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Nanofretting behaviors of monocrystalline silicon (1 0 0) against diamond tips in atmosphere and vacuum

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ABSTRACT

With an atomic force microscopy, the tangential nanofretting behaviors of monocrystalline silicon (1 0 0) were investigated by using spherical diamond tips under atmosphere and vacuum conditions, respectively. Different from fretting, the nanofretting damage of silicon may successively experience two progresses, the generation of hillocks and grooves, with the increase in normal load. The critical contact pressure corresponding to the transition of the damage mode was found to be close to the hardness of Si(1 0 0). Due to the absence of water and oxygen in vacuum, the tangential force in nanofretting was a little lower than that in atmosphere. Compared to those in atmosphere, the nanofretting scars in vacuum exhibited higher hillock at low load but shallower groove at high load, which could be explained as the "soft coating" effect of oxide layer on Si(1 0 0) surface.

1. Introduction

Nanofretting refers to cyclic movements of contact interfaces with the relative displacement amplitude in nanometer scale, where the contact area and normal load are usually much smaller than those in fretting [1]. As an excellent structural material, monocrystalline silicon has been widely used in micro/nanoelectromechanical systems (MEMS/NEMS) [2–4]. Due to the mechanical vibration and temperature variation, nanofretting of monocrystalline silicon may exist in the contact interfaces of microdevices. In order to improve the reliability and stability, a large quantity of MEMS/NEMS need to be encapsulated in vacuum environment, such as micro-mass spectrometer, thermopile based sensors, resonators, and so on [5–8]. Therefore, with the development in MEMS/NEMS, the understanding and control of the nanofretting behaviors of monocrystalline silicon both in atmosphere and vacuum has become an important issue of concern [9–11].

Due to the limitation of experimental technique, only a few papers were found to discuss the nanofretting behaviors of materials [1,12,13]. Varenberg et al. [12] observed the nanofretting wear on both Si(1 0 0) surface and silica microspheres in atmosphere even the displacement amplitude of nanofretting was as small as 29 nm. Qian et al. [1] found that nanofretting was different from fretting in aspects of the variation of tangential force versus number of nanofretting cycles, the value of friction coefficient, and the damage mechanism. These differences were further attributed to the single-asperity contact in nanofretting and multi-asperity contact in fretting. More recently, the nanofretting behaviors of Si(1 0 0) against SiO_2 microspheres in vacuum was reported [13]. The results indicated that the adhesion force exhibited a strong effect on the nanofretting. Even though, the nanofretting behaviors of materials are still far from understand.

In this paper, the tangential nanofretting behaviors of monocrystalline silicon (1 0 0) against spherical diamond tips were investigated in atmosphere and vacuum, respectively. The mechanism of nanofretting damage was emphasized, and the differences of nanofretting behaviors between in atmosphere and in vacuum were discussed.

2. Material and methods

The p-Si(1 0 0) wafers with a thickness of 0.5 mm were purchased from MEMC Electronic Materials, Inc., USA. With an atomic force microscopy (AFM, SPI3800N, Seiko, Japan), the root-mean-square roughness of the silicon wafer was measured as 0.07 nm over a 500 nm × 500 nm area. To simulate the real surface of dynamic MEMS/NEMS, the native oxide layer on Si(1 0 0) surface was not removed by any chemical method, whose thickness was about 0.5 nm measured by a scanning Auger nanoprobe. All the nanofretting tests and in situ topography scanning were performed by an AFM equipped with a vacuum chamber. The SEM images in Fig. 1

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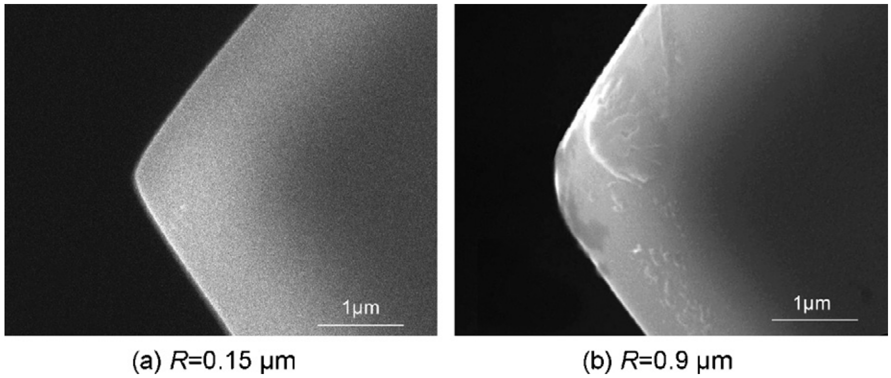

Fig. 1. The SEM images of spherical diamond tips used in tangential nanofretting tests.

