Large non-reciprocal propagation of surface acoustic waves in epitaxial ferromagnetic/semiconductor hybrid structures

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Abstract

Non-reciprocal propagation of sound, that is, the different transmission of acoustic waves traveling along opposite directions, is a challenging requirement for the realization of devices like acoustic diodes and circulators. Here, we demonstrate the efficient non-reciprocal transmission of surface acoustic waves (SAWs) propagating along opposite directions of a GaAs substrate coated with an epitaxial Fe3Si film. The non-reciprocity arises from the acoustic attenuation induced by the magneto-elastic (ME) interaction between the SAW strain field and spin waves in the ferromagnetic film, which depends on the relative angle between SAW propagation direction and magnetization. The acoustic transmission non-reciprocity, defined as the difference between the transmitted acoustic power for forward and backward propagation under ME resonance, reaches record values of up to 20%. The experimental results are well accounted for by a model for ME interaction, which also shows that non-reciprocity can be further enhanced by optimization of the sample design. These results make Fe3Si/GaAs a promising platform for the realization of efficient non-reciprocal SAW devices.
I. INTRODUCTION

In the last years, there has been an increasing interest in the realization of non-reciprocal acoustic systems for the efficient manipulation of sound.\(^1\) There are several strategies that have been proposed to create such kind of systems. For instance, as acoustic propagation is reciprocal in linear systems preserving time reversibility,\(^2\) one way to obtain non-reciprocal transmission is to introduce non-linear effects.\(^3,4\) Another possibility is to preserve linearity, but to break time-inversion symmetry by e.g. coupling the acoustic vibrations to a circulating fluid.\(^5\) An alternative strategy is to induce local non-reciprocity by taking advantage of topologically protected acoustic modes propagating along the boundaries of periodic structures.\(^6-9\)

The previous approaches have been mainly applied to low-frequency sound waves ($\lesssim 1$ MHz) with wavelengths on the order of few millimeters. Therefore, their implementation in miniaturized, high-frequency acoustic devices like those based on surface acoustic waves (SAWs) might be challenging. SAWs are elastic vibrations propagating along the surface of a solid with wavelengths reaching down to the sub-µm regime and frequencies of several GHz. Due to their efficient piezoelectric generation and low propagation velocities, SAWs have been successfully applied in on-chip acoustic devices as frequency filters, as well as for other kinds of signal processing.\(^10\)

Non-reciprocal propagation has been observed for SAWs traveling along non-magnetic metals\(^11\) and semiconductor heterostructures.\(^12\) In the former case, non-reciprocity was caused by coupling the lattice strain to the cyclotron motion of free carriers under a strong magnetic field, while in the second case it was related to the non-symmetric transfer of momentum between the acoustic wave and electric currents applied parallel or anti-parallel to the SAW. Another way of controlling SAW propagation is to couple the acoustic fields to the magnetization of a thin ferromagnetic material placed on the sample surface.\(^13-23\) As the time-reversal symmetry is broken in a ferromagnet, the magneto-elastic (ME) interaction will cause non-reciprocal acoustic propagation.\(^24-28\) This effect has been demonstrated for SAWs propagating along a LiNbO\(_3\) substrate covered by a poly-crystalline Ni film.\(^14,15,20\) However, the intrinsic structural disorder of poly-crystalline Ni leads to a magnetization response with a relatively large Gilbert damping coefficient $\alpha \sim 0.05$,\(^29\) and therefore to wide ME resonances with weak non-reciprocal effects.\(^14,20\)
Here, we present an alternative hybrid structure for non-reciprocal ME applications consisting of a Fe$_3$Si film grown epitaxially on a GaAs semiconductor substrate. Fe$_3$Si is a binary Heusler-like ferromagnetic metal which has attracted interest as possible component in magneto-electronic devices.$^{30,31}$ As its cubic crystal structure is almost lattice-matched to the GaAs substrate (mismatch $\leq 0.01\%$), it is possible to grow epitaxial films with high interfacial perfection and structural quality,$^{32-34}$ thus leading to narrow ferromagnetic resonance (FMR) lines$^{35,36}$ characterized by damping coefficients as low as $\alpha \approx 3 \times 10^{-4}$. Moreover, in contrast to other epitaxial ferromagnetic-semiconductor hybrid structures like GaMnAs/GaAs where efficient ME coupling has also been reported,$^{16,38-41}$ the high Curie temperature (above 800 K)$^{42}$ of Fe$_3$Si makes this material suitable for room-temperature applications. Finally, the shear magneto-elastic coefficient, $b_2$, for thin films of this material has been estimated to be $b_2 \approx 2 - 7$ T.$^{36}$ This value is of the same order of magnitude as e.g. crystalline Fe and Ni,$^{43}$ thus making Fe$_3$Si a promising material for ME applications.

