Dynamical stability switching of a magnet by spin-orbit torques

We discovered a novel magnetic reversal process promoted by spin-orbit torque excitation. This can only be achieved by a specific energy landscape where we only have one local minimum in the classical analog of the Bloch sphere. We experimentally show the magnetization reversal using magnetoresistance and ferromagnetic resonance experiments, fully supporting an idea that the moments can be excited to point around the energy maximum upon large excitation.

Year 2022 would be the time where we started slowly building confidence that we can come out of the restricted life posed by the pandemic outbreak. I was one of those who were eager to feel the academic normality as was granted in the past and this visiting fellowship was spot-on for that. Personally, this is a special one since I was a student at Tohoku university a long time ago.

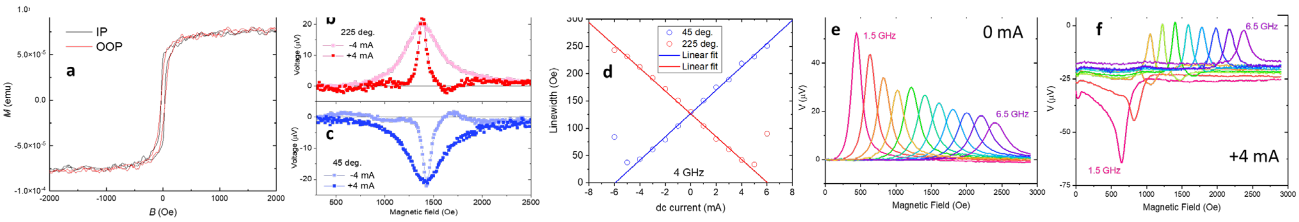
Within the field of spintronics, an efficient control of magnetization has been the central topic since its birth. This is due to its direct relevance to the majority of memory and logic applications based on the spin degree of freedom, where information is stored and processed using magnetic moments. In general, the non-volatility of magnetism, arising from magnetic anisotropies, is an essential component for spintronic memories and the community has devoted a great deal of efforts to achieve a large size of magnetic anisotropies in a spintronic memory cell, at the nanometer lengthscale. In this project, we consider the opposite side of this limit, namely making a magnet isotropic as much as we can and exploring new spintronic phenomena based on isotropic magnets. Magnetic Materials Lab at IMR has world-class capability of growing thin-films at an atomic level, an ideal place to pursue this ambitious project. During the period of this visiting professorship between July and August 2022, I was able to grew thin-films, optimized their magnetic properties, measured the patterned devices and analyzed the results, all by myself with Dr Seki. It reminded me my postdoc period a long time ago and I am very fortunate to have that back again, which was truly enjoyable.

We first grew multilayer stacks of MgO/CoFeB/W on SiO_2/Si substrates. When we normally grow this type of stacks, the magnetic dipole interaction (often called the demagnetization) due to the thin-film nature is fully activated, creating the magnetically easy plane anisotropy. In order to counteract to this, which is essential to create a magnetic film with zero magnetic anisotropy, we employ the spin-orbit driven surface anisotropy. Therefore, the first task in this project was to find the optimal growth/annealing conditions that can level the surface anisotropy to the demagnetization. After growing more than ten different multi-layers and testing a number of annealing conditions during three weeks, we found conditions where hysteresis loops for in-plane and out-of-plane magnetic field directions almost match to each other as shown in Fig. 1a.

We then patterned a few of these multilayers to produce micro-bars for spin-torque excitation measurements. We extensively studied these micro-bars using microwave current excitation techniques and discovered that the magnetic relaxation, measured by the linewidth of magnetic resonance peaks, can be modified considerably by a dc current insertion, as shown in Fig. 1b&c. The Gilbert damping coefficient α represents the intrinsic magnetic relaxation and is extracted by the frequency dependence of linewidth. When we apply a dc current, spin-transfer torques are created due to the spin-Hall effect and modify α by following the phenomenological equation [1]:

$$\alpha = \frac{\sin\phi}{(H_{\mathrm{ext}}+0.5M_{\mathrm{eff}})\,\mu_0 M_s t}\,\frac{\hbar}{2e}\,\theta_{\mathrm{SH}} J_c$$

Fig.1: **a** Magnetic hysteresis loops, in-plane (IP) and out-of-plane (OOP), for **MgO/ CoFeB/W** sample after optimization. **b&c** the ferromagnetic resonance peaks under dc current injections. **d** The linewidth as a function of dc excitation. **e&f** The frequency dependence of FMR peaks with and without dc excitation.



