Flipping the Switch on Antiferromagnets

For the past 20 years, so-called *multiferroic materials* have fascinated researchers across the globe. But what is a multiferroic material? Step back for a moment and look at a simple "ferroic" material like e.g. a ferromagnet. In a ferromagnet the magnetic moments originating from all the electrons in the material order across long distances so that the material exhibits a macroscopic magnetic moment. Using an external magnetic field the magnetic moment can be manipulated and its direction and even its magnitude can be set. A compass needle is an example of such a ferromagnetic material. The compass needle exhibits a magnetic moment that will align with the magnetic field of the earth. Something similar happens in a ferroelectric material where the sample can maintain an electric polarization after it was exposed to an electric field. In such a material the application of an external electric field leads to a local imbalance between the negative polarization of the electrons and the positive polarization of the atoms. Altogether, a ferroelectric material will exhibit a macroscopic electric polarization after exposed to an electric field.

But, what if a material is both ferrolectric and ferromagnetic? And what if the ferromagnetism could be used to manipulate the ferroelectricty and vice versa. Such a material is then called multiferroic. This particular case of combining ferroelectricity and ferromagnetism has become one of the holy grails of technology over the past decade. Ferromagnetic materials are used to store and process information today on hard drives and in certain cases on magnetic random access memories (MRAM). But in these devices the magnetic bits are always manipulated with magnetic fields, which are difficult to contain and focus on the nanoscale, since magnetic fields always extend far away from their source. On the other hand, much is known about how to produce and contain electric fields on the nanoscale since this is done routinely in conventional silicon-based microprocessors. So if ferromagnetic order could be manipulated by applying electric fields on short length scales, a device could store information permanently, but be operated by electric fields.

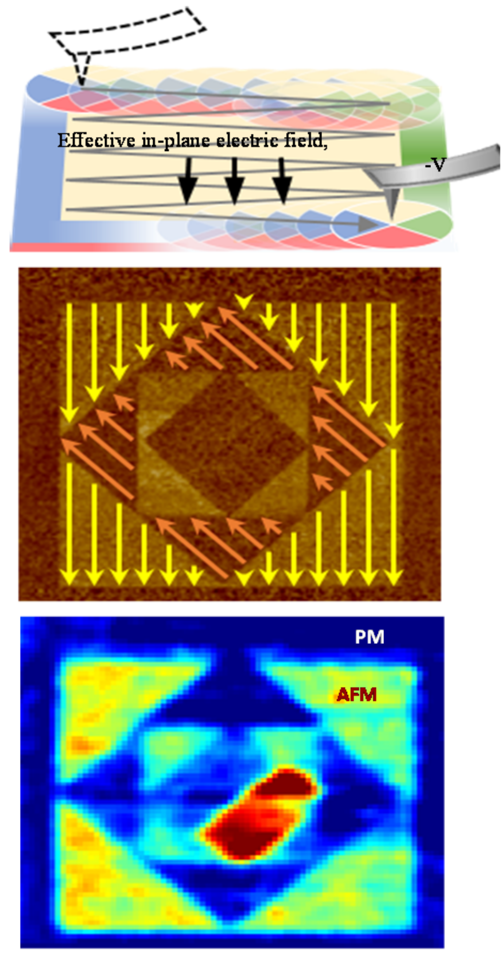

Figure. *Top,* A schematic for explaining the tip-based generation of an effective in-plane electric field. During scanning a rectangular box with a negatively biased tip, only the in-plane component of field parallel to the slow scan axis has the final influence on the sample because the written effects by the other components are erased and reversed in the next several line scans. *Middle*, An out-of-plane PFM image for a multiple poling box area to elucidate the reversibility and repeatability of the switching in a $Bi_{0.9}La_{0.1}FeO_3$ thin film. *Bottom*, A spatially resolved XAS image measured at 707.9 eV on the same poling area at room temperature. The red rectangle arose from accidental damage during poling.

The goal of this project was exactly to demonstrate that multiferroic material can be used to control magnetic order using an electric field. For this purpose the research team used a disruptive approach compared to previous groups. For example, $BiFeO_3$ is a classic antiferromagnetic multiferroic material that has been studied for over a decade. Instead of trying to find electric field conditions and geometries to manipulate the ferroelectricity in a way that it allows to control the magnetism, the team decided to not look at the pure material, but instead dope it with lanthanum. This allowed them to control the temperature at which the material exhibits its multiferroic properties and move it very close to room temperature, exhibiting a so-called thermodynamic triple point. Ultimately they were then able to switch the antiferromagnetic order on and off at room temperature using an electric field.

After growing the La-doped $BiFeO_3$ samples on STO substrates at KAIST the samples underwent extensive characterizations using lab-based techniques like piezo force microscopy, transmission electron microscopy with electron energy spectroscopy. These showed that the application of an electric field on the materials does not affect the chemistry or stoichiometry of these samples, which is crucial for the interpretation of the synchrotron data. Using the tip of the piezo force microscope at KAIST the researchers applied an alternating positive and negative field in a pattern as shown. Always leaving part of the pattern unchanged between polarization changes. The direction of polling was also changed to exclude any systematic dependence. The samples were then sent to SSRL to be studied using the scanning transmission x-ray microscope (STXM) at Beam Line 13-1. The special feature of this microscope is that it can be operated in ultra-high vacuum. And, whereas conventional transmission microscopes can only be used to study very thin samples, this microscope allows researchers to study high quality samples grown on single crystalline samples. By tuning the energy of the incoming photons to a particular energy within the Fe L-resonance the method is very sensitive to the presence of antiferromagnetic order, and by monitoring the x-ray absorption they could then obtain a map of the antiferromagnetic order. The lower panel in the figure on the left shows the result. Blue areas do not exhibit magnetic order (paramagnetic), while green areas exhibit antiferromagnetic order. The red patch in the STXM image indicates that the sample had been damaged there during the writing process, probably because the tip was too close, meaning that particular attention has to be paid to proper writing process in the future.

By using this particular compound the researchers observed that it is possible to fully control antiferromagnetic order using an electric field. A positive field can be used to switch the order on, while a subsequent negative field will turn it off again, etc.. By coupling the AFM compound to a ferromagnetic compound one can then ultimately use this to build a new generation of devices.

Primary Citation

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