 1970s but only as a laboratory tool), a new projection system, and new photoresists. This article concentrates on studies of the properties of optical materials used in projection systems, on new developments in designing and processing photoresists, and on initial studies to fabricate devices and to extend the resolution limits of 193-nm lithography.

## Optical Materials at 193 nm

The shorter wavelength of the argon-fluoride laser causes many unexpected phenomena to occur in the optical materials used in a photolithography system. We must understand the behavior of these optical materials at 193 nm in order to build high-performance lithographic systems suitable for a manufacturing environment.

The near-diffraction-limited projection optics in photolithography can be classified as *all refractive* (using only lenses) or *catadioptric* (a combination of lenses and mirrors). A catadioptric system has an inherent advantage in that it can accommodate a relatively broad bandwidth of the laser. Systems classified as *all reflective* (using only mirrors) are excluded from this discussion. An all-reflective system with high numerical aperture and near-diffraction-limited performance over a large field—properties required of lithographic systems—has not yet been designed.

The argon-fluoride laser emits radiation over a range of wavelengths centered around 193 nm. This range, frequently referred to as *linewidth*, is 250 pm (picometers) in a free-running laser. Although the linewidth is only slightly larger than one-thousandth of the center wavelength, it can have profound implications on the design of the projection optics. The reason for this effect is the dispersion inherent in all optical materials, i.e., the variation of the refractive index $n$ with wavelength. Because of the dispersion, refractive elements (lenses) react to the slightly different wavelengths emitted by the laser in slightly different ways, but enough so that the final image may become too blurred. This phenomenon, known as *chromatic aberration*, is also encountered in ordinary cameras designed for use in visible light.

In the case of near-diffraction-limited projection optics for 193-nm lithography, the dispersion in an all-refractive or catadioptric system imposes limits on the acceptable linewidth of the laser and on the design of the projection optics. Specifically, the best known design of a projection-optics system with a numerical aperture of 0.5, that of SVG Lithography Systems, works with the full 250-pm linewidth of a free-running argon-fluoride laser, or it may require modest line narrowing (to $\delta\lambda \geq 20$ pm) at higher numerical apertures. All-refractive designs, however, necessitate line narrowing to a range of 0.3 to 1.0 pm, which places a significant burden on the performance characteristics of the laser, such as energy per pulse and long-term stability of the center wavelength.

All refractive elements, whether components of all-refractive systems or catadioptric systems, must be prepared from transparent optical materials. Few optical materials, however, are fully transparent at the short wavelength of 193 nm and meet the other requirements of size, uniformity, and mechanical and chemical stability as well. Because of limitations on size, homogeneity, reproducibility of volume manufacturing, and other factors, practical choices for the optical material are synthetic fused silica and single-crystal calcium fluoride. Of these, the synthetic fused silica is widely preferred because of an established infrastructure of supply, polishing, and testing.

The requirement of unvarying refractive index, in addition to limiting the laser linewidth, imposes an important constraint on the optical material itself—it must be nearly fully transparent at 193 nm. In other words, it should absorb no more than a minute fraction of the laser power incident on it. The ability of the material to transmit radiation (and its converse, to absorb it) is commonly expressed in terms of the material's absorption coefficient $\alpha$, which should be zero for fully transparent materials. Quantitatively, a sample of optical material of thickness $L$ transmits a fraction of incident power, neglecting surface losses, which is given by $10^{-\alpha L}$.

While the requirement that $\alpha$ be equal to zero seems like an easily achieved goal, it is far from being so. Even a small absorption coefficient such as 0.01 $cm^{-1}$, combined with typical laser powers of approximately 10 W, can cause a small temperature rise of approximately 0.1 K. However, the refractive index $n$ varies with temperature $T$ as well as with wavelength $\lambda$. In fact, $dn/dT \approx 22$ ppm/K (where ppm is parts per million) at a wavelength of 193 nm for the material of choice, synthetic fused silica [1]. Thus if the refractive index $n$ cannot vary by more than 1 ppm (and often less), then the hypothetical temperature rise of 0.1 K mentioned above would be unacceptable. Indeed, a target value of 0.002 $cm^{-1}$ as the upper limit of the absorption coefficient $\alpha$ has been established by

SEMATECH, the consortium of U.S. semiconductor manufacturers, in consultation with all the major lithographic lens suppliers.

An accurate determination of such small values of the absorption coefficient is critical to the feasibility of 193-nm lithography, and has proven to be quite difficult. By using spectrophotometric and calorimetric methods, we have established that at least two grades of fused silica and two grades of crystalline calcium fluoride meet the above specifications, while other grades of fused silica have absorption coefficients that are too high [2].

Optical materials, even if mostly transparent, may develop laser-induced defects after prolonged irradiation. Calcium fluoride has been observed to develop color centers, which effectively reduce its transmission [3]. Fused silica exhibits a more complex array of laser-induced phenomena [4]. It also forms color centers that reduce the transmission and increase the absorption, and it is densified, or compacted, so that its thickness and refractive index change over time.

Figure 1 shows the spectrum of laser-induced added absorbance to two grades of fused silica, designated here as A and B, which are both irradiated at 1.2 mJ/cm$^2$/pulse for one billion pulses. The sample lengths were 2.5 cm each. Although both grades of silica are similar in composition and level of impurities, this figure shows that their response to laser irradiation is markedly different. Material A has an added absorbance of almost 0.02 at the 193-nm wavelength of interest, while material B shows practically no change in absorption. Clearly, material B would be much more suitable, from the standpoint of a lesser degree of damage, for use in 193-nm lithography. The compaction in fused silica also causes stress-induced birefringence in areas adjacent to the areas compacted by the laser. Furthermore, a recently observed phenomenon is the formation of microchannels that propagate in the fused-silica material along the direction of the laser beam.

