

Review of technology for 157-nm lithography

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This paper outlines the critical issues facing the implementation of 157-nm lithography as a sub-100-nm technology. The status of the present technology for mask materials, pellicles, optical materials, coatings, and resists is presented.

Introduction

Lithography with 157-nm fluorine lasers is rapidly emerging as a viable technology for the post-193-nm era [1–3]. In fact, it may become the technology of choice for 100- to 70-nm nodes. It is attractive for several reasons, the most important being that it is fundamentally an extension of optical lithography at the longer wavelengths of 248 and 193 nm. Therefore, it holds the promise that the tool-manufacturing and wafer-processing infrastructures can be adapted to it relatively easily, and that optical-resolution-enhancing techniques (phase-shifting masks, off-axis illumination, etc.) can be applied to it as well. Nevertheless, the transition to the 157-nm wavelength is by no means straightforward. It is expected to encounter difficulties comparable to those of earlier shifts in lithographic wavelength, from I-line to 248 nm, and from 248 nm to 193 nm. This paper summarizes the status of some of the critical issues facing 157-nm lithography. These include the availability of suitable optical materials and coatings, mask materials and pellicles, ambient control to minimize contamination of optical surfaces, as well as

high-performance resists optimized for 157-nm applications.

Wafer exposure systems for 157-nm lithography

The development of this new technology relies on the simultaneous development of exposure systems and photoresists, because each will assist in the evaluation and improvement of the other. No full-field 157-nm exposure systems exist today. The simplest small-field microsteppers rely on all-reflective Schwarzschild imaging systems. The first such microstepper, built at MIT Lincoln Laboratory in 1997, has been used since then for patterning and resist screening. It has a numerical aperture of 0.5 and a field size of ~ 0.1 mm. The smallest features patterned with it are 80-nm lines, which were obtained with a chromeless phase-shifting mask [1]. More recently, several microsteppers have been built with 0.6 numerical aperture and field size of ~ 2 mm. Their optics are catadioptric, including a partial reflector, a full reflector, and refractive elements [4]. The next generation of small- and mid-field projection systems will have even higher numerical apertures (0.75) and larger field size. They are expected to be operational in 2001. The first generation of full-field exposure systems is expected by 2003.

The engineering of such systems depends on the availability of several critical components, which are discussed below. These are lasers with appropriate pulse repetition rate, bandwidth, and power; transparent, damage-resistant optical materials for optics and photomasks; low-absorption, damage-resistant optical

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Table 1 Laser linewidth guidelines for projection lens systems.

Projection lens type	Optical materials	Laser linewidth (pm)
Catadioptric	CaF ₂	<1
All-refractive (CaF ₂ + second material)	CaF ₂ + BaF ₂	<0.5
All-refractive (CaF ₂ only)	CaF ₂	<0.2

Table 2 Performance parameters and target values for lens optical materials in projection optics for a ten-year lifetime.

Parameter	Target value	Conditions
Total absorption (1/cm, base 10)	<0.002	1 × 10 ¹¹ pulses at 0.5 mJ/cm ² /pulse
Index homogeneity (ppm)	<0.5	Over lens clear aperture
Stress birefringence (nm/cm)	<1.0	Over lens clear aperture
Dispersion difference (no units)	>30%	For second refractive material

coatings; the maintenance of a contamination-free ambient; and photoresists.

Lasers

Three lithography laser suppliers offer 157-nm excimer lasers with output powers greater than 10 watts. These fluorine gas lasers can emit output energy in as many as six different closely spaced wavelengths, with the majority of the energy emitted at 157.63 nm. Line selection of a single output wavelength has been demonstrated; however, the natural linewidth [~ 1 picometer (pm)] is not adequate for an all-refractive projection lens design (see the next section). **Table 1** lists laser linewidth guidelines for different types of projection lens designs that may be used in wafer exposure systems. Two-stage laser systems employing separate oscillator and amplifier chambers providing laser linewidths approaching 0.2 pm have been demonstrated in Reference [5]. The oscillator employs prisms and a grating for bandwidth reduction, and its low-energy output is injected into the amplifier. Extensive evaluation is still required in order to ensure the stability of the bandwidth and the stability of the center frequency. Nevertheless, these initial reports are encouraging.

