Fabrication of metal nanodots and nanowires by atomic force microscopy nanomachining

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Abstract

The fabrication of metal nanostructures by a combination of atomic force microscopy nanomachining on a thin polymer resist, metal coating and lift-off is reported. Nanodots with sizes and nanowires with widths ranging between 50 and 100 nm have been successfully created. The present work exemplifies the feasibility and effectiveness of using a single-layer resist in comparison with a two-layer resist. In addition, the localized surface plasmon resonance peaks of the metal nanostructures have been measured and the selective growths of zinc oxide nanowires on the metal nanostructures are demonstrated.

1. Introduction

Metal nanostructures have been the focus of extensive research activities in recent years due to their unusual electrical, magnetic and optical properties, and applications as masks for chemical etching, templates for immobilization of bio-receptors, chemical sensors, catalysts for the selective growth of nanomaterials, nano-photonic devices, nanointerconnects, data storage bits, etc. Fabrication techniques are naturally of great interest, and various physical, chemical or even biological approaches have been developed. In particular, scanning probe lithography (SPL) has been employed since more than a decade ago and in continual usage and improvement due to the advantages of ease of operation and relatively low cost. Among the various SPL techniques, atomic force microscopy (AFM) nanomaching has been adopted since the early years. By controlling the contact force between the AFM tip and the sample, desired nanopatterns can be created. Furthermore, with the use of a resist and the application of a subsequent lift-off process, metal nanodots (NDs) and nanowires (NWs) with widths down to 40 nm have been fabricated. However, the resists in reported works usually have a bi-layer or tri-layer structure and are more complicated than a single-layer resist. This study reports the successful fabrication of metal NDs and NWs with the use of a single-layer resist. Furthermore, the surface plasmon resonance peaks of the metal nanostructures have been measured and the selective growths of zinc oxide NWs on the metal nanostructures are demonstrated.

2. Experiment

![Schematic diagram of the experimental procedures for the fabrication of metal (a) NDs and (b) NWs, respectively](image)

Fig. 1 Schematic diagram of the experimental procedures for the fabrication of metal (a) NDs and (b) NWs, respectively.
The resist was made of a 50 nm thick PMMA film and prepared by spin-coating on a Si or a sapphire substrate. A commercial AFM (Smena-B, NT-MDT, Russia) and rectangular silicon probes (NSC15, MikroMasch, Russia) were employed for the experiment. The AFM was operated in the intermittent-contact mode for imaging. The experimental procedures are depicted in Figs. 1(a) and 1(b) for NDs and NWs, respectively. Each indentation was realized by moving the tip in the vertical direction toward the sample. A desired pattern of holes was created by locating the tip on designated positions controlled by the software. A straight groove could also be produced by indenting and moving the tip along a straight line. A metal film was then coated on the sample by e-beam evaporation or sputtering. The sample was soaked in acetone in an ultrasonic bath to remove the resist and finally dried by nitrogen gas. Details of the experimental procedures can be found in our previous publications.\textsuperscript{12,13}

3. Results and discussion

With the use of an indentation force of 3.8 $\mu$N, a nanohole array was generated on the PMMA film on a sapphire substrate and the AFM image is shown in Fig. 2(a). The pile-up around each hole is apparent, which is similar to those reported previously. After coating a 10 nm thick gold film and removing the PMMA, a gold ND array with a smallest dot size of around 70 nm was fabricated and the result is shown in Fig. 2(b).\textsuperscript{12} In addition to regular arrays, complicated dot patterns were also constructed. In Fig. 2(c), the scanning electron microscope (SEM) image of a pattern “NANO” is presented. With the use of different forces, NDs with sizes down to 20 nm can be created and the results are shown in Fig. 2(d). The AFM images of a nanogroove array after nanoscratching and a single nanogroove are shown in Figs. 3(a) and 3(b), respectively. The nanogrooves appear as though they are elevated lines in Fig. 3(a) due to the pile-up of the displaced polymer, which was also observed in previous works. The SEM image of the gold NWs fabricated from the pattern is shown in Fig. 3(c). A zoomed image is presented in Fig. 3(d) and the width is around 70 nm. By similar scratching, contact pads were connected to a single NW and a linear current-voltage relationship was observed. Various NWs of different metals have been fabricated and the results are summarized in Table 1.\textsuperscript{13}

![AFM images](image)

Fig. 2 AFM images of (a) a nanohole array on PMMA and (b) the corresponding gold nanodot array after lift-off. SEM images of (c) a gold ND pattern “NANO” on sapphire and (d) gold NDs on silicon created with different forces.

The localized surface plasmon resonance (LSPR), which is the collective oscillation of conduction electrons in metal with incident optical wave at a specific frequency,\textsuperscript{1} of the NDs and the NWs were studied by using dark-field optical microscopy. The SEM image of a gold ND array after thermal annealing at 900 °C is shown in Fig. 4(a). From a zoomed image shown in Fig. 4(b), the average diameter is around 72 nm. The optical image of the array is presented in Fig. 4(c) and appears green. The scattering spectrum is plotted in Fig. 4(d) and the resonance peak is located at 548 nm, which is consistent with reports in the literature.