

Fabrication Methods for an Encapsulated Silicon Ball Bearing Mechanism

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Abstract

We report on the first encapsulated rotary ball bearing mechanism using silicon microfabrication and stainless steel balls. The method of capturing stainless steel balls within a silicon race to support a silicon rotor both axially and radially is developed in support of a low flow, silicon centrifugal fuel pump as well as future MEMS ball bearing tribology studies. Initial measurements show that speeds up to 6.8krpm without lubrication and speeds up to 15.6krpm with lubrication are possible.

Keywords: Ball bearing, Deep reactive ion etching, Bonding

1 - Introduction

MEMS fabricated silicon rotary elements for micro-motors, micro-generators, and micro-turbomachinery have received growing attention with applications in power conversion and actuation. The rotational bearing support mechanism is a critical component of the rotary elements and is a primary determinant of device operation and reliability. To date, contact passive bearing mechanisms have poor reliability characteristics and are limited to low speeds due to the high frictional forces of sliding motion [1]. In contrast, non-contact bearings based on active elements, or pressurized gas, have been demonstrated to achieve high speeds but require complex fabrication procedures [2].

Tan et al. [3] have reported on a linear ball bearing mechanism which shows that the frictional properties between 440C stainless steel balls and silicon are quite low due to the rolling nature when compared to pure sliding motion. The low frictional properties of ball bearings allow the possibility for higher speeds and better reliability than other contact bearings relying on sliding motion while maintaining fabrication simplicity and stability. In the case of Tan et al., only the normal force due to gravity maintained the contact between the stator/ball/slider system. When taking their approach for a rotational device such as a centrifugal pump, the rotor must be mechanically constrained in all directions in order to maintain stable operation.

Hence, a rotary ball bearing mechanism is reported in which the rolling elements are encapsulated at the periphery of the rotor to enable high speed rotation without relying on gravity or the need of an attractive force between the rotor and stator. Experimental results for both dry and lubricated, full compliment bearings are also reported leading toward the development of a liquid fuel pump.

2 - Fabrication and Experimental Setup

The design and fabrication of the rotary ball bearing is based on commercially available 440C stainless steel balls with a diameter, d_{ball} , of 285 μ m (see Fig. 1). The design features balls housed at the periphery of the rotor to enable a two layer fabrication sequence for encapsulation via bonding. At the same time, this scheme of encapsulation allows for features to be patterned on either side of the rotor while having minimal influence from the bearings. A square groove race was chosen to house the balls in order to ease fabrication requirements and to control the orientation of the contact points. The radius, r , of the race is 4mm to the center of the race. The width of the outer ring, w_1 , is 300 μ m to ensure the ball will fit into the race with the fabrication tolerances involved. The width of the nested race, w_2 , is $d_{ball} / \sqrt{2}$, so that the balls contact at the 90° corners or 205 μ m with tolerances added in. The total height of the race between the contact points, h_1 , is the same as the width, w_2 . Both h_1 and w_2 have included the necessary tolerances due to misalignments and thermal expansions. Furthermore, the ratio of h_1/w_2 can be varied

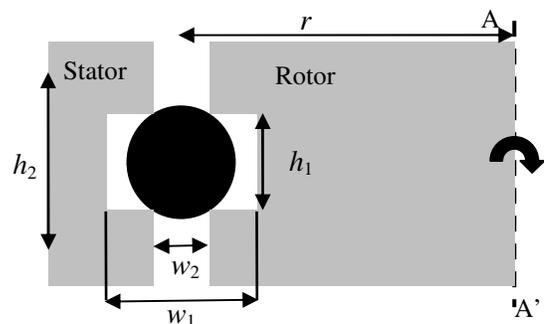


Fig. 1. Schematic drawing for the design of the rotary ball bearing. The rotational axis of the rotor is shown by the A-A' dashed line on the right-hand side of the drawing.

to change the incident angle of the load on the corners of the race where the wear rate of the silicon will be at a maximum.

The bearing mechanism is fabricated in three major steps: 1) silicon races are fabricated on the wafer level; 2) balls are placed into the race and an identical race is bonded on top to encapsulate them; and 3) silicon deep reactive ion etching (DRIE) is used to release the rotor.

Fig. 2 shows the steps used to fabricate the silicon races. A double-sided polished silicon wafer with a thickness of $440\mu\text{m}$ and with a $1.1\mu\text{m}$ silicon dioxide layer thermally grown on the surfaces is used. The silicon dioxide on the top-side of the wafer is patterned with the outer ring of width w_1 and a 4mm radius. The silicon dioxide on the bottom-side of the wafer is patterned with the concentric ring of width w_2 . Fig. 2a shows these steps with both the top and bottom silicon dioxides patterned. A concentric ring of width, w_2 , is then aligned and patterned into photoresist on the top-side of the wafer, shown in Fig. 2b. Together, the patterned photoresist and patterned silicon dioxide form a nested masking layer. Two DRIE steps are used to etch the silicon using the photoresist first and the silicon dioxide second as shown in Fig. 2c. This forms a silicon race in which two identical die on a wafer can be bonded together to encapsulate the balls.