The underlying processes that occur on the atomic level, and whose manifestations are the various effects listed above, are far from being fully understood. While such fundamental understanding is clearly desirable, it has become imperative in the near term (the industry time frame is short) to quantify the magni-

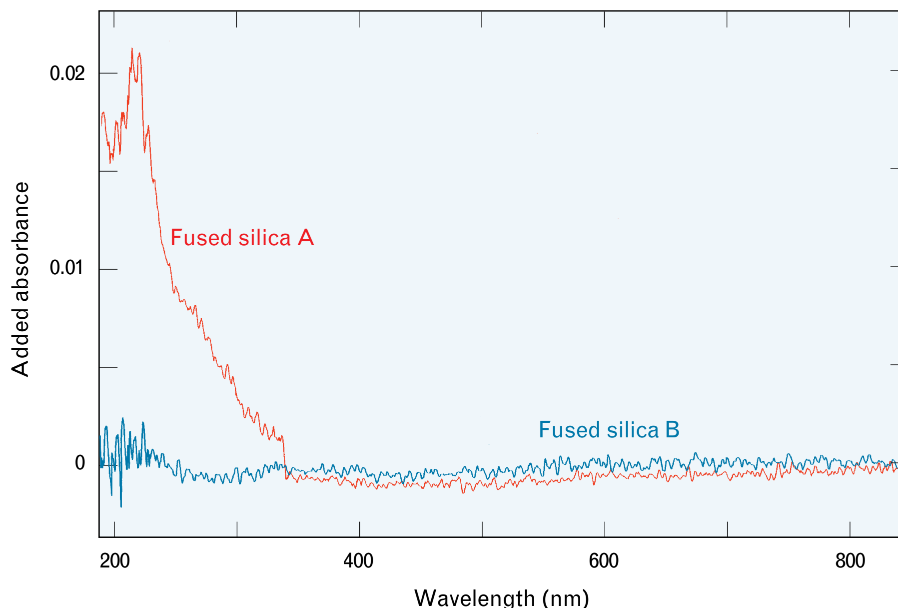


**FIGURE 1.** Added absorption spectra of two grades of fused silica, each 2.5 cm in length, and both irradiated under identical conditions. Although both grades of fused silica are similar in composition and level of impurities, fused silica A has an added absorbance of nearly 0.02 at the 193-nm wavelength of interest. Fused silica B is clearly much more suitable for use in 193-nm lithography because it is less susceptible to laser-induced damage.

**FIGURE 2.** Samples of fused silica being irradiated at 193 nm in the Lincoln Laboratory test and evaluation facility for optical materials. Research at this facility is being done to quantify the magnitude of various laser-induced effects on optical materials, and their scaling with laser intensity, pulse count, and geometry of irradiation. The visible fluorescence seen above indicates that the fused-silica materials in this experiment are not fully transparent at 193 nm.

tude of the various effects and their scaling with laser intensity, pulse count, and geometry of irradiation. We must also understand how universal these phenomena are across suppliers and grades of material.

Lincoln Laboratory, in collaboration with SEMATECH, has established a test and evaluation facility for optical materials at 193 nm. Figure 2 shows part of this facility, with samples of fused silica being irradiated at 193 nm. Optical materials are irradiated under conditions similar to those expected in projection lithography systems (where the fluence is less than 1 $mJ/cm^2$/pulse) for one billion pulses and more, and then tested for transmission and compaction. Our studies with fused silica have shown that color-center formation saturates with exposure dose and can be kept at an acceptably low level. On the other hand,

compaction grows as $(NI^2)^x$, where $N$ is the number of pulses, $I$ is the peak intensity, and $x$ is a parameter in the range from 0.5 to 0.7. The fractional change in volume can exceed tens of ppm if $I$ is not kept low enough, when the number of pulses $N$ is on the order of $10^{11}$ (this value of $N$ is typical of a ten-year operation of a projection lithography system). Such apparently small values of compaction are still much too high. Thus an upper limit on $I$ may exist, which has an impact on the choice of material (e.g., calcium fluoride versus fused silica) and system throughput. Indeed, current designs of projection systems call for some elements to be fabricated with fused silica, while other elements are to be fabricated with calcium fluoride. The choice is made to a large extent on the basis of expected levels of laser-induced damage.

## Projection Systems at 193 nm

Several projection systems have been constructed to operate at 193 nm. Most of these systems are intended to be research tools used in the development of photoresists. They therefore have fields only several millimeters in diameter and are not capable of level-to-level alignment, a key requirement in the fabrication of devices. The one exception is a full-field step-and-scan system built by SVG Lithography Systems in collaboration with Lincoln Laboratory. This system is a prototype microchip manufacturing tool with a large field (32.5 × 22 mm) and an off-axis alignment subsystem. It is currently the first and only 193-nm tool in the world with which devices and circuits can be fabricated. Table 1 lists the experimentally measured performance characteristics of this prototype system.

