Subwavelength interference lithography based on a unidirectional surface plasmon coupler

Zhang, Shuxia; Zhang, Dao Hua; Wang, Yueke; Wang, Jian; Yang, Xuefeng

2013

Yang, X., Zhang, S., Zhang, D. H., Wang, Y., & Wang, J. (2013). Subwavelength interference lithography based on a unidirectional surface plasmon coupler. *Optical engineering*, 52(8), 086109-.

<https://hdl.handle.net/10356/79423>

<https://doi.org/10.1117/1.OE.52.8.086109>

© 2013 Society of Photo-optical Instrumentation Engineers. This paper was published in *Optical Engineering* and is made available as an electronic reprint (preprint) with permission of Society of Photo-optical Instrumentation Engineers. The paper can be found at the following official DOI: [<http://dx.doi.org/10.1117/1.OE.52.8.086109>]. One print or electronic copy may be made for personal use only. Systematic or multiple reproduction, distribution to multiple locations via electronic or other means, duplication of any material in this paper for a fee or for commercial purposes, or modification of the content of the paper is prohibited and is subject to penalties under law.

Downloaded on 26 Apr 2023 22:33:38 SGT

Optical Engineering

SPIEDigitalLibrary.org/oe

Subwavelength interference lithography based on a unidirectional surface plasmon coupler

Xuefeng Yang
Shuxia Zhang
Dao Hua Zhang
Yueke Wang
Jian Wang

Subwavelength interference lithography based on a unidirectional surface plasmon coupler

Xuefeng Yang
Shuxia Zhang

Henan Polytechnic University
School of Physics and Chemistry
Jiaozuo 454000, China
E-mail: xfyang@hpu.edu.cn

Dao Hua Zhang

Nanyang Technological University
School of Electrical and Electronic Engineering
639798, Singapore

Yueke Wang

Jiangnan University
School of Science
Wuxi 214122, China

Jian Wang

Henan Polytechnic University
School of Physics and Chemistry
Jiaozuo 454000, China

Abstract. A subwavelength interference lithography method is numerically demonstrated based on surface plasmon polaritons excited by unidirectional couplers, and the unidirectional coupler is composed of a conventional nanoslit with a nanochannel excavated from one side of this nanoslit. Simulation results show that a feature size of 50 nm half-pitch pattern can be obtained at the working wavelength of 365 nm, and this method can enhance the intensity of the interference pattern with higher contrast and field depth and is advantageous to the fabrication process in practical applications. © 2013 Society of Photo-Optical Instrumentation Engineers (SPIE) [DOI: [10.1117/1.OE.52.8.086109](https://doi.org/10.1117/1.OE.52.8.086109)]

Subject terms: lithography; interference; optical limiting.

Paper 130908 received Jun. 19, 2013; revised manuscript received Jul. 16, 2013; accepted for publication Jul. 18, 2013; published online Aug. 8, 2013.

1 Introduction

With the rapid development of nanotechnology, especially in the semiconductor industry, nanoscale features have tremendous importance in microelectronics, integrated circuit, biosensing, and other applications for higher performances. Compared with other methods such as nanoimprint lithography,¹ electron-beam lithography,² and scanning probe lithography,³ photolithography is more attractive for high-resolution patterning for its low cost and mass fabrication. However, due to the optical diffraction limit, it is difficult to obtain critical dimensions at a subwavelength scale with traditional optical lithography techniques. Recently, interference lithography^{4–14} and imaging lithography^{15–17} recurring to surface plasmon polaritons (SPPs) generated by metallic nanostructure have been proposed to overcome the diffraction limit. This is more beneficial than the SPPs at their wavelength is smaller than that of light in free space at the same frequency.¹⁸ Thus, this allows nanopatterning far beyond the free space diffraction limit.

Recently, interference lithography with SPPs excited by unidirectional couplers has been proposed and it has the advantage of extending the exposure area and shortening the exposure time.¹⁹ The SPPs can be efficiently launched with normal illumination by unidirectional nanoslit couplers,²⁰ nanoslits with different effective indices,^{19,21,22} and asymmetric single-nanoslit filled air in it.^{23,24} Though the surface plasmon interference proposed in Ref. 19 shows some merit compared with the case of using a grating mask for nanoscale lithography, it has to face the challenge of filling different materials in these two adjacent nanoslits for practical performance.

