CONTACTLESS MAGNETIC MICRO-BEARING BASED ON 3D SOLENOIDAL MICRO-COILS FOR ADVANCED POWERMEMS COMPONENTS

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Abstract: We present for the first time a contactless magnetic micro-bearing based on multi-turn high aspect-ratio 3D micro-coils manufactured with a wirebonder in a fully MEMS-integrated technology. We demonstrate levitation of a 25µm thick Al plate with diameters between 1700 and 2700µm to a levitation height up to 120µm for 1.8MHz, $20V_{pp}$ AC excitation voltage. An important issue of frictionless systems is the overall stability. In order to stabilize the levitation of the Al plate, we report the successful simulation, design and testing of a stabilization micro-coil, coaxial with the levitation micro- coil, which centers the Al plate by constraining it laterally.

Keywords: micro-bearing, micro-levitation, micro-coils, micro-motors

INTRODUCTION

Performance of micro-motors and micro-generators is often limited by the problems of fabricating low-friction bearings at the micro-scale with reasonable lifetime. Friction reduces the output torque of a motor and eventually causes mechanical failure [1]. Thus, the mechanism support for the rotor should have several key features: low friction, high stability, and high resistance to wear.

Several supporting mechanisms have been reported as technological solutions for the fabrication of micro-motors and micro-generators. A conventional micro-motor has a center-pin design [2], which usually results in friction, wear, fracture and stiction related failure. Gas-lubricated bearings reported by Epstein et al. [3, 4] suffer from a very complex fabrication process requiring a stack of wafers. Recently, Ghodssi et al. [5, 6, 7] reported the micro-ball bearing technology as a reliable, high stability support mechanism for the rotor.

However, none of the above-mentioned solutions completely eliminates the mechanical contact between the stator and the rotor, therefore friction and wear are still present limiting the device performance to a certain extent. An alternative approach to eliminate friction is to levitate the rotor using electromagnetic induction. Such a magnetic micro-bearing has the potential to support the micro-motor at high rotational speeds without mechanical degradation. This technological solution has been employed by Shearwood et al. [8, 9] and more recently by Zhang et al. [10, 11] in the development of a levitated micro-motor for application as a gyroscope. The operation principle of such an active magnetic micro-bearing is the electromagnetic induction. Applying a high-frequency AC current to the stator coil induces eddy currents in the rotor consisting in a conductive plate. These currents interact with the excitation current to produce a repulsive force that levitates the plate.

Previous efforts to build an active magnetic micro-bearing use planar photolithography and successive metallization-passivation steps for the levitation and stabilization coils. This limits the amount of current allowed for excitation as well as the total number of windings per coil.

In this paper we report on an alternative technique to realize a magnetic micro-bearing based on three-dimensional micro-coils manufactured with an automatic wirebonder [12] in conjunction with traditional microfabrication techniques in a fully MEMS-compatible process [13]. Insulated Au wire 25µm-thick is used to fabricate the levitation and stabilization micro-coils providing not only an increased excitation current in comparison with the planar techniques but also a larger number of windings per micro-coil (up to 25), limited only by the supporting structure of the micro-coil.

DEVICE DESIGN AND FABRICATION

We have introduced a method to fabricate coils with sub-millimeter dimensions on PCB substrates exploiting the unique capabilities of an automatic wirebonder [12]. However, this was not compatible with wafer-scale fabrication, therefore unsuitable for MEMS applications. Recently, we have reported on a fully MEMS-integrated process for micro-coil fabrication using the automatic wirebonder in conjunction with well-established microfabrication techniques [13]. This technology represents the key point in the fabrication of the 3D micro-coils used for levitation purposes in this work.