In this contribution, we demonstrate the non-reciprocal propagation of high-frequency SAWs (3.45 GHz) traveling on a Fe$_3$Si/GaAs hybrid structure. For well-defined orientations of the magnetization in the Fe$_3$Si film, the ME interaction transfers energy from the acoustic into the magnetic system, thus inducing SAW attenuation. The high structural quality of the film leads to very narrow ME-resonances lines (i.e., with full widths at half maximum as narrow as 2 mT). The strength of the ME-induced attenuation depends on the relative angle between magnetization orientation and SAW wave vector. The resulting acoustic transmission non-reciprocity, defined as the difference between the transmitted acoustic power for forward and backward SAW propagation under ME resonance, reaches values up to 20%. This non-reciprocal behavior is significantly larger than that reported in Ni/LiNbO$_3$ hybrid structures operating at similar frequencies, thus making Fe$_3$Si/GaAs structures a promising platform for the realization of non-reciprocal SAW devices.

We have organized the manuscript as follows. Section II describes the fabrication process and the experimental procedure. In Section III, we characterize the magnetic and acoustic properties of our sample, and we present the experimental results on the non-reciprocal SAW propagation. In Section IV, we compare the results with the predictions of the theoretical model and give an outlook. Finally, Section V summarizes the main results of the manuscript.
II. EXPERIMENTAL DETAILS

The experiments were performed on a slightly non-stoichiometric Fe$_{3+x}$Si$_{1-x}$ film with $x = 0.16$ (corresponding to a Si concentration of 21%) grown epitaxially on a GaAs(001) substrate by molecular beam epitaxy. Despite the non-stoichiometry, we will further refer to the material as Fe$_3$Si since the structural and magnetic properties of Fe$_{3+x}$Si$_{1-x}$ epitaxial alloys are qualitatively very similar for $-0.07 \leq x \leq 0.6$.\textsuperscript{44,45}

We fabricated the magneto-acoustic device sketched in Fig. 1 as follows. First, a clean c(4+4)-reconstructed GaAs surface was prepared by growing a 500-nm-thick GaAs buffer layer in a dedicated III-V semiconductor growth chamber using conventional growth parameters. The substrate was then transferred in ultra-high-vacuum into an As-free chamber, where the Fe$_3$Si film with a thickness $d = 50$ nm was grown by co-deposition from high temperature effusion cells onto the GaAs at 200 °C.\textsuperscript{32} Next, we patterned the Fe$_3$Si film by optical lithography and wet chemical etching into octagonal mesas with a distance $L = 1.2 \text{ mm}$ between opposite sides. In the final fabrication step, we deposited pairs of interdigital transducers (IDTs) for the generation and detection of SAWs. The IDTs were patterned on the GaAs substrate at the opposite sides of the octagonal Fe$_3$Si mesa by electron beam lithography, metal evaporation and lift-off. Each IDT consists of 180 split-finger\textsuperscript{10} pairs with a 150 $\mu$m-wide aperture. The finger periodicity determines the SAW wavelength, which was set to $\lambda_{\text{SAW}} = 800 \text{ nm}$.

Radio-frequency (RF) signals applied to the IDTs excite SAWs propagating with wave vector $k_{\text{SAW}} = 2\pi/\lambda_{\text{SAW}}$ parallel ($+k_{\text{SAW}}$) or anti-parallel ($-k_{\text{SAW}}$) to the [110] direction of the Fe$_3$Si/GaAs hybrid structure. The acoustic delay line was characterized by measuring with a vector network analyzer the amplitude of the power transmission coefficient $s_{21}$ of a SAW traveling from IDT$_1$ to IDT$_2$ ($+k_{\text{SAW}}$), as well as its $s_{12}$ counterpart ($-k_{\text{SAW}}$). As the SAW is a Rayleigh mode, the strain tensor consists of three non-zero $\varepsilon_{XX}$, $\varepsilon_{ZZ}$ and $\varepsilon_{XZ}$ components,\textsuperscript{46} expressed with respect to a rotated reference frame where the X−, Y−, and Z−axes point along the [110], [\bar{1}10] and [001] crystallographic directions, respectively.

The ME experiments were performed by placing the magneto-acoustic device between the poles of an electromagnet for the application of a static in-plane magnetic field, $\mathbf{H}$. The sample was mounted on an electrically controlled rotation stage that settles the angle $\varphi_H$ between $\mathbf{H}$ and the [110] surface direction of the Fe$_3$Si/GaAs hybrid structure (see Fig. 1).
FIG. 1. Schematics of the magneto-acoustic device. Interdigital transducers (IDTs) at opposite ends of an Fe$_3$Si film launch and detect SAWs with wave vectors $\pm k_{\text{SAW}}$ along the [110] crystallographic direction of the Fe$_3$Si/GaAs hybrid structure. The angles $\phi_H$ and $\phi_0$ determine the orientation of the external magnetic field, $\mathbf{H}$, and the equilibrium magnetization, $\mathbf{M}_0$, respectively, with respect to the [110] surface direction.