**Table 1. Experimentally Measured Performance Specifications of the 193-nm Micrascan Prototype System**

| *Property* | *Performance* |
|---|---|
| Resolution | ≤150 nm |
| Depth of focus | >1 μm at 200 nm |
| Dynamic distortion | |
| (maximum vector) | 76 nm |
| (average vector) | 28 nm |
| Field curvature | 0.25 μm |
| Dynamic astigmatism | 0.19 μm |
| Flare | |
| (99% bright field mask) | 9% |
| (50% bright field mask) | 4.50% |
| Overlay (mean + 3σ) | <75 nm |
| Laser-to-wafer transmission | 0.014 |
| Maximum laser power | >10 W |
| Laser polarization | >85% |
| Wafer-plane laser power | ~150 mW |
| Exposure time | |
| (15 mJ/cm$^2$ resist) | <800 ms |

The prototype system at Lincoln Laboratory has been adapted from the commercially available SVG Lithography Systems Micrascan II, which was designed for operation at 250 nm. As with the Micrascan II, the projection optics of the prototype system are catadioptric, and therefore it requires no narrowing of the argon-fluoride laser linewidth. The refractive elements are made of fused silica, whose absorption coefficient at 193 nm was measured to be 0.002 cm$^{-1}$. The numerical aperture is 0.5, which was considered high in the early 1990s when the system was built. Today, numerical apertures greater than 0.6 are found in state-of-the-art steppers (248 nm and I line), and numerical apertures of 0.7 and above will be available in a few years when 193-nm manufacturing systems go into production.

This prototype 193-nm Micrascan system, which has been operational in the Microelectronics Laboratory at Lincoln Laboratory since late 1994, has been instrumental in several projects, including those funded by the Department of Defense and those funded under cooperative research and development agreements with resist companies. The absorption coefficient of fused silica, small as it is, has been demonstrated to have profound effects on the imaging. Lens heating can cause a change in magnification of several parts per million and a shift in best focus of over one micron. These are large values, but future production tools can be designed to compensate for them.

## Photoresists at 193 nm

As we stated earlier, the photoresist can be seen as the "emulsion" in the photolithography process. The device-circuit pattern is "exposed" on the photoresist by the laser and the projection optics. A number of techniques have been developed over the years to create resists at progressively smaller critical dimensions. Practically all photoresists developed for use at longer wavelengths are classified as single-layer resists; i.e., they have uniform composition through their thickness. They are applied by spin coating from solution, followed by baking to remove residual solvents.

The photoresists developed for 248 nm have several characteristics that must be present in 193-nm resists as well. They are chemically amplified; i.e., they employ photoacid generators so that suitable post-exposure baking activates the photogenerated acids and changes the dissolution properties of the resist [5]. Furthermore, positive resists (in which the exposed area is removed in the development step after post-exposure baking) are developed in aqueous bases. The bulk of the resist is typically a polymer or copolymer that contains benzene derivatives, or aromatic rings. These rings endow the polymer with critical resistance to plasma etching in subsequent steps, when the pattern must be transferred to the underlaying layers of silicon oxide, polysilicon, or metal. Unfortunately, the same aromatic rings exhibit such strong absorption at 193 nm that the polymer cannot be exposed to more than approximately 100-nm thickness at this wavelength. In order to utilize resists with thicknesses of 0.5 to 0.7 $\mu$m, we must use other polymers that do not have the highly absorptive conjugated carbon-carbon bonds. Such polymers may be found among the class of polyacrylates (of which polymethylmethacrylate, or PMMA, may be the best known). Indeed, the first single-layer resists, developed in a collaboration between IBM/Almaden Research Center and Lincoln Laboratory, were based on copolymers of polyacrylates [6]. These photoresists were appropriate for evaluating the performance of projection optics and for patterning silicon-oxide layers in fluorine-based plasmas. However, in order for the resist to stand up in the more aggressive chlorine-based plasmas used to etch metal and polysilicon layers, a higher ratio of carbon to hydrogen is required in the resist. Future photoresists are expected to be as resistant to plasma etching as novolac (the main constituent of I-line resists), if not more.

Figure 3 shows the effect of polymer composition and molecular structure on the etch rate in a chlorine-based plasma of polymers that are candidate 193-nm resists. The ring parameter, which is used here as the relevant metric, is defined as the ratio of the mass of carbon atoms that exist in ring structures (both conjugated and alicyclic) to the total mass of the polymer. The figure clearly indicates the overall trend that the higher the ring parameter the lower the etch rate. As the graph in Figure 3 indicates, only polymers with ring parameters in excess of 60% have etch rates that are low enough to be compatible with future device-fabrication needs.

In recent years, several photoresist systems have been developed that have alicyclic groups (cyclic configurations with single carbon-carbon bonds) and are thus more plasma etch resistant and also semitransparent at 193 nm [7]. None of these systems is yet commercially available, since numerous technical problems still need to be resolved, including the photosensitivity of the resist (less than 20 mJ/cm$^2$ is preferred), the intrinsic resolution of the resist (which should be capable of printing 0.10-$\mu$m features), and various processing issues. Nevertheless, we expect that experimental quantities of first-generation 193-nm single-layer resists will become available in the next year.

We have successfully developed a different type of 193-nm resist by using a process that is a variation of so-called top-surface imaging [8]. In this process an absorptive polymer (polyvinylphenol) is crosslinked by 193-nm radiation. Following exposure, the wafer is placed in a vapor of organosilicon compound (dimethylsilyldimethylamine), which diffuses into the unexposed areas, and then the wafer is processed in an oxygen-based plasma etch. The latter step etches the crosslinked unsilylated regions down to the underlying substrate. Careful optimization of the exposure, silylation, and plasma-etching steps is required in top-surface imaging, but the resultant high-resolution wide-latitude patterning proves the value of the process [9].

