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Piezoelectric-on-silicon Lorentz force magnetometers based on radial contour mode disk resonators

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ABSTRACT

In this paper, we realize two unique design topologies for Lorentz force magnetometers (LFMs) based on radial contour (RC) mode piezoelectric-on-silicon disk resonators for the detection of out-of-plane magnetic fields (i.e. normal to the plane of fabrication). The proposed topologies take advantage of the strong electromechanical coupling from the piezoelectric Aluminum Nitride (AlN) layer to enhance the sensitivity of the devices while operating under ambient pressure, thus avoiding the need for vacuum encapsulation. Compared to previously reported modes, we show that RC mode provides a higher coupling efficiency. This ultimately leads to higher responsivity (defined here as the ratio of the pre-amplified output resonant current to the external magnetic field strength, normalized over the excitation current applied) compared to other modes previously reported. Having shown the advantages of the disk LFM, we then extend the advantages of a single disk LFM by mechanically coupling two disk resonators to increase the responsivity. We show that the quality (Q) factor, which determines the responsivity at resonance, does not degrade substantially by mechanically coupling the disks. The responsivity of our coupled disk LFM (21.20 ppm/mT) is 8 times higher compared to a state of art vacuum sealed LFM based on capacitive readout, but without the contraint of requiring vacuum.

1. Introduction

Electronic compasses are a part of the navigation apparatus in smart phones today, mainly comprising Hall-effect sensors [1,2] and magnetoresistive (MR) sensors [3]. Silicon (Si) Hall-effect sensors provide a low-cost solution with the additional benefit of CMOS-compatibility in contrast to MR sensors that are based on magnetic materials [4]. But Hall-effect sensors are known for their higher power consumption as a trade-off for improving resolution. More recently, microelectromechanical systems (MEMS) Lorentz force magnetometers (LFMs) [4–11] have been proposed as a potential alternative to Hall-effect and MR sensors towards low-cost and low-power electronic compasses. In addition to low power consumption, small form factor and improved resolution, the CMOS compatibility of MEMS processing allows for highly-integrated multi-degree of freedom (DOF) inertial measurement units (IMUs) by adding to existing accelerometers and gyroscopes [9].

Most of the previously reported MEMS LFMs are based on capacitive readout, and these typically are operated at resonance to maximize the output response. As such, a high Q factor is desired to maximize the amplitude response at resonance, thus these capacitive LFMs typically employ vacuum packaging [4–6] to enhance the Q factors. The high Q factor helps to compensate for the rather poor electromechanical coupling from capacitive transducers. Besides, frequency-modulated (FM) LFMs also require high Q factor to improve the resolution of the resonant peak detection [7,8]. While piezoresistive readout MEMS LFMs provide strong electromechanical coupling to allow operation in air [10,11], the DC bias current required in such a set-up increases the overall power consumption of the device while also adding thermal noise.

In this paper, we present a piezoelectric-on-silicon MEMS LFM based on a fundamental radial contour (RC) vibration mode disk resonator. We explore both a single disk as well as a mechanically-coupled pair of disks. We apply piezoelectric transduction as an alternative to existing capacitive and piezoresistive sensing approaches for the detection of out-of-plane (i.e. z-axis) magnetic fields. Table 1 compares the performances of our fabricated sensors with the state-of-art capacitive and piezoresistive readout MEMS LFMs. The comparison is made in terms of the responsivity, defined here as the output motional current at resonance over the applied

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Table 1
Summary of previously reported AM mode MEMS LFMs for detecting out-of-plane (i.e. normal to the plane of fabrication) magnetic fields.

MEMS LFMs	Transduction methods	Resonant frequency (unit)	Responsivity (ppm/mT)	Operating condition	Q factor
Coupled disk pair	Piezoelectric	6.38 (MHz)	21.20	Air	1732
Single disk resonator	Piezoelectric	6.32 (MHz)	12.55	Air	1946
M. Li et al. [4]	Capacitive	20.55 (kHz)	2.45	Vacuum (0.75 Torr)	1400
V. T. Rouf et al. [9]	Capacitive	40.5 (kHz)	0.05	Vacuum (15 Torr)	110
E. Mehdizadeh et al. [10]	Piezoresistive	2.6 (MHz)	9	Air	1674
V. Kumar et al. [11]	Piezoresistive	400 (kHz)	53.08×10^6	Air	10,000

Note: As the resonant frequencies of the various MEMS LFMs reported in the literature span over two orders of magnitude, we have quoted their units in brackets.

magnetic field strength per unit excitation current. Therefore, the responsivity here is expressed in terms of ppm/mT (μA/mT A). Normalizing the responsivity with respect to the input excitation current provides a more direct comparison as the Lorentz force acting on a given LFM scales proportionally with the input excitation current. The devices proposed herein are based on the principle of amplitude modulation (AM), where the vibration amplitude of the resonators was modulated under the action of Lorentz force. On a side note, piezoelectric AlN resonators have been used previously to implement magnetic sensor but based on a frequency modulation (FM) scheme by adopting a magnetostrictive material that strains the resonator to shift its resonant frequency in the presence of a magnetic field [12].

