Applied Surface Science 257 (2011) 3153–3157

Contents lists available at ScienceDirect

Applied Surface Science

journal homepage: www.elsevier.com/locate/apsusc

DLC nano-dot surfaces for tribological applications in MEMS devices

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ARTICLE INFO

Article history:
Received 14 May 2010
Received in revised form 22 October 2010
Accepted 27 October 2010
Available online 3 November 2010

Keywords:
Nano
Micro
Adhesion
Friction
Wear
Tribology
Diamond-like carbon

ABSTRACT

With the invention of miniaturized devices like micro-electro-mechanical systems (MEMS), tribological studies at micro/nano-scale have gained importance. These studies are directed towards understanding the interactions between surfaces at micro/nano-scales, under relative motion. In MEMS devices, the critical forces, namely adhesion and friction restrict the smooth operation of the elements that are in relative motion. These miniaturized devices are traditionally made from silicon (Si), whose tribological properties are not good. In this paper, we present a short investigation of nano- and micro-tribological properties of diamond-like carbon (DLC) nano-dot surfaces. The investigation was undertaken to evaluate the potential of these surfaces for their possible application to the miniaturized devices. The tribological evaluation of the DLC nano-dot surfaces was done in comparison with bare Si (1 0 0) surfaces and DLC coated silicon surfaces. A commercial atomic force microscope (AFM) was used to measure adhesion and friction properties of the test materials at the nano-scale, whereas a custom-built micro-tribotester was used to measure their micro-friction property. Results showed that the DLC nano-dot surfaces exhibited superior tribological properties with the lowest values of adhesion force, and friction force both at the nano- and micro-scales, when compared to the bare Si (1 0 0) surfaces and DLC coated silicon surfaces. In addition, the DLC nano-dot surfaces showed no observable wear at the micro-scale, unlike the other two test materials. The superior tribological performance of the DLC nano-dot surfaces is attributed to their hydrophobic nature and the reduced area of contact projected by them.

1. Introduction

Over the last decade, the field of MEMS has expanded considerably, catering to a wide variety of applications ranging from industrial, consumer, defense, aerospace, to biomedical applications [1]. MEMS devices can be categorized into two main classes, namely: (i) sensors and (ii) actuators. Sensors-based MEMS have only sensing elements, whereas the actuators-based MEMS have elements that undergo relative mechanical motion. Sensors-based MEMS devices are commercially available. However, the actuators-based MEMS have not been commercialized yet, owing to the fact that there exist no robust tribological solutions at micro/nano-scale which can make the devices operate smoothly and reliably. For the smooth functioning of the elements in the actuators-based MEMS, the contact between them must be properly lubricated. But lubrication becomes difficult when the dimensions of machine elements are in micro/nano-scale. At the micro/nano-scale, the surface-area-to-volume ratio is very large. Due to this, the surface forces such as adhesion and friction restrict the smooth operation and reliability of the actuator-based MEMS. In order to reduce these surface forces, solid lubricants (such as graphite or MoS_2) cannot be used as they are about the same size as those of the MEMS elements [2]. In addition, conventional liquid lubricants can also be hardly used, as they generate liquid-mediated adhesion [3]. Thus, minimizing the surface forces at small-scales is a real challenge.

Miniaturized devices are traditionally made from silicon (Si) due to the well established designing and fabrication processes related to the IC technology. However, Si does not have good tribological properties [4,5]. In order to improve the tribological properties of Si, researchers world-wide have resorted to a variety of surface modification techniques such as chemical and topographical modifications [5]. Chemical modification includes thin films/coatings such as self-assembled monolayers (SAMs) and DLC coatings [5–8]. Topographical modification includes roughening of surfaces [9] and surface texturing/patterning [10–14].

In this paper, we report a short investigation on the nano- and micro-tribological properties of DLC nano-dot surfaces. The aim of the investigation was to examine the suitability of the surfaces for tribological applications in MEMS devices.

2. Test specimens and experimental details

The DLC nano-dot surfaces were created by depositing DLC films on nano-sized nickel (Ni) dots fabricated on Si (1 0 0) wafers by

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doi:10.1016/j.apsusc.2010.10.131

Table 1
Water contact angle values of the test specimens.

Test material	Water contact angle (degrees)
Bare Si (1 0 0) flat surfaces	22
DLC coated silicon flat surfaces	78
DLC nano-dot surfaces	95

annealing Ni thin films. As the first step, Ni thin films (thickness ~9 nm) were deposited on Si (1 0 0) wafers by DC magnetron sputtering at room temperature. Next, the Ni thin films were converted into nano-sized Ni dots by annealing in a rapid thermal process furnace at 800 °C for 15 min in pure hydrogen atmosphere. As the final step, DLC films (thickness ~100 nm) were deposited by radio-frequency plasma assisted chemical vapor deposition method (bias voltage: −150 V, deposition pressure: 1.33 Pa) using methane gas. More details on the fabrication process and material characterization can be found in Refs. [15,16]. Representative scanning electron microscope (SEM) images of DLC nano-dot surfaces are shown in Fig. 1(a) top view and (b) side view. Fig. 1(c) shows an atomic force microscope (AFM) image of the DLC nano-dot surfaces (scan size ~2 μm × 2 μm, data scale ~100 nm), taken using a commercial AFM.

Tribological investigation at nano- and micro-scales were conducted on test materials that included bare Si (1 0 0) flat surfaces, DLC coated silicon flat surfaces and the DLC nano-dot surfaces. At the nano-scale, adhesion force and friction force were measured using an atomic force microscope (Multimode SPM, Nanoscope IIIa, Digital Instruments). A borosilicate ball (diameter ~1.25 μm) mounted on cantilever (Contact Mode type, nominal spring constant 0.58 N/m) was used as the tip. Adhesion measurements were conducted in the force-displacement mode. Tests were performed for 20 times and the average values were plotted. Friction force was measured in LFM (Lateral Force Microscope) mode (applied normal load ~0–120 nN, sliding speed ~2 μm/s, scan size ~5 μm × 5 μm). Each test was repeated for about 20 times and average values were plotted. At the micro-scale, friction was measured using a soda lime ball (radius ~0.5 mm, Duke Scientific Corporation) under reciprocating motion (applied normal load ~3000 μN, sliding speed ~1 mm/s, scan length ~3 mm) using a custom-built ball-on-flat type micro-tribotester [4,5,7,12]. Each test was conducted for about 15 min and the steady state values were recorded. Tests were repeated more than five times and the average values were plotted. All experiments were conducted at controlled temperature of 24 ± 1 °C and relative humidity of 45 ± 5%. Static water contact angles were measured for all the test materials using the sessile drop method, and the values are given in Table 1.

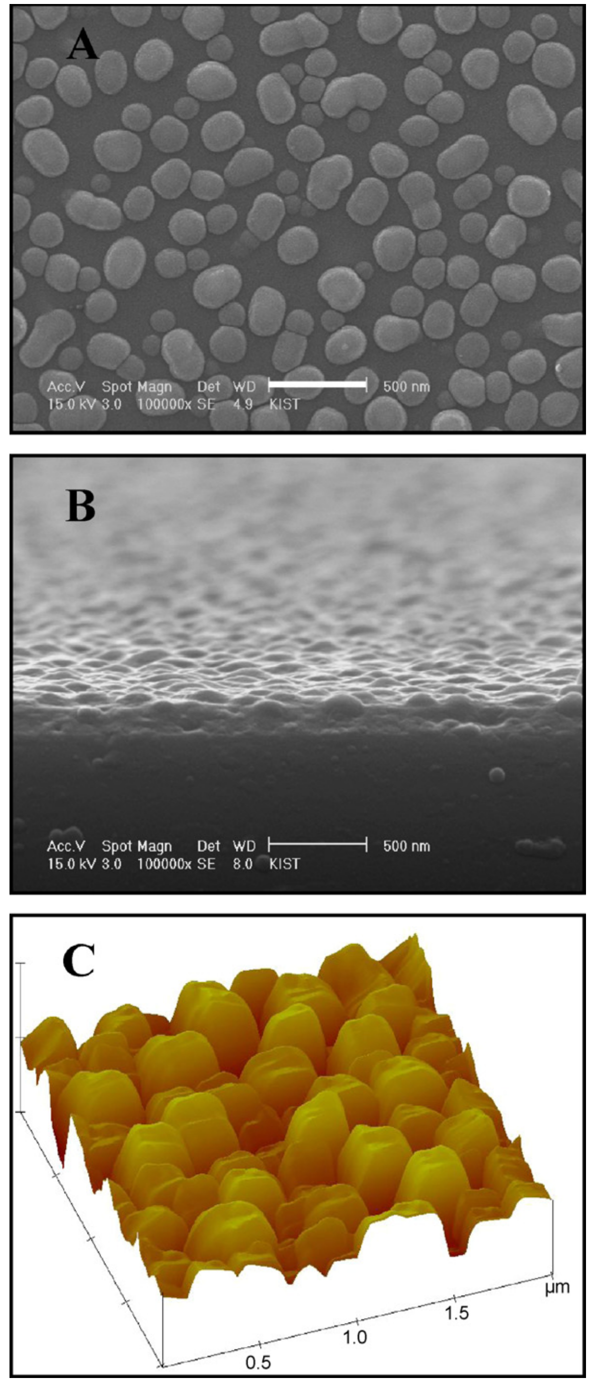

Fig. 1. Representative scanning electron microscope (SEM) images of DLC nano-dot surfaces: (a) top view (scale bar ~500 nm) and (b) side view (scale bar ~500 nm). (c) A representative atomic force microscope (AFM) image of the DLC nano-dot surfaces (scan size ~2 μm × 2 μm, data scale ~100 nm), taken using a commercial AFM.

3. Results and discussion

Fig. 2 shows the adhesion force values at the nano-scale of the test materials, namely the bare Si (1 0 0) flat surfaces, DLC coated silicon flat surfaces and the DLC nano-dot surfaces. The error bars indicate the minimum and maximum values of adhesion force observed from the test results. It could be observed from the figure that the DLC nano-dot surfaces exhibit adhesion force values that are significantly lower than those of the bare Si (1 0 0) flat surfaces and DLC coated silicon flat surfaces. Under tribological contact, adhesion force is caused due to various forces such as capillary, electro-static and van der Waals forces [3]. Amongst these forces, the capillary force, which occurs as a result of water condensation from the environment that leads to the formation of meniscus bridge, is the strongest [3]. Eq. (1) gives the expression for the adhesive force generated due to the formation of meniscus bridge [4].

$$F_m = 4\pi R\gamma \cos\theta \quad (1)$$

where R is the tip radius, γ the surface tension of water and θ the contact angle of water.

In the present case, the bare Si (1 0 0) flat surfaces show the highest values of adhesion force, owing to their hydrophilic nature (lowest water contact angle value, Table 1), which supports strong capillary force (Eq. (1)) [4]. The DLC coated silicon flat surfaces exhibit lower values of adhesion force than the bare Si (1 0 0) flat surfaces due to the increased water contact angle value (Table 1),