Lens optical materials

In this section we discuss all relevant optical materials that we have investigated for use in illuminator and projection optics. Because of the development work for 193-nm lithography, lens-quality CaF₂ is available and is the primary optical material choice for 157-nm projection optics applications. We have also investigated the optical properties of candidate second refractive materials: barium fluoride (BaF₂), strontium fluoride (SrF₂), and lithium fluoride (LiF). These materials could be used in an all-refractive projection lens system in combination

with CaF₂ to accommodate a larger 157-nm laser linewidth. An all-refractive solution has the advantage that it utilizes the infrastructure already in place for the exposure tool suppliers who have historically provided all-refractive 193-nm and 248-nm lithography exposure systems. A second refractive material may also be useful in catadioptric designs to reduce the design constraints imposed by a single refractive material. Proposed designs for catadioptric exposure systems use an off-axis optical system, a central obscuration optical system, or a polarizing beamsplitter cube configuration. **Table 2** lists the target values, under the specified conditions, for lens optical materials to be used in projection optics. The absorption, index homogeneity, and stress birefringence target values at 157 nm are the same as for optical materials at 193 nm.

Measurements of the dispersion of the index of refraction of CaF₂ at 157 nm and the proposed second refractive materials BaF₂, SrF₂, and LiF were recently completed by NIST [6]. Only BaF₂ has adequate dispersion (approximately 70% difference from CaF₂) to be used in combination with CaF₂ to accommodate projection lens system designs with laser linewidths of ~ 0.5 pm. BaF₂ must also meet the other performance requirements listed in Table 2 for it to be useful in projection lens systems.

The absorption of CaF₂ and BaF₂ prepared by various suppliers has been determined experimentally. The values were obtained from *in situ* transmission measurements after samples of varying lengths were irradiated for 250 million pulses at a fluence of 2–4 mJ/cm²/pulse. In CaF₂ large grade-dependent variations were observed, the absorption coefficient ranging from 0.001 to 0.005 cm⁻¹. Nevertheless, a majority of the CaF₂ samples met or came close to meeting the target value for absorption.

The BaF₂ samples exhibit much larger bulk and surface losses. The relatively large bulk losses (0.008 to 0.07 cm⁻¹) may be the result of impurities in the raw materials used to grow the BaF₂ crystals. One supplier obtained higher-purity raw materials, and the result was a dramatic reduction in bulk absorption from 0.072 to 0.008 cm⁻¹. This improvement demonstrates that it may be possible to improve the absorption performance for BaF₂ crystals. Surface losses are also much larger in the BaF₂ samples than in the CaF₂ samples (1–5% vs. 0.2–1.5%, respectively). We believe that this is a result of the inferior quality of the polishing process used for the BaF₂ samples, but it is expected to improve as more experience with handling this material is gained.

Coatings for 157-nm lithography

Dielectric coatings applied to lithographic elements fall into three main categories: 1) antireflectance designs for throughput enhancement and ghost image suppression; 2) high reflectors for beam-steering purposes; and 3) partial reflectors/beamsplitters employed primarily in catadioptric designs. The coating stacks consist of alternating layers of materials having a high and low index of refraction compared to the substrate index. The layers must be transparent enough at 157 nm to enable an efficient design and to ensure good damage resistance. The choice of coating materials is primarily limited to fluorides, because most oxide compounds (such as the silicon dioxide and hafnium oxide used at longer wavelengths) are too absorptive at 157 nm. For instance, low-index materials may include magnesium and aluminum fluorides, while high-index materials may include lanthanum and gadolinium fluorides. In general, oxides are expected to be more robust and resistant to laser damage than fluorides. On the other hand, magnesium fluoride is a commonly used low-index material at longer wavelengths as well, and the technology for its deposition is well established. The coating material requirements at 157 nm are more stringent, mainly because of the potential for residual absorption at this short wavelength. Furthermore, the effect of the adsorption of water and other contaminants is more pronounced at 157 nm than at longer wavelengths [7].

