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Magnetism in Multiferroic $BiFeO_3$

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IMS Journal Club Presentation
17-04-2012

Outline

- Reborn of $BiFeO_3$
- Magnetic Properties
  - Magnetoelectric effect
  - Exchange coupling
- Electrical control of Ferromagnetic domains and device applications
- Conclusion and Outlook
- References

Reborn of $BiFeO_3$

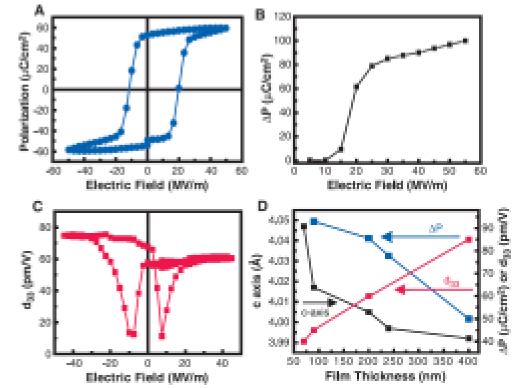
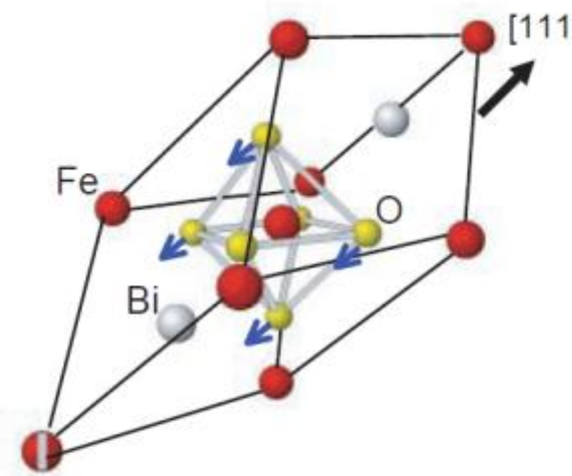


Fig. 2. (A) A ferroelectric hysteresis loop measured at a frequency of 15 kHz, which shows that the film is ferroelectric with $P_r \sim 55\ \mu C/cm^2$. (B) Pulsed polarization ΔP versus electric field measured with electrical pulses of 10-μs width. (C) A small signal d_{33} for a 50-μm capacitor. (D) A summary of the thickness dependence of out-of-plane lattice parameter, polarization, and d_{33}. The small signal dielectric constant (27) follows the same trend as the d_{33}.

- High quality single crystal thin films
- G-type Antiferromagnetic Ferroelectric at RT
  - T_C~870˚C and T_N~370˚C
- Rhombohedral R3c



Epitaxial $BiFeO_3$ Multiferroic Thin Film Heterostructures

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Reborn of $BiFeO_3$

- Magnetic moment detected (?)

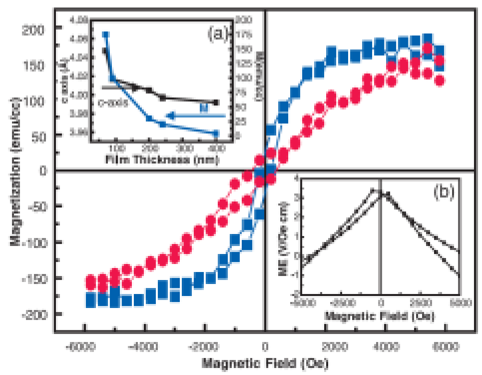
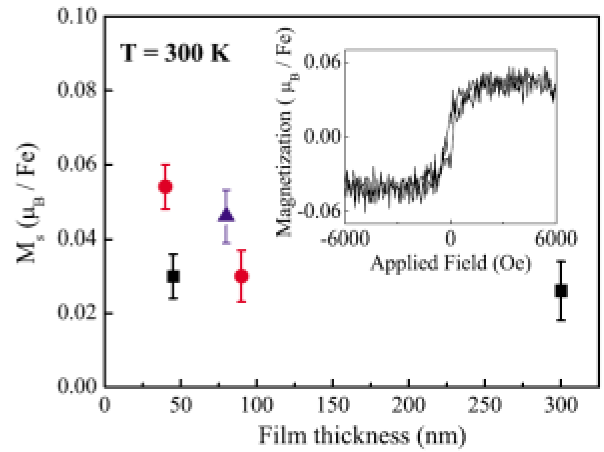
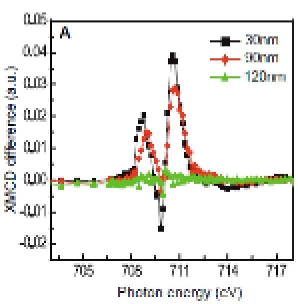


