Nanomachining on Si (100) Surface using an Atomic Force Microscope with a Lateral Force Transducer

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ABSTRACT

Nanoscale machining on Si surfaces has been performed using an atomic force microscope combined with a two-axis capacitive force/displacement transducer. In scratching on Si (100) surfaces by a diamond tip with a radius of about 50 nm, the minimum normal force where a reproducible groove is generated is about 25 μN. It is possible to produce a nanoscale groove with a depth of 0.2 nm and a width of 20 nm at a normal force of 30 μN. The nanoscale scratch grooves are produced by very complicated processes including rubbing, ploughing, nanoscale-wear, chemical action and so on. In addition, it is demonstrated that the fine letters "UUPE" (a letter with dimensions 600×600×3 nm^3) are successfully written by mechanical scratching.

Keywords: Nanomachining, Atomic force microscope, Nanoscale scratching, Lateral force transducer, Single crystal silicon

1 INTRODUCTION

In recent years, surface modification with a scanning probe microscope has attracted special interest as one of the nanomachining techniques for processing surface on a nanometer scale [1-3]. In particular, nanoscale processing using an atomic force microscope (AFM) will play an increasingly important role in the field of the ultrafine fabrication for manufacturing electronic or micromechanical devices [4-5]. In order to enhance the utilization of this technique, it is essential to clarify the processing mechanism and characteristics.

The objective of this study is to make clear the possibility of nanometer–scale processing by a scratching method with the atomic force microscope. A series of nanometer-scale scratching experiments on polished Si (100) surfaces has been carried out by using AFM with a lateral force transducer to investigate the effects of applied forces and probe tip shapes on the processing characteristics.

2 EXPERIMENTAL PROCEDURE

Nanomachining experiments on Si surfaces were performed using an AFM combined with a two-axis capacitive force/displacement transducer, a schematic illustration of which is shown in Figure 1. The X-axis transducer (lateral force transducer) is composed of two additional sensors that are mounted transversely to the Z-axis force transducer (normal force transducer). The two-axis transducer applies and measures force and displacement in both the Z and X-axis. A three-sided pyramidal diamond tip (cube corner tip) with a nominal radius of 50 nm, which is set up in the center of the Z-axis force transducer was used for both nanomaching and imaging in this experiments. The scanning electron microscope micrograph of the diamond tip is shown in Figure 2. It shows that the diamond tip has a real radius of 30~50 nm.

Scratching experiments for generating nanoscale straight grooves were carried out in the normal force range of 5~200 μN in air. A Si sample was placed on the AFM sample holder located on a piezoelectric tube scanner, as shown in Figure 1.

Figure 3 shows a top view of diamond tip and scratching methods used for processing straight grooves in this study. To investigate the effect of tip shapes on the scratching characteristics, the diamond tip was moved in two directions as shown in the figure, namely, in the edge direction and the face direction. The straight grooves were always processed along the [110] direction on Si (100) surface. Experimental conditions for processing straight grooves are shown in Table 1.

After nanomachining, the modified surface was immediately imaged at a normal force of about 0.5 μN using the same diamond tip.

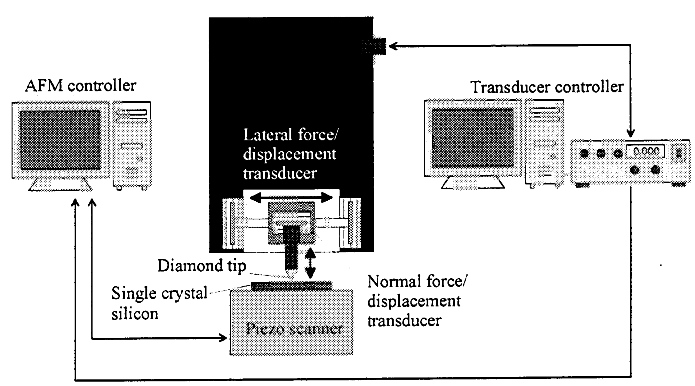


Figure 1: Schematic diagram of the experimental setup for nanomaching.

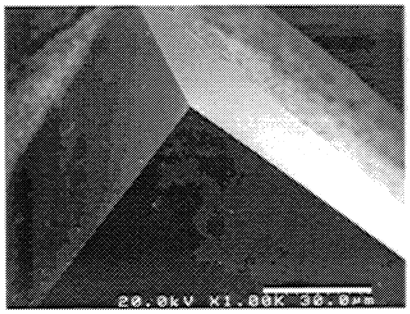


Figure 2: SEM micrograph of a three-sided pyramidal diamond tip used for nanoprocessing.

