

Photonic-Crafting of Non-Volatile and Rewritable Antiferromagnetic Spin Textures

Their remarkable properties make antiferromagnets a promising candidate in the development of next-generation spintronics devices.

Spintronics has revolutionized the field of magnetic recording/reading and it is hoped that it will complement semiconductor-based microelectronics beyond Moore's law for information technologies. Whether designed for sensing, memory, or logical applications, the most studied spintronics are based on ferromagnets. Spintronics based on antiferromagnets (AFM) is a recently emerging field in non-volatile data storage and information processing. The zero net magnetization and zero stray field of antiferromagnetic materials eliminate the interference between neighboring units, leading to high-density memory integrations. The dynamic spin behavior in AFM compared to ferromagnets can be more responsive to stimuli, leading to a shorter switching interval between two antiferromagnetic states. These remarkable properties make AFM a promising candidate in the development of next-generation spintronics devices.

Further extending the concept of AFM spintronics, multiferroic systems that possess correlated ferroic orders might offer alternative solutions to renovate AFM-based spintronic devices. The coexisting order parameters and inherent couplings in multiferroics provide a playground, allowing one to manipulate their multi-functionalities with different external stimuli. Of the numerous multiferroic systems, only a few exhibit ordered spin textures at room temperature and the most promising and well-studied of these is BiFeO_3 (BFO). Bulk BFO exhibits ferroelectric polarization (P) and AFM ordering with a characteristic temperature of 640 K, far above room temperature. The correlation between the P and AFM orders endows BFO with an innate capability to achieve electrical and magnetic control of its AFM axes.

To address the puzzle of the correlation between the P and AFM orders, Chang-Yang Kuo (National Yang Ming Chiao Tung University), Jan-Chi Yang (National Cheng

Kung University) and their teams discovered two bistable and reversibly controllable AFM states in strained BFO film grown on an NdFeO_3 substrate. The capability of manipulating the AFM axis is the key to realizing practical AFM spintronics. They have developed an approach combining both optical and magnetic methods to write and read the reversible AFM states at desired areas on the BFO film. The concept is schematically illustrated in Fig. 1(a). They first applied a magnetic field of 6 T along the a axis of the BFO film by using high magnetic field facility at TLS 11A, aligning the entire AFM spin along a "line" domain. An appropriate power (360 mW) for the laser beam was then chosen to thermally write the illuminated area of the BFO film over its Néel temperature. The area illuminated by the laser is able to set AFM spin to the type of cross domain. Figure 1(b) shows a sample mapping image taken by measuring the intensity ratio of the X-ray magnetic linear dichroism (XMLD). The spot size of the synchrotron beam at TPS 45A used for mapping the image is approximately $2 \mu\text{m} \times 3 \mu\text{m}$. The brown region

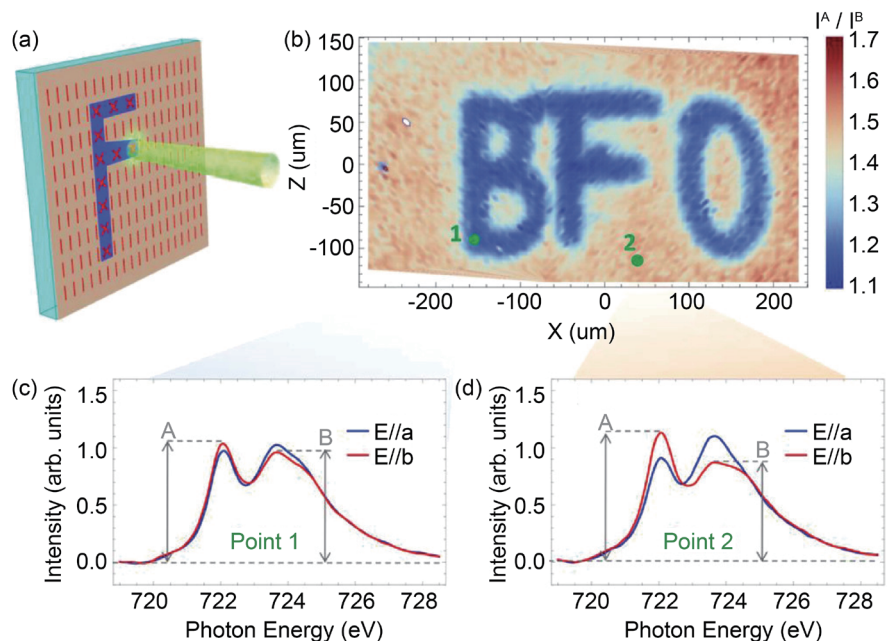


Fig. 1: Non-contact optical writing of the designed AFM pattern. (a) Schematic of the designed pattern composed of two distinct AFM configurations written by laser illumination. (b) XAS spectra mapping taken by measuring I^A/I^B , where I^A (I^B) is the intensity of the spectra taken at the energy A (B) for E//b as marked in (c) and (d). XAS polarization-dependent spectra for E//a and E//b taken at (c) Point 1 inside the word "BFO" and at (d) Point 2 outside the word "BFO". [Reproduced from Ref. 1]

