# Research of photolithography technology based on surface plasmon*

Li Hai-Hua(李海华)†, Chen Jian(陈 健), and Wang Qing-Kang(王庆康)

*National Key Laboratory of Micro/Nano Fabrication Technology, Key Laboratory for Thin Film and Microfabrication Technology of Ministry of Education, Research Institute of Micro/Nano Science and Technology, Shanghai Jiao Tong University, Shanghai* 200240, *China*

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This paper demonstrates a new process of the photolithography technology, used to fabricate simply fine patterns, by employing surface plasmon character. The sub-wavelength periodic silica structures with uniform silver film are used as the exposure mask. According to the traditional semiconductor process, the grating structures are fabricated at exposing wavelength of 436 nm. At the same time, it provides additional and quantitative support of this technique based on the finite-difference time-domain method. The results of the research show that surface plasmon characteristics of metals can be used to increase the optical field energy distribution differences through the silica structures with silver film, which directly impact on the exposure of following photosensitive layer in different regions.

**Keywords:** surface plasmons, lithography, finite-difference time-domain, sub-wavelength periodic structure

**PACC:** 4225B, 4230, 4230H, 7320J

## 1. Introduction

Photolithography has been a key technique in semiconductor nano- and micro-fabrication for several decades. With the development of super-large-scale integration and integrated optics, high resolution photolithography has become more and more important.[1−3] Using the immersion lithography, off-axis illumination optical proximity correction and phase-shifting mask technology, etc., we can obtain 60 nm line width which greatly improve the lithography resolution. However, such 'photolithography' is expensive and complex, and the resolution of the technique is fast approaching the diffraction limit.

The phenomenon of surface plasmon resonance (SPR) was first found by Wood through optical experiments in 1902.[4] The SPR physical optical phenomenon is caused by optical coupling of metallic thin film.[5] The recent discovery of extraordinary transmission through perforated metal films shows that the surface plasmons (SPs) on the metal surface can greatly enhance the light transmission and redistribute the electromagnetic field in the nanometer scale. The SP nano-lithography technology was proposed by Srituravanich *et al.* in 2003.[6] Through the preparation of sub-wavelength periodic structures, the spread of light is controlled by the principle of SPs, and the transmission with high resolution of the ultraviolet band of light is achieved.[7−9] But these techniques require quite expensive equipment and cannot meet the industrial mass fabrication requirements.

In this paper, we took a new and simple process which used silica grating structures with silver film as the exposure mask. It can be the same structure as the scale of the lithography through utilising the SPs on the metal silver surface. Using silica mask with silver film as the exposure mask, by ordinary lithography technology without off-axis illumination optical proximity correction and phase-shifting mask technology, we obtained the same scale of the lithography as the periodic structures. The electromagnetic field distribution through the mask was investigated by using the finite-difference-time-domain (FDTD) method. The experiment and numerical results show that by using the silica mask with silver film as the exposure mask, the energy of the light through the mask is redistributed. As the optical field enhancement of the metal silver surface, the photosensitive layer can be greatly exposed locally through the ridge sites of the mask. This technique operates simply and rapidly, and sub-wavelength structures can be produced using

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†Corresponding author. E-mail: lihaihua@sjtu.edu.cn

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wide-range visible light by the ordinary lithography technology.

## 2. Experiment

The silica mask was used in experiment (Fig. 1). The 40 nm silver film on the silica mask was deposited by the MPS-3000-HC5-type ultra-high vacuum thin film sputtering machine, whose sputtering rate was 2–4 nm/min. The deposition thickness of silver film was 40 nm. Because of slow sputtering rate, silver film is uniformly deposited on the entire silica mask without effect on the structures. The silica mask with silver film was used as SPs mask in the lithography experiment (Fig. 3(a)).

Lithography process was shown in Fig. 2. A layer of photoresist (S1805, Shipley Company) was coated on silicon substrate. The photoresist was coated less than 500 nm for 30 seconds at 4000 r/min. Then put the silicon substrate in the oven to soft bake at 110 °C for half an hour. The contacting lithography was used by MA6/BA6 lithography machine (Karl Suss Company). The exposure light wavelength was 436 nm, and the exposure time was 60 s. The atomic force microscope (AFM) image in Fig. 3(b) is an exposure result obtained from the mask that consists of an array of grating of 410 nm line width and 1.5 $\mu$m in period.