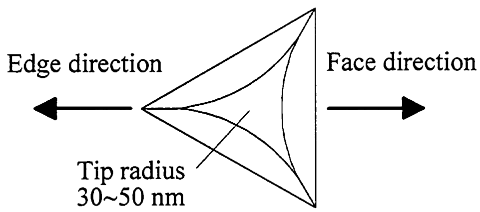


Figure 3: A top view of diamond tip and processing directions used for processing straight grooves.

3 RESULTS AND DISCUSSION

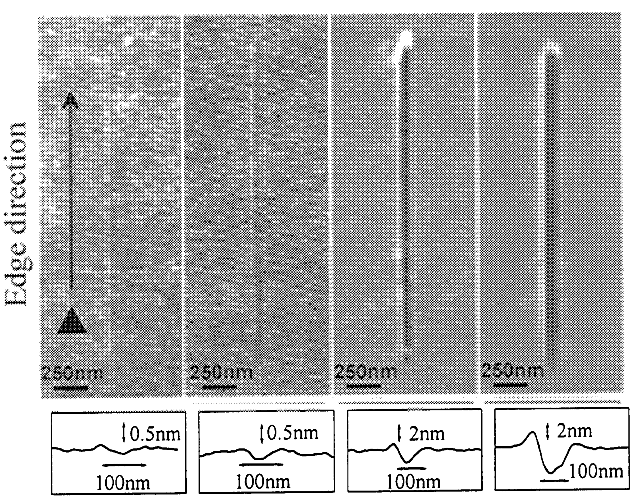
3.1 Processing of Nanoscale Grooves

Figure 4 shows typical AFM images of the straight grooves with a length of 2 μm generated at various normal forces from 30 to 100 μN in processing in the edge direction. The surface profile curves at a section perpendicular to the longitudinal direction of groove also are shown under the AFM images, respectively. Although we have tried to process a groove at a normal force below 20 μN, the grooves were unobservable. However, at a normal force of 30 μN a very fine straight groove with a constant depth of about 0.2 nm and a constant width of about 20 nm was successfully generated, as shown in this figure. It is confirmed that the minimum normal force where a reproducible groove is generated on the Si surface is between 20 and 30 μN. Both depth and width of straight groove increase with an increase of the normal force. In particular, when the normal force exceeds 70 μN, both depth and width of straight groove increase rapidly with an increase of the normal force. Moreover, a pile up and side flow based on active plastic deformation at both sides of groove are generated at a normal force larger than 100 μN. In addition, nanoscale wear debris is slightly observed at both sides and the end of groove.

From these AFM observations, the relationships between the groove depth D_g, groove width W_g and normal force F_n when processing in both edge and face directions were measured, as shown in Figure 5. These results show that the reproducible groove begins to be generated when the normal force exceeds approximately 25 μN in the both processing directions. And then it is confirmed that although the relationships between the groove depth, groove width and normal force are not affected by the processing direction when the normal force is lower than 50

Table 1: Experimental conditions for processing straight grooves

Processing tool	Three-sided pyramidal diamond tip
Normal force F_n	5~200 μN
Processing speed V_m	100 nm/s
Processing length L_m	2 μm
Processing times	20 s
Workpiece	Single crystal Si (100)
Atmosphere	In air



(a) F_n=30μN (b) F_n=50μN (c) F_n=75μN (d) F_n=100μN

Figure 4: Typical AFM images of straight grooves processed at normal forces F_n = 30~100 μN in the edge direction (Processing speed V_m = 100 nm/s, Scratching length L_m = 2 μm).

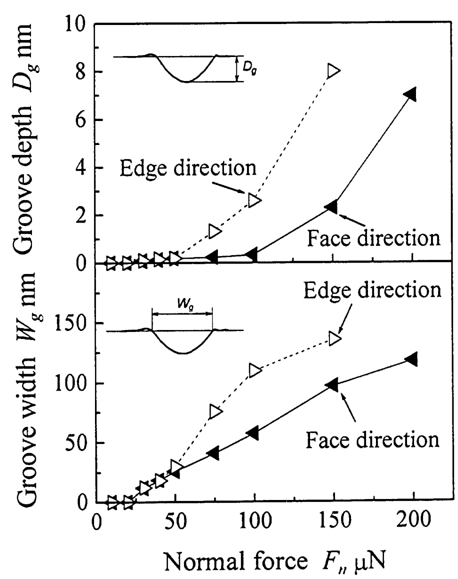


Figure 5: Effects of normal force F_n on groove depth D_g and groove width W_g.

