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Sub-quarter micron contact hole fabrication using annular illumination

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ABSTRACT

Details of an experimental demonstration of a contact hole imaging system are reported in which the depth of focus is increased by a factor of about 3.5 using annular illumination. Due to spatial filtering and nonlinearity of the photoresist, the resolving power was enhanced by 52% and it was possible to pattern a 0.28 μm contact hole in photoresist deposited on a silica substrate. This technique is capable of fabricating sub-quarter micron holes using excimer laser radiation at 193 nm.

Keywords: annular aperture, microlithography, depth of focus

1. INTRODUCTION

The fabrication of extremely small contact holes is one particular challenge in ultra large scale integrated circuits manufacturing. The resolving power (W) of an imaging system is determined by diffraction effects and is given by $W=0.61\cdot\lambda/NA$ [1] , where λ is the wavelength and NA is the numerical aperture of the projection lens. Recently several "super" resolution techniques have been proposed [2-6] to overcome this limit in the resolution power. On the other hand, the loss of depth of focus with increasing resolution is a fundamental problem in optical lithography. The depth of focus is given by $DOF\sim W/NA$ [1]. From these relationships it can be seen that a simultaneous enhancement of the DOF and the resolution power is not possible with a simple modification of either the NA or the wavelength. It has been known for some time that blocking out the centre of the aperture of an optical system - using an annular aperture - makes the central maximum in the Airy pattern narrower and increases the depth of focus. In this paper we experimentally demonstrate this simultaneous enhancement of the resolution power and DOF.

2. THEORY

The intensity distribution near the focus in error-free diffraction patterns of circular and annular apertures has been theoretically investigated by several authors[7-12]. This section summarizes the most important theoretical results.

Consider a lens of focus length f and let it be illuminated by plane waves of wavelength λ (see Figure 1). The radius of the lens aperture is R. To describe the intensity distribution near the focus two variables u and v are introduced which are defined as

$$u = \frac{2\pi R^2}{\lambda f^2} z, \qquad v = \frac{2\pi R}{\lambda f} r; \tag{1}$$

where r is polar coordinate ($r^2 = x^2 + y^2$), and z is the axial distance from the focus point.

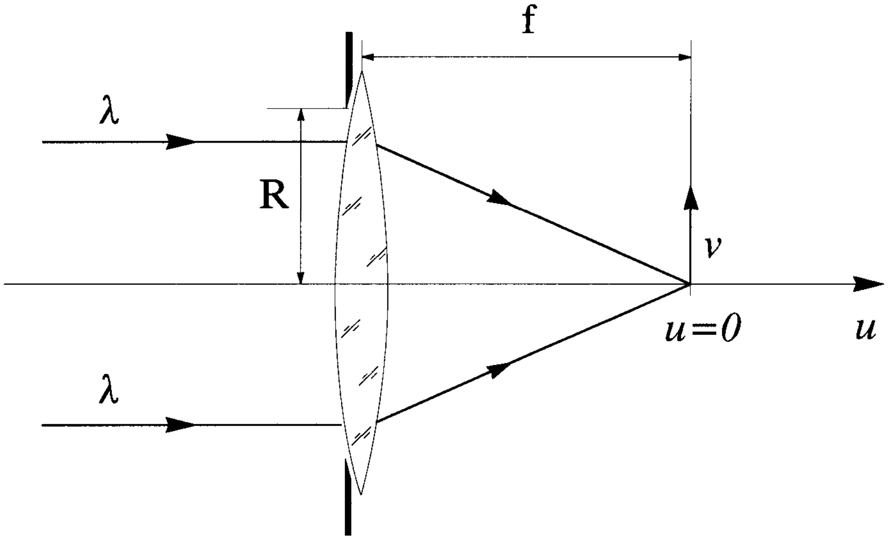

Figure 1. Illustration of the focusing properties of a lens.

