Optical microlithography with nearly nondiffracting beams

Miklós Erdélyi[a] , Zoltán L. Horváth[a], Zsolt Bor[a], Gábor Szabó[a]
Joseph R. Cavallaro[b], Michael C. Smayling[b], Frank K. Tittel[b]

[a] JATE University, Department of Optics and Quantum Electronics,
H-6720, P. O. Box 406, Szeged Dóm tér 9, Hungary
[b] Rice University, ECE Department, MS 366, 6100 Main
Houston, TX 77005-1892, USA, Tel.:(713) 527-4719

ABSTRACT

A new concept based on a Fabry-Perot interferometer for the generation of nearly nondiffracting Bessel beams is described experimentally and theoretically, and proposed for potential applications in microlithography such as the fabrication of small isolated patterns. It was demonstrated that the depth of focus can be increased by a factor of about 2, and simultaneously the transverse resolution improved by a factor of 1.6, when using this technique to image contact holes. The theoretical curves show very good agreement with the measured intensity distribution. The properties of simultaneous imaging of two contact holes were also investigated. It was shown experimentally that even in the most critical case (when the first diffraction rings overlap), undesirable interference effects between the adjacent contact holes can be eliminated by means of a phase shifting technique.

Keywords: microlithography, nondiffracting beams, phase shifting, depth of focus

1. INTRODUCTION

Photolithography is the current leading technology in modern microlithography. The main "yardstick" of lithographic techniques is the Depth Of Focus (*DOF*) and the Critical feature size (*CD*). As projection optics reach its resolution limits, new techniques are necessary for further enhancement of *CD* and *DOF*. The principal problem is that both the critical feature size and the depth of focus are functions of the wavelength (λ) and the numerical aperture of the lens (NA): when the wavelength is reduced *CD* and *DOF* also decrease, and when *NA* is increased *CD* and *DOF* also decrease [1]. To address this issue new "super resolution" techniques have been proposed. The essential requirements for these methods are: simplicity, low cost, minimal technical changes in the steppers and easy implementation. Off-axis illumination [2] improves the imaging of periodic patterns but does not offer advantages for imaging other features, and special optical proximity correction (*OPC*) is needed to avoid image distortions. Different phase shifting methods [3] can increase the resolution by a factor of about 1.5, but the design and fabrication issues cause several problems. The phase layer must have the correct transmission and phase shift; the required accuracy

0277-786X/97/$10.00

is generally 5°. Multiple focal plane exposure techniques (FLEX [4], SUPERFLEX) are especially effective for imaging isolated patterns such as contact holes. A combination of such techniques will apply to excimer laser illumination sources optical microlithography towards sub-quarter micron geometries.

This paper reports a new technique based on image multiplication which similarly to FLEX (where several focal planes are created at different positions along the optical axis, and exposures are made at each focal plane), creates multiple images of the mask onto the wafer without requiring any mechanical shift. In this process not the intensities but the electric fields have been added, and hence the phase difference between the images becomes an important factor.

2. THEORY AND THE EXPERIMENTAL SETUP

The application of a Fabry-Perot (FP) interferometer as a spatial filter was reported by Indebetouw [5]. He already used the simple interpretation that "If an image is projected between the plates of a FP, the multiple reflections on the mirrors of the cavity produce a set of images spaced longitudinally by a distance $2d$ (where d is the separation of the mirrors). The field producing such a set of images is periodic with a period $2d$." Such a statement is true if the separation of the images is significantly larger than the depth of focus belonging to one image. If the separation of the images are equal or smaller than the DOF, then interference effects play primary role. The phase conditions strongly determine the final image properties.

Since in optical microlithography a DOF of 1 to 2 μm is sufficient, our purpose (in contrast with that of Ref. [6,7]) is not to generate a large-range constant-axial-intensity beams, but increase the DOF only by a factor of about 2. In Ref. [6,7] the generation of nearly nondiffracting Bessel beams was based on the imaging of an annulus placed in the focal plane of the lens. This annulus was created either with a circular slit or imaging and filtering the ring system of a Fabry-Perot interferometer. In our experiments the Fabry-Perot interferometer is placed directly in front of the projection lens, and no other lens is used as in Ref. [7]. The schematic arrangement of our experimental setup is shown in Figure 1.

