RESEARCH ARTICLE | FEBRUARY 05 2024

Anomalies in the magnetostrictive modulation of love surface acoustic waves

Special Collection: 68th Annual Conference on Magnetism and Magnetic Materials

J. D. Aguilera ; R. Loriente ; L. Soria; A. Begue ; R. Ranchal ; I. Gràcia ; S. Vallejos ; A. Hernando ; P. Marín; P. de la Presa ; D. Matatagui

AIP Advances 14, 025208 (2024)
https://doi.org/10.1063/9.0000749

Anomalies in the magnetostrictive modulation of love surface acoustic waves

Cite as: AIP Advances 14, 025208 (2024); doi: 10.1063/9.0000749
Submitted: 2 October 2023 • Accepted: 30 November 2023 •
Published Online: 5 February 2024

J. D. Aguilera,[1] R. Loriente,[1] L. Soria,[1] A. Begue,[2] R. Ranchal,[1,2] I. Gràcia,[3] S. Vallejos,[3] A. Hernando,[1] P. Marín,[1,2] P. de la Presa,[1,2,a)] and D. Matatagui[1,2]

AFFILIATIONS

[1] Instituto de Magnetismo Aplicado (UCM-ADIF-CSIC), A6 km 22.500, 28230 Las Rozas, Spain
[2] Dpto. de Física de Materiales, Facultad de Ciencias Físicas, Universidad Complutense de Madrid, Plaza de las Ciencias 1, 28040 Madrid, Spain
[3] Instituto de Microelectrónica de Barcelona (IMB, CSIC), Campus UAB, Bellaterra 08193, Spain

Note: This paper was presented at the 68th Annual Conference on Magnetism and Magnetic Materials.
[a)] **Author to whom correspondence should be addressed:** pmpresa@ucm.es

ABSTRACT

A magnetic surface acoustic wave (SAW) sensor is built by growing a 100 nm galfenol ($Fe_{72}Ga_{28}$) film by sputtering between the interdigitated transducers of a SAW delay line. Love waves are produced when the shear waves excited on the piezoelectric substrate are guided by a 3.1 μm layer of amorphous SiO_2. Due to the magnetostrictive nature of galfenol deposited on top, the application of magnetic fields modulates the propagation of the mechanical excitations along the sensor by the strain coupling. By introducing the delay line in a feedback loop circuit, these changes are studied as resonant frequency variations. Magnetic field cycles of ±40 mT are applied to the sample and the resonant frequency shift is tracked simultaneously. The sensor exhibited hysteretic frequency behavior that depends on the orientation of the applied magnetic field relative to the direction of Love wave propagation. In the configuration in which the wave vector and the applied field form an angle of 45°, the resonant frequency seems to increase with the magnetization induced by the external field. When the wave vector propagation is parallel to the field, two positive peaks appear close to the coercive field of the film, which has not been reported before. This is probably due to a more complex relationship between the acoustic wave and the magnetic state of the film which could be exploited to give rise to new models of magnetic sensors.

There is a wide range of high-performance, small size, low cost and low consumption sensors that are based on the variation of the parameters that characterize a surface acoustic wave (SAW) propagating through a piezoelectric substrate.[1] These waves are generated by a pair of interdigitated transducers (IDTs) excited by an AC signal. By the piezoelectric effect, the AC excitation creates a dynamical deformation that propagates along the material. In this way, when an alternating signal excites one of the pairs of IDTs, this transducer creates a dynamic deformation in the piezoelectric substrate and the energy of the disturbance travels through the substrate in the form of a wave to the facing IDT, which converts this wave again in an alternating electrical capable of being measured. SAW devices can be functionalized to be made sensitive to different phenomena or substances, and they have already proved to be effective biochemical, chemical, temperature, pH, or light sensors.[2,3] The basic principle is the change in the speed of propagation of SAW produced by the target stimulus. The velocity changes can be acquired indirectly, using the device as a resonant element in a delay line oscillator circuit that allows measuring the changes in their frequency, because they are proportional magnitudes.[4]