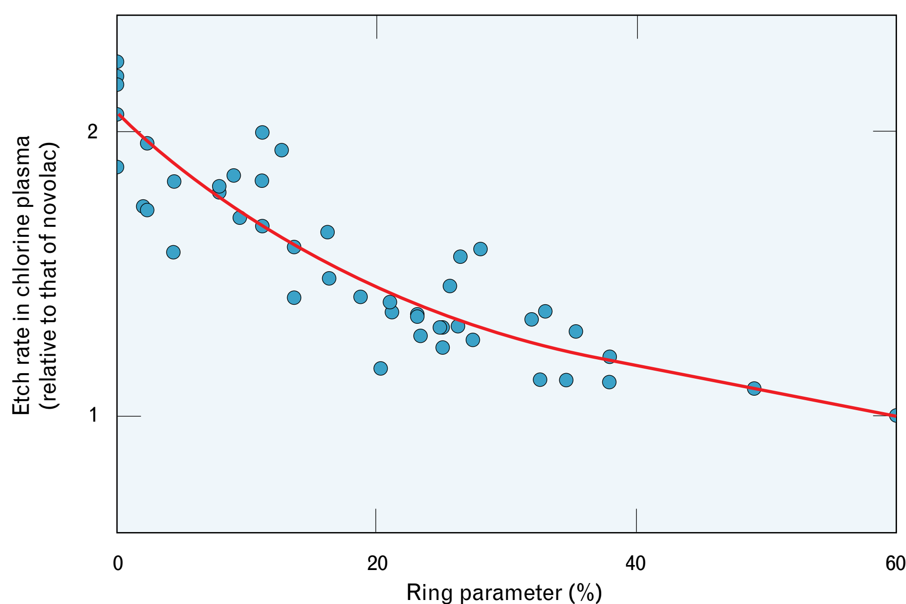


**FIGURE 3.** The etch rate of resists in a chlorine-based plasma as a function of the ring parameter. The ring parameter is the ratio of the mass of carbon atoms that exist in ring structures to the total mass of the resist. The etch rates are compared to that of novolac, which is widely used in I-line resists. Future resists must have etch rates no higher than that of novolac. Therefore, polymers with ring parameters in excess of 60% have etch rates low enough to be compatible with future device-fabrication needs.

Figure 4 demonstrates the results that can be achieved by top-surface imaging. The scanning electron micrographs in the figure show 0.175-$\mu$m lines and spaces printed in a silylation resist over a dose range of 20% and a defocus range of 1.4 $\mu$m. The feature size corresponds to a value of $k_1$ = 0.45 in Equation 1, which is lower than that used in current microchip manufacturing. In spite of this small value, the process latitude of the resist is quite remarkable: 20% exposure dose at best focus and 1.2-$\mu$m DOF at best dose. In particular, the experimentally achieved DOF is twice as large as the minimum DOF requirement described earlier, and therefore provides a wide process margin. Unfortunately, top-surface imaging represents a significant deviation from common resist processing procedures, and therefore it entails certain risks and challenges. Nevertheless, given the uncertainties of single-layer resists described above, it is currently being studied carefully as a potential manufacturing technology.

An unusual variation of the top-surface imaging process described above has also been developed at Lincoln Laboratory. This variation involves the deposition of the polymer on the wafer not by conventional spin coating from solution and baking, but by plasma-enhanced chemical-vapor deposition, or PECVD [10]. The PECVD photoresist deposition, followed by silylation and plasma etching, has been demonstrated, and raises the prospect of all-dry resists. Figure 5 shows the resolution capability of such resists. In this figure we show scanning electron micrographs at two different magnifications of 0.2-$\mu$m features printed in a PECVD resist deposited from the plasma of the vapor of cycloheptatriene mixed with oxygen. This process does not require solvents or other liquids, and thus has the potential advantage of reducing both the environmental impact and the associated cost of handling and disposing of solvents.

## Devices Fabricated with 193-nm Lithography

The first-ever complementary metal-oxide-semiconductor (CMOS) devices fabricated with all-193-nm lithography were recently completed at Lincoln Laboratory [11]. Their successful processing required integration of single-layer resists, top-surface imaging, and organic bilayer resists with ion implantation