While a proof-of-concept LFM based on an AlN-on-Si RC mode disk was previously reported in [13], we here describe a modified AlN-on-Si RC mode disk LFM with an enhanced Q factor. In addition to the RC mode disk LFM, we also present an LFM based on a mechanically-coupled disk resonator pair. As seen from Table 1, the responsivity of the proposed coupled disk resonator pair (tested in atmospheric pressure) is 8 times of a vacuum-sealed capacitive MEMS LFM reported in [4]. Its Q factor in air is also 20% higher than the vacuum-sealed device in [4]. In the case of capacitive MEMS LFMs, we see that reducing the level of vacuum from 0.75 Torr to 15 Torr reduces the responsivity by 49 times due mostly to the notable drop in Q factor from 1400 to 110 [9]. Apart from capacitive LFMs, piezoresistive LFMs have also been demonstrated in [10,11] with enhanced responsivity, with the tradeoff of additional power consumption required to bias the piezoresistors. Moreover, the single disk and coupled disk LFMs illustrated herein mark the best responsivities and Q factors compared to our previously reported width-extensional mode LFM [14] and square-extensional mode LFM [15]. This is due to the higher transduction factor associated with the RC mode compared to the other modes we have reported previously. The coupled disk LFM also possesses a lower offset compared to the single disk LFM as well as our previously reported amplitude modulated AlN-on-Si LFMs.

As mentioned earlier, the single disk resonator presented herein has been redesigned from our initial results presented in [13] to enhance performance notably with almost a doubling of the sensitivity (despite having halved the area of the output patch electrode) due to an almost threefold increase in Q factor. In addition, we also present herein an approximate-analytical model for the device, which is described in the next section along with the coupled disk resonator pair LFM. The aim of presenting this approximate-analytical model is to provide insight into the dependence of key parameters on the material properties and the dimensions of the devices.

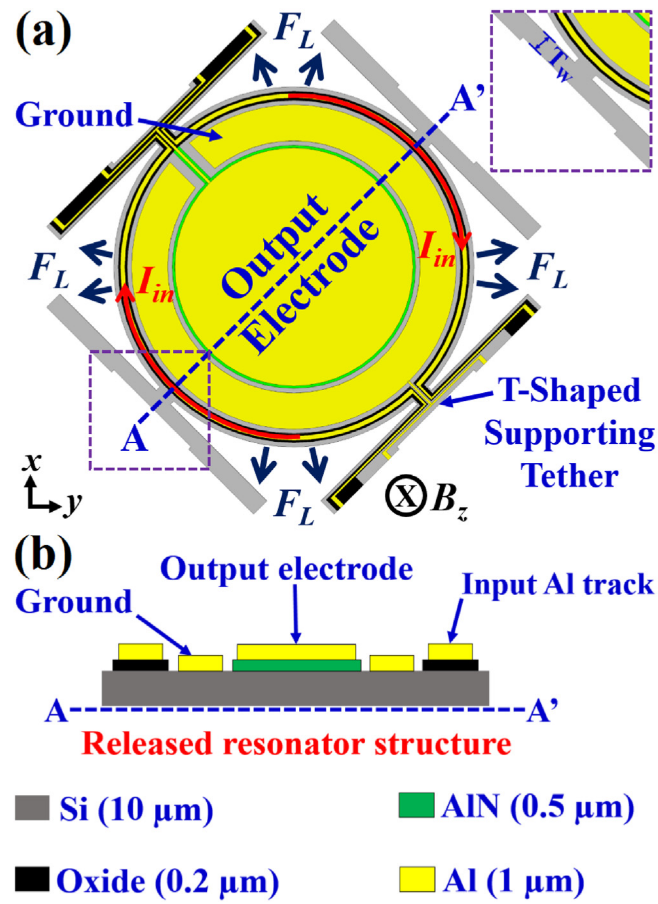

Fig. 1. (a) Top view schematic of the radial contour mode AlN-on-Si single disk MEMS LFM. I_{in} is the input excitation AC current, B_z is the out-of-plane (z-axis) magnetic field, and F_L is the radially-directed Lorentz force acting on the device. The width of the T-shaped tether is denoted by T_W as shown in the inset; (b) Side view schematic as seen across line section AA' of Fig. 1a where the thicknesses of the respective layers are quoted in the brackets.

2. Device description and modeling

2.1. Single disk LFM

2.1.1. Device description

A top view schematic of the radial contour (RC) disk AlN-on-Si MEMS LFM is depicted in Fig. 1a. As shown in Fig. 1a, the device comprises a free-standing disk with a radius of 400 μm, supported by four T-shaped tethers clamped along the circumference of the disk. An input excitation current (I_{in}) runs along the circumference of the disk through a metal (Al) loop. At the centre of the disk is the output patch electrode of the piezoelectric transducer. The metal loop and output patch electrode are separated by a ground shield in between which contacts the underlying silicon (Si) device layer (which is 10 μm thick). These three metal structures are routed through the T-shaped tethers. As shown from the cross-sectional view of the device in Fig. 1b, the metal loop is isolated from the Si device layer by a 200 nm thick thermally grown oxide layer. The Al-AlN-Si piezoelectric stack is grounded through the Si device layer.

In the presence of a z-axis magnetic field, a Lorentz force develops normal to the direction of the excitation current I_{in}. As the direction of I_{in} is circumferential, a radial Lorentz force (F_L) acts