The angle $\phi_0$ determines the direction of the equilibrium magnetization, $\mathbf{M}_0$, defined as the direction that minimizes the magnetic free energy of the Fe$_3$Si film in absence of SAWs (see Supplemental Information). For each values of $\phi_H$ and the magnetic field strength, $H$, we measured both the forward ($s_{21}$, corresponding to a wave vector $+k_{\text{SAW}}$) and the backward ($s_{12}$, corresponding to $-k_{\text{SAW}}$) transmission coefficients of the SAW delay line. Then, we Fourier transformed the frequency-dependent measurements into the time domain to analyze the amplitude of the SAW-related transmission peak. All measurements were performed at room temperature.

III. RESULTS

The magnetic properties of the Fe$_3$Si/GaAs hybrid structure were studied by FMR experiments. The color plot of Fig. 2(a) displays the dependence of the FMR signal on the static $\mathbf{H}$ field applied along [110] (horizontal axis) and on the frequency of an ac magnetic field (vertical axis) applied perpendicularly to $\mathbf{H}$. The low magnetic field branch ($\mu_0 H < 10$ mT) of the FMR curve represents the unsaturated state, where $\mathbf{M}_0$ rotates towards $\mathbf{H}$ as the magnetic field strength increases. The high magnetic field branch ($\mu_0 H > 10$ mT) corre-
sponds to the saturated state, where \( \mathbf{M}_0 \) and \( \mathbf{H} \) are fully aligned. This behavior indicates that the [110] direction is one of the in-plane hard axes of the magnetization. The narrow FMR lines, with a width of less than 2 mT, attest to the good structural quality and low magnetic damping of the epitaxial material.\(^{37}\) Figure 2(b) summarizes the dependence of the FMR frequency, \( f_{\text{FMR}} \), on the magnetic field strength when \( \mathbf{H} \) is applied along [100] (black squares), [\( \overline{1}10 \)] (red circles) and [110] (blue triangles). The solid curves are fittings according to the theoretical model discussed in the Supplemental Information. The results confirm that the in-plane magnetization is dominated by the fourfold cubic crystalline anisotropy with easy axes pointing along \( \langle 100 \rangle \) and hard axes along the \( \langle 110 \rangle \) surface directions. The overlap of the [110] and [\( \overline{1}10 \)] curves indicates a negligible in-plane uniaxial anisotropy.\(^{35,36,47}\)

Figure 3(a) displays the dependence of \( s_{21} \) on the RF frequency applied to IDT\(_1\). The measurement was time-gated to remove the electromagnetic cross-talk between IDTs. The transmission spectrum shows a clear maximum at the IDT resonant frequency \( f_{\text{SAW}} = v_{\text{SAW}}/\lambda_{\text{SAW}} = 3.455 \text{ GHz} \), where \( v_{\text{SAW}} \) is the SAW propagation velocity in GaAs. By Fourier transforming the frequency spectrum, we also obtained the profiles of \( s_{21} \) in the time domain shown in Fig. 3(b). The peak at the time delay \( \Delta t \approx 610 \text{ ns} \) is attributed to the arrival of the SAW after traveling from IDT\(_1\) to IDT\(_2\). The value of \( \Delta t \) corresponds closely to the acoustic propagation time \( \Delta l/v_{\text{SAW}} \) over the center-to-center distance (\( \Delta l = 1.75 \text{ mm} \)) between the IDTs. The same peak is observed for the time-resolved \( s_{12} \) coefficient (i.e., for SAW transmission from IDT\(_2\) to IDT\(_1\)).

If the external magnetic field brings the frequency and wave vector of spin waves in the Fe\(_3\)Si film into resonance with those of the SAW, then the ME interaction will excite spin waves in the ferromagnet for certain angles between \( \mathbf{M}_0 \) and the SAW wave vector.\(^{15}\) Under these conditions, the ME coupling will convert acoustic into magnetic energy as the SAW propagates along the film, thus resulting in SAW attenuation.\(^{14–21}\) As indicated by the horizontal dashed line in Fig. 2(b), SAWs excited by the IDTs match spin waves with the same frequency in the Fe\(_3\)Si film for two different strengths of \( \mathbf{H} \) applied either along [110] or [\( \overline{1}10 \)]. Here, we have neglected the wave vector dependence of the spin wave frequency. This is justified because the spin wave stiffness constant \( D = 240 \text{ meV Å}^2 \) of Fe\(_3\)Si (cf. Ref. 48) leads to a frequency shift \( \Delta f \propto Dk^2_{\text{SAW}} \) for the spin waves of only 36 MHz with respect to the precession mode with zero wave vector measured in the FMR experiments.