In this paper, we demonstrate an alternative SPP interference lithography method with two counter SPP waves generated by the proposed unidirectional coupler. We numerically demonstrate that the SPP waves generated are sensitive to the dimension of the proposed coupler and this proposed coupler can tailor the surface plasmons efficiently. With the help of SPP waves excited by unidirectional couplers, nanoscale pattern with high contrast can be well performed by the proposed scheme.

2 Structure of the Unidirectional Coupler

The proposed unidirectional coupler is composed of a conventional metallic (aluminum in this work) nanoslit with a nanochannel excavated from one side of this nanoslit, as presented in Fig. 1. The proposed unidirectional coupler, coated by a photoresist (PR) layer, can be well performed on quartz by focused ion beam. The width of the nanochannel and nanoslit are denoted as L and W , respectively. And their

Fig. 1 Schematic of the proposed unidirectional coupler and geometrical parameters.

Fig. 2 (a) The total electrical field intensity distribution at the left point, I_L , with varied L and h_1 . (b) The total electrical field intensity distribution at the right point, I_R , with varied L and h_1 . (c) The electrical field intensity distribution of the proposed structure at the working wavelength of 365 nm with the dimensions $L = 280$ nm, $h_1 = 245$ nm, $W = 150$ nm, and $h = 100$ nm. (d) The electrical field intensity distributions of the proposed (blue solid line) and an Al nanoslit (red dash line) structures at the plane 50 nm above the Al-PR interface.

depths are denoted as h_1 and h , respectively. With a p -polarized light illumination from the backside of the coupler, SPPs on the front Al-PR interface will be excited and without doubt interfere constructively on one side and interfere destructively on the other side of the structure if the coupler parameters are properly provided.

3 Results and Discussions

For the proposed structure, we first investigate the effect of L and h_1 of the nanochannel on the unidirectional generation, with the fixed $W = 150$ nm and $h = 100$ nm under a

working wavelength of 365 nm with p -polarization. The extinction ratio is defined as the ratio between the SPP intensities on the two points (right and left points), which have equal distance to the center of the nanoslit (see Fig. 1). The SPP generation efficiency is defined as the quotient between the SPP intensities on the front metal surface with and without the nanochannel. The electrical field intensity distribution of the proposed structure was numerically calculated by the finite element method, using COMSOL MULTIPHYSICS 3.5a. In the calculation, the proposed structure is illuminated from the back by a p -polarized light of 365 nm. The permittivity of the Al and the PR are $-19.66 + 4.4i$ (Ref. 25) and 2.89, respectively. Figure 2(a) and 2(b) shows the intensity distributions at the left (I_L , $x = -3.5$ μm) and right (I_R , $x = 3.5$ μm) points, respectively, with varied L and h_1 . Note that these two fixed points we assigned are always 50 nm away from the Al-PR interface. As expected, the value of I_R (or I_L) varies periodically with the length of the nanochannel L and the period is not sensitive to the depth of the nanoslit h_1 . The Fabry-Perot effect²³ is also observed and it is sensitive to the height of the nanochannel. In order to obtain SPP waves by the proposed unidirectional coupler, a higher SPP generation ratio is needed. From the data in Fig. 2(a) and 2(b), an extinction ratio as large as 1750 occurs under the dimensions of $L = 280$ nm and $h_1 = 245$ nm. Figure 2(c) presents the electrical field intensity distribution of the proposed structure. As expected, the SPP waves are clearly generated on the right side of the structure. As a comparison, we also calculated the electrical field intensity for a structure that has only an Al nanoslit with a width of 150 nm and height of 345 nm. Figure 2(d) shows electrical field intensity distributions in the plane 50 nm above the Al-PR interface of the proposed structure (with an Al nanoslit and an excavated nanochannel) and the Al nanoslit only. As can be seen, the intensity of the SPP waves will be symmetrically distributed around the single Al nanoslit. With the nanochannel excavated on one side as shown in Fig. 1, the left-going SPP waves interfere constructively on the right side and the SPP generation efficiency can increase to 2 owing to the constructive interference.

