Sensitivity Enhancement of Lorentz Force MEMS Resonant Magnetometers via Internal Thermal-Piezoresistive Amplification

Emad Mehdizadeh, *Student Member, IEEE*, Varun Kumar, and Siavash Pourkamali, *Member, IEEE*

***Abstract*— This letter presents sensitivity enhancement of MEMS resonant magnetometers using the thermal-piezoresistive internal amplification effect in silicon microstructures. Preliminary results show up to $\sim$15X improvement in sensitivity per bias current for a resonator operated as a Lorentz force magnetometer. Magnetometer sensitivity figure-of-merit, defined as sensitivity (mV/T) over sensor dc bias current, has increased from 0.29 Ω/T(mV/Tesla/mA) to 4.22 Ω/T via internal thermal-piezoresistive amplification that also led to resonator effective quality factor (*Q*) increasing from its intrinsic value of 1140 to 16 900 (in air). Previous work on the thermal-piezoresistive amplification effect suggests that amplification factors up to 3–4 orders of magnitude can be achieved using optimally designed structures, which can lead to ultra-high sensitivities for the presented sensors. It should be noted that the main focus of this letter is not to demonstrate a highly sensitive magnetometer, but rather to demonstrate the ability to improve magnetometer sensitivity as the resonator internal *Q*-amplification kicks-in. Although the resonant structure in this letter has not been optimized to operate as a magnetometer, sensitivities as high as 262 mV/T in air (minimum detectable field in the μT range) have been achieved.**

***Index Terms*— Internal thermal-piezoresistive *Q*-amplification, Lorentz force, MEMS resonant magnetometer, sensitivity enhancement.**

I. INTRODUCTION

MAGNETIC field sensors have numerous industrial and biomedical applications including magnetic memory readout, magnetic compass, mineral prospecting, and brain function mapping [2]. With their small size, low-cost and simplicity, MEMS magnetometers offer an attractive solution for many applications. Available MEMS magnetometers however cannot compete with some of the conventional technologies such as superconducting quantum interference device (SQUID) and search coils in applications requiring ultra-high resolution (in the few pT and fT range) [3]. Among MEMS magnetometers Lorentz force resonant magnetometers offer desirable features such as amplification of the displacement resulting from Lorentz force by the *Q* factor of the resonant structure, and operation at frequencies in the tens to hundreds of kHz that helps significantly suppress the low frequency noise [4]–[6]. However, with the typical MEMS resonator quality factors in the tens to hundreds in air, or tens of thousands under vacuum, sensitivities are limited to several hundred mV/T, with minimum detectable fields in the μT and nT (5–6 orders of magnitude less sensitive than SQUIDs). Parametric amplification has been used to demonstrate close to 2 orders of magnitude improvement in sensitivity over linear operation for similar resonant Lorentz force magnetometers. Increasing the force-to-displacement transduction of a resonant sensor by modulating the device's spring constant at twice the natural frequency, the sensitivity of a Lorentz force magnetometer was parametrically amplified by 82.5X [6]. Other attempts have been made to increase sensitivity of MEMS resonant magnetometers using novel topologies [7], and exploiting the effect of nonlinearity on sensitivity [8]. In this letter, it is demonstrated how the internal interactions between piezoresistivity and thermal effects in micromechanical silicon resonant structures [1] can improve the sensitivity of Lorentz force magnetometers by increasing the resonator vibration amplitude for the same input Lorentz force.

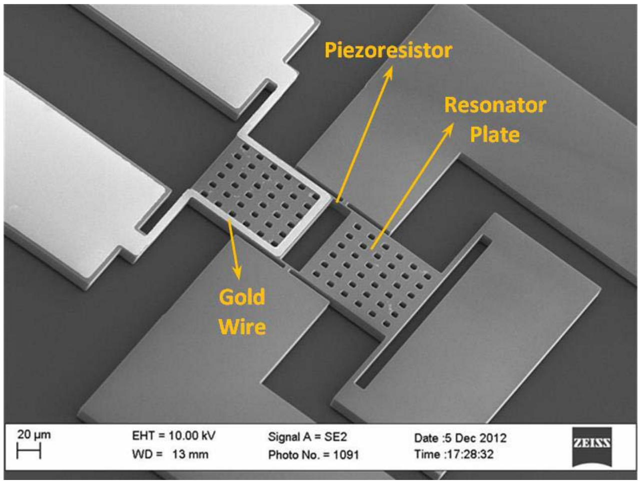

Fig. 1. SEM view of the 2.6 MHz 10 µm-thick dual plate in-plane resonator with integrated gold trace.

