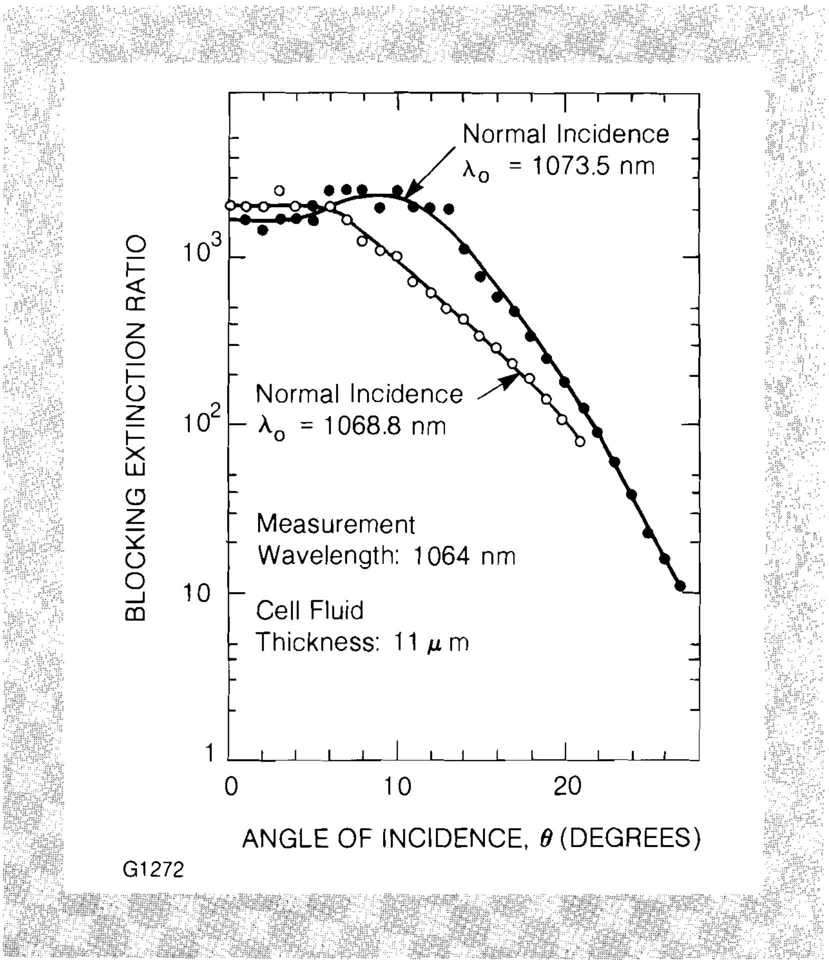

Fig. 30
Angular acceptance for liquid-crystal laser-blocking filters. The blocking extinction ratio is enhanced at angles of incidence away from the normal by adjusting the liquid-crystal composition in the filter to shift the normal incidence peak to a longer wavelength.

4.B Sub-Micron X-Ray Lithography Using UV-Laser-Produced Plasma as a Source

The production of integrated circuits in the computer and electronic industries is currently done by photolithography. In the future, more powerful circuits will have to contain smaller circuit elements. Photolithography will not be effective in producing elements smaller than ~ 1 μm, because light diffraction causes loss of resolution. Instead, the most probable solution would be to (a) fabricate masks with an electron beam, and then to (b) mass-replicate these masks with x rays.

X-ray lithography has been used successfully over the last few years to produce relief structures of submicron dimensions. The commercial application of x-ray lithography to the production of integrated circuits will depend on progress in a few interrelated areas: the resist, the mask, the relative placement and alignment of mask and resist, and the x-ray source. Any development in any one area may change the design philosophy and optimal parameters considerably.

The plasma produced by focusing a laser onto a target is an intense x-ray source of very small dimensions, which makes it very well suited for high-resolution lithography. In addition, our x-ray lithographic experiments show that a modest pulse energy (35 J) is sufficient for pattern registration in PBS and other resists at a distance of 10 cm from the laser target. These characteristics make laser plasma a promising source for commercial x-ray lithography.

