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How practical is 193 nm lithography?

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The use of 193 nm ArF lasers to extend optical projection lithography to its limits was proposed as early as the mid 1980s. Since then steady progress has been made in this area, and the last two years in particular have witnessed an exponentially growing interest in and commitment to its development. At present, 193 nm lithography is a leading candidate for printing 0.18 and 0.13 μm devices. This article reviews the state of development of this technology at Lincoln Laboratory. Significant progress has been made in most areas: qualification of optical materials, characterization of a prototype large-field projection system, development of photoresist processes, and the fabrication of complementary metal-oxide semiconductor devices. © *1996 American Vacuum Society.*

I. INTRODUCTION

The potential for high resolution with 193 nm projection lithography was demonstrated a decade ago, when 0.125 μm lines and spaces were printed with a 36×0.50 NA microscope objective using binary (chrome-on-quartz) masks.[1] In the intervening years significant effort has been applied towards developing the various practical aspects of this technology. From a laboratory curiosity, 193 nm lithography has become one of the main candidates for printing devices with 0.18 μm critical dimensions. Keeping in mind that mass production of such devices is expected to begin within the next five years, it is none too soon to examine the issues which may accelerate or impede the insertion of 193 nm lithography into manufacturing lines. These include optical materials, the availability of high-performance projection systems, and the availability of photoresists with adequate process latitude and compatibility with other device fabrication steps (ion implantation, plasma etching). This article reviews the progress and recent results obtained in these areas at MIT's Lincoln Laboratory, where much of the U.S. effort has centered until recently.

II. OPTICAL MATERIALS

Synthetic fused silica and crystalline calcium fluoride appear to be the only two practical materials of which high-performance refractive optics can be fabricated. Such materials must meet stringent requirements with respect to index homogeneity, residual stress birefringence, and surface forming and polishing properties. Our own work has focused on two other properties, namely transparency at 193 nm and long-term changes (''damage'') caused by 193 nm irradiation.[2]

Obviously, refractive elements should be as transparent as possible at the operating wavelength. In the case of 193 nm lithography any residual absorption may have at least two effects, both undesirable: one is a reduction of transmission, which necessitates increase in laser power and/or photoresist sensitivity; the other is laser induced heating, which can severely degrade the optical performance of near diffraction limited optics, since the change in index can be significant (for fused silica $dn/dT\approx20\times10^{-6}{}^{\circ}\mathrm{C}^{-1}$). A quantitative specification on maximum allowable absorption is, however, difficult, and it relates to system performance and the specifics of the optical design. We have conservatively established a target value on the absorption coefficient of 0.001 cm^{-1} (base 10), and have begun to systematically measure the absorption coefficients of fused silica and calcium fluoride samples obtained from most major suppliers. The measurements were performed with a laser calorimetry apparatus specifically developed for this purpose. Details on the experiment and results can be found in Ref. 3. Here we note only that the lowest absorption coefficients (base 10) measured to date are 0.003 cm^{-1} for fused silica and 0.002 cm^{-1} for calcium fluoride. These values are probably too high for most refractive or catadiotropic designs.

Irradiation with pulsed 193 nm lasers has been shown to cause color center formation in fused silica and in calcium fluoride, and compaction accompanied by index change in fused silica.[4] Fused silica tested in the last two years at 5 mJ/cm^2/pulse has exhibited saturation of added absorbance with increasing number of pulses, and sublinear dependence on fluence in the 3–50 mJ/cm^2/pulse range. As with initial absorption, we have recently begun a systematic evaluation of samples from most major suppliers. With fluences of 1 mJ/cm^2/pulse, several materials have exhibited added absorption coefficients of less than 0.0005 cm^{-1}, even after 1×10^9 pulses (see Fig. 1). If these results are confirmed by

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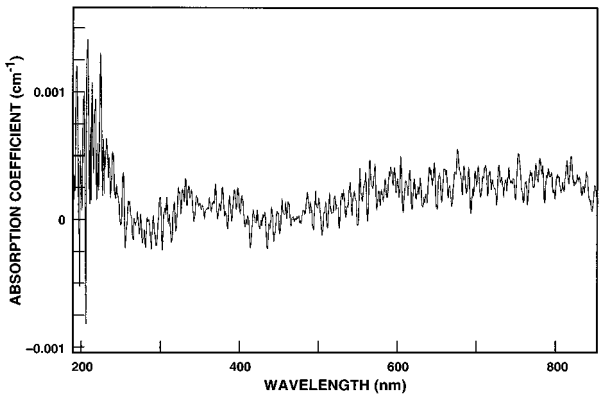

