05 Enabling the future of Big Data using materials with unique magnetic properties

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Magnetic materials have underpinned the evolution of digital data storage technologies for over six decades and are still relied upon in ultra-large capacity long-term tape archival systems, and in the too many to enumerate armies of spinning hard drives humming along tirelessly in the rapidly growing strategic data centres worldwide. Systematic performance improvements have been dusted with a couple of little revolutions, introducing new ways of building both the magnetic storage media and the heads, which are used to read and write the data. Synergies with optical and microwave technologies are poised to allow for even higher density recording, pushing the boundaries of density and speed.

In all of these success stories ferromagnetic and ferrimagnetic materials (where the moments are aligned essentially parallel) with high net magnetization have been the main players, with secondary roles being played by antiferromagnets with anti-aligned moments or more complicated order. For the last decade the support players have been trying to come from behind the curtain and claim the centre stage, with promises of speed, efficiency and robustness. To make this transition a reality, a few paragons are needed to break the performance limits and drive a paradigm shift.

One unique combination of properties, that has been predicted to exist for over 20 years, but only recently been given a real experimental prototype, is the near-zero net moment and high conduction electron polarization. The Magnetism and Spin Electronics Group at Trinity's School of Physics and the CRANN institute has been at the forefront of this research, demonstrating, understanding and engineering the properties of the Zero-Moment Half-Metal (ZMHM) Mn2RuGa (MRG for short) and related materials.

Two inequivalent crystal and magnetic sub-lattices are needed to build MRG, both comprised of manganese, and essentially anti-aligned, as illustrated in Fig 1. Because of the difference in symmetry of the local environment of the two types of manganese, the net magnetic moment can be brought to near-perfect compensation (at least in a chosen range of temperatures), while the electronic current, which is predominantly affected by only one of the two sub-lattices is indeed, highly spin-polarized. While the optimization of the application of MRG in thin film devices requires precise control over its composition, lattice constants and surface roughness, demonstrations of useful functionality have already been achieved, with appreciable tunneling magnetoresistance which is persistent through its compensation temperature region. The very high ferromagnetic resonance frequencies (over 270 GHz have been demonstrated with the help of collaborators in Ireland's first EC FET Open project TRANSPIRE) offer a strong motivation for the design and prototyping of tunable low-power microwave oscillators, relying on the passage of highly polarized current in micro and nano-pillars incorporating thin film stacks, featuring MRG.

More recently, exploration involving the Photonics Laboratory of CRANN, revealed that the unique microwave properties of the MRG family of

FIG 1

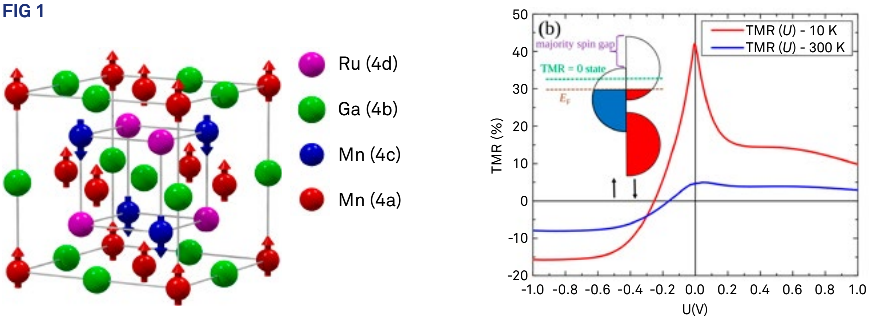

FIG 1 – Left: Crystal and spin structure of Mn2RuGa. Right: Adapted from K. Borisov, et al. Appl. Phys. Lett. 108, 192407 (2016)) TMR (*U*) scans at 300 K and 10 K for a chip annealed at 350 oC. The top left inset represents the spin split density of states of MRG for x = 1:0.

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FIG 2 – [Adapted from, C. Banerjee et al. Nature Com. 11, 4444 (2020)] Toggling of the magnetization in Mn2Ru1Ga. Magnetization patterns are shown as a function of the number of applied pulses. Pulse energy was 11.6 mJ cm–2. The scale bar represents a length of 50 μm.

FIG 3 – Left: [Adapted from, G. Bonfiglio, et al. Phys. Rav. B 100, 104438 (2019)] Time resolved Faraday effect recorded at T = 290 K in applied fields ranging from 1 T to 7 T. After the initial demagnetisation seen as a sharp increase in the signal at t ~ 0 ps, magnetisation is recovered and followed by precession around the effective field until fully damped. The lines are fits to the data. Right: Effective SO inductance for a Hall bar of MRG.

materials also translate to unique optical functionality, courtesy of the spin-polarized conduction close to the Fermi level and the controllable exchange coupling within and between sub-lattices. For only the second time (and the first in a material devoid of rare-earths), ultra-fast optical toggling of the magnetization, using single femtosecond laser pulses, has been demonstrated, as visualized in Fig. 2. This opens a realm of possibilities for the incorporation of magnetic functionality, with all the benefits of long-term memory and radiation hardness (just to mention a couple), into optical control and memory devices and laser-driven upper microwave and THz-region tunable generators (see Fig. 3), harnessing more of the special properties of MRG. Devices incorporating the technology could open previously nonexistent ways to the densification of the fibre-optic communication networks' information traffic and extend the useful life of existing infrastructure for another generation, in a green and cost-effective manner.

In a final twist, the MRG-type ZMHM materials may offer yet more functionality for the control of the magnetic state of memory, logic and optical interfacing components on-ship, using in-plane electronic currents and spin-orbit torques (see Fig. 3), ensuring that magnetism will still have a role to play in the data society of tomorrow.

FIG 2

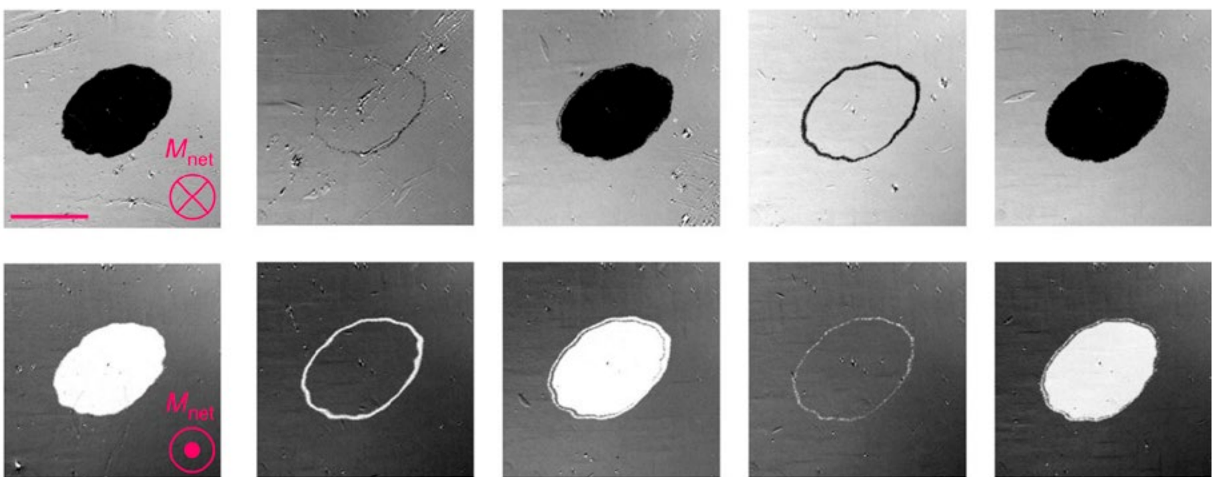

FIG 3