Chapter 2

Magnetism and Magnetic Materials

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量子材料科学中心

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提纲

1. Introduction to magnetism

2. How to induce magnetic moment

3. How to control magnetization

Review of last class

- **Magnetism of Electrons**
- **Spin orbit Coupling**
- **Magnetism**

  Diamangetism, Paramagnetism,
  FM, AFM, Ferrimagnet, Half metallic
- **Magnetic resonance**
- **Magnetic domains**

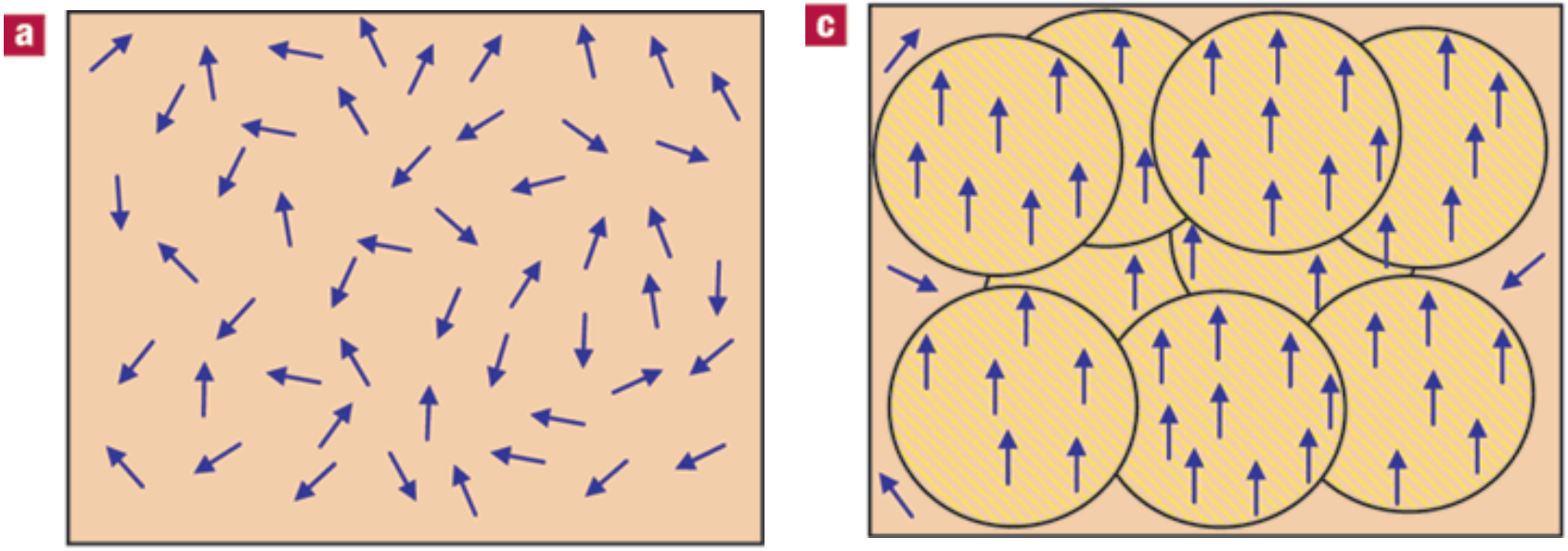
提纲

2. How to induce magnetic moment

Mainly two methods

1) Impurity doping

Mn impurity in GaMnAs



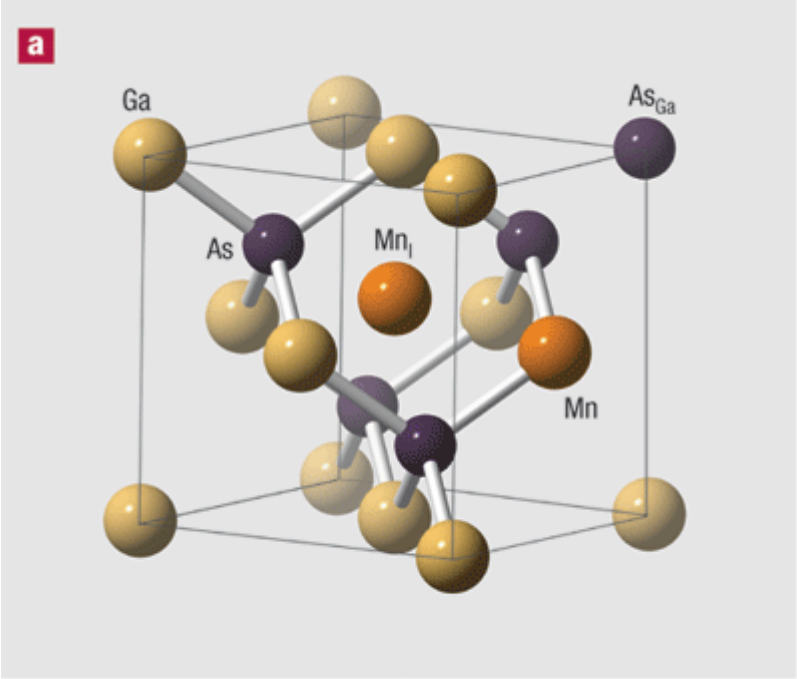
Low doping

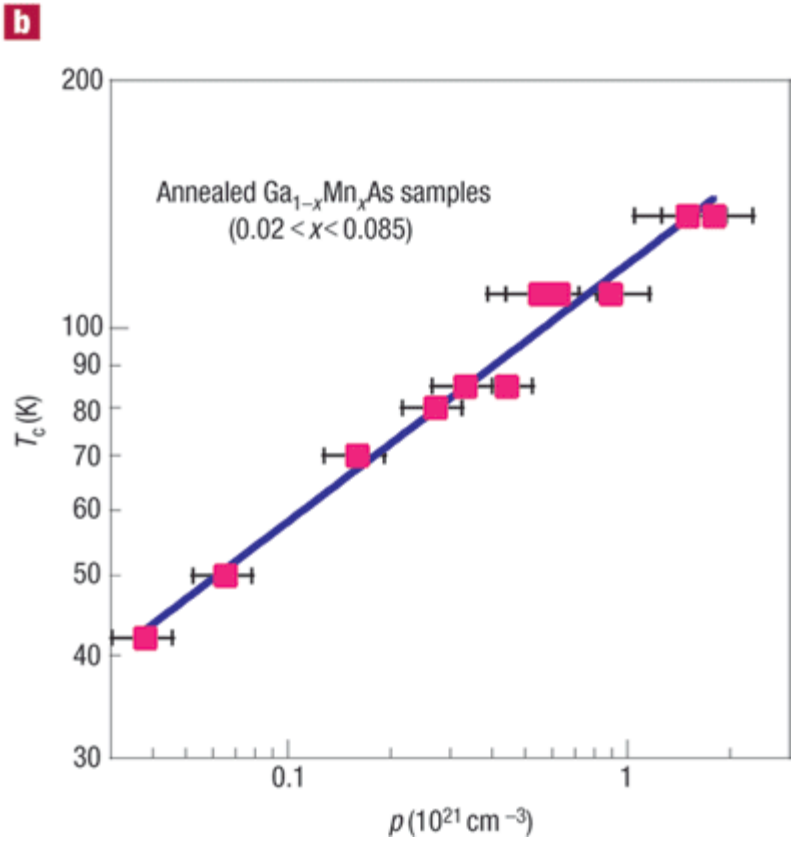
High doping

MacDonald, et al, Nature Mater. (2005)

Mainly two methods

1) Impurity doping



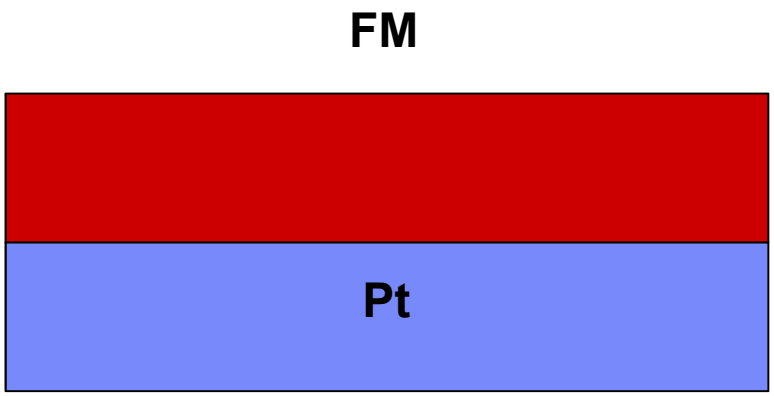


MacDonald, et al, Nature Mater. (2005)

Mainly two methods

2) Proximity effect

At the atomic level, when two atoms come into proximity, the highest energy, or valence, orbitals of the atoms change substantially and the electrons on the two atoms reorganize.

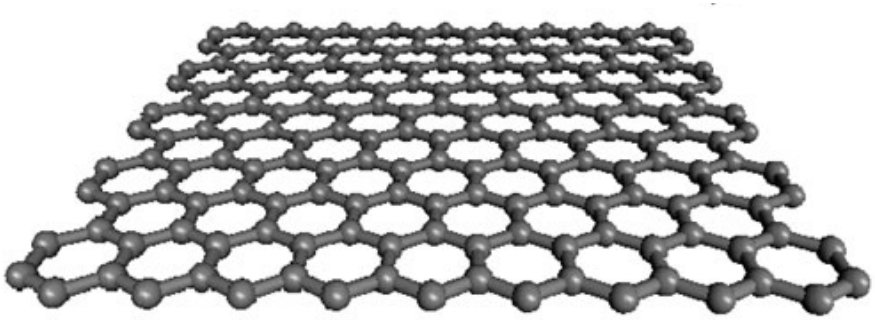


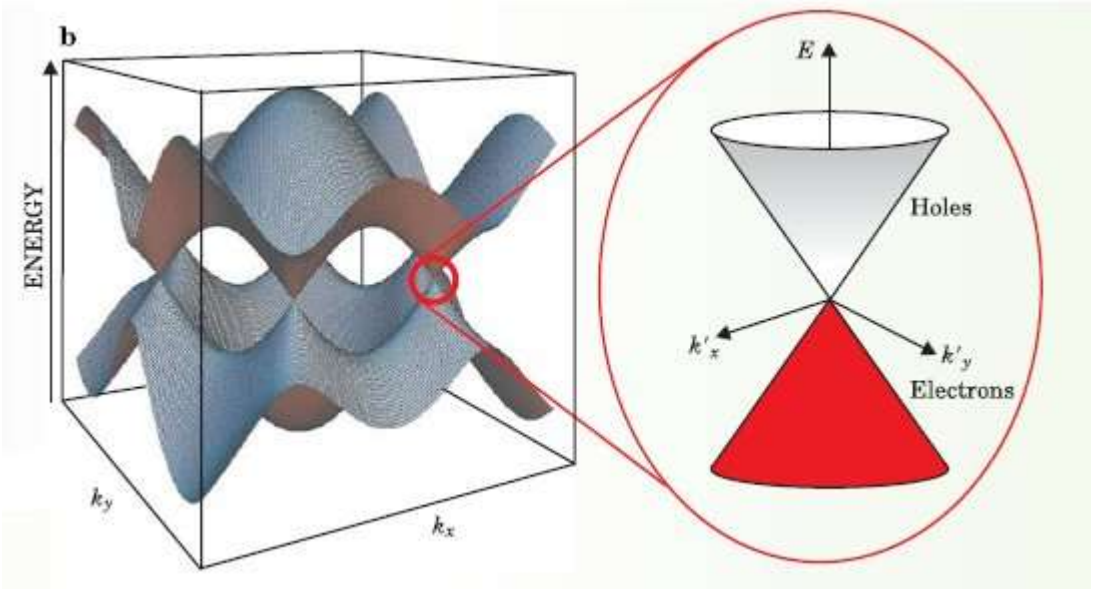
Interface hybridization

Induce M in two Quantum Materials

Two Dirac Materials

Graphene

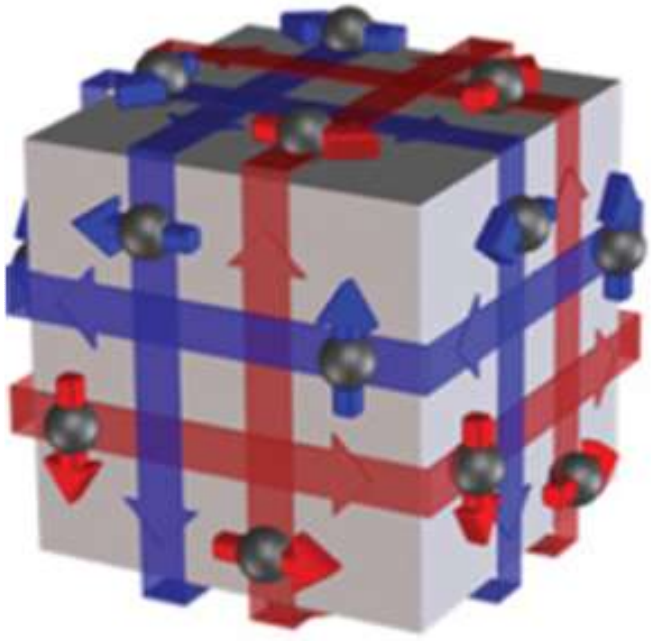




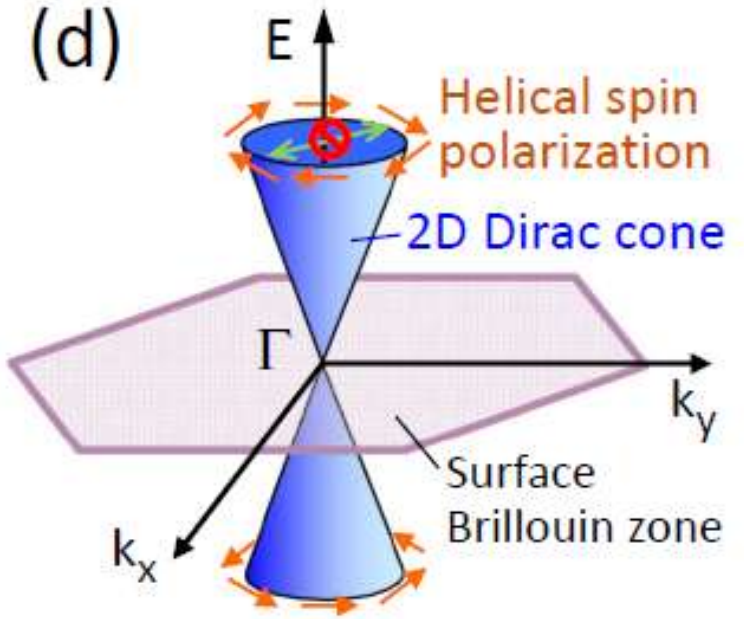
Induce M in two Quantum Materials

Two Dirac Materials

Topological Insulator

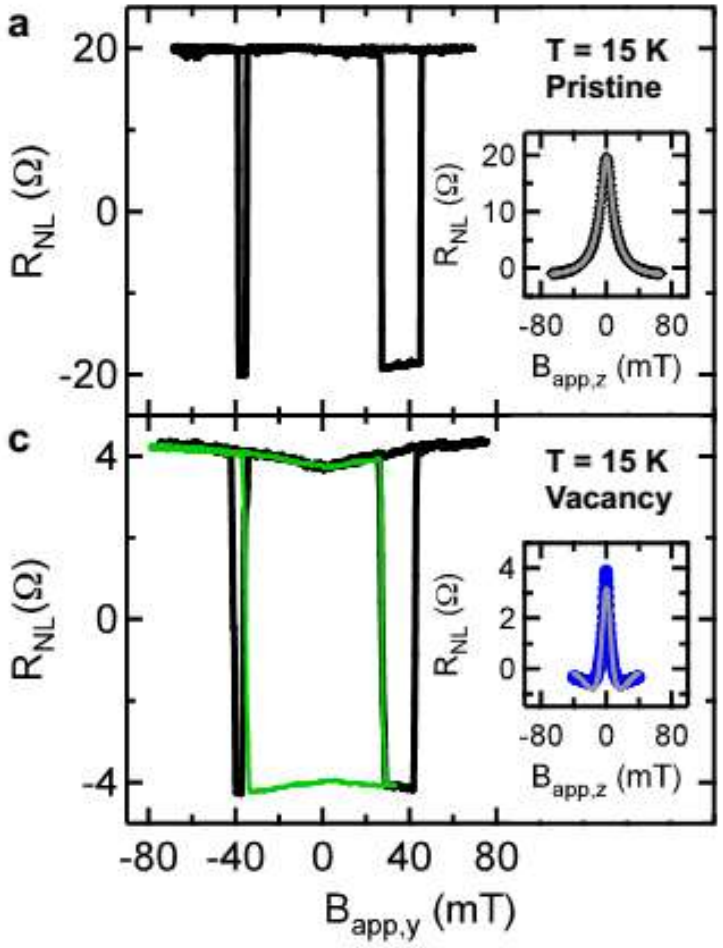


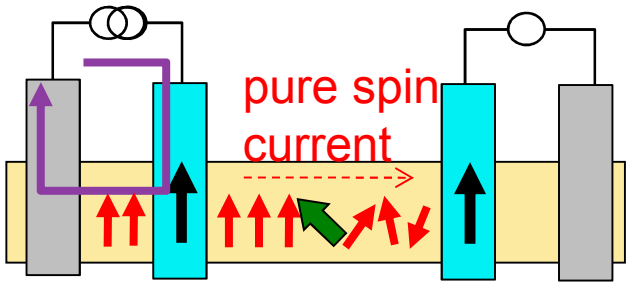
3D Topological insulator



Vacancies Defects

Using the spin current approach





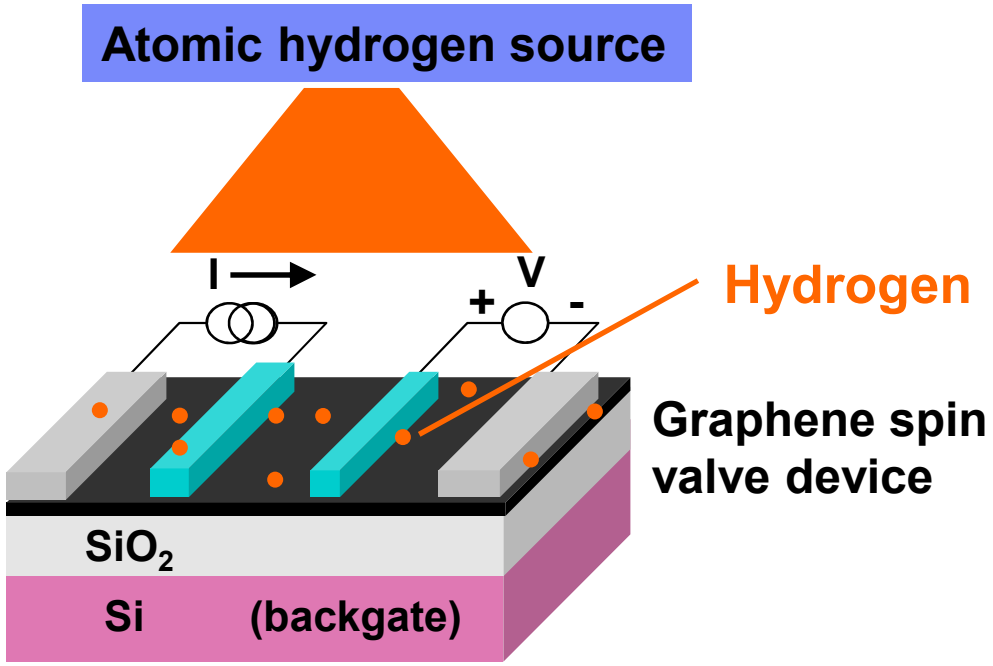
At high field

$\vec{S}_e$ and $\vec{S}_M$ decouple!

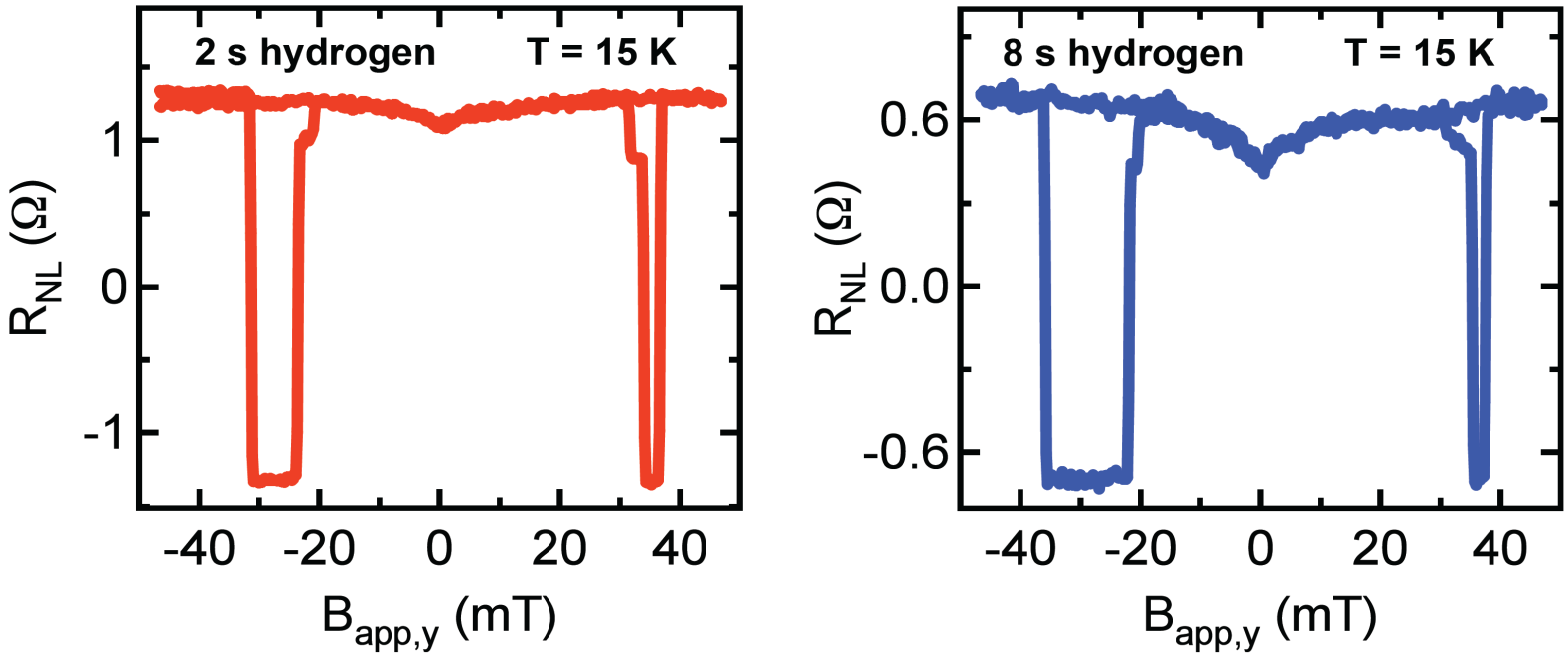
Scattering by exchange coupling is suppressed

More spins at detector

Hydrogen Doping



Hydrogen Doping

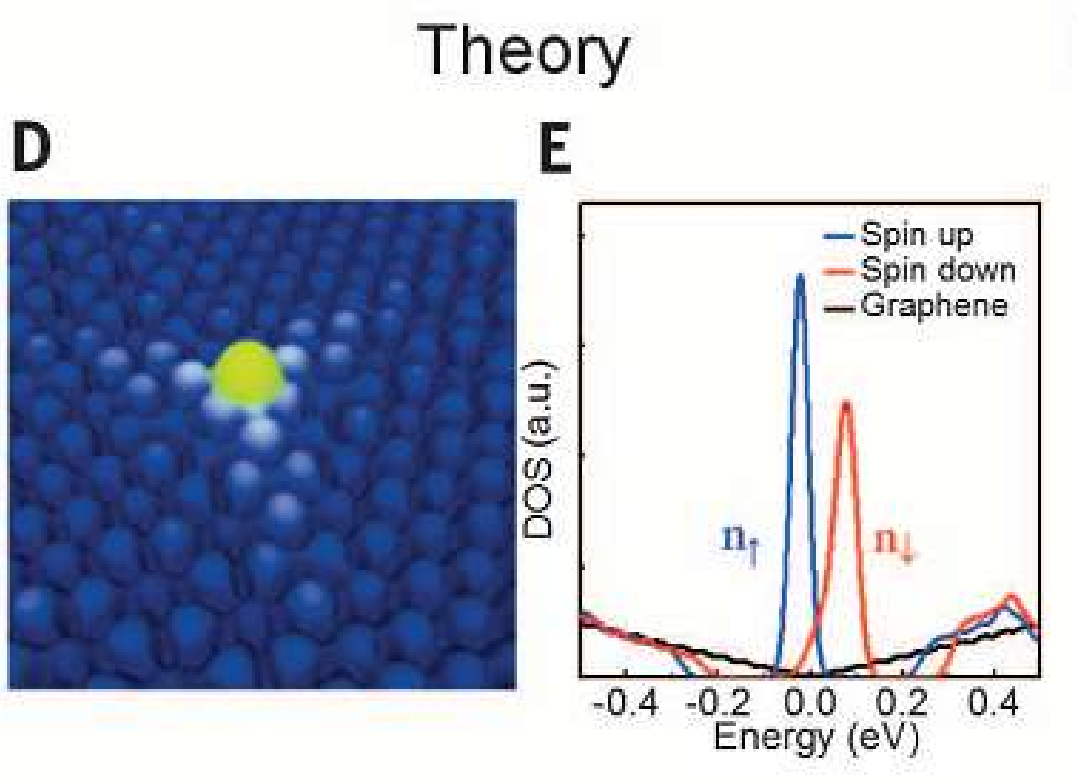


Paramagnetic at 15 K!

