Deliverable Report
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Deliverable	Deliverable name (Short name)	WP No.	Lead participant	Type	Diss. Level	Date
D1.1	Low moment ferrimagnet on high-Z seed	1	TCD	Report	Public	M6

Progress beyond state-of-the-art: Growth of spin-polarised materials with magnetisation less than 100 kA/m on high-*Z* seed materials	
Partner	**Contribution**
TCD	Film optimisation and growth; Structural characterisation; Magnetisation measurements; Hall measurements

Trinity College Dublin investigated two sets of materials, Mn_2Ru_xGa (MRG) and GdFeCo on different high-*Z* seed materials, with a view to, in the near future, demonstrate spin pumping from the magnetic layer used. Spin pumping is a technique for the production of a spin current in a non-magnetic layer when an adjacent magnetic layer is precessing, and is complementary to spin transfer torque, as at least one of the layers can be dielectric. The spin pumping effect requires an efficient spin sink to convert the spin current into a charge voltage, which can be measured, typically a heavy metal such as Pt is used. Similarly, heavy metals are also required to excite a magnetic layer to resonance through spin-orbit-induced torques. One of the main materials of interest is W (Z = 72) as the β-phase has a good lattice match to MRG. If we wish to utilise this technique, we must determine if our low moment ferrimagnets can successfully be grown on heavy metal seed layers. The goal is to demonstrate such a structure with a magnetisation of < 100 kA/m while maintaining a high spin-polarisation.

MRG

MRG is a ferrimagnetic Heusler alloy, considered to be a zero-moment half-metal at its compensation temperature. Many of its properties are related to its crystal structure, a tetragonally distorted cubic $L2_1$. Due to this, the use of seed layers can alter its properties as the seed can strain the unit cell of MRG. MgO is typically used as a substrate for MRG due to close lattice matching, which allows for properties to be refined with changes in composition. We have demonstrated that MRG can successfully be grown on other materials such as TiN. We also deposited 20nm thick films $Mn_2Ru_{0.7}Ga$ on MgO substrates with a thin W seed. The W film was deposited either by DC sputtering (black curve in Figure 1) or by RF sputtering (yellow curve). It can be seen from the X-ray diffraction (XRD) data in Figure 1 that the RF sputtered W exhibits a much stronger and narrower crystal peak at 58.1º which corresponds to the (310) plane of β-W. Of note are the Kiessig fringes around the W peak, which indicate a highly uniform and epitaxial growth of the layer. In order to produce the high quality W film, the MgO substrate must be annealed at 500 ºC to remove moisture, before cooling to room temperature and depositing the film. The substrate is then heated again to the appropriate deposition temperature for MRG.

We can see the MRG (004) peak of the film grown directly onto the substrate at 61.4º is almost overlapped by the same peak of the film grown on TiN. However, when deposited on the DC-sputtered W the (004) MRG peak moves to 63.6º and becomes very broad, indicating a poor texturing. This results in a significantly lower *c* lattice parameter than MRG grown directly onto MgO (5.88 Å vs 6.04 Å). This results in the moment residing in-plane of the film, as shown by the in-plane SQUID measurement (figure 2). On the RF-sputtered W seed, the *c* spacing is 5.95 Å. Given the *a* lattice parameter is approximately 5.96 Å, this results in a *c*/*a* of nearly unity.