FIG. 1. Spectrum (190–800 nm) of 193 nm laser induced absorption in a sample of fused silica. The specturm was normalized to that of an unexposed portion of the same sample. Exposure was at 1 mJ/cm^2/pulse for 1 billion pulses. A color center peaked at ~220 nm is barely discernible.

TABLE I. Experimentally measured performance specifications of the 193 nm Micrascan prototype.

Property	Performance
Resolution	≤150 nm
Depth of focus	>1μm at 200 nm
Dynamic distortion (max vector)	76 nm
Dynamic distortion (avg vector)	28 nm
Field curvature	0.25μm
Dynamic astigmatism	0.19 μm
Flare (99% bright field mask)	9%
Flare (50% bright field mask)	4.5%
Overlay (mean+3σ)	<75 nm
Laser-to-wafer transmission	0.014
Max laser power	>10 W
Laser polarization	>85%
Wafer-plane laser power	~150 mW
Exposure time (15 mJ/cm^2 resist)	<800 ms

further tests, it appears that laser induced color center formation in state-of-the-art fused silica may not affect optics performance over practical lifetimes. Similar conclusions seem to apply to state-of-the-art calcium fluoride.

The effect of laser induced compaction appears at present to be more ambiguous. First, it does not appear to saturate at low levels (~1 ppm), and second, it appears to scale quadratically with laser fluence. Thus, the compaction of each element strongly depends on the local fluence. The practical lifetime of the whole system is a function of the specifics of the optical design, the throughput, and the resist sensitivity.[5] Studies are in progress to assess grade-to-grade variability and establish fundamental limits on compaction.

III. PROJECTION SYSTEMS

Several small-field steppers are now available commercially, and a few are already operational throughout the world. These have numerical apertures of 0.55–0.60, and field sizes of 2–3 mm, without level-to-level overlay capability. Presently there is only one full-field prototype projection system in the world. This is a step-and-scan tool with a 5×22 mm slit and a fully scanned field of 32.5×22 mm. It was built by SVG Lithography on a Micrascan II frame, and its projection optics are based on the catadioptric design of the Micracan II (4× reduction, 0.5 NA). This system also has an off-axis alignment system, and it therefore is suitable for device fabrication. Because of the catadioptric nature of the projection optics, no narrowing of the natural laser bandwidth is required. Experimentally measured system performance characteristics are detailed in Table I.

This prototype tool has been operating in Lincoln Laboratory's class 10 cleanroom since the end of 1993. It has served three main purposes. First, it has been an experimental test bed for evaluation of 193 nm projection optics, laser, and beam delivery systems. Second, it has been the mainstay of 193 nm photoresist development in the U.S. for the past two-and-a-half years, and third, it has been used to debug system and resist issues associated with fabricating 0.2 μm gate length complementary metal-oxide semiconductor (CMOS) devices.

IV. LASER SOURCES

Lincoln Laboratory has several ArF excimer lasers used for resist development, evaluating optical materials, and operating the step-and-scan prototype. We have gained considerable experience with operation, modes of failure, and component lifetime. These lasers, all with un-narrowed bandwidth, operate at 350–400 Hz, with average power of 10–15 W, and a lifetime of gas fill approaching 100 million pulses. At present, chamber lifetimes have exceeded 2 billion pulses, without the need to replace them yet. The thyratron based switches have a typical lifetime of ~2 billion pulses. The components that fail most commonly are the optics: windows on the discharge chambers, mirrors, and output couplers. These develop color centers, or their optical coatings may be damaged by the laser radiation. Their lifetime can be as high as ~500 million pulses, with the appropriate choice of grade.