Antireflectance coatings

The transmission of antireflectance (AR) coatings depends on the prescribed bandwidth (or the range of incident angles) for a given design. The International SEMATECH performance targets refer exclusively to AR coatings designed for near-normal-incidence, narrow-bandwidth operation. For such a coating, the targets specify an initial transmission of 99% and a final transmission of 98.8% after 100×10^9 pulses at a fluence of 0.5 mJ/cm²/pulse. Lifetime laser durability results for three coatings from

two suppliers show marked variations. One sample had a lower transmission (~96.5%), but when irradiated at an average fluence of 2–3 mJ/cm²/pulse, showed no significant degradation for pulse counts over 500×10^6 . In contrast, the other two samples initially reached a relatively high transmission of 97.5%, but they degraded to 96% after 250×10^6 pulses for an incident fluence of 2–3 mJ/cm²/pulse or after 100×10^6 pulses for fluences about two times higher. The damage responsible for the transmission drop appears to be nearly linear with incident fluence. Additionally, the damage rate appears to increase with the number of pulses for a fixed fluence, suggesting that more than one mechanism may be responsible for the transmission drop.

We note that the maximum transmission, reached after an initial cleaning (96.5% and 97.5%), does not meet the initial transmission targets of International SEMATECH (99%). We note that the coatings are experimental and do not represent the technologically achievable best results from either supplier. Improvement is expected in both overall transmission and durability as the deposition processes are further optimized. In comparison, 193-nm AR coatings were shown to have transmission exceeding 99% and to withstand 1×10^9 pulses of 15 mJ/cm²/pulse without noticeable degradation [8].

High-reflectivity coatings

Designs of high-reflectivity coatings for 157-nm applications can be divided into two broad classes:

1. Dielectric stacks comprising alternating high- and low-index fluoride layers, similar to those developed for antireflectance applications. These designs are expected to have the highest 157-nm reflectance and the best durability. However, their bandwidth per angle of incidence is limited to a relatively narrow range. The International SEMATECH target is >95% initial reflectance for a normal-incidence design and 94% reflectance after a lifetime dose of 100×10^9 pulses at 0.5 mJ/cm²/pulse.
2. Broadband metal reflectors comprising a reflecting metal layer such as aluminum, possibly with a protecting dielectric overcoat, such as a magnesium fluoride thin film. These reflectors are expected to be wavelength-insensitive; however, their maximum reflectance and laser durability are expected to be inferior to those of dielectric stack-based reflectors.

Data on dielectric high-reflectivity coatings from three different manufacturers have been obtained to date. These coatings were used as beam-turning mirrors to direct the 157-nm laser into one of our sample exposure chambers. For a typical incident fluence of 10–15 mJ/cm²/pulse, the dielectric high reflectors from two suppliers displayed a

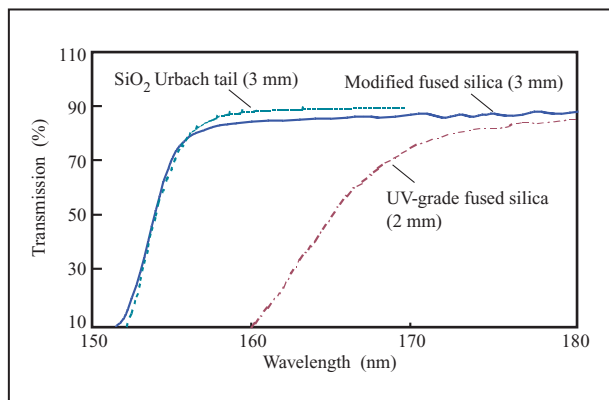


Figure 1

Transmission of modified fused silica and UV-grade fused silica in the VUV range. The theoretical Urbach tail fit is also shown (see text for details).

Table 3 Summary of 157-nm durability tests for modified fused-silica material for reticle applications. Incident fluence is 0.1–0.2 mJ/cm²/pulse. Degradation has been observed at pulse counts larger than those listed.

ID	6-mm transmission (%)	Pulse counts without degradation (millions of pulses)
1	85	>300
2	80.5	80
3	73.5	60

degradation of more than 20% in 45-degree reflectivity for pulse counts under 100×10^6 . Coatings obtained subsequently from a third supplier showed a significant improvement in durability. After 700×10^6 pulses, no degradation in mirror performance has been observed.

For broadband metal reflectors, samples from two suppliers were tested at near-normal incidence and a fluence of 2 mJ/cm²/pulse. After 120×10^6 pulses, the reflectance of both samples dropped by more than 30%. Further tests on metal reflecting mirrors must be conducted, and improvement in performance is expected as fabrication techniques mature.

