ELECTROSTATICALLY DRIVEN ROTOR ON CONDUCTIVE LIQUID RING BEARINGS

G. Sun[1], T. Liu[1], P. Sen[2], W. Shen[2], C. Gudeman[2], and C.-J. Kim[1]*

[1]University of California, Los Angeles (UCLA), Los Angeles, California, USA

[2]Innovative Micro Technology (IMT), Santa Barbara, California, USA

ABSTRACT

This paper presents an electrostatically side-driven rotary stage featuring ionic liquid rings as both mechanical bearings and electric connections between the rotor and the substrate. An SOI-based device with multiple through-silicon vias has been fabricated and self-assembled by the liquid rings. The device has operated successfully by applying sequential voltages of 50 V_{DC} between the rotor and the stators placed outside the rotor. Separately, the electric transmission has been verified by powering an LED on a rotating rotor (> 300 rpm) from the substrate. This is the first report of an electrostatically actuated microdevice with a liquid bearing and also the first report of a direct power transmission onto an infinitely rotating microdevice.

INTRODUCTION

Miniaturized rotating devices have been being designed over two decades by using different bearing and actuation methods. Micromotors with solid bearings, including surface dimples [1] and micro balls [2], have been actuated electrostatically [1,3], ultrasonically [4] and magnetically [5]. However, the solid-solid friction, large in microscale, requires high voltage or large current to overcome the friction and often causes serious wear [6]. Gas or air bearing [7], created through electrostatic or magnetic levitation, has no surface friction and wear but requires complicated dynamic control mechanism. Liquid bearings are considered to have a low static friction and no wear. Recently, a liquid bearing in the form of a single large droplet [8, 9] has been reported by actuating the rotor with electrowetting [8] or magnetically [9]. While the rotor assembly was micromachined in [9], unfortunately the device was operated with a conventional electromagnetic coil placed below the chip. More advancement is needed before one can fully utilize the advantages of liquid bearings for microdevices. In addition to the friction issue, perhaps more importantly, none of the reported micro rotating devices could transmit appreciable electrical power on to the rotor through available means (e.g., direct contacts, inductive or capacitive coupling), which has been limiting the utility of such devices.

Here, we propose to use multiple, concentric, conductive, and ring-shaped liquid bearings as both mechanical bearings and direct electric connections between the rotor and the substrate. Compared with conventional solid bearings [1, 2], liquid bearings avoid dry friction, eliminate wear and enhance reliability; compared with gas bearing [7], liquid bearings can be designed to stabilize the rotation without active control using the strong surface tension in microscale; compared with a single liquid droplet [8,9], multiple conductive liquid rings allow direct electric connections; compared with multiple droplets [10], concentric liquid rings are free of contact-angle hysteresis, i.e., essentially no static friction.

By studying volume control, static and dynamic stability, payload capability, electric conductivity, and electrochemistry properties of liquid bearings, we have successfully created a new family of micro bearings: conductive liquid ring bearings. In this work, we use an ionic liquid (EMIM DCA) to form the liquid rings and incorporate them into a three-phase electrostatic side-driven rotary stage device. Direct transmission of electrical power onto the rotating rotor has also been verified. In this report, we present principle and design of the conductive liquid rings, fabrication and assembly of the electrostatically side-driven rotary stage, and testing results of the completed devices.

PRINCIPLE AND DESIGN

Figures 1 and 2 schematically show the perspective view and cross-sectional view, respectively, of electrostatically side-driven rotary stage on conductive liquid rings. Two concentric liquid rings are formed by confining the liquid inside wetting grooves and repelling it from the non-wetting superhydrophobic outer surfaces.

