Photon-sieve lithography

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Photon-sieve lithography

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We present the first lithography results that use high-numerical-aperture photon sieves as focusing elements in a scanning-optical-beam-lithography system [J. Vac. Sci. Technol. B **21**, 2810 (2003)]. Photon sieves are novel optical elements that offer the advantages of higher resolution and improved image contrast compared with traditional diffractive optics such as zone plates [Nature **414**, 184 (2001)]. We fabricated the highest-numerical-aperture photon sieves reported to date and experimentally verified their focusing characteristics. We propose two new designs of the photon sieve that have the potential to significantly increase focusing efficiency. © 2005 Optical Society of America

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1. INTRODUCTION

Lithography has been the leading contributor to the exponential increase in computing power achieved via semiconductor electronics. As a result, the development of lithographic technology has led to systems that put a premium on high throughput and reliability, with cost, flexibility, and broader applicability largely overlooked. The expansion of nanoscale science and engineering will require lithographic techniques and systems other than those employed in the semiconductor industry, for reasons of both cost and limited flexibility. The research presented in this paper is a step in the direction of providing low-cost, highly flexible lithography.

Maskless zone-plate-array Lithography (ZPAL) uses an array of diffractive lenses, such as zone plates, to focus incident collimated light into an array of spots on a resist-coated substrate.[1] The light incident on each zone plate is modulated by means of an upstream spatial light multiplexer, while the substrate is scanned underneath. Hence patterns of arbitrary geometry are written in a dot-matrix fashion. Since a large number of focused optical beams are writing simultaneously, ZPAL can achieve practical writing speeds.

High-numerical-aperture diffractive lenses can be reliably fabricated with planar fabrication processes.[2] These ensure that focal characteristics are uniform across the array, which is very difficult to achieve with refractive microlenses. Moreover, diffractive lenses operate well at the short wavelengths that are required to extend lithography, to the 10-nm regime. Recently we have demonstrated the feasibility of ZPAL[3] and its potential for the fabrication of novel devices.[4] Although binary-phase zone plates were shown to be capable of high-quality lithography at high resolution, it was recognized that image contrast could be improved with wave-front engineering techniques, as illustrated by the photon sieve. Kipp *et al.* pointed out that the photon sieve can be designed to minimize background in the focal plane.[5] In addition, photon sieves provide the advantage that the size of the focused spot is not limited by the size of the smallest zone, as is the case for traditional zone plates.

2. PHOTON-SIEVE FABRICATION

A photon sieve is composed of pinholes arranged in the radial direction such that their center locations correspond to the open zones of a zone plate. This arrangement ensures that a portion of the light diffracted from the pinholes interferes constructively at a focal point. Azimuthally, the centers of the pinholes are randomly located. The size of a given pinhole is a factor K larger than the corresponding zone width of a zone plate having the same diameter and focal length. K is chosen to maximize the field contribution at the focus.[6,7] The size of the focal spot is smaller by a factor K than the diameter of the outermost pinholes. This reduction factor K relaxes the fabrication requirements for the photon sieve compared with a zone plate of the same numerical aperture (NA). This is especially important when the zones of the zone plate approach the lithographic limits. The random azimuthal arrangement of pinholes eliminates diffraction into higher orders, thereby reducing the background and increasing the overall image contrast. The pinhole density within each zone may be varied with distance from the center to apodize the photon sieve and achieve a further reduction of background.

We fabricated amplitude photon sieves consisting of transparent pinholes on an opaque chromium background, using scanning-electron-beam lithography and self-aligned selective etching of chromium,[8] as illustrated in Fig. 1(a).

A scanning electron micrograph of the central region of an amplitude photon sieve is shown in Fig. 1(b). We fabricated photon sieves with NAs ranging from 0.7 to 0.9, operating at $\lambda = 400$ nm and focal length of 40 μm. These were inserted into our ZPAL system, which uses an exposure wavelength of 400 nm to lithographically define various test patterns.

