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## Excimer projection lithography at 193-nm wavelength

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ABSTRACT

Excimer laser projection lithography is expected to become a widely used technique, capable of high throughputs at resolution well below  $0.5\ \mu\text{m}$ . In this paper we demonstrate excimer projection patterning with  $0.13\ \mu\text{m}$  resolution, and we address issues related to laser engineering and optical materials, which are encountered in the design of practical excimer projection systems.

1. INTRODUCTION

Excimer laser projection lithography is emerging as a potentially significant production tool in the microelectronics industry. The driving force behind this development is the continuing trend towards smaller feature size and higher chip complexity. In optical projection printers smaller features can be achieved by reducing the wavelength or increasing the numerical aperture (NA) of the imaging optics. The preferred method is changing the wavelength since this has a smaller effect on defocusing tolerance than increasing NA.<sup>1,2</sup> It is therefore expected that, in order to achieve resolution well into the submicrometer region, the 248-nm and 193-nm wavelengths of the excimer laser will replace the 436-nm and 365-nm lines of the conventional mercury lamp. While these ideas are conceptually sound, their practical implementation must overcome several technological challenges. In this paper we address three such aspects which are specific to the short wavelength and pulsed operation of excimer lasers: the development of new resist materials, specifically optimized to the laser output characteristics; pertinent properties of optical materials at short wavelengths; and the effects of laser pulse-to-pulse fluctuations on linewidth control and system performance.

2. RESISTS

At Lincoln Laboratory, resolution of  $0.13\ \mu\text{m}$  lines and spaces was demonstrated at 193 nm in several single-layer resists. These materials include self-developing diamond-like carbon (Fig. 1) as well as spun-on, wet-developed polymethylmethacrylate (PMMA) (Fig. 2). Note that exposure with a single pulse is sufficient for patterning these films. As a result, extremely high throughputs are possible with step-and-repeat systems employing excimer lasers, the limitations being the laser pulse repetition rate and the alignment overhead. The high resolution seen in Figs. 1 and 2 is directly attributable to careful optimization of the exposure conditions and the high order of nonlinearity of the resist response.<sup>2,3</sup>

3. OPTICAL MATERIALS

The design of high-performance optical elements always hinges to a large degree on the properties of the optical materials to be used. In the visible there is a large variety of optically transmissive materials, and the designer can, as a starting point, choose those with preferred properties, such as refractive index, dispersion, sensitivity to temperature and chemical ambients, ease of polishing, and homogeneity, to name a few. However, in the wavelength range of interest for excimer projection systems, namely, below  $\sim 300\ \text{nm}$ , there are only a handful of materials which are candidates for transmissive optical elements. These materials include fused silica, calcium fluoride, lithium fluoride, and magnesium fluoride. They all have certain limitations. In particular, magnesium fluoride is birefringent, and this excludes its use in many optical components. Lithium fluoride is hygroscopic, and is also difficult to polish to the exacting surface tolerances required in projection lenses. In addition, all these materials exhibit small, but nonnegligible absorption at shorter wavelengths, as shown in Fig. 3. It is seen that at 248 nm LiF has an absorption coefficient  $\alpha = 0.04\ \text{cm}^{-1}$ , while  $\text{CaF}_2$  and fused silica have residual absorption

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$\alpha < 10^{-2} \text{ cm}^{-1}$ . At 193 nm, all three absorb to some degree, with  $\alpha$  in the range 0.02 - 0.08  $\text{cm}^{-1}$ . For current projection system designs in which the optical pathlength is ~15-30 cm, the overall transmission is still expected to be within practically acceptable limits,  $T > 0.3$  for all three materials. However, irradiation in the UV induces formation of absorptive color centers, accompanied by a significant reduction in transmission. For instance, after  $2 \times 10^6$  pulses at 193 nm with  $0.1 \text{ J cm}^{-2}/\text{pulse}$ , the absorption coefficients of  $\text{CaF}_2$  and  $\text{LiF}$  are  $\sim 0.15 \text{ cm}^{-1}$ , and that of fused silica is  $0.06 \text{ cm}^{-1}$  and rising (with increasing number of pulses). The transmission of a complex optical system fabricated of these materials may be therefore too low. The mechanism of formation of this UV-induced degradation is still under study. Impurities may play a role, as well as intrinsic point defects. It is nevertheless clear that at 193 nm, at least, projection optics of refractive materials must be limited in thickness. Alternatively, progress in the growth of high quality materials may alleviate these concerns.

