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2015

Prabhathan, P., & Murukeshan, V. M. (2015). Dielectric supported bimetal layer configuration for long-range surface plasmon polariton interference-based subwavelength lithography. *Optical Engineering*, 54(9), 097107-.

<https://hdl.handle.net/10356/81084>

<https://doi.org/10.1117/1.OE.54.9.097107>

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Dielectric supported bimetal layer configuration for long-range surface plasmon polariton interference–based subwavelength lithography

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Abstract. Long-range surface plasmon polariton (LRSP) interference in a dielectric supported bimetal layer configuration is analyzed for nanoscale periodic feature fabrication. The single metal layer in a conventional configuration has been split into a bimetal layer configuration supported by a dielectric layer to enable LRSP interference in different layers. It is shown that the configuration can be implemented in two different ways to record the interference pattern with high exposure depth and high contrast. Subwavelength periodic pattern having a half-pitch resolution of 65 nm at 446-nm wavelength is illustrated with the proposed two-beam and four-beam LRSP interference configurations. © 2015 Society of Photo-Optical Instrumentation Engineers (SPIE) [DOI: 10.1117/1.OE.54.9.097107]

Keywords: surface plasmons; plasmonics; nanolithography.

Paper 150315 received Mar. 16, 2015; accepted for publication Aug. 20, 2015; published online Sep. 23, 2015.

1 Introduction

Surface plasmon interference in metal^{1–5} or dielectric metamaterials^{6,7} has been explored as a potential alternative to conventional laser interference to achieve higher resolution and smaller feature size in photolithography. For a better lithography performance, these methods should be improved so that they can be employed in practical lithography applications.^{8,9} Surface plasmon polariton (SPP) is a bound electromagnetic mode that may exist at the metal–dielectric interface when excited with the required momentum matching condition. In the case of a thin metallic film confined by two identical dielectric claddings, SPPs are generated at each metal–dielectric interface. These SPPs at each interface couple each other to produce symmetric and antisymmetric film modes inside the metal known as long-range surface plasmon polariton (LRSP) and short-range SPP, respectively.¹⁰ The modal index of LRSP is lower than the SPP. This gives a weak electric field confinement for the LRSP mode inside the metal. The weak electric field confinement of the LRSP mode is beneficial as this would enable higher exposure depth in SPP interference lithography.¹¹ However, the LRSP mode is highly sensitive to the dielectric environment and two identical dielectric layers are required for the mode generation.¹² For practical lithography applications, the metal layer should be placed in close contact with the photoresist (PR) layer. This can be achieved by depositing the metal layer over a substrate that has the same refractive index as that of PR. It has been reported that LRSP modes can also be generated in a dielectric supported bimetal configuration.¹³ The mode generated in such a configuration is observed to be similar to a single metal layer configuration.

Here, the dielectric supported bimetal layer-based configuration is analyzed for multiple beam LRSP interference

to record the periodic pattern with a high exposure depth and high contrast in different layers.

2 System Configuration and Analysis

The bimetal layer configuration for LRSP interference is shown in Fig. 1. The configuration consists of two thin metal layers having thicknesses t_{m1} and t_{m2} , respectively, supported by a dielectric layer, D2. This geometry is surrounded by two similar dielectric layers D1 on the upper side and D3 on the lower side. The thickness and dielectric constant of the dielectric layers are t_1 , ϵ_1 , t_2 , ϵ_2 , and t_3 , ϵ_3 , for D1, D2, and D3, respectively. The proposed configuration can be implemented in two different ways for recording the interference pattern. In the first configuration, the bottom dielectric, D3, is taken as the PR layer with an identical layer taken as the top dielectric, D1. The middle dielectric D2 can be any material which satisfies the conditions for the LRSP mode propagation, which will be explained later. In the second configuration, D2 is taken as the PR layer. The other two dielectric layers, D1 and D3, are two identical dielectric layers with the same dielectric constants. Here, the interference patterns are recorded at D2. The advantage of this arrangement is that it is easy to transfer the recorded pattern to the bottom metal layer through metal etching. The patterned metal layer can be used as a mask for further deep etching of the material.

Full-wave numerical simulation using three-dimensional finite-difference time-domain method is performed to analyze the lithography configurations. A perfectly matched layer boundary condition is applied in the Y -direction and periodic boundary conditions are applied in the X and Z directions. When a transverse magnetic polarized light illuminates the interface between the prism and the geometry at resonance angle, the momentum matching between the

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Fig. 1 Schematic of bimetal layer-based long-range surface plasmon polariton (LRSP) interference lithography configuration.