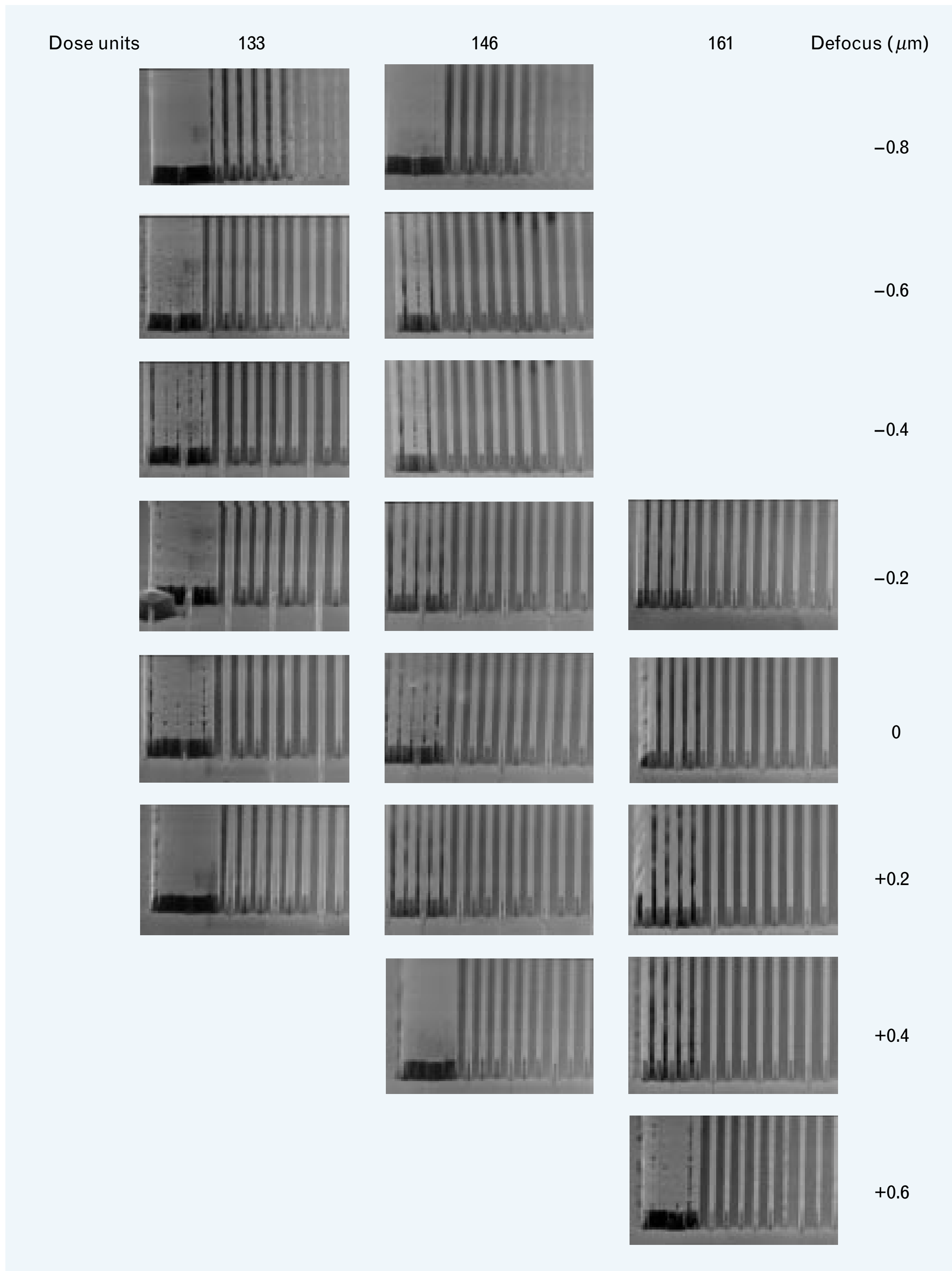


**FIGURE 4.** Exposure-defocus matrix of silylated resist profiles for 0.175-$\mu$m gratings. The left side of each scanning electron micrograph shows 0.15-$\mu$m gratings. Each 193-nm dose unit corresponds to 1 mJ/cm$^2$. This figure demonstrates the process latitude of silylation resists at 193 nm. The 0.175-$\mu$m features are sharply delineated even when the exposure dose is varied by $\pm$10% of the optimal value of 146, and even when the resist surface is moved out of best focus by approximately $\pm$0.5 $\mu$m.

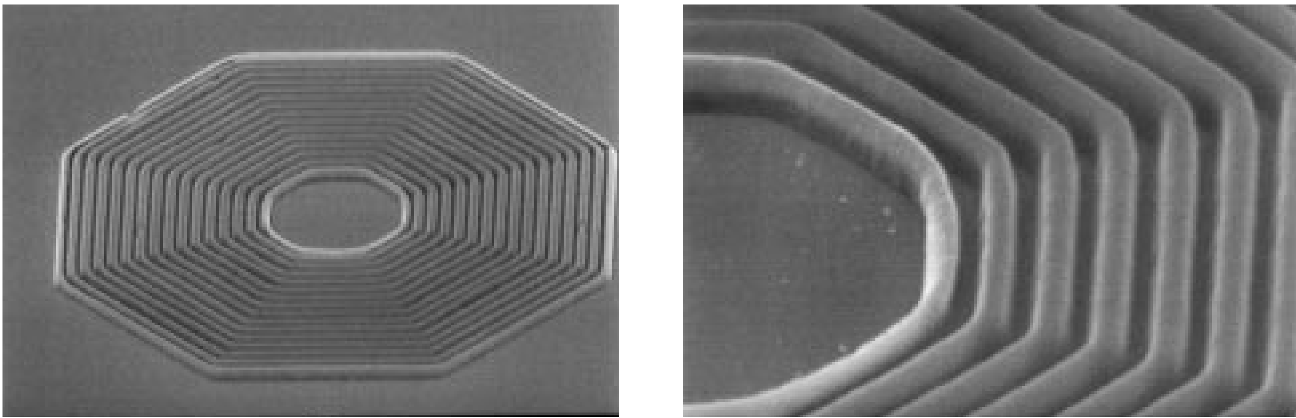

**FIGURE 5.** Scanning electron micrographs of 200-nm features printed with a positive-tone all-dry silylation resist deposited from cycloheptatriene and oxygen. The process of plasma-enhanced chemical-vapor deposition, or PECVD, that was used to deposit this resist on a silicon wafer does not require solvents or other liquids, and thus has potential advantages of reducing the environmental impact and the associated cost of handling and disposing of solvents in microchip manufacturing.

and plasma-etching steps, and the use of the prototype 193-nm Micrascan system described above. These devices were fully scaled metal-oxide-semiconductor field-effect transistors (MOSFET) on silicon-on-insulator (SOI) wafers, with a minimum feature size of 0.2 $\mu$m. Eleven levels of lithography were performed, all at 193 nm. Figure 6 shows two scanning electron micrographs of a section of a ring oscillator composed of transistors manufactured by the 193-nm system. The electrical characteristics of the devices were well within the designed values, which indicated successful processing. For instance, a 49-stage ring oscillator had a 29-psec delay/stage at a supply voltage of 3 V, and a 57-psec delay/stage at 1 V.