Liquid Ring as Mechanical Bearing

In vertical direction, the rotor is balanced by Laplace pressure, surface tension, and gravity (Fig. 2(a)). As the vertical liquid gap h between rotor and substrate decreases, the supporting force resulted from Laplace pressure ΔP increases, resisting the further decrease of the gap, i.e., providing a self-regulation of the gap. Once the liquid ring is formed with rotor assembled, additional weight from the payload (i.e. static load) or acceleration shock (i.e. dynamic load) tends to decrease the liquid gap h and leads to a higher Laplace pressure, maintaining the bearing until the meniscus angle α exceeds the advancing contact angle of the non-wetting outer surfaces.

In horizontal direction, the rotor always tends to self-center to the substrate due to the restoring force from the surface tension of the liquid (Fig. 2(b)). This restoring force can be increased by increasing the number of liquid rings. Other than vertical and horizontal stabilities, proved by our experiments, well-designed liquid rings also provide restoring force against tilting of the rotor caused by external forces.

Overall, the rotor becomes more resistant to collapsing, shifting and tilting as the liquid gap h is reduced. For the device presented in this report, the gap h is maintained between 100 and 200 µm, which is much smaller than ring width (1 mm) and ring diameters (1 cm for inner ring and 2 cm for outer ring), in order to have good stability.

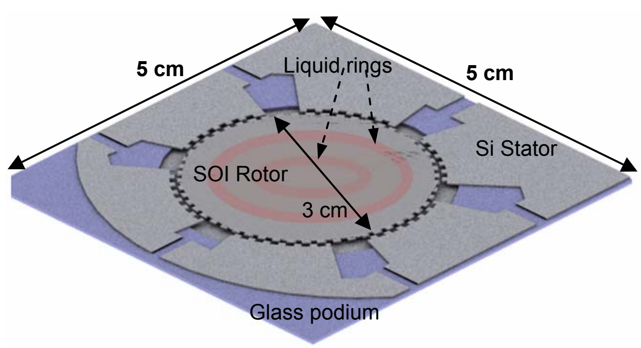

Figure 1: Perspective view of the side-driven rotary stage on conductive liquid rings. The rotor is drawn as if half-transparent to show the two rings underneath.

Power Transmission

In terms of power transmission, electric current i flows between the substrate and the rotor through the liquid rings and the through silicon vias (Fig. 2(c)). Each liquid ring carries an independent electrical signal. Liquid metal, e.g., mercury, has been demonstrated as an electrical signal transmission media [11]. However, most liquid metals require special operation environment or advanced packaging to prevent their oxidation, which makes the utilization of liquid metal more difficult. Instead, we have chosen ionic liquid as the conductive media as well as the mechanical bearing.

In order to deliver appreciable electrical power, ionic liquid with large electrochemical window and high electrical conductivity is preferred. Moreover, the solid-liquid interface where the electrochemical reaction happens must be taken into consideration. In the design shown in Fig. 2, each ionic liquid ring serves as an independent electrical path between rotor and substrate. Silicon on insulator (SOI)-based configuration and additional isolation trenches are used to ensure a good electrical isolation between two ionic liquid rings. In each groove, the entire bottom surface area is covered by gold (which has been confirmed to have no reaction with the ionic liquid used here) and serves as the electrodes. From this point, the ionic liquid is regarded as an electrolyte accordingly. To avoid electrolysis, the potential voltage applied on the ionic liquid should not exceed its electrochemical window.

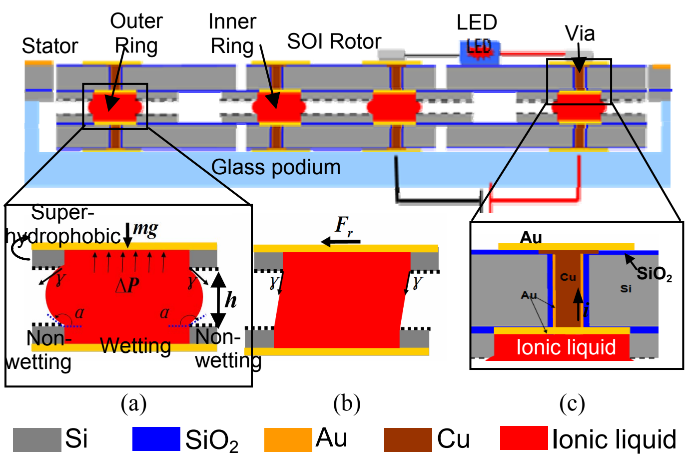

Figure 2: Cross-sectional view of the rotary stage. (a) Vertical stability provided by Laplace pressure. (b) Horizontal stability provided by surface tension. (c) Electric transmission through liquid bearing and vias.

