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Design and fabrication of a tip-on-aperture probe for resolution enhancement of optical patterning

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ABSTRACT

A variety of near-field scanning optical microscope (NSOM)-based lithography techniques have been developed for different applications through the use of a sub-wavelength aperture probe. The light transmission efficiency of an NSOM probe decreases markedly as the aperture diameter decreases. Apertureless NSOM yields a much higher resolution by concentrating the light field near the tip apex. However, far-field illumination by a focused laser beam deteriorates the resolution in optical patterning process. In this report, a tip-on-aperture (TOA) probe was fabricated to achieve high pattern resolution beyond that obtained from conventional NSOM probes. The shape of the probes was designed using the results of numerical analysis based on a finite-difference time-domain (FDTD) algorithm. The results showed that a probe with a triangular shape tip confined the electromagnetic energy with a 6.7 times larger intensity than the value obtained from a probe with a cylindrical shape tip. The TOA probes were fabricated by generating a triangular tip on a metal-coated NSOM probe using a focused ion beam (FIB) process. The resolution enhancement was experimentally demonstrated by the formation of the developed pattern on photo-resist.

1. Introduction

Nanopatterning and lithography seek to build structure with nanoscale features that can be used as components, devices, or systems. Most current technologies used in the nanofabrication field have evolved from conventional lithographic processes for preparing microelectronic circuits and components; however, conventional lithographic techniques face many challenges as they approach their fundamental resolution limits. Many novel processes, including near-field photolithography [1–5], imprint lithography [6–7], and surface plasmon-assisted nanolithography [8], have been devised to further reduce the feature size beyond the diffraction limit. Scanning probe-based lithography offers a potential low-cost alternative to the fabrication of nanoscale structure and features with several technical advantages [9–10]. Near-field scanning optical microscope (NSOM) lithography is one of the typical probe lithography techniques, which is applicable to conventional photoresist and photochemical surface with high optical resolution. The optical near-field generated at the tip with an order of tens of nanometers, interacts with a sample to produce nanometer-size patterns. However, the light throughput decreased markedly as the aperture diameter decreased, and a large aperture probe yielded a relatively poor patterning resolution. To overcome the aperture dependent resolution and light throughput, apertureless near-field patterning was proposed [11–13]. In this case, a laser light irradiated on a nanoprobe induces topological or photochemical changes on the surface. The optical nano-antenna or tip-on-aperture (TOA) probe compromises these disadvantages, by positioning a nanoscale tip at the end of a metal-coated aperture NSOM probe [14–16]. The TOA probe is geometrically modeled as apex placed to an aperture in a perfectly electrically conducting (PEC) plate for calculations of the electric field distribution near the tip.

This paper describes a plasmonic probe with a specially shaped tip on an aperture probe to yield enhancement of resolution on scanning patterning. The tip-on-aperture probe was illuminated through an aperture and electromagnetic interactions between the structured sharp tip at the end of the probe and the surface were expected to be a nanoscale light source for material processing. The electromagnetic energy distributions at the near-field end of the probe were calculated numerically using a finite-difference time-domain (FDTD) algorithm. The geometric relationship between the tip and the polarization direction was analyzed, and an effective shape of the tip was proposed. Focused ion beam (FIB) processes were used for the fabrication of the designed tip-on-aperture probes. The pattern resolution enhancing effects were verified by NSOM patterning on photoresist.

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2. Theory and method

2.1. Numerical model

The configuration of the tip-on-aperture probe for the simulations of the electric field distribution is shown in Fig. 1. To consider the electromagnetic wave only from the aperture, perfectly conductive walls were constructed around the probe, and the sharpened tip was illuminated through an aperture. The incident light was modeled as a linearly polarized plane wave. The wavelength of the incident electromagnetic wave was set to 400 nm. For numerical analysis, optical properties of fused silica were used as an optical fiber material, and dielectric properties of silver for the coating layer was calculated with the modified Debye model [17,18]. The Debye model is described by using the following equation:

$$\tilde{\varepsilon}(\omega) = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + i\omega\tau} + \frac{\sigma}{i\omega\varepsilon_0}. \tag{1}$$

The parameters in Eq. (1) for silver at a wavelength of 400 nm were $\sigma = 1.35099 \times 10^7$ S/m, $\varepsilon_\infty = 10.9975$, $\varepsilon_s = -7081.99$, and $\tau = 4.64857 \times 10^{-15}$ s, respectively. All parameters were treated as fitting constants in the fit to the experimental data [19].