McCreary, et al, PRL (2012)

Hydrogen Doping

STM probe of H-graphene



González-Herrero, et al, Science (2016)

Hydrogen Doping

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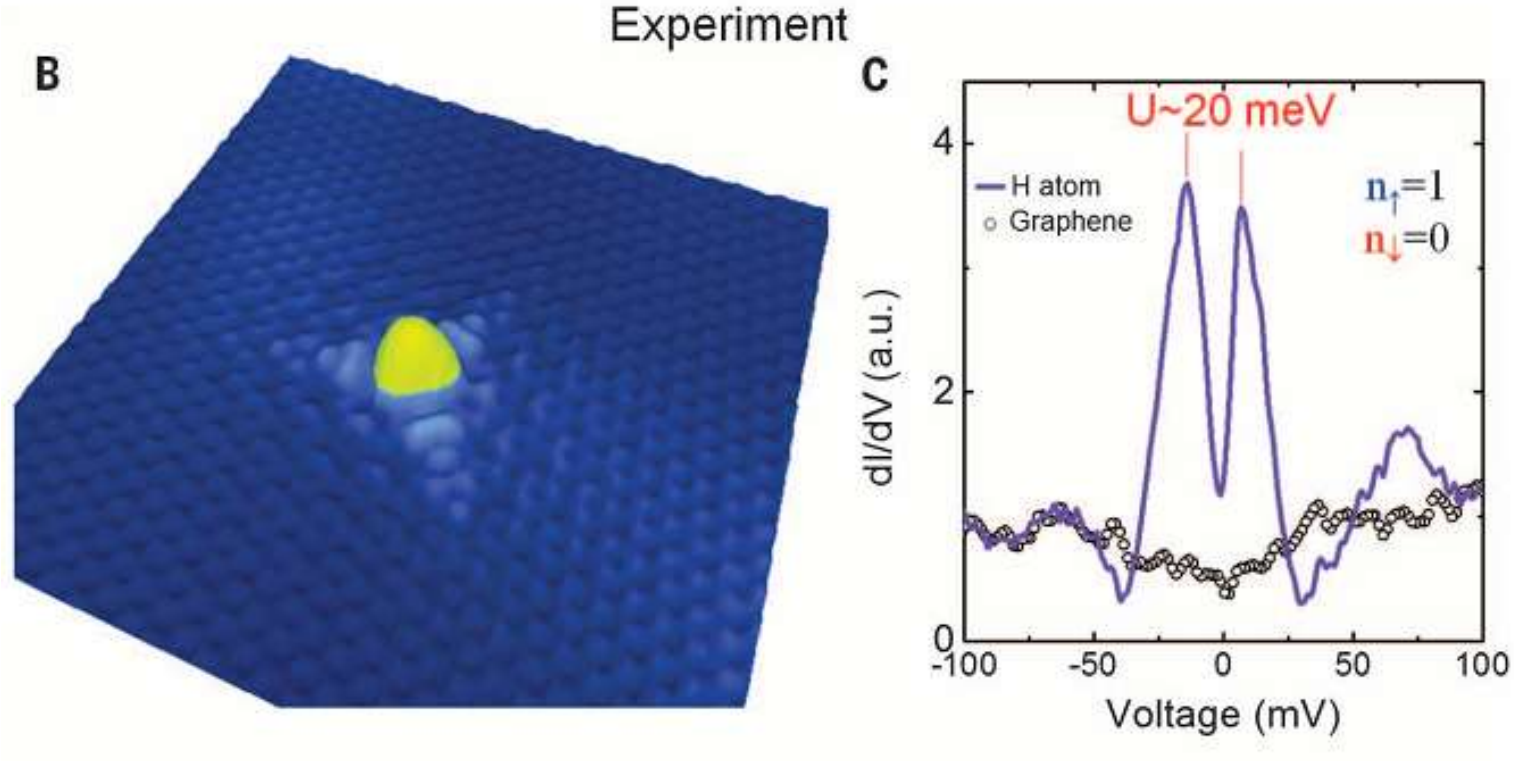

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Hydrogen Doping

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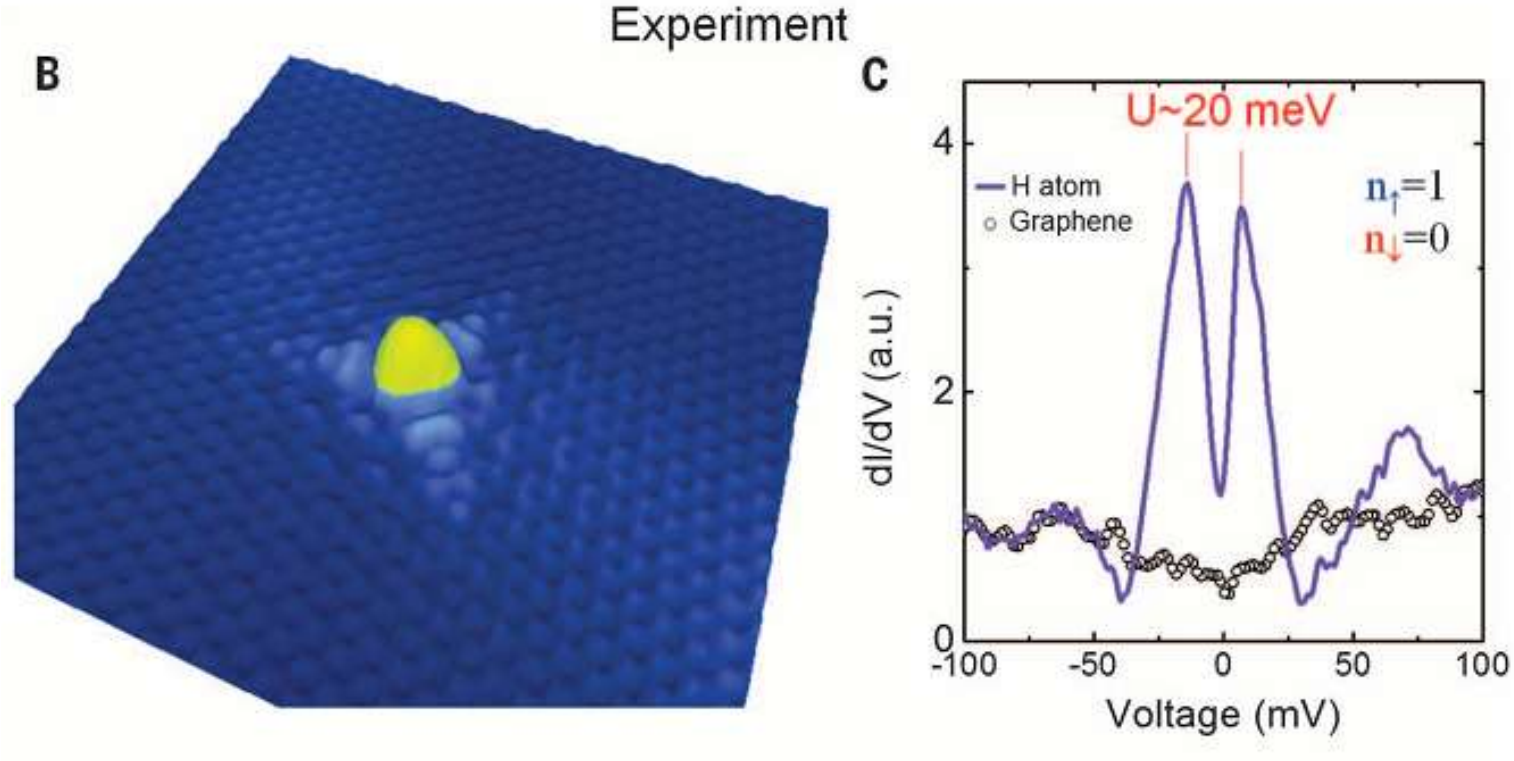

T = 5 K

González-Herrero, et al, Science (2016)

Hydrogen Doping

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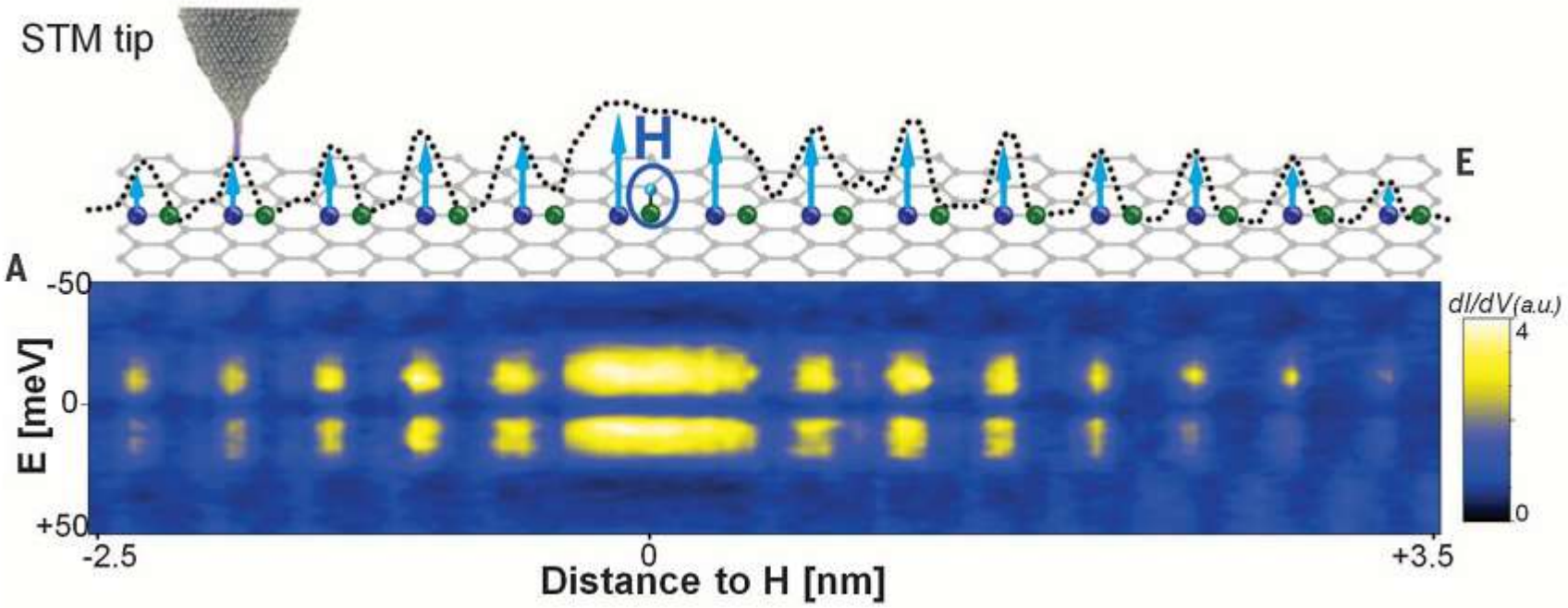

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Hydrogen Doping

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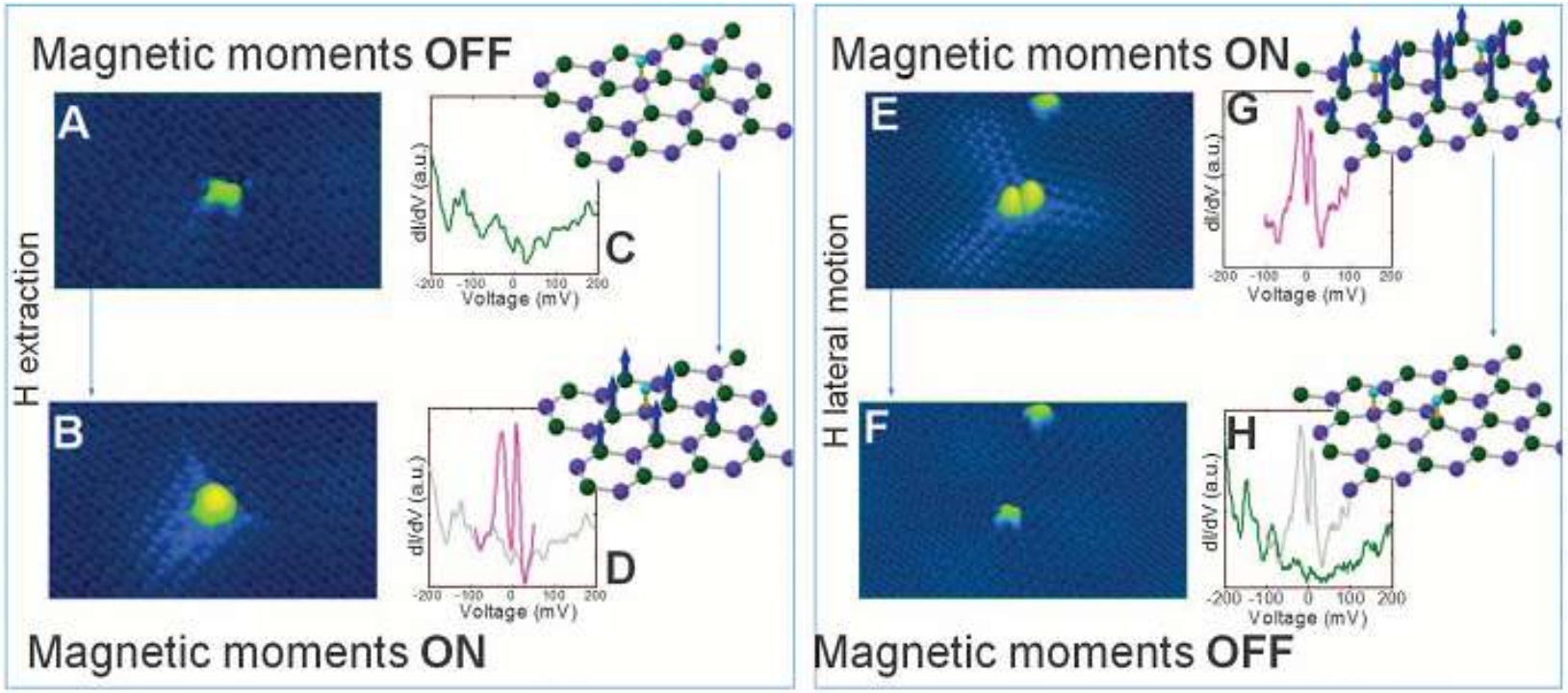
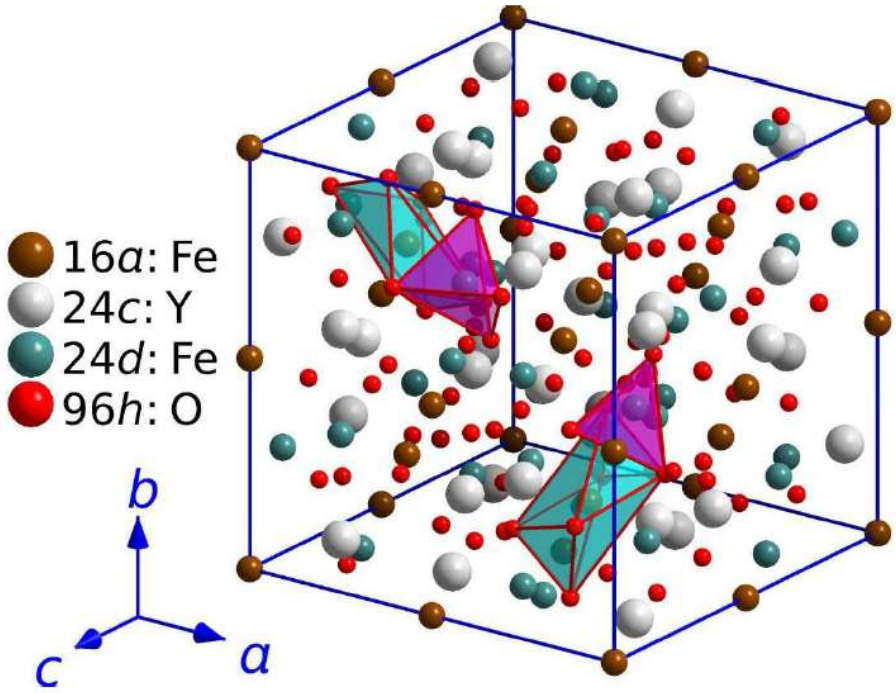


González-Herrero, et al, Science (2016)

Proximity effect

Graphene on YIG



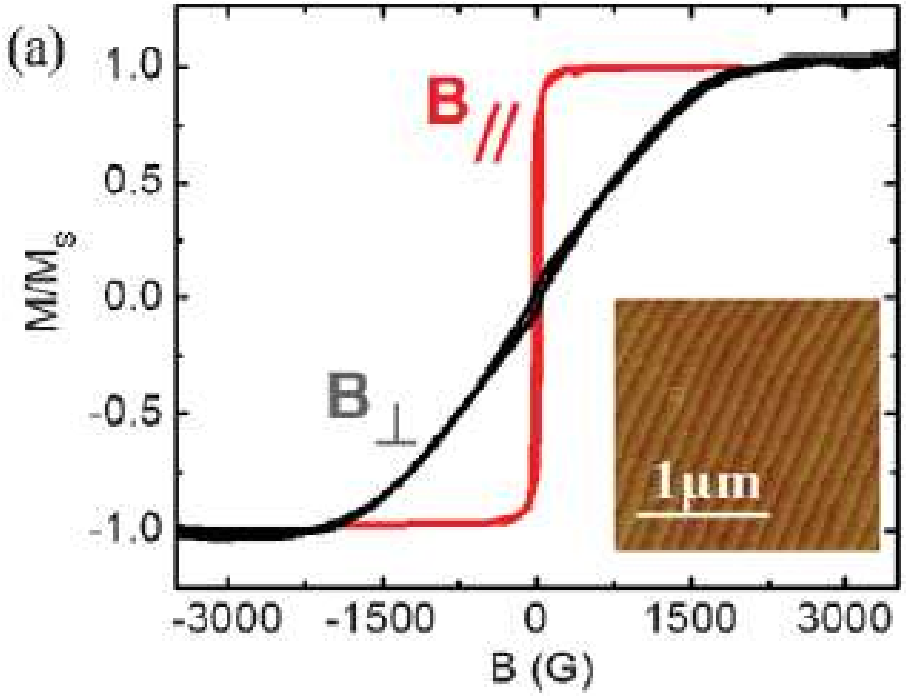
yttrium iron garnet (YIG):

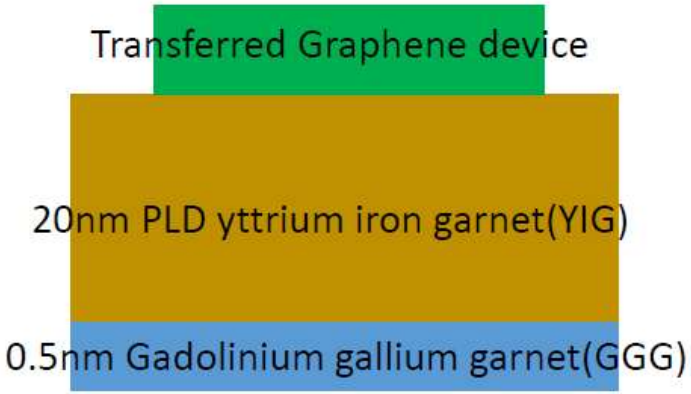
- **high Tc~550K;**
- **Extremely small intrinsic damping constant ($3x10^{-5}$);**
- **Insulating behavior;**
- **In-plane magnetic anisotropy.**

$Y_3Fe_5O_{12}$, YIG: A FM insulator

Proximity effect

Graphene on YIG

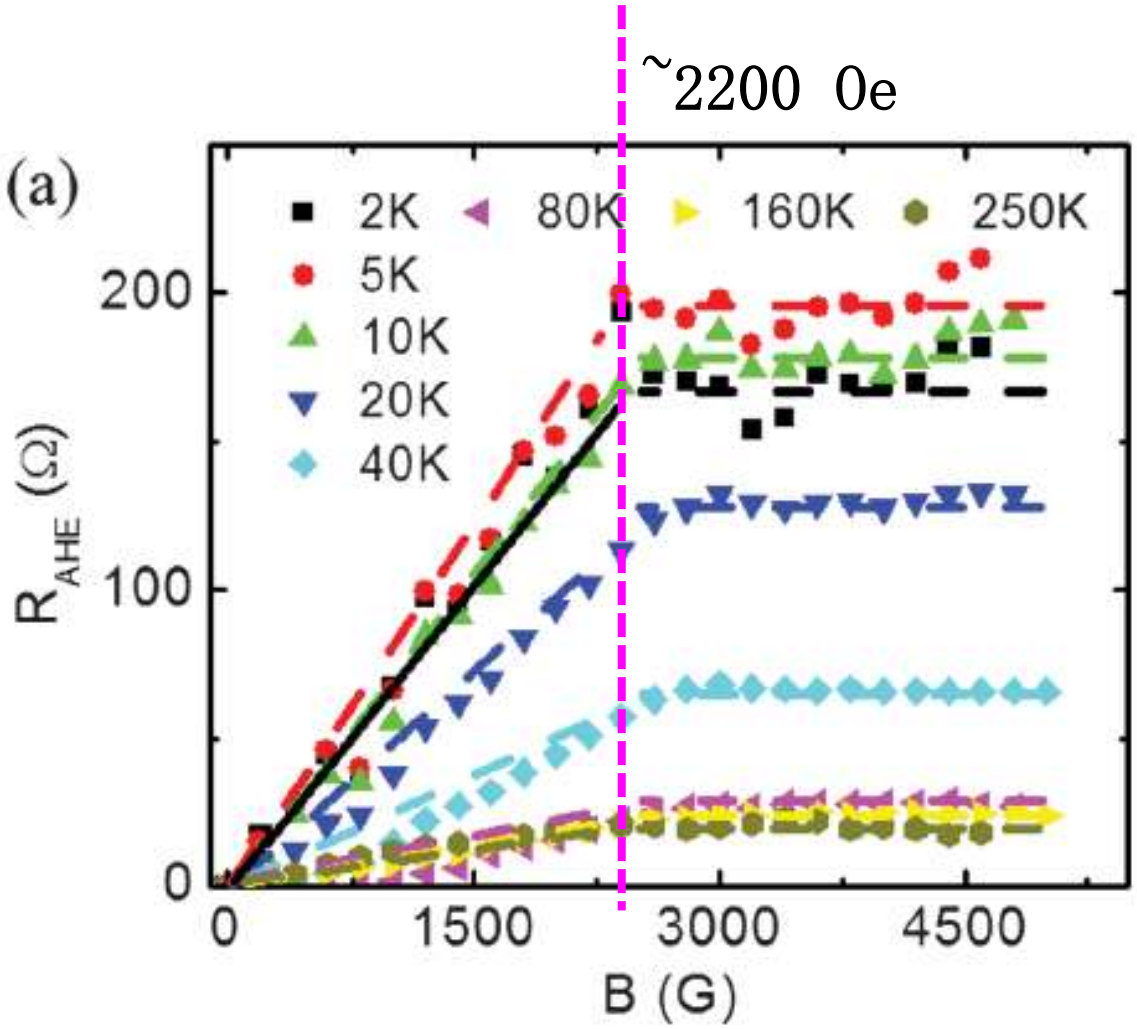


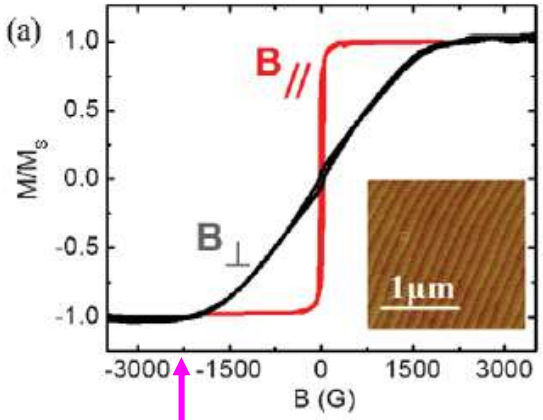


Wang, et al, PRL (2015)

Proximity effect

Graphene on YIG





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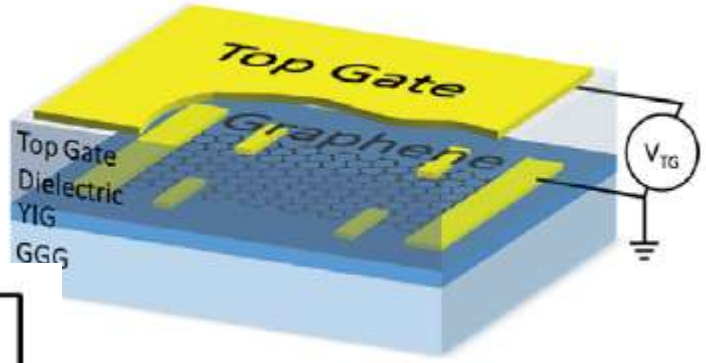
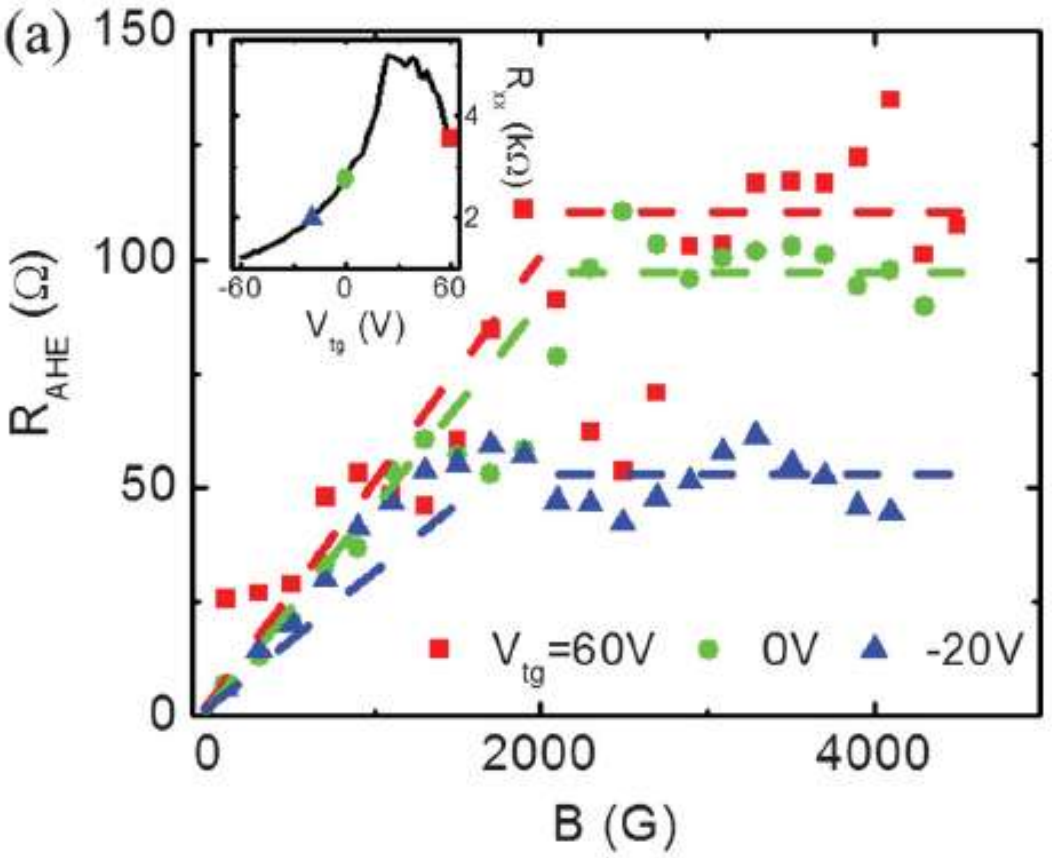
Proximity effect

Graphene on YIG





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Proximity effect

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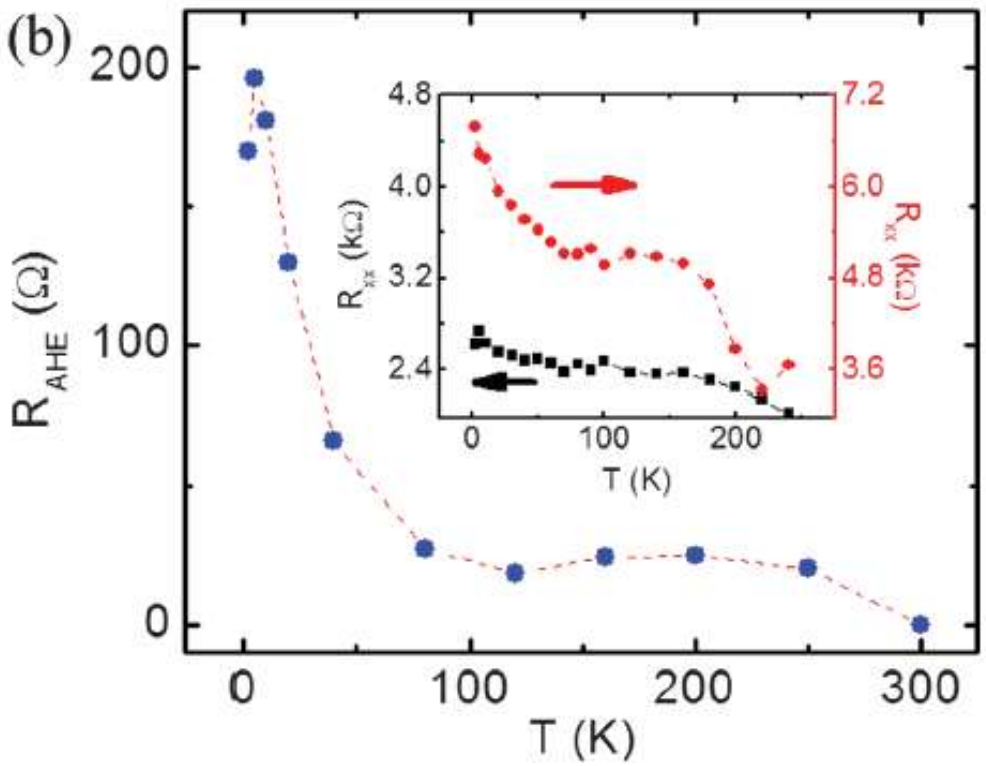
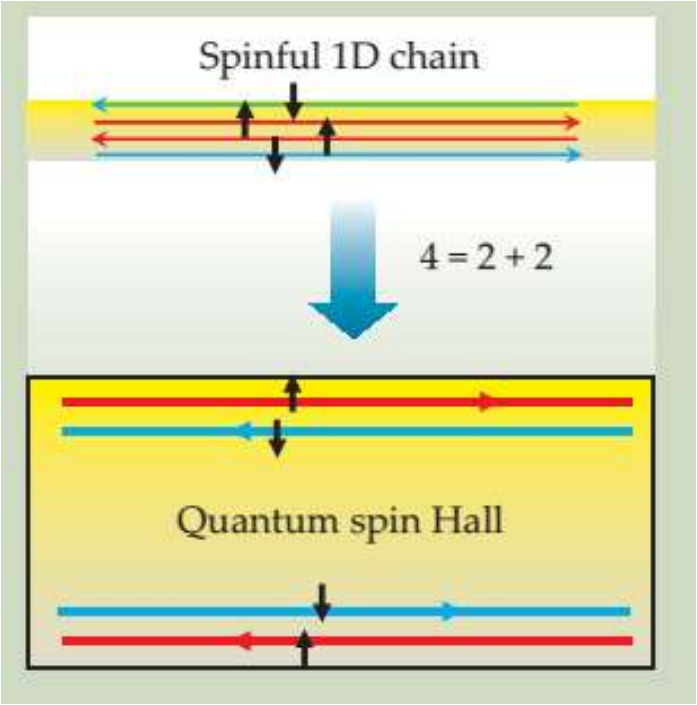


