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An Integrated Magnetic Programming Technique for Mechanical Microresonators

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***Abstract-* Mechanical memory devices are needed for harsh environments where electronic components fail to operate. An integrated electro-thermal technique for local magnetic annealing, which enables post-production programming capabilities for mechanical micro-resonators is presented. It is verified by a prototype with ferromagnetic resonating elements suspended on top of a polysilicon resistive heater. The magnetization (M-H) loop, with and without post-fabrication annealing are measured to prove the validity of technique.**

I. INTRODUCTION

Post-fabrication tuning of physical characteristics is highly desirable, yet difficult to achieve, for resonant sensors. Active methods are commonly used where real-time tuning is needed, while passive tuning is attractive for its zero power consumption during operation [1]. It is even more challenging for magnetism based devices due to difficulty in selectively addressing any part of one transducer or an array of transducers for tuning. One can typically tune the properties of the whole sensing chip; however, this is of little use.

Example applications for programmable micro-devices include surveillance tags e.g. RFID tags. Thereby, unique mechanical or electromagnetic characteristics of resonators generate signatures that can be used for identification purposes. Figure 1 illustrates a sample tag for bio-banking applications [3]. It operates based on Lorentz force applied to current carrying conductive elements in MEMS chip on the tag. The reader coil transmits an interrogation signal to induce electrical current in the tag coil; hence in conductive elements on the MEMS chip. The interaction of permanent magnet with current carrying conductors generates a mechanical force that leads to the mechanical resonance of suspended elements i.e. resonating cantilevers. Magnitude of the applied force depends on unique shapes of conductors among the other parameters, as illustrated in the magnified inset (see Figure 1). The conductive elements can be programmed by electrical fusing, which could be carried out in a post-fabrication process. However, the magnitude of the force achieved by this method is so small that each time the vials containing biological samples should be removed from their cryogenic containers for identification. Integration of magnetic material in the MEMS chip, to replace current carrying elements, can increase the mechanical force that translates to longer read distances for the tags.

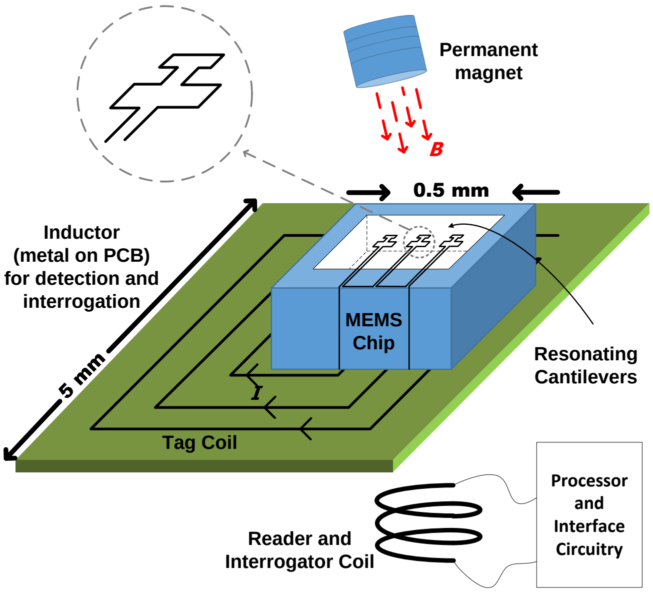

Fig. 1. An example application for electrically programmable mechanical memory elements: Contactless electromagnetic surveillance system [7].

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The research focused on integration of magnetic material in standard MEMS processes has led to significant achievements in several applications such as sensors, energy harvesters, etc. [2] and [3]. However, a straightforward tuning technique is required to enable programming of magnetic properties for the concept of magneto-mechanical memory.

This paper reports on an integrated local tuning technique of magnetic properties for ferromagnetic microresonators, whereby one can tune individual elements on a sensing chip without affecting any other sensory element [4]. At one hand, it enables new applications like mechanical memories [5], [6] and magneto-mechanical elements for identification in harsh environments [7], whose resonance response to interrogating transponders depends on their individual physical attributes. For example, unique resonance signatures can be created in a post-processing step to program the magnetic anisotropy of these elements, so that resonators with/without magnetic

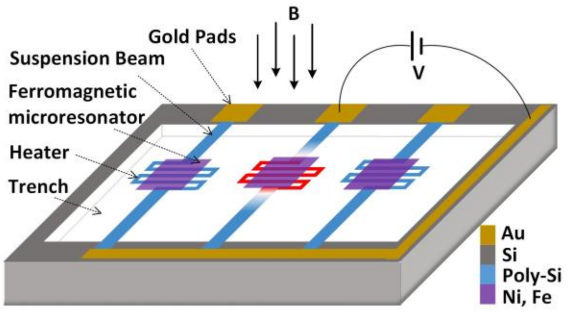


Fig. 2. The perpendicular magnetic field (B) is supplied externally to the whole chip. The field makes permanent influences on the selected resonators only (middle resonator is connected to voltage power supply).

annealing can resemble digital ones/zeros. At the same time, it will also enable mismatch compensation in an array of sensors.

II. PROPOSED MAGNETIZATION METHOD

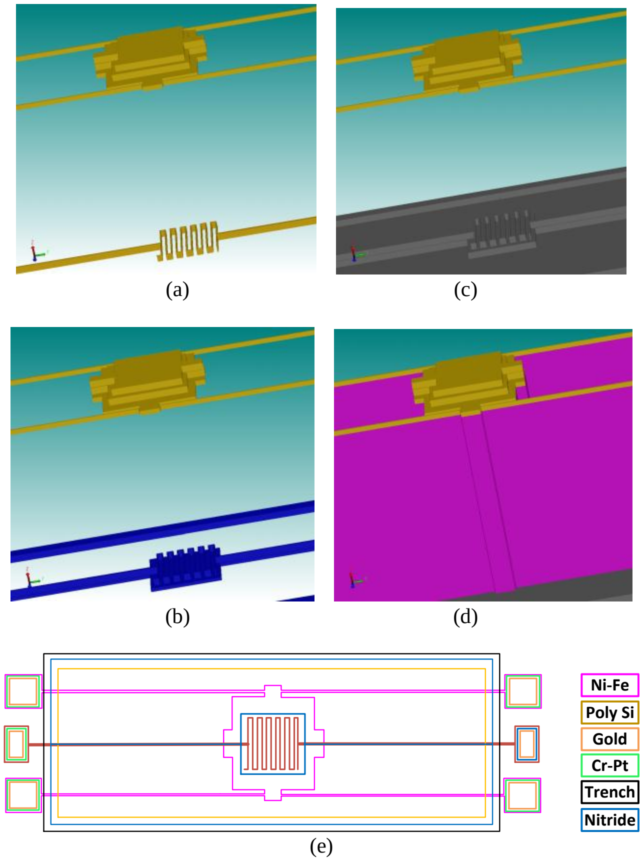
Anisotropy of ferromagnetic materials can be enhanced by magnetic annealing below the Currie temperature under the influence of an intense external magnetic field. This phenomenon can be utilized for tuning a whole chip of such sensors with a heating element. More importantly, however, using on-chip resistors embedded in the micro-device structure [8], one can heat selective regions of the sensors thereby ensuing magnetic annealing will only affect this region when the heated chip is under an external magnetic field. Figure 2 illustrates a schematic view of the proposed transducer. The micro-resonator device consists of ferromagnetic plates suspended on top of serpentine resistive heaters. By providing suitable current, one can increase the temperature of ferromagnetic layer by the heat produced by the resistor and coupled through the air gap, between each heater and the ferromagnetic resonator. Consequently, one or few resonators can be selected for magnetic annealing by applying electrical power to its corresponding heater, while being exposed to a strong magnetic field.

Developing a process that can provide these layers is straightforward and needless of highly equipped cleanrooms. However, in order to use a standard method we selected a Multi-User MEMS Process (MUMP) that can provide a ferromagnetic layer and a resistive layer for heating [9]. Metal-MUMPS include Nickel (Ni) with minor Iron (Fe) impurities as a structural mechanical layer and Polysilicon (Poly) as the resistive heater with 20um and 0.7um thickness, respectively. Heaters are etched in Poly layer and can be individually connected to the electrical power supply via deposited gold pads.

Figure 3 demonstrates the layout and three-dimensional (3D) model of the main layers. The silicon substrate and isolation oxide layers are not shown here for a clear illustration of main layers. The heater and gold over-plate are shown in Figure 3(a). Silicon-Nitride layer (Nitride) covers Poly layer for electrical isolation as illustrated in Figure 3(b). At this step sacrificial material (PSG) is deposited to release mechanical structures built on top of Poly layer after etching. In a normal 3D model this layer is expected to be removed by model builder, however, in order to simulate the heat conduction through air we modified the process to keep it as shown in Figure 3(c). Ni is electroplated next in a chamber that contains Fe impurities as shown in Figure 3(d). Anchor metals that fix metal structure on the substrate and metal pads are illustrated in the layout only (Figure 3(e))

Figure 4 shows the temperature distribution of metal resonator attached to the heater underneath, which is obtained by finite element electro-thermo-mechanical analyses undertaken in Coventor. The simulation is needed to find the value of required electrical voltage applied to the heater for any desired temperature profile. In a real fabrication after building 3D model there should be an air gap between heater and metal layer. However, from the simulation perspective the model builder leaves a gap with no defined material properties. In order to avoid thermal insulation caused by empty layer and conduct a valid heat conduction through air, as stated earlier the process is altered to keep the sacrificial material while replacing its thermomechanical properties with corresponding air properties.

