How to manipulate magnetic states of antiferromagnets

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1/18/2019

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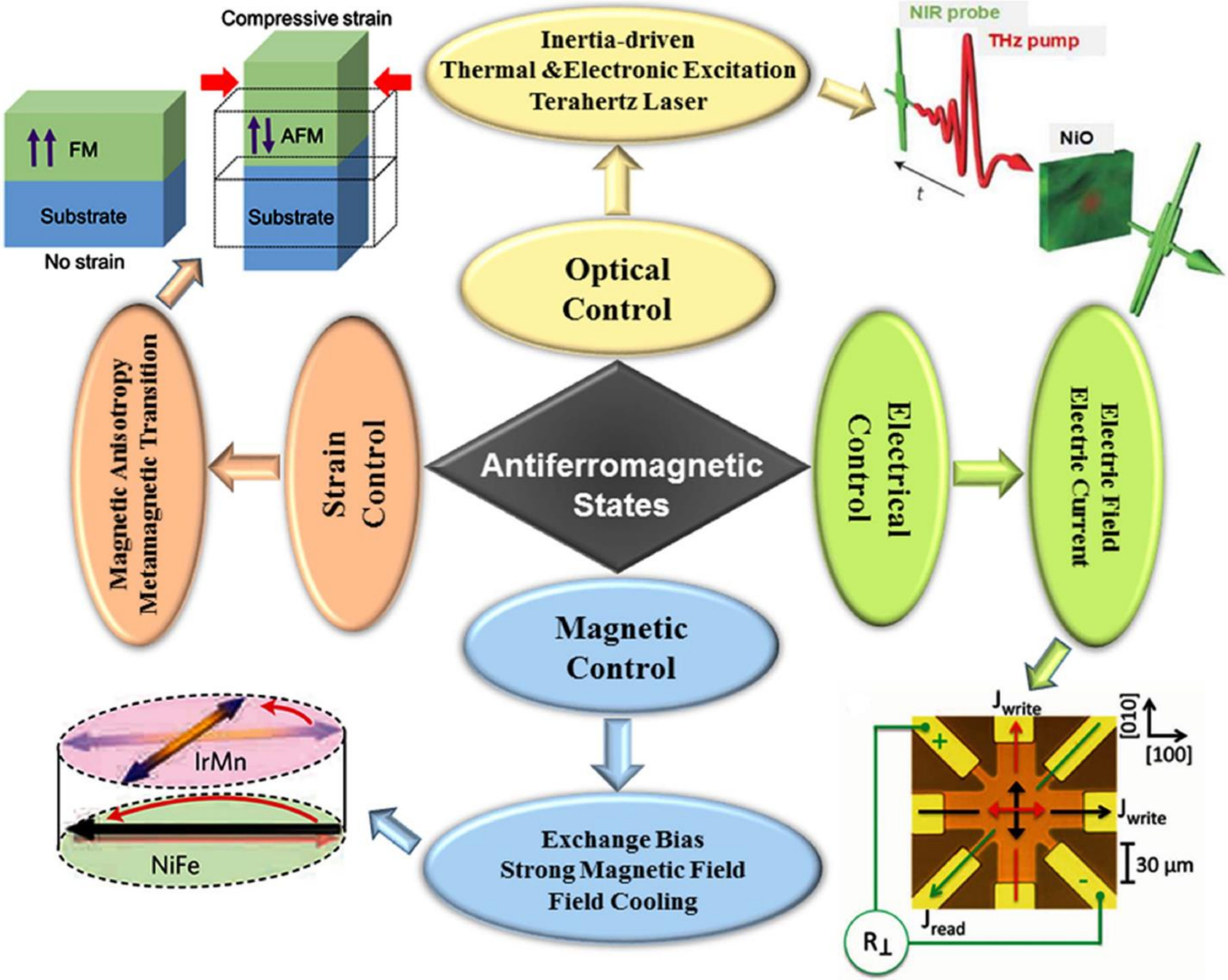
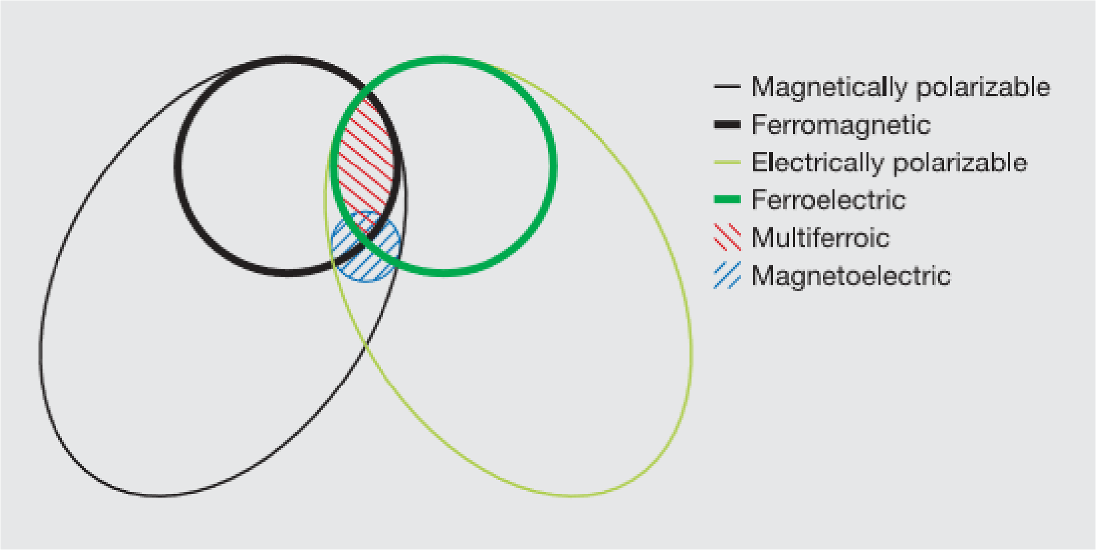
Four main methods to control magnetic states



