Sensors and Actuators A 211 (2014) 145–152

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

Frequency-based magnetic field sensing using Lorentz force axial strain modulation in a double-ended tuning fork☆

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ARTICLE INFO

Article history:
Received 15 September 2013
Received in revised form 13 January 2014
Accepted 13 January 2014
Available online 22 January 2014

Keywords:
MEMS
Resonator
Resonant microsensors
Magnetic field sensors
Quality factor

ABSTRACT

This paper presents a frequency-based silicon micromechanical resonant magnetic field sensor with a high quality factor by using a double-ended tuning fork (DETF). The sensing mechanism is based on the detection of resonant frequency shift of the DETF resonator due to the exertion of a Lorentz force generated under the presence of a magnetic field. By designing the strain-sensitive resonator as a DETF, we are able to achieve a quality factor (Q) of over 100,000 for the anti-phase mode. An analytical and finite element (FE) model describing the sensitivity of the magnetic field sensor is presented. Good agreement between the FE model and measurements is obtained, which are close to the analytical model estimates. Through more careful choice of the device physical dimensions, we show that the current sensitivity of 215.74 ppm/T can be improved tenfold. Given this level of field sensitivity, we envisage that magnetic noise floor levels in the μT range are achievable using the device concepts described in this paper.

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1. Introduction

Magnetic field sensors are widely used in various modern industrial applications, such as magnetic storage, navigation systems and position sensing [1]. The superconducting quantum interference device (SQUID) for example is capable of detecting weak magnetic fields down to femto-tesla (fT) precision [2]. As such, SQUIDs to date represent the highest end among the spectrum of different kinds of magnetic field sensors in terms of resolution. However, their high cost and requirement for low temperature operation conditions are some drawbacks that prevent their use in more ubiquitous applications. At the other end of the performance-price spectrum are Hall-effect sensors, which belong to a class of more mainstream magnetic field sensors. Hall-effect sensors are characterized by low cost with the tradeoff of poorer field resolution which improves at the expense of increasing their power consumption [3]. With the development of silicon micromachining technology, micromechanical magnetic field sensors with comparatively lower power consumption, improved resolution and reduced barriers to CMOS integration have emerged as attractive device implementations.

Various micromechanical magnetic field sensors have been developed [4–8]. Most of these designs rely on the effect of an associated Lorentz force on the resonant structure as a means to detect a desired magnetic field. The device can be designed in such a way that the amplitude of the resonator's oscillation is desirably sensitive to perturbations by the Lorentz force. This change in amplitude can in turn be detected electronically as a voltage output via capacitive plates or fingers on the device [9,10]. In this paper, we refer to this class of devices as amplitude-based resonant magnetic field sensors. Alternatively, the device can be designed in another way such that the resonant frequency (instead of the amplitude) of the oscillation is sensitive to the action of the induced Lorentz force. The Lorentz force, and thus also the related magnetic field to be measured, is thus monitored by tracking the shifts in the oscillation frequency of the resonator [11,12]. We here refer to this class of devices as frequency-based resonant magnetic field sensors.

For the frequency-based magnetic field sensor, the sensitivity is determined by the geometry and material properties of the device. Although the sensitivity does not benefit from having higher Q, a higher Q is nonetheless desirable as it provides for larger output signal by increasing the displacement amplitude, leading to better signal to noise ratio and also higher resolution by decreasing the short-term frequency noise in a closed-loop implementation. Previous reports on frequency-based magnetic field sensors also mention the importance of Q in enhancing performance, but did place much emphasis on implementing designs with high Q.

☆ Selected Paper based on the paper presented at The 17th International Conference on Solid-State Sensors, Actuators and Microsystems, June 16–20, 2013, Barcelona, Spain.

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0924-4247/$ – see front matter © 2014 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.sna.2014.01.022

Q is largely dependent on the structural design, and can thus be enhanced through choice of geometry and physical dimensions [13].

In this paper, we propose a frequency-based readout magnetic field sensor shaped in the form of a double-ended tuning fork (DETF). Being a frequency-based sensor, its nominal resonant frequency is perturbed due to the action of a magnetic-field-induced Lorentz force on the micromechanical resonator. By driving the DETF in the anti-phase vibration mode, we can obtain a high quality factor (100,000), which is beneficial for improving the resolution of the sensor. Next in Section 2, more details on the design of our fabricated device are presented along with a finite-element model. An analytical model is derived to describe the effect of the Lorentz force on the resonant frequency, which defines the sensitivity of the magnetic field sensor. To provide a reference to compare against the DETF, another device design based on parallel beam resonators is described. Likewise, both the analytical and finite element (FE) models are presented. In Section 3, experimental results from the characterization of these device concepts that have been fabricated in a silicon-on-insulator (SOI) micromachining process are presented. These results are compared against predictions from the analytical and FE models, where good agreement is shown. In Section 4, possible reasons for mismatches between the models and measurement results are discussed and verified. We also discuss how the sensitivity of the proposed frequency-based DETF resonant magnetic field sensor can be further enhanced through a more favorable choice of device physical dimensions. This will help illustrate the potential limits of the device concepts presented herein.