incident light and LRSP mode occurs. Unlike the single metal layer configuration, in this case, LRSP will be generated at four different interfaces, viz., D1-metal, metal-D2, D2-metal, and metal-D3. The fields at two metal-D2 interfaces couple each other and modification in the field distribution occurs inside the middle dielectric. The H field distribution of the configuration at any interface can be written as

$$H(x, y, z) = \bar{z} H_z(y) \exp(i\beta x - i\omega t). \quad (1)$$

Here, the surface plasmons propagate along the X -direction with the H field along the Z -direction and Y as the surface normal. The dispersion characteristics of the dielectric supported bimetal layer LRSP mode have been presented by Mu and Ketterson.¹³ If the dielectric layer thickness t_2 satisfies the following relationship, then the LRSP mode in a bimetal configuration is similar to an original LRSP mode in a single metal configuration:

$$k_{2y} t_2 = m\pi, \quad (2)$$

where m is an integer, and

$$k_{2y} = (\epsilon_2 k_0^2 - \beta_{\text{LRSP}}^2)^{1/2} \quad (3)$$

is the out of plane wave vector in the dielectric D2 with k_0 as the free-space wave vector and β_{LRSP} as the LRSP wave vector.

$$\beta_{\text{LRSP}} = n_0 k_0 \sin \theta = n_0 \frac{2\pi}{\lambda} \sin \theta, \quad (4)$$

where n_0 is the refractive index of the coupling prism, λ is the incident laser wavelength, which is taken as 446 nm, and θ is the LRSP resonance angle. The coupling prism used is N-LASF ($n_0 = 1.93$). The metal thickness is set to $t_{m1} = t_{m2} = 15$ nm. Silver (Ag) is chosen as the metal layer with a frequency-dependent dielectric constant.¹⁴ The middle

Fig. 2 Electric field intensity distribution of two-beam LRSP interference in a bimetal configuration at 446-nm wavelength.

dielectric D2 layer thickness t_2 is calculated from Eq. (2) for satisfying the LRSP propagation condition. For the first configuration, if the middle dielectric D2 is a glass material (N-LAK8, $\epsilon_2 = 2.9853$), with the bottom dielectric D3 taken as the PR layer (AZ9260, $\epsilon_3 = 2.89$), and the upper dielectric D1 as an identical dielectric, the D2 thickness is calculated as 557 nm and $1.1 \mu\text{m}$ for $m = 1$ and $m = 2$, respectively. For the second configuration, if the middle dielectric D2 is taken as PR (AZ9260, $\epsilon_2 = 2.89$) layer and D1 and D3 are identical dielectric layers (here, N-LAK7, $\epsilon_1 = \epsilon_3 = 2.9853$), the thicknesses are calculated as 875 nm and $1.75 \mu\text{m}$ for $m = 1$ and $m = 2$, respectively. For the configurations, the LRSP resonance angle is measured as $\theta = 60.5$ deg through the incident angle sweep and transmission power measurement. The simulated electric field intensity distribution in the XY plane for a two-beam interference in the first configuration is shown in Fig. 2. The periodic pattern is observed to have a half-pitch resolution of 65 nm with a periodicity $\Lambda = 130$ nm. This shows an LRSP wavelength of 260 nm for the configuration at the 446-nm incident wavelength from the following relationship:

$$\lambda_{\text{LRSP}} = 2\Lambda. \quad (5)$$

Fig. 3 Electric field distribution of LRSP interference in bimetal configuration (a) E_x component and (b) E_y component. Variation in E_x and E_y electric field (c) in dielectric layer D3 at 5 nm below the interface (d) in the dielectric D2 at the middle.

Fig. 4 (a) Intensity contrast variation with respect to decay depth, (b) electric field decay in LRSP and surface plasmon polariton interference, (c) excitation efficiency of LRSP, with coupled field intensity (inset), and (d) four-beam LRSP interference pattern.

Approximately, a similar value in λ_{LRSP} is also calculated through Eq. (4).

The intensity contrast or visibility (V) of the periodic pattern is measured through the following equation:

$$V = \frac{E_y^2 - E_x^2}{E_y^2 + E_x^2}, \quad (6)$$

where E_x and E_y are the X and Y components of the electric field. The E_x and E_y components have a half period $[\pi/2 \text{Re}(\beta_{\text{LRSP}})]$ shift in space, since they have a phase difference of $\pi/2$ between them. This can be observed from the E_x and E_y field distributions and field variations, as shown in Fig. 3. The half period shift in the field components will have a strong impact on the intensity contrast of the interference pattern. In order to minimize this effect, the E_y component should be much higher than the E_x component. A minimum contrast of ~ 0.4 is required for a positive PR in a modern lithographic fabrication process.

