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Limitations of Submicron Holographic Lithography

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Abstract

Hologram recording geometry using total internal reflection (TIR) from a photo sensitive material surface was used to achieve 0.5 micron resolution at $\lambda = 457$ nm with a readout of reconstructed image on photoresist. Such a geometry has demonstrated stability to parallel displacement within the illuminated area, and a rotation of ± 2 degrees. The TIR recording system provided double fringe sets for each plane component inside the volume hologram. Therefore, diffraction efficiency as high as 80% was observed. The result is applicable to high volume submicron lithography and can be expanded for an eight-inch semiconductor submicron pattern. The use of a large aperture, well collimated laser beam provides us with much higher throughput than existing lightography machines have.

1.0 Introduction

Holographic lithography is still an attractive goal for researchers due to the inexpensive and lensless technology it implies[1]. In order to meet the growing requirement for submicron resolution, all holographic aberration should be eliminated as first proposed by E. B. Champagne [2]. However, the diffraction limit has restricted the resolution of a pattern which could be transferred from an original to a hologram. It is well known [3] that the maximum spatial frequency of a sinusoidal component which will produce a diffracted plane wave in free space is $\nu \leq 1/\lambda$. In this paper, the Argon laser wavelength $\lambda = 457.9$ nm, which imposes a half-micron resolution limit, was employed. Another approach is the use of evanescent wave illumination described in Reference 4. Theoretically, it seems to be applicable to submicron lithography. Here we report the first half-micron holographic lithography process using large aperture, well collimated light and no scanning device.

Since K. A. Stetson's pioneering work [5,6], there has been continuous interest in improving resolution and signal-to-noise ratios by using TIR holograms. We revise the previous non-paraxial optical image work [7] by combining TIR illumination of a holographic mask which is made of volume holographic material and maintaining identical geometries for recording and reconstruction. In this paper, a volume holographic recording system utilizing TIR geometry which has initially resulted in 0.5 micron resolution and a signal-to-noise ratio better than 10 dB in the reconstructed image is reported.

Recently a holographic printing system was installed in a conventional proximity printer by European researchers to obtain submicron resolution[8]. A scanning reconstruction regime was used to provide highly uniform illumination and to maximize 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 which is of the order of twice the hologram-to-photoresist spacing" [9]. Considering that this conclusion has to be proven, we tested the simultaneous illumination of the holographic mask as a whole. In this way we were able to provide uniform illumination (with up to 1% accuracy) over the 2 x 2 square inch area of the holographic mask.

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2.0 EXPERIMENT

The same arrangement has been used for the recording and the reconstruction process (Figure 1). For the reconstruction, the hologram was rotated 180 degrees around a perpendicular axis so that the same reference beam could be used as a conjugated beam. A schematic explanation of the holographic geometry used is shown in Figure 2. A transparent object (master mask), when illuminated, produces a set of plane waves according to the Fourier expansion of the transmittance. Two sets of interference fringes are generated by each of the object plane waves. For example, the zero-order harmonic is shown in Figure 2. The double fringe structure increases diffraction efficiency to as high as 80% and produces a sharp Bragg diffraction peak that can be seen from spectrophotometric measurements (Figure 3). The relatively high absorption of the polymer film [10] employed in our recording would normally produce considerable nonuniformity. However, this is compensated for by the advantage gained by appropriate post-exposure processing. No shift of the Bragg diffraction peak was observed during and after the hologram formation process. It was found both theoretically and experimentally that the most crucial point for submicron resolution holographic lithography is the separation between the object and hologram in the recording process, and between the hologram and photoresist plane in reconstruction. The separation distance should be kept exactly the same for both processes. Indeed, reproducible results were consistently achieved when fixed spacer of 50 micron thickness was used for recording and reconstruction.

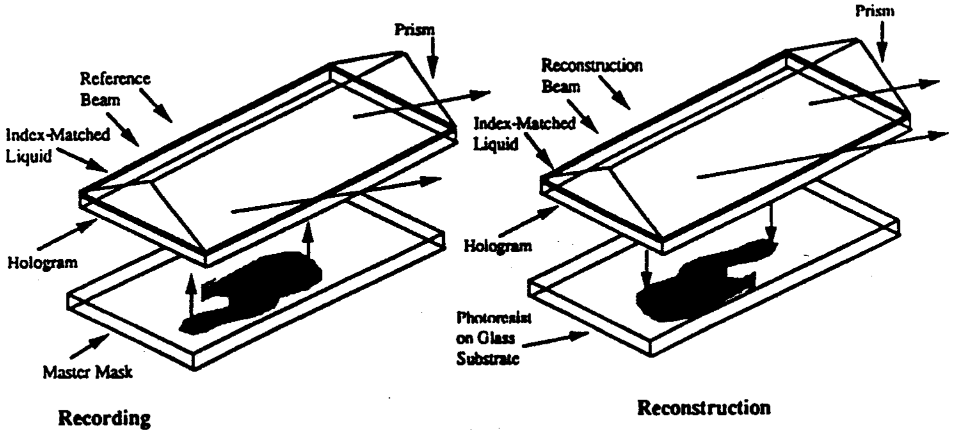

Figure 1 Holographic microlithography with TIR set up.