Electrostatic Actuation

Compared with most other actuation mechanisms, electrostatic actuation is expected to have low power consumption as no direct current flows through. A three-phase side-driven configuration has been designed for electrostatic actuation as shown in Fig. 3. The device consists of a 30 mm-diameter rotor and 6 stators, containing multiple teeth-like electrodes (56 on rotor and 7 on each stator). The device layer (with teeth-like electrodes) of both rotor and stator is designed to be ~250 μm thick. The electrostatic gap between rotor and stator is 150 μm. With this configuration, if 50 V_{DC} is applied, a maximum torque of ~10 nN•m and an open-loop control of angular accuracy of ~2° can be achieved. Figure 3 shows the simulation result of the electrostatic field between the rotor and a stator.

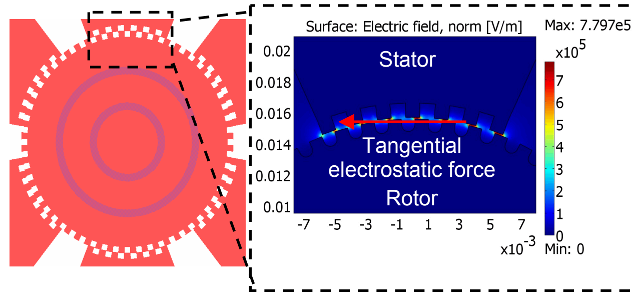

Figure 3: Layout of a three-phase side-driven rotor and simulation of its electrostatic field between the rotor and a stator that induces the electrostatic force to rotate the rotor.

FABRICATION AND ASSEMBLY

Deep reactive ion etching (DRIE) of SOI wafers, through-silicon via (TSV), black silicon, and adhesive bonding techniques were used to fabricate the rotary stage. Figure 4 shows the main fabrication steps.

An SOI wafer with highly doped layers was used. First, through-silicon vias (60 μm in diameter; 250 μm deep) were formed by DRIE and Cu electroplating using Innovative Micro Technology (IMT) "Super-fill" plating recipe. After polishing the surface, ~2 μm thick Au bonding pads were formed atop each Cu via to provide a large contact area for electrical connection. Next, electrostatic actuation electrodes and isolation groove (250 μm deep) were etched in device layer by DRIE. Then, the handle layer was thinned down to 100 μm. A superhydrophobic surface was then formed by DRIE black silicon method, followed by another DRIE to define the wetting and non-wetting areas, which define the liquid rings. The vias were then uncovered in the wetting area followed by a ~200 nm thick Au layer evaporated to ensure a direct contact with liquid rings. The stators were then bonded on a glass podium to be level with the rotor. At last, ionic liquid rings were formed and the rotor self assembled by the liquid rings.