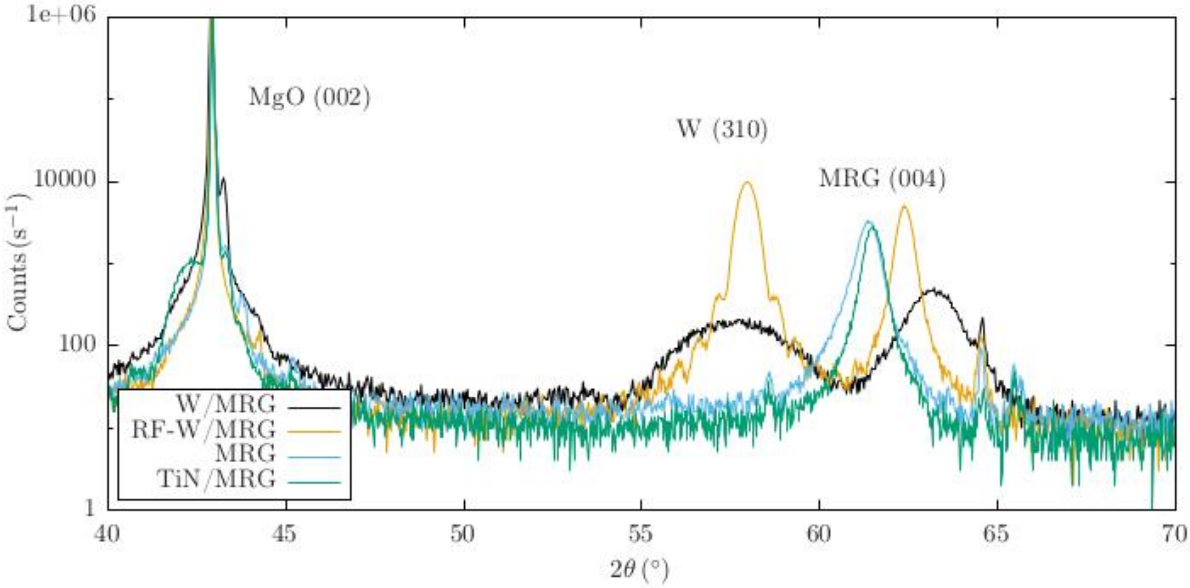

Figure 1 - XRD of MRG grown directly onto substrate versus different seeds. Substrate is always MgO

For both films, we can see that the MRG saturation magnetisation M_s in Figure 2 is low, approximately 60 and 50 kA/m for the films grown on W and RF-sputtered W film respectively. This well below the set target. The *c*/*a* ratio closer to unity is why we see an out-of-plane component in the magnetisation loop for this film.

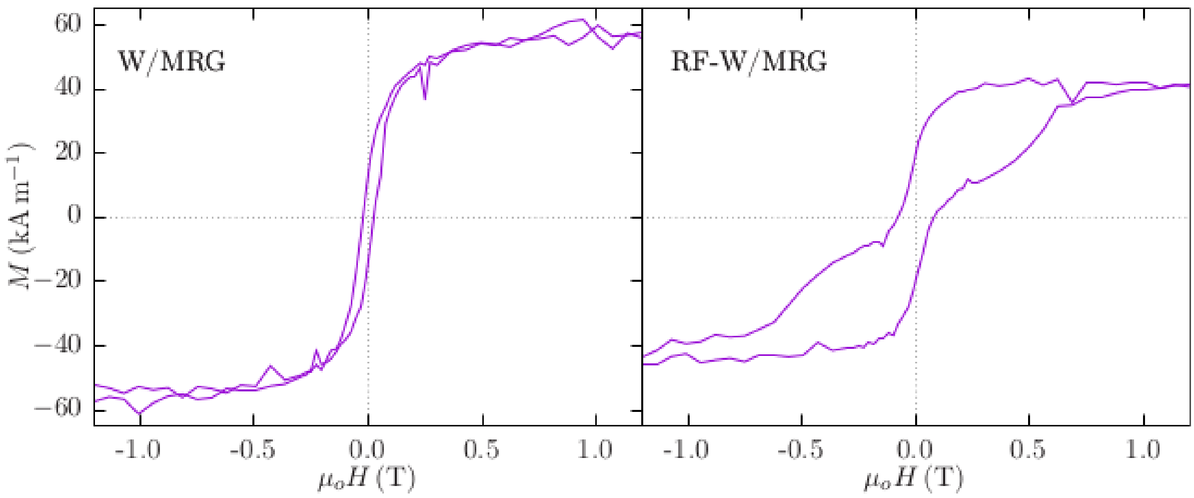

Figure 2 – In-plane SQUID magnetisation loops of MRG grown on DC-sputtered W and RF-sputtered W

