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Conformality effects on the wear of low-speed, large aspect ratio silicon journal microbearings

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ABSTRACT

The development of a novel microbearing test apparatus to investigate the wear behavior of large length to diameter aspect ratio silicon-based journal microbearings is presented. The apparatus is characterized by a manually assembled rotor–hub system driven by compressed air through rectangular microchannels. Hub and rotor fabrication, test fixture fabrication, wear assessment, and speed measurement methodology are described in detail. The deep reactive ion etching (DRIE) fabrication process produces small axial tapers on rotor and hub surfaces which allows for the assembly of conformal and non-conformal bearing system configurations. A set of repeatable durability tests indicate that the wear rate on conformal bearing configurations is consistently greater than that found in non-conformal configurations. It is also shown that the measured volumetric wear trends cannot be attributed to an adhesion wear model, and observed wear morphology is strongly suggestive of impact or surface fatigue wear.

1. Introduction

Microturbine systems [1,2] offer the potential for large power densities and the ultimate promise of efficient, small, localized power sources. Other promising applications employing rotating machinery at the microscale involve micropumps for lab-on-chip applications [3], microgear train assemblies for microactuation [4], and novel methods of polarizing light that do not rely on material properties [5]. Successful operation of these rotating microsystem devices rely heavily on the performance of journal bearings whose dimensional specifications and duty cycles (loads and kinematics) are quite different from those found at the macroscale.

Microactuator devices have relatively small journal diameters (typically 10–200 μm) and are designed to operate at a relatively low rotational speed (typically 10,000–100,000 rev/min.), while microturbine systems have substantially larger diameters (typically 4 mm) but are designed to operate at rotor speeds exceeding 1,000,000 rev/min. Both low- and high-speed rotating microsystems have been traditionally fabricated using conventional surface lithography techniques found, for example, in commercially available SUMMIT and MUMPS processing methods which unfortunately constrain designs to relatively small journal length to diameter aspect ratios (typically of the order of 0.05–0.1) and relatively large radial clearance to journal diameter ratios when compared with their conventional macroscale counterparts. Low aspect ratio journal microbearings at low rotational speeds are believed to operate in a boundary lubrication mode, and high wear rates have been reported [6–8]. High-speed microturbine systems employ a combination of low aspect ratio gas lubricated journal and thrust bearings, which are either self-acting, hydrostatic, or involve special feed arrangements [9,10], but the devices remain susceptible to whirl instability leading to sudden seizure [2].

Recent work in microsystems design has focused on various ways to increase bearing aspect ratio. Wear characteristics of large aspect ratio (~0.6) nickel journal bearings fabricated using X-ray lithography and subsequently coated with tungsten alloys have been reported [11]. A mold fabrication method for gas microbearings using SU-8 and nickel bearing materials with relatively large length to diameter ratios (of the order of 0.25) has been recently published, but performance results have not yet been disclosed [12].

This paper describes the development of a novel microbearing test apparatus to quantify the wear behavior of low-speed, large aspect ratio silicon-based gas journal microbearings fabricated with conventional MEMS surface lithography techniques. The apparatus is characterized by a manually assembled rotor–hub system driven by compressed gas through small rectangular channels. The paper focuses on hub and rotor fabrication, test fixture

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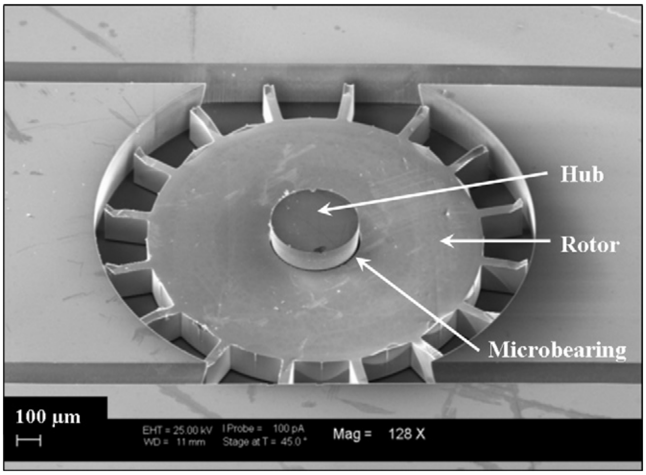

Fig. 1. SEM micrograph of a manually assembled microbearing system (rotor and hub).

fabrication, bearing duty cycle, and speed measurement methodology. Wear trends are investigated for hubs and rotors in two different geometric configurations, denoted as conformal and non-conformal, respectively, which are a result of hub and rotor fabrication processes.

2. Test system

Fig. 1 shows a scanning electron microscope (SEM) micrograph of the microbearing test system comprised of a rigid rotor which has been manually assembled onto a fixed hub to form the microbearing. Rotor bearing length and average rotor diameter are $165 \pm 2\,\mu m$ and approximately $400\,\mu m$, respectively, resulting in a relatively large length to diameter ratio of approximately 0.4. The rotor, depicted in Fig. 2, is pneumatically driven by nitrogen gas which is delivered through one of the rectangular microchannels.