Fig. 4. Magnetic hysteresis loops measured by vibrating sample magnetometry for a 70-nm-thick BFO film, showing an appreciable saturation magnetization of ~150 emu/cm^3 and a coercive field of ~200 Oe. The in-plane loop is shown in blue, and the out-of-plane loop is in red. Inset (a) shows the thickness dependence of saturation magnetization, illustrating the effect of heteroepitaxial constraint. Inset (b) is a preliminary ME measurement result showing a maximum value of ~3 V/cm-Oe and hysteresis about 200 Oe.

vs.



Eerenstein et. al. *Science* 307, 1203 (2005)



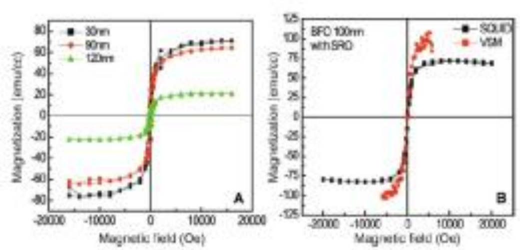


Fig. 1. (A) Magnetic response from BFO films grown on 001 STO with different thickness. (B) Comparison of VSM and SQUID results on the 100-nm BFO/SRO/STO (001) sample used in (2). Care was taken to remove any silver spots on the substrate by grinding with emery paper.

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Magnetic Properties

- Ferromagnetism in ferroelectric domain walls of antiferromagnetic multiferroics

Ferroelectrics, 375:122–131, 2008

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DOI: 10.1080/00150190802437969

Landau Theory of Ferroelectric Domain Walls in Magnetoelectrics

M. DARAKTCHIEV,* G. CATALAN, AND J. F. SCOTT

$$
\begin{aligned}
G_{MP} &= G_0 + \frac{\kappa}{2}(\nabla P)^2 + \frac{\lambda}{2}(\nabla M)^2 + L_{MP}(P,M) \\
&= G_0 + \frac{\kappa}{2}(\nabla P)^2 + \frac{\lambda}{2}(\nabla M)^2 + \frac{\alpha}{2}P^2 + \frac{\beta}{4}P^4 + \frac{\eta}{6}P^6 + \frac{a}{2}M^2 \\
&\quad + \frac{b}{4}M^4 + \frac{n}{6}M^6 + \frac{\gamma}{2}P^2M^2
\end{aligned}
$$