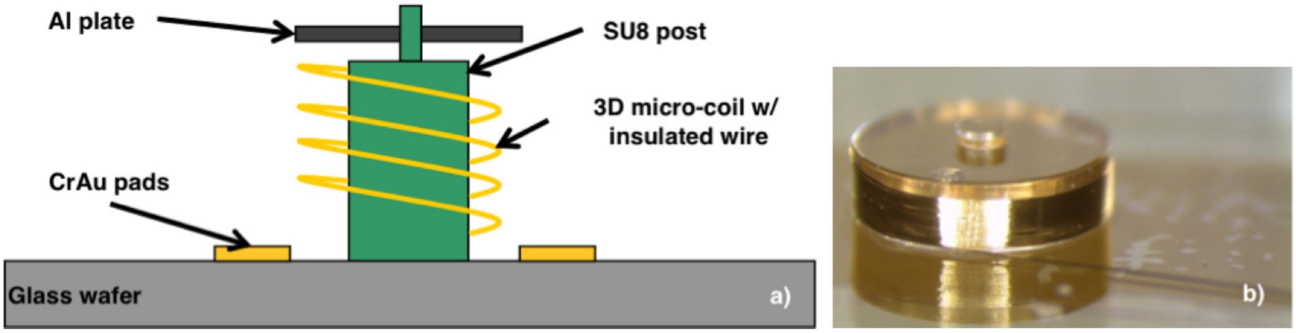

Figure 1: Magnetic micro-bearing structure with center pin stabilization: a) schematic, b) photo.

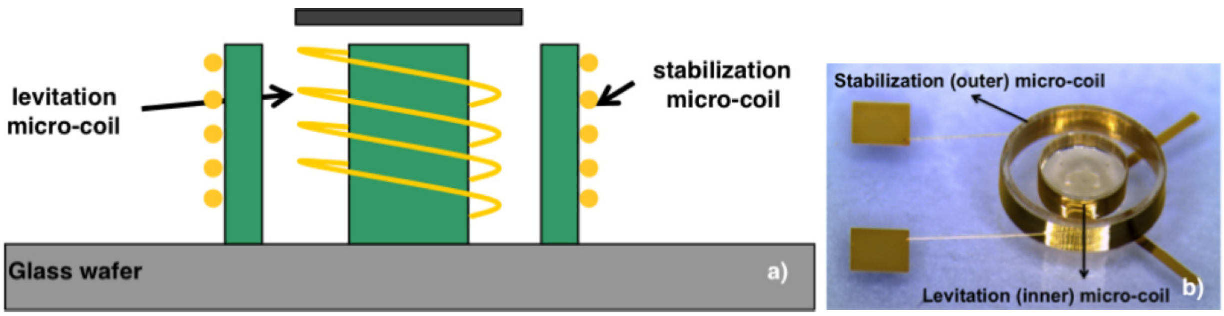

Figure 2: Magnetic micro-bearing with secondary stabilization micro-coil, a) schematic, b) photo.

The micro-coils used in this work are fabricated as described in [13] using glass substrate in order to avoid the induction of eddy currents: CrAu (50/500nm) is patterned to define metal pads for micro-coil winding; a 650µm-thick SU8 layer is used to define cylinders which act as support for micro-coils. Finally, 25 windings micro-coils are wound in a serial but ultra-fast process [13].

The process described above, and in detail in [13] represents the building block of the active magnetic micro-bearing reported in this paper. Two different designs have been elaborated and fabricated. The first version is a center-pin micro-bearing. The thick SU8 layer to define the cylinder which acts as support for the micro-coil is not developed after the post-exposure baking step, and another thinner (~100 µm) SU8 is spun on top and patterned to obtain the center-pin to laterally stabilize the rotor. In the end the two SU8 layers are developed in the same step. Figure 1 presents a schematic of the center-pin magnetic micro-bearing design as well as an image of the fabricated structure.

It is well known that an important issue in frictionless systems is the overall stability. In order to stabilize the levitation of the Al plate, as presented later in the measurement and characterization section of this paper, we report a second design and successful testing of a stabilization micro-coil, coaxial with the levitation micro-coil. This is intended to center the Al plate by constraining it laterally.

