Embedded metal mask enhanced evanescent near field optical lithography

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Embedded metal mask enhanced evanescent near field optical lithography

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Abstract

Simulation of evanescent optical lithography using an embedded metal mask (EMM) shows that resolution and throughput are significantly enhanced over conventional ENFOL, due to coupling between surface plasmons and cavity mode excitations. The key role played by surface plasmon polaritons and the effects of wave vector matching between the incoming photon and the EMM mask grating are clear from the simulation. In particular a double peaked resonant intensity distribution is revealed for the first time within the dielectric filled mask cavity, for the shorter wavelengths only. This effect is highly conducive to efficient sub wavelength lithography and has not been discovered by previous simulations. The EMM–ENFOL process has considerable potential for cheap, high throughput nanolithography with resolution well below diffraction limits.

Keywords: Evanescent near field; Optical lithography; Surface plasmon polaritons; Embedded metal masks

1. Introduction

Evanescent near field optical lithography (ENFOL) is a form of simple contact lithography in which a patterned metal absorber layer is carried on a transparent, conformable membrane which is forced into intimate contact with the resist [1]. It can produce nanoscale features using a range of wavelengths, including visible and ultraviolet. Paulus et al. [2] analysed conventional contact optical lithography with a mask in which the metal absorber is embedded in a dielectric, which they called a metal embedded mask, or MEM. (We prefer the term embedded metal mask, with the abbreviation EMM, to avoid confusion with microelectromechanics or MEMS.) EMM mask lithography has also been investigated theoretically for the case of ENFOL by McNab et al., using the Multiple Multipole Programme (MPM) [3]. In their work, the refractive indices of the mask dielectric and photoresist are assumed to be identical and the programme cannot model interactions between domains, thus reducing the validity of the simulation for sub-wavelength gratings. In contrast, our work employs a finite element method (FEM), providing a full vector solution to Maxwell's equations to obtain a comprehensive model evaluation of EMM–ENFOL, including the effects of coupled surface plasmon polaritons and cavity modes. The results shown below reveal several phenomena not presented previously by other authors. In particular, we report the existence of a cavity resonance with a double peaked intensity distribution, with favourable consequences for lithography without the need for refractive index matching between mask and photoresist.

Our work focuses attention on the influence of surface plasmon polariton excitation and cavity modes. Surface plasmon polaritons (SPPs), due to metallic free electrons, are coupled oscillations of electron density and electromagnetic field. SPP modes have greater momentum (shorter wavelength) than the incident light. When excited in a nanoscale structure, the lateral intensity variation of SPP fields is governed by the nanostructure dimensions, rather than the incident light wavelength, thus overcoming the

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diffraction limit [4]. These effects are well known in surface-enhanced Raman scattering and nanolithography relying on SPP near-fields [5].

2. EMM–ENFOL simulation

The modelled EMM–ENFOL process is shown schematically in Fig. 1. The embedded metal mask is patterned to form a grating pattern of 115 nm pitch with a slit width of 30 nm; the thickness of the embedded absorber film may be varied for simulation purposes but is typically of the order of 50 nm. The illumination radiation is TM – polarized, as shown.

The modelling software used is FEMLAB^{TM}, from COMSOL Inc. This provides a full vector solver of Maxwell's Electromagnetic Equations in the EMM–ENFOL geometry, revealing details of the physics of light transmission through the system. The simulation is predictive: interactive interrogation and interpretation of the outputs reveals the key mechanisms of the lithography process, which are not assumed a priori.

The illuminating wavelength was varied from deep u.v. at 248 nm, through G-line (436 nm) to the visible (600 nm) with a mask membrane dielectric of silicon nitride having a refractive index of 2.15. SPP waves are formed, due to coupling between electromagnetic radiation and surface plasmon oscillations of the free electrons in the metal surface of the grating [6]. The excitation of SPP waves in our EMM–ENFOL case may be inferred from the electric field plot shown in Fig. 1; they are TM-polarized like the incoming radiation. The formation of an SPP is determined by the momentum matching equation, which is the resonant condition matching the SPP wave momentum $\pm\hbar k_{\mathrm{spp}}$ to that of the incoming radiation photon and the quasi-momentum provided by the grating periodicity, thus

$$\vec{k}_0 + \vec{k}_{\mathrm{gx}} = \vec{k}^{\pm}_{\mathrm{spp}} \tag{1}$$

This wave vector matching determines the wavelength of the SPP which will vary with illuminating wavelength λ_0 for the fixed grating conditions in our model case:

$$\lambda_{\mathrm{spp}} = \frac{\lambda_0}{1 + \frac{\lambda_0}{\lambda_{\mathrm{gx}}}} \tag{2}$$

The SPPs form as a result of the strong plasmon oscillations associated with the high time-varying electric stress, which peaks on adjacent edge facets, as shown in Fig. 2.

The second key phenomenon in EMM–ENFOL is the formation of electromagnetic cavity mode EM field oscillations within the confines of the mask slit. These are modified in the presence of SPPs to determine the ultimate variation of electromagnetic energy within the slit cavity, as seen in Fig. 3; the results are sensitive on the nanometer scale to absorber thickness, which is 52 nm in this case.

The results predict a five times intensity enhancement of the output SPP radiation, compared with the incident light intensity, due to SPP-cavity mode coupling, when the grating resonance condition of Eq. (1) is obeyed. Details of the result for the variation of intensity through the slit are shown in Fig. 4. The in-slit intensity variation shows significant differences for different wavelengths. The oscillation mode is strongly dependent on wavelength, displaying double – peaked intensity distribution for the deep u.v. wavelengths in contrast to a single peaked distribution for the longer wavelengths between 365 nm and 600 nm; the double peak mode is shown schematically in Fig. 4 (inset).

The embedded absorber in the EMM configuration is necessary for the double peaked mode to form, as seen in Fig. 5, which shows a single peak even for deep u.v. illumination at 248 nm, for the case when there is no dielectric in the slit.

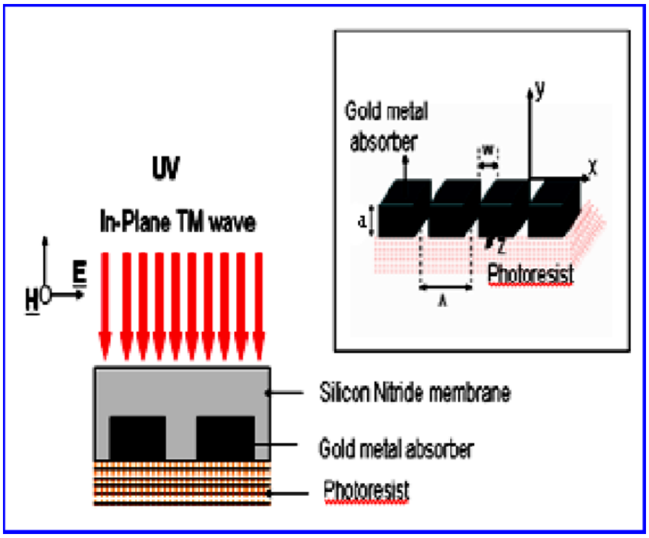

Fig. 1. Schematic of EMM–ENFOL with grating mask (pitch $\Lambda = 115$ nm; slit width $w = 30$ nm).

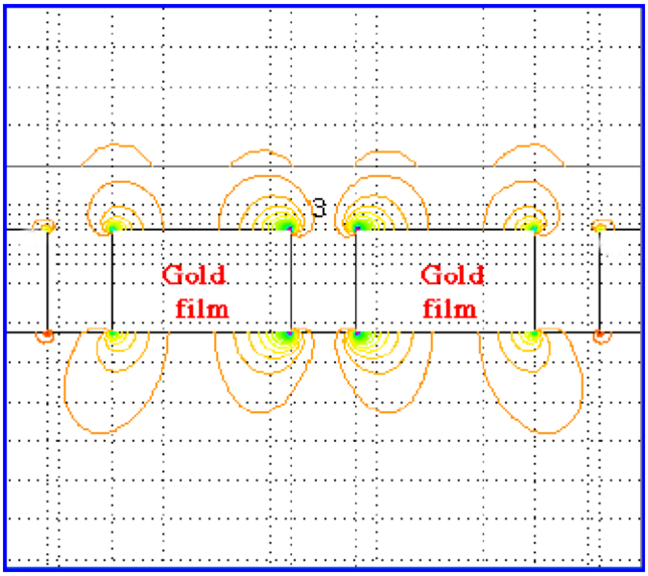

Fig. 2. Excitation of SPP modes, revealed by calculated field stress contours.

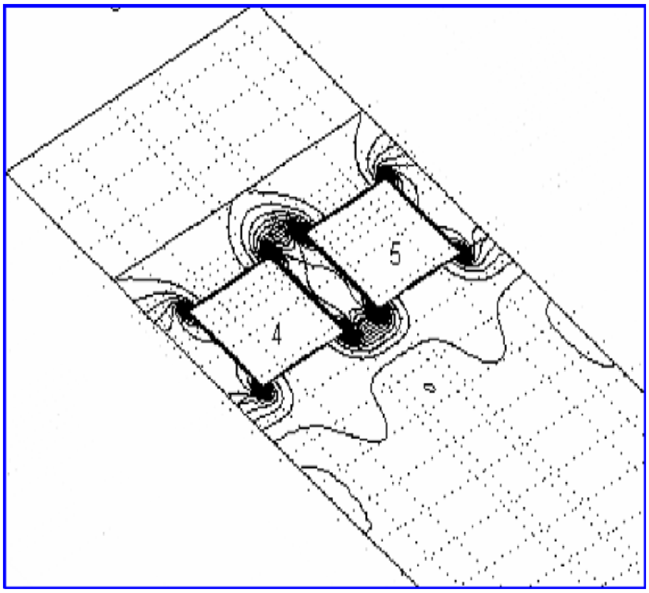

Fig. 3. Contours of electromagnetic energy in the slits. The energy flow travels along the slit walls to form a cavity mode.

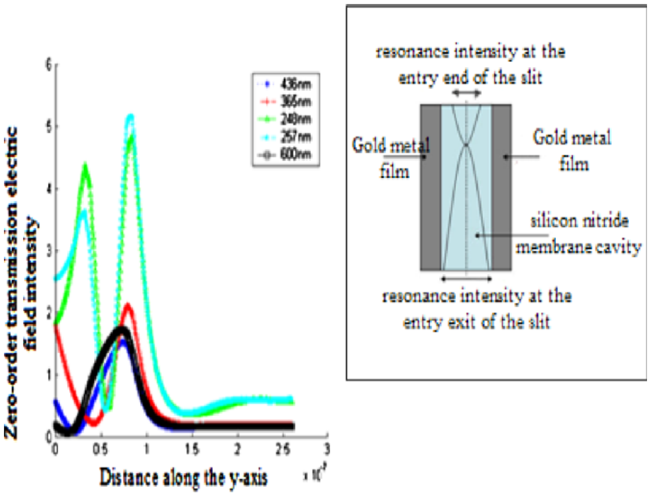

Fig. 4. Transmission calculations for EEM–ENFOL (52 nm embedded gold film forming 115 nm grating with 30 nm slits).

The nanofunneling effect, which provides concentration of wave energy in the slit and locally beyond in the photoresist, is shown clearly by plotting the time average Poynting vector, which represents the magnitude and direction of electromagnetic wave energy flow. The results, shown in Fig. 6, reveal the existence of cavities in the energy flow field, centered on the lateral mid points of the absorber, with strongly funnelled flow through the slits, as required for lithography.

The usefulness of the method for sub-wavelength nanolithography is illustrated by Fig. 7, which shows the intensity distribution laterally across the grating at the mask-resist interface and at 30nm into the resist for 248 nm incident radiation with double peaked resonance in the cavity, as seen above. This condition is associated with high resolution lithography, with pattern definition, determined by the mask dimensions, being well below diffraction limits, as shown in Fig. 7. The results show that there is a loss of resolution with depth into the resist, but the process is still viable for nanolithography with resolution almost an order of magnitude smaller than the illuminating wavelength.

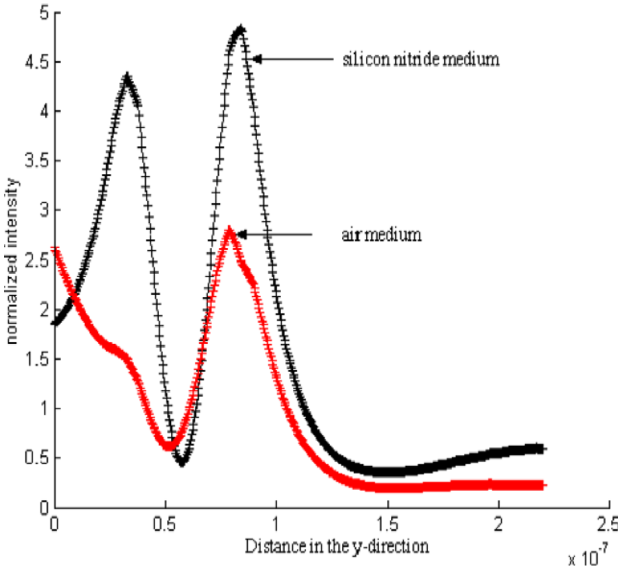

Fig. 5. Resonant transmission intensity plots through air cavity (red) and silicon nitride membrane cavity (black); incident wavelength 248 nm. (For interpretation of the references in colour in this figure legend, the reader is referred to the web version of this article.)

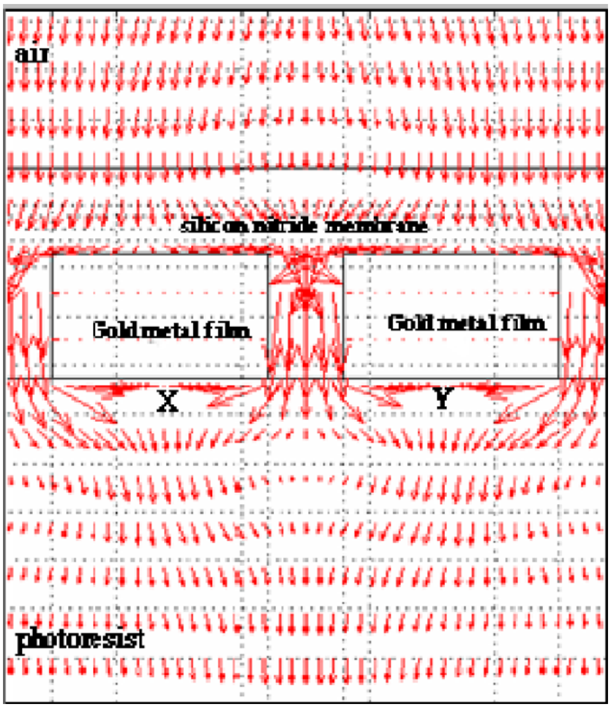

Fig. 6. Power flow field revealed by plots of the Poynting vector. Regions X and Y are "cavities" in the flow.

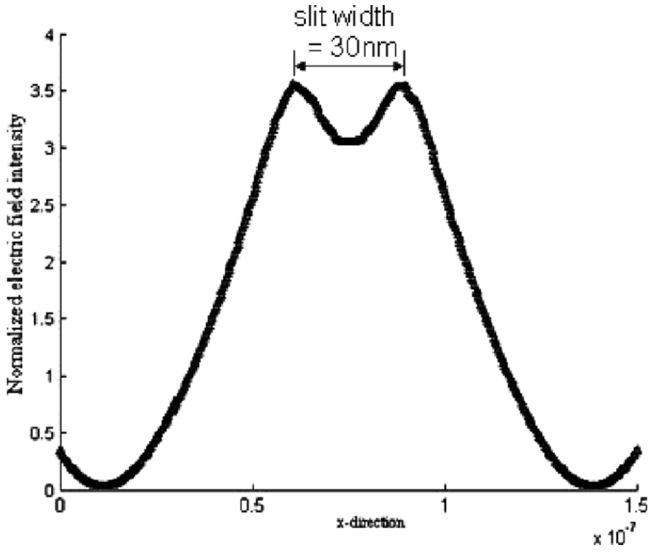

Fig. 7. Lateral intensity distribution due to 248 nm radiation 30 nm into the resist.

3. Conclusions

Finite element vector simulation of evanescent near field optical lithography with an embedded metal mask (EMM–ENFOL), has been carried out using the FEMLAB^{TM} software from COMSOL Inc. The simulations show the effects of SPP-cavity mode coupling at the resonant condition where the incoming and outgoing photon wave vectors are matched through the grating quasi-momentum. The SPP-modified cavity modes for deep u.v. wavelengths are different from those at longer wavelengths. In particular, coupling between the SPP and cavity modes has, for the first time, been shown to create a double peaked resonant intensity distribution in the dielectric-filled cavity of the EMM. This is a new result and is not found in the case of an air cavity (protruding metal mask).

Nanonoscale resolution is obtained with five times intensity enhancement, and with no need for refractive index matching of mask dielectric and resist, when resonant conditions are met using a 15 nm grid with 30 nm slits and 248 nm incident radiation.

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