Nanotechnology 29,112001 (2018)

Motivation

- Relying on the combination of **field cooling** and **large magnetic fields** or subsidiary ferromagnets to alter the magnetic configuration is not so convenient.
- Coupling between magnetization and the electric field by multiferroic, magnetoelectric materials or exchange bias helps to realize the manipulation of antiferromagnets and the design of **low power** spintronics architectures such as information storage devices.
- In recent years, manipulation by electric current has become more popular as an innovative and effective method.



Nature, vol 442,17 August 2006

Electrical field-multiferroic materials

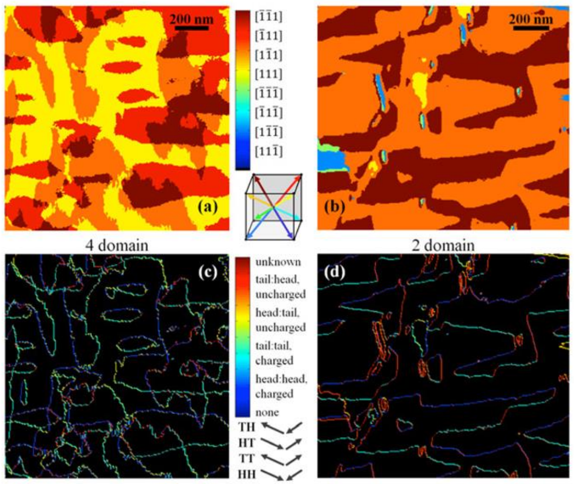
$BiFeO_3$
- A room-temperature single-phase magnetoelectric multiferroics with a ferroelectric Curie temperature (T_C) of ~1,100 K and an antiferromagnetic Neel temperature (T_N) of ~640 K.

✓ A single-phase multiferroic material is one that possesses two—or all three—of the so-called ‘ferroic’ properties: ferroelectricity, ferromagnetism and ferroelasticity.

