Controlling spins with Electric field in Multiferroic architectures

Agnès Barthélémy

Unité Mixte de Physique CNRS/Thales, Palaiseau, France

Agnes.barthelemy@thalesgroup.com

http://www.trt.thalesgroup.com/ump-cnrs-thales
The electron has:

- a charge (-e)
- a spin (↑, ↓)

**Electronics**
- Information is carried by Charge
- Control: Electric field

**Magnetism**
- Information is carried by Magnetization
- Control: Magnetic field

**Spintronics**
- Information is carried by Electron spin
- Control: Magnetic field, spin-polarized current
Key improvement in spintronics: Electric Control of magnetization or spin polarization

Non volatile Magnetic (Magnetoresistive) Random Access Memories (MRAMs)
STT-RAM architecture simpler, Size smaller
Reduction of the power

Nevertheless inevitably Joule heat losses

Other solution: E field control in heterostructures with ferroelectric or piezoelectric and magnetic materials: multiferroic architectures
The electron has:

- a charge (-e)
- a spin (↑, ↓)

Information is carried by:
- Charge
- Magnetization
- Electron spin

Control:
- Electric field
- Magnetic field

Electronics
Magnetism
Spintronics

Why?
Intrinsic Multiferroics or Artificial multiferroic heterostructures combining ferroelectric and magnetic materials:

- **Magnetic anisotropy**
- **Magnetic moment**
- **Exchange bias**
- **Magnetic order**
- **Curie temperature**
- **Spin polarization**

- Various magnetic properties can be controlled by electric field

Basics of Ferroelectricity / Piezoelectricity

FM materials: magnetic moment $\vec{\mu}$ / FE (FerroElectric) materials: dipolar moment $\vec{p}$

Prototypical FE: BaTiO$_3$

$T>T_C$: Cubic. Paraelectric $P=0$

$T<T_C$: Tetragonal. Ferroelectric $P\neq 0$

$\Rightarrow$ Polarization $\vec{P}$: $\vec{P}=\frac{d\vec{p}}{dV} = \frac{p_{\text{unit cell}}}{V_{\text{unit cell}}} \neq 0$
Polarization vs electric field loops

Very similar to the shape of magnetic loop
BUT not possible for the polarization to rotate (always along a high symmetry axis).
Polarization vs electric field loops

Usually reversal through nucleation and growth of domains

\[ U = U_0 - \vec{E} \cdot \vec{P} \]

At coercive field, Ec same proportion of up and down domains

Very similar to the shape of magnetic loop
BUT not possible for the polarization to rotate (always along a high symmetry axis).
Polarization vs electric field loops

Usually reversal through nucleation and growth of domains

At coercive field $E_c$ same proportion of up and down domains

Another difference: FM DWs are large (hundreds of unit cells), FE DWs are very thin (few unit cells)

Very similar to Stoner Wohlfarth BUT not possible for the polarization to rotate (always along a high symmetry axis).
Every Ferroelectric material is a Piezoelectric material

Piezoelectric effect

Converse Piezoelectric effect
Every Ferroelectric material is a Piezoelectric material

Converse Piezoelectric effect
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Every Ferroelectric material is a Piezoelectric material

Converse Piezoelectric effect

Effect used in actuator, transducers, microsensors…
This piezoelectric character can be used to image ferroelectric domain: Piezo-response force microscopy (PFM)

\[ V = V_0 \cos(\omega t) \]
\[ \Delta Z = d_{33} V_0 \cos(\omega t + \phi) \]
with \( \phi = 180^\circ \) for \( P_{\text{up}} \) domains and \( \phi = 0 \) for \( P_{\text{down}} \) ones

Allows to image FE domains

Image of written FE domains in BiFeO₃ \( t_{\text{BFO}}/(\text{La,Sr})\text{MnO}_3/\text{SrTiO}_3 \) heterostructure
This piezoelectric character can be used to image ferroelectric loops: Piezo-response force microscopy (PFM)

Allows to determine $E_c$

$$V = V_{DC} + V_0 \cos(\omega t)$$

Evolution of Phase and amplitude of PFM signal for BiFeO$_3$ BaTiO$_3$(2 nm)/(La,Sr)MnO$_3$ //NdGaO$_3$ heterostructure

