Research Highlight: Efficient Spintronics in Thin Film Magnetic Insulators
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Background: Sanyum Channa, a 5th year graduate student in Stanford Professor Yuri Suzuki’s research group, won first prize at the 2023 nano@stanford Open House poster competition. I thought that this first issue of the nano@stanford Newsletter would be the perfect opportunity to highlight his award-winning spintronics research.

Grace Hsieh and I recently had the opportunity to sit down with Sanyum to get to know him better and learn about his research. Sanyum was born and raised in the Middle East, where he and his friends developed a love for physics. In 2015, he made the courageous leap to move to an entirely new country to major in Physics at the University of California, Berkeley with the aspiration of becoming a theoretical physicist. At Berkeley, Sanyum was incredibly fortunate to cross paths with an up-and-coming physics professor, Professor James Analytis, who invited Sanyum to be an undergraduate researcher in his group and help them investigate exotic quantum materials. This research experience and a senior year class in novel magnetic materials inspired Sanyum to shift away from theoretical physics and pursue a higher degree
in applied physics, with a focus on magnetic materials. Sanyum considered several universities for his PhD, but ultimately decided on Stanford after meeting Professor Yuri Suzuki (who works in the field of novel magnetic materials) during an open house and then feeling “at home” decompressing after the event on the warm, grassy Science & Engineering Quad.

Sanyum joined Professor Suzuki’s lab in 2019 and spent his first year and half at Stanford working on another condensed matter system research project, which he told us was frustrating and not producing the results he wanted. On the side, he started collaborating with another graduate student in the Suzuki Lab, Xin Yu Zheng, to try to grow a new type of magnetic material for the first time. The results were incredibly promising, which led Sanyum to pivot his PhD project to this new topic: novel ferromagnetic insulators for spintronics.

Spintronics is a relatively new technology for electronic devices in which information is carried by electron spin instead of only by electronic charge like traditional devices. The dream is that this technology will help make next generation devices better, faster, more efficient, and smaller - perhaps to even enable us to exceed Moore’s Law! Market researchers think that spintronics technology is a strong market space and well-positioned for long-term growth, with companies like IBM, Intel, TSMC, and Samsung as key industry players in the field.

I have to admit that my background is in bioanalytical chemistry, so applied physics and spintronics is well outside my comfort zone. I really appreciated Sanyum's willingness to tell us about this research and boil down super complex science for the non-expert. I can only hope that my synopsis does justice to this ground-breaking work! Some of Sanyum's research was recently published in Nature Communications if you'd like to check out the official version (https://doi.org/10.1038/s41467-023-40733-9).

**Sanyum's Research:** Spintronic devices require some kind of ferromagnetic material to allow the propagation of spin waves, which carry information. Ferromagnetic insulators, or FMIs, are advantageous over more traditional metallic ferromagnets because FMIs localize all the spins, which allows spin current generation without any dissipative electrical currents. Sanyum’s PhD project focuses on engineering an entirely new FMI that can further advance spintronic devices. In particular, he has been fabricating and characterizing ultra-thin (~4-15nm) films of Li$_{0.5}$Al$_{1.0}$Fe$_{1.5}$O$_4$ (LAFO) that boast low-damping, perpendicular magnetic anisotropy (PMA), and high-quality interfaces between the LAFO film and adjacent layers in the structure. I personally needed a simple description of “PMA”, and Sanyum explained that it
is a really important property for magnetic applications and involves the direction of a film’s magnetization. In very thin films, the magnetic field innately wants to orient parallel to the plane of the film; however, the out of plane (or perpendicular) spin direction has a lot of desirable performance advantages (like temperature stability and miniaturization potential).

Let’s dig into the fabrication process used for the publication! The structure consisted of an ultrathin LAFO layer sandwiched between (1) an epitaxial platinum (Pt) spin-to-charge conversion layer on top and (2) a (001)-oriented magnesium gallate (MgGa$_2$O$_4$, or MGO) substrate (Figure 1). We’ll see later that the (001) MGO crystal orientation was quite important. The LAFO films were created by pulsed laser deposition onto the MGO substrate. In other words, a solid piece of Li$_{0.6}$Al$_{1.0}$Fe$_{1.5}$O$_4$ and the MGO substrate were placed into a deposition chamber facing each other. The MGO substrate was heated to a high temperature (450°C) and a high-power laser beam blasted the Li$_{0.6}$Al$_{1.0}$Fe$_{1.5}$O$_4$, converting some of the solid material into a plasma. The plasma then recondensed onto the MGO substrate as a LAFO thin film. Finally in some cases, a Pt layer was deposited on top of the LAFO at the Stanford Nanofabrication Facility (SNF) using the Kurt J. Lesker PRO Line PVD 200 thin film deposition system. Platinum is a great material for converting charge currents into spin currents and organizing the spin directions.