Here, μ_0, H_{ext}, M_{eff}, M_{s}, t, $\hbar$, e, θ_{SH} and J_{c} are the magnetic permeability of free-space, the externally applied magnetic field, the effective magnetisation, saturation magnetisation, the thickness of the magnetic layer, the reduced Planck constant, the elementary charge, the spin-Hall angle and the charge current density, respectively. The extracted θ_{SH} using this equation and the slope in Fig. 1d is 0.22 which is consistent with reported values in the literature [2]. We attribute the large damping modulation to the minimized M_{eff} in our devices. What is noticeable is that when the damping is fully compensated by injected spin transfer torques, we do observe the sign change of the FMR peak amplitude as shown in Fig. 1f, which is absent in the same experiments without dc current excitation (Fig. 1e). Phenomenologically, the FMR amplitude is determined by the phase relationship between the input microwave current and the dynamic component of magnetization precession (excited by the microwave current). The sign switching therefore means the π shift of the precessional phase, indicating the reversal of static magnetization.

To identify whether indeed the magnetization reversal is present or not, we performed magnetoresistance experiments with the spin-torque excitation. Figure 2a shows that there is a peak-like magnetoresistance only for the magnetic field direction when the spin-torques compensate the magnetic damping (so when we take the same set of data by reversing the magnetic field, this peak is absent).

The peak position represents the point where the intrinsic damping is fully compensated by the injected spin torques. We went on to analyse the peak position as a function of applied field direction/magnitude, as shown in Fig. 2b. The dependence excellently matches to the damping compensation model, e.g. the solid lines/curve are those calculated by the model.

Figures 2c&d would visually explain how the damping modulation leads to the magnetization reversal. The magnetization is equilibrated at the energy minimum defined by the Zeeman energy due to the applied magnetic field. What is interesting is that by applying anti-damping torques, the moments start to be excited away from the energy minimum and at high excitation, the time-averaging position of the moments can even be situated around the maximum of the energy landscape. The numerical simulations based on the stochastic Landau-Lifshitz-Gilbert equation capture the magnetization reversal phenomenon as shown in Fig. 2d where the color dots are used to relate the moment position with respect to energy potential in Fig. 2c.

Working with our theorists (Prof. Gerrit Bauer and Dr Yamamoto, JAEA), we are now developing an analytical model that can fully capture our observation. This study potentially offers a model system to explore the dynamical stability in spin systems and we are very fortunate to have had this visiting professorship opportunity that allowed this discovery.

References

[1] Liu, L., Moriyama, T., Ralph, D. C. & Buhrman, R. A. Phys. Rev. Lett. 106, 036601 (2011)

[2] Sinova, J., Valenzuela, S. O., Wunderlich, J., Back, C. H. & Jungwirth, T. Spin hall effects. Rev. Mod. Phys. 87, 1213–1260 (2015).

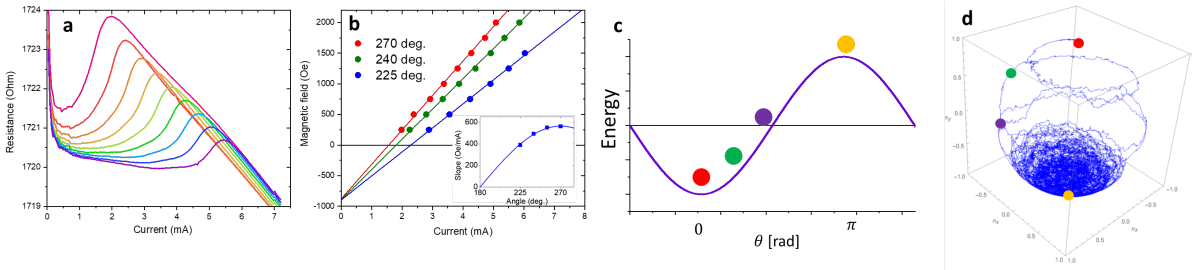


Fig.2: **a** Magnetoresistance under dc current excitation. **b** The peak analysis for different field amplitudes and directions. **c** A schematic of an energy landscape defined by the Zeeman energy. **d** A time-evolution of magnetic moments with a negative damping coefficient. A magnetic field is applied towards the north pole defined as θ = 0. Color dots are used for indicating corresponding states in the energy landscape in Fig 2c.

Keywords: spin current, spintronic, sputtering

Hidekazu Kurebayashi (University College London)
E-mail: h.kurebayashi@ucl.ac.uk
https://www.ucl.ac.uk/spintronics