<table>
<thead>
<tr>
<th>Material</th>
<th>Polarization (µC/cm²)</th>
<th>Tc (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BaTiO₃</td>
<td>26</td>
<td>393</td>
</tr>
<tr>
<td>PbTiO₃</td>
<td>75</td>
<td>763</td>
</tr>
<tr>
<td>PbZr₀.₅₂Ti₀.₄₈O₃ (PZT)</td>
<td>25</td>
<td>670</td>
</tr>
<tr>
<td>BiFeO₃</td>
<td>100</td>
<td>1100</td>
</tr>
</tbody>
</table>
**Sum up**

- **FE materials are characterized by their hysteresis loop** $P(E)$:
  
  - **Two states at remanence**: can be used to store information FERAM (equivalent to MRAM): FERAM = capacitor with $P_{up}$ or down: disadvantage: necessary to reverse the polarization to read whereas in MRAM: information simply read by measuring the resistance
  
  - **As in FM materials reversal through domain nucleation and expansion**
  
  - **Polarization** $\Rightarrow$\exists of charges on surface $Q=PxA$ $\rightarrow$ can be used to control magnetism

- **Also Piezoelectric**: their size changes when an electric field is applied:
  
  - Used to design actuators, transducers, sensors...
  
  - Used to image FE domains in PFM experiments $\rightarrow$ can also be used to control magnetism: straintronics
Multiferroics: definition

H. Schmid, Ferroelectrics 162, 317 (1994): “Crystals can be defined as multiferroic when two or more of the primary properties are united in the same phase”

Intrinsic multiferroic (BiFeO$_3$, BiMnO$_3$, YMnO$_3$…) or artificial: combination of FE and magnetic

H. Schmid, Ferroelectrics 162, 317 (1994): “Crystals can be defined as multiferroic when two or more of the primary properties are united in the same phase”

Piezoelectric
Ferroelectric
Magnetoelectric
Piezomagnetic
Ferroelastic
Ferromagnetic

Intrinsic multiferroic (BiFeO$_3$, BiMnO$_3$, YMnO$_3$...) or artificial: combination of FE and magnetic

1. **Few materials are Multiferroics**
   In perovskite $\text{ABO}_3$: Ferroelectricity related to the displacement of the TM atom from the center of the $\text{O}_6$ octaedra to form a strong covalent bond: only possible for $d^0$ TM. On the contrary, magnetism necessitates $d^N$ atom.
   
   
   Solution: A cation responsible of FE character & B cation at origin of magnetism.

2. **Most of them are AFM or WFM** (Noticeable exceptions of $\text{La}_x\text{Bi}_{1-x}\text{MnO}_3$, $\text{CoCr}_2\text{O}_4$)

<table>
<thead>
<tr>
<th>Magnetism</th>
<th>Type of order</th>
<th>Critical temperature (K)</th>
<th>Ferroelectricity Type of order</th>
<th>Critical temperature (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>YMnO$_3$</td>
<td>AF</td>
<td>70</td>
<td>FE</td>
<td>920</td>
</tr>
<tr>
<td>TbMnO$_3$</td>
<td>AF</td>
<td>42</td>
<td>FE</td>
<td>27</td>
</tr>
<tr>
<td>$(\text{La, Bi})\text{MnO}_3$</td>
<td>FM M=3.6µμ/μ</td>
<td>105</td>
<td>FE</td>
<td>770</td>
</tr>
<tr>
<td>BiFeO$_3$</td>
<td>AF, WF</td>
<td>640</td>
<td>FE</td>
<td>1100</td>
</tr>
</tbody>
</table>

3. **Low (magnetic) critical temperature**

4. All of them do not present magnetoelectric coupling.

$$F = F_0 - \mu_0 M_s \cdot H - \frac{1}{2} \varepsilon_0 \chi_E E^2 - \frac{1}{2} \mu_0 \chi_M H^2 - \alpha E \cdot H$$

$$\mu_0 M = - \frac{\partial F}{\partial H} = \mu_0 M_s + \mu_0 \chi_M H + \alpha E$$

with $\alpha = \mu_0 \frac{\partial M}{\partial E} = \frac{\partial P}{\partial H}$ in T.m.$V^{-1}$ = s.$m^{-1}$

and coupling limited by: "Cannot be larger than the geometric mean of electric and magnetic permeability" *Brown et al.; Phys. Rev. 168, 574 (1968)*


**Solution:** artificial multiferroic architecture: combination of FE and magnetic materials.
Mechanisms of control of magnetism by ferroelectricity:

In artificial multiferroics FE/FM architectures through:

✓ strain-mediated coupling

✓ effect of polarization direction on electronic structure of FM:
  → Field effect: accumulation/depletion

→ Different hybridization

✓ direct coupling using an intrinsic multiferroic

Wang et al.; NPG Asia Mater. 2, 61 (2010)
Mechanisms of control of magnetism by ferroelectricity:

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Mechanisms:

In artificial multiferroics FE/FM architectures through:

- strain-mediated coupling

\[ \mu_0 \Delta M = \alpha \Delta E \]

Wang et al.; NPG Asia Mater. 2, 61 (2010)
La$_{0.7}$Sr$_{0.3}$MnO$_3$

Pb(Mg$_{1/3}$Nb$_{2/3}$)$_{0.72}$Ti$_{0.28}$O$_3$

Reflects the piezoelectric loop

Thiele et al.; PRB 75, 054408 (2007)
Example: Fe//BaTiO$_3$(001): control of magnetic anisotropy

Epitaxial Fe is rotated by 45° on BaTiO$_3$ (001):
(100) BaTiO$_3$≡(110) Fe

Reflects the ≠ strains states imposed by the ≠ phases of BaTiO$_3$

Shirahata et al.; APL 99, 022501 (2011)

Venkataiah et al.; APL 99, 102506 (2011)

Shirahata et al.; APL 99,022501 (2011)
**BaTiO$_3$/Fe; BaTiO$_3$ in T phase**

*Magnetic anisotropy*

**Optical microscopy experiments: image of Fe and FM domains**

**BTO**

- $3.992 \text{ Å}$
- $4.036 \text{ Å}$

**Fe**

- $-1.6\%$

On a domains: uniaxial anisotropy
c domains: fourfold anisotropy (magnetocrystalline anisotropy)

Transfer of FE domain pattern onto the FM

Lahtinen et al.; APL 101, 262405 (2012)
Electric field control of magnetic anisotropy via strain

Example: $\text{Pb}(\text{Zr}_x\text{Ti}_{1-x})\text{O}_3$ actuator with Ni polycrystalline film

$V_p < 0$: $y =$ easy axis; $x =$ hard axis

$V_p > 0$: $y =$ hard axis; $x =$ easy axis

$\Rightarrow$ Clear Rotation by $\approx 90^\circ$ while changing the voltage polarity

Electric field control of magnetic anisotropy via strain

Example: Pb(Zr\textsubscript{x}Ti\textsubscript{1-x})O\textsubscript{3} actuator with Ni polycrystalline film

**How it works?**

**Principle:**
E-field applied to PZT: change in PZT dimensions due to *converse piezoelectric effect*

- Change in dimensions induced in Ni: strain effect
- Due to *magnetostriction* in Ni, strain modifies the magnetic properties

Electric field control of magnetic anisotropy via strain

\[ F = F_{\text{Zeeman}} + F_{\text{magstat}} + F_{\text{magnetocryst}} + F_{\text{magel}} \]

\[ F_{\text{Zeeman}} = -\mu_0 \vec{M} \cdot \vec{H} = -\mu_0 MH \cos(\Theta - \theta) \]

\[ F_{\text{magel}} = \frac{3}{2} \lambda \left( c_{12}^{\text{Ni}} - c_{11}^{\text{Ni}} \right) \left( 1 + \nu \right) \varepsilon_2 \cos^2(\Theta) \]

(\lambda: \text{magnetostriction}) \quad c_{ij}: \text{elastic coefficients of Ni} \quad \varepsilon_2: \text{Strain along y}

\[ \left( c_{12}^{\text{Ni}} - c_{11}^{\text{Ni}} \right) \text{ and } \lambda \text{ are both negative in Ni} \]