2. Design and modeling of the device

2.1. DETF frequency-based resonant magnetic field sensor

The schematic of the device is shown in Fig. 1. The central part of the sensor is a DETF resonator formed by two parallel beams or tines (600 μm long and 8 μm wide), clamped on both ends. Two rows (instead of just a single row) of comb drives are attached to each tine to increase the electromechanical coupling area. As illustrated in Fig. 1, a set of comb drive electrodes on one of the tines is used for actuation while another set of comb drive electrodes on the other tine is used for sensing the motional current. The electrostatic force drives the DETF to vibrate in the anti-phase mode within the plane of fabrication, which is depicted in Fig. 1. The anti-phase vibration mode has the benefit of realizing higher Q

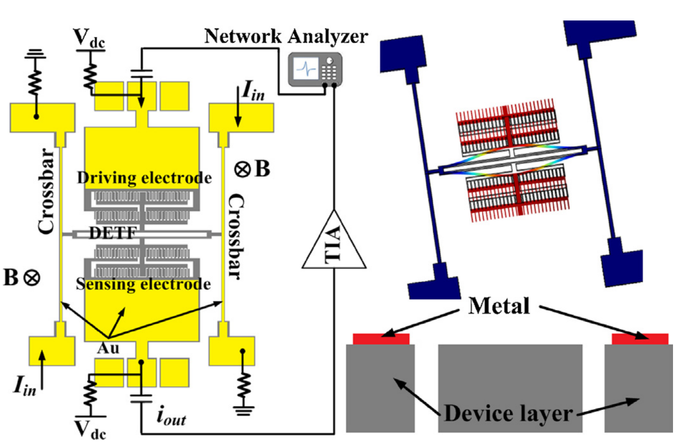

Fig. 1. Schematic of the DETF resonator magnetic field sensor with biasing configuration including transimpedance amplifier (TIA) at the sensing port. The right hand side shows the eigenmode simulation of the anti-phase mode of the DETF and a cross section schematic view of the device.

by merit of having mutual cancellation of opposing stress waves in the coupling-ends of the tines [14]. Changing the overlap between the comb fingers produces a motional current at the sensing electrode which is then further enlarged by a transimpedance amplifier. Having two rows of comb drives instead of one helps improve the signal to noise ratio of the output motional current. In addition to the anti-phase mode, the in-phase mode will also be excited and detected by the abovementioned electrical probing configuration, though the associated Q is expected to be much lower.

As shown in Fig. 1, the longitudinal axis of the DETF tines lies perpendicular to a pair of suspended crossbars, which also form the clamping boundary condition of the tines. Each of the crossbars is anchored on either sides, across which a DC bias current (I_{in}) is applied. The current running through the crossbars will heat up the structure, leading to a thermally-induced frequency shift due to softening of the material. To minimize the effect of joule heating, a 500 nm metal stack of chromium and gold was deposited on the silicon device layer (only along the crossbars) to reduce the resistance across the crossbars as indicated in Fig. 1.

A Lorentz force is generated normal to the crossbars in the plane of fabrication when I_{in} is passed through the crossbar under the presence of an out-of-plane magnetic field (B). The current in the crossbars on each end are running opposite to each other such that the induced Lorentz forces will axially stretch or compress the vibrating tines. This results in a corresponding upward or downward shift in the resonant frequency from which the value of the magnetic field (B) can be inferred. We model this axial-strain frequency-tuning effect in the following.

The resonant frequency of a generic device vibrating in the fundamental lateral mode is given by:

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{k_b}{M_{eff}}} \tag{1}$$

where k_b is the spring constant and M_{eff} is the effective mass of the device under vibration. By simplifying the vibration of tines to that of a doubly-clamped beam under axial load, k_b can be approximately expressed as [15]

$$k_b = \frac{4EI\gamma^3}{\gamma L - 4\tanh\left(\gamma L/4\right)} \tag{2}$$

where E is the Young's modulus of single crystal silicon, I is the moment of area of the tines, and L represents the length of each tine. Here the parameter γ is defined as $\gamma^2 = F/EI$ [11], where F is the axial force applied to the tines. Given a width W and thickness H, for in-plane vibrations, the moment of area is given by $I = HW^3/12$. Expanding Eq. (2) as a Taylor series yields

$$\begin{aligned} k_b(\gamma) &= \frac{192EI}{L^3} + \frac{24EI}{5L}\gamma^2 - \frac{EIL}{700}\gamma^4 + O\left(\gamma^6\right) \\ &\approx \frac{192EI}{L^3}\left(1 + \frac{L^2}{40}\gamma^2\right) \end{aligned} \tag{3}$$

Substituting Eq. (2) into Eq. (1), we obtain

$$f = f_0\sqrt{1 + \frac{0.3L^2}{EHW^3}F} \tag{4}$$

Expanding Eq. (4) once again as a Taylor series, the frequency shift Δf as a function of Lorentz force is given by

$$\Delta f = f_0\left(\frac{0.15L^2}{EHW^3}\right)F \tag{5}$$

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