II. DEVICE DESCRIPTION

The dual-plate silicon micro-resonator of Fig. 1, with an integrated gold trace (7 μm wide, 200 nm thick) on one of its plates, was fabricated on a low-resistivity n-type Silicon-On-Insulator (SOI) substrate. The SOI substrate device and buried oxide layer thicknesses are 10 μm and 2 μm, respectively.

Manuscript received November 8, 2013; revised November 25, 2013; accepted November 26, 2013. Date of publication December 11, 2013; date of current version January 23, 2014. This work was supported by the National Science Foundation under ECCS Award 1345161. The review of this letter was arranged by Editor Massood Tabib-Azar.

The authors are with the Department of Electrical Engineering, University of Texas at Dallas, Richardson, TX 75080 USA (e-mail: emad.mehdizadeh@utdallas.edu).

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Digital Object Identifier 10.1109/LED.2013.2293349

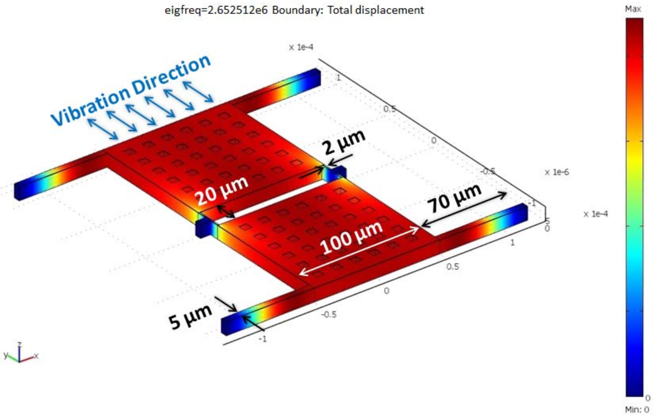

Fig. 2. COMSOL finite-element modal analysis of the in-plane extensional resonant mode of a dual-plate 2.6 MHz resonator.

The two narrow beams in the middle of the structure, connecting the resonator plates, act as piezoresistors undergoing periodic tensile and compressive stress when the resonator vibrates in its in-plane resonant mode. Passing an ac current at the natural resonance frequency of the resonator through the gold trace, in presence of a perpendicular magnetic field, results in a Lorentz force that can actuate the resonator in its in-plane extensional mode (Fig. 2). In this mode the resonator plates move back and forth in opposite directions. The resulting magnetically-induced mechanical vibration amplitude is amplified by the mechanical Q factor of the resonator. The alternating stress in piezoresistors leads to increased fluctuations in their electrical resistance. When biased with a dc current, such resistance fluctuations modulate the voltage across the device terminals resulting in an ac voltage used for detecting the vibration amplitude.

III. INTERNAL AMPLIFICATION

Q-amplification of thermally actuated micro-resonators, resulting from interaction of thermal-expansion forces and piezoresistivity of the thermal actuator elements has been previously demonstrated [1]. As an example, for a self-Q-amplifying 18 MHz thermally actuated resonator, the effective Q increased from the intrinsic value of 2 000 to 2 100 000 as the resonator bias current increased from 6.009 mA to 6.200 mA [1]. This effect can be explained by the fact that as the resonator vibrates, the resulting stress in the thermal actuator beams modulates their electrical resistance due to piezoresistivity. Modulation of the electrical resistance, while connected to a constant current or voltage source, modulates the ohmic loss and therefore Joule heating in the actuators. This leads to an extra thermal actuation force component (Fig. 3) which, in case of structural materials with negative piezoresistive coefficient e.g. n-type single-crystalline silicon structures, amplifies the resonator vibration amplitude at resonance frequency. This results in an electronic amplification of the resonator quality factor to effective resonator Q values potentially much higher than the mechanical limits imposed by different loss mechanisms such as air damping and thermoelastic dissipation. In effect, the resonator absorbs energy from the DC source and uses it to partially compensate the mechanical losses that limit the Q. Increasing the piezoresistor bias current increases the absorbed energy leading to higher effective Q values and eventually even self-sustained oscillation of the resonator (absorbed energy larger or equal to mechanical losses). In this letter, the same principle has been utilized to amplify the displacement resulting from Lorentz actuation force (Fig. 3).