This second generation magnetic micro-bearing is fabricated in a single step SU8 process, defining at the same time both the central cylinder to support the levitation micro-coil and the outer SU8 wall to support the stabilization micro-coil. A schematic as well as an image of the fabricated second-generation device is shown in Figure 2.

The Al plates have a thickness of 25 µm and were fabricated by laser cutting a commercially available Al foil.

DEVICE CHARACTERIZATION

An excitation signal of $20V_{pp}$ was applied to the micro-coil, while sweeping the frequency up to 1.8MHz. Figure 3 is a side-view microscope image of an Al plate levitating at a height of about 90 µm.

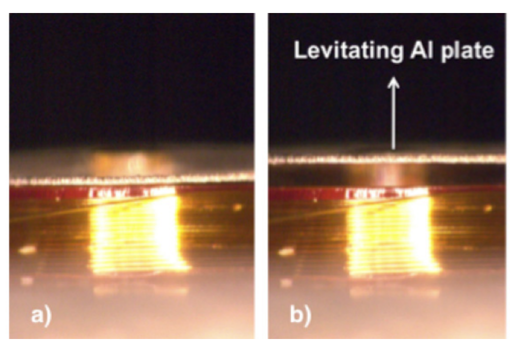

Figure 3: Side view optical micrograph of the levitation micro-coil and the Al plate: a) no signal is applied to the levitation micro- coil: the Al plate is in contact with the SU8 post supporting the micro-coil; b) AC signal is applied to the levitation micro-coil: the Al plate is levitated to a height of approx. 90µm.

Figure 4 is a plot of the experimental levitation height against excitation frequency for a constant amplitude of the signal applied of $20V_{pp}$. As shown in Figure 4, a maximum levitation height of 120μm was achieved for 1.8MHz, limited by stiction of the plate to the SU8 stabilization pole. The levitation height is experimentally determined by focusing a calibrated microscope objective on the top of the levitated rotor and then on the top of the micro-coil.

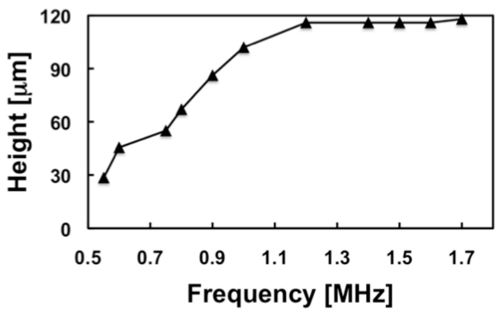

Figure 4: Levitation height versus excitation frequency of a 2700μm diameter Al plate on top of a 2500μm diameter coil. The amplitude of the signal was $20V_{pp}$.

In order to analyze the levitation stability of the Al plate, we have simulated the magnitude of the lateral Lorentz force for different displacements of the Al plate with respect to the center of the device. This relationship is illustrated in Figure 5. When the Al plate is levitated exactly in the center of the stator, there is almost no lateral resultant force. This is because the electromagnetic force distributed in the plate is axis-symmetrical and the lateral force counteracts to zero. However, as shown in Figure 5, a small displacement of the Al plate in either direction results in a lateral Lorentz force that has the same orientation as the displacement, thus acting as a runaway force. The centered position of the plate is an instable equilibrium position.