#### 4. PULSE-TO-PULSE STABILITY

Most commercially available excimer lasers are currently specified to have a certain amount of pulse-to-pulse fluctuation in their energy/pulse, for example, typically  $\pm 3-4\%$  at 248 nm, and almost double this value at 193 nm. These fluctuations impose a lower limit on the number of pulses that each field must be exposed to in an excimer stepper. This lower limit derives from the need to smooth out the effect of energy fluctuations, and is related to the predetermined tolerance on linewidth control via the modulation transfer function (MTF) of the aerial image and the material response  $R$  of the photoresist.

It can be shown that for equal lines and spaces of width  $L$ , the relative fluctuations in linewidth,  $\delta L/L$ , from field to field are given by

$$\delta L/L = \frac{\delta R/R}{\pi \text{MTF}(L)} \quad (1)$$

where  $\text{MTF}(L)$  is the linewidth-dependent MTF and  $\delta R/R$  is the corresponding relative fluctuation in resist response. The latter depends on the relative pulse-to-pulse energy fluctuation,  $\delta\phi_0/\phi_0$ , via the functional relationship  $R(\phi)$ , as shown below. The more familiar case, commonly encountered in Hg-lamp photolithography, is that of a reciprocal photoprocess, i.e., the exposure dose is simply additive. For a reciprocal process with excimer lasers, it can be shown that

$$\delta R/R = (\log_{10} e) \gamma^*(\phi_{\text{total}}) \frac{\delta\phi_0/\phi_0}{n^{1/2}} \quad (2)$$

where  $\phi_{\text{total}}$  is the total dose,  $n$  is the number of pulses ( $\phi_{\text{total}} = n \phi_0$ ), and

$$\gamma^*(\phi) \equiv \frac{d(\ln R)}{d(\ln \phi)} \quad (3)$$

Because of the shorter wavelength of excimer lasers as well as their high peak intensity, a growing number of photoprocesses have been found to be nonreciprocal, i.e., the resist response per pulse is the additive quantity. An example is a typical self-developing resist: the etch rate of these materials is usually highly nonlinear in fluence, and therefore it is not a single-valued function of  $\phi_{\text{total}}$ . On the other hand, the total amount of etched material is proportional to  $n$  at any fixed  $\phi_0$ . In such nonreciprocal instances,

$$\delta R/R = (\log_{10} e) \gamma^*(\phi_0) \frac{\delta\phi_0/\phi_0}{n^{1/2}} \quad (4)$$

Comparing Eqs. (2) and (4), one finds that the difference between reciprocal and nonreciprocal processes manifests itself in the value of  $\phi$  at which  $\gamma^*(\phi)$  is to be evaluated, and therefore it depends on the functional relationship of  $R(\phi)$ . In either case, combining Eq. (2) or Eq. (4) with Eq. (1) provides the connection between the laser parameters ( $\delta\phi_0/\phi_0$  and  $n$ ) and the pattern tolerance on the wafer ( $\delta L/L$ ), as mediated by the performance of the optical system (MTF) and the resist response ( $\gamma^*$ ). Figure 4 illustrates these interconnections by plotting  $n$  vs  $\delta\phi_0/\phi_0$  for several values of MTF in the reciprocal and nonreciprocal cases for a fixed  $\delta L/L$ . The resist

response was assumed to vary as a power of  $\phi$ . Other relationships between  $R$  and  $\phi$  yield slightly different results, but the trend is the same: more pulses are needed for a nonreciprocal response than for a reciprocal one, and  $n$  increases sharply with decreasing MTF. Since the MTF is commonly smaller for lower values of  $L$ , the foregoing analysis illustrates the more stringent requirements imposed on  $n$  and  $\delta\phi_0/\phi_0$  with increasing resolution. Further improvements in laser engineering are clearly desirable in order to reduce  $\delta\phi_0/\phi_0$ , in particular for high-resolution patterning of high- $\gamma$  resists.