The ME coupling was investigated by measuring \( s_{21} \) and \( s_{12} \) as a function of \( \mathbf{H} \) applied
FIG. 2. (a) Dependence of the ferromagnetic resonance (FMR) signal of the Fe$_3$Si film on the strength of a static magnetic field $\mathbf{H}$ applied along the [110] direction (horizontal axis), and the frequency of the ac field (vertical axis) applied perpendicular to $\mathbf{H}$. (b) FMR frequency, $f_{\text{FMR}}$, as a function of $H$ when the static magnetic field is applied along [100] (black squares), [110] (red circles) and [110] (blue triangles). The solid curves are fittings according to the theoretical model (see Supplemental Information). The horizontal dashed line indicates the frequency of the SAW ($f_{\text{SAW}}$) used in our magneto-acoustic device.

along the [1̅10] and [110] directions. We did not observe SAW attenuation for $\mathbf{H}$ parallel to [1̅10]. In contrast, the SAW is clearly attenuated for well-defined values of $\mathbf{H}$ applied along [110]. Figure 3(b) compares the time-resolved $s_{21}$ and $s_{12}$ coefficients for two magnetic field strengths applied at an angle $\varphi_H = -0.6^\circ$. Away of the ME resonance (for $\mu_0H = 7.3$ mT), the intensities of the $s_{21}$ (gray dashed curve) and $s_{12}$ (light red dotted curve) transmission peaks are exactly the same. When the magnetic field increases to $\mu_0H = 11.3$ mT, the acoustic and magnetic systems enter into resonance leading to a decrease of both peaks. Most important, the SAW attenuation under ME resonance is clearly different for SAWs
FIG. 3. (a) Dependence of $s_{21}$ scattering parameter (corresponding to the RF power transmission coefficient) on the RF frequency applied to IDT$_1$. The spectrum was time-gated to remove the electromagnetic cross-talk. The maximum transmission occurs at the resonance frequency $f_{SAW} = 3.455$ GHz. (b) Time-resolved $s_{21}$ and $s_{12}$ coefficients measured for $\varphi_H = -0.6^\circ$ for two different magnetic field strengths. The peak delays at $\Delta t = 610$ ns correspond to the SAW propagation time between the IDTs. The curves are normalized to the magnitude of the $s_{21}$ transmission peak for $\mu_0H = 7.3$ mT.

propagating with wave vectors $+k_{SAW}$ and $-k_{SAW}$. For $s_{21}$ (solid black curve), the ME coupling reduces the transmitted SAW power to 50% of the corresponding out-of-resonance value, while for $s_{12}$ (solid red curve) the transmission of the SAW peak is still 70% of the out-of-resonance one. The difference between these values yields a transmission non-reciprocity of 20% for SAWs traveling along opposite directions.

To get further insight into the non-reciprocal behavior, we have measured $s_{21}$ and $s_{12}$ for a range of $H$ and $\varphi_H$ values to determine the SAW attenuation $A = 1 - T$. Here, $T$ represents the area of the SAW transmission peak in the time-domain spectrum, normalized to the corresponding area for $H$ away from the ME resonance. Figure 4 shows the dependence of
FIG. 4. Dependence of the ME-induced SAW attenuation, $A$, on the magnetic field amplitude, $H$, for SAWs with $+k_{\text{SAW}}$ (black squares) and $-k_{\text{SAW}}$ (red circles). The panels show measurements taken for magnetic field angles: (a) $\phi_H = -2.6^\circ$, (b) $\phi_H = -0.6^\circ$, (c) $\phi_H = 1.4^\circ$, and (d) $\phi_H = 3.4^\circ$. The solid curves are Lorentzian fits to the ME resonance lines. $A(\pm k_{\text{SAW}})$ on $H$ measured at four angles $\phi_H$. In agreement with Fig. 2(b), each trace shows two ME resonances at two field values. For the resonance at the low magnetic field, $M_0$ is still rotating towards $H$, while $M_0$ and $H$ are fully aligned for the resonance at high magnetic field. The difference between the two resonant fields reaches a maximum for $\phi_H \approx 0$. As $H$ rotates away from the [110] direction, the resonances move towards each other until they merge at $|\phi_H| \approx 4^\circ$. For larger values of $\phi_H$, the frequency of the spin waves lies above the SAW frequency, and no ME resonances can be excited.

