Deliverable Report
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TRANSPIRE

Deliverable	Deliverable name (Short name)	WP No.	Lead participant	Type	Diss. Level	Date
D2.2	FMR below 50 GHz on a ferrimagnet	2	HZDR	DEM	Public	M10

Report on the FMR dispersion of a tailored ferrimagnet with a resonance frequency < 50 GHz
Progress beyond state-of-the-art:
Electrical detection of in-phase and out-of-phase magnetic resonance modes in thin ferrimagnetic films

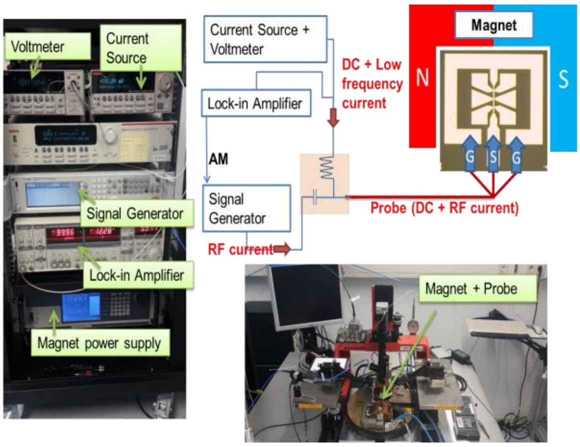
Partner	Contribution
TCD	Film optimisation and growth; Structural characterisation; Room temperature magnetoresistance measurements; Magnetisation measurements
HZDR	Device patterning; Room temperature magnetoresistance measurements; High frequency electrically detected magnetic resonance; Fitting of spectra; Comparison with literature on unpatterned films

The deliverable was met with the demonstration of excitation and detection of magnetic resonance modes in a synthetic ferrimagnet. Electrically detected ferromagnetic resonance (ED-FMR) was used to obtain the dispersion of both the in-phase (low-frequency) and the out-of-phase (high-frequency) mode. This is a step towards D2.3, the proof-of-concept of spin pumping in a high anisotropy MnGa-based alloy. The synthetic ferrimagnetic thin films will behave the same as the ferrimangets we investigate in TRANSPIRE, with the exception that our electrical excitation is limited to ~50 GHz.

To enable electrical detection below 50 GHz, i.e. in the frequency band where the transport measurements were initially optimised for at HZDR, Trinity College Dublin grew different synthetic ferrimagnets, while in parallel exploring avenues for growing ferromagnetic Heusler alloys with anisotropies compatible with the existing facilities. The generic structure of the synthetic ferrimagnets was NiFe / Ru / NiFe, with different thicknesses of the two NiFe layers. NiFe was chosen due to its high mangetoresistive response, and the Ru thickness was chosen to ensure strong antiparallel coupling of the NiFe layers. Variations of this base structure were grown to obtain un-balanced and balanced ferromagnetic structures, which model the two sublattices of ferrimagnetic Heusler half-metal systems, above, below and at the compensation temperature, depending on the relative thickness of the two NiFe layers (see Table 1).

Table 1: Sample structures used for this deliverable

Sample name	Structure
GD7	Substrate // Ta 5 / NiFe 3 / Ru 0.85 / NiFe 3 / Ru 3
GD8	Substrate // Ta 5 / NiFe 3 / Ru 0.85 / NiFe 6 / Ru 3
GD9	Substrate // Ta 5 / NiFe 6 / Ru 0.85 / NiFe 3 / Ru 3
GD10	Substrate // Ta 5 / NiFe 3 / Ru 0.85 / NiFe 9 / Ru 3



All samples were patterned into Hall bars using the UV photolithography facilities available at HZDR. The contact pads were designed to allow the connection of high frequency ground-signal-ground (GSG) probes to the sample. All samples were patterned successfully and showed the same magnetoresistive response as the extended films. ED-FMR experiments were performed on samples with different structures in the setup shown here. More details can be found in [1].

The films were pre-characterised at TCD and HZDR to prove the antiferromagnetic coupling of the system and to determine the saturation magnetisation, anisotropy and exchange fields (figure 1 (a), (b) and (c)). This information is necessary to fit the dispersion curves obtained from the electrically detected ferrimagnetic resonance experiments. ED-FMR spectra of sample GD10 are shown for various frequencies in figure 1 (d). A high frequency current source is used to excite magnetization dynamics through the Ørsted field produced by the current. This produces a non-zero DC voltage offset which is present only at when the magnetic resonance condition is satisfied [2]. The amplitude of this excitation is modulated by the internal oscillator of a lock-in amplifier (LIA).