In situ fabrication of rotor and hub from a single wafer for the high-aspect ratio bearings considered here results in unacceptably large rotor to hub clearance due to lithographic constraints with current MEMS based surface or bulk manufacturing techniques. Rotors and hubs are instead fabricated on separate silicon wafers and are subsequently assembled manually to form the microbearing system. Separate fabrication and manual assembly allows for rotors and hubs to be mixed and matched to obtain a radial clearance range of the order of 1–10 μm for bearing aspect ratios considered here.

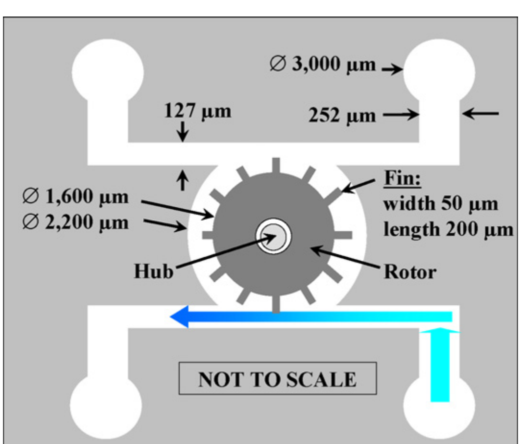

Fig. 2. Microbearing assembly schematic depicts nitrogen gas flowing through one channel in order to rotate the rotor.

3. Rotor fabrication methodology

Fig. 3 shows the fabrication sequence for the rotor, characterized by novel "sprue" and "float" etching techniques. The sprue holds the rotor in place during the KOH etch process. The sprue is patterned using the deep reactive ion etching (DRIE) mask and starts off as a thin silicon fastener, located in between the rotor fins, connecting the outer diameter of the rotor to the rest of the wafer frame. The sprue is then fully oxidized during an oxide growth step and finally etched away during the rotor release etch step. The "float" etching technique entails floating the device wafer on top of the KOH etchant bath. During this backside etch, the rotors are oriented upward (away from the bath). This is done in order to prevent the rotors' top and critical vertical bearing surfaces from being etched.

Several advantages arise from the incorporation of the sprue and float etching procedures.

Cumbersome and costly protective rigging of the wafer that is standard operating procedure with KOH etching is now eliminated. Visualization of the etch process is enhanced. A visual etch end-point-detection scheme is introduced, thereby eliminating the need for multiple inspection withdrawals of the wafer from the hot KOH bath.

Process safety is enhanced and the possibility of cross-contamination is reduced as a direct result of the minimization of inspection withdrawals and associated logistical handling throughout the fabrication facilities. Multiple insertions and withdrawals of the device wafer into the heated KOH bath are eliminated, thereby minimizing induced thermo-mechanical stresses. Messy "black" waxes that are typically used for device masking are eliminated, thereby reducing cleaning and maintenance costs to equipment as well as to actual device wafers.

An SEM micrograph of the rotor is shown in Fig. 4. The pitting seen on the rotor flat surface is due to micromasking by hydrogen bubbles and pre-existing contaminants in the KOH etch bath. The pitting does not appear to affect rotor performance for the test studies herein.

4. Hub fabrication methodology

The fabrication sequence for the hubs follows that of the rotors and is completed at procedure step 5 in Fig. 3. The starting wafer need not be double-side polished, and the DRIE depth must be greater than that of the rotor in order to seal the microbearing fixture. Upon completion of the DRIE process step, the wafer is first diced, resulting in approximately 20 mm × 20 mm bearing hubs, to which the rotors are manually assembled. The nitrogen access holes on each hub are then high-speed drilled using a diamond coated drill bit. In a final cleaning sequence, the drilled hubs are immersed first into acetone and then into isopropyl alcohol before being air dried. Fig. 5 shows a diced hub and an SEM micrograph of the hub geometry.

A single chamber inductively coupled plasma/reactive ion etcher (Unaxis 770 SLR ICP Deep Silicon Etching system) was used in the DRIE fabrication steps for hubs and rotors. The passivation step of the DRIE process is performed for 5 s at 24×10^{-3} Torr, with mass flow settings of 70 sccm, 2 sccm, and 40 sccm for C_4F_8, SF_6, and Ar, respectively. RIE and ICP power settings for the passivation step are 0.1 W and 850 W, respectively. The passivation step is followed by a 2 s etch step at 23×10^{-3} Torr to remove the passivated coating at the bottom of the channel, with mass flow settings of 2 sccm, 70 sccm, and 40 sccm for C_4F_8, SF_6, and Ar, respectively. RIE and ICP power settings for this first etch step are 8 W and 850 W,