Reticles

Reticle materials present a different set of challenges. Transmission and lifetime requirements are not as stringent as for a lens material because of limited mask utilization. Materials used for mask blanks, absorbers, phase shifters, and pellicles must be prepared with dimensions of 6 × 6 inches and with excellent transmission uniformity over the full area. Reticles must

undergo a sequence of dry and wet processing steps involved in depositing and patterning absorber layers.

Photomask blank materials

All of the potential lens materials could also satisfy optical transparency and durability requirements for reticle materials; however, the fluoride crystals (CaF₂, BaF₂, etc.) have thermal expansion coefficients 40–80 times higher than that of fused silica. The high thermal expansion coefficient can cause pattern distortion during e-beam mask writing and image distortion during wafer exposure through the mask. In fact, studies have shown an order of magnitude larger distortion of CaF₂ during e-beam patterning compared to fused silica [9].

While conventional fused silica is not transmissive enough at 157 nm, progress has been made to substantially improve the transmission of fused silica in the 155–175-nm-wavelength region. These transmission improvements have been obtained by preparing fused silica with low OH content and by incorporating fluorine into the glass network. These modifications have the effect of moving the absorption edge to shorter wavelengths by eliminating electronic states at the top of the valence band [10]. In **Figure 1** we show the transmission of conventional UV-grade fused silica and modified fused silica. The transmission of modified fused silica is about 82% at 157 nm, as measured in a vacuum-UV spectrophotometer. We may compare this value to the theoretical maximum of 88%, obtained by allowing for only the Fresnel reflection losses. The actual transmission of this material under laser irradiation can be several percent higher than that in the spectrophotometer because of laser cleaning of surface adsorbates. In **Figure 1** we also show a solid line fit to the UV absorption band edge of modified fused silica, modeled by the Urbach rule, as

$$\alpha = \alpha_0 \exp[(E - E_0)\sigma(T)/kT]. \quad (1)$$

In Equation (1), α_0 is the pre-exponential coefficient, σ is a temperature-dependent parameter related to the strength of exciton–phonon coupling, E_0 is approximately equal to the peak in the exciton absorption band, and k is the Boltzmann constant. We obtain a reasonable fit of the modified fused silica absorption cutoff to Equation (1) using values of α_0 and $\sigma(300 \text{ K})$ from an earlier work [11] on vitreous SiO₂ and adjusting E_0 to 8.85 eV as compared to the value of $8.7 \pm 0.05 \text{ eV}$ [11]. Note that the model reproduces the sharp transmission cutoff of the modified fused silica quite well compared to a longer OH-induced absorption tail of the conventional fused silica.

In **Table 3** we summarize test results for three different grades of fused silica that were exposed to fluences of 0.1–0.2 mJ/cm²/pulse. We observe that at least one grade of modified fused silica meets the target requirements of International SEMATECH for mask materials. For the

best grade of fused silica, we can derive a bulk attenuation coefficient of 0.02/cm, base 10, and a loss per each surface of 0.002, base 10. We do observe considerable variations in performance for different grades of fused silica. However, progress is being made by the suppliers, and we expect that improvements in other grades will soon be achieved. All of the samples evaluated to date were relatively small, about 1 in. in diameter. Transmission uniformity and durability of reticles over the full 6-in. $\times$ 6-in. area will have to be evaluated in the future.

Pellicles

To prevent particulate contamination of photomasks, it has been customary to employ thin organic membranes ("pellicles") that are placed a few millimeters away from the mask in a sealed package. These pellicles must satisfy a number of critical requirements, primarily transmission at the actinic wavelength and damage resistance to laser irradiation. The pellicle must be thin, usually less than 1 μm , so that its transmission is determined by thin-film interference effects and is maximized at the actinic wavelength. The pellicle materials that have been designed for use at 248 and 193 nm are fluorocarbon polymers, but their 157-nm properties are not satisfactory: They are not transparent enough and are easily damaged by the laser [3]. Therefore, there are three strategies to pursue at 157 nm, and at present all three are being considered: First, new polymers may be engineered that are transparent and damage-resistant at 157 nm and possess mechanical properties to enable their preparation in very thin pellicle form. Such polymers almost certainly will have to be based on fluorocarbons, but they may differ in particulars from 193- or 248-nm materials. To date, no fluorocarbon-based candidate materials possess all of the desired properties. Some are highly transmissive at 157 nm but are not conveniently formed into membranes. Others, of which membranes can be made, absorb more than 1% of 157-nm radiation in 1- μm thickness and subsequently become even more absorptive within 2–5 J/cm² total dose (at $\sim$ 0.1 mJ/cm²/pulse). The details of this process of photochemical "darkening" are not yet fully understood. The rate of darkening may be related to the initial absorption of the membrane material. At 193 nm, by comparison, the absorption of pellicles is significantly lower; also, the rate of photoinduced degradation is typically a thousandfold smaller [12]. For these reasons, organic pellicles for 157 nm are at present the subject of intensive efforts both at the fundamental photochemistry level and at the engineering and implementation levels.