A $He - Ne$ laser operating at 632.8 nm illuminates a microscope objective ($NA = 0.65$). Due to the relatively high numerical aperture, the objective creates a nearly point like light source (I_0). This point source illuminates a scanning Fabry-Perot interferometer (Tropel CL-100) which produces a concentric ring system behind the etalon. The aperture of an objective lens placed after the interferometer is adjusted so that it transmits only the first Fabry-Perot ring (at the rim of the aperture) and blocks all the others. Due to multiple reflections in the interferometer, the real point like source I_0 creates several virtual images (I_1, I_2, I_3, ...). The distance between these images is $2d$, and the intensity ratio is R^2 between adjacent individual sources, where R is the reflectivity of the Fabry-Perot mirrors. The measured value of R is 96.2%. The distance between the virtual point sources can be changed as the separation of the interferometer is adjustable with a piezo translator.

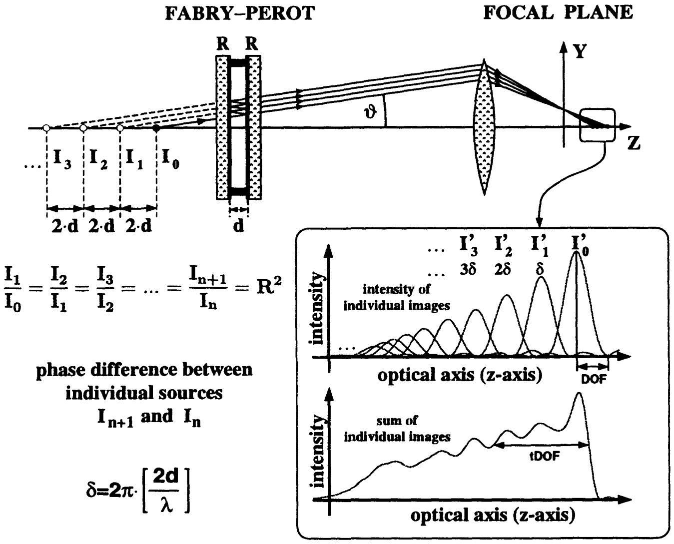

Figure 1: The image produced by the objective lens is the superposition of the images of the individual point sources.

The relative phase difference (δ) between the adjacent point sources is related to d by

$$\delta = 2\pi \cdot \frac{2d}{\lambda} \,. \tag{1}$$

The image produced by the objective is the superposition of the images of individual point sources. The distance between these points is $2dM^2$, where M^2 is the longitudinal magnification of the objective lens. (The transverse magnification M was measured using USAF Test Target and was found to be $M = 0.156$.) The spatial intensity distribution was calculated numerically using a wave optical model.

3. EVALUATION OF THE EXPERIMENTS

The image produced by the objective lens was magnified by two microscope objectives in tandem (with about 100 overall magnification) and monitored with a CCD camera (horizontal center-to-center spacing of pixels: 23 μm). The theoretically predicted intensity distribution in planes perpendicular to the optical axis is a J_0 function. The measured intensity distribution supports this prediction (see Figure 2). The circles depict the measured intensity distribution, and the solid line shows the fitted J_0 Bessel function. The intensity of the high order diffraction rings of the measured curve attenuates somewhat faster than the J_0 function. The small difference between the two curves can be explained by the finite size of the aperture. Each diffraction ring of the zero order Bessel function contains roughly equal amounts of energy; therefore, over an infinite plane the energy would be infinite. It is obvious that beams with infinite energy cannot be realized experimentally, and therefore the higher diffraction rings of the measured beam disappear. For instance, the intensity of the 12th and higher diffraction rings of the measured pattern depicted in the inset of Figure 2 is effectively zero.