X-ray lithography using laser-produced plasma as a source has been reported in the past. In one such study,[1] 40-ns, 100-J pulses of a wavelength of 1060 nm were used. As many as 60 to 90 laser shots had to be integrated over, in order to obtain PBS exposure at a distance of 5 cm from the target. Using the GDL laser system in the configuration shown in Fig. 31, we find here that a single, λ = 351 nm, 1-ns laser shot of energy 35 J, is sufficient to produce submicron patterns in PBS at a distance of 10 cm from the target. This improved performance can be attributed to two factors:

a) By using a UV (λ = 351 nm) rather than an IR laser, the x-ray production efficiency for given focusing conditions is greatly improved.[2] This also means a concomitant reduction in the remainder of the absorbed energy which appears as kinetic energy of the target debris. Hence, the damage to the mask for a given x-ray flux is reduced, permitting the use of a thinner, more transmissive filter for protecting the mask. Even though we lose intensity when frequency-tripling the IR laser (the conversion efficiency[3] actually exceeds 50%), this is more than compensated by the higher efficiency of x-ray production.
b) We find that the x-ray flux sufficient to produce resist exposure is lower than that predicted by published sensitivity data for the same resist and processing conditions. We tentatively attribute this to some combination of two factors: the short (~ 1-ns) duration of the exposure pulse, and an abrupt rise in the temperature of the resist due to heat generated when the target debris strike the filter which is used to protect the mask.

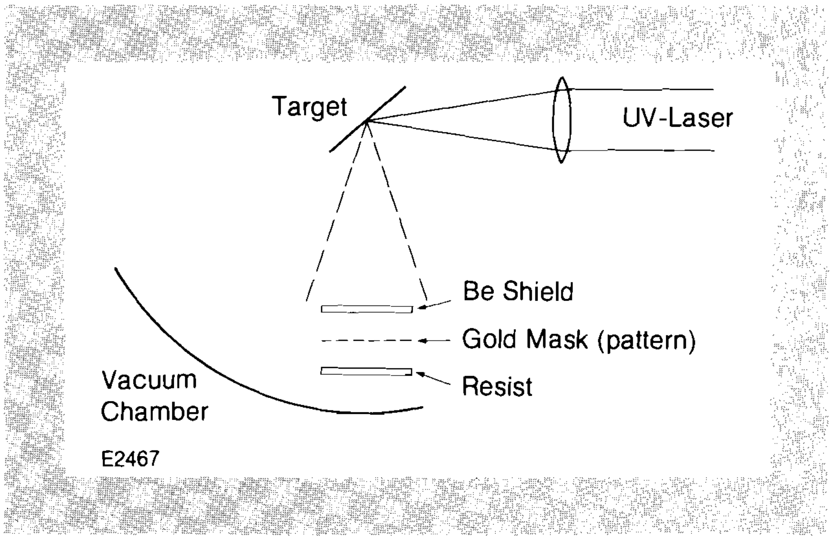

Fig. 31
Geometry for x-ray lithography using laser-produced plasma as a source. The shield protects the mask and resist from the impact of target debris.

In order to determine the resist sensitivity in our exposure system, we have to sum up contributions of the various energy groups comprising the emitted x-ray spectrum. The spectrum emitted by an iron target is shown in Fig. 32. It comprises a K-shell emission feature near 8 keV (unresolved lines of Fe^{+24}) as well as a broad continuum. Integrating over the spectrum and angles (using a measured angular distribution[2]), we find 5.7 J of x rays emitted, or 27% of the laser energy absorbed in the target.

