Multiferroics and magnetoelectrics

Neil Mathur

Device Materials Group

Department of Materials Science

University of Cambridge

J. Scott, M. Bibes, A. Barthélémy

**S. Kar-Narayan, V. Garcia, C. Israel, W. Eerenstein, M. Wiora,
J. Prieto, S. Fusil, K. Bouzehouane, S. Enouz-Vedrenne**

Multiferroics and magnetoelectrics

Basics
- Ferromagnetism and ferroelectricity
- Multiferroic materials
- Magnetoelectric materials

Renaissance

$BiFeO_3$ – a room-temperature multiferroic
- Bad start
- Happy end

Control of adjacent FM layer (exchange bias/strain)

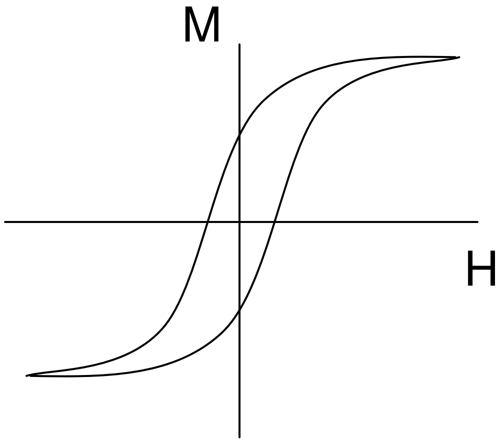
Cheap magnetoelectric elements

$BaTiO_3$ tunnel barriers

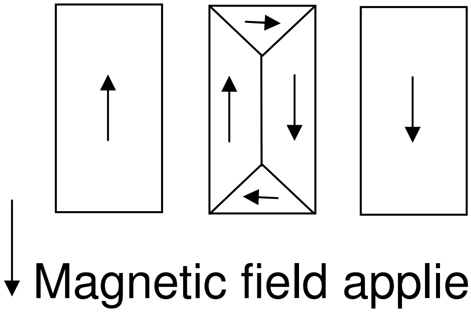
Future goals

Ferromagnetism and ferroelectricity

Ferromagnetic hysteresis

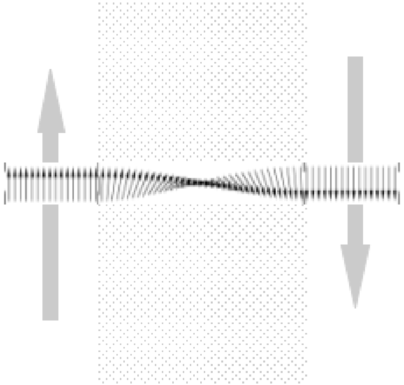


Domains form within sample

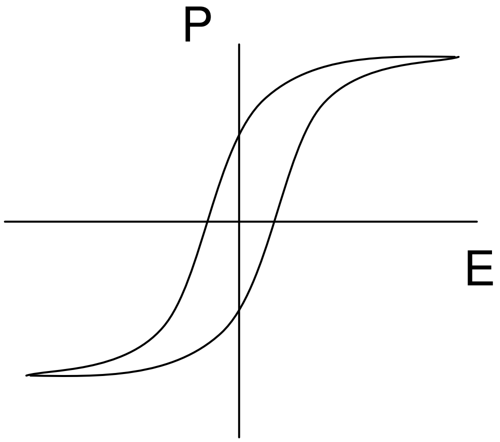


Magnetic field applied

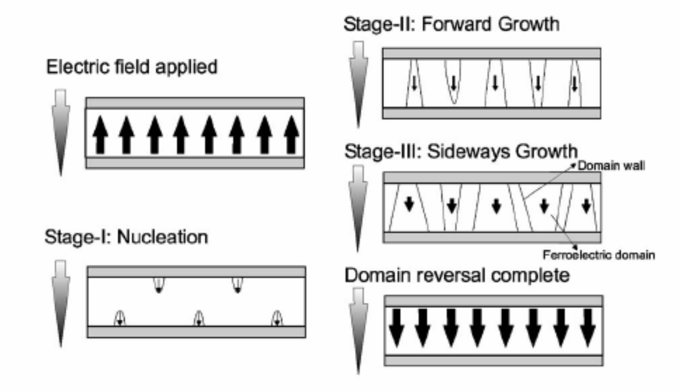
Domain walls can be wide



Ferroelectric hysteresis

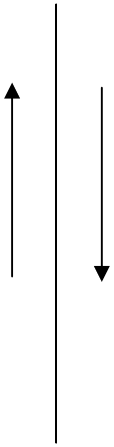


Domains form at electrodes



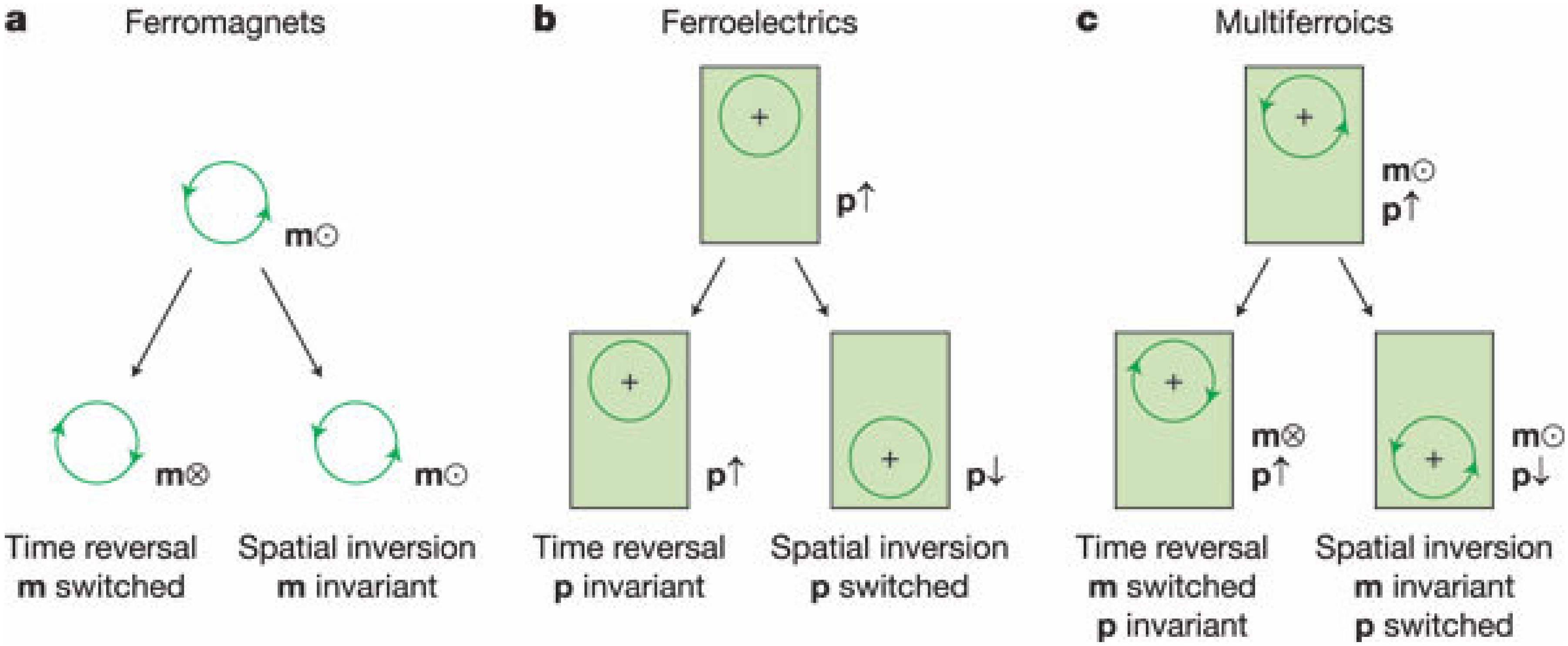
Dawber, Rabe & Scott
Rev Mod Phys **77** (2005) 1083

Domain walls are narrow



Multiferroic materials

More than one ferroic order



Nature **442** (2006) 759

Magnetoelectric materials

For a single material without stress or ferroic order:

$$-F(E,H) = \frac{1}{2}\varepsilon_0\varepsilon_{ij}E_iE_j + \frac{1}{2}\mu_0\mu_{ij}H_iH_j + \alpha_{ij}E_iH_j + \frac{\beta_{ijk}}{2}E_iH_jH_k + \frac{\gamma_{ijk}}{2}H_iE_jE_k + \cdots$$

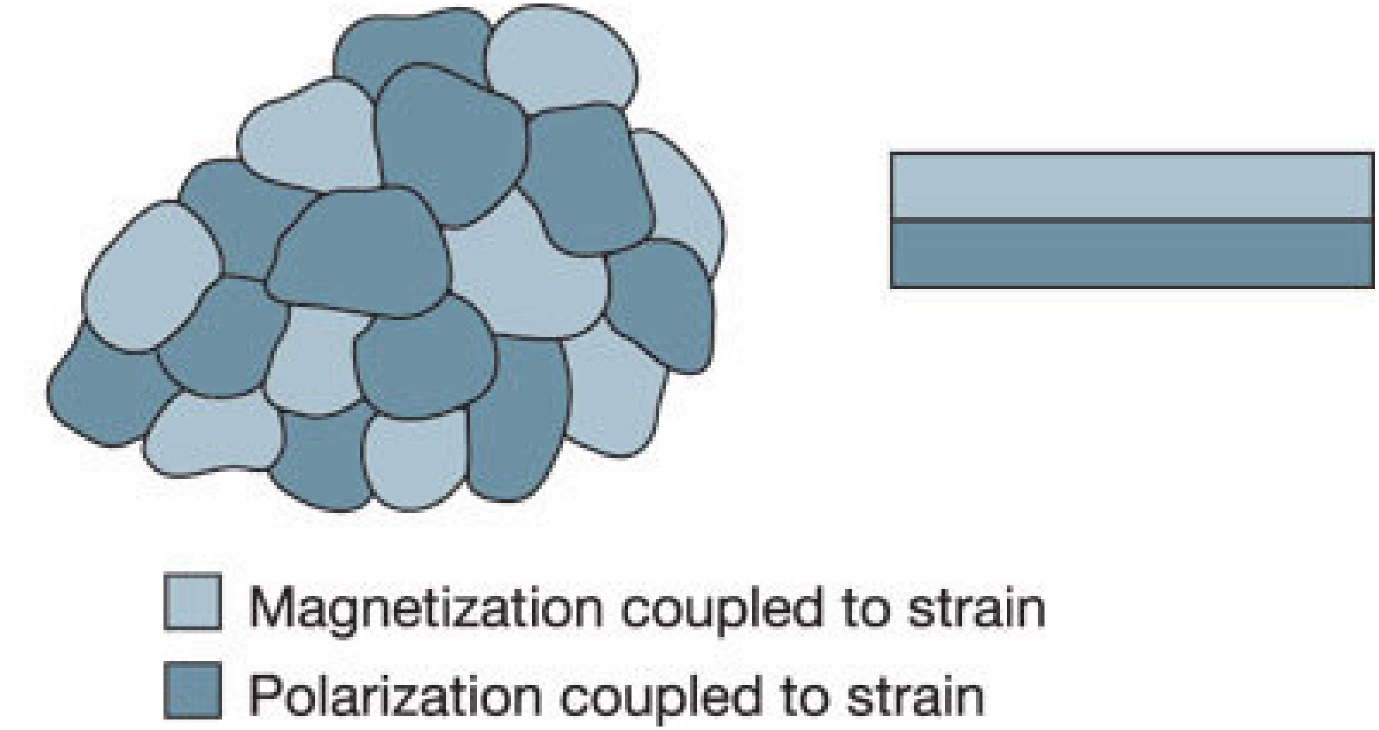
$$\boxed{\begin{aligned} P_i &= \alpha_{ij}H_j + \frac{\beta_{ijk}}{2}H_jH_k + \cdots \\ \mu_0 M_i &= \alpha_{ji}E_j + \frac{\gamma_{ijk}}{2}E_jE_k + \cdots \end{aligned}}$$

$$\alpha = \underset{\substack{\uparrow \\ \text{direct}}}{\frac{dP}{dH}} = \mu_0 \underset{\substack{\uparrow \\ \text{converse}}}{\frac{dM}{dE}}$$

$$\alpha_{ij}^2 \le \varepsilon_0\mu_0\varepsilon_{ii}\mu_{jj}$$

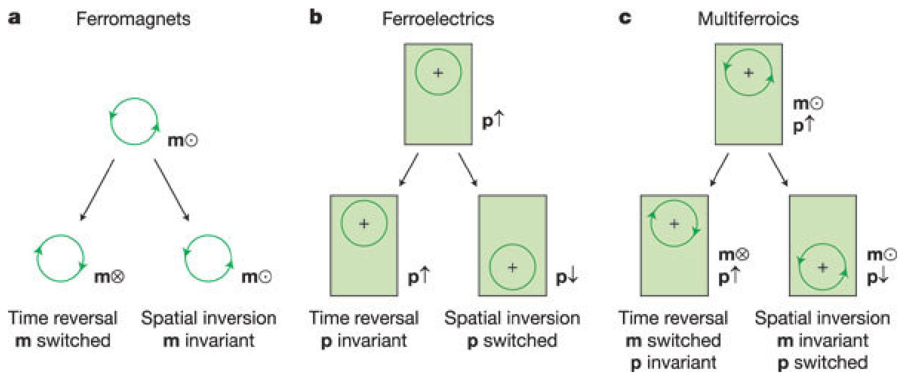
Nature **442** (2006) 759

Magnetoelectric two-phase systems



Nature **442** (2006) 759

Multiferroic systems



Nature **442** (2006) 759

Magnetoelectric systems

$$-F(E,H)=\frac{1}{2}\varepsilon_0\varepsilon_{ij}E_iE_j+\frac{1}{2}\mu_0\mu_{ij}H_iH_j+\alpha_{ij}E_iH_j+\frac{\beta_{ijk}}{2}E_iH_jH_k+\frac{\gamma_{ijk}}{2}H_iE_jE_k+\cdots$$

$$\boxed{\begin{aligned}P_i&=\alpha_{ij}H_j+\frac{\beta_{ijk}}{2}H_jH_k+\cdots\\ \mu_0M_i&=\alpha_{ji}E_j+\frac{\gamma_{ijk}}{2}E_jE_k+\cdots\end{aligned}}$$

$$\alpha=\underset{\substack{\uparrow\\ \text{direct}}}{\frac{dP}{dH}}=\mu_0\underset{\substack{\uparrow\\ \text{converse}}}{\frac{dM}{dE}}$$

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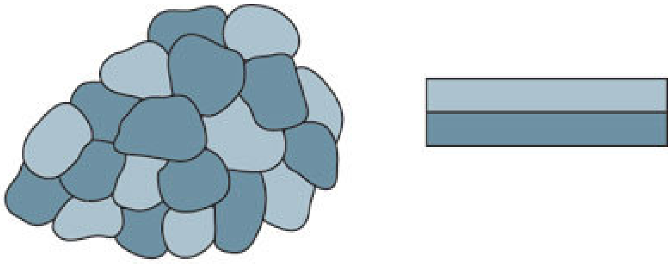
Nature **442** (2006) 759

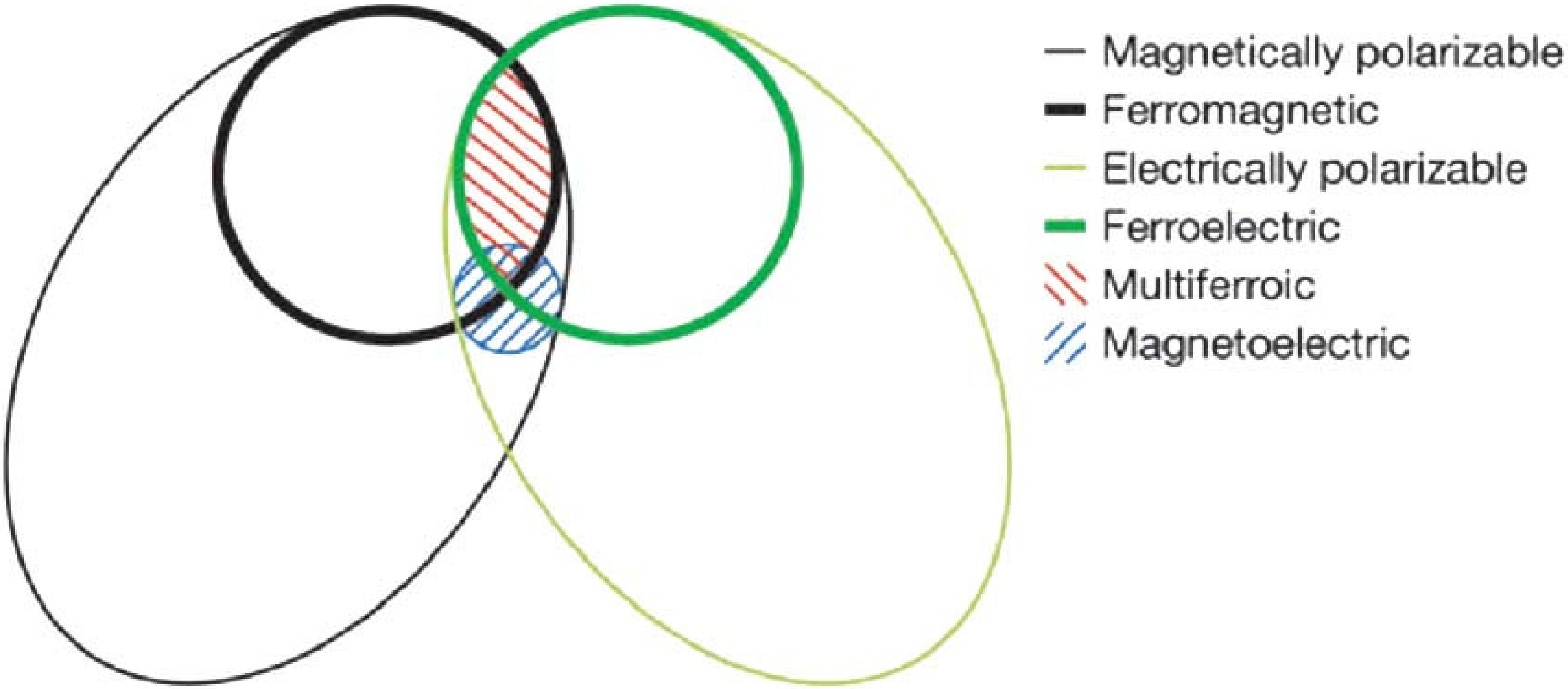


▢ Magnetization coupled to strain

▨ Polarization coupled to strain

Nature **442** (2006) 759

Multiferroic v magnetoelectric



Nature **442** (2006) 759

Renaissance

Why are there so few magnetic ferroelectrics?
[N. A. Hill, J. Phys. Chem. B **104** (2000) 6694]

Experimental machinery

- Thin-film growth
- Imaging

Possible applications

- Sensors – continuous P(H)
- Data storage – discontinuous M(E) for electric-write magnetic-read

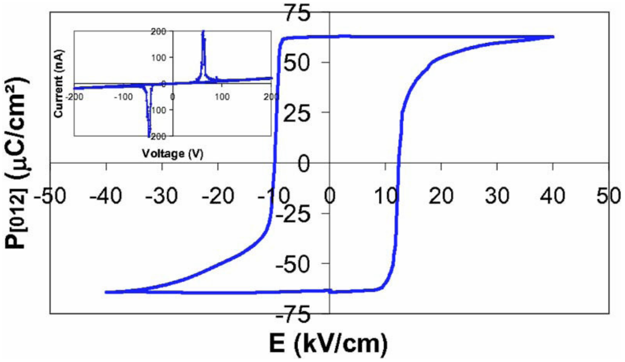
BiFeO$_3$ – bad start

Epitaxial BiFeO$_3$ multiferroic thin film heterostructures [*Science* **299** 1719 (2003)]

$\left.\begin{array}{l} P \text{ from 6 to 60 } \mu\text{C cm}^{-2} \\ M \text{ from 0 to 1 } \mu_B\text{/f.u.} \end{array}\right\}$ due to epitaxial strain

However:

Large *P* was previously expected [*Solid State Comm.* **8** 1073 (1970)]
… and subsequently observed [*Appl. Phys. Lett.* **91** 022907 (2007)]

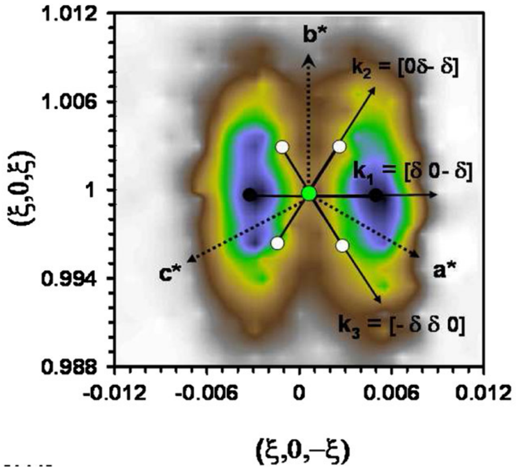


The magnetism could not be reproduced [*Science* **307** (2005) 1203a]

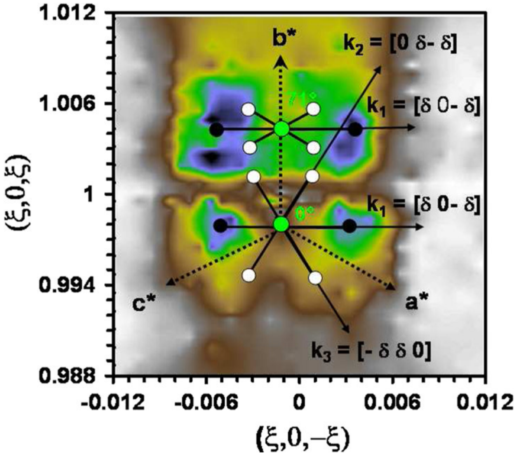
$BiFeO_3$ – happy end

Platelet prepared as single FE domain, single AFM domain:

Before E



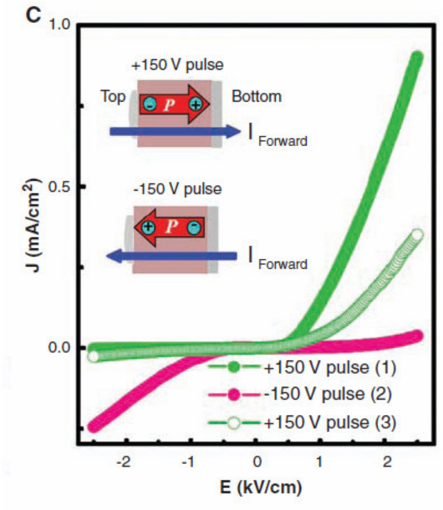
After E

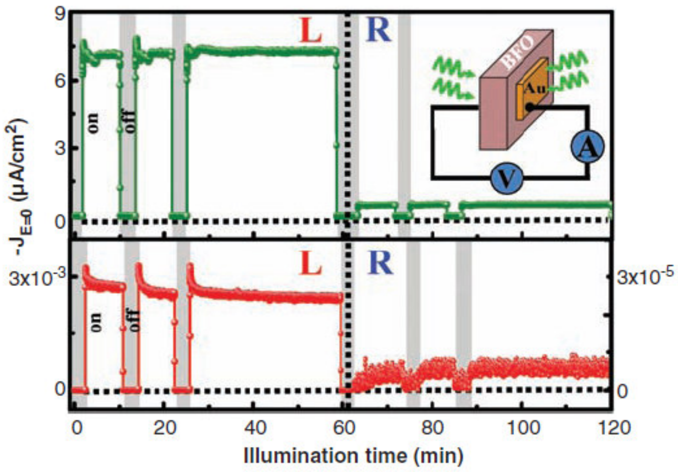


PRL **100** (2008) 227602

See also:
APL **92** (2008) 192906

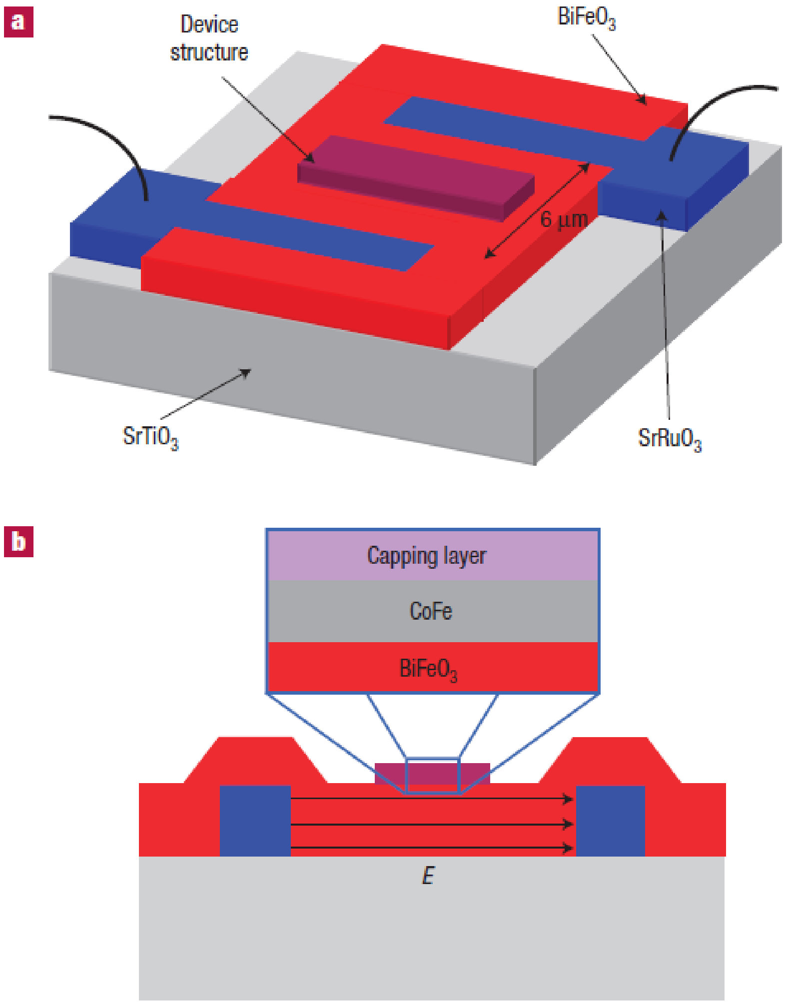
Electrically reversible rectification and photovoltaic effect:



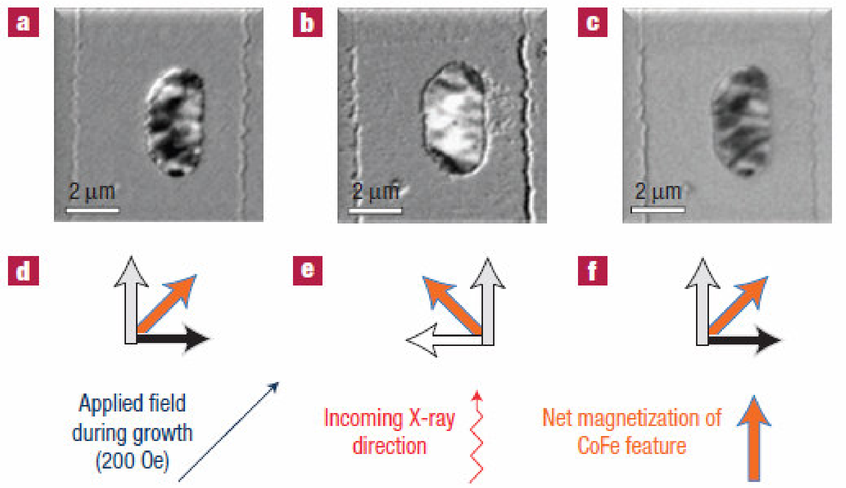


Science **324** (2009) 63

$BiFeO_3$ – control of adjacent FM layer



XMCD PEEM



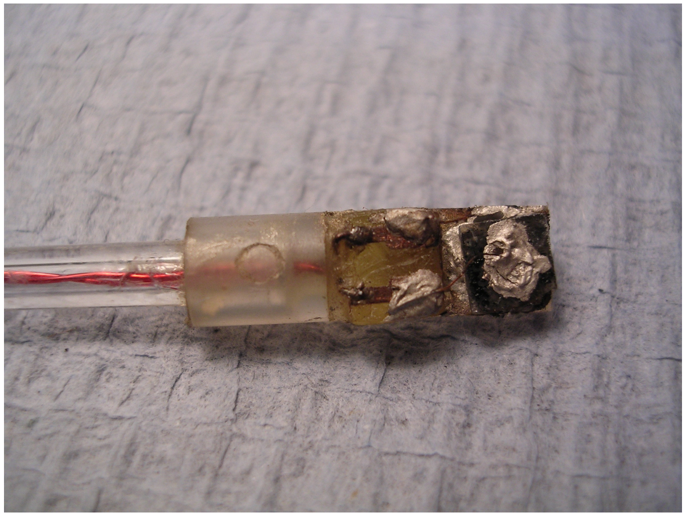
Nature Materials **7** (2008) 478

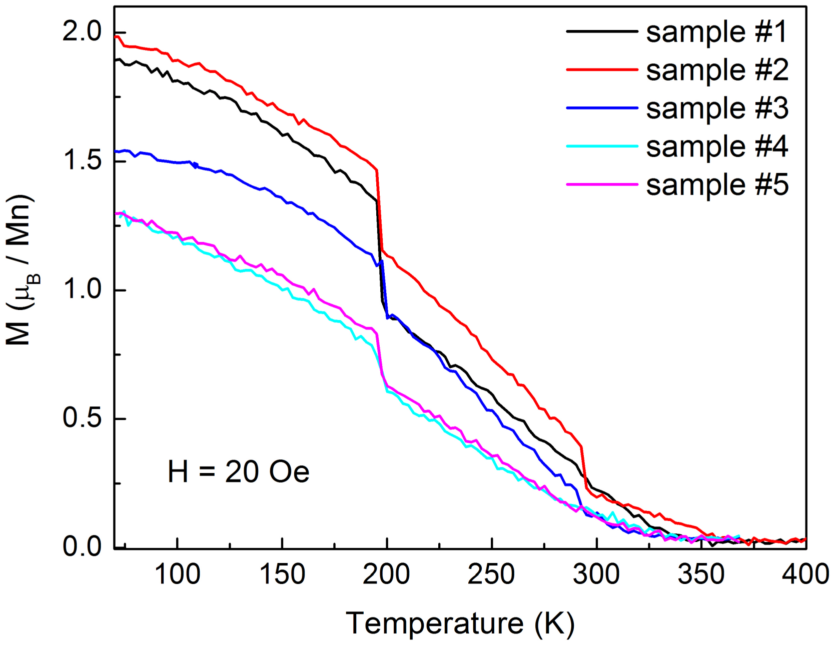
Exchange bias or strain? [*Nature* **454** (2008) 591]

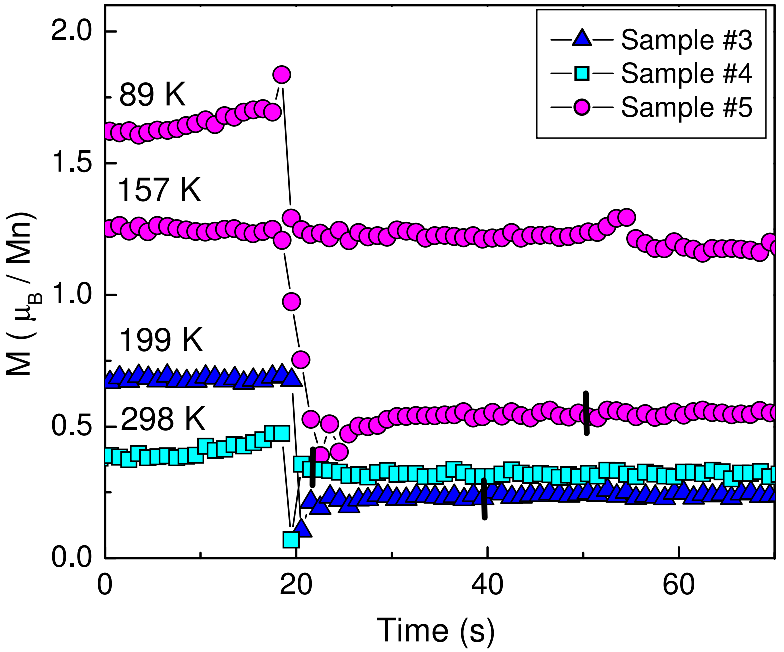
Strain control of adjacent FM layer

$La_{0.67}Sr_{0.33}MnO_3$ film
$BaTiO_3$ substrate

Nature Materials **6** (2007) 348

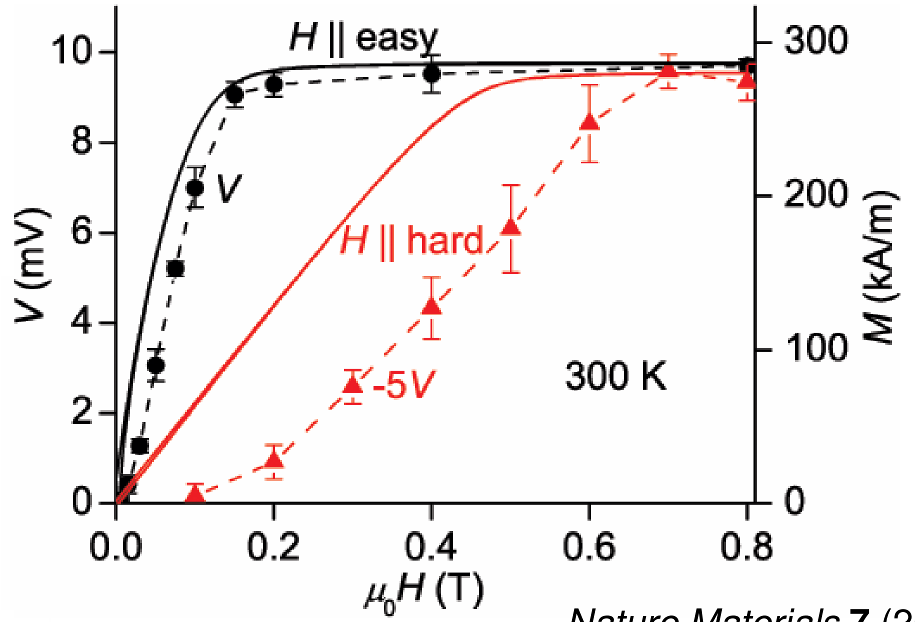






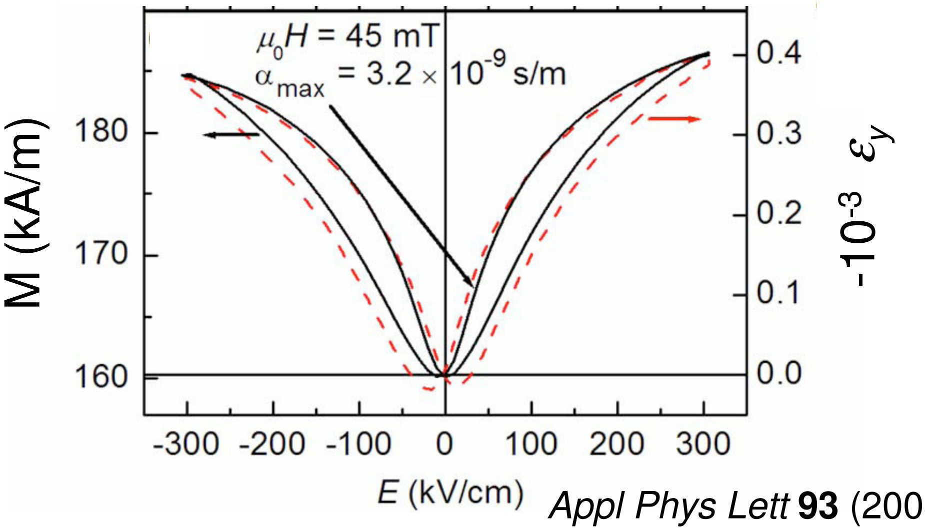
One-cent magnetoelectric elements

AVX MLC



Nature Materials **7** (2008) 93

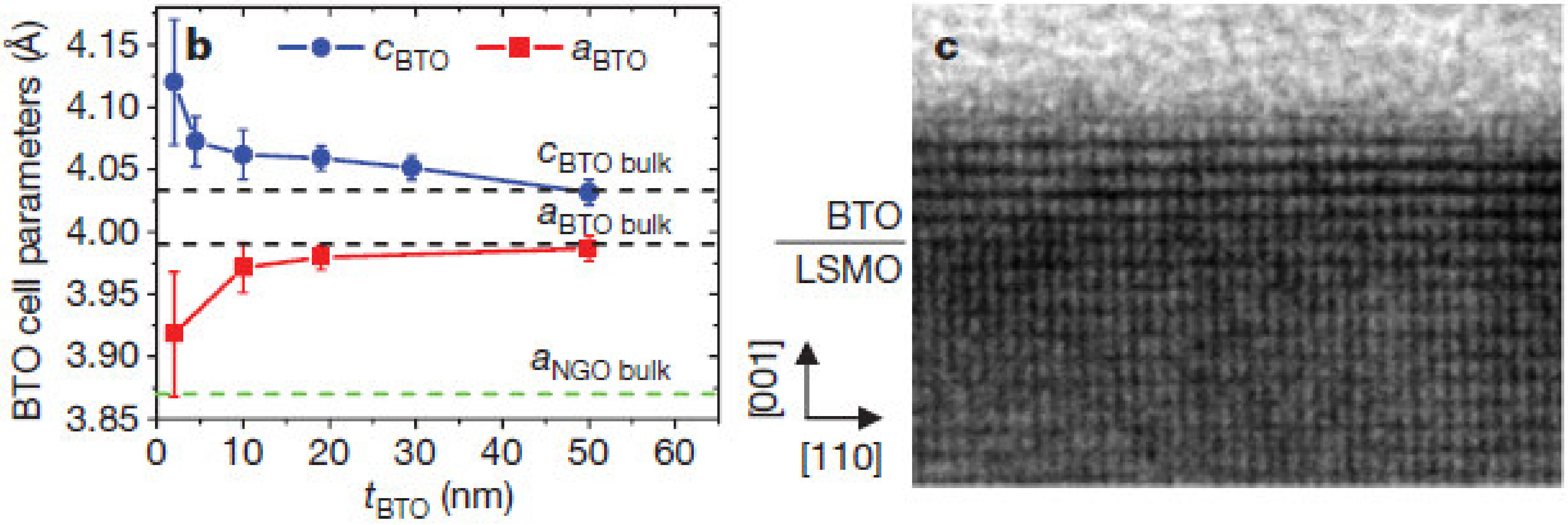
- Cheap
- No electrical power
- Only a few mV



Appl Phys Lett **93** (2008) 173501

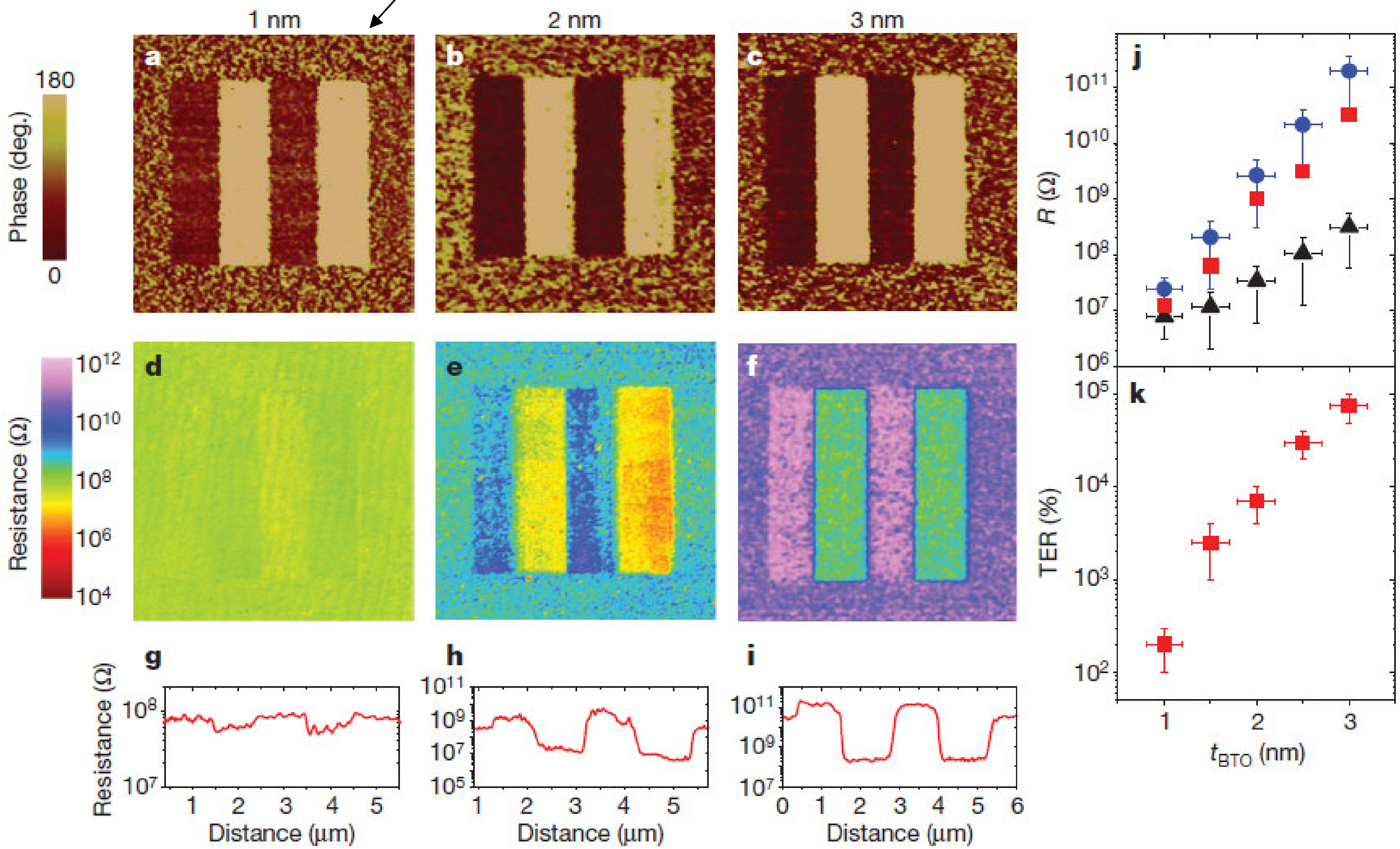
$BaTiO_3$ tunnel barriers

Large tetragonality $c/a = 1.051$



Nature **460** (2009) 81

BaTiO$_3$ tunnel barriers



Robust FE at 1 nm

TER = 75000% for 3 nm barriers
Non-destructive FE read

Nature **460** (2009) 81

Future goals

Room-temperature FE-FM

Robust FE and FM at any temperature

Reversal of M with E

Applications: sensors, data storage…