Convection and radiation could be added to simulation, In order to run the simulation, however, we assume conduction is

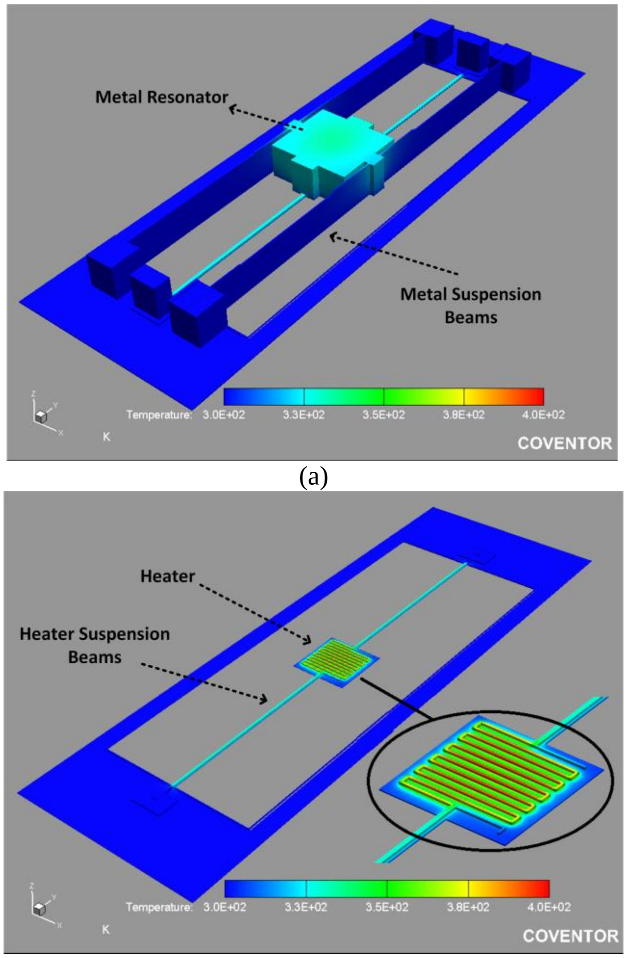


(a) (c)

(b) (d)

(e)

Fig. 3. Three-dimensional model of the MEMS resonator, (a) Poly heater and gold over-plate, (b) Nitride, (c) Sacrificial layer (PSG), (d) Metal (Ni-Fe) and (e) Two dimensional layout.



(a)

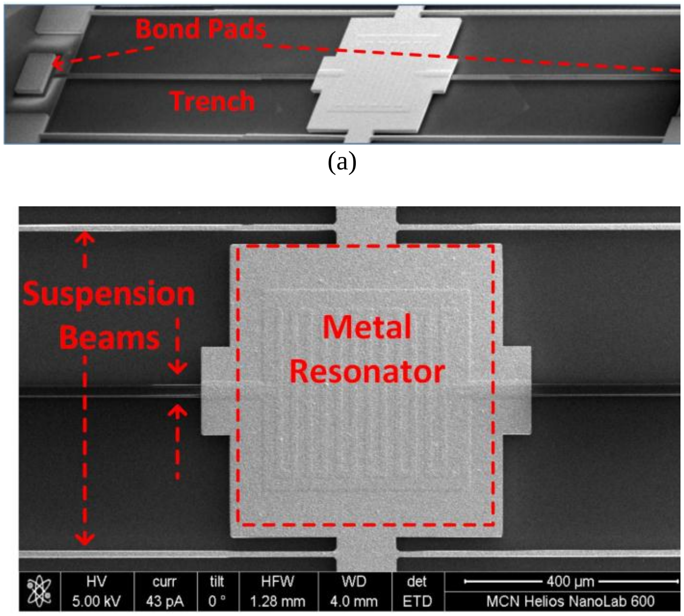
(b)

Fig. 4. Temperature distribution simulation for local electrothermal heating of suspended resonator in Coventor, Horizontal slicing of (a) metal top, and (b) the polysilicon heater.

the main heat transfer mechanism. Ambient temperature is assumed to be 300K while 100V dc voltage is applied to the heater through gold pads. Fixed points of the device are anchored pads of the heater. Simulation results are shown in Figure 4. The metal temperature is around 350K while Poly heater reaches 400K.

