Functionalization of Magnetoelectrics for Spintronics

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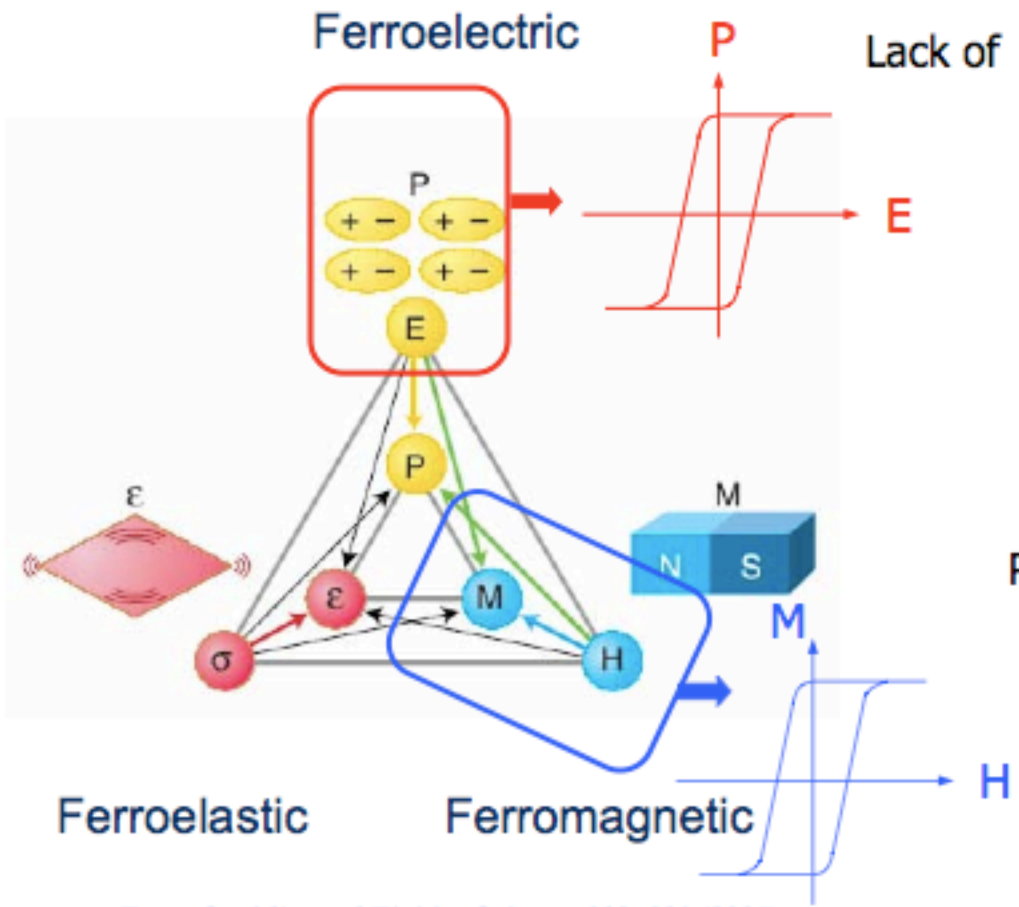
Outline

- What are magnetoelectrics?
- Magnetoelectrics for spintronic:
  - Mechanisms
  - Materials
  - Heterostructures
- Examples:
  - $BiFeO_3$
  - $BiMnO_3$
- Conclusion