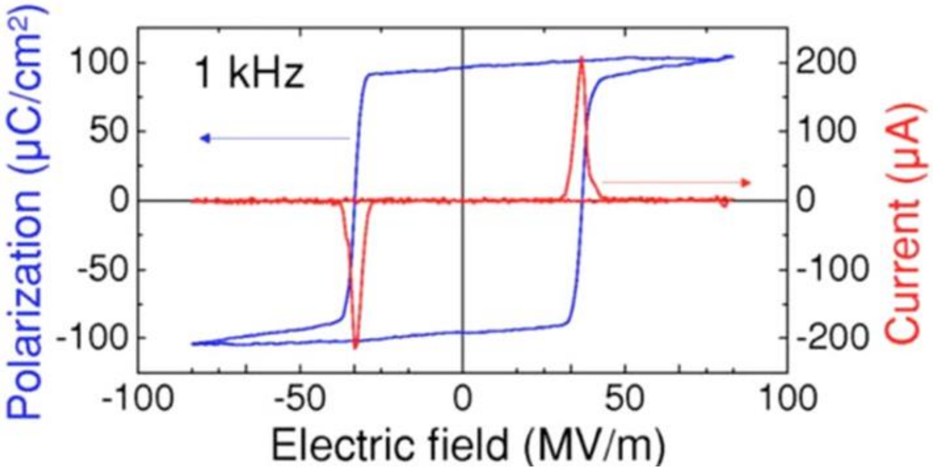
✓ Moreover, the classification of a multiferroic has been broadened to include antiferroic order.

A large ferroelectric polarization and a small magnetization are observed in $BiFeO_3$ thin films with a large magnetoelectric coupling.

PFM



Capacitor geometry



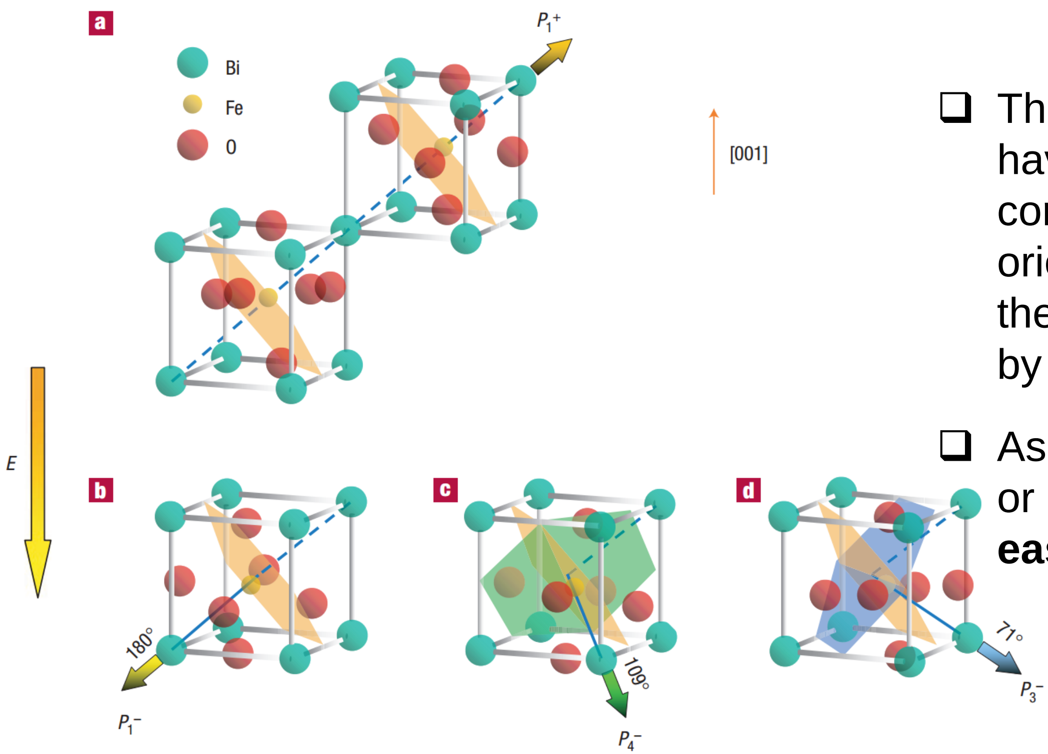
Recent small angle neutron scattering (SANS) experiments showed that the spins actually also **cant** away from the rotation plane by up to about **one degree**.

J. Phys.: Condens. Matter 26 (2014) 473201 (23pp)

Electrical field-multiferroic materials

$BiFeO_3$

- The orientation of the antiferromagnetic sublattice magnetization therefore seems to be coupled to the ferroelastic strain state of the system and should always be **perpendicular** to the ferroelectric polarization.



- The ferroelectric polarization in $BiFeO_3$ can have **eight possible orientations**, corresponding to positive and negative orientation along the four cube diagonals, and the direction of the polarization can be switched by 180◦, 109◦ and 71◦
- As a result, polarization switching by either 71◦ or 109◦ should **change the orientation of the easy magnetization plane**.

Nat. Mater. 5 823–9(2006)

Electrical field-multiferroic materials

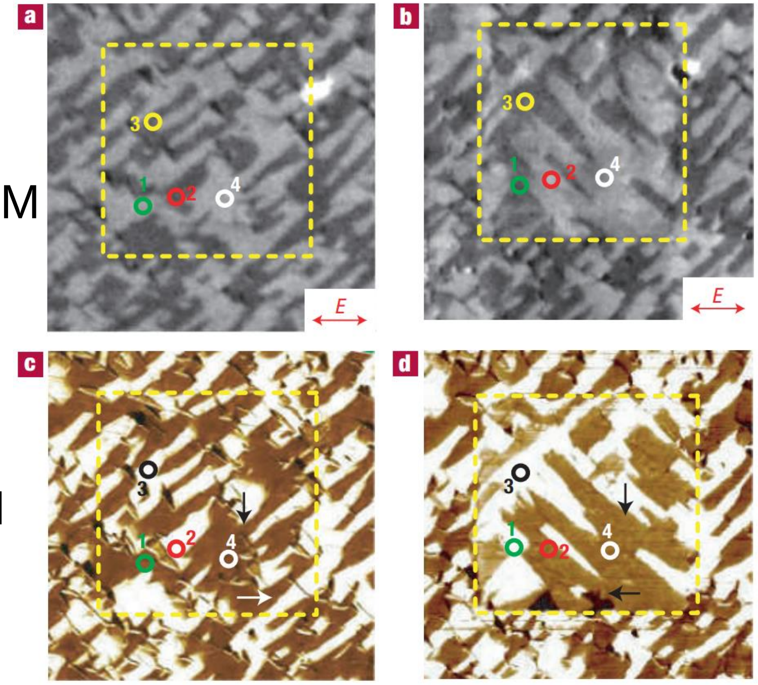
$BiFeO_3$

- The key to electrical control of antiferromagnetic domains in multiferroic $BiFeO_3$ films at room temperature lies in the coupling between ferroelectricity and antiferromagnetism in $BiFeO_3$ thin films.

Before poling　After poling

PEEM

PFM



Regions 1 and 2 correspond to 109◦ ferroelectric switching,
3 and 4 correspond to 71◦ and 180◦ switching

- The switching, originating from the coupling of antiferromagnetic and ferroelectric domains to the underlying **ferroelastic domain structure**, has been demonstrated experimentally by piezoelectric force microscopy (PFM), photoemission electron microscopy (PEEM) and theoretically by first-principles calculation.

Nat. Mater. 5 823–9(2006)

Electrical field-multiferroic materials

$BiFeO_3$

- Recently, the **magneto transport** and **electronic transport** in $BiFeO_3$ were found to occur across **domain walls** by external fields, clarifying the manipulation mechanism of $BiFeO_3$ antiferromagnetic moments and promoting the development of multiferroic materials in spintronics.

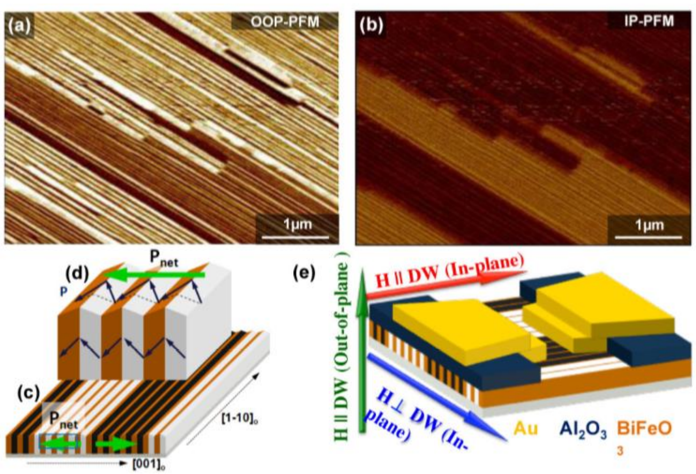
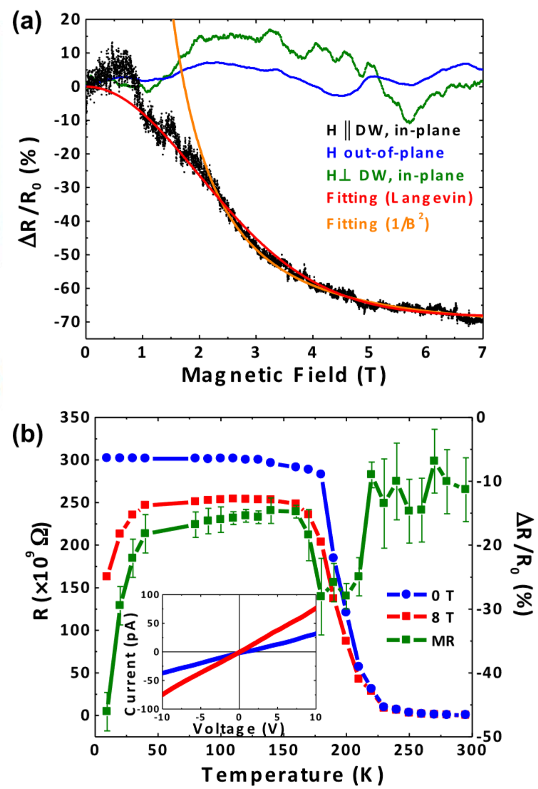
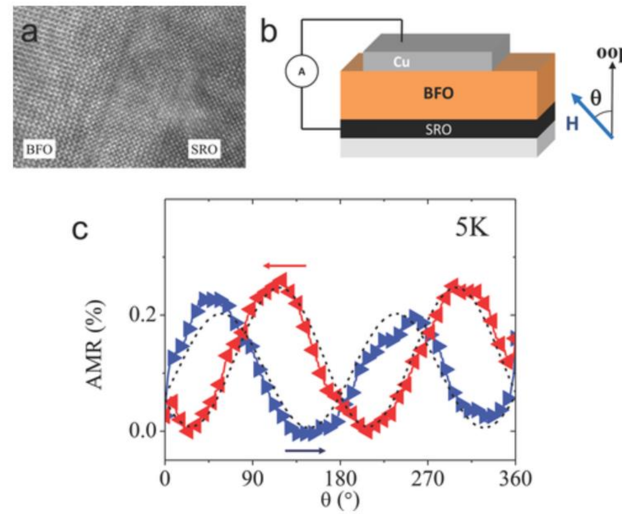


FIG. 1 (color online). Domain structures in $BiFeO_3$ on 109° domain wall samples. (a),(b) OOP- and IP-PFM images of 109° domain pattern. (c) Schematic of 109° domain pattern with different domain clusters. Domain colors follow the contrast of the IP-PFM image as shown in (b). The green arrow shows the net ferroelectric polarization within each domain cluster. (d) Schematic of detailed 109° domain structure within one domain cluster. Blue (or dark gray) arrows show the ferroelectric polarization components in $[001]_{pc}$ and $[010]_{pc}$ planes. (e) Schematic of the device structure, an example of current path parallel to the domain walls.





- Anisotropic magnetoresistance showing strong hysteresis, which implies a net magnetic moment of the DWs.

PRL 108, 067203 (2012)

Adv. Mater. 2014, 26, 7078–7082

Electrical field-magnetoelectric materials

Cr_2O_3

- Magnetoelectric coupling may exist whatever the nature of magnetic and electrical order parameters, and can for example occur in paramagnetic ferroelectrics.
- Magnetoelectric coupling may arise directly between the two order parameters, or indirectly via strain.
- Magnetoelectric Cr_2O_3 is also used to electrically control antiferromagnetic domains

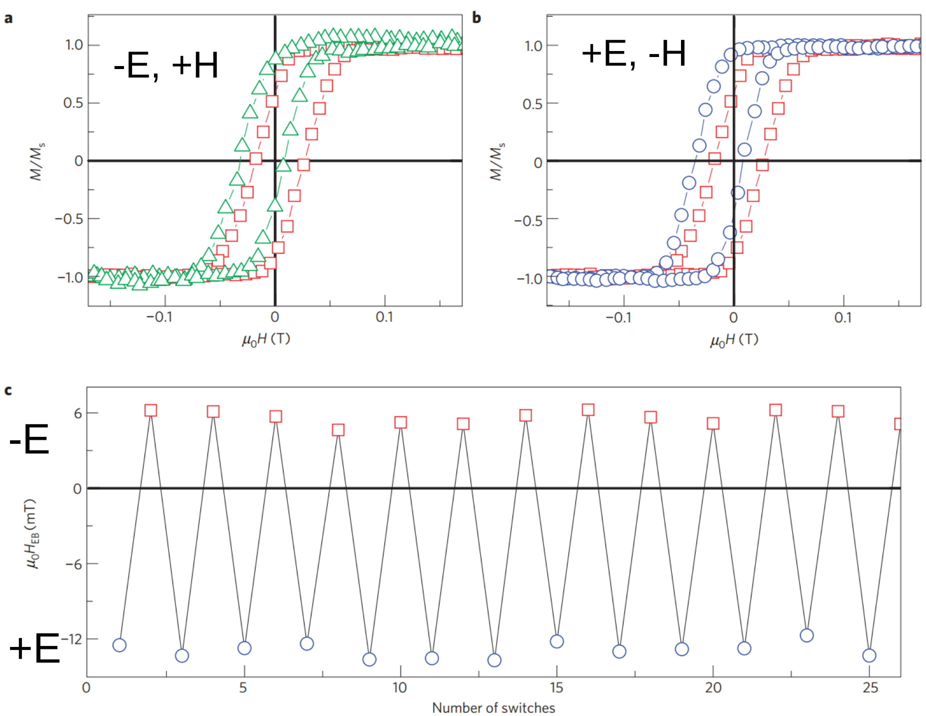


Figure 3 | Isothermal electric switching of the exchange-bias field. a, Exchange-biased hysteresis loops of Cr_2O_3 (0001)/Pd 0.5 nm/ (Co 0.6 nm Pd 1.0 nm)$_3$ at $T = 303$ K after initial magnetoelectric annealing in $E = 0.1$ kV mm^{-1} and $\mu_0H = 77.8$ mT. Hysteresis loops are measured by polar Kerr magnetometry in $E = 0$, respectively. The red squares show the virgin curve with a positive exchange-bias field of $\mu_0H_{EB} = +6$ mT. Isothermal-field exposure in $E = -2.6$ kV mm^{-1} and $\mu_0H = +154$ mT gives rise to a loop with a negative exchange-bias field of $\mu_0H_{EB} \approx -13$ mT (green triangles). **b**, The red squares show the same virgin reference loop. The blue circles show the hysteresis loop after isothermal-field exposure in $E = +2.6$ kV mm^{-1} and $\mu_0H = -154$ mT, giving rise to the same negative exchange bias of $\mu_0H_{EB} = -13$ mT. **c**, μ_0H_{EB} versus number of repeated isothermal switching through exposure to $E = +2.6$ kV mm^{-1} (blue circles) and $E = -2$ kV mm^{-1} (red squares) at constant $\mu_0H = -154$ mT, respectively.

- Sample structure: Cr_2O_3 (0001)/Pd 0.5 nm/ (Co 0.6 nm Pd 1.0 nm)^3

- Global magnetization reversal and reversible isothermal magnetoelectric switching can be realized at room temperature.
- The isothermal switching of the exchange-bias field implies **a field-induced switching of the antiferromagnetic single-domain state of Cr_2O_3 into the opposite antiferromagnetic registration.**

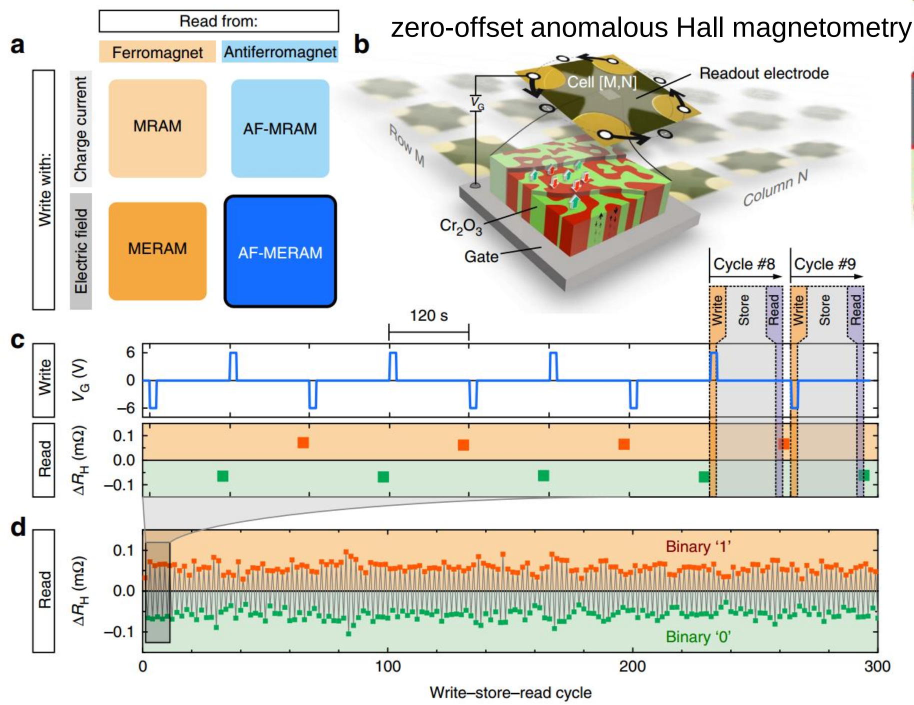
Nat. Mater. 9 579–85, 2010

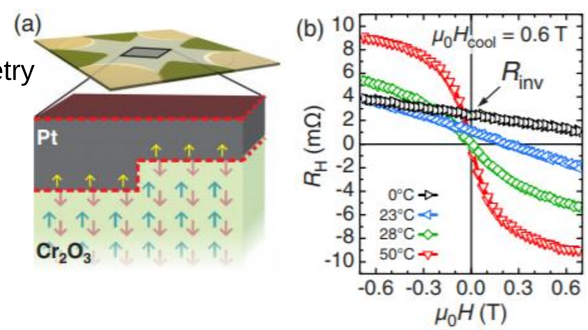
Electrical field-magnetoelectric materials

Cr_2O_3

- Purely antiferromagnetic magnetoelectric random access memory using Cr_2O_3 as the antiferromagnetic element has also been designed, opening an appealing avenue for magnetoelectric antiferromagnet research.

zero-offset anomalous Hall magnetometry





- This invariant signal appears only below the Néel temperature (28 ℃) ,hinting clearly at its origin in the uncompensated magnetic moment at the surface of the Cr_2O_3 film.

- Epitaxial layer stack of Pt(20 nm)(for gate)/ a-Cr_2O_3(200 nm)/Pt(2.5 nm) (for readout by proximity effect) that is prepared on Al_2O_3(0001) substrates.

- An isothermal magnetoelectric switching experiment that was carried out at 19℃ in a permanent magnetic field of H≈ +0.5 MA m^{-1} along the film normal.

PRL 115, 097201 (2015)

Nat. Commun. 8 13985, 2017

Summary

Table 3. Summary of different electrical manipulation methods of antiferromagnets. T_C, T_N, T_T, and T_B represent ferroelectric Curie temperature, Néel temperature, antiferromagnetic–ferromagnetic transition temperature, and blocking temperature, respectively.

System	Mechanism	Target		Temperature	References
$BiFeO_3$ films	Electric field	Antiferromagnetic domains	T_C	~1100 K;	[131]
			T_N	~640 K	
$BiFeO_3$ bulk and films	Electric field	Spin flop	T_C	~820 °C	[133]
			T_N	~370 °C	
Ni/NiO	Electric field	Antiferromagnetic moments		—	[134]
Cr_2O_3 (0001)	Electric field	Antiferromagnetic domains		—	[137]
Cr_2O_3	Electric field	Antiferromagnetic order parameter		—	[141]
[Co/Pt]/IrMn	Electric field	Antiferromagnetic spins		—	[142]
[Co/Pt]/FeMn	Electric field	Antiferromagnetic moments	T_B	>150 K (5 nm);	[147]
				<200 K (6 nm);	
				>200 K (15 nm)	
Mn_2Au	Electric current	Antiferromagnetic moments	T_N	>1500 K	[151, 155, 156]
CuMnAs films	Electric current	Antiferromagnetic domains	T_N	~500 K	[154]

- Electrical control of antiferromagnets is prosperous for application in storage devices because the manipulation process can be conducted at room temperature, with no need for a magnetic field, field cooling, or ferromagnets.

Thanks for your attention