Next, it was time for Sanyum and the rest of the research team to test what they made and determine whether it would be a good fit for spintronic devices. Specifically, the characterization work studied the Pt/LAFO/MGO atomic-level structure (e.g., crystallinity, epitaxial quality, interface integrity, film thickness) and its magnetic performance using resources available at the Stanford Nano Shared Facilities (SNSF), the Advanced Light Source at Lawrence Berkeley National Labs (LBNL), and additional facilities in Stanford’s McCullough Building.

The primary structural characterization tools included transmission electron microscopy (TEM), X-ray diffraction (XRD), and X-ray reflectivity (XRR). TEM is an imaging technique that can “see” down to the atomic scale by transmitting a focused beam of high energy electrons through a very thin sample (<100nm). Sanyum used super-fancy and advanced TEM-based techniques (e.g., atomic resolution high-angle annular dark-field scanning TEM (HAADF-TEM) and aberration-corrected high-resolution TEM (HRTEM)) to reveal very clear and uniform boundaries between the LAFO and MGO layers and the Pt and LAFO layers (Figure 2). Next, he collaborated with Arturas Vailionis at the Stanford Nano Shared Facility (SNSF) to examine the crystal structures of the LAFO and Pt films using the Malvern PANalytical Empyrean and X’Pert PRO XRD instruments. During XRD measurements, a single wavelength X-ray beam is directed
at the sample at varying angles and the X-rays reflected off the sample are analyzed. The reflected X-rays have a diffraction pattern that is characteristic of a specific chemical composition and the size and shape of the unit cell in the crystal. The XRD results for the LAFO film indicated that it was high quality and had a highly ordered crystal structure (Figure 3). Significantly, the shift in the XRD peak position for the LAFO thin film, relative to the peak position for a solid chunk of LAFO, meant that the size of the LAFO unit cell had (in layman's terms) stretched out, matching the crystal size of the MGO. The resulting strain on the LAFO from this stretching caused the electron spins to adopt a perpendicular orientation (in other words, the desired PMA - hooray!!). Additional XRD data indicated that the Pt and LAFO layers had matched interfacial crystallinity which is advantageous compared to how Pt grows on other FMIs. High quality interfaces like those Sanyum observed for LAFO/MGO and Pt/LAFO will enable efficient electron spin current transfer, which is critical for spintronics!

For the magnetic characterization, Sanyum relied on superconducting quantum interface device magnetometry (SQUID) and ferromagnetic resonance (FMR) available in Stanford’s McCullough Building. SQUID uses sensitive superconducting loops to measure a sample’s magnetization very precisely. The SQUID results indicated that the LAFO film had the desired PMA, requiring only a very small external magnetic field (~1.5mT) to saturate the magnetization value (Figure 4). FMR measurements involve exposing a sample to an oscillating magnetic field which causes the magnetic moments in the sample to “wobble”, or precess, around their equilibrium state. The time it takes for this wobbling to die down is related to the system’s damping (damping = reduction of the precession amplitude). The FMR data was used to determine a dimensionless constant, called the damping factor, $\alpha$. This damping factor turned out to be around $6 \times 10^{-4}$ for the 15nm thick LAFO film which was the lowest a value (and damping) yet reported for this type of FMI film. These results from the LAFO film are quite significant because spintronic devices can benefit from the simpler crystal structures and lower synthesis temperatures (enabling compatibility with a wider range of materials) of FMIs, while still having comparable/desirable damping as other ferromagnetic materials.

