A Highly Sensitive Magnetic Field SAW Sensor on Metglas

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***Abstract*— The properties of a surface acoustic wave magnetic field sensor (MSAW) based on a piezoelectric /magnetoelastic heterostructure are investigated and presented. It consists of a ZnO piezoelectric layer and a magnetoelastic metallic amorphous ribbon of 1K101 Metglas, which is a Fe-Si-B alloy, as a sensitive material. The aim is to exploit the high ΔE effect, i.e. the change of elastic properties under magnetic field, in Metglas to cause a significant change in the wave velocity and thus of the frequency in SAW resonator. We first describe the design and fabrication of the MSAW resonator, which is based on a Rayleigh wave at 422 MHz. Then, we study the sensor's resonance frequency that was determined under (a) an in-plane magnetic field in the acoustic wave propagation direction and, (b) an out-of-plane field perpendicular to the plane. The experimental results show very high sensitivities of 2793 ppm/mT and 1482 ppm/mT, respectively, in a quite thin, compact and easy to fabricate sensor. To the best of our knowledge, the out-of-plane sensitivity is the largest reported so far, and it is of great importance for practical industrial implementations.**

Keywords*— *SAW, resonators, magnetic field sensor, ΔE effect.

I. Introduction

Surface acoustic waves occupy a very important place in the field of microwaves. SAW devices can also have high sensitivity to physical or chemical measurands, which makes them particularly attractive for the use as sensors.

In particular, SAW systems in magnetic field sensing have gained importance in recent years. As a result, several works on these magnetic sensors have been published, with various types of structures, combinations of piezoelectric and magnetoelastic sensitive materials and patterns [1]–[3].

In short, the general principle of these structures is the following: the application of an external magnetic field causes a change in the stiffness parameter of a sensitive magnetoelastic layer which is part of the propagating medium of the SAW. This leads to a change in the phase velocity of the elastic wave and consequently of the frequency. As shown in expression (1) [4], the change in the elastic modulus of magnetoelastic materials in the presence of a magnetic field directly affects the frequency of the surface wave:

$$-\frac{\Delta f}{f} \propto \frac{1}{2}\frac{\Delta E}{E} \quad (1)$$

Moreover, the ΔE effect in a magnetoelastic material is linked to the elastic modulus at magnetic saturation E_0, the magnetic parameters of the material (magnetic anisotropy K, saturation magnetization M_S and saturation magnetostriction coefficient λ_S [5]). Furthermore, the sensitivity depends on many other factors, including the relative thickness of magnetoelastic materials to the acoustic wavelength and the acoustic mode. Table 1 summarizes the properties of some MSAW devices from the literature, their structures, sensitive layers and sensitivities. Whilst in plane sensitivities are regularly reported in literature, the sensitivity for the field being applied perpendicular to the SAW surface is rarely addressed. However, the latter is required for many industrial applications designed/used for the measure of the field component emerging from surfaces on which the sensor is fixed. Since many devices use magnetoelastic thin films, either as full films or IDTs, which in any case causes a shape anisotropy [6], saturation fields are high, close to $4\pi M_S$, leading to poor sensitivity.

In this work, a new type of MSAW sensor is proposed based on 1K101 Fe-Si-B amorphous Metglas ribbon as a substrate and ZnO as piezoelectric layer. The advantages of this structure stems from the high ΔE effect, and the high relative thickness of sensitive material.

Table I. Comparison of structure and performance of several magnetic sensors based on acoustic wave

Piezoelectric material	Configuration	Sensitive layer	Relative sensitivity (Max)	Reference
Quartz (ST-90X)	SAW Resonator	Ni	2.2 ppm/mT (in plane)	Kadota JAP (2011)
$LiNbO_3$ (128°Y-X) + ZnO	SAW Resonator	25×[$TbCo_2$/FeCo]	4.3 ppm/mT	H.Mishra et al.,Smart Matter. & Struct. (2019)
Quartz (ST-90X) + ZnO	SAW Resonator	CoFeB	36 ppm/mT	H.Mishra et al., Smart Matter. & Struct (2020)
$LiNbO_3$ (128°Y-X)	SAW Delay line	FeCo	59 ppm/mT	Wang et al. AIP Advances 8, 015134 (2018)
$LiNbO_3$ (Y cut)	SAW Delay line	FeCo/$TbCo_2$	48 ppm/mT	Zhou et al. Appl. Phys.Letter; A04, 114101 (2014)
ST-cut Quartz + SiO_2	SAW Delay line	FeCoSiB	300 ppm/mT	Kittmann et al. Scientific rep. 8:278 (2018)
Quartz (ST-90X)+ZnO+SiO_2	SAW Resonator	CoFeB	390 ppm/mT-620 ppm/mT	Yang et al. Advanced Mater.Tech.(2021) 2100860
ZnO on FeCoSiB	SAW Resonator	FeCoSiB	Around 15000 ppm/mT	Smole et al.proc. 2003 IEEE IFC Sym. (2003)
$TbCo_2$/FeCo on Quartz ST cut	SAW Delay line	$TbCo_2$/FeCo	2500 ppm/mT	Mazzamurro et al. Phys. Rev. 044001 (2020)
ZnO on Metglas Substrate	SAW Resonator	FeSiB	2793 ppm/mT (in plane)	**This work**
ZnO on Metglas Substrate	SAW Resonator	FeSiB	1482 ppm/mT (out-of-plane)	**This work**

In the first section, a brief summary of the fabrication techniques of the SAW magnetic field sensor is given, and the second section deals with the results focusing on the magnetic properties of the fabricated MSAW device.