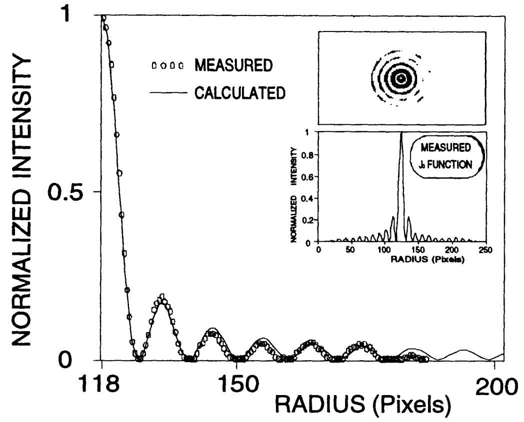

Figure 2: The measured intensity distribution perpendicular to the optical axis is quasi equivalent to a zero order Bessel function. The solid line shows the fitted curve to the measured intensity distribution (depicted by circles)

A comparison of the measured Bessel distribution and the Airy pattern shows (with good agreement of the theoretical description [8]) that the FWHM of the Bessel beam is 1.6 times smaller than the FWHM of the Airy pattern. This decrease means an enhancement in the transverse resolution power, but it also has some disadvantages. The intensity of the successive diffraction rings are 16%, 9%, 6.2% ..., while the same values for the Airy pattern are 1.7%, 0.42%, 0.16% .... The interference of these relatively high intensity rings can cause problems if several points are imaged simultaneously. The overlapping of the first rings is critical for microlithography, as these rings have the highest intensity of all the diffraction rings.

The image produced by the objective lens is the superposition of images of the individual point like sources. The depth of focus of all these individual images are the same (i.e. in our case it was 213 μm). It is possible to distinguish different cases depending on how many individual image points are in the range of one DOF. Let us define the relative image density (N) as

$$N = \frac{DOF}{2dM^2}. \tag{2}$$

The relative image density is an important factor in determining the shape of the axial intensity distribution. The distance between the image points (I'_0, I'_1, I'_2 ...) gradually decreases by increasing the N ratio (reducing d). Four different experimental cases were studied and compared with the theory (see Figure 3).

In the first case ($N = 0.5$), the distance between the image points is twice the DOF, and therefore the images can be observed separately. By decreasing the distance between the image points, the sharp peaks disappear and the intensity decreases faster on the optical axis. From a microlithographic point of view, oscillations in the intensity distribution are undesirable. By increasing N, the curves become smoother and the oscillations disappear. In the last case ($N =$