Considering a linear dependence of the length L of the actuator with voltage:

\[ \varepsilon_2 = \frac{\Delta L_{\text{max}}}{L_0} \frac{V_p}{V_{\text{max}}} \]

Piezoelectric properties of the PZT actuator;
\[ \Delta L_{\text{max}}/L_0 = 1.3 \times 10^{-3}; \ V_{\text{max}} = 180 \ V \]

\[ F_{\text{magel}} \propto \frac{V_p}{V_{\text{max}}} \cos^2(\theta) \]

Easy axes of magnetization determined by the energy minima of F vs \( \theta \)
Electric-field induced control of magnetization easy axis

Electric field control of magnetic transition via strain

Example: $\text{BaTiO}_3$//FeRh

- $\gamma$ phase: fcc
- $\alpha'$ phase: Fe/Rh ordered bcc: 1st order transition from G-AFM to FM @ 370°C
- Associated with large resistivity drop
- Jump of cell volume by ~1% at $T^*$: coupling between structural and magnetic orders

van Driel et al, JAP 85, 1026 (1999)
Kouvel et al, JAP 33, 1343 (1962)
Maat et al, PRB 72, 214432 (2005)
BaTiO$_3$ under electric field (X-ray diffraction study)

At 0 V, coexistence of a and c domains
At 20 V, the proportion of c domains increases
At 60 V, only c domains are present
**BaTiO$_3$ under electric field (X-ray diffraction study)**

- **Diagram:**
  - At 0 V, coexistence of a and c domains.
  - At 20 V, the proportion of c domains increases.
  - At 60 V, only c domains are present.
  - Applied voltage increases the proportion of c domains.

- **Graphs:**
  - Voltage vs. % c domains:
    - 60 V: Only c domains are present.
    - 20 V: Proportion of c domains increases.
    - 0 V: Coexistence of a and c domains.
  - Voltage vs. Polarization (μC/cm$^2$):
    - Graphs showing hysteresis.

- **X-ray diffraction study:**
  - Peaks at different voltages:
    - 60 V: Sharp peak at 45.6°.
    - 20 V: sharper peak at 45.3°.
    - 0 V: Broad peak at 45.0°.
BaTiO$_3$ under electric field (X-ray diffraction study)

- Increase of the in plane compressive strain by 0.47% → Increase in the FeRh out of plane parameter by 0.52%: in good agreement with strain (Poisson ratio: = 0.31)
Influence of voltage on magnetic properties

- At 0V at 20 kOe, $T^* \approx 360$ K
- Voltage shifts $T^*$ by ~20K
- Effect is reversible
- Positive or negative voltages give roughly similar effect

Virgin

At 0V at 20 kOe, $T^* \approx 360$ K
- Voltage shifts $T^*$ by ~20K
- Effect is reversible
- Positive or negative voltages give roughly similar effect
Influence of voltage on magnetic properties

- At 0V at 20 kOe, $T^* \approx 360$ K
- Voltage shifts $T^*$ by $\sim 20$K
- Effect is reversible
- Positive or negative voltages give roughly similar effect

- Max magnetization change $\sim 550$ emu/cm$^3$
- Very large magnetoelectric coupling: $\alpha = 1.6 \times 10^{-5}$ s/m

Electric field control of magnetism via strain:

Advantages:

- Effect is bulk-related, i.e. it applies to the whole ferromagnetic film
- It can be applied to all ferromagnetic materials with magnetostriction and not too large intrinsic magnetocrystalline anisotropy

Inconveniences:

- No modification at remanence
- Limited to piezoelectric with large coefficients
- Needs to be demonstrated with low voltages
- Fatigue?
Mechanisms of control of magnetism by ferroelectricity:

In artificial multiferroics FE/FM architectures through:

- strain-mediated coupling

- effect of polarization direction on electronic structure of FM:
  → Field effect: accumulation/depletion

  → Different hybridization

  ✓ direct coupling using an intrinsic multiferroic
**Effect of polarization direction on electronic structure and magnetism of FM:**

**Principle:** like in standard FET the gate voltage locally decreases / increases the carrier density, effect efficient over the Thomas-Fermi screening length $\lambda_{TF}$

$$\lambda_{TF} \text{ proportional to } \sqrt{\text{DOS} \times E_F}$$

\[
 n = n_0 e^{-t / \lambda_{TF}}
\]

→ Very thin channel ($\lambda_{TF}=0.1$ nm in metals, 1 nm in SC).  
→ particularly efficient in ferromagnets with a carrier-mediated magnetic interaction like mixed-valence manganites like La$_{0.7}$Sr$_{0.3}$MnO$_3$, diluted magnetic semiconductors like Mn-doped GaAs.

