A Magnetically Excited and Sensed MEMS-Based Resonant Compass

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An all-magnetic micromachined resonant compass was designed, fabricated by a low-temperature CMOS-compatible microfabrication technique, and characterized. The microelectromechanical sensor consists of a silicon micromachined mechanically resonant disk structure bearing a small permanent magnet. The resonant structure is powered using an electromagnetic excitation coil, which requires very little operating voltage. The interaction between the external magnetic field surrounding the sensor (such as the Earth's field) and the permanent magnet generates a rotating torque on the disc, changing the stiffness of the beam and therefore the resonant frequency of the sensor. By monitoring changes of the resonant frequency while changing the orientation of the sensor with respect to the external magnetic field, the direction of the external magnetic field can be determined. The fabricated device can measure the direction of the magnetic field of the Earth with a resolution of 15°, for a 100-mV resonator excitation voltage.

***Index Terms*—Compass, excitation coil, low-voltage actuation, magnetic sensor, magnetically driven, microelectromechanical systems (MEMS), resonant sensor.**

I. Introduction

THERE have been increasing demands for an electronic compass in a variety of mobile electronic systems. An example includes a wristwatch with personal navigation and motion-sensing functionalities added to its original time-keeping function. These applications generally require compact size, low voltage/power operation, and CMOS process compatibility for additional integration with other electronics.

Flux gate magnetometers and Hall-Effect devices are widely used to measure magnetic fields, and they possess both small size and CMOS compatibility. However, the operating power requirements of these devices are typically prohibitive for long-term, portable applications [1]. Recently we proposed a resonant Earth magnetic field sensor by adopting a micromachined polymer epoxy (SU8)-based resonator with a soft magnetic material [2]. The minimum resolution of rotational angle was 45° at 30 μT at an excitation voltage of 10 V with a power consumption of approximately 20 nW [2]. With an angular resolution of 45°, it can clearly distinguish the eight azimuthal directions, thereby functioning as an ultralow-power compass. Although it did demonstrate the capability of measuring the Earth's magnetic field, it required relatively high driving voltage, which is not desirable for portable electronic devices. Fabrication was also challenging as it required a very small, high-aspect-ratio gap for electrostatic excitation.

In this paper, we report an all-magnetic microelectromechanical systems (MEMS)-based resonant compass, driven electromagnetically by an excitation coil and sensed using a Hall-Effect sensor. The magnetic amplification provided by the permanent magnet and resonator allows sensing of the Earth's magnetic field in a compact, low-voltage, and low-power-consumption fashion, making it potentially suitable for portable navigation systems. The silicon substrate enhances the performance of the sensor over previous epoxy resonators in terms of improved mechanical properties such as consistent thermal coefficient, higher frequency operation, and good quality factor as well as CMOS compatibility. In particular, low-voltage electromagnetic actuation does not require a step-up voltage conversion circuit such as electrostatic devices might require.

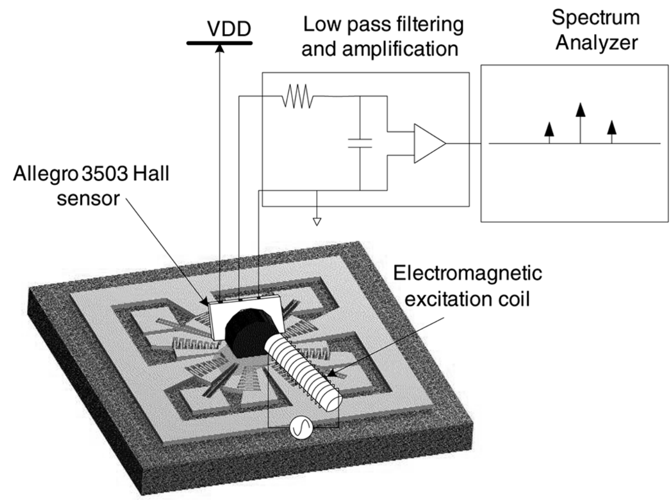

Fig. 1. Schematic of the proposed compass.

II. Micromachined Resonant Compass Design

Fig. 1 shows a schematic of the proposed microcompass. The mechanically resonant structure consists of a permanent magnet supported on a silicon disk by laterally bending silicon beams. The interaction between an external magnetic field $\boldsymbol{H}$ such as the Earth's magnetic field and the magnetization of the permanent magnet $\boldsymbol{M}$ generates a torque which changes the resting rotational angle of the beams and the effective rotational stiffness of the disk [2], resulting in a change of the resonant frequency of the sensor. By monitoring the changes of the resonant frequency while changing the orientation of the sensor with respect to the external magnetic field $\boldsymbol{H}$, the direction of the external magnetic field can be determined as a function of the resonant frequency as described in Fig. 2.