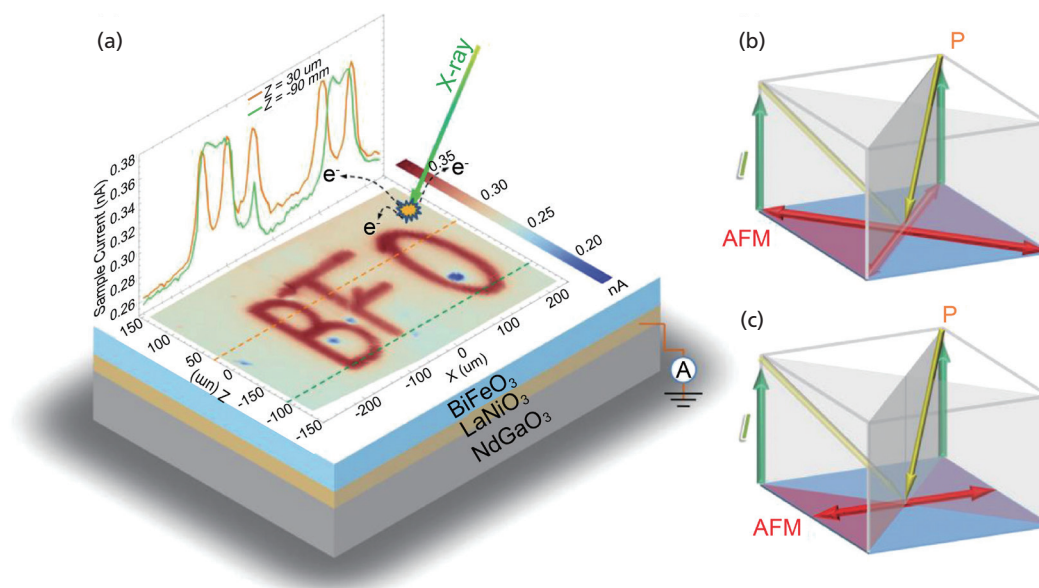


Fig. 2: Conductivity of two non-volatile switchable AFM textures. (a) Image of the sample current mapping taken at a photon energy of ~ 719.5 eV, and the sample current across $Z = 30$ nm and $Z = -90$ nm, which are shown as the orange and green dashed lines, respectively. Geometric relationships of the ferroelectric polarization (P), AFM-axis, and sample current (I_e) for the (b) AFM cross domain and (c) AFM line domain. [Reproduced from Ref. 1]

in **Fig. 1(b)** indicates a larger XMLD signal corresponding to the AFM line domain, and the blue region indicates a smaller XMLD signal corresponding to the AFM cross domain. Excitingly, this resulted in a “BFO” pattern as designed (shown in **Fig. 1(b)**), which was composed of the two distinguishable AFM states. With this approach, one can write AFM domain patterns on strained BFO films in any shape. Given that the AFM domain size of BFO films can be trimmed down to the scale of tens of nanometers, the size of the written AFM domain pattern can be expected to be in the nanometer scale as well, offering tremendous potential for high-density memory integrations. To reset the AFM status, one can erase all written patterns by applying a magnetic field along the a axis once again.

Importantly, it is possible to read the written AFM pattern electrically. In **Fig. 2(a)**, we present the same sample mapping image as in **Fig. 1(b)**, but now with the absorption sample current (I_e) taken at a photon energy of 719.5 eV, which is below the onset of the range of the Fe L_2 absorption resonance energy. In **Fig. 2(a)**, we also present the sample current across the orange and green dashed cross-section lines shown in the mapping image. Remarkably, a high contrast of approximately 30% in the absorption sample current between the inside and outside of the written “BFO” pattern was observed. The mechanism of the I_e measurement is also schematically illustrated in **Fig. 2(a)**. Electrons are ejected by photons from the exposed surface into the vacuum and equilibrium occurs when the ejected electrons are replaced by electrons flowing in from the ground electrode, the LNO metallic layer, at the same rate. Thus, the measured I_e is proportional to the time interval of electrons traveling from the ground to the sample surface. This traveling time depends on

the electron drift velocity, which is inversely proportional to the conductivity. In other words, the difference in the absorption sample current I_e can be treated as a difference in resistance. This indicates that the resistance of the AFM cross domain is lower than that of the AFM line domain by at least 30%.

The possibilities of causing a resistance difference between two non-volatile AFM textures is related to the geometric relationship between the ferroelectric polarization and the AFM axis, as illustrated in **Figs. 2(b) and 2(c)**. For the AFM cross domain, the inherent ferroelectric polarization, the AFM-axis and the I_e share the same plane, as shown in **Fig. 2(b)**. By contrast, such a sharing scheme, as shown in **Fig. 2(a)**, is broken for the AFM line domain, resulting in the change of the electron scattering events, thus causing a different resistance. Naturally, of future interest is quantitative modeling of the resistance difference of the two AFM textures that takes into account the relationship between the ferroelectric polarization and the AFM axis found in this work.