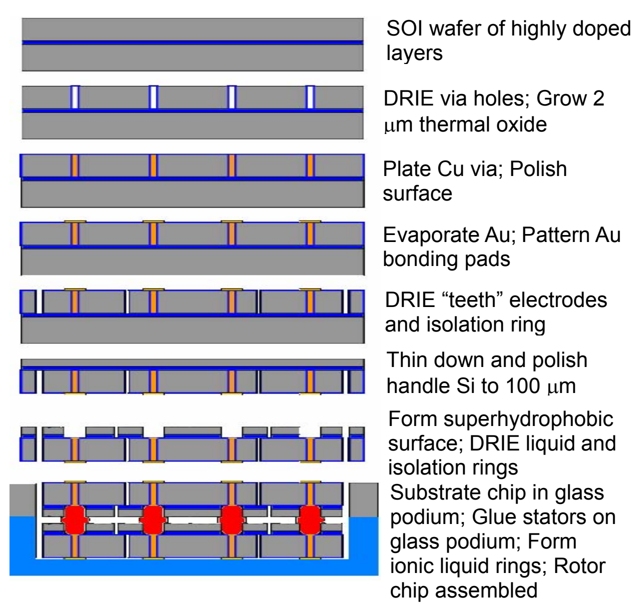

Figure 4: Fabrication process of the electrostatically side-driven rotary stage developed in this report.

Figure 5 shows the fabrication results. On the bottom surface (i.e., the groove side) of the rotor, the black part is the non-wetting area, which is made of highly dense arrays of nanostructures. Those nanostructures have apexes of < 50 nm diameter, heights of 2–3 µm and average pitch (i.e., period) of ~ 400 nm. After being treated with low surface energy coatings, e.g., Teflon® or Cytop, the nanostructured surface exhibits high superhydrophobicity (contact angle ~160º for ionic liquid EMIM DCA). For assembly, ionic liquid EMIM DCA-- $C_8H_{11}N_5$, 1-Ethyl-3-methylimidazolium dicyanamide (Sigma-Aldrich®) was chosen for its high conductivity (27 mS/cm), low dynamic viscosity (15-20 mPa•s), high surface tension (64 mN/m) [12] and negligible evaporation. After forming ionic liquid rings on both the rotor and the substrate, surface tension helped the rotor self-assemble centrally to the substrate and without tilting (Fig. 5 (c)). The liquid gap (rotor-substrate gap) is between 100 µm and 200 µm.

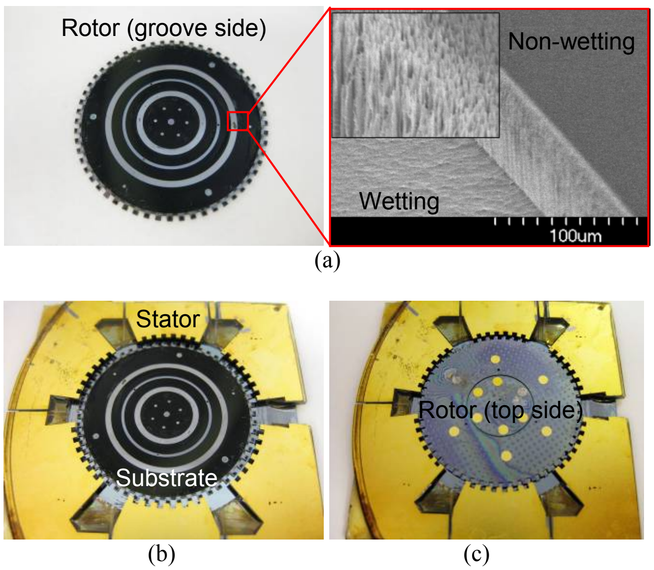

Figure 5: Fabrication result of side-driven rotary stage on conductive liquid ring bearing. (a) Rotor (bottom surface shown) and SEM picture showing the groove. (b) Substrate and six stators bonded on it. (c) Completed device after the rotor is self-assembled on the substrate by the liquid rings.

RESULTS AND DISCUSSION

Electrostatic Actuation

For the electrostatic actuation test, only the outer ionic liquid ring was formed to reduce the complexity of assembly. Figure 6 schematically shows the driving strategy. The rotor was electrically floated all the times during the operation, while the stators were connected in an alternating sequence with three distinct electrical phases. In each phase, a pair of diagonal stators was activated by applying a certain voltage. When a given phase was activated, a voltage difference (50 V_{DC} in our case) between the activated stators and the rotor generated an electrostatic force. The tangential component of the electrostatic force generated a torque, which tends to realign the teeth of the rotor with the teeth of the activated stator. When the teeth of the activated stator were perfectly aligned with the teeth of the rotor, the teeth of the other two pairs of stators had a misalignment. At this point, the driving voltage switched to another phase, which activated another pair of stators. By programming the voltage phase in an appropriate sequence, a stepwise continuous rotation has been achieved in either clockwise or counterclockwise directions for more than 10 hours in a regular hotel exhibition hall without special protection.

