Hybrid AFM-Based Nanolithography on Brittle Material

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Introduction

Generally, several successful attempts for nanofabrication have been made at using scanning probe microscopy (SPM), electron beam (EB), and focused ion beam (FIB) lithography to fabricate nanoscale to microscale structures. Especially, the remarkable challenges related to the 2 or 3-dimensional fabrication in micro- to nano-scale in these days are the electrochemical machining through localized anodic dissolution of a substrate using ultrashort pulse [1] and scanning probe microscope (SPM) nanofabrication using sharp cantilever/probe based on atomic force microscope (AFM) and scanning tunneling microscope (STM) [2]. Yoshida and Morita [3] developed the mechanical patterning process of mapping images from an AFM using a lab-made micro cantilever for machining. Mirkin and co-workers [4] have shown the novel writing process named dip-pen nanolithography which uses an AFM tip as a nib, a solid-state substrate as paper, and molecules with a chemical affinity for the solid-state substrate as ink. Kolb and co-workers [5] reported the precise positioning of small copper clusters on gold electrode using a copper-deposited STM tip in an electrochemical environment. This paper demonstrates hybrid nanolithography of brittle material using an atomic force microscope with a polycrystalline diamond (PCD) tip cantilever.

Experimentals

Diamond tip cantilevers are generally fabricated based on the combination of photolithography and HF-CVD. An n-type {100}-oriented silicon with silicon dioxide was patterned by photolithography with variable length for providing wide-range flexural rigidities as shown in Table 1.
The silicon was anisotropically etched in 35 mass % KOH solution at 80 °C. As a consequence, pyramidal etch pits of 80 × 80 μm^2 were formed because silicon etching stops on the {111} plane. These etch pits were used as molds to produce the diamond tips. Then, the oxide layer on the silicon surface was removed by etching in 25 mass % buffered hydrofluoric acid (BHF). The diamond layer was subsequently deposited on the silicon mold utilizing an HF-CVD process following a diamond nucleation process using an ultrasonic agitator with diamond powders. The diamond layer was mechanically polished in order to divide the diamond tips. A silicon mold with a diamond tip was etched in a KOH solution in order to dissolve the silicon mold. Finally, the diamond tip was bonded on a silicon lever by an epoxy bonder. The silicon lever was fabricated by a photolithographic technique. The bonding of diamond tip was supported by a lab-made micro manipulator.

Table 1 Flexural rigidity of cantilevers

Length (mm)	Width (mm)	Thickness (mm)	Flexural rigidity(N/m)
500	50	45	2660
750	50	45	789
1000	50	45	333
1250	50	45	170

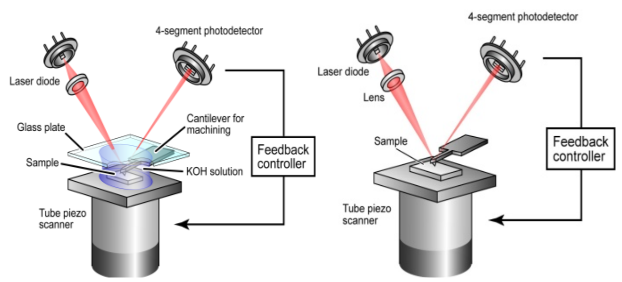

Fig. 1 Schematic diagram of experimental method for simple nanoscale scratching (left) and hybrid nano-fabrication.

The experimental procedure is illustrated in Fig. 1. The developed cantilever on AFM-based TNL apparatus modifies the (100) silicon surface with predefined normal load. Next, the processed silicon sample is etched with sonication in aqueous KOH solution at 24°C for 5 minutes. After rinsing and drying the sample, the processed part is imaged by commercial cantilever for imaging under contact mode AFM. Finally, the etching selectivity against KOH between processed (as an etch mask) and non-processed area shows protruded 2D or 3D nanostructures.

