Electric field control of magnetization using AFM/FM interfaces

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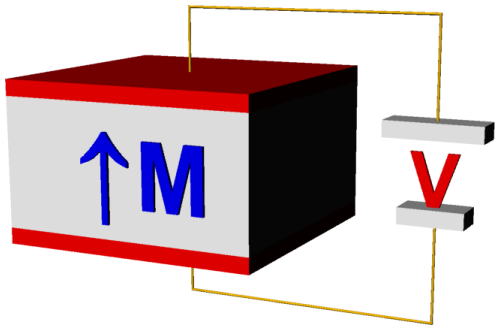
Magnetoelectric effects

$$\alpha = \mu_0 \left(\frac{\partial M}{\partial E}\right)_H$$

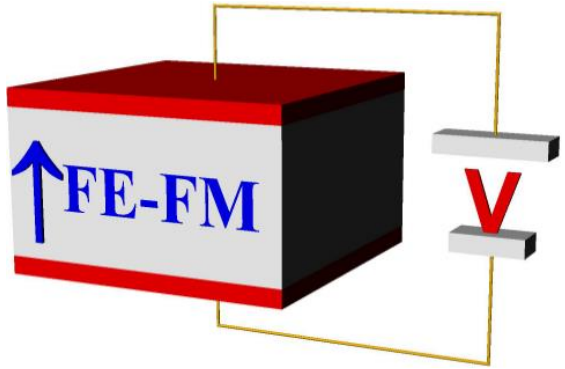
- $M(H = 0, E = 0) = 0$ (General magnetoelectrics)
- $M(H = 0, E = 0) \neq 0$, $\mathrm{P}(H = 0, E = 0) \neq 0$, (Multiferroics)
  - E Change M
  - E Reverse M

Goal:

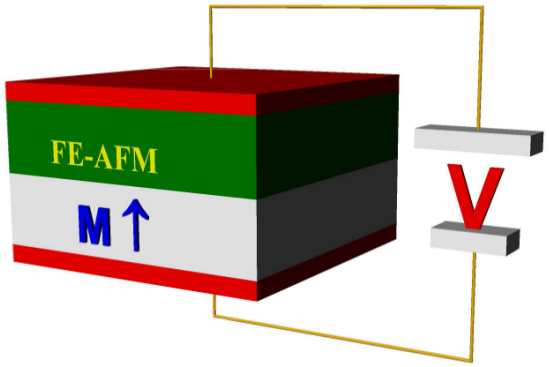
- Reverse M
- Room temperature
- Repeatable



ME effect



Single phase material



Heterostructure/interface

Goal:

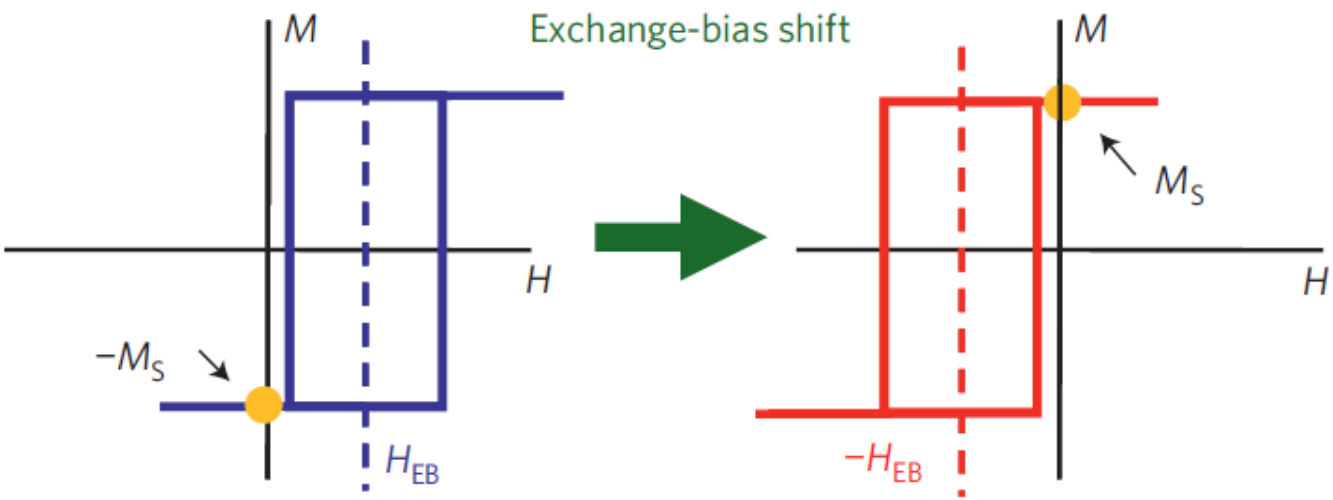
- Reverse M
- Room temperature
- Repeatable

Interface mechanism: exchange bias

1) At the AFM/FM interface, there is a significant coupling between the $\vec{L}$ and $\vec{M}$ vectors.
2) If the $\vec{L}$ vector is aligned at the interface, then there is an effective exchange field on the FM.
3) Since the $\vec{L}$ vector is not susceptible with external magnetic field, the M-H loop of the FM will be shifted by the exchange field.

- To align the vector, one has to cool down the heterostructure in a magnetic field from above T_N. In this case, the $\vec{M}$ vector in the FM exerts an exchange bias on the L vector. When the AFM transits into the ordered state, the $\vec{L}$ vector will be aligned.

