Submicrometer lithography using lensless high-efficiency holographic systems

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A hologram recording geometry that was total internal reflection of the reference and reconstruction beams from a photosensitive material surface is used to achieve 0.5-μm resolution at $\lambda = 457$ nm in the readout of a reconstructed image on a photoresist. Such a geometry has demonstrated stable image quality for parallel displacement within the illuminated area and diffraction efficiency tolerance within a $\pm 2°$ tilt about the axis of the reconstruction beam. The total-internal-reflection recording system provides double-fringe sets for each plane component inside the volume hologram; therefore, a diffraction efficiency as high as 80% was observed. The result is applicable to high-volume submicrometer lithography and can be expanded to a 20-cm (8-in.) semiconductor submicrometer pattern. The use of a large-aperture, well-collimated laser beam provides us with much higher throughput than that of existing lithography machines.

We relate holographic lithography to the imaging of an integrated microcircuit pattern by using a holographic mask instead of a conventional chromium mask. This is a two-step recording and reconstruction procedure that is highly suited for proximity printing geometry (i.e., not in contact with, but with a small separation distance between, the mask and wafer).

Even though there are recognized difficulties in converting the idea into a real device, holographic lithography is attractive to researchers because of the inexpensive and lensless technology it offers.[1] In order to meet the requirement for submicrometer resolution, all holographic aberrations must be eliminated. Champagne's expressions[2] for general hologram imagery can be used to derive the methods to achieve an aberrationless image. However, diffraction restricts the resolution of a pattern that could be transferred from any original to a hologram. It is well known[3] that the maximum spatial frequency of a sinusoidal pattern that will produce a diffracted plane wave in free space is $\nu \leq 1/\lambda$. In a recent experiment we used an argon laser, whose wavelength of $\lambda = 457.9$ nm imposed a half-micrometer image resolution limit. We combined our previously developed approach of applying a volume hologram for proximity printing with an identical geometry for recording and reconstruction[4] and with total internal reflection (TIR) of the reference and reconstruction beams on the surface of the holographic mask. Note that the TIR of a reference–reconstruction beam on a hologram was first introduced by Stetson.[5,6] In addition, the evanescent wave[7] and the surface plasmon wave[8] as methods of creating reference and reconstruction beam illumination to avoid overlapping of a reconstruction beam, and a real image can be considered. An additional study of these two methods needs to be pursued for holographic lithography.

In this Letter, a volume holographic recording system utilizing TIR geometry (Fig. 1) is reported that has already resulted in 0.5-μm image resolution and a signal-to-noise ratio of better than 10 dB in the reconstructed image. We also discuss some of the attractive features of the proposed holographic system.

Recently, a TIR holographic printing system was installed in a conventional proximity printer by European researchers to obtain submicrometer resolution.[9] In their experiment, a scanning reconstruction regime was used to provide highly uniform illumination and to maximize utilization of the laser output. Their decision to use the scanning technique was based on the assumption that "The effective diameter of the portion of the hologram being transformed into a real image ... is on the order of twice the hologram-to-photoresist spacing."[10] Having decided that this conclusion had to be proved, we tested the simultaneous illumination of the holographic mask as a whole and were able to provide uniform illumination (to 1%) with a well-collimated beam over the 5 cm × 5 cm (2 in. × 2 in.) area of the holographic mask.

The same arrangement was used for the recording and the reconstruction process (see Fig. 1). For the reconstruction, the hologram was rotated 180° around a perpendicular axis so that the reference beam could be used as the reconstruction beam. A schematic explanation of the TIR holographic geometry used is shown in Fig. 2. A transparent object (master mask), when illuminated, produces a set of plane waves according to the Fourier expansion of the transmittance.

To record a hologram with a zero-order object beam only, the mask was taken away and the diffraction efficiency of the hologram when it was reconstructed was measured. The resulting double-fringe pattern increased the diffraction efficiency to as high as 80%. The wavelength selectivity of this hologram was also measured. The hologram was illuminated with a normal incident beam, as in a standard spectrophotometer configuration. When the wavelength met the Bragg condition, the light became coupled into a glass substrate, producing a sharp Bragg diffraction peak that could be detected in transmittance measure-

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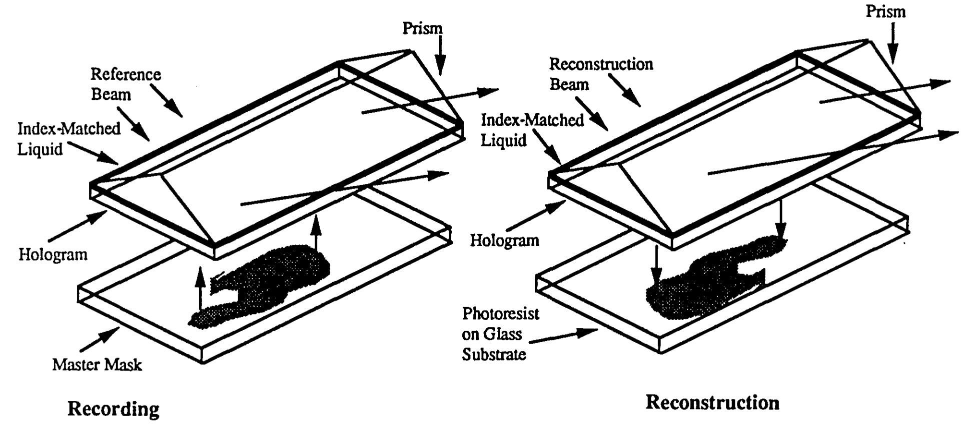

Fig. 1. Holographic microlithography with a TIR setup.

