# How to manipulate magnetic states of antiferromagnets

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10/26/2018



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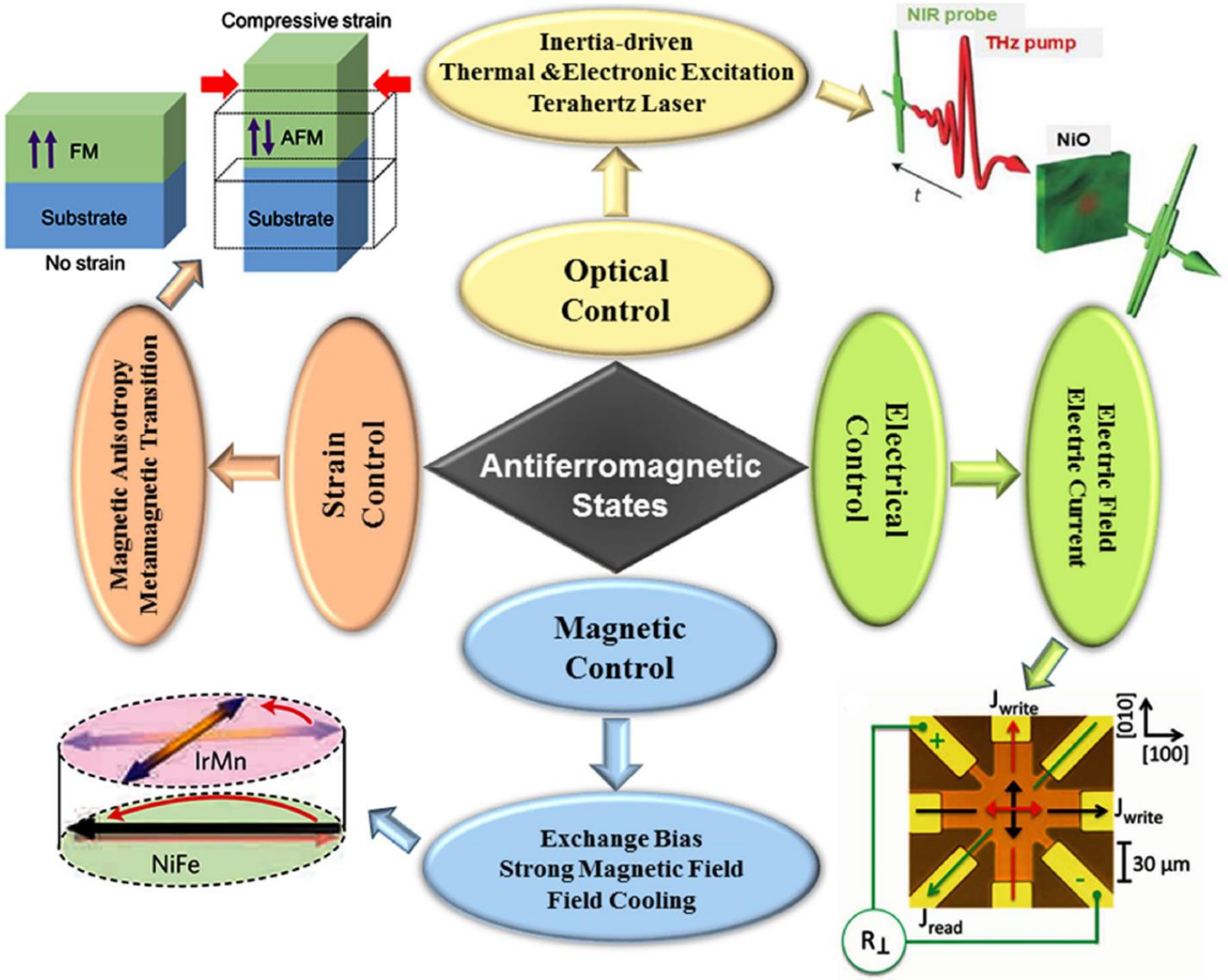
# Four main methods to control magnetic states




Nanotechnology 29,112001 (2018)

# Motivation

- To avoid perturbations in the external magnetic field and to control magnetic moments in antiferromagnets without the influence of ferromagnets, strain is proposed as an intriguing means of manipulation via either the **magnetic anisotropy effect** or **metamagnetic transition**.
- Strain exerts an influence on the lattice parameter and spin–orbit coupling, which has a strong relationship with magnetic anisotropies related to the ground-state energy, chemical potential, and density of states, being the origin of antiferromagnets'magnetic moment orientation.

# Magnetic anisotropy effect

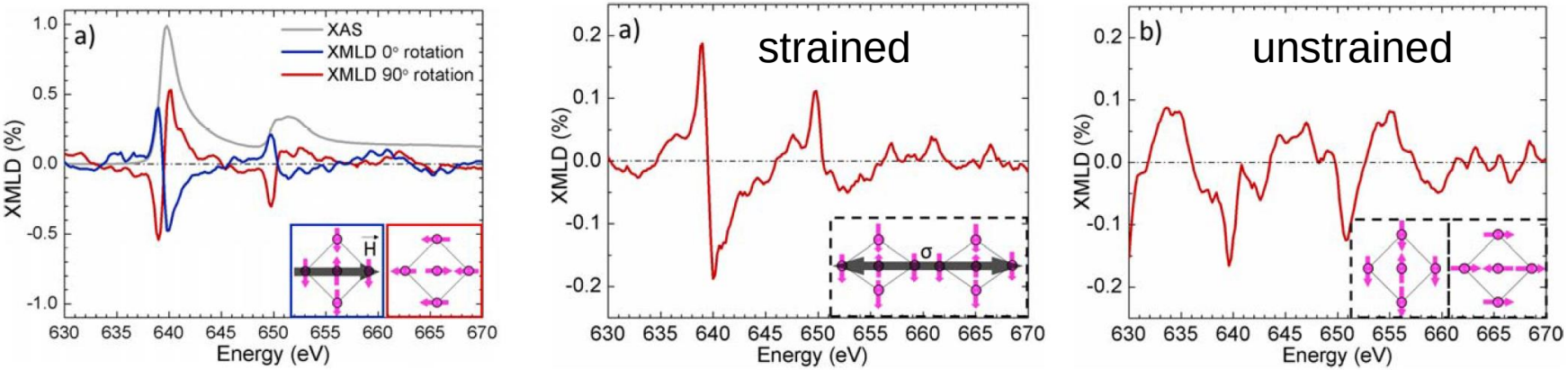
**Why $Mn_2Au$ and MnIr ?**

- Large spin–orbit coupling on the 5d shell of the noble metal as well as the large moment on the Mn 3d shell.

**How to control antiferromagnets by strain?**

- The staggered moments of $Mn_2Au$ could rotate in different directions by applying various sufficiently strong strain along the easy axis triggered by magnetocrystalline anisotropy energy;
- For example, strain may cause lattice distortion and reduce in-plane symmetry from 4-fold to 2-fold in $Mn_2Au$(001) crystal structure, leading to an uniaxial anisotropy with preference for a certain Néel vector orientation compared to samples without strain. Therefore, the magnetic moments rotate spontaneously.

**$Mn_2Au$,Tetragonal crystal structure, the easy axes parallel to the [110] directions**



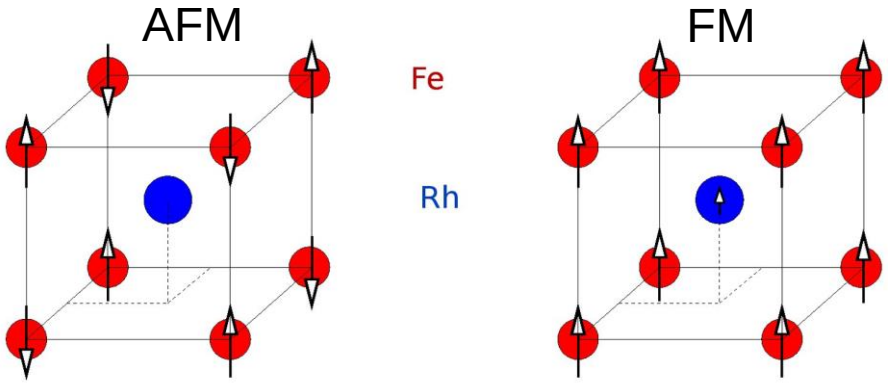

- Mn spins in $Mn_2Au$ prioritize the alignment along the direction with the shorter lattice spacing

Physical Review B 81, 212409 (2010)

Phys. Status Solidi RRL 11, No. 4, 1600438 (2017)

# Metamagnetic transition

**FeRh**




- **Metamagnetism** is a sudden increase in the magnetization of a material with a small change in an externally applied magnetic field.

- The metamagnetic transition temperature from antiferromagnetic order to ferromagnetic order is approximately **350 K**, meaning that **FeRh** may exhibit an antiferromagnetic state at room temperature which is suitable for information storage. (eg. thermally assisted magnetic recording (TAMR)).
- Hall and photoemission data have evidenced **strong changes in the electronic structure** between both magnetic states, **with an unusually low carrier density in the AFM phase.**
- Strain produced during the epitaxial growth process can also control the metamagnetic transition **by modifying the electronic structure** under tetragonal lattice distortion, resulting in **magnetocrystalline anisotropy** in thin films.

# Metamagnetic transition

**Fe Spin Reorientation across the Metamagnetic Transition in Strained FeRh Thin Films**

**Sample information – a good way to induce strain effect**

- **MgO** crystal a=b=c=4.212 Å
- **IBAD MgO** on the a-SiOx/Si, biaxially-textured, a = 4.228 Å along [020] and b = 4.202 Å along [200] (IBAD = ion-beam-assist-deposited)

an increase in the out-of-plane lattice parameter c, because a and b are constrained by the substrate

| | AFM | | | | FM | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | $a = b$ (Å) | $c$ (Å) | $c/a$ | $\mathbf{m_{Fe}(\mu_B)}$ | $a = b$ (Å) | $c$ (Å) | $c/a$ | $\mathbf{m_{Fe}(\mu_B)}$ | $\mathbf{m_{Rh}(\mu_B)}$ |
| FeRh//MgO | 2.980 | 3.004 | 1.008 | **3.139** | 2.980 | 3.028 | 1.016 | **3.228** | **1.016** |
| FeRh//IBAD MgO | 3.005 | 2.959 | 0.985 | **3.095** | 3.005 | 2.983 | 0.993 | **3.199** | **1.020** |

TABLE I. Room temperature lattice constants (measured for the AFM phase and extrapolated for the FM phase using the experimental linear thermal expansion coefficient of $1.13 \times 10^{-5}$ $K^{-1}$, as determined from the thermal variation of the out-of-plane lattice constant), corresponding $c/a$ ratio, and calculated spin magnetic moments (bold) of FeRh thin films in the AFM and FM phases.

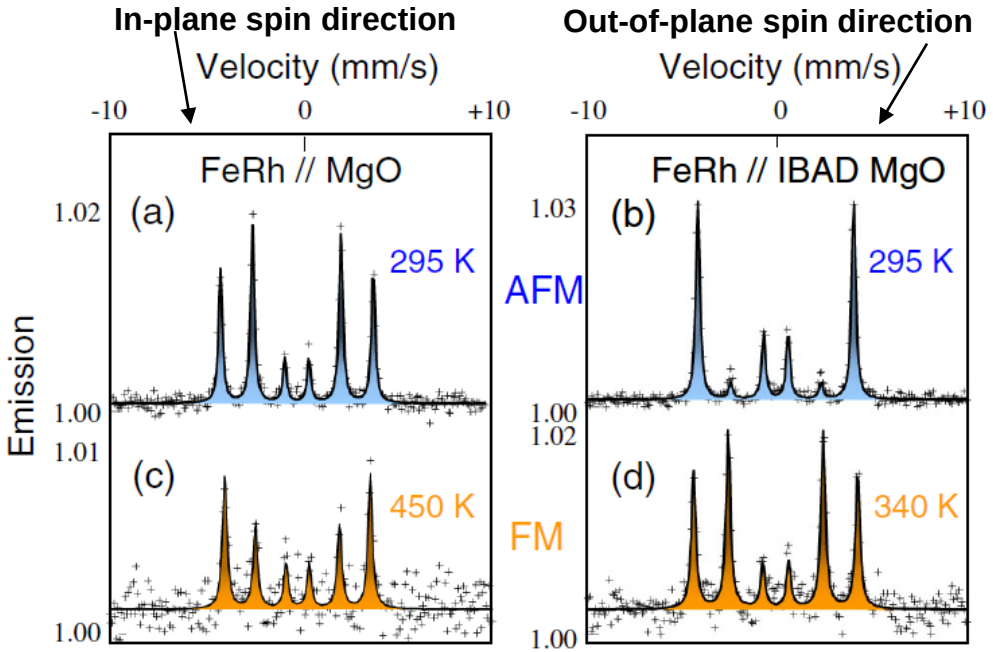
PRL 109, 117201 (2012)

Rev. Sci. Instrum. 82, 023908 (2011)

# Metamagnetic transition

## Fe Spin Reorientation across the Metamagnetic Transition in Strained FeRh Thin Films

**Fe magnetic moment direction – another way to detect the spin direction**




❖ **Mössbauer spectroscopy** probes tiny changes in the energy levels of an atomic nucleus in response to its environment. Typically, three types of nuclear interactions may be observed: isomer shift, also called chemical shift in the older literature; quadrupole splitting; and magnetic hyperfine splitting (see also the Zeeman effect). Due to the high energy and extremely narrow line widths of gamma rays, Mössbauer spectroscopy is a very sensitive technique in terms of energy (and hence frequency) resolution

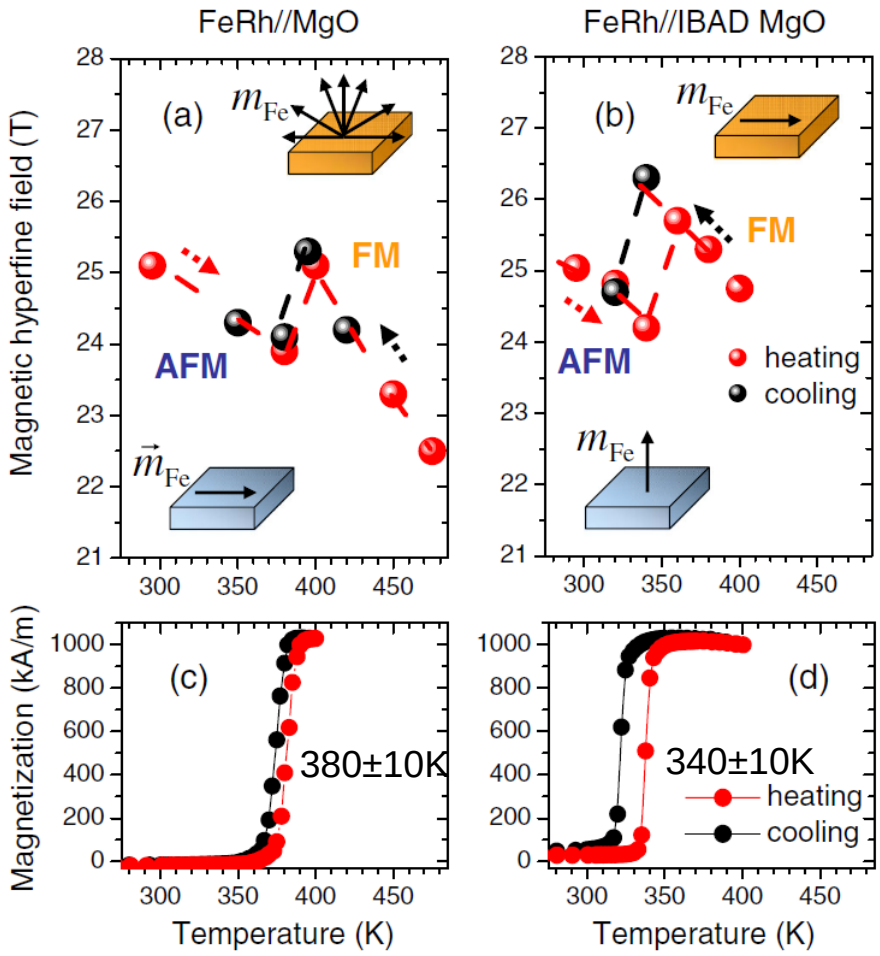
- ❑ The direction of an Fe magnetic moment can be determined from the line intensity ratio (x) of the second (or fifth) and the third (or fourth) line of the magnetically-split Mössbauer sextet.
- ❑ x ratio is related to β the angle between the local magnetic hyperfine field (Bhf ) at the Fe nucleus and the incident γ ray direction. $\cos^2 \beta = (4 - x)/(4 + x)$
- ❑ For incident γ ray perpendicular to the sample plane, **x changes from 4 to 0, for in-plane (β = 90°)** and **out-of-plane (β = 0°) spin configurations**, respectively

PRL 109, 117201 (2012)

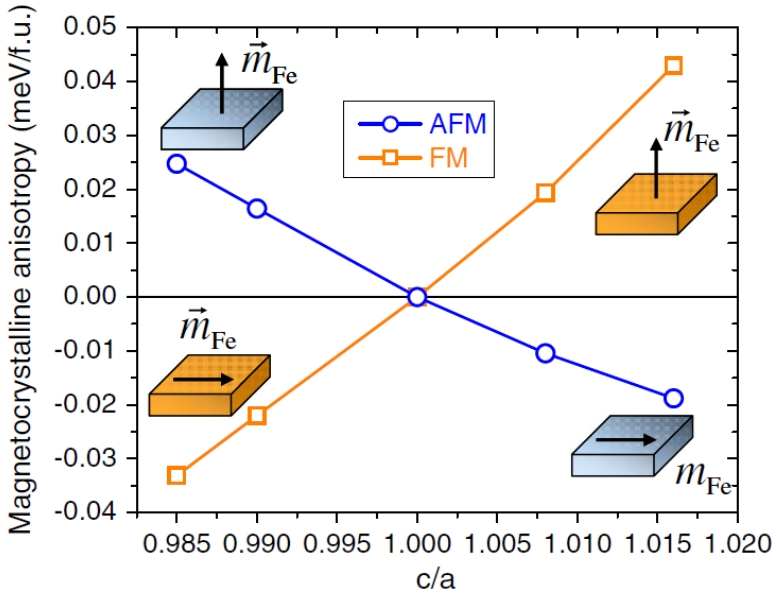
# Metamagnetic transition

**Fe Spin Reorientation across the Metamagnetic Transition in Strained FeRh Thin Films**

**M-T loops for phase transition**




**Magnetocrystalline anisotropy energy calculated as a function of the c=a ratio for each of the two magnetic phases**



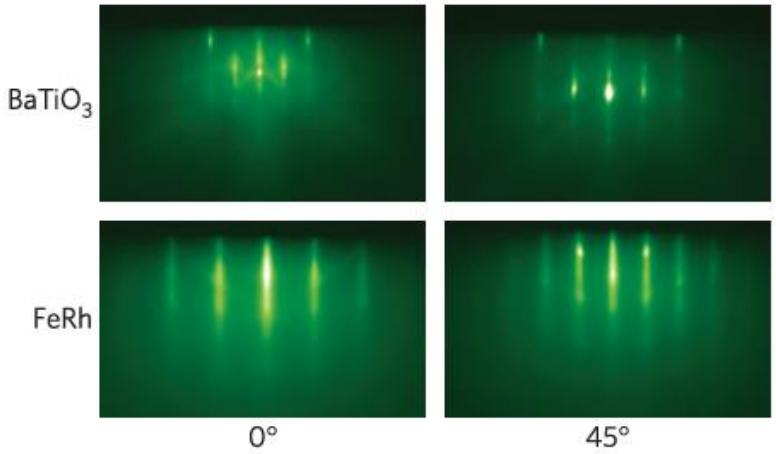

- ✓ The local magnetic moment carried by Fe is higher in the FM phase than in the AFM phase for both samples.
- ✓ This result suggests **a decrease in transition temperature** under the influence of tensile strain.

PRL 109, 117201 (2012)

# Metamagnetic transition

**Electric-field control of magnetic order above room temperature**

FeRh films on ferroelectric $BaTiO_3$ single crystals

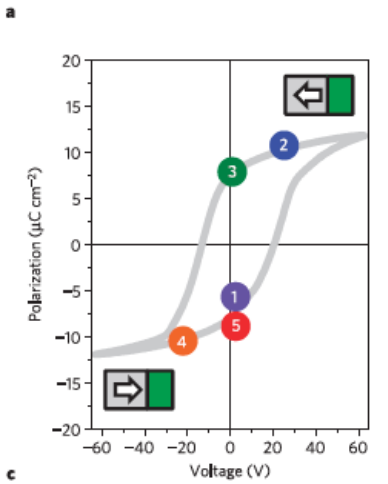


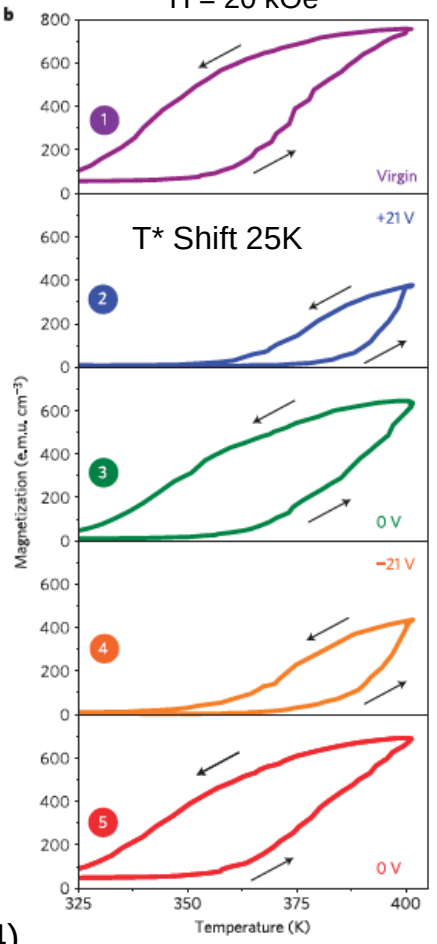

- **Influence of an applied voltage on the temperature dependence of the magnetization in FeRh/$BaTiO_3$.**
- Phase transition temperature shift 25 K
- Maximum magnetization variations reaching 550 emu/cc
- A gigantic magnetoelectric coupling $\alpha = \mu_0 \Delta M/E = 1.6 \times 10^{-5} sm^{-1}$ much higher than previous reports in composite multiferroic heterostructures (for example, $BaTiO_3$=$La_{0.67}Sr_{0.33}MnO_3$, α = $2.3 \times 10^{-7} sm^{-1}$ $Pb(Mg_{1/3}Nb_{2/3})_{0.7}Ti_{0.3}O_3$/$Co_{40}F_{e40}B_{20}$, , α = $2 \times 10^{-6} sm^{-1}$

AFM→FM

Magnetization 50 emu/cc to 800 emu/cc

H = 20 kOe



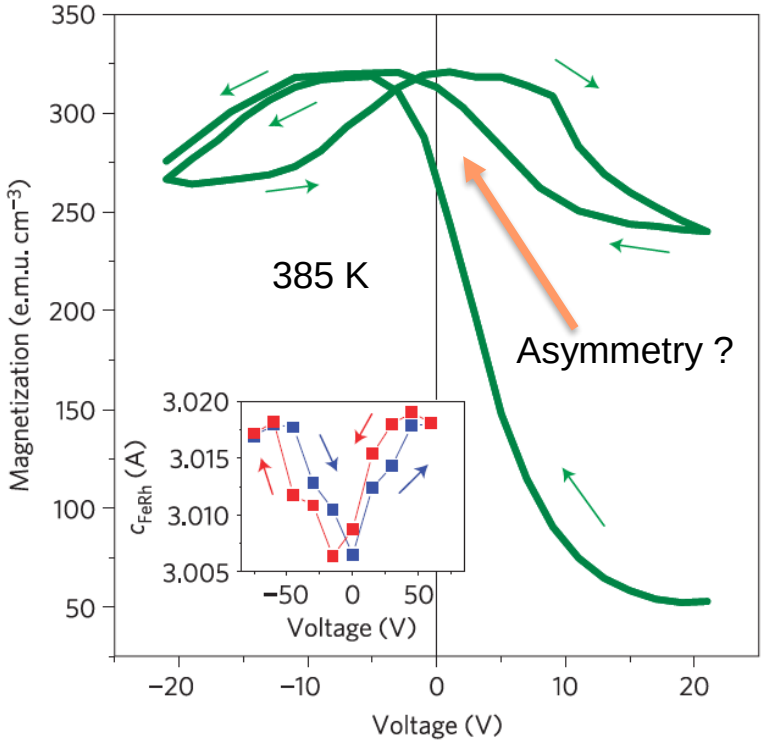




Nat. Mater. 13 345–51 (2014)

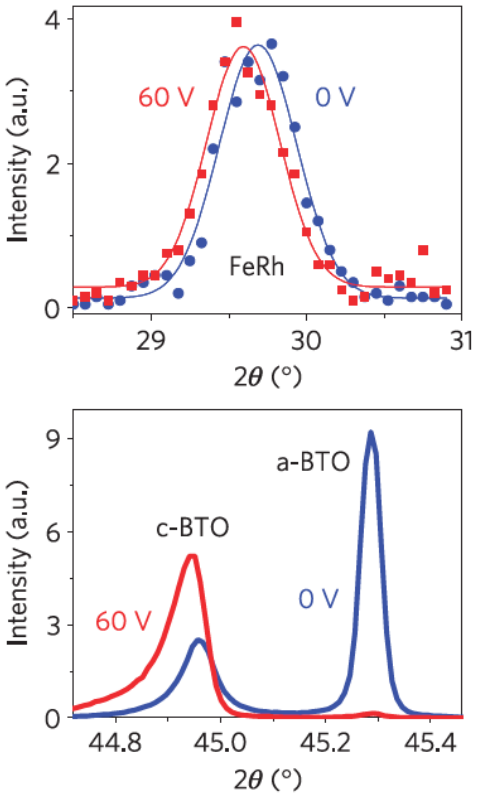
# Metamagnetic transition

**Electric-field control of magnetic order above room temperature**

- Electrical control of magnetism: ferroelectrics through **piezoelectricity** (which produces voltage-induced strain) and the **field effect** (which depletes or accumulates carriers in a material adjacent to the ferroelectric).




**Stain effect**

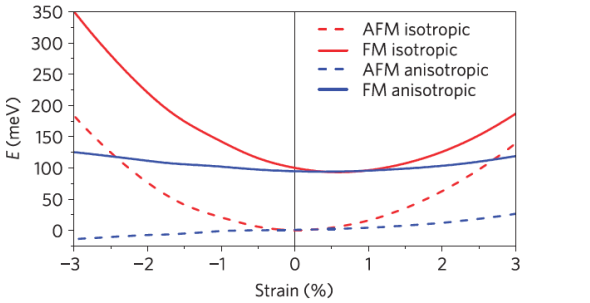


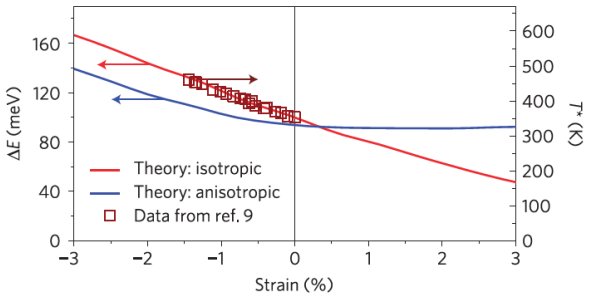

Nat. Mater. 13 345–51 (2014)

# Metamagnetic transition

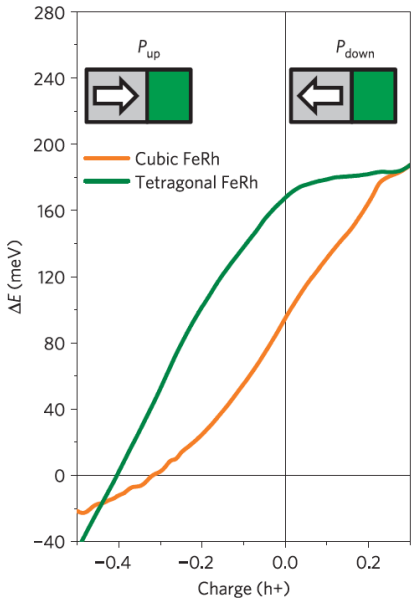
## Field effect

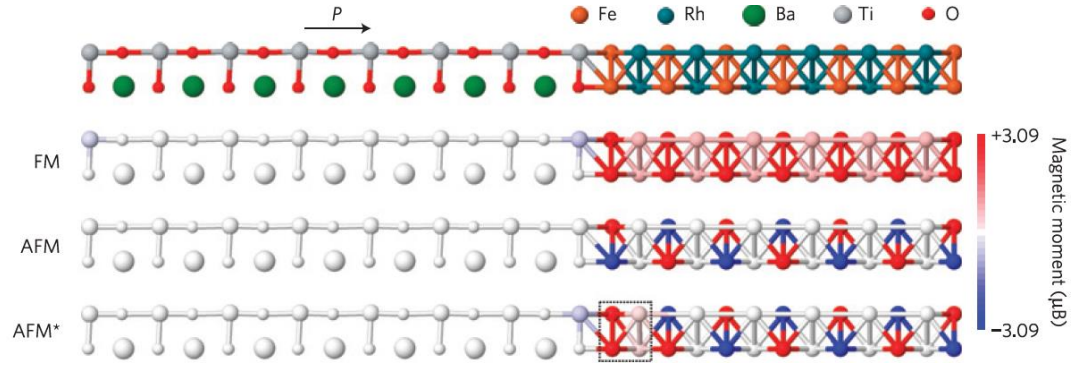
in-plane compressive strain on the FeRh of -0.47%.




The energy difference between the FM and AFM states as a function of the injected charge




- Whereas hole injection into FeRh does not significantly alter the relative stability between the two magnetic phases, **electron injection progressively stabilizes the FM phase.**
- The $P_{down}$ state (polarization away from the interface) has only a weak effect on the stability of the magnetic order but the $P_{up}$ configuration (polarization towards the interface) should promote the stabilization of ferromagnetism.

Nat. Mater. 13 345–51 (2014)

# Summary

**Table 2.** Summary of different strain-related manipulation methods of antiferromagnets. $T_N$, $T_B$, and $T_T$ represent Néel temperature, blocking temperature, and antiferromagnetic–ferromagnetic transition temperature, respectively.

| System | Mechanism | Target | Temperature | |
|---|---|---|---|---|
| $Mn_2Au$ | Magnetic anisotropy effect | Antiferromagnetic moments | $T_N$ | ~1500 K |
| IrMn/[Co/Pt] | Magnetic anisotropy effect | Antiferromagnetic moments | $T_B$ | 200 K (8 nm); |
| $Mn_2Au$ | Magnetic anisotropy effect | Antiferromagnetic domains | $T_N$ | ~1500 K |
| FeRh thin film | Metamagnetic transition | Fe spins | $T_T$ | ~350 K |
| $FeRh/BaTiO_3$ | Metamagnetic transition | Antiferromagnetic to ferromagnetic order | $T_T$ | ~350 K |

- Compared to the magnetic control of antiferromagnets, the range for strain manipulation is **narrower and often combined with other effects such as the electric field**.
- However, this topic still inspires international research interest given its unique characteristics such as **energy saving and ease of reaching room temperature**.
- The essence of strain-controlled antiferromagnets lies in **the change of electronic structure and strain-induced spin–orbit coupling, which can be applied to other materials**. To this point, it is possible to control magnetic moments of more antiferromagnetic materials through strain or strain-related methods, which may expand the application of antiferromagnetic spintronics.

Thanks for your attention

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