Love waves are a type of SAW in which the energy associated to the excitation concentrates on the surface of the device due to the presence of a guiding layer, with a much lower wave velocity, on top of it.[5]

In this work, a magnetic sensor based on surface acoustic waves and magnetostriction is studied. Only few examples can be found in literature that combine SAW with magnetism.[6–12] A possibility to achieve this is employing magnetostrictive materials, in which magnetization and strain are not independent, inducing a relationship between the magnetic field and the mechanical properties. Magnetostrictive layers grown on SAW devices alter the propagation of the mechanical waves when a magnetic field is applied and, hence, changes in frequency, phase or velocity can be measured. Specifically, this sensor is based on the study of the variation in the resonance frequency of the SAW when applying a magnetic field.

MATERIALS AND METHODS

Device fabrication

The sensor fabricated (4 mm × 9 mm × 0.5 mm) consists of a piezoelectric substrate of ST-90°X cut quartz, on which two aluminum IDTs with a thickness of 200 nm are patterned by lithography. Therefore, delay line configuration was chosen. The structure of each IDT consists of four strips per period, it is called double electrode type or split electrode type. The period formed by four fingers (λ) is 28 μm, the center-to-center separation between both IDTs (Lcc) is 150 λ and the acoustic aperture (W) is 75 λ, which is the length of the strips. The choice of the substrate and the configuration of the IDTs favors the propagation of shear horizontal (SH) waves. On top of the quartz substrate an amorphous SiO_2 layer with a thickness of 3.1 μm is deposited by plasma enhanced chemical vapor deposition (PECVD), guiding the SH-waves, thus becoming Love waves. Then, magnetic sensitivity is achieved by growing a 100 nm layer of polycrystalline galfenol ($Fe_{72}Ga_{28}$) by sputtering on the space between the two IDTs. For this $Fe_{72}Ga_{28}$ thickness, a magnetostriction constant (λ_s) of around 73 ppm and an effective magnetoelastic coefficient (B_{eff}) of −7.5 MPa is expected.[13,14] The magnetic film is protected from oxidation by two 20 nm layers of molybdenum grown just below (also improving the adherence with the guiding layer) and on top. A 3D scheme of the device can be seen in Figure 1. The hysteresis curve of the galfenol film was measured with magneto-optic Kerr effect (MOKE) microscopy.

Experimental setup

A feedback loop circuit is built by connecting both IDTs and introducing an amplifier that compensates the losses produced at the delay line. This leads to resonating behavior. A directional coupler is added to the assembly, which allows measuring a small fraction of the signal that is traveling through the oscillator. A spectrum analyzer (Agilent N9010A) receives the signal and yields the resonant frequency of the system in real time.

To test the response of the device to the different applied magnetic fields, it is introduced between the poles of an electromagnet (Newport Instruments) and subjected to cycles of applied field while the resonant frequency of the circuit is recorded. A custom-made program controls the power supply that excites the electromagnet and stores the data from the spectrum analyzer.

Measurement procedure

The resonant frequency has been measured by changing the applied field from 0 mT to +40 mT to −40 and 0 mT again.

Different response curves are obtained depending on the orientation of the applied field respect to the SAW wave vector.

The orientation of the device with respect to the poles of the electromagnet is 0° when the direction and sense of the positive applied field coincide with those of the wave vector of the SAW. The changes in the resonance frequency of the circuit are recorded in real time as a function of the variation of the applied magnetic field, and are investigated for 0°, 45°, 90° and 135°. Due to the symmetry of the experiment respect to the plane perpendicular to the surface of propagation and parallel to the propagation of Love waves, identical results are obtained for an angle α and 360°-α, so only the α<180° region is explored.

RESULTS

The deposition process assures that the sample has no macroscopic anisotropy (easy or hard axes). A coercivity of about 5 mT has been determined from the hysteresis loop measured by MOKE (Fig. 2).