II. Results and Discussion

The Al/ZnO/ Metglas MSAW structure (see Fig. 1) is made out of a 25 µm × 2.5 cm × 2 cm 1K101 Metglas ribbon piece (Fe(91.8%)-Si(5.4%)-B(2.8%), Anhui Corporation, China).

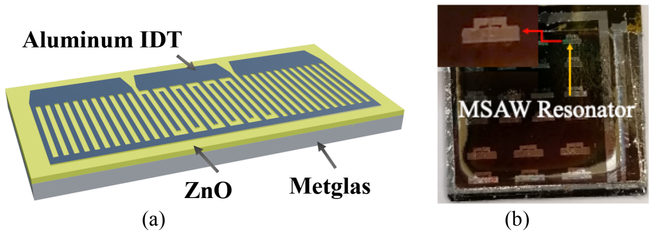

Fig. 1. (a) Schematic view of the one-port SAW resonator (b) Top view of the manufactured MSAW resonator

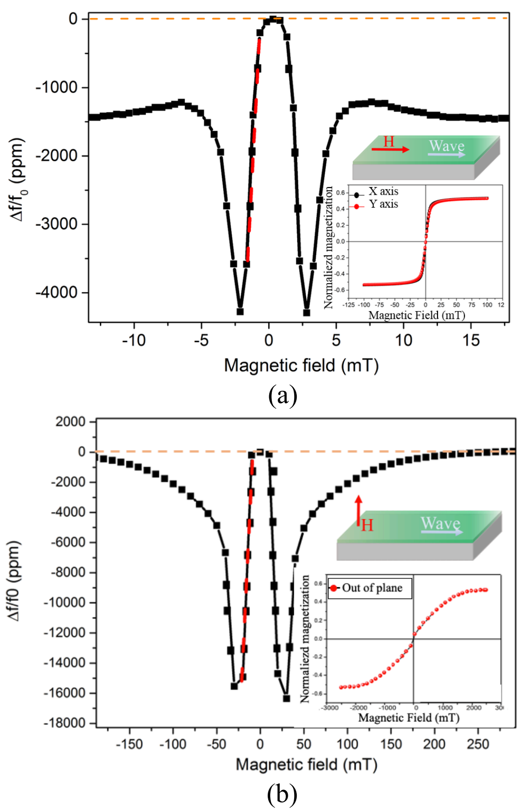

Fig. 2. MSAW measurements on the device. (a) Field applied along the propagation axis, (b) perpendicular to the propagation plane of the elastic wave. Inset: measured magnetization curves of the structure at room temperature.

A 2 µm thick ZnO layer is deposited by reactive magnetron sputtering according to the parameters given in [7]. The ZnO layer is deposited at 170°C, which prevents the crystallization of the Metglas alloy. The sample was then fixed with double-sided adhesive tape on silicon piece serving as a temporary carrier. Finally, the synchronous resonator was fabricated with a wavelength λ of 6.5 µm, 100 pairs of IDTs, 200 reflectors on both sides, a 40λ aperture and 150 nm of aluminum. (Fig. 1b)

The fabricated Rayleigh wave MSAW device shows a central resonant frequency at 422 MHz (near the 433 MHz ISM band). Fig. 2.a and 2.b show the relative variation of the resonant frequency as a function of the magnetic field and the magnetization curves. It shows a quasi-linear behavior from -2.1 to -0.6 mT with a sensitivity of 2793 ppm/mT (1.18 Hz/nT) when the magnetic field is parallel to the acoustic propagation direction, and -19.8 to -9.92 mT with a sensitivity of 1482 ppm/mT (0.638 Hz/nT) when the magnetic field is perpendicular to the sensor plane. These results are very promising and join the table of the highest sensitivities to the magnetic field obtained in the MSAW devices, they are only outperformed by the results of [4].

III. Conclusions

In this work, a novel MSAW sensor on a magnetoelastic amorphous Metglas ribbon was developed with the aim of improving the magnetic sensitivity of SAW sensors by exploiting the high ΔE effect of this material. The fabricated ZnO/Metglas resonator was characterized near the operating frequency of 422 MHz. When the magnetic field is parallel to the acoustic propagation axis, the maximum sensitivity is 2793 ppm/mT, and when the magnetic field is perpendicular to the Metglas plane, the maximum sensitivity is 1482 ppm/mT. To the best of our knowledge, this is the second best reported in-plane sensitivity and by far the best out-of-plane sensitivity.

It also has to be pointed out that this sensor was rather easy to fabricate, starting from a an extremely low-cost material, is very thin (27 µm) and compact (< 4mm^2) and easy to laminate on any target/carrier object. The large out-of-plane sensitivity and compactness make the structure a strong candidate for industrial / automotive applications.

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