Surface Topography Analysis

The silicon substrate is easily machined with a sharp tip under high normal load, whereas it cannot be machined with a blunt tip under low normal load. The former produce a rough depression several tens or hundreds of nanometers deep in proportion to the normal tip force, similar to the mechanical removal process. The latter leaves a slightly protruding silicon layer several nanometers high, and the surface covered with the thin damaged layer is somewhat smoother than in the former case as shown in Fig. 2. Fig. 3 (left) shows an SEM image of a cutting tip after machining a silicon substrate. It can be observed that cutting chips generated in the machining process adhered to the PCD tip. However, there was no disturbance from adhered cutting chips in the machining process. In addition, burrs are generated around the cutting mark, as shown in Fig. 3 (right). These burrs are generated by an unstable cutting edge due to rapid tool wear expansion upon initial machining. In addition, under hybrid nanofabrication conditions as shown in Fig. 1 (right), a slant nanostructures can be fabricated by on step process as shown in Fig. 4.
The fabrication of a slant (3-dimension) nanostructure is possible by taking advantage of the time lag of deformed layer formation during etching in KOH solution.

Conclusion

This study demonstrates simple and hybrid nanolithography for single crystal silicon using specially designed cantilever with a pyramidal PCD tip. The silicon surface could be removed to a depth from several to hundreds of nanometers Thus, successful nanomachining of single crystal silicon could be realized. In addition, those scratched surface acts as an etch mask during wet chemical etching process, hence a slant nanostructure can be fabricated under AFM-based nanofabrication.

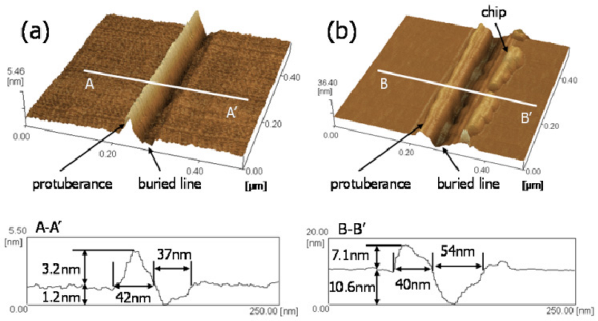

Fig. 2 Enlarged AFM topography image of single line fabricated (a) using a blunt tip. (b) using a sharp tip.

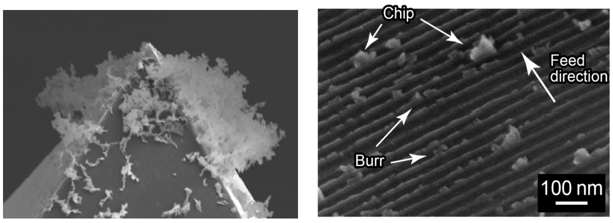

Fig. 3 SEM image of pyramidal diamond tip after machining a silicon substrate(left) and machined silicon surface(right).

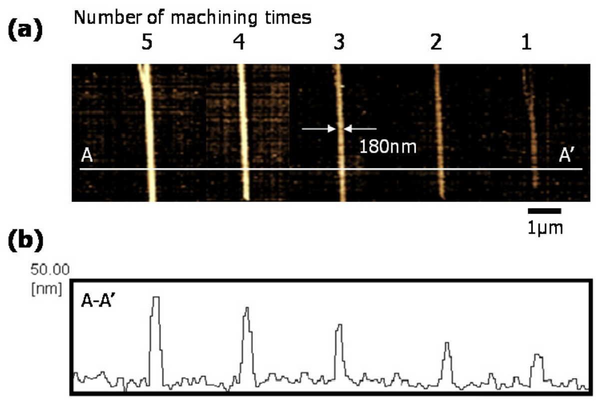

Fig. 4 (a) An array of silicon bars prepared according to hybrid nanofabrication (b) Cross-sectional topography trace of a line marked A-A' in (A).

References

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