#### 5. ACKNOWLEDGMENTS

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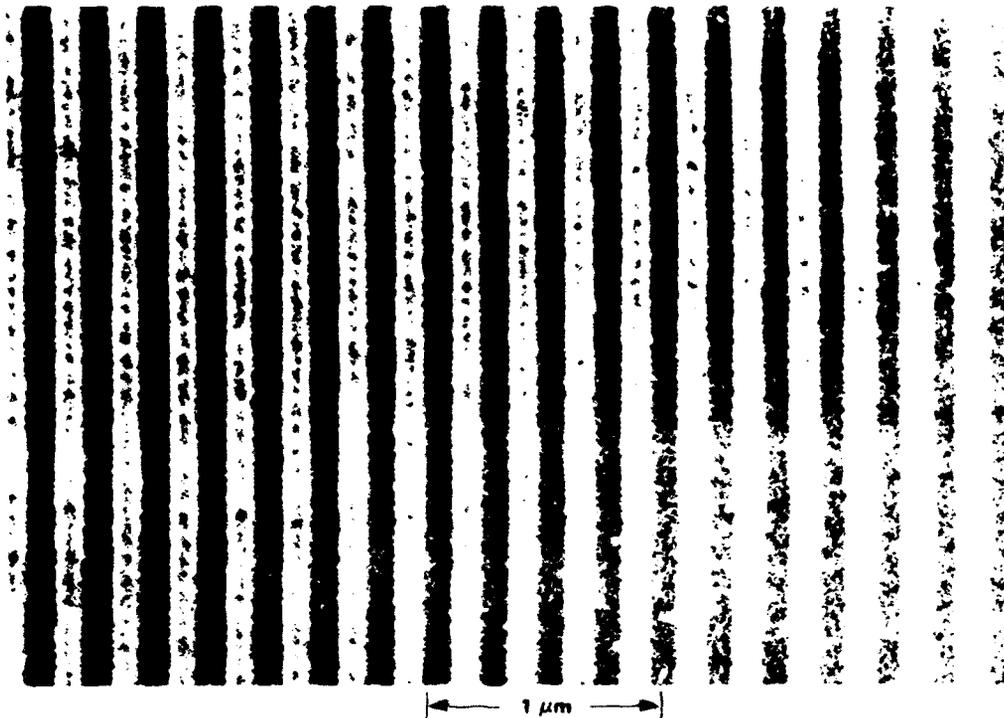


Figure 1. Scanning electron micrograph (SEM) of 0.13- $\mu\text{m}$  lines and spaces patterned in 200-nm-thick diamond-like carbon on GaAs. Exposure in projection was with one 193-nm laser pulse ( $\sim 100 \text{ mJ cm}^{-2}$ ) in air.

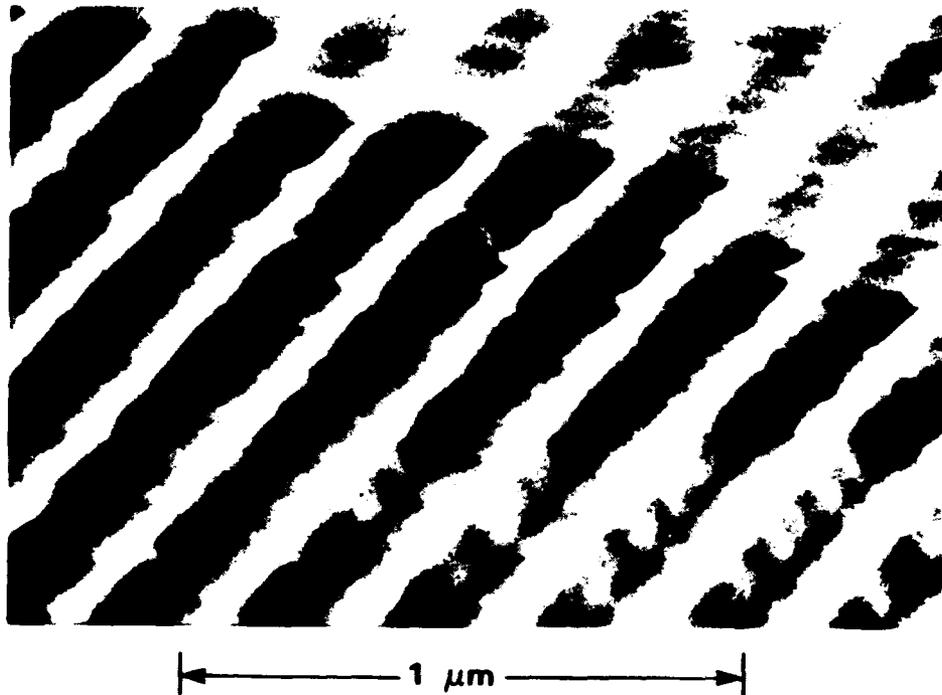


Figure 2. Scanning electron micrograph (SEM) of nominal 0.13- $\mu\text{m}$  lines and spaces patterned in 150-nm-thick PMMA on Si. Exposure was with one 193-nm pulse ( $-1 \text{ J cm}^{-2}$ ) in air. Wet development was in a solution of methyl isobutylketone in isopropanol.