V. PHOTORESIST PROCESSES

Lincoln Laboratory currently has four relatively mature photoresist processes. First is the original methacrylate terpolymer resist jointly developed with IBM-Almaden Research Center.[6] It is a positive-tone chemically amplified resist and has, for the past four years, been the benchmark resist for performing optical tests such as distortion, astigmatism, field curvature, scattered light, etc. Figure 2 shows an example of a thinned version of this resist. The one shortfall of this resist is its unacceptably poor plasma etch resistance (~2.2 times faster than novolac in Cl_2/BCl_3 metal etch). An improved second generation resist, also jointly developed with IBM, which incorporates isobornyl methacrylate in the polymer and has a cholate-ester dissolution inhibitor, exhibits improved etch resistance (~1.4 times faster than novolac in metal etch).[7] An example of this resist is shown in Fig. 3.

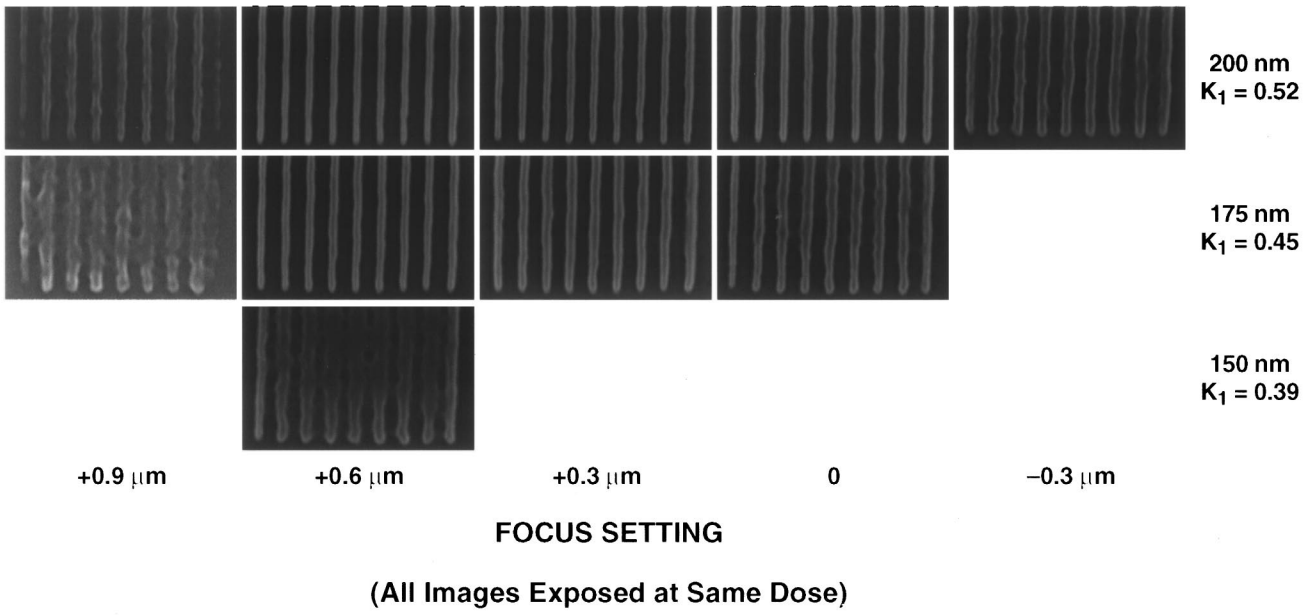

FIG. 2. Electron micrographs showing results using the version 1.0 b acrylic resist at a thickness of 250 nm. The 200 nm features printed through 1.2 μm of focus, the 175 nm printed through 0.6 μm of focus, and the 150 nm were just barely resolvable.

This improved resist has been used for implant and contact hole levels in the all-193 nm CMOS device lot at Lincoln Laboratory. Although these current resist formulations do not exhibit the same high contrast or acceptable etch resistance as the most advanced deep ultraviolet (248 nm) resists, future improvements are expected[8] and should ultimately yield a 193 nm single-layer resist that matches the best deep-UV resists of today. To complement these new resists, an antireflective layer formulated from a dyed epoxy methacrylate has been developed and has been shown to perform well with both chemically amplified and nonchemically amplified 193 nm single-layer resists.[9,10]