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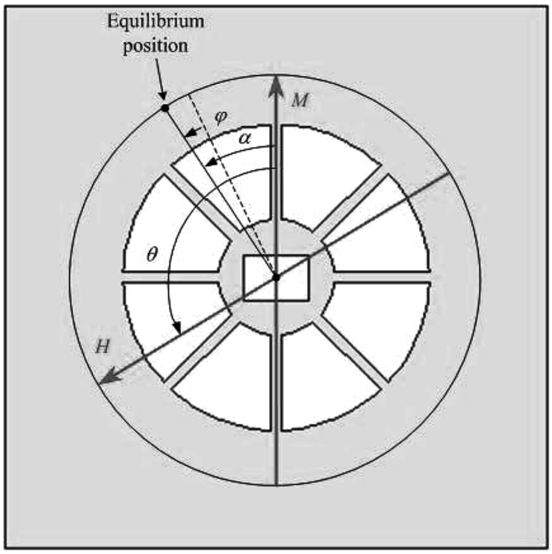


Fig. 2. Principle of operation. M is the magnetization direction of the permanent magnet. H is the direction of the external magnetic field. α is the rotational angle of the permanent magnet generated by rotational torque. ϕ is the small oscillation angle. θ is the angle between the external magnetic field H and the magnetization M of the permanent magnet.

A time-varying magnetic field generated by the excitation coil drives the mechanical resonator bearing the permanent magnet into oscillatory motion. To find the resonant frequency, a Hall-Effect sensor is used to detect the motion of the permanent magnet. The output signal from the Hall-Effect sensor is low-pass filtered to remove high-frequency noise and harmonics, and contains information about the amplitude of the oscillatory motion. This signal is monitored by a spectrum analyzer, and the frequency of excitation is swept until the amplitude signal is maximized. This frequency is taken as the resonant frequency of the compass.

III. Fabrication

The fabrication of the MEMS-based compass includes two major processes: 1) fabrication of mechanical resonator using inductively coupled plasma (ICP) silicon etching and 2) assembly of the permanent magnet, excitation coil, and the Hall-Effect sensing components.

A. Fabrication of Mechanical Resonator

Sensor fabrication is based on a two-mask, two-wafer silicon bulk micromachining process. An insulation oxide layer is thermally grown on a silicon substrate followed by fusion bonding of two wafers [Fig. 3(a) and (b)]. The mechanical resonator is created in the top silicon wafer, and the bottom silicon wafer is used as a handling substrate. A cavity is etched into the backside of the bottom silicon wafer using ICP etching [Fig. 3(c)]. By removing this bottom silicon substrate in the region under the resonator, the device can be released without stiction. The upper silicon wafer is etched by ICP to realize the movable resonant disc structure (containing a recess for the permanent magnet), support beams, and contact electrodes [Fig. 3(d)]. Although not utilized in all-magnetic operation, a comb-drive structure is created simultaneously for optional electrostatic operation of the resonator. The permanent magnet is adhered to the center of the moving disk [Fig. 3(e)], and the external excitation coil and the Hall-Effect sensor are assembled for actuation and sensing of the fabricated device.

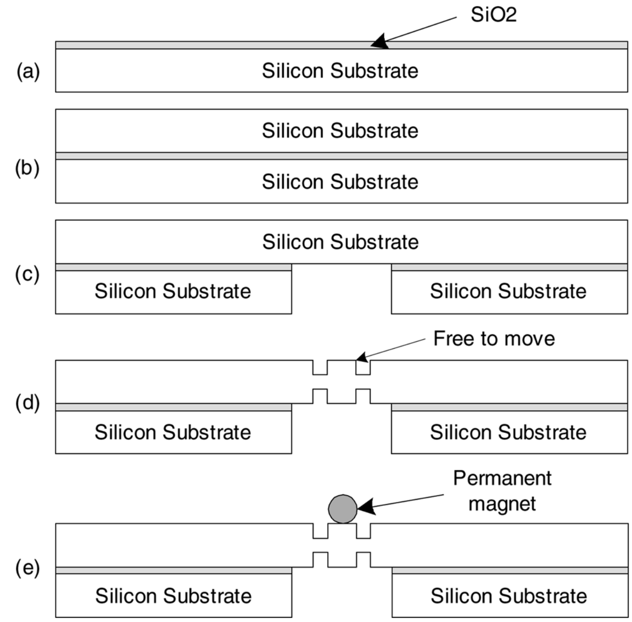
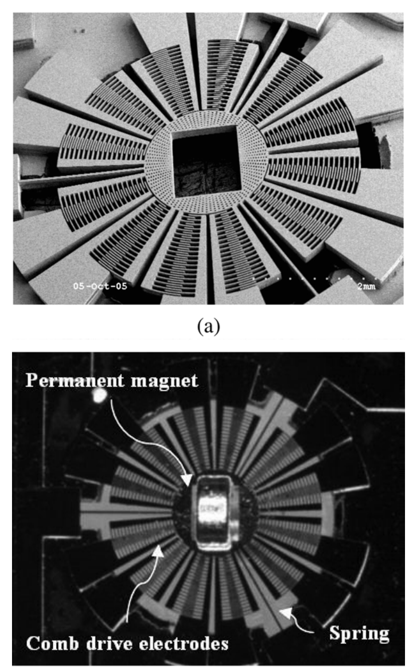


Fig. 3. Fabrication process for the proposed microcompass.



(a)

(b)

Fig. 4. Photograph of (a) mechanical resonator without permanent magnet and (b) with permanent magnet assembled onto it.