Interestingly, the ME resonances in Fig. 4 appear at fields $H$ slightly larger than those expected from the FMR measurements in Fig. 2(b). This behavior suggests a stronger magnetic anisotropy of the Fe$_3$Si film for the SAW experiment than for the FMR one. Although a better understanding of this phenomenon requires additional measurements that go beyond the scope of this manuscript, we attribute this shift to the different nature of the ac fields driving the magnetization precession in each case. While in the FMR experiment
FIG. 5. ME-induced attenuation maps as a function of magnetic field strength, $H$, and angle, $\varphi_H$, for SAWs propagating with wave vectors (a) $+k_{\text{SAW}}$ and (b) $-k_{\text{SAW}}$. (c) SAW attenuation difference, $\Delta A$, calculated from the data in panels (a) and (b). (d) Simulation of the magnetic power dissipated by the Fe$_3$Si film, $P_{\text{mag}}$, as a function of $H$ and $\varphi_H$ for SAW with wave vector $+k_{\text{SAW}}$. (e) Same as (d), but for SAW with wave vector $-k_{\text{SAW}}$. (f) Difference $\Delta P_{\text{mag}}$ between panels (d) and (e).

The ac field is a real magnetic field excited in a co-planar wave guide, the magnetization response in the SAW experiment is caused by lattice deformations of the Fe$_3$Si film.

For all four orientations of $\varphi_H$ in Fig. 4, $A(+k_{\text{SAW}})$ (black squares) is clearly different from $A(-k_{\text{SAW}})$ (red circles) at the ME resonance, reaching a non-reciprocal attenuation efficiency $\Delta A = A(+k_{\text{SAW}}) - A(-k_{\text{SAW}}) \approx \pm 20\%$. Moreover, the sign of $\Delta A$ depends on the sign of the magnetic field angle: for $\varphi_H < 0$, $\Delta A > 0$, cf. Figs. 4(a) and 4(b), while for $\varphi_H > 0$ the situation reverses and $\Delta A < 0$, cf. Figs. 4(c) and 4(d).

The two-dimensional color plots of Fig. 5(a) and 5(b) summarize the dependence of the
SAW attenuation on the strength $H$ and angular direction $\varphi_H$ (cf. sketch in the upper part of the figure) of the magnetic field. The resonant ME interaction (and, consequently, SAW attenuation) takes place only on a $\varphi_H \times H$ lobe defined by a very narrow range of angles $\varphi_H$ around 0$^\circ$ and 180$^\circ$. Figure 5(a) shows experimental data recorded for H directions quasi-parallel (right panel, $-5^\circ < \varphi_H < 5^\circ$) and quasi-antiparallel (left panel, $175^\circ < \varphi_H < 185^\circ$) to $+k_{SAW}$. Figure 5(b) displays the corresponding data for SAW with wave vector $-k_{SAW}$. For all configurations, the attenuation changes as the magnetic field moves away from the [110] axis. For the quasi-parallel configurations (right panel of Fig. 5(a) and left panel of Fig. 5(b)), the magnitude of the attenuation is strongly angular dependent with clear different values in the upper and lower side of the $\varphi_H \times H$ lobes. In the quasi-antiparallel case, in contrast, the angular dependence is less pronounced. As will be discussed in the next section, this weaker dependence arises from small deviations of the SAW wave vector from the [110] axis.

Finally, we show in Fig. 5(c) the non-reciprocal attenuation efficiency, $\Delta A$, determined from the difference between the data in the corresponding panels of Fig. 5(a) and 5(b). Both panels of this figure show different signs of $\Delta A$ in the upper and lower sides of the $\varphi_H \times H$ lobes. As in Fig. 4, $\Delta A$ in Fig. 5(c) reaches values as large as ±20%. Taking this value together with the length $L$ of the ferromagnetic film, we estimate a non-reciprocal attenuation rate, $\eta \approx \Delta A/L \approx 16 \%$/mm. For comparison, we have also estimated $\eta$ from the attenuation values reported in the Ni/LiNbO$_3$ hybrid structures working at 2.24 GHz SAW frequency, obtaining $\eta \sim 1.6 \pm 0.9 \%$/mm. The latter is one order of magnitude lower than the ones obtained in the Fe$_3$Si/GaAs structures reported here.

IV. DISCUSSION

To theoretically analyze the experimental results, we have taken into account that, according to energy conservation, the attenuated SAW power must equal the power dissipated by the spin waves. Therefore, as a first approximation to the problem, we have just estimated the response of the magnetization to the SAW-induced ME field, and compared the power dissipated by the spin waves to the SAW attenuation profiles of Fig. 5. The magnetization dynamics is described by the Landau-Lifshitz-Gilbert (LLG) equation:
\[ \mathbf{m} = -\gamma \mathbf{m} \times \mu_0 \mathbf{H}_{\text{eff}} + \alpha \mathbf{m} \times \dot{\mathbf{m}}, \]  