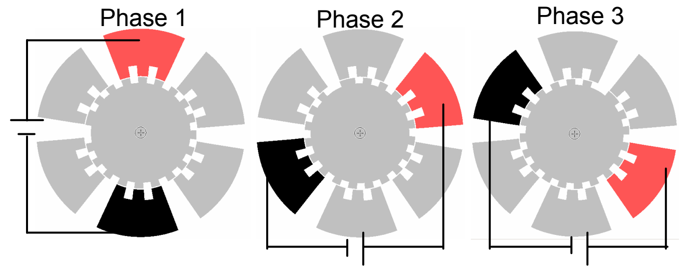

Figure 6: Three-phase electrostatic actuation.

The rotation was open-controlled and the speed was kept at a rate of ~5º/s at all times. The wobble of rotor was measured to be less than 0.012 rad. The leakage current flow from the power supply was observed less than 10^{-3} µA.

Power Transmission

To verify the electrical power transmission onto a rotating rotor, we used an assembled device without outside stators, which easily facilitates the investigation of the liquid ring height, stability of rotor, and dynamic motion of high-speed rotation. An LED was placed on top of rotor and electrically connected to the Au bonding pads. Two ionic liquid rings were formed both on rotor and substrate with accurate volume control, followed by the assembly of rotor to substrate as described in the previous section. Air blowing was used to keep the rotor rotating at a rate of ~300 rpm. During the rotation, a 4 V_{DC} was applied to the substrate vias, across each of the two liquid rings, through corresponding through-rotor vias, and to the LED on the rotor. A current flow of ~ 0.1 mA was observed. Figure 7 shows the side view (top) and a snap shot (top) of a rotating device with an LED. The weight of rotor, LED, and bonding wires was ~ 700 mg, which has demonstrated a considerable payload capability of the liquid ring bearing. The LED blinking has further been confirmed on an electrostatically driven rotor, although the rotation was much slower and not continuous.

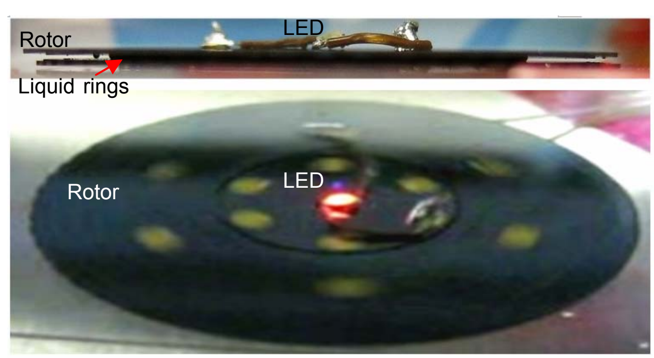

Figure 7: A red LED blinking at the center of a rotor (no stator in this device) that is being rotated by blowing air.

Further Discussion

The stability of liquid bearing has also been verified experimentally. The volume change of ionic liquid EMIM DCA over 30 hours at atmosphere was found less than 10%, and an assembled rotary stage without protective packaging resumed even after 3 months on the shelf and remained operational for electrostatic actuation.

Although we did not discuss any application of our rotary stage, a rotating device with electrical power transmission can be potentially utilized as a secondary in-situ calibration platform for micro positioning, navigation, and timing (micro-PNT) devices, e.g., accelerometer, gyroscope, and atomic clock. In the future work, we will focus on the capacitance feedback control, optimized design of liquid rings, and further understanding of electrochemical properties of ionic liquid as a conductive element.