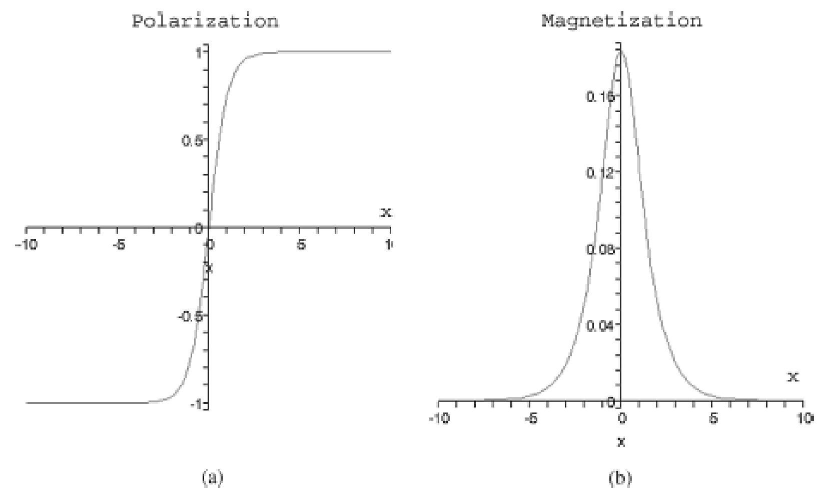


Figure 3. Shape of the ferroelectric polarization and magnetization across the domain wall. A net magnetization appears in the centre of the domain wall even though the domains themselves are still paramagnetic. (See Color Plate IX)

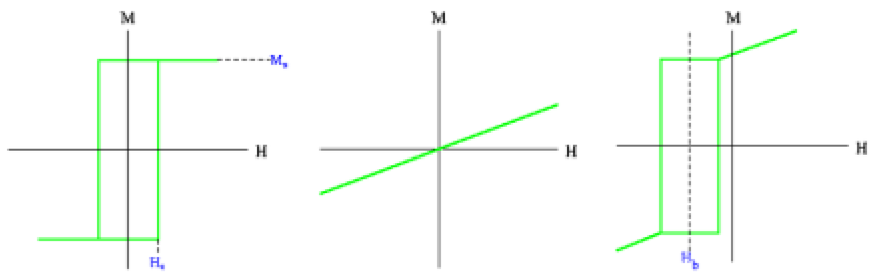
Magnetic Properties

- Magnetoelectric effect

$$P_i = \sum \alpha_{ij} H_j + \sum \beta_{ijk} H_j H_k + \ldots$$

$$M_i = \sum \alpha_{ij} E_j + \sum \beta_{ijk} E_j E_k + \ldots$$

- Exchange bias



Easy axis magnetization curves of a) Soft ferromagnet b) Antiferromagnet c) Exchange biased bilayer

Magnetoelectric effect in BFO

- Coupling between the ferroelectric and antiferromagnetic domains via ferroelasticity

Zhao et al. *Nat. Mater. 5*, 2006.

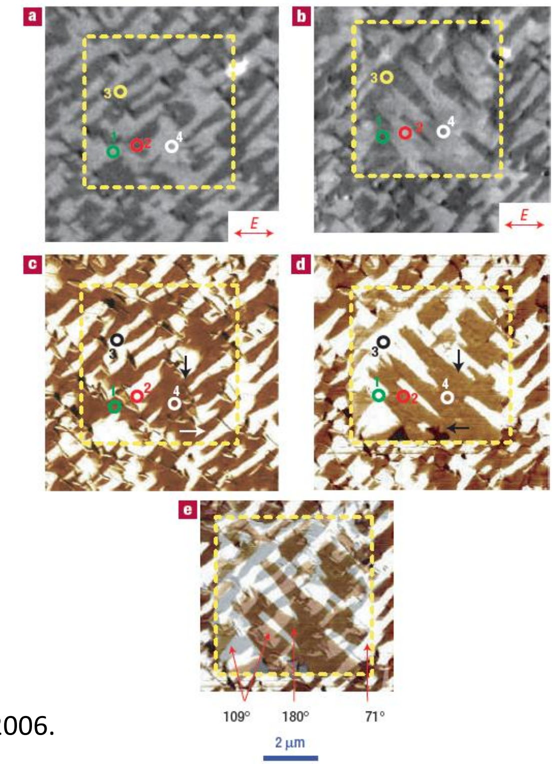


Figure 5 PEEM and in-plane PFM images of the same area of a $BiFeO_3$ film before and after electrical poling. a,b, PEEM images before (**a**) and after (**b**) poling. The arrows show the X-ray polarization direction during the measurements. **c,d,** In-plane PFM images before (**c**) and after (**d**) poling. The arrows show the direction of the in-plane component of ferroelectric polarization. Regions 1 and 2 (marked with green and red circles, respectively) correspond to 109° ferroelectric switching, whereas 3 (black and yellow circles) and 4 (white circles) correspond to 71° and 180° switching, respectively. In regions 1 and 2 the PEEM contrast reverses after electrical poling. **e,** A superposition of in-plane PFM scans shown in **c** and **d** used to identify the different switching mechanisms that appear with different colours and are labelled in the figure.