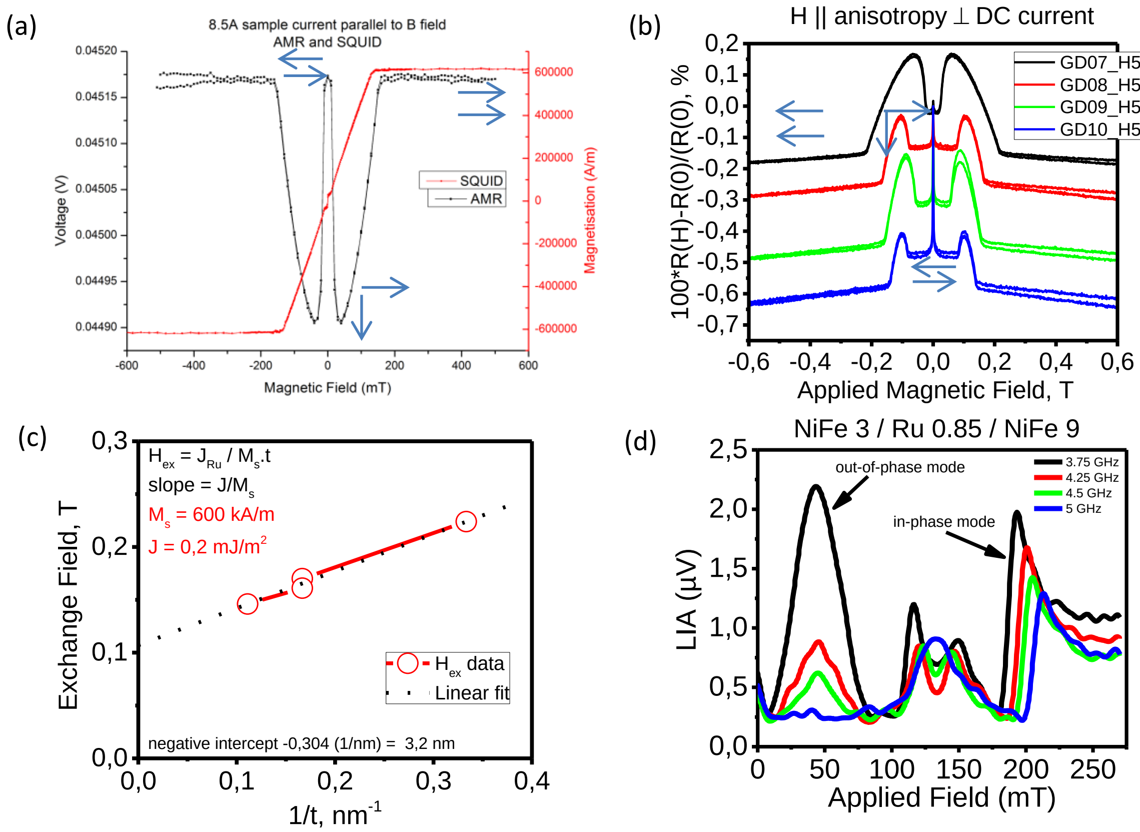


Figure 1: (a) Preliminary magnetisation and magnetoresistance data from the initial growth run in Dublin. The magnetisation orientation of the Py layers is shown by arrows in (a) and (b), close to zero field the layers are antiparllel, switching to an orthogonal configuration between 50 and 200 mT and finally becoming parallel to the applied field beyond 200 mT (b) Magnetoresistance measurements performed in HZDR showing the antiparallel alignment of the two Py layers close to low field as well as the spin reorientation at larger fields (between approximately 0.1 T and 0.2 T). These exchange fields were used to calculate the interlayer coupling energy, J, derived in (c). (d) shows a typical ED-FMR response for the most unbalanced sample, GD10. The out-of-phase exchange mode is observed over a wide range of low fields. The in-phase mode moves to higher fields at higher frequencies. These spectra are used to generate data shown in figure 2.

