Magnetization modification through magnetoelastic effect in a thin Nickel film

Author: Miquel Ortells Corral
Facultat de Física, Universitat de Barcelona, Diagonal 645, 08028 Barcelona, Spain.

Advisor: Ferran Macià

Abstract: Taking advantage of the magnetoelastic effect to modify magnetic states of ferromagnets, is becoming a trending alternative to the more traditional procedure of just applying an external magnetic field. In this paper, we study the dynamic magnetoelastic effect using surface acoustic waves as a function of the different magnetic states in a hybrid device made of a piezoelectric substrate and a Nickel thin film. Our data shows that the absorption of the acoustic waves changes with the applied magnetic field. We identify resonance peaks that vary with the acoustic wave frequency, and we compare it with a conventional ferromagnetic resonance technique.

I. INTRODUCTION

Traditionally, variation of magnetization, $\boldsymbol{M}$, is achieved by means of an external magnetic field, $\boldsymbol{H}$. To generate said field, in most cases, an electric current is needed, involving either energy dissipation due to Joule effect or ultra low temperatures to be able to work in a superconductor regime. Moreover, if the variation in magnetization is to be localized (within the μm, for example), even though the technology exists, it is expensive, far from efficient energy wise, and it generates stray fields, which may affect the neighboring magnetic moments.

Currently, alternative methods to modify magnetic states are gaining popularity, as for example, taking advantage of the coupling between magnetization and lattice deformation, which is called magnetoelastic effect[1]. To study this effect in a static regime, for example, one could apply a mechanical tension to a bulk of ferromagnet and study the changes in magnetization of the whole sample as a function of the applied tension or the deformation caused, if there were any. Another manner of achieving changes in the magnetization of a ferromagnet would be using electric fields. Even though electric fields and magnetization are not strongly coupled in general, one could apply the field to a piezoelectric, causing deformation. Depositing a magnetoelastic ferromagnet on a piezoelectric substrate and applying an electric field to this hybrid device, one can achieve lattice deformation of the ferromagnet, thus changing its magnetic state.

Commonly, the magnetoelastic effect is referred as the inverse magnetostrictive effect, which was first observed by J Joule in 1842. It was not until 1865 that the magnetoelastic effect was studied by E Villari[2]. This coupling between lattice deformation and magnetization or magnetic susceptibility is not only regarded as a more efficient alternative to currents, but also as a better way to create localized changes in magnetization, ranging down to the nanoscale and minimizing stray fields. Changes of $\boldsymbol{M}$ using the mangetoelastic effect have been mostly studied in a static regime as in [3].

Taking into consideration the setup of the hybrid device above mentioned, it should be possible to apply an oscillating electric field signal, creating an oscillating deformation both in the piezoelectric and the ferromagnet[4]. The deformation is typically in the form a surface acoustic wave (SAW, see section II-C) and in the range of the microwaves. The changes in magnetization achieved this way, involve magnetization dynamics, and since they are performed in the microwaves, the variation of magnetic states is resolved spatially in microns and temporally in nanoseconds.

This paper aims to study the dynamic magnetoelastic effect on a Nickel thin film induced by SAW. The propagation of the deformation wave is measured in a hybrid device made of a piezoelectric substrate ($LiNbO_3$) and a Nickel thin film 10 nm thick. It is found that different magnetic states produce attenuation at different frequencies of the deformation wave that propagates through the device[5]. To compare the results, microwave ferromagnetic resonance of another identical Nickel thin film 10 nm thick is performed as well.

II. THE THEORY

A. Magnetoelastic coupling

Magnetization is, in an isolated atom, a contribution of electron spin, electron orbit and spin-orbit interaction. By Hund's rule, to minimize energy in absence of magnetic field, the first rule states that electron spins tend to align in the same direction, and the second rule states the same for the angular momentum of their orbits,when permitted by the first rule. This may work for certain materials, but it is certainly a bold approximation for solids, and tends to fail at calculating total magnetic moments.