Magnetoelectric materials for interfaces

Multiferroic materials



Lack of inversion symmetry

Sensors

FeRAM

Partially filled d/f shells

Magnetic Data Storage

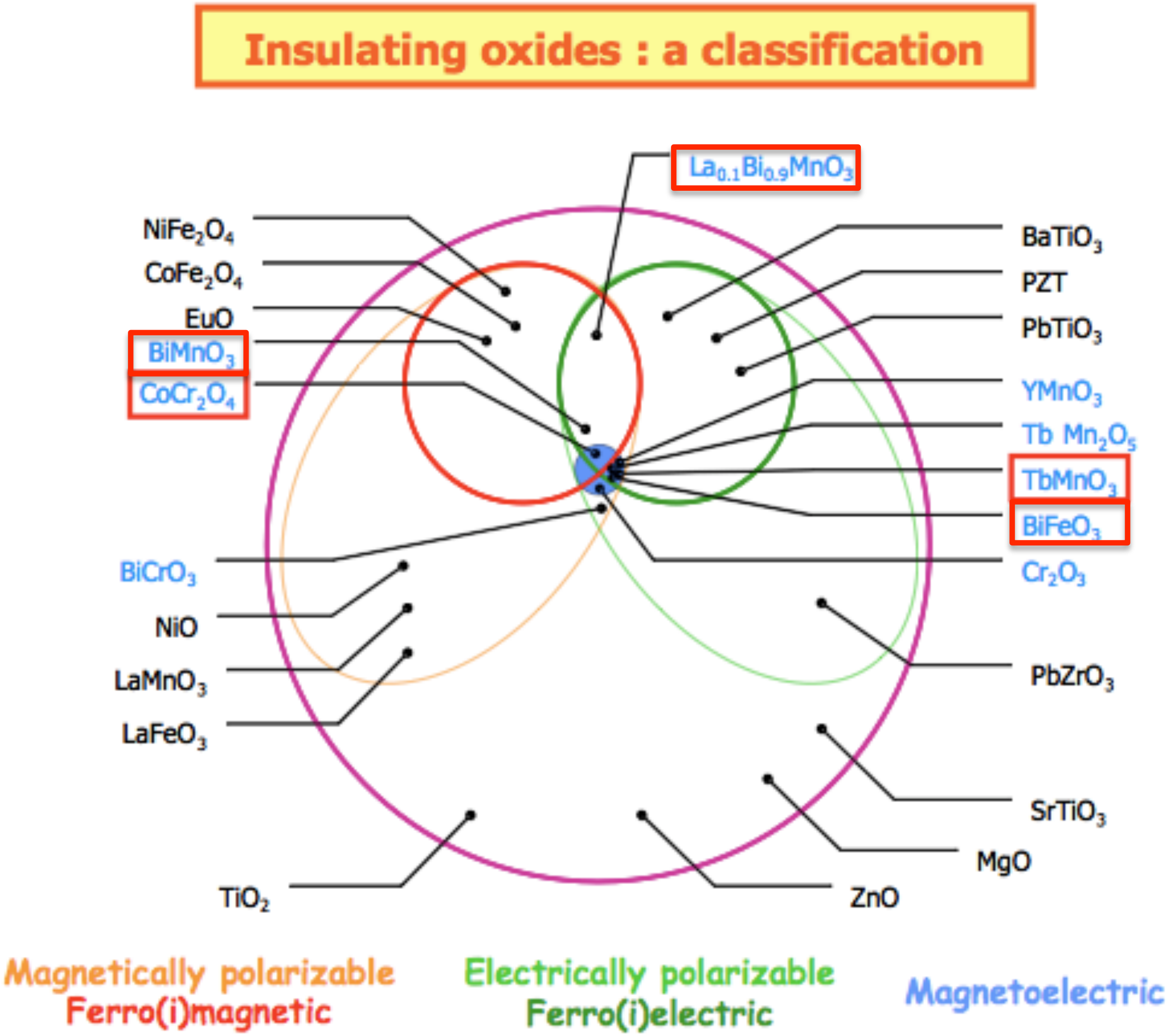
Spintronics

From Spaldin and Fiebig, Science 309, 391 (2005)

Switchable parameter : M, P
External stimulus : H, E

- **Multiple-state memories**
- M switching by E
- P switching by H

Magnetoelectric materials for interfaces

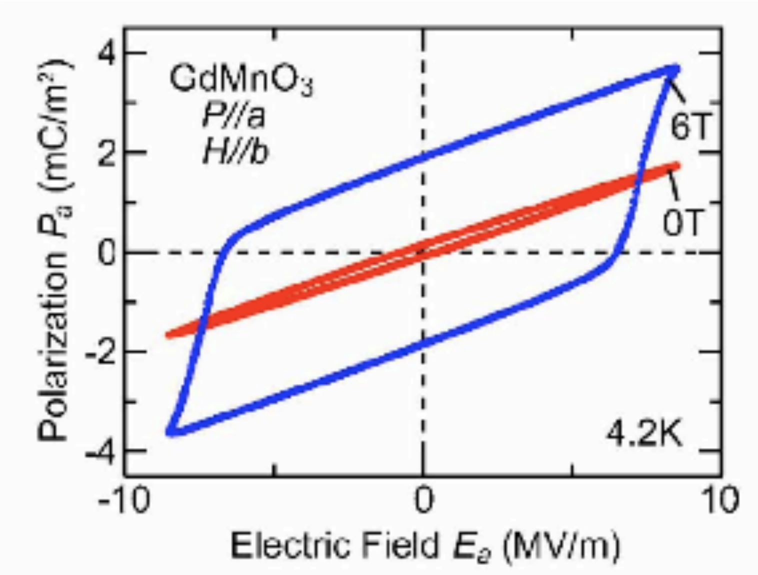


Derived from Eerenstein, Mathur and Scott, Nature 442, 759 (2006)

Magnetoelectric materials for interfaces

$(Gd,Dy,Tb)MnO_3$: spiral magnets

Spiral ordering breaks inversion symmetry
➔ (improper) ferroelectricity appears
(but **no** finite magnetization)

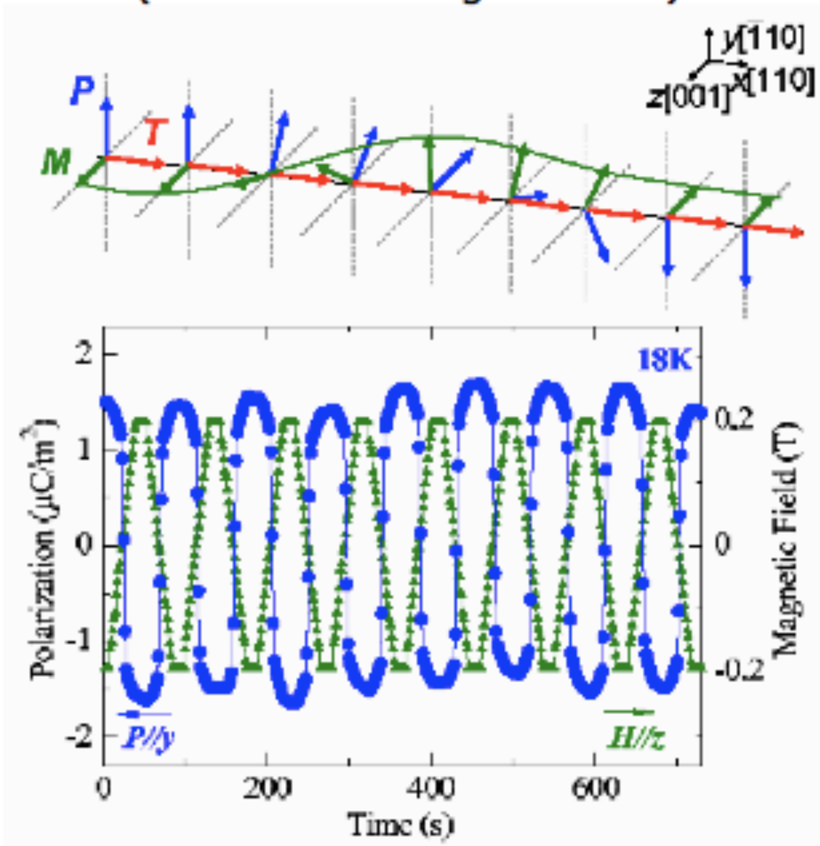


Apply a magnetic field : change magnetic state
➔ switch polarization on/off

Kimura et al, PRB 71, 224425 (2005)

$CoCr_2O_4$: conical magnet

Conical ordering breaks inversion symmetry
➔ (improper) ferroelectricity appears
(**with** a finite magnetization)



Flip polarization direction by a magnetic field

Yamasaki et al, PRL 96, 207204 (2006)

Magnetoelectric materials for interfaces

Magnetoelectrics:

Control

electric polarization (magnetization) by magnetic (electric) field

Spintronics: electrical control of spin transport.

Main goal: develop artificial structures using ME/MF materials as barriers - multifunctional epitaxial heterostructures to be used as electrically driven tunnel junctions and spin filters.

Main advantage: Electric field controlled nano-sized devices are attractive than those driven by magnetic fields.

Magnetoelectric materials for interfaces

Improving ME coupling:

- chemically control of their functionality by site substitution
- size effect enhancement of the linear ME effect

Materials with ME effect

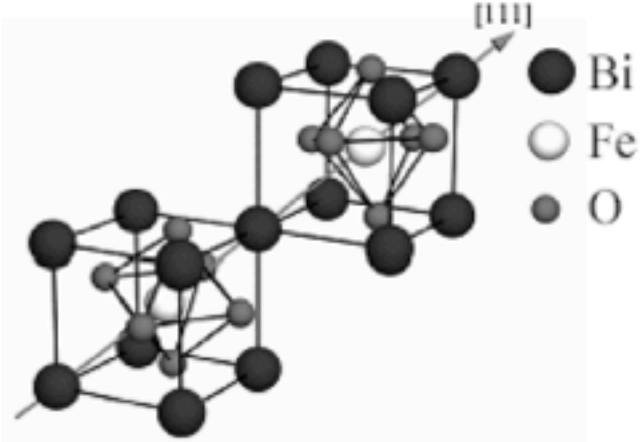
- $BiFeO_3$
- $Bi_{1-x}La_xFe_{1-y}Mn_yO_3$
- $BiMnO_3$
- La-doped $BiMnO_3$
- Rare-earth manganites: $TbMnO_3$, $DyMnO_3$, $(Eu,Y)MnO_3$)

BiFeO_3

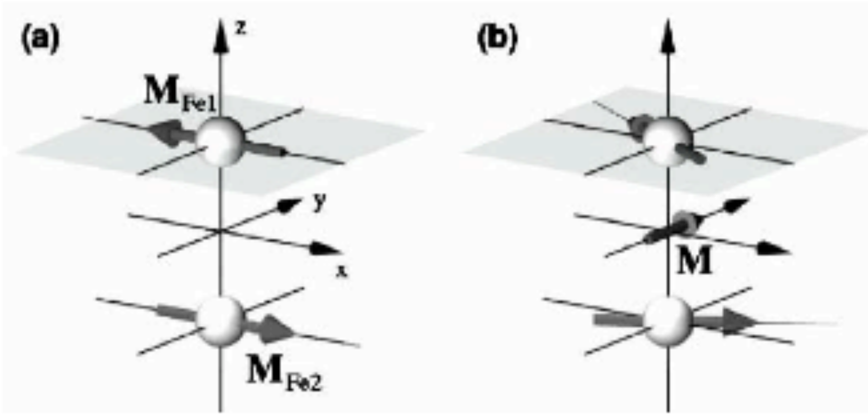
A room-temperature antiferromagnetic ferroelectric

Magnetoelectric materials for interfaces

Rhombohedral Perovskite (R3c)
a=3.96Å, α=89.4°



Neaton et al. Phys. Rev. B, 71, 014113 (2005)



Ederer et Spaldin, Phys. Rev. B, 71, 060401 (R) (2005)

Ferroelectric

T_C=1100K

P_S=6μC/cm² (1970 paper, bad crystal)

J. R. Teague et al., Solid State Commun., 8, 1073 (1970)

P_S=60μC/cm² (2007 paper, good crystal)

D. Lebeugle, M. Viret et al, PRB in press
Condmat/0706.0404

G-type Antiferromagnetic

T_N=640K

Canted spins → weak FM

M_S=0.01μ_B/f.u.

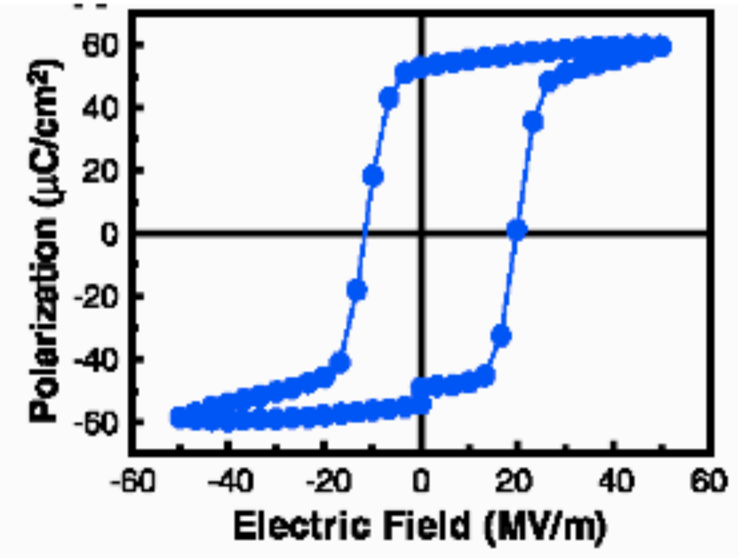
Incommensurate cycloidal modulation

P. Fisher et al., J. Phys. C,13, 1931 (1980)
Popov et al. in Magnetoelectric Interaction Phenomena in Crystals (NATO Science Series, 2004) p. 277

Magnetoelectric materials for interfaces

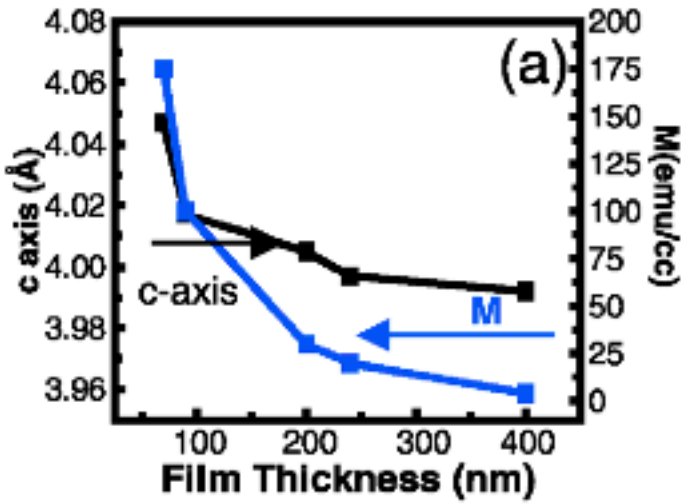
Wang et al., Science, 299, 1719 (2003) : BFO//STO (001)

t_{BFO}=200nm : P_S=55μC/cm²



t_{BFO}=70nm : M_S=150emu/cm³ (~1μ_B/fu)

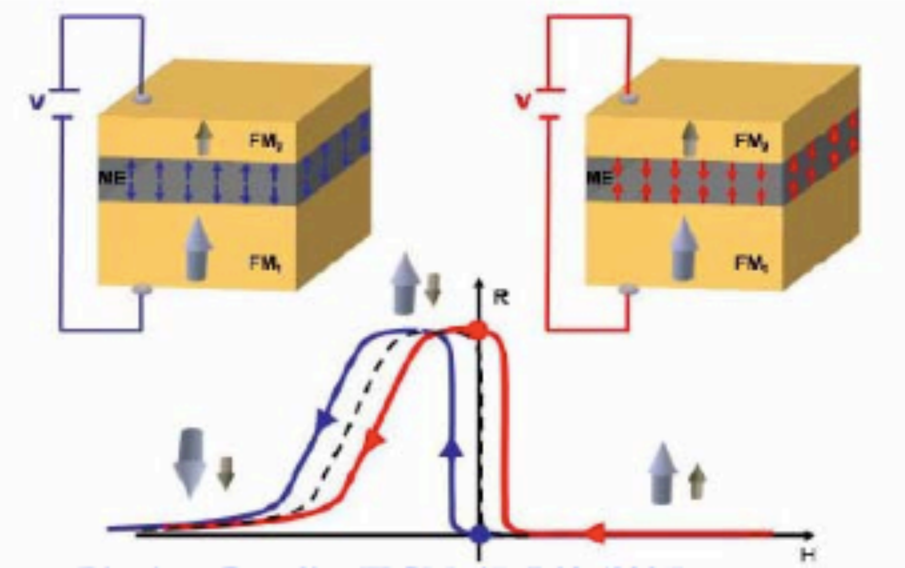
t_{BFO}=400nm : M_s=5emu/cm³ (0.03μ_B/f.u.)



Claim of enhanced polarization and magnetization compared to bulk

Magnetoelectric materials for interfaces

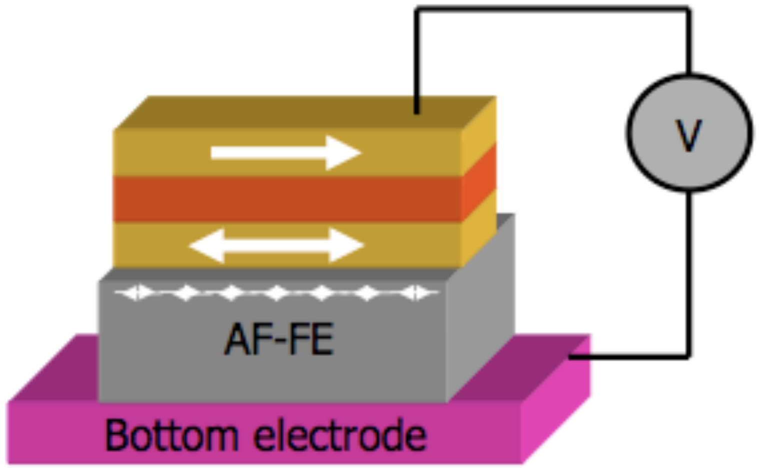
Principle : voltage-controlled exchange bias



Binek et Doudin, JPCM, 17, L39 (2005)

Magnetic tunnel junction with ***multiferroic barrier*** (FE and AFM)

Electric field control of the junction resistance state



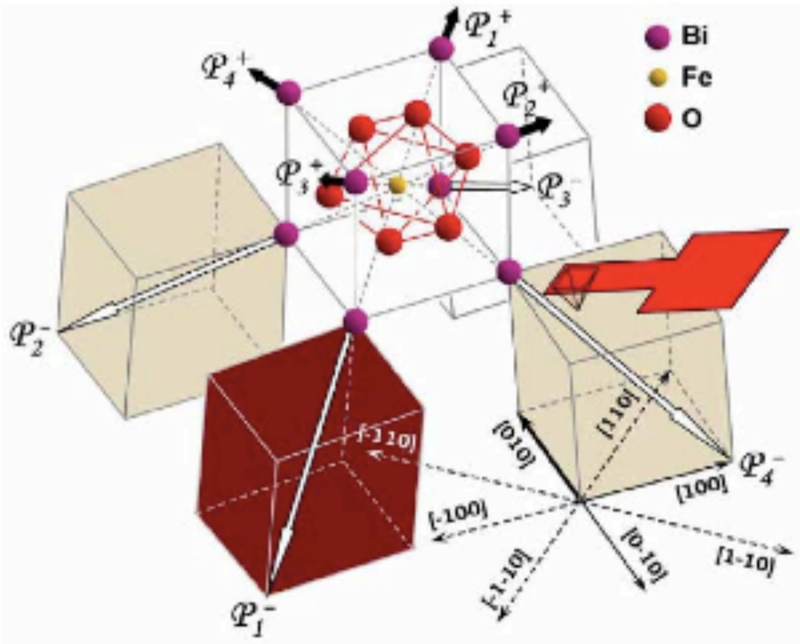
Spin-valve on top of a ***multiferroic film*** (FE and AFM)