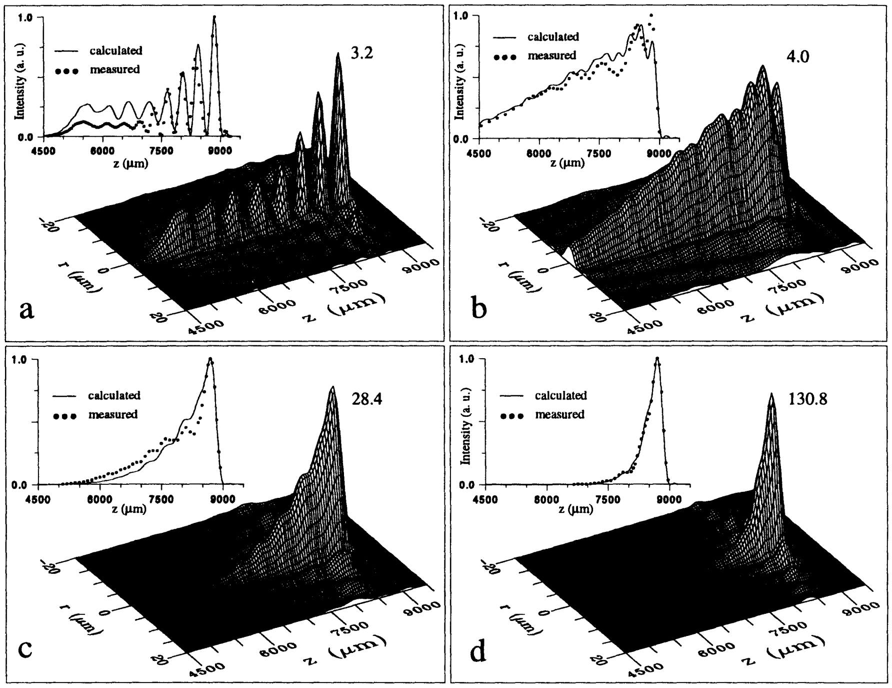

Figure 3: The spatial intensity distribution for different values of image densities ($N = 0.5; 1.5; 4; 10$). The inset show a comparation of the measured and the calculated axial intensity distribution. The numbers close to the peaks shows the intensity maxima in arbitrary units.

10), no oscillations occur. Since in case of superimposed images the first minimum is not zero, it is necessary to give a new definition of DOF denoted by $tDOF$. $tDOF$ is defined as the range where the intensity is larger than half of the main peak. The insets of the figures show normalized intensity, but in reality (due to the law of conservation of energy) by increasing N, the intensity of the main peak increases. The numbers close to the peaks show the intensity maxima in arbitrary units. The $N = 4$ case is optimum for microlithographic applications. The oscillations have disappeared, and the $tDOF$ range is twice as large as without the Fabry-Perot interferometer.

The depth of focus enhancement can be roughly predicted using a very simple model. Combining the relations that describe the intensity difference is $1 - R^2$ and the distance is $2dM^2$ between two adjacent image points, we can write

$$\ln(I) = -\frac{1 - R^2}{2dM^2} z . \tag{3}$$

From Eq. 3 a simple estimate can be given for $tDOF$.

$$tDOF = K \cdot DOF \quad \text{where} \quad K = \frac{1}{N} \cdot \frac{\ln(2)}{1 - R^2} . \tag{4}$$

If $N = 4$ the predicted increase of depth of focus is $K_p \approx 2.21$, while the measured value is about $K_m \approx 2.05$. Such a model is valid for a range of N. The two main limitations are: (1) The model does not consider that for $N < 1$ the image points separate and thus the $tDOF$ is approximately equal to DOF; (2) From Eq. 4 it can be seen that with increasing N, K (and thus $tDOF$) decreases and tends to zero. Fortunately, the range where the approximation is valid (from $N = 3.2$ to $N = 7$ the difference between the measured and the predicted value is less than 20%) coincides with the range that is applicable to microlithography.

4. SIMULTANEOUS IMAGING OF TWO POINT SOURCES

In microlithography it is often necessary to expose several contact holes simultaneously. To study the properties of imaging two contact holes (with special regard to the most critical case, when the first diffraction rings overlap), we placed a Michelson interferometer in front of the Fabry-Perot etalon. The experimental setup is shown in Figure 4.