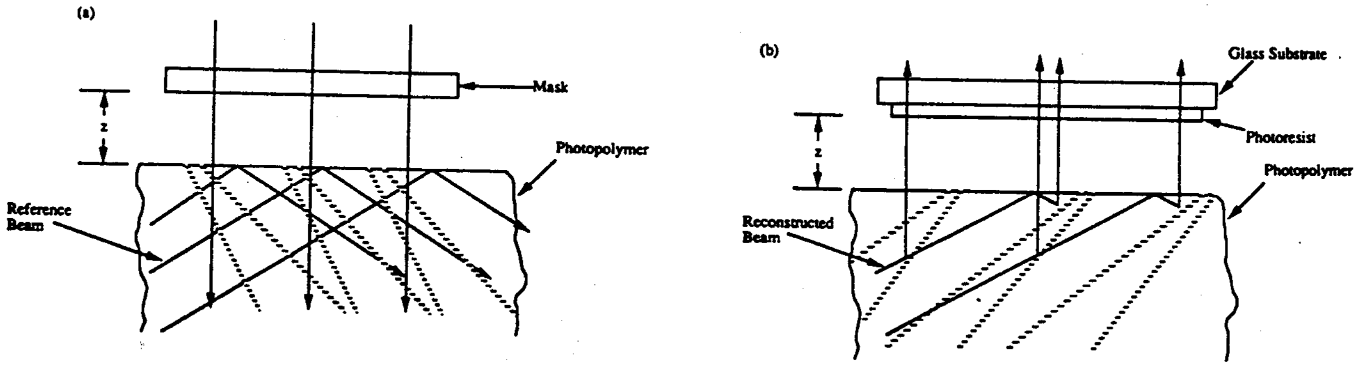

Figure 2 (a) Recording and (b) reconstruction geometries. Two sets of fringes ar shown by dashed lines. The hologram has been rotated on 180° for readout

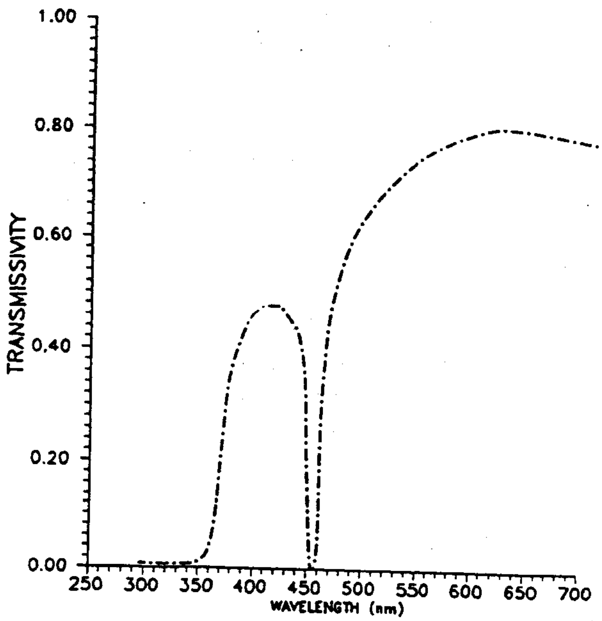

Figure 3 **Spectral transmittance of the volume hologram recorded without mask.**

The master mask consists of e-beam 0.5 micron width chromium lines on glass substrate and the whole length is 1 inch. The resulting holographic image was reconstructed on a photoresist plate [Figure 1(b)]. Figure 4 is a picture of the half-micron size holographic image recorded on photoresist, taken under reflected light. The 1 x 1 square inch image was found fairly uniform due to the accuracy of the aforementioned spacer thickness. To show how small this deviation should be we refer to "self-imaging" phenomena. It is well-known [11] that a spatial harmonic with frequency υ can repeat itself under plane wave illumination in observation planes which are located at a distance $z_s = 2/\lambda\upsilon^2$ from each other, starting from the object plane. In intermediate planes the amplitude of the spatial harmonic is changed gradually until it has fully vanished. Based on this explanation, it is clear that the thickness variation of the space should be much less than z_s. For 0.5 μm resolution with main spatial frequency 2,000 mm^{-1}, we find $z_s \approx$ 1 μm. This value shows that it is extremely important to maintain separation uniformity.