GdFeCo

$Gd_x(Fe_{90}Co_{10})_{1-x}$ is an amorphous ferrimagnet. Due to this, it can be used with a large number of potential seed materials as they should not greatly change the intrinsic properties of the material. It has historically found favour in applications of optical switching, and is a good candidate for spin pumping as well. The compensation temperature of GdFeCo can be controlled by changing the composition. It is important to note that the moment becomes perpendicular to the plane around the compensation temperature, and is otherwise in-plane due to demagnetising effects. Room temperature compensation is typically seen around a composition of x = 0.22. We have optimised the composition for the GdFeCo compensate above and below room temperature, as can be seen from the increasing coercivity and change of sign in the anomalous Hall measurements as we approach a composition of x = 0.22 (curves Gd-42W and Gd-43W in figure 3).

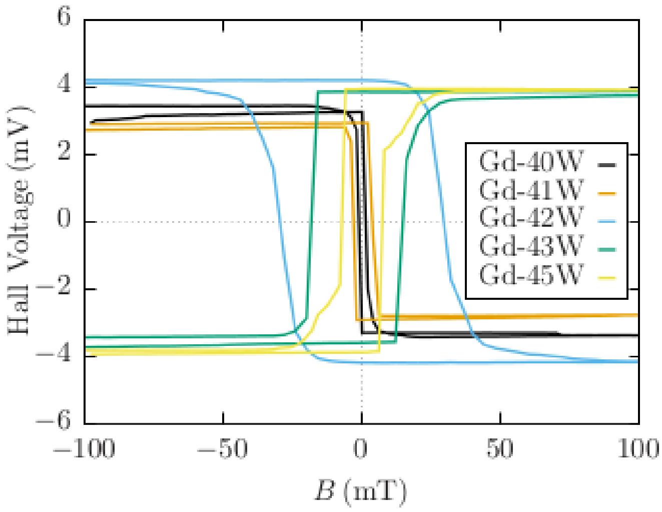

Figure 3 - EHE loops of GdFeCo films with increasing Gd sputtering power. FeCo sputter power is kept constant.

Films in figure 3 were grown on SiO_2, with a Ta seed and cap, to ensure adhesion and prevent oxidation of the film respectively. Following this, films of SiO_2//Z(4)/GdFeCo(20)/Ta(4) were grown, with Z = Ta, Pt, Ru, and W. We chose a composition with compensation slightly below room temperature.

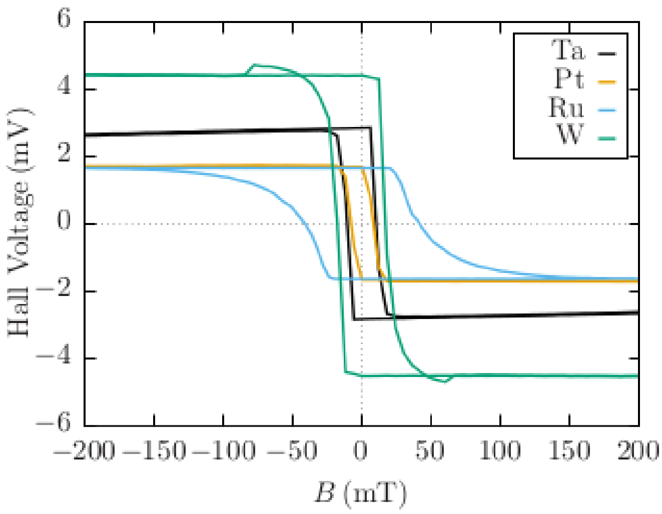

Figure 4 - EHE loops of GdFeCo on various seed layers

EHE in Figure 4 and SQUID magnetisation in Figure 5 indicate that the properties of GdFeCo are only moderately affected by the seed layer. M_s of the GdFeCo appears to change slightly, and is typically below 60 kA/m, and there is some variation in coercivity, however this may result from changes in grain size due to the different seed layers. The exception is the case where W is used as a seed layer. We see a much larger magnetisation, 110 kA/m. An important point here the differences between the EHE and the magnetisation as measured by SQUID magnetometry. While the SQUID loops for Ta, Pt and Ru seeds almost overlap with the loops recorded by EHE, this is not the case for W. A possible origin is a non-collinear magnetic structure induced by either strain from the seed layer, or intermixing between the two layers. Non-collinear ('topological') magnetic texture is a recent topic of interest in magnetism, and we intend to pursue this study in that direction.

