NEMS fabrication of metal coated sub-wavelength size aperture array and its optical characterization

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Abstract

We successfully fabricated the sub-wavelength size silicon oxide aperture array as a near-field optical probe in order to examine the possible light resonance-tunneling phenomenon. Initially, using a magnetic enhanced reactive ion etching (MERIE) system, a (50\texttimes;50) array of the (5\texttimes;5) m\textsuperscript{2} size patterns was fabricated on the silicon wafer followed by V-groove formation using alkaline solution Si bulk micromachining. The silicon oxide aperture array with sub-wavelength size was revealed after the water-diluted HF acid etching. The nano-size aperture on the top of the pyramidal array with an opening rate of \(\sim 27\,\text{nm/min}\) was carefully controlled with (50:1) water-diluted HF acid solution. The Al thin film was thermally evaporated on the (50\texttimes;50) array pattern and for sub-wavelength size aperture fabrication. The initial diameter greater than 300 nm of the aperture was reduced down to \(\sim 100\,\text{nm}\). The far-field diffraction pattern was clearly observed. The optical intensity revealed the extraordinary amounts of the light transmission through the nano-aperture array.

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1. Introduction

Considerable interests have been in fabricating a sub-wavelength aperture for a near-field optical sensor due to its potential application for promising near-field optical recording and other biological applications\,[1\textendash;3]. There has been a dramatic increase in storage density to as high as \(\sim 100\,\text{Gbyte/in.}^2\) in near-field optical recording because it can circumvent the diffraction limit\,[4\textendash;6]. However, the low optical generated through the tip of the fiber probe limits the scanning speed and hinders the development of the optical storage device. Recently, in order to improve the data storage rate, parallel processing technique using cantilever array seems to be a key solution for a faster data rate\,[6\textendash;8].

In this paper, the nano-fabrication techniques of the sub-wavelength aperture arrays and the sub-wavelength aperture on the cantilever array using directional plasma etching and isotropic-diluted HF etching are presented. The fabrication techniques for sub-wavelength size aperture array using photore sist removal technique and sputter-etching in addition to focused ion beam milling have also been reported.

2. Experimental procedures

The etching of the Si using alkaline solutions such as KOH, ethylenediamine/pyrocatechol (EDP), and tetra methyl ammonium hydroxide (TMAH), is anisotropic due to the different atomic density of the Si crystal surface. The etch ratio of the Si(100) surface to the Si(111) surface is order of a few hundreds. The intersection of the Si(111) surfaces will from eventually V-type groove or pyramidal shape at the bottom Si(100) surface\,[9,10]. The oxidation rate is dependent upon both the crystal plane and the angle of the plane intersection. Because of the difference in atomic packing density, Si(111) surface will have a higher oxidation rate than the Si(100) surface. Due to either the stress-induced retardation of oxidation or the volume expansion of oxide at a concave surface during thermal oxidation\,[11,12], inner surfaces of V-groove or hollow pyramid will be non-uniformly oxidized.

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during an appropriate thermal oxidation procedure. That is, the oxide layer at the bottom or apex of hollow pyramid is thinner than the oxide at side surfaces. Isotropic oxide etching technique using water-diluted HF solution has been employed to fabricated nano-size apertures at the apexes of oxide pyramids [13]. And then, we deposited metal on the nanosize aperture array to reduce the hole size.