The magnetic performance of the LAFO was further evaluated in spin-orbit torque (SOT) switching devices. Spin-orbit torque switching is an important phenomenon in spintronics in which a material’s magnetic moments are switched by a current. In order for this current-induced magnetic switching to occur in the LAFO films, a critical current density of $6 \times 10^5$ A/cm$^2$ was needed, which was the lowest ever observed for PMA FMIs at room temperature (Figure 5). Another SOT-related parameter, called the “damping-like spin torque efficiency” ($\theta_{d}$), was found to be 0.57 which is a value that also indicated fantastic spintronics
performance. Sanyum thinks that the excellent quality of Pt/LAFO interface likely contributed to this high spin torque efficiency and spin transfer efficiency. The take-home message is that Sanyum and the team from the Suzuki lab **proved this new FMI can have many desirable attributes for spintronics including PMA, low magnetic damping, pristine crystal structure, excellent interfacial quality, record-low critical current densities and magnetization switching currents, and high spin-orbit torque efficiencies.** Sanyum thinks the key to this success was a combination of the iron-to-aluminum ratio in the LAFO, the strain induced in the LAFO by the MGO substrate, and the high-quality interfaces. What’s next? Sanyum would love to find out if he can send signals across a device using these magnetic structures, such as two adjacent but non-contacting platinum wires.

Grace and I asked Sanyum to tell us about some challenges he’s faced in graduate school. Truly, he has found there are challenges every day so if you’re out there struggling, know that you are not alone! He has experienced setbacks in his research when equipment, like the SQUID, stopped working properly and he needed to make repairs with minimal external support. Sanyum also relayed to us that the publication process can be quite lengthy and exasperating. This Nature Communications paper took two years to publish and was rejected from a few other journals because of the editor or difficult reviewers.

Sanyum had several pieces of advice for future graduate students. He urges prospective students to be sure they are passionate about their research topic and also to seriously think early on about what they want to do after earning their degree. It’s helpful to be open-minded about your end goal and to be willing to pivot to alternative pathways. Sanyum also advised that a PhD is “a long journey, not a race, but a marathon” and that the journey should not be taken alone. Sanyum thinks that the most important thing in graduate school is working together with other people, bouncing ideas off each other, commiserating over the challenges, and celebrating the successes.

![Figure 1. Schematic showing the cross-section of the Pt/LAFO/MGO structure.](image)
Figure 2. TEM structural characterization of the LAFO film on MGO. a) TEM image showing a high-quality LAFO/MGO interface. b) TEM image of the Pt/LAFO interface revealing that transition between layers occurred within a monolayer. Inset: digital fast Fourier Transform of the TEM data showing the crystal orientation from the boxed region.

Figure 3. a) X-ray diffraction (XRD) data of a LAFO/MGO sample for the (004) peak. The broad hillocks in the blue plot (i.e., for the 15nm thick film) indicated the film had a coherent diffraction, meaning it was a high quality, crystallographically aligned film. These hillocks were absent in the red plot because that film was too thin to detect this oscillation behavior and therefore its quality and crystallinity were less certain. The vertical dotted black line marks the peak position for bulk LAFO. The peak position shifted for the LAFO film because the larger unit cell size of the MGO substrate “stretched out” the LAFO cell size to match. b) XRD data of a Pt/LAFO/MGO sample. The symmetry of the Pt peak indicated that Pt layer was epitaxial (Inset: “rocking curve” on the Pt (111) peak).
Figure 4. SQUID results showing LAFO magnetization (M) as a function of an applied external magnetic field ($\mu_0 H$). The blue curve is the perpendicular (out-of-plane) magnetization, and the red curve is the parallel (in-plane) magnetization. a) shows the curve for the entire magnetic field range and b) is a zoom-in of a narrow range near zero. The data indicates that perpendicular magnetization requires a very small external magnetic field (~1.5mT) to switch the spin direction and saturate the signal. Conversely, the parallel magnetization required 500mT for saturation.

Figure 5. “Hall bar” devices were created using Pt/LAFO/MGO to test the spin-orbit torque switching behavior of the system. a) Magnetic reluctance ($R_{xy}$) as a function of electric current density ($J_{DC}$) when a magnetic field of ±3mT was applied in the same direction as the current. The critical current density ($J_c$ = the $J_{DC}$ value at the sharp inflection points) was about $1.5 \times 10^6$ A/cm². The data also shows that the switching polarity reverses direction upon reversing the applied field direction (from +3mT to -3mT). b) Critical switching current density ($J_c$) as a function of in-plane magnetic field strength ($\mu_0 H$). A record-breaking minimum $J_c$ of $6\times10^5$ A/cm² was achieved.
References:


