

Voltage-controlled Unconventional Magnon Spin Polarization for Logic-in-memory

CNF Project Number: 598-96

Principal Investigator(s): Daniel Ralph

User(s): Yuhang Liang

Affiliation(s): Laboratory for Atomic and Solid State Physics, Cornell University

Primary Source(s) of Research Funding: United States Department of Energy

Contact: dcr14@cornell.edu, yl3779@cornell.edu

Primary CNF Tools Used: Heidelberg MLA 150 Maskless Aligner, AJA Ion Mill, C4500 Even-Hour Evaporator, AJA Sputter Deposition

Abstract:

Spin current provides an energy-efficient approach for manipulating magnetization, when its spin polarization aligns with the magnetization direction [1]. However, conventional spin-source materials possess high crystalline symmetry, restricting spin polarization to lie within the sample plane [2]. Here, we overcome this limitation by utilizing the concept of magnon-mediated spin-orbit torque through integration of a conventional spin-source material with the insulating multiferroic BiFeO_3 [3]. We observe that spin polarization generated by a conventional spin-source material can excite out-of-plane unconventional magnon polarization in BiFeO_3 . We further demonstrate a field-free spin-based logic-in-memory device controlled by ferroelectric polarization. Our results establish multiferroic-based heterostructures as symmetry-engineered magnon spin sources, paving the way for low-power spintronic devices.

Summary of Research:

By utilizing the collective excitation of magnetic materials, magnons [4], to carry the spin current, we experimentally demonstrate that the ferroelectric polarization in multiferroic BiFeO_3 enables control over magnon spin polarization in $\text{SrRuO}_3/\text{BiFeO}_3/\text{Ni}_{80}\text{Fe}_{20}$ heterostructures. Figure 1 shows a schematic of the device geometry and a micrograph of a completed spin-torque ferromagnetic resonance device used to detect the magnon spin polarization components. The SrRuO_3 layer is a high-symmetry spin-source material at room temperature, generating spin current polarization only along y-axis (within plane). The BiFeO_3 layer converts electron-mediated spin current from SrRuO_3 into magnon-mediated spin current. The $\text{Ni}_{80}\text{Fe}_{20}$ layer serves as detector to probe the orientation of magnon spin polarization in BiFeO_3 . To make electrical contact to the oxide and metal layers, we performed photolithography (Heidelberg MLA 150 Maskless

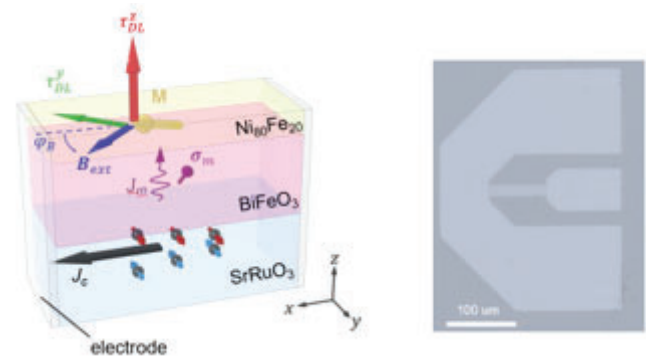


Figure 1: (left) Schematic for spin-torque ferromagnetic resonance measurement geometry and (right) optical image of fabricated device.

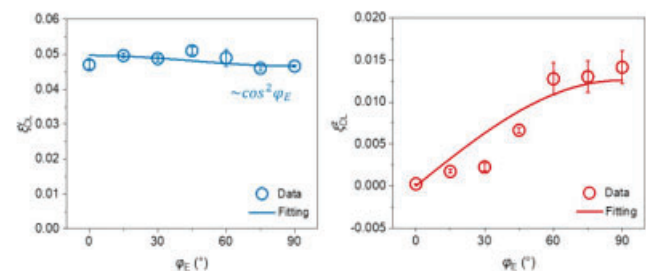


Figure 2: (left) Observation of conventional magnon spin polarization lies within sample plane and (right) out-of-plane unconventional magnon spin polarization.