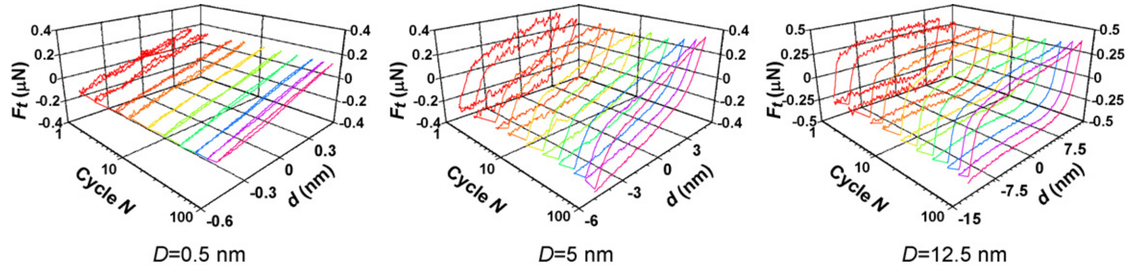

Fig. 2. The frictional logs of Si(1 0 0)/diamond pair at various displacement amplitudes D in atmosphere. $R = 0.15$ μm, $F_n = 5$ μN.

indicate that the radii R of the spherical diamond tips (Microstar Technologies, USA) are about 0.15 μm and 0.9 μm, respectively. Through a calibration probe with a force constant of 27.14 N/m (CLFC-NOBO, Veeco, USA), the normal spring constants of the cantilevers of two tips were calibrated as 219.2 N/m and 224.7 N/m, respectively. By using a silicon grating with a wedge angle of 54°44′ (TGF11, MikroMasch, Germany), the friction force of the tests was calibrated by a modified wedge method [14,15]. All the nanofretting tests were performed in atmosphere with a relative humidity of 50–60%, or in vacuum with a pressure below 5.0×10^{-6} Torr (6.7×10^{-4} Pa).

During the nanofretting, the spherical diamond tips moved horizontally on silicon surface with a displacement amplitude D under a normal load F_n. The applied normal loads F_n were varied between 0.5 μN and 70 μN. The adhesion force between tip and sample was measured as 0.1 μN. The displacement amplitudes D were ranged from 0.5 nm to 100 nm. The frequency was 2 Hz and the number of nanofretting cycles N was varied between 1 and 500. After nanofretting, the topography of scars was scanned by a sensitive silicon nitride tip, which has a curvature radius of 20 nm and a nominal normal spring constant of 0.1 N/m (MLCT, Veeco, USA). The scan size of the AFM images is 500 nm × 500 nm.

3. Experimental results

3.1. The nanofretting frictional logs

Fig. 2 shows the typical frictional logs (variation of the tangential force F_t and displacement d with number of cycles N, or F_t–d–N curves) of Si(1 0 0) against the diamond tip in atmosphere. Similar

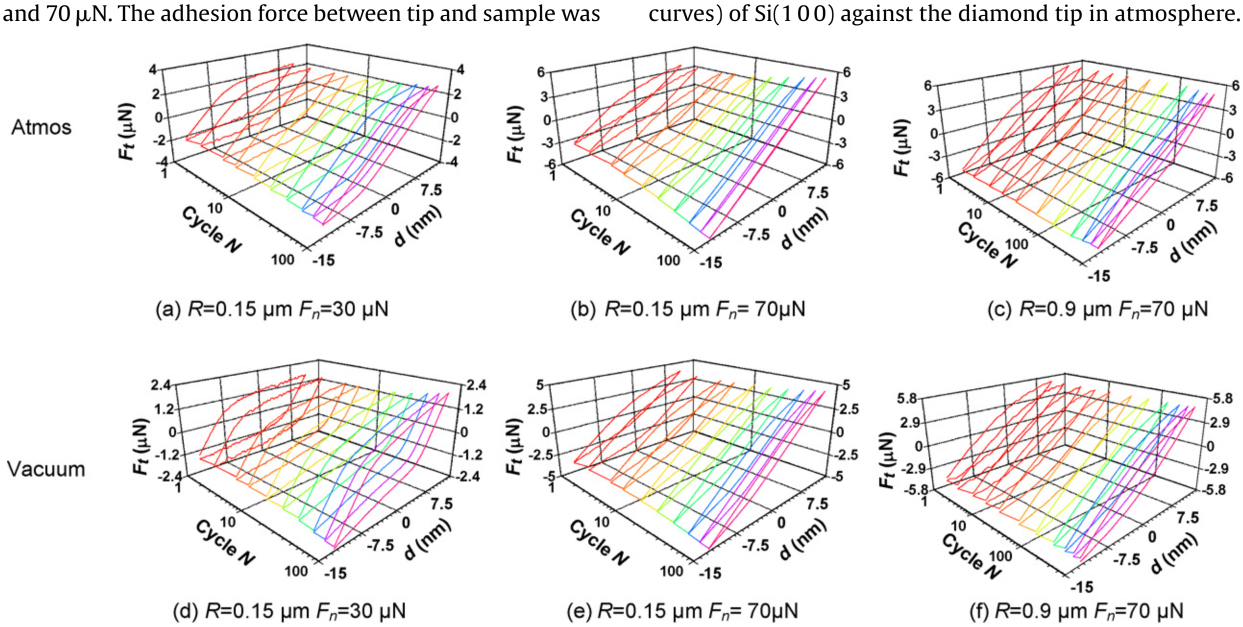

Fig. 3. The F_t–d–N curves of Si(1 0 0)/diamond pair at $D = 12.5$ nm.