# Chapter 2

# Magnetism and Magnetic Materials

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# Review of last class

- Magnetism of Electrons
- Spin orbit Coupling
- Magnetism

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

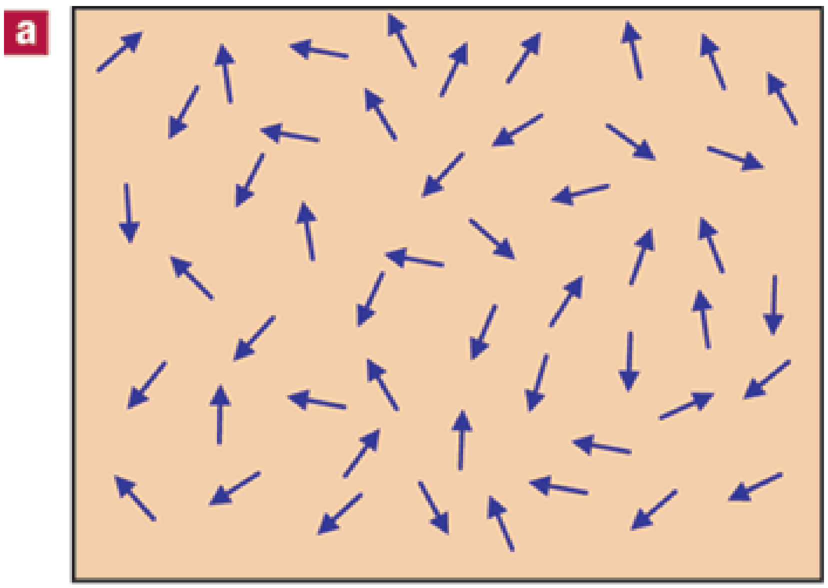
# 提纲

# 2. How to induce magnetic moment

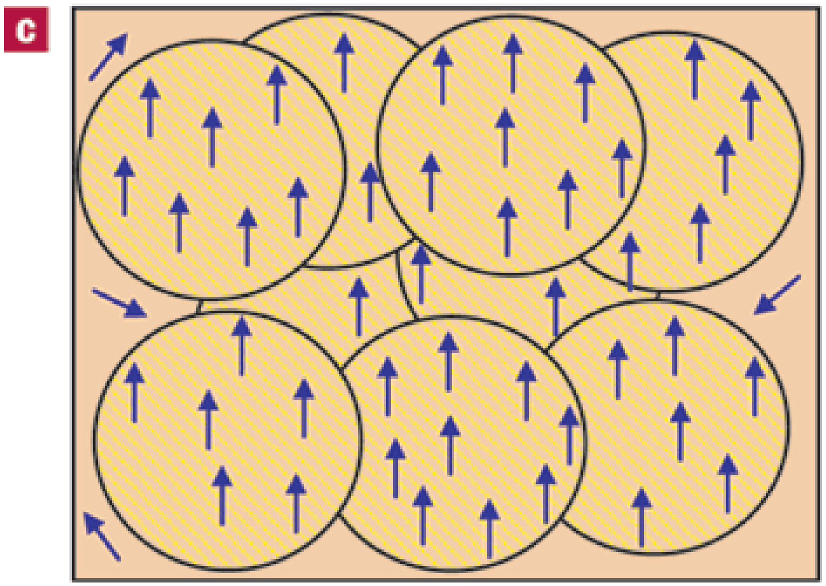
# Mainly two methods

1) Impurity doping

**Mn impurity in GaMnAs**




Low doping

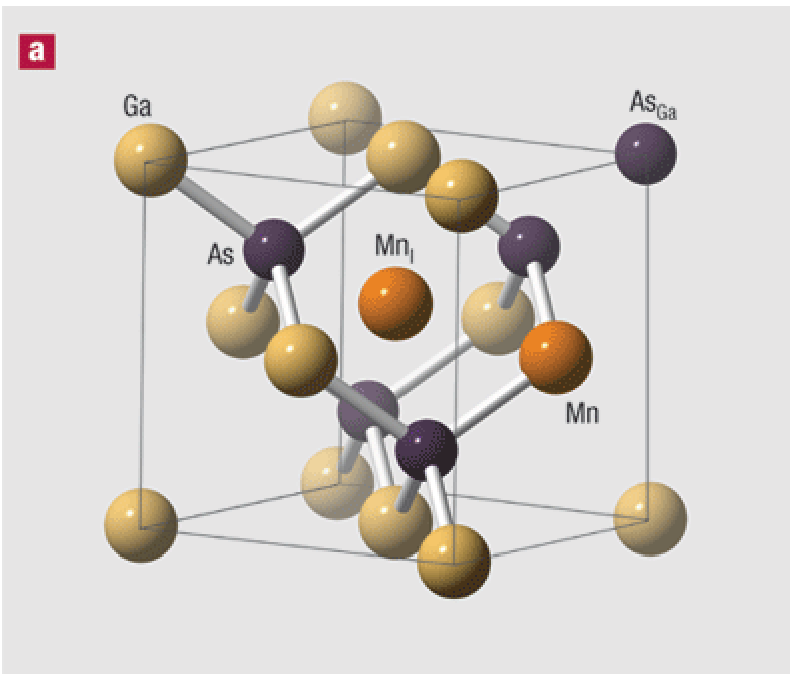


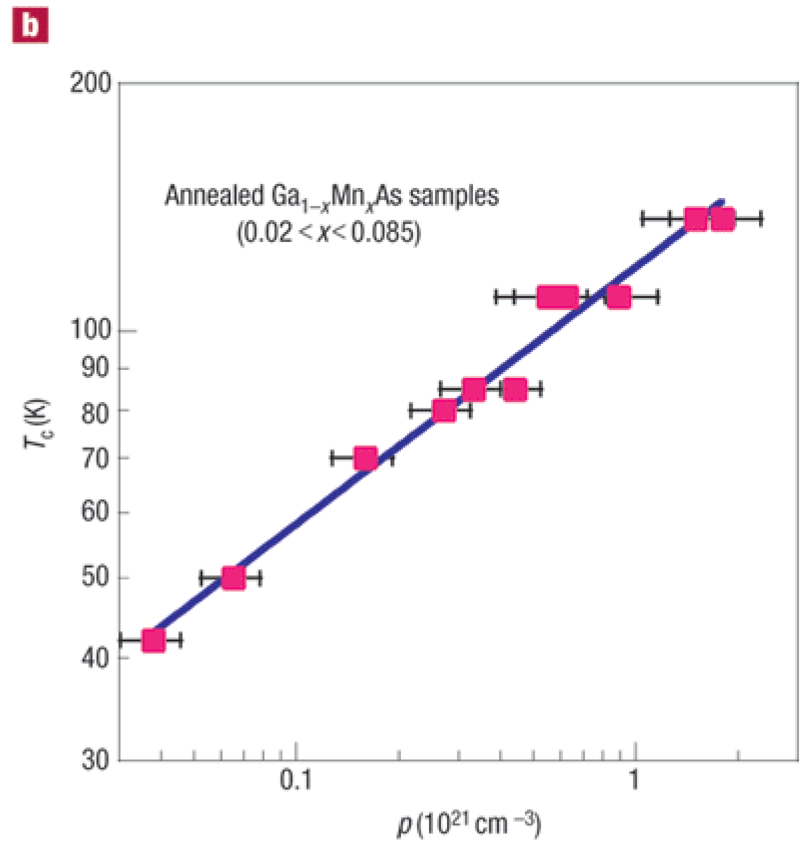

High doping

MacDonald, et al, Nature Mater. (2005)

# Mainly two methods

1) Impurity doping



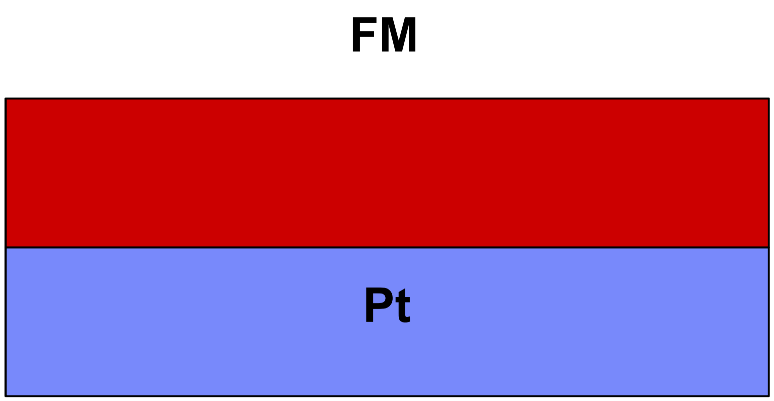




MacDonald, et al, Nature Mater. (2005)

# 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.

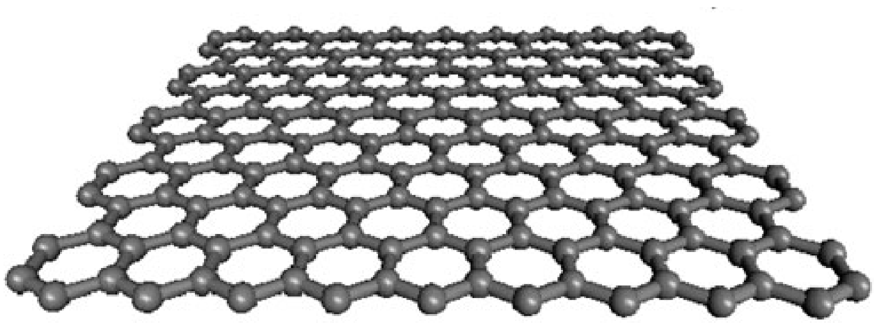


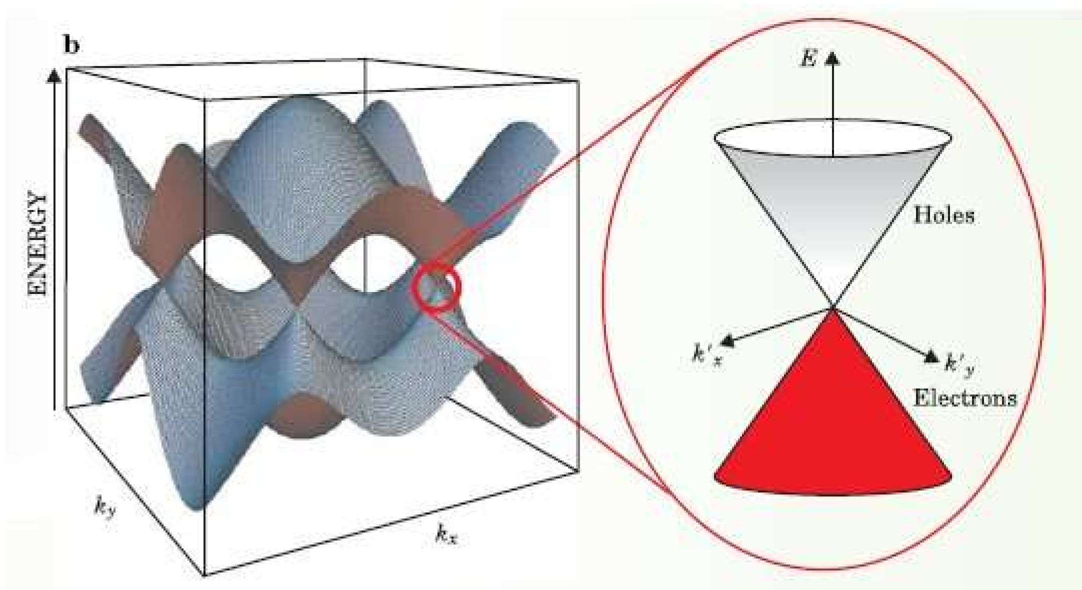

**Interface hybridization**

# Induce M in two Quantum Materials

## Two Dirac Materials

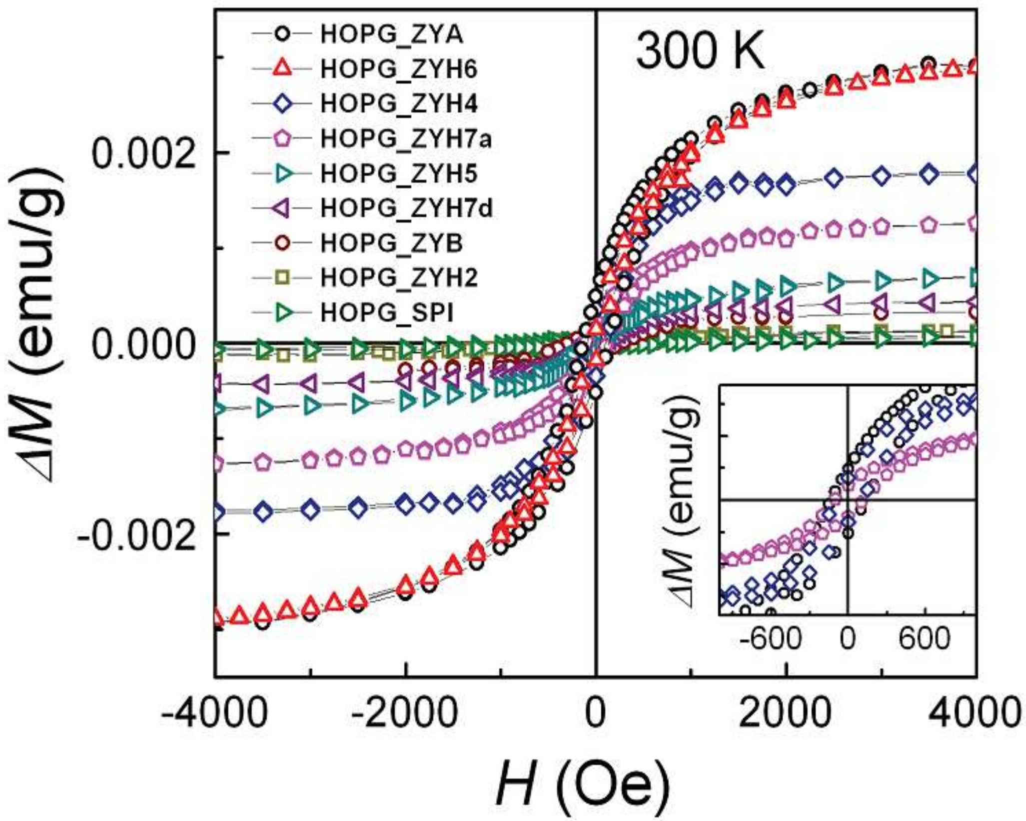
Graphene





# Vacancies Defects

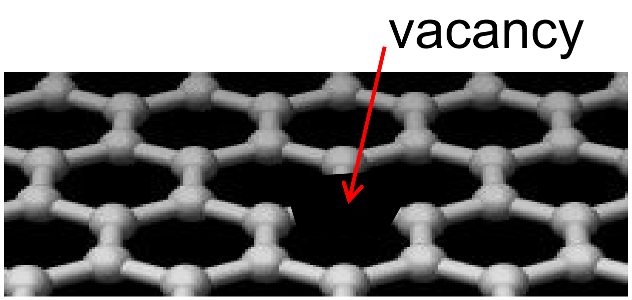
Vacancies Defects→ PM




Nair, et al, Nature Phy. (2012)

# Vacancies Defects

**Question?**

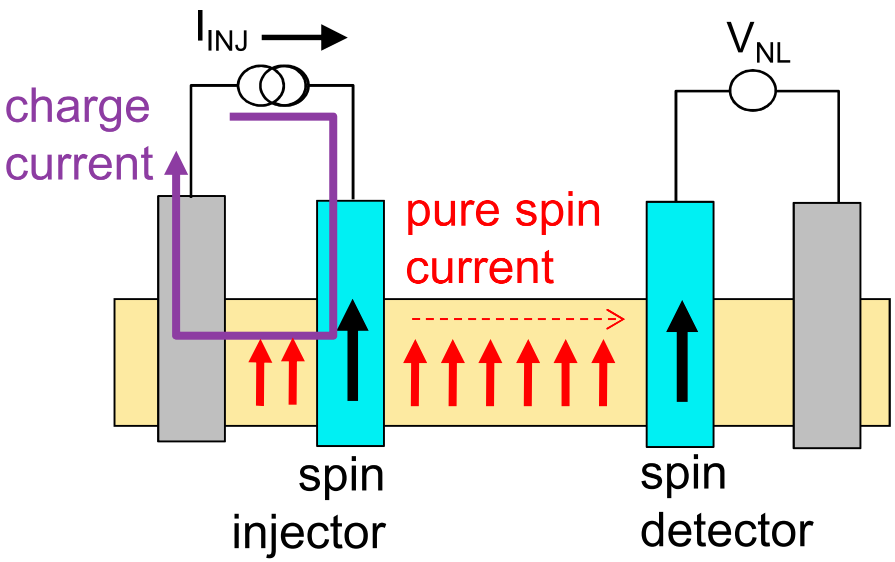



**Ferromagnetic ??**

**Paramagnetic ??**

# Vacancies Defects

Using the spin current approach

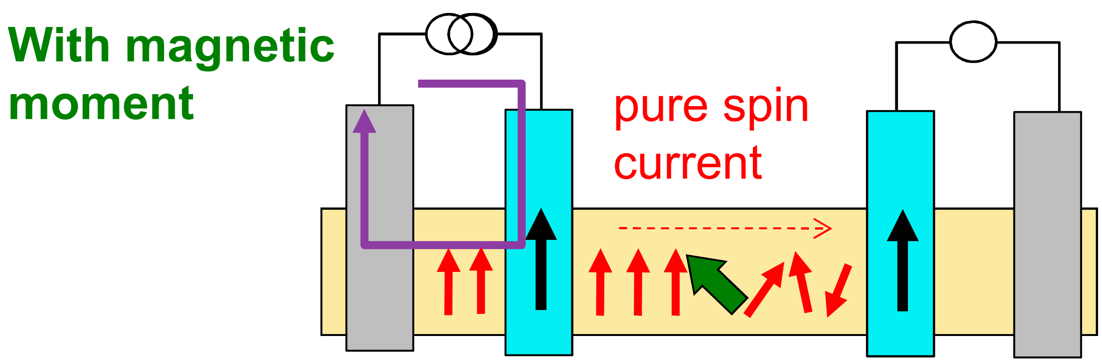



**Nonlocal spin transport geometry**

**graphene**

# Vacancies Defects

Using the spin current approach




Magnetic moment could scatter pure spin current through exchange interaction:

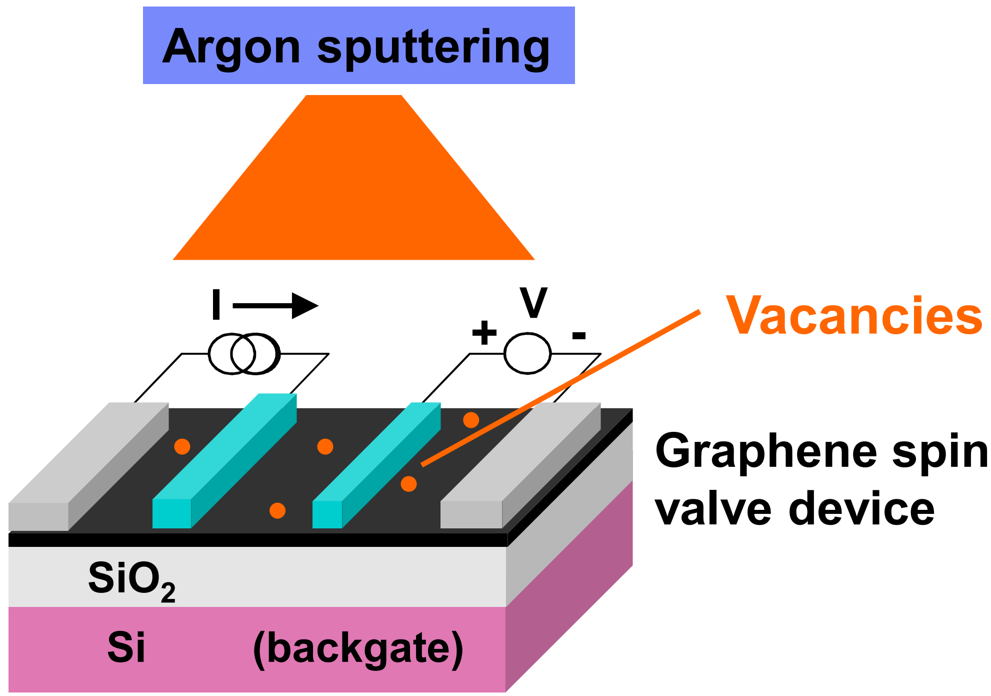
$$\mathcal{H}_{ex} = A_{ex}\, \vec{S}_e \cdot \vec{S}_M$$

- Localized measurement
- Direct coupling of spin to magnetic moment

# Vacancies Defects

Using the spin current approach

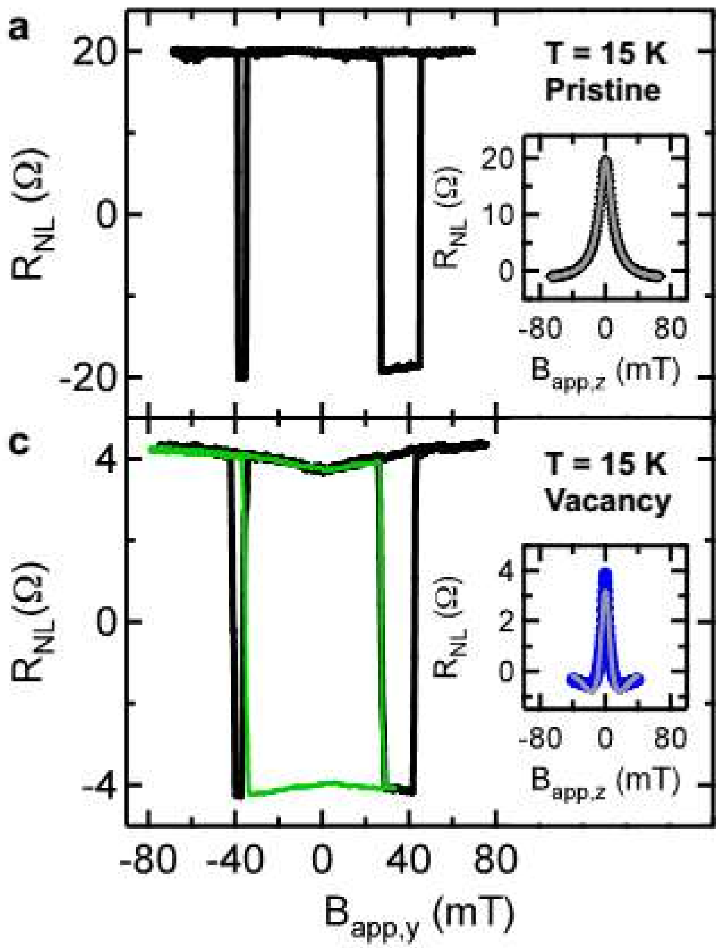
- **All measurements done in ultrahigh vacuum (UHV)**
- **Compare immediately before and after hydrogen doping**

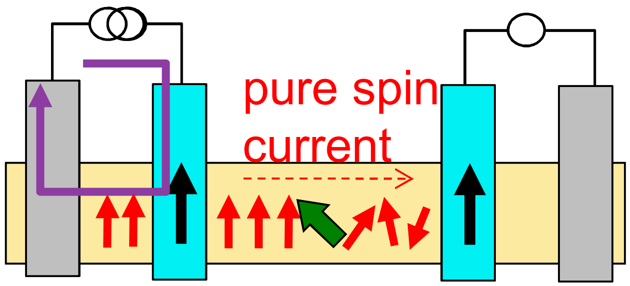



McCreary, et al, PRL (2012)

# Vacancies Defects

Using the spin current approach




**At zero field**

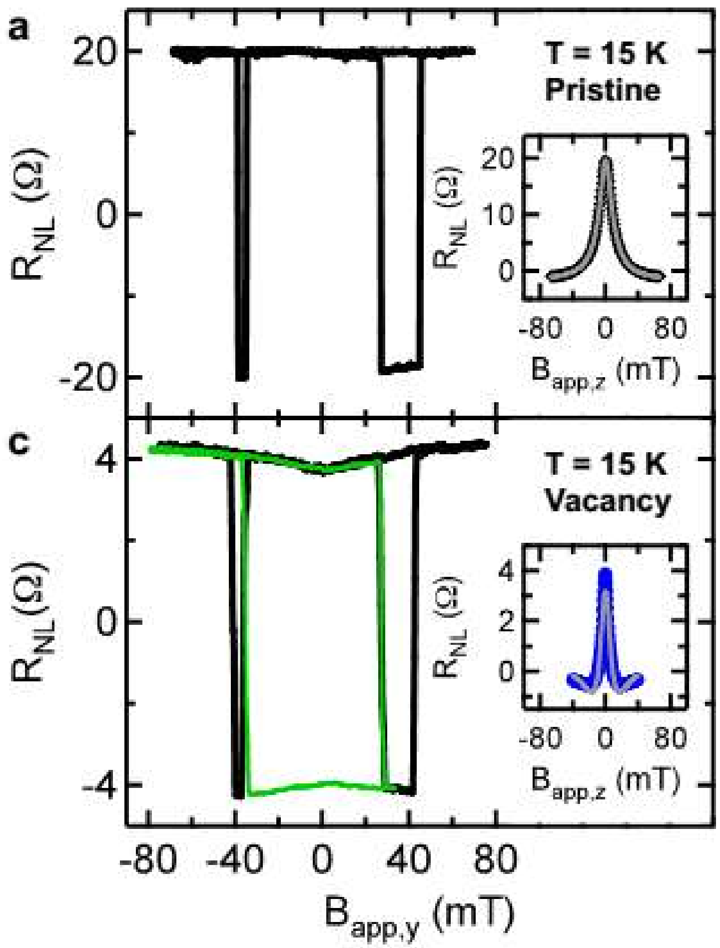
$$H_{ex} = A_{ex}\, \vec{S}_e \cdot \vec{S}_M$$

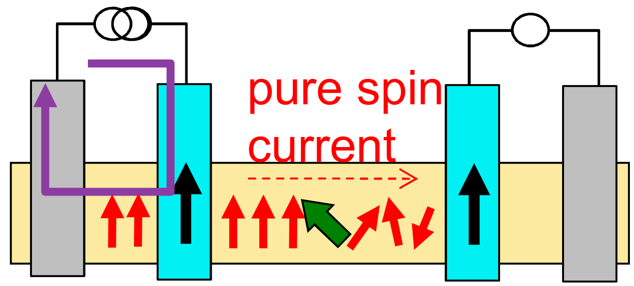
Due to exchange coupling,
pure spin current is scattered
by magnetic moment

Fewer spins at detector

# Vacancies Defects

Using the spin current approach




**At high field**

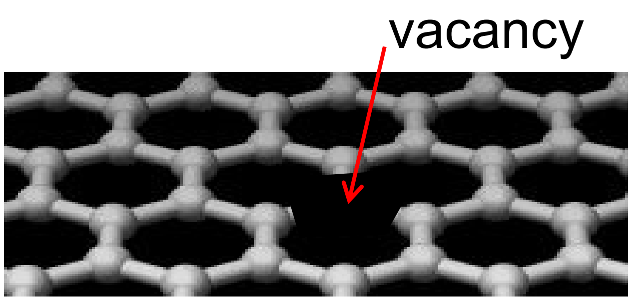
$\vec{S}_e$ and $\vec{S}_M$ decouple!

Scattering by exchange coupling is suppressed

More spins at detector

# Vacancies Defects

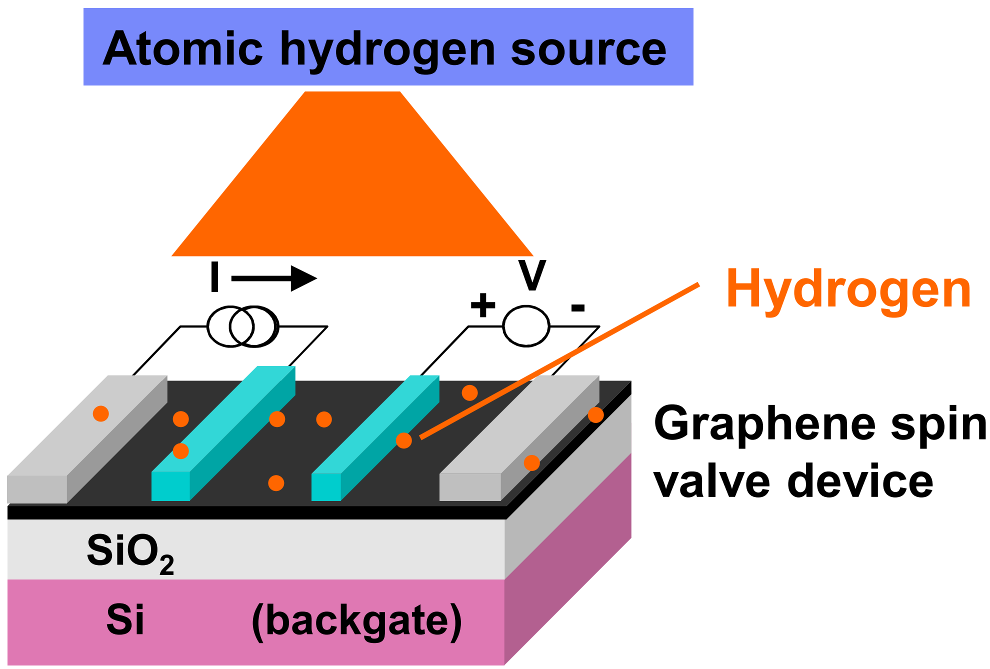
**Question?**



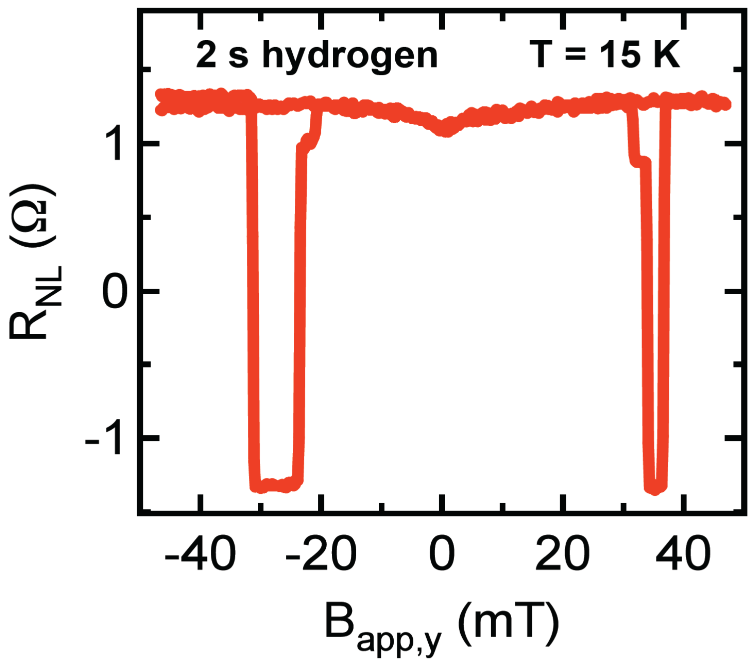

**Ferromagnetic ??**

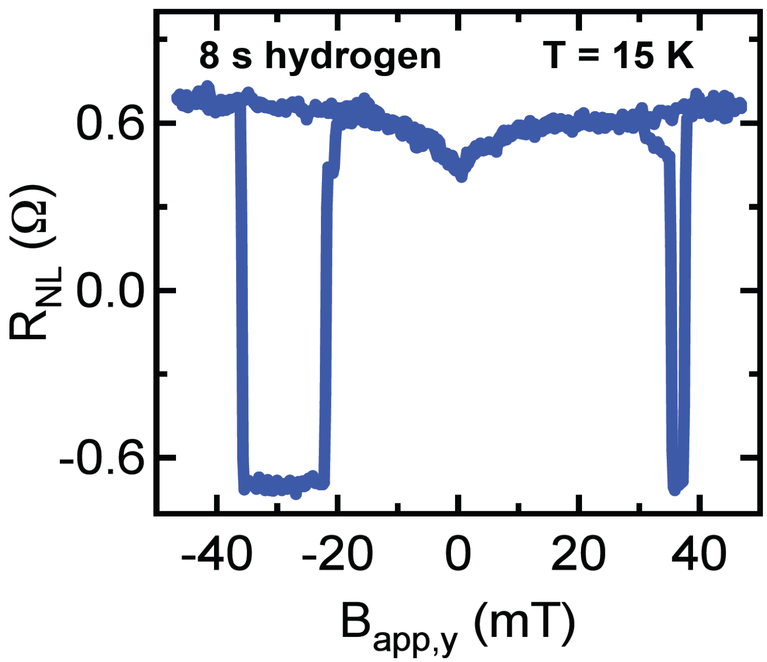
**Paramagnetic > 15 K**

# Hydrogen Doping



# Hydrogen Doping



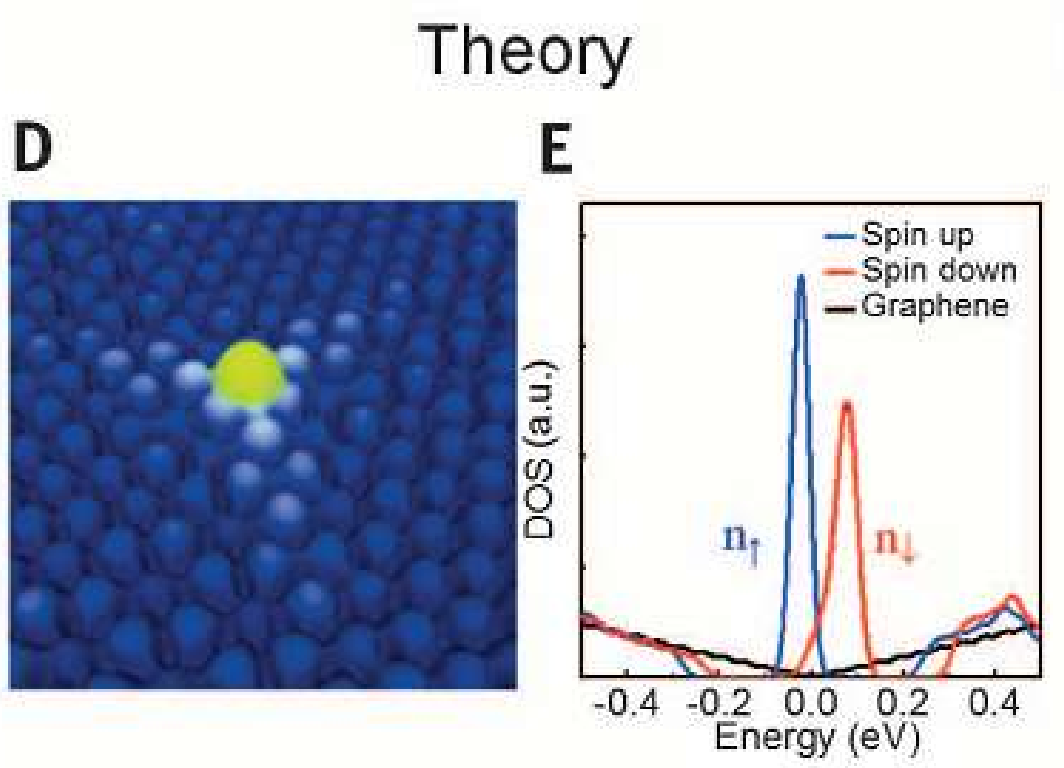




**Paramagnetic at 15 K!**

McCreary, et al, PRL (2012)

# Hydrogen Doping

STM probe of H-graphene




González-Herrero, et al, Science (2016)

# Hydrogen Doping

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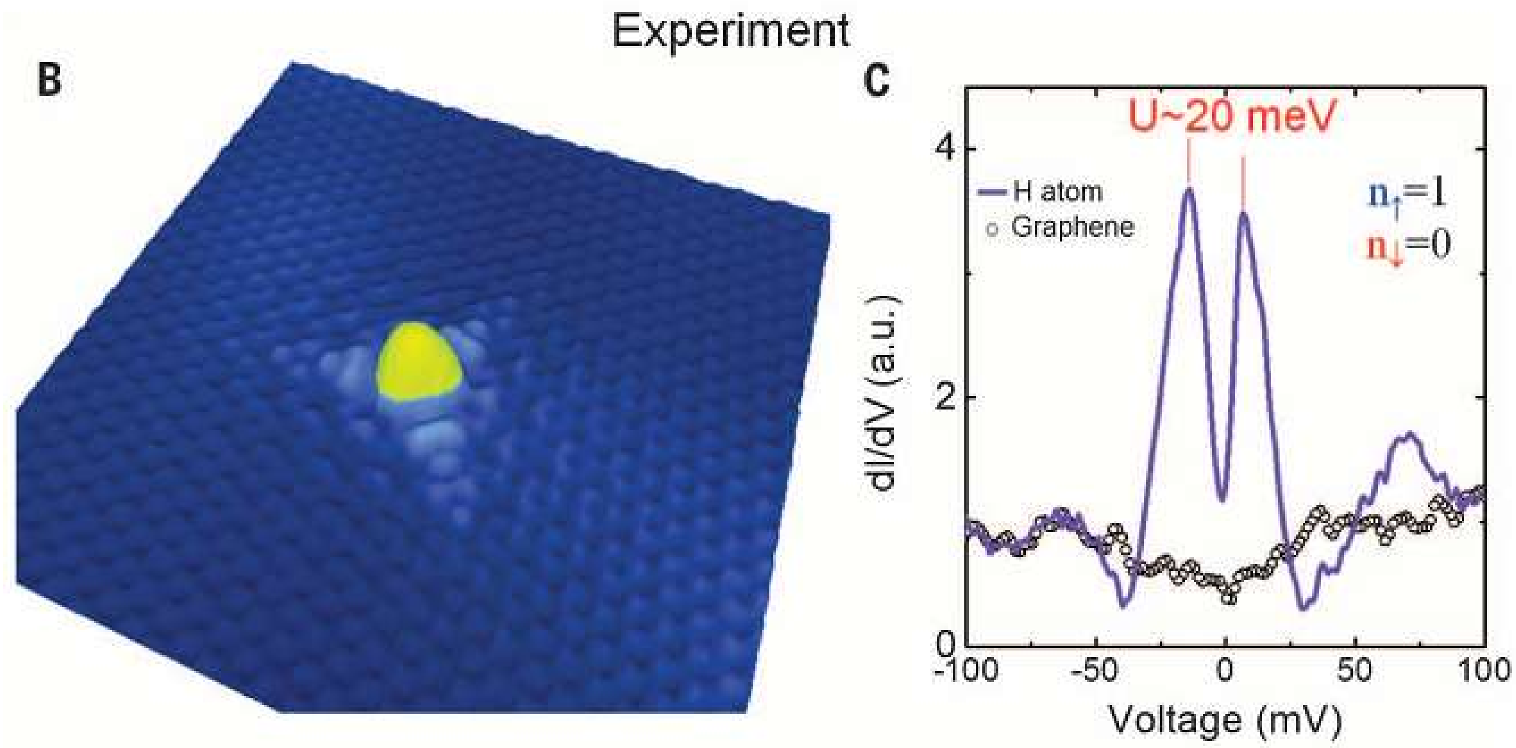


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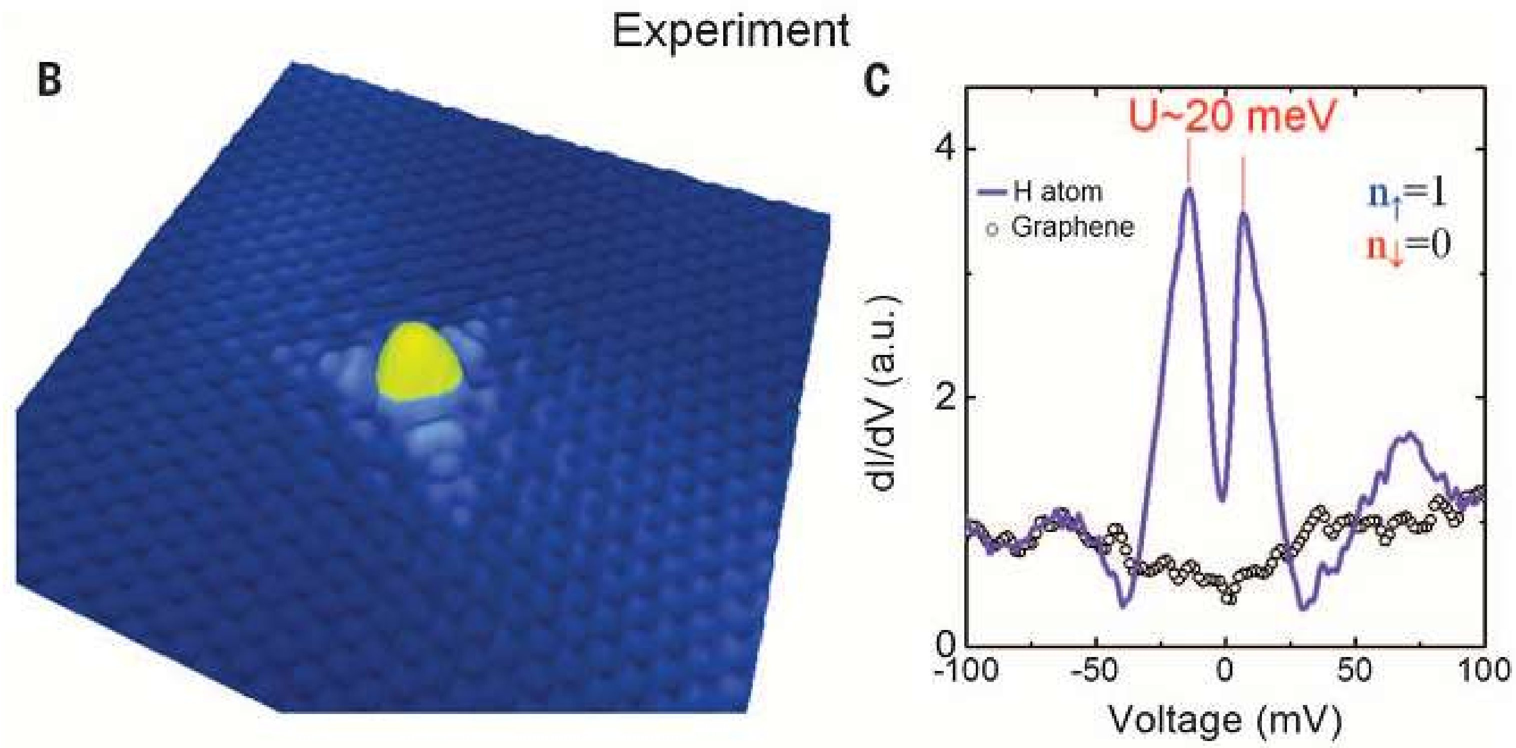


T = 5 K

González-Herrero, et al, Science (2016)

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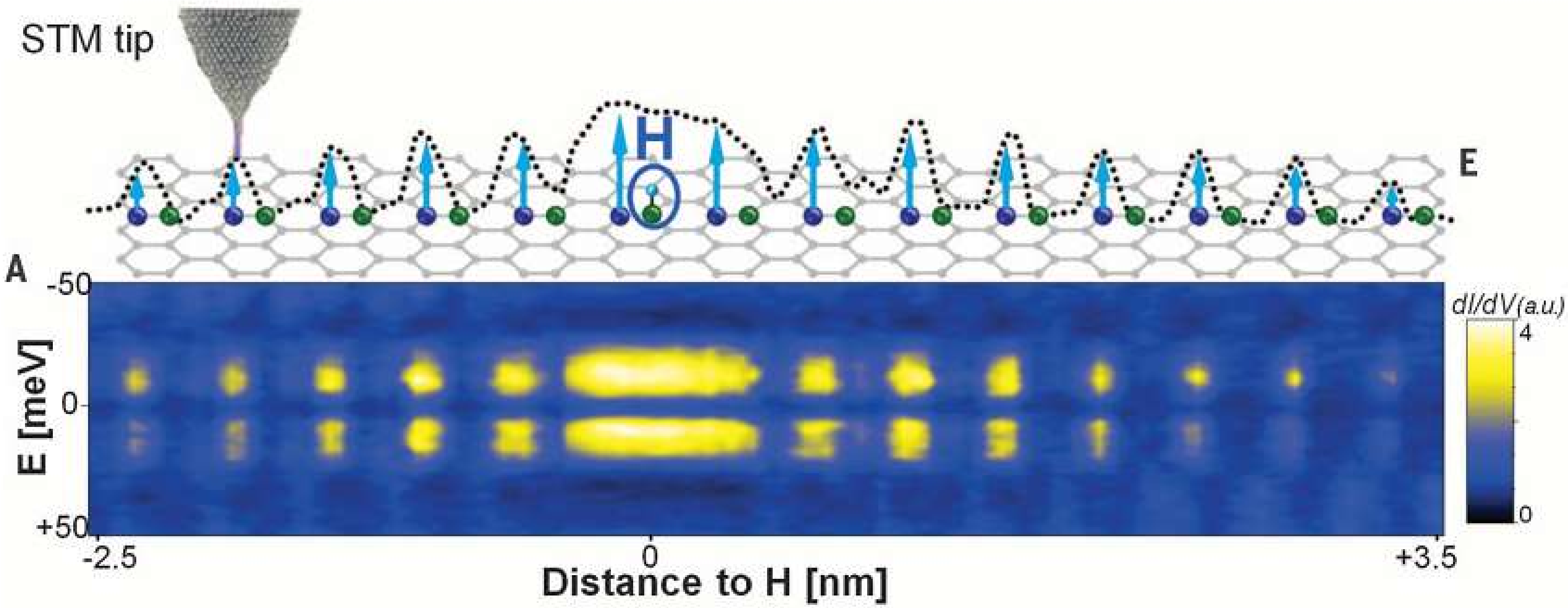


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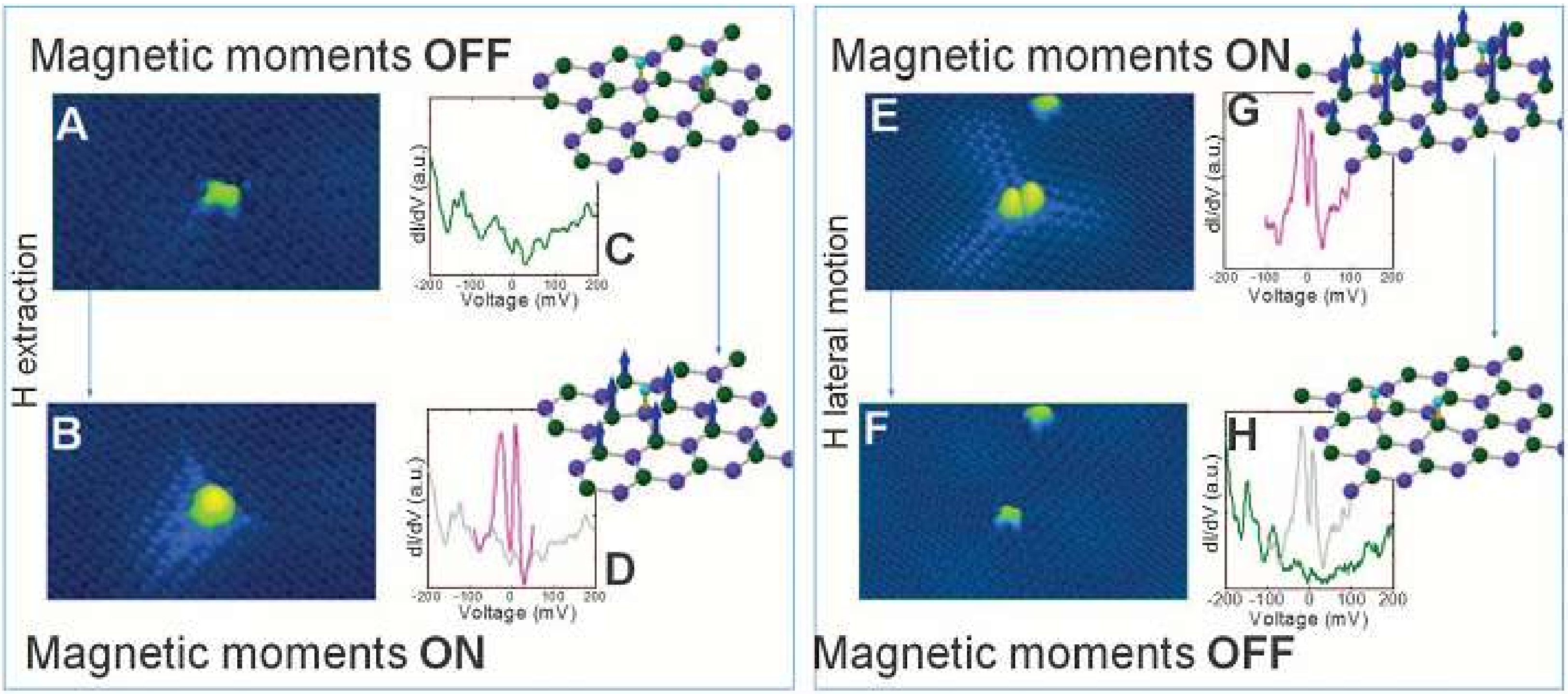
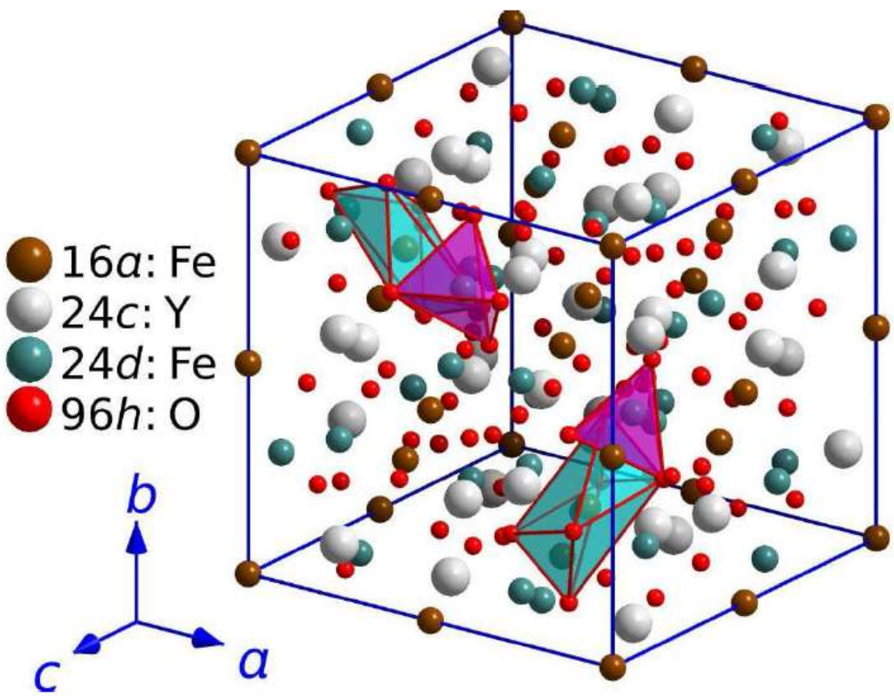



González-Herrero, et al, Science (2016)

# Proximity effect

Graphene on YIG



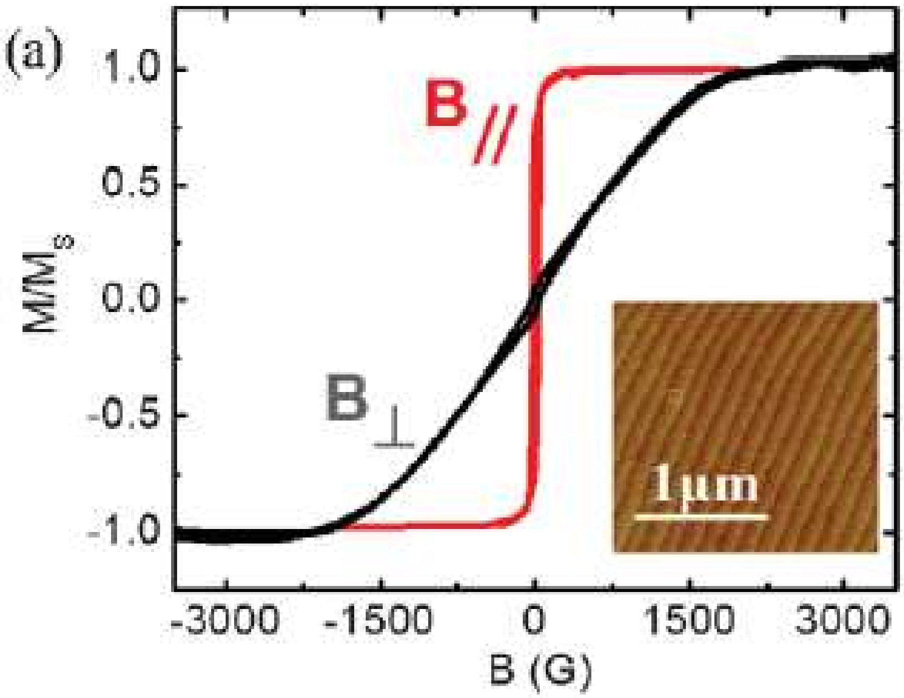

**yttrium iron garnet (YIG):**

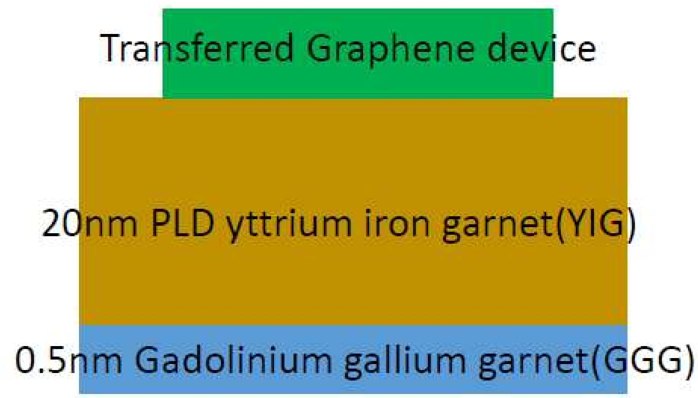
- **high Tc~550K;**
- **Extremely small intrinsic damping constant ( $3x10^{-5}$);**
- **Insulating behavior;**
- **In-plane magnetic anisotropy.**

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

# Proximity effect

Graphene on YIG

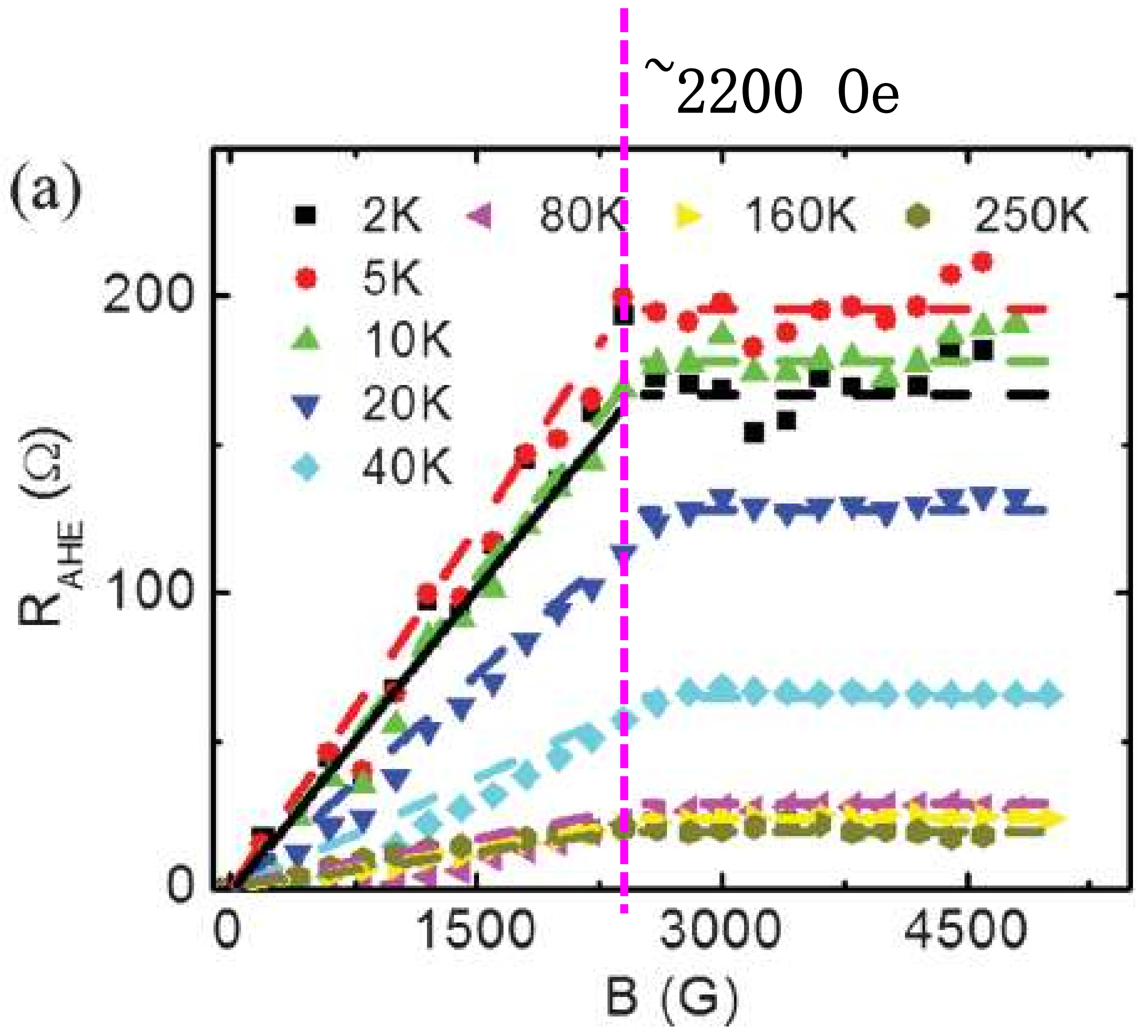


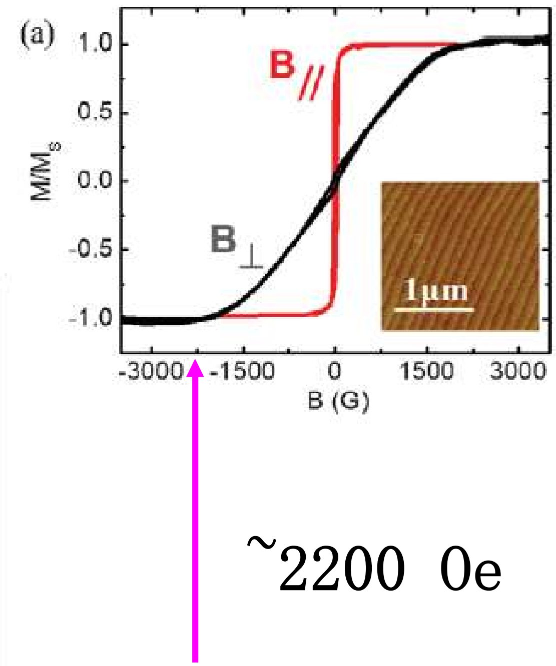




Wang, et al, PRL (2015)

# Proximity effect

Graphene on YIG



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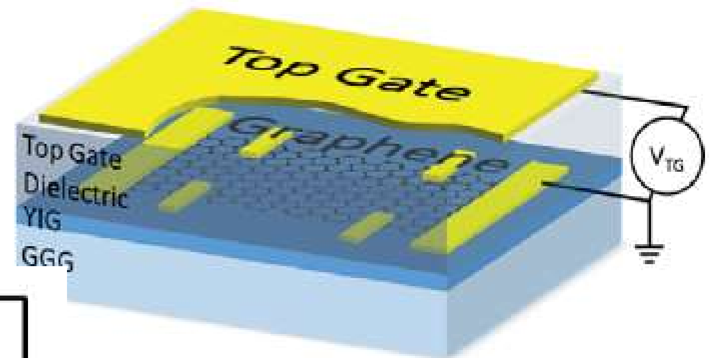
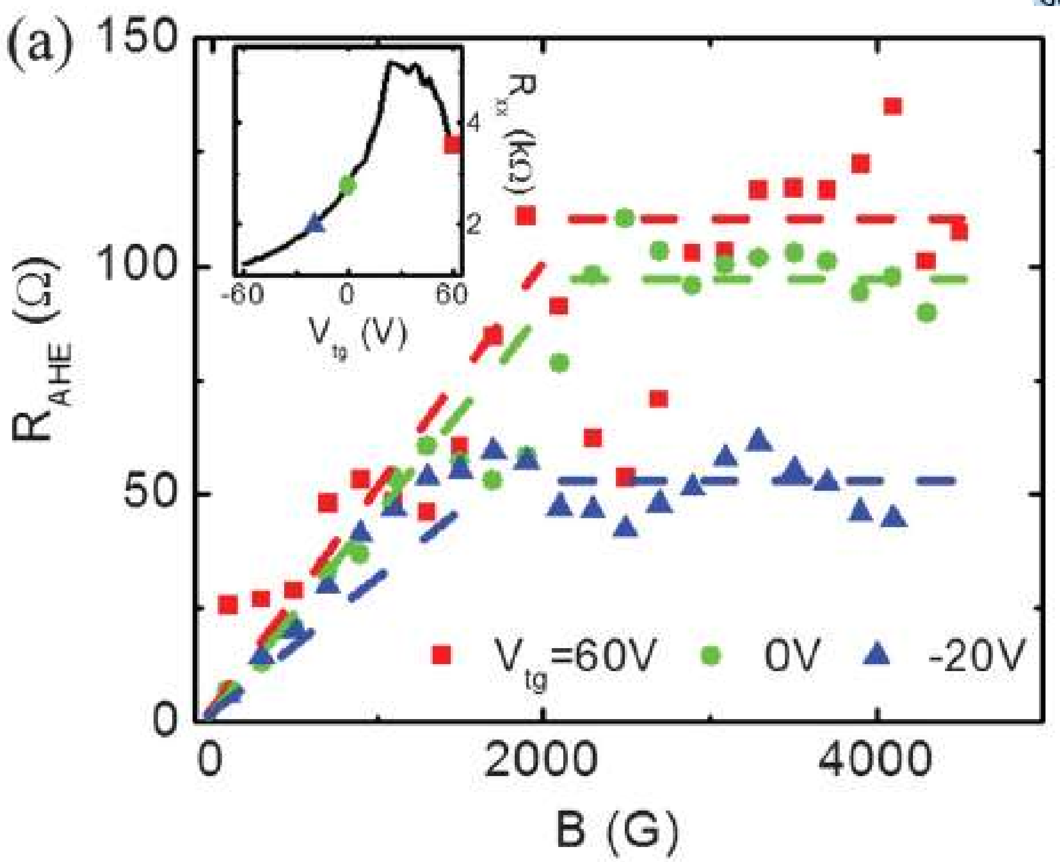
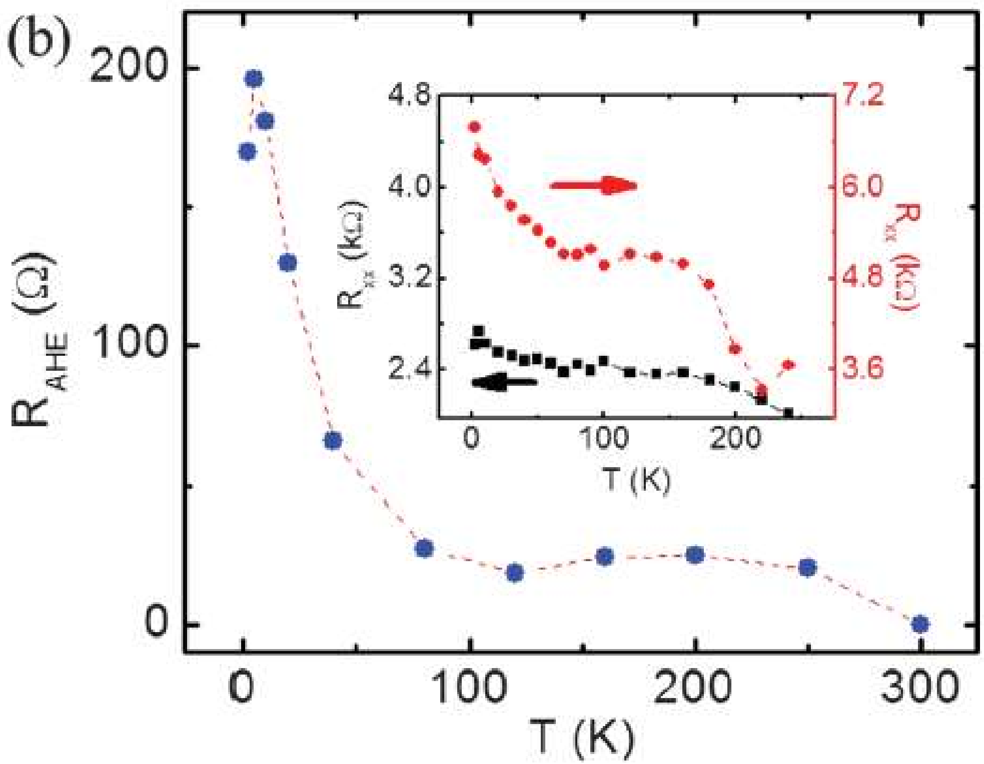



Wang, et al, PRL (2015)

# Proximity effect

Graphene on YIG

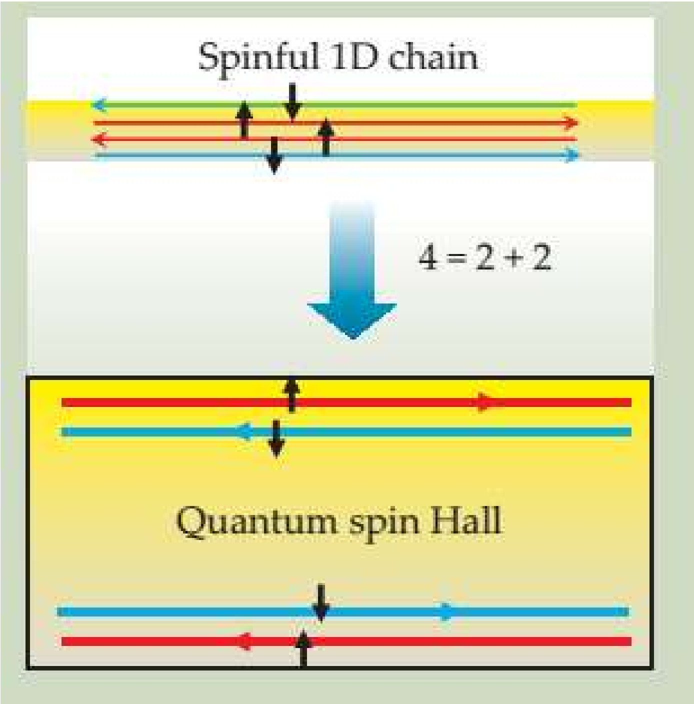


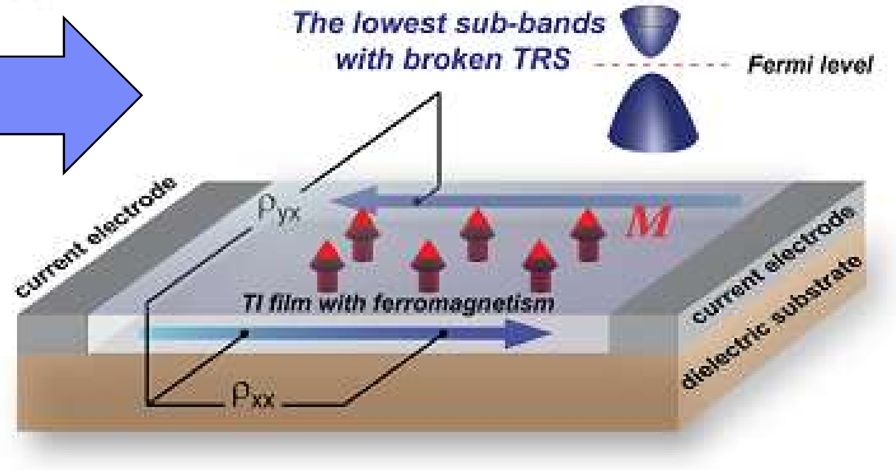

$$R_{xy} = R_H(B) + R_{\mathrm{AHE}}(M) = \alpha B + \beta M$$

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

# Induce M in Topological Insulator

Why making TI magnetic

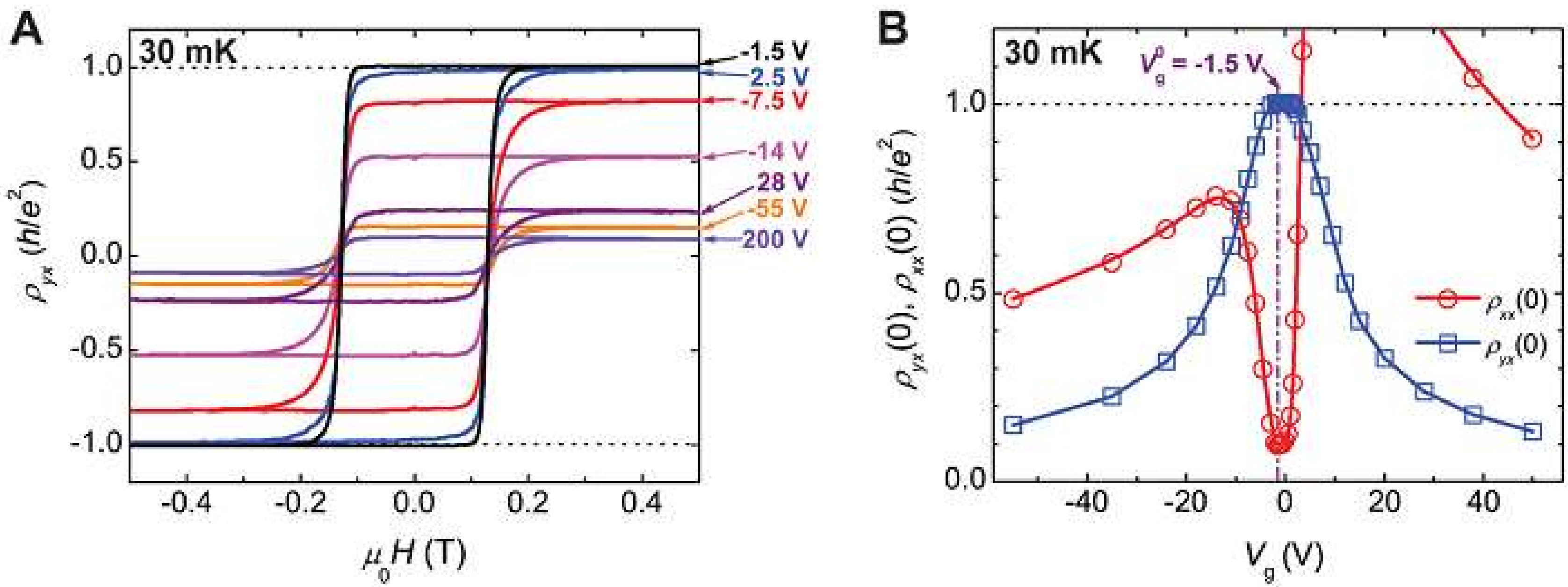



**Quantum Anomalous Hall effect**

# Doping of Magnetic impurity

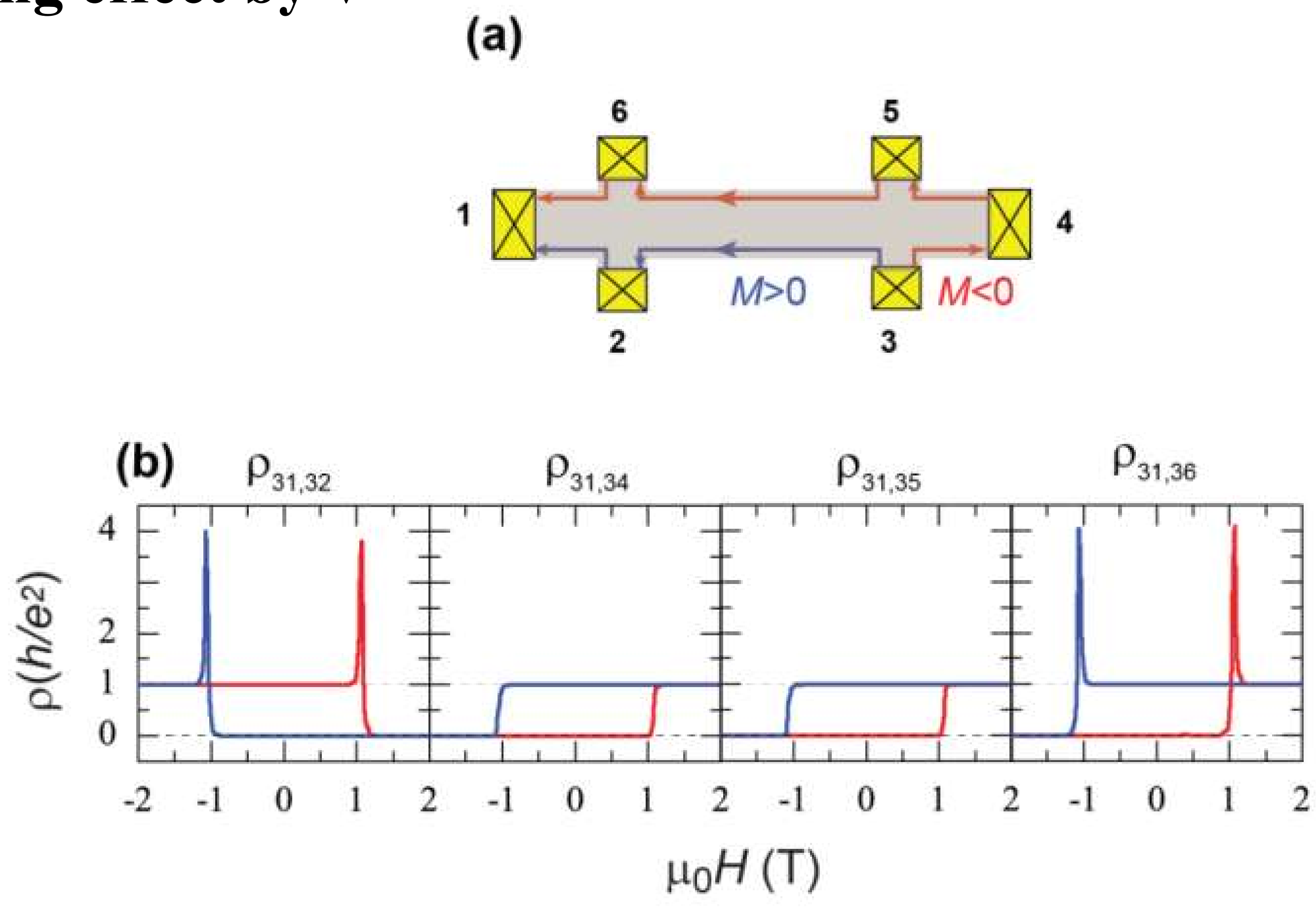
**Doping effect by Cr**




Chang, et al, Science (2013)

# Doping of Magnetic impurity

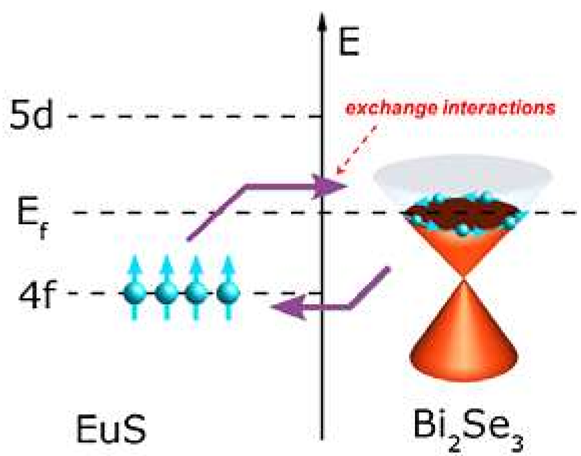
**Doping effect by V**

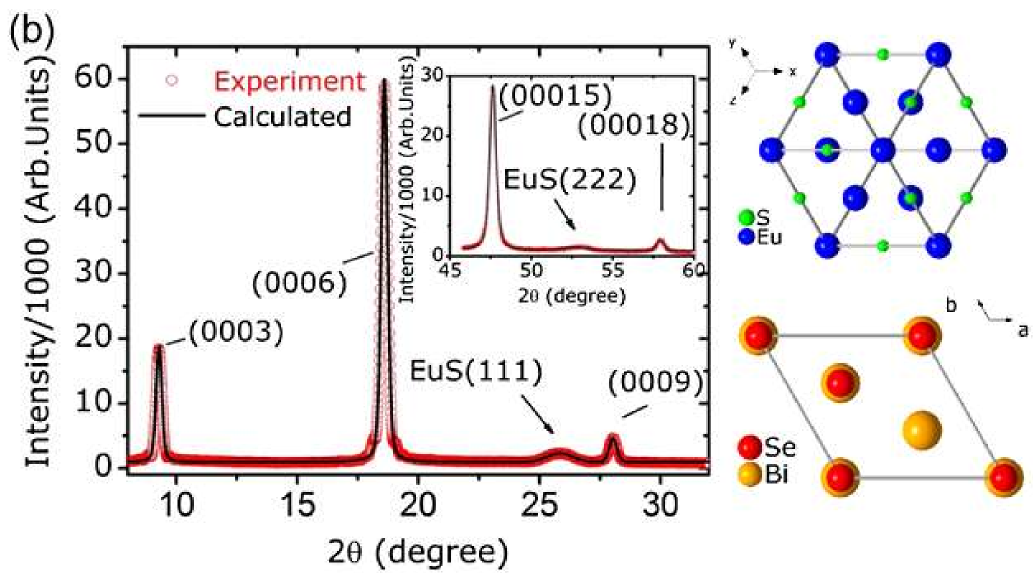



Chang, et al, Nat. Mater. (2015)

# Proximity effect

## EuS: magnetic insulator

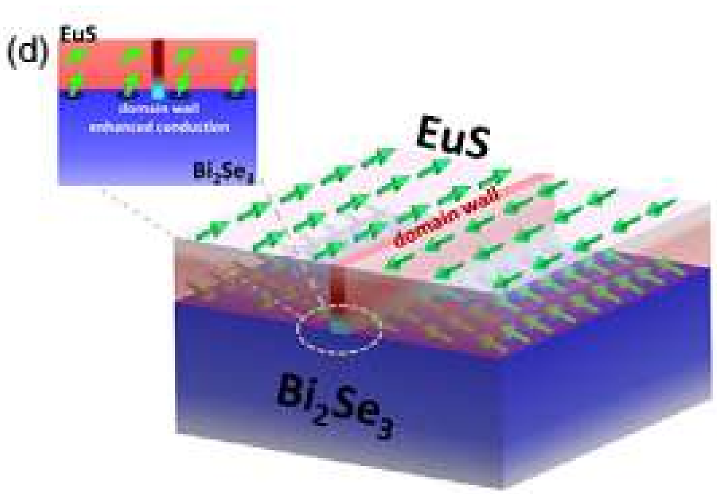


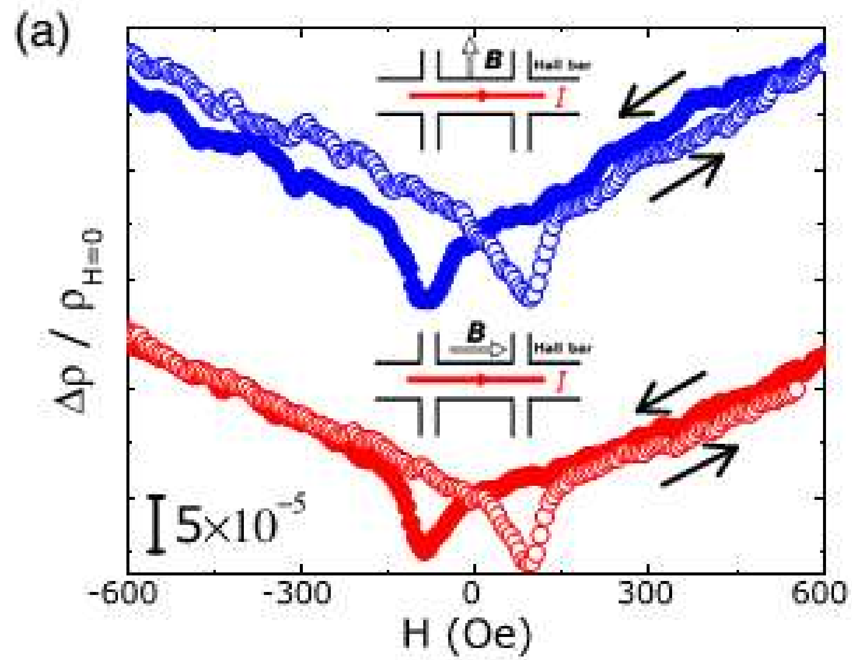




Wei, et al, PRL (2013)

# Proximity effect

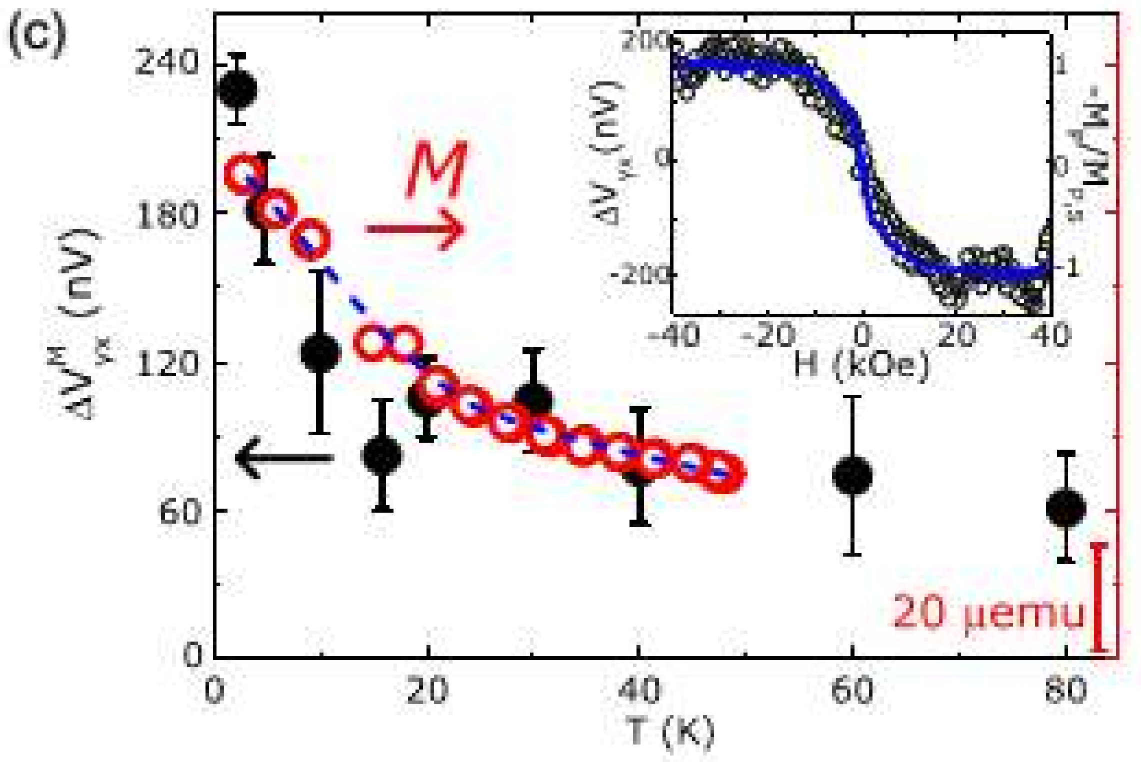
**EuS: magnetic insulator**



# Proximity effect

**EuS: magnetic insulator**

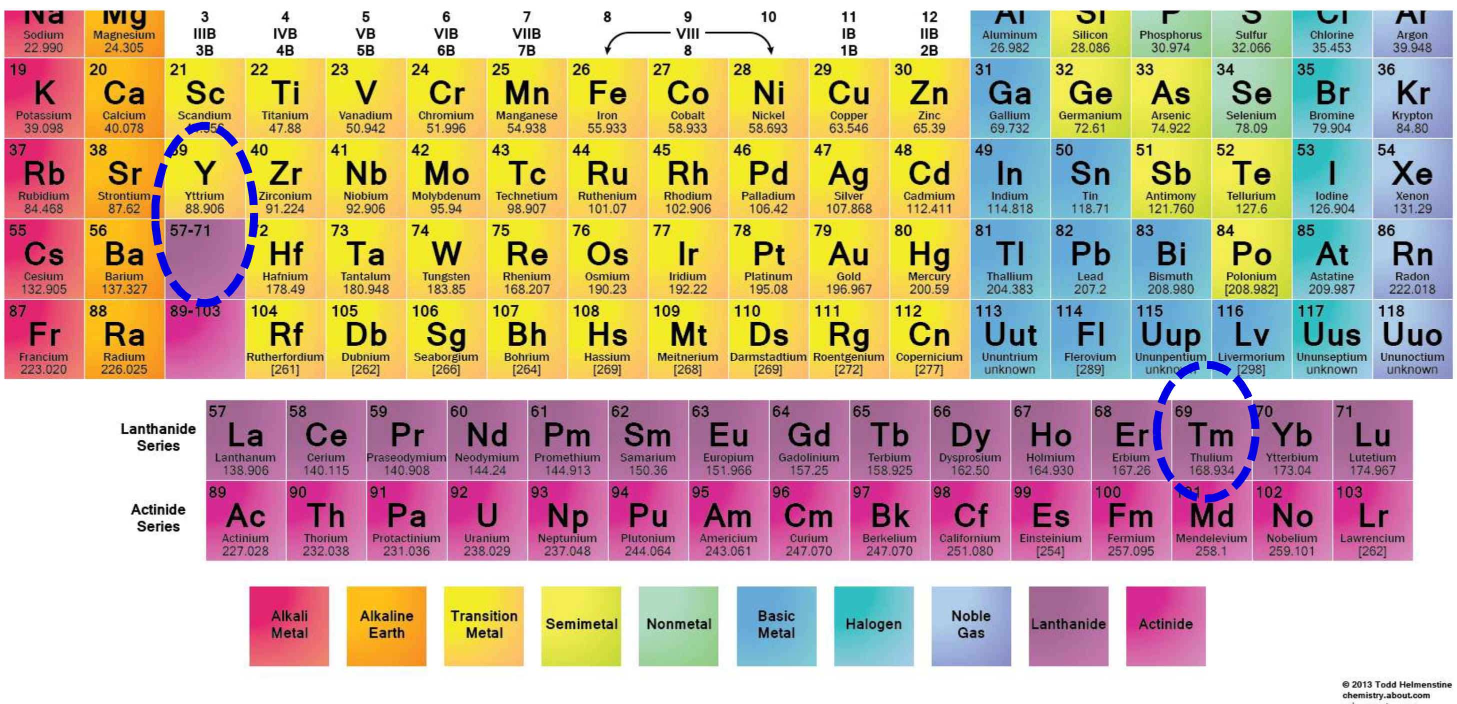



Wei, et al, PRL (2013)

# Proximity effect

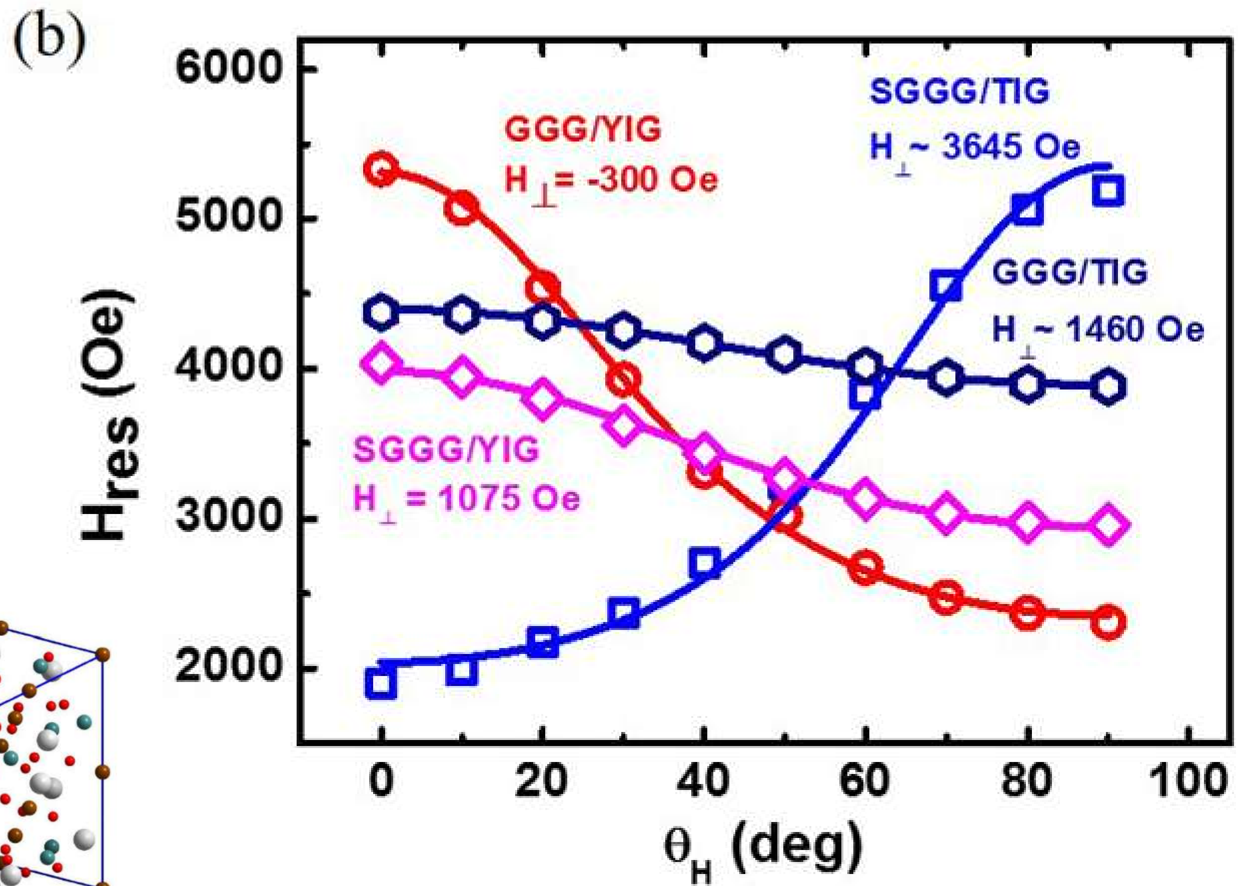
**TIG, a magnetic insulator with perpendicular easy axis**

***$Y_3Fe_5O_{12}$*** → ***$Tm_3Fe_5O_{12}$***



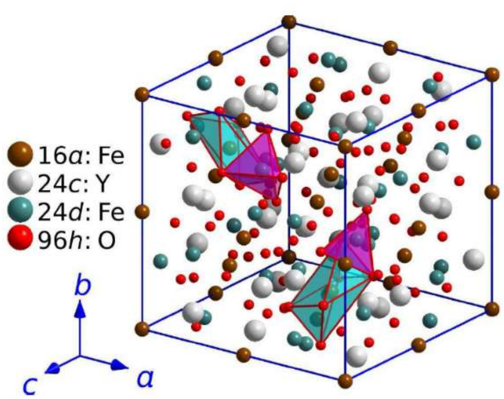
# Proximity effect

**TIG, a magnetic insulator with perpendicular easy axis**




*$Y_3Fe_5O_{12}$*

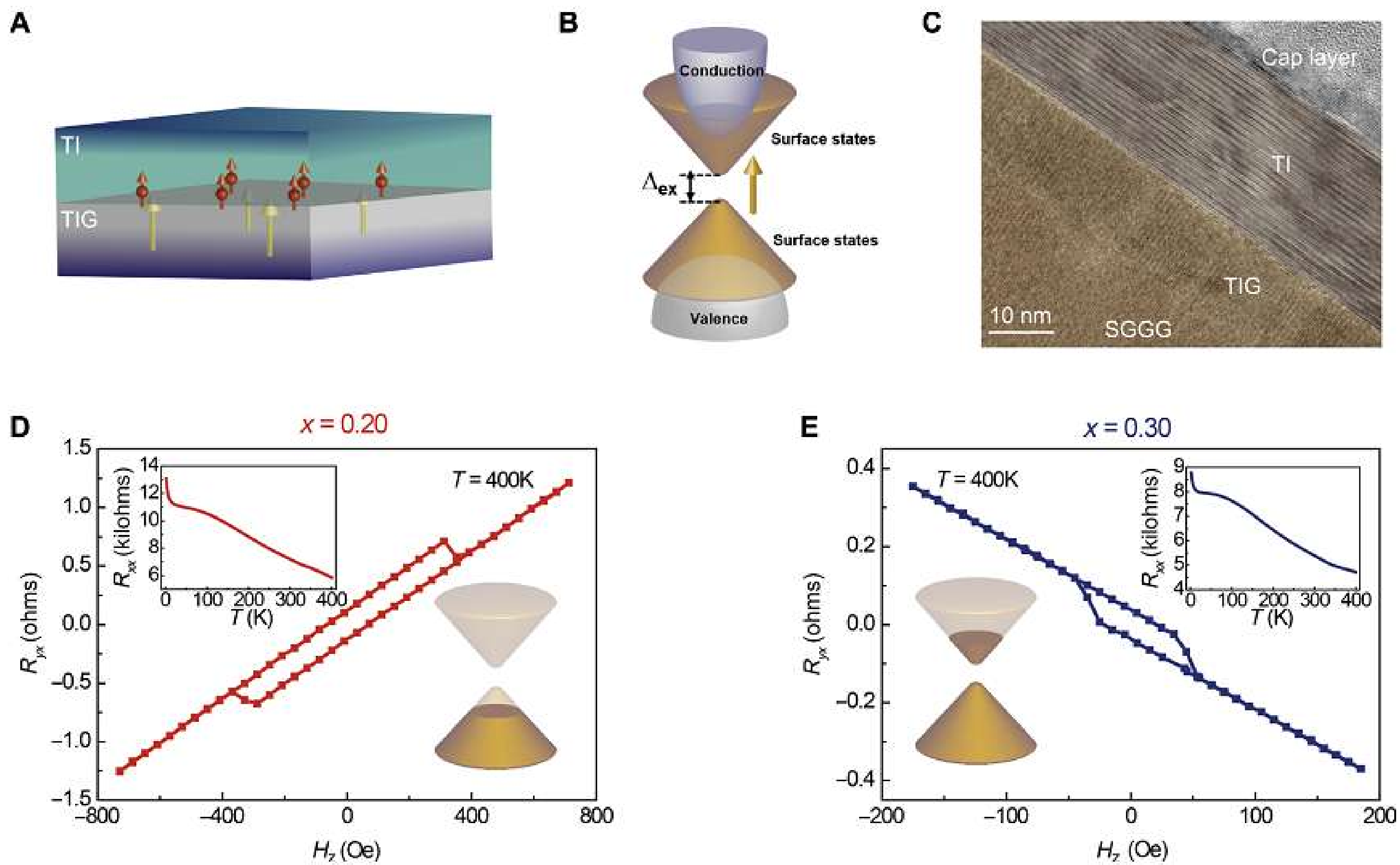
*$Tm_3Fe_5O_{12}$*




Tang, et al, PRB (2017)

# Proximity effect

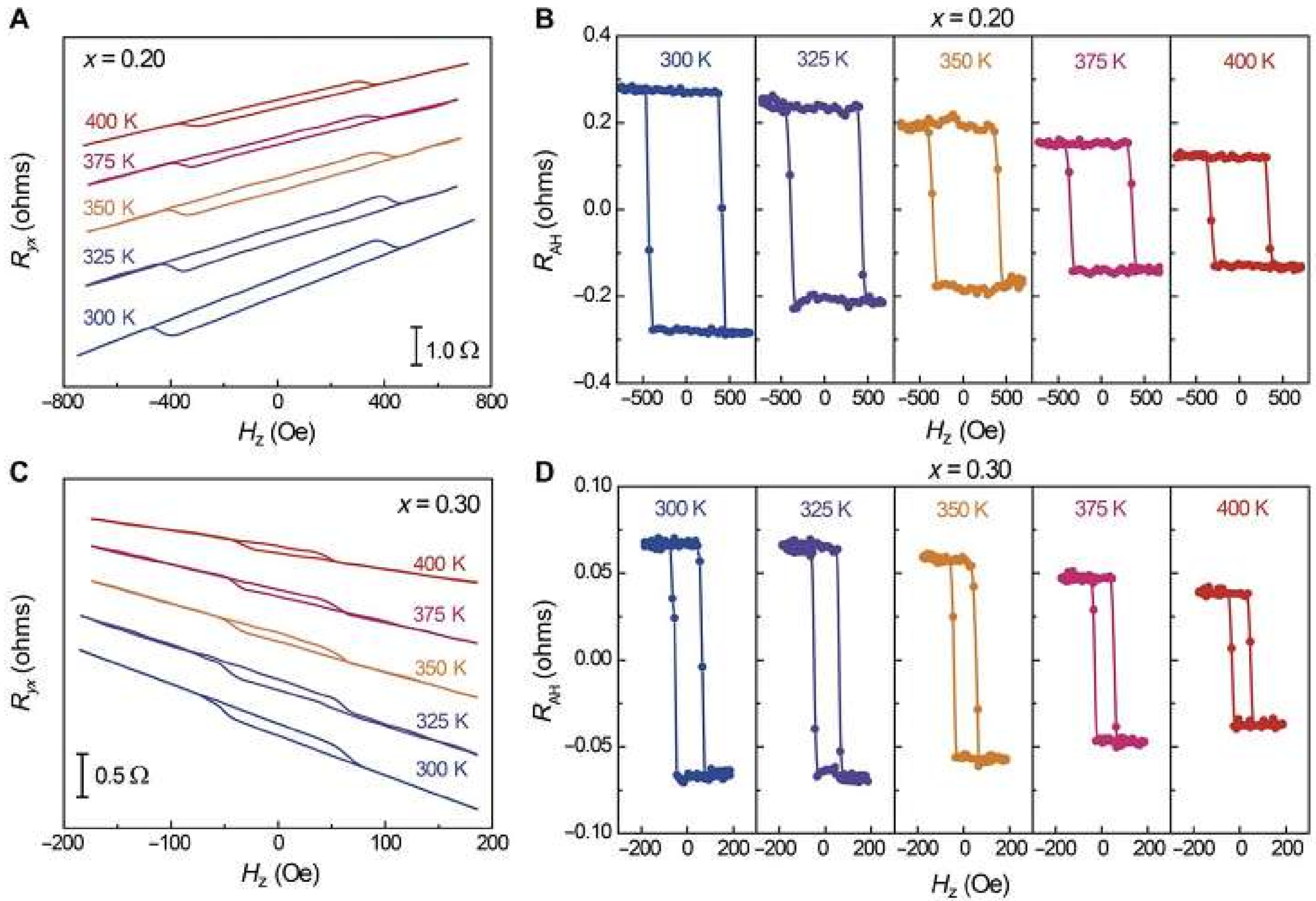
**TIG, a magnetic insulator with perpendicular easy axis**




Tang, et al, Science Advances (2017)

# Proximity effect

**TIG, a magnetic insulator with perpendicular easy axis**



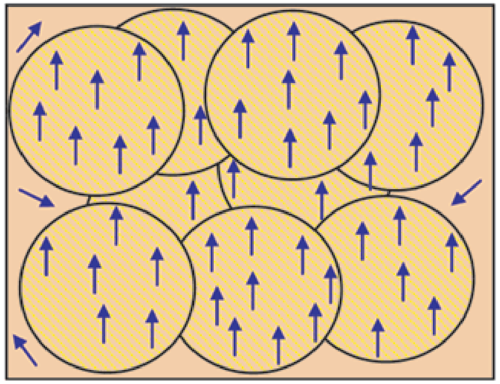

Tang, et al, Science Advances (2017)

# Summary

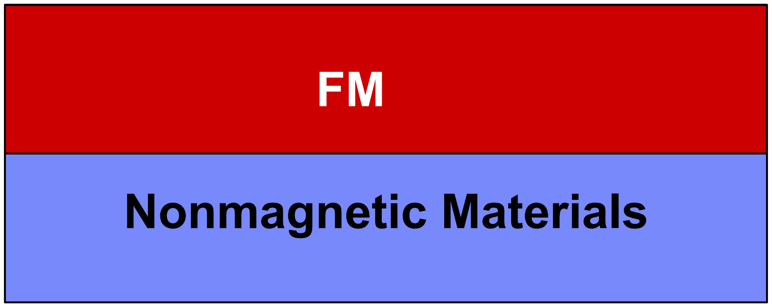
## How to induce magnetic moment

**Doping**

c



**Proximity effect**




**Interface hybridization**

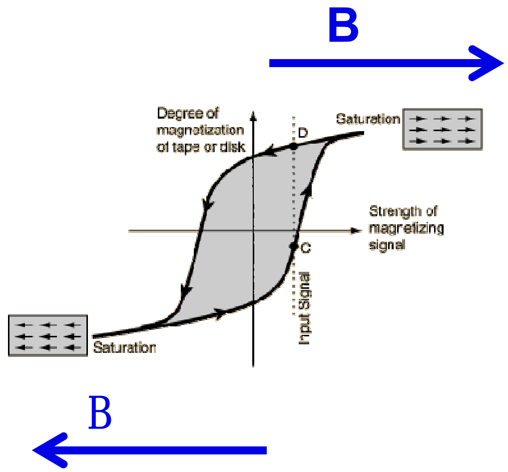
# 休息10分钟

# 提纲

# 3. How to control magnetization

# How to control the magnetization

Magnetic field

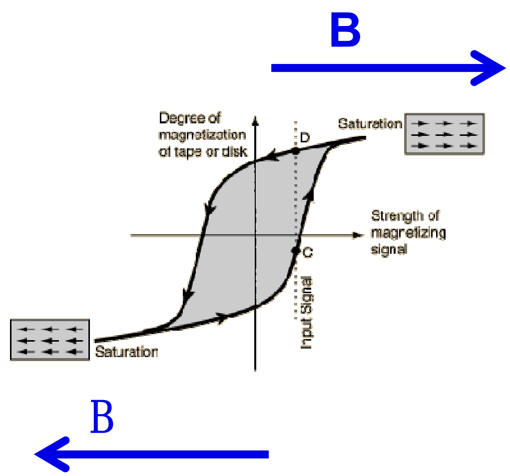



Without B

???

# How to control the magnetization

Magnetic field




Without B
???

**Control??**

**Electric field**

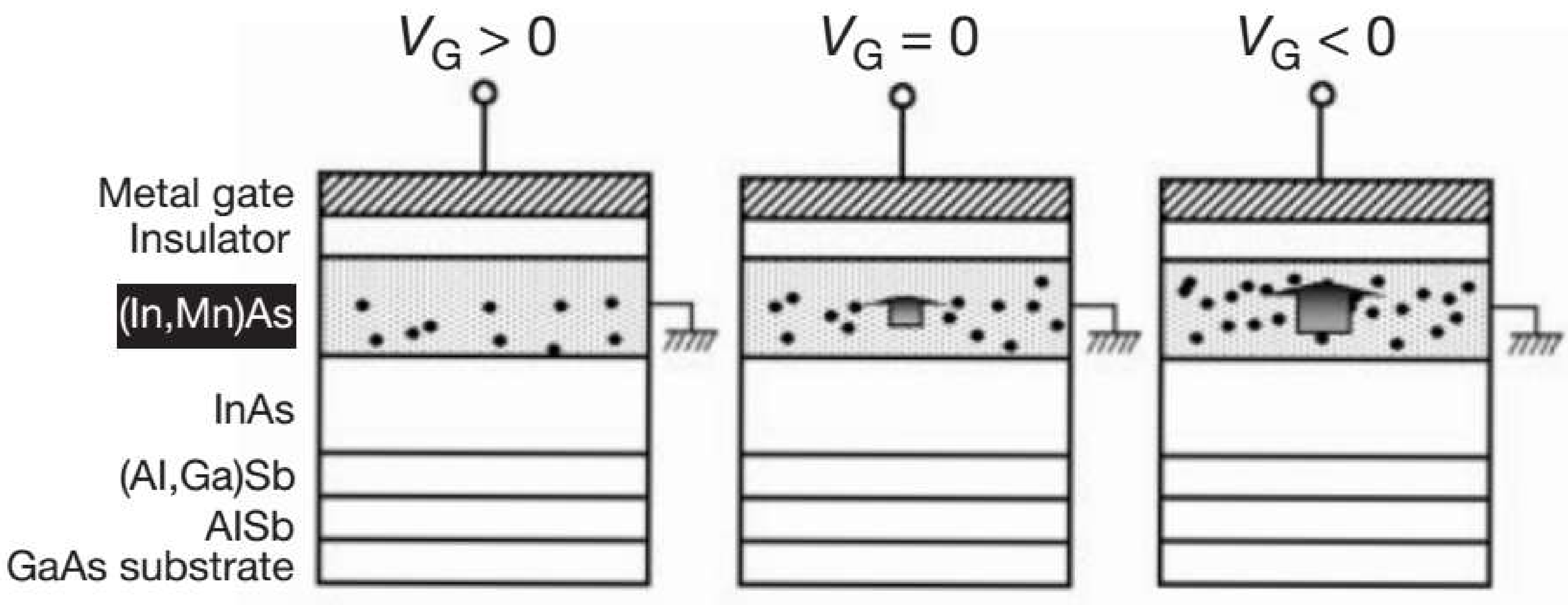
**Ultrafast Laser**

**Spin torque**

**Interface Strain**

# Electric field control the magnetization

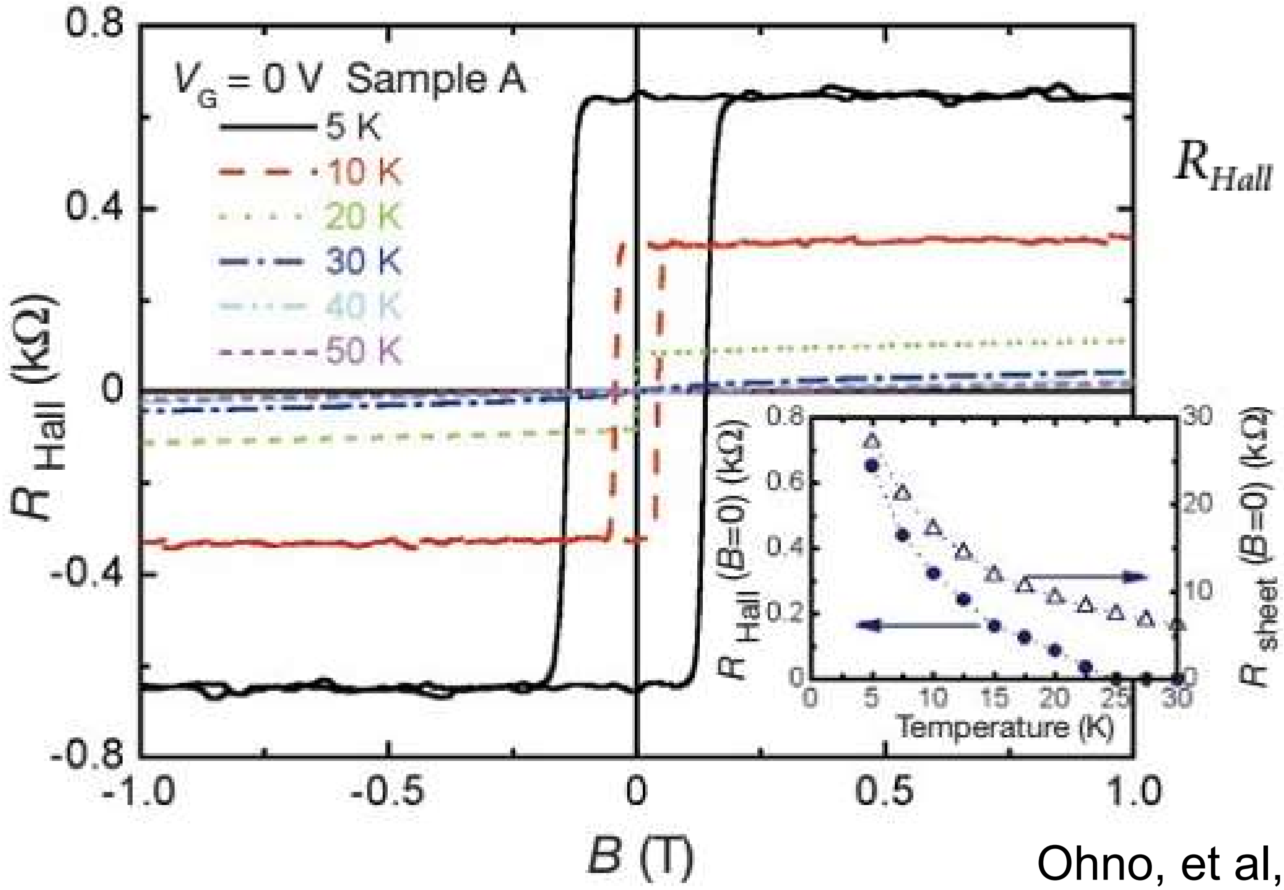
Electrical field effect in magnetic semiconductor




Ohno, et al, Nature (2000)

# Electric field control the magnetization

Magnetic properties of InMnAs (AHE)

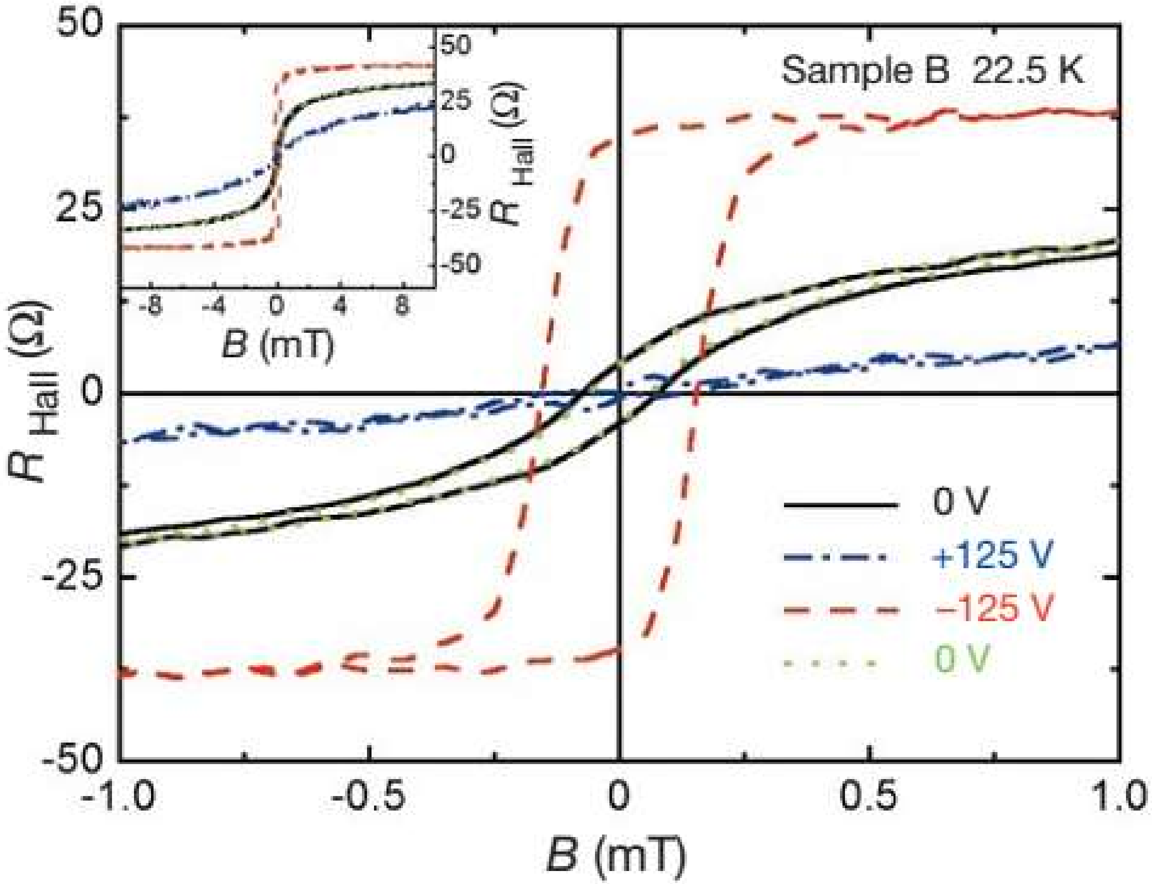



$$R_{Hall} = \frac{R_0}{d} B + \frac{R_S}{d} M$$

Ohno, et al, Nature (2000)

# Electric field control the magnetization

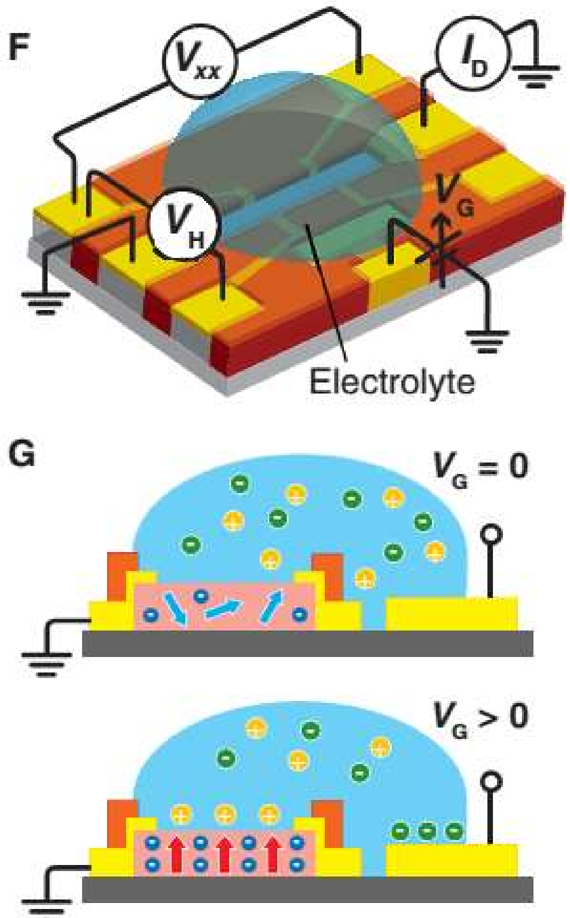
Electrical field effect on InMnAs

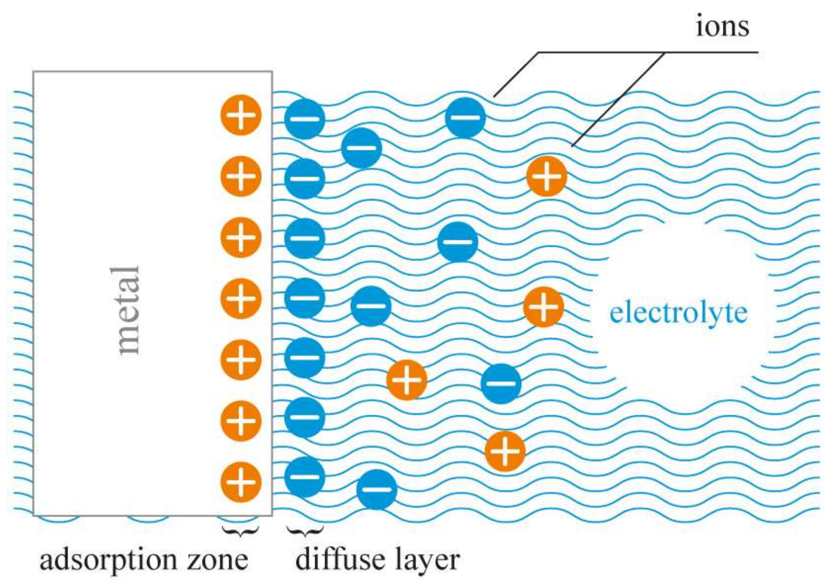



Ohno, et al, Nature (2000)

# Electric field control the magnetization

Ionic liquid gate control



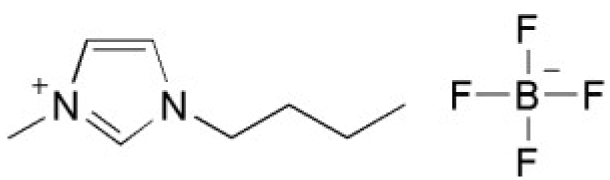

**Large electric field on the surface**

Yamada, et al, Science (2011)

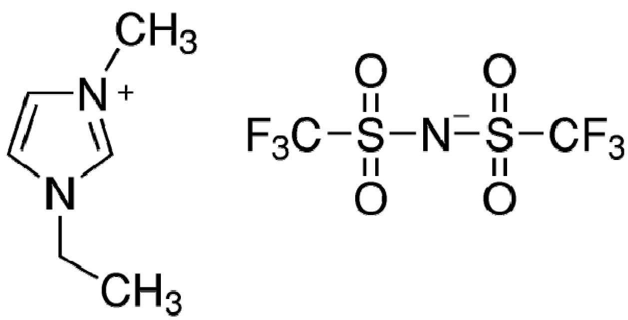
# Electric field control the magnetization

Ionic liquid

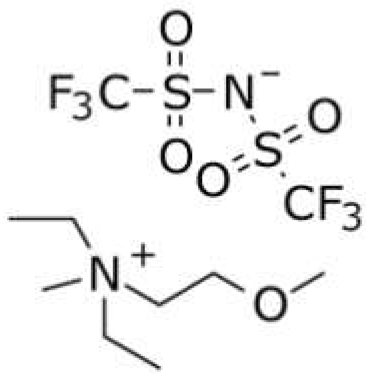
HMIM $BF_4$




EMIM TFSI

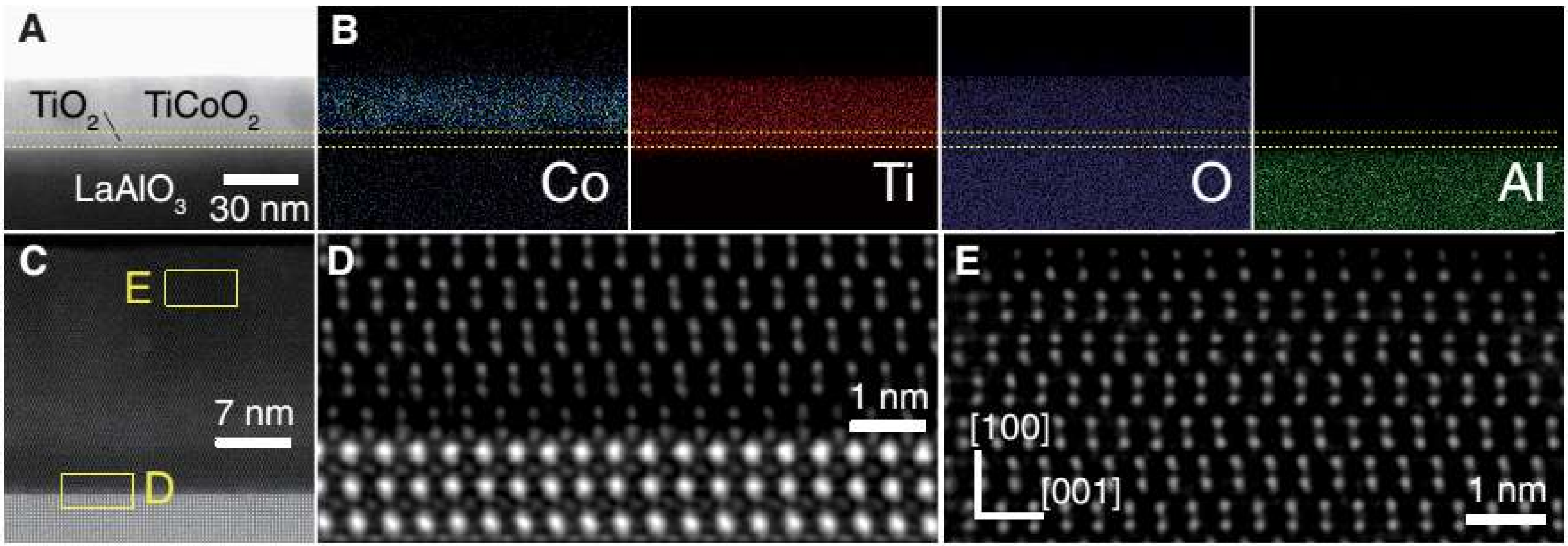



DEME TFSI



# Electric field control the magnetization

Ionic liquid gate control



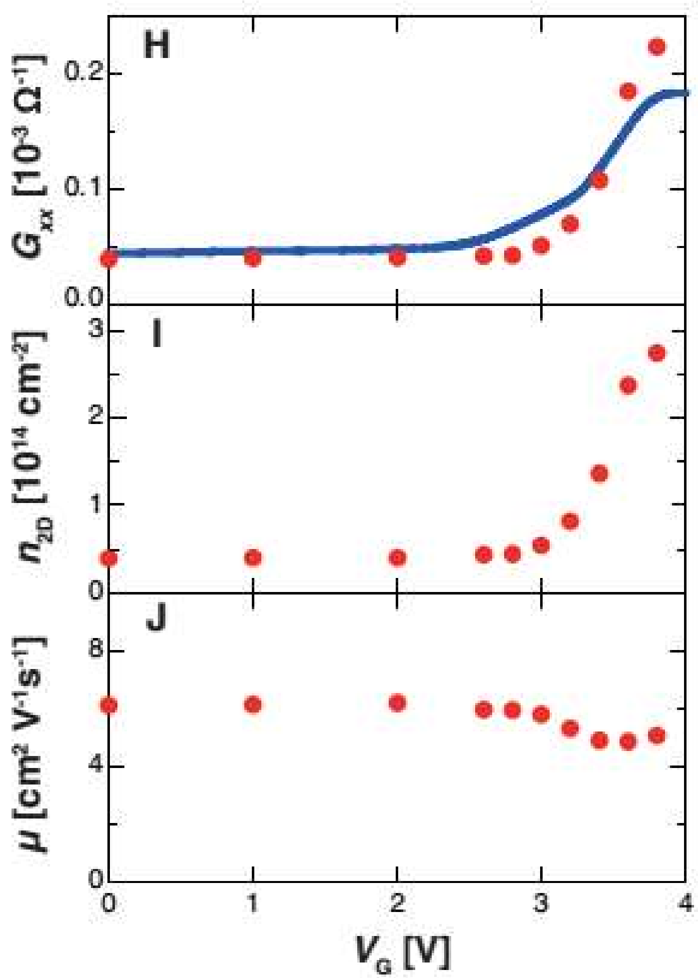

$Ti_{0.9}Co_{0.1}O_2$

$T_C > 300$ K

Yamada, et al, Science (2011)

# Electric field control the magnetization

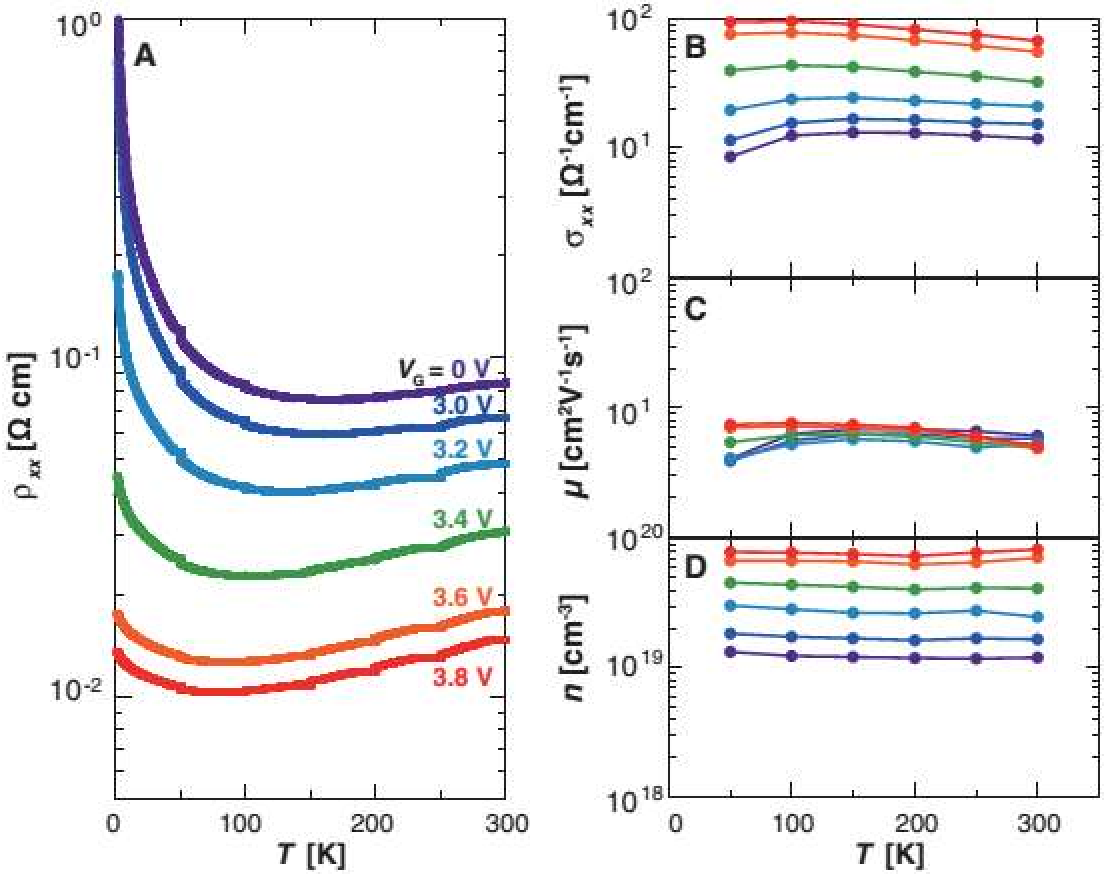
Ionic liquid gate control electronic properties




Yamada, et al, Science (2011)

# Electric field control the magnetization

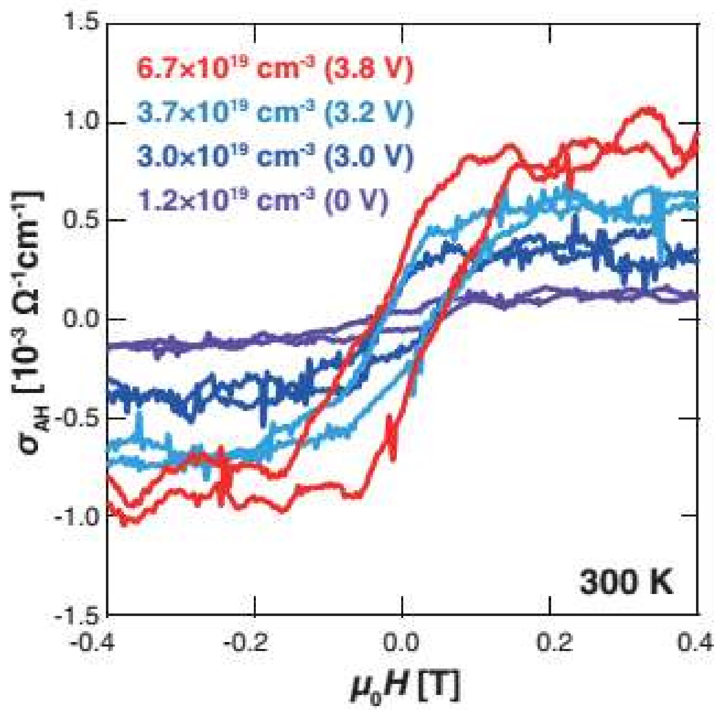
Ionic liquid gate control electronic properties

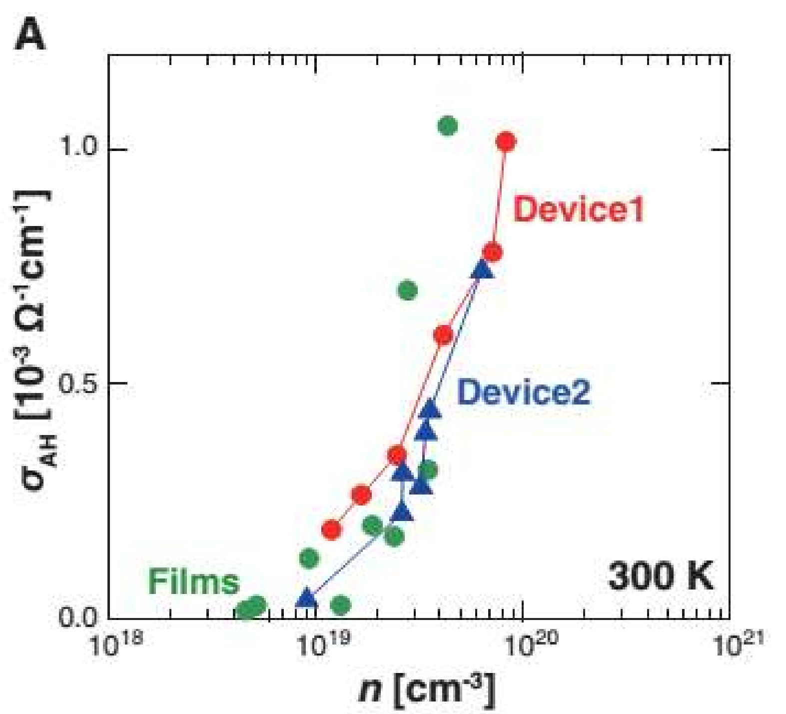



Yamada, et al, Science (2011)

# Electric field control the magnetization

Ionic liquid gate control magnetic properties

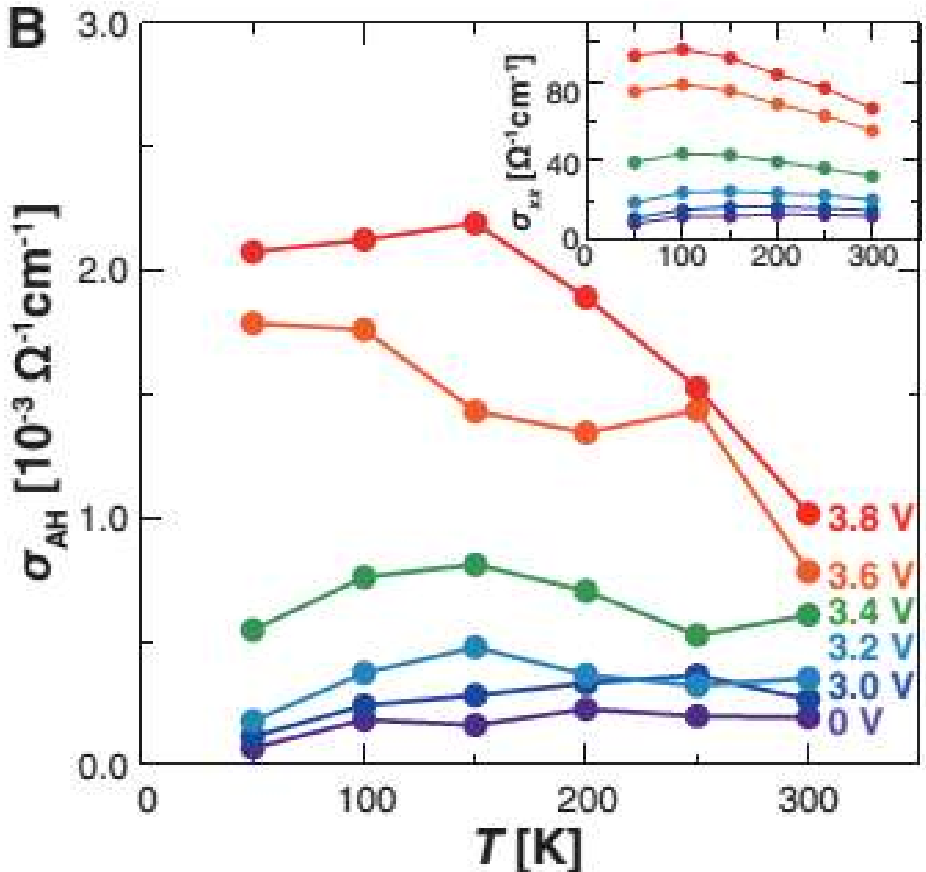



Yamada, et al, Science (2011)

# Electric field control the magnetization

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

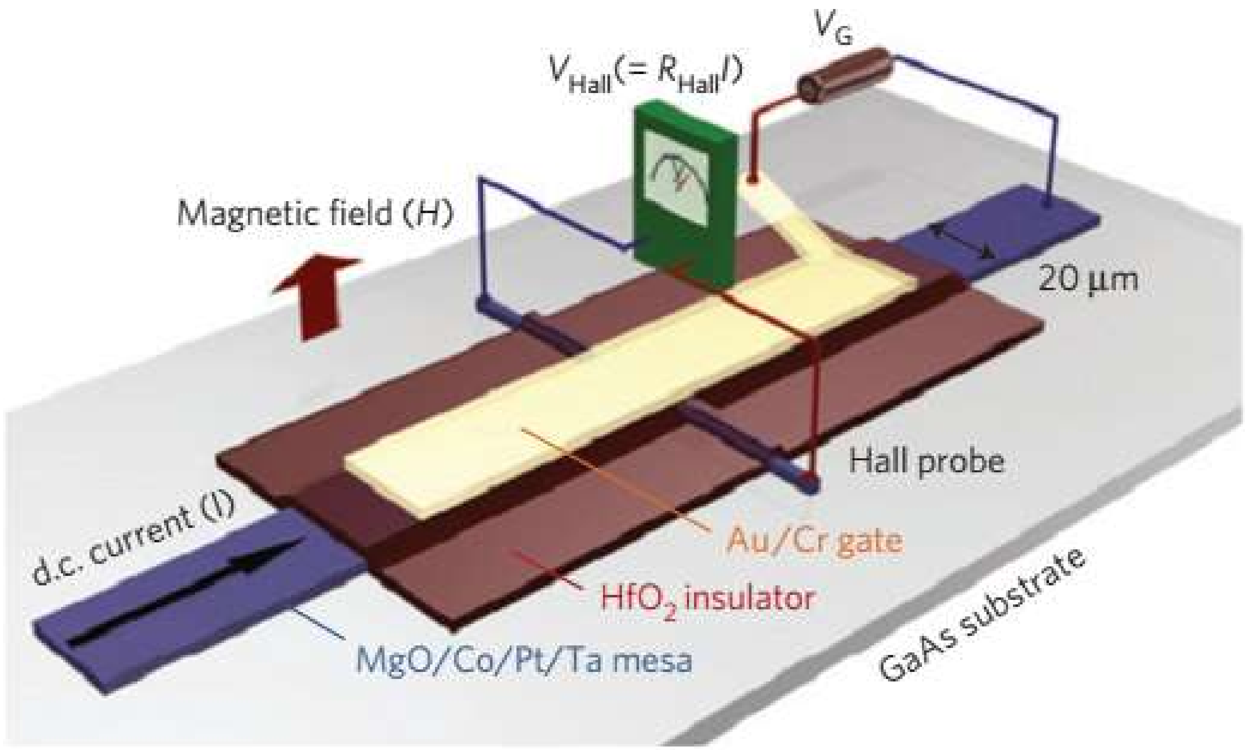
PUBLISHED ONLINE: 2 OCTOBER 2011 | DOI: 10.1038/NMAT3130

## 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

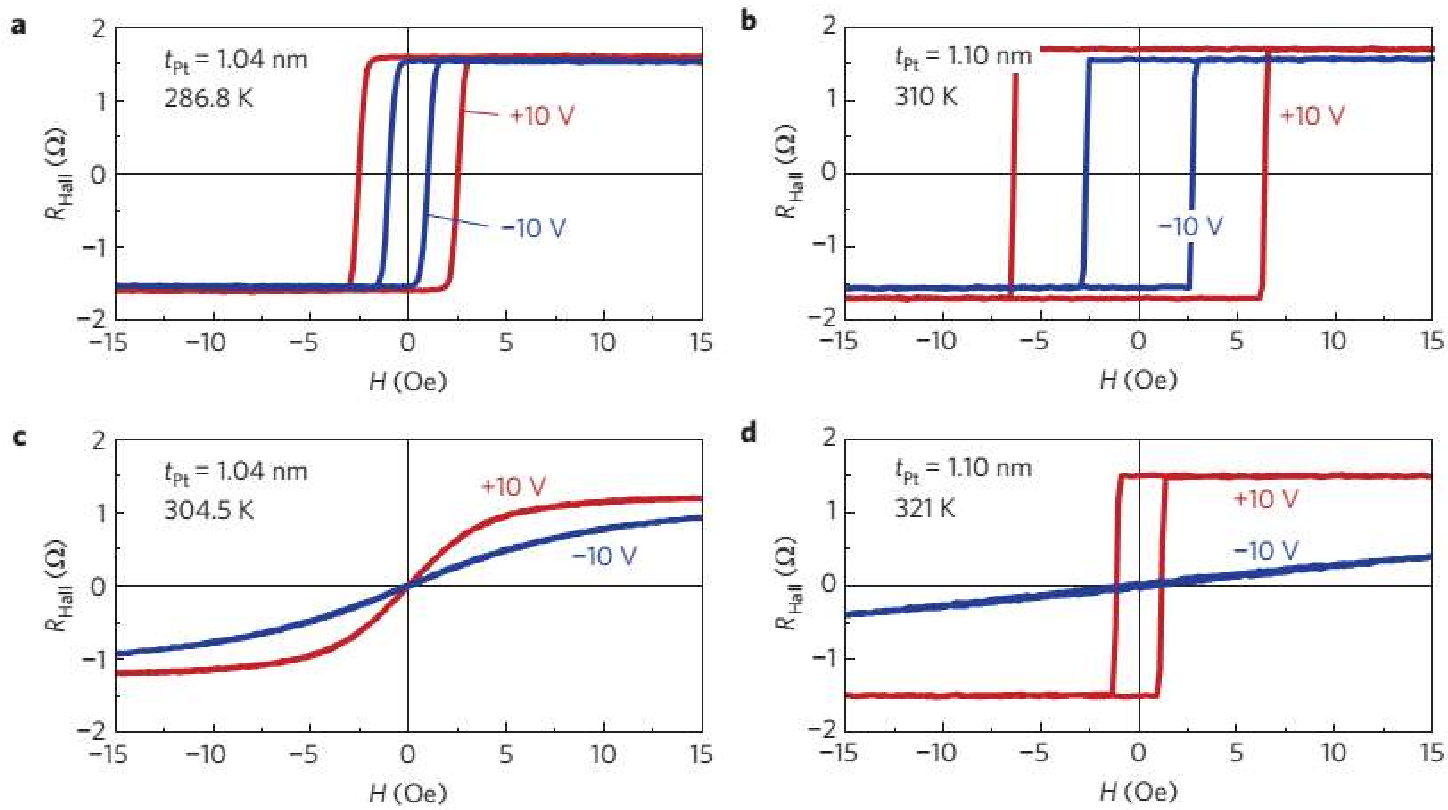
Electric field control in Metallic FM




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

# Electric field control the magnetization

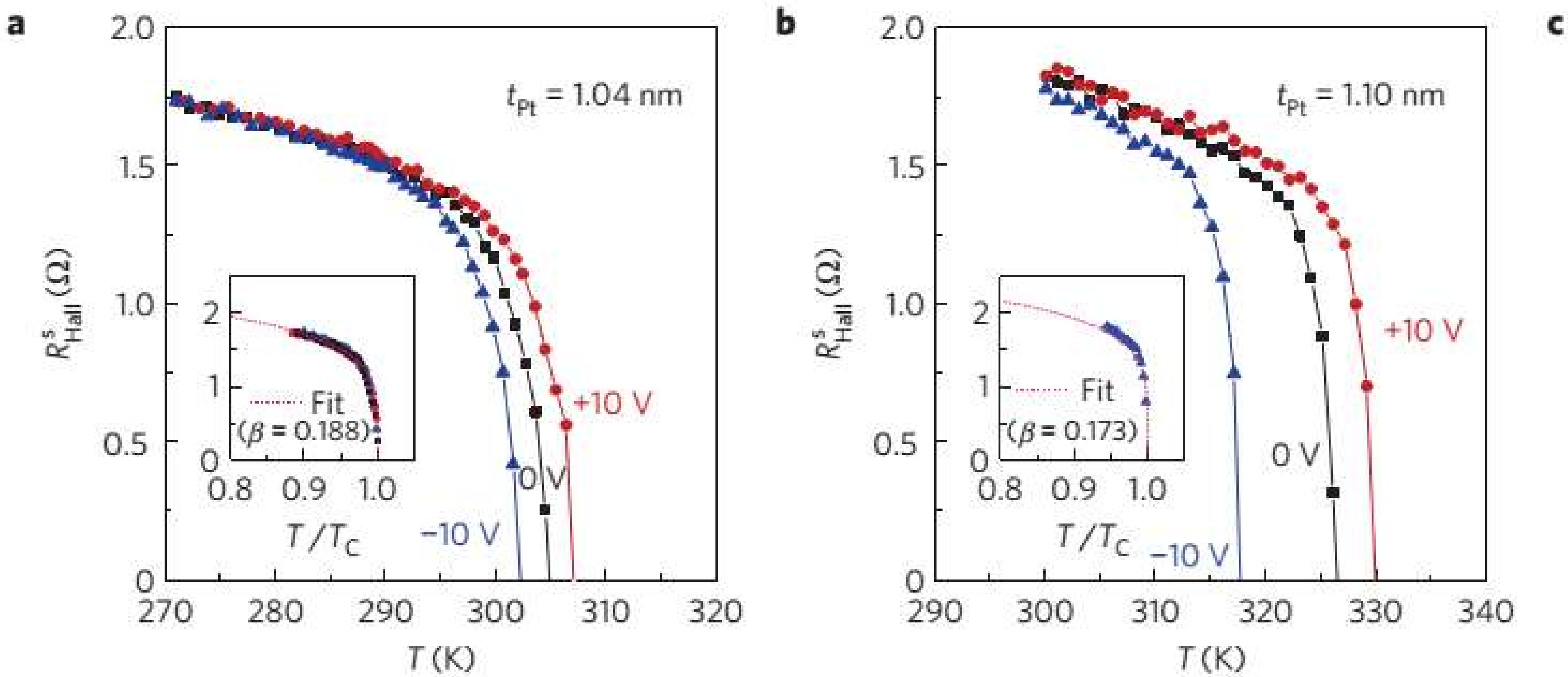
Electric field control in Metallic FM




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

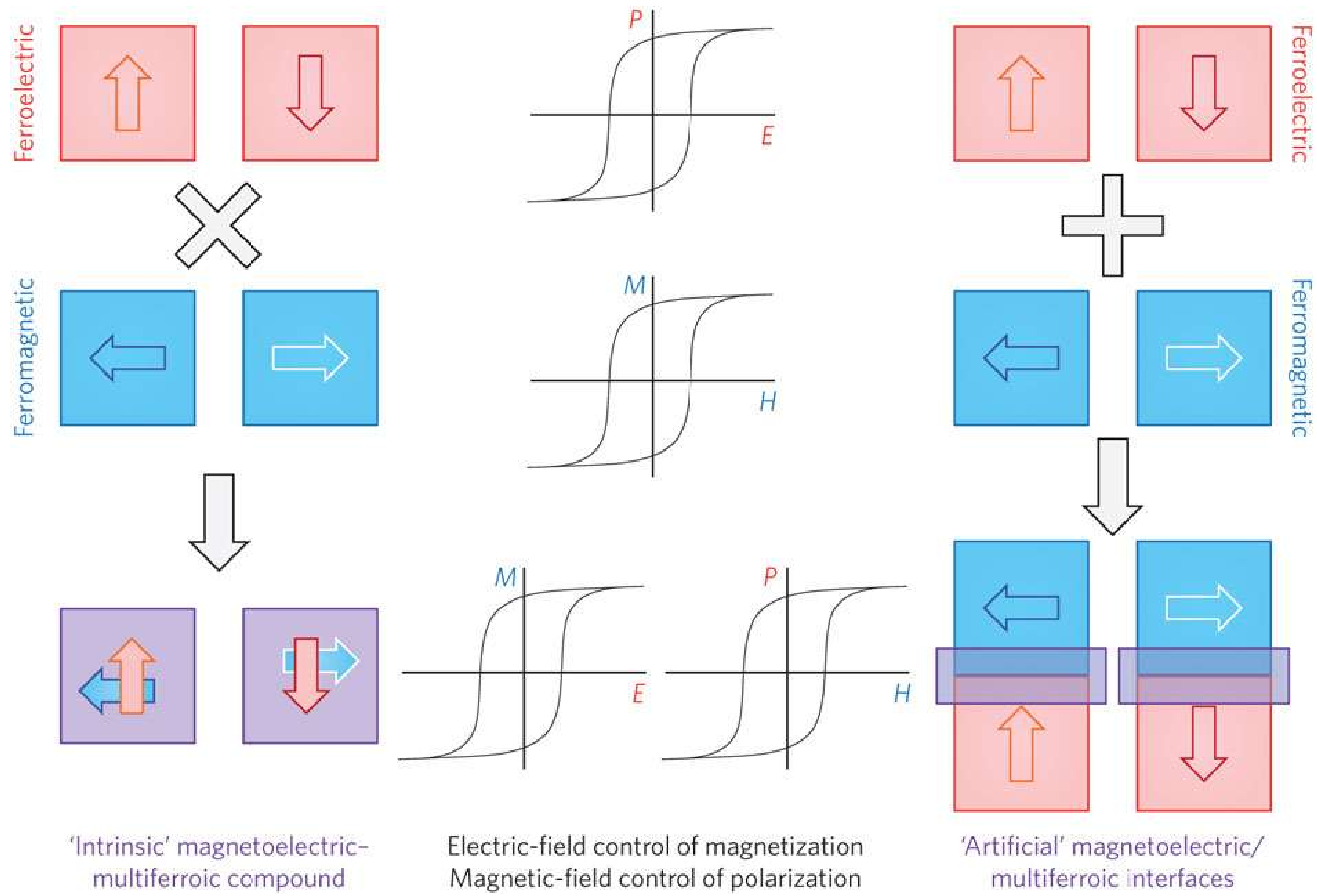
# Electric field control the magnetization

Electric field control in Metallic FM



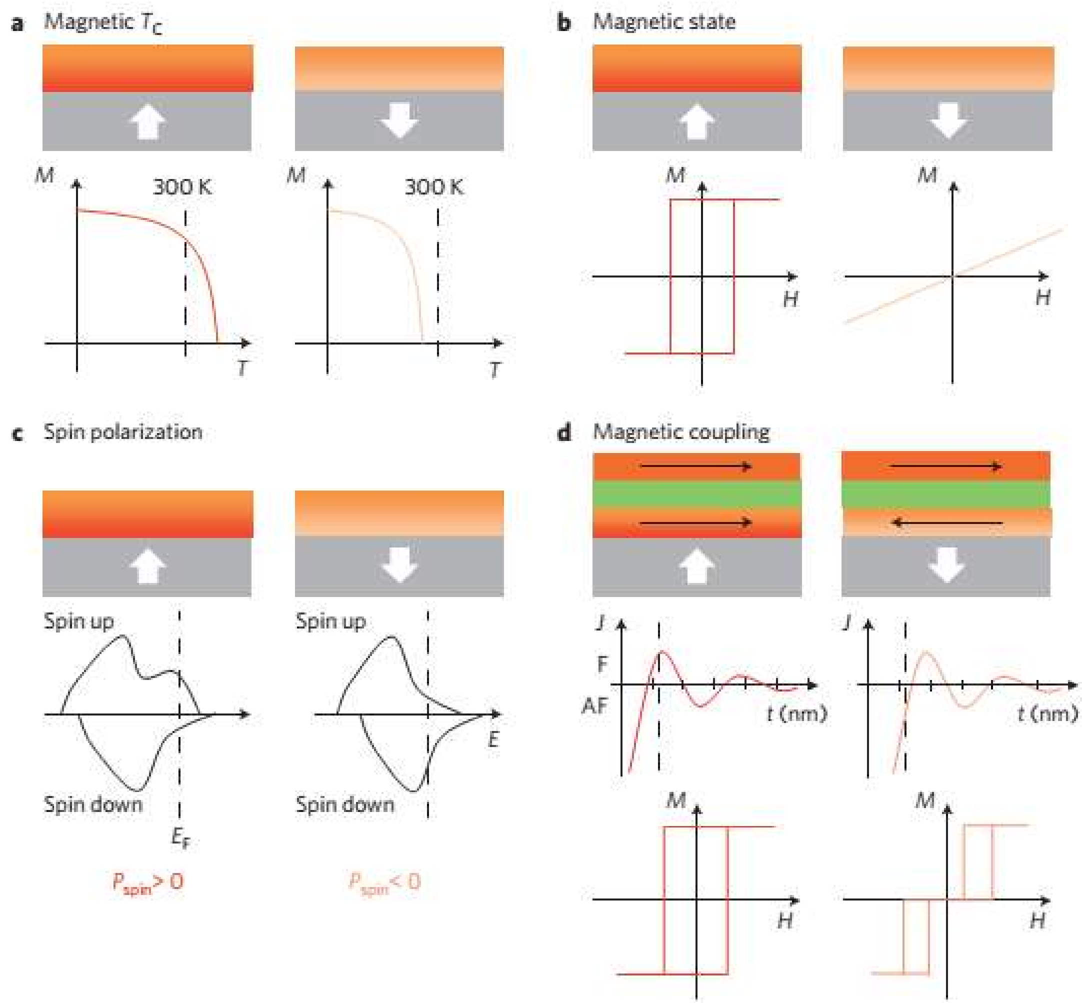

Chiba, et al, Nat. Mater. (2011)

# Multiferroics



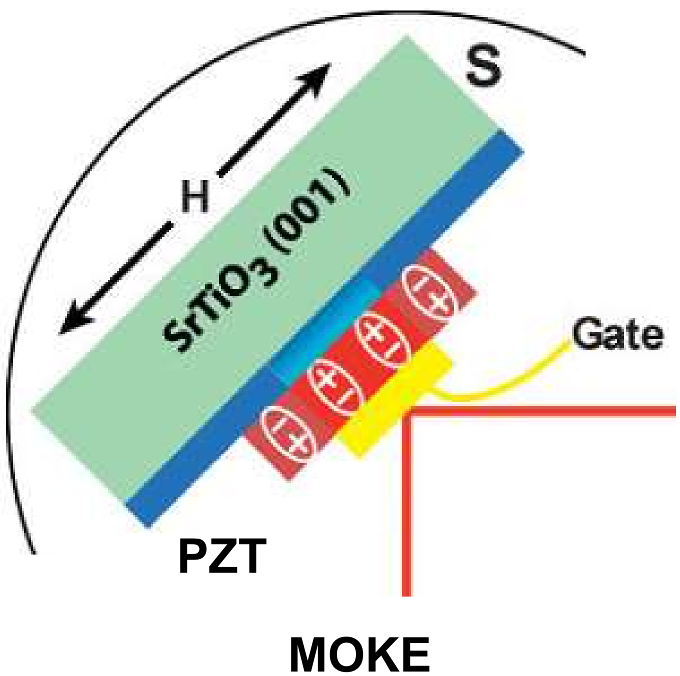

Bibes, Nat. Mater. (2012)

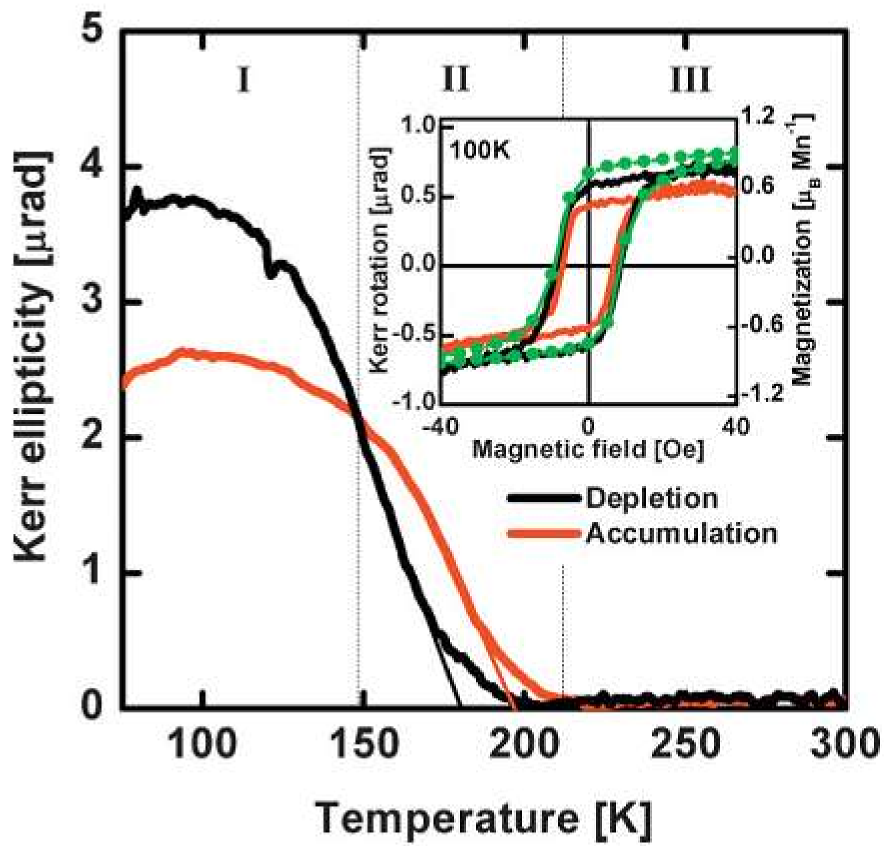
# Multiferroics




Bibes, Nat. Mater. (2012)

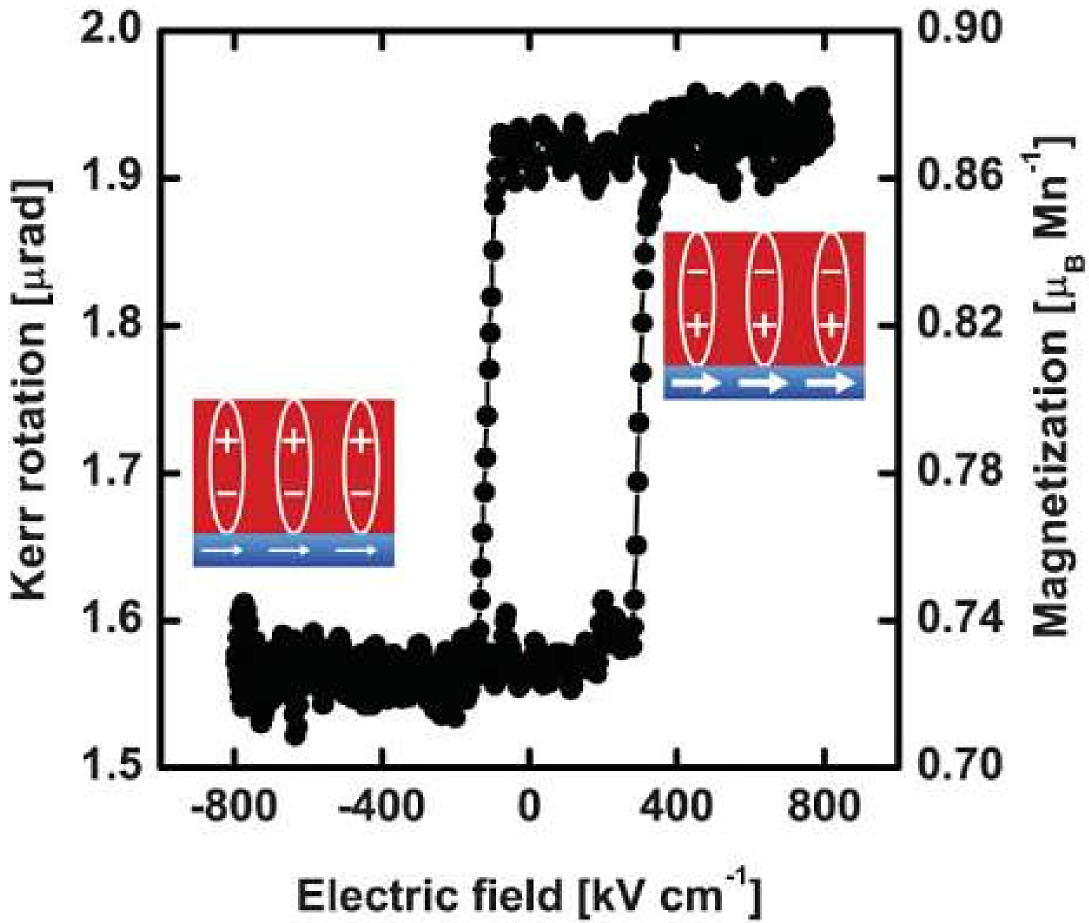
# $T_C$ by Multiferroics



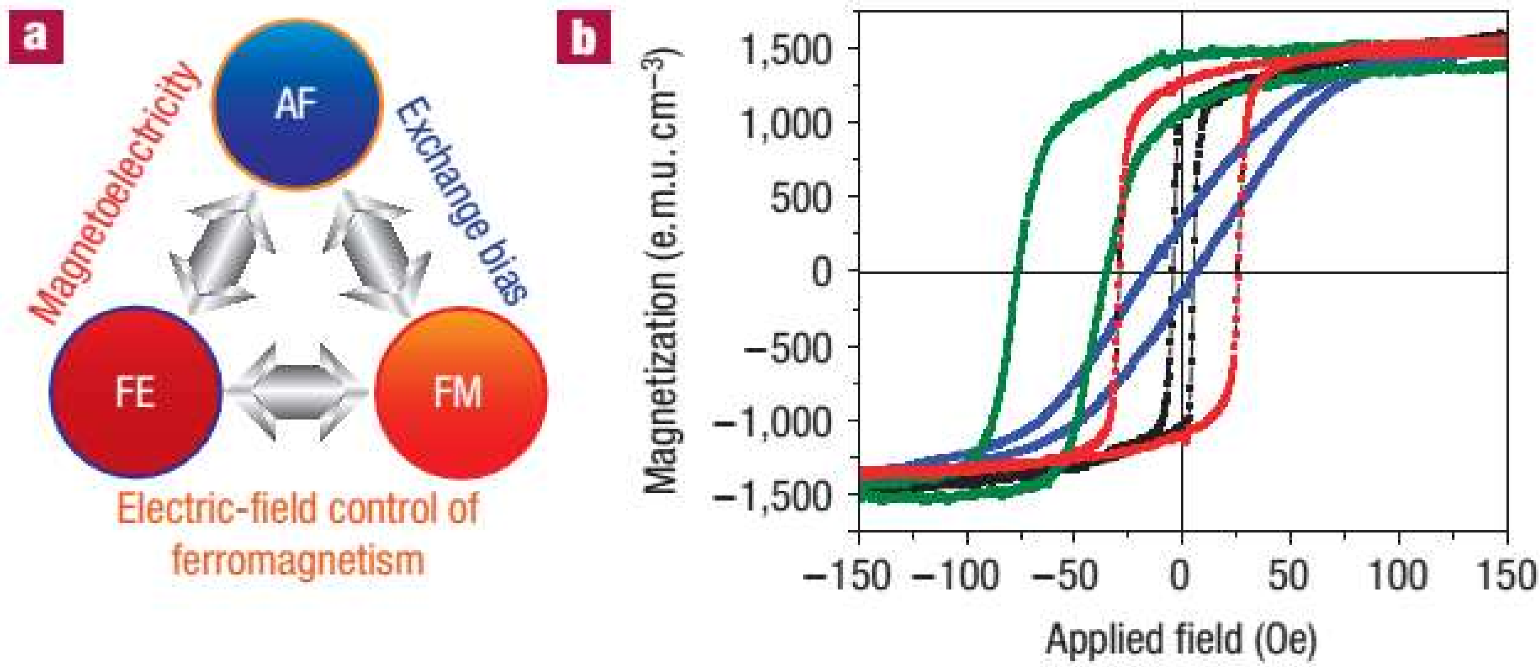

Molegraaf, et al, Adv. Mater. (2009)

# $T_C$ by Multiferroics



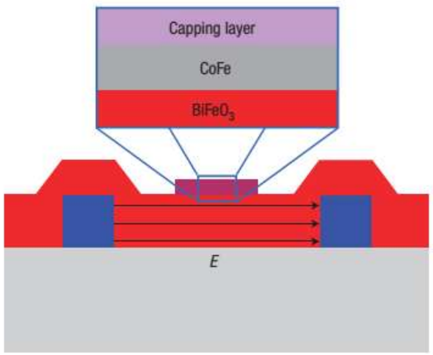

Molegraaf, et al, Adv. Mater. (2009)

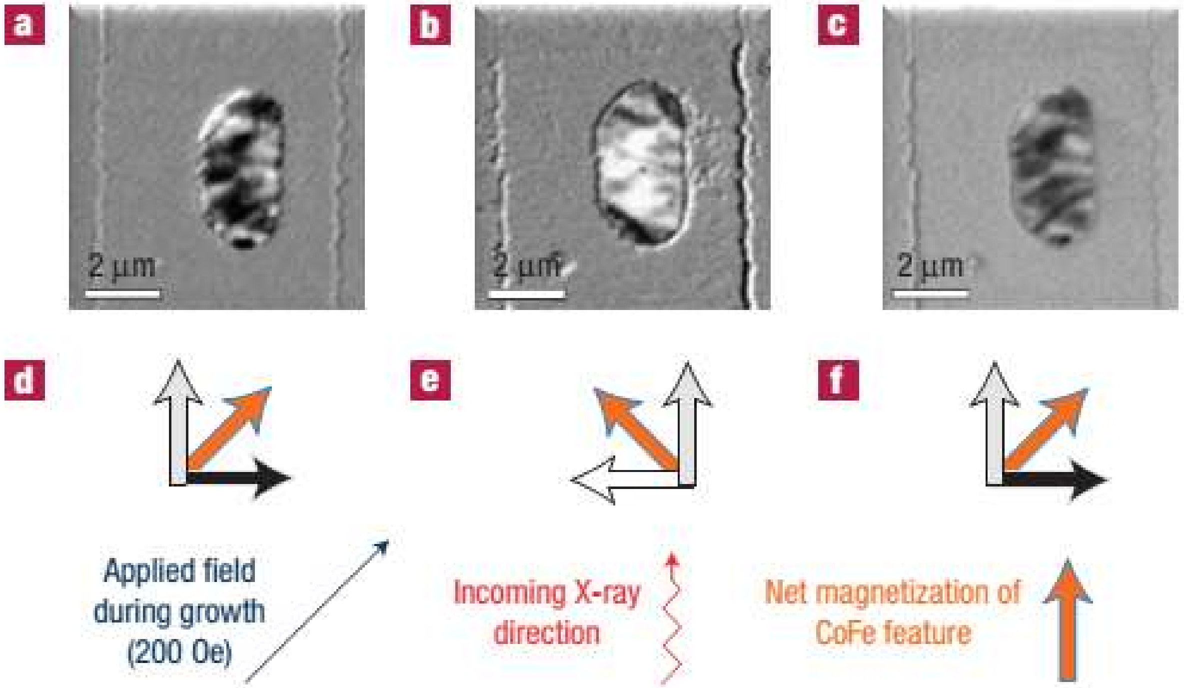
# FM magnetization by Multiferroics




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

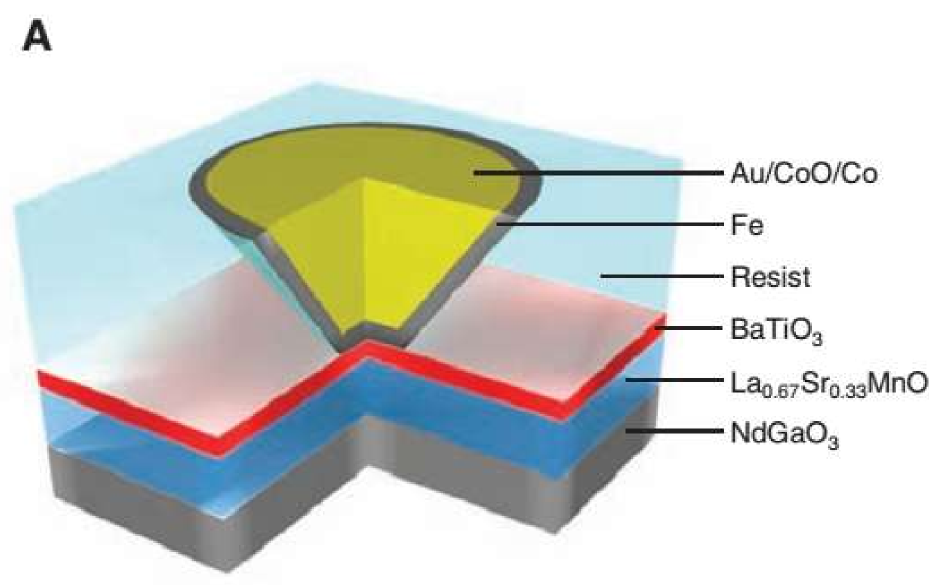
# FM magnetization by Multiferroics

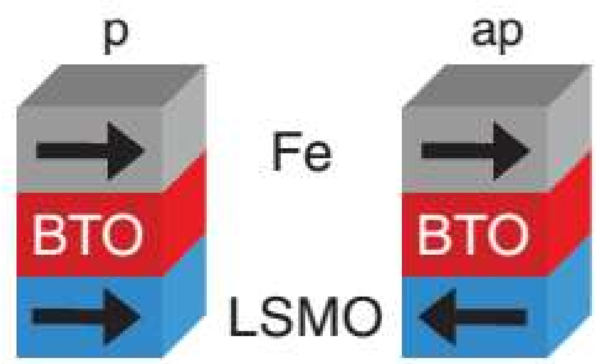



Chu, et al, Nat. Mater. (2008)

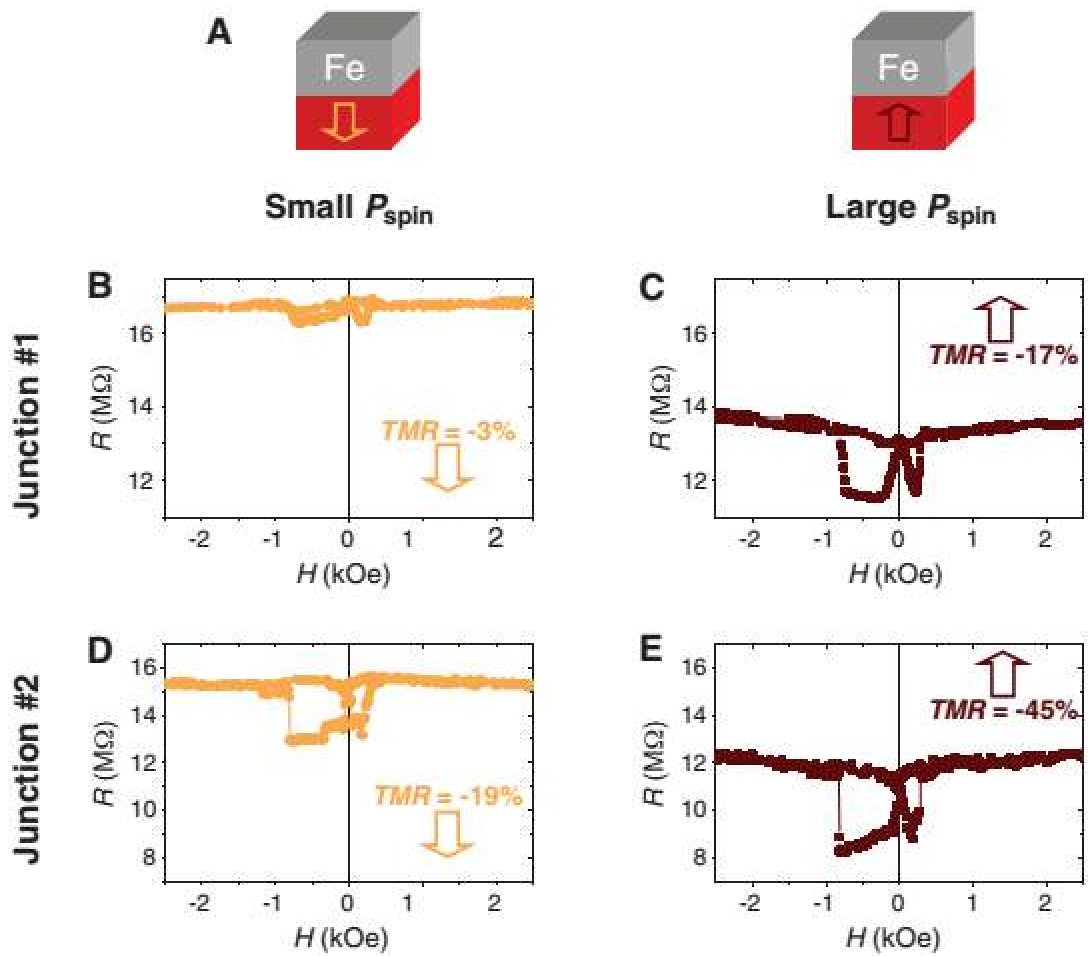
# Spin polarization by Multiferroics



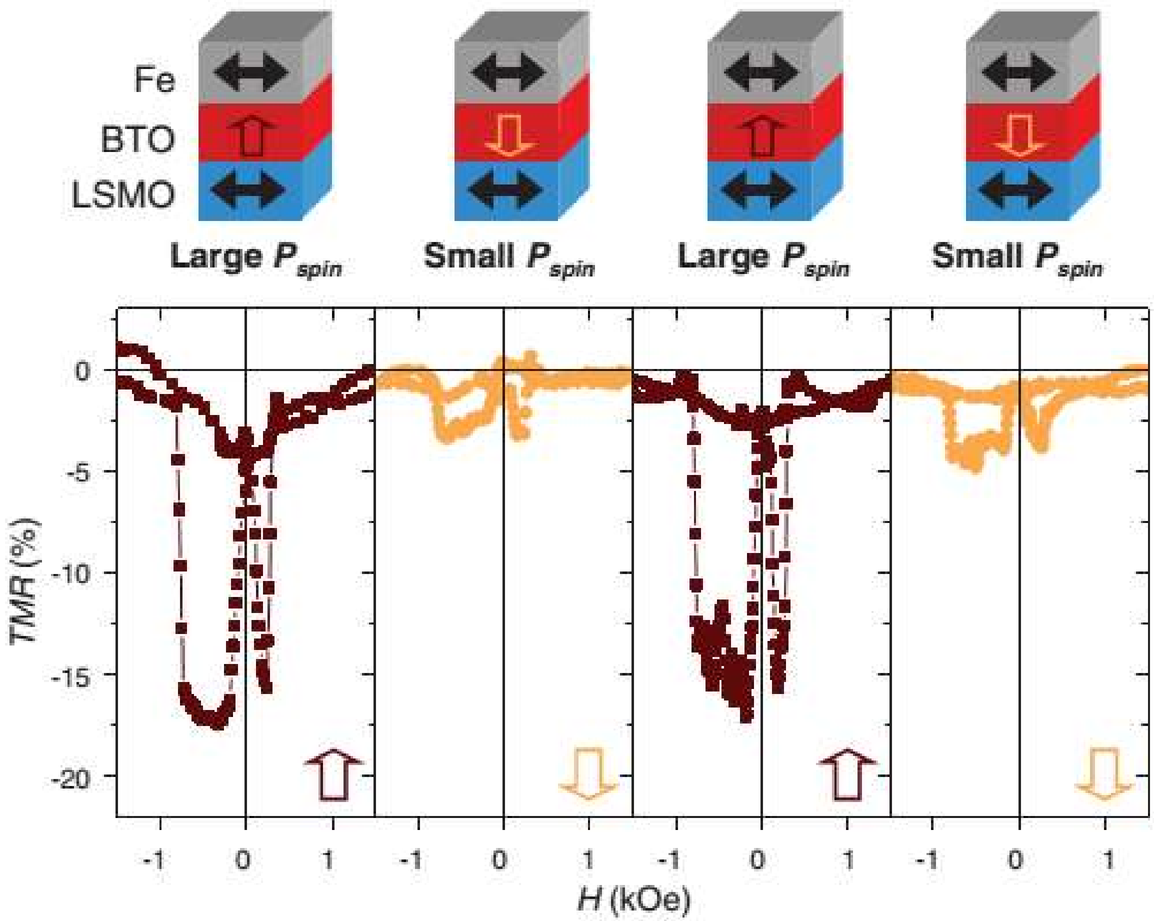

Garcia, et al, Science (2010)

# Spin polarization by Multiferroics




Garcia, et al, Science (2010)

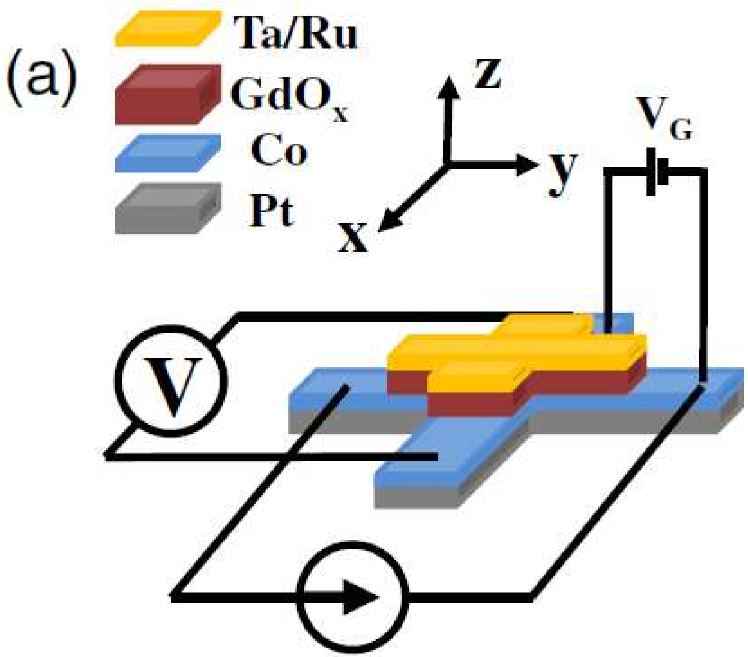
# Spin polarization by Multiferroics




Garcia, et al, Science (2010)

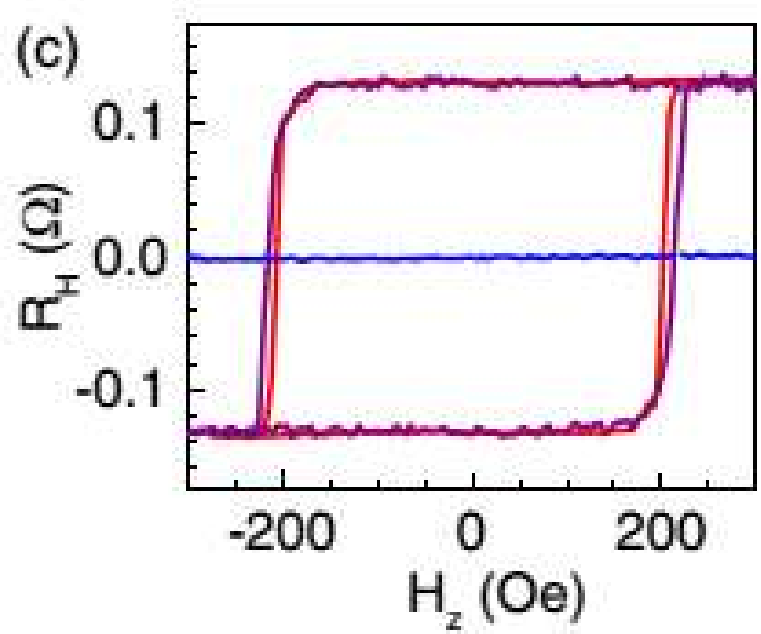
# Ionics of Oxygen

Electric field via $GdO_x$/FM




Blue curve: Negative electrical field

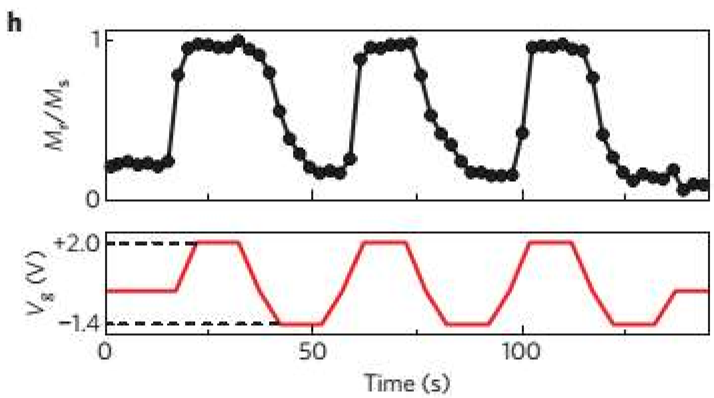
Purple curve: positive electrical field

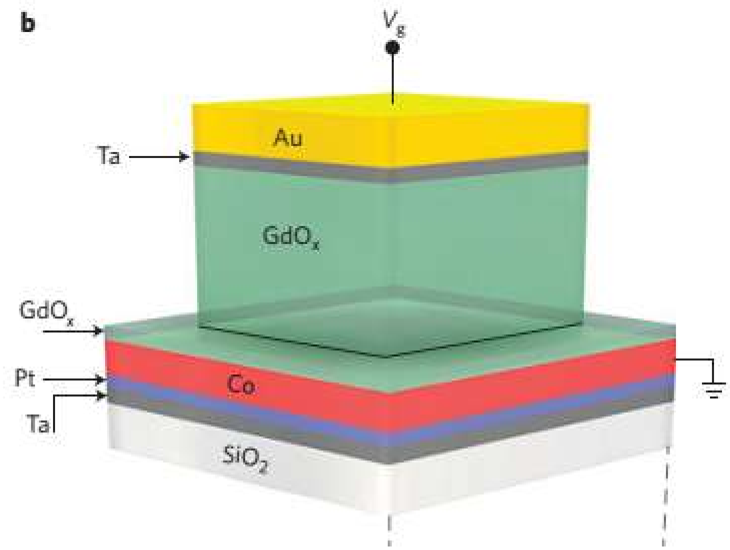


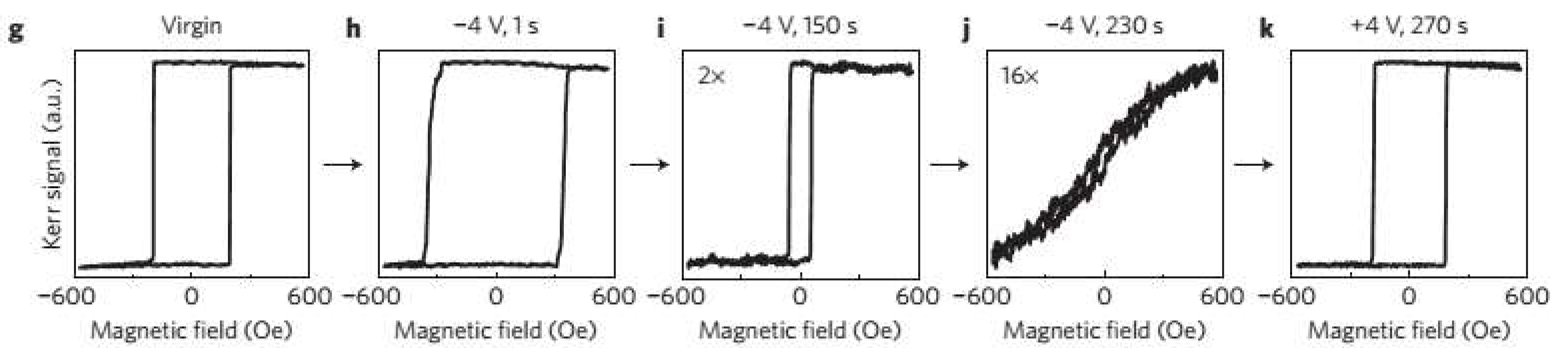

Bi et al PRL (2014)

# Ionics of Oxygen

Electric field via $GdO_x$/FM



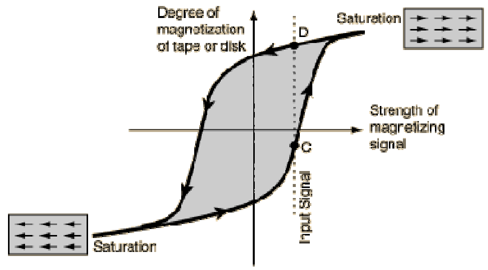




Bauer, et al Nat. Nano. (2014)

# How to control the magnetization

Magnetic field

B




B

Without B
???

**Control??**

**Electric field**

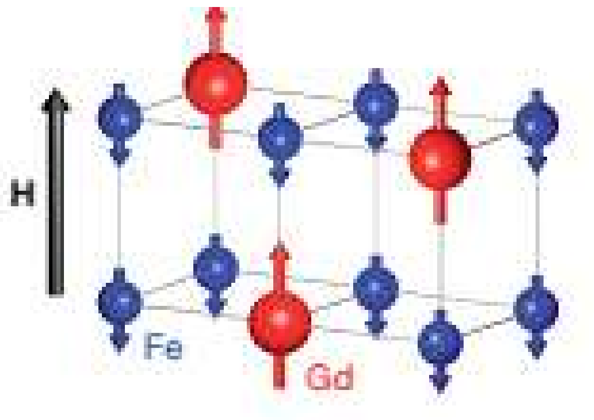
**Ultrafast Laser**

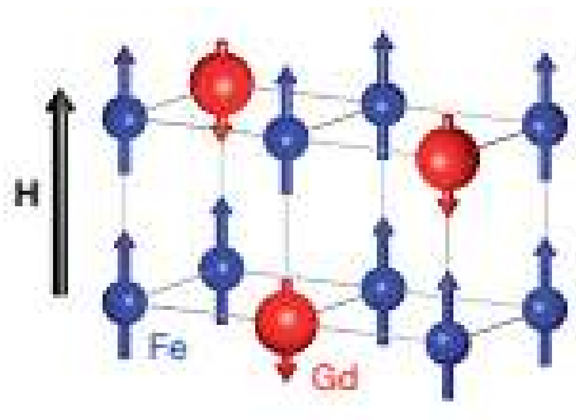
**Spin torque**

**Interface Strain**

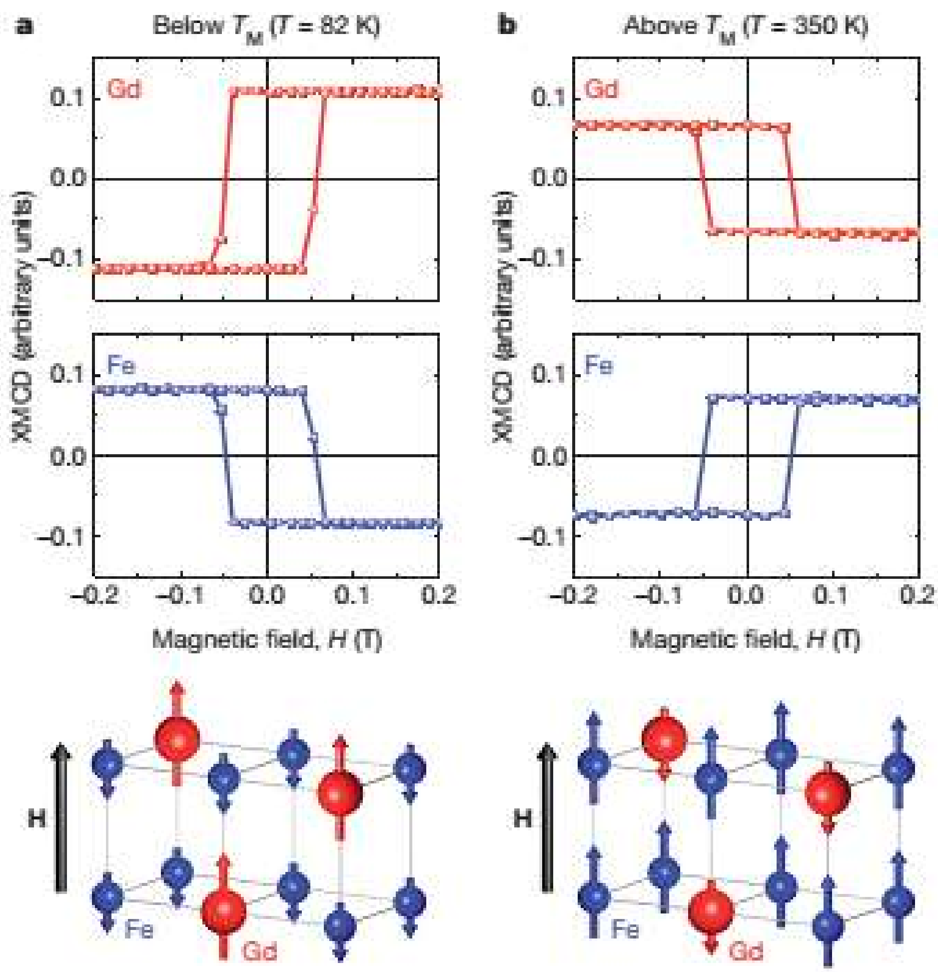
# FM by Ultrafast Laser

Ferrimagnet



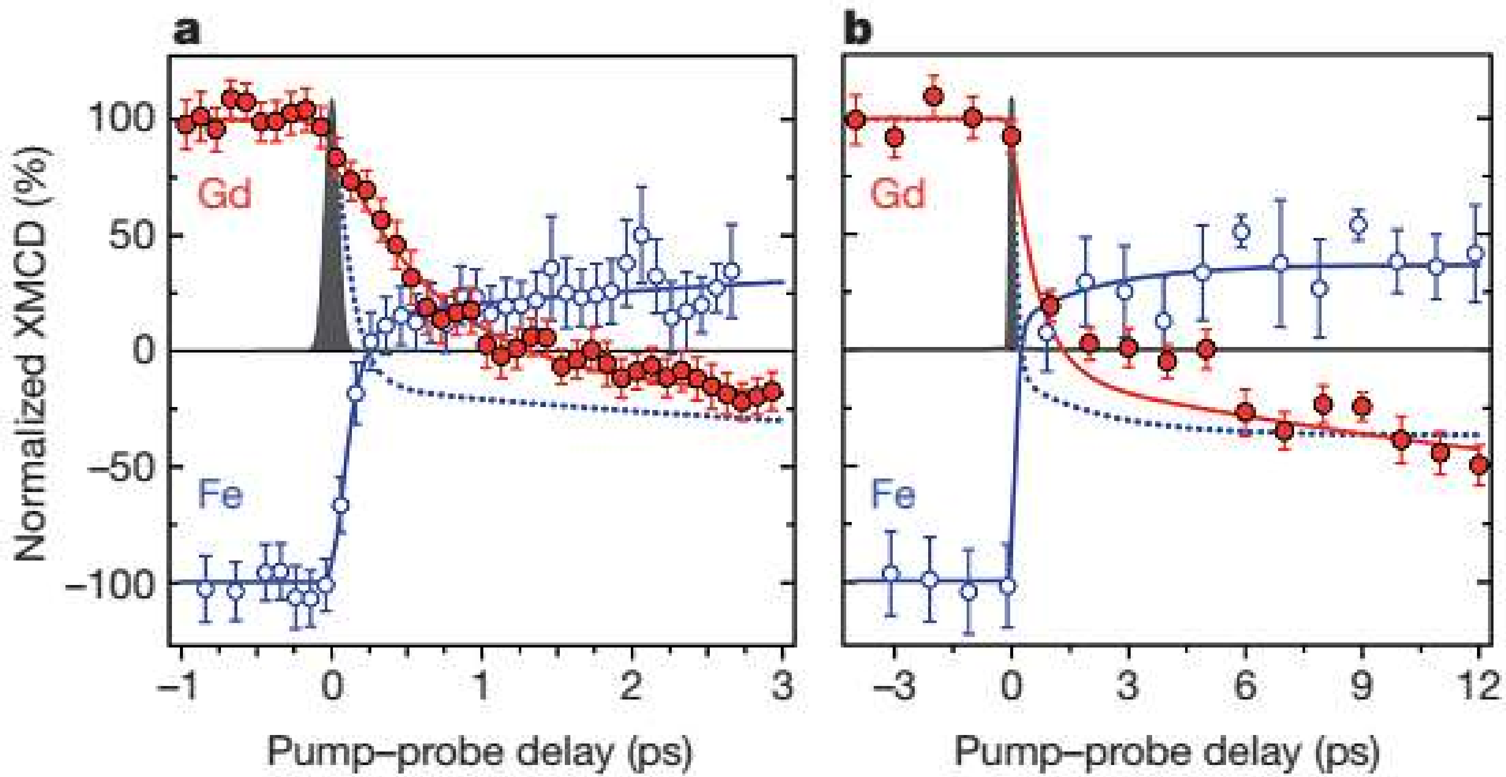



# FM by Ultrafast Laser



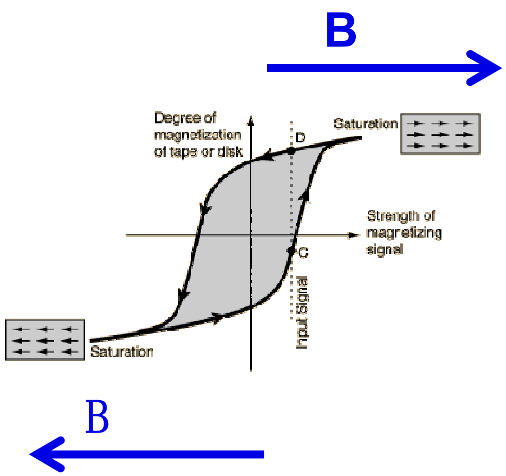

Radu, et al Nature (2011)

# FM by Ultrafast Laser



# How to control the magnetization

Magnetic field




Without B
???

**Control??**

**Electric field**

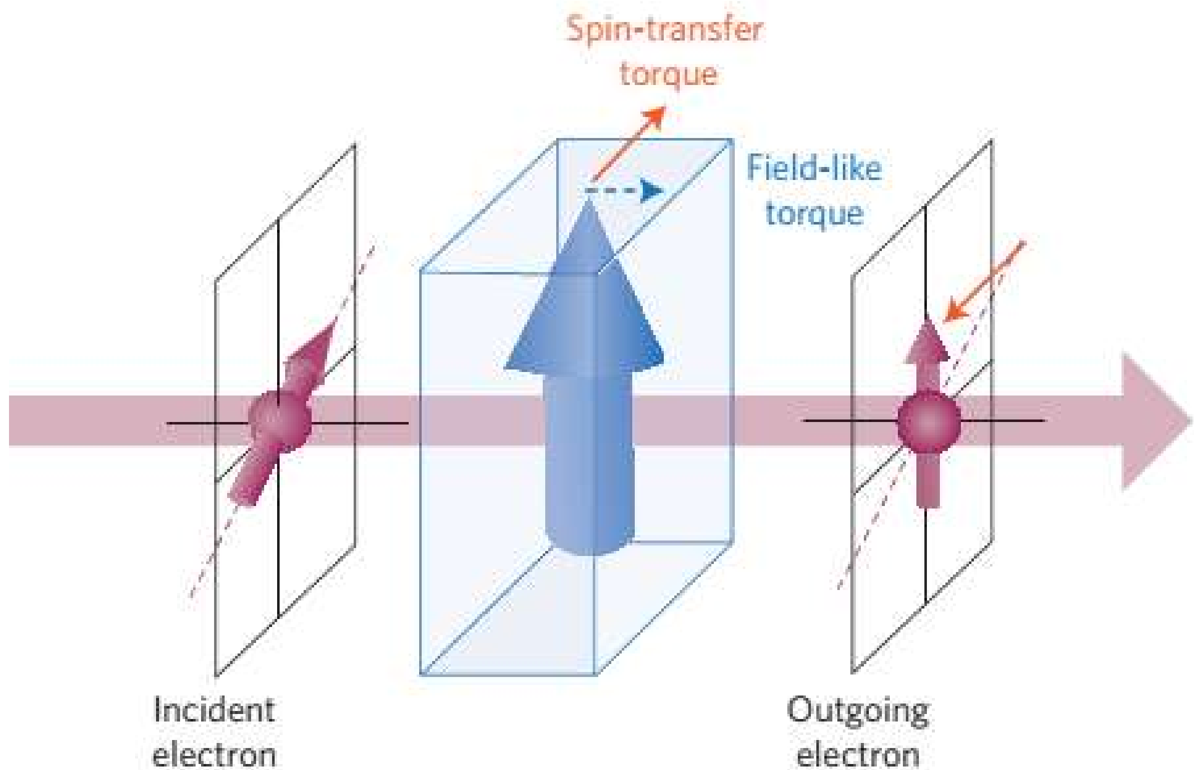
**Ultrafast Laser**

**Spin torque**

**Interface Strain**

# Magnetization by spin current

Spin transfer torque




$$\tau_{ST} = \frac{\hbar}{2}\hat{m} \times (\hat{\sigma} \times \hat{m})$$

Brataas, et al. Nature Mater. (2012)



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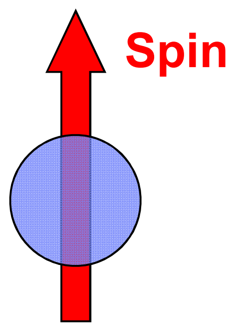
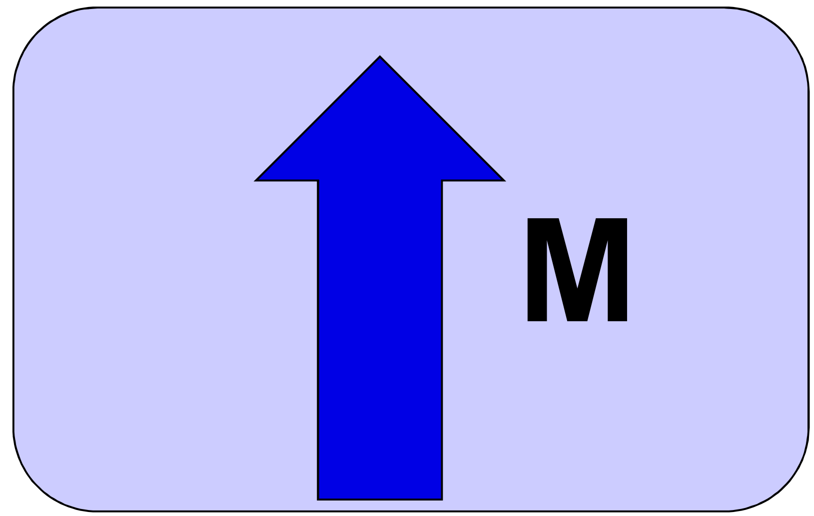
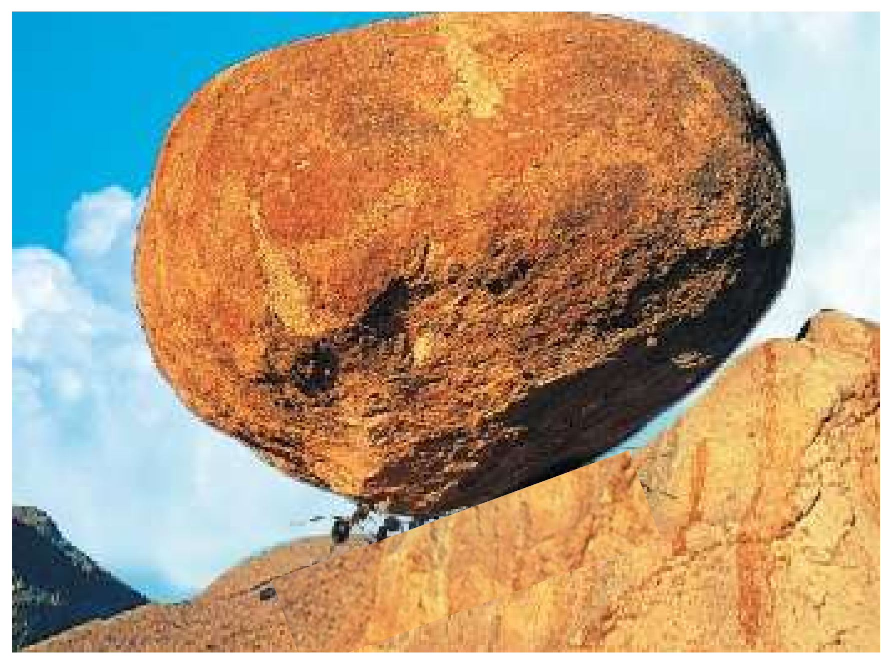
# Magnetization by spin current

Spin transfer torque




$$\frac{\hbar}{2}$$



# Magnetization by spin current

S



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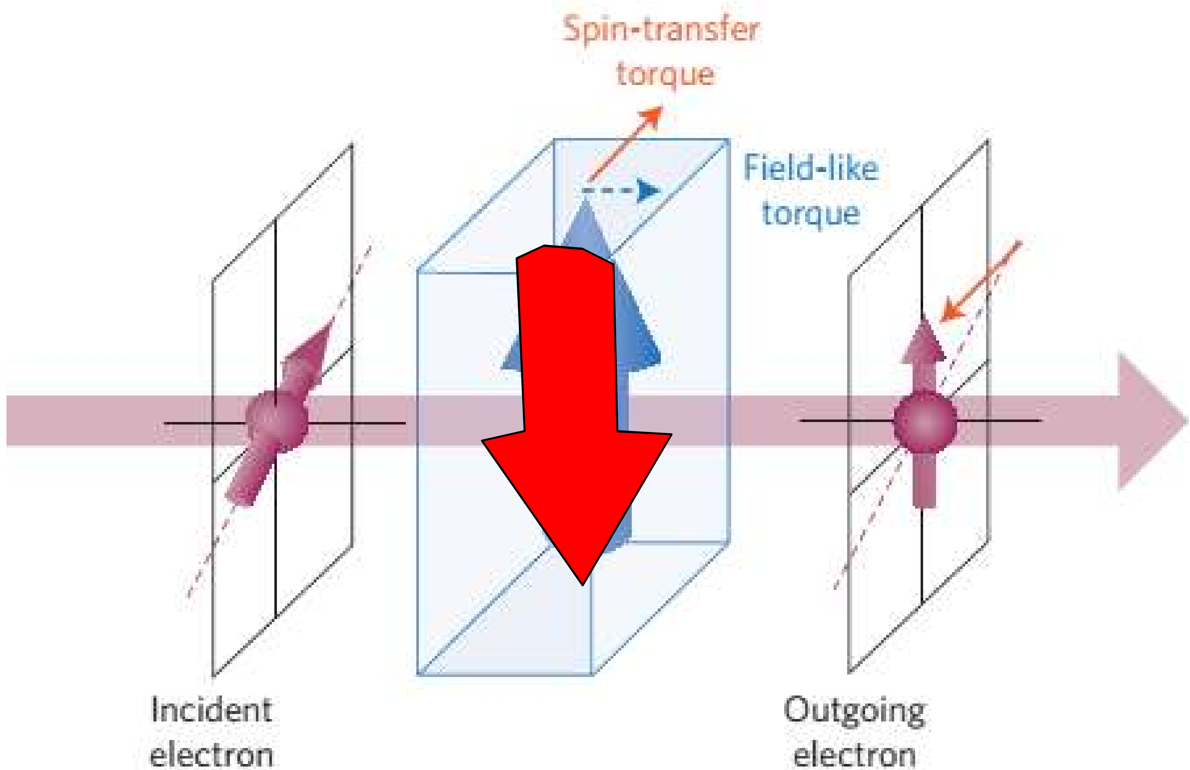
