How to manipulate magnetic states of antiferromagnets

Yu Yun

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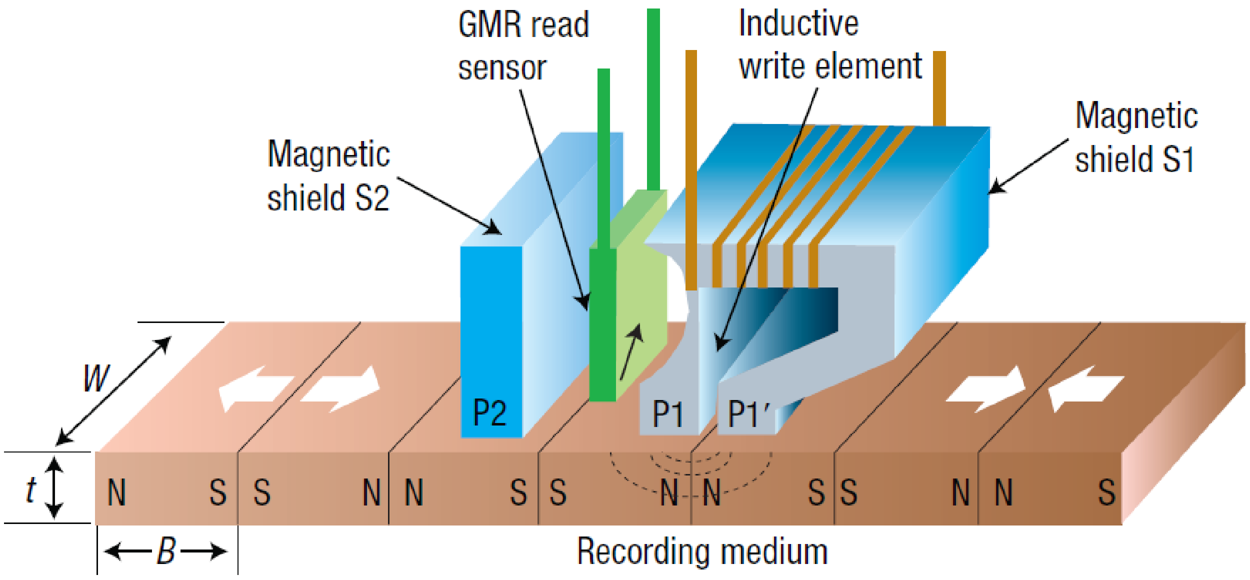
UNIVERSITY OF Nebraska Lincoln

UNIVERSITY OF Nebraska Lincoln

Background

➢ Conventional spintronic devices depend on the manipulation of magnetic moments in ferromagnets



❑ Schematic structure of the magnetoresistive head introduced by IBM for its hard disk drives in 1991.
❑ A magnetic sensor based on anisotropic magnetoresistance.

Nat. Mater. 6 813–23 (2007)

Background

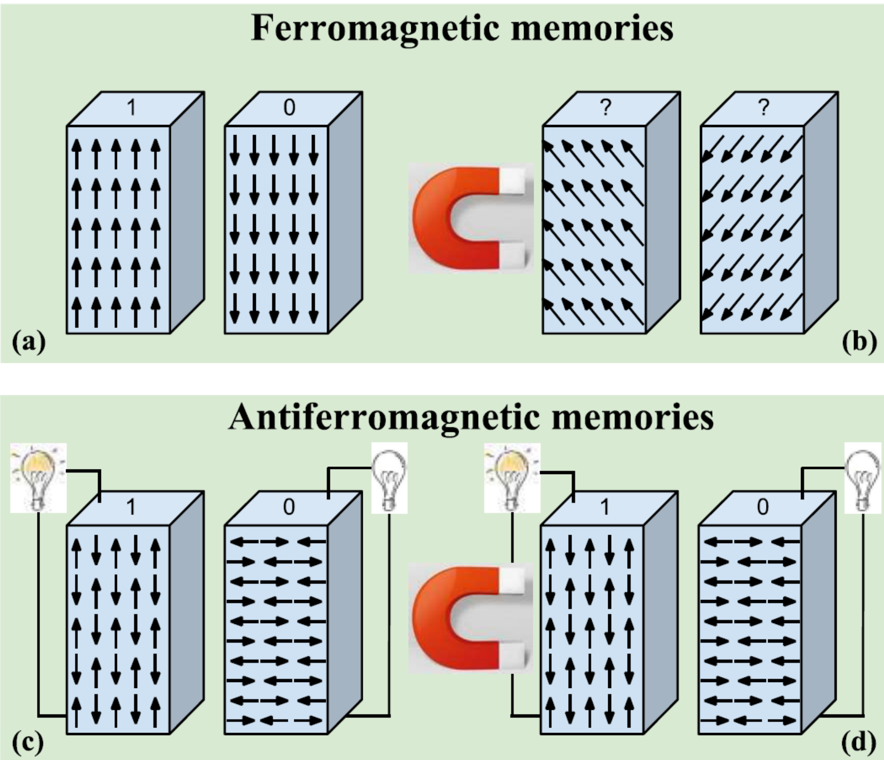


Figure 1. a,b FM memory sensitive to magnetic field perturbations. c,d AFM memory insensitive to magnetic field perturbations.

Ferromagnetic materials:

- ❖ magnetic field perturbations to being a weakness for data retention
- ❖ the ferromagnetic stray fields to an obstacle for high-density memory integration.

Antiferromagnetic materials

- ✓ Resist perturbation well
- ✓ Produce no stray fields,
- ✓ Demonstrate ultrafast dynamics
- ✓ Generate large magneto-transport effects

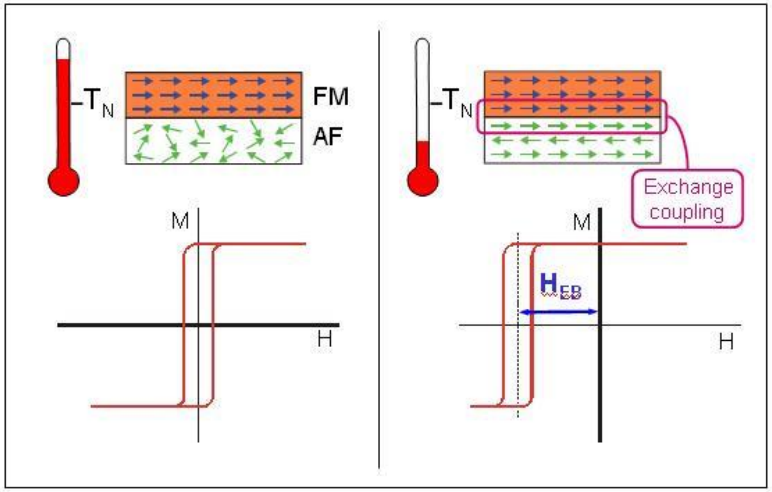
The macroscopic magnetization is zero

IEEE Transactions On Magnetics, Vol. 51, No. 4, April 2015

Backgroud

Earlier research mainly focusing on:

- Exchange bias
- The spin-flop field



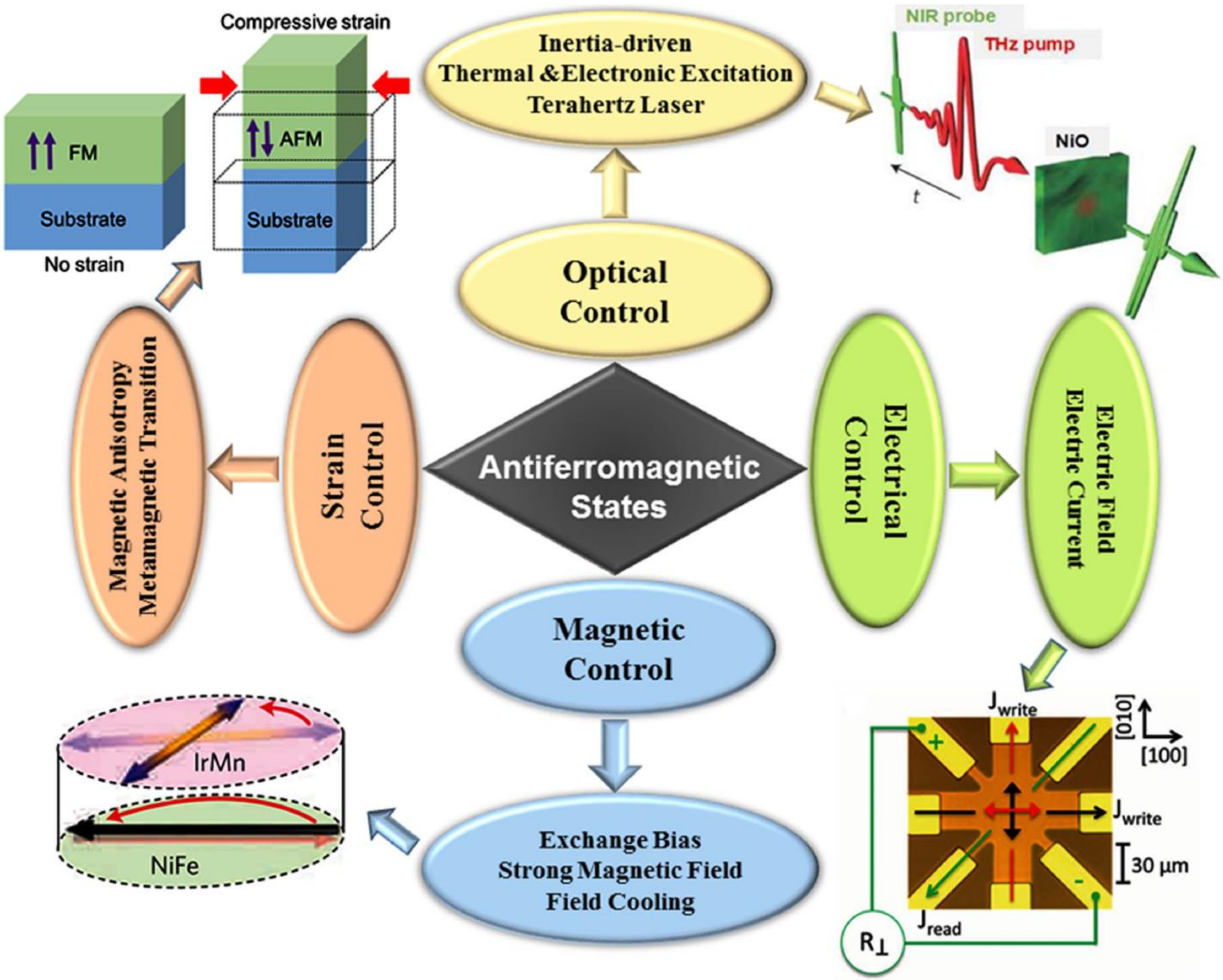
New phenomena in antiferromagnets:

- ✓ Large anomalous Hall effect
- ✓ Spin Hall magnetoresistance
- ✓ Skyrmions
- ✓ Spin Seebeck effect
- ✓ Field-free switching of magnetization through spin–orbit torque

[1] Nature 527 212–5(2015)
[2] Phys. Rev. Lett. 118, 067202 (2017)
[3] Phys. Rev. Lett. 115, 266601 (2015)
[4] Nat. Nanotechnol. 11 878–84(2016)

Therefore, determining how to manipulate the magnetic states of antiferromagnets efficiently is key to further development

Four main methods to control magnetic states

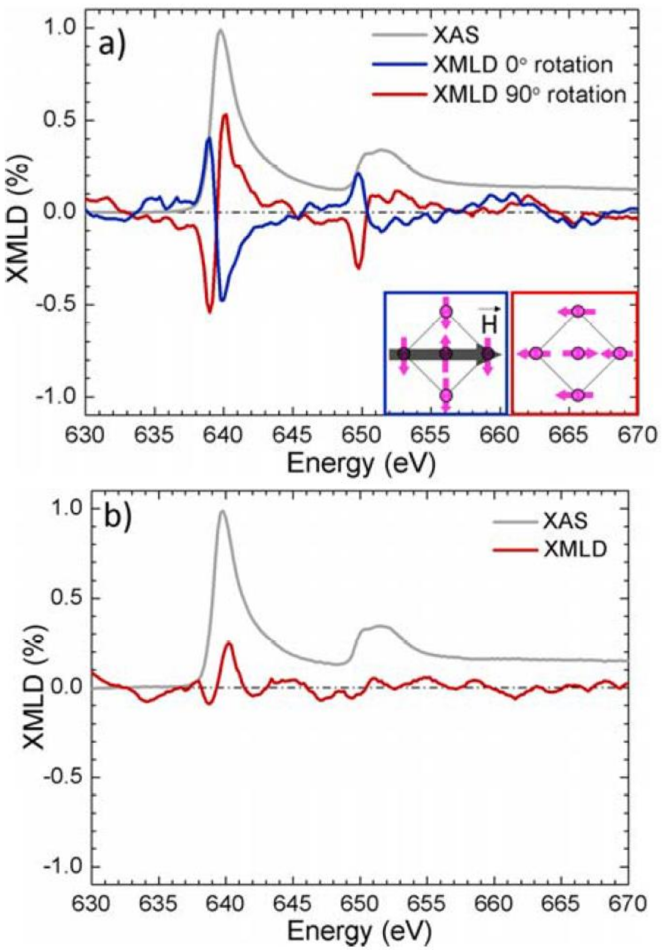


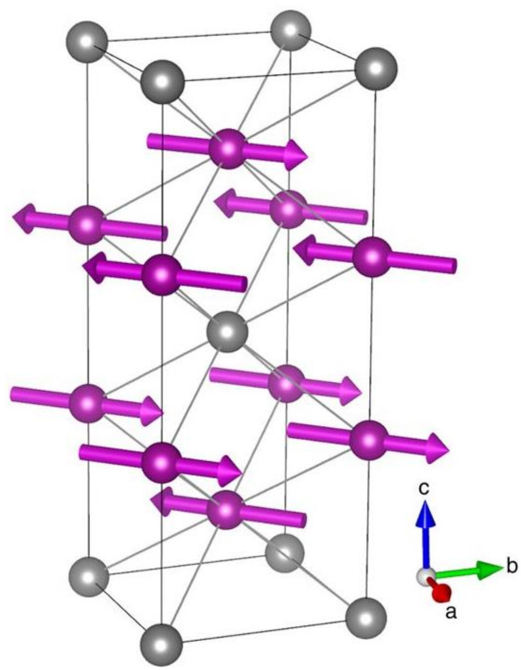
Nanotechnology 29,112001 (2018)

Magnetic field

A strong magnetic field

The magnetic moments can be manipulated merely by applying an external magnetic field that exceeds a certain value, but the magnetic field required for aligning magnetic moments or domains is quite strong.





Al_2O_3/Ta (15 nm)/Mn_2Au (10 nm) /Fe(1 nm)/AlOx(2 nm)

- The easy axes of Mn2Au are oriented parallel to the [110] directions. Thus in general AFM domains with two different in-plane orientations
- a **70 T** in-plane magnetic field, the generation of a preferential AFM domain orientation is obtained.

Nature Communications 4, 2892 (2013)
Phys. Status Solidi RRL 11, No. 4, 1600438 (2017)

Exchange bias

- Exchange bias was first discovered by Meiklejohn and Bean in 1956. (Co/CoO particles)
- The center of magnetic hysteresis loop shifts along the horizontal axis due to the interfacial coupling of ferromagnets and antiferromagnets

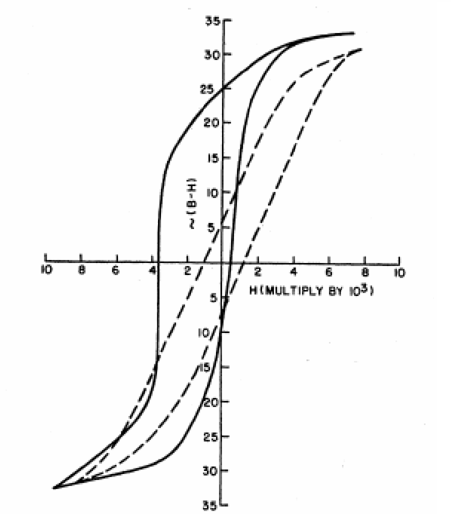
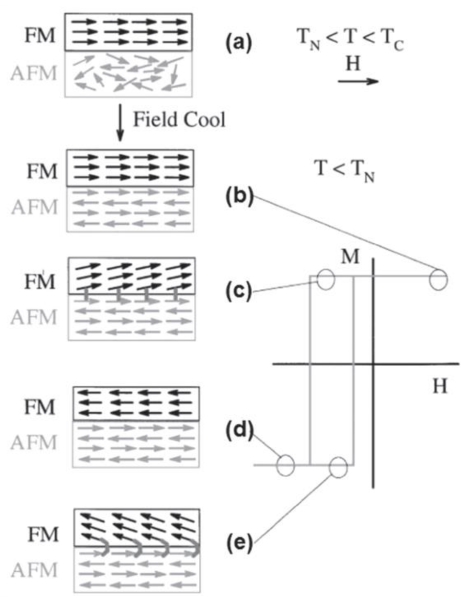
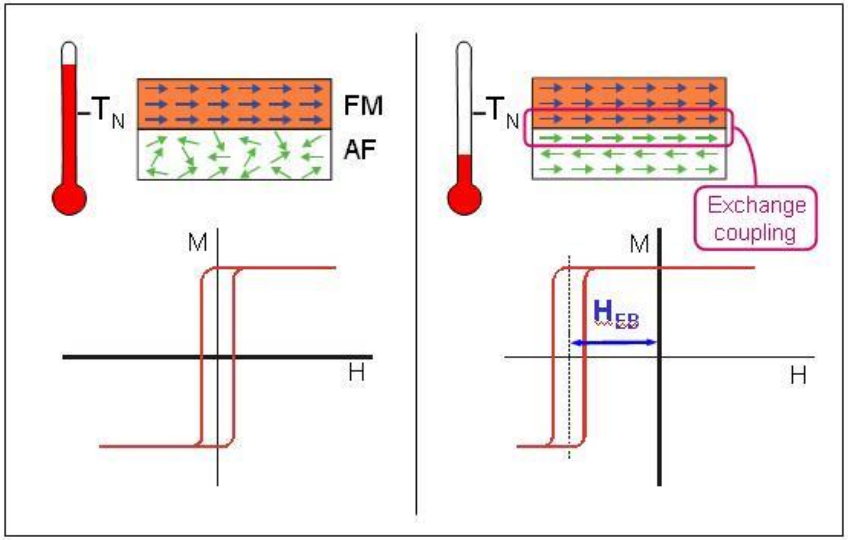


Fig. 3. Hysteresis loops of fine oxide-coated particles of coba taken at 77°K. The dashed lines show the hysteresis loop whe the material is cooled in the absence of a magnetic field. The soli lines show the hysteresis loop when the material is cooled in saturating magnetic field.





IEEE Trans. Magn. 102 3866–76(1956)

Exchange bias

Different interface coupling mechanisms

Type of coupling	Materials
Parallel ferromagnet /antiferromagnet coupling	Co/$LaFeO_3$/$SrTiO_3$(001), CoFe/NiO (111), Co/NiO(001), MnPd(001)/Fe/MgO(001) ,FeMn/Co , IrMn(002)/Fe/MgO(001)
Antiparallel coupling	Co/FeF_2/MgF_2(110), CoO/CoPt multilayers
Perpendicular coupling (spin-flop)	CoO/Fe/Ag(001),Co/NiO(001), NiO/Fe(001), Fe/NiO/Ag(001), Fe_3O_4/CoO(001), IrMn/[Co/Pt]

How to change exchange bias?

- ✓ Film thickness
- ✓ Temperature
- ✓ Atomic-steps
- ✓ Substrates
- ✓ Interlayer spacer
- ✓ Layer termination
- ✓ Cooling magnetic field

Mat. Sci. Eng. R 105 1–20 (2016)
J. Magn. Magn. Mater. 192 203–32 (1999)

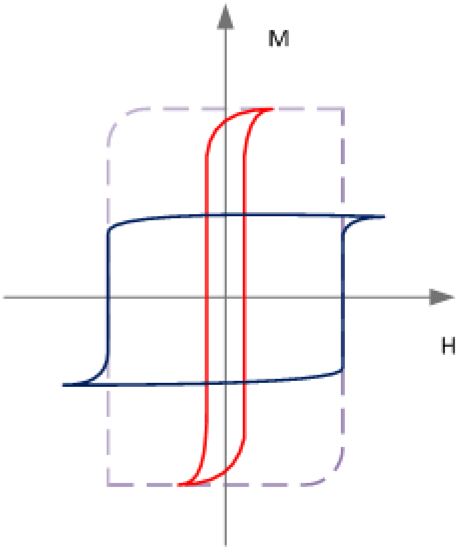
Exchange bias

Existing problems:

- Mainly emphasized ferromagnets and the interface.
- Antiferromagnets are only passively used to pin ferromagnets

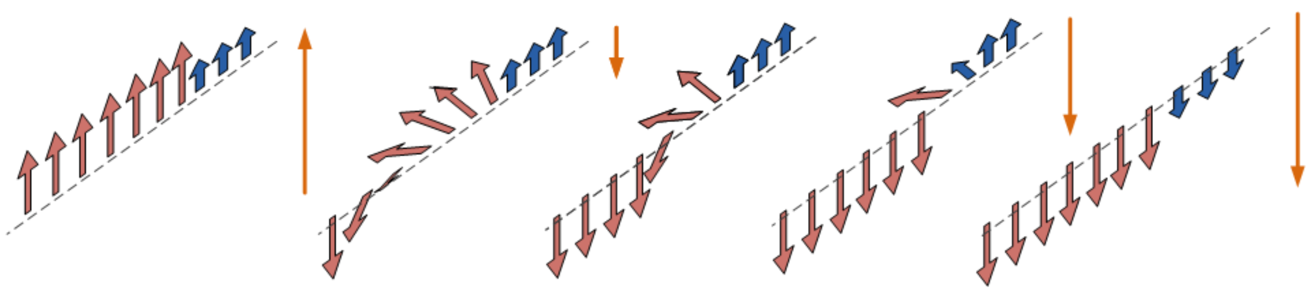
How to make antiferromagnets play a leading role ?

Exchange spring



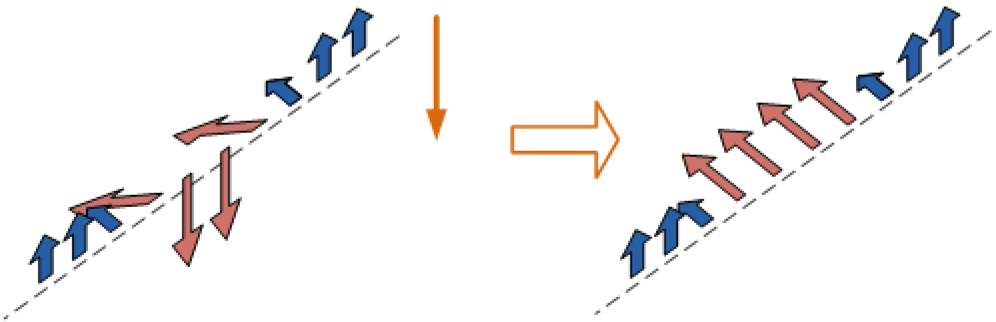
An Exchange Spring Magnet is a magnetic material with high coercivity and high saturation properties derived from the exchange interaction between a hard magnetic material and a soft magnetic material, respectively

- Blue arrows stand for the magnetic moments in the hard phase
- Red arrows stand for those in soft phase.



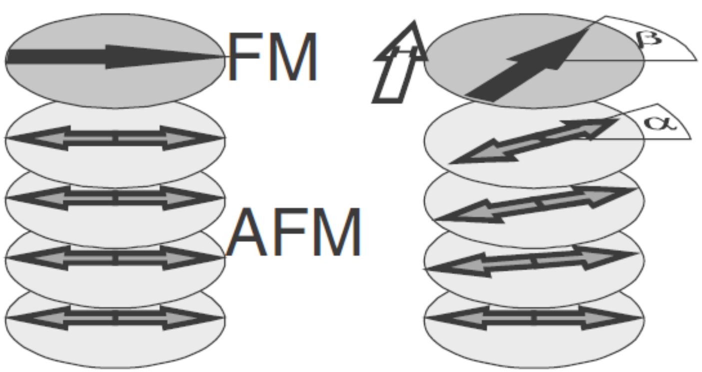
- ❑ The chain of magnetic moments acts like a spring
- ❑ The width of the transition **region becomes smaller** as the **exchange energy density increases**
- ❑ When the exchange energy density in the transition region is comparable to **the anisotropy energy density** in the hard phase, the rotation of magnetic moments in the soft phase starts to affect the hard phase.

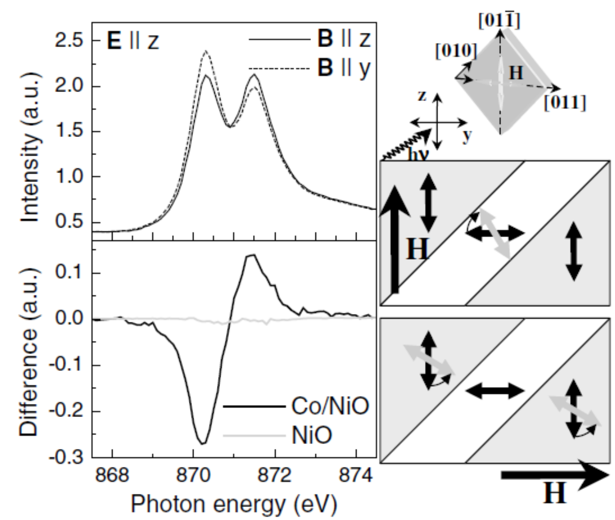
Exchange spring



- When the external field is removed, the remnant magnetization can recover to a value close to its original. The name "**exchange spring magnet**" is derived from the reversibility of magnetization

For the “Antiferromagnetic Exchange Spring”





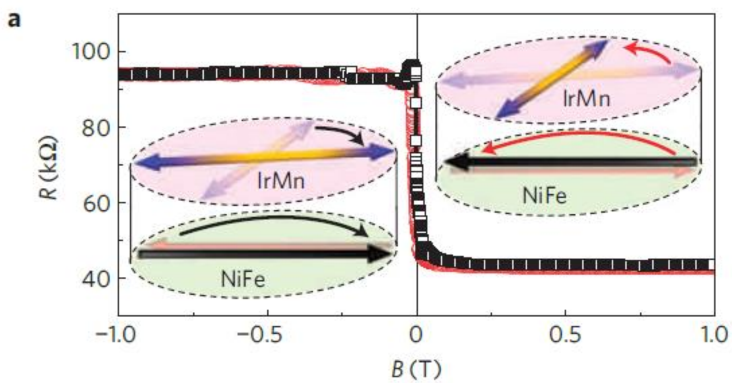
XMLD spectra

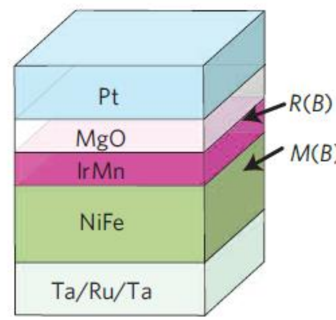
Phys. Rev. Lett. 92 247201 (2004)

Exchange spring

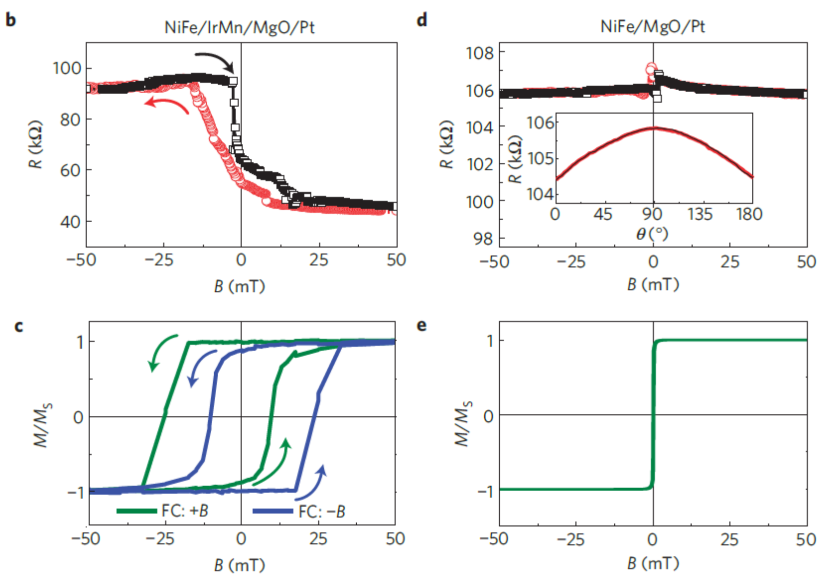
A spin-valve-like magnetoresistance of an antiferromagnet-based tunnel junction

Tunneling Anisotropic Magnetoresistance (TAMR)





NiFe ferromagnetic
IrMn antiferromagnetic



- The external magnetic field is sensed by the NiFe ferromagnet whereas the tunnelling transport is governed by the IrMn antiferromagnet

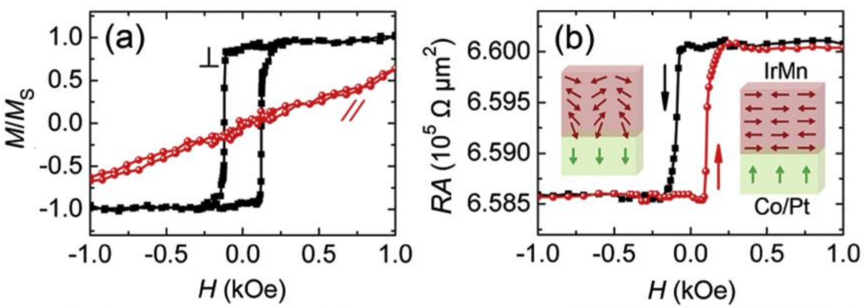
Nat. Mater. 10, 347–51(2011)

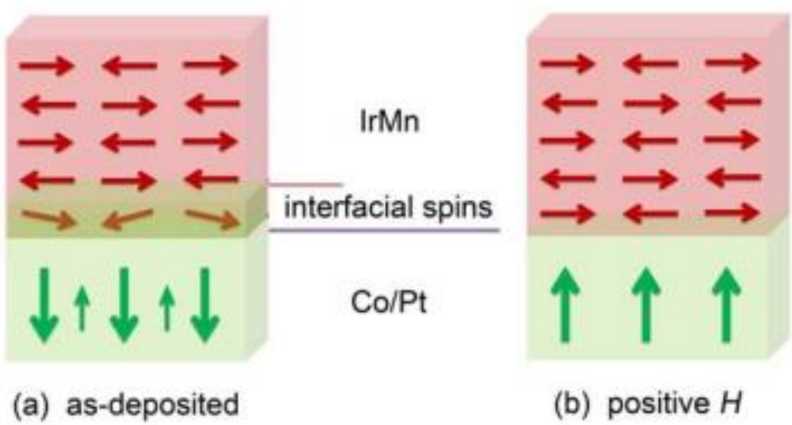
Exchange spring

Room-Temperature **Perpendicular Exchange Coupling** and Tunneling Anisotropic Magnetoresistance in an Antiferromagnet-Based Tunnel Junction

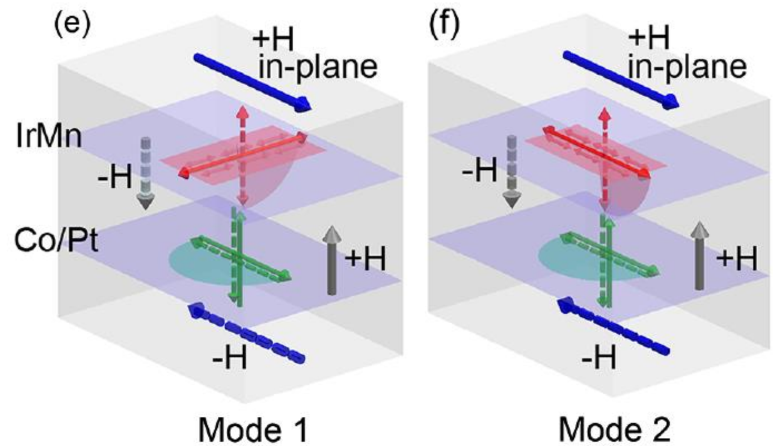
Pt(5)/[Co(0.5)/Pt(1)]$_4$/Co(0.5)/IrMn(6)/AlOx(2)/Pt(5)

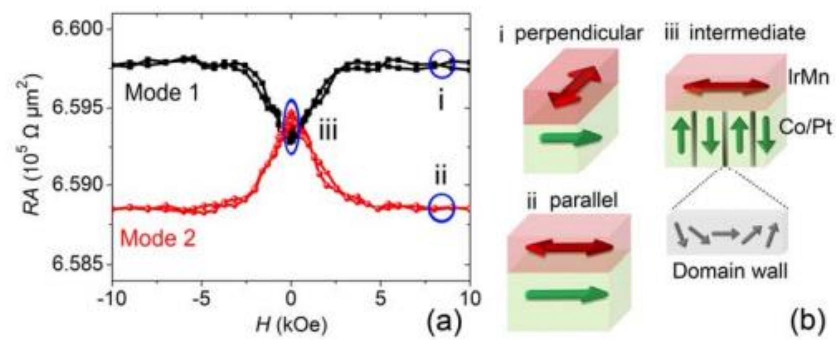
Out of plane





In plane





Phys. Rev. Lett. 109 137201 (2012)

Limits of using exchange bias to manipulate the magnetic moments in an antiferromagnet

1. The thickness of the antiferromagnetic layer

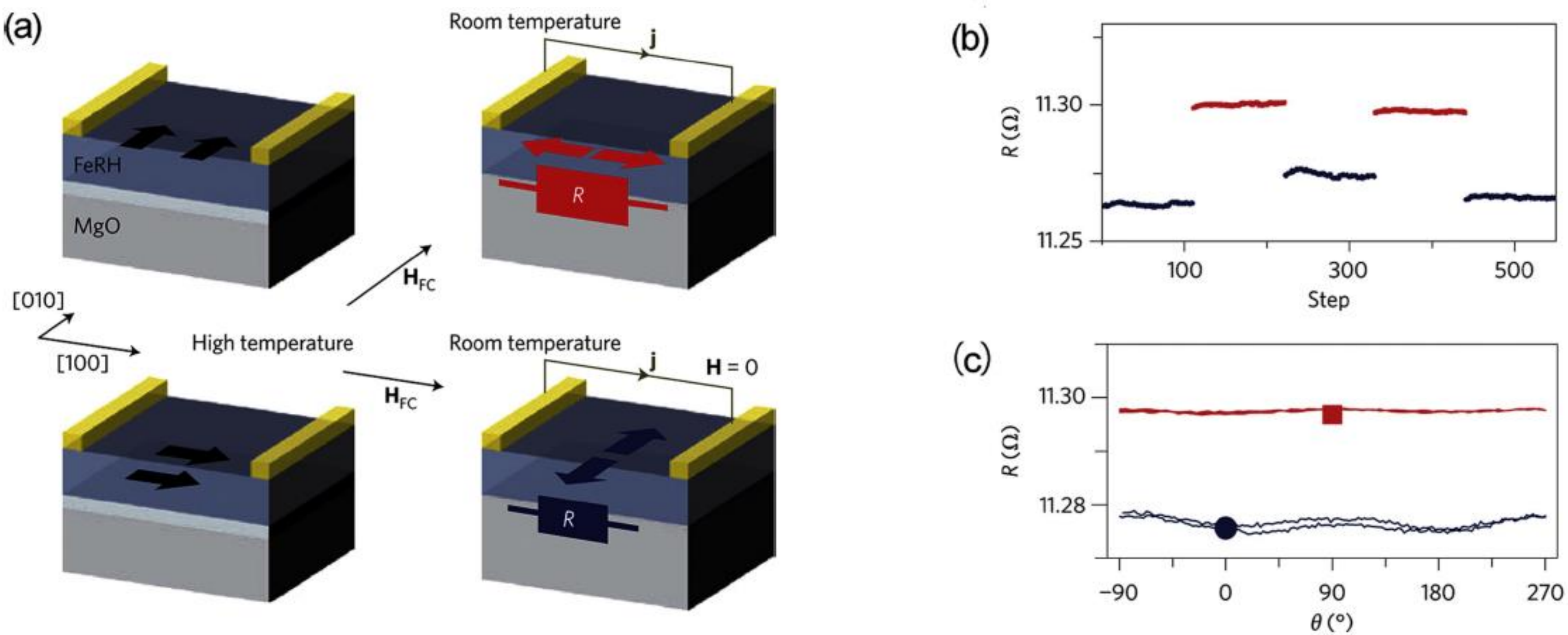
Thinness - exchange-spring rotation to cross the width of the antiferromagnet
Thickness - size effects to avoid the descending Néel temperature

2. Being interfered by weak magnetic field perturbations

Because of the ferromagnets within them

Field cooling

Room-temperature antiferromagnetic memory resistor



- Different resistance states can be designed by field cooling the devices from above their Néel temperature along different orientations
- The difference between scattering matrix elements for an electron with the momentum parallel and perpendicular to the spin axis is due to the relativistic spin-orbit coupling.

Nat. Mater. 13 367–74 (2014)

Summary

System	Mechanism	Target	Temperature	
NiO(111) single crystal	Strong magenetic field	Antiferromagnetic moments	T_N	551 ± 16 K
Mn_2Au thin films	Strong magenetic field	Antiferromagnetic domains	T_N	~1500 K
NiFe/IrMn/MgO/Pt stack	Exchange bias	Antiferromagnetic moments		—
[Pt/Co]/IrMn-based junctions	Exchange bias	Antiferromagnetic moments		—
Py/IrMn/MgO/Ta stacks	Exchange bias	Antiferromagnetic moments		—
Fe/CuMnAs bilayers	Exchange bias	Antiferromagnetic spin-axis		—
Co/NiO(001) bilayers	Exchange bias	Antiferromagnetic domain wall		—
IrMn/NiFe Stacks	Exchange bias	Antiferromagnetic moments		—
$La_{2/3}Sr_{1/3}MnO_3/Sr_2IrO_4$	Exchange bias	Antiferromagnet spin-axis	T_N	<240 K
Disordered-$IrMn_3$/insulating-$Y_3Fe_5O_{12}$	Exchange bias	Antiferromagnetic moments		—
Fe_2CrSi/Ru_2MnGe bilayers	Exchange bias	Antiferromagnetic spins		—
[Co/Pt]/FeMn	Exchange bias	Antiferromagnetic spins		—
LSMO/SMO/LSMO	Exchange bias	Antiferromagnetic moments		—
Ta/MgO/IrMn tunneling junctions	Field cooling	Antiferromagnetic spin configurations	T_N	173 K
FeRh/MgO	Field cooling	Antiferromagnetic moments	T_T	~400 K

- Magnetic control of antiferromagnets warrants continued research and development to further diminish the applied magnetic field as well as to increase resistance to external perturbations.

Thanks for your attention