The resonant frequency of the oscillator circuit is around 161 MHz. For representing the cycles, a regression line is subtracted from the raw data to discard the continuous drift due to changes in the temperature of the laboratory affecting both the device and the electromagnet. Figure 3 shows the resonant frequency shift versus applied magnetic field.

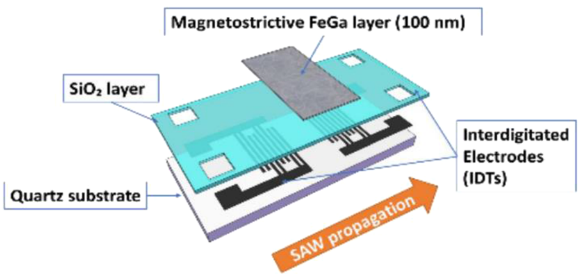

FIG. 1. Schematics of the deposited Love wave-based sensor.

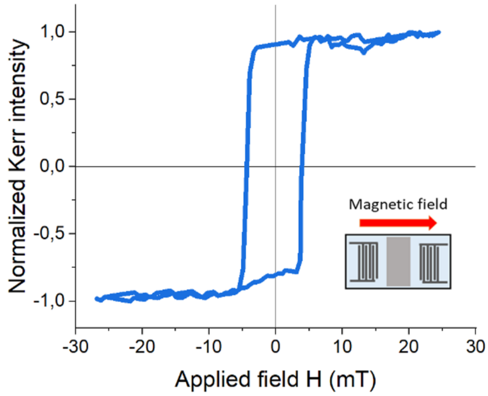

FIG. 2. Intensity (proportional to magnetization) obtained by MOKE measurements on the sample. The applied field is parallel to the direction of propagation of SAWs.

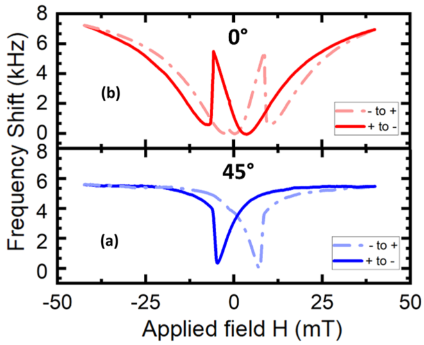

FIG. 3. Evolution of the resonant frequency shift Δf (kHz) as the applied magnetic field H (mT) varies between +40 mT to −40 mT (and back) for orientations (a) 45° and (b) 0°.

The sensor response shows the same qualitative behavior for the orientations of 0° and 90°, and another shared behavior appears for the 45° and 135° directions. The cycles for ±90° rotated orientations yield different maximum frequency shifts but share the same shape. Both 0° and 45° configurations are represented to discuss the different behaviors. The measurements were repeated to verify that the results were reproducible.

DISCUSSION

When the applied external magnetic field changes, the magnetostrictive layer modulates the propagation of Love waves due to the strain coupling. In any of the configurations tested, the resonant frequency is affected by the application of a magnetic field, showing hysteresic behavior with the applied field.

The graph of the frequency shift in the 45° orientation (Figure 3(a)) resembles a simple hysteresis cycle, showing saturation at high fields (around 40 mT). For this angle (and 135°) configuration, the frequency shift seems close to be a monotonic increasing function of the modulus of the magnetization of the film, $\Delta f = \Delta f(|M|)$. Therefore, the hysteretic behavior of the resonant frequency would be closely related to the magnetic hysteresis of the FeGa film. The frequency minima are reached close to the coercive field of the FeGa film, measured to be around 5 mT (Figure 2), supporting this idea.

In the case of 0° (and 90°), the situation is quite different (Figure 3(b)). First, the maximum applied field is not enough to observe a stabilisation of the resonant frequency. A second difference is that two positive peaks appear near the coercive field, so the frequency shift passes by two local minima and one maximum (the peak) instead of just one minimum when the applied field sweeps from +40 mT to −40 mT (continuous line in Figure 3(a)). This anomaly has no clear explanation but two key characteristics are believed to allow the observation of positive peaks in this orientation. In the first place, polycrystalline galfenol is used instead of an amorphous material with neglectable microscopic magnetic anisotropy (see Ref. 10), the higher coercivity of galfenol could give rise to two separate peaks and a different magnetic behavior under the effects of the induced strain by SAWs. Also, shear waves are used, so that the main axes of the deformation associated with the SAW waves (and therefore the associated magnetic fields) form a certain angle with the wave propagation vector.