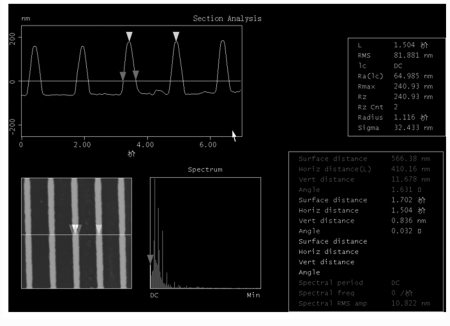



**Fig. 1.** The AFM map of the quartz template.

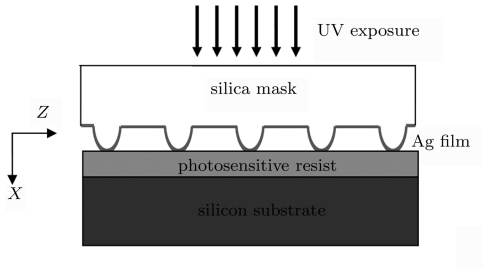
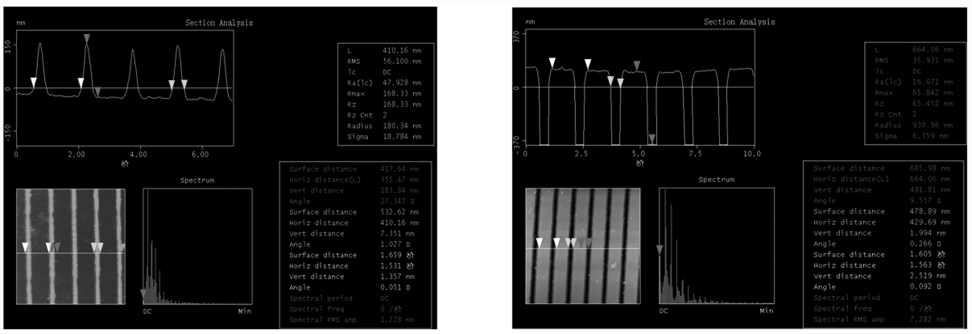



**Fig. 2.** Lithography process.




(a) The mask with silver for lithography (b) The structures after lithography

**Fig. 3.** The structure contrast before lithography and after lithography and development.

## 3. Analysing and discussion

In Fig. 3(a), the grating line width of the silica mask deposited by silver was about 410 nm and the period is about 1.5 $\mu$m. After the exposure and development, the line width of the resist grating structures is about 430 nm and the period is about 1.5 $\mu$m in Fig. 3(b). As the resist is corroded excessively by developer, the line-width of the resist gratings is wider than that of the mask. The results showed that the silver film deposited on the silica template could play the role as a mask. The strong field is located on the ridge of the silver film on the mask, rather than the flat of the silver film on the mask. A number of numerical simulations of the lithography were conducted to further investigate the field transmitted through the silica mask with silver film by FDTD methods. Several conditions were defined in our description. First, we

assumed that monochromatic plane wave $\lambda = 436$ nm, which is the exposure wavelength and the maximum sensitivity range of the S1805 resist. Second, the mask had the same parameters as those of the experiment. Last, the boundary condition along $x$, $z$ is set to be perfectly matched layer (PML) and periodic respectively in Fig. 2. According to the template shown in Fig. 3(a), the grating periodicity of the model was 1.5 $\mu$m, the cross-section was parabolic strip grating, the bottom length of the grating structures was 410 nm, and the height of the grating structures was 180 nm.

Based on the following Maxwell's equations (Eqs. (1)–(3)) and the boundary conditions of Bloch theory (Eq. (4)),[10] we calculate transverse electric (TE) mode and transverse magnetic (TM) mode of the transmission by FDTD method. The transmission modes of the structures (Fig. 1) were shown in Fig. 4(a). Using Drude model (Eq. (5)) and Bloch boundary conditions (Eq. (4)) to simulate the transmission of the structures (Fig. 3(a)), we show the result in Fig. 4(b). The Maxwell's equations are

$$\mu_0 \frac{\partial H_x}{\partial t} = \frac{\partial E_y}{\partial z}, \tag{1}$$

$$\mu_0 \frac{\partial H_z}{\partial t} = -\frac{\partial E_y}{\partial x}, \tag{2}$$

$$\varepsilon \frac{\partial E_y}{\partial t} + \sigma E_y = \frac{\partial H_x}{\partial z} - \frac{\partial H_z}{\partial x}. \tag{3}$$

According to Bloch theory, the periodic structures of the boundary conditions are used as follows:

$$\psi(\boldsymbol{r} + \boldsymbol{R}, t) = \psi(\boldsymbol{r}, t)\, \mathrm{e}^{\mathrm{j}\boldsymbol{k}\cdot\boldsymbol{r}}, \tag{4}$$

where $\boldsymbol{R}$ is lattice vector and $\boldsymbol{k}$ is wave vector.