Exchance coupling in BFO heterostructures

APPLIED PHYSICS LETTERS 89, 242114 (2006)

Tunnel magnetoresistance and robust room temperature exchange bias with multiferroic $BiFeO_3$ epitaxial thin films

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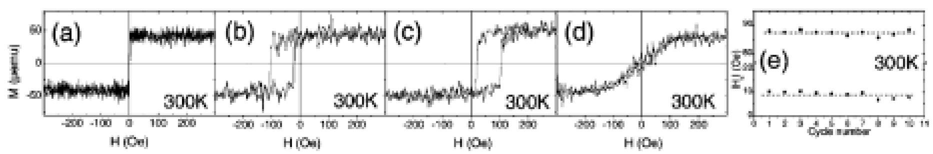


FIG. 4. (a) Hysteresis loop along the [100] direction of CoFeB (5 nm)//Si layer. Hysteresis loops along (b) the [100] direction, (c) the [−100] direction, and (d) the [010] direction of CoFeB (5 nm)/BFO (35 nm)//STO bilayer. (e) Coercive fields of a similar sample for successive H cycles (up to ±300 Oe). Dashed lines are guides to the eyes.

CoFe/Si and CoFe/BFO/STO/Si

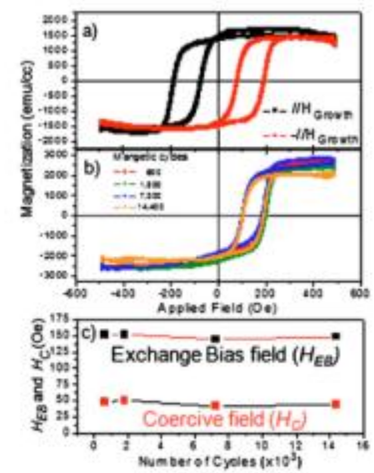
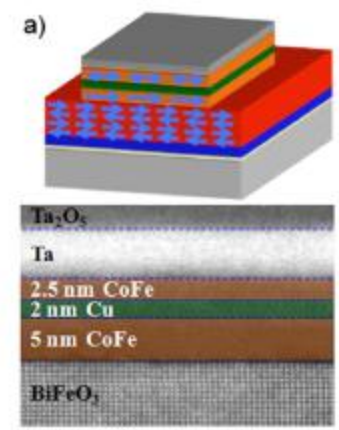


FIG. 2. (Color online) Typical magnetic properties for bilayer CoFe/BFO heterostructures. (a) Magnetization hysteresis loops reveal large negative exchange bias. (b) Repeated magnetic cycling results in very little change in the magnetic properties. (c) Exchange bias field and coercive field as a function of magnetic cycle—no training effect is observed.



APPLIED PHYSICS LETTERS 91, 172513 (2007)

Room temperature exchange bias and spin valves based on $BiFeO_3/SrRuO_3/SrTiO_3/Si$ (001) heterostructures

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Nanoscale Control of Exchange Bias with $BiFeO_3$ Thin Films

Lane W. Martin,[*,†,‡] Ying-Hao Chu,[†,§,⊥] Mikel B. Holcomb,[†,§] Mark Huijben,[§] Pu Yu,[§] Shu-Jen Han,[‖] Donkoun Lee,[‖] Shan X. Wang,[‖] and R. Ramesh[†,‡,§]