The second strategy is to design inorganic "pellicles" made of materials that have proven themselves at 157 nm. In particular, the mask substrate (modified, fluorinated fused silica) may be appropriate. However, there are significant impediments, because it cannot be prepared in

submicron thicknesses, as organic pellicles are. Fused silica will have to be polished as thin as possible while retaining rigidity and uniform thickness. The optimal thickness is $\sim$ 1 mm, and this requires the pellicle to be considered (and manufactured) as part of the optical system. Tolerances, alignment procedures, and the need for antireflective coatings may make this a daunting option.

The third approach is to dispense with the need for any pellicle, and instead focus attention on processing and handling conditions of the mask that all but eliminate particulate contamination. Since at present there is considerable uncertainty as to the probability of success of the three options, they must therefore all be pursued concurrently.

Photomask patterning materials

Traditionally, the absorber material in photomasks has been based on chromium thin films, possibly in combination with chromium oxide or nitride to reduce back reflections. Such a stack would be $\sim$ 80 nm thick. The absorption at 157 nm of chromium, its oxide, and its nitride depends strongly on the thin-film deposition conditions. At MIT Lincoln Laboratory it has been determined experimentally that the 157-nm transmission of chromium oxide and nitride thin films, $\sim$ 80 nm thick, is sufficiently low, less than 0.1%. Furthermore, the transmission is unchanged, within experimental uncertainty, by prolonged 157-nm laser irradiation. Thus, absorbers used in 193-nm lithography appear to be suitable at 157 nm as well. A more uncertain area is that of attenuating phase-shifting mask materials at 157 nm. These may have to be engineered specifically for 157 nm, and at present little information is available on their performance and availability.

Contamination and cleaning of optical elements

Lithography at 157 nm is an extension of photolithography at longer wavelengths; however, operation at 157 nm is significantly more sensitive to contaminants on optical surfaces. Most common airborne contaminants absorb strongly at 157 nm. We have observed surface losses of up to 4% for CaF₂ samples and coated optics exposed to ambient conditions for several hours [13]. Upon irradiation, the 157-nm laser is also an efficient initiator for laser-induced deposition of "graphitic"-type films from organic contaminants in the gas phase, further degrading transmission. Given the large number of optical surfaces in high-performance projection optics (i.e., >30) and strong absorptivity of hydrocarbon-based contaminants, we estimate that even several monolayers of laser-induced deposited film over each element will in effect render the projection optics useless. We note that qualitatively similar

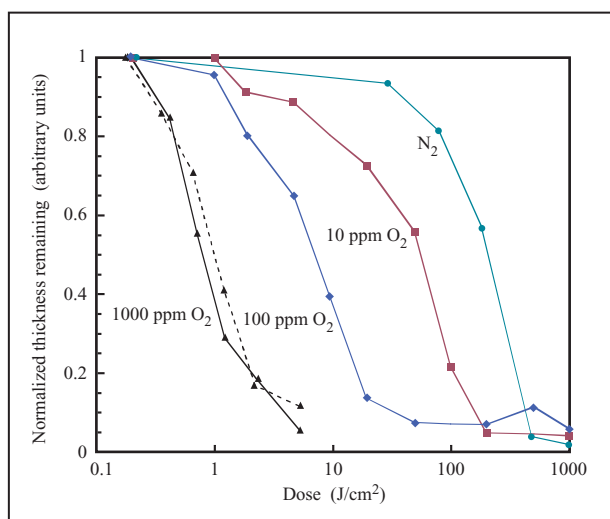


Figure 2

Normalized thickness remaining of graphitized poly(norbornene) film irradiated at 157 nm in different concentrations of oxygen. Thickness values were estimated from the absorption of “graphitized” films at 157 nm (absorption coefficient approximately $8 \mu\text{m}^{-1}$). The laser fluence was $5 \text{ mJ/cm}^2/\text{pulse}$ for the traces shown with solid curves. For the case in which 1000 ppm of oxygen was introduced into the purge gas, the cleaning experiment was also repeated at a laser fluence of $0.5 \text{ mJ/cm}^2/\text{pulse}$ (dashed curve).