According to Drude model, when the impact of ions is ignored, the relative dielectric constant of non-magnetised plasma can be written as

$$\varepsilon_{\mathrm{r}} = 1 - \frac{\omega_{\mathrm{p}}^2}{\omega(\omega - \mathrm{i}\nu)} = 1 - \frac{\omega_{\mathrm{p}}^2}{\omega^2 + \nu^2} - \mathrm{i}\frac{\nu}{\omega}\frac{\omega_{\mathrm{p}}^2}{\omega^2 + \nu^2}, \tag{5}$$

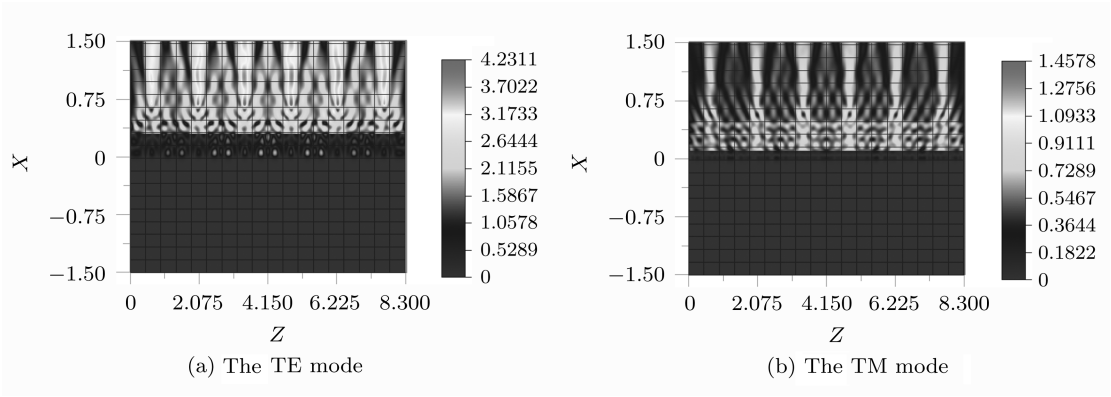
where $\omega_{\mathrm{p}}$ is the plasma frequency, $\gamma$ is the damping frequency, $\omega_{\mathrm{p}} = 1.346390 \times 10^{16}$ rad$\cdot$s$^{-1}$, $\nu = 9.617120 \times 10^{13}$ rad$\cdot$s$^{-1}$.

The incident plane wave illumination is linearly polarised along $x$ direction with an $E$-field amplitude of 1 V/m. Figures 4 and 5 showed the simulated $E$-field and $H$-field amplitude at the cross-sectional view. When the silica mask without silver was used, the light energy of TE mode in the ridge of the structures was a little stronger than that in the flat site from Fig. 4(a). The maximum relative intensity of the ridge of the structures was about 3.8, and the maximum relative intensity of the flat site was about 2.4. It should be emphasized that the $E$-field amplitude is strongly enhanced on the silver film on the ridge sites by a factor of 1.6 compared to that of silver film on the flat sites. When the silica mask without silver was used, the light energy of TM mode in the ridge of the structures was a little stronger than that in the flat site from Fig. 4(b) also. The maximum relative intensity of the ridge sites was about 1.1, and the maximum relative intensity of the flat site was about 0.8. The $H$-field amplitude is enhanced on the silver film on the ridge sites by a factor of about 1.4 compared to that of silver film on the flat sites. When the silica mask with silver film was used, the light energy of TE mode in the ridge of the structures was stronger than that in the flat site from Fig. 5(a). The maximum relative intensity of the ridge of the structures was about 2.8, and the maximum relative intensity of the flat site is about 0.2. It should be emphasized that the $E$-field amplitude is strongly enhanced on the silver film on the ridge sites by a factor of 14 compared to that of silver film on the flat sites. Similarly, the light energy of TM mode in the ridge sites was stronger than that in the flat site from Fig. 5(b) also. The maximum relative intensity of the ridge sites was about 1.9, and the maximum relative intensity of the flat site was about 0.4. The $H$-field amplitude is strongly enhanced on the silver film on the ridge sites by a factor of 4–5 compared to that of silver film on the flat sites. The difference of energy distribution of the ridge and the flat site was not obvious in Fig. 4(a), so photoresist under mask was all exposed. From Fig. 5, SPs was excited on silver film's surface when the mask deposited with silver was exposed by 436 nm UV-light. Because the excited SPs was TM mode, the light energy of TM mode was enhanced greatly in the ridge of the structures in Fig. 5(b). As the incident light was injected vertically, SPs were not excited on the flat site of silver mask, whose component of momentum along the interface between the dielectrics was zero and could not satisfy the conversation of momentum in order to produce the SPs. The resulting momentum mismatch between light and SPs of the same frequency must be bridged if light is to be used to generate SPs.[11] There are three main techniques by which the missing momentum can be provided.[12] The first makes use of prism coupling to enhance the momentum of the incident light. The second involves scattering from a topological defect on the surface, such as a sub-wavelength protrusion or

