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A novel optical lithography implement utilizing third harmonic generation via metallic tip enhanced near field

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ABSTRACT

A novel scheme for near-field optical lithography utilizing a metallic tip illuminated by femtosecond laser pulses with proper polarization has been presented. The strongly enhanced near field at the metallic tip offers a localized excitation source for the third harmonic generation in the nonlinear material. The generated third harmonic via excitation of nonlinear photoresist provides good exposure contrast due to the cubic intensity dependence. The spatial resolution of this novel lithography scheme is shown to be better than that of the conventional lithography technique.

1. Introduction

Optical lithography has become the advantageous fabrication technology in the manufacturing process of electronic and photonic devices due to the dramatic increase in spatial resolution. As the size of devices decreases rapidly, in order to meet the higher fabrication resolution, especially to achieve nano-scale device dimension, basically two approaches are feasible and commonly exploited: The fabrication scale of conventional photolithography is restricted by the diffraction limit [1], so one potential solution that has actually been pursued for years is to increasingly shorten the illumination wavelengths. For example, the used wavelengths of light source were shortened to the deep ultraviolet [2,3], the extreme ultraviolet [4] or the x-ray region [5]. However, using the shorter optical wavelengths to reach the desired feature sizes is becoming more difficult and complicated, because they require significantly difficult adjustments of the lithographic process, including the development of new light sources, photoresists, and optics. Another common solution is to substitute the focused particle beams for the illumination light beam. For example, the focused electron beam lithography [6] and ion beam lithography [7] have been explored for the nanolithography in recent years. But the new equipments for these nano-optical lithographic techniques are extremely sophisticated. Moreover, the development of new materials, different process schemes, and new infrastructure of tools are required, all of which cause the huge costs of the research and development.

Recently, however, various explorations related to plasmonic lithography, which belongs to optical contact or near-field photolithography, have been undertaken to overcome the diffraction limit and to achieve a resolution that is several times smaller than the wavelength of the incident light [8–10]. In essence, all of the plasmonic lithography technologies utilize the unique nature of surface plasmons: its enhanced electromagnetic field localizes near the metallic nanostructures [11]. The conventional light source, such as the g-line, h-line, and i-line types, are available in plasmonic lithography. To further decrease the device line width, the third-harmonic generation could be exploited due to the cubic intensity dependence. In addition, given that most of the conventional photolithography light sources are ultraviolet-wavelength light sources, so, the ultraviolet (UV) light source is the key operator that can be functioned with the common device materials. Through the third harmonic generation, the infrared light source can be converted to the UV light source. For example, Yupapin et al. have proposed a system of a third harmonic generation for a new generation optical lithography by using a soliton pulse circulating in the integrated micro-ring devices [12]. By extension, any specific wavelength of exposure light can be obtained by using the triple wavelength light as the illuminated light source. Therefore, by this technique, the specific source, especially, UV wavelength region can be easily generated.

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In this paper, we proposed a new scheme for near-field optical lithography utilizing a metal apertureless probe illuminated by femtosecond laser pulses with proper polarization. The strongly enhanced electric field at the metal tip results in a localized excitation source for the third harmonic generation in the nonlinear material. The generated third harmonic via excitation of nonlinear photoresist provides better spatial resolution than that of the conventional lithography technique. Here, we numerically investigate the excitation and enhancement of third-harmonic generation (THG) via tip enhancement of a metal apertureless probe for the purpose of using the THG as the photolithography exposure light to achieve the even greater exposure contrast.

2. Structure details and calculation methods

The apertureless metal tip structure is widely exploited in tip-enhanced Raman scattering [13], field-enhanced scanning near-field optical microscopy [14], two-photon nanolithography [15], and tip-enhanced fluorescence microscopy [16]. All of these applications use the near-field enhancement effect of the metallic tip nanostructure. In this numerical simulation, the photoresist layer assumed infinitely thick can be prepared on a substrate by spin-coating method, and an Au tip hung over the sample, as shown in Fig. 1. The gap distance between the bottom of metal tip end and the top of photoresist layer is G, the flare angle of metal apertureless probe is φ, and the radius of the semicircle tip end is R. The incident light source, which is Gaussian optical pulse, illuminated on the metal tip end at an angle θ. The parameters, plasma frequency $\omega_p = 1.339 \times 10^{16}\ \mathrm{s}^{-1}$ and damping coefficient $\gamma = 1.143 \times 10^{14}\ \mathrm{s}^{-1}$, for gold are taken according to Ref [17]. Some of other parameters are set as: the electric field amplitude of the illumination light is 50 kV/m, the waist radius of Gaussian beam is 300 nm, the laser pulse width is 10 fs, the central wavelength of optical pulse is $\lambda_0 = 1064$ nm, and the third-order nonlinear optical susceptibility is $\chi^{(3)} = 1 \times 10^{-20}\ \mathrm{m}^2/\mathrm{V}^2$. Here, the main component of the incident electric field is y component E_y, and only the component of nonlinear coefficient corresponding to this main field component is considered for simplicity. The red dotted line on the upper surface of photoresist layer represents a row of dot monitors. A total of 100 dot monitors were symmetrically placed under the metal tip, and every two monitors is 2 nm apart.

