Electromagnetic Coupling Effects in Thin Film Ferroics

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Summary: This project seeks to explore direct, rather than indirect, coupling effects between magnetic spin behaviour in one material and bound-charge-induced electric fields in an adjacent one. Specifically, we hope to probe the way in which spin-polarised electron transport and magnon propagation might be affected by the intense electric fields and changes in electric fields, which can be realised by manipulating ferroelectric domain states. Characterisation will involve electrical spin-based measurements as well as direct pump-probe imaging, using a newly installed nitrogen-vacancy centre microscope at Queen's University Belfast (QUB). The research is part of a large (£6.6M) recently funded EPSRC Programme Grant involving QUB, Leeds and Imperial College London.

Background: Magnetoelectric coupling in multiferroics has been a major research theme over recent decades, partly because of fundamental interest [1], but also partly because of possible applications in novel transducers and in new kinds of low energy data storage and data processing devices [2-4]. Two main approaches for generating magnetoelectric multiferroics have been developed, involving either single phase materials (which have both electrical dipolar and spin ordering) [1,5,6] or, perhaps more commonly, coupling between two different materials (usually one ferroelectric and the other ferromagnetic) across a shared interface [2, 7]. While there is an intimate and fundamental relativistic link between electricity and magnetism, coupling is most often realised indirectly, through some kind of "intermediary", such as strain: materials with significant magnetoelastic responses have often been combined with those which show strong piezoelectric, or electrostrictive, effects.

For coupling magnetostatic and electrostatic effects, this intermediary is generally necessary. However, when obvious dynamics, such as charge transport, spin wave propagation or domain wall motion, are involved, direct magnetoelectric interactions become possible [8]. Indeed, direct coupling of this nature is now coming to the fore as a research topic of international significance as it may have far-reaching implications for next-generation memory and data processing [4].

The PhD Programme: In this PhD we will attempt studies within the following themes:

Spin Diffusion Lengths in Metallic Films and in Domain Walls:

Ferroelectric surfaces can have extremely high local potentials; indeed, such surface potentials have previously been used to generate ionising and accelerating fields sufficient to induce fusion of Deuterium nuclei [9]. Exposing conducting films or domain walls to such intense fields should, in principle, therefore allow coupling between the spin of the moving electrons and the Lorentz transform of the electrostatic field, as seen from the rest frame of the conducting electron. We suspect that this interaction will influence the spin diffusion lengths in both metallic thin films (deposited onto ferroelectric surfaces) and in conducting ferroelectric domain walls inside the ferroelectric itself. Such conducting interfaces are generally realised by creating significant polarisation discontinuities at head-to-head or tail-to-tail domain walls and this can readily be engineered in thin film $LiNbO_3$ (and we have done this as a matter of course in, for example, our recent studies on domain wall magnetotransport [10] and domain wall memristors [11]). For both the metallic films and the domain walls, injection of spin-polarised currents will require additional magnetic or semi-metal injection pads and detection of spin diffusion lengths would also either need lateral spin-valve geometries or NV-centre microscopy detection (we do not know whether the NV-centre system will be able to distinguish spin-state-related magnetic fields and Oersted fields, but will examine this as part of the work).

Mapping the Influence of Magnetoelectric Coupling on Magnon Propagation in YIG:

There have been a number of very recent publications in which nitrogen vacancy-related imaging of magnons in YIG has been achieved [12,13]. Indeed, mapping of excited magnons and their scattering have been explicitly demonstrated recently using NV-centre microscopy (figure 1a) [12]. We would like to extend this kind of work to specifically examine how adjacent ferroelectric domain configurations, bound charge distributions and domain rearrangement might affect magnon dynamics, using the newly configured NV-centre system in QUB. In principle, this could involve YIG thin film deposition onto the z-cut LNO single crystal films discussed above. However, we may be more successful in depositing thin film LNO onto FIB-cut single crystal YIG lamellae and then imaging the bilayers after “flipping” onto a support substrate. We have decades of experience in handling such FIB-cut single crystals, integrating them into circuits and imaging microstructural dynamics under fields (figure 1b), so although this approach sounds implausible, we have shown it to work many times and have been able to generate extremely clear dynamical insight [14-17].