In addition to the single-layer resists, 193 nm top-surface imaged silylation resists have been under development at Lincoln Laboratory for the past seven years.[11–13] The preferred process uses pure poly(4-hydroxystyrene) silylated with dimethylsilyldimethylamine, and represents the most robust and mature 193 nm resist process.[13] This resist has exhibited resolution to 150 nm ($k_1 = 0.39$), linearity to 175 nm ($k_1 = 0.45$), and depths of focus of 0.6 and 1.0 μm at 175 and 200 nm, respectively. Its present formulation requires a dose to size of $\sim$100 mJ/cm^2, which is too high for large volume production purposes. Work is presently in progress to reduce the dose requirements. Figure 4 shows an example

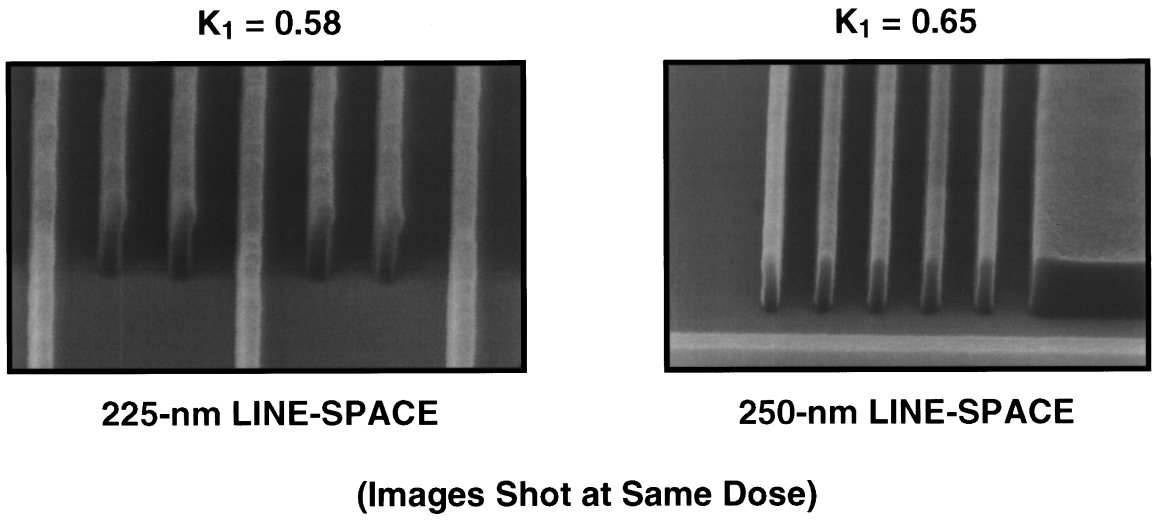

FIG. 3. Electron micrographs showing results using the version 2.0 alicyclic acrylic resist at a thickness of 650 nm. The features shown are 225 and 250 nm line/space pairs.

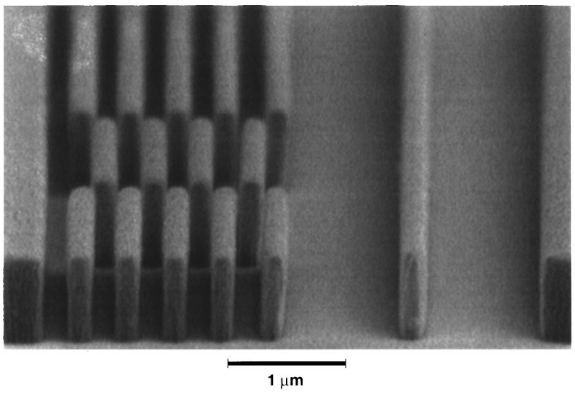

FIG. 4. Electron micrographs showing results using poly(4-hydroxystyrene) resist at a thickness of 700 nm. The features are 200 nm line/space pairs. The silylating agent was dimethylsilyldimethylamine and the pattern transfer was performed using a helicon etcher and pure oxygen gas.

of this resist process. The processing of the resist is currently being performed in production-grade silylation and etch equipment, where wafer processing times average 1–2 min per wafer for a cassette of 25 wafers. This silylation resist has been used to transfer 0.15 μm patterns into 0.3-μm-thick polysilicon (Fig. 5). It has been used for the active area, polysilicon gate, and metal levels of the all-193-nm device lot described below.