The intensity distribution in the geometrical focal plane is given by the well-known Airy pattern

$$I(0,v) = \frac{4\pi^2 R^4}{\lambda^2 f^2} \left(\frac{2J_1(v)}{v} \right)^2, \tag{2}$$

where J_1 is the first order Bessel function. The v value characteristic of the first dark ring is 3.832. Thus the resolution power (in terms of the Rayleigh criterion) can be given as

$$W \approx 0.61 \cdot \frac{\lambda}{NA} \qquad \text{where} \qquad NA = \frac{R}{f} \tag{3}$$

The intensity distribution along the axis ($v = 0$) is

$$I(u,0) = \frac{4\pi^2 R^4}{\lambda^2 f^2} \left(\frac{\sin(1/4\,u)}{1/4\,u} \right)^2 . \tag{4}$$

The argument of the sine function equals π in the case of the first minimum. *DOF* can be expressed as the distance between the first minimum and the main maximum:

$$DOF = 2 \cdot \frac{\lambda}{(NA)^2} \quad \left(\approx 3.28 \cdot \frac{W}{NA} \right) \ . \tag{5}$$

If the central portion of the exit pupil is blocked out so that the aperture consists of an annulus between circles R and ϵR, the obstruction ratio (ϵ) can vary in the range from 0 to 1. The intensity distribution in the focal plane becomes

$$I(0,v) = \frac{4\pi^2 R^4}{\lambda^2 f^2} \cdot \left(\frac{2J_1(v)}{v} - \epsilon^2 \frac{2J_1(\epsilon v)}{\epsilon v} \right)^2 . \tag{6}$$

This equation shows that the diffraction pattern of an annular ring is the diffraction pattern of the whole aperture extending to the outer circumference, minus that of the inner, opaque, region. An increase in ϵ leads to a decrease in the radius of the first dark ring. As ϵ tends to unity, the expression inside the bracket of equation 6 tends to $(1-\epsilon^2)J_0(v)$, where $J_0(v)$ is the zero order Bessel function of the first kind. In the limiting case the FWHM of the Bessel beam is 1.6 times smaller than the FWHM of the Airy pattern.

The intensity distribution along the optical axis is given by

$$I(u,0) = \frac{4\pi^2 R^4}{\lambda^2 f^2} \cdot \left(\frac{\sin 1/4u\,(1-\epsilon^2)}{1/4u} \right)^2 . \tag{7}$$

A comparation of this expression with equation (4), indicates that the separation of the successive dark points on the optical axis is increased by a factor of $1/(1-\epsilon^2)$, and tends to infinity as ϵ tends to unity. Equations (6) and (7) show that the DOF and resolution power can be enhanced simultaneously using an annular aperture. The drawback of this technique is that an n-fold gain in focal depth leads to an n-fold loss in the intensity of the illumination light.

3. EXPERIMENT

This section reports on an experimental demonstration in which the DOF is increased by a factor of about 4 without any loss in transversal resolution, based on the theory described above.

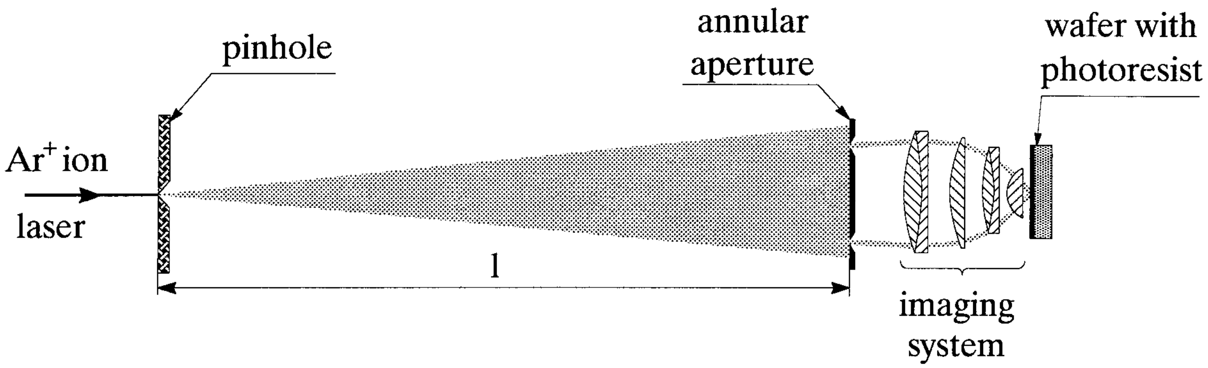

Figure 2. Schematic diagram of the experimental arrangement.

The experimental arrangement is shown in Figure 2. An Ar$^+$ ion laser beam (λ=457 nm) illuminates a pinhole of 50 μm in diameter (*D*).

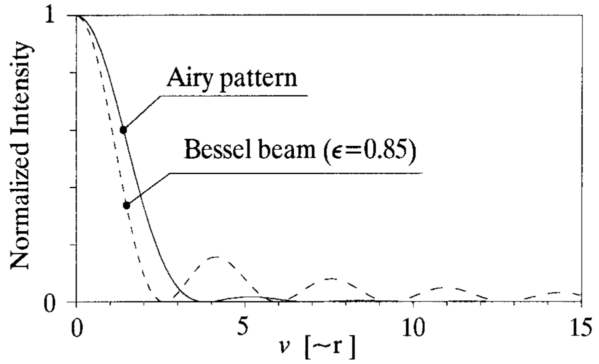

Figure 3. Comparison of the transversal intensity distribution of the Airy pattern and Bessel beam (for the case of ε=0.85).

The distance between the pinhole and the annular aperture (l) was chosen so that the illumination of the aperture was homogeneous $(l\cdot\lambda/D\approx 3R)$. The outer and inner radius of the annular aperture was 4.75 mm and 4 mm respectively, corresponding to an obstruction ratio of $\epsilon=r/R\approx 0.85$. The projection optics consisted of a microscope objective (*M*=40, *NA*=0.65). During the experiment the whole NA was not used, just 74% of it, so thus the effective numerical aperture (*NA'*) was 0.48. Thus the theoretically predicted (see equation 3) hole diameter without annular aperture was 0.58 μm and a 0.44 μm hole was expected using the annular aperture. Figure 3 shows the theoretically calculated intensity distributions in the focal plane of the circular and annular (ϵ=0.85) aperture. However, due to the nonlinearity of the resist, the diameter of the hole could in fact be even further decreased by 36 %. Figure 4 depicts a 0.28 μm contact hole exposed in photoresist (Shipley XP 94314).

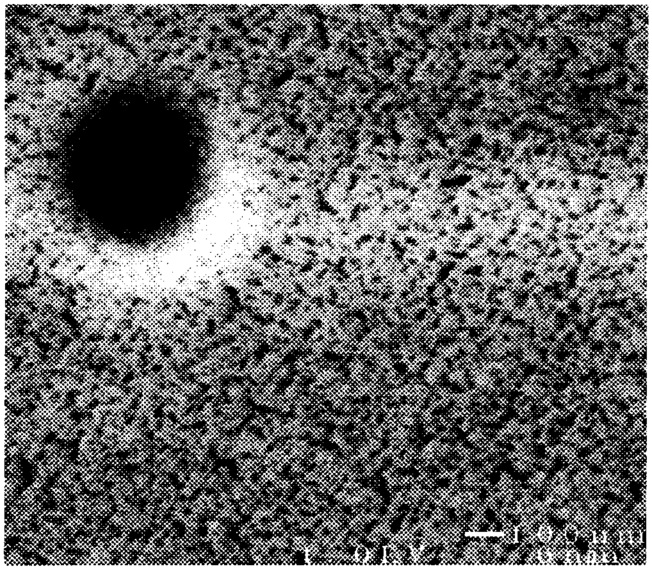

Figure 4. SEM picture of a 0.28 μm contact hole exposed in photoresist.

4. CONCLUSIONS

This paper experimentally demonstrated the simultaneous enhancement of resolution power and *DOF* using annular aperture. Due to the spatial filtering and the nonlinearity of the photoresist the theoretically expected 0.58 μm hole diameter was decreased by 52% and thus a 0.28 μm hole was patterned in photoresist. This technique is capable of fabricating sub-quarter micron holes using excimer laser radiation at 193 nm.

5. ACKNOWLEDGEMENT

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