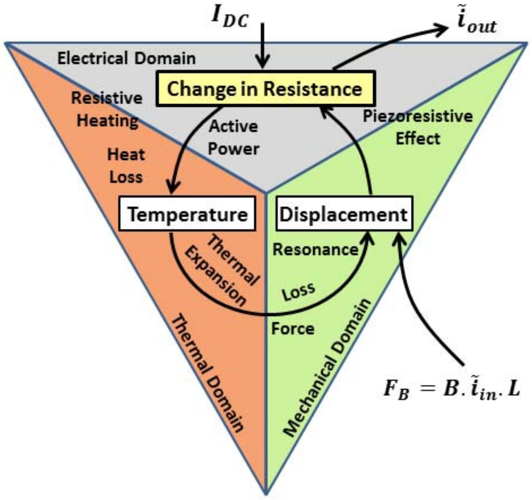

Fig. 3. Schematic diagram of mechanisms in a Lorentz resonant magnetometer with internal thermal-piezoresistive amplification.

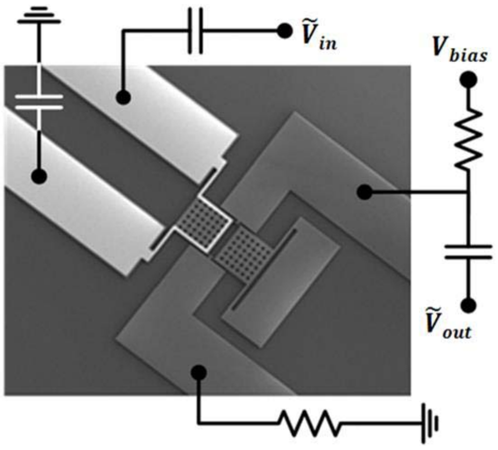

Fig. 4. Schematic view of the test setup electrical connections.

IV. MEASUREMENT RESULTS AND DISCUSSION

To test the resonator of Fig. 1 as a magnetometer, RF output of the network analyzer was applied across the gold trace for magnetic actuation, while DC current passing through the silicon beams allows piezoresistive readout of resonance (Fig. 4). The resonator frequency responses were obtained by placing a magnet at different distances from the device with piezoresistor bias current increasing step by step. Fig. 5 shows frequency responses at maximum field intensity of 0.4T for different piezoresistor bias currents showing how the output signal amplitude increases by increasing the bias current. Fig. 6 illustrates the measured output voltage amplitudes at resonance versus the magnetic field intensity for different bias currents. The increase in output amplitudes (sensitivity) at

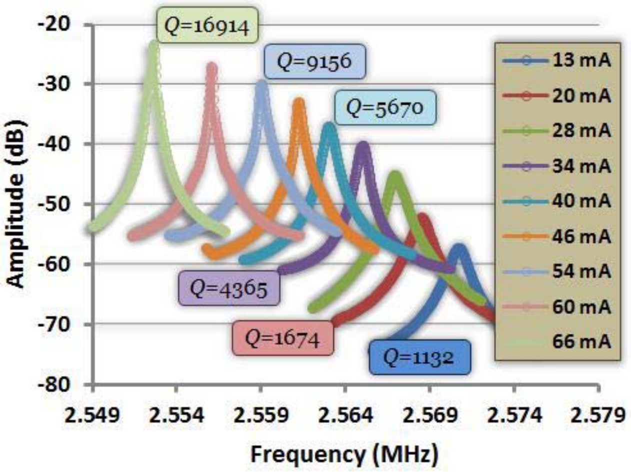

Fig. 5. Resonant responses of the device of Fig. 1 with different bias currents under constant magnetic field intensity of 0.4T showing resonance Q and amplitude increase under higher bias currents.