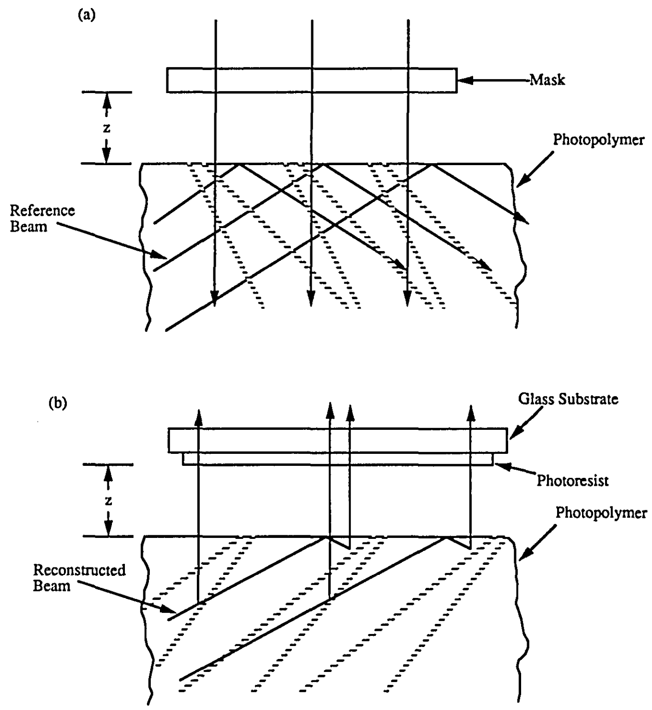

Fig. 2. (a) Recording and (b) reconstruction geometries. Two sets of fringes are shown by the dashed lines. The hologram has been rotated 180° for readout.

ments (Fig. 3). The relatively high absorption of the polymer film employed in our recording would normally produce considerable nonuniformity; however, the nonuniformity was compensated for by the advantage gained by dry-exposure processing. Dry-exposure processing reduces the chances of shrinkage and swelling of the hologram. No shift of the Bragg diffraction peak, which was noted in Ref. 11, was observed during and after the hologram formation process.

The diffraction of the TIR hologram was found to be insensitive to lateral movement within the illuminated area, and significant degradation of diffraction efficiency did not result when the hologram was tilted ±2°. The latter is in good agreement with Kogelnik's theoretical expression for the dephasing measure φ,[12]

$$\varphi = \Delta\theta K \sin(\phi - \phi_0) - \Delta\lambda K^2/4\pi n, \qquad (1)$$

where K is the grating vector, ϕ is the slant angle, and θ_0 is the angle of incidence. The wavelength dispersion $\Delta\lambda = 20$ nm (half-width of the Bragg peak in Fig. 3) implies that an angular selectivity

$$\Delta\theta = \frac{\Delta\lambda}{\lambda} \tan(\phi - \phi_0) = 4.5° \qquad (2)$$

is expected.

It was found both theoretically and experimentally that the most crucial parameter for submicrometer-resolution holographic lithography is the separation between the object and the hologram in the recording process and between the hologram and the photoresist plane during reconstruction. Each separation distance should be kept the same for both processes. Indeed, reproducible results were consistently achieved when a fixed spacer, 50 μm thick, was used for recording and reconstruction.

The master mask consisted of e-beam 0.5-μm-width

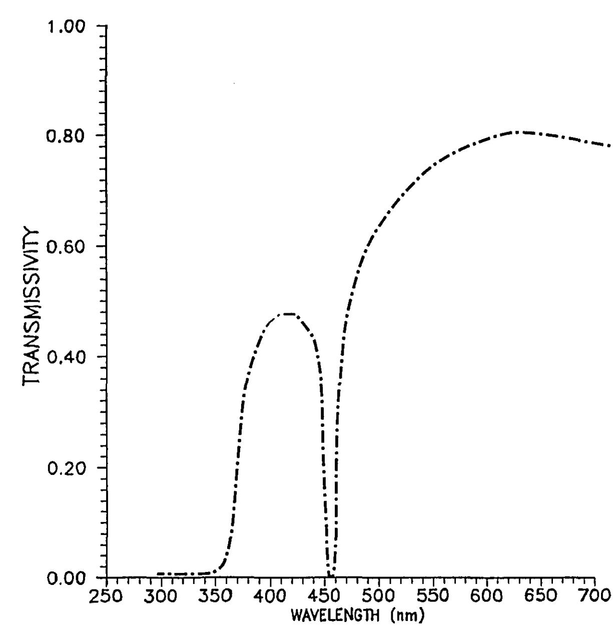

Fig. 3. Spectral transmittance of the volume hologram, recorded without a mask.