hole, which provides a convenient way to generate SPs locally. The third makes use of a periodic corrugation in the metal's surface. The mask in the experiment is the periodic corrugation in the metal's surface. If the metal and dielectric materials are both semi-infinite, from the boundary we solve Maxwell's equations, then determine the dispersion relation of SPs as

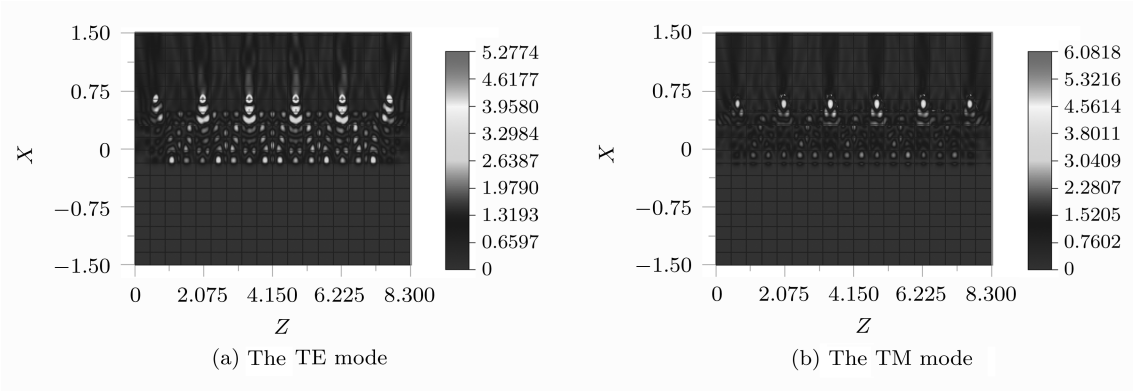
$$k_{\mathrm{sp}} = k_0 \sqrt{\frac{\varepsilon_{\mathrm{d}}\varepsilon_{\mathrm{m}}}{\varepsilon_{\mathrm{d}} + \varepsilon_{\mathrm{m}}}}, \tag{6}$$

where $k_{\mathrm{sp}}$ is the wave vector of the surface plasmon, $\varepsilon_{\mathrm{m}}$ and $\varepsilon_{\mathrm{d}}$ are the permittivity of the metal and dielectric material respectively. The $\varepsilon_{\mathrm{m}}$ and $\varepsilon_{\mathrm{d}}$ must have opposite signs if SPs are to be possible at such an interface. This condition is satisfied for metals because $\varepsilon_{\mathrm{m}}$ is both negative and complex. After calculation, $k_{\mathrm{sp}} > k_0$, which shows that SPs lead to a near-field enhancement. In this paper, contact exposure was used, the structures after exposure are shown in Fig. 3(b).




(a) The TE mode (b) The TM mode

**Fig. 4.** The simulation results of transmission about mask without silver film by FDTD.




(a) The TE mode (b) The TM mode

**Fig. 5.** The simulation results of transmission about mask with silver film by FDTD.

## 4. Conclusion

The silica structures with silver film were used as the exposure mask in this paper. Utilising SP characteristics that SPs was excited on silver film's surface by 436 nm UV-light exposure, we transfer the pattern from the mask coated with silver to the photoresist layer. The energy distribution of the transmission through the mask with silver film was analysed by FDTD method. According to the analysis above, the SP characteristics of metal silver can be used to increase the optical field energy distribution differences through the exposure mask, the silica template deposited with the silver film could play the role as a mask. This technique is simple, rapid and accurate. It can be used in wide-range visible light scale to exposure the photosensitive layer to produce subwavelength structures.

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