A MICROMACHINED RESONANT MAGNETIC FIELD SENSOR

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ABSTRACT

A micromachined magnetic field sensor has been designed, fabricated and tested. Its principle of operation is based on the change of resonant frequency of a magnetically sensitive micromechanical resonator as a function of applied external magnetic field. Magnetic sensitivity is achieved by incorporating magnetically soft (permeable) or hard (permanent magnet) materials into the resonator structure. The fabrication of these devices is based on electroplating through sacrificial molds and is completely CMOS-compatible. The functionality of the device has been demonstrated as both an intensity sensor and an angular sensor (i.e., compass). The intensity sensor demonstrated a sensitivity of 20 Oersted in magnetic field intensity, while the angular sensor demonstrated a resolution of approximately 20 degrees. Performance improvements are expected upon integration of these devices with appropriate circuitry.

INTRODUCTION

The measurement of the direction and amplitude of magnetic fields is widely used in many applications. A variety of micromachined structures have been developed to perform this sensing function, including Hall-effect devices and fluxgate magnetometers, and are reviewed in [1]. In general, there is a tradeoff between power consumption and sensitivity of these devices, making highly sensitive, low power devices difficult to achieve. For example, in a compass application, a micromachined device for magnetic field measurement would need to be sufficiently sensitive to determine the direction of the magnetic field of the earth while simultaneously being sufficiently low power to be suitable for portable applications such as watches.

The work presented here focuses on a resonant approach to the sensing of magnetic field amplitude and/or direction. The motivation for this approach is twofold: (1) resonant structures can be fabricated that require very little actuation power; and (2) the resonant frequency of the structure can be made extremely sensitive to small stresses, e.g., the stress caused by the interaction of an external magnetic field with the structure.

Since the excitation and detection of these devices is most desirably done with on-chip circuitry, it is important to consider fabrication techniques that are CMOS-compatible in the realization of the devices.

DEVICE CONCEPT

A conceptual view of the device is shown in Figure 1. It consists of a freestanding plate attached to two anchor pads by means of two beams. The device can be driven into oscillation by means of an applied voltage, which results in an oscillatory electrostatic force on the plate. By applying an AC, superposed with a DC, voltage, frequency-doubling effects due to the electrostatic drive can be suppressed. Variation of the frequency of the drive voltage until the amplitude of the vibration of the plate is a maximum results in determination of the resonant frequency of the system.

The resonant frequency of the system depends on the geometry and material properties of the system as well as certain external forces acting on the system. For example, if the plate incorporates magnetic material, and an external magnetic field is applied, the interaction between the applied field and the magnetization induced (or present) in the material will result in a shift in the resonant frequency of the system. This shift, after proper calibration, can be used as a measure of the intensity of the applied magnetic field. Alternatively, if the intensity of the external magnetic field is constant, the degree of resonant frequency shift will depend on the angular orientation of the sensor with respect to the applied magnetic field vector. This shift, after proper calibration, can therefore be used for determination of angular orientation.

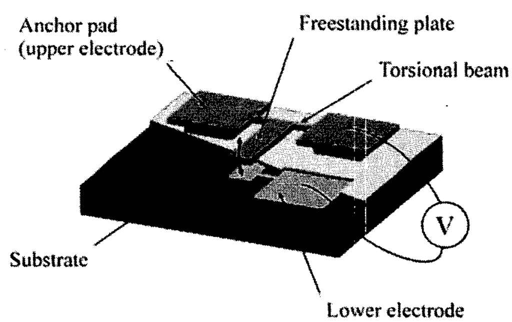

Figure 1. *Schematic of the resonant magnetic field sensor.*

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DESIGN AND FABRICATION

The resonator is excited at its fundamental frequency, in its first torsional mode of resonance. The fundamental, or natural, frequency of the resonator can be written as:

$$f = \frac{1}{2\pi}\sqrt{\frac{2k}{I}} \qquad (1)$$

where k is the torsional spring constant of one beam and I is the moment of inertia of the plate. However, due to non-idealities in the motion of the plate, including the potential for non-rigid-body rotation, it is most appropriate to consider finite element modeling to determine the plate resonant frequency. For example, for a torsional resonator as depicted in Figure 1, with typical geometry values of 13 microns thickness, 600 microns beam length, 200 microns beam width, 800 microns plate width, and 3400 microns plate length, and bulk mechanical properties for nickel-iron alloy, ANSYS finite element analysis predicts a fundamental resonant frequency of 1218 Hz (Figure 2).