Spintronics has revolutionized magnetic reading/writing technology and is expected to facilitate the development of next-generation semiconductor-based nanochips/ devices. Whether designed for sensing, memory, or logical applications, the active development of spintronics is closely related to antiferromagnetism. An antiferromagnet generates no stray field and thus offers great potential for high-density data storage. The dynamic behavior of spin in AFM, compared to ferromagnets, can be more responsive to stimuli, leading to a shorter switching interval between two antiferromagnetic states. These remarkable properties make AFM a promising candidate in the development of

next-generation spintronics. The findings of this work show an efficient route to read and write the bistable AFM state, shedding light on the path toward practical AFM-based spintronics. (Reported by Chang-Yang Kuo, National Yang Ming Chiao Tung University)

*This report features the work of Chang-Yang Kuo, Jan-Chi Yang and their collaborators published in Adv. Mater. **34**, 2200610 (2022).*

TPS 45A Submicron Soft X-ray Spectroscopy TLS 11A1 (Dragon) MCD, MLD, XAS.

- Soft X-ray Absorption
- Materials Science, Condensed-matter Physics

Reference

1. C.-Y. Kuo, Y.-D. Liou, Z. Hu, S.-C. Liao, H.-M. Tsai, H.-W. Fu, C.-Y. Hua, Y.-C. Chen, H.-J. Lin, A. Tanaka, C.-T. Chen, J.-C. Yang, C.-F. Chang, Adv. Mater. **34**, 2200610 (2022).

Weaving Single-Crystal Thin Films

Weave epitaxy: a breakthrough approach to fabrication of twisted lateral homostructures depicts an entirely different conceptual scene for epitaxial growth.

Heteroepitaxy has attracted great interest as it is a key element in modern technologies for delivering high-quality thin films, and it has also been a promising approach to the integration of different materials. Over the past decades, epitaxial growth has enabled the efficient interface and strain engineering of functional materials, which has played a focal role in reinvigorating modern science across a wide spectrum of technically important applications. In terms of epitaxial growth, the selection of single crystal substrates determines the foundation template for the deposited materials. Namely, the lattice constraints and crystalline orientations of deposited materials are subject to the selected template beneath and, thus, the allowed epitaxial degrees of freedom are determined once a specific substrate is chosen. To portray a concrete scenario for epitaxial growth, Jan-Chi Yang (National Cheng Kung University) and his group proposed a new approach, weave epitaxy, to achieve growth of twisted oxide lateral homostructures with multiple conjunction degrees of freedom.

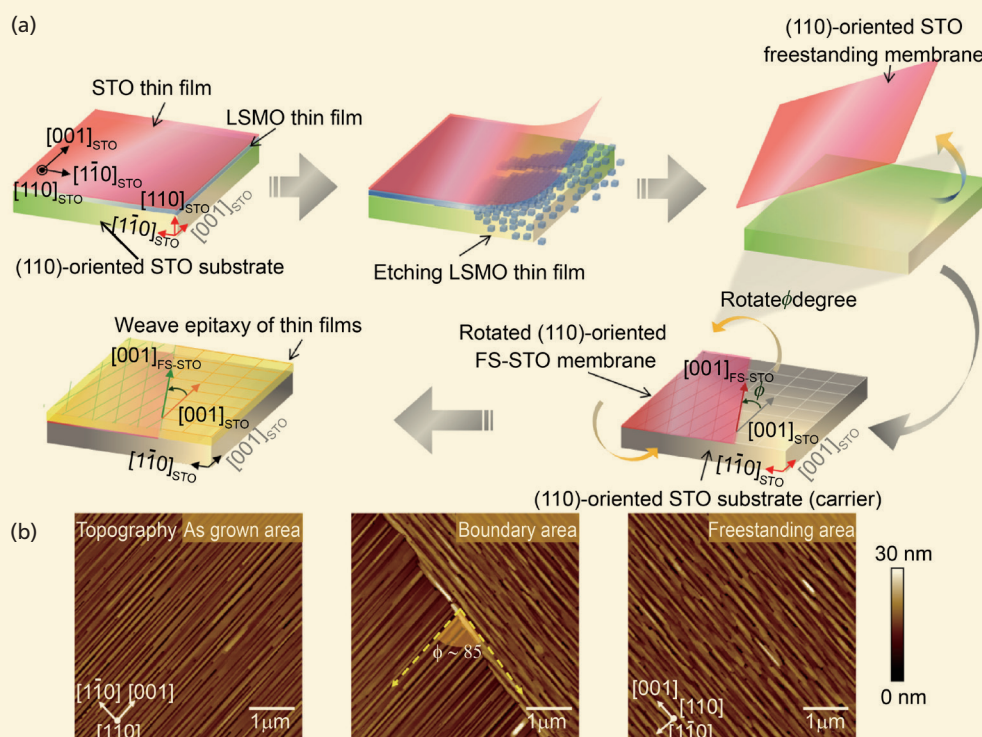


Fig. 1: Twisted oxide lateral homostructures. (a) Schematic illustration of the fabrication of lateral oxide homostructures. (b) Topography images of (110)-oriented BFO grown on FS-STO, the border, and pristine STO regions (from left to right). [Reproduced from Ref. 1]