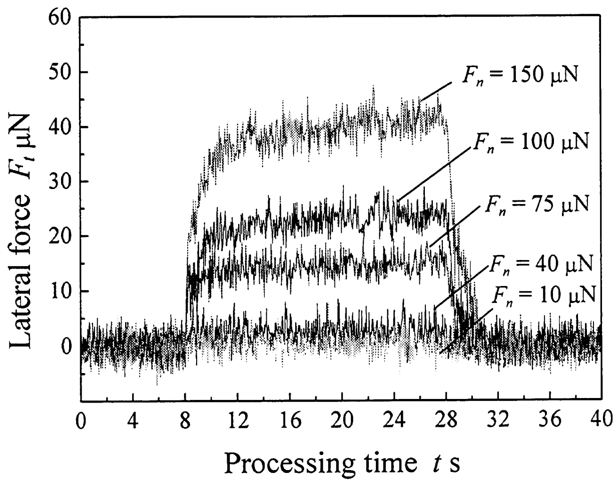


Figure 6: Typical examples of recording results for lateral force measured in processing straight grooves at normal forces F_n = 10~150 μN in the edge direction (Scratching speed V_m = 100 nm/s, Scratching length L_m = 2 μm).

μN, but are affected apparently by the processing direction when the normal force is higher than 50 μN. Namely, at a normal force more than 50 μN the groove depth and width obtained in the edge direction become larger than those obtained in the face direction, respectively.

3.2 Feature of Lateral Force

Figure 6 shows typical examples of recording results for the lateral force measured in processing the straight grooves with a length of 2 μm at a speed of 100 nm/s in the edge direction. Although the lateral force has a variation of about 8 μN, its average value maintains roughly a constant value for a processing time of 20 s.

Average lateral force F_t and ratio of force component F_t/F_n (friction coefficient) are obtained from these results, as shown in Figure 7. It is confirmed that although the relationships between the lateral force, ratio of force components and normal force are not affected by the processing direction when the normal force is lower than 50 μN, but are affected apparently by the processing direction when the normal force is higher than 50 μN. Namely, at a normal force more than 50 μN the lateral force and ratio of force components in the edge direction become larger than those in the face direction, respectively. These relationships are closely similar to the relationships between the groove shapes and normal force shown in Figure 5. Particularly, when the normal force is lower than 50 μN, the ratio of force components increases with a decrease of normal force. It seems that the effects of additional forces such as van der Waals force, coulomb force, surface tension force based on adsorption layer and so on, on the lateral force become larger relatively with a decrease of the normal force. The effects are especially enhanced at the elastic region where the groove is not generated.

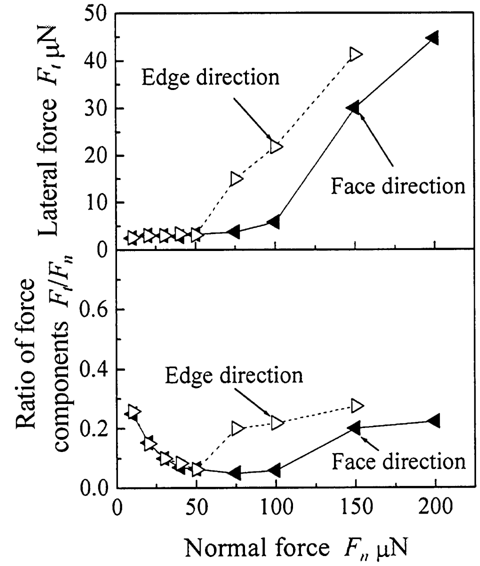


Figure 7: Relationships between lateral force, ratio of force components and normal force.

3.3 Effects of Tip Shapes on Processing Characteristics

To consider the processing mechanism of nanoscale grooves, we have classified the scratching process by using the groove depth D_g and ratio of force component F_t/F_n that are very important parameters to evaluate the scratching characteristics. Figure 8 shows the effects of processing direction on the relationships between these parameters and the normal force. In the figure, F_{np} is the minimum normal force where a reproducible groove is generated, that is, the critical normal force in transition from elastic to plastic deformation zone. Namely, A and B are describe the

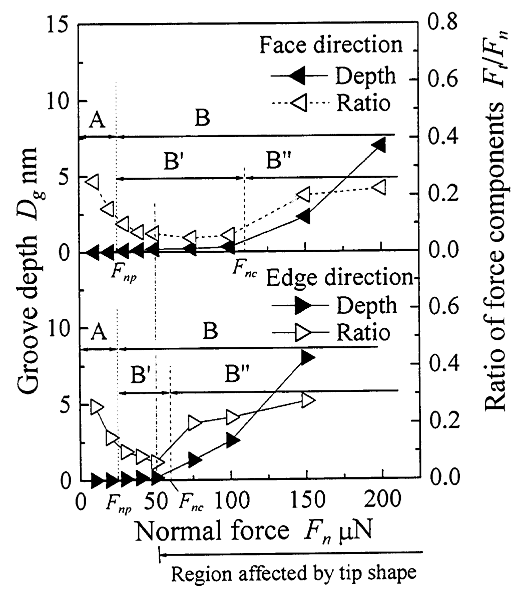


Figure 8: Effect of processing direction on the relationships between groove depth, ratio of force components and normal force.

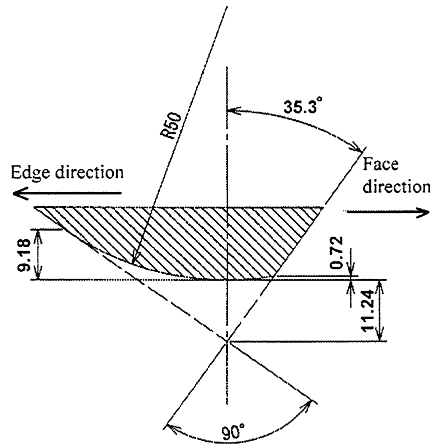


Figure 9: Relationship between processing direction and diamond tip shape.

following zones,

A: elastic deformation zone (rubbing zone)

B: elastic/plastic deformation zone (ploughing zone)

On the other hand, F_{nc} denotes the critical normal force where the groove depth increases rapidly by increasing the normal force. The zone B is divided to two zones indicated by B' and B". The groove depth is very small in the B' zone and larger than about 1 nm in the zone B".

When the normal force is lower than about 50 μN, the processing characteristics do not affected by the processing direction and the critical force F_{np} is about 25 μN in both processing directions, as mentioned above. However, when the normal force is higher than about 50 μN, the processing characteristics are affected apparently by the processing direction and the critical force F_{nc} in the face direction is about 2 times higher than that in the edge direction. These results are due to the tip shapes which is dominated by the processing direction, as shown in Figure 9.

3.4 Processing of Fine Letters

We have tried to generate a fine letter on the basis of the experimental results mentioned above. For instance, the fine letters "UUPE" were processed by scratching with diamond tip at a normal force of 100 μN and a scratching speed of 100 nm/s, as shown in Figure 10. Although the depth and width of grooves are affected by scratching direction, it is demonstrated that a fine letter which has dimensions of 600×600×3 nm^3 is successfully processed by mechanical scratching.

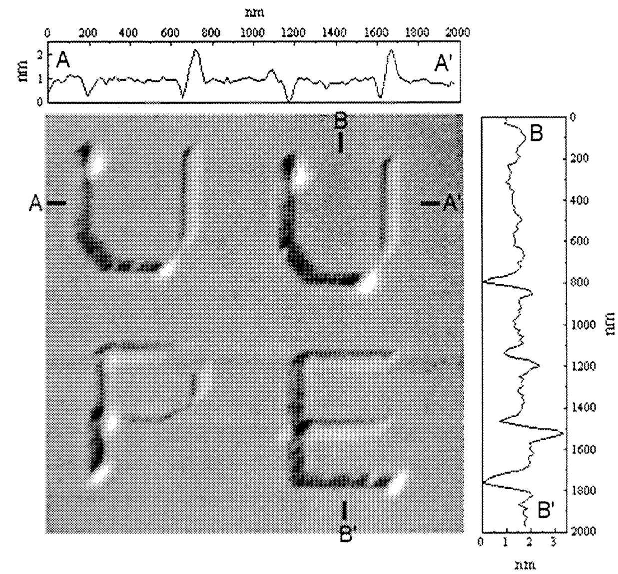


Figure 10: A typical AFM image of fine letters "UUPE" which were generated at normal force F_n = 100 μN and processing speed V_m = 100 nm/s.

5 CONCLUSIONS

Nanoscale mechanical scratching experiments on polished Si (100) surfaces have been conducted in air with an atomic force microscope combined with a two-axis capacitive force/displacement transducer. The main results obtained in this study are summarized as follows:

(1) The minimum normal force where a reproducible groove is generated is approximately 25 μN.

(2) The nanoscale groove with a depth of 0.2 nm and a width of 20 nm is successfully generated by scratching at a normal force of 30 μN.

(3) The formation mechanism of scratch groove is affected by the tip shape when the normal force is higher than about 50 μN.

(4) The nanoscale scratch grooves are produced by very complicated processes including not only rubbing and ploughing, but also nanoscale wear, chemical action and so on.

(5) A fine letter with dimensions of 600×600×3 nm^3 is successfully produced by mechanical processing.

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