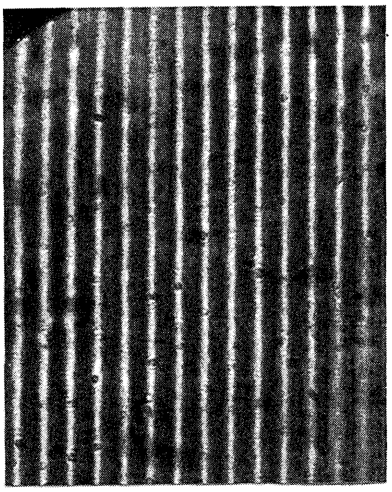

Fig. 4. Photograph of the 0.5-μm-resolution holographic image recorded on a photoresist.

chromium lines on a glass substrate. The glass substrate was 2.5 cm (1 in.) long. The resulting holographic image was reconstructed on a photoresist plate (Fig. 1). Figure 4, taken under reflected light, is a picture of the half-micrometer holographic image recorded on a photoresist.

The 2.5 cm × 2.5 cm (1 in. × 1 in.) image was found to be fairly uniform owing to the placement and the accurate sizing of the spacer mentioned above. To show how small the image tolerance should be, we refer to self-imaging phenomena. It is well known[13] that a spatial harmonic with frequency ν can repeat itself under plane-wave illumination at observation planes that are located at a distances $z_s = 2/\lambda\nu^2$ from each other, starting from the object plane. In intermediate planes, the amplitude of the spatial harmonic changes gradually until it vanishes. It is clear, then, that the thickness variation of the spacer should be much less than z_s. For 0.5-μm resolution with a main spatial frequency of 2000 mm^{-1}, we find that $z_s \approx 1$ μm. This value shows that it is extremely important to maintain separation uniformity.

In order to make the holographic techniques presented here applicable to submicrometer lithography, and to stay in keeping with the solutions to the common problems of uniformity of illumination, one should take into account the effect of the large hologram size. In diffraction theory it is known that a larger hologram size permits an increase in image distance, while the same resolution is maintained. Numerical analysis of the image distance problem was performed in Ref. 14, where the diffraction pattern of each spatial harmonic was found to be modulated by a diffraction pattern of a clear aperture of the size of the hologram. The diffraction pattern of a clear aperture in the near field repeats the aperture profile, but with ripples, and can be described by using a Fresnel integral function with only the unitless parameter $p = R(2/\lambda z)^{1/2}$, where R is the linear size of the hologram. Thus, if the a proper value of p is chosen, to make the ripples' effect on the clear-aperture pattern unnoticeable we can increase the separation distance as the size of the hologram becomes larger.

In summary, we conclude that a combination of TIR geometry and volume holography can provide holographic microlithography in the submicrometer range. By fixing the distance between the holographic plate and the image plane, a reproducible aberration-free result has been achieved. The submicrometer holographic imaging system is relatively simple and, therefore, dramatically lower in cost than existing microlithography patterning systems. In contrast to the holographic lithography setup installed in a conventional stepper,[10] the method reported here generates a lensless holographic lithography system with high throughput by introducing a large-aperture, well-collimated beam. Furthermore, the holographic imaging system provides us with a half-micrometer resolution image when a 457.9-nm visible argon line is used. Such resolution can only be achieved using UV light in a conventional lithography machine. Advancement of this program will be reported in future publications.

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References

1. D. J. Ehrich and J. Y. Tsao, *Laser Microfabrication* (Academic, San Diego, Calif., 1989), Part I, pp. 3–26.
2. E. B. Champagne, J. Opt. Soc. Am. **57,** 51 (1967).
3. J. W. Goodman, *Introduction to Fourier Optics* (McGraw-Hill, New York, 1968), Chap. 3, p. 86.
4. Yu. S. Andreev, L. Sadovnik, and V. V. Tarnovetsky, USSR patent 1508190 A1 (October 1985).
5. K. A. Stetson, Appl. Phys. Lett. **11,** 225 (1967).
6. K. A. Stetson, Appl. Phys. Lett. **12,** 363 (1968).
7. H. Nassenstein, Opt. Commun. **2,** 231 (1970).
8. J. J. Cowan, Proc. Soc. Photo-Opt. Instrum. Eng. **402,** 25 (1983).
9. R. Dändliker and J. Brook, in *Proceedings of IEE Conference on Holographic Systems, Components and Application* (Institution of Electrical Engineers, London, 1989), p. 311.
10. J. Brook and R. Dändliker, Solid State Technol. **32,** 91 (1989).
11. K. A. Stetson, Optik **5,** 520 (1969).
12. H. Kogelnik, Bell Syst. Tech. J. **48,** 2909 (1969).
13. J. T. Winthrop and C. R. Worthington, J. Opt. Soc. Am. **58,** 629 (1968).
14. L. Sadovnik, Yu. S. Andreev, and V. V. Tarnovetsky, Opt. Spectrosc. (USSR) **63,** 363 (1987).