The third resist process is a bilayer, where the ~100-nm-thick imaging layer is a polysilyne. This material is selectively photooxidized upon 193 nm exposure in air, and wet or dry etching is used to remove unexposed areas.[14] This negative-tone process is particularly useful when high etch resistance is required.

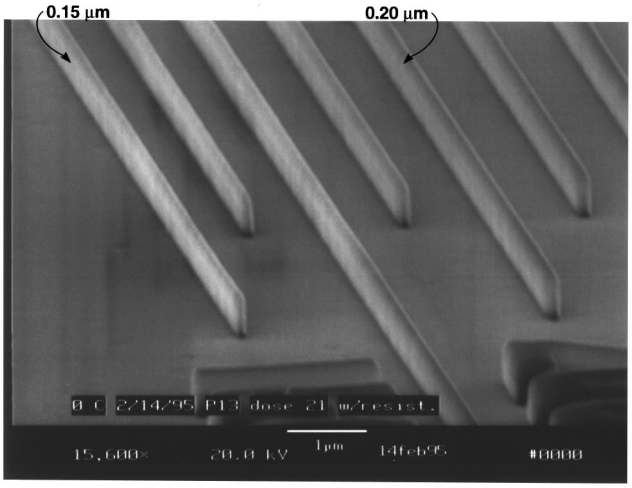

FIG. 5. Electron micrograph of patterns (down to 150 nm) etched in 300-nm-thick polysilicon, using silylation resist. The pattern transfer was performed with a HBr-based plasma in a helicon etcher. The etching stopped on 5 nm of gate oxide. The micrograph shows the polysilicon after resist stripping.

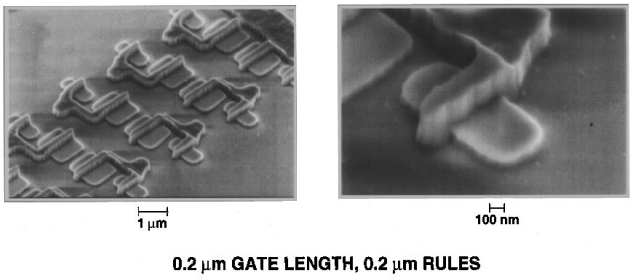

FIG. 6. Electron micrographs showing 200 nm polysilicon gates patterned over 60-nm-thick silicon islands, all on a substrate of SiO_2/Si. The polysilicon gates were patterned using the silylation top-surface imaged resist process. Note the absence of any reflective notching. When these devices were fully fabricated, the maximum switching speed measured from a 49-stage oscillator was 29 ps when run at 3 V and 57 ps when run at 1 V.

VI. DEVICE FABRICATION

Lincoln Laboratory's first all-193-nm devices were completed in early 1996. This device run used eleven lithography levels to define a series of discrete *n*- and *p*-channel transistors, ring oscillators, via chains, and proximity effect structures with minimum drawn features of 200 nm, all on silicon-on-insulator substrates.[15] The most aggressive transistor designs had fully scaled 0.2 μm gate lengths with 0.3 μm contact holes. The devices, after the polysilicon gate patterning step, are shown in Fig. 6. The measured delays per stage for a 49-stage ring oscillator were 29 ps at 3 V and 57 ps at 1 V.

VII. CONCLUSIONS

Photolithography using the 193 nm output of ArF excimer lasers is rapidly developing into a production worthy technology, capable of manufacturing devices with dimensions of 0.18 μm and below. Several photoresist schemes have been developed, including single-layer, top surface imaging (silylation), and bilayers. These possess, to various degrees, the attributes of good working resists, if not yet fully optimized in all respects (resolution, contrast, dose, process latitude, etch resistance, etc.). A major milestone has recently been achieved with the successful completion of an all-193-nm CMOS device lot at Lincoln Laboratory using these resist processes. We expect rapid improvements in resist performance in the next few years, as growing efforts are applied to their development around the world. These efforts are further enhanced by the growing installed base of 193 nm microsteppers.

The performance of lasers and optical materials has been improving in recent years, and there are ongoing programs to more accurately qualify and ultimately improve on them. Areas of uncertainty still include initial absorption of materials and control of compaction in fused silica. Strategies to reduce the impact of these on optical performance and system throughput may have to be further pursued.

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