The calculation approach based on the finite element time domain technique was exploited to solve Maxwell's equation in the simulation. Firstly, a focused laser pulse beam illuminated the tip end from the left boundary of the calculation domain and excited the enhanced surface plasmon field decaying exponentially into the vicinal domain of the tip end. If the localized field is strong enough, it would locally interact with the nonlinear photoresist beneath the tip end and lead to the third-harmonic generation optical response. In this time-domain calculating process, the field intensity of every monitor location could be simultaneously recorded by the line of dot monitors on the upper surface of the photoresist layer. Then, the frequency-domain spectrum line could be obtained by the Fourier transform. At last, the peak values of field intensity corresponding to fundamental signal (FS) and third-harmonic generation could be respectively extracted from the frequency-domain spectrum line. For example, in a calculating process, the time-domain spectrum line recorded by the monitor right under the tip axis was plotted in Fig. 2(a). Through the Fourier transform, the corresponding frequency-domain spectrum line was shown in Fig. 2(b).

Processing the data recorded by all the 100 monitors through the same process, and then plotting the distribution of THG signal peak values on the monitor line, the distribution of signal peak

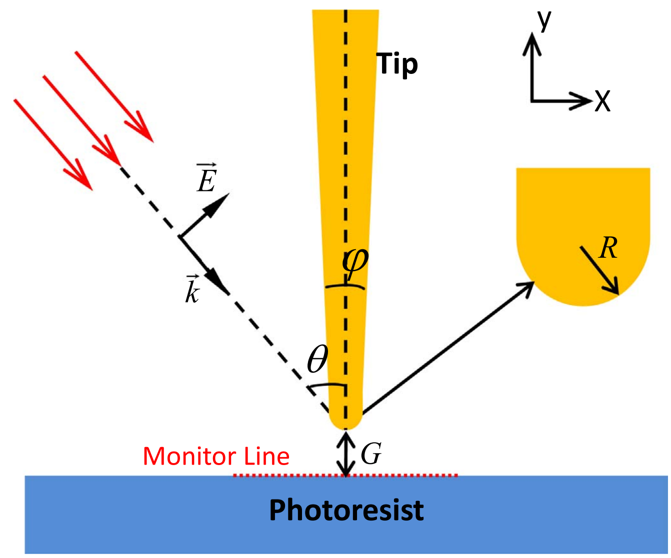

Fig. 1. Schematic configuration of the structure under study.

values on the monitor line could be obtained, which represents the minimum line width of the optical lithography. The photoresist is sensitive to the optical field intensity. The intensity contrast (or visibility) needs to be not less than 0.4 for positive photoresist in modern lithographic fabrication processes [18]. So, it is appropriate to use the full-width at half-maximum (FWHM) of the optical field intensity spatial distribution to refer to the line width of nanolithography. Moreover, the sensitive spectral range is limited for one kind of the photoresist. So, for the photoresist sensitizing in the spectral range of the THG, the FS field is invalid in photolithography because its spectral range is far out of the THG.

3. Numerical results and analysis

The field enhancement effect at a metal tip definitively relies on the excitation of the surface plasmon mainly localized near the tip end. In order to induce the field enhancement effect at the tip end, the incident light must have a polarization component along the tip axis, which is very important and has been pointed out by many researchers [19,20]. Aiming at this point, we used our simulation method in this work to make verification calculation. As shown in Fig. 3, the metal tip was placed in air environment, and a focused illumination beam horizontally radiated to the tip end from the left boundary of calculation domain. In Fig. 3(a), the polarization of incident wave was parallel to the axial direction, which gave rise to the field enhancement effect at the tip end; moreover, in Fig. 3(b), the excitation field had no component along the metal probe axis. In this case, no field enhancement was obtained.

Therefore, it is crucial that the excitation field has a large component along the metal tip axis to obtain a high field enhancement. In the simulation, the angle between the direction of incident laser pulse and the axial direction of metal tip fixed at $\theta = 15^{\circ}$. The flare angle of metal apertureless probe fixed at $\varphi = 10^{\circ}$, which does not much affect the field enhancement effect within a certain range.

The field enhancement of metal tip relying on the plasmon resonance relates to its shape and geometrical dimensions [20]. In this simulation, we mainly studied the common metal probe structure with semicircle tip end. In addition, the excited surface plasmon field having the property of evanescent waves localizes at the tip end and decays exponentially in a direction perpendicular