CONCLUSIONS

Novel characteristics have been seen when studying the behavior under the magnetic field of a SAW device with a magnetostrictive component: at 0° and 90° configurations, two positive peaks appear between the maxima corresponding to the highest fields when a magnetic field cycle is performed. This is something new since it does not appear in the bibliography of previous studies similar topics. It is believed that employing polycrystalline galfenol, with a higher coercivity than amorphous materials, is a key point that enables the observation of two peaks, being another important factor the use of Love waves, which are polarized in plane and confined at the surface. It is noteworthy that the unusual behavior observed emerges in a system without magnetic anisotropy: it is the result of strain coupling without the need of any spontaneous or induced magnetic anisotropy.

This feature can lead to an enhancement of the sensitivity of the device at the fields corresponding to the slopes of the peaks.

Once these mechanisms can be clarified, it is believed that the development of robust magnetic SAW devices with tunable characteristics through the application of magnetic fields is possible. Therefore, it could be used as a basis for a magnetic field sensor with the advantages of current SAW technology and potenetially much higher sensitivity than the current ones. It can be concluded that the combination of SAW and magnetostrictive materials offers a much richer phenomenology than expected.

ACKNOWLEDGMENTS

The authors acknowledge the Spanish Ministry of Science and Innovation for financing the projects PID2021-123112OB-C21 (AEI/FEDER), PDC2022-133039-I00 (AEI/FEDER), PID2021-122980OB-C51 (AEI/FEDER) and Comunidad de Madrid (NANOMAGCOST-CM S2018/NMT-4321. J.D.A. received funding from Next Generation EU, Ministerio de Trabajo y Economía, Comunidad de Madrid, Spain, Programa Investigo from grant 96-UCM-INV. D. M. acknowledges financial support from the Spanish Ministry of Science and Innovation through the Ramón y Cajal grant RYC2021-031166-I.

AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

J. D. Aguilera: Data curation (equal); Formal analysis (equal); Investigation (equal); Methodology (equal); Writing – original draft (equal). **R. Loriente**: Data curation (equal); Formal analysis (equal); Writing – original draft (equal). **L. Soria**: Conceptualization (equal); Data curation (equal); Formal analysis (equal); Funding acquisition (equal); Investigation (equal); Resources (equal); Validation (equal); Writing – review & editing (equal). **A. Begue**: Data curation (equal); Investigation (equal); Methodology (equal). **R. Ranchal**: Conceptualization (equal); Data curation (equal); Formal analysis (equal); Funding acquisition (equal); Investigation (equal); Resources (equal); Writing – review & editing (equal). **I. Gràcia**: Data curation (equal); Formal analysis (equal); Investigation (equal); Resources (equal); Writing – review & editing (equal). **S. Vallejos**: Conceptualization (equal); Data curation (equal); Formal analysis (equal); Resources (equal); Supervision (equal); Validation (equal); Writing – review & editing (equal). **A. Hernando**: Conceptualization (equal); Formal analysis (equal); Supervision (equal); Validation (equal). **P. Marín**: Funding acquisition (equal); Project administration (equal); Resources (equal); Writing – review & editing (equal). **P. de la Presa**: Conceptualization (equal); Formal analysis (equal); Funding acquisition (equal); Investigation (equal); Project administration (equal); Resources (equal); Software (equal); Supervision (equal); Writing – review & editing (equal). **D. Matatagui**: Conceptualization (lead); Formal analysis (equal); Funding acquisition (equal); Investigation (equal); Project administration (equal); Software (equal); Supervision (equal); Writing – review & editing (equal).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

REFERENCES

[1] D. Mandal and S. Banerjee, "Surface acoustic wave (SAW) sensors: Physics, materials, and applications," Sensors **22**, 820 (2022).