In a more general approach, one should take into consideration anisotropy in the cells of a crystal, and interaction between atoms in the same cell at the very least. Notwithstanding, the general idea of Hund holds: the electronical configuration of individual magnetic moments must minimize the energy of the system. Because ferromagnetism is a direct consequence of neighboring interaction, in a ferromagnet, lattice configuration should be coupled with magnetization, so that deformation of

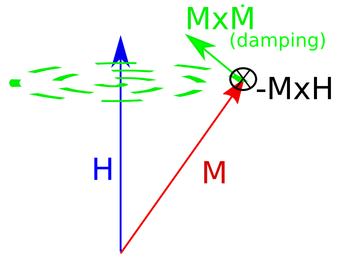

FIG. 1: Schematic example of precession of magnetization in a magnetic system

the lattice is translated to a change in magnetic susceptibility. That is called the magnetoelastic effect, and different approaches can be found in[1][5]. In this paper, this new effective field caused by strain $\boldsymbol{H}_{\mathrm{me}}$ will be regarded as another term in the total effective field $\boldsymbol{H}_{\mathrm{eff}}$ with no further effects.

B. Magnetization Dynamics

The study of magnetization dynamics, is often limited to the semiclassical approach and starts by looking at the Landau-Lifschitz-Gilbert equation for the precession (see Fig. 1) of magnetization, $\boldsymbol{M}$, around a static magnetic field, $\boldsymbol{H}$:

$$\dot{\boldsymbol{M}}(\boldsymbol{r},\boldsymbol{t}) = -\gamma(\boldsymbol{M}\times\boldsymbol{H}_{\mathrm{eff}}) + \frac{\boldsymbol{\alpha}}{|\boldsymbol{M}|}(\boldsymbol{M}\times\dot{\boldsymbol{M}}) \quad (1)$$

where $\boldsymbol{M}$ is magnetization of the material, γ is the gyromagnetic ratio, α is a phenomenological damping coefficient and $\boldsymbol{H}_{\mathrm{eff}}$ is the effective field, which contains the static magnetic field and any other contribution such as $\boldsymbol{H}_{\mathrm{me}}$. A solution to this equation, is $\boldsymbol{M}$ parallel to $\boldsymbol{H}_{\mathrm{eff}}$, leading to no precession.

If magnetization did not depend on space, but only depended on time, one could apply an adapted harmonic oscillator solution for small amplitudes. This solution indicates the precession (see Fig. 1) of magnetization around $\boldsymbol{H}_{\mathrm{eff}}$, with a working frequency depending on the magnitude of $\boldsymbol{H}_{\mathrm{eff}}$. Because of this, it is expected a resonance behavior in the amplitude of the precession when exciting magnetization at its working frequency. For a paramagnetic system, the resonance frequency upon a static magnetic field would be $f_{\mathrm{r}} = \frac{\gamma}{2\pi}H_0$, with H_0 the external static field, that for a paramagnet is in good approximation of the same magnitude as H_{eff}. On the other hand, ferromagnetic materials exhibit strong interaction between atoms, creating additional terms in the effective field. If we consider the demagnetizing field $\boldsymbol{H}_{\mathrm{d}} = \overline{\boldsymbol{D}}\boldsymbol{M}$, where $\overline{D}$ is the demagnetizing tensor, the resonance condition for a $\overline{D}$ diagonal, changes to:

$$f = \frac{\gamma}{2\pi}\sqrt{(H_0 + (D_{\mathrm{x}} - D_{\mathrm{z}})H_{\mathrm{M}})(H_0 + (D_{\mathrm{y}} - D_{\mathrm{z}})H_{\mathrm{M}})} \quad (2)$$

where $H_{\mathrm{M}} = 4\pi M_{\mathrm{S}}$ is the amplitude of the field for the magnetic saturation of the material. Adding further terms to the effective field, like anisotropy and exchange fields, makes the solution to Eq. 2 more complicated, but contemplates the dependence of magnetization as a function of space and the appearance of spin waves[6].