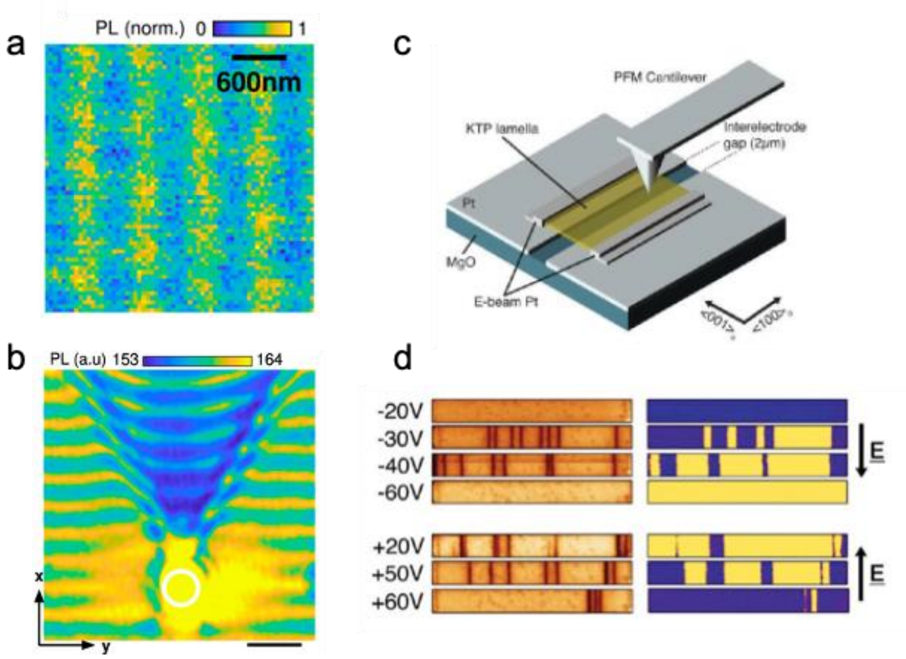

Figure 1: Magnons in YIG imaged very recently using NV-centre microscopy (a), along with their scattering from a permalloy disc on the YIG surface (b). We have considerable experience in handling and integrating FIB-cut lamellae into simple circuits (c) to allow in-situ domain switching dynamics (d) in scanning probe microscopes. This approach could be used for YIG-ferroelectric imaging experiments to reveal coupling behaviour.

References: [1] H. Schmid *Ferroelectrics* **427**,1 (2012); [2] C. Israel *et al. Nat. Mater.* **7**, 93 (2008); [3] M. Bibes and A. Barthelemy, *Nat. Mater.* **7**, 425 (2008); [4] S. Manipatruni *et al., Nature* **565**, 35 (2018); [5] J. Wang *et al. Science* **299**, 1719 (2003); [6] Q. Song *et al. Nature* **602**, 601 (2022); [7] C-W. Nan, *J. Appl. Phys.* **103**, 031101 (2008); [8] C. A. F. Vaz *et al.* Appl. Phys. Rev. **8**, 041308 (2021); [9] B. Naranjo *et al. Nature* **434**, 1115–1117 (2005); [10] C. McCluskey *et al. Adv. Mater.* **34** 2204298 (2022); [11] J. P. V. McConville *et al. Adv. Func. Mater.* **30** 2000109 (2020); [12] T. X. Zhou *et al. PNAS* **118** e2019473118 (2021); [13] I. Bertelli *et al. Sci. Adv.* **6** (2020); [14] J. R. Whyte and J. M. Gregg *Nat. Commun.* **6** 7361 (2015); [15] J. R. Whyte *et al. Adv. Mater.* **26** 293 (2014); [16] R. G. P. McQuaid *Nat Commun.* **2** 404 (2011); [17] P. Sharma *et al. Adv. Mater.* **25** 1323 (2013).