Fig. 3 (a) The total electrical field intensity distribution structure with two symmetric unidirectional SPP couplers separated about 1.64 μm . (b) The total electrical field intensity distribution of a control structure with only an Al nanoslit structure separated about 1.64 μm . The insert parts are the enlarger of the rectangular zones, respectively. (c) Comparison of the interference pattern intensities obtained from the proposed (blue solid line) and an Al nanoslit (red "+") structures at the plane 20 nm above the Al-PR interface.

The SPP wave propagation length for its electrical field E (Ref. 26) on the metal–dielectric interface can be described by

$$\delta_{\text{SPP}} = \frac{1}{k''_{\text{SPP}}} = \lambda_0 \frac{(\epsilon'_m)^2}{\pi \epsilon_m''} \left(\frac{\epsilon'_m + \epsilon_d}{\epsilon'_m \epsilon_d} \right)^{\frac{3}{2}},$$

where k''_{SPP} is the imaginary part of the surface plasmon polariton wave vector, ϵ'_m and ϵ_m'' are the real part and imaginary part of the permittivity of the metal, and ϵ_d is the relative permittivity of the dielectric. The SPP propagation length on the Al–PR interface is $\sim 1.64 \mu\text{m}$ for the working wavelength of 365 nm.

Two symmetric couplers can be used to excite two counterpropagating SPP waves. The total electrical field intensity distribution in Fig. 3(a) clearly demonstrates that an interference pattern with ~ 50 nm half-pitch ($\lambda/7$) is formed in the PR, which agrees well with the theoretical prediction $\Lambda = \lambda_{\text{sp}}/2 \sim 100$ nm. The insert part is the enlarger figure of the rectangular zone presented in Fig. 3(a). The SPP interference was also calculated for a conventional nanoslit structure with the same width of 150 nm, as shown in Fig. 3(b). And the insert part is the enlarger figure of the rectangular zone is also presented. Even the pattern contrast,

$$C = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}},$$

obtained by these two compared structures are both ~ 0.72 . The electrical field intensity of the pattern (at the plane of 20 nm above the Al–PR interface) obtained for the proposed structure is about two times as large as only the nanoslit case, as presented in Fig. 3(c), and the field penetration depth in the PR layer with the proposed structure (~ 100 nm) is also higher than with only the Al nanoslit case (~ 70 nm), which are the evidences for our intention to design the proposed unidirectional coupler. This enhancement can also extend the exposure area and shorten the exposure time in the process of lithography.

4 Conclusion

In conclusion, we numerically demonstrate an alternative interference nanolithography scheme with surface plasmon polariton waves excited by proposed unidirectional couplers. The unidirectional coupler consists of a conventional metallic nanoslit with a nanochannel excavated on one side. The surface plasmon wave generated by the coupler is sensitive to the width of the nanochannel. Simulation results show that the proposed structure has much intense subwavelength interference patterns with 50 nm half-pitch feature at a working wavelength of 365 nm. We believe this technique will provide a new alternative and more effective fabrication method for nanostructures and relative plasmonic devices.

Acknowledgments

This work is supported by the National Natural Science Foundation of China (Grant Nos. 11104063 and 11204068), A*Star (Grant No. 0921540099), Singapore, and Doctor Funding Project of Henan Polytechnic University (Grant No. B2011-082).