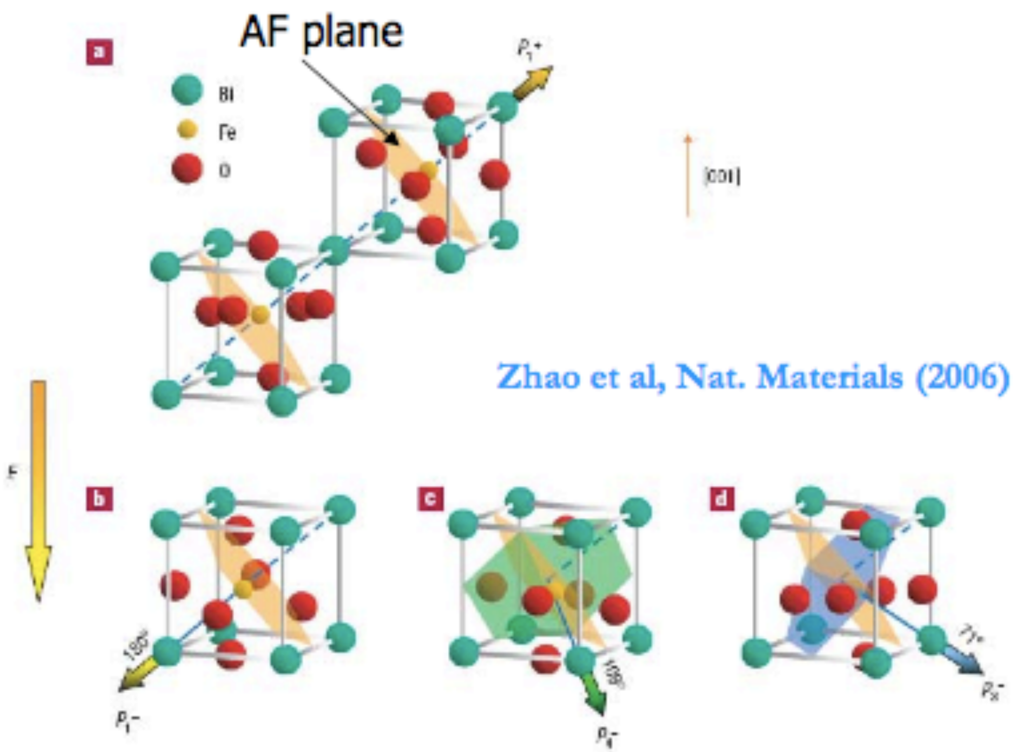
Prerequisites :

1. observe robust exchange bias at room-temperature
2. spin-dependent tunneling through multiferroic barrier
3. switch exchange bias direction by E-field (magnetoelectric coupling)

Magnetoelectric materials for interfaces

Domain structure and magnetoelectric switching





Zhao et al, Nat. Materials (2006)

P along <111> directions :
8 possible variants

When an electric field is applied, P can be switched to different directions
Only some of them yield a rotation of the AF plane