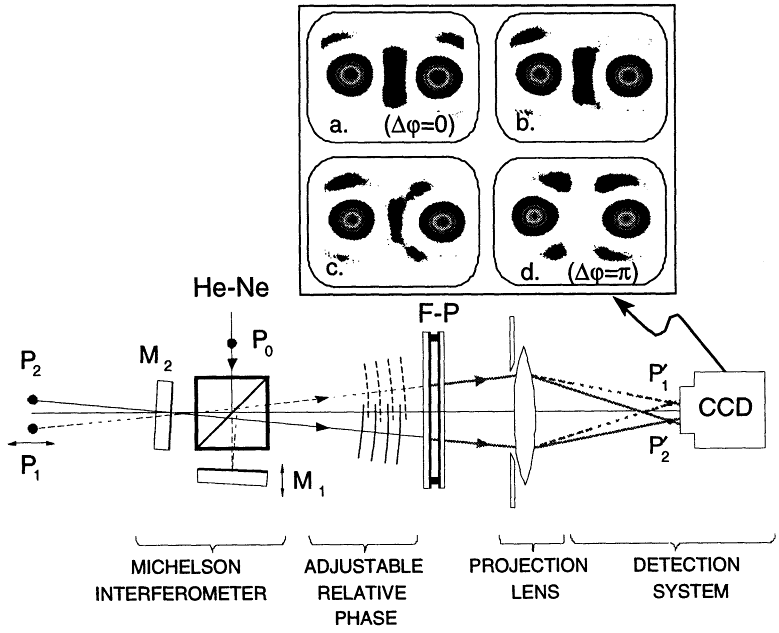

Figure 4: Imaging of two coherent point sources formed by a Michelson interferometer. The transverse distance and the relative phase difference between the sources was adjustable by translating and tilting the mirrors. The inset shows CCD images for different phase conditions

The interferometer created two virtual point sources (P_1 and P_2) behind the mirror M_2. By slightly turning the mirrors M_1 and M_2, the relative transverse separation of P_1 and P_2 could be adjusted. Mirror M_1 was equipped with a PZT translator; thus, the relative phase difference between the virtual P_1 and P_2 could be arbitrarily adjusted. The inset of Figure 4 shows four different cases. In case *a* there is constructive interference between the first diffraction rings (the phase shift is 0), and the intensity between the two main peaks can reach 64%. Pictures *b* and *c* show intermediary cases, when the phase shift is in the range of 0 to π. In case *d* the phase difference is π and, due to the destructive interference, the intensity maximum between the main peaks is zero. These experiments, where the effect of a phase shift mask was simulated by a Michelson interferometer, show that even in the most critical case the undesirable effects of the interference of the diffraction rings can be considerably reduced with a phase s hifting mask.

5. DISCUSSION AND CONCLUSIONS

Our experiments have demonstrated that for appropriate phase conditions the depth of focus can be increased significantly and that the transverse resolution improved by a factor of 1.6 when this technique is used to image isolated patterns such as contact holes. These experimental results agreed very well with the numerically calculated intensity distributions. Although these results were performed with visible laser illumination, this method can be employed for i-line and deep UV lithography. For applications in a real optical stepper, further investigations are neccessary to determine the appropriate insertion point, reflectivity and thickness of the Fabry-Perot etalon. Insertion of a thin Fabry-Perot layer between the lens and the wafer has several advantages (e.g. separation of the images is independent of the magnification), however scattering may decrease the image quality.

ACKNOWLEDGEMENT

This research was supported in part by Texas Instruments, NSF under grants DMI-9202639 and INT-9020541, and by the OTKA Foundation of Hungary (No. T20910, F020889 and W015239).

REFERENCES

1. D. J. Ehrlich and J. Y. Tsao, *Laser Microfabrication* pp 59, Academic Press INC. 1989.
2. P. Luehrmann, P. van Oorschot, H. Jasper, S. Stalnaker, S. Brainerd, B. Rolfson and L. Karklin: 0.35 μm Lithography Using Off-Axis Illumination, Proc. SPIE **1927**, 103, (1993).
3. M. D. Levenson: Extending the Lifetime of Optical Lithography Technologies with Wavefront Engineering, *Jpn. J. Appl. Phys.* **33**, 6765-6773, (1994).
4. H. Fukuda, N. Hasegawa and S. Okazaki: Improvement of defocus tolarance in a half-micron optical lithography by the focus latitude enhancement exposure method: Simulation and experiment, *J. Vac. Sci. Technol. B* **7(4)**, Jul/Aug (1989)
5. G. Indebetouw: Self-imaging through a Fabry-Perot interferometer, *Optica Acta*, **30(10)**, 1463-1471, (1983).
6. J. Durnin, J.J. Miceli, Jr., and J.H. Eberly: Diffraction-Free Beams, *Phys. Rev. Lett.* **58**, 1499 (1987).

7. A.J. Cox and D.C. Dibble: Nondiffracting beam from a spatially filtered Fabry-Perot resonator, *J. Opt. Soc. Am.* **9**, 282 (1992).

8. W.T. Welford: Use of Annular Aperture to Increase Focal Depth, *J. Opt. Soc. Am.* **50**, 749 (1960).