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Evaluation of Edge Domains in Giant Magnetoresistive Junctions

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We demonstrate that the spin-Seebeck effect can be used to estimate the volume of edge domains formed in a giant magnetoresistive (GMR) device. The thermal gradient induced by Joule heating can be harnessed by the addition of a ferromagnetically insulating channel of Fe₂O₃ on the sides of the GMR pillar. This generates a spin wave in the Fe₂O₃ which couples with the free-layer edge magnetisation and controls the reversal of the ferromagnetic layers in one direction only, increasing current density from (1.1 ± 0.1) × 10⁷ A/cm² to (7.0 ± 0.5) × 10⁷ A/cm². By simple assumption, we estimate the effect of the edge domain on magnetisation reversal to be (10-15)% by spin-transfer torque.

Spintronics has been attracting intensive studies over the last decades for efficient computing and sensing. In spintronics, the generation and manipulation of spin-polarised electrons and current control the efficiency. One method is to use thermal gradient. Spin-caloritronic devices represent an excellent avenue to improve device performance, efficiency and running cost by exploiting the waste heat produced in all current-driven devices. The thermal effects caused by Joule heating are ubiquitous in device operation and act as an unavoidable source of wasted power, as well as affecting device performance due to thermal effects. However, the generated thermal gradient in a current-driven device can be exploited by the spin-Seebeck, Peltier and Nernst effects, depending upon which device geometry is needed.

Ferromagnetic insulators (FMI) such as Fe₂O₃ or yttrium iron garnet (YIG) are extremely sensitive to these thermal gradients to exhibit strong spin-caloritronic effects when exposed to them. A spin wave can be generated via the spin-Seebeck effect when a current is applied to a device containing a FMI due to the Joule heating mentioned above. Therefore by including a FMI in a current-driven device the thermal gradients can begin to be used as a source of spin-current.

If this spin-current can be introduced to the ferromagnetic layers of a magnetoresistive device then the switching behaviour can be manipulated. The generated spin wave should act as a secondary source of torque as current flows through the device. In turn, this should lower the required current density for magnetisation switching as the required torque remains unchanged. As such the efficiency of the device can be improved by harnessing the wasted energy that is usually detrimental to device performance.

In this study a standard current-perpendicular-to-plane (CPP) giant magnetoresistance (GMR) device based on Heusler alloys has been modified to exhibit these effects. Heusler alloys have been used as they represent a family of materials with excellent potential for device application due to high values of saturation magnetisation and Curie temperature (Mₛ >1000 emu/cm³ and Tᵥ >900 K for Co₂FeSi) and the potential for 100% spin polarisation at the Fermi level. The standard insulator around the GMR pillars was replaced with Fe₂O₃ to act as a spin-wave source. This spin-wave generation controls the current density for switching and introduces a strong asymmetry due to the coercivity differences between the Heusler alloy layers and the FMI, allowing us to estimate the volume of the edge domains in a pillar.

An unconventional GMR pillar was fabricated, as shown in fig. 1. A typical Heusler-based GMR multilayer consisting of Co₂Fe₅₆Mn₀₂₆Si (CFMS) (5)/Ag₀.₇₈Mg₀.₂₂ (5)/CFMS (5) was grown on a Cr (20)/Ag (40) seed layer on an MgO(001) substrate under ultrahigh vacuum via magnetron sputtering, where all thicknesses are given in nanometres. The Cr/Ag seed layer was used to remove island growth and to promote strong texture in the CFMS layer and was acted as the bottom electrode of a CPP-GMR junction. A capping layer of Ag (2 nm)/Au (5 nm) was added. The seed and Heusler-alloy layers were annealed at 650°C and 500°C respectively to improve the interfacial smoothness and to promote crystallisation and ordering of the CFMS and the Ag₀.₇₈Mg₀.₂₂ layers.

Photo- and electron-beam lithography and Ar-ion milling were used to fabricate a series of elongated pillars with long axes from 100 nm to 800 nm, however as shown in fig. 1 the milling stopped 1 nm into the lower FM layer. The Fe₂O₃ was then deposited around the pillar in place of the usual AIO insulator. For adhesion, it was necessary to add a secondary
seed layer consisting of Cr (1 nm)/AlO (2 nm). Due to the lack of adhesion it was not possible to stably anneal Fe$_2$O$_3$. Therefore the crystallinity of the FMI channels is limited.

Device properties were measured using a HiSOL HMP400-SMS probe station with a Keithley 2400 sourcemeter and a Keithley 2182A nanovoltmeter, giving high resolution. Magnetisation reversal was induced using both field- and current-driven switching systems. Here we consider three contributions for the magnetisation switching, (i) conventional STT by the pinned layer, (ii) the influence of the edge domains exchange-coupled with a spin wave generated in Fe$_2$O$_3$, and (iii) Joule heating.

As observed without Fe$_2$O$_3$, a negligible asymmetry is measured in the GMR curves from negative to positive saturation and vice versa. However, with Fe$_2$O$_3$, a prominent asymmetry is measured as seen in fig. 2(a), which contains the above explained edge magnetic domains coupled to the spin wave (ii) generated in Fe$_2$O$_3$ by the thermal gradient al-

FIG. 2: GMR curves for a pillar (120 and 60 nm in long and short axes, respectively) (a) with and (b) without Fe$_2$O$_3$ with a sensing current of 100 μA. Red and blue curves represent the field sweep from negative to positive and vice versa respectively. Note that the shape of the GMR curves are independent of the amplitude of the sensing current up to 1 mA.