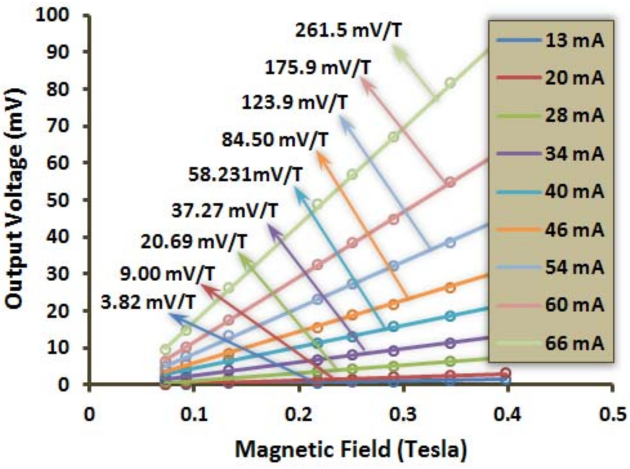

Fig. 6. Output voltage amplitude of the resonator versus the magnetic field intensity for different bias currents.

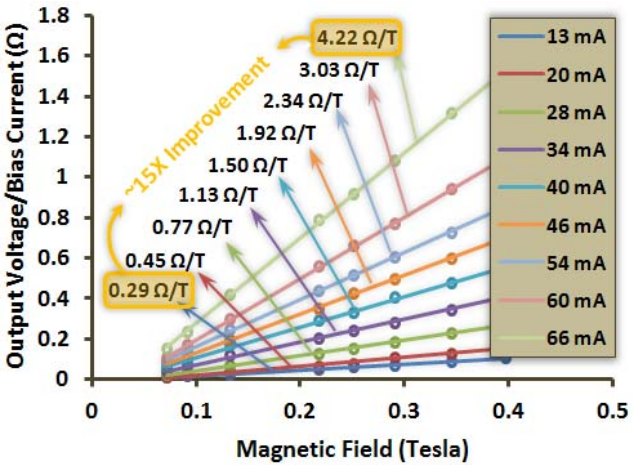

Fig. 7. Output voltage amplitudes divided by the associated bias currents versus magnetic field intensity for different bias currents. The change in slope of the lines for higher bias currents shows the effect of Q-amplification on magnetometer sensitivity.

higher currents is partly due to higher piezoresistive sensitivity (higher piezoresistor bias current) and partly due to resonator Q-factor (vibration amplitude) amplification. To demonstrate the effect of Q-amplification alone, sensitivity figure of merit (FOMS), defined as sensitivity divided by the bias current, is shown in Fig. 7 by the slope of the lines at different bias currents. Fig. 7 clearly shows that FOMS increases proportional to the resonator effective Q-factor as the bias current increases.

It should be noted that although the thermo-mechanical noise will also be amplified due to internal amplification, only noise components at close vicinity of the resonance frequency will be amplified by a factor close to the sensor output signal. Therefore, overall signal to noise ratio of the sensor is expected to improve. Furthermore, even if there is no net increase in overall signal to noise ratio of the MEMS sensor due to the internal amplification, a sensor with higher sensitivity (internally amplified output) is still likely to offer lower detection limits. This is considering the fact that in most cases the electronic noise from the readout circuitry is the dominant or a significant portion of the overall sensor output noise, and lower electronic amplification gain required to read the output of a more sensitive MEMS sensor lowers the added electronic noise.

V. CONCLUSION

It was demonstrated that the internal thermo-electromechanical interactions in microscale resonant structures made of n-type silicon could increase sensitivity of MEMS Lorentz magnetometers. Up to ~15X improvement in sensitivity of a magnetometer with piezoresistive readout was demonstrated using this effect. According to previously published results [1], 3–4 orders of magnitude amplification in sensitivity of such magnetometers can be achieved by thinning down the actuator beams and using one actuator beam instead of two that will facilitate reaching significant Q-amplifications at lower bias currents before the device reaches very high temperatures and its breaking point [1].

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