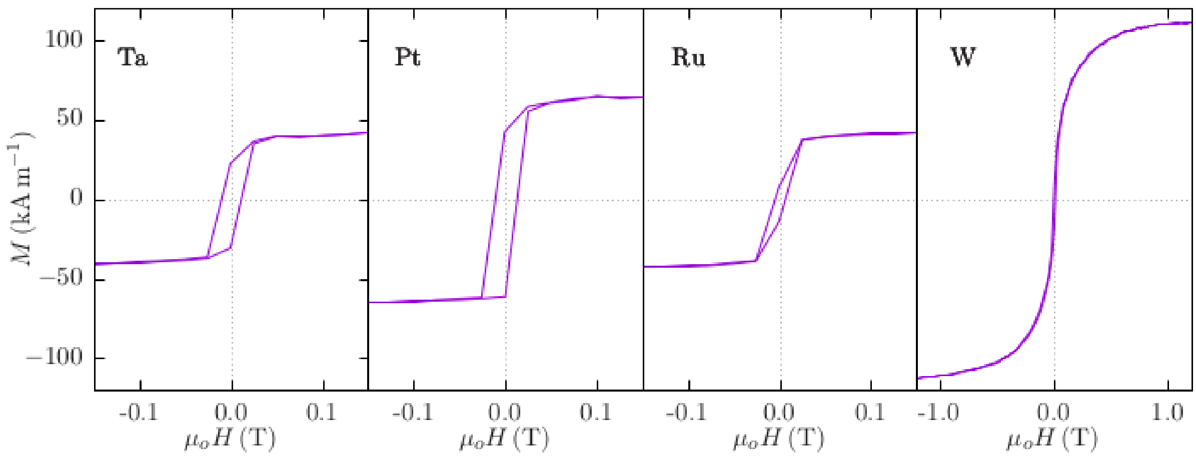

Figure 5 – Out-of-plane SQUID magnetisation loops taken of GdFeCo on various seed layers

Risk Management

We were unable to process other high-*Z* seeds for use with MRG due to technical reasons. Other candidates have been attempted i.e. Ta, Ru, Pt, and Hf. However, MRG grown on Ta and Hf so far has been amorphous, which leads to a loss of ideal magnetic properties. Due to the presence of Ru in the structure of MRG, using Ru as seed leads to extra Ru being incorporated into the structure, altering its properties. Finally, in order to grow properly oriented Pt films, the substrate must be heated to high temperature and the Pt is deposited in a mixed argon/oxygen environment. However, this would lead to oxidation of the Mn_2Ga target used for deposition of MRG, and so would lead to poor quality films.

Outlook

The growth requires optimisation of the seed to ensure a highly epitaxial β-W layer, necessary for increasing the *c*/*a* ratio > 1. This ensures that the anisotropy of the material is perpendicular to the plane. Further work is required to improve upon this and promote perpendicular anisotropy, and to develop additional materials upon which crystalline MRG can be grown.

Conclusion

We have demonstrated the growth of MRG and GdFeCo layers with magnetisation < 100 kA/m on heavy metals, with primary focus on W as a seed layer. For both materials, we can control the compensation temperature by changing the composition, giving us significant control. This is easier to control in MRG, as small changes in GdFeCo result in large changes of compensation temperature. In order to promote the growth of highly crystalline MRG on W, we need to sputter W using an RF source at room temperature, however the substrate must have been annealed to remove any moisture.

The films grown here have an accessible compensation temperature, which can be tuned above and below room temperature, as well as a low magnetisation. They are suitable for further development in spin pumping device structures.

Indications of a non-collinear magnetic state in GdFeCo have been observed when the thin film is grown on a W seed.