**Additional effects in FM:**
→ Anisotropy is determined by electron occupation of orbitals: by affecting orbital occupation at the interface, should change the interface anisotropy.  
→ $n^{\uparrow} \neq n^{\downarrow}$: the screening is different for the two spin direction and will affect differently the DOS for spin up and spin down: results in modification of the magnetization \((Zhang; Phys. Rev. Lett. 83, 640 (1999))\)

→ change in the orbital overlap between the FM and FE materials: change in DOS of spin$^{\uparrow}$ and spin $^{\downarrow}$ \((Duan et al., PRL 97,047201 (2006))\)
Change in hybridization at the interface

Duan et al., PRL 97,047201 (2006)

Change direction of P: change in orbital overlap between Fe and Ti: change in the charge transfer between Fe and Ti: change in the DOS of Fe at interface. DOS for spin $\uparrow \neq$ spin $\downarrow$: affect differently the two DOS: change in spin polarization
Mechanisms of control of magnetism by ferroelectricity:

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Wang et al.; NPG Asia Mater. 2, 61 (2010)
Diluted magnetic semiconductors: Mn-doped GaAs

The Curie temperature is strongly dependent on the carrier density

➔ Changing the carrier density by an electric field should modify $T_C$
The application of a positive or negative gate voltage (electric field) changes the $T_C$.

At a given temperature, the electric field can be used to change the magnetic properties (anisotropy) or even suppress ferromagnetism.


However, the effect is volatile.
How to make the field effect non-volatile? Use a ferroelectric gate insulator.

\[ \Delta n_{sq} = \frac{2P}{e} = 6.10^{14} \text{ / cm}^2 \quad \text{for } P = 50 \mu \text{C} / \text{cm}^2 \]

\[ d = 6 \text{nm} \Rightarrow \Delta n = \frac{P}{ed} = 10^{21} \text{ / cm}^3 \]
FE Gating on magnetism

(Ga,Mn)As

How to make the field effect non-volatile? Use a ferroelectric gate insulator.

FE Gating on magnetism

Manganites

La$_{1-x}$Sr$_x$Mn$^{3+}_{1-x}$Mn$^{4+}$$_x$O$_3$
La$_{1-x}$Ca$_x$Mn$^{3+}_{1-x}$Mn$^{4+}$$_x$O$_3$

Mn$^{3+}$

$dx^2$-$y^2$
$dz^2$
$dx$y
$dy$z $dz$z $dx$z

Mn$^{4+}$

$dx^2$-$y^2$
$dz^2$
$dx$y
$dy$z $dz$z $dx$z

T$_<T_c$
$\mathbf{t}_2g$

$\mathbf{e}_g$

T$_\approx T_c$
$\mathbf{t}_2g$

$\mathbf{e}_g$

$T \approx \cos(\theta/2)$
Switching P in PZT produces charge accumulation/depletion in manganite

- Change $T_C$ of manganite
- Change in magnetization amplitude

Attribute to change in carrier concentration that induced a transition from FM (to AFM order at interface)

Field effect control of magnetism at RT?

Need to use TM-FM
Pb: have a large carrier density $10^{23}$/cm$^3$ compared to DMS or manganites ($10^{21}$/cm$^3$)
BUT feasible:

Change in magnetic coercive field at 300K induced by an electric field in an ultrathin FePt film:
Accumulation/depletion change the orbital occupancy at interface: changes the interface anisotropy
thus the coercive field

Change in hybridization at the interface

Duan et al., PRL 97, 047201 (2006)

Change direction of P: change in orbital overlap between Fe and Ti: change in the charge transfer between Fe and Ti: change in the DOS of Fe at interface. DOS for spin $\uparrow \neq$ spin $\downarrow$: affect differently the two DOS: change in spin polarization
Change in hybridization at the interface

**FM tunnel Junctions**  Fe/ BaTiO\textsubscript{3} 1nm/La\textsubscript{0.7}Sr\textsubscript{0.3}MnO\textsubscript{3} : **TMR**

- Clear negative tunnel magnetoresistance (TMR)
- Negative spin-polarization at Fe/BTO interface

\[
\text{TMR} = \frac{R_{AP} - R_P}{R_P} = \frac{2 \text{SP}_1 \text{SP}_2}{1 - \text{SP}_1 \text{SP}_2}
\]

- $\downarrow \uparrow$ Fe / BTO
- $\downarrow \uparrow$ (La,Sr)MnO\textsubscript{3}
- $\downarrow \uparrow$ BaTiO\textsubscript{3}

**Density of states (electrons / eV)**

\[
\text{SP} = \frac{N_{\uparrow}(E_F) - N_{\downarrow}(E_F)}{N_{\uparrow}(E_F) + N_{\downarrow}(E_F)} < 0
\]
Change in hybridization: Electric control of the spin polarization

FM & FE tunnel Junctions Fe/ BaTiO₃ 1nm/ La₀.₇Sr₀.₃MnO₃:

→ Change in the TMR amplitude reflects change in the DOS of Fe at the interface and the consequent change in spin polarization when FE polarization direction is changed. Measured at 4K (due to LSMO) but in principle feasible at RT.

Garcia et al.; Science 327, 1106 (2010)
Change in hybridization: Electric control of the spin polarization

FM & FE tunnel Junctions  Co/ PbZrTiO₃ 1nm/ La₀.₇Sr₀.₃MnO₃:

→ Change in the TMR sign
→ reflects change in the DOS of Fe at the interface and the consequent change in spin polarization when FE polarization direction is changed.

FE control of electronic structure

Very rich physics with large number of mechanisms

Advantages: Substantial change in \( T_C \) may be achieved
close to \( T_C \) the magnetic properties can be tuned
Substantial change in anisotropy
Change in spin polarization: particularly attractive in MTJs

Inconveniences: very local modification (over a thickness of a few nm at most)
effect is small
effect is mostly restricted to carrier-mediated ferromagnets
Mechanisms of control of magnetism by ferroelectricity:

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  → Field effect: accumulation/depletion

→ Different hybridization

- direct coupling using an intrinsic multiferroic

Wang et al.; NPG Asia Mater. 2, 61 (2010)
**BiFeO$_3$ (BFO): an AFM-FE Multiferroic @ RT**

Rhombohedrally distorted perovskite (R3c) \( a=3.96\,\text{Å} \ \alpha=89.5^\circ \)

Polarization along [111] direction

\( T_c=1100\,\text{K} \)

\( P_s=100\,\mu\text{C/cm}^2 \)

Lebeugle et al.; APL 91, 022907 (2007)

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**Antiferromagnetic of G type:**

Superexchange: AF \( T_N=640\,\text{K} \)

Canted spins → weak ferromagnet \( M_S=0.01\mu_B/\text{f.u.} \)


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**BiFeO$_3$ (BFO): an AFM-FE Multiferroic @ RT**

C. Ederer & N. Spaldin, PR B, 71, 060401 (R) (2005)

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**Review by G. Catalan & J. Scott; Adv. Mat. 21, 2463 (2009)**

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**Antiferromagnetic vector magnetization**

**cycloidal modulation ⇒ Averaging to zero of the linear ME effect**
**BiFeO$_3$ (BFO): an AFM-FE Multiferroic @ RT**

In bulk: Above 20T: the cycloidal modulation is destroyed:
- recovery of a small magnetic moment
- linear magnetoelectric coupling reflected by the linear dependence of the magnetically induced polarisation


In thin film the cycloidal modulation is destroyed (Béa et al., Phil. Mag. Lett. 87, 165 (2007)): the linear magnetoelectric coupling is allowed

Review by G. Catalan and J. Scott; Adv. Mat. 21, 2463 (2009)
FE domain structure (PFM) in BiFeO3 thin films

Stripe-like domains: mainly 71° DWs
Mosaic-like domains: 109° + 71° + 180° DWs

Martin et al.; Nano.Lett. 8, 2050 (2008)
**BFO: evidence for the magnetoelectric coupling**

Combination of PFM and XLD-PEEM experiments

1 & 2: 109° ferroelectric switching
3: 71° switching
4: 180° switching
1 & 2 the PEEM contrast reverses after electrical poling.
71 & 109: change in the AFM plane
180°: same AFM plane

To exploit this magnetoelectric coupling it is necessary to couple BFO with a ferromagnetic materials through an exchange bias interaction: i.e. to design an artificial multiferroic
How to exploit such AFM–FE material to obtain an electric control of magnetic properties? Couple it by exchange bias with a FM.
Discovery in 1956

New Magnetic Anisotropy

W. H. Meiklejohn and C. P. Bean

General Electric Research Laboratory, Schenectady, New York
(Received March 7, 1956)

Fig. 3. Hysteresis loops of fine oxide-coated particles of cobalt taken at 77°K. The dashed lines show the hysteresis loop when the material is cooled in the absence of a magnetic field. The solid lines show the hysteresis loop when the material is cooled in a saturating magnetic field.

Meiklejohn and Beam: Co/CoO particles

Appears when a FM/AF system is cooled in a magnetic field through the Néel temperature of the AFM

$T_C > T > T_N$

Field cooling

$T < T_N$

- Simple picture assumes the presence of *uncompensated spins* at the interface (due to the presence of defects)
- Some are *pinned* (by the magnetic anisotropy in the antiferromagnet): *these are the ones responsible for the exchange bias: shift of the loop*
- Some of the uncompensated spins are *unpinned* (free to rotate with the magnetic field, like the magnetization of the ferromagnet): *the loop is enlarged*
On BFO, $M(H)$ cycle is enlarged (coercivity enhancement) and shifted (exchange bias).

- Stripe like domains: only 109° DWs: only enlarged hysteresis loop
- Mosaic like domains: 71° + 109° + 180° DWs: $M(H)$ cycle is enlarged (coercivity enhancement) and shifted (exchange bias)

Béa et al.; PRL 100, 017204 (2008); Martin et al.; Nano.Lett. 8, 2050 (2008)
Malozemoff’s model extended to multiferroics: 

\[ H_e = - \frac{2zS_{AF}S_{FM}J_{ex}}{\mu_0M_{FM}t_{FM}aL} \]

- \( H_e \) varies as the inverse of the \textbf{FE domain size}

- \textbf{Strong suggestion of Magnetoelectric coupling}

Béa et al., PRL 100, 017204 (2008)
exchange bias with BiFeO₃

\[ |H_e| (Oe) \]

\[ \frac{1}{\text{domain size (nm}^{-1})} \]

V = -8V

V = +8V

BFO(70nm)/SRO//STO (001)

\[ L_{FE} \text{ large } \rightarrow H_e \text{ small} \]

BFO(70nm)/SRO//STO (111)

\[ L_{FE} \text{ small } \rightarrow H_e \text{ large} \]
Towards the electric control of magnetic layer

Combination of PFM and XMCD-PEEM

$V = 200\text{V}$

$180^\circ$ shift in the AMR: switching of magnetization

E. Chu et al.; Nat. Mat. 7, 478 (2008)
Heron et al.; PRL 107; 217202 (2011)
Towards the control of the spin valve by E-field

- Sizeable GMR effect
- Shifted by the exchange bias
Towards the control of the spin valve by E-field

- Change with E-field reflecting the change in exchange bias (related to FE domain)
- But non reversible
- Reversible effect obtained at LT using LuMnO₃ a FE/AFM non ferroelastic material (Skumryev et al.; PRL 106, 057206 (2011))

J. Allibe et al.; Nanoletters 12, 1141 (2012)
Electric control of Exchange-bias using a multiferroic

Advantages: 180° reversible rotation demonstrated at RT in planar device: so feasible applicable to all TM-FM

Inconvenients: As to be demonstrated in vertical device: high density and small voltage Mechnanisms not yet very clear
That’s it!

Thank you for your attention

Reviews: