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Fabrication of Micro/Nano-patterns using MC-SPL(Mechano-Chemical Scanning Probe Lithography) Process

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ABSTRACT

In this work, a new non-photolithographic micro-fabrication technique is presented. The motivation of this work is to overcome the demerits of the most commonly used photolithographic techniques. The micro-fabrication technique presented in this work is a two-step process which consists of mechanical scribing followed by chemical etching. This method has many advantages over other micro-fabrication techniques since it is simple, cost-effective, rapid, and flexible. Also, the technique can be used to obtain a metal structure which has sub-micrometer width patterns. In this paper, the concept of this method and its application to microsystem technology are described.

Key Words : Abrasive interaction, Mechano-chemical process, Nano wear, Self-assembled monolayer

1. Introduction

Today, the patterning technology widely employed in manufacturing is optical lithography, a process that uses ultraviolet light or x-ray to define submicron-sized features in photosensitive polymers [1-4]. Such photolithography techniques have provided excellent dimensional accuracy and intricate structures. However, photolithography is a relatively high-cost process and requires extensive processing time and heavy capital investment to build and maintain the fabrication facilities. Also, most of the conventional photolithography techniques require multi-step processing which may be more adequate for mass production but are not suitable for prototype fabrication of micro-parts with different geometries in small numbers and for processing of various materials. Above all, since the technique is rapidly approaching the fundamental resolution limitations in forming sub-100 nm fine patterns, new high-resolution patterning techniques such as *nano-machining, nano-imprinting, and scanning probe nano-*lithography may be required to continue the industry's trend toward higher performance electron devices and higher density memories.

Recent developments related to flexible nano-machining can be found in micro-EDM (Electrical Discharge Machining), focused ion beam, and laser machining works [5,6]. They provide the flexibility in terms of the geometries that can be fabricated, but are poor in terms of throughput (writing speed) and have the demerits of high energy requirement. Nano-molding techniques such as nano-imprinting and micro-contact printing are also emerging as one of the promising candidates for next generation lithography techniques [7-9]. Features with high aspect ratios on metals and polymeric materials can be obtained by using these techniques. However, some problems including the requirement of fine alignment and the pattern distortion that can occur during the releasing process still have to be resolved. High resolution patterning methods known as scanning probe lithography that uses a sharp tip with nanometer-scale radius might meet the future lithography needs [10-13].

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However, they also have disadvantages such as low throughput and the requirements of additional facilities for applying vacuum or electrical field.

In consideration of all the methods currently being researched and developed for the purpose of nano-structure fabrication, there is an on-going need for a new lithography technique that is more cost-effective, rapid and flexible with overcoming some of the shortcomings of the processes mentioned above.

The so-called 'mechano-chemical micro/nano-fabrication method' has been proposed based on this motivation [14-18]. Mechano-Chemical Scanning Probe Lithography (MC-SPL) indicates its advanced process using scanning probe microscope system with a nano-probe.

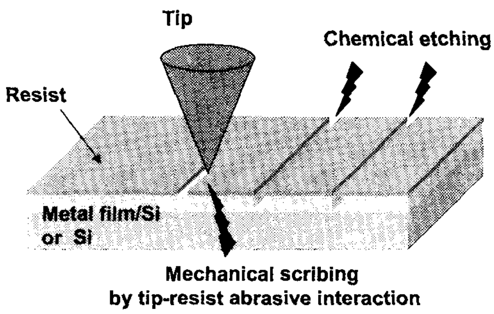


Fig. 1 Schematic diagram of mechano-chemical process

Fig. 1 illustrates the basic concept of the technique that consists of two simple processes, namely, mechanical scribing and chemical etching. Mechanical scribing is the process that removes a resist with the tribological interaction between a tip and a sample surface. In the process, the resist serves as a protective layer against chemical etchant. The desired depth of cut is controlled by the thrust force applied to the tip. In the subsequent chemical etching, the chip and burr that might be produced during the mechanical scribing can be removed from the surface and the desired patterns can be obtained at the locations where the resist has been removed. By using this technique, 3-dimensional micro/nano-structures with high aspect ratios on various metal surfaces as well as silicon-based surfaces can be fabricated and also flexible change of pattern design can be readily achieved. These advantages of the technique are very attractive, compared with the traditional photolithography technique in which pattern design change can be obtained only by utilizing a new photomask. Moreover, the technique can be extended to fabricate various structures for many application fields such as micro-molding and micro-fluidic devices. The mechano-chemical lithography technique is a novel process that is based on the fundamental understanding of the nano-scale wear phenomena.

2. Fabrication method and setup

2.1 Machining setup

In order to perform mechanical scribing, a custom-built micro-machining setup [14] and a commercial scanning probe microscope were used. In the micro-machining setup, a diamond tip (radius: ~5 μm, hardness: 8000~10000 HV) was used as the cutting tool, and a precision micro-stage equipped with 3-axes ultra-precision linear actuators (feed resolution: ~60 nm, maximum travel distance: 25 mm) was used for moving the tool. The thrust force applied to the sample by the tool could be measured by the precision balance and a desired value could be maintained by the feedback of the detected force signal. Mechanical machining is carried out by the relative motion of the tool tip against the fixed sample on the precision balance according to numerically programmed machining path.

In order to verify the possibility of a nano-scale pattern fabrication as an extension of the capabilities of the mechano-chemical micro-machining technique, a scanning probe microscope was used with a diamond-coated tip (tip radius: ~150 nm) mounted on a cantilever.

2.2 Specimens and resists

As for the sample specimens, Si (100) and pure metal films of Cu and Au (film thickness: ~180, 250 nm, respectively) were used. Metal films were prepared by the deposition on a silicon surface using e-beam evaporation or sputtering techniques.

Among various materials such as polymers, metals, and ceramics, earlier studies revealed that silicon dioxide (SiO_2) was most appropriate as the resist material for silicon from the viewpoint of the shape and the dimensional accuracy of the machined pattern [14]. Therefore, the thermally-grown silicon dioxide with about 80 nm thickness was used as the resist for silicon. On the other hand, as the resist for metal surfaces, Self-

Assembled Monolayer (SAM) was chosen since it could form an ultra-thin film with 2-3 nm thickness that may be advantageous to narrower pattern fabrication [19,20]. Especially, based on the fact that SAMs with longer alkyl chains (CH_2) have the tendency to form more densely packed layer and consequently possess better etch resistance characteristics, HDT ($HS(CH_2)_{15}CH_3$, hexadecanethiol) SAM was used. Generally, the thickness of SAM may depend on the dipping time and the chemical state of a metal surface. In the experiment, SAM was deposited with the thickness of 5~6 nm on the metal specimens.

2.3 Chemical etching

Wet chemical etching was performed to remove the specimen material at regions where the resist has been removed in order to obtain the desired pattern, as mentioned previously. The most important requirement of the chemical etchant is the etching selectivity, which means that the etchant must only attack the substrate material and not the resist. The scribed region of the silicon surface was etched anisotropically with potassium hydroxide (KOH) solution [14]. In the case of metal etching, Cu was etched with iron(III) chloride ($FeCl_3$) solution and Au with oxygenated cyanide solution (KCN/KOH). It has been reported that the regions protected by thiol-SAM etch 10^6 times slower than the thiol-removed regions [21].

3. Results and discussions

Fig. 2 shows the images of the micro-patterns fabricated on a Si (100) surface by using a diamond tip with 5 μm radius. The applied force was 40 mN. The width and spacing of the patterns are about 2~2.5 μm and 5 μm, respectively. Micro-structures with various shapes as well as line patterns can be successfully fabricated by controlling the feed and path of the tool tip [14,15].

As for the metal micro-machining, previous work showed the direct machining process of the metal specimen using the plowing abrasion phenomena followed by a de-burring process. This resulted in the machined surfaces with low integrity and large amount of burrs around the patterns [14,15]. As an attempt to overcome these problems, an organic SAM was coated on top of the metal film as the resist for metals. From the experimental results, it was found that thiol-SAM functioned as a good etch resist against the wet chemical etchants for metals, although it could be easily removed from the surface by mechanical scribing under a few nN level loads.

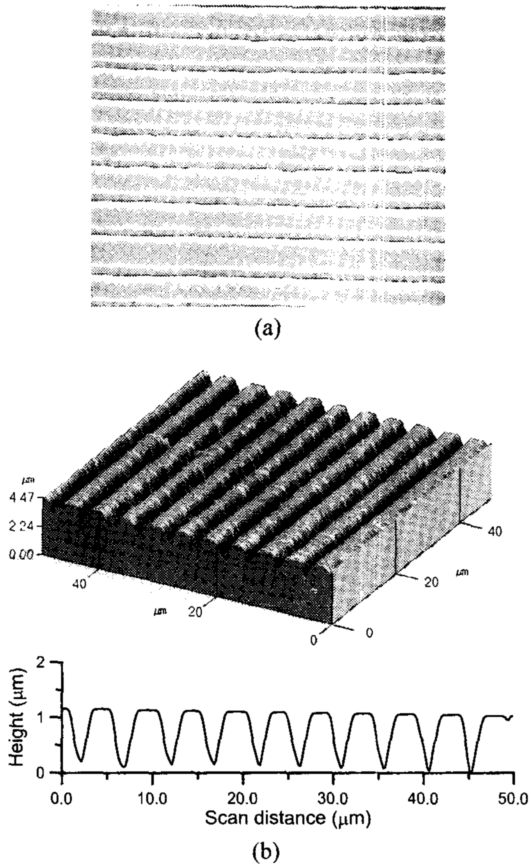
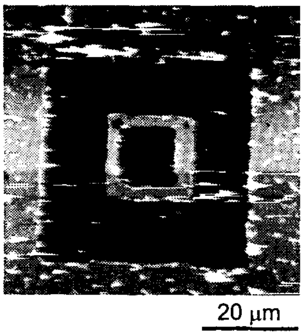


