Fabrication of Metallic Nanostructures by Atomic Force Microscopy Nanomachining and Lift-off Process

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We report a simple method to fabricate metallic nanostructures by a combination of atomic force microscopy (AFM) nanomachining and subsequent lift-off process. By controlling the force of an AFM tip on a thin PMMA resist, nanoscale holes and grooves are first created. By coating a metal film and performing the lift-off process, metallic nanodots with a size of 70 nm and nanowires with a width of 120 nm are successfully fabricated. In addition, nanoelectrodes with a gap of around 50 nm are also produced by cutting a nanowire with the tip. The present method demonstrates the feasibility and effectiveness of using single-layer resist in AFM mechanical lithography instead of two-layer resist reported in the literature.

Introduction

Scanning probe lithography has been used extensively in recent years for the fabrication of nanostructures and nanodevices.[1] Among the various techniques, atomic force microscopy (AFM) nanomachining has long been adopted since the initial era due to its ease of operation and applicability on insulating substrates.[2,3]

With the use of a thin resist on the substrate, holes or grooves can be first created by indenting or plowing the tip into the resist.[4–6] The use of one-layer resist has a claimed disadvantage that the tip still experiences damage. A further modification is the use of two-layer resist. In this approach, the nanomachining is performed on the top layer and the tip damage is therefore minimal. With following chemical etching, evaporation, and lift-off processing, metallic nanostructures have been successfully generated.[7–9]

As the two-layer approach is more complicated, it is desirable that the one-layer approach can be combined with standard evaporation and lift-off processing. In this article, the above goal is achieved and metallic nanostructures including nanodots, nanowires, and nanoelectrodes are successfully fabricated. In addition, it has also been verified that more than 5000 nanodots of sizes less than 100 nm can be created by a single tip, showing the simplicity and effectiveness of the present method.

Experiment

The experimental procedure is show in Fig. 1. A 1.25 wt% PMMA (molecular weight 96,500 g) solution was spin-coated on a sapphire or silicon. After a 30-min soft baking at 150 °C, the PMMA film was produced and also free of pin-holes. A commercial AFM (Smena-B, NT-MDT, Russia) and rectangular silicon probes (NSC15, MikroMasch, Russia) with a tip radius of 10 nm and a spring constant of 32.5 N/m were employed for the experiment.

The AFM was operated in the intermittent-contact mode for imaging. The contact mode operation was not adopted since the PMMA surface was frequently damaged due to the large spring constant of the employed probes. Each indentation was realized by moving the scanner and thus the tip in the vertical (z-axis) direction toward the sample. A desired pattern was created by locating the tip on designated positions controlled by the software. A metal film was then coated on the sample, and the sample was finally soaked in acetone to remove the PMMA and dried by nitrogen.

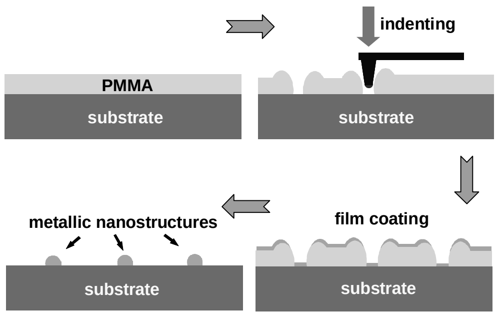

Fig. 1. Schematic diagram of the experimental procedure.

Results and Discussion

By moving a tip distance of 180 nm, which corresponded to an indentation force of 3.8 μN, a nanohole array was generated on the PMMA film and the image is shown in Fig. 2(a). After coating a 10 nm thick gold film and removing the PMMA, a gold nanodot array with a smallest dot size of 70 nm and a period of 250 nm was fabricated and the result is shown in Fig. 2(b). In addition to regular array patterns, complicated dot patterns were also created. In Fig. 2(c), the scanning electron microscope (SEM) image of the pattern "NANO" is presented, showing the ease and effectiveness of the present method to generate nanoscale patterns.

With the use of the 3.8 μN indentation force, the tip damage is minimal even after hundreds of indentations. The SEM images of a new tip, the tip after 625 indentations and the resultant gold nanodot array are show in Fig. 3.