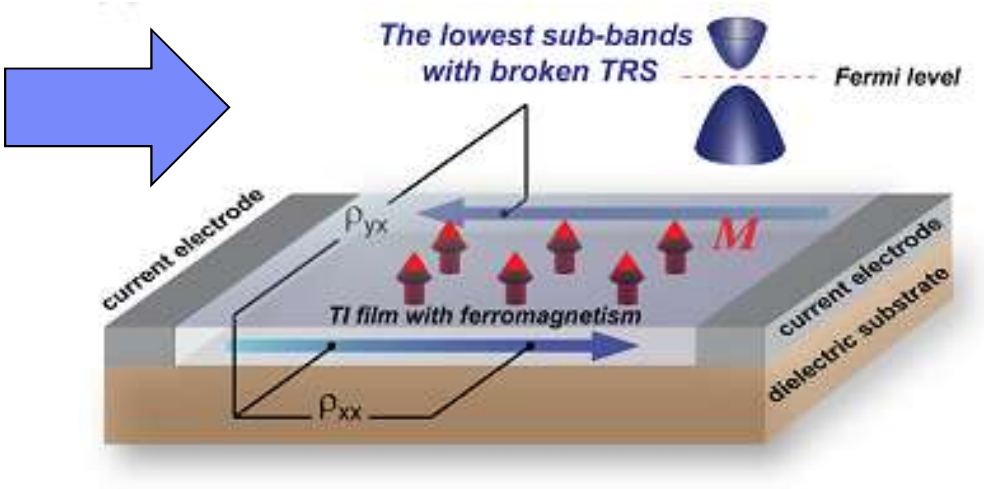
$$R_{xy} = R_H(B) + R_{\mathrm{AHE}}(M) = \alpha B + \beta M$$

$$R_{\mathrm{AHE}} \propto M_G R_{xx}^n$$

Induce M in Topological Insulator

Why making TI magnetic

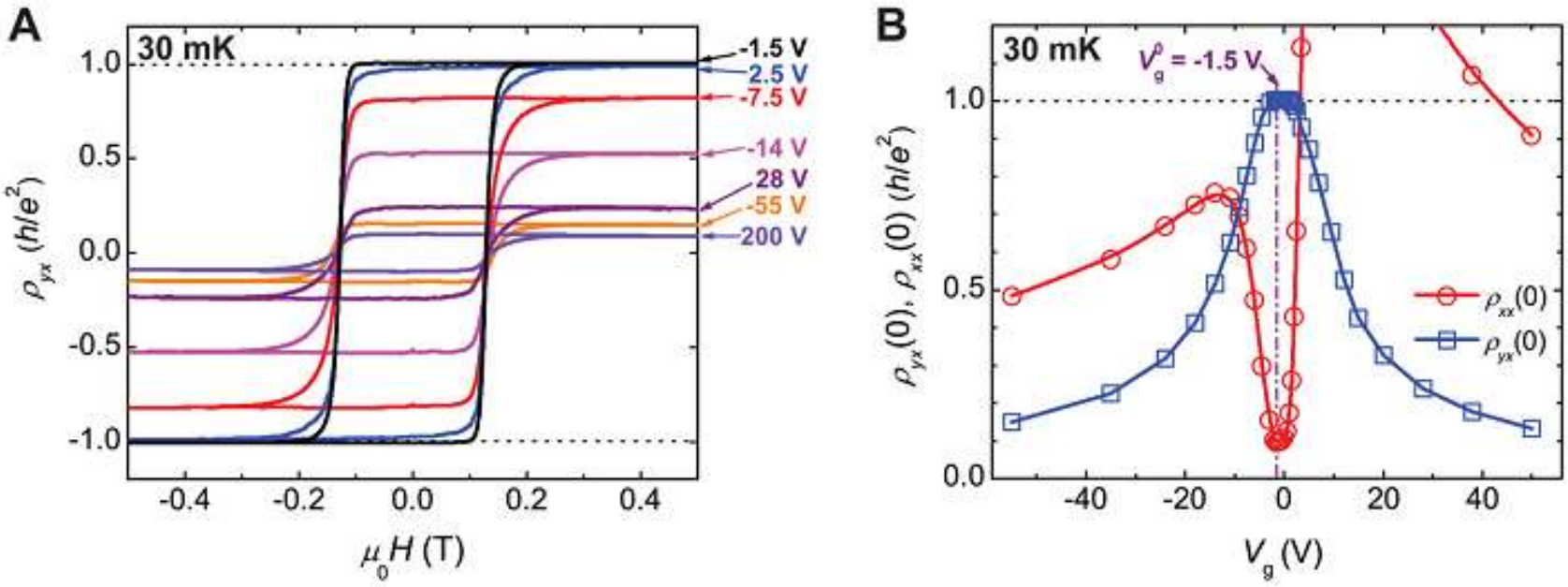




Quantum Anomalous Hall effect

Doping of Magnetic impurity

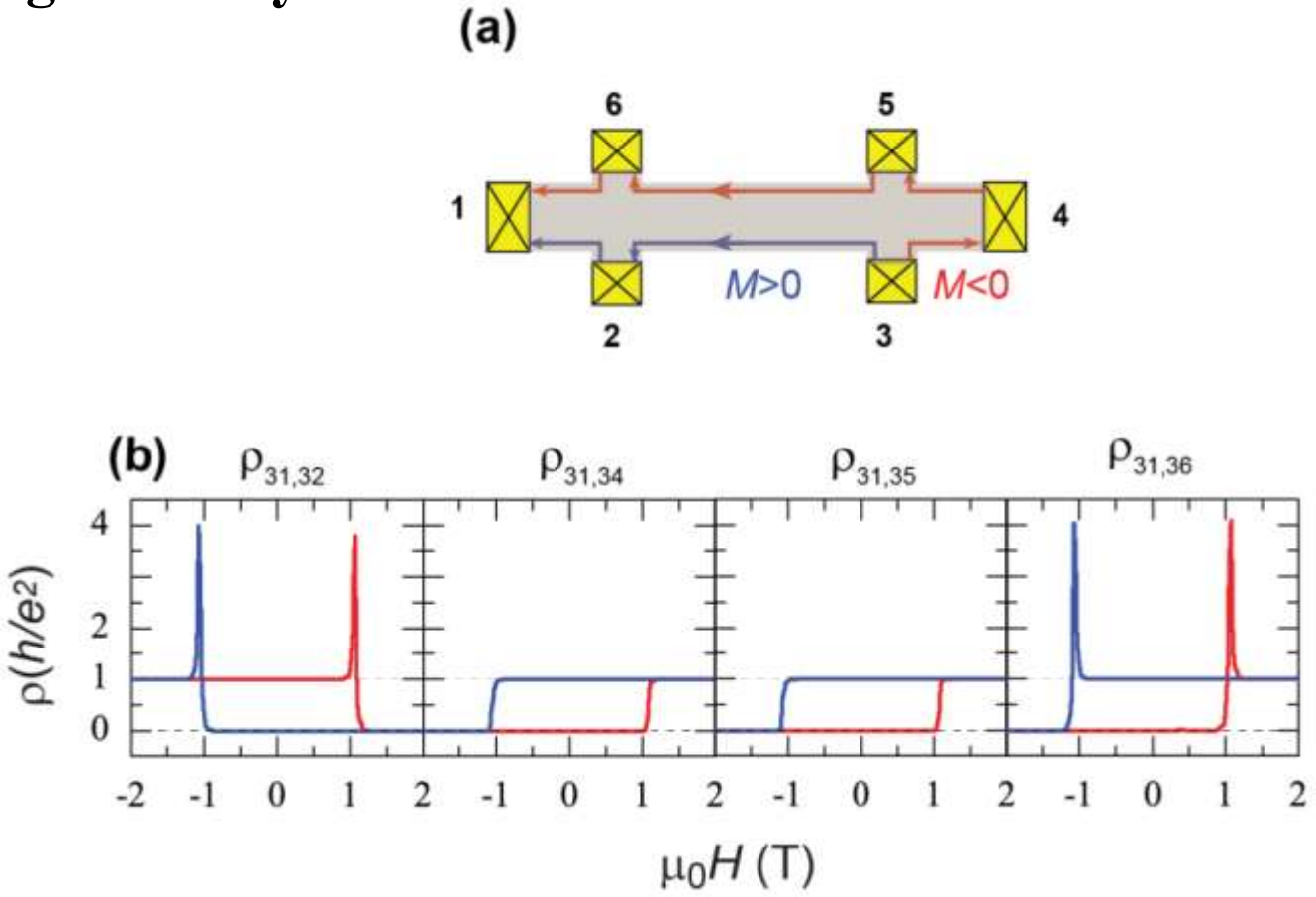
Doping effect by Cr



Chang, et al, Science (2013)

Doping of Magnetic impurity

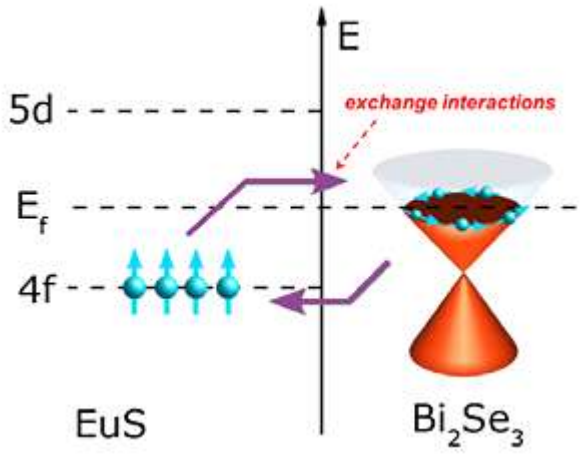
Doping effect by V

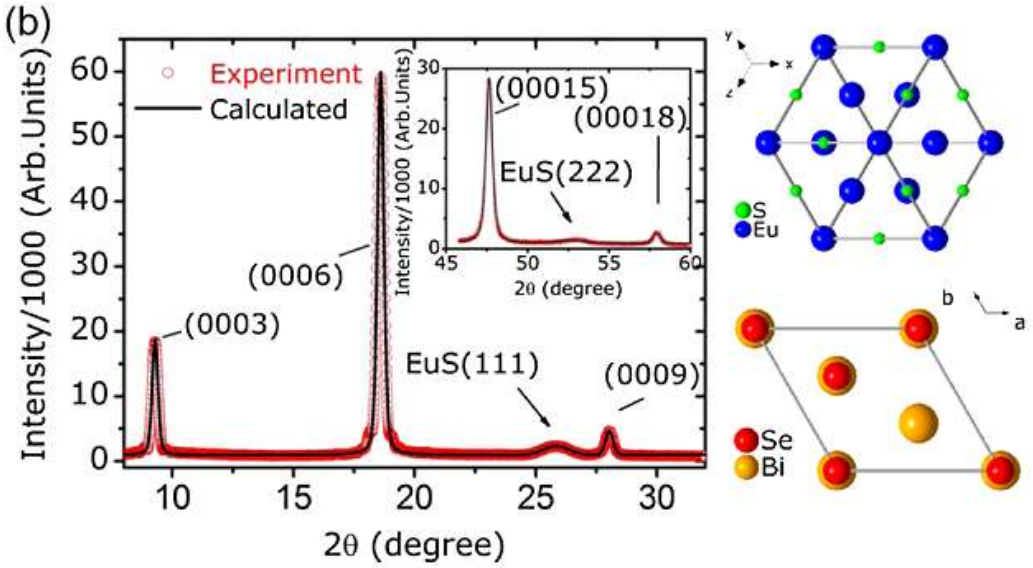


Chang, et al, Nat. Mater. (2015)

Proximity effect

EuS: magnetic insulator

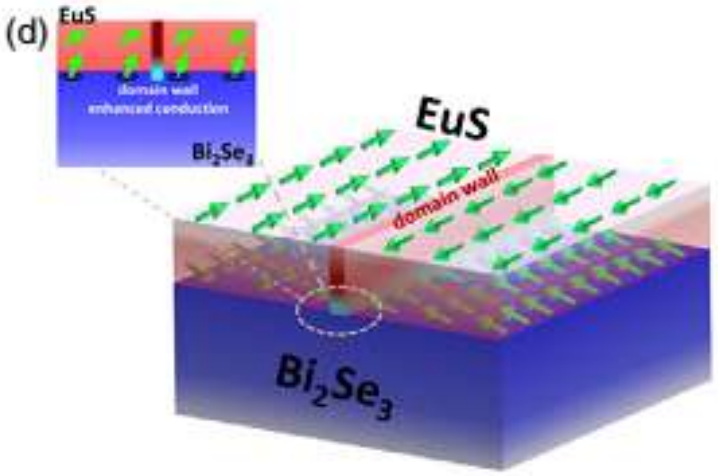


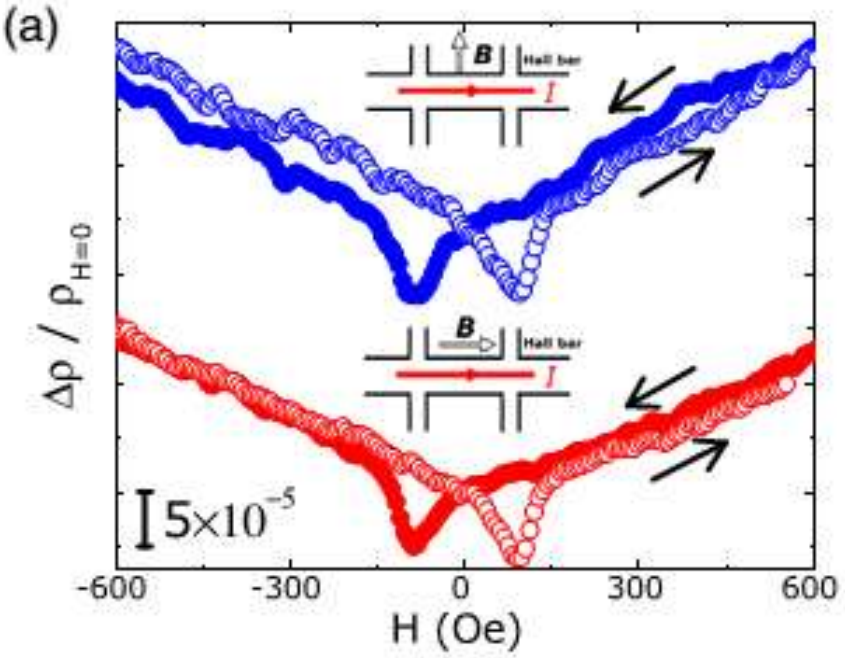


Wei, et al, PRL (2013)

Proximity effect

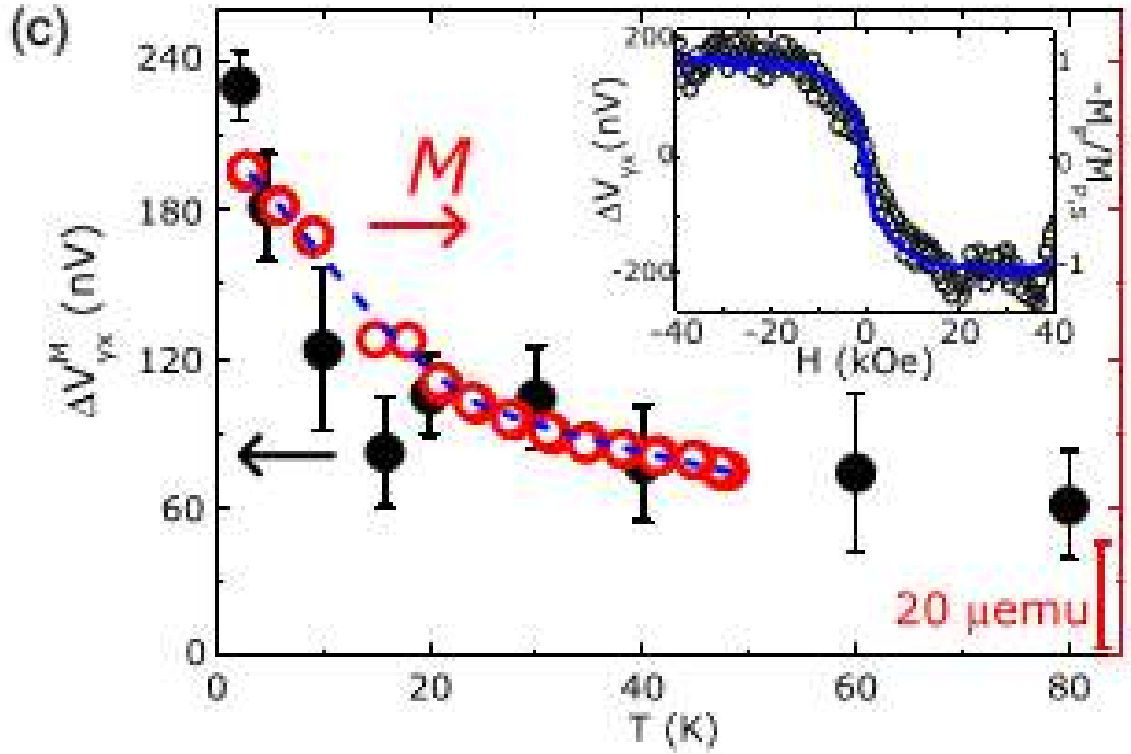
EuS: magnetic insulator





Proximity effect

EuS: magnetic insulator

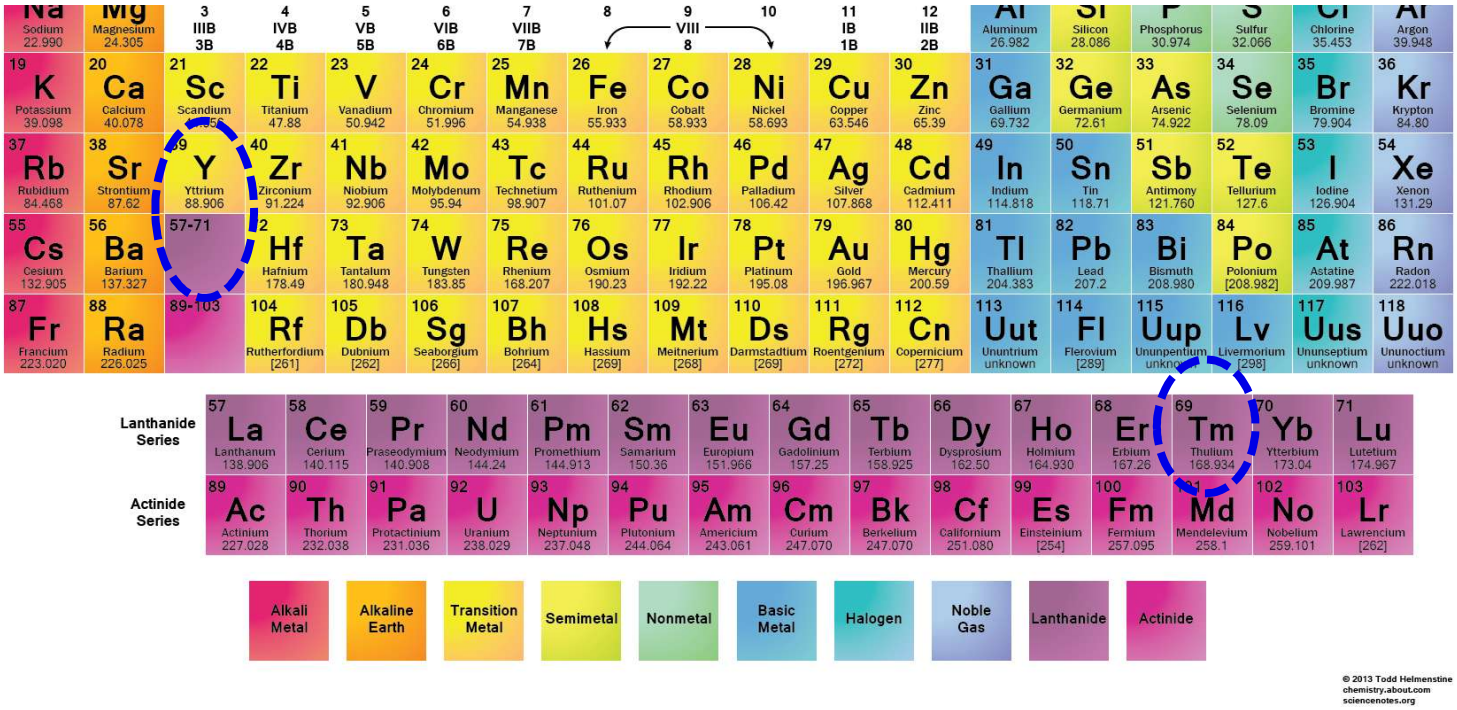


Wei, et al, PRL (2013)

Proximity effect

TIG, a magnetic insulator with perpendicular easy axis

$Y_3Fe_5O_{12}$ → $Tm_3Fe_5O_{12}$

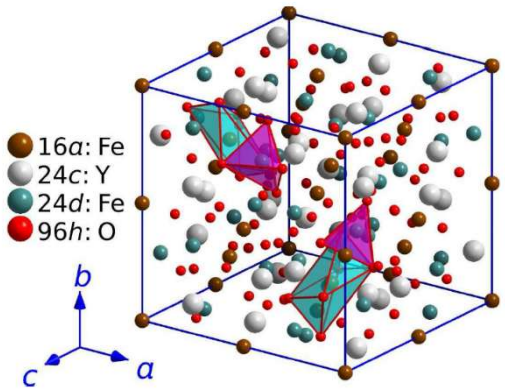


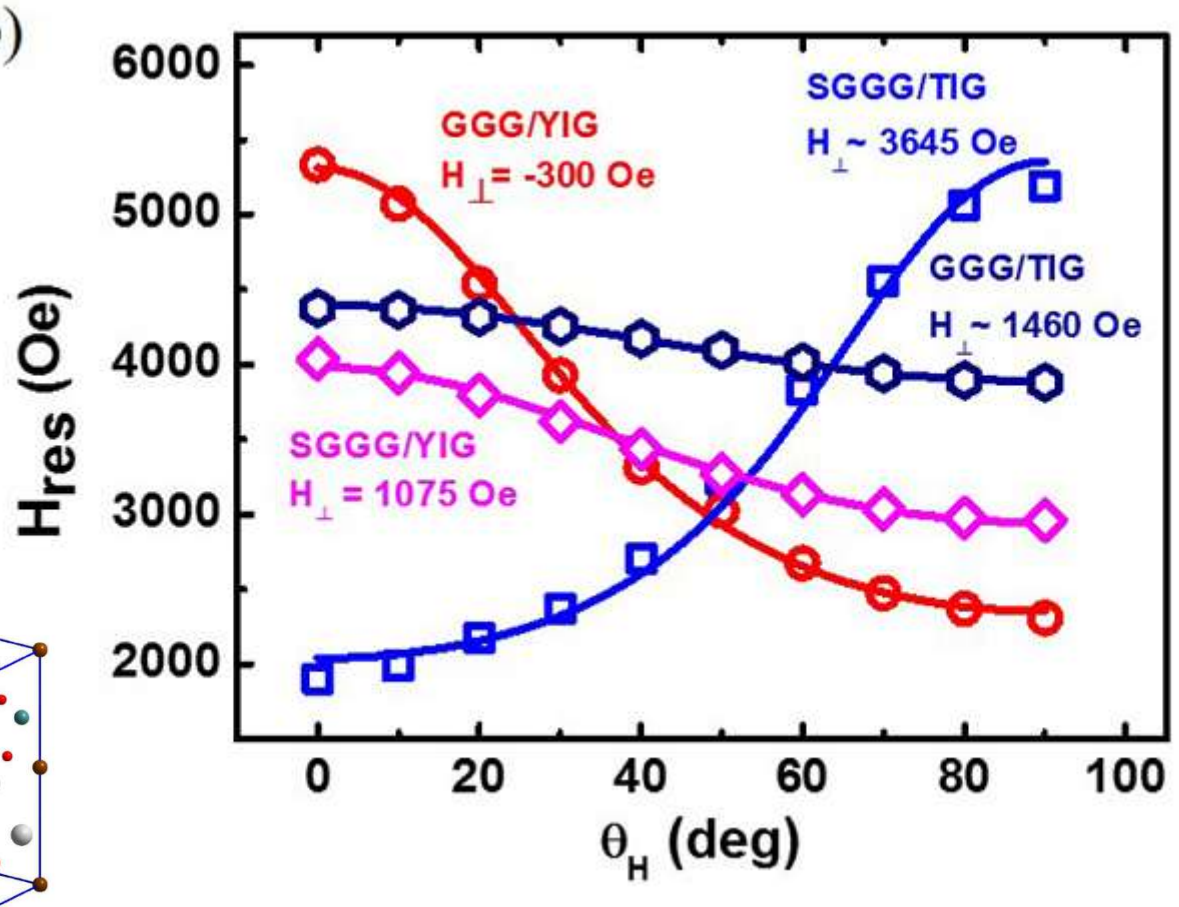
Proximity effect

TIG, a magnetic insulator with perpendicular easy axis

$Y_3Fe_5O_{12}$

$Tm_3Fe_5O_{12}$

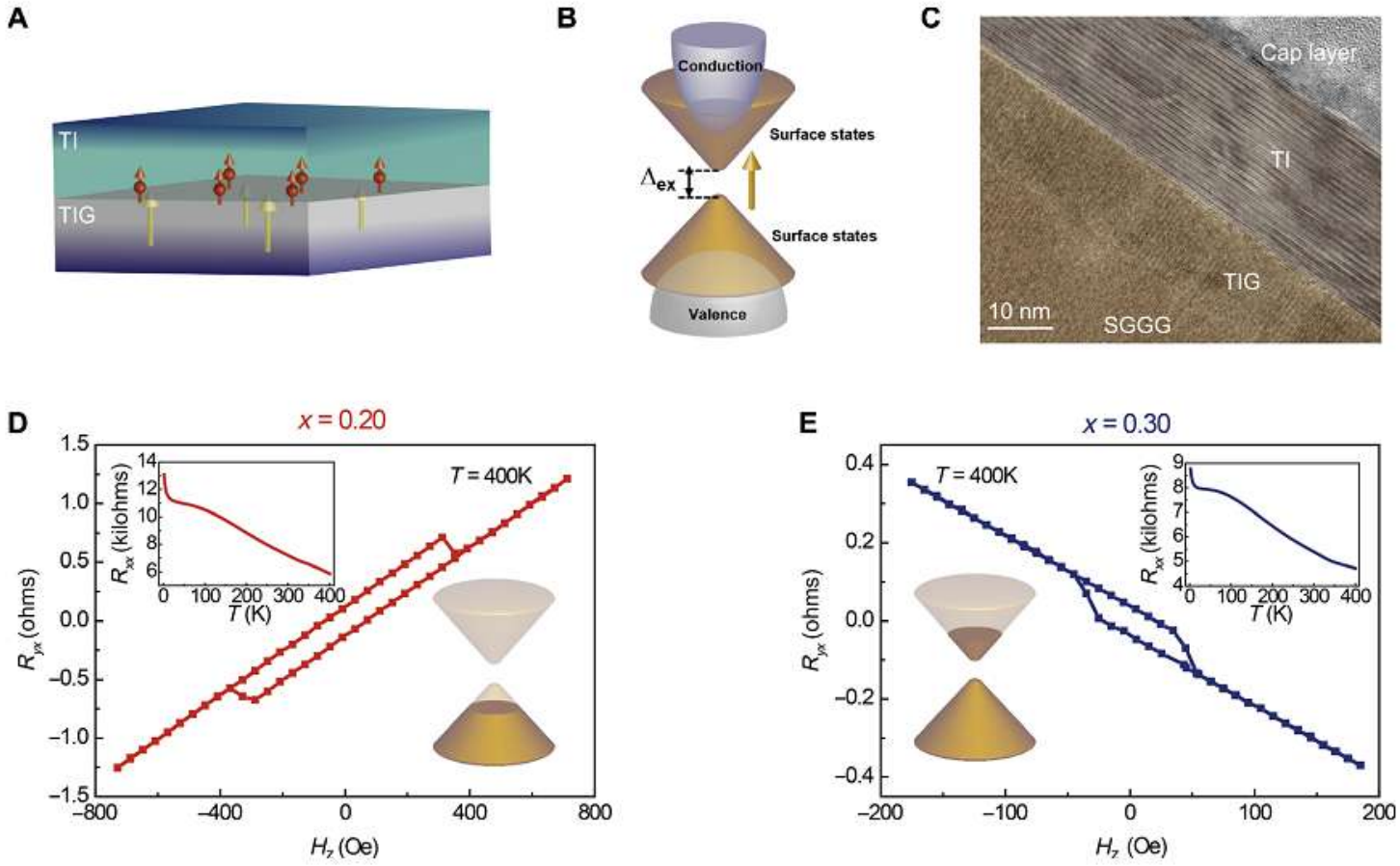




Tang, et al, PRB (2017)