3. Results and discussion

The fabrication procedure of a nano-aperture array is illustrated in Fig. 1. At first, SiN and SiO2 double layer were formed on a 4-in. Si(100) wafer and (50×50) dot arrays were patterned. The square dots with various sizes from 2×2 to 10×10 µm² were patterned and the SiN/SiO2 layer was dry-etched for opening etch window using RIE as Fig. 1(b). Anisotropic Si etching using 20 wt.% TMAH at 80 °C generated hollow pyramids as shown in Fig. 1(c). As a next step, thermal steam oxidation has been performed at 1000 °C for 72 min, which has generated a thin oxide layer at inner surfaces of hollow pyramids as shown in Fig. 1(d). Fig. 2(a) is a typical cross-sectional SEM image of a V-groove after oxidation and Fig. 2(b) is the magnified image of the circled region in Fig. 1(e). It reveals non-uniform oxide thickness near the bottom of V-groove and the oxide on Si(111) surface becomes thinner as approaching to the apex. The oxide thickness at Si(111) and the bottom surface were examined by field emission SEM and found to be ~500 and ~300 nm for 4×4 µm² dot patterns. The thicker oxide at the Si(111) surface will act as an etch mask during the nano-aperture opening process at apexes of pyramids. Regardless of dot pattern size, the non-uniform oxide growth was observed and the boundary between vacuum and inner oxide surfaces looks like similar for all the samples. Backside Si bulk etching was followed to release pyramid arrays as in Fig. 1(f) and the resulting oxide pyramid size was observed to be slightly bigger than the original pattern size due to both oxide expansion into Si during the thermal oxidation and over-etch beneath the etch mask during backside etching process. Next, isotropic oxide etching using 10:1 or 50:1 diluted HF solution was employed to open oxide apertures at pyramid apexes as in Fig. 1(g). Although very careful treatment is required because of the thin oxide at the edges of the oxide tetrahedron, we have successfully brought the procedure under control for the tested arrays. From a series of repeated experiments, the progression of aperture opening with the span of etch time has been observed and the aperture diameter increased linearly with etch time as in Fig. 3(a) and the SEM image of the finally completed oxide nano-aperture array is presented in Fig. 3(a). And then, we experimented on the oxide nano-aperture array samples with the diluted HF etching solution to study the etched shape and to control the size of hole. Briefly, after we immersed the pyramidal tip array samples in 50:1 water-diluted HF solution, dumped in D.I. water for 30 min and dried in room temperature. We inspected dried samples using SEM to measure the size of holes. Fig. 3(b) shows which positions of aperture were measured in whole sample. We inspected 15 apertures for each 4 corners, totaling 60 apertures in one sample. When we inspect the hole of aperture, we measured lengths for the four directions such as width, length and two of diagonal lines in a hole as in Fig. 3(c). Fig. 4 shows the SEM images of the
samples that were etched in water-diluted solution for 15, 17 and 25 min and the sizes of holes are 128.3 ± 12 nm (a), 161.1 ± 15 nm (b), and 267.4 ± 47 nm (c), respectively. Through these data, we got the increasing linear graph with 23.6 nm/min opening rate as a function of time as in Fig. 5(d). Additional experiment probes that hole opening rate is 20.2 ~ 24.0 nm/min on average.

After the hole opening experiment as shown in the Fig. 4, we progressed a series of Au deposition on pyramidal tips 50 nm thickness at once using sputter. The deposition of Au carried out at 20 mTorr of working pressure and 300 W of RF power. The flow rate of Ar gas was 20 sccm and deposition rate was 20 nm/min. Then, we inspected one of hole using SEM to investigate change of hole size as thickness of Au
increased. Initially, we inspected that 300 nm size of hole diameter was formed on pyramidal tip and it was reduced to 260 nm after 50 nm of Au deposition (Fig. 5(a)). Next, we additionally deposited 50 nm of Au, totaling 100 nm; hole diameter was reduced to 210 nm. In this way, 140 nm of deposition reduced hole diameter to 160 nm and we also investigated that it can be reduced to 95 nm (Fig. 5(b)) after 170 nm deposition of Au. Additionally, we progressed a series of Al deposition on pyramidal tips 50 nm thickness at once using metal sputter deposition method. After we deposited 50 nm thickness of Al, the diameter of hole was reduced to 80 nm from 337 nm initial hole diameter (Fig. 5(c) and (d)). With these nano-aperture arrays, we investigated far-field diffraction patterns in order to examine the possible lights resonance tunneling phenomena. In Fig. 6(a), the far-field diffraction pattern was clearly observed from the pyramidal array with nano-size apertures. The optical intensity shown in Fig. 6(b) revealed the extra-ordinary amounts of the light transmission through the nano-aperture array. Currently, the detailed optical characterization for the near-field optical probe with nano-size aperture holes is still under investigation.

4. Summary

The sub-wavelength size silicon oxide aperture array as a near-field optical probe was fabricated in order to examine the possible light resonance-tunneling phenomenon. We used various semiconductor fabrication processes including anisotropic Si etching using 20 wt.% TMAH alkaline solution and isotropic HF etching technique to open the nanosize pyramidal oxide apertures. HF etching time was proved to be a control parameter for the aperture-opening rate. In this experiment, we showed that oxide etch rate is not constant but is dependent on etch time. Also, deposition thickness of metal such as Au or Al was probed to be a control parameter for the aperture-closing rate. For example, we investigated that it can be reduced to 95 nm with 170 nm Au deposition from an initial of 300 nm. With these nano-aperture arrays, we investigated far-field diffraction patterns.
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References