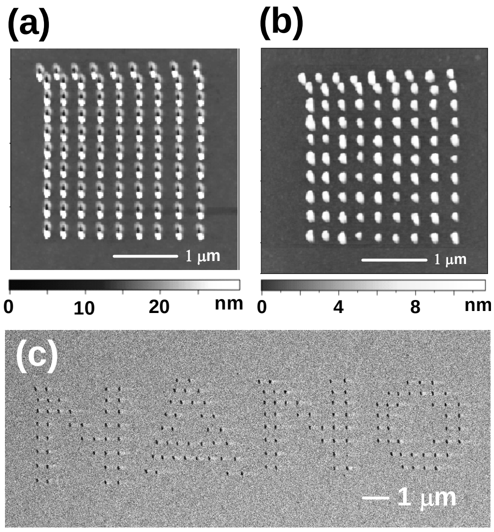

Fig. 2. AFM images of (a) a nanohole array on PMMA and (b) the corresponding gold nanodot array after lift-off. (c) SEM image of a gold nanodot pattern "NANO".

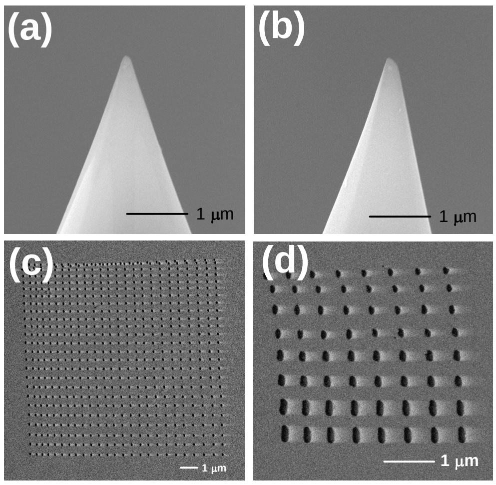

Fig. 3. SEM images of (a) a new tip, (b) the same tip after 625 indentations, (c) the resultant 25 × 25 gold nanodot array, and (d) a gold nanodot array created by 4 different forces of 4.3, 5.6, 6.8, and 8.1 μN (top to bottom for every 2 rows).

In addition, it has also been verified that more than 5000 nanodots of sizes less than 100 nm can be fabricated by a single tip. With the use of higher forces, on the other hand, the dot size increases as expected. The results for 4 different forces, which are 4.3, 5.6, 6.8, and 8.1 μN (top to bottom for every 2 rows), are shown in Fig. 3(d). It is interesting to note that the dots become elongated under high forces in one direction, which may be caused by the twisting of the tip due to a high load.

In addition to the fabrication of nanodots, nanowires can also be created by indenting the tip continuously along a straight line. By evaporating a 4 nm thick gold film and a 20 nm thick copper film, a copper nanowire with a width of 120 nm was produced after the lift-off process and the image is shown in Fig. 4(a). The obtained current-voltage curve is plotted in Fig. 4(b). With a further effort, nanoelectrodes were also fabricated on a nanowire by a direct cutting with the AFM tip. A pair of nanoelectrodes with a gap of around 50 nm was produced and the image is shown in Fig. 4(c). Simultaneous current measurement during cutting is also plotted in Fig. 4(d), and the zero current after cutting certifies that the nanowire wire was cut off completely. The present method of producing nanoelectrodes is again simple and effective.

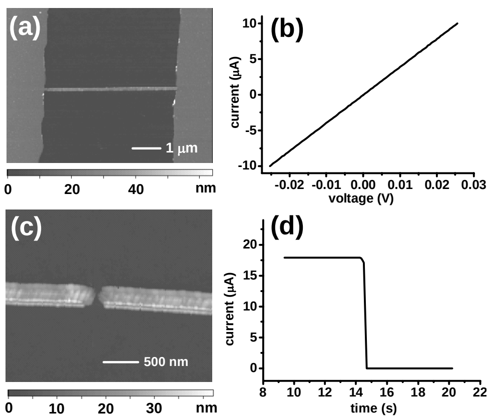

Fig. 4. (a) AFM image of a copper nanowire with a width of 120 nm, and (b) the corresponding *I–V* curve that shows a resistance of 2.54 kΩ. (c) A pair of nanoelectrodes created by direct cutting a nanowire, and (d) the simultaneous obtained current versus time relationship.

Conclusion

To summarize, we have presented a technique based on the combination of AFM nanomachining and lift-off process for the fabrication of metallic nanostructures such as nanodots, nanowires and nanoelectrodes. The major advantage is the use of one-layer resist instead of two-layer resist reported in the literature. In addition, tip wear has been proven minimal as is opposed to the common impression for the one-layer approach.

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