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)

\[ M(H = 0, E = 0) \neq 0, \quad P(H = 0, E = 0) \neq 0, \]

(Multiferroics)

Goal:
- Reverse M
- Room temperature
- Repeatable
ME effect

Heterostructure/interface

Single phase material

Goal:
- Reverse M
- Room temperature
- Repeatable
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.
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.
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 magnetoresistance (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

Observation:
• After application of 0.6 and 1.2 V, exchange bias changes, accompanied by the change of magnetization.
• Application of -1.2V cannot reverse the exchange bias.

Mechanism:
• $AFM/FE$ domain wall motion?

Heterostructure: (90 nm film)
Py(15 nm)/YMnO3(90 nm)/Pt(8 nm)
Magnetization Reversal by Electric-Field Decoupling of Magnetic and Ferroelectric Domain Walls in Multiferroic-Based Heterostructures

Heterostructure: Ni$_{81}$Fe$_{19}$ (Py)/LuMnO$_3$(12µm)

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

Mechanism
- Domain boundary motion

PRL 106, 057206 (2011)
Magnetoelectric Switching of Exchange Bias

Observation:
1: 350 to 298 K, \( \mu_0 H = 0.6 \) T, \( E = 0 \)
2: 298 to 250 K, \( \mu_0 H = 0.6 \) T, \( E = -500 \) kV/m
3: 298 to 250 K, \( \mu_0 H = 0.6 \) T, \( E = 500 \) kV/m

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

PRL 94, 117203 (2005)
Robust isothermal electric control of exchange bias at room temperature

**Observation:**
- Changing annealing E field can reverse the exchange bias

**Mechanism**
- Boundary magnetization determines exchange bias

Heterostructure: (bulk)
Cr2O3 (0001)/Pd 0.5 nm/
(Co 0.6 nm Pd 1.0 nm)3

- $E=0.1 \text{kV/mm}, \mu_0H=77.8 \text{ mT}$
- $E=2.6 \text{kV/mm}, \mu_0H=-154 \text{ mT}$
- $E=2.6 \text{kV/mm}, -2 \text{kV/mm}$
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
Electric-Field-Induced Magnetization Reversal in a Ferromagnet-Multiferroic Heterostructure

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.
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 (50–200 nm)/SrRuO3 (SRO) (25–50 nm)

Observation:
• Apply E (in-plane), M changes.

Mechanism
• Strain effect?

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

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

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)