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Numerical and experimental study of near-field scanning optical lithography using nanoscale bowtie apertures with ultrasmall gap size

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Abstract. Nanoscale ridge apertures have been demonstrated to be applied for high-resolution lithography. We performed a numerical study of nanoscale bowtie apertures with different outline dimensions and gap sizes to analyze their detailed field distribution for near-field scanning optical lithography (NSOL). It is found that the high image contrast, which is necessary for good quality lithography, is obtained in the near-field region and decays quickly with increasing distance. Furthermore, a smaller gap size achieves higher image contrast and deeper depth of focus. With the NSOL system, static and scanning lithography experiments are conducted. Combined with the passive flexure stage for contact control, we achieved 18-nm lithography resolution. *© 2016 Society of Photo-Optical Instrumentation Engineers (SPIE)* [DOI: 10.1117/1.JMM.15.3.031611]

Keywords: bowtie aperture; near-field scanning optical lithography; high resolution.

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1 Introduction

Due to the rapid development of the semiconductor industry and its urgent demand for shrinking feature size, traditional mainstream photolithography technique is restricted by the diffraction limit and is not able to satisfy the future needs of industrial development.[1] As a result, new low-cost high-resolution nanolithography techniques, such as surface plasmon-assisted nanolithography,[2,3] nanoimprint lithography,[4,5] and scanning probe lithography,[6] are gradually being widely considered. Advances in near-field optics using a nanoscale light source have achieved spatial resolution much better than the diffraction limit.[7,8] However, the transmission of commonly used regular shape apertures, such as square or rectangular apertures, is very low. Numeral and experimental studies have demonstrated high transmission and field concentration of certain types of ridge apertures, such as C, H, and bowtie-shaped apertures.[9–13] These studies showed that subwavelength ridge apertures are capable of confining the light to subwavelength spots, along with a much higher transmission efficiency than that of commonly used regular shaped apertures. As a result, these ridge apertures provide enormous potential to realize high-resolution lithography.

In this paper, finite difference time domain (FDTD) simulations of light transmitted through nanoscale bowtie apertures were performed to study their transmission intensity and image contrast for lithography. Particularly, we paid attention to image contrast, which is a very significant factor for achieving high-resolution lithography.[10] The numerical results demonstrate that the gap size rather than the outline dimension determines the quality of lithography. To realize an ultrasmall gap size in bowtie apertures, we proposed a unique process and fabricated samples to carry out the lithography experiments.

2 Numerical Study of Bowtie Apertures for Near-Field Lithography

2.1 *Simulation Model*

In order to analyze optical properties in real metals, rigorous vectorial analysis must be applied. The FDTD numerical method simulates the optical near-field of light transmitted through subwavelength apertures by numerically solving Maxwell's equations. In this paper, the FDTD method is also used to compute the near-field lithography capability of a nanoscale bowtie aperture. The simulated geometry is shown in Fig. 1, which consists of a 100-nm-thick metal film mask and a semi-infinite photoresist layer. The nanoscale bowtie aperture has two open arms and a nanometer-size gap g, as shown in Fig. 1. The bowtie aperture has outline dimensions of a and b. The incident light is polarized along the y direction. Chromium is selected as the metal film for its good hardness, high reflectivity, and small skin depth.

In the nanolithography process, the photoresist is sensitive to the total field intensity and sufficient image contrast is needed for exposing the designed area to obtain good quality patterns. The image contrast is expressed as

$$M(z,y) = \frac{I_{\max}(z) - I(z,y)}{I_{\max}(z) + I(z,y)}, \tag{1}$$

where z is the distance from the exit plane of the aperture and y is the distance from the bowtie aperture center in the y

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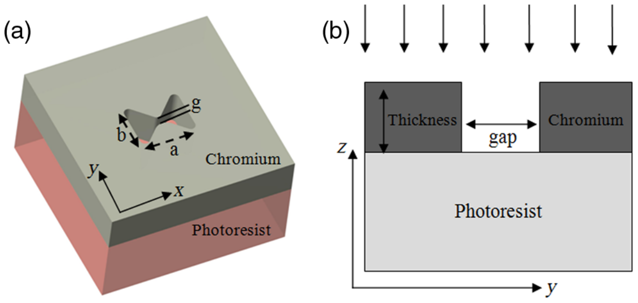

Fig. 1 Schematic diagram of (a) the bowtie aperture and (b) a cross-section through the gap.

direction. $I_{\max}(z)$ is the peak intensity in the plane with a distance z from the exit plane and $I(z,y)$ is the intensity where the image contrast needs to be evaluated. In this paper, image contrasts are calculated at $y = 20$ nm. In addition, we also consider the depth of focus (DOF) of the transmitted light for achieving a specified resolution, which is the distance into the photoresist where image contrast meets the exposure requirement. For a Shipley S1805 photoresist, the minimum image contrast required to form a high-quality exposed pattern is around 0.1.[10,14,15]

2.2 *Comparison of Bowtie Apertures with Different Geometric Parameters*

In this part, we discussed image contrast and field intensities obtained from nanoscale bowtie apertures with different outline dimensions and gap sizes. Benefiting from the unique fabrication process proposed below, the gap size of the bowtie aperture is able to reach 12 nm. Bowtie apertures with 125, 150, and 200 nm outline dimensions and 12, 18, and 24 nm gap sizes are calculated with FDTD simulation methods.

Figure 2 shows the intensity distributions in the x-y plane of the transmitted field and image contrast for 40-nm resolution as a function of distance from the exit plane. It is found that when the depth z increases, the image contrast decreases exponentially. Through the inset pictures in Fig. 2, it is obvious that for the same outline dimension when the gap size decreases, the maximum electric intensity at $z = 24$ nm becomes smaller. Once the gap size is determined, the outline dimension has little effect on image contrast. When the gap size decreases with fixed outline dimensions, the image contrast becomes higher. It is worth mentioning that when the gap size of the bowtie aperture is as small as 12 nm, significantly high image contrast and very deep DOF can be achieved. Furthermore, the image contrasts of bowtie

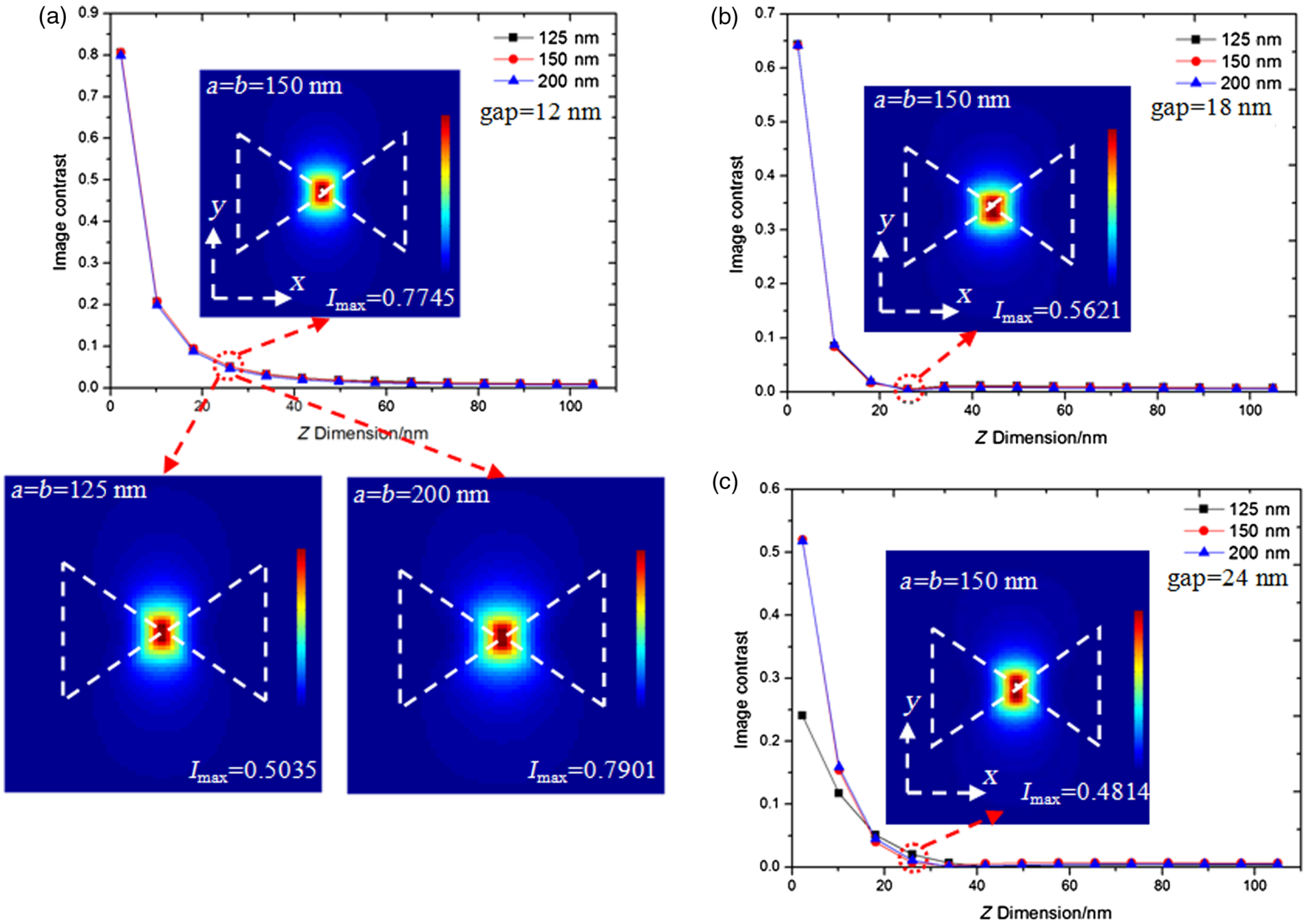

Fig. 2 Image contrast for 40-nm resolution in x-y plane as a function of depth z from the exit plane for bowtie apertures with different geometric parameters: (a) $g = 12$ nm, $a = b = 125$ nm, (b) $g = 18$ nm, $a = b = 150$ nm, and (c) $g = 24$ nm, $a = b = 200$ nm. The inset pictures show the intensity distributions in the x-y plane of transmitted field of the bowtie aperture at $z = 24$ nm with different outline dimensions.

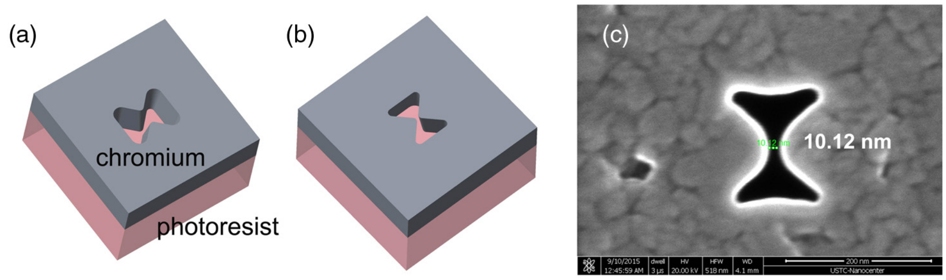

Fig. 3 The 3-D models of different bowtie apertures. (a) Bowtie aperture milled from back side. (b) Bowtie aperture milled from front side. (c) Bowtie aperture with 10.12-nm gap size.

apertures with different outline dimensions are almost the same, which demonstrates that the fabrication error in the outline dimension has little effect when the gap size is small enough. Therefore, a small gap size is desired for high image contrast.

3 Experiments and Results

To verify the above simulations, bowtie apertures with an ultrasmall gap are milled using the back-side milling method shown in Fig. 3(c), which has been described in detail in other papers.[16] Due to the Gaussian profile of the focused ion beam,[17,18] the bowtie apertures usually suffer from non-vertical side-walls, which is the major reason for the larger gap size in the front-side milling method. On the contrary, the back-side milling method overcomes this problem by fabricating bowtie apertures from the back side and effectively guarantees the gap size in the exit-plane. The three-dimensional (3-D) models of different bowtie apertures are shown in Figs. 3(a) and 3(b). However, the mask fabricated in this method is very fragile, especially when the mask and the substrate are brought into contact. Slide contact is undesirable in the process of lithography without lubricant oil or the mask will be destroyed by friction. A new orientation stage based on a flexure mechanism is design to hold the vacuum chunk, which can tightly fix the mask, and it can generate smooth motions by elastic deformations. In addition, the polarization of the light is controlled by a Glan–Taylor prism, which is parallel to the direction across the bowtie gap. The substrate is mounted to a piezoelectric stage, which can scan in three directions with a resolution of 2 nm. The whole optical path diagram is shown in Fig. 4.

Lithography experiments including static lithography and scanning lithography are conducted to verify the performance of the near-field scanning optical lithography system. The wavelength of the solid-state laser is 355 nm and the power density measured at the exposure plane is 132 $\mathrm{mW/cm^2}$. A layer of 150 nm photoresist (Shipley S1805), which is diluted 1:4 using propylene glycol monomethyl acetate, is spun on the substrate at the speed of 4000 rpm. The exposure time is controlled by an electrical shutter. Through precisely controlling the exposure dose and exposure time, the resolution of a single dot reaches 21 nm as shown in Figs. 5(a) and 5(b). The calculated exposure dose is 26.4 $\mathrm{mJ/cm^2}$, which is in the same order of other published results.[10] In scanning lithography, a layer of perfluoropolyether (PFPE, Fomblin Z-dol) is spin-coated on the mask and baked at 170°C for 30 min. After that, the mask is soaked in perfluorinated cleaning solvent (PFS-2), leaving a thin PFPE of about 1 nm. The scanning speed is adjusted according the lithography result to ensure every single dot in the scanning path has enough exposure doses. A line with a resolution of 18 nm is obtained by the near-field scanning optical lithography (NSOL) system shown in Fig. 5(c).

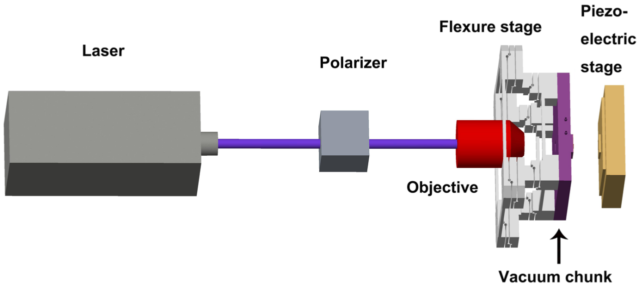

Fig. 4 The schematic drawing of NSOL system.

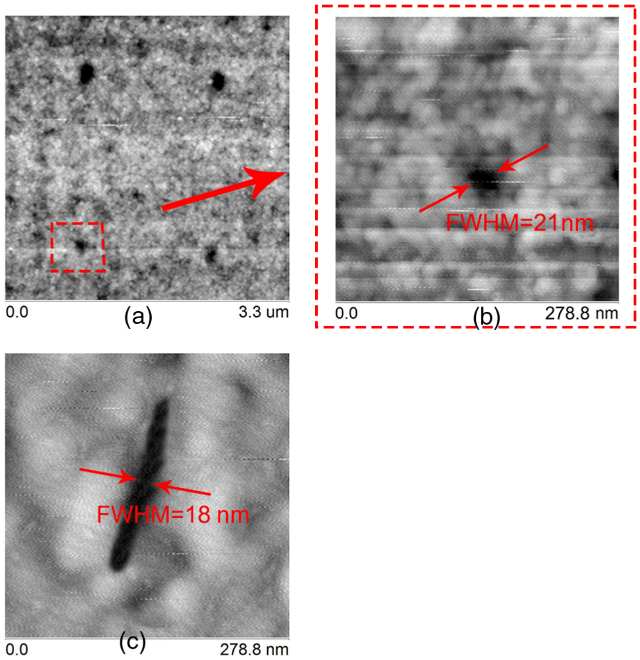

Fig. 5 (a) AFM image of the lithography results using NSOL system. (b) A zoom-in scan of the region labeled with red dashed box. (c) AFM image of a line produced by NSOL system.

4 Conclusion

In summary, the image contrast of nanoscale bowtie apertures with different geometric parameters is numerically studied. The simulation results show that the high image contrast is obtained in the near-field region and decreases quickly with increasing distance. It is worth noting that smaller gap size achieves higher image contrast and deeper DOF. Static lithography and scanning lithography are conducted using bowtie apertures with an ultrasmall gap size fabricated by the back-side milling method. Twenty-one-nm lithography resolution of a single dot and 18-nm lithography resolution of a line have been achieved.

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