2.2. Fabrication of a plasmonic probe

The TOA probes were fabricated in similar manner for fabricating conventional aperture NSOM probes. Sharp glass tips were created by heat-pulling single-mode glass fibers using a pipette puller. Next, the probes were coated by evaporation with a chromium adhesion layer a few nanometers thick and a 150 nm silver layer. Finally, focused ion (Ga^+) beam (FIB) milling was applied under two different angles, to create well-defined tip on a flat end of the probe next to the circular aperture as shown in Fig. 2.

2.3 Experimental setup

An NSOM system manufactured by NT-MDT, Ltd. was used to control the tip-sample distance and plane motion. A continuous wave GaN semiconductor UV (wavelength 405 nm, maximum output power 20 mW, TEM_{00} mode) was induced as the light source. A variable neutral density (ND) filter was installed at the laser output side to control the laser beam power. The beam polarization direction was adjusted using a half-wave plate and a linear polarizer. To measure the power incident on the TOA probe, the laser beam was split into two beams, of which one is coupled to the optical fiber and another is directed to the photodetector for measurement. An electromagnetic shutter was employed to turn on and off the laser light during scanning. The schematic of experimental setup is depicted in Fig. 3.

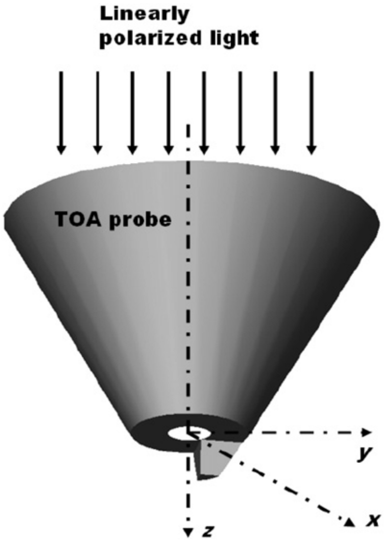

Fig. 1. Tip-on-aperture (TOA) probe configuration with a sharp tip for FDTD simulation.

A multi-range positive photoresist (DPR-i5500, Dongjin Semichem) was used as the patterning material. The photoresist was modulated by mixing the photoresist solution with a solvent to obtain a coating thickness less than 100 nm. The photoresist was scanned by moving the sample on the 2-axis piezo-stage. Beam irradiated sample was developed in a developer solution for 1 min and rinsed with deionized solution and water. The width of the pattern was measured using a scanning electron microscope (SEM).

3. Results and discussions

The TOA is illuminated through an aperture at the near-field of the probe, and electromagnetic interactions between the structured sharp tip at the end of the probe and the substrate can be used for material processing and measurements. A novel probe with a polygonal cross-sectional tip can strongly enhance the local electromagnetic field [11,14–16]. We numerically calculated the electromagnetic energy distributions in the near-field of tip prepared with various shapes using FDTD methods. The results were then analyzed to design an efficient tip configuration. Fig. 4 shows the instantaneous electric field distribution for the modeled tips with the maximized the electric field intensity. The calculated planes were positioned 4 nm from the tip end and perpendicular to the propagation direction of the incident light. The results showed that the location and value of the maximum intensity of the electric field was highly dependent on the tip cross-sectional shape and the polarization direction of the incident light. The electric field distribution on the cylindrical tip in Fig. 4(a) was similar to that obtained using a conventional NSOM probe, which creates a local maximum field intensity at the right angle intersection between the tip edge and the beam polarization direction. Two square cross-sectional tips are shown in Fig. 4(b) and (c), revealing a local field enhancement effect related to the polarization direction of the incident beam. The two apices in Fig. 4(c), oriented along the axis of polarization, showed higher maximum electric field intensities than were observed at the 4 points of the square cross-sectional tip shown in Fig. 4(b). To maximize and localize this effect in a small area, an asymmetric tip, having a vertex and a vertical line junction oriented along the direction of the beam polarization was proposed and modeled, as shown in Fig. 4(d) and (e). The numerical results showed that the TOA probe with a triangular cross-sectional tip could confine the electromagnetic energy at one point with an intensity that was 6.7 times higher than the intensity obtained from typical probes with a circular or square cross-sectional tip. These results also revealed that a right triangularly shaped tip provide the most efficient point for electromagnetic field confinement.

The FDTD results obtained for various polygonal tips, permitted calculation of the electric field intensity at the near-field of a triangular tip on an aperture to predict the effects of the tip length. In fabrication process of TOA probe, FIB milling was applied to create an aperture and a tip simultaneously. In this process the tip length, l, was defined as the distance between the end of the tip and the aperture, as shown in the inset of Fig. 5. The calculated maximum magnitude of the electric field is plotted in Fig. 5 as a function of the tip length at beam wavelength of 400 nm. The electromagnetic field intensity reached a peak of 16.11 V/m at 310 nm for a tip length. As the tip length decreased, the electric field transfer efficiency from the aperture to the tip is increased; however, the short tip was