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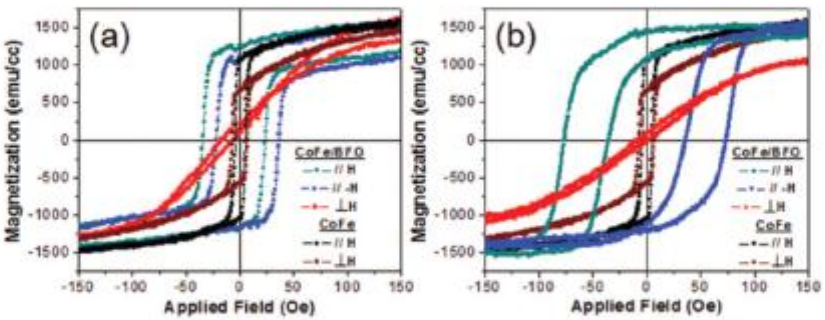

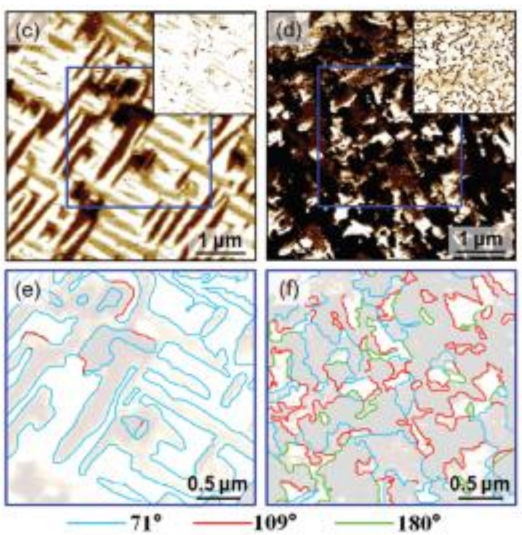

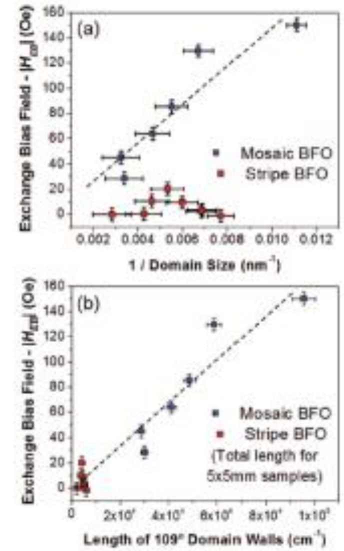

Figure 2. (a) Dependence of exchange bias field on domain size for CoFe/BFO heterostructures grown on mosaic-like (blue) and stripe-like (red) BFO films. (b) Exchange bias field of the same samples here graphed as a function of the total length of 109° domain walls/sample surface area in 5 × 5 mm samples.

- 109˚ DWs are influential
- Might be the origin of uncompensated spin at the surface

How to make more functional?

- Electrical control of Ferromagnetic layers by exchange coupling

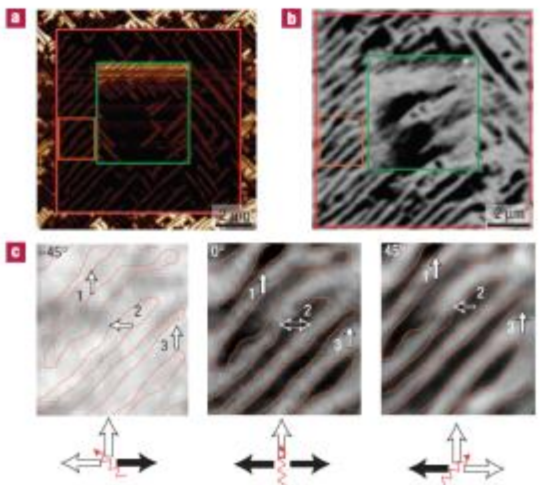

Figure 3 Microscopic evidence for coupling. a, In-plane PFM image showing the ferroelectric domain structure of a BFO film with a large (10 μm, red square) and small (5 μm, green square) electrically switched region. **b**, Corresponding XMCD–PEEM image taken at the Co L-edge for a CoFe film grown on the written pattern. Direct matching of domain structures is evident. Black contrast is interpreted as a spin pointing side-to-side in the image and grey as spin pointing up. **c**, Rotation of the sample in reference to the incoming right-circularly polarized light enables full determination of the nature of magnetism in the CoFe layer.