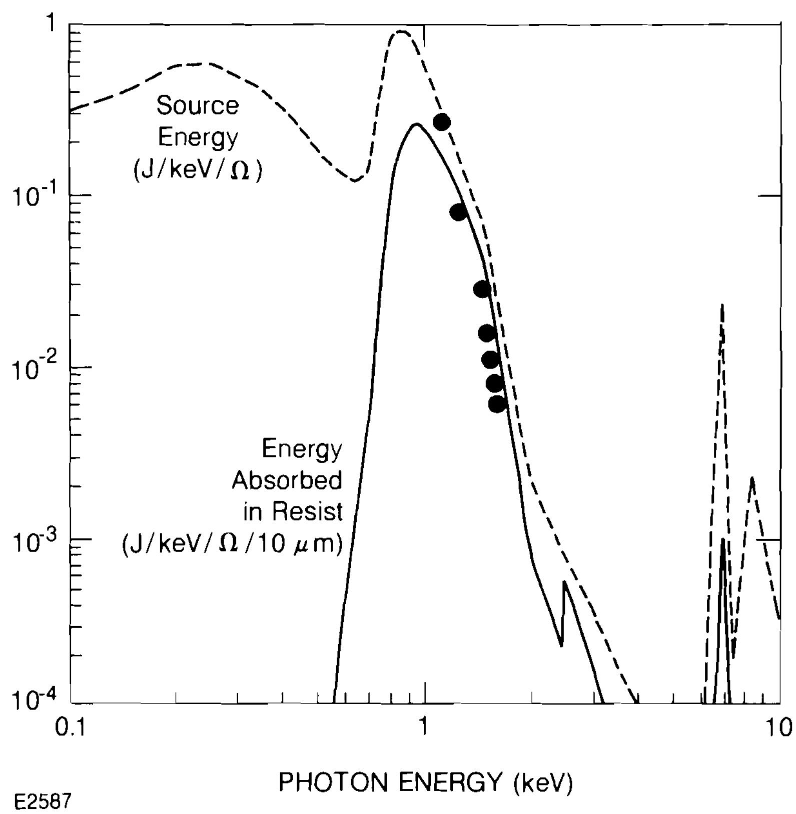

Fig.32
X-ray spectrum emitted by an iron target irradiated by a 1-ns, 351-nm laser pulse of energy 35 J. The solid curve is obtained from the emitted spectrum after multiplying by the beryllium window transmission and the resist (PBS) absorption coefficient. The circles and the spectral features above 7 keV represent measurements; the emitted continuum is from numerical simulation.

We next calculate the spectrum transmitted through the 18-μm-thick beryllium filter. This has the effect of essentially removing the subkilovolt part of the spectrum while leaving the intensity above ~ 1 keV almost unaffected. The energy absorbed per unit depth at the surface of the resist is obtained by multiplying the incident x-ray intensity by the linear absorption coefficient. The result is shown by the solid line in Fig. 32.

The total x-ray energy transmitted through a beryllium filter is 0.72 J. The x-ray-energy-density incident on the resist, located 10 cm from the target is 0.57 mJ/cm^2. Finally, the total x-ray energy per unit volume absorbed at the surface of the resist is 0.9 J/cm^3. The sensitivity expressed as energy absorbed per unit volume is essentially independent of wavelength,[4] and can be directly compared with published data. The published sensitivity data for PBS,[5,6] processed in the same way as here, is 14 J/cm^3. Our exposure system appears, therefore, to be more sensitive by about one order of magnitude than the results of published PBS sensitivity data.

We show in Fig. 33 examples of imprinted mask patterns in PBS resists using as a mask an unsupported gold grating of 0.45-μm linewidth.

(a)

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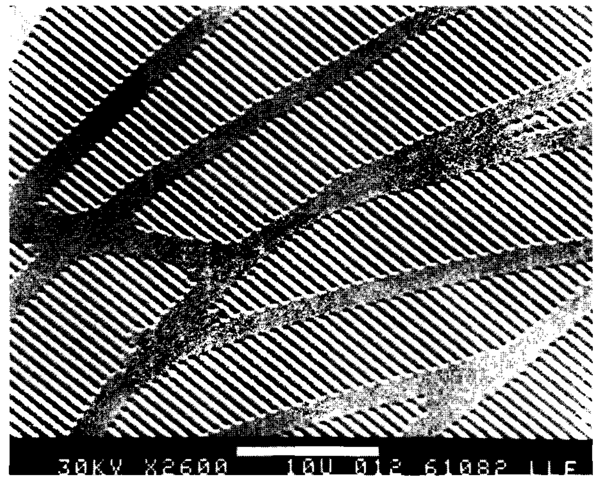
(b)



E2236

Fig. 33
Examples of PBS resist registration through a 0.45-μm-linewidth gold grating. The coarse struts (of gold) serve as a support structure but the mask is free-standing (unbacked). A single, 35-J pulse of UV laser was used.

a) Phase-contrast optical microscope image of imprinted image.

b) Scanning electron-microscope image of imprinted image.

In summary, the favorable exposure characteristics found here, in addition to the more obvious relative advantages, make the laser-produced x-ray source promising for sub-micron lithography. Some of these advantages over other x-ray sources are: (a) small dimensions (< 0.1 mm), (b) reproducibility of source positioning (to a few μm), (c) almost complete freedom in choosing the target material (which affects the spectral characteristics), and (d) mechanical stability in single-pulse operation.

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