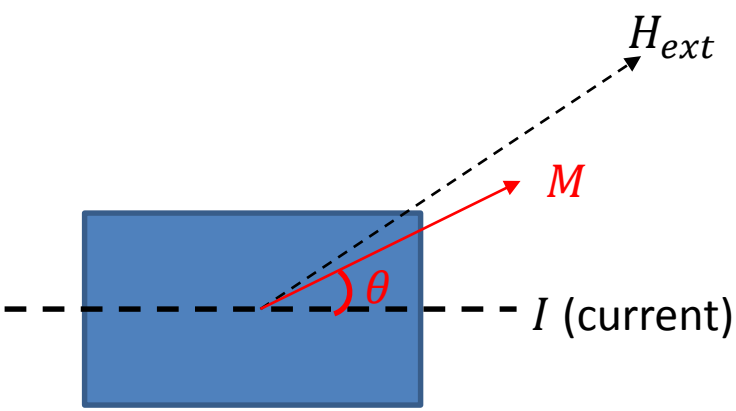
Controlling M in FM using exchange bias

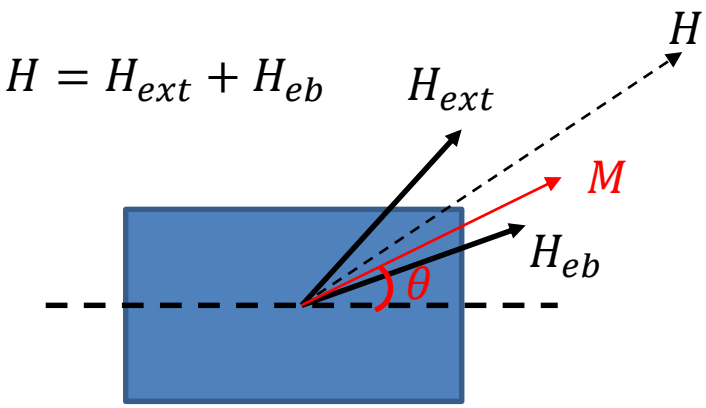


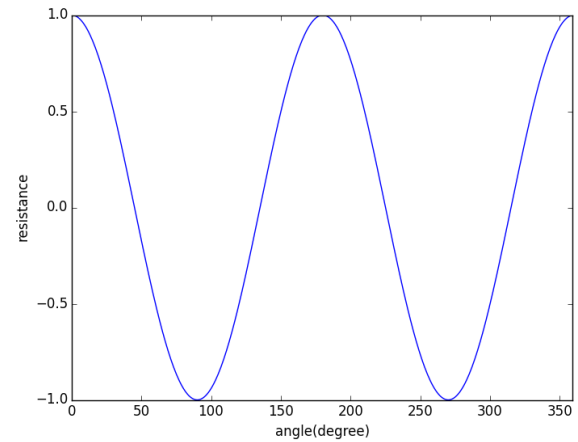
1) If one can control the L vector, the exchange bias field H_{EB} can also be controlled. So the $\vec{M}$ vector can be modified.
2) In the extreme case that the H_{EB} is larger than the coercivity H_C, reversing H_{EB} suggests reversing $\vec{M}$ vector in the FM.

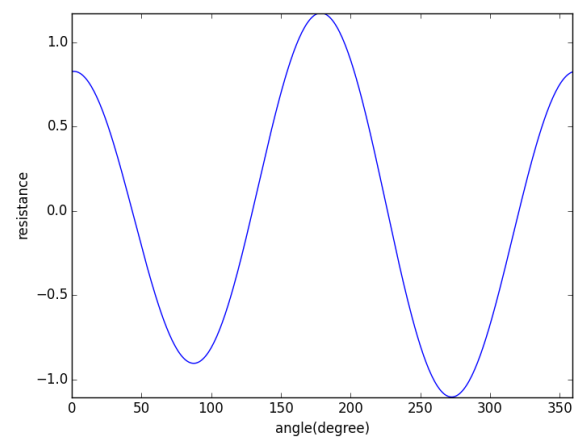
Anisotropic magnetoresistance (AMR)

$$\rho = \rho_0 + \Delta\rho \cos^2\theta$$



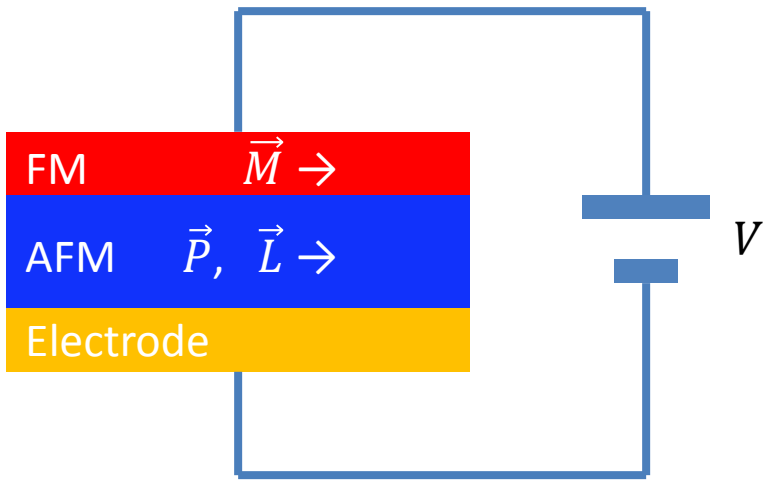






- AMR measures magnetic anisotropy.
- AMR can be used to measure exchange bias.
- Change of exchange bias can also be detected using AMR.

Controlling M using E-field via exchange bias



1) Extending the concept in the previous slide, if one can control the $\vec{L}$ vector using an electric field $\vec{E}$, the $\vec{M}$ vector can then be controlled by $\vec{E}$.
2) This is promising in AFM/FE multiferroics, particularly in $BiFeO_3$.

The advantages of using FM/AFM(FE) interface to realize E-field control of M are
1) Larger magnetic polarization
2) High T_N

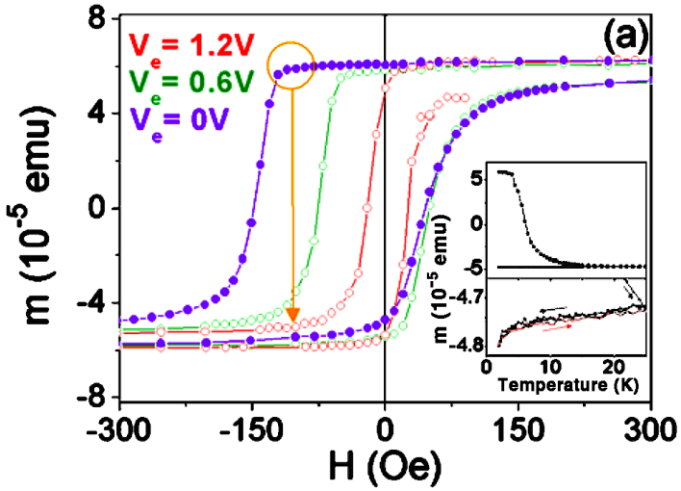
The disadvantages of using FM/AFM(FE) interface to realize E-field control of M are
1) The M/E coupling is large only when $H_{EB} > H_C$, which is not common.
2) Oxides/metal interface is unstable.

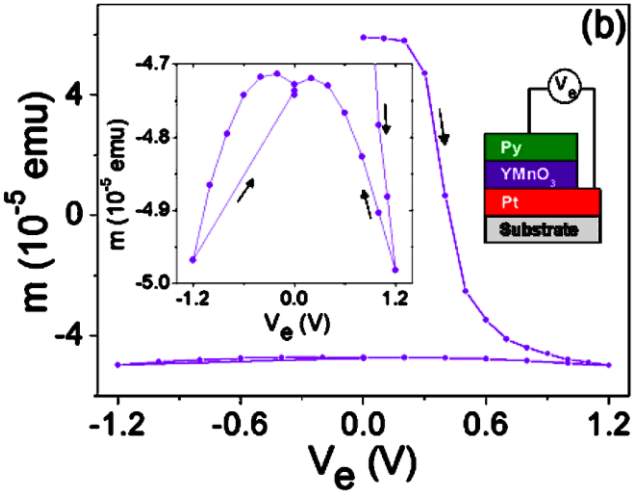
Previous work on heterostructures

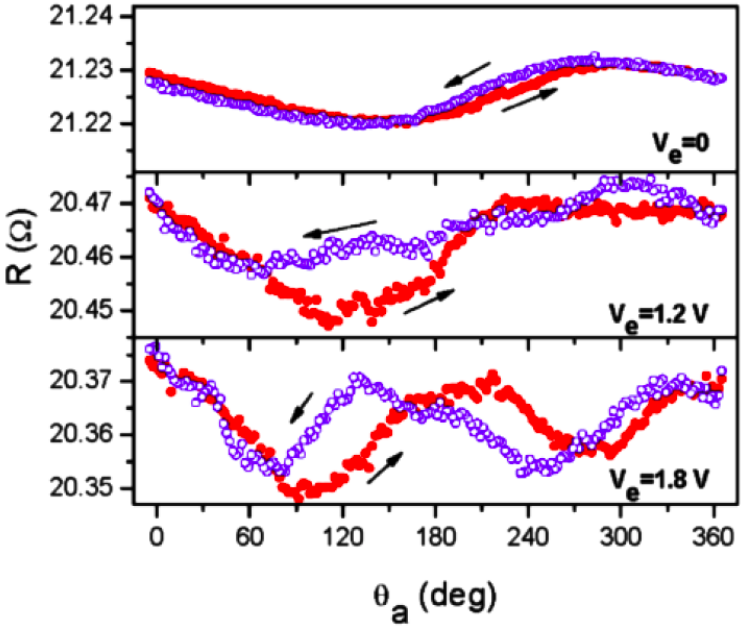
- Change of exchange bias after E field
- Change of magnetoresustabce (MR) after E field
- Change of M after E field
  - Sign reversal of M after E field

CHANGE OF EXCHANGE BIAS AFTER E FIELD

Electric-Field Control of Exchange Bias in Multiferroic Epitaxial Heterostructures







Heterostructure: (90 nm film)

Py(15 nm)/YMnO3(90 nm)/Pt(8 nm)

Observation:

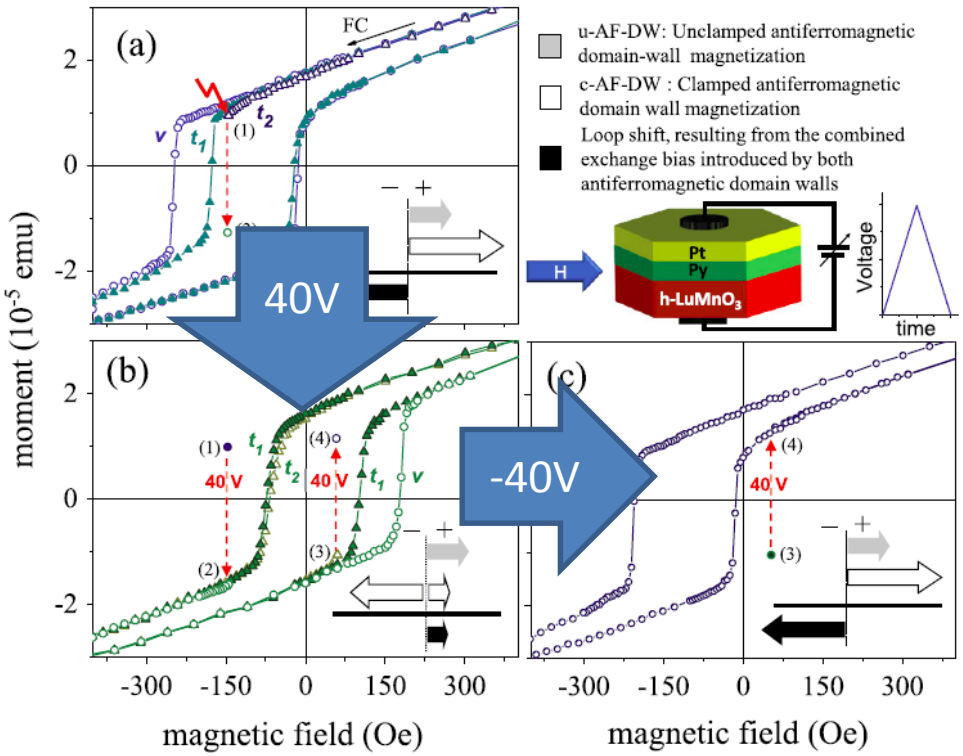
- After application of 0.6 and 1.2 V, exchange bias changes, accompanied by the change of magnetization.
- Application of -1.2V can not reverse the exchange bias.

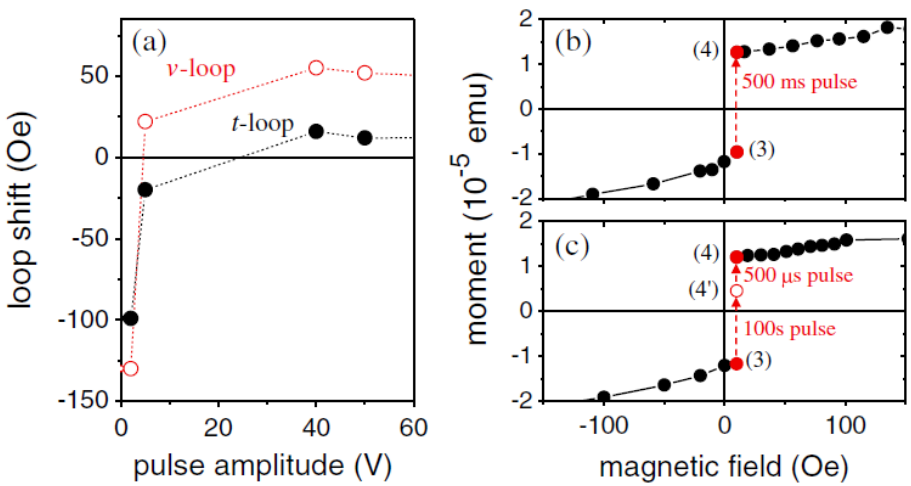
Mechanism

- AFM/FE domain wall motion?

PRL **97,** 227201 (2006)

Magnetization Reversal by Electric-Field Decoupling of Magnetic and Ferroelectric Domain Walls in Multiferroic-Based Heterostructures





Heterostructure:

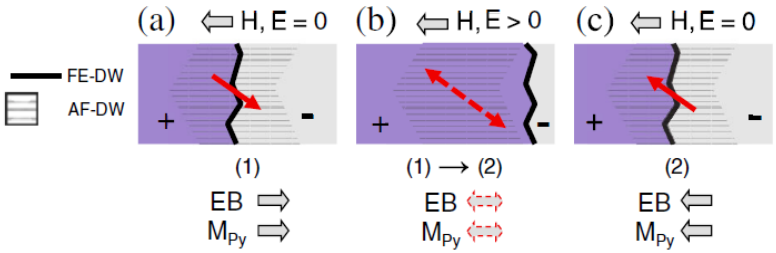
Ni81Fe19 (Py)/LuMnO3(12um)

Observation:

- Field cool in 3000Oe
- Apply 40V at H=-145Oe
- Apply 40V at H = 60 Oe to bring it back.
- Asymmetric

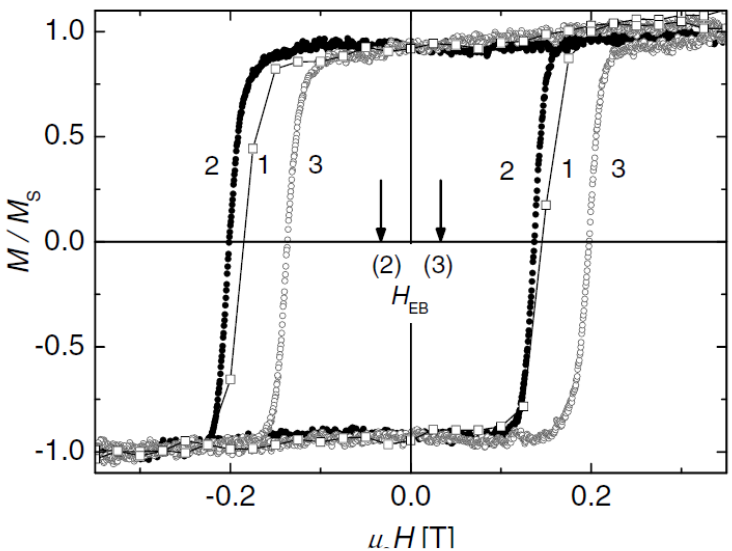
Mechanism

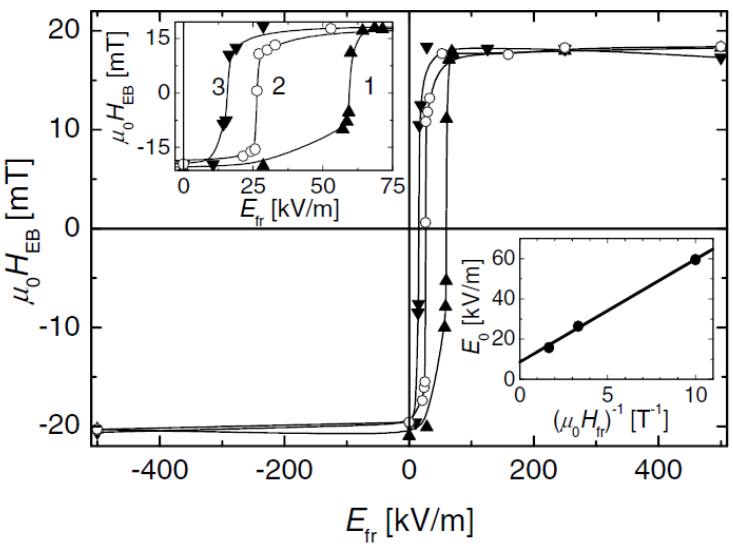
- Domain boundary motion



PRL 106, 057206 (2011)

Magnetoelectric Switching of Exchange Bias





PRL **94,** 117203 (2005)

Heterostructure: (bulk)

Cr_2O_3(111)/ Pt0.5 nm/[Co0.3nm/Pt1.5nm]$_3$/Pt1.5 nm

Observation:

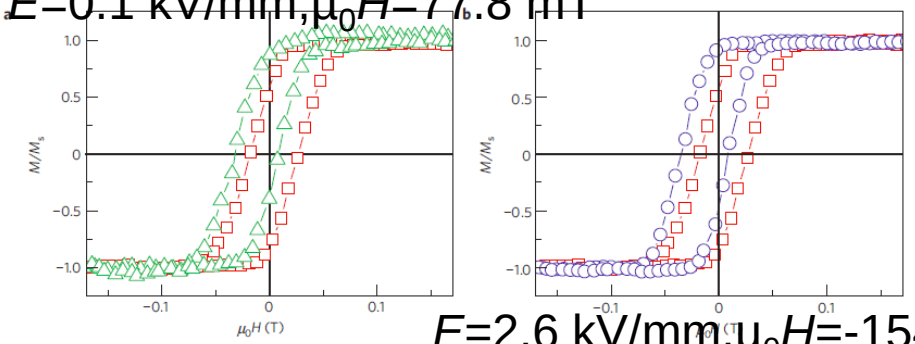
1: 350 to 298 K, μ_0H=0.6 T, E=0
2: 298 to 250 K, μ_0H=0.6 T, E=-500kV/m
3: 298 to 250 K, μ_0H=0.6 T, E=500kV/m

Mechanism

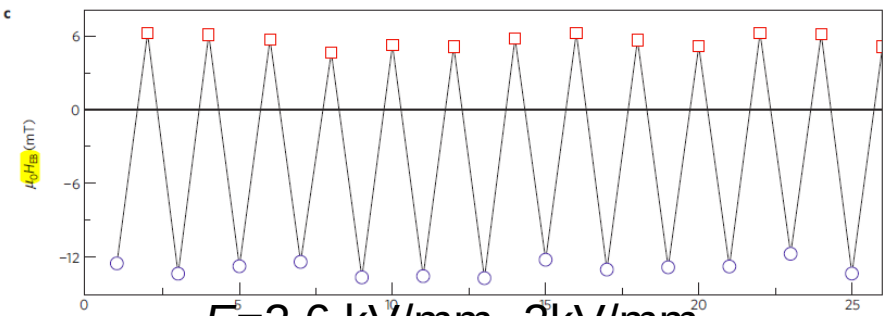
- $W_{ME} = 2\alpha_{zz} H_{fr} E_{fr}$
- Two domains have different α_{zz}.
- Domain can be aligned using E and H field together.

Robust isothermal electric control of exchange bias at room temperature

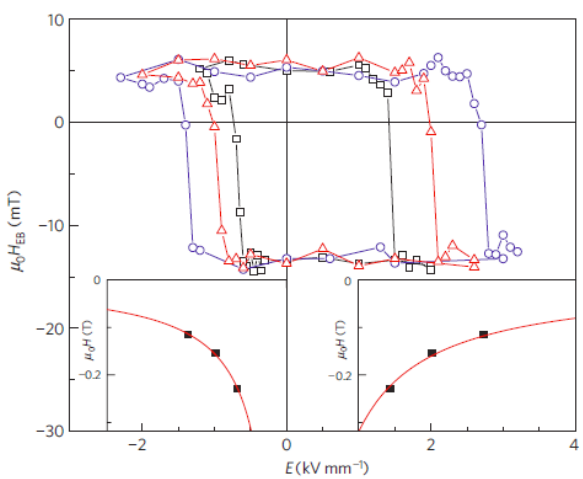
E=0.1 kV/mm,$\mu_0 H$=77.8 mT



E=2.6 kV/mm,$\mu_0 H$=-154mT



E=2.6 kV/mm,-2kV/mm



Heterostructure: (bulk)

Cr2O3 (0001)/Pd 0:5 nm/
(Co 0:6 nm Pd 1:0 nm)3

Observation:

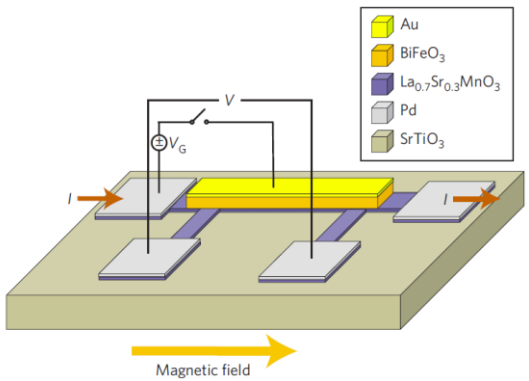
- Changing annealing E field can reverse the exchange bias

Mechanism

- Boundary magnetization determines exchange bias

CHANGE OF MR AFTER E FIELD

Reversible electric control of exchange bias in a multiferroic field-effect device



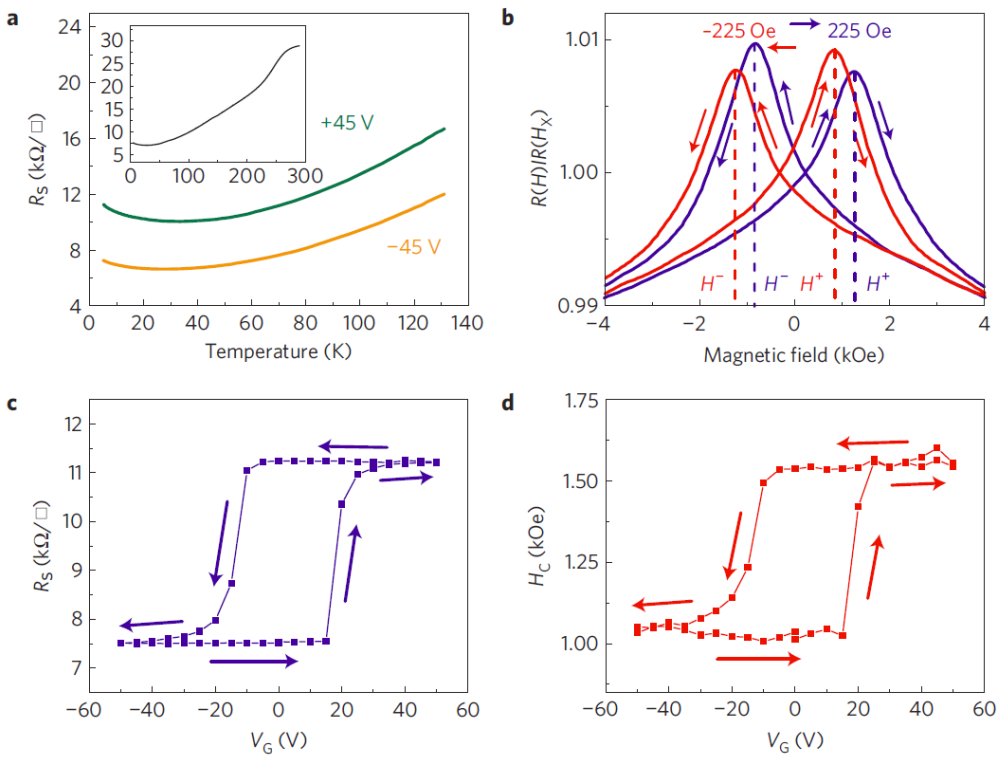
Heterostructure:
BFO(600nm)/LSMO(3-5nm)/STO

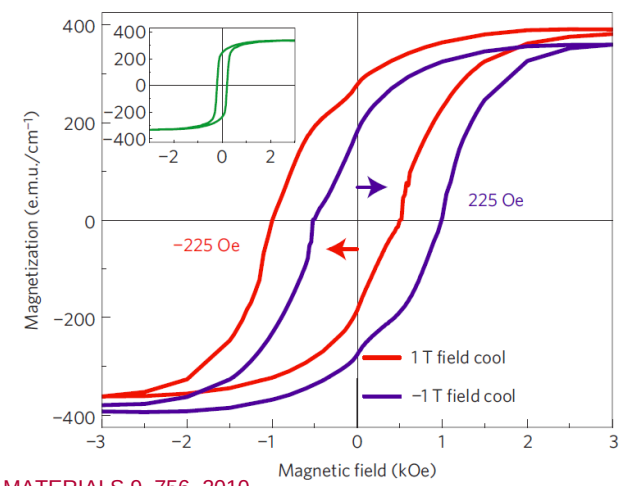
Observation:

- Change V_G to affect the MR
- Exchange bias can be extracted from MR

Mechanism

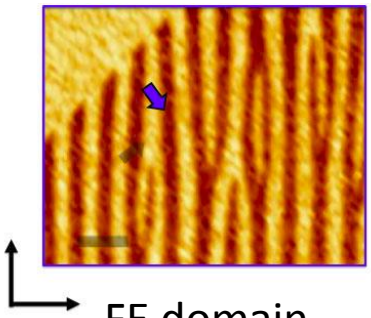
- Exchange bias, no detail



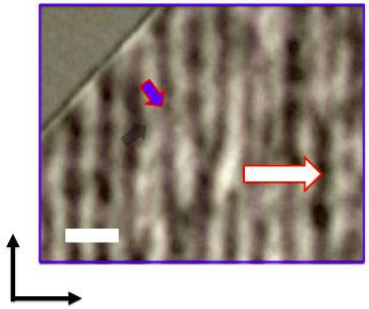


NATURE MATERIALS 9, 756, 2010.

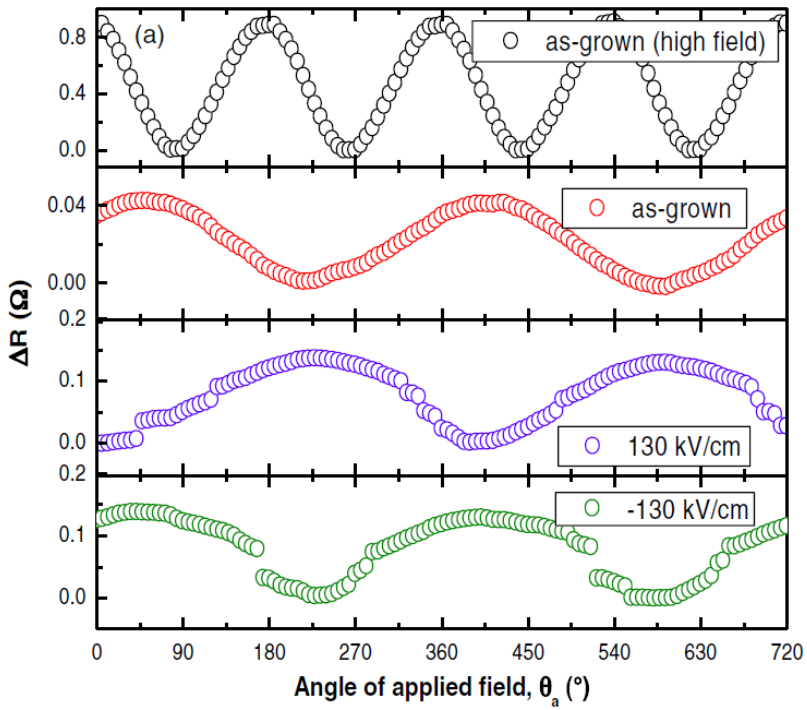
Electric-Field-Induced Magnetization Reversal in a Ferromagnet-Multiferroic Heterostructure



FE domain



CoFe/BFO FM domain



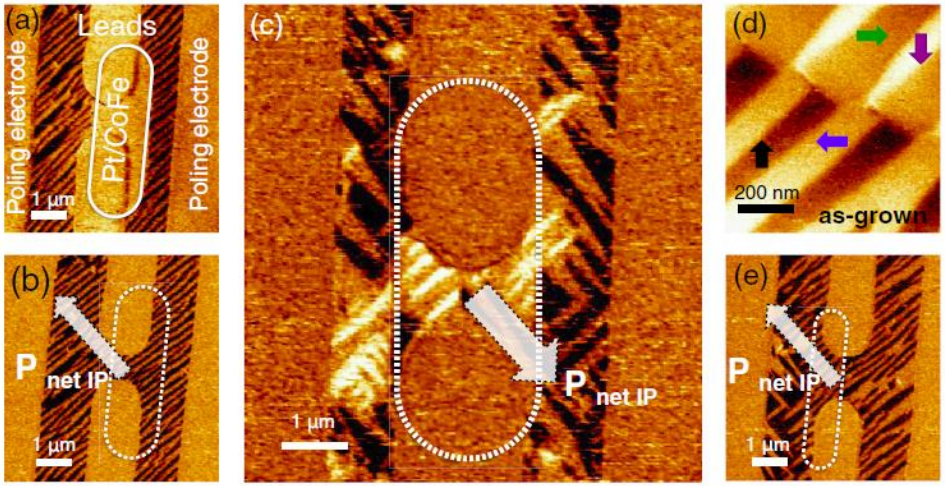
Heterostructure:
Pt (2.5nm)/CoFe(2.5nm)/BFO(70-100nm)

Observation:

- Apply E (in-plane), then AMR changes.

Mechanism

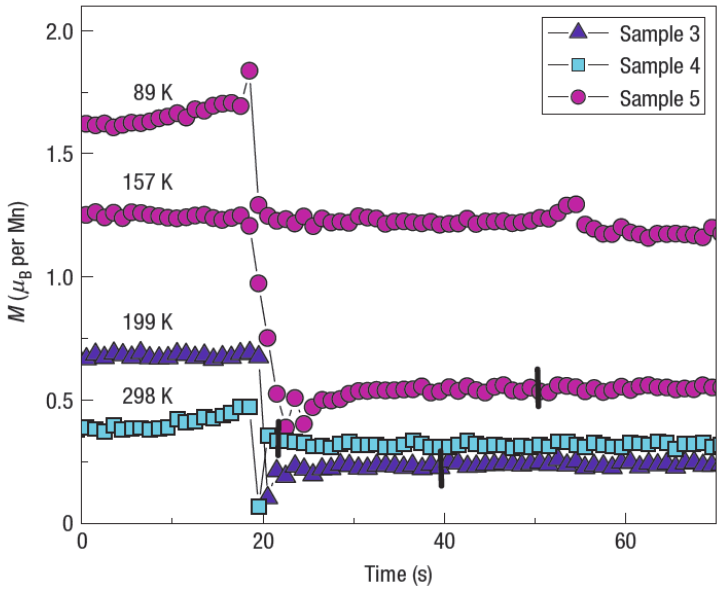
- E changes P, and L. So the exchange bias changes AMR.

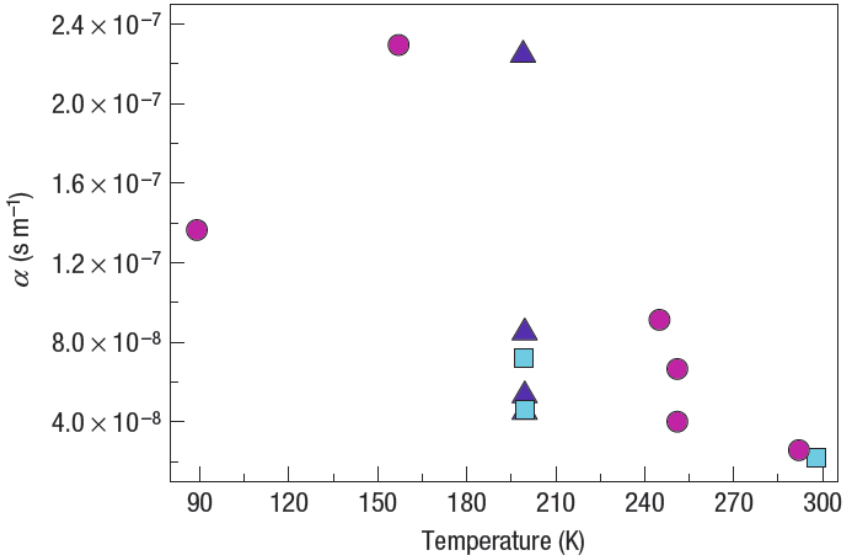


PRL 107, 217202 (2011)

CHANGE OF M AFTER E FIELD

Giant sharp and persistent converse magnetoelectric effects in multiferroic epitaxial heterostructures





Heterostructure:
LSMO(40nm)/BTO(0.5mm)

Observation:

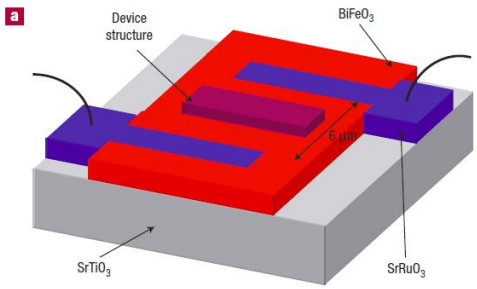
- 8000 Oe field cool from 470 K to 70K
- Apply E, M changes.

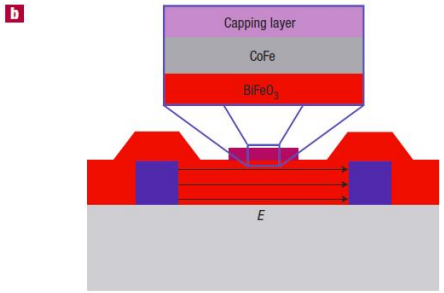
Mechanism

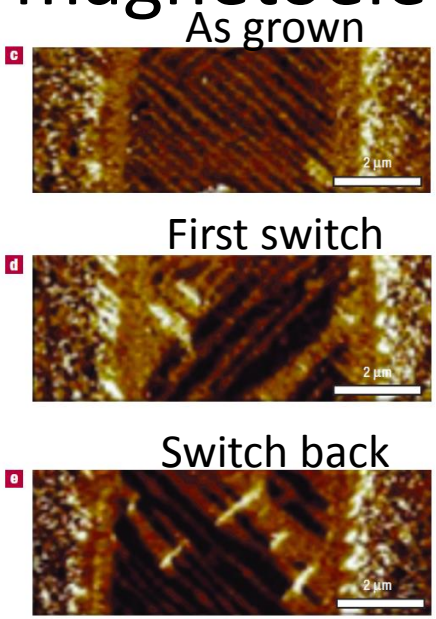
- Strain effect?

nature materials VOL 6,348 (2007)

Electric-field control of local ferromagnetism using a magnetoelectric multiferroic







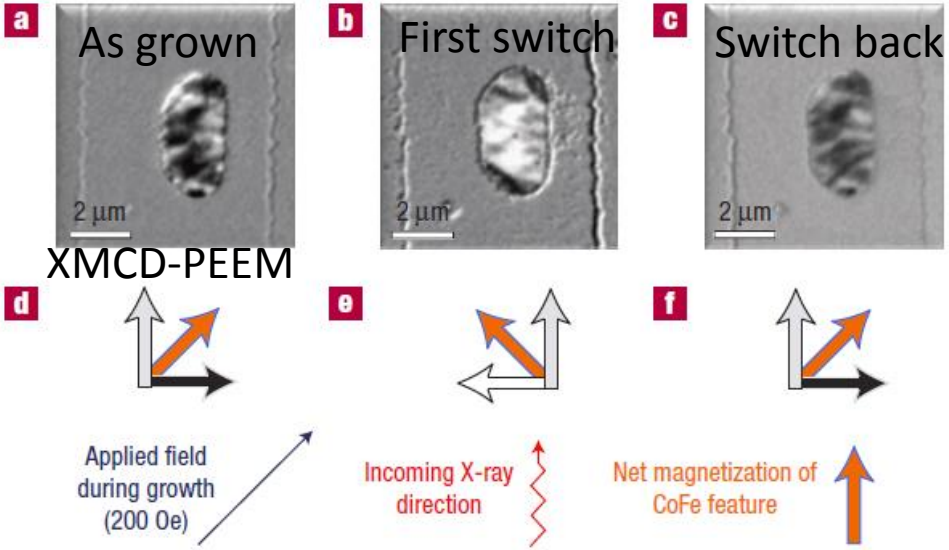
Heterostructure:
Au (2 nm)/CoFe (2.5–20 nm)/BFO (50–200nm)/SrRuO3 (SRO) (25–50 nm)

Observation:

- Apply E (in-plane), M changes.

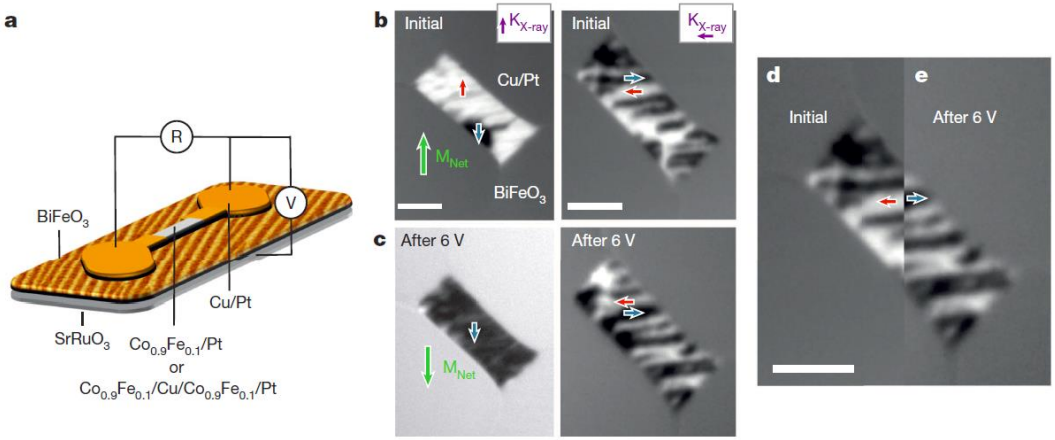
Mechanism

- Strain effect?



nature materials 7,478 (2008).

Deterministic switching of ferromagnetism at room temperature using an electric field



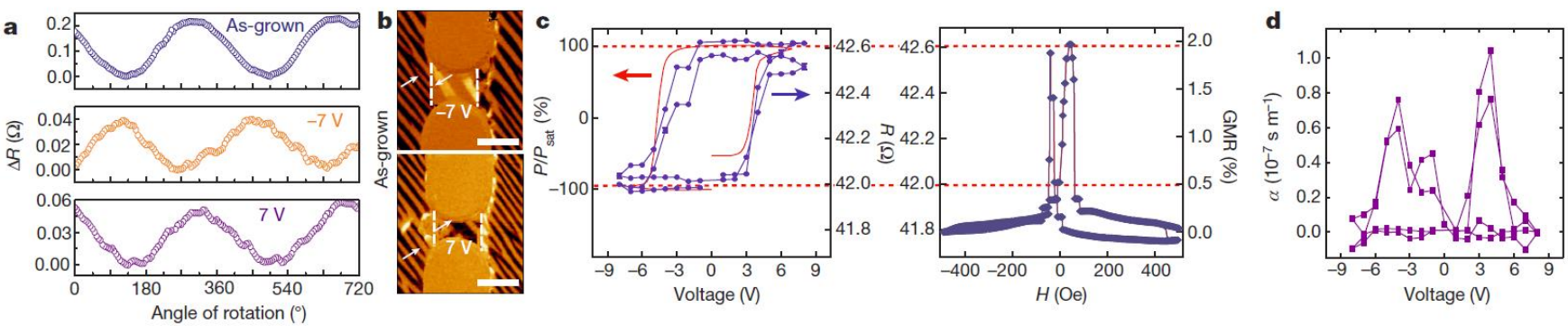
Heterostructure:
Pt/Co0.9Fe0.1/(001)p BiFeO3 (100 nm)/(001)p SrRuO3 (8 nm)/(110)DSO

Observation:

- Apply E out of plane, M switches, MR changes

Mechanism

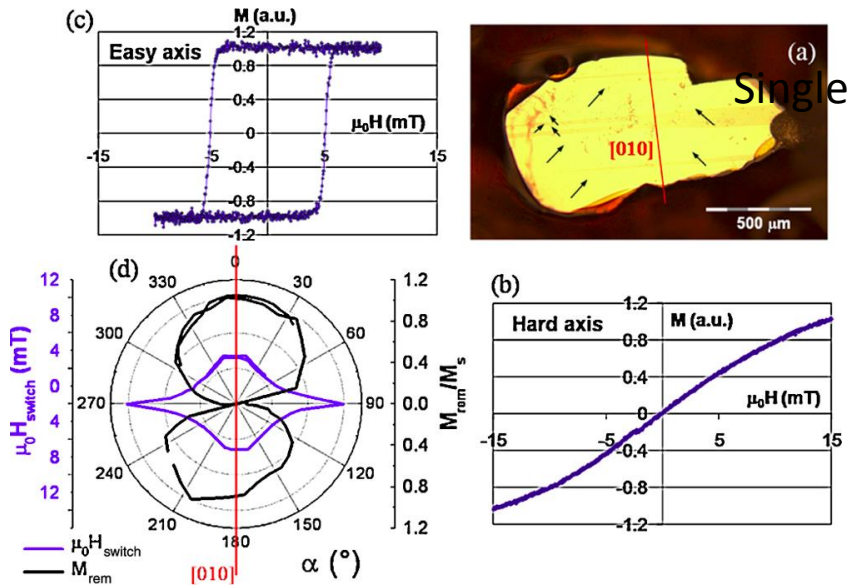
- Probably not exchange bias



Nature 516, 370, 2014.

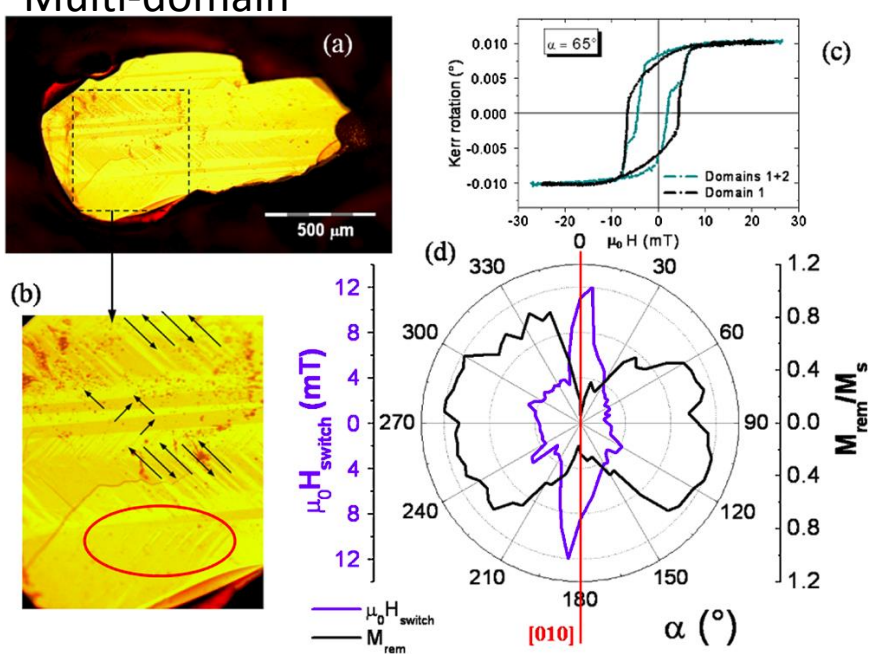
OTHERS

Electric Field Switching of the Magnetic Anisotropy of a Ferromagnetic Layer Exchange Coupled to the Multiferroic Compound BiFeO3



Single domain

Multi-domain



Heterostructure:

Au (3 nm)/Py(5-20nm)/BFO (bulk)

Observation:

- Apply E in-plane, anisotropy changes.

Mechanism

- Easy axis is linked to the crystallographic axes of BFO.
- Changing P changes the cycloid direction.

PRL 103, 257601 (2009)