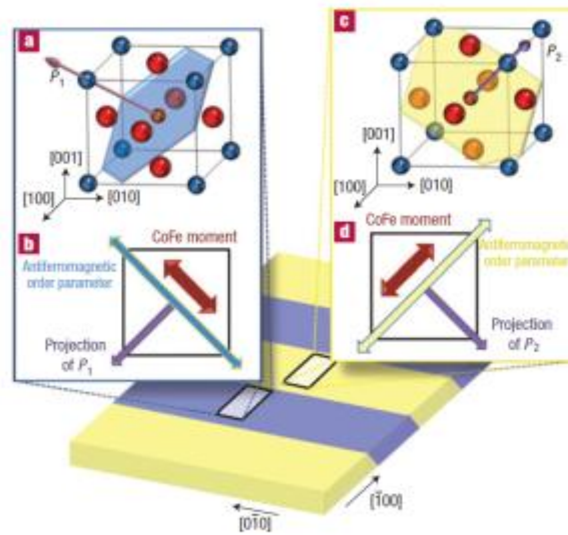

Figure 4 Mechanism of coupling in CoFe/BFO heterostructures. a–d, Schematic diagrams of two adjacent domains in the [001]-oriented BFO crystal (**a**,**c**), in which the [111] polarization directions as well as the antiferromagnetic plane (that is perpendicular to this P direction) are identified, and the corresponding projections of the polarization direction, the antiferromagnetic plane onto the [001] and the corresponding M-directions in the CoFe layer (**b**,**d**).

ARTICLES

Electric-field control of local ferromagnetism using a magnetoelectric multiferroic

YING-HAO CHU, LANE W. MARTIN, MIKEL B. HOLCOMB, MARTIN GAJEK, SHU-JEN HAN, QING HE, NINA BALKE, CHAN-HO YANG, DONKOUN LEE, WEI HU, QIAN ZHAN, PEI-LING YANG, ARANTXA FRAILE-RODRIGUEZ, ANDREAS SCHOLL, SHAN X. WANG AND R. RAMESH

How to make more functional?