In our experiment, the applied static magnetic field will go up to 50 mT at most, which experimentally locates the corresponding resonance frequencies between the hundreds of MHz and the GHz.

C. Surface acoustic waves (SAW)

Surface acoustic waves (SAW), or Rayleigh waves, were first observed by Lord Rayleigh in 1887, and consist in a composition of transverse and longitudinal motion with respect of the propagation direction, meaning that for an isotropic solid, the trajectory of a single particle would be an ellipse. These waves have most of their energy confined between the surface and a depth of λ inside the elastic medium they propagate through. Moreover, these perturbations are extremely sensitive to anomalies in the surface, which makes them perfect candidates for this experiment. Another advantage these waves have is that the propagation modes can be excited by surface devices, with no need of making the bulk of the solid oscillate. It is also important to notice that a SAW will have a wavelength several orders of magnitude shorter than an electromagnetic wave of the same frequency, reaching few microns in the microwave range and even nm. As mentioned above, when this strain wave is coupled with the magnetoelastic effect, magnetic states can be modified at the nanoscale due to the short wavelength of the SAW, being able to control magnetization locally at a very low cost of energy.

To generate SAW, it is common practice to place Interdigital Transducers (IDTs) on a piezoelectric substrate[7]. An IDT consists of a two comb-like electrodes, interpenetrated, so that when an AC voltage is applied to the electrodes, an alternate electric field is generated on the piezoelectric material by each comb finger (Fig. 2). This electric field, due to the inverse piezoelectric effect, creates a periodic deformation on the surface of the material that propagates through it. A second IDT can act as a receiver by reading the electric field generated by the deformation in the piezoelectric.

When working with IDTs, only a mode with acoustic wavelength equal to the separation between the teeth of the transducer (or higher harmonics) will be excited, since the rest of SAW modes get attenuated due to interference before leaving the area of the transducer.

III. SAMPLE FABRICATION

To perform the experiment, a device with a similar configuration to Fig. 2 is fabricated. We start with a

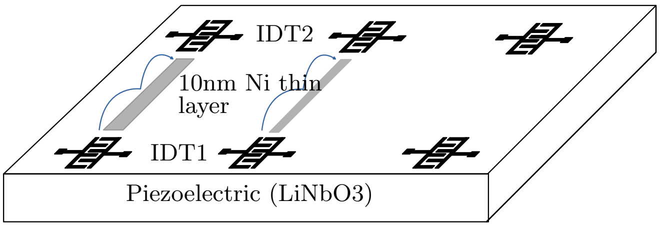

FIG. 2: Drawing of the hybrid sample with the piezoelectric substrate and the Nickel thin film. In this drawing, IDT1 would be the emitter and IDT2 the receiver of the signal.

piezoelectric substrate made of $LiNbO_3$ and the IDTs imprinted on it. This was provided by Dr. Alberto Hernandez[4]. The IDTs, have a separation between their fingers that nominally allows an acoustic wave of $f_0 = 125$ MHz, and its higher harmonics to be propagated (Fig. 3).

Secondly, to achieve a strain wave travelling along the Ni thin film, the ferromagnetic material is deposited on the piezoelectric substrate, directly in the path of a SAW, using a liftoff technique. This fabrication procedure was performed mostly in 'Sala Blanca' of ICMAB (UAB), with Ferran Macià, and consists of several steps:

- First, the substrate is submerged in light alcohol to get rid of the debris. Then it is blown upon with an inert gas and heated up to 70°C to help evaporate any fluid left in the surface.
- Afterwards, the photoresist solution is applied on the center of the substrate, and by spinning it (in this case 4000 rpm), the solution spreads thin all over the material. By changing the spinning speed, it is possible to control the thickness of the photoresist. This technique is called spin coating. The sample is later soft baked to better fix the photoresist to the piezoelectric substrate.
- With a laser, a pattern is drawn unto the photoresist, so that later, with a developer fluid, only the exposed photoresist will be removed.
- The desired material is deposited with e-beam vaporization (in our case, a stripe of Nickel, 10 nm thick). This was performed at ICN2 by Ferran Macià.
- Finally, the remaining photoresist is washed off, leaving only the deposited Nickel in the form of the pattern drawn with the laser.

Additionally, the IDT are wirebonded to the contacts in the edges of the sample so that an electric signal can be applied to the IDTs.

At the same time the Ni thin film is deposited on the piezoelectric substrate, in the ICN2, another identical Ni thin film 10 nm thick is deposited on silicon, creating a waffer. The fabrication of this additional sample is to test Ni properties separately and compare the effects of magnetic states with those induced by the magnetoelastic effect in the hybrid device.

IV. EXPERIMENTAL DATA

The experiment performed aims to study the coupling between SAW and magnetizationin a thin film as a function of the magnetic state. To do so, a static magnetic field is applied, by means of an electromagnet, whose intensity is controlled by a power source. Between the poles of the magnet, the sample will be placed, and a Hall probe will register the magnetic field. Also, a network analyser will provide the input signal in the desired frequency as an electromagnetic wave, and read the output. The power source, the Hall probe and the network analyser are all connected to a computer, that controls the devices and reads the outputs using Labview. The acquired data consists of measurements of S_{12}, which is the direct transmission coefficient of the signal, and is related to the amount of transmitted energy along the sample. All of the measurements were performed in UB, Facultat de Física.

A. SAW driven magnetoelastic effect

In the first part of the experiment, the S_{12} of a SAW travelling through a ferromagnet as a function of the magnetic state is studied. The sample used is the hybrid device described above, made of a piezoelectric substrate of $LiNbO_3$, with a Nickel thin film 10 nm thick deposited on it. The sample is connected to a network analyser using the contacts belonging to the IDTs in the middle (see Fig. 2). The network analyser will provide an electric signal that upon reaching IDT1, generates a SAW that travels both through the piezoelectric and the Ni thin film (see Section II-C). IDT2 is excited by the electric field the SAW generates on the piezoelectric, and the network analyser reads the output. By multiplying input and output signals, the network analyser can measure difference in amplitude (S_{ij}) and phase shift. For this paper, only the measurements of S_{12}, the transmission coefficient, have been taken into consideration.

A first measurement with applied magnetic field 0 T, reveals transmission peaks for $f_0 = 124$ MHz $\pm$ 1 MHz and its harmonics (see Fig. 3). Also, there appears to be an oscillating offset that becomes greater with higher frequencies. This is probably an artifact of the wires and plays no further role in this experiment, so it is disregarded. Additionally, for frequencies higher than approximately 1.2 GHz, it is found that most of the contribution to S_{12} comes from the IDTs performing as antennae, transmitting and receiving microwaves through the air. Therefore, a time domain technique has been applied to represent only the signal created by the SAW. The technique is called 'gating', and consists in performing

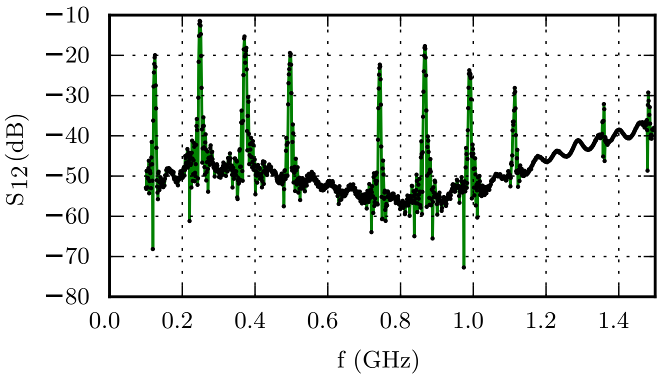

FIG. 3: S_{12} as a function of different frequencies at magnetic field 0 T.

the Fourier antitransformation on the ensemble of data, passing from the frequency domain, to the time domain. There, it is possible to see the pulses travelling through the line, and since electromagnetic waves are faster than SAW, one can cut out the first pulse, leaving only the pulses belonging to the SAW.

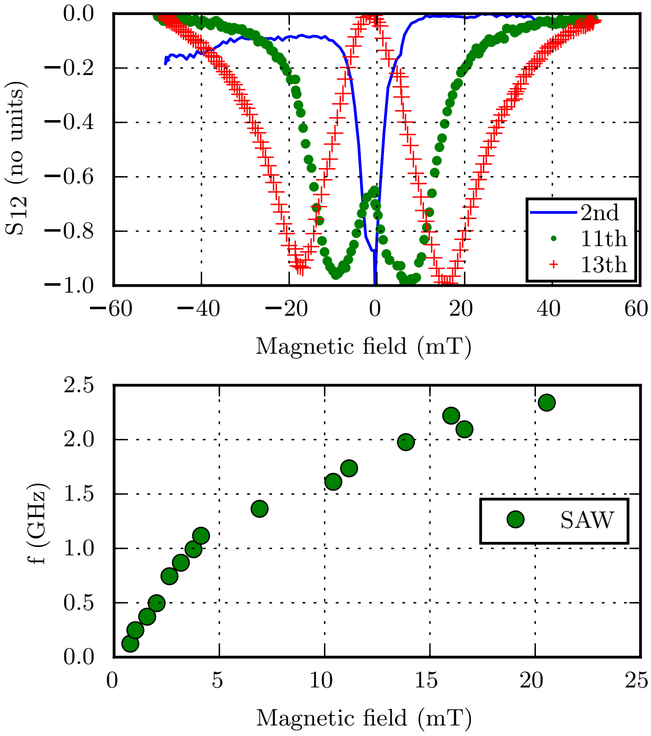

FIG. 4: (A) Examples of normalized S_{12} as a function of applied magnetic field, showing the behavior of the 2nd, 11th and 13th harmonics of the fundamental frequency. (B) For each frequency, the magnetic field at which the abrupt drop in S_{12} appears.

When focusing on the first harmonics, it is observed a significant drop in transmission at applied magnetic field 0 T. As frequency increases, this abrupt drop splits in two (see Fig. 4-A). This drops in transmission could mean that some of the acoustic energy carried by the SAW was absorbed by the sample. Also this absorption peaks occur at different magnetic fields for different frequencies. All this facts seem to indicate that this absorbed energy is dissipated in the thin ferromagnetic film of Nickel, much likely as in traditional microwave FMR, where the energy would be provided by an electromagnetic wave. This drop is treated like a resonance peak, and a double Lorentzian-like function has been adjusted for every harmonic using Python, obtaining the magnetic field at which the drop in transmission occurs. This results have been presented in Fig. 4-B.

B. Ferromagnetic resonance (FMR)

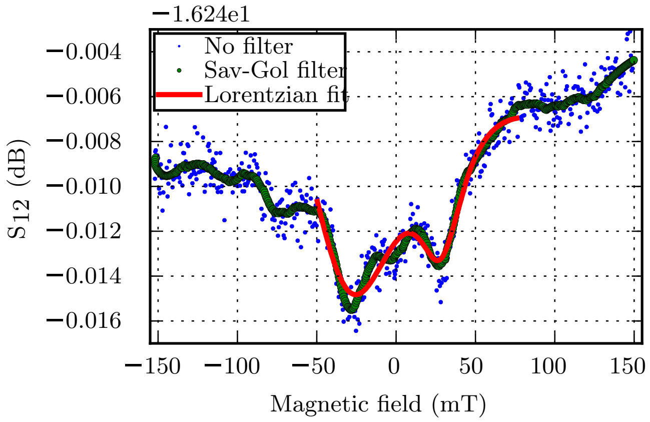

FIG. 5: Experimental data for $f = 3$ GHz. The Lorentzian fit has some problems fitting this and higher frequencies due to the unexpected behavior around $B = 0$ T.

In order to compare the obtained results with a conventional probing method of magnetic states, FMR is performed on the Nickel thin film 10 nm thick deposited in a sylicon waffer. The waffer is cleaved and then put in a coplanar wave guide, which is connected to the network analyser. Placed between the poles of the electromagnet, the Nickel thin film will be subjected to static magnetic fields ranging from -150 mT up to 150 mT, and an input signal in the range of the GHz will be used to perform the resonance. Again by multiplying input and output signals, measurements of the S_{12} are performed.

Using a Savitzky-Golay filter to minimize the noise, it is observed sudden diminishing amplitude of the S_{12} coefficient, depending on the frequency and the applied field (see Fig. 5). Much like in the first part of the experiment, for frequencies below 1.5 GHz, it is found a single absorption peak, while for higher frequencies, this peak starts to double. These peaks are interpreted as energy absorption peaks corresponding to ferromagnetic resonance (see Fig. 5), fitted using a double peak Lorentzian function like in the first part of the experiment, for a range of frequencies. A comparative graphic containing the resonance field for each frequency both for FMR and SAW driven

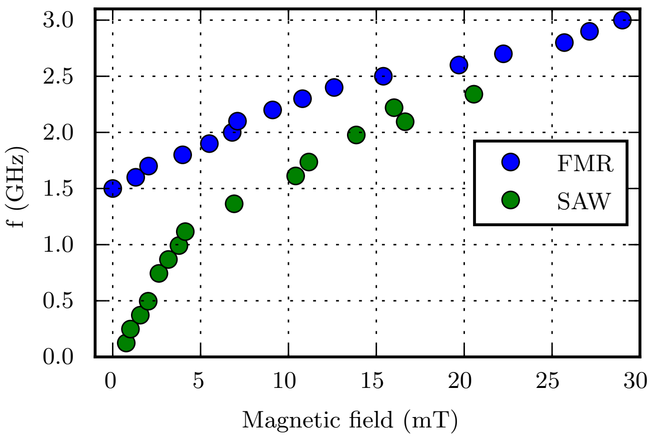

FIG. 6: Resonance fields for FMR and SAW driven magnetoelastic effect.

magnetoelastic effect, is presented in Fig. 6. Although both phenomena exhibit resonance behavior, when compared, a small discrepancy is observed in the whole range of frequencies studied.

V. CONCLUSIONS

Our experiments show that the magnetoelastic interaction of a SAW with a Nickel thin film allows us to perturbate the magnetic state of the Nickel dynamically. This provides an alternative to vary magnetization locally without directly applying an external oscillating magnetic field.

We observed that the transmission coefficient of a SAW travelling through a Nickel thin film, depends on the applied magnetic field. We show that absorption peaks appear at different applied magnetic fields depending on the frequency of the SAW.

Our data seem to indicate that the induced magnetization dynamics is similar to the FMR[5]. However, we found a small discrepancy between FMR measurements and SAW induced magnetoelastic effect, as shown in Fig. 6. The causes of this discrepancy may be:

- In this experiment, FMR is performed so that the wavelength of the electromagnetic wave varies from 1 m to 1 dm, causing magnetization to be weakly dependent on space. On the other hand, the SAW have a wavelength of the order of few microns, leading to a strong space dependence of magnetization. This might cause a dominant exchange interaction, and might induce spin waves in the sample.

- In Fig. 6, it is observed that at frequency 1.5 GHz, the corresponding resonance field is 0 T. This seems to indicate that the material exhibits a small anisotropy, that could have been acquired during deposition on the silicon wafer.

Acknowledgments

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