(1)

where \( \mu_0 \) is the vacuum permeability, \( \gamma \) is the gyromagnetic ratio, \( \alpha \) is the Gilbert damping constant, \( \mathbf{m} = \mathbf{M}/M_0 \) is the time-dependent magnetization normalized to its equilibrium magnitude, and the dot denotes the time derivative. The temporal evolution of \( \mathbf{m} \) depends on the effective magnetic field \( \mu_0 \mathbf{H}_{\text{eff}} = -\nabla_{\mathbf{m}} F_{\text{total}} \). Here, \( F_{\text{total}} \) is the total magnetic free energy normalized with respect to \( M_0 \). It consists of the terms \( F_{\text{total}} = F_Z + F_s + F_c + F_{\text{me}} \) representing the Zeeman \( (F_Z) \), shape \( (F_s) \), and crystalline \( (F_c) \) anisotropy energies, as well as the magneto-elastic energy, \( F_{\text{me}} \), that couples the oscillating strain of the SAW to the magnetization. In a material with cubic symmetry, the lowest order contributions to \( F_{\text{me}} \) can be expressed as:

\[
F_{\text{me}} = b_1 [\varepsilon_{xx} m_x^2 + \varepsilon_{yy} m_y^2 + \varepsilon_{zz} m_z^2] \\
+ 2b_2 [\varepsilon_{xy} m_x m_y + \varepsilon_{xz} m_x m_z + \varepsilon_{yz} m_y m_z],
\]

(2)

where \( b_1 \) and \( b_2 \) represent the longitudinal and shear ME coefficients, respectively, while \( \varepsilon_{ij} \) and \( m_i \) are the projections of the strain and magnetization components onto the \( \hat{x} \parallel [100], \hat{y} \parallel [010] \) and \( \hat{z} \parallel [001] \) directions of the cubic lattice. As mentioned above, it is convenient to rewrite Eq. 2 as a function of the three non-zero strain components \( \varepsilon_{XX}, \varepsilon_{ZZ} \) and \( \varepsilon_{XZ} \) of the SAW expressed in the rotated \( XYZ \) reference frame, see Fig. 1. We will also describe \( \mathbf{m} \) in spherical coordinates with azimuthal and polar angles, \( \varphi \) and \( \theta \), expressed with respect to [110] and [001], respectively. A detailed derivation of the equations is presented in the Supplemental Information. For small angular deviations \( \delta \varphi \) and \( \delta \theta \) of \( \mathbf{m} \) with respect to its equilibrium direction \( \mathbf{m}_0 = \mathbf{M}_0/M_0 \), the effective ME field driving the magnetization precession, \( \mu_0 \mathbf{h} = -\nabla_{\mathbf{m}} F_{\text{me}}, \) consists of the following in-plane and out-of-plane components perpendicular to \( \mathbf{m}_0 \), \( h_\varphi \) and \( h_\theta \), respectively:

\[
\mu_0 h_\varphi = 2b_2 \sin(\varphi_0) \cos(\varphi_0) \varepsilon_{XX},
\]

(3)

\[
\mu_0 h_\theta = 2b_2 \cos(\varphi_0) \varepsilon_{XZ}.
\]

(4)

The in-plane component \( h_\varphi \) is proportional to the longitudinal strain of the SAW, \( \varepsilon_{XX} \), while the out-of-plane component \( h_\theta \) is proportional to the shear strain, \( \varepsilon_{XZ} \). Both components
depend on the in-plane orientation of $m_0$ through $\varphi_0$ (see Fig. 1). In the absence of an external magnetic field, $m_0$ points along one of the $\langle 100 \rangle$ easy axes (i.e., $\varphi_0 = \pm 45^\circ$). When $H$ points along the $[\bar{1}10]$ direction, $m_0$ rotates toward $\varphi_0 \approx 90^\circ$, so that both $h_\varphi$ and $h_\theta$ vanish and no ME coupling is excited, thus explaining the absence of ME coupling for this $H$ orientation. In contrast, when $H$ points along $[110]$, $m_0$ rotates toward $\varphi_0 \approx 0$. Here, $h_\varphi$ also tends to zero, but now $h_\theta$ approaches its maximum value. The SAW strain component $\varepsilon_{XZ}$ vanishes at a free surface. Therefore, for thin ferromagnetic films and/or large SAW wavelengths, $\varepsilon_{XZ}$ is very small compared to $\varepsilon_{XX}$, and $h_\theta$ can normally be neglected. For thicker films and/or shorter SAW wavelengths, however, $\varepsilon_{XZ}$ becomes relevant, and the contribution of $h_\theta$ to the magnetization dynamics must be taken into account. To visualize this effect, we display in Fig. 6(a) the amplitude of $\varepsilon_{XX}$ and $\varepsilon_{XZ}$ as a function of sample depth calculated for a $\lambda_{\text{SAW}} = 800$ nm SAW. The calculations of the SAW strain were carried out using an elastic model that takes into account the elastic properties of Fe$_3$Si and GaAs. While $\varepsilon_{XX}$ decreases from its maximum value as it crosses the film, $\varepsilon_{XZ}$ increases from zero and reaches a value $\varepsilon_{XZ} \approx 0.5\varepsilon_{XX}$ at the Fe$_3$Si/GaAs interface (marked as a vertical dashed line in Fig. 6(a)).

