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Sensor Phenomena

Enhancing magnetoelastic coupling in shear surface acoustic waveguide based on ST-Cut Quartz substrate and Ni thin films with uniaxial magnetic anisotropy induced by thermal annealing

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Abstract— In this study, we conduct a comprehensive investigation to enhance the performance of shear surface acoustic wave (SAW) magnetic sensors. We explore the interaction between SAW and a nickel film deposited on ST-cut quartz in a delay line configuration. The nickel film, measuring 2 mm in width and 100 nm in thickness, undergoes vacuum annealing at 500 °C to induce magnetic anisotropy through the anisotropic thermal properties of ST-cut quartz. Our research combines theoretical and experimental approaches to evaluate the S_{21} phase shift in response to an applied magnetic field. The results demonstrate a remarkable agreement between theoretical predictions and experimental data. To interpret the sensor's response behavior, we introduce a custom piezomagnetic model. Notably, we observe a phase shift difference between minimum and maximum of approximately 30° for a propagation path of 2 mm. We further investigate the impact of incorporating an SiO_2 layer on top of the magnetic thin film. This addition doubles the phase shift difference, as shear SAWs become more confined near the surface or entirely waveguided within the SiO_2 layer. Additionally, we explore an innovative approach for modifying the sensor's response behavior by manipulating the magnetic thin film's anisotropy. These findings contribute to the advancement of SAW magnetic sensor technology, offering enhanced sensitivity and performance through the integration of magnetic thin films and SiO_2 layers.

Index Terms—Surface acoustic wave (SAW), magnetic field measurement, thin film of Nickel, theoretical model.

I. Introduction

Over the past two decades, significant progress has been made in the field of magnetic sensors using magnetoelastic thin films, also known as magnetostrictive materials. These sensors utilize the interaction between magnetization and strain in composite structures typically made of magnetic and piezoelectric materials enabling the transduction of strain (charge, voltage or modulation) [1,2]. Their primary application is in detecting current and magnetic fields for various domain nondestructive testing, medical applications (biosensing, bio magnetic signals measurements) [3,4].

There are two main measurement principles in these sensors. The first is called the direct magneto-electric effect, where an AC magnetic field induces magnetization oscillations. This causes stress in the piezoelectric material, resulting in a voltage across the piezoelectric layer. The sensitivity of this effect, known as the magnetoelectric coefficient α_{ME} , is highest when the AC magnetic signal matches the electromechanical resonance frequency of the structure [1,2]. However, using this design under resonance conditions limits its ability to detect both DC and AC magnetic fields with the same sensitivity.

The second principle is the ΔE effect, which involves modulating the frequency in a resonant electromechanical structure. This effect

overcomes the limitations of the direct magneto-electric effect but has a reported limit of detection (LOD) of $\frac{1 nT}{\sqrt{Hz}}$, which is relatively modest compared to the earlier method.

Recently, there has been renewed interest in integrating magnetoelastic thin films with surface acoustic wave (SAW) devices for various sensor applications. One approach focuses on increasing the proportion of the magnetoelastic thin film to the wavelength by using confined acoustic waves, which enhances the ΔE effect. The second approach involves exploring Ferro Magnetic Resonance (FMR) driven by acoustic waves, occurring when the operational frequency of the surface acoustic wave (SAW) matches the frequency of FMR.

Current research has explored various strategies to further enhance sensitivity. These strategies include using functionalized Love waveguides [5,6], thin film bulk acoustic waves [7], and the direct utilization of magnetoelastic materials as Love waveguiding layers on ST-Quartz-cut. This direct usage allows for reaching the inherent limit sensitivity of the magnetoelastic thin film [8,9,10].

In contrast to previous studies, which focused on shear waveguided surface acoustic wave magnetic sensing involving the deposition of the magnetoelastic layer atop the waveguide, our innovative approach marks a significant advancement. By successfully inducing magnetic anisotropy through substrate annealing at 500°C, we have enabled the

deposition of the magnetic thin film before the guiding layer. This breakthrough enhances sensitivity and allows the guiding layer to act as an effective protective shield, guarding the film against potential degradation. Furthermore, our study demonstrates the feasibility of tailoring the device's response behavior by reducing the magnetic field anisotropy magnitude.

II. Designing, manufacturing and integrating of devices

The SAW sensor used in this study were constructed as delay lines, featuring two interdigital transducers (IDT). Specifically, we selected a piezoelectric substrate made of ST-Cut Quartz with a thickness of $500 \mu\text{m}$. Surface acoustic waves were generated using Ti (20 nm) / Au (200 nm) interdigital transducers, the wavelength is close to $16 \mu\text{m}$. The SAW delay line exhibited a central frequency of 305.75 MHz for the shear wave. Following the fabrication of the SAW device, we enhanced its functionality by depositing a precisely controlled 100 nm thick Nickel layer with a 2 mm width using the evaporation technique. For a visual representation of the SAW device fabrication process and integration, please refer to figure 1, which also includes an optical image of the device.

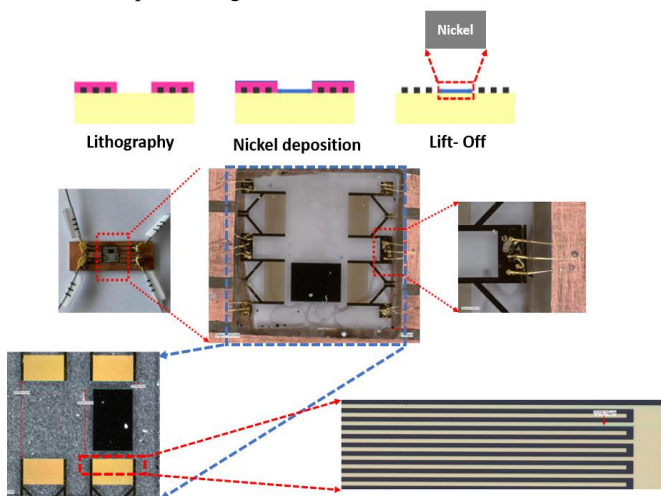


Figure 1 : Steps of the IDTs fabrication process, optical image of the fabricated device and integration overview.

III. Magnetic characterization of Nickel

The initially isotropic Nickel layer, as-deposited, lacked the desired properties for serving as a magnetic field-sensitive layer. To address this issue, an extensive investigation was carried out to identify the optimal annealing temperature for Nickel deposition on ST-cut Quartz. The primary goal was to utilize the Quartz substrate's thermal coefficient to induce thermal stress and therefore magnetic anisotropy within the Nickel layer, leading to the establishment of distinct easy and hard axes. This anisotropy is a crucial factor in creating a highly sensitive SAW sensor with substantial magnetoelastic coupling, enabling it to respond effectively to changes in the applied magnetic field. After thorough experimentation, the ideal annealing temperature was determined to be 500°C , and a vacuum furnace was employed to achieve the desired outcomes.

To assess the in-plane magnetization, a Vibrating Sample Magnetometer (VSM) was used, applying the magnetic field along both the x and y axes. As depicted in figure 2, the results reveal a significant uniaxial anisotropy, where the x-axis corresponds to the Hard-magnetic axis (indicated in blue), and the y-axis represents the Easy-magnetic axis (highlighted in red). The estimated value of the anisotropy field (H_A) was approximately 350 Oe .

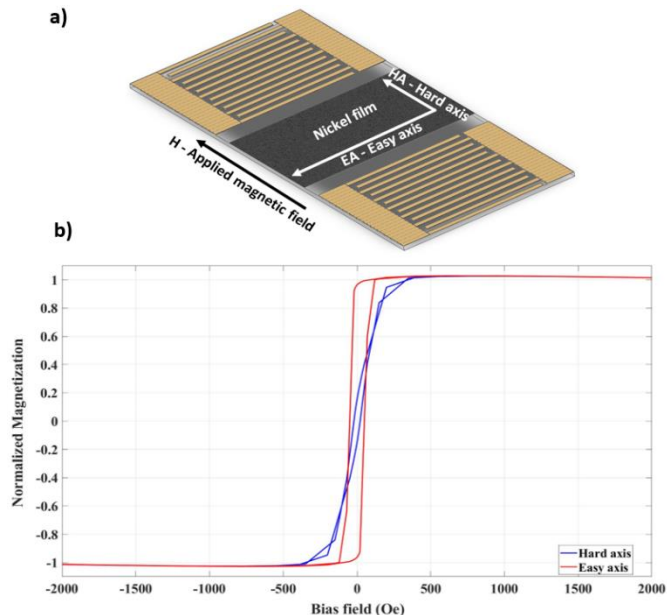


Figure 2 : a - Direction of magnetic field application in respect of surface acoustic wave propagation. b - Nickel thin film magnetization characteristics measured along the easy axis (red) and the hard axis (blue).

IV. Theoretical model

The authors of this study have previously developed an equivalent piezomagnetic model to investigate the magnetoelastic coupling in piezo-electro-magnetic composites. For a more comprehensive understanding, readers are referred to the detailed information provided in [6,11].

The piezomagnetic equations are derived by considering the propagation of a magnetoelastic wave in a ferromagnetic thin film, which is deposited on a piezoelectric substrate. The coupled equations for the mechanical and magnetic systems, namely Newton's equation of motion and the Landau-Lifshitz equation, are linearized around a ground state position of the magnetization. The specific direction and magnitude of the bias magnetic field determine the position of the ground state magnetization. The piezomagnetic equations are given by :

$$\rho \frac{\partial^2 u_i}{\partial t^2} = \frac{\partial \sigma_{ij}}{\partial x_j}, \quad (1)$$

$$\frac{\partial b_i}{\partial x_i} = \frac{\partial (u_0 (h_i + m_i))}{\partial x_i} \quad (2)$$

Where, the variable ρ represents the density of the ferromagnetic thin film, u_i the components of the displacement of particles in the film, and x_i the Eulerian coordinates (utilizing Einstein's summation

convention where i, j, k , and l range from 1 to 3, corresponding to x, y, z axes). In the model the components of the dynamic stress tensor σ_{ij} and of the dynamic magnetic induction b_i are given by :

$$\sigma_{ij} = (C_{ijkl} + \Delta C_{ijkl}) \frac{\partial u_k}{\partial x_l} - q_{ij} h_l, \quad (3)$$

$$b_i = q_{ijkl} \frac{\partial u_k}{\partial x_l} + u_{il} h_l, \quad (4)$$

These equivalent piezomagnetic constitutive equations involves the elastic stiffness constants C_{ijkl} and the corrections to the effective magnetic permeability μ_{ij} and elastic stiffness constants corrections ΔC_{ijkl} .

$$u_{il} = u_0 (\delta_{il} + \chi_{il}), \quad (5)$$

$$\Delta C_{ijkl} = b_{ijmn} (M_n^0 q_{mkl} + M_m^0 q_{nkl}), \quad (6)$$

b_{ijmn} are the magnetoelastic constants. Here the magnetostrictive is supposed isotropic and b_{1111} corresponds to $b^{\nu,2}$ in Callen's notation [12]. The piezomagnetic constants q_{ijk} , as well as the expressions for the magnetic susceptibility χ_{il} , can be found in [13]. As ΔC_{ijkl} (as shown in Eq. (6)), both q_{ijk} and χ_{il} depend on the static magnetization \mathbf{M}^0 of the magnetostrictive film and so on the applied external magnetic field. To take into account all the complexity of the magnetization process in thin magnetic films, the link between the external applied magnetic field and the induced static magnetization used in the model is the one obtained from the measured magnetization characteristics (see figure 2b).

The velocity of the surface acoustic waves propagating in the multilayer system composed of the magnetostrictive thin film, the piezoelectric substrate and the SiO_2 layer are obtained with the described effective piezomagnetic material model, in conjunction with the numerical Legendre/Laguerre polynomial expansion method described in details in [11]. The phase shift of the S_{21} parameter $\Delta\varphi$ is linked to the velocity variation Δv of the considered SAW mode by:

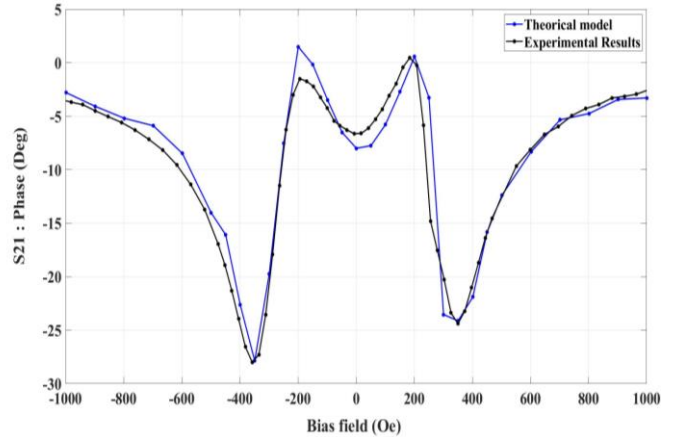
$$\frac{\Delta\varphi}{\varphi_0} = \frac{\Delta v}{v_0}, \quad (7)$$

where $\Delta v = v(H) - v_0$ with v_0 the velocity of the SAW without magnetic field and $v(H)$ the velocity for a given applied magnetic field H . Moreover, $\Delta\varphi = \varphi(H) - \varphi_0$ with $\varphi(H)$ the S_{21} parameter phase for a given applied magnetic field H and $\varphi_0 = 2\pi f \frac{L}{v_0}$ where L is the propagation distance and f the used frequency.

In this study, we focus on a uniaxial thin film consisting of sputtered nanostructured Nickel subjected to a bias magnetic field (with a magnetoelastic constant of $b^{\nu,2} = 5 \text{ MPa}$ and an anisotropy field of $H_A = 350 \text{ Oe}$). We assume that the magnetization of the thin film remains confined within the film plane. In our calculations, the magnetic field is applied perpendicular to the easy axis of the magnetostrictive thin film.

V. Experimental Results Versus Theoretical Model

A measurement was conducted to analyze the phase variation of the SAW sensor under different applied fields. The Shear wave exhibited



a phase shift difference between minimum and maximum of approximately 30° for a propagation path of 2 mm . Figure 3, demonstrate a remarkable agreement between theoretical predictions and experimental data.

Figure 3 : The S_{21} phase response of the SAW delay line, operating at frequencies of 305.75 MHz is shown as a function of the bias magnetic field applied along the hard axis of the Nickel thin film. The experimental result is depicted in black, while the theoretical results shown in blue.

Figure 4 shows that, in accordance with expectations for a shear horizontal surface acoustic wave, and considering the alignment of the easy relative to the propagation direction, the evolution of the phase with respect to the bias magnetic field applied along the hard axis of the thin nickel film deposited on the ST-Cut quartz substrate, is dominated by the C_{66} elastic stiffness constant.

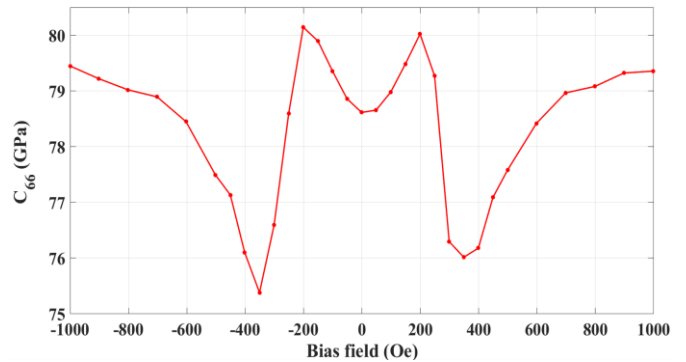


Figure 4 : Magnetic field dependency of C_{66} elastic stiffness constant when a bias magnetic field is applied along the hard axis of a Nickel thin film on Quartz ST-Cut.

Figure 5, provides a theoretical investigation using the model outlined in part IV, that examines the influence of adding SiO_2 layer on top of magnetic thin film. As described above we calculate first the velocity shift versus applied magnetic field, and we deduce the phase shift.

The study shows that as we increase the thickness of the SiO_2 layer, the difference between the maximum and minimum phase shift also increases, indicating a higher device sensitivity. However, this sensitivity improvement plateaus when the SiO_2 thickness reaches around $2.5 \mu\text{m}$, suggesting a saturation effect or sensitivity decrease. To understand this, we need to look at how SiO_2 affects the shear

wave properties. Normally, in Quartz, shear waves penetrate deeply into the substrate, but by adding SiO_2 , we gradually shift from deep penetration to more confined waveguiding. This transformation improves the mode's confinement near the sensitive layer, explaining the sensitivity enhancement.

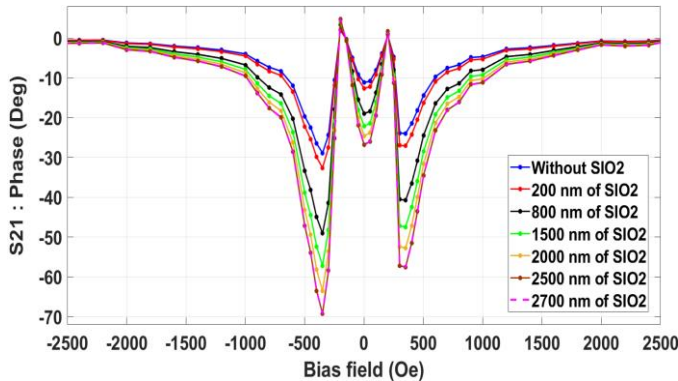


Figure 5 : The sensitivity enhancement of the SAW sensor, in terms of phase variation with the applied magnetic field, is observed with the increase in the thickness of the deposited SiO_2 layer.

As depicted in figure 3, the device's response to an applied magnetic field is nonlinear. To address this issue, we conducted a theoretical investigation into the effect of magnetic field anisotropy magnitude on the device's response. We reduced H_a from 350 Oe to 100 Oe. Figure 6, illustrates the comparison between the two responses, revealing a completely different behavior: the response is now linear around 0 and sensitivity is increased by a factor of around 1.5. These findings confirm the experimental results reported in reference [7,10]. As anticipated from the analysis above, the addition of SiO_2 further improves sensitivity. Our analysis suggests that the figure of merit for this design is directly proportional to the square of the magnetoelastic coupling divided by the magnetic field anisotropy magnitude [10].

$$FOM = \alpha * \frac{(b^{y,2})^2}{H_A}, \quad (8)$$

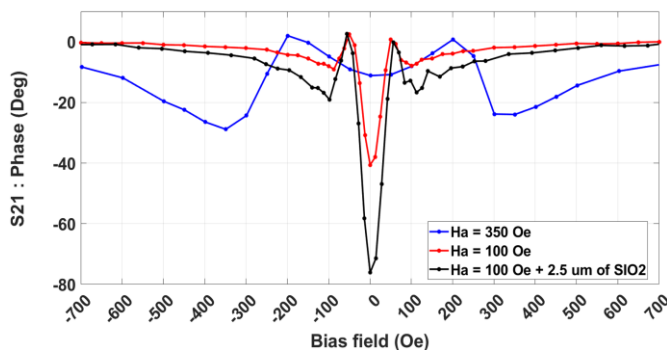


Figure 6 : Evolution of the SAW sensor response in terms of phase variation with the applied magnetic field .VS the reduction of the anisotropy saturation H_a and adding the optimum thickness of SiO_2 .

VI. Conclusion

In this study, we investigated theoretically and experimentally the magneto-elastic coupling in shear surface waveguide combined with

a Nickel film. By leveraging the thermal coefficients of ST-cut Quartz, we successfully induced magnetic anisotropy in the Nickel layer. We compared our experimental findings with a homemade piezomagnetic model. We initially examined the impact of adding SiO_2 layers on the sensitivity of device to applied magnetic field. We explored the effect of reducing magnetic anisotropy (H_a) on both response behavior and sensitivity. This study paves the way into the design of most promising SAW configuration to achieve highly sensitive magnetic field sensor.

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