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RESUBMISSION

Section number – Surface Acoustic Waves for magnetic field sensing

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Status

Surface Acoustic Wave (SAW) sensors are gaining prominence in various sectors including automotive, aeronautics, medical industries, and the Internet of Things. SAW sensors are very sensitive to a large variety of physical parameters including magnetic fields when combined with a magnetoelastic layer (Fig.1). Thanks to their wireless, battery-free and identification capabilities, SAW sensors offer significant advantages over conventional magnetic sensors such as magneto-resistive or inductive devices and are particularly suited for industrial monitoring, remote sensing in harsh environments, and biomedical applications.

Magnetic field sensitive SAW devices were first introduced by Ganguly *et al.* [1] as phase shifters. Magnetic field SAW sensors (MSAW) are particularly suitable for detecting weak ($> 1\text{nT}$), low-frequency ($> 1\text{Hz}$) magnetic fields and serving as current sensors due to their wide dynamic range and bandwidth. Based on magnetoelastic materials, they leverage non-linear alterations in the material's elastic parameters caused by magnetostrictive strain, which in turn modify the SAW velocity, impacting resonance frequencies or propagation delays [2,3,4,5,6], and more rarely the SAW amplitude [7,8]. The variations of each elastic constant under magnetic field, sometimes summarized using the " $\Delta E/\Delta G$ effect" denomination, impacts differently each type of mode, for example Rayleigh or Love waves.

There are two main geometries of MSAW sensors: resonator [2] and delay line [9]. Both configurations allow for the detection of subtle magnetic field changes (Fig.1). Resonators are very compact, while delay lines can yield a high absolute phase sensitivity, separate acoustic wave generation and sensing parts, and can provide identification, using reflector banks with variable delays to generate a code. The magnetoelastic material can constitute the interdigital transducers (IDTs), or be used in full film form on top of resonators [3], [4] or within delay lines [9], [5], [10], [6]. Alternatively, magnetic sensing is achievable by monitoring the amplitude changes in the SAW reflected signal, influenced by impedance changes in an externally coupled GMI sensor [7].

The applications of MSAW sensors span a broad spectrum. They can detect fields exceeding the Earth's Magnetic Field (EMF) at 1 mT and higher, critical for remote magnetic field and current sensing (ex. power lines), or sensing within motors. These sensors also perform well sensing EMF disturbances ranging from 0.1 to 10 μT (ex. autonomous sensors for smart parking or traffic control). Furthermore,

they can achieve detection limits as low as 1 nT and below, essential for critical biomedical applications.

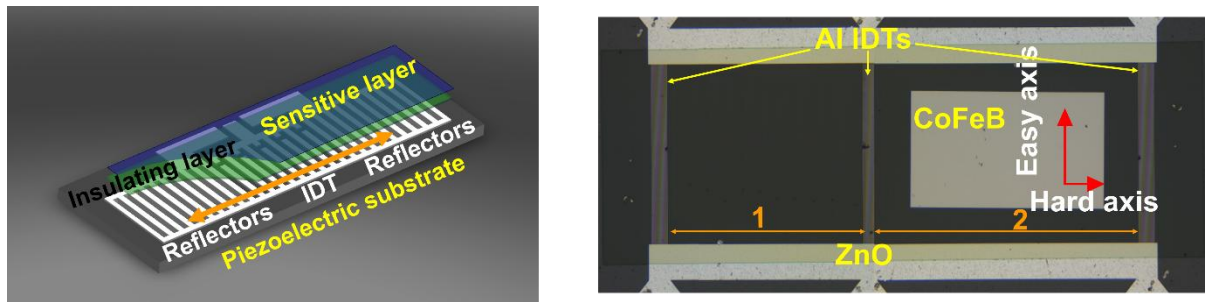


Figure 1. MSAW sensors (a) schematic view of a resonator configuration, with an insulating layer and a full film magnetoelastic layer. The SAW propagation direction is indicated in orange, (b) top view of a sample in delay line configuration with a CoFeB magnetoelastic layer between IDTs (path 2) and temperature compensation (path 1). Adapted from [9].

Current and Future Challenges

Table 1. MSAW sensors structures and performances. R: resonators, DL: delay lines, QST: quartz ST-cut

Substrate & structures	Sensitive layer	Freq.	Max. sensitivity	Limit of detection	Ref.
FeCoSiB/ZnO (R)	FeCoSiB	1.6 GHz	around 11500ppm/mT	/	[2]
QST X+90 (DL)	[TbCo ₂ /FeCo]x25	1.2 GHz	2500 ppm/mT	/	[5]
QST X+90/ZnO/SiO ₂ (R)	CoFeB	1GHz	620ppm/mT	/	[3]
QST X+90/SiO ₂ (R)	FeCoSiB	450 MHz	14000 ppm/mT	/	[4]
QST X+90/SiO ₂ (DL)	FeCoSiB/NiFe/ MnIr (x2)	142.5 MHz	~ 45-49000 ppm/mT @25dBm* ~ 28000 ppm/mT @5dBm*	~50 pT/√ Hz at 10Hz @25dBm 28 pT/√ Hz at 10Hz @5 dBm	[6]

*assuming a delay of 1.389 ns

Since the earlier breakthroughs [2], the field of MSAW sensors has experienced remarkable advancements in sensitivity and lower limit of detection, as evidenced in Table 1. Notably, researchers from the University of Kiel have made significant contributions [9], [6]. These advances stem from intensive studies focused on engineering the properties of both the magnetoelastic layer and the piezoelectric substrate.

Regarding the piezoelectric substrate, studies have shown that Shear and Love waves based on ST-cut Squartz (QST) X+90° (refer to Table 1) or Lithium Niobate Y-X cut [10] typically outperform Rayleigh waves in terms of MSAW device sensitivity. This superiority is often attributed to the substantial variation of the elastic stiffness constant C_{66} under field [5]. Concerning the magnetoelastic overlayer, research has highlighted the critical role played by the relative angles between the acoustic wave vector, the anisotropy direction, and the magnetic field orientation [4], [5].

Moreover, to detect low magnetic fields and obtain high sensitivity sensors a balance must be found between relatively high magnetostriction and low anisotropy, with FeCoSiB appearing as the leading candidate so far. Additionally, to achieve low limits of detection, mastering the magnetic domain and domain walls configuration is essential to minimize the associated noise [11]. Moreover, the thickness and quality of the magnetoelastic layer have a significant influence on sensor performance [1], [12], [13], as magnetic sensitivity tends to amplify with these attributes.

However, numerous challenges persist in the realm of MSAW sensors [14]. Optimizing operational conditions often requires applying a bias field, which can increase size and power consumption. Solutions entail engineering intrinsic bias fields and aligning a field along a hard axis for efficient operation at zero field, always taking into consideration the occurrence of hysteretic behaviours that can hinder field determination.

Moreover, temperature sensitivity poses a significant challenge frequently overlooked in literature. This issue encompasses both the Temperature Coefficient of Frequency (TCF) values, defined as $TCF = \Delta f / (f\Delta T)$, and the influence of temperature fluctuations on the magnetic anisotropy within the sensitive layer. Addressing this challenge can be approached in two ways: integrating materials in multilayers to achieve nearly zero TCF and maintain magnetic stability [3], or utilizing a magnetically insensitive acoustic path for temperature compensation [10]. In such cases, SAW devices become multifunctional, enabling the simultaneous sensing of multiple parameters. Additionally, due to acoustic and magnetic losses, as well as often poor impedance matching, MSAW devices frequently exhibit mediocre electrical properties for wireless operation. Exploring novel approaches such as implementing electromagnetic resonator geometries or employing insulating magnetostrictive ferromagnets could potentially solve some of these issues.

Advances in Science and Technology to Meet Challenges

Building on recent advancements in magnonics, SAW-FMR technology holds the potential to develop sensors with significantly enhanced sensitivity and directionality due to the resonant nature of the magnetoacoustic interaction [15]. These conditions are achievable by employing low damping magnetostrictive materials with SAW-frequencies close to the ferromagnetic resonance (FMR), known as SAW-FMR [16], [17]. The spin current emitted from the induced magnetization precession can moreover be detected in the DC regime [18,19], making it potentially more readily implementable, although the low signal to noise ratio needs to be improved.

Experimental demonstrations of SAW-FMR magnetic field sensing include Rayleigh waves traversing an epitaxial Iron film on GaAs [15] and shear horizontal-type SAWs excited in a FeCoSiB layer on LiTaO₃ [12]. Future SAW-FMR developments target 1-10 GHz. High frequencies demand electron beam lithography for IDT fabrication, advanced signal processing, and wireless addressing. Challenges can be tackled by selecting high-phase-velocity piezoelectric substrates or adjusting the field direction to lower SAW frequencies. [15]. The integration of magnetorotational coupling notably expands the range of magnetic materials suitable for SAW-FMR devices, accommodating both magnetostrictive and non-magnetostrictive materials, such as softer, non-magnetostrictive permalloy. Additionally, the non-reciprocal nature of these interactions could enable to sense not only the field axis but also its direction (**CROSSREF 08 Weiler**)

Achieving a three-axis determination of the magnetic field orientation remains a challenge with MSAWs. Furthermore, the literature often overlooks the issue of very low capability to sense the out-of-plane component of the magnetic field, despite its necessity in certain space-constrained applications. Thicker magnetoelastic layers present a promising solution to address this concern.

In the context of remote magnetic sensing in harsh environments such as in the gas, aerospace, steel and automotive industries, selecting materials capable of withstanding extreme conditions is essential. (**CROSSREF 17 Schmidt**) In this context, piezoelectric substrates like Langasite can withstand temperatures up to 1000°C. However, their effectiveness in such harsh environments depends on their compatibility with magnetostrictive materials that preserve their magnetic properties even under such extreme temperatures.

In order to achieve extremely low detection limits, and to mitigate low-frequency noise arising from magnetic domains interacting with propagating SAWs strategies such as leveraging exchange bias with antiferromagnetic materials have been explored. For instance, Schell *et al.* showcased exceptional

detection capabilities, achieving remarkably low detection limits of 28 pT/Hz^{1/2} at 10 Hz and 10 pT/Hz^{1/2} at 100 Hz [6]. These results represent a significant advancement towards biomedical applications demanding the detection of extremely weak biomagnetic fields. If Magnetocardiography and very low field Magnetic Anomaly Detection applications now seem within grasp, exploring new paradigms is essential to achieve femtotesla range magnetoencephalography with MSAW technology.

Concluding Remarks

Magnetic SAW sensors present an appealing option for various industrial uses, yet further research is necessary, especially for magnetic field sensing involving harsh environments. When compared to existing magnetic sensors on the market, MSAW sensors offer several distinct advantages. These include their capability to probe magnetic fields across a very broad spectrum of amplitudes and frequencies, the integration of wireless technology, the combination of SAW sensitivity to various physical parameters (e.g. magnetic field, temperature, strain, gases) within a single device, and the relatively low cost of fabrication. The potential applications of MSAW sensors could be further explored and require additional research, particularly in areas such as flexible and wearable devices, local 3D magnetometry for precise spatial measurements, as well as space applications where radiation resilience is critical. Finally, we believe that the recent advancements in the use of SAWs for magnonics and spintronics, particularly through the interaction between SAW and spin waves in the GHz regime [[CROSSREF 09 OTANI](#)], could yield significant benefits for enhanced sensing capabilities. For a deeper understanding of this topic, the reader is encouraged to consult Reference [18]. It is essential that the magnonics and SAW communities engage in dialogue to fully realize this potential.

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