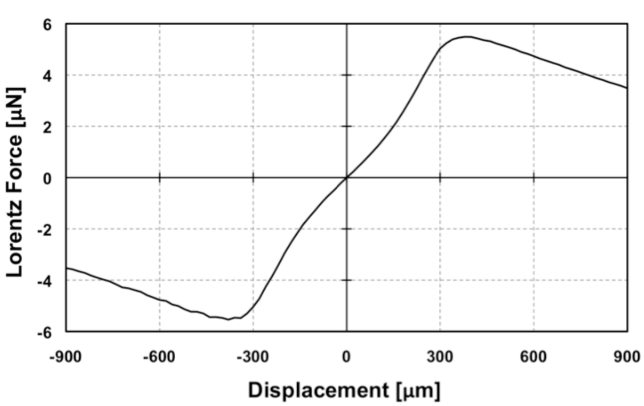

Figure 5: Simulation of the lateral Lorentz force component in the first generation magnetic micro-bearing structure

Centering the Al plate has been achieved by designing a second, stabilization micro-coil as explained in the "Device Design and Fabrication" section of this paper, and illustrated in Figure 2. Figure 6 shows a simulation of the restoring force as a function of the off-center displacement when considering the stabilization micro-coil. The force and the off-center displacement have opposite signs. Therefore the force acts as a restoring force, pushing the Al plate back into the stable equilibrium position. For this simulation, the levitation micro-coil has a diameter of 1500 μm and the gap between the levitation micro-coil and the stabilization micro-coil is 700 μm.

However, the forces that provide lateral stability tend to reduce the lift on the rotor since the stabilization micro-coil works in opposition with the levitation micro-coil. Figure 7 is only intended to demonstrate that the stabilization works properly, according to the simulation. The Al plate has been repeatedly placed off-center and it slides towards the middle of the device as the two micro-coils are switched on.

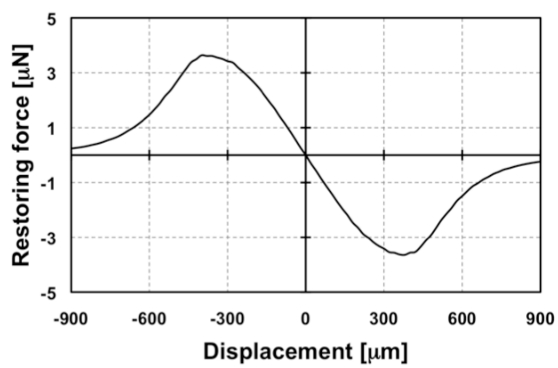

Figure 6: Restoring force as a function of the off-center displacement for a 1500μm diameter levitation micro-coil and 700μm gap between the levitation and stabilization micro-coils. The displacement and the force have opposite signs, thus the force acts as a restoring force.

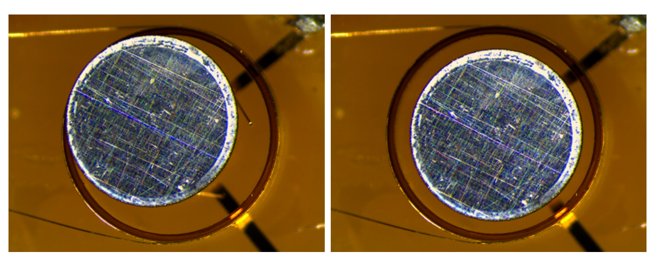

Figure 7: a) Top view of the Al plate off-center before applying signal to the stabilization micro-coil; b) Top view of the successfully centered Al plate upon applying 2.2MHz, $20V_{pp}$ signal to the stabilization micro-coil.

CONCLUSION

In this paper we have demonstrated an active contactless magnetic micro-bearing based on a 3D solenoidal micro-coil technology and electromagnetic induction to levitate an Al plate. The plate has been successfully levitated up to 120 µm. However, because of the lack of friction, the levitation is not stable and plate slides sideways. A second-generation device has been designed in order to achieve stable, centered levitation by introducing an additional stabilization micro-coil. The Al plate is centered in a repeatable, reliable manner once the micro-coils are switched on. However, simultaneous levitation and centering is difficult to achieve, most probably due to a combination of factors: first, centering and lateral stability are achieved at the expense of reducing the total levitation force since the stabilization micro-coil works in opposition with the levitation micro-coil. Second, stiction of the plate to the SU8 cylinder may also contribute to prevent levitation. Future work will improve the current design in order to achieve stable levitation.

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