## Limits of Resolution with 193 nm

Several optical and computational methods have been under intense development for several years to extend the usefulness of photolithography at longer wavelengths (e.g., 365 nm and 248 nm). In effect, these methods can reduce $k_1$ in Equation 1 while increasing the corresponding $k_2$ in Equation 2. The terms *wavefront engineering* and *resolution enhancing techniques* have often been used to describe these methods. Some of the methods include off-axis illumination, phase-shifting masks, and optical proximity correction. Lincoln Laboratory has begun investigating the applicability of these methods to 193 nm [12]. One

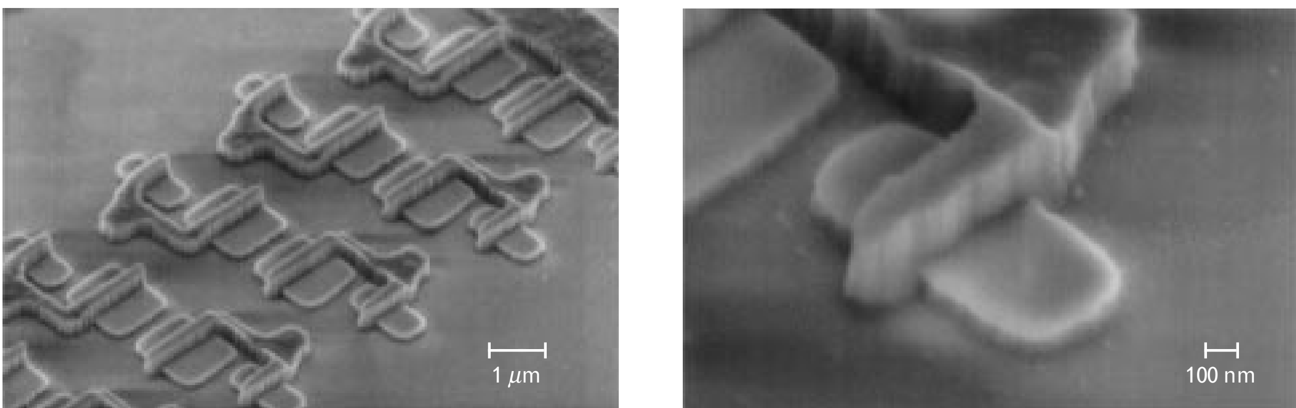


**FIGURE 6.** Scanning electron micrographs of 200-nm polysilicon transistor gates patterned over 50-nm-thick silicon islands, all on a substrate of silicon dioxide on a silicon wafer. The gates were patterned by using the silylation top-surface-imaged resist process. When these devices were fully fabricated, the maximum switching speed measured from a 49-stage ring oscillator was 29 psec when the devices were run at 3 V and 57 psec when they were run at 1 V, indicating successful processing.