References

1. S. Y. Chou et al., "Imprint lithography with 25-nanometer resolution," *Science* **272**(5258), 85–87 (1996).
2. R. S. Dhaliwa et al., "PREVAIL-electron projection technology approach for next generation lithography," *IBM J. Res. Dev.* **45**(5), 615–638 (2001).
3. E. B. Cooper et al., "Terabit-per-square-inch data storage with the atomic force microscope," *Appl. Phys. Lett.* **75**(22), 3566 (1999).
4. X. Luo et al., "Surface plasmon resonant interference nanolithography technique," *Appl. Phys. Lett.* **84**(23), 4780 (2004).
5. Z. W. Liu et al., "Surface plasmon interference nanolithography," *Nano Lett.* **5**(5), 957–961 (2005).
6. M. Derouard et al., "Polarization-sensitive printing of surface plasmon interferences," *Opt. Express* **15**(7), 4238–4246 (2007).
7. T. Xu et al., "Sub-diffraction-limited interference photolithography with metamaterials," *Opt. Express* **16**(18), 13579–13584 (2008).
8. Y. Xiong et al., "Projecting deep-subwavelength patterns from diffraction-limited masks using metal-dielectric multilayers," *Appl. Phys. Lett.* **93**(11), 111116 (2008).
9. X. Yang et al., "Breaking the feature sizes down to sub-22 nm by plasmonic interference lithography using dielectric-metal multilayer," *Opt. Express* **17**(24), 21560–21565 (2009).
10. X. Yang et al., "Deep subwavelength photolithography based on surface plasmon polariton resonance with metallic grating waveguide heterostructure," *J. Opt.* **12**(4), 045001 (2010).
11. E. A. Bezus et al., "Diffraction gratings for generating varying-period interference patterns of surface plasmons," *J. Opt. A: Pure Appl. Opt.* **10**(9), 095204 (2008).
12. Q. Wang et al., "High-resolution 2D plasmonic fan-out realized by subwavelength slit arrays," *Opt. Express* **18**(3), 2662–2667 (2010).
13. E. A. Bezus et al., "Grating-assisted generation of 2D surface plasmon interference patterns for nanoscale photolithography," *Opt. Commun.* **283**(10), 2020–2025 (2010).
14. Y. Li et al., "Two-surface-plasmon-polariton-absorption based nanolithography," *Appl. Phys. Lett.* **102**(6), 063113 (2013).
15. D. O. S. Melville et al., "Submicron imaging with a planar silver lens," *Appl. Phys. Lett.* **84**(22), 4403 (2004).
16. N. Fang et al., "Sub-diffraction-limited optical imaging with a silver superlens," *Science* **308**(5721), 534–537 (2005).
17. X. Yang et al., "Designing arbitrary nanoscale patterns by a nanocavity waveguide with omnidirectional illumination," *Appl. Phys. B* **109**(2), 215–219 (2012).
18. H. Raether, *Surface Plasmons on Smooth and Rough Surface and on Gratings*, Springer, Heidelberg (1998).
19. T. Xu et al., "Subwavelength nanolithography based on unidirectional excitation of surface plasmons," *J. Opt. A: Pure Appl. Opt.* **11**(8), 085003 (2009).
20. F. López-Tejeda et al., "Efficient unidirectional nanoslit couplers for surface plasmons," *Nat. Phys.* **3**(5), 324–328 (2007).
21. T. Xu et al., "Directional excitation of surface plasmons with subwavelength slits," *Appl. Phys. Lett.* **92**(10), 101501 (2008).
22. D. Li et al., "Unidirectional surface plasmon-polariton excitation by a compact slot partially filled with dielectric," *Opt. Express* **21**(5), 5949–5956 (2013).
23. J. Chen et al., "Efficient unidirectional generation of surface plasmon polaritons with asymmetric single-nanoslit," *Appl. Phys. Lett.* **97**(4), 041113 (2010).
24. P. Lalanne et al., "A microscopic view of the electromagnetic properties of sub- λ metallic surfaces," *Surf. Sci. Rep.* **64**(10), 453–469 (2009).
25. P. B. Johnson et al., "Optical constants of the noble metals," *Phys. Rev. B* **6**(12), 4370–4379 (1972).
26. W. L. Barnes, "Surface plasmon-polariton length scales: a route to sub-wavelength optics," *J. Opt. A: Pure Appl. Opt.* **8**(4), S87–S93 (2006).

Xuefeng Yang received his BS degree in optics from Henan Normal University (2003), MS degree in atomic and molecular physics from University of Science and Technology of China (2006), and PhD in optical engineering from Institute of Optics and Electronics, Chinese Academy of Sciences (2010). He currently serves as principal investigator for super-resolution imaging and nanolithography. His research interests include super-resolution imaging, nanofabrication techniques, metamaterials, and plasmonics.

Shuxia Zhang received her PhD in theory and new technology of electrical engineering from Institute of Electrical Engineering, Chinese Academy of Sciences (2012). Her research interest is mainly focused on nanofabrication.

Biographies and photographs of the other authors not available.