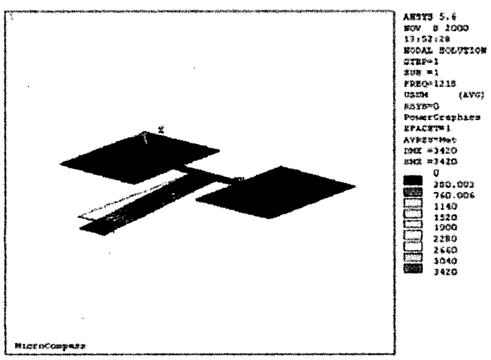

Figure 2. *Extraction of the first resonating mode and frequency of the structure by an ANSYS modal analysis.*

As mentioned above, it is desirable to maintain CMOS compatibility in the fabrication technology chosen for realization of the devices. It has been demonstrated that magnetic materials, both soft **[2]** and hard **[3]**, can be deposited in a CMOS-compatible fashion. The fabrication of the device is based on these technologies, including conventional UV photolithography, micromolding and electroplating of ferromagnetic alloys and copper. The fabrication process starts with deposition and patterning of aluminum electrodes on a glass substrate, followed by the spin and cure of a polyimide insulator layer. A sacrificial layer is then deposited and patterned and a photoresist mold is created into which the metallic structure is electroplated. Finally, the resonator is released by removing the mold and the sacrificial layer. Two sets of devices have been fabricated, one made of nickel (80%) - iron (20%) magnetic alloy and the other made of copper (which will ultimately bear subsequently-deposited magnetic material). Figure 3 shows a photograph of a set of completed nickel-iron structures on a glass substrate.

The detailed fabrication sequence of the nickel-iron structure is shown in Figure 4. It starts with the deposition of a 300 Å titanium / 2000 Å aluminum layer on a glass substrate. This metal layer is patterned using photolithography and wet-etched to create the bottom electrode. An insulator (10 µm of PI2611 polyimide) is then spun and cured on top of the electrodes. A seed layer of 200 Å titanium / 3000 Å copper is evaporated on top of the polymer. Photoresist (AZ 4620) is then spun and processed in order to create a 30 µm thick mold. A 5 µm thick copper layer is first electrodeposited in the mold as a sacrificial layer. A 13 µm thick nickel (80%) - iron (20%) magnetic alloy is electroplated on top of the copper to create the resonant structure.

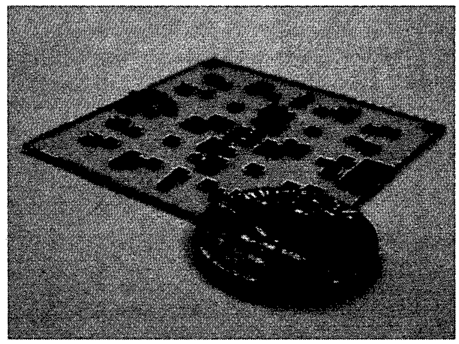

Figure 3. *Photograph of fabricated structures and a quarter. Several device geometries can be seen.*

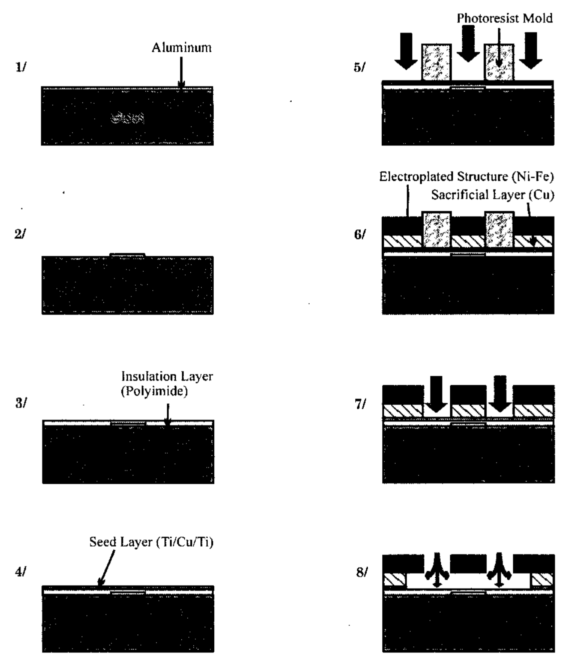

Figure 4. *Fabrication Process: 1/Deposition of the aluminum layer; 2/After patterning of the electrode; 3/Insulation of the electrode; 4/Deposition of seed layer; 5/Creation of micro-mold; 6/Electroplating of the sacrificial layer (Cu) and the structure itself (Ni-Fe); 7/Removal of the mold; 8/ Release of the structure by Cu isotropic etch.*

The photoresist mold is dissolved and the copper sacrificial layer is then selectively and isotropically removed. Since the pads and anchors of the device are larger than the support beams or the resonating portion, no patterning of the sacrificial layer is required as long as the wet etch is stopped as soon as the moving plate is released. The glass substrate is then optionally diced and the devices are tested. Figure 5 shows an optical photomicrograph of a completed nickel-iron resonator.