FIG. 3: Current switching profiles for the same device as shown in fig. 2(a) with applied fields of (a) −10 and (b) 75 Oe corresponding to the fields to form distinctive magnetic configurations as appeared in Fig. 2, where (b) has a current in the opposite direction. In (a), red, blue and green curves represent the current sweep from 0 to negative, from negative to positive and vice versa respectively, while in (b), that from 0 to positive, from positive to negative and vice versa respectively.
most perpendicular to the plane. Therefore the current-driven switching must be affected by FeO around the edge of the free layer, which are aligned parallel to the pinned layer by the initial application of the negative field as described above and therefore will produce two contributions (i) and (ii) as schematically shown in the figure. The STT (i) switches a central region of the magnetisation of the free layer, while those in the edge domain are maintained by (ii), forming the partially antiparallel state. It is therefore possible for the magnetisation to be reversed using a negative current from antiparallel to parallel states. Removal of the applied current does not reorient the free layer but the minor increase in the resistance suggests the decrease in the volume of the edge domains (ii) in addition to the Joule heating by the current (iii). It should be noted that the magnetisation switching from the parallel to antiparallel state cannot be achieved by a current up to 40 mA, which indicates that STT (i) may not be strong enough for switching although some minor increase and instability in resistance can be seen in the positive current in the figure.

Figure 3(b) shows the same process in the opposite field orientation starting from the partially antiparallel state as achieved at 75 Oe in fig. 2(a). Here $j_{sw}$ has a value of $(7.0 \pm 0.5) \times 10^7$ A/cm$^2$ controlled by the competition between the three contributions (i)-(iii). First, a reduction in the resistance at very low currents is observed, which can be associated with gradual magnetisation rotation in the minor domains formed between the central region and the edge domains in the free layer as shown in grey in fig. 3(b). This may possibly due to STT through the central domain to instabilise the minor domains (i) and the exchange coupling induced by the outer edge domains. A metastable state is then reached as the edge domains (ii) and Joule heating (iii) are not strong to reverse the magnetisation in the central region of the free layer up to $j_{sw}$ as the partial antiparallel configuration is stable from the viewpoint of the STT (i). Above $j_{sw}$, spin-torque oscillation may start to occur as reported in a similar system,$^{13}$ which makes the magnetisation of the central region to be unstable and assists the magnetisation reversal by the processes (ii) and (iii). This may lead to the significant instability of the device resistance at high currents. It is also possible that the instability is due to the lack of total crystallinity in FeO without annealing, local spin waves may be generated, which in turn perturb the magnetisation in the edge domains of the free layer, causing variations in the resistance. Additional imperfections from diffusion or intermixing in FeO may create pinholes in FeO which further change local spin-wave environments.

Figure 4 shows the current switching data by the conventional STT (i) in a similar device without FeO as shown in fig. 2(b). It is clear that the antiparallel state is more uniform in this device with two distinct plateaus separated by sharp switching. The switching current densities are lower than for the case above with values of $j_{sw}$ of $(1.1 \pm 0.1) \times 10^7$ A/cm$^2$ and $(2.2 \pm 0.2) \times 10^7$ A/cm$^2$ for the negative and positive currents respectively. The increased stability is due to the removal of the influence of FeO no longer forming the edge/minor domains. The reversal is simply controlled by a nucleation event, most likely at an edge where damage from milling has occurred as similarly observed in our earlier studies without FeO.$^{12,14}$ The difference in $j_{sw}$ confirms the magnetic stability of the edge domains induced by FeO in fig. 3, which may not be ideal for fast and coherent magnetisation reversal for device applications. It is therefore important to estimate the volume of the edge domains.

These results indicate that the presence of the spin wave in FeO can assist the magnetisation reversal only when the spin-wave generated in FeO is in parallel with the magnetisation of the free layer as discussed above, however, the edge/minor domains magnetically coupled to FeO are found to further increase $j_{sw}$. The presence of FeO, which has non-ideal crystallinity, may induce strong pinning sites at the interface with the Heusler-alloy layer inducing a significant rotational component to the magnetisation reversal. Since the rotational components account for 10–15% of the total resistance change, the edge domain volume can be estimated as this proportion of the free layer as compared with the central region consisting of approximately a half of the volume switched at $j_{sw}$ in fig. 3, leaving the remaining almost 1/3 of the volume to from minor domains between them. Such estimation can be complementary to the conventional activation volume analysis for the magnetisation reversal$^{15}$ and suggests the elimination of such minor domains can reduce $j_{sw}$.

Furthermore the presence of any disorders or dislocations will reduce the spin polarisation of the Heusler-alloy layer. If the spin polarisation of the pinned layer is reduced, the associated STT is reduced and $j_{sw}$ is increased. Therefore improvements are needed to the fabrication of the pillars with FeO, especially the improvement of the crystallinity of FeO, in order to realise the potential to effectively take advantage of thermally-induced spin waves.

In summary, we have shown that a FMI in contact with the edge of a GMR device can heavily influence its behaviour. Significant asymmetry is induced in the current-induced magnetisation switching depending upon the relative magnetisation of the FMI and the free layer due to the thermal gradients from Joule heating, which in turn create spin waves in the device coupling with the edge domains in the free layer. This may also create different field dependent behaviour. This is useful for determination of the volume of edge domains and for the evaluation of the nature of coupling between FMI and GMR structures. Control of GMR devices for niche application or asymmetric reversal may be possible using FMI edge channels.

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All data are available on the dedicated database of the University of York.

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