3. LITHOGRAPHY RESULTS

All the lithography experiments were performed on 7.5-cm silicon wafers, spin coated first with 200 nm of BarLi ARC (spun at 3000 rpm and baked on a hot plate at 175 °C for 90 s) and then with 150 nm of Shipley S1813 photoresist (spun at 5000 rpm and baked on a hot plate at 90 °C for 90 s). After exposure, the substrate was developed in a diluted 351 developer (1:1 with water) for 45 s. Finally, the substrate containing patterns in photoresist was inspected in a scanning electron microscope.

Figure 2 shows scanning electron micrographs of single-spot exposures made with two photon sieves of NA = 0.7 but different values of K. In Fig. 2(a) the photon sieve has $K = 2$; i.e., the minimum pinhole diameter of this sieve was two times the width of the smallest corresponding zone. Accordingly, the exposed spots were 296 nm in diameter, which is approximately half of the diameter of the smallest pinhole in the sieve (573 nm). In Fig. 2(b) the photon sieve has $K = 1.5$. The corresponding exposed spots had a diameter of 314 nm, which is approximately 1.5 times smaller than the diameter of the smallest pinhole (443 nm). This is, to our knowledge, the first quantitative experimental verification of the focusing properties of photon sieves.

Figure 3 shows scanning electron micrographs of dense lines patterned by use of photon sieves of two NAs (0.7 and 0.8) operating at $\lambda = 400$ nm and the reduction factor, $K = 2$. In Fig. 3(a) the photon sieve of NA = 0.7 has a minimum pinhole diameter of 570 nm. The smallest linewidths patterned with this sieve were approximately 270 nm. The lines in Fig. 3(b) were patterned with a photon sieve of NA = 0.8 with a minimum pinhole diameter of 500 nm. The width of the smallest lines in this case was 244 nm. Figure 3(c) shows lines and spaces printed with a photon sieve of NA = 0.9. These results indicate that photon sieves of NA as high as 0.9 focus as expected. Note that these sieves were designed on the basis of scalar diffraction theory. Therefore we would expect some improvement in their performance when a full vector theory is used for their design.

In the case of amplitude photon sieves, the pinholes are transparent, and the rest of the area is opaque. The focusing efficiency of such a photon sieve is lower than that of a zone plate of the same diameter and focal length. To improve efficiency, we propose two new forms of the photon sieve. In the alternating-phase photon sieve, pinholes in alternate zones have a π phase shift. If we ensure that the area of the pinholes in the odd zones is equal to that in the even zones, the zero-order diffraction efficiency is significantly reduced, and, consequently, the focusing efficiency is enhanced. In the phase photon sieve, the entire aperture is transparent, and the pinholes have a phase shift of π with respect to the rest of the aperture. When the area of the phase-shifted pinholes is matched to the area of the rest of the aperture, the zero order is suppressed. Since all incident light is transmitted, proper design can achieve a high focusing efficiency.

In conclusion, we have experimentally shown that high-numerical-aperture amplitude photon sieves function as theoretically predicted. We have used such ele-