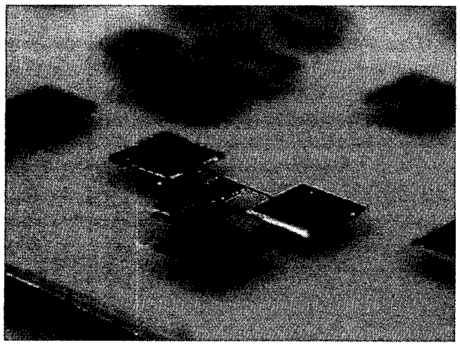

Figure 5. *Photograph of a fabricated Ni-Fe device.*

The fabrication process of the copper structures differs from that of the nickel-iron structures only in the final few steps. As the structures themselves are made of copper, a thick negative photoresist (Futurrex NR9-8000) is used to create the sacrificial layer as well as the mold for the electroplated structure. After the evaporation of the seed layer on the insulator layer, a 60 μm thick photoresist sacrificial layer is spun, cured and patterned and the copper anchors are electroplated. Then, another seed layer of 200 Å titanium / 3000 Å copper is evaporated on top of the sacrificial layer, and another layer of negative photoresist is processed to create the 20 μm thick mold. Copper is then electroplated into the mold to form the resonator. Before releasing the structures (by removing the sacrificial layer and the micro-mold with acetone), a permanent magnet made of ferrite powder suspended in a PI2611 polyimide matrix [3] is screen-printed on the top of the plate. Figure 6 shows a photograph of the copper resonator including a permanent magnet.

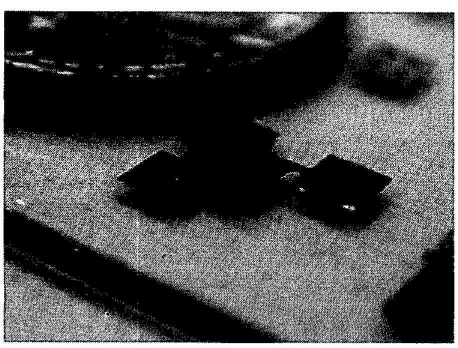

Figure 6. *Photograph of a fabricated Cu device.*

MEASUREMENTS AND RESULTS

Functional nickel-iron devices have been successfully fabricated and tested. Since the as-fabricated device was a one-port resonator, the same two electrodes have been used to excite the resonator as well as to detect the resonant frequency by measuring the capacitance change between the excitation plates as a function of frequency. The read-out circuit shown in Figure 7 was used to sense the change of capacitance of the resonator at its resonant frequency by measuring the displacement current resulting from the difference of capacitance between the sensor and the compensation capacitor. An HP4194A gain-phase analyzer generated the signal that was applied, after amplification, to the resonator. Assessment of the frequency dependence of the magnitude and phase of the resultant displacement current by means of the gain-phase analyzer provided the sensor resonant frequency. Figure 8 shows a typical output of the gain measurement as a function of frequency under zero applied magnetic field. The measured resonant frequency of the device is 1231 Hz.

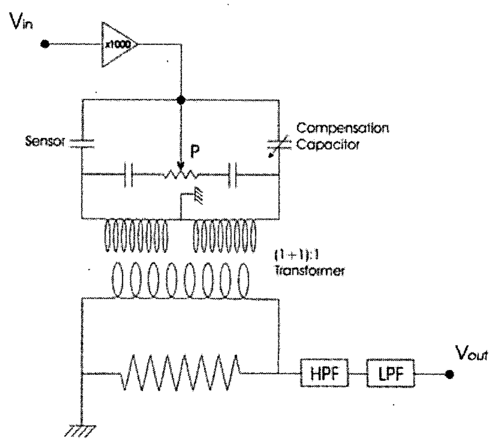

Figure 7. *Schematic of the electronic circuit used to excite the resonator and measure the change of capacitance.*

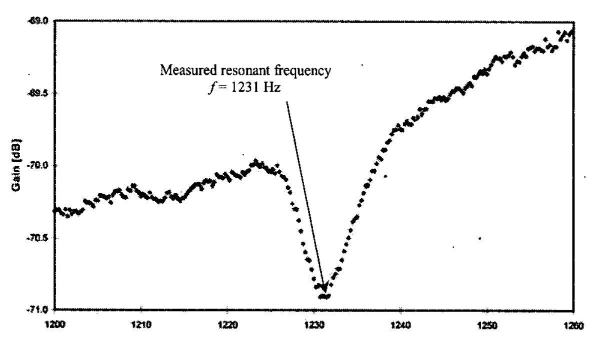

Figure 8. *Gain of the circuit in Figure 7 as a function of the frequency of the actuating signal.*

For magnetic sensing assessment, the device was placed inside an electromagnet that generated the magnetic field in the plane of the resonator. A schematic of the experimental setup is shown in Figure 9. The intensity of the magnetic field, as well as the rotational angle of the sensor relative to the field, could be varied. The applied magnetic field was independently measured by means of a Hall probe integral with the electromagnet.

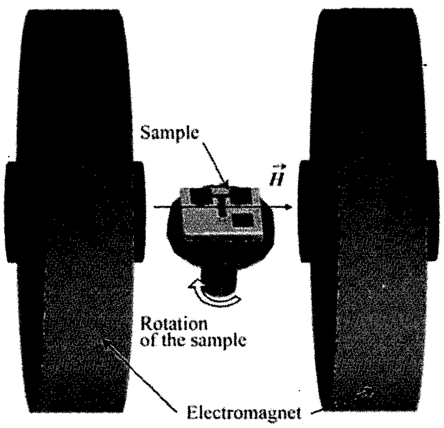

Figure 9. *Schematic of the experimental setup for magnetic sensor assessment.*

The resonant frequency was measured as a function of incident magnetic field amplitude and direction. Figure 10 shows the variation of the resonant frequency of the device (in Hz) as a function of the applied magnetic field (in Oe) when the direction of the field is parallel to the plate.

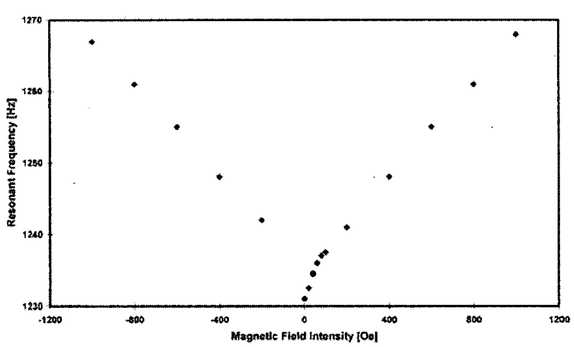

Figure 10. *Resonant frequency of the sensor as a function of the magnetic field intensity (when the direction of the field is parallel to the resonator plate).*

As expected, due to the symmetry of the device, an absolute-value type response is seen, with minimum resonant frequency at the point of zero applied magnetic field. Resolutions of 20 Oersted in amplitude of the field have been achieved.

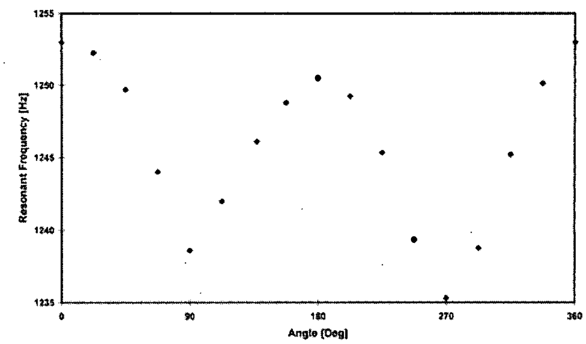

Figure 11. *Resonant frequency of the sensor as a function of the direction of the magnetic field (the intensity of the field is 500 Oe). An angular orientation of zero degrees indicates that the applied magnetic field is parallel to the long axis of the plate.*

The dependence of the resonant frequency on the rotational angle between the applied magnetic field and the device was also studied, and is given in Figure 11 for a magnetic field excitation of 500 Oersted. An angular resolution of 20 degrees in the direction of the field has been achieved.

CONCLUSION

A resonant magnetic field sensor has been designed, fabricated, and tested. The device is made from magnetic materials and the fabrication processes utilized are CMOS-compatible. The device has been successfully demonstrated as both an intensity sensor and an angular sensor. Due to the low power nature of electrostatic resonant excitation, this device may have the potential to sense weak magnetic fields at low power consumption. Performance improvements are expected upon integration of these devices with appropriate circuitry.

REFERENCES

1. J. E. Lenz, "A review of magnetic sensors", *Proceedings of the IEEE*, vol.78, no.6, June 1990, pp.973-89.

2. M. Schneider, R. Castagnetti, M. G. Allen, H. Baltes, "Integrated flux concentrator improves CMOS magnetotransistors", *Proceedings IEEE Micro Electro Mechanical Systems*, Amsterdam, Netherlands 29 Jan.-2 Feb. 1995, pp.151-6.

3. L. K. Lagorce, M. G. Allen, "Magnetic and mechanical properties of micromachined strontium ferrite/polyimide composites", *Journal of Microelectromechanical Systems*, vol.6, no.4, Dec. 1997, pp.307-12.