- Electrical control of Ferromagnetic layers by exchange coupling

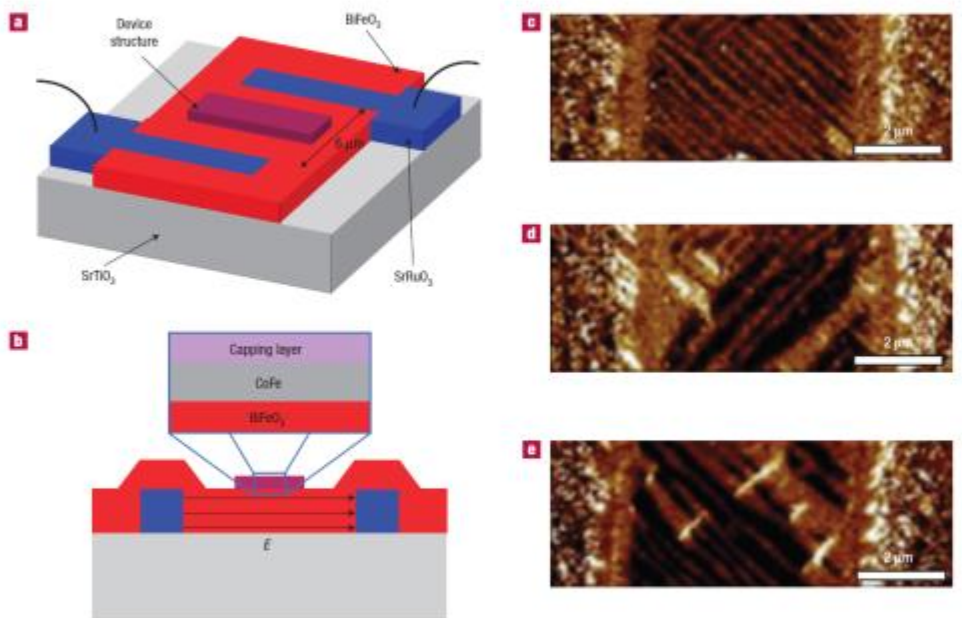

Figure 5 Dynamic switching device structure. a,b, Three-dimensional (**a**) and cross-sectional (**b**) schematic diagrams of the coplanar epitaxial electrode device showing the structure that will enable controlled ferroelectric switching and electrical control of local ferromagnetism in the CoFe features. **c–e**, In-plane PFM images showing the ferroelectric domain structure for a device in the as-grown state (**c**), after the first electrical switch (**d**) and after the second electrical switch (**e**).

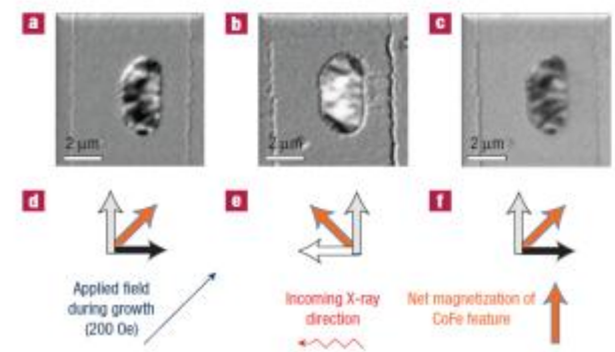

Figure 6 Electrical control of local ferromagnetism. a–c, XMCD–PEEM images taken at the Co *L*-edge revealing the ferromagnetic domain structure of the CoFe features in such a coplanar electrode device structure in the as-grown state (**a**), after the first electrical switch (**b**) and after the second electrical switch (**c**). **d–f**, Schematic descriptions of the observed magnetic contrast (grey, black and white) in the corresponding XMCD–PEEM images, respectively. Application of an electric field is found to rotate the next magnetization of the structures by 90°. The direction of the applied growth field and the incoming X-ray direction are labelled as well.

Device Applications

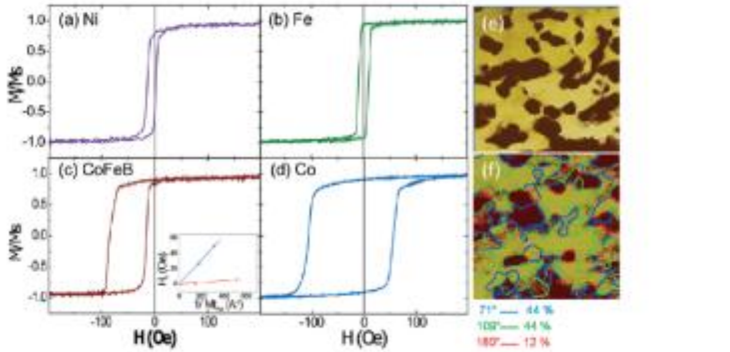

Figure 1. (a−d) Exchange bias for different 4 nm FM/BFO/BFO-Mn samples. Typical out-of-plane (e) and in-plane (f) PFM images of ferroelect domain pattern and DW analysis of the BFO-Mn/BFO bilayer. The scan area is 1 × 1 μm^2. Inset: corresponding evolution of the exchange bias a function of $1/Mt_{FM}$

NANO LETTERS

Room Temperature Electrical Manipulation of Giant Magnetoresistance in Spin Valves Exchange-Biased with $BiFeO_3$

