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A MEMS-based magnetic field sensor with simple resonant structure and linear electrical response

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A B S T R A C T

We present a microelectromechanical system (MEMS)-based magnetic field sensor with simple structural configuration, low power consumption, and linear electrical response. This sensor operates with Lorentz force and uses piezoresistive sensing. Its resonant silicon structure consists of a perforated plate (472 × 300 × 15 μm), four flexural beams (18 × 15 × 15 μm), two support beams (60 × 36 × 15 μm), and an aluminum loop (9 × 2 μm cross-section), which are fabricated using a standard bulk micromachining process. The sensor works at its first seesaw resonant frequency without a vacuum packaging. Analytical and finite element method (FEM) models are developed to predict the mechanical behavior of the sensor structure considering the main damping sources. The experimental seesaw resonant frequency and quality factor of the sensor are 100.7 kHz and 419.6, respectively. The sensor has a linear electrical response and its detection range can be easily adjusted. For a DC bias voltage (V_{in}) of 3 V and a bandwidth of 240 Hz, the sensor has sensitivity, resolution, and power consumption of 230 mV·T^{-1}, 2.5 μT, and 12 mW, respectively. This sensor could be used in non-destructive magnetic testing for monitoring geometrical defects and corrosion of ferromagnetic materials.

1. Introduction

Magnetic field sensors have numerous applications now encompassing sensors for the automotive industry, consumer electronics products, telecommunications, military instruments, electronic compass, non-destructive testing, and biomedical sector [1–7]. Resonant magnetic field sensors based on microelectromechanical system (MEMS) have important advantages, including small size, lightweight, low power consumption, and high resolution [8–10]. These sensors use the Lorentz force to detect an external magnetic field. This force is caused by the interaction between an electrical current and a magnetic field, which can modify the displacement of the sensor structure. These changes can be detected using capacitive, piezoresistive, or optical sensing techniques.

Choi et al. [11,12] developed a magnetic field sensing system to detect the direction of the Earth's magnetic field. This system consists of a disk-type silicon resonator, a permanent magnet, excitation and sensing coils, and a magnetic feedback loop. It has low power consumption (138 μW) and it could be used in wristwatch-type personal navigation applications. However, the performance of the system can be affected when the permanent magnet is not exactly adhered at the resonator center. Li et al. [13] presented a three-axis magnetic field sensor composed of a resonant polysilicon structure to measure both out-of-plane and in-plane magnetic field components. It has capacitive sensing, low power consumption (0.58 mW), and sensitivities and resolutions of 12.98 V·T^{-1} and 135 nT·Hz$^{-1/2}$ for the out-of-plane displacement and, 0.78 V·T^{-1} and 445 nT·Hz$^{-1/2}$ for the in-plane field displacement. This sensor however requires vacuum (1 mbar) packaging, and presents a residual motion induced by the electrostatic force, which generates an offset at its electrical response. Wu et al. [14] designed a magnetic field sensor with a square-extensional mode silicon resonator and a planar induction coil. It uses capacitive driving and electromagnetic induction to detect the external magnetic field. This sensor has a sensitivity of 3 mV·T^{-1} and a large output voltage offset (~1.9 mV). Langfelder et al. [15] fabricated a magnetic field sensor formed by capacitive polysilicon plates with high aspect ratio that can have potential applications in inertial measurement units (IMUs). It has a compact structure with a sensitivity of 150 V·T^{-1} at 250 μA of peak driving current. This sensor needs vacuum packaging (1 mbar) and has a non-linear electrical response. Herrera-May et al. [16] reported a resonant magnetic field sensor composed of a silicon plate (400 × 150 × 15 μm), an aluminum loop, and a Wheatstone bridge of four p-type piezoresistors. It has a sensitivity of 403 mV·T^{-1}, a resonant frequency of 136.52 kHz, a quality factor of 842, and a power consumption close to 10 mW. This sensor had a non-linear electrical response with a high offset (close to 4 mV) under

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an external magnetic field. After, Herrera-May et al. [17] designed a magnetic field sensor formed by a seesaw rectangular loop (700 × 400 × 5 μm) of thin silicon beams, a single aluminum coil, and a piezoresistive sensing technique. It presented a resonant frequency of 22.99 kHz, a quality factor of 96.6 at atmospheric pressure, a power consumption close to 16 mW, and a sensitivity of 1.94 $V \cdot T^{-1}$. Also, its electrical response registered a high offset due to residual stresses generated during the fabrication process and the Joule effect caused by the excitation electrical current on its large silicon beams. We present a MEMS-based magnetic field sensor with simple resonant structure and piezoresistive sensing, which has a linear electrical response with reduced offset under different conditions of DC bias voltages and excitation currents. The detection range of this magnetic field sensor can be easily tuned without affecting the linear behavior of its electrical response. In addition, it is small in size, with low power consumption, high resolution, and does not need a vacuum package. Based on these characteristics, the proposed sensor could be used in non-destructive magnetic testing for monitoring geometrical defects and corrosion of ferromagnetic materials.

This paper is organized as follows: Section 2 describes the structural and electrical design of the magnetic field sensor based on analytical and finite element method (FEM) models, which include the main sources of energy dissipation. Section 3 presents the bulk micromachining process of the MEMS sensor. Section 4 reports the results of the experimental mechanical and electrical characterization of the MEMS sensor. Finally, the conclusions and perspectives of this work are drawn in Section 5.