III. EXPERIMENTAL RESULTS

A prototype was implemented in a standard MEMS fabrication process (Metal-MUMPs). Its structural layer is a 20μm thick electroplated Nickel (Ni) with Iron (Fe) impurities. The heater is implemented by a 0.7μm thick doped Polysilicon layer. Etching the sacrificial layer between Ni-Fe and Polysilicon leaves a 1.1μm thin air gap in between. Figure 5(a) provides the SEM image of the prototype. It consists of a ferromagnetic plate, suspension beams and gold pads that connect the heater to an external voltage (V). One can observe the traces of serpentine Poly heater on the plate surface in Figure 5(b). The ability to selectively heat an element was first verified using a thermocouple to measure the heat produced and is reported in in Figure 6. The measurement result at 100 V input voltage is in good agreement with the simulation results shown in Figure 4. The measured temperature from metal surface (52 C) at 100 V corresponds to 330 K in simulation (Figure 6(b)). The maximum temperature in Figure 3(b) is 400 K due to the Poly heater, which is inaccessible for thermocouple measurement.



(a)

(b)

Fig. 5. SEM image of the magnetomechanical memory device, (a) tilted view of the whole device(b) Zoomed-in on the hot plate (top view)

Once heated, the samples were placed between two strong permanent magnets, thereby applying perpendicular magnetic field for an hour, while connected to the external voltage, thereby continuing heating. The magnetization (hysteresis loop) of the chips, with and without annealing process, was measured at identical directions with a high precision vibrating sample magnetometer (VSM) as shown in Figure 7. One can observe a higher saturation for a certain magnetic field density, which approves the desired permanent change in anisotropy, thereby verifying the ability to selectively program a magnetic structure.

IV. CONCLUSION

A prototype magneto-mechanical programmable memory device is presented as a proof of concept to demonstrate the feasibility of tuning magnetic properties of micro-resonators in a post-fabrication process. The proposed approach is implemented in a standard MEMS process and tested in a very high precision vibrating sample magnetometer. The magnetization hysteresis loops of the samples before and after selective magnetic annealing confirm the effectiveness of the proposed approach. Superior magnetization results are expected in a customized fabrication process where it is possible for the designer to select an optimum Ni-Fe combination and the heater could be designed to increase the metal temperature to higher extents.

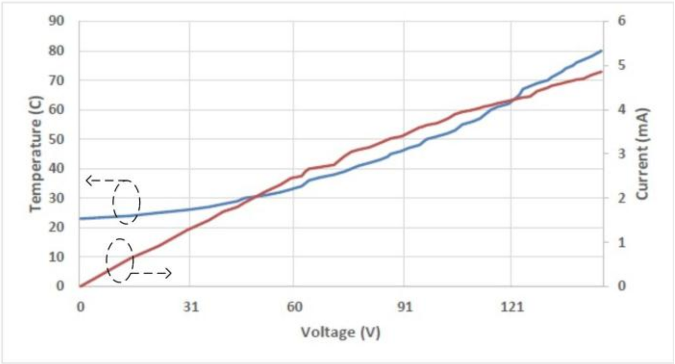


Fig. 6. Temperature distribution simulation for local electrothermal heating of suspended resonator in Coventor, Horizontal slicing of (a) metal top, and (b) the polysilicon heater.

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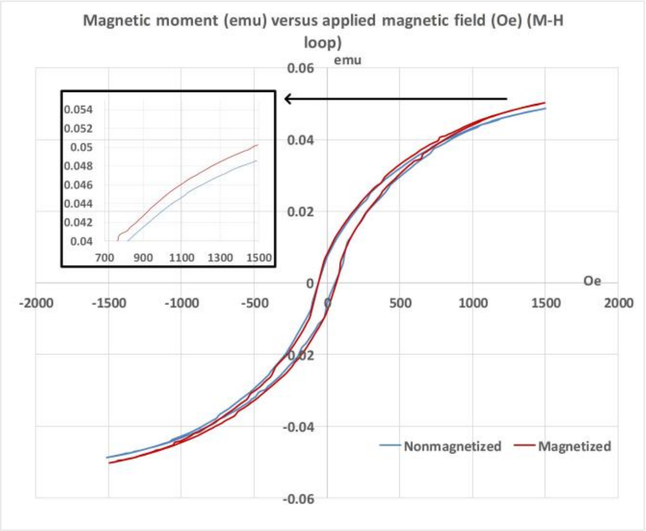

Fig. 7. Measured magnetization of a sample with and without magnetic annealing in vibrating sample magnetometer.