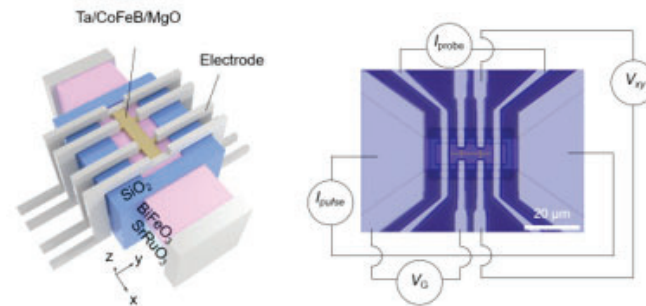


Figure 3: (left) Schematic of in-situ logic-in-memory device and (right) false-color optical image.

Aligner) and ion mill etching (AJA Ion Mill) to first expose micro-strips for microwave measurements. We then deposited Ti/Pt contacts with magnetron-sputtering deposition (AJA Sputter Deposition). We performed spin-torque ferromagnetic resonance measurements to characterize the orientation of magnon spin polarization. We observed efficient generation of conventional magnon spin polarization along y-axis, and out-of-plane unconventional magnon spin polarization along z-axis, with overall spin polarization rotated by up to 14° from the sample plane (Figure 2).

We then fabricated an *in-situ* device to control the out-of-plane unconventional magnon spin polarization via the ferroelectric polarization (see schematic in Figure 3). We deposited $\text{SrRuO}_3/\text{BiFeO}_3/\text{Ta}/\text{CoFeB}/\text{MgO}$ heterostructures, and then fabricated them into micro-strips (photolithography via Heidelberg MLA 150 Maskless Aligner and ion mill etching via AJA Ion Mill). We carefully etched the top CoFeB layer, ending at the BiFeO_3 surface (photolithography via Heidelberg MLA 150 Maskless Aligner and ion mill etching via AJA Ion Mill). We then deposited SiO_2 to isolate the top CoFeB channel and bottom SrRuO_3 channel (photolithography via Heidelberg MLA 150 Maskless Aligner and deposition via C4500 Even-Hour Evaporator). Finally, we deposited Ti/Pt contacts with magneto-sputtering deposition (AJA Sputter Deposition) (see optical image and measurement set-up in Figure 3).

In this *in-situ* device, a current pulse I_{pulse} applied along SrRuO_3 channel can switch the perpendicular magnetization of top CoFeB channel, and a gate voltage V_G can switch the ferroelectric polarization in BiFeO_3 . The CoFeB magnetization state is read out by small probe current $I_{\text{probe}} = 10 \mu\text{A}$ to probe the Hall resistance R_{xy} . By switching ferroelectric polarization through the gate voltage V_G , we successfully reversed the polarity of out-of-plane magnon spin polarization and demonstrated a spin-based logic-in-memory functionality at room temperature without any external magnetic field (Figure 4).

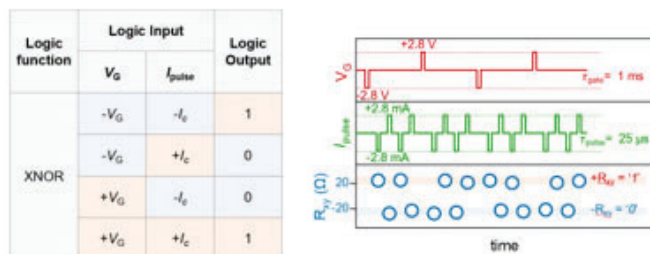


Figure 4: Truth table of spin-based XNOR gate (left) and experimental realization (right).

Conclusions and Future Steps:

In summary, we have shown that control of the ferroelectric polarization in multiferroic materials provides a route to control the magnon spin polarization, and we experimentally demonstrated an XNOR gate application. Our results may open pathways for advanced functionalities in future magnon-based spintronic devices.

References:

- [1] Manchon, A. et al. Rev. Mod. Phys. 91, 035004 (2019).
- [2] MacNeill, D., Stiehl, G., Guimaraes, M. et al. Nat. Phys. 13, 300–305 (2017).
- [3] Spaldin, N.A., Ramesh, R. Nat. Mater. 18, 203–212 (2019).
- [4] Chumak, A., Vasyuchka, V., Serga, A. et al. Nat. Phys. 11, 453–461 (2015).