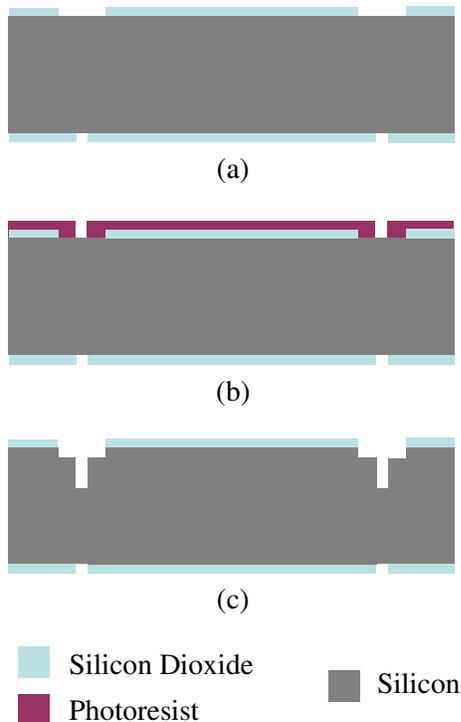


Fig. 2: Simplified fabrication flow for the silicon race using a nested masking layer and two DRIE steps.

Fig. 3 shows the encapsulation using a $1.15\mu\text{m}$ Cr/Au/AuSn/Au adhesion layer and the release using DRIE. The metal adhesion layer is deposited using electron beam evaporation through a silicon shadow mask, shown in Fig.3a. After metal deposition, the wafer is diced into individual die for bonding. Balls are manually placed into the silicon race of one die, Fig. 3b, and an identical silicon race die is aligned using the balls placed into square pits at the corner of the die. The die are then pressed and bonded at 315°C . After bonding, DRIE is used to etch through the silicon using the previously patterned silicon dioxide shown in Fig. 3c.

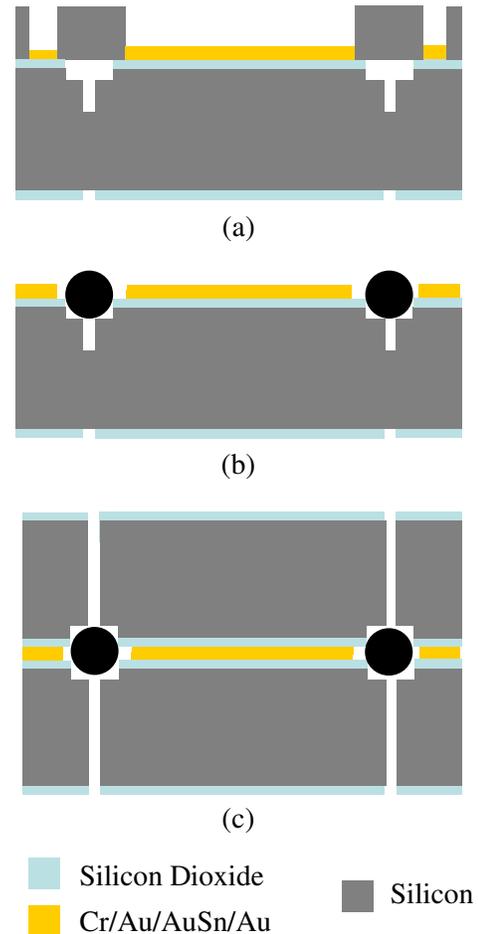


Fig. 3: Fabrication flow showing encapsulation using Cr/Au/AuSn/Au adhesion layer and release using DRIE.

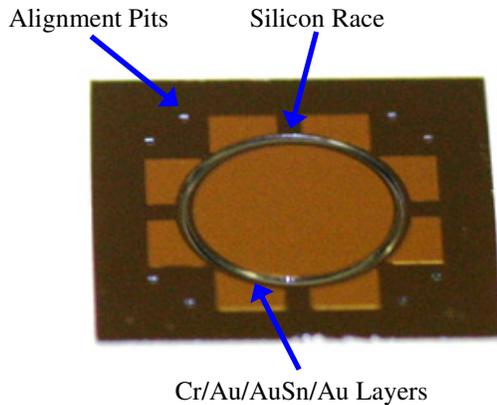


Fig. 4: Optical picture of a die showing the patterned race, metal, and alignment pits.

in some cases metal particles formed in the bearing race due to the softening of the metal adhesion layer during the bonding process. After the final release some of the particles are too large to be removed from the race preventing the rotor from spinning and lowering fabrication yield. Process optimization and the adaptation of silicon bonding are underway to achieve higher fabrication yields.

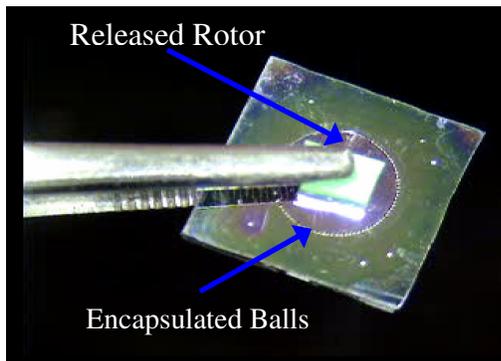


Fig. 5: Optical picture of a released silicon rotor supported by stainless steel balls at the periphery. A full compliment configuration was used with more than 60 balls.

3 - Testing and Discussion

The device was tested using the setup shown in Fig. 6. Standoffs are placed on both the top and bottom of the rotor and the stack is held in place using a mechanical vice. A Nitrogen line is placed within 2mm of the die corner using a second mechanical vice. The flow from the Nitrogen line causes the outer portion of the die to spin about the clamped center.

A Philtec D6 Fiberoptic displacement sensor is used to measure the revolution rate of the spinning square die. A

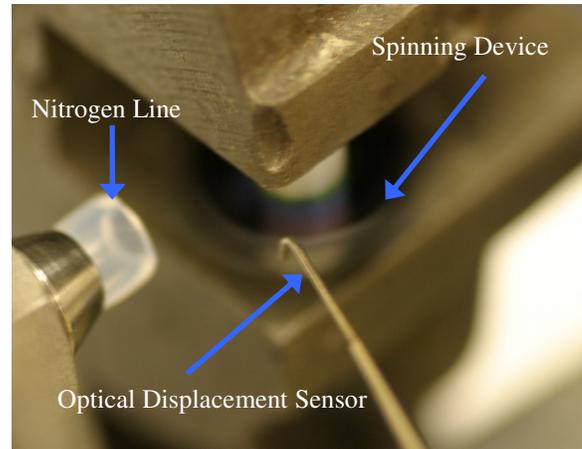


Fig. 6: Optical picture of the test set-up used to measure the speed of the rotating bearing mechanism.

square wave voltage is produced from the sensor due to the revolving corners of the die. The frequency of the square wave signal read from the oscilloscope is then used to extract the rate of revolution of the spinning die.

The device shown in Fig. 6 was started using a pressure of 10psi. Lower pressures were not able to produce enough force on the face of this square die to counteract the static friction, which is normally much higher than the dynamic friction of a rotating device. In some cases, bearings have to be manually started to overcome this initial friction. Once spinning, line pressures as low as 1psi have been used to maintain spinning.

Fig. 7 shows the results of the nitrogen line pressure versus rotational rate for two cases: 1) dry bearings and 2) lubricated bearings. The pressure was started out at 10psi and increased by 5psi after each measurement over a period of 12 minutes. The maximum open pressure of the nitrogen line used was 25psi. After the 12 minutes, the device came to a sudden halt due to the jamming of the balls. Fig. 8 is an optical picture of bearing that has jammed.

The same device was restarted with 2 drops of a lubricating liquid added into the bearing opening. The device was turned manually to allow a uniform lubricating coating around the silicon race and over the stainless steel balls. Again the pressure was increased from 10psi to 25psi and measurements taken at 5psi increments over a period of 10 minutes. The lubrication dried soon thereafter and the bearing stopped suddenly again due to ball jamming. An increase of 8-9krpm can be seen between the dry condition and the lubricated condition for each pressure point.

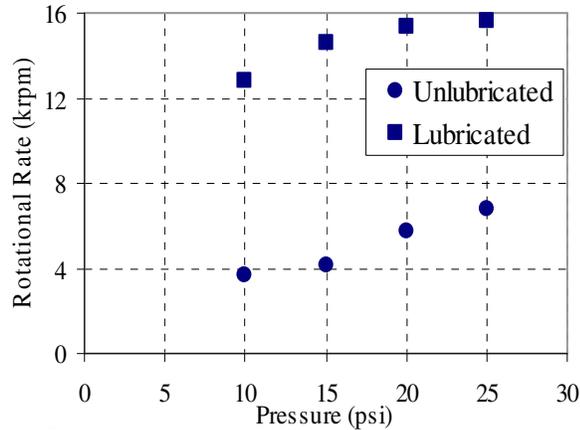


Fig. 7: Measured speed of a bearing versus nitrogen line pressure with and without JP-8 lubrication.

The jamming that occurred in both of the experimental cases reported here is an inherent problem when full compliment type bearings are used. Implementation of a low wear material on top of the silicon race along with tighter fabrication tolerances can reduce the probability of jamming to occur, but not eliminate it completely. Instead, a retainer ring (or cage) could be used to isolate the balls from one another. In addition to eliminating ball jamming, the use of a retainer ring can greatly reduce the friction since a much smaller number of balls can be used. A full compliment bearing requires the race to be more than half filled with balls so the rotor cannot fall out if all of the balls compact together. A retainer ring, however, maintains a separation distance between the balls allowing for a minimum number of balls to be used. Reduction in the friction by decreasing the number of balls will similarly lead to much higher speeds as well as better reliability.

4 - Conclusions

We have demonstrated the first encapsulated rotary ball bearing platform using silicon microfabrication processes. The platform developed enables further investigations on the tribological characteristics for not only the silicon race



Fig. 8: Optical picture of ball jamming occurring within the ball bearing race.

design reported here, but other race/ball designs and materials for MEMS ball bearing mechanisms. The implementation of an encapsulated rotary ball bearing will lead to the development of centrifugal pumping mechanism for fuel delivery applications as well as other Microsystems applications.

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