The observed non-reciprocal SAW attenuation can be understood as an interplay between the $h_\varphi$ and $h_\theta$ components. Due to the $\pi/2$ time phase shift between $\varepsilon_{XX}$ and $\varepsilon_{XZ}$, the ME driving field $h = h_\varphi \hat{\varphi} + ih_\theta \hat{\theta}$ is, in general, elliptically polarized. Its helicity depends on the ratio $\varepsilon_{XZ}/\varepsilon_{XX}$ and changes signs when one reverses the SAW propagation direction. As the magnetization precession described by the LLG equation has also a well-defined helicity, the strength of the ME coupling will depend on the helicity of $h$. For example, for a SAW propagating with $+k_{\text{SAW}}$, $\varepsilon_{XX} \propto \cos \omega t$ and $\varepsilon_{XZ} \propto \sin \omega t$. If $H$ rotates $m_0$ towards $0 < \varphi_0 < 45^\circ$, $h$ and $m$ will precess with opposite helicities and the coupling of the SAW to the magnetization dynamics will be weak, see right panel in Fig. 5(a). However, if $H$ orients $m_0$ towards $-45^\circ < \varphi_0 < 0$, the sign of $h_\varphi$ will reverse and now both $h$ and $m$ will precess with the same helicity. Under these conditions, the ME coupling will be strong, thus inducing a larger SAW attenuation. When $H$ reverses and $m_0$ points against the SAW wave vector, $h_\theta$ changes sign and inverts the helicity dependence of $h$ on $\varphi_0$. The same happens if the magnetization stays along $[110]$, but the SAW propagates with $-k_{\text{SAW}}$, causing $\varepsilon_{XZ} \propto \sin \omega t$ to be replaced by $\varepsilon_{XZ} \propto -\sin \omega t$. Finally, when both magnetization and SAW wave vector are reversed, $h_\theta$ remains positive and the original dependence on the
FIG. 6. (a) Dependence of the longitudinal and shear strain amplitudes, $\varepsilon_{XX}$ (black curve) and $\varepsilon_{XZ}$ (red curve), respectively, on sample depth for a SAW with 800 nm wavelength. The curves are normalized with respect to the amplitude of $\varepsilon_{XX}$ at the top surface. The vertical dashed line indicates the position of the Fe$_3$Si/GaAs interface. (b) Difference in dissipated magnetic power, $\Delta P_{\text{mag}}$, for the parallel and anti-parallel configurations of $H$ and $k_{\text{SAW}}$, as a function of the effective damping coefficient $\alpha$. The data were calculated for $f_{\text{SAW}} = 3.45$ GHz, $\varphi_H = -1.5^\circ$, $\varepsilon_{XZ} = 0.5\varepsilon_{XX}$ and $\beta = 0$, and are normalized with respect to the maximum value for $\alpha = 0.005$.

relative angle between $H$ and SAW wave vector is recovered, see the left panel in Fig. 5(b).

According to this discussion, the SAW attenuation profiles for quasi-parallel and quasi-antiparallel configurations of $H$ and SAW wave vector in Fig. 5(a) and 5(b) should be mirror images of each other. However, as already mentioned in the previous section, this is not exactly the case for the experimental data. We attribute this discrepancy to a small, unintentional misalignment angle $\beta$ between the SAW wave vector and the [110] direction, probably
caused during the patterning of the IDTs. This misalignment breaks the symmetry of $h_\varphi$ and $h_\theta$ by introducing additional terms that depend on $\beta$ and $b_1$ (see Supplemental Information). As a consequence, the non-reciprocity with respect to $\varphi_0$ is enhanced in the quasi-parallel configuration, but partially compensated in the quasi-antiparallel configuration. To confirm this assumption, we have estimated the dependence on $H$ and $\varphi_H$ of the power dissipated by the spin waves and compared it to the profiles in Fig. 5(a) and (b). The dissipated magnetic power, $P_{\text{mag}}$, can be calculated as:

$$P_{\text{mag}} = -\text{Im} \left[ \frac{\mu_0}{2} \int_{V_0} (\mathbf{h}^* \mathbf{\chi h}) \, dV \right],$$