Figure 4(a) shows the intensity contrast variation of the LRSP interference pattern in a bimetal configuration. It is observed that an exposure depth of ~ 600 nm can be achieved with a minimum contrast of 0.4 in this lithography. The intensity contrast is observed to be higher in the middle dielectric (D2) region. This is the outcome of the coupled interaction of LRSP modes between two metals. During the LRSP coupling, the reflected E_x field forms the lower metal that has a π -phase shift, whereas for the E_y component, there is no π shift, as shown in Figs. 3(a) and 3(b). Thus, the LRSP coupling between the metal layers is nearly destructive for the E_x component and constructive for the E_y component in D2. Hence, the E_x field amplitude is much less in D2 when compared to that of D3, as shown in Figs. 3(c) and 3(d). This difference in amplitudes will give a higher intensity contrast for the pattern recorded in the second configuration, where the middle dielectric is a PR. An intensity

contrast of 0.974 is calculated along the center line of D2 with PR as the dielectric. This value is higher when compared to a single metal layer SPP interference, where the maximum intensity contrast that is achievable is 0.73.

The electric field intensity in the LRSP interference is observed to be higher due to the weak electric field confinement of the LRSP mode inside the metal. The critical parameter for an efficient LRSP excitation is the angle of incidence of the laser beam. This is explained by the excitation efficiency plot, as shown in Fig. 4(c). A maximum field coupling happens when the momentum matching condition is satisfied, depending upon the system configuration and material parameters. The electric field decay depth is enhanced in the LRSP interference when compared to SPP, as shown in Fig. 4(b). The electric field decay depth of SPP interference ($n_0 = 1.93$, $\theta = 64$ deg, Ag layer thickness = 50 nm) is ~ 200 nm, while that of LRSP reaches beyond 600 nm. Four beam interference patterns are also generated in the proposed bimetal layer configuration. The two-dimensional interference pattern, which is shown in Fig. 4(d), has a periodicity of ~ 250 nm and spot size of ~ 62.5 nm. The experimental demonstration of this novel concept of surface plasmon interference lithography is in progress in our lab.

3 Conclusion

Multiple beam LRSP interference in a dielectric-supported bimetal layer configuration is analyzed for nanoscale periodic pattern generation with a high-contrast and high-exposure depth. The single metal layer in a conventional configuration has been split into a bimetal layer configuration to generate the LRSP interference at different layers. Two-beam and four-beam LRSP interference results show that periodic patterns having a half-pitch resolution of ~ 65 nm at a 446-nm wavelength are achievable. It is also shown that the contrast of the pattern can be as high as 0.974 and the exposure depth of the pattern can reach up to ~ 600 nm with sufficient intensity contrast.

Acknowledgments

The authors acknowledge the financial support received through MOE- RG 98/14 and MOE- RG 34/10.

References

1. X. Luo and T. Ishihara, "Surface plasmon resonant interference nanolithography technique," *Appl. Phys. Lett.* **84**, 4780–4782 (2004).
2. V. M. Murukeshan and K. V. Sreekanth, "Excitation of gap modes in a metal particle-surface system for sub-30 nm plasmonic lithography," *Opt. Lett.* **34**, 845–847 (2009).
3. K. V. Sreekanth and V. M. Murukeshan, "Four beams surface plasmon interference nanoscale lithography for patterning of two-dimensional periodic features," *J. Vac. Sci. Technol. B* **28**, 128–130 (2010).
4. B. Zeng et al., "Plasmonic interference nanolithography with a double-layer planar silver lens structure," *Opt. Express* **17**, 16783–16791 (2009).
5. X. Guo and Q. Dong, "Coupled surface plasmon interference lithography based on a metal-bounded dielectric structure," *J. Appl. Phys.* **108**, 113108 (2010).
6. X. Yang et al., "Breaking the feature sizes down to sub-22 nm by plasmonic interference lithography using dielectric-metal multilayer," *Opt. Express* **17**, 21560–21565 (2009).
7. T. Xu et al., "Sub-diffraction-limited interference photolithography with metamaterials," *Opt. Express* **16**, 13579–13584 (2008).
8. S. Shi et al., "Surface-plasmon-polaritons-assisted nanolithography with dual-wavelength illumination for high exposure depth," *Opt. Lett.* **37**, 247–249 (2012).

9. P. Zhu, H. Shi, and L. J. Guo, "SPPs coupling induced interference in metal/dielectric multilayer waveguides and its application for plasmonic lithography," *Opt. Express* **20**, 12521–12529 (2012).
10. I. Avrutsky et al., "Highly confined optical modes in nanoscale metal-dielectric multilayers," *Phys. Rev. B* **75**, 241402 (2007).
11. X. Guo and Q. Dong, "Long range surface plasmon interference lithography," *Microelectron. Eng.* **88**, 2184–2187 (2011).
12. P. Berini, "Long-range surface plasmon polaritons," *Adv. Opt. Photonics* **1**, 484–588 (2009).
13. W. Mu and J. B. Ketterson, "Long-range surface plasmon polaritons propagating on a dielectric waveguide support," *Opt. Lett.* **36**, 4713–4715 (2011).
14. E. D. Palik, *Handbook of Optical Constants of Solids*, Academic Press, Orlando (1985).

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