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Lubrication of polycrystalline silicon MEMS via a thin silicon carbide coating

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ABSTRACT

The contacting surfaces of a microfabricated polycrystalline silicon (polysilicon) double-clamped beam adhesion test structure have been modified with a thin ultra-hard, wear-resistant, and conformal silicon carbide (SiC) film. Adhesion forces in SiC-coated interfaces as a function of apparent area of contact have been determined quantitatively and compared with those in uncoated polysilicon contacts. Furthermore, contact reliability studies have been carried out by following the changes in physicochemical properties of the surfaces after >100 billion contact cycles. The results highlight the tribological benefits of SiC coating as a solid lubricant in devices undergoing cyclic contacts.

1. Introduction

Successful deployment of silicon-based microelectromechanical systems (MEMS) necessitates proper passivation and lubrication of the contacting surfaces to prevent irreversible interfacial adhesion (*stiction*) and wear [1–4]. Unwanted adhesion, more commonly known as *stiction*, remains a common failure mechanism in silicon-based microelectromechanical systems and in advanced microelectronics with high aspect ratio structures due to a variety of factors, including propensity of silicon to form a layer of hydrophilic, high surface energy native oxide [2,5]. Although release-related *stiction* has been addressed through several schemes including vapor HF [6–9], critical point drying [10–13], by roughening the surfaces [14,15], or by self-assembled monolayer coating schemes [16–21], in-use *stiction* still poses a significant issue to the reliability of MEMS. This phenomenon occurs when surface forces such as van der Waals, capillary, and/or electrostatic force dominate over the restoring force and causes a malfunction during device operation. The rough contacting surfaces of microfabricated structures built out of polysilicon have been also shown to be mechanically weak due to high contact pressures generated at the asperity contacts. As a consequence, it is expected that silicon microstructures designed for repetitive contacts during operation likely fail due to wear which severely limits the lifetime of the devices. Additionally, silicon-based MEMS are challenged for operating under harsh environmental conditions of elevated temperatures, oxidative and corrosive environments, and in mechanically demanding applications, e.g., for combustion monitoring and power generation [22–25].

One effective way to resolve these reliability issues is by coating the wafers with a thin silicon carbide layer across the surface to reduce the surface energy of the device [26]. SiC is a material of choice for solid lubrication in polysilicon MEMS due to its many outstanding properties, including the ability to tailor its doping level to enhance conductivity and minimize charging, high specific strength and creep resistance, thermal stability and conductivity, chemical inertness, mechanical strength (hard), wear resistance, low surface energy, hydrophobic, and the synthesis ability for conformal coating of surfaces that are not in line of sight. The incorporation of ultra-hard, wear-resistant, and conformal SiC hard coatings in MEMS architecture takes advantage of these attractive properties and at the same time allows the preservation of the overall microsystem design.

With the introduction of a new tribological interface, that of the SiC coating that interacts directly with adsorbates or lubricant species present in the operating environment, it is desirable to study and predict the failure mechanisms sooner than they occur in normal MEMS operation to pave the way for full scale implementation of MEMS to the mainstream. Experimentally, adhesion forces in polycrystalline SiC (polySiC) interface as a function

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of apparent contact area have been determined quantitatively using a microfabricated test structure. This paper also presents a detailed, systematic study of the evolution of physicochemical properties of the interface for over 100 billion contact cycles. The correlated results of adhesion and lifetime studies are then compared to those obtained on polysilicon interfaces with comparable topography.

2. Experimental details

2.1. Device structure, fabrication and surface modification

An array of double-clamped beam (DCB) test structures designed to measure adhesion forces in micrometer-scale surface interactions were fabricated through standard PolyMUMPS (MEMSCAP, Inc.) multilayer micromachining processes. The fabrication processes including the release procedure are described in detail in Ref. [27]. Fig. 1(a)–(c) depicts the schematic top and side views of the fabricated DCB test structure illustrating both non-contact and contact states. The beam (also called source electrode by convention) is suspended 2 μm above a landing pad (drain electrode) and two symmetrically positioned actuation pads through which the actuation (bias) voltage is applied. A representative scanning electron microscopy (SEM) image of a DCB device with 275 μm long beam is shown in Fig. 1(d). The beam and the landing pad are both grounded. An extra probe pad attached to the drain electrode is designed to enable four-point current vs. voltage (I–V) measurements. A dimple with 0.75 μm thickness is incorporated in the middle of the beam and directly above landing pad to define the apparent area of contact. The separation between the dimple and the landing pad is 1.25 μm.

A series of DCB test structures with 275 and 350 μm long beams and with dimple sizes in the range from 4 μm × 4 μm to 12 μm × 12 μm were used for this study. The devices were released [27] and then coated with SiC film. The SiC layer was deposited on the released structures via low pressure chemical vapor deposition (LPCVD) using disilabutane (DSB) precursor. The LPCVD reactor (TekVac) was pumped down to a base pressure of $<5 \times 10^{-6}$ Torr. The gas phase DSB reagent was introduced at a flow rate of 5 sccm for 4 min at a reactor temperature of 780 °C. The resultant SiC layer has a thickness of 50 nm as determined by prior calibration done on a separate flat Si(1 0 0) substrate and verified through AFM measurements. The film also yielded a smoother surface with an average root-mean-square (rms) roughness of 10.2 nm in comparison with as-released polysilicon substrate which has an rms roughness of ~15.1 nm. After SiC layer deposition, the separation between the beam and a landing pad is decreased from 1.25 μm to 1.15 μm. A bias of ~75 V is typically required to actuate a 275 μm long SiC-coated DCB into contact with the landing pad, whereas polysilicon DCB of the same length requires ~25 V. The DCB design was chosen to ensure symmetric contact and enable precise measurements of adhesion forces using a methodology outlined in Refs. [27,28].

2.2. Measurement of adhesion forces

Adhesion measurements using DCB devices were carried out in a similar scheme to that reported previously [27,28]. For direct comparison, similar measurements were done on as-fabricated (native oxide-coated) polysilicon structures and on SiC-coated structures. Optical interferometric techniques have been used to systematically determine the beam profile and the pull-in and pull-off voltage

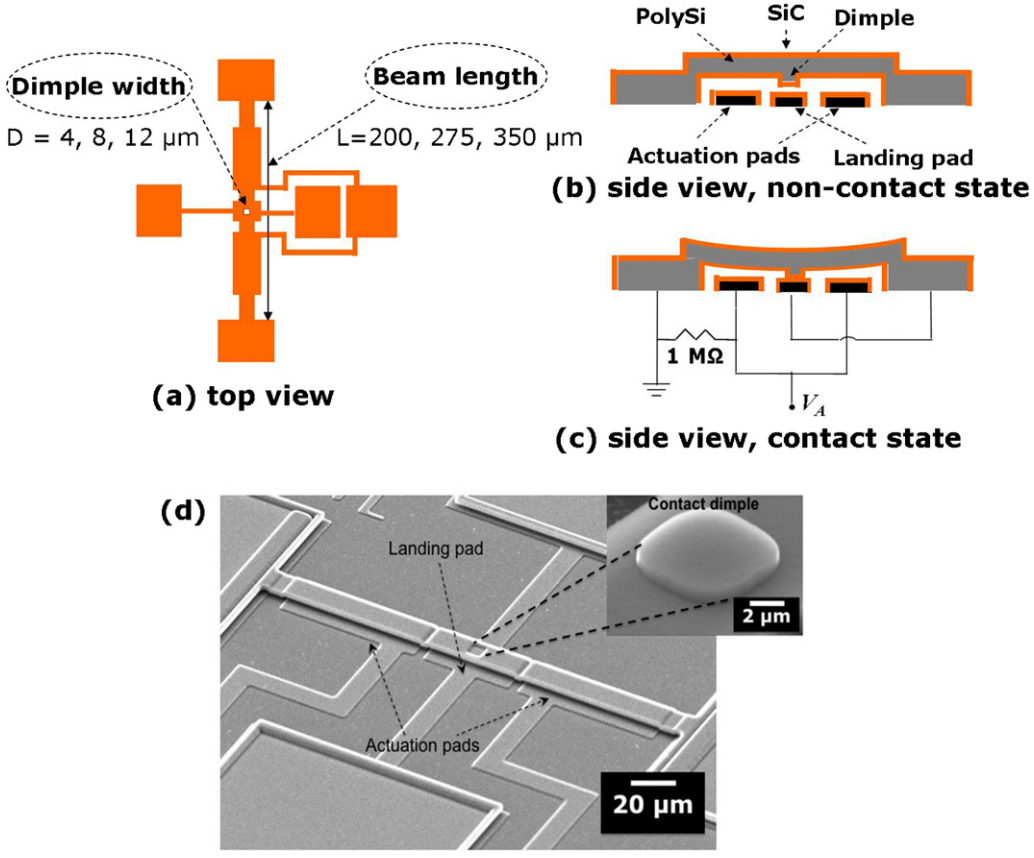

Fig. 1. (a)–(c) Schematic representations of the electrostatically actuated double-clamped beam test structure. The same designs were also coated with a polycrystalline SiC film for comparison. (d) Representative SEM micrograph of a 275 μm long polysilicon DCB device (inset is an inverted dimple).