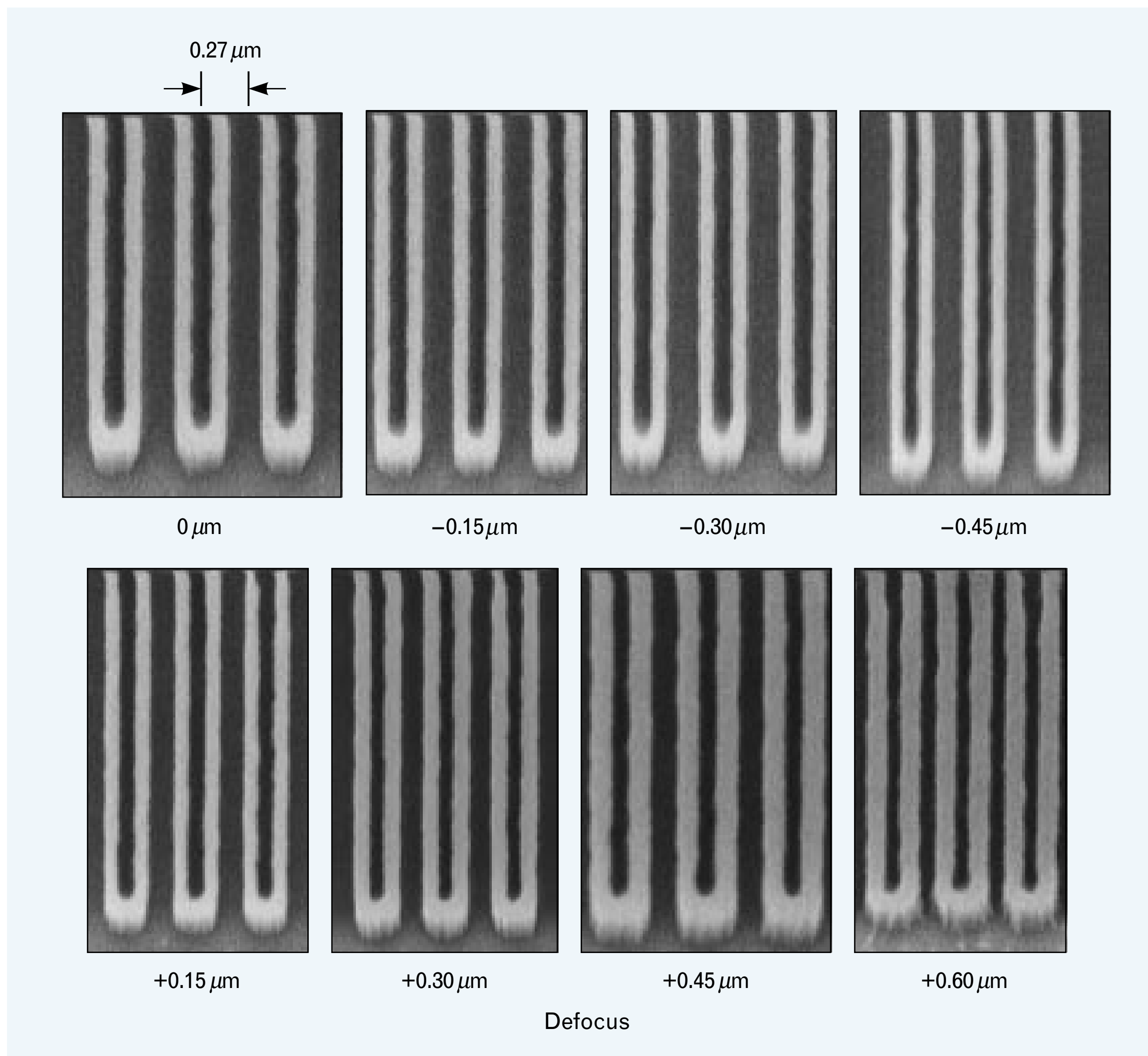


**FIGURE 7.** Scanning electron micrographs of 0.11-μm lines on 0.27-μm pitch. These features were made by using a chromeless phase-shifting mask and a 0.5-numerical-aperture lens. We obtained a depth of focus larger than 1 μm, which is significantly more than the 0.6-μm value the semiconductor manufacturing industry expects for a minimum depth of focus.

example, using top-surface imaging and the prototype 193-nm Micrascan system, is shown in Figure 7. The example involves a chromeless phase-shifting mask instead of the traditional chrome-on-quartz reticle. The chromeless edge shifter enhances the sharpness of the image of edges on the mask by relying on destructive interference, and is capable of resolution approaching the fundamental limit of $k_1$ = 0.25. Figure 7 illustrates the power of this method by showing that 0.11-μm features can be printed in the laboratory with a DOF approaching 1 μm. The magnitude of this value of the DOF is significantly higher than the minimum required. The combination of very high resolution and large DOF strongly indicates that 193-nm lithography may be extendable in a manufacturing environment to at least 0.13 μm and possibly beyond.

## Conclusions

Optical projection lithography has had a remarkable track record in the last two decades. It has always met, sometimes against expectations, the need for higher and higher resolution at a reasonable cost. Its next frontier is 193-nm lithography, which is now in the

midst of a transition from proof of concept to manufacturing technology. There are still many concerns, however, regarding the practical implementation of 193-nm lithography in manufacturing. These concerns include the commercial development and effectiveness of optical materials, optical coatings, projection systems, photoresists, process integration, and extendability to smaller features. Apparently, 193-nm lithography is already too late for the first generation of 0.18-$\mu$m devices. It will probably become the mainstream technology for second-generation 0.18-$\mu$m devices, as well as for 0.15-$\mu$m and 0.13-$\mu$m devices. It will almost certainly require the use of wavefront engineering methods being developed at longer wavelengths, and maybe new optical and processing techniques, which could push it down to 0.10 $\mu$m or even less.

**Acknowledgments**

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**MORDECHAI ROTHSCHILD**
is the leader of the Submicrometer Technology group. His research speciality is in laser processing and lithography. He received a B.S. degree in physics from Bar-Ilan University and a Ph.D. in optics from the University of Rochester. Following research at the University of Illinois and the University of Southern California in the areas of laser photochemistry and laser-induced nonlinear processes, he joined Lincoln Laboratory in 1984. His responsibilities include managing projects in advanced lithography, binary optics, and several other microfabrication activities.

**MARK W. HORN**
is a staff member in the Submicrometer Technology group. He received a B.S. degree in 1982, an M.S. degree in 1985, and a Ph.D. degree in 1989, all in engineering science and mechanics at the Pennsylvania State University. He has been at Lincoln Laboratory since 1988, and he is currently working on optical materials, photoresist processes, and near-field optical lithography using 193-nm and 157-nm photons.

**CRAIG L. KEAST**
is the leader of the Advanced Silicon Technology group. He received a B.A. degree from Hamilton College, in Clinton, New York, and S.M., E.E., and Ph.D. degrees in electrical engineering and computer science from MIT. His doctoral research included the development of a CCD/CMOS process technology, and the design and fabrication of a parallel analog focal-plane processor for real-time early-vision signal processing using this technology. From 1981 to 1988 he was employed at Lincoln Laboratory, where he worked on semiconductor processing and technology development for the Digital Wafer-Scale Electronics group. After completing his Ph.D. degree, he returned to Lincoln Laboratory, where he first worked with the Submicrometer Technology group on deeply scaled device development using advanced optical lithography techniques. In addition to his duties in the Silicon Technology group, he is currently the director of operations for the Microelectronics Laboratory. His present research activities center on sub-0.25-$\mu$m, low-power CMOS process development on both bulk silicon and silicon-on-insulator wafers.

**RODERICK R. KUNZ**
is a senior staff member in the Submicrometer Technology group. His focus of research is in many areas of advanced photolithography, including photoresist development and formulation, exposure-tool evaluation, application of resolution enhancements to lithographic exposure tools, laser-surface reactions limiting lens durability, and pellicle testing. He received a B.S. degree in chemistry from Rensselaer Polytechnic Institute and a Ph.D. degree in chemistry from the University of North Carolina, Chapel Hill. He has been at Lincoln Laboratory since 1988.