Important to know and control the ferroelectric domain structure

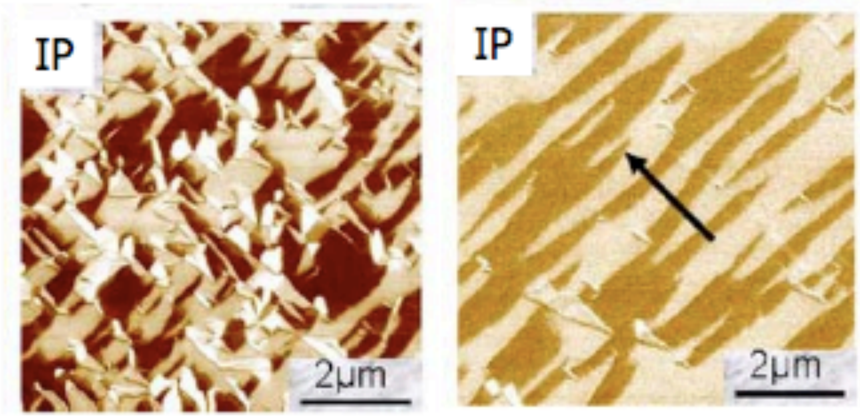
Magnetoelectric materials for interfaces

Domain structure

Piezoresponse force microscopy (PFM)

(001) film
0.8° miscut

(001) film
4° miscut



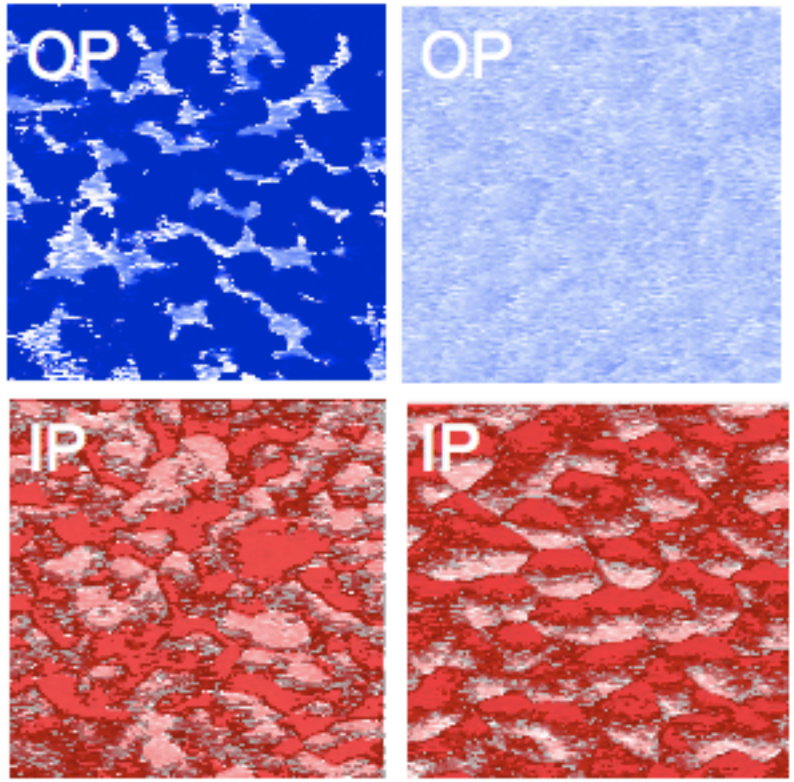
8 variants are present

only 4 variants are present

Das et al., APL, 88, 242904 (2006)

Domain structure can be controlled by playing with the substrate miscut angle and/or orientation.

(001) films (111) films



8 variants are present

only 4 variants are present

Ideally, one type of domain orientation would be required, with the appropriate polarization switching mechanism (109° ?)

SUMMARY

- Magnetoelectrics: candidates for spintronics

Materials:

- $BiFeO_3$
- $Bi_{1-x}La_xFe_{1-y}Mn_yO_3$
- $BiMnO_3$
- La-doped $BiMnO_3$
- Rare-earth manganites, $TbMnO_3$, $DyMnO_3$, $(Eu,Y)MnO_3$

- Main advantage: electric control of magnetization