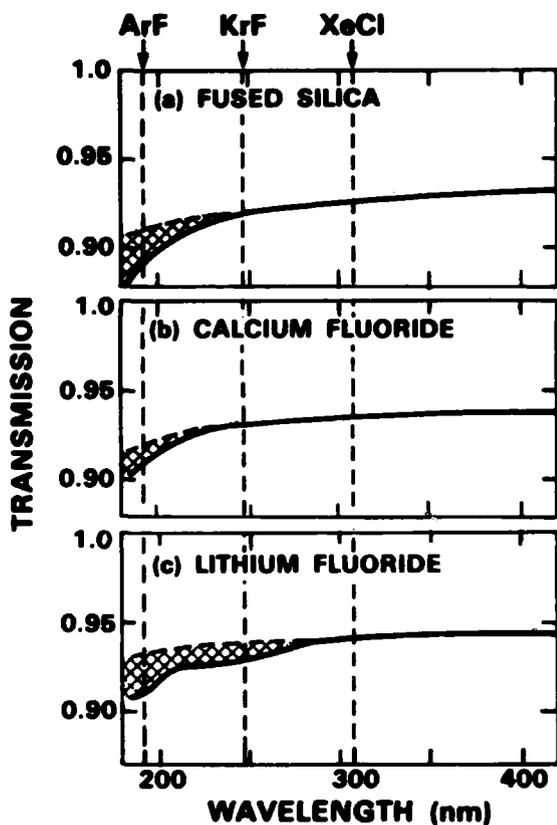


Figure 3. Transmission of 1-cm-thick high grade UV-quality fused silica,  $\text{CaF}_2$ , and  $\text{LiF}$ , prior to exposure to high-intensity excimer irradiation. The solid lines are the experimentally measured transmission, and the broken lines are the calculated transmission in the presence of only Fresnel reflections. The shaded areas represent residual absorption (experimental transmission minus reflective Fresnel losses). The wavelengths of the ArF, KrF, and XeCl excimer lasers are indicated by the broken vertical lines.

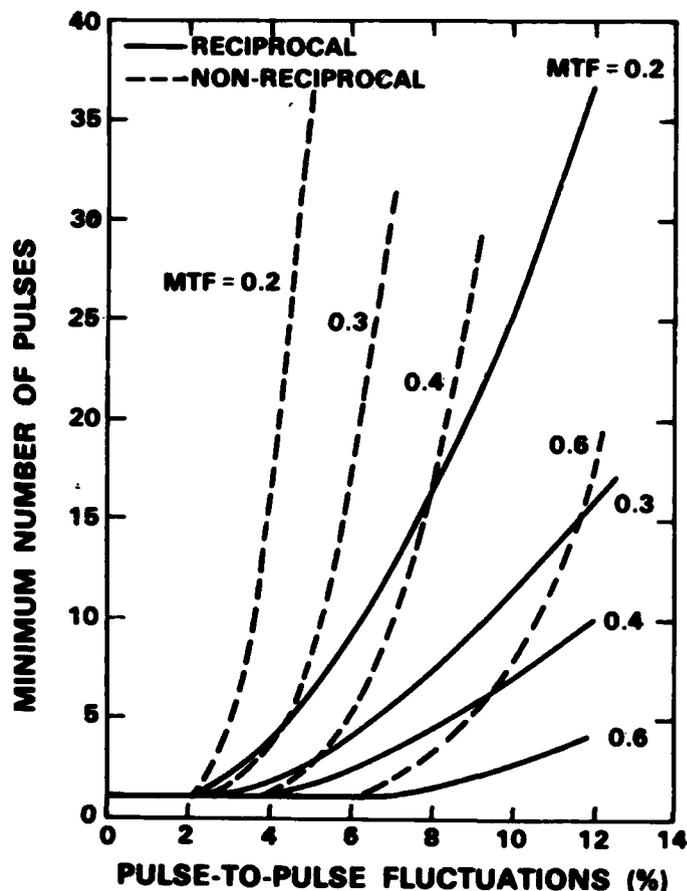


Figure 4. The minimum number of laser pulses per field which is necessary to maintain field-to-field linewidth variations below 4%, as a function of pulse-to-pulse fluctuations in laser energy. The curves are calculated for several values of the optical modulation transfer function (MTF), for the two cases of reciprocal and nonreciprocal resist response. A moderate order of nonlinearity,  $\gamma = 3$ , was assumed throughout.



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