**VLADIMIR LIBERMAN**
is a staff member in the Submicrometer Technology group. He received a B. S. degree in physics from Princeton University in 1986 and a Ph.D. degree in applied physics from Columbia University in 1991. From 1991 to 1993 he was a postdoctoral fellow at the University of California, Santa Barbara Center for Quantized Electronic Structures. From 1994 to 1996 he was employed at Lawrence Livermore National Laboratory, where he was involved in characterization of vapor-deposited polyamides and their implementation into advanced packaging processes. Currently he is working on optical material characterization for 193-nm lithographic applications.

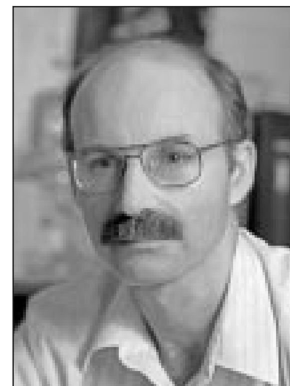
**SUSAN C. PALMATEER**
is a staff member in the Submicrometer Technology group. She received a B.S. degree in chemistry from Monmouth University, and M.S. and Ph.D. degrees in electrical engineering and electrophysics, respectively, from Cornell University. Prior to joining Lincoln Laboratory she worked at the Electronics Laboratory of General Electric Corporation, where she was responsible for the development of high-purity molecular-beam epitaxial GaAs and AlGaAs for microwave device applications. She joined Lincoln Laboratory in 1985 and worked on the development of organometallic chemical vapor deposition and gas-source molecular-beam epitaxy for the growth of group III-arsenides and phosphides for optoelectronic applications. In 1993 she joined the Submicrometer Technology group, where she is developing resist processes for 193-nm lithography.

**SCOTT P. DORAN**
is an assistant staff member in the Submicrometer Technology group. His primary area of research is in 193-nm semiconductor lithography. He received an S.B. degree from MIT and an M.S. degree from Northeastern University, both in electrical engineering. He has been at Lincoln Laboratory since 1985.

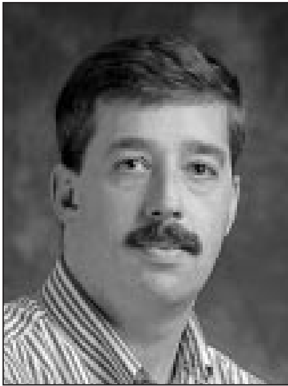
**ANTHONY R. FORTE**
is an assistant staff member in the Submicrometer Technology group. He received an A.E. (Associate of Engineering) degree in computer engineering from the Franklin Institute in Boston. He began working at Lincoln Laboratory in 1980 with the Microelectronics group, concentrating primarily on the development of dry-etched processes for metals. He also worked on the development of noncrystallographic dry-etch processes for GaAs, as well as high-aspect-ratio dry etching of silicon for permeable base transistors. He joined his current group in 1988 and developed plasma-deposited electrochromic thin films for use in 193-nm lithography. Currently, he is developing silylation processes for top-surface imaging and the corresponding dry-etch processes for pattern transfer in 193-nm lithography.

**RUSSELL B. GOODMAN**
is an assistant staff member in the Submicrometer Technology group. His primary research interests are in advanced deep-ultraviolet lithography. He received a B.S. degree in premedical studies and a B.A. degree in classical languages from the University of Massachusetts at Amherst, where he was a member of Phi Beta Kappa and Phi Kappa Phi. Before coming to Lincoln Laboratory in 1983, he was a middle-school science teacher for five years.

**JAN H.C. SEDLACEK**
is an assistant staff member in the Submicrometer Technology group. He received a B.A. degree in physics from Reed College in 1976. After joining Lincoln Laboratory in 1982, he worked on laser photochemistry for laser direct-write processing. Since 1989 he has been involved in studies of optical materials for 193-nm lithography. He is a member of AAAS and SPIE.



**RAYMOND S. UTTARO**
is an assistant staff member in the Submicrometer Technology group. He received a B.S.E.E. degree in control systems and communications from the University of Massachusetts at Amherst. He has been at Lincoln Laboratory since 1981. The current emphasis of his research is in the study of optical materials for lithography.



**DAN CORLISS**
is a member of the technical staff at Digital Semiconductor (a Digital Equipment Corporation business) in Hudson, Mass. He was a Digital Semiconductor assignee to SEMATECH as the program manager for 193-nm optical systems development at Lincoln Laboratory from August 1994 through March 1997. He received the SEMATECH Corporate Excellence Award for establishing and managing this program. Dan joined Digital Semiconductor after receiving a B.S. degree in chemical engineering from the University of Massachusetts at Lowell in 1985. He spent a year with the Manufacturing Engineering group at Digital Semiconductor, then moved to the Advanced Semiconductor Development group, where he has been a strategic player in generations (G-line, I-line, 248 nm, 193 nm, and X ray) of lithographic research and development. He is currently responsible for the exploration of novel process enhancements to extend 248-nm lithography, leadership of the 193-nm lithography development program, and the evaluation and integration of strategic forward-looking technologies in photolithography.

**ANDREW GRENVILLE**
is a staff member at Intel Corporation in Santa Clara, California, where his research speciality is 193-nm photolithography. He is currently on research assignment at Lincoln Laboratory under the SEMATECH-sponsored Cooperative Research and Development Agreement on the study of optical materials. He received a B.S. degree in engineering physics from Queen's University in Kingston, Ontario, and a Ph.D. degree in applied physics from Stanford University. His graduate research was on short-wavelength limits of optical lithography.