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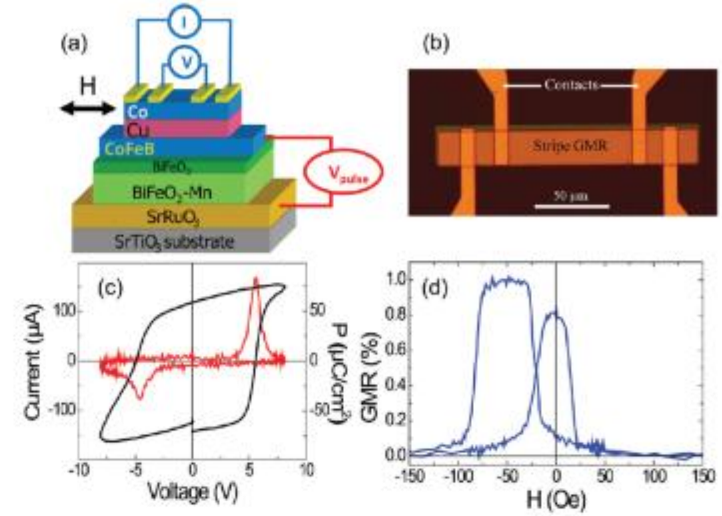

Figure 2. (a) Schematic of the device, (b) micrograph of the stripe with the electrical contacts, and (c) current and polarization versus electric field for a BFO/BFO-Mn bilayer. (d) Giant magnetoresistance of a Au 6 nm/Co 4 nm/Cu 4 nm/CoFeB 4 nm spin valve after patterning (30 × 185 μm^2 stripe).

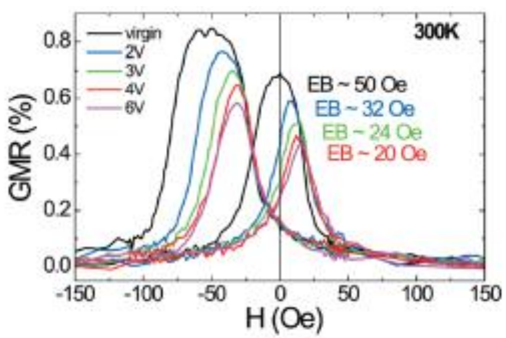

Figure 3. (a) GMR curves of a Au 6 nm/Co 4 nm/Cu 4 nm/CoFeB 4 nm spin valve after different poling events applied to the BFO/BFO-Mn bilayer. The stripe is 210 μm long and 20 μm wide.

Conclusions and Outlook

- Exchange coupling mechanism to be investigated more
- Possibility of BFO to be implemented in spintronics devices
- Increasing the efficiency of devices

References

- Wang et al. "Epitaxial $BiFeO_3$ Multiferroic Thin Film Heterostructures" *Science* **299,** 1719 (2003)
- Eerenstein et al. "Comment on Epitaxial $BiFeO_3$ Multiferroic Thin Film Heterostructures" *Science* **307**, 1203 (2005)
- Daraktchiev et al. "Landau Theory of Ferroelectric Domain Walls in Magnetoelectrics" *Ferroelectrics* **375**, 122 (2008)
- Zhao et al. "Electrical Control of Antiferromagnetic Domains in Multiferroic $BiFeO_3$ films at Room Temperature" *Nat. Mater.* ***5***, 823 (2006)
- Béa et al. "Tunnel Magnetoresistance and Robust Room Temperature Exchange Bias with Multiferroic $BiFeO_3$ Epitaxial Thin Films" *Appl. Phys. Lett.* **89**, 242114 (2006)
- Martin et al. "Room temperature exchange bias and spin valves based on $BiFeO_3$/$SrRuO_3$/SrTiO3/Si (001) heterostructures" *Appl. Phys. Lett.* **91**, 172513 (2007)
- Martin et al. "Nanoscale Control of Exchange Bias with $BiFeO_3$ Thin Films" *Nano Letters* **8,** 2050 (2008)
- Chu et al. "Electric field control of local ferromagnetism using a magnetoelectric multiferroic" *Nat. Mater.* **7**, 478 (2008)
- Allibe et al. "Room Temperature Electrical Manipulation of Giant Magnetoresistance in Spin Valves Exchange-Biased with $BiFeO_3$" *Nano Letters* **12**, 1141 (2012)