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Micro/nanotribological characterization of PDMS and PMMA used for BioMEMS/NEMS applications

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Abstract

Tribology is the primary cause of concern for various micro/nano-electromechanical systems (MEMS/NEMS) and biological applications of MEMS/NEMS (BioMEMS/NEMS) due to failures resulting from high adhesion and friction. Polymers are gaining significant importance due to their myriad advantages over conventional silicon-based components and the related micromachining techniques. Micro/nanotribological characterization of polymers is therefore essential. Adhesion and friction of single crystal silicon with native oxide layer and two polymers—poly(dimethylsiloxane) (PDMS) and poly(methylmethacrylate) (PMMA)—are studied and their dependence on rest time, relative humidity and sliding velocity is evaluated. Contact angle measurements and Laplace force calculations show that both PDMS and PMMA are highly hydrophobic and unlike silicon, their adhesive force is independent of rest time and relative humidity. Coefficient of friction for both polymers is lower than that for silicon. Velocity dependence studies indicate higher energy dissipation and localized melting for PMMA at high velocities. The PDMS sample absorbs asperity impacts and hence friction is lower for PDMS even at high velocities. Overall, owing to their highly hydrophobic surfaces and low friction PDMS and PMMA are ideally suited for use in micro/nanodevices that operate in varying environmental conditions and at high relative sliding velocities.

Keywords: BioMEMS/NEMS; PDMS; PMMA; Adhesion; Friction; High sliding velocity

1. Introduction

Silicon has been the primary choice as a structural material for many micro/nanoelectromechanical system (MEMS/NEMS) applications and biological applications of MEMS/NEMS (BioMEMS/NEMS) owing to the well-developed silicon micromachining techniques. These techniques, however, are expensive and time consuming for prototype development and require access to special facilities [1–4]. Intensive research, focused on exploring fluid applications, has led to the

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introduction of alternative materials and fabrication technologies [4–9]. The first microfluidic devices were made from silicon but the intrinsic stiffness of these materials posed a challenge for making devices with moving parts. Apart from this, many biomedical applications require delicate surface chemistry that is difficult to achieve with the high temperatures required to bind silicon. Soft polymeric materials overcome many of these limitations and are having an impact in two application areas: microfluidic devices and nanoscale mechanical and electrical devices.

Commercial use of polymers involves many benefits that include reduced cost and simplified manufacturing procedures, particularly when compared to silicon. The wide range of available polymer materials allows manufacturers to choose materials' properties suitable for their specific application [4,8,9]. For example, polymers have the distinctive mechanical property that their Young's modulus can be changed over two orders of magnitude by controlling the amount of cross-linking between polymer chains. Moreover, polymers can form a tight seal with silicon, permitting one to design hybrid micro/nanodevices that can contain silicon electronics, light sources and detectors with silicon fluidics.

Tribology and mechanics of micro/nanodevices has been a major concern, however, and has limited their promising broad based impact on everyday lives [4,10]. It is well known in computer hard disk drive industry that the stiction (static friction) force at the head–disk interface increases rapidly with an increase in rest time [11–14]. Stiction is also a leading cause of failure in many MEMS/NEMS applications [4,15] including the accelerometers used in air bag deployment in automobiles [16,17] and digital micromirror devices (DMDs) used in commercial digital light processing (DLP) equipment [18,19]. Velocity dependence of friction is another issue critical to the reliable and failure-proof design of MEMS applications such as microgear sets, microgas turbines and micromotors that operate at velocities in the range of tens of mm/s to few m/s [4,20–26]. Considering their potential to overhaul silicon as a structural material, tribology and mechanics of polymer materials needs to be investigated in as rigorous a manner as has been done for other materials, coatings and lubricants such as silicon, diamondlike carbon, self-assembled monolayers and perfluoropolyethers [20–27]. In this paper, we have selected two polymer materials, poly(dimethylsiloxane) (PDMS) and poly(methylmethacrylate) (PMMA), that have been most actively developed for microfluidic and other applications [6,8,9]. We study the effect of rest time and humidity on adhesion and the velocity dependence of friction for single crystal silicon (1 0 0) sample having a native oxide layer, and for the PDMS and PMMA samples. We present a scale dependence study comparing results obtained on microscales using a microtriboapparatus and on nanoscales using an atomic force microscope (AFM).

2. Experimental details

Tribological investigations were conducted using a microtriboapparatus and a modified AFM. The microtriboapparatus that uses a silicon ball sliding on the sample surface provides data on the microscale while the AFM cantilever tip sliding on the sample surface provides data on the nanoscale. For high sliding velocity studies on the nanoscale, we use the modified AFM setup developed by Tambe and Bhushan described in Ref. [28].

2.1. Instrumentation and test details

Microscale experiments were conducted using a microtriboapparatus (Tetra Inc., Ilmenau, Germany) (see Fig. 1(a)). The detailed description and working of the instrument can be found in Ref. [22]. Experiments were run using a single crystal Si (1 0 0) ball mounted on a stainless-steel cantilever having a stiffness of 57 N/m along the vertical axis (normal load axis). The 1 mm diameter, 5×10^{17} atoms/cm^3 boron-doped balls were obtained from Ball Semiconductor Inc., Allen, TX, USA. The friction force was calibrated based on the description in Ref. [22].

For nanoscale experiments, a modified commercial AFM setup (D3100, Nanoscope IIIa controller,