effects have been observed at longer wavelengths, especially at 193 nm. However, their magnitude is significantly larger at 157 nm, both because many molecules are more absorptive at 157 nm and because the photochemical reaction quantum yields are more efficient at this wavelength. These phenomena pose two primary challenges for the successful implementation of 157-nm technology. First, the contamination of optics from laser-induced deposition must be prevented. Strict levels of purge-gas purity and careful selection of assembly materials with minimal outgassing will be required. These are self-evident steps that have been—or should be—implemented even at 193 nm, although at 157 nm they have to be much stricter. In addition, some form of *in-situ*-based cleaning must be developed, both after assembly and alignment of the projection system and in the event that contamination does occur during operation of the system. To address these issues, two studies have been implemented at MIT Lincoln Laboratory. In the first, an experimental apparatus was developed to study laser deposition rates of gas-phase impurities to determine acceptable levels. Secondly, an *in situ* technique for cleaning contaminated optics has been investigated using the 157-nm laser source in combination with trace levels of oxygen in the purge gas.

Laser-induced contamination rates are being compiled for a range of impurity levels of a number of organic volatile species in order to study the effect of contaminant chemistry on deposition rate. The resulting contamination rate is determined by the laser-induced deposition rate minus the laser-induced removal or cleaning rate. A number of mechanisms may compete with the deposition of films from gas-phase impurities. Trace levels of oxidizing species such as oxygen or water in the purge gas, as well as a direct ablative component, may contribute to a non-negligible cleaning rate component. As an example, no contamination was observed when toluene was added to the purge stream at levels of 50, 100, and 200 ppb for total doses of at least 10 kJ/cm^2 (100 million pulses at approximately $0.1 \text{ mJ/cm}^2/\text{pulse}$). At 400 ppb contamination was evident, resulting in an approximate contamination rate of $0.25\%/ \text{kJ/cm}^2$.

In the event that contamination does occur at any point during the operation of the equipment, laser-based cleaning of hydrocarbon-based contaminants is being studied. In a previous report [14] we found that regardless of the initial chemical nature of a thin contaminating hydrocarbon-based film, upon irradiation the material also undergoes significant bond rearrangement, forming a more tightly bound highly conjugated network with similar properties. In investigating *in situ* cleaning using the 157-nm laser source, we have therefore studied films in their “graphitized” state, because this reflects the worst case for removal and more likely closely reflects contaminant residues that might be formed on optical components. In addition, we have investigated the use of trace levels of oxygen to enhance the removal rates. It is well established that the removal rates of hydrocarbon-based polymers are significantly enhanced in the presence of oxygen under ultraviolet radiation [15]. Ultraviolet-induced carbon radicals formed in the polymer films react readily with oxygen, forming volatile products such as CO , CO_2 , H_2O , and CHO derivatives [16]. The generation of atomic oxygen, which forms at unit efficiency for irradiation at wavelengths below 185 nm, and ozone significantly enhances the process. The primary constraint with respect to adding oxygen is the strong absorption at 157 nm of approximately $1\%/ \text{meter/ppm}$ [17]. This restricts practical levels of oxygen to the range of 10–1000 ppm. **Figure 2** shows the estimated remaining film thickness as the exposure dose is varied for a graphitized thin polymer film irradiated at 157 nm for three different concentrations of oxygen and the baseline case in “pure” nitrogen. Also shown are the results of irradiating the samples at two different laser fluences. Over the measured range from 10 ppm to 1000 ppm, a linear dependence in removal rate with oxygen concentration is observed, indicating that the process is reaction-rate-limited over the region investigated. The total removal rate is approximately

3 nm/(kJ/cm²)/ppm oxygen or, equivalently, approximately 5%/(kJ/cm²)/ppm oxygen for a graphitized film. Furthermore, up to at least 5 mJ/cm²/pulse, no significant nonlinear processes have been observed in the removal process. The results indicate that significant enhancements in cleaning rate can be achieved by injecting low levels of oxygen into the purge gas. This may be performed according to a predetermined protocol when transmission values fall below a specific threshold. In addition, trace levels may be purposely introduced on a continuous basis to increase threshold values for contamination.

Continued work is in progress for studying contamination and cleaning rates in different levels of hydrocarbon impurities and oxygen, particularly on coated optics, where the more porous nature of the thin films may affect the results. The initial findings on CaF₂ substrates are, however, very promising. Although the propensity for contamination is significantly greater at 157 nm, the corresponding cleaning mechanism using trace levels of oxygen is also more efficient, indicating that contamination levels can be appropriately managed.

Resists

Each new lithographic wavelength has required the development of new photoresists specifically tailored to it. Fundamentally, the issue is always the same: How to engineer more transparent resists without sacrificing plasma etch resistance. Because the I-line novolac resists were too opaque at 248 nm, p-hydroxystyrene (PHOST) materials were developed. PHOST was too opaque at 193 nm, so acrylic and alicyclics were developed and are still being fine-tuned. The fundamental obstacle currently facing the development of photoresists at 157 nm is the same [3, 18, 19]. It was found that resists formulated for use at 193 and 248 nm are so absorptive at 157 nm that their practical thickness is limited to ~60 nm, assuming a maximum optical density of 0.4. The absorbance at 157 nm was determined for a total of 25 different resists from resist suppliers. The resists included phenolic resists employed for 248-nm lithography and both acrylic and cyclo-olefin resists used in 193-nm lithography. The aromatic functionality of the phenolic resists was expected to be highly absorbing at 157 nm, and it was hoped that the substitution of aliphatic groups, as commonly used with 193-nm resists, would yield reduced 157-nm absorption. Unfortunately, even the resists based on aliphatic groups proved to be highly absorbing at 157 nm. The absorption coefficient of most resists turned out to be between 6 and 8 μm⁻¹. Only two types of experimental resists fall outside this range. These are materials containing high levels of silicon-oxygen bonding, which decreases absorbance, and those which contain silicon-silicon bonding, which increases absorbance.

The optimal thickness of a practical resist is determined by the interplay among three trends:

1. The optical density should not be more than 0.4 in order to maintain near-uniform exposure throughout the resist thickness; therefore, for an absorption coefficient of 6 μm⁻¹, the resist thickness is limited to less than 67 nm.
2. The resist aspect ratio should be less than ~3 in order to prevent pattern collapse; therefore, for the 70-nm node, the resist thickness is limited to ~200 nm.
3. The resist etch resistance should be such that pattern transfer into polysilicon, metal, gate oxide, etc., is achievable.

Keeping the second condition in mind, the absorption coefficient of the resist should be less than ~2 μm⁻¹, without loss of etch resistance compared to currently used 248-nm resists.

Resists more transparent than those used at 248 or 193 nm may be prepared from hydrofluorocarbon polymers, in which absorptive C-H bonds are replaced with transparent C-F bonds. However, the synthesis of such polymers is only a first step. The materials must satisfy numerous other requirements, such as adhesion, change in aqueous-base solubility upon chemical deprotection, and so on. Furthermore, the resists formulated from such polymers must include other highly absorbing components (photoacid generator, dissolution inhibitor). The encouraging news is that such resists can indeed be synthesized and formulated. Their lithographic behavior derives from the same chemical reactions as those of all 248- and 193-nm resists: chemically amplified deprotection, based on photon-generated acids and post-exposure bake, followed by development in aqueous base. Therefore, the underlying processing and performance (post-exposure bake, acid diffusion, etc.) will be similar to the familiar corresponding issues at longer wavelengths. In fact, the very first 157-nm resist candidates have exhibited photosensitivities comparable to those of 193- and 248-nm resists (the dose required to clear the resist is less than 10 mJ/cm²), and high contrast. New difficulties may be encountered in the areas of adhesion and plasma etch resistance. Failures of resist adhesion could be caused by the fluorine content of the polymer, but few systematic data have been obtained to date. The plasma etch resistance of candidate materials is in the early stages of evaluation. Preliminary etch-rate results indicate that fluorination is accompanied by the loss of etch resistance [20]. The tradeoffs are still unclear. There may still be an advantage to developing thicker, more transparent resists, but it will have to be quantified more carefully.

Of necessity, the lithographic performance of new candidate resist materials is being evaluated with existing

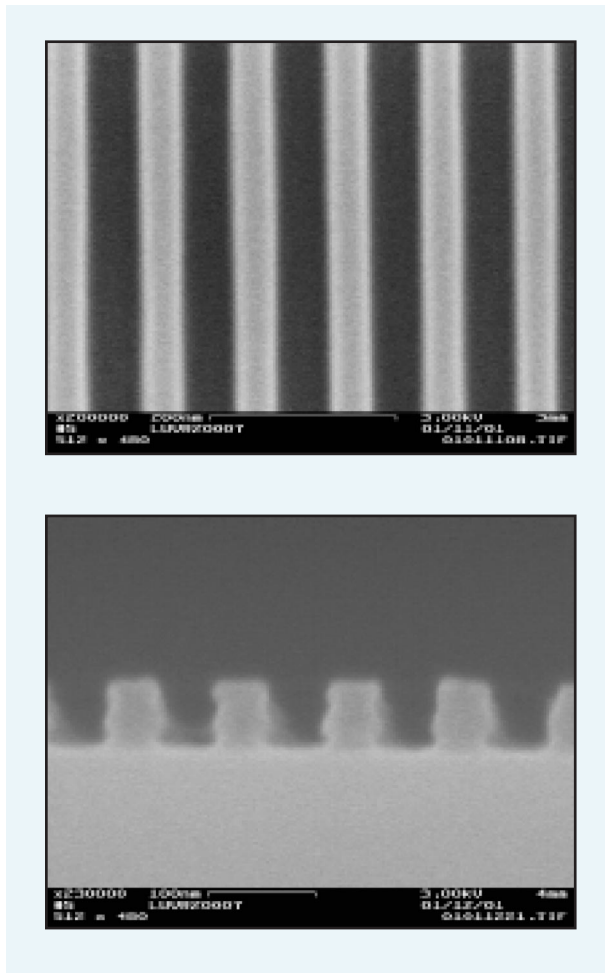


Figure 3

Fluorocarbon-based 157-nm resist showing 40-nm dense lines with a 100-nm pitch from an interference lithography system.

small-field projection systems whose numerical aperture is a modest 0.5–0.6. Nevertheless, in combination with phase-shifting masks, a resolution of ~ 90 -nm lines and spaces has been demonstrated with several materials [21]. This corresponds to a lithographic k_1 factor of 0.34, which is a remarkably aggressive value, indicating that high-performance 157-nm resists are within reach. Furthermore, one can evaluate the intrinsic limitations of the resists by decoupling the optical performance of the projection system from the observed resist pattern. Such decoupling has been achieved through the implementation of interference lithography at 157 nm [22]. The geometry of this system enables lensless printing of 40-nm lines with a 100-nm pitch, and allows study of ultimate resolution, cross-sectional profile, and line-edge roughness. Indeed, specially synthesized, partially fluorinated copolymers have

been shown to print with good profile and minimal line-edge roughness at these dimensions (**Figure 3**). Their transparency manifests itself in the standing-wave patterns seen in the figure, which imply that these resists can have thicknesses of 100 nm. Work is in progress in several laboratories to synthesize transparent materials that will enable even thicker resists, in the 200-nm range.

Summary

In summary, lithography at 157 nm is an active area of research, and the interest in it as a 100- to 70-nm technology is growing rapidly. There are still major challenges that must be overcome if it is to become a manufacturing technology within a few years. It is encouraging that no technical show-stoppers have yet been encountered, and that the overall path to improving its various aspects is understood. Nevertheless, significant progress must still be demonstrated in materials design, engineering, and processing, to be followed by implementation in full-field projection systems.

Acknowledgment

This work was performed in part under the Advanced Lithography Program of the Defense Advanced Research Projects Agency under Air Force Contract F19628-00-C-0002, and in part under Cooperative Research and Development Agreements between MIT Lincoln Laboratory and SEMATECH, between MIT Lincoln Laboratory and Intel, and between MIT Lincoln Laboratory and SVG Lithography. Opinions, interpretations, conclusions, and recommendations are those of the authors, and do not necessarily represent the view of the United States government.

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Received September 25, 2000; accepted for publication April 2, 2001

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