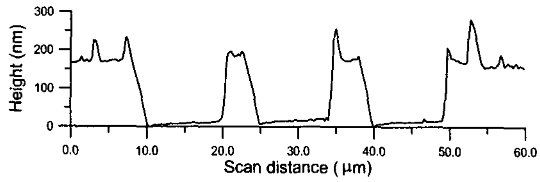
Fig. 2 Micro-patterns on Si(100) surface : (a) SEM image (b) AFM image and cross-sectional profile

The AFM image of the dual pockets fabricated on HDT SAM-coated Au surface is shown in Fig. 3. The dimensions of the inner and outer pockets were designed to be 10 x 10 (μm), 40 x 40 (μm), respectively. By using the mechano-chemical technique and backside etching of the silicon substrate, the inner pocket with high aspect ratio may be utilized as a micro-duct.

Figs. 4 and 5 show the grating surface with 4 μm spacing and the nano-patterns with 1 μm spacing and about 300~350 nm width fabricated on HDT SAM-coated Cu surfaces. It is expected that these surfaces can be applied to micro-molds for micro/nano-structure replication.

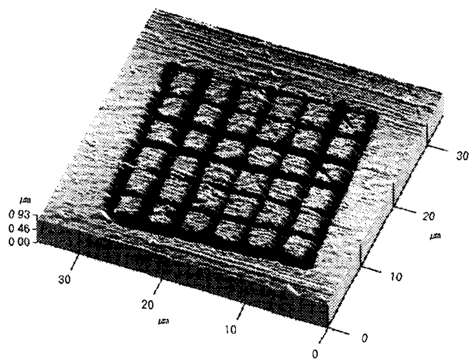


(a)

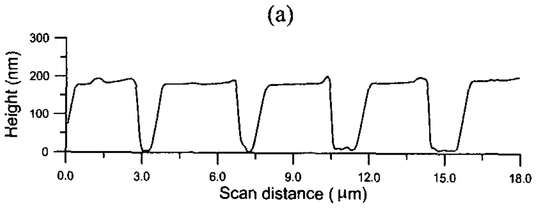


(b)

Fig. 3 (a) AFM image and (b) cross-sectional profile of machined pocket on HDT SAM-coated Au/Si(100) surface



(a)



(b)

Fig. 4 AFM images of micro-grating on HDT SAM-coated Cu/Si(100) surface (4 μm spacing)

From the results presented above, it can be concluded that the mechano-chemical lithography technique has the potential for ultra-fine structure fabrication. Additionally, it is expected that the pattern width and surface integrity will be dramatically improved if the fabrication process will be performed under well-controlled environment against contaminant and humidity.

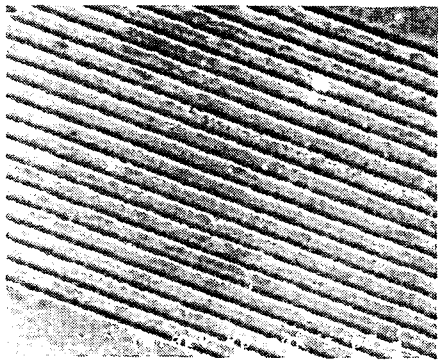


Fig. 5 SEM image of nano-grooves on HDT SAM-coated Cu/Si(100) surface (1 μm spacing)

4. Conclusions

In this work, the so-called mechano-chemical scanning probe lithography (MC-SPL) based on the basic understanding of the nano-tribological interaction between the tip and the sample surface was introduced. From the results, it could be found that the technique could be effective in prototype fabrication of nano-structures on various material surfaces with the flexibility of pattern design change. It is also suggested that in consideration of the traditional lithography techniques that have the limitations in materials and the change in pattern design, the technique will be very useful to fabricate nano-scale structures at low cost and short processing time. By using the mechano-chemical nano-lithography process with SAM resists, high-resolution patterns with 250~350 nm width and 100~200 nm depth could be successfully fabricated.

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