CONCLUSIONS

We have successfully demonstrated conductive liquid ring bearings as both mechanical bearings and electrical connection component. Fabrication of defect-free liquid rings has been the key to achieve a very small static friction – small enough to allow rotation by side-driven electrostatic actuation under a relatively low voltage (50 V_{DC}). The stability and reliability of liquid ring bearing have also been verified through a long-term testing. More importantly, a direct electrical power transmission to an infinitely rotating device has been demonstrated for the first time, which opens the window for meaningful applications of miniature rotating devices.

ACKOWNLEDGEMENT

This work is supported by the Defense Advanced Research Projects Agency (DARPA) under grant W31P4Q-10-1-0008. The authors would like to thank Prof. Ken Yang and Mr. Jong Jin Kim for their help on the electrostatic actuation test.

REFERENCES

[1] L.-S. Fan, Y.-C. Tai, and R.S. Muller, “IC-Processed Electrostatic Micromotors”, Sensors and Actuators, 20, 41 (1989).

[2] N. Ghalichechian, A. Modafe, M.L. Beyaz, and R. Ghodssi, “Design, Fabrication, and Characterization of a Rotary Micromotor Supported on Microball Bearings”, Journal of Microelectromechanical Systems, 17, 632 (2008).

[3] M. Mehregany, S.F. Bart, L.S. Tavrow, J.H. Lang, S.D. Senturia, and M.F. Schlecht, "A Study of Three Microfabricated Variable-Capacitance Motors", Sensors and Actuators, 21, 173 (1990).

[4] P. Muralt, “Ultrasonic Micromotors Based on PZT Thin Films,” Journal of Electroceramics, 3, 143 (1999).

[5] C. H. Ahn, Y. J. Kim, and M. G. Allen, “A Planar Variable Reluctance Magnetic Micromotor with Fully Integrated Stator and Coils,” Journal of Microelectromechanical Systems, 2, 165 (1993).

[6] M. Mehregany, S.D. Senturia, and J.H. Lang, "Measurement of Wear in Polysilicon Micromotors", IEEE Transactions on Electron Devices, 39, 1136 (1992).

[7] L.G. Frechette, S.F. Nagle, R. Ghodssi, S.D. Umans, M.A. Schmidt, J.H. Lang, “An Electrostatic Induction Micromotor Supported on Gas-lubricated Bearings”, Technical Digest of the 2001 International Conference on Micro Electro Mechanical Systems, Interlaken, Switzerland, 1/21-25/01, (2001), pp. 290 – 293.

[8] A. Takei, K. Matsumoto, and I. Shomoyama, “Capillary Motor Driven by Electrowetting”, Lab on a Chip, 10, 1781 (2010).

[9] M. Chan, B. Yoxall, H.Park, Z. Kang, I. Izyumin, J. Chou, M.M. Megens, M.C. Wu, B.E. Boser and D.A. Horsley, “Low Friction Liquid Bearing MEMS Micromotor”, Technical Digest of the 2011 International Conference on Micro Electro Mechanical Systems, Cancun, Mexico, 1/23-27/11, (2011), pp. 1237 – 1240.

[10] B.E. Yoxall, M. Chan, R. S. Harake, T. Pan, and D.A. Horsley, “Rotary Liquid Droplet Microbearing”, to appear in Journal of Microelectromechanical Systems.

[11] W.Shen, R.T. Edwards, and C.-J.Kim, "Electrostatically-Actuated Metal-Droplet Microswitches Integrated on CMOS Chip", Journal of Microelectromechanical Systems, 15, 879 (2006).

[12] S.I. Fletcher, F.B. Sillars, N.E. Hudson, and P. J. Hall, "Physical Properties of Selected Ionic Liquids for Use as Electrolytes and Other Industrial Applications", Journal of Chemical & Engineering Data, 55, 778, (2010).

CONTACT

*G. Sun, tel: +1-310-825-3977; guangyi@ucla.edu