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Section number – SAW-driven straintronics

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Status

This section provides a brief history and status, why the field is still important, what will be gained with further advances. (350 words max)

[348 words]

The interaction of acoustic waves and magnetic excitations (spin waves) through magnetoelasticity was proposed in the late 50's, when Kittel showed that their resonant coupling under conditions of equal frequency and wave-vector lead to mixed magnon-phonon modes. The acoustic excitation of GHz ferromagnetic resonance (FMR) modes, or on the contrary, the generation of GHz phonons by spin-waves excited using radio-frequency (rf) magnetic fields was studied in the following decades. The research then mainly focused on Nickel and Yttrium Iron Garnet (YIG) – moderately magnetostrictive, but well understood ferro-/ferri-magnets. This coupling was then implemented in the field of electronic device engineering, for instance to turn surface acoustic wave (SAW) delay-lines into magnetically tunable rf components or field sensors [1]. The strong field-induced variations of acoustic wave velocity are indeed particularly well suited to the detection of low amplitude, low frequency magnetic fields, which can be challenging using other magnetometry techniques.

The past ten years have seen a clear revival of the topic with a much stronger focus on potential applications in the field of magnetic data storage, spintronics or magnonics. Information is then encoded by the magnetic state of micro- or nano-structures, the spin-polarization of electrons, or the amplitude/phase of spin-waves. With their low attenuation, their typical frequencies of the order of magnetic precession frequencies, and power-flow confined to the surface, SAWs rapidly emerged as a relevant tool. The effective rf field they induce tickles the magnetization into ferromagnetic resonance. This can in turn lead to the generation of pure electron spin currents in the presence of a heavy-metal top layer [2] (Fig. 1a), or to the full reversal of static magnetization provided a non-linear coupling regime is reached [3] (Fig. 1b). SAW-driven “straintronics” [4] have thus joined the likes of spintronics (using current), valleytronics (using valley-dependent properties), caloritronics (using temperature gradients) or multiferroic-based systems (using electrical fields) for non-inductive control of magnetization. Contrary to local electric-field-driven switching however, SAW-driven switching offers the possibility of high efficiency, and remote control of magnetic bits using waveguiding and focusing, or reconfigurable addressing using interference patterns, without the need for local metallic contacts.

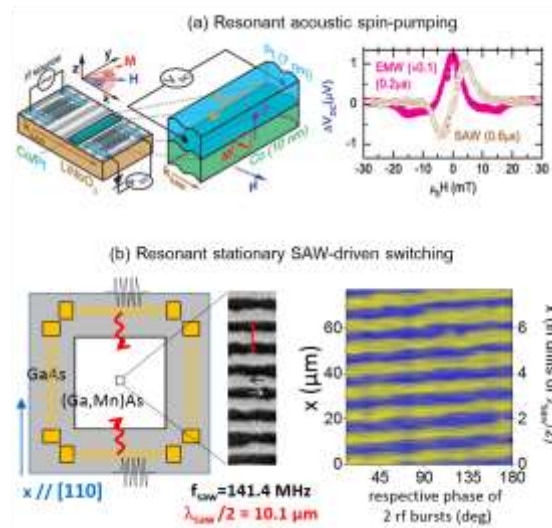


Figure 1. Acoustic-driven magnetization dynamics at resonance. The rf field created by the SAW through magnetoelasticity triggers the magnetization into precessing. (a) Adapted from Weiler *et al.* [2]. When these oscillations are of small amplitude, they generate a transverse spin current detected by the V_{DC} voltage on a Pt strip through the inverse spin Hall effect. (b) Adapted from Kuszewski *et al.* [3]. When the coupling is large enough, the SAW drives the precessional reversal of magnetization. In a stationary geometry, magnetic domains $\lambda_{SAW}/2$ -wide can be created, and positioned precisely by tuning the relative phase of the exciting bursts.

Current and Future Challenges

This section discusses the big research issues and challenges. (350 words max)

[401 words]

The interaction between SAWs and magnetization is now fairly well understood, but much remains to be done to harness it to actual magnetic architectures. SAWs could for instance be the missing ingredient in magnonics, for now limited by the fact that the attenuation distance of spin waves is of the order of a few micrometers for most ferromagnetic materials, limiting prototypes to extremely low damping materials like YIG. Remotely excited SAWs could act as a relay for spinwaves through resonant coupling, and modify locally their amplitude or phase. The optimization of mixed phononic-magnonic crystals, up to now mainly studied numerically [5], could be key for spin-wave-based computational circuits.

Concerning the manipulation of static magnetization, localized switching has now been demonstrated using stationary and focused SAWs [3],[6]. Novel architectures which would most benefit from magnetoacoustic coupling now need to be elaborated, since current schemes will not be competitive for dense storage devices. The smallest accessible switching size is indeed “large”, i.e of the order of the SAW wavelength, a few hundreds of nanometers at best. SAW-switching could for instance provide an interesting alternative for remote addressing of moderately dense magnetic bit arrays, provided the transducer design is adapted, using wave-front shaping for example.

