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Atomic Force Microscopy-Based Repeatable Surface Nanomachining for Nanochannels on Bare Silicon Substrates

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Abstract—**The Atomic Force Microscopy (AFM)-based repeatable nanomachining for nanochannels on bare silicon surface is investigated experimentally. A relationship between the normal force applied on the AFM cantilever and the channel depth is established. Thus, current results can be regarded as the calibration reference in order to accurately predict the nanochannel depth for additional nanotechnology related applications. An accurate prediction of the depth is not only for accuracy and efficiency, but also to prevent a costly diamond tip from unnecessary wearing out. Furthermore, the experimental results also reveal that the fabrication procedure is repeatable, and multiple scratching will further increase the depth of the nanochannel.**

I. INTRODUCTION

AMONG current nano applications, the design and fabrication of nanochannels are one of the major challenges. So far, the methods for fabricating nanochannels have included bulk nanomachining and wafer-bonding [1-2], surface nanomachining [3], buried channel technology [4] and nanoimprint lithography [5-7], and nanochannels that are 50 nm deep and 5 μm wide [1-2], 20-100 nm deep and 0.5-20 μm wide [3], and 10 nm deep and 50 nm wide [5] have been demonstrated. With these methods, nanochannels usually reach to nano-level in only 1-dimension. Although nanoimprint lithography can fabricate 2-dimensional nanochannels [6-7], these channels are all fabricated by complex processing methods that require sophisticated masking and etching. Thus, a means, by which nanochannels are able to be fabricated without complex processing and reach to nano level in 3-dimension, is popular.

Since Atomic Force Microscopy (AFM) was invented in 1986 [8], it has been widely used in fields of material science, biomedicine, and nanofabrication. AFM-based nanolithography [9] offers a simple and reliable technique for mechanically machining nanochannels on substrates such as polymer [10-12], metal [13], semiconductor [14-16], and insulator [17]. However, nanochannels on a bare silicon substrate created by AFM-based nanolithography with a diamond tip have not been reported yet. In this paper, a study of the nanochannels on bare silicon surfaces fabricated by the AFM-based nanoscratching is introduced, and the current experimental results show that this technique can be applied

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in the fabrication of Carbon Nanotube (CNT)-Ion Sensitive Field Effect Transistor (ISFET) based structure, where relatively large nanochannels on the silicon substrate are needed for the deposition and alignment of bundle of CNTs [18].

II. EXPERIMENTAL SETUP

The experiment is performed using an Agilent 5500 AFM (Agilent Technologies Inc., Santa Clara, CA, USA) with the Head Electronics Box that provides an oscillating voltage for AC (tapping) Mode imaging as shown in Fig.1. A hand-crafted high force cantilever with a diamond tip for nanoindenting/nanoscratching is used for creating the nanochannels (DNISP, Bruker Corporation). The cantilever is pre-calibrated with a normal spring constant (K_C) of 244 N/m, and normal radius of the diamond tip is 40 nm. The diamond tip apex is like the corner of cube so that three right angle planes form an "A"-shape apex, which is used for all nanolithography-related operations. The cantilever is made of stainless steel with a normal elastic modulus (E) of 193 GPa and a shear modulus (G) of 80 GPa. The sensitivity (S_Z) of position-sensitive-detector (PSD) is 255 nm/V.

Figure 2 illustrates schematic of the experimental setup for creating nanochannels on a polished silicon layer (625μm thick). The topographies are scanned under AC Mode, while scratching is completed under Contact Mode where the vertical deflection of the cantilever is kept constant and controlled by the setpoint (S_T in V). Therefore, once the setpoint is specified, the scratching normal force (F_N) can be computed as shown in Equation (1) [19]:

(1)

III. EXPERIMENTAL RESULTS

Before scratching on samples, three user-controllable parameters that may affect the dimensions of the nanochannels need to be determined, and they are the setpoint, the scratching velocity and the number of times that we scratch. Through the single nanomachining experiment, we find out that the variation of scratching velocity is negligible for predicting the dimensions. Figure 3 presents 25 5-μm-long nanochannels that are fabricated by single-scratch, but with different F_N from (a) to (e) at different scratching velocities from I to V. Take Fig. 3 (a) for example: it has five channels, all of which are fabricated under FN=31.11μN, but the scratching velocity varies from 0.1 μm/s, 0.25 μm/s, 0.5 μm/s, 0.75 μm/s and 1 μ/s for nanochannel I, II, III, IV, and-

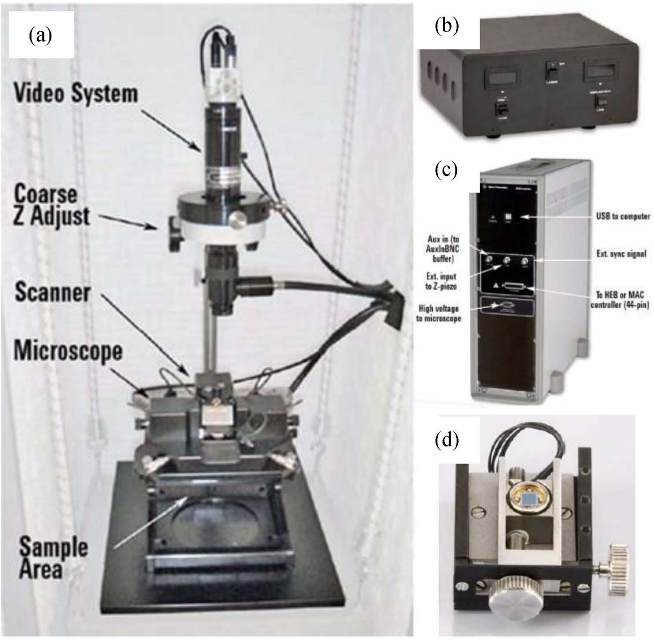

Fig. 1. Experimental setup for AFM-based nanolithography: (a) the microscope; (b) head electronics box; (c) AFM controller; and (d) PSD bottom-view.

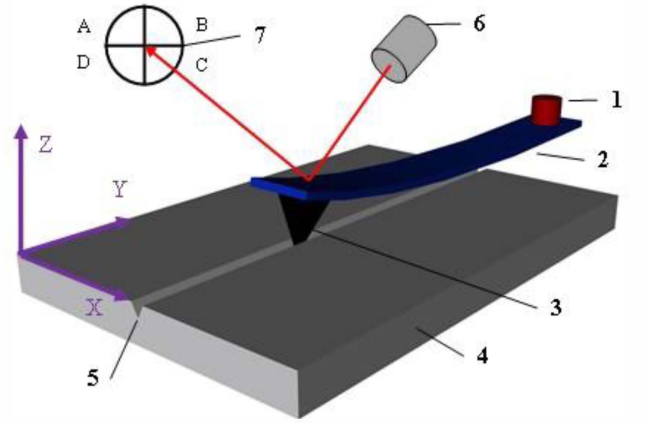

Fig. 2. Schematics of nanoscratching: (1) piezo scanner for XYZ movement; (2) cantilever; (3) diamond tip; (4) silicon; (5) nanochannel; (6) laser; and (7) four-quadrant PSD.

V, respectively. No trends about significant dimensional changes have been seen either from the vision of figure or the measurement of nanochannel depth and width as the scratching velocity increases.

In order to investigate the relationship between the dimension of nanochannels and the scratching normal force, single surface nanomachining is implemented. In this test, the scratching velocity is kept constant at 0.1 μm/s, and five 5-μm-long nanochannels are fabricated at different normal forces of 31.11 μN, 62.22 μN, 93.33 μN, 124.44 μN and 155.55 μN. Then, five dimensional measurements for each nanochannel are recorded as shown in Table I, and Fig. 4 presents the topography where the nanochannels are. Moreover, Fig. 5 shows how to take the dimensional measurement by drawing arbitrary cross-section line over - target. Finally, the linear relationship between the depth of nanochannels and the scratching normal force for single surface nanomachining is obtained as shown in Fig. 6.

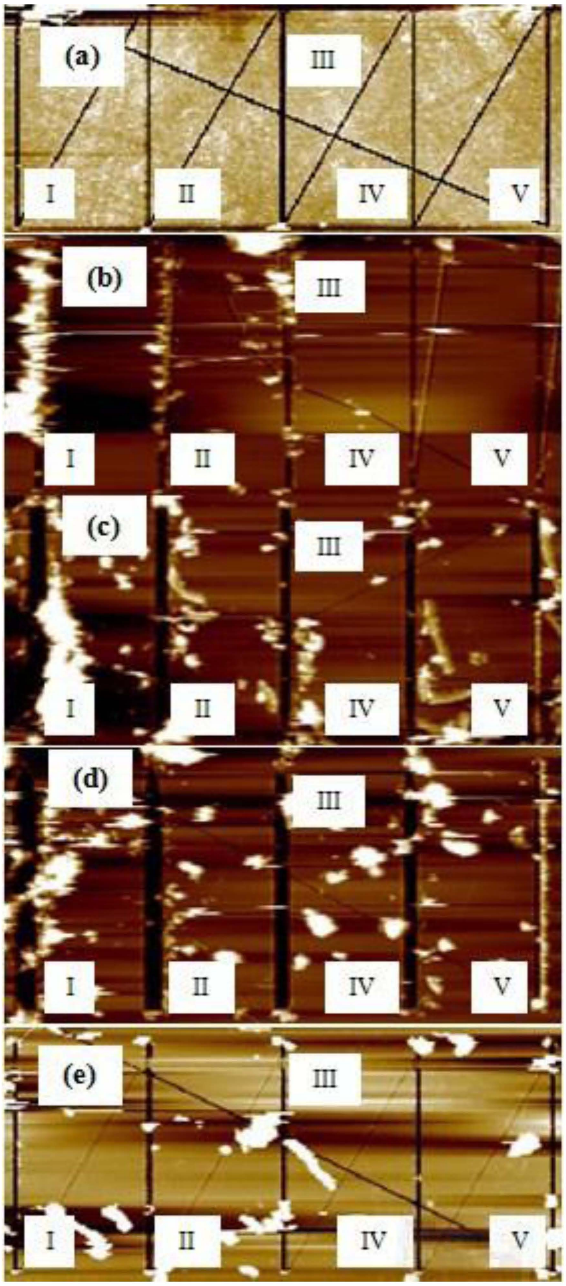

Fig. 3. AFM topographies of nanochannels (5μm) scratched at different normal forces (μN) of (a) 31.11, (b) 62.22, (c) 93.33, (d) 124.44 and (e) 155.55, and scratching velocities (μm/s) of I 0.1, II 0.25, III 0.5, IV 0.75 and V 1.

TABLE I. DEPTH MEASUREMENT FOR SINGLE SURFACE NANOMACHINING

Channel (L to R)	Force (μN)	Depth (nm)					Mean (nm)	Stdev. (Nm)
1	31.11	5.32	4.55	7.90	6.42	6.29	6.09	1.26
2	62.22	16.2	17.4	18.2	18.8	15.3	17.2	1.42
3	93.33	28.0	22.3	25.3	23.0	25.8	24.9	2.28
4	124.44	30.3	28.0	33.5	29.5	31.8	30.6	2.11
5	155.55	32.3	35.0	35.5	36.7	40.7	36.1	3.04

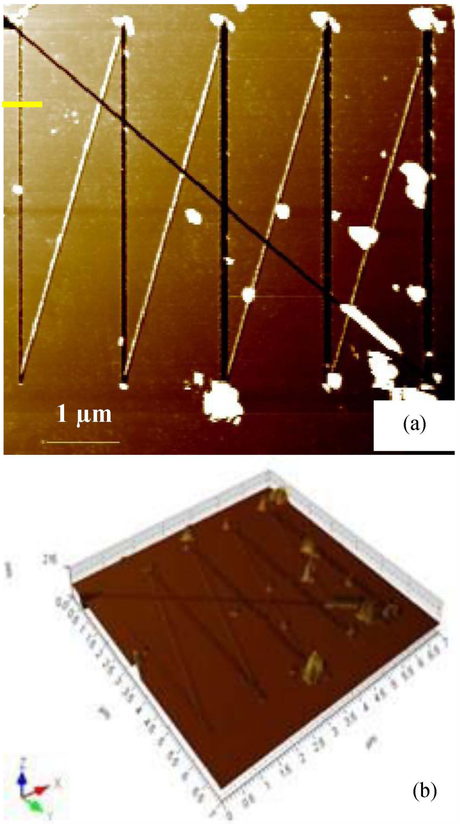

Fig. 4. Single-scratching test at a constant velocity (0.1µm/s): (a) 5-µm-long channels scratched from left to right at normal forces (µN) of 31.11, 62.22, 93.33, 124.44 and 155.55, respectively; (b) 3D view of (a).

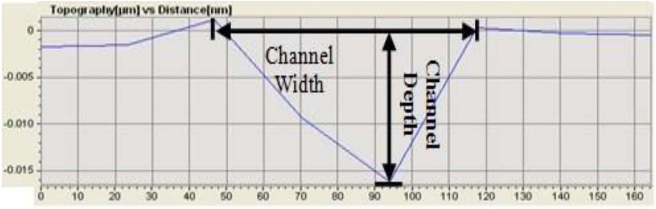

Fig. 5. Illustration of nanochannel dimensional measurement: give the Z-axis information of the yellow cross-section line in Fig. 4 (a).

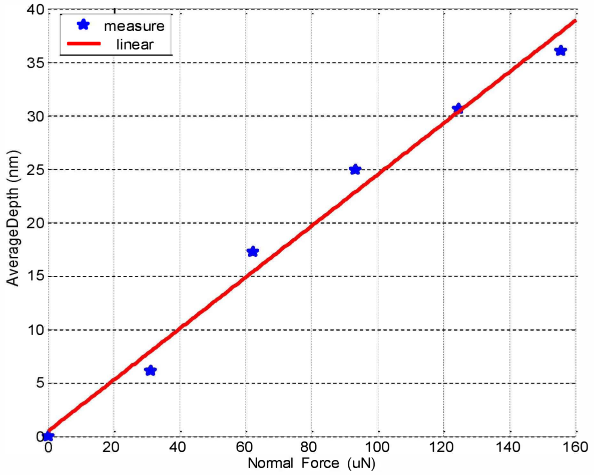

Fig. 6. Relationship between depth and force for single-scratching. Linear fit slope and R^2 value are 0.2402 nm/µN and 0.9859, respectively.

Furthermore, the relationship between the depth of nanochannel and the normal force in double surface machining is also studied. The scratching velocity is still 0.1 µm/s, but the surface will be scratched twice by the diamond tip to fabricate each 5-µm-long channel at different normal forces of 31.11 µN, 62.22 µN, 93.33 µN, 124.44 µN and 155.55 µN. Figure 7 shows the topography of the channels, and their depth information is recorded in Table II. At last, the linear relationship between the depth of nanochannels and the scratching normal force for double surface nanomachining is shown in Fig. 8.

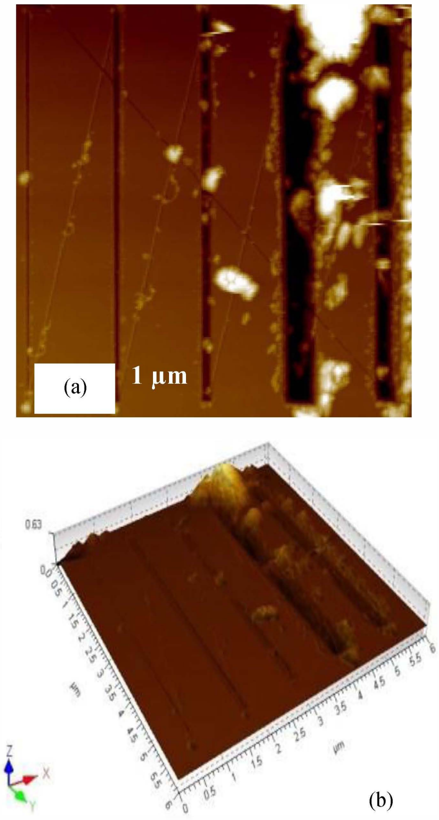

Fig. 7. Single-scratching test at a constant velocity (0.1µm/s): (a) 5-µm-long channels scratched from left to right at normal forces (µN) of 31.11, 62.22, 93.33, 124.44 and 155.55, respectively; (b) 3D view of (a).

TABLE II. DEPTH MEASUREMENT FOR DOUBLE SURFACE NANOMACHINING

Channel (L to R)	Force (µN)	Depth (nm)					Mean (nm)	Stdev. (Nm)
1	31.11	7.55	16.5	10.3	13.9	14.6	12.6	3.60
2	62.22	35.7	32.4	35.0	37.4	34.3	35.0	1.82
3	93.33	49.0	45.2	48.7	44.9	36.3	44.8	5.12
4	124.44	136	141	91.0	130	148	129	22.4
5	155.55	107	113	101	92.2	106	104	7.67

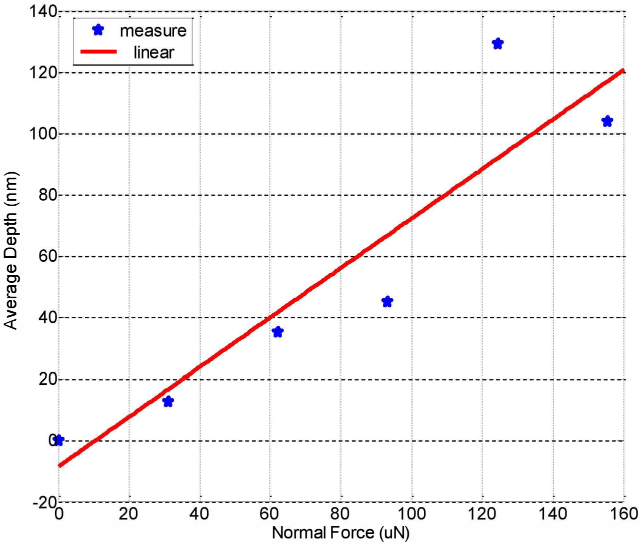

Fig. 8. Relationship between depth and force for double-scratching. Linear fit slope and R^2 value are 0.8069 nm/μN and 0.8352, respectively.

IV. CONCLUSION

This paper proposes an AFM-based repeatable surface nanomachining for fabricating nanochannels on bare silicon substrate, which is simple and effective. A hand-crafted high force cantilever with a diamond tip for nanoindenting/nanoscratching is involved. Nanochannels are fabricated to study the relationship between the channel depth and various combinations of parameter setting. Based on the current results, we find that the normal force and the number of scratching are the key factors which dominate the fabrication performance but the scratching velocity is negligible. The approximated linear relationship between the channel depth and applied normal force is of great value for accurately predicting the scratching performance when the nanochannels are fabricated in such a system. The experimental results can be regarded as a reference in order to increase the efficiency and prevent the costly diamond tip from unnecessary wear-out in the future when nanochannels with depth range between 5 nm to 100 nm are needed on Si surface.

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