B. Assembly of the Excitation Coil and the Hall Sensor

Fig. 4 shows scanning electron microscope (SEM) photographs of the fabricated silicon resonator before [Fig. 4(a)] and after [Fig. 4(b)] mounting a Nd-Fe-B permanent magnet. The silicon resonator is 300 μm in thickness with three beam-spring structures which are 20 μm in width and 2 mm in

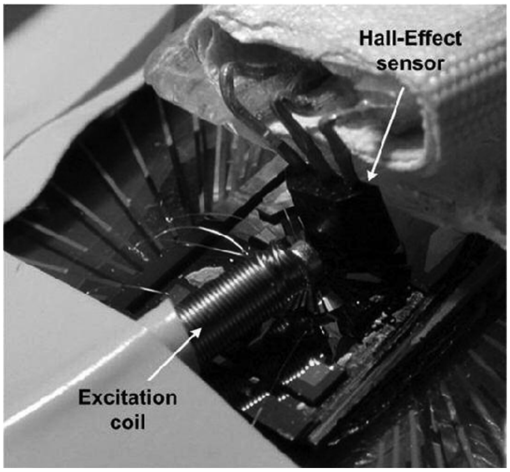


Fig. 5. Completed Earth magnet field sensor with the external excitation coil and the Hall-Effect sensor mounted.

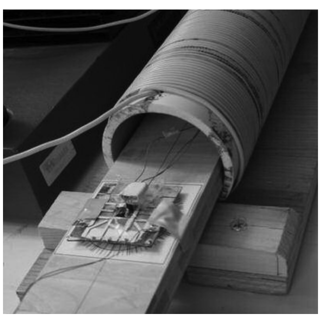


Fig. 6. Measurement setup showing the solenoid coil and the magnetic resonant MEMS sensor.

length. The beam-spring structures mechanically support the attached permanent magnet and provide restoring force to the displacement resulting from interaction between the permanent magnet and the external magnetic field. The gap between the Hall-Effect sensor and the permanent magnet is less than 500 μm to make the Hall-Effect sensor sufficiently sensitive to the vibration of the permanent magnet (Fig. 5). The external excitation coil has 200 turns, a diameter of 1.64 mm, and a length of 16.8 mm, and a resistance of approximately 50 Ω.

IV. Measurement Results and Discussion

Performance of the fabricated compass was measured by rotating the compass in 15° angular increments relative to the direction of either an externally applied uniform magnetic field or the magnetic field of the Earth as shown in Fig. 6. To drive the compass, a sinusoidal driving signal was applied to the coil with a peak-to-peak voltage of 100 mV and the resonant frequency determined as discussed in Section II. Fig. 7 shows the system resonant frequency as a function of orientation angle in two cases: one for the Earth's magnetic field ($\sim$50 μT) and the other for an applied external field of 0.4 mT. The resonant frequency of the system was successfully measured as a function of the direction of the Earth's magnetic field. To obtain error bars on the Earth's field measurement, multiple measurements were performed; the error bars in Fig. 7 show the minimum and max-

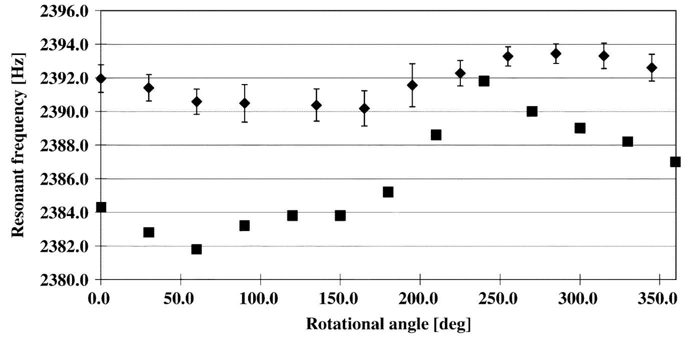


Fig. 7. Resonant frequency as a function of the angle between the permanent magnet orientation and external magnetic field. (Top) Magnetic field of the Earth. (Bottom) External field of 0.4 mT. For the Earth's field measurement, diamond marks represent the mean value, and error bars represent maximum and minimum values from multiple measurements.

imum deviations from the mean during these multiple measurements. As expected, both external fields show a similar trend with a different magnitude of frequency shift. This approach demonstrates that magnetic amplification combined with resonant MEMS structures can be used to sense the direction of the Earth's magnetic field.

V. Conclusion

We have developed a silicon-based MEMS resonant sensor combined with an electromagnetic driving coil for excitation and a Hall-Effect sensor for detection to achieve a low-voltage, low-power, compact, magnetic compass application. The device was successfully tested by low-voltage electromagnetic excitation. Although an azimuthal direction application with 15° resolution was initially targeted, interpolating the data points and utilizing appropriate read-out circuitry can result in improved resolution. The fabricated device demonstrates the potential for measuring the direction of the Earth's magnetic field and possible integration with mobile electronics. The incorporation of a MEMS-based magnetic compass with portable electronics or even wrist watches provides additional customer-demanded features such as personal navigation, and motion-sensing functionalities to these devices.

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