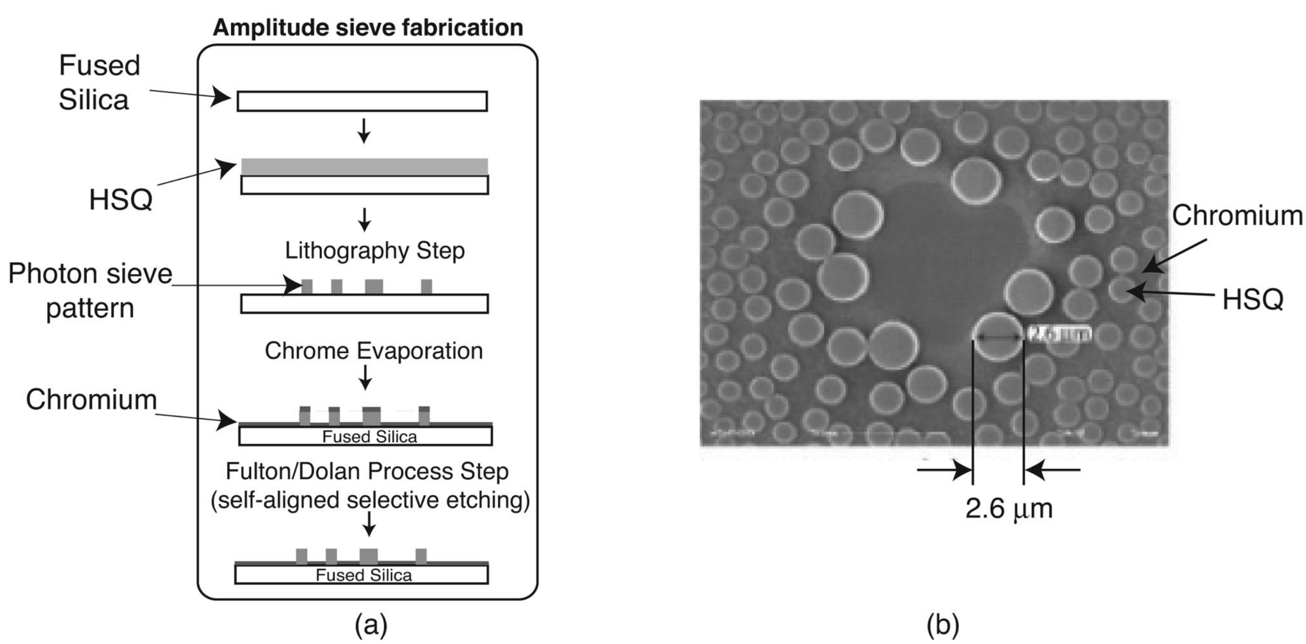

Fig. 1. Fabrication of an amplitude photon sieve. (a) The fabrication process. Hydrogen silsesquioxane (HSQ) is a negative electron-beam resist that has optical properties similar to fused silica at $\lambda = 400$ nm. (b) Scanning electron micrograph of the center of an amplitude photon sieve of NA = 0.7, operating at $\lambda = 400$ nm with focal length equal to 40 μm and containing 2214 pinholes.

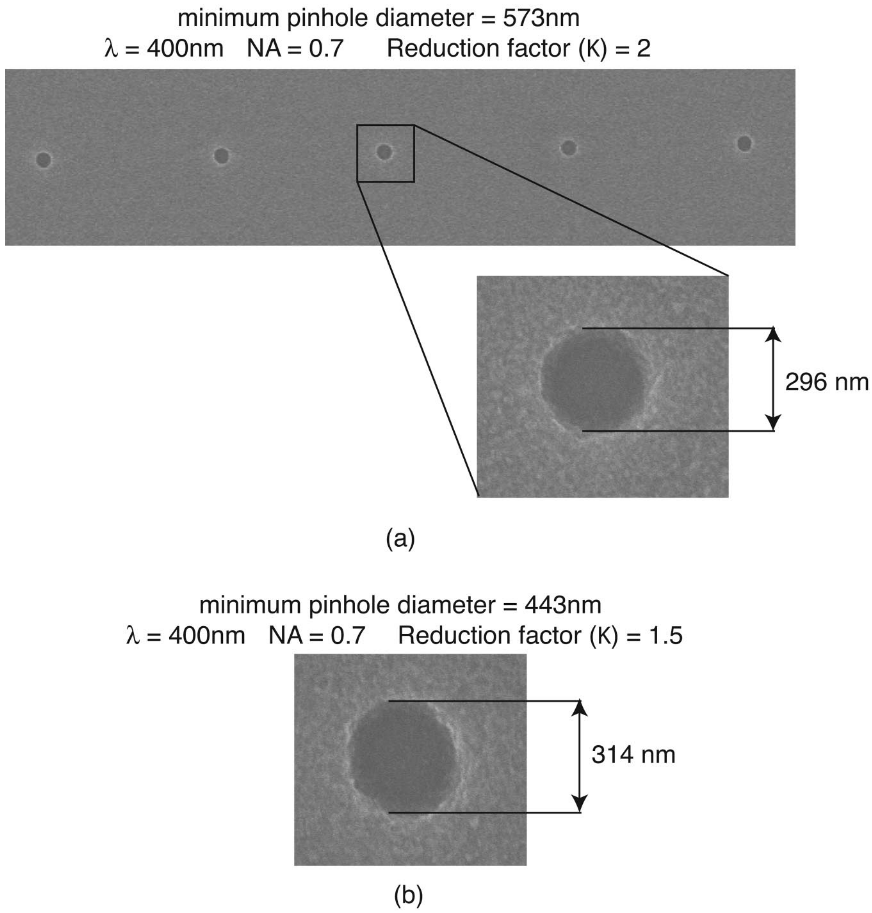

Fig. 2. Printing spots with photon sieves. Scanning electron micrographs of single-exposure spots patterned with two photon sieves of the same NA (0.7) but different K. (a) $K = 2$. The exposed spot is approximately half the size of the smallest pinhole on the sieve. (b) $K = 1.5$. The exposed spot is approximately 1.5 times smaller than the smallest pinhole in the sieve. The experiments were performed at $\lambda = 400$ nm.

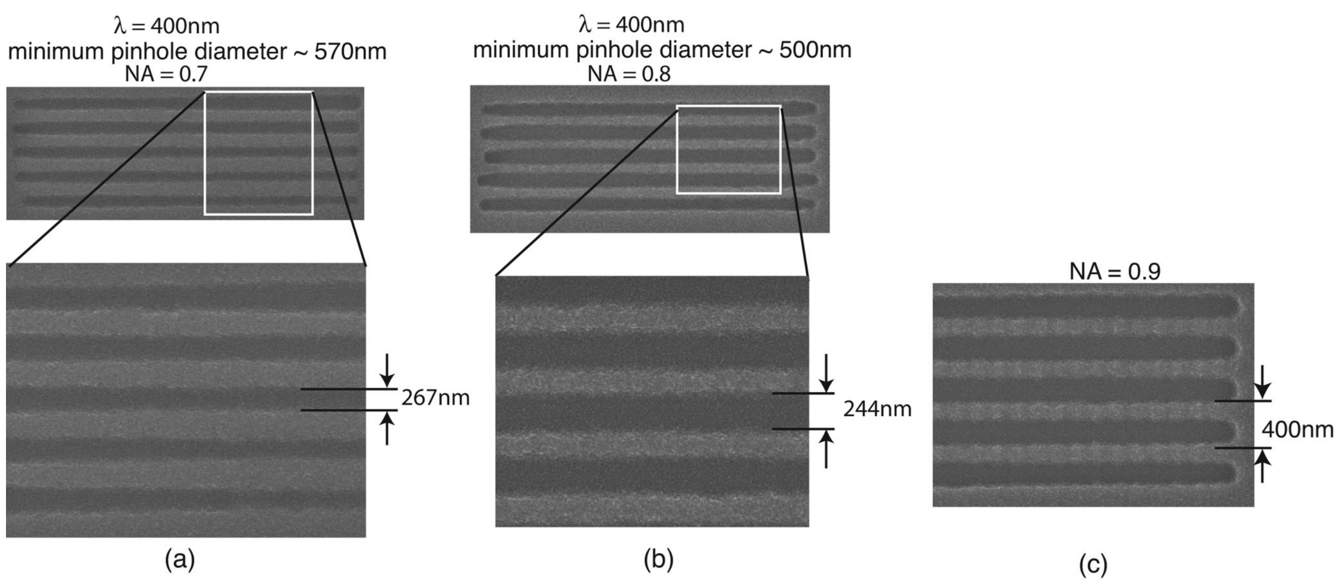

Fig. 3. Printing dense lines and spaces with photon sieves. Scanning electron micrographs of gratings patterned with three photon sieves of the same K (equal to 2), but different NA. (a) NA = 0.7. The exposed lines were approximately 270 nm, close to half the size of the smallest pinhole on the sieve (570 nm). (b) NA = 0.8. The exposed linewidths were 244 nm, again approximately half the diameter of the smallest pinhole in the sieve (500 nm). (c) NA = 0.9. The experiments were performed at $\lambda = 400$ nm.

ments for focusing light in scanning-optical-beam lithography and shown their efficacy. We also propose two new forms of the photon sieve that improve the focusing efficiency.

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