[2] D. Matatagui, F. A. Bahos, I. Gràcia, and M. d. C. Horrillo, "Portable low-cost electronic nose based on surface acoustic wave sensors for the detection of BTX vapors in air," Sensors **19**(24), 5406 (2019).

[3] J. R. Fragoso-Mora, D. Matatagui, F. A. Bahos, J. Fontecha, M. J. Fernandez, J. P. Santos, I. Sayago, I. Gràcia, and M. C. Horrillo, "Gas sensors based on elasticity changes of nanoparticle layers," Sensors and Actuators B: Chemical **268**, 93–99 (2018).

[4] G. Gonzalez, *Foundations of Oscillator Circuit Design* (Artech House Boston, 2007).

[5] P. Kiełczyński, *Properties and Applications of Love Surface Waves in Seismology and Biosensors* (2018).

[6] Y. Yang, H. Mishra, P. Mengue, S. Hage-Ali, S. Petit-Watelot, D. Lacour, M. Hehn, H. M'Jahed, T. Han, and O. Elmazria, "Enhanced performance love wave magnetic field sensors with temperature compensation," IEEE Sensors Journal **20**(19), 11292–11301 (2020).

[7] Y. Yang, P. Mengue, H. Mishra, C. Floer, S. Hage-Ali, S. Petit-Watelot, D. Lacour, M. Hehn, T. Han, and O. Elmazria, "Wireless multifunctional surface acoustic wave sensor for magnetic field and temperature monitoring," Advanced Materials Technologies **7**(3), 2100860 (2022).

[8] H. Mishra, J. Streque, M. Hehn, P. Mengue, H. M'Jahed, D. Lacour, K. Dumesnil, S. Petit-Watelot, S. Zhgoon, V. Polewczyk *et al.*, "Temperature compensated magnetic field sensor based on love waves," Smart Materials and Structures **29**(4), 045036 (2020).

[9] H. Mishra, M. Hehn, S. Hage-Ali, S. Petit-Watelot, P. W. Mengue, H. M. Jahed, D. Lacour, O. Elmazria, and S. Zghoon, "Multifunctional sensor (magnetic field and temperature) based on micro-structured and multilayered SAW device," in *2020 IEEE International Ultrasonics Symposium (IUS)* (IEEE, 2020), pp. 1–4.

[10] A. Kittmann, C. Müller, P. Durdaut, L. Thormählen, V. Schell, F. Niekiel, F. Lofink, D. Meyners, R. Knöchel, M. Höft *et al.*, "Sensitivity and noise analysis of SAW magnetic field sensors with varied magnetostrictive layer thicknesses," Sensors and Actuators A: Physical **311**, 111998 (2020).

[11] A. Kittmann, P. Durdaut, S. Zabel, J. Reermann, J. Schmalz, B. Spetzler, D. Meyners, N. Sun, J. McCord, M. Gerken *et al.*, "Wide band low noise love wave magnetic field sensor system," Scientific Reports **8**, 278 (2018).

[12] J. M. Meyer, V. Schell, J. Su, S. Fichtner, E. Yarar, F. Niekiel, T. Giese, A. Kittmann, L. Thormählen, V. Lebedev *et al.*, "Thin-film-based SAW magnetic field sensors," Sensors **21**, 8166 (2021).

[13] I. Hontecillas, I. Figueruelo, S. Abad, and R. Ranchal, "Tuning the magnetic anisotropy of Ga-rich FeGa thin films deposited on rigid substrates," Journal of Magnetism and Magnetic Materials **494**, 165771 (2020).

[14] P. Bartolomé, A. Begué, A. Muñoz-Noval, M. Ciria, and R. Ranchal, "Unveiling the different physical origins of magnetic anisotropy and magnetoelasticity in Ga-rich FeGa thin films," The Journal of Physical Chemistry C **124**(8), 4717–4722 (2020).