2. Sensor design

In this section, the structural and electrical configuration of the magnetic field sensor is presented. In addition, analytical and FEM models to estimate the mechanical behavior of the sensor are described. These models consider the main damping sources on the resonant structure of the MEMS sensor.

2.1. Structural and electrical configuration

The resonant structure of the magnetic field sensor consists of a perforated silicon plate (472 × 300 × 15 μm), two support beams (60 × 36 × 15 μm), and four flexural beams (18 × 15 × 15 μm), as shown in Fig. 1. The perforated plate has an array of square holes (18 μm width), whose dimensions are shown in Fig. 2. This plate has an aluminum loop (9 × 2 μm cross-section) around its perimeter, which is used to drive the sinusoidal excitation current. The piezoresistive transducer of the sensor is defined by a Wheatstone bridge, which is composed of four p-type piezoresistors. Two of these piezoresistors (named active piezoresistors) are placed on two flexural beams and the two other piezoresistors (called passive piezoresistors) are located on a free-strain substrate area, as shown in Fig. 3a. A schematic of the electrical connection of the four piezoresistors is shown in Fig. 3b.

The interaction between a sinusoidal excitation current (I_e) and an external magnetic field (B_x) parallel to the length of the plate generates a Lorentz force (F_L), which causes a seesaw motion of the silicon plate (see Fig. 4). When the frequency of the sinusoidal current matches with the first seesaw resonant frequency of the sensor structure then it vibrates at resonance. This Lorentz force can be determined as

$$F_L = I_e B_x L_y, \tag{1}$$

with

$$I_e = I_{max} \sin(2\pi f t), \tag{2}$$

where L_y is the width of the silicon plate, t is the time, and I_{max} is the maximum value of the sinusoidal current, t and f are the time and frequency, respectively.

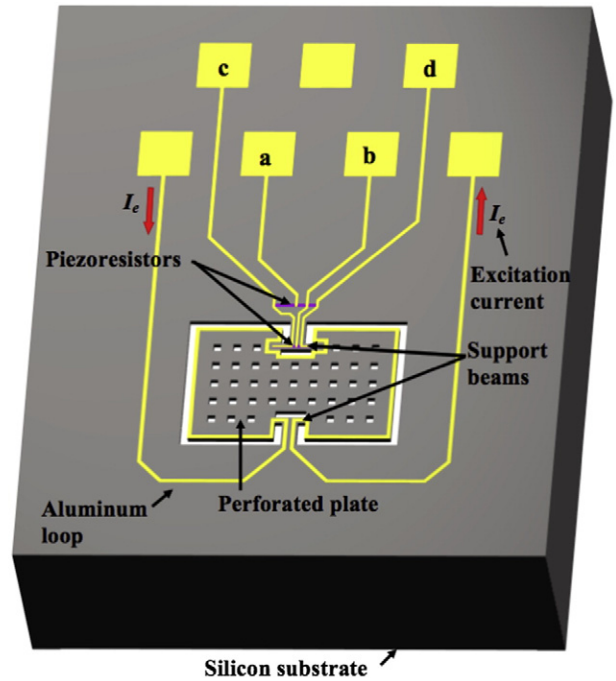

Fig. 1. A 3D schematic view of the magnetic field sensor.

Considering a sinusoidal current and a constant magnetic field then the Lorentz force F_L will be a sinusoidal function depending of the time.

The Lorentz force causes a bending on the flexural beams that induces a bending stress (σ_b) on each active piezoresistor. The magnitude of this stress changes along the piezoresistor length, which can reach maximum and minimum values on the fixed and free ends of each piezoresistor. This fixed end is placed in the join of the piezoresistor with the support beam. Therefore, we use a mean stress (σ_{bm}) value on the piezoresistor that considers the average of its maximum and minimum stress (σ_{bmax} and σ_{bmin}), respectively.

This mean stress causes a variation (ΔR_i) of the initial resistance (R_i) of each active piezoresistor, which can be expressed as

$$\Delta R_i = \pi_l \sigma_{bm} R_i, \tag{3}$$

$$\sigma_{bm} = \frac{\sigma_{b\max} + \sigma_{b\min}}{2}, \tag{4}$$

where π_l is longitudinal piezoresistive coefficient.

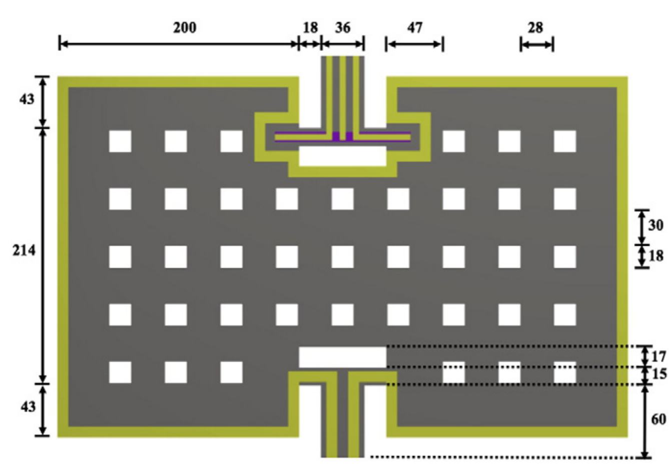

Fig. 2. Dimensions (μm) of the sensor-resonant structure.