3.0 FURTHER DISCUSSION

The TIR hologram was found to be insensitive to parallel shifting within the illuminated area and rotation within ±2° range. The latter is in good agreement with Kogelnik's theoretical expression for the dephasing measure ϑ [12],

$$\vartheta = \Delta\theta\, K \sin(\phi - \theta_0) - \Delta\lambda\, K^2 / 4\pi n \qquad (1)$$

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 Figure 3) implies that an angular selectivity

$$\Delta\theta = \frac{\Delta\lambda}{\lambda}\tan(\phi - \theta_B) = 4.5^0 \qquad (2)$$

is expected.

In order to make the present holographic technique applicable to submicron lithography (in addition to the common precautions such as uniformity of illumination), one should take into account the effect of the large hologram size. In diffraction theory it is known that the larger hologram size allows an increase in the separation distance, while the same resolution is maintained. Numerical consideration of this problem was done in Ref. [13] where a diffraction image of each spatial harmonic was found to be modulated by a diffraction image of a clear aperture of the size of the hologram. The diffraction pattern of a clear aperture can be described using a Fresnel function with the only unitless parameter $p = R\sqrt{\frac{2}{\lambda z}}$, where R is the linear size of the hologram. Thus, once a proper value of p is chosen, to make the clear aperture effect 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 the capability of holographic microlithography in the submicron range. By fixing the distance between the holographic plate and the image plane, a reproducible aberration free result was achieved. Further theoretical calculation ensures that the technology reported herein is capable of producing large area, submicron lithography. The submicron holographic imaging system is relatively simple and, therefore, the cost is expected to be reduced drastically. In contrast to the holographic lithography set up installed in a conventional stepper [9], the method reported herein 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-micron resolution image when a 457 visible Argon line is used. Such resolution can only be achieved using deep UV in a conventional lithography machine. Advancement of this program will be reported in future publications.

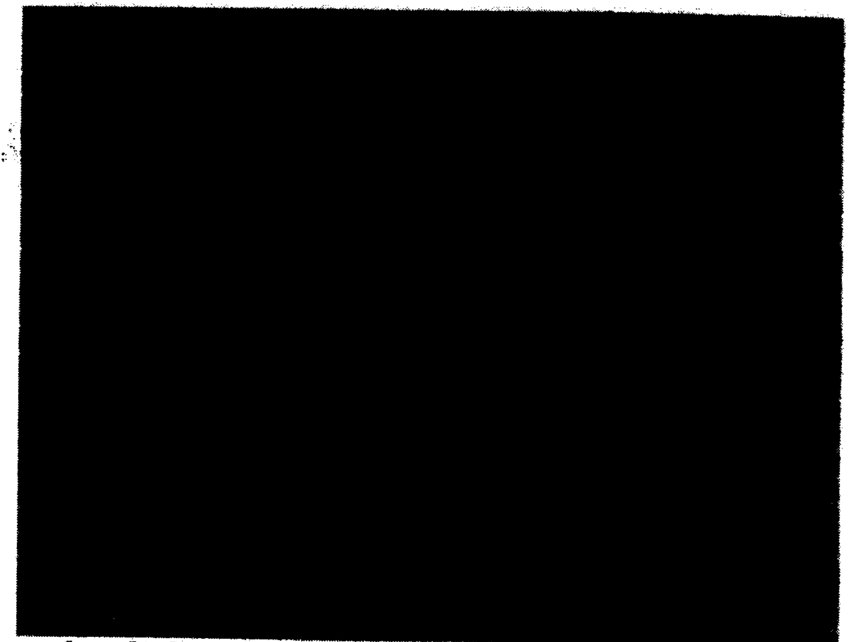

Figure 4 **Photograph of the 0.5 micron resolution holographic image recorded on photoresist. Magnification 1500 x (original photograph is magnified four times).**

4.0 REFERENCES

1. D. J. Ehrich and J. Y. Tsao, Laser Microfabrication, (Academic Press Inc, San Diego, 1989), Part I, p. 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. H. Nassenstein, Opt. Comm., 2, 231 (1970).
5. K. A. Stetson, Appl. Phy. Lett. 11, 225 (1967).
6. K. A. Stetson, Appl. Phys. Lett., 12, 363 (1968).
7. Yu. S. Andreev, L. Sadovnik, V. V. Tarnovetsky, USSR Patent No. 1508190 A1, Oct. 1985.
8. R. Dändliker and J. Brook, IEE Conf. Proc. Holographic Systems, Components and Application (Bath, UK, 1989), p. 311.
9. J. Brook and R. Dändliker, Solid State Technology, November, 91 (1989).
10. B. L. Booth, Appl. Opt. 14, 593, (1975).
11. J. T. Winthrop and C. R. Worthington, J. Opt. Soc. Am., 58, 629 (1968).
12. H. Kogelnik, Bell System Tech. J. 48, 2909 (1969).
13. L. Sadovnik, Yu. S. Andreev, V. V. Tarnovetsky, Opt. Spectrosc. 63, 363 (1987).