(5)

where $\mathbf{\chi}$ is the Polder susceptibility tensor describing the response of the magnetization to $\mathbf{h}$, and $V_0$ is the volume of the ferromagnetic film traversed by the SAW. To obtain $\mathbf{\chi}$, we have solved the linearized LLG equation supposing harmonic solutions for $\varepsilon_{XX}$, $\varepsilon_{XZ}$, $\delta\theta$ and $\delta\varphi$. A detailed derivation is presented in the Supplemental Information. In the simulations, we have assumed the amplitude of the SAW strain to be constant across the thin Fe$_3$Si film and calculated $\mathbf{h}^* \mathbf{\chi h}$ at the Fe$_3$Si/GaAs interface. The strain at this depth yields the largest degree of elliptical polarization, see Fig. 6(a), and it is, therefore, where one expects the strongest non-reciprocal effects. In the simulation, we have adjusted the values of the gyromagnetic ratio, shape and cubic anisotropies so that the resonances take place at similar values of $H$ and $\varphi_H$ as in Figs. 5(a) and 5(b). The width of the ME resonance depends on the damping coefficient, which was set to $\alpha = 0.005$. The degree of non-reciprocity depends on the values of $b_1$, $b_2$, $\varepsilon_{XX}$, $\varepsilon_{XZ}$ and $\beta$, which we have set to $b_1 = 6$ T, $b_2 = 2$ T, $\varepsilon_{XX} = 10^{-4}$, $\varepsilon_{XZ} = 0.5 \times 10^{-4}$ and $\beta = 1^\circ$. Figures 5(d) and 5(e) display $P_{\text{mag}}$ for $H$ and SAW wave vector in the quasi-parallel and quasi-antiparallel configurations, respectively, while the difference $\Delta P_{\text{mag}}$ between both configurations is shown in Fig. 5(f). Although the theoretical model does not replicate exactly the position and amplitude of the experimental ME resonances, it reflects qualitatively well their dependence on $H$ and $\varphi_H$ and the non-reciprocal behavior.

To conclude, we briefly discuss the reasons for the superior non-reciprocal SAW propagation of the Fe$_3$Si/GaAs hybrid structure compared to the poly-crystalline nickel on LiNbO$_3$. First, the SAW wavelength in our experiment (800 nm) is about two times shorter than in the Ni/LiNbO$_3$ (1.5 µm) structures. This implies a larger $\varepsilon_{XZ}/\varepsilon_{XX}$ ratio at the ferromagnetic film and, therefore, a larger degree of elliptical polarization of the ME effective field driving the magnetization precession. In fact, we expect the largest non-reciprocal
behavior when the SAW-induced ME field fulfills the condition $h_x \approx h_\theta$. In our case, the non-reciprocity can be increased by optimizing the sample geometry and SAW frequency to obtain the optimal depth distribution of the strain fields, combined with the optimal angle of the in-plane equilibrium magnetization $\varphi_0$. The second reason is the high degree of structural quality of our epitaxial Fe$_3$Si film, which ensures the low Gilbert damping coefficient required for the strong non-reciprocal effects. To illustrate this point, we have estimated $\Delta P_{\text{mag}}$ as a function of $H$ for a fixed value of $\varphi_H$ (as well as $f_{\text{SAW}}$, $b_1$, $b_2$, $\varepsilon_{XX}$, $\varepsilon_{XZ}$ and $\beta$) and several values of $\alpha$. The results are displayed in Fig. 6(b) and are normalized with respect to the maximum value for $\alpha = 0.005$. We observe that $\Delta P_{\text{mag}}$ is inversely proportional to $\alpha$, and becomes ten times smaller when $\alpha$ increases from 0.005 to 0.05. This is in good agreement with the difference in the calculated values of $\eta$ for the Fe$_3$Si/GaAs and Ni/LiNbO$_3$ systems. Additional optimization of the Fe$_3$Si structural quality (e.g. by modification of its stoichiometry) should leave to $\alpha \sim 10^{-4}$, thus further enhancing the degree of non-reciprocal SAW propagation in our Fe$_3$Si/GaAs hybrid structure.

V. CONCLUSIONS

In this contribution, we have demonstrated non-reciprocal propagation of SAWs along a GaAs substrate covered with an epitaxial Fe$_3$Si film. For well-defined values of the external magnetic field, the magneto-elastic coupling transfers energy from the acoustic into the magnetic system, thus inducing attenuation of the SAW. The strength of the SAW attenuation depends on the relative orientation between magnetization and SAW wave vector, and leads to attenuation differences of up to 20% for SAWs propagating along opposite directions. We attribute the non-reciprocal behavior to the dependence of the magnetization dynamics on the helicity of the elliptically polarized magneto-elastic field associated to the SAW. Our simulations confirm these results and show that non-zero longitudinal and shear strain at the ferromagnetic film, as well as low magnetic damping, are critical to observe significant non-reciprocal effects. Due to the combination of large magnetostriction and low magnetic damping, epitaxial Fe$_3$Si films are a promising material for the future implementation of non-reciprocal SAW devices in GaAs-based heterostructures.
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