The resonant, non-linear behaviour of magnetization dynamics submitted to large amplitude SAWs could also be exploited beyond switching, for instance in magnetic solid-state neuromorphic systems. These require tuneable non-linear oscillators which can act as artificial neurons, as recently demonstrated using current-driven spin transfer torque nano-oscillators [7]. SAWs could enable

interneuronal synchronization via magnetoacoustic coupling, or even drive the magnetization dynamics, offering the added possibility of a surgical addressing of a given “neuron” within an assembly.

While most of the above considerations focus on magnetic applications, magnetoacoustics are also highly relevant to the field of phononics. Breaking time-reversal symmetry with magnetism for instance leads to non-reciprocal acoustic propagation, with the tantalizing prospect of making phononic diodes. This was studied in the ‘80s, but could be revisited in thin magnetic films making use of Dzyaloshinski Moriya interaction [8], or astute patterning to engineer the relevant strain components (Fig. 2). In graphene-like phononic crystals, magnetism could moreover lead to field-tunable topological protection of SAW propagation: an ultrasonic structure made immune to defects [9]. Elegant demonstrations of this have been shown at low frequencies and large dimensions (Hz/cm) using moving elements, but experiments are still lacking in the realm of the nm/GHz.

Advances in Science and Technology to Meet Challenges

This section discusses the advances in science technology needed to address the challenges. (350 words max)

[303 words]

SAW-driven magnetization switching has up to now been demonstrated using *resonant* interaction, at low temperature [3], or fairly inefficient *non-resonant* coupling in room-temperature ferromagnets[6]. This results from the difficulty of matching SAW frequencies (typically a few GHz) and magnetic ones (often over 10 GHz) at reasonable magnetic fields. Materials presenting both high magnetostriction and low precession frequencies must now be sought after to enable low (or zero) field resonant switching at room temperature. Moreover, while the industrial sector has optimized very magnetostrictive materials such as Terfenol-D in the bulk form, there is a real need for the synthesis of high quality crystalline magnetostrictive materials in thin-film or multi-layer form. Last but not least, these highly magnetostrictive materials should be grown on efficient piezo-electric films for generation of high SAW amplitude, which demands efforts in synthesis optimization and characterization of these hybrid multiferroic heterostructures.

On the device side of things, magnetoacoustics has so far only exploited a small portion of the elaborate SAW transducer designs optimized by electronic engineers. These can now be implemented in the search of broader bandwidths, more efficient electro-mechanical transduction, but mostly, higher SAW frequencies. This will decrease minimum addressable dimensions and boost the coupling efficiency to magnetization or magnetic defects, making SAWs well suited for sensing NV centers [*ref to other roadmap article ?*], or inducing magnetocaloric effects, as has been shown on MnAs [10].

Finally, the race towards higher frequencies and smaller feature size will entail the need for experimental tools other than optics to study magnetoelastic interaction, be it from the point of view of strain or magnetization dynamics. X-ray diffraction techniques such as PEEM or XMCD, are viable solutions [11], but they remain cumbersome to implement. Eventually, local electrical probing of the magnetic state by magneto-resistive effects and near-field techniques compatible with SAW excitation should prove to be more adapted lab-ready approaches.

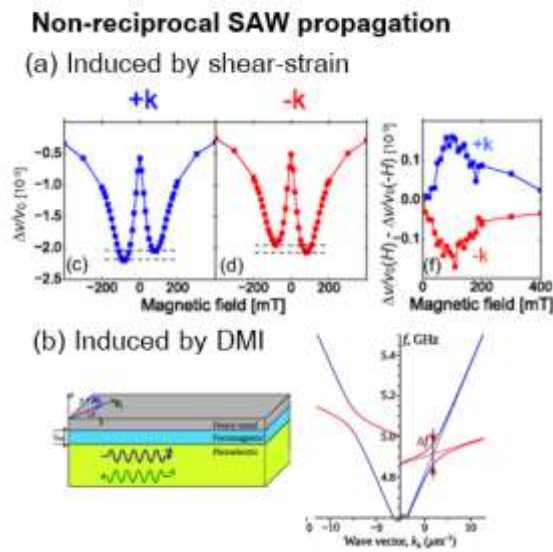


Figure 2. Magnetism-induced non-reciprocal SAW propagation. (a) From [12] : the interference of shear and longitudinal magnetoelastic coupling leads to small but finite non-reciprocal SAW velocity variations in Ni/LiNbO₃. (b) From [8] : a much bigger non-reciprocity may be expected in the presence of Dzyaloshinskii-Moriya interaction (DMI). The magnon-phonon anticrossing then takes place at different SAW wave-vectors, leading to a different acoustic absorption for + k_{SAW} and $-k_{\text{SAW}}$.

Concluding Remarks

Include brief concluding remarks. This should not be longer than a short paragraph. (150 words max)
[80 words]

SAWs have proven a very useful tool to probe elementary excitations [ref to other roadmap articles?], and magnons are no exception. Far from the academic world, SAWs are commonly used in microelectronic devices, sensors and filters, and are as such a mature technology allowing low power, high efficiency and broad tunability operation. The time is now ripe to harvest the benefits of the fundamental studies of magnetoacoustic interactions of the past decades, and implement these effects into magnetic field-tunable phononic devices, or strain-controlled magnetic structures.

References (separate from the two page limit)

Limit of 10 References. Please provide the full author list, and article title, for each reference to maintain style consistency in the combined roadmap article. Style should be consistent with all other contributions

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