Both peaks shift in field when the frequency of the ac current is changed. Figure 2 shows the full dispersions for the balanced (a), slightly unbalanced (b), and very unbalanced (c) artificial ferrimagnets with in-phase and out-of-phase modes. The in-phase 'ferromagnetic' mode is fitted with the Kittel formalism and the out-of-phase mode matches with the exchange energy derived in figure 1 (c). VNA-FMR was employed at HZDR to characterize extended films, but the out-of-phase mode was not detected [3].

In summary, we have shown that electrical detection of magnetic resonance is feasible in thin artificial ferrimagnetic systems. The chosen system was representative of the compensated tunable ferrimagnetic systems to be investigated in TRANSPIRE. Full characterization below 50 GHz was performed. The out-of-phase optical mode was shown to be detected easier in samples that are not fully compensated.

Risks Managed/Mitigated

As discussed in the kick-off meeting, during the free scientific discussion, intermediate samples mimicking the behaviour of ferrimagnetic Heusler alloys were needed. The choice of the synthetic ferrimagnet was that intermediate 'stepping-stone'. The detection of the out-of-phase mode in the completely symmetric sample is not possible using only the AMR response of the trilayer. For the asymmetric structures however, this mode could be resolved (as seen in figure 3 (b)).

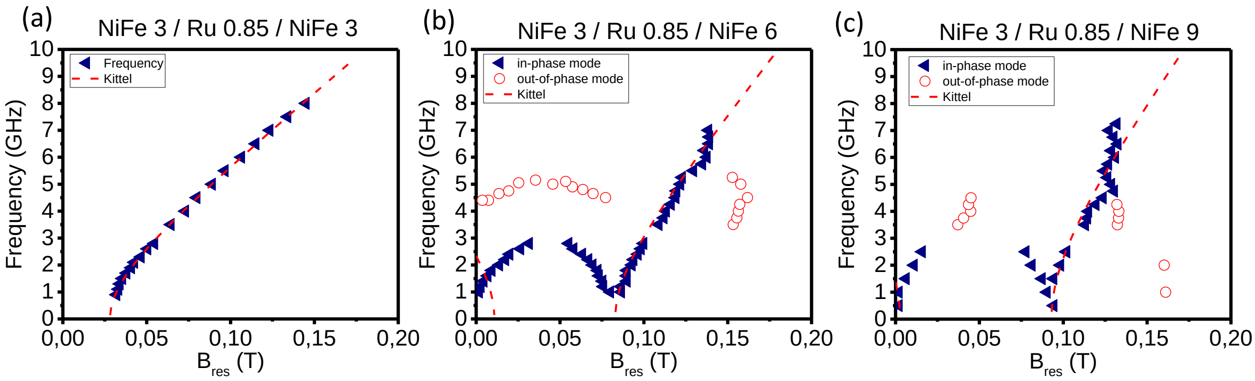


Figure 2: Fitted resonance peaks from electrically detected magnetic resonance for the balanced (a), slightly unbalanced (b), and very unbalanced (c) artificial ferrimagnets. In the fully balanced system the out-of-phase mode is most difficult to detect as the contribution to the change in resistance of each layer is effectively cancelled.

Outlook / Future work

The data presented on the artificial ferrimagnet at frequencies below 50 GHz is directly applicable to frequencies above 50 GHz with high anisotropy MnGa-based alloys. The detection of the out-of-phase mode in half-metallic systems should be easier, due to the fact that only one sub-lattice contributes to the transport, thus producing large scattering coefficients and large magnetoresistance and Hall effect, but can precess at two distinct frequencies. The deliverable sets in place our ability to measure spin-pumping from a high anisotropy Heusler (D2.3). It is also possible to reduce the FMR frequency of high anisotropy films into the accessible range by applying a reverse field and performing ED-FMR. ED-FMR can be combined with other excitation mechanisms e.g. laser induced excitation or direct excitation using the THz source at TELBE. The current setup will be used to test sub-harmonic detection of precession as well.

References

[1] Z Duan et al., Phys. Rev. B **90**, 024427 (2014)

[2] N. Mecking et al., Physical Review B 76, (2007)

[3] M Belmeguenai et al., J. Phys. Cond. Mat. **20**, 345206 (2008)