Proximity effect

TIG, a magnetic insulator with perpendicular easy axis



Tang, et al, Science Advances (2017)

Proximity effect

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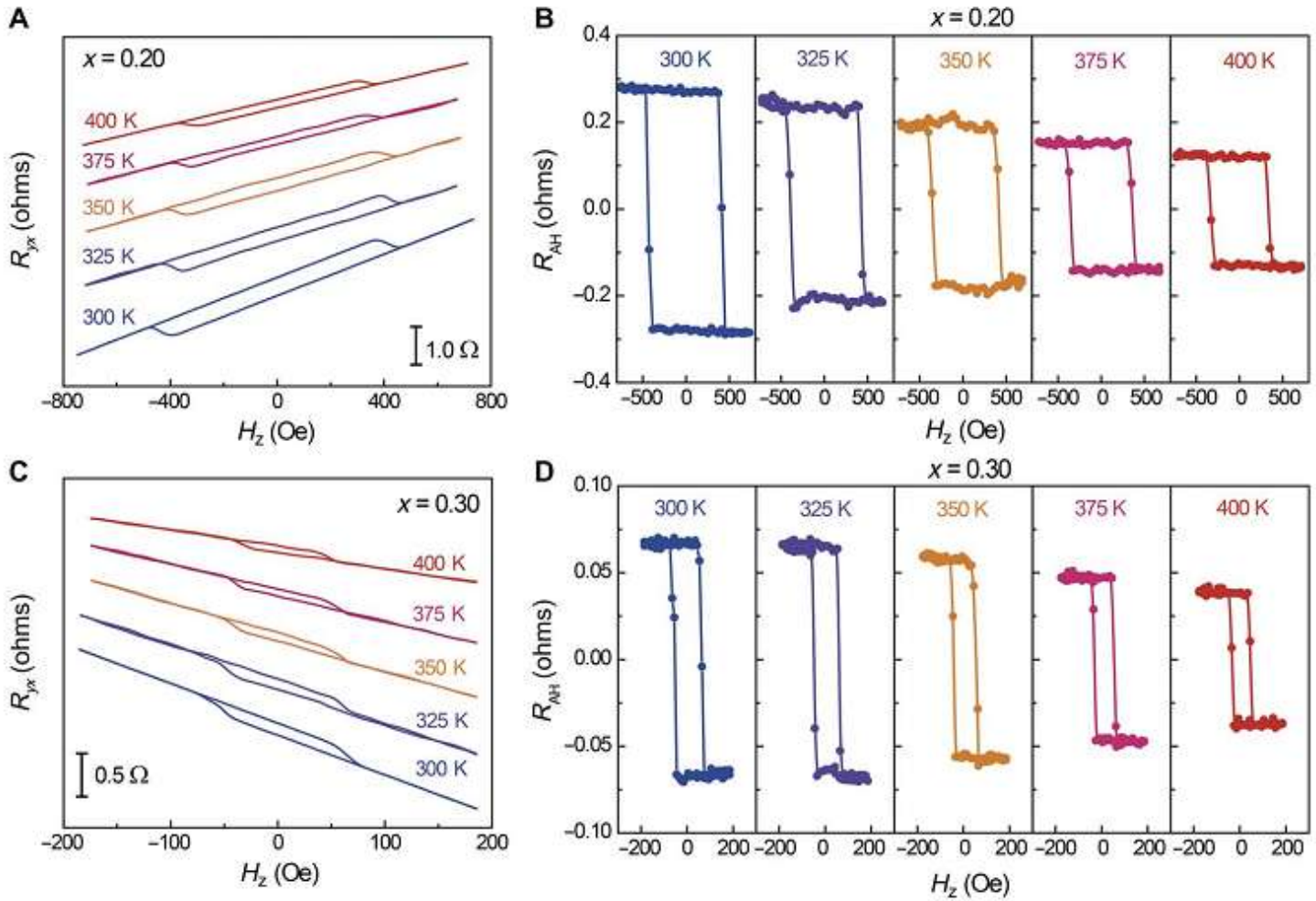
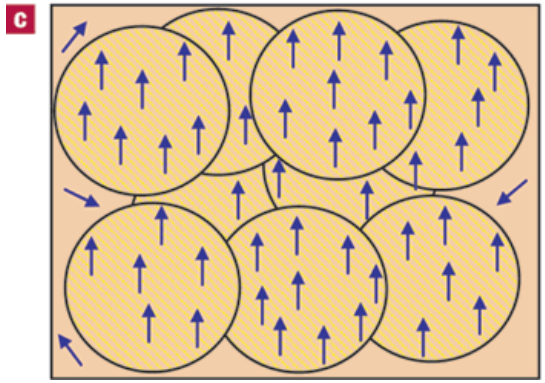


Tang, et al, Science Advances (2017)

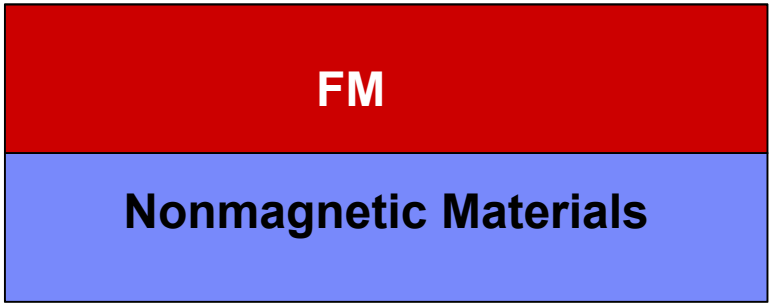
Summary

How to induce magnetic moment

Doping



Proximity effect



Interface hybridization

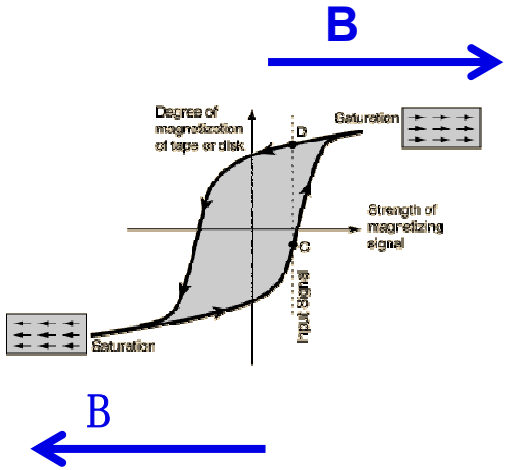
休息10分钟

提纲

3. How to control magnetization

How to control the magnetization

Magnetic field



Without B

???

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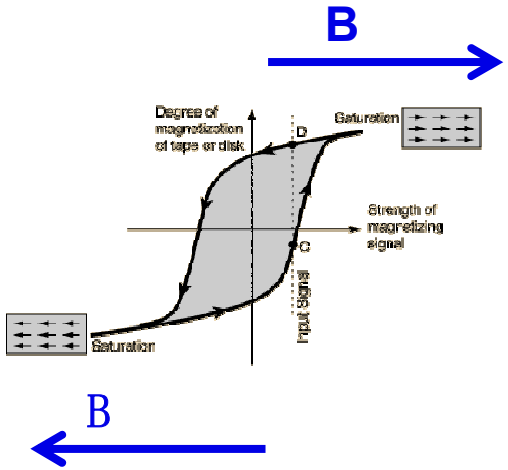
How to control the magnetization

Magnetic field



Without B

???

Control??

Electric field

Ultrafast Laser

Spin torque

Interface Strain

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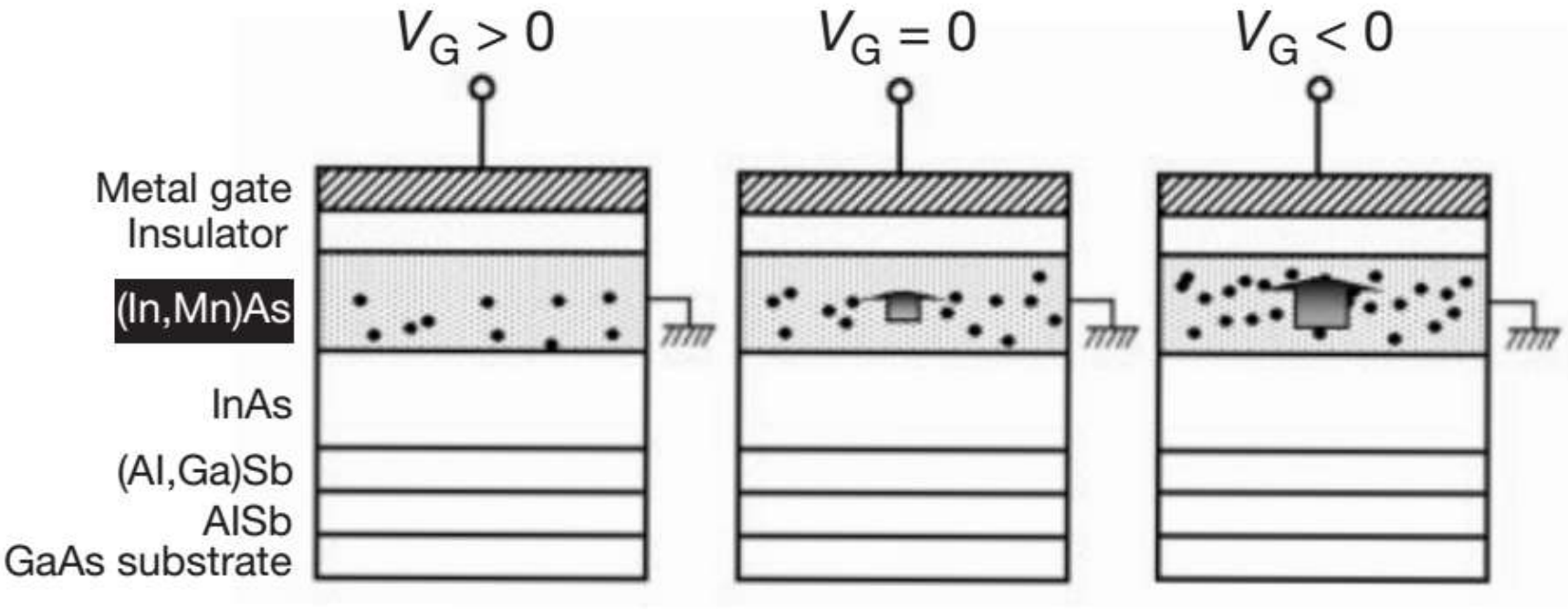
Electric field control the magnetization

Electrical field effect in magnetic semiconductor



Ohno, et al, Nature (2000)

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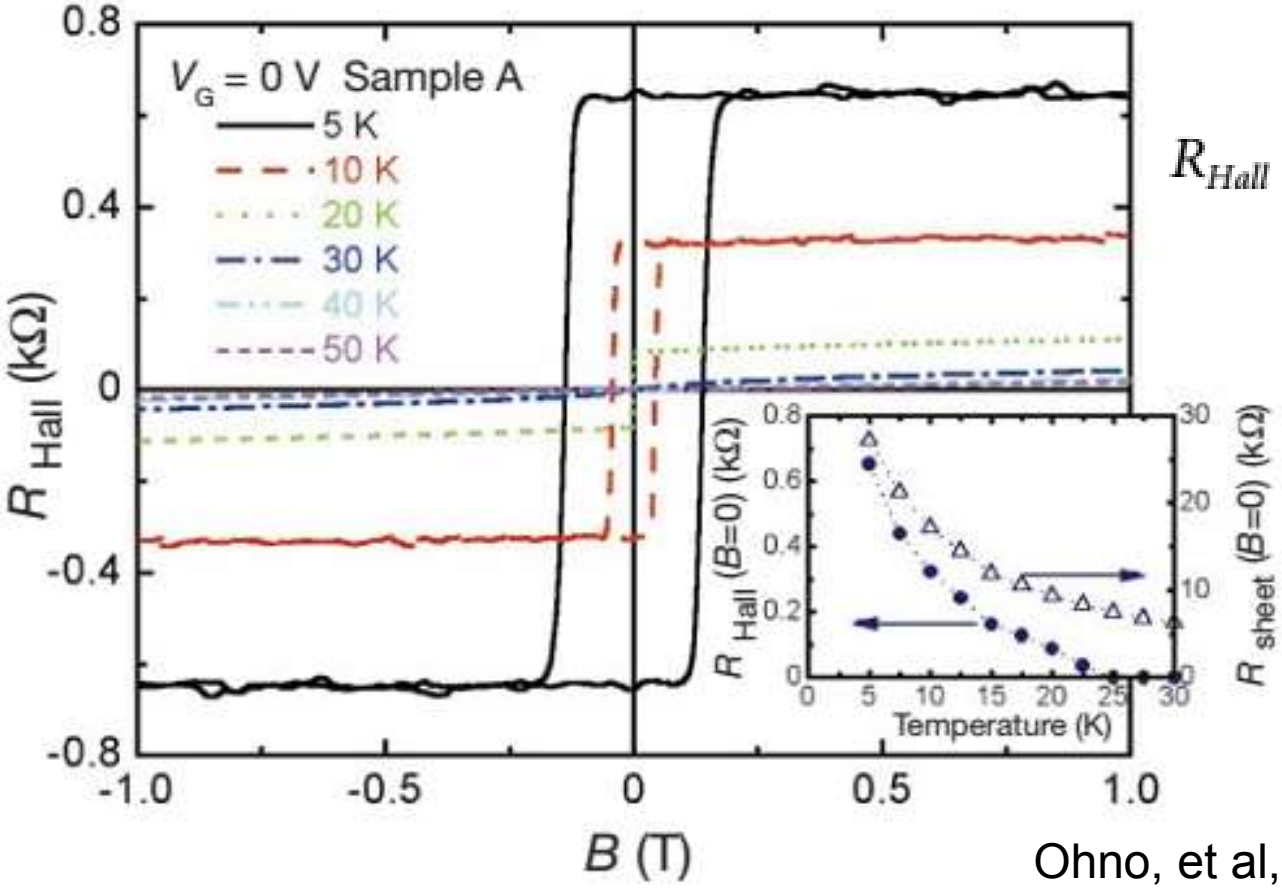
Electric field control the magnetization

Magnetic properties of InMnAs (AHE)



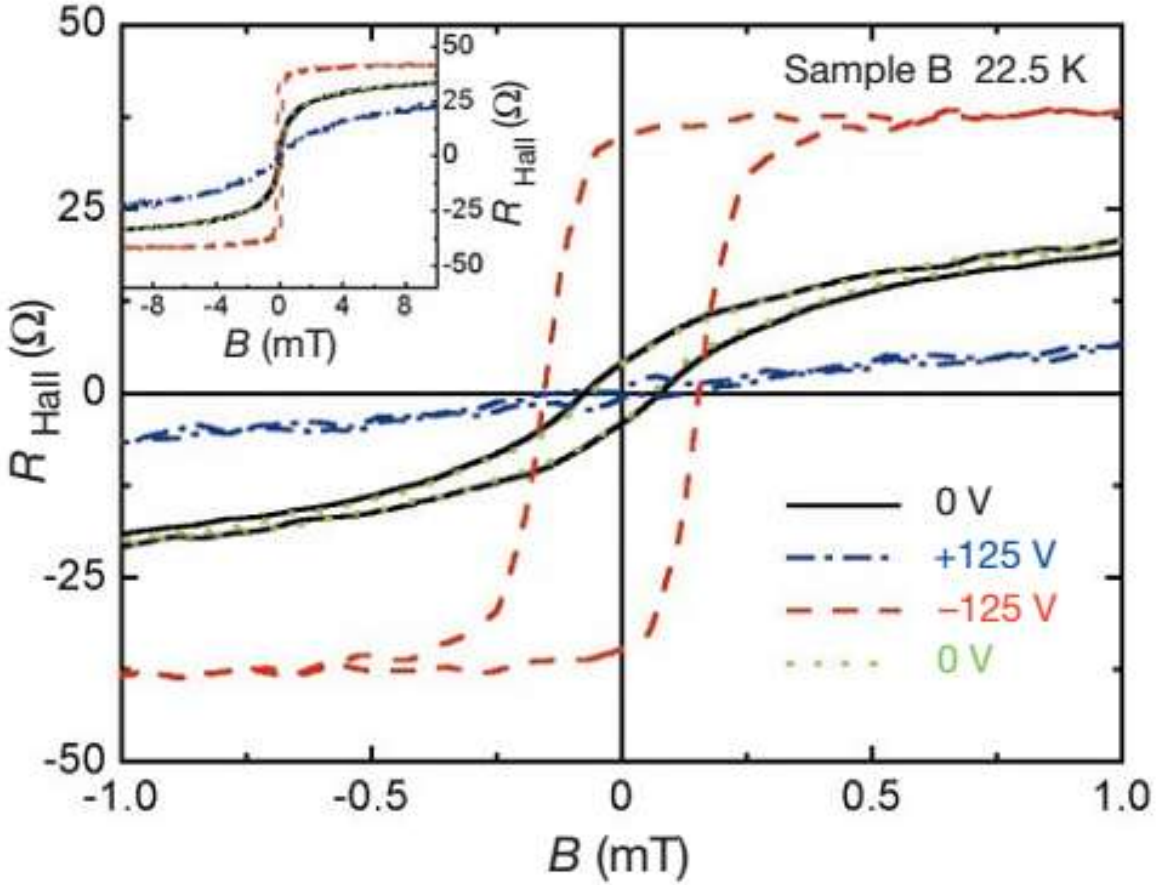
$$R_{Hall} = \frac{R_0}{d}B + \frac{R_S}{d}M$$

Ohno, et al, Nature (2000)

40

Electric field control the magnetization

Electrical field effect on InMnAs



Ohno, et al, Nature (2000)

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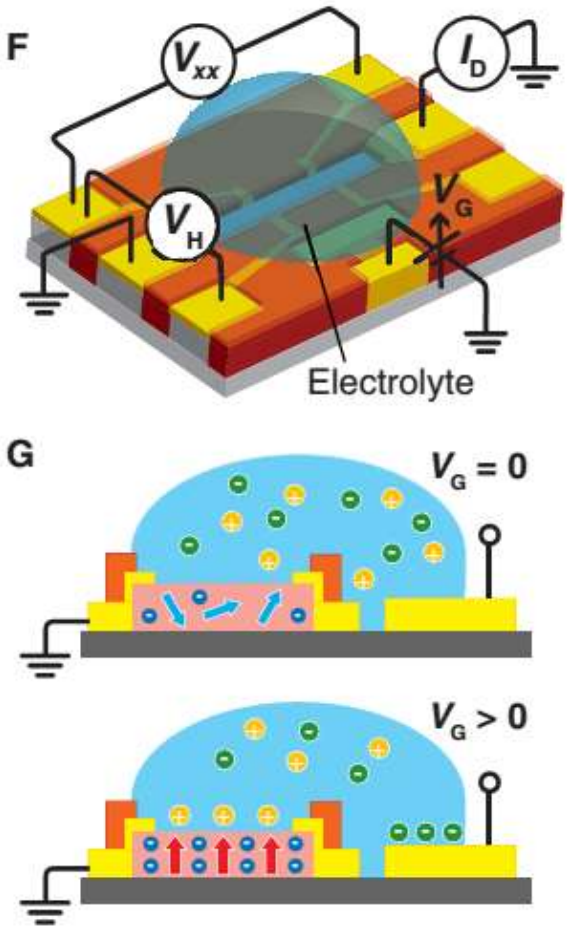
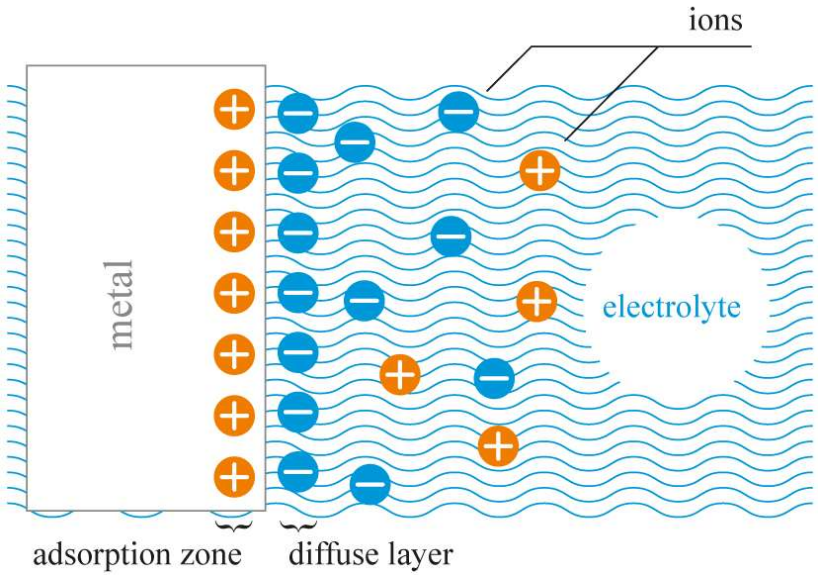
Electric field control the magnetization

Ionic liquid gate control





Large electric field on the surface

Yamada, et al, Science (2011)

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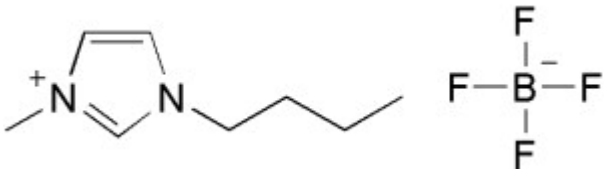
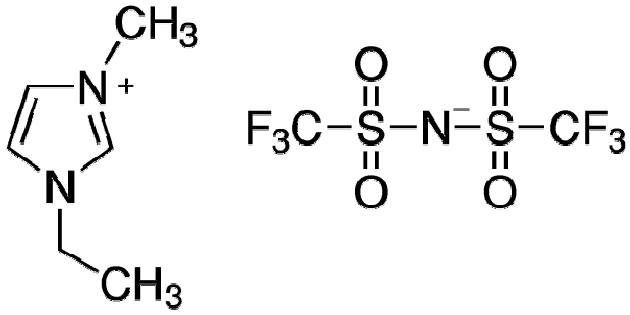
Electric field control the magnetization

Ionic liquid

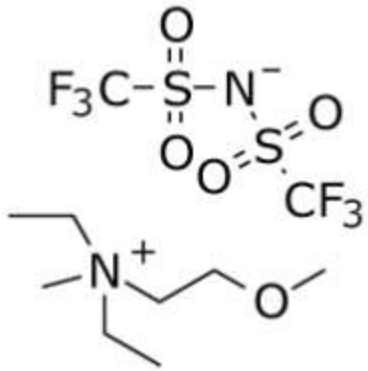
HMIM BF_4



EMIM TFSI



DEME TFSI



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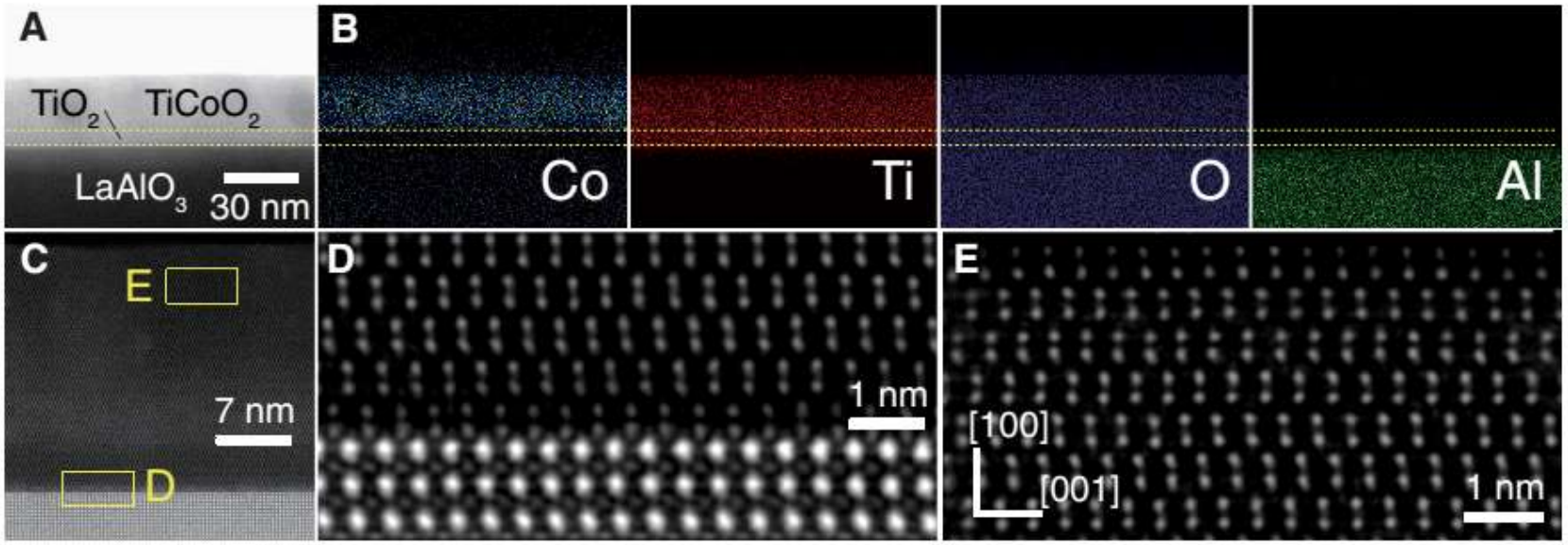
Electric field control the magnetization

Ionic liquid gate control



$Ti_{0.9}Co_{0.1}O_2$

$T_C > 300$ K

Yamada, et al, Science (2011)

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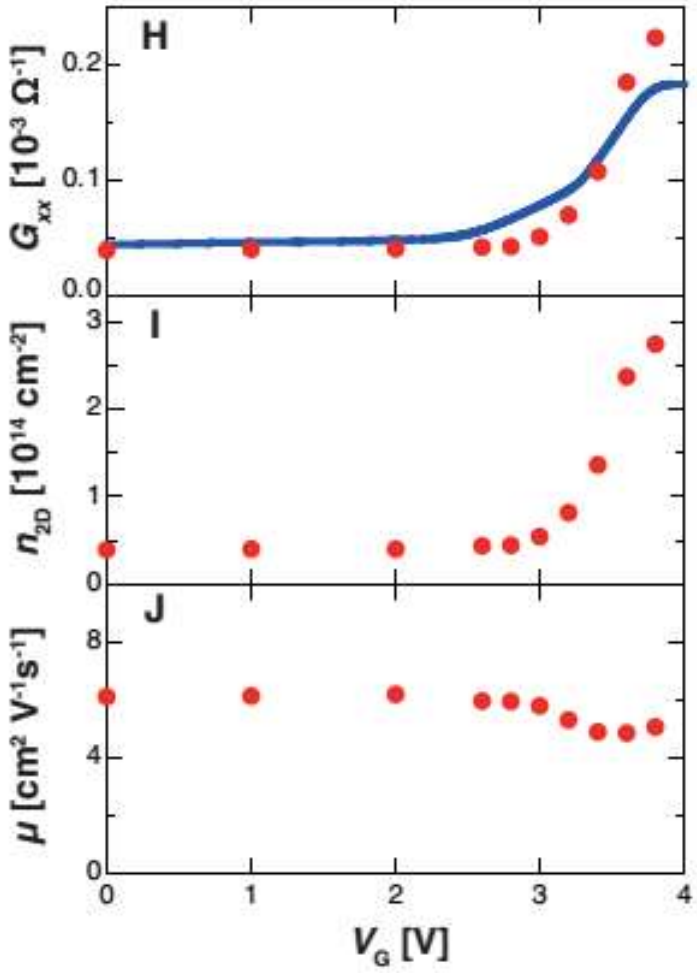
Electric field control the magnetization

Ionic liquid gate control electronic properties

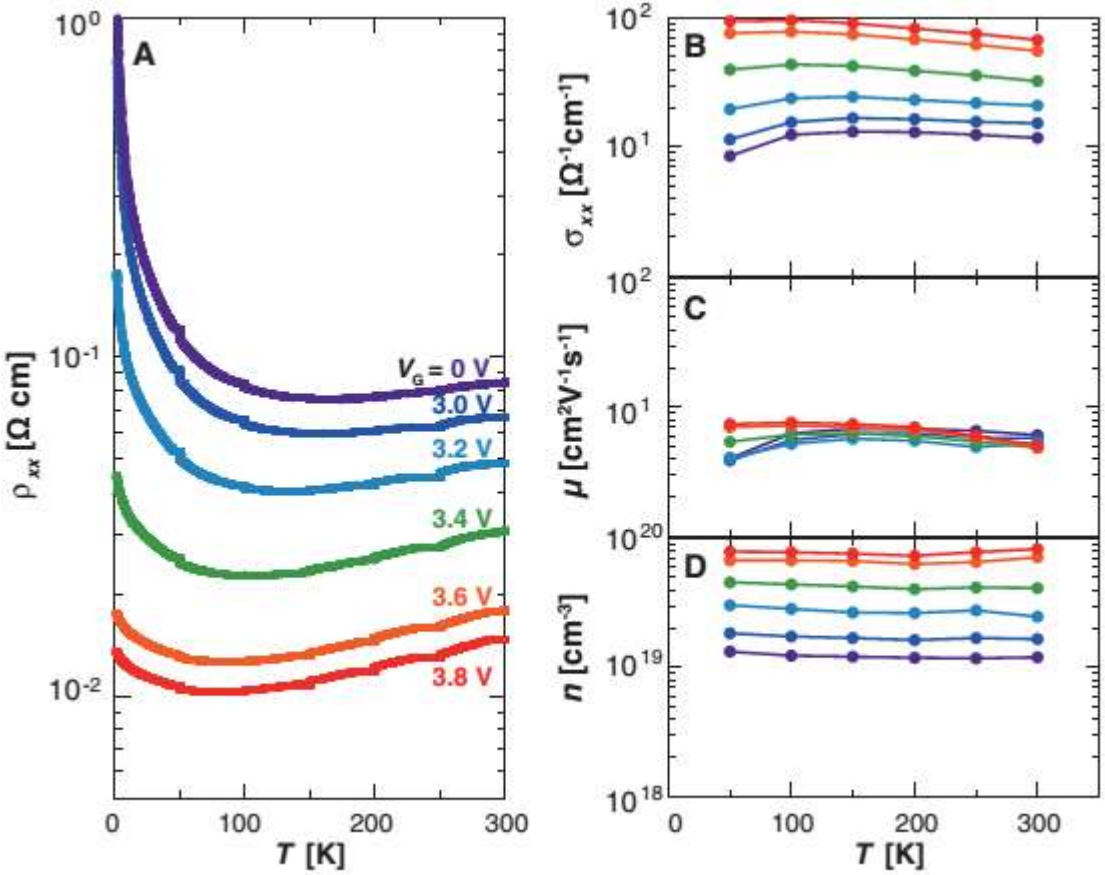


Yamada, et al, Science (2011)

45

Electric field control the magnetization

Ionic liquid gate control electronic properties

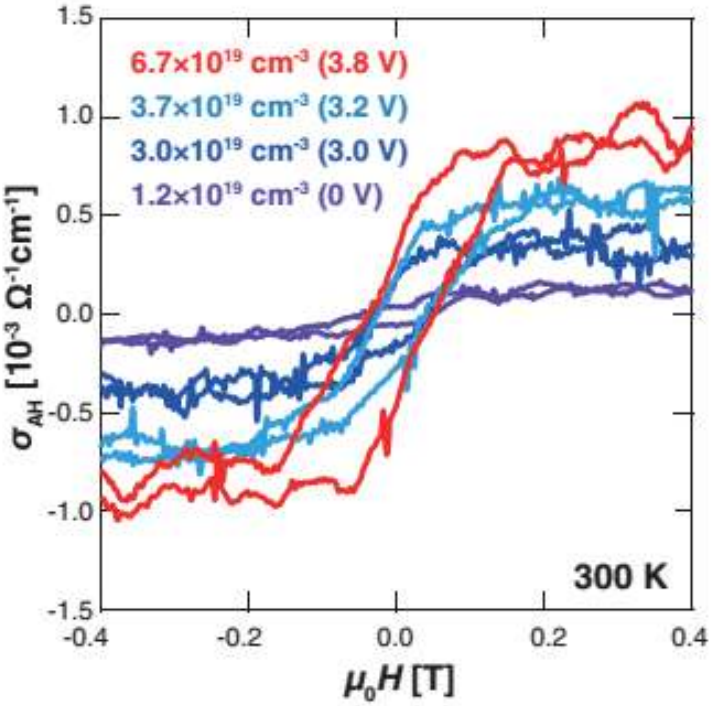


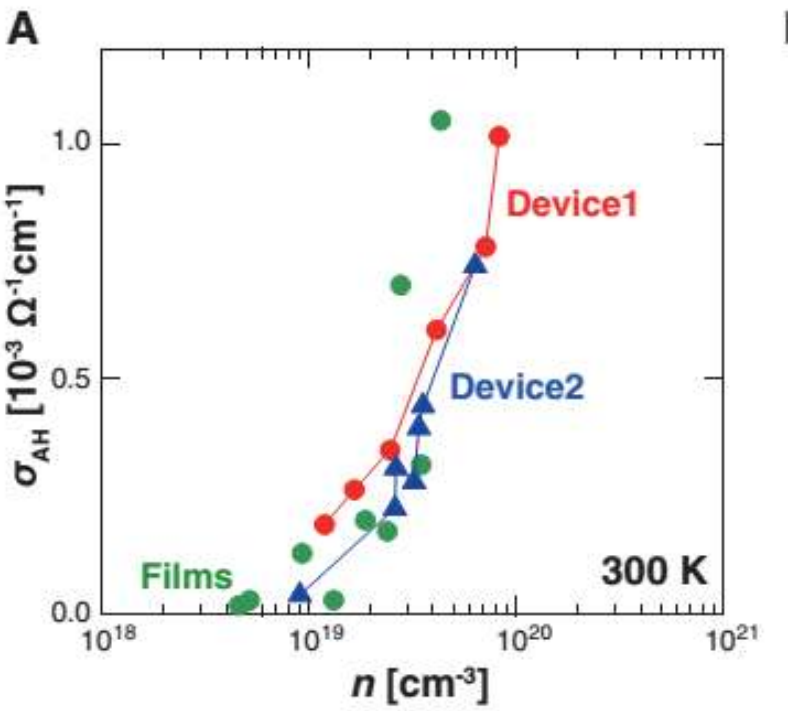
Yamada, et al, Science (2011)

46

Electric field control the magnetization

Ionic liquid gate control magnetic properties

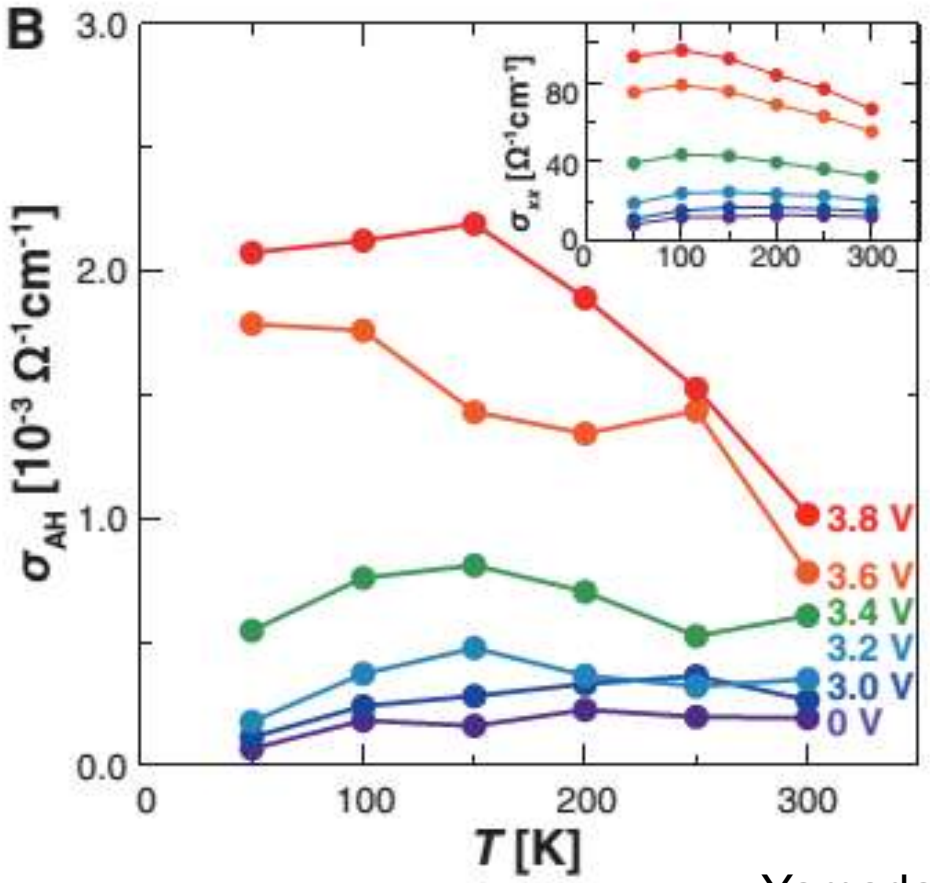




Yamada, et al, Science (2011)

Electric field control the magnetization

Ionic liquid gate control magnetic properties



Yamada, et al, Science (2011)

Electric field control the magnetization

Electric field control in Metallic FM

nature materials

LETTERS

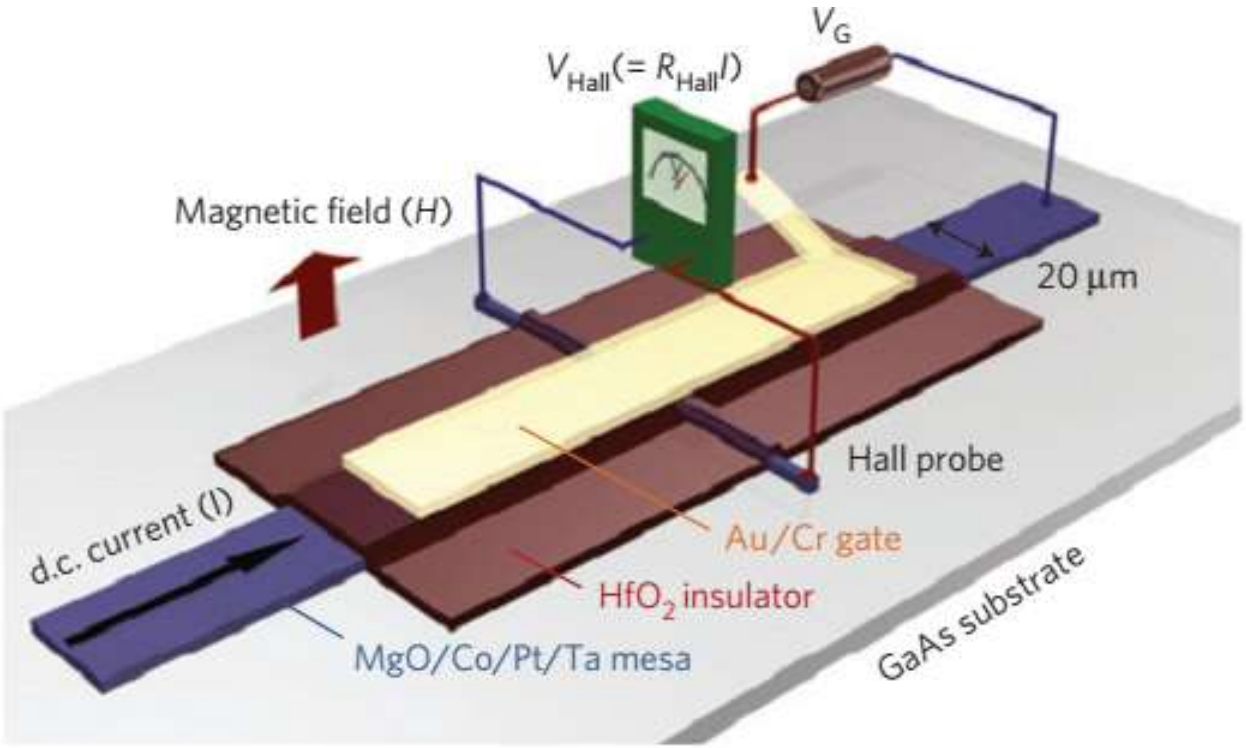
PUBLISHED ONLINE: 2 OCTOBER 2011 | DOI: 10.1038/NMAT3130

Electrical control of the ferromagnetic phase transition in cobalt at room temperature

D. Chiba[1,2]*, S. Fukami[3], K. Shimamura[1], N. Ishiwata[3], K. Kobayashi[1] and T. Ono[1]

Electric field control the magnetization

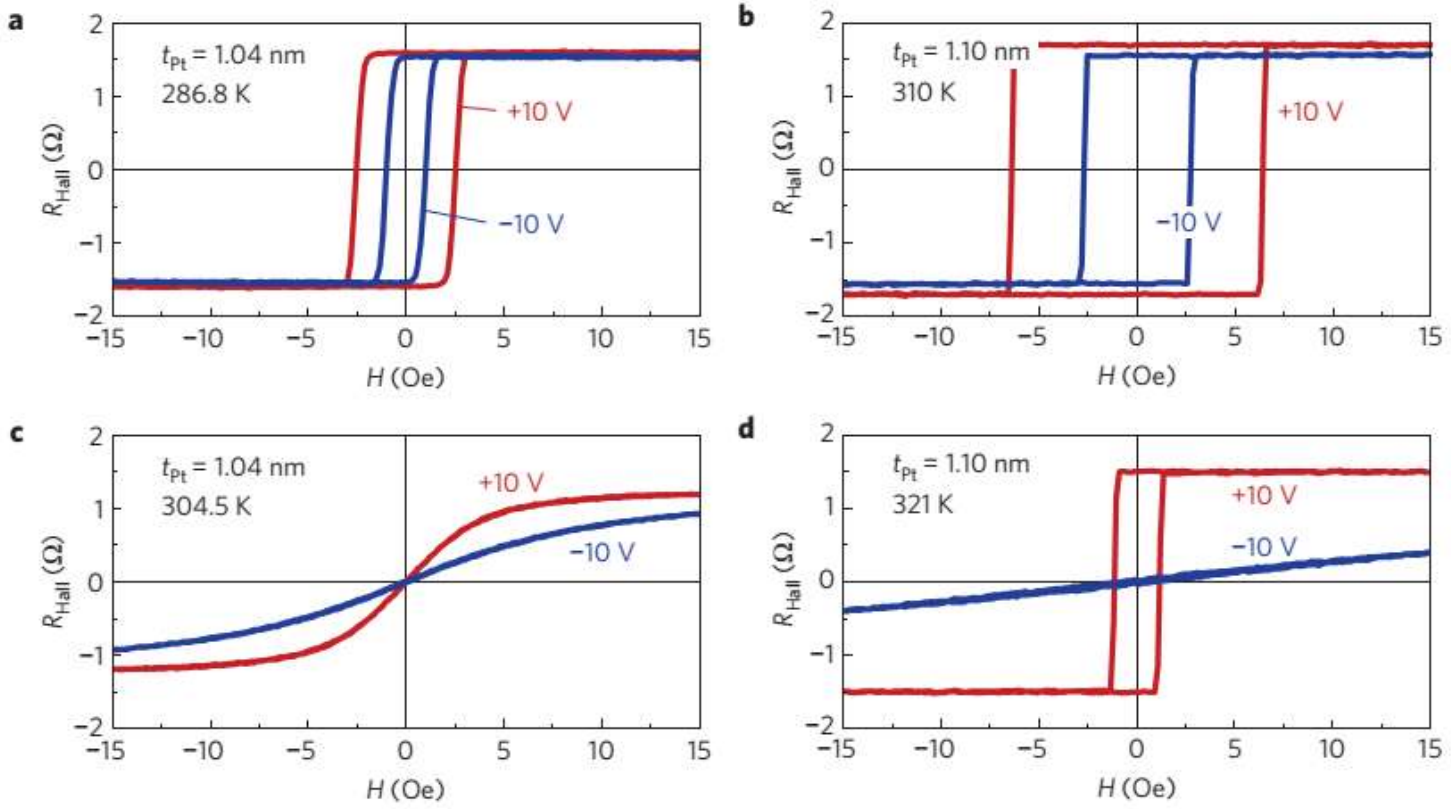
Electric field control in Metallic FM



Chiba, et al, Nat. Mater. (2011)

Electric field control the magnetization

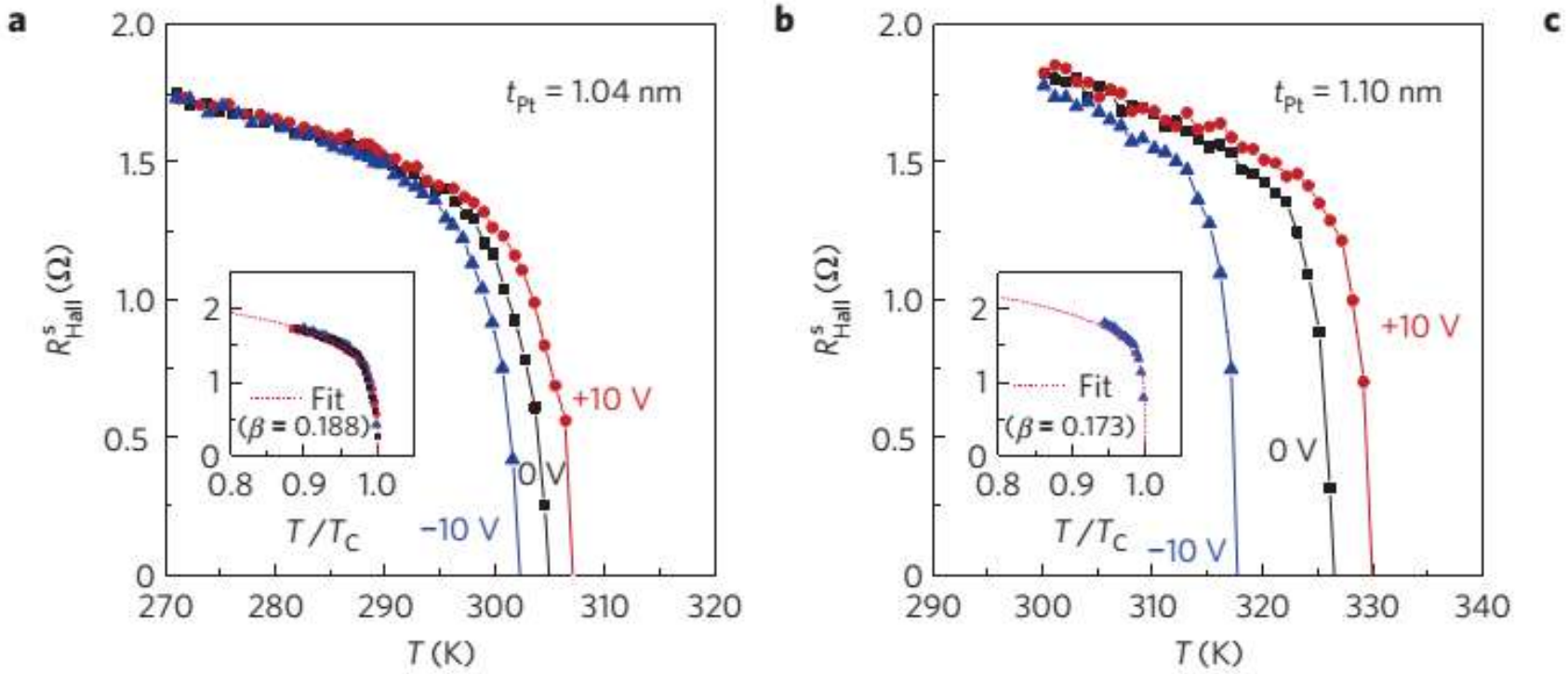
Electric field control in Metallic FM



Chiba, et al, Nat. Mater. (2011)

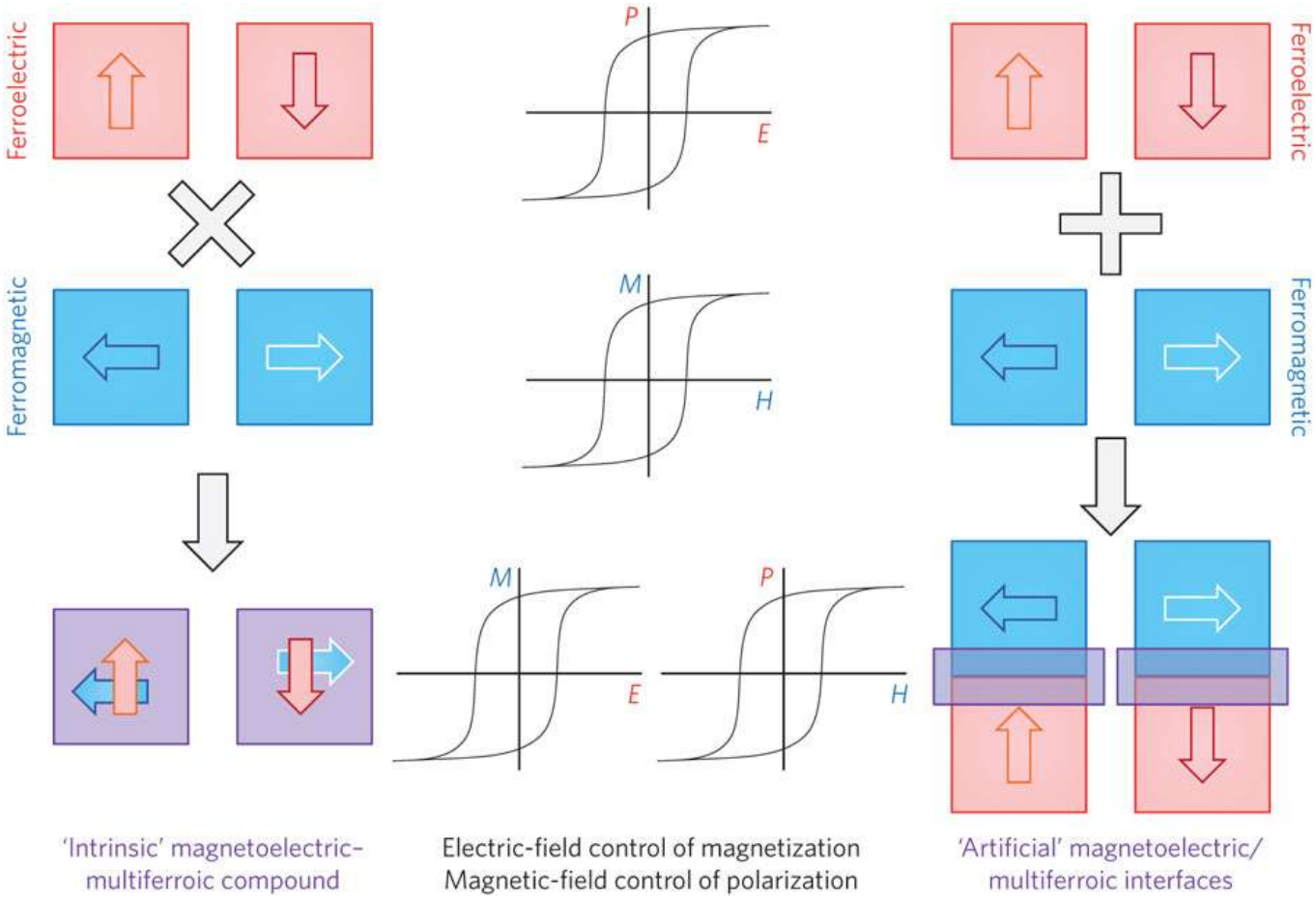
Electric field control the magnetization

Electric field control in Metallic FM



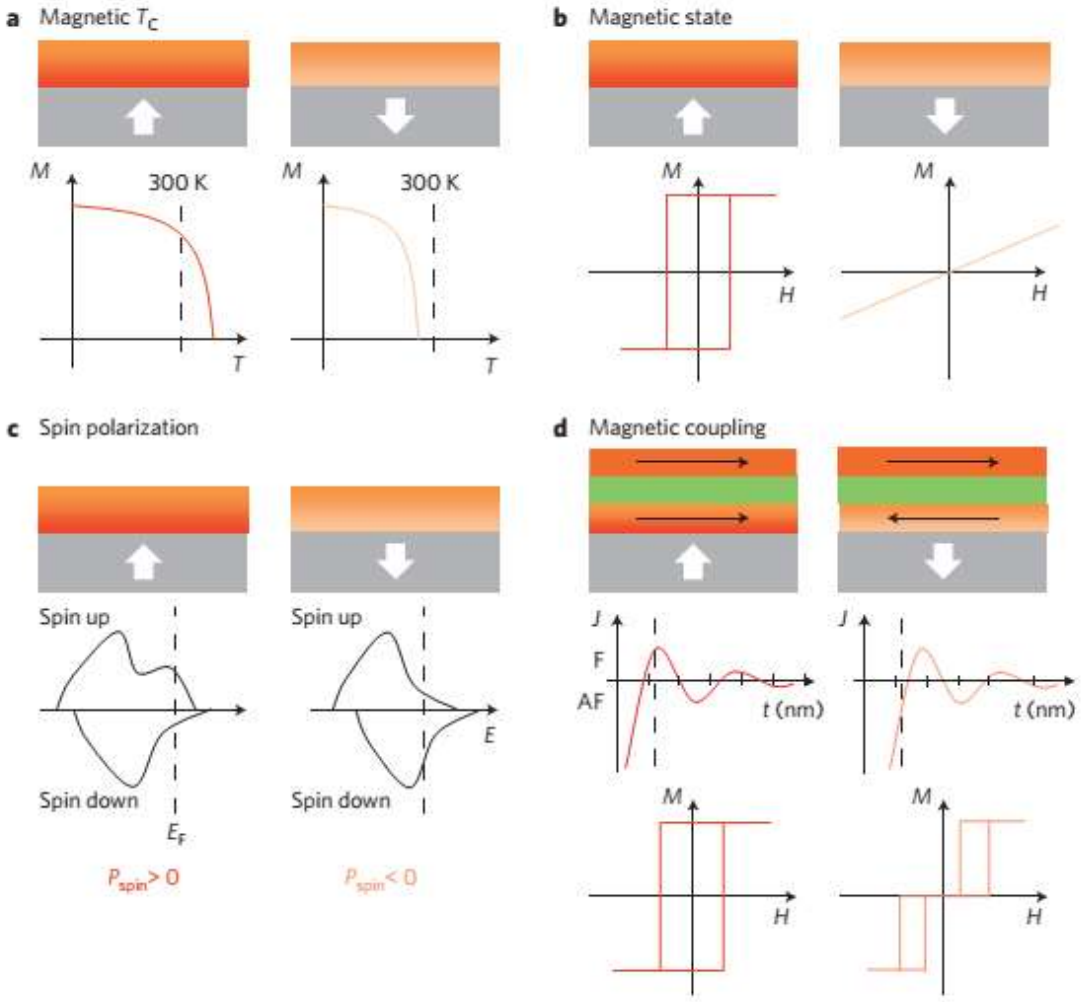
Chiba, et al, Nat. Mater. (2011)

Multiferroics



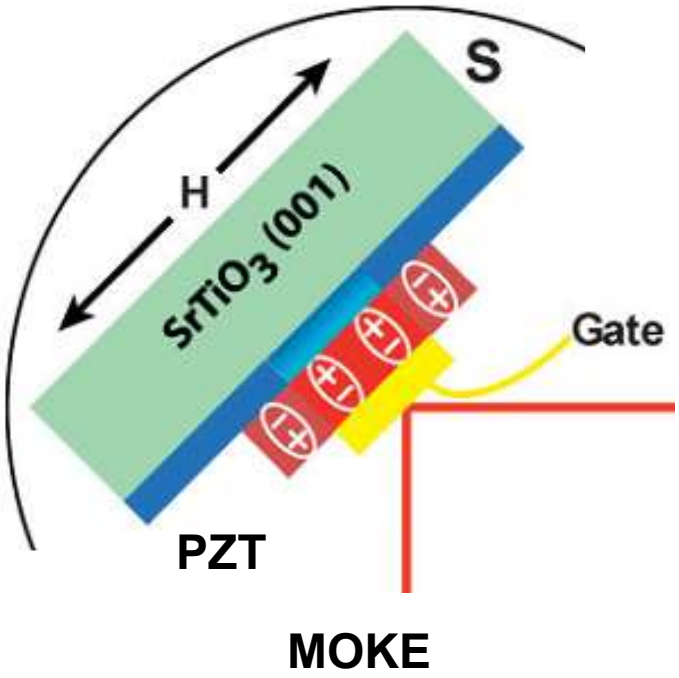
Bibes, Nat. Mater. (2012)

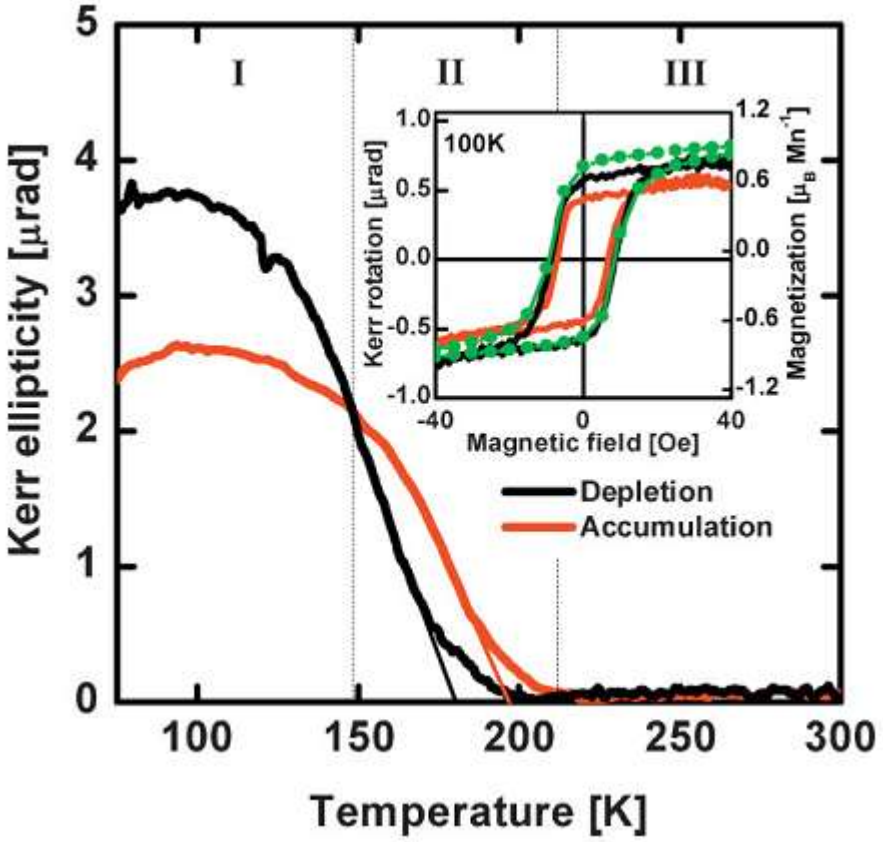
Multiferroics



Bibes, Nat. Mater. (2012)

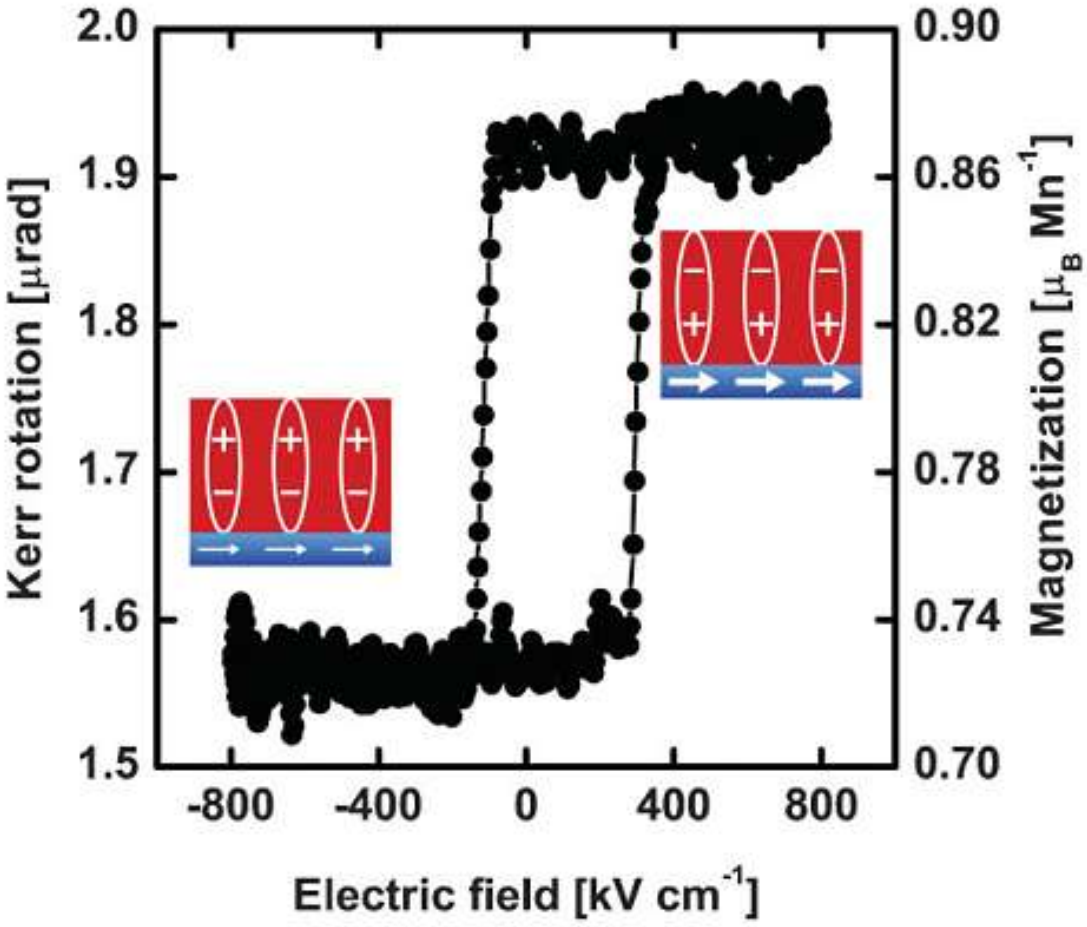
T_C by Multiferroics





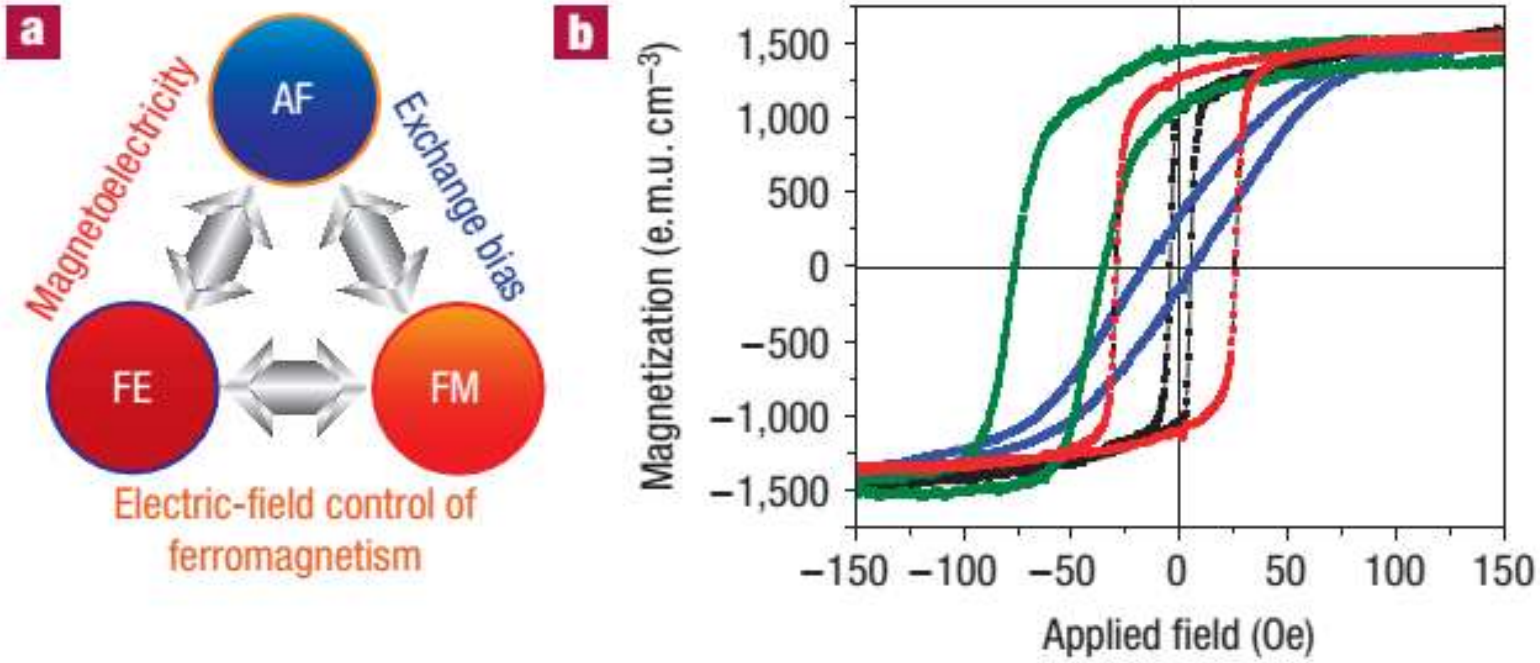
Molegraaf, et al, Adv. Mater. (2009)

T_C by Multiferroics



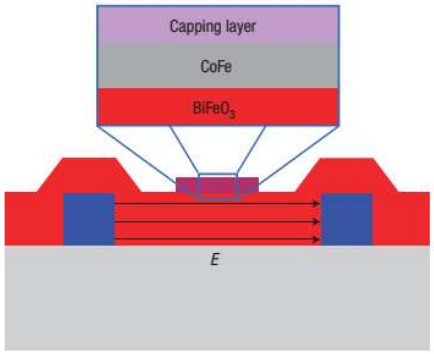
Molegraaf, et al, Adv. Mater. (2009)

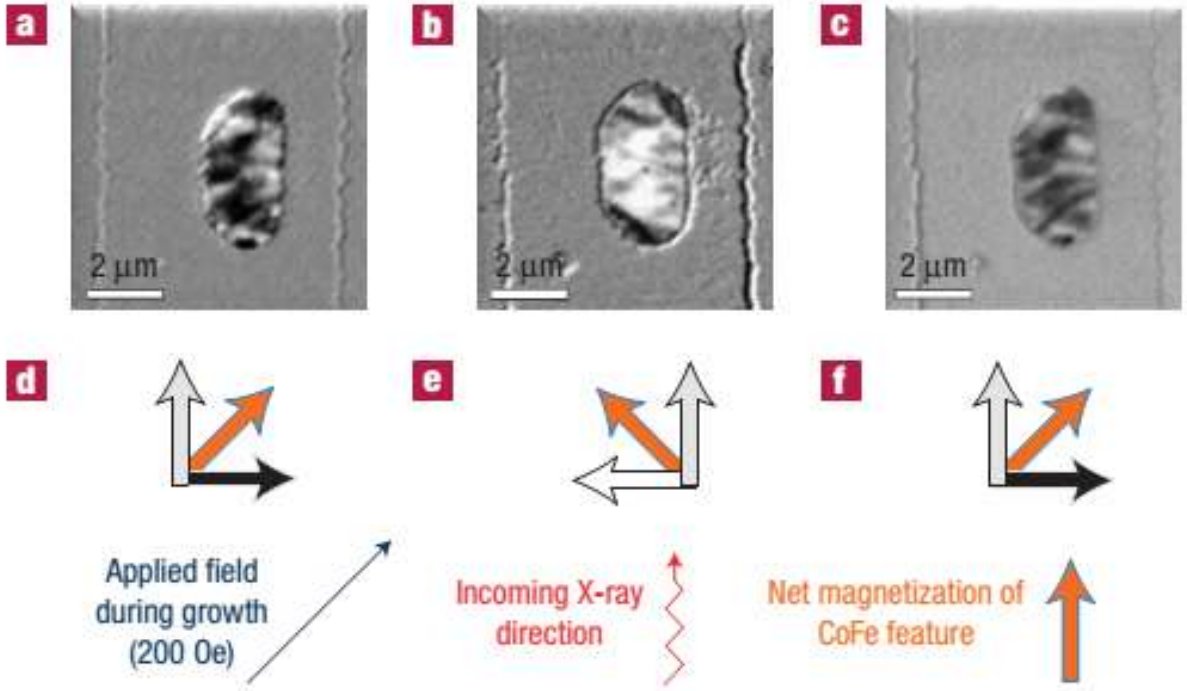
FM magnetization by Multiferroics



Chu, et al, Nat. Mater. (2008)

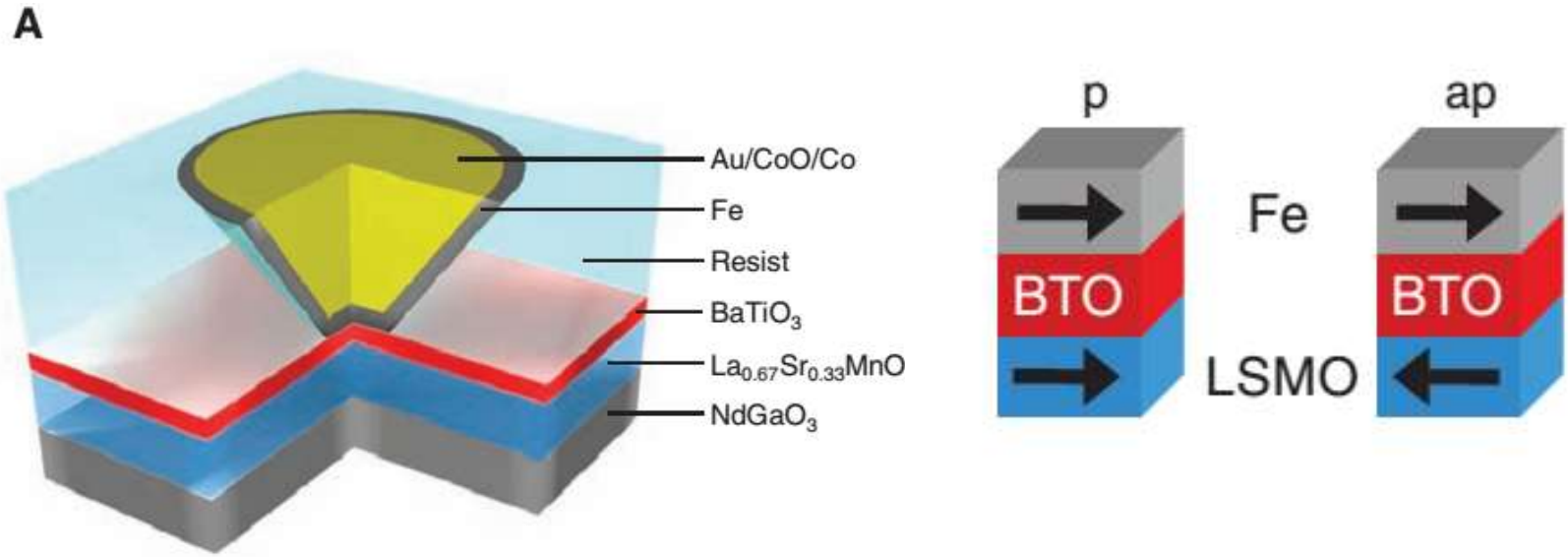
FM magnetization by Multiferroics





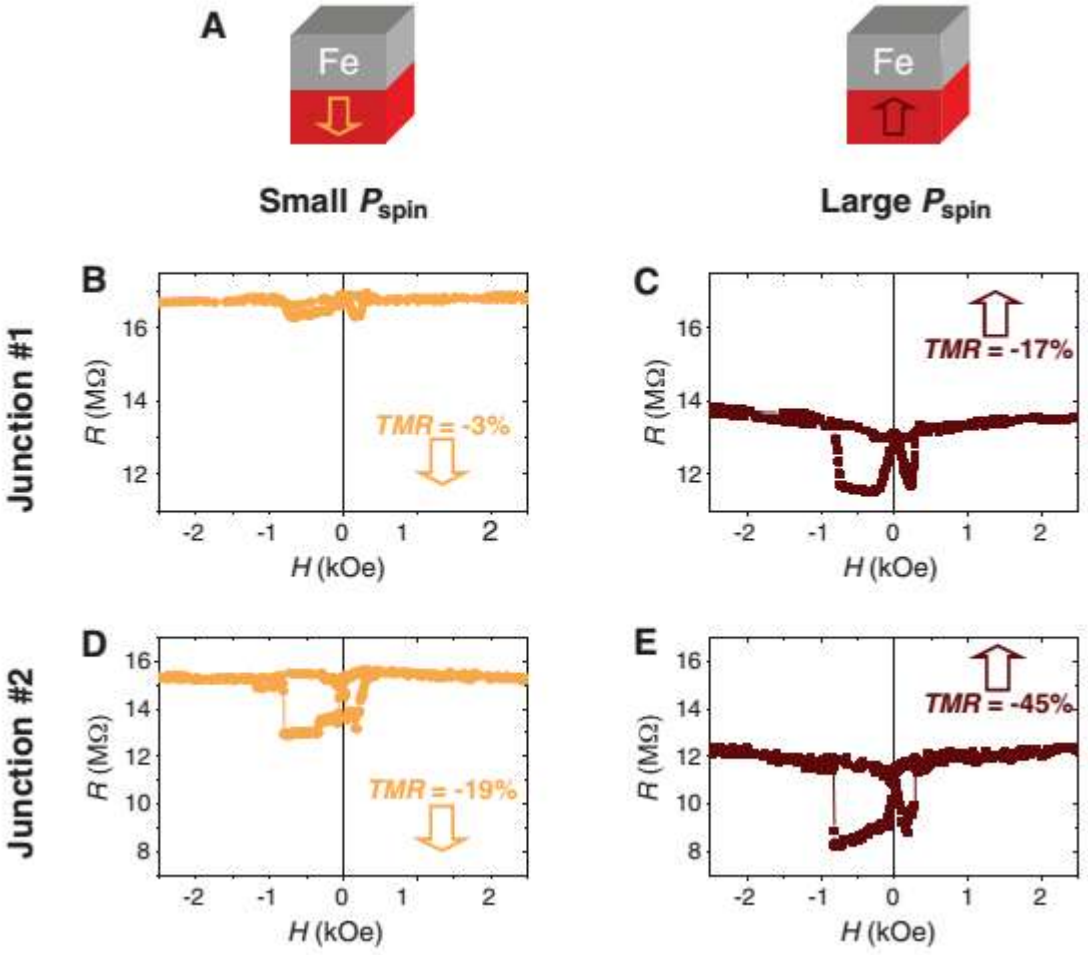
Chu, et al, Nat. Mater. (2008)

Spin polarization by Multiferroics



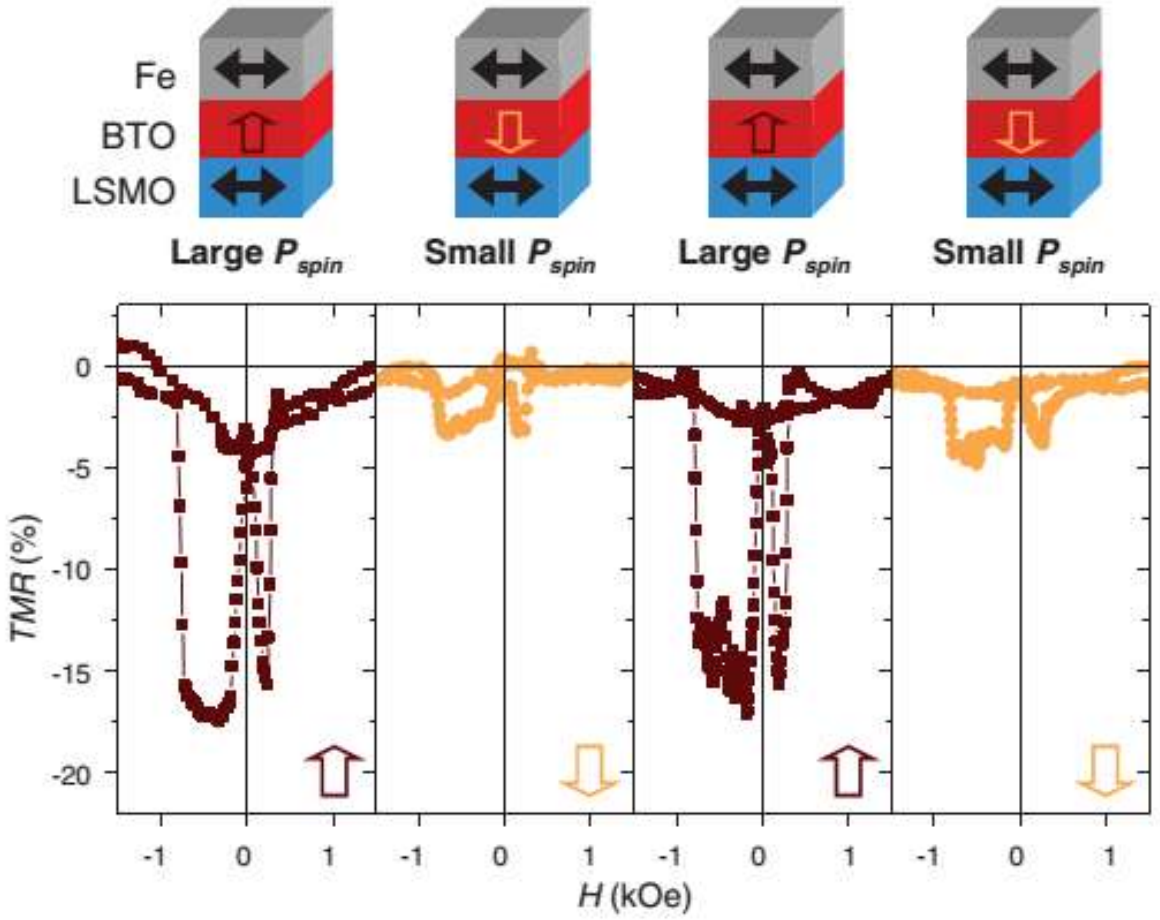
Garcia, et al, Science (2010)

Spin polarization by Multiferroics



Garcia, et al, Science (2010)

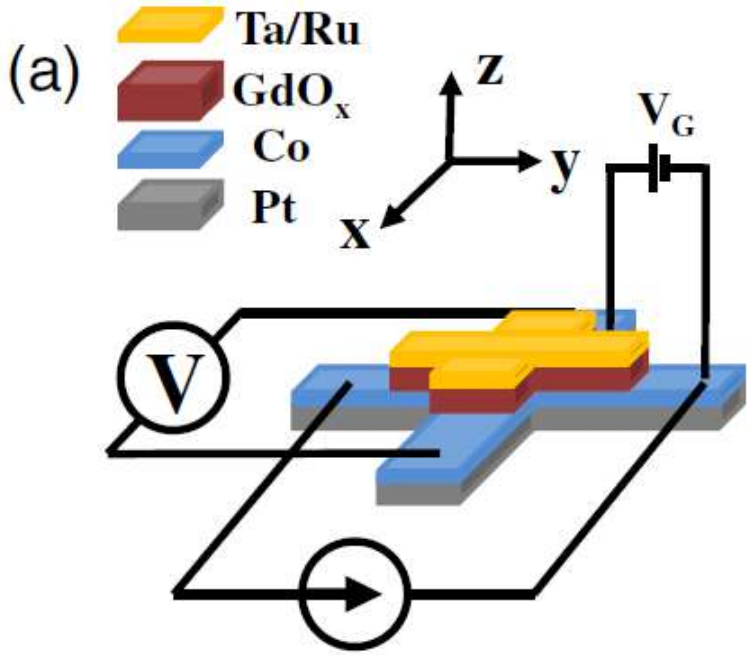
Spin polarization by Multiferroics



Garcia, et al, Science (2010)

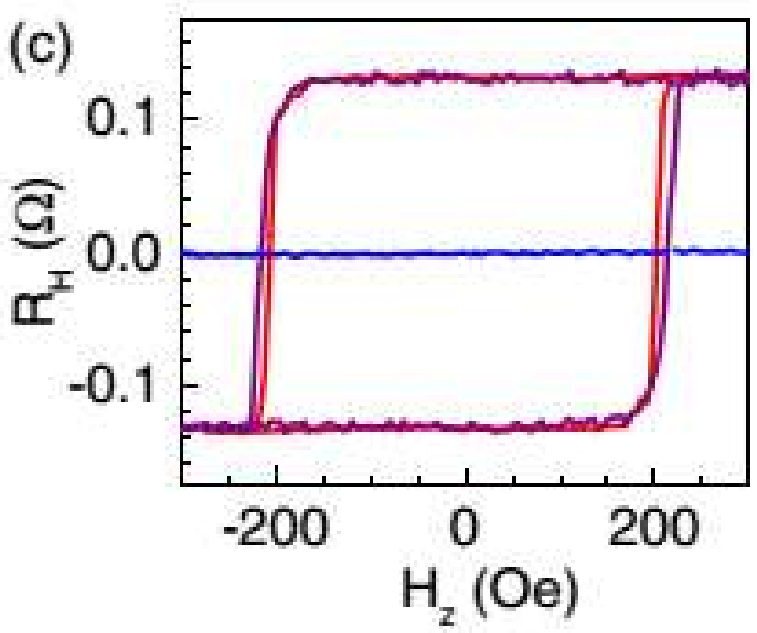
Ionics of Oxygen

Electric field via GdO_x/FM



Blue curve: Negative electrical field

Purple curve: positive electrical field



Bi et al PRL (2014)

Ionics of Oxygen

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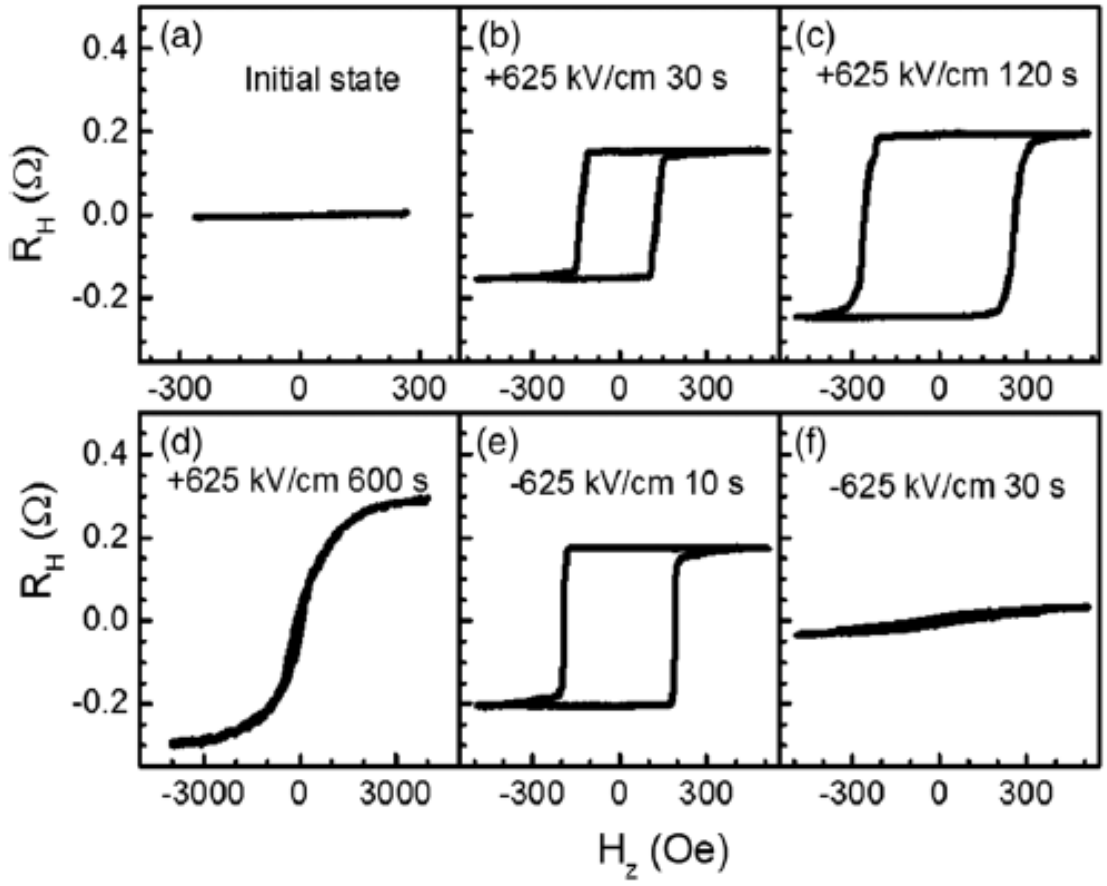

Bi et al PRL (2014)

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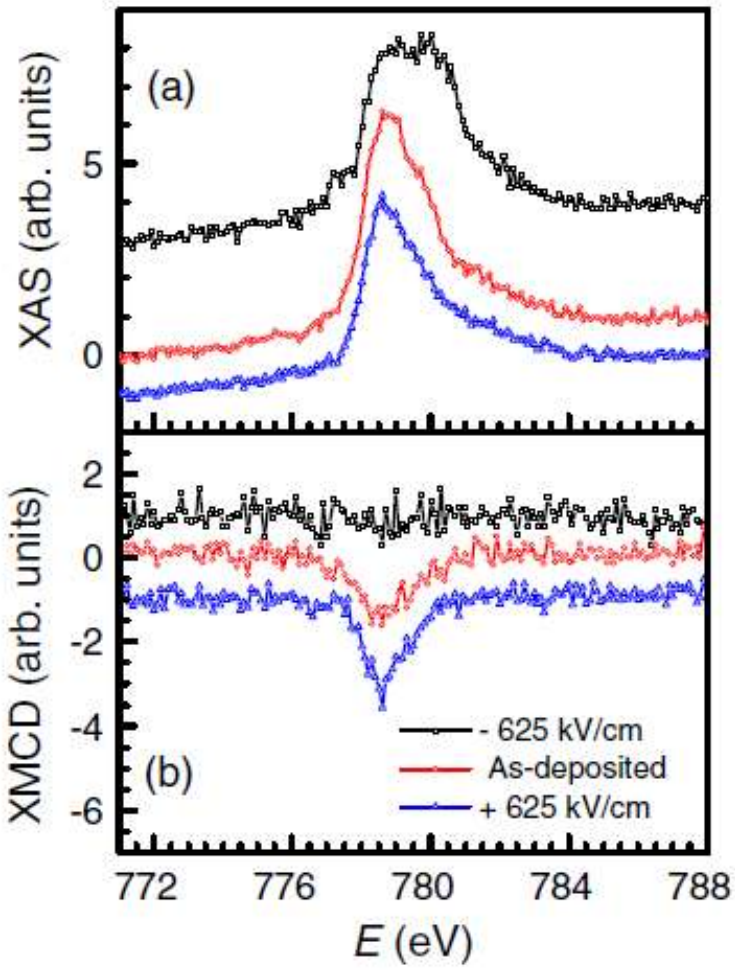


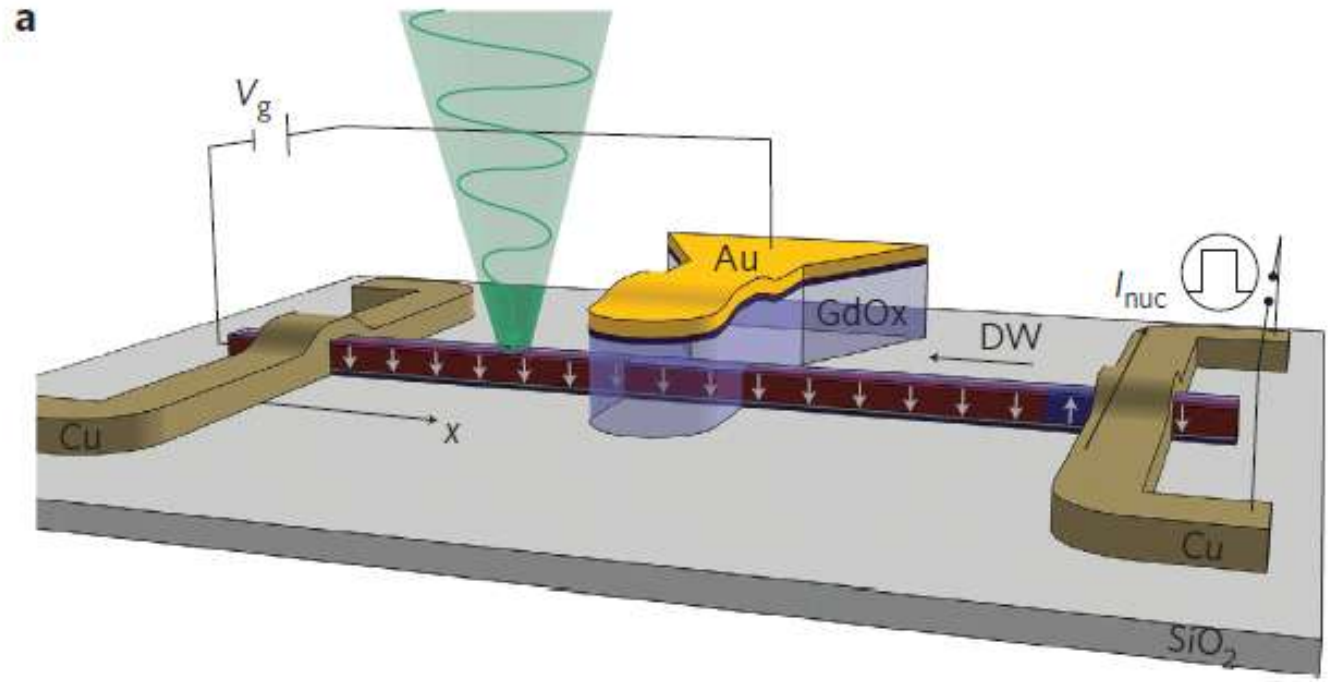
Co→ CoO

CoO→ Co

Bi et al PRL (2014)

Ionics of Oxygen

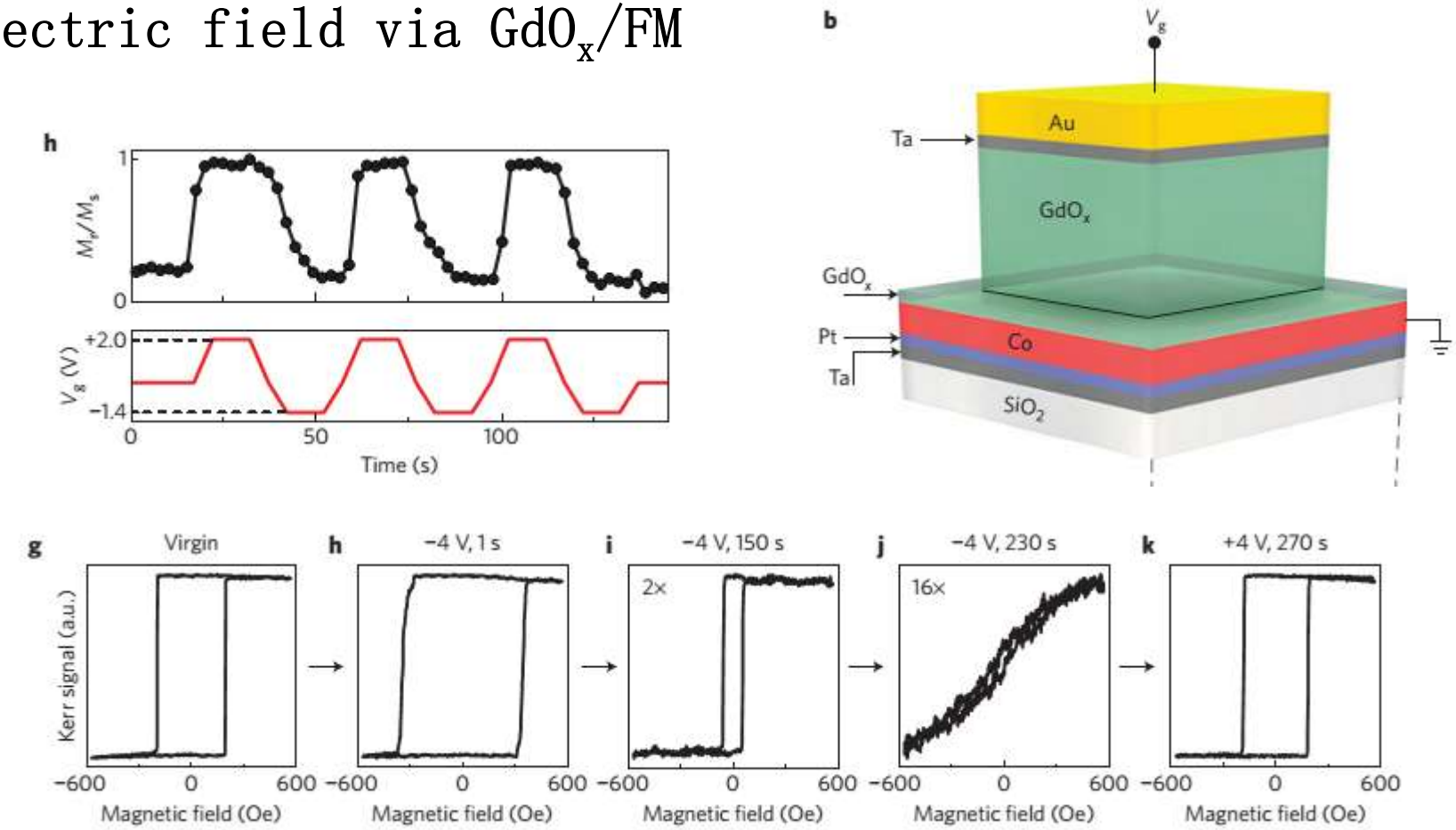
Electric field via GdO_x/FM



Bauer, et al Nat. Nano. (2014)

Ionics of Oxygen

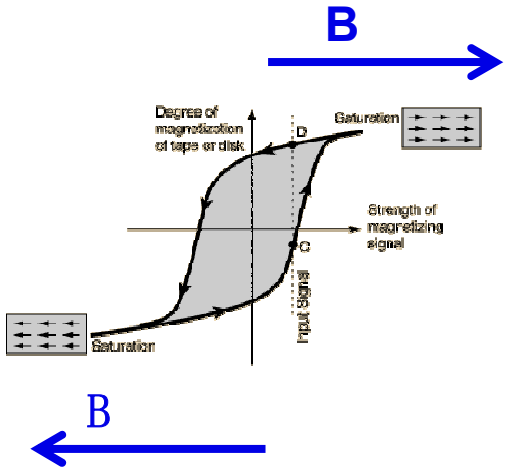
Electric field via GdO_x/FM



Bauer, et al Nat. Nano. (2014)

How to control the magnetization

Magnetic field



Without B

???

Control??

Electric field

Ultrafast Laser

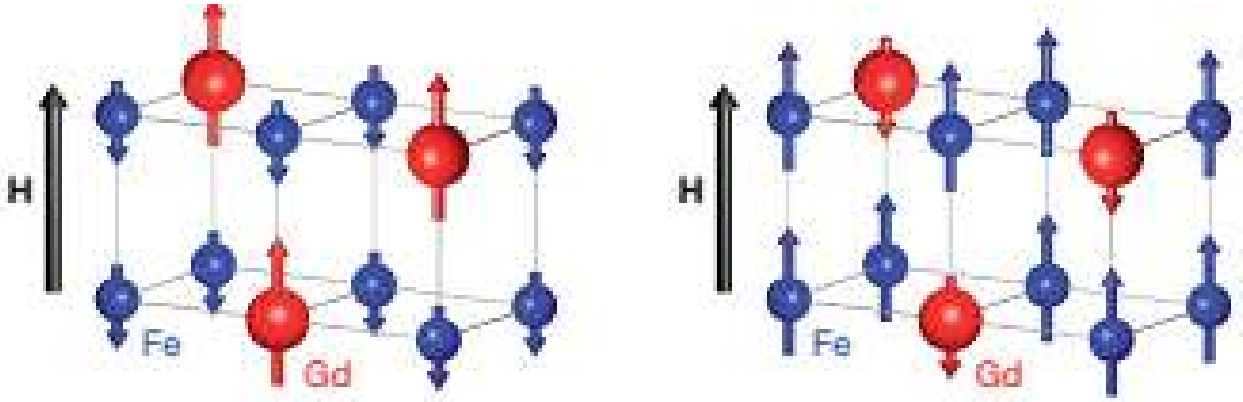
Spin torque

Interface Strain

67

FM by Ultrafast Laser

Ferrimagnet



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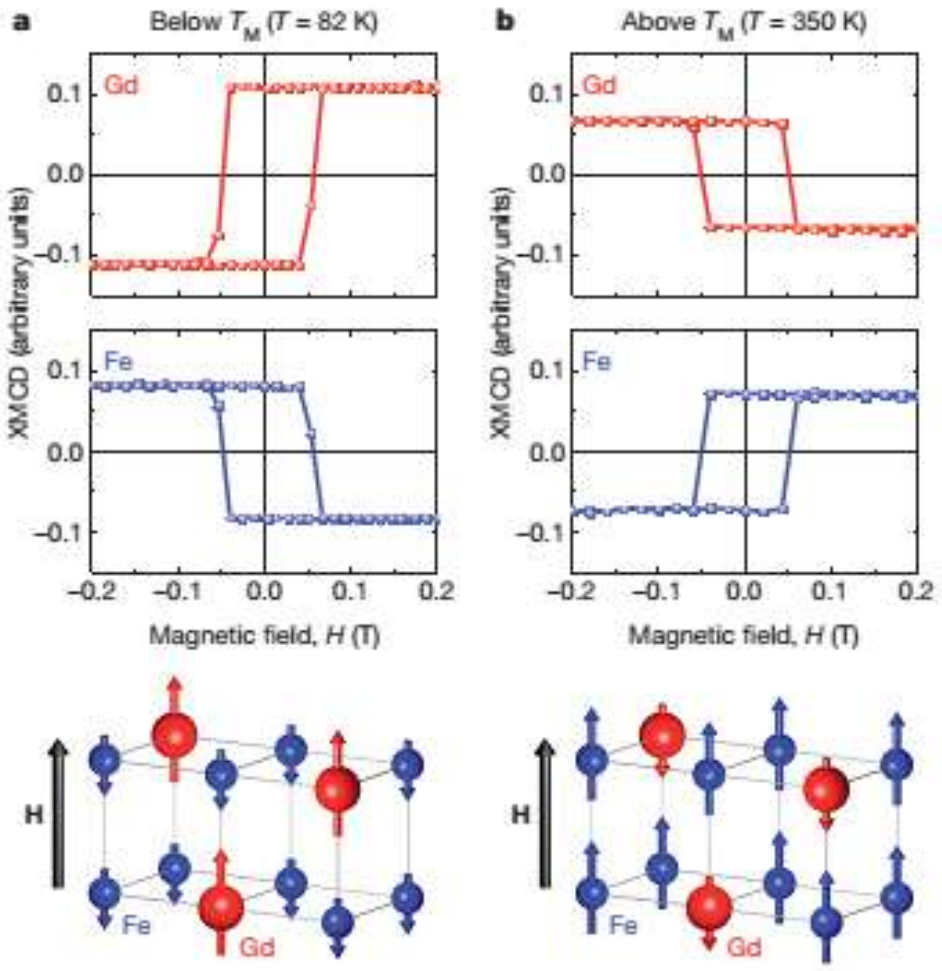
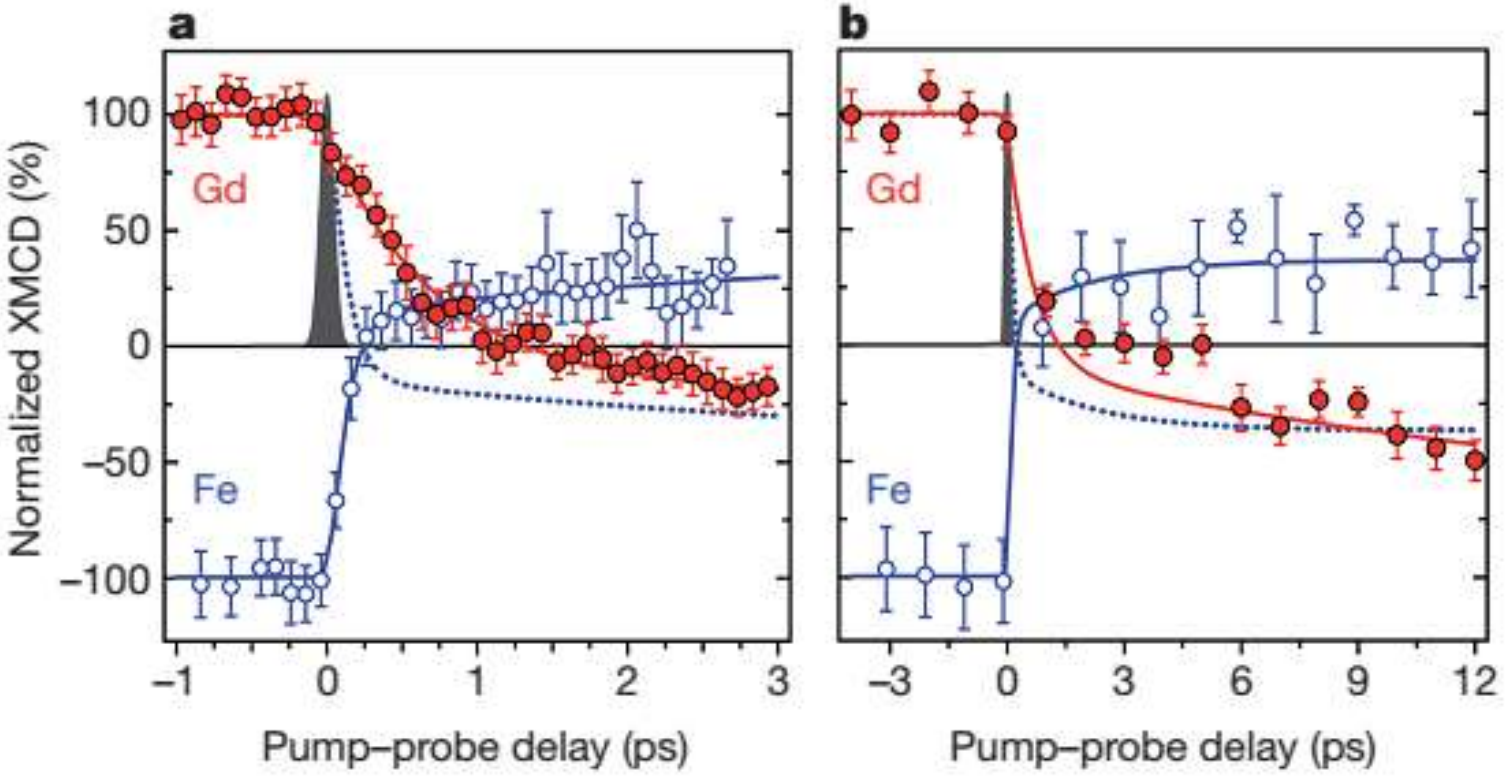
FM by Ultrafast Laser



Radu, et al Nature (2011)

69

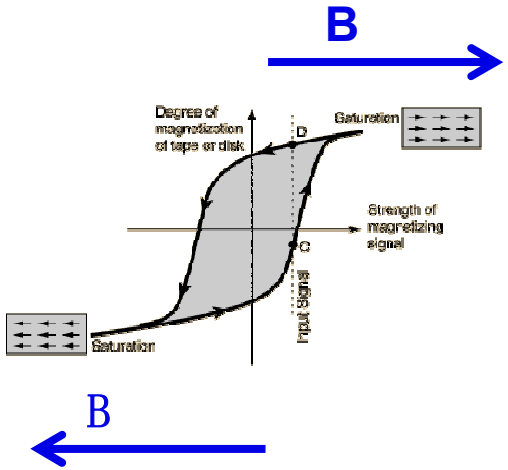
FM by Ultrafast Laser



70

How to control the magnetization

Magnetic field



Without B

???

Control??

Electric field

Ultrafast Laser

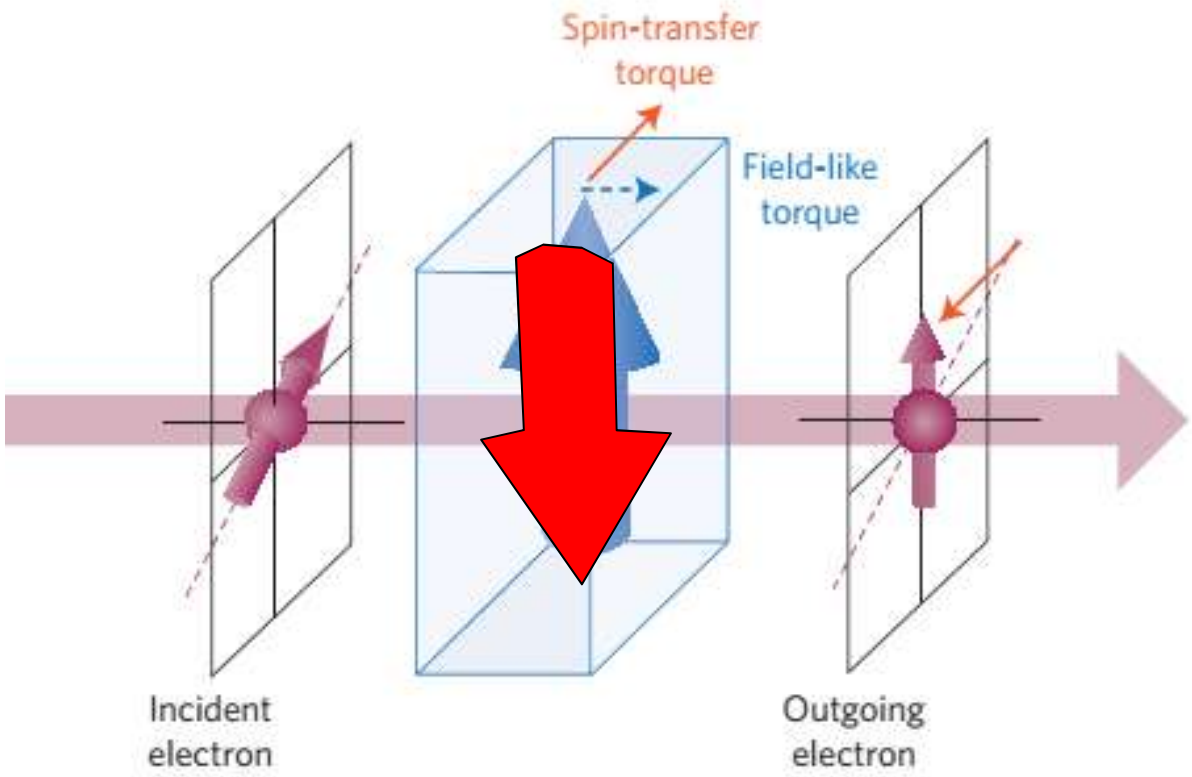
Spin torque

Interface Strain

71

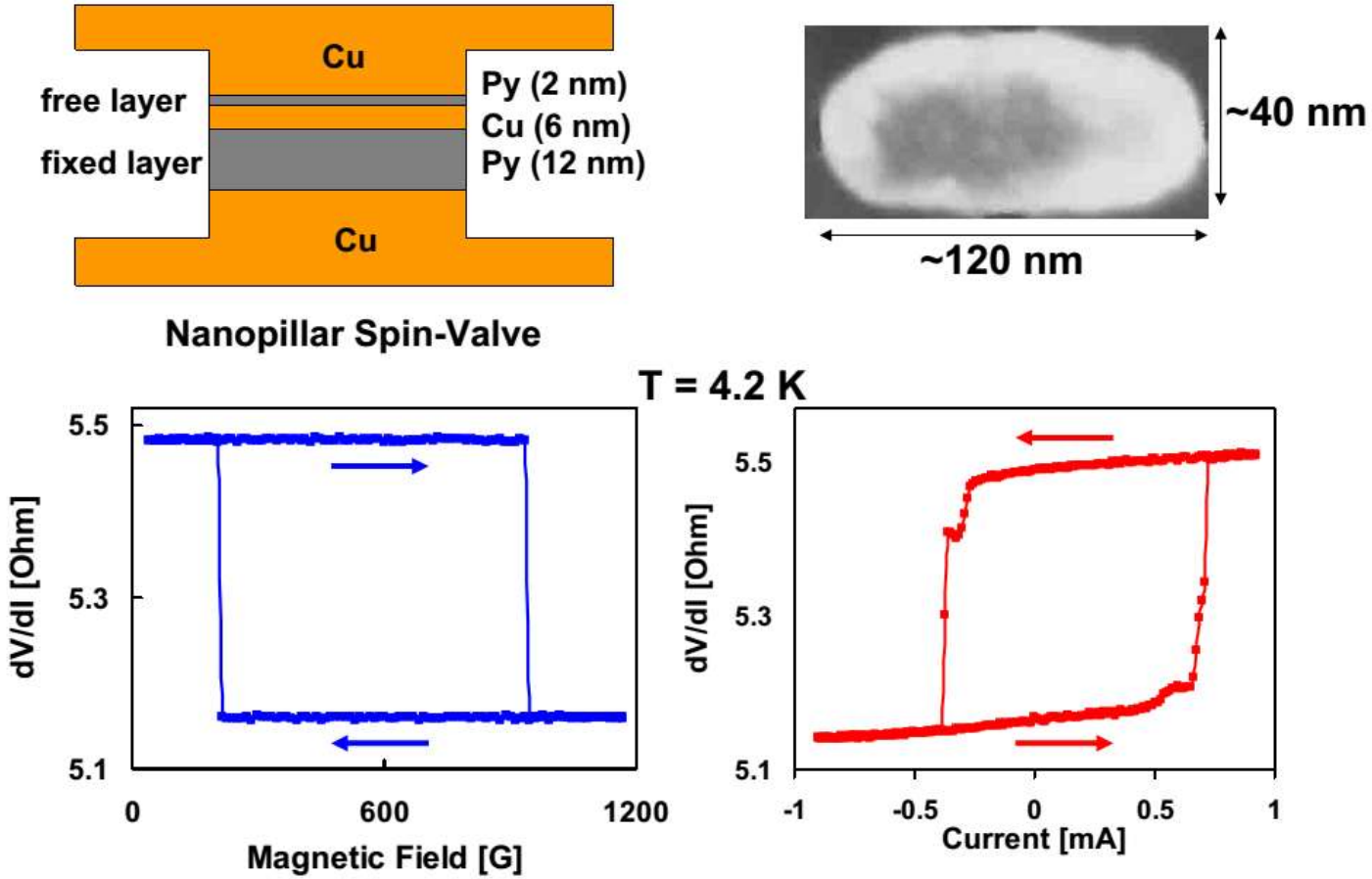
FM by Spin transfer torque

Spin transfer torque



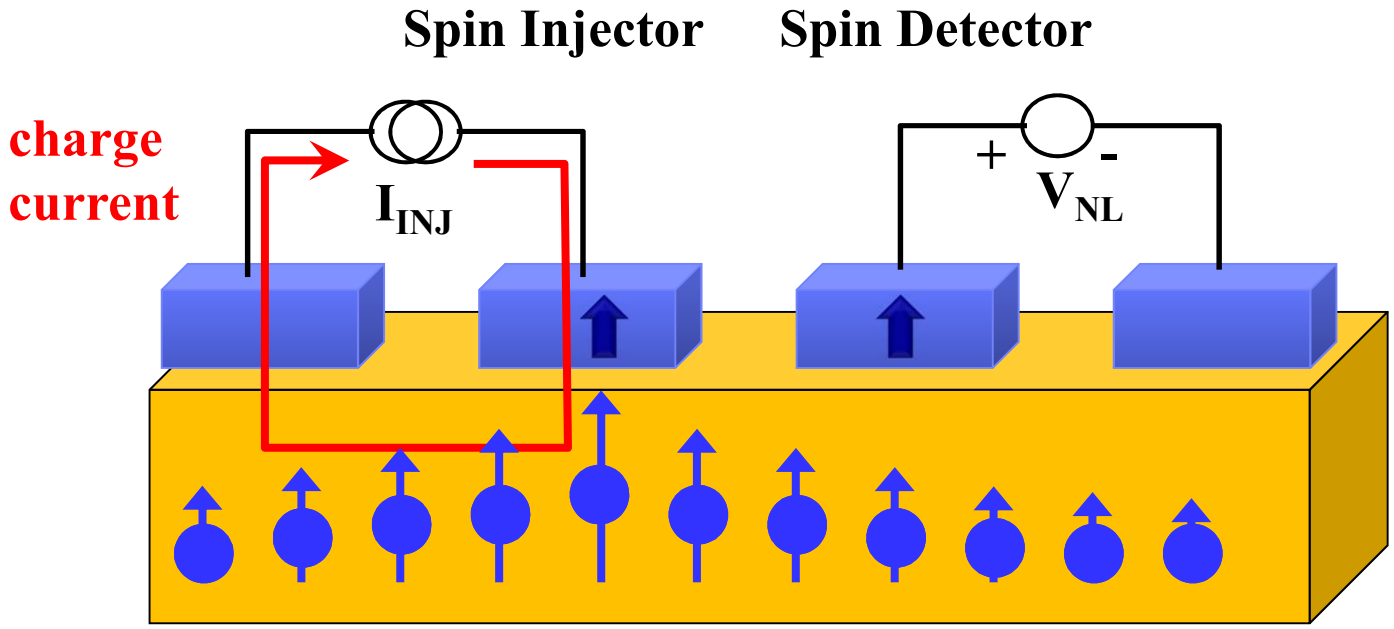
Brataas, et al. Nature Mater. (2012)

Spin transfer torque

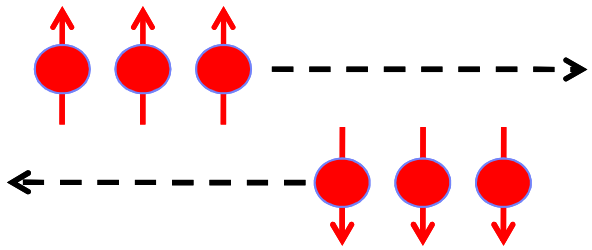


Ralph & Stiles, JMMM (2008)

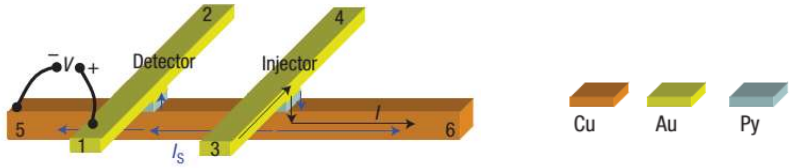
Pure Spin current torque

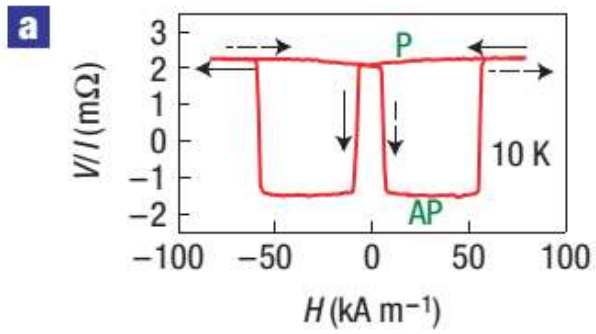


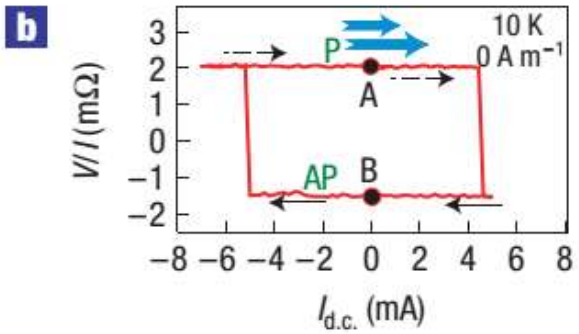
Pure spin current: Flow of spin without net flow of charge

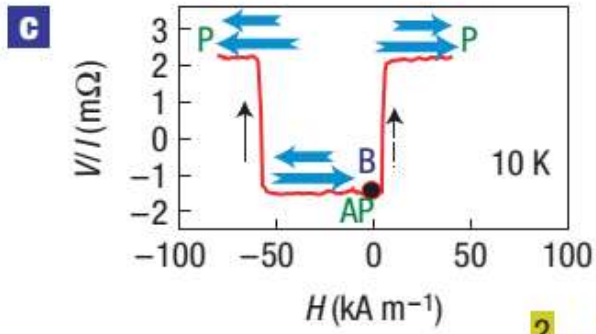


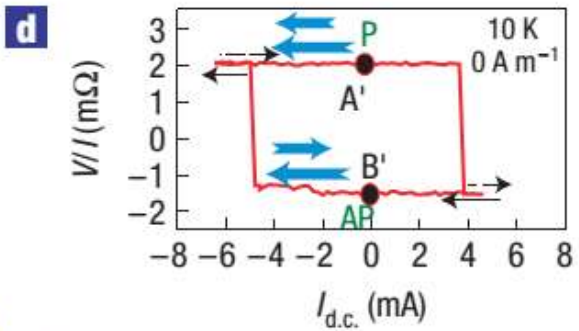
Pure Spin current torque

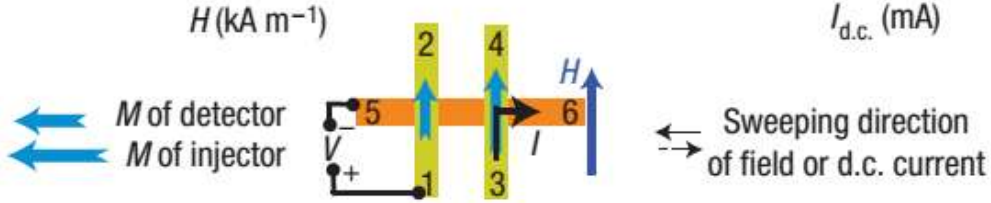






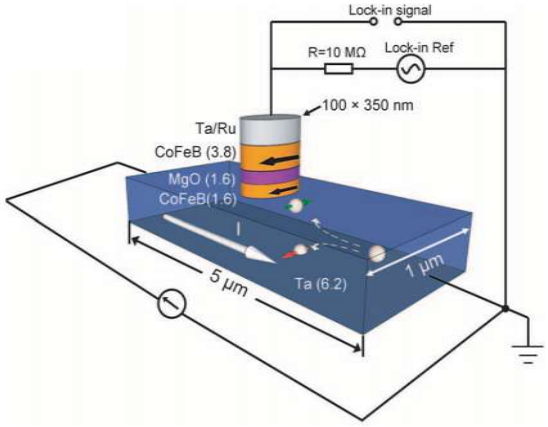


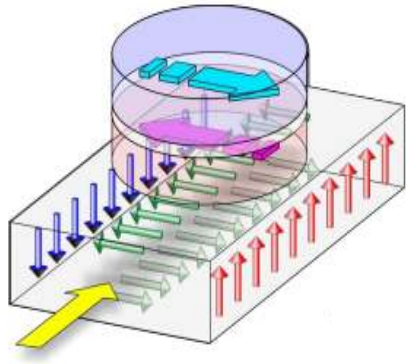


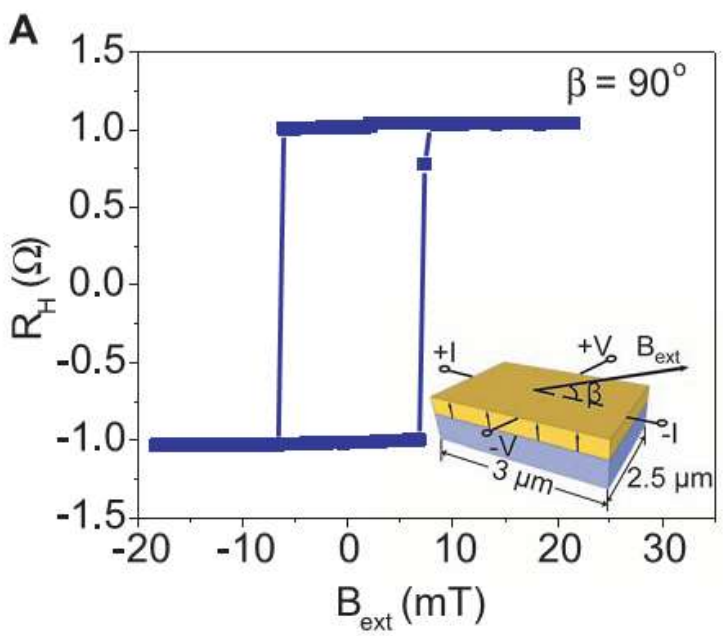


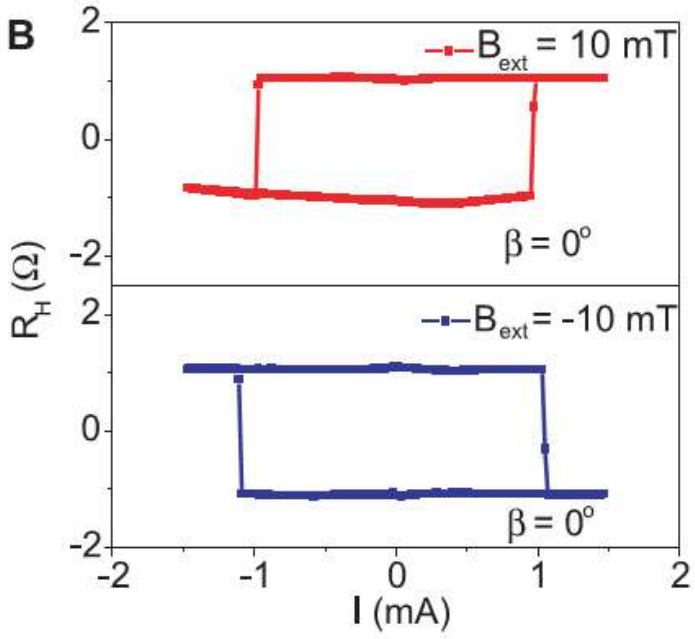
Yang et al, Nature Physics (2008)

Spin Orbit torque









Liu et al, Science (2012)

Spin transfer torque

More details at

一、自旋电子学简介

二、磁性和磁性材料

三、磁阻效应

四、自旋阀

五、自旋转移力矩

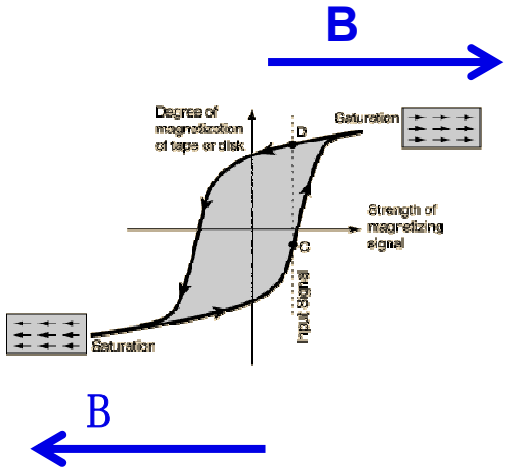
六、热自旋电子学

七、拓扑自旋流

八、反铁磁自旋电子学

How to control the magnetization

Magnetic field



Without B

???

Control??

Electric field

Ultrafast Laser

Spin torque

Interface Strain

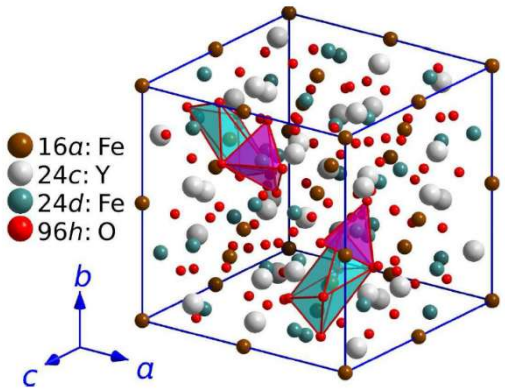
78

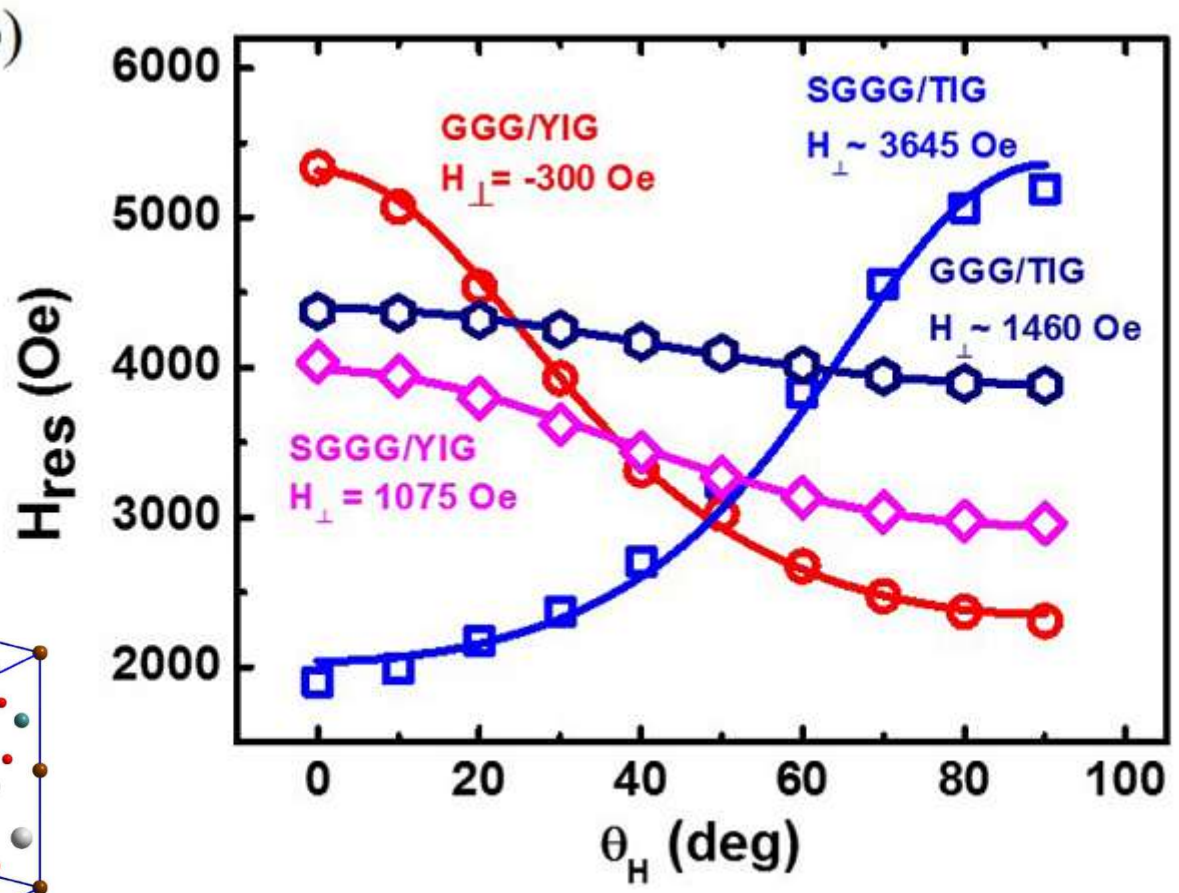
Magnetization by Strain

TIG, a magnetic insulator with perpendicular easy axis

$Y_3Fe_5O_{12}$

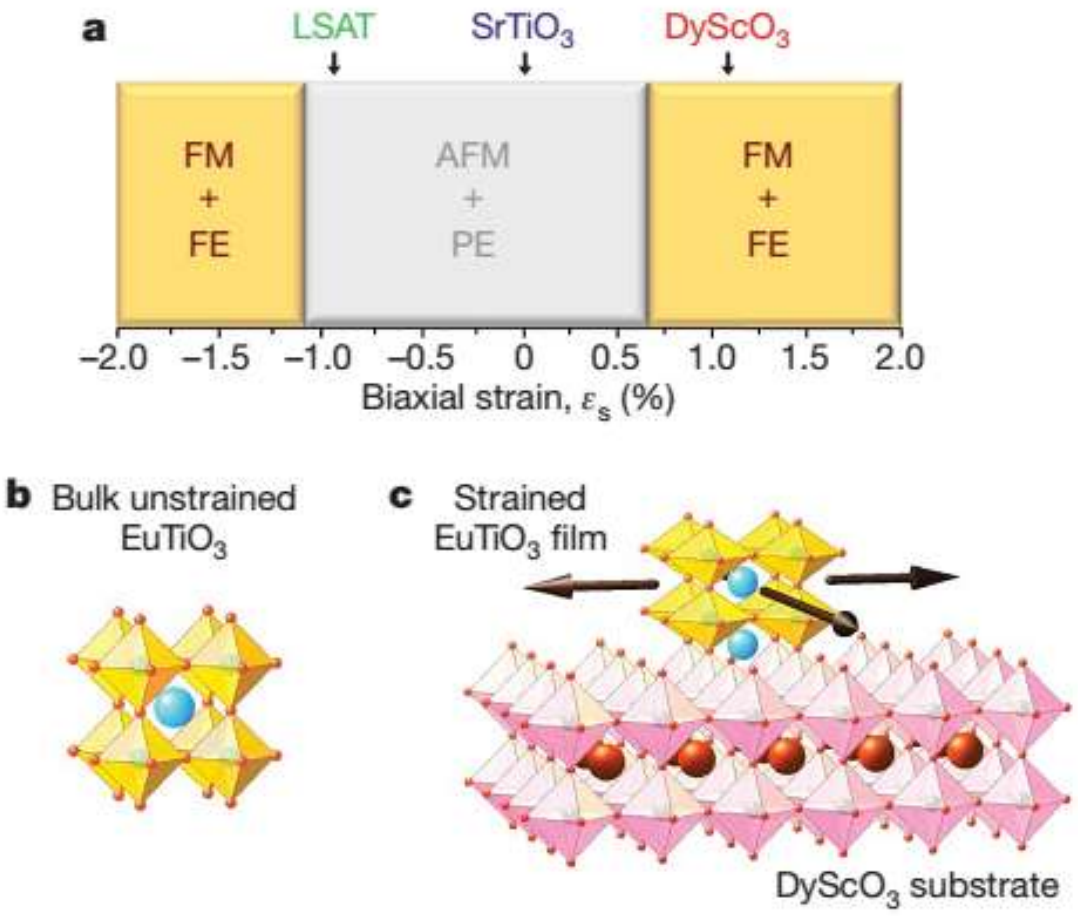
$Tm_3Fe_5O_{12}$





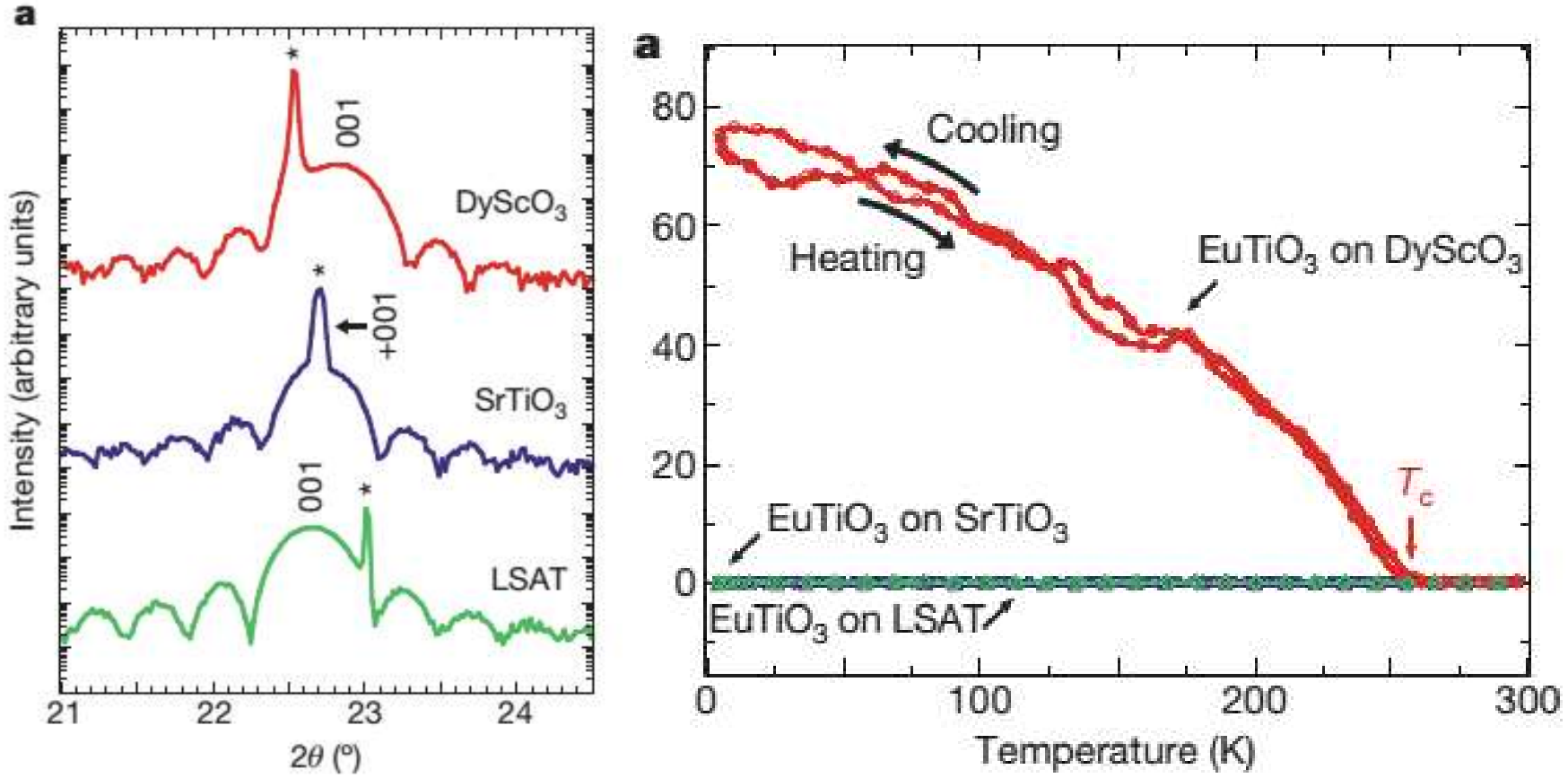
Tang, et al, PRB (2017)

Magnetization by Strain



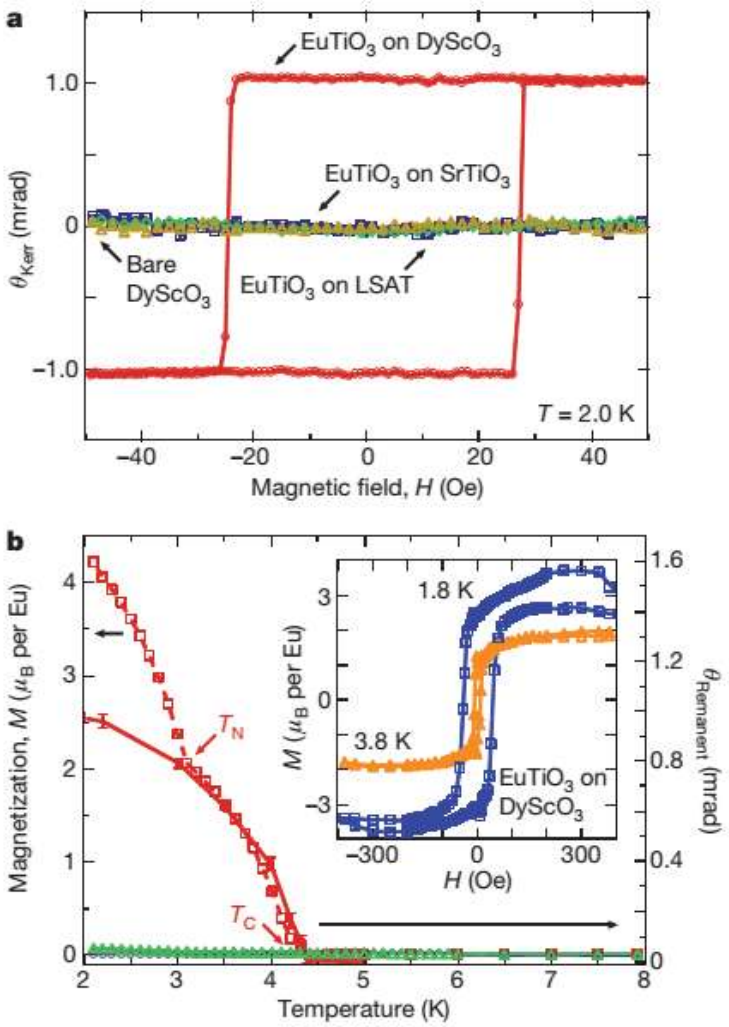
Lee 2010, et al. Nature (2011)

Magnetization by Strain



Lee 2010, et al. Nature (2011)

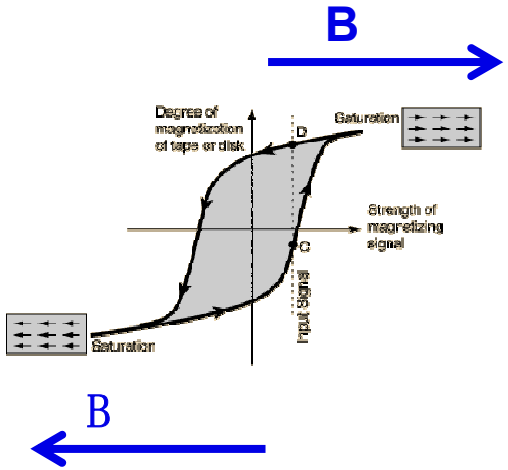
Magnetization by Strain



Lee 2010, et al. Nature (2011)

Summary

Magnetic field



Without B
???

Control

Electric field

Ultrafast Laser

Spin torque

Interface Strain

下一节课: Oct. 13rd

Chapter 3: Magnetoresistance

课件下载：
http://www.phy.pku.edu.cn/~LabSpin/teaching.html

谢谢！