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Aging of a fluorinated lubricant on bare and DLC-coated silicon-based MEMS

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Abstract

The aging of Fomblin Zdol® on a silicon-based MEMS device was investigated. The MEMS device used was an electrostatic lateral output motor. Devices freshly coated with Zdol performed exceedingly well compared to uncoated devices, but their performance deteriorated on storage in air. This is apparently due to the decomposition of the fluorinated lubricant in contact with the polysilicon surface for an extended period. XPS and AFM studies show that the composition and morphology of the Zdol-coated polysilicon surface change on aging. A stable, cohesive barrier layer deposited to prevent direct contact of the fluorinated lubricant with polysilicon enhanced the stability of the lubricant. As widely used in hard disk lubrication, a thin film of diamond-like carbon (DLC) acted as an excellent barrier layer extending the life of unlubricated devices and preventing degradation of those lubricated by Zdol.

Keywords: MEMS lubrication; Aging; Barrier layer; Fomblin Zdol®; Diamond-like carbon (DLC)

1. Introduction

Large surface area to volume ratios in microelectromechanical systems (MEMS) results in the predominance of friction and electrostatic forces over inertial and gravitational forces. Thus, stiction and friction assume greater importance in MEMS compared to macrosystems, and must be reduced to provide operational reliability. Reducing friction and wear assumes critical importance in MEMS that have contacting surfaces in relative motion. Several surface modification techniques and lubrication schemes have been developed to reduce stiction, friction and wear in micro devices. These include self-assembled monolayers (SAMs), Langmuir–Blodgett films, fluid lubrication, solid film lubrication, hard wear resistant coatings and vapor-phase lubrication [1–15]. While these approaches have led to varying degrees of improvement, further enhancements in reproducibility and reliability are still required to achieve a high level of performance. Perhaps the problems observed are inherent in the very structure and fabrication of these devices. In order to ascertain uniform performance when several hundreds of miniature devices are mass-produced on a single silicon wafer, it is essential to control the thickness and chemistry of each layer of material that is deposited during fabrication. It is equally important that the layers used during processing, such as the photo resist and the sacrificial layer are as completely removed as required. Entrapment of a small particle or an air bubble in a device can prevent complete solvent or HF access to all the required areas, thereby leading to a dysfunctional device.

Our recent studies with SAMs derived from octadecyltrichlorosilane (OTS) on electrostatic lateral output motors have shown that performance is improved, but in time, the coating wears off exposing the uncoated surface, which

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leads to failure [15]. It is well established that the reproducibility of such coatings derived from chlorosilanes is difficult to achieve since the monolayer formation is very sensitive to reaction conditions [2]. Application of bound and mobile phases of Fomblin Zdol® directly on these silicon-based motors, extended performance by at least an order of magnitude, the mobile phase providing replenishment of the lubricant at exposed interfaces [16]. Tribological studies on Zdol for application to MEMS have been conducted using atomic force microscopy (AFM) [17,18]. We noticed that, when silicon-based motors coated with Zdol were examined after several months of storage, their performance had deteriorated considerably.

Our attempts to improve the durability or storage stability of these silicon-based motors coated with Zdol led to deposition of a diamond-like carbon (DLC) coating on the silicon surface before depositing a fluorinated lubricant layer. This modification of the surface was to prevent direct contact between the polysilicon surface and the fluorinated lubricant. Similar approaches have proved highly successful in hard disc application where a thin layer of carbon or other inert material deposited over the magnetic layer helps prevent its corrosion and degradation [19]. The tribological properties of the DLC coating alone and those of Zdol lubricated surfaces are studied. This paper deals with the aging effect of Zdol on silicon-based MEMS and our efforts to provide a useful and durable lubrication scheme.

2. Experimental

The MEMS device studied was an electrostatic lateral output motor shown in Fig. 1 and described in detail elsewhere [20]. The large curled cantilever serves as the fundamental drive mechanism of the motor. Applying voltage across the cantilever and underlying conductive substrate drove the motor. A link arm, attached to the cantilever tip and lateral output slider by floating hinges, converts the vertical deflection of the cantilever tip to lateral motion of the slider. The motor provides a reciprocating lateral output of 10 μm, and a variety of different contact interfaces of polysilicon/polysilicon and polysilicon/silicon nitride that must be properly lubricated for sustained operation. Dynamic experiments were conducted inside an environmental chamber to determine the functional life of the motors. A square wave voltage input of 0/100 V was used to drive the motor at a drive frequency of 1 kHz. The temperature inside the environmental chamber was 22±2 °C, and the relative humidity (RH) was maintained below 3% during experiments. Low RH was selected as the test environment because it is a severe environment for accelerating wear in air. A motor was considered failed when there was hardly any slider movement or when the motor ceased operation, whichever occurred earlier. For performance evaluation, at least five devices were tested in each category and the results were averaged to obtain a data point.

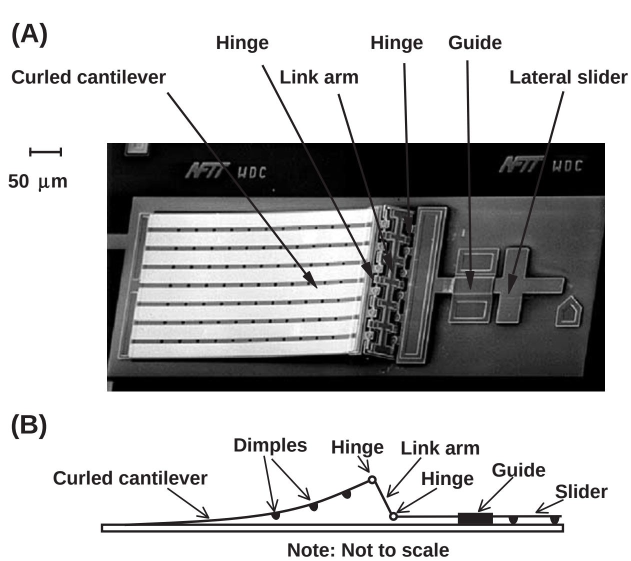

Fig. 1. (A) SEM micrograph of an electrostatic lateral output motor. (B) Cross-sectional schematics of the lateral output motor.

The DLC coating was deposited on microdevices as well as polysilicon wafers by plasma-enhanced, chemical vapor deposition (CVD). Different thicknesses of DLC coatings were applied by controlling deposition parameters. A 0.1% (w/w) solution of Fomblin Zdol® 2000 in perfluoro-(2-butyltetrahydrofuran) (PBTH) was used to coat some MEMS devices, and a 0.2% (w/w) solution was used for polysilicon wafers. Thin lubricant layers were applied by dip coating from dilute solutions. The dies containing the MEMS devices as well as the polysilicon wafers were vertically mounted on a holder for dip coating. These were dipped into the PBTH solution of Zdol at a constant rate of ~1.0 mm/s, held immersed for 1 min, and then withdrawn at the same rate. Coating conditions were kept constant, as the lubricant thickness obtained in dip coating on a planar surface is a function of concentration and withdrawal speed among other factors [21]. The coated die or the wafer was then heated at 150 °C or 175 °C for 1 h, cooled to ambient, washed 3 times (5 min each) in PBTH, and then dried at 125 °C for 5 min.

Accelerated tribological tests were conducted on coated and uncoated polysilicon wafers. A ball-on-flat tribometer was used for accelerated friction and wear tests. Polysilicon wafers coated with DLC and DLC+Zdol were used in the study. Silicon nitride balls (3.0 mm diameter) were used at 10 g normal load and 20 mm/s sliding speed. The mean Hertzian normal contact stress over the contact area was ~350 MPa. The relative humidity (RH) was controlled at ~15% during these friction measurements. The bare polysilicon wafers and the silicon nitride balls were subjected to ultrasonic cleaning separately in hexane, acetone and methanol for 30 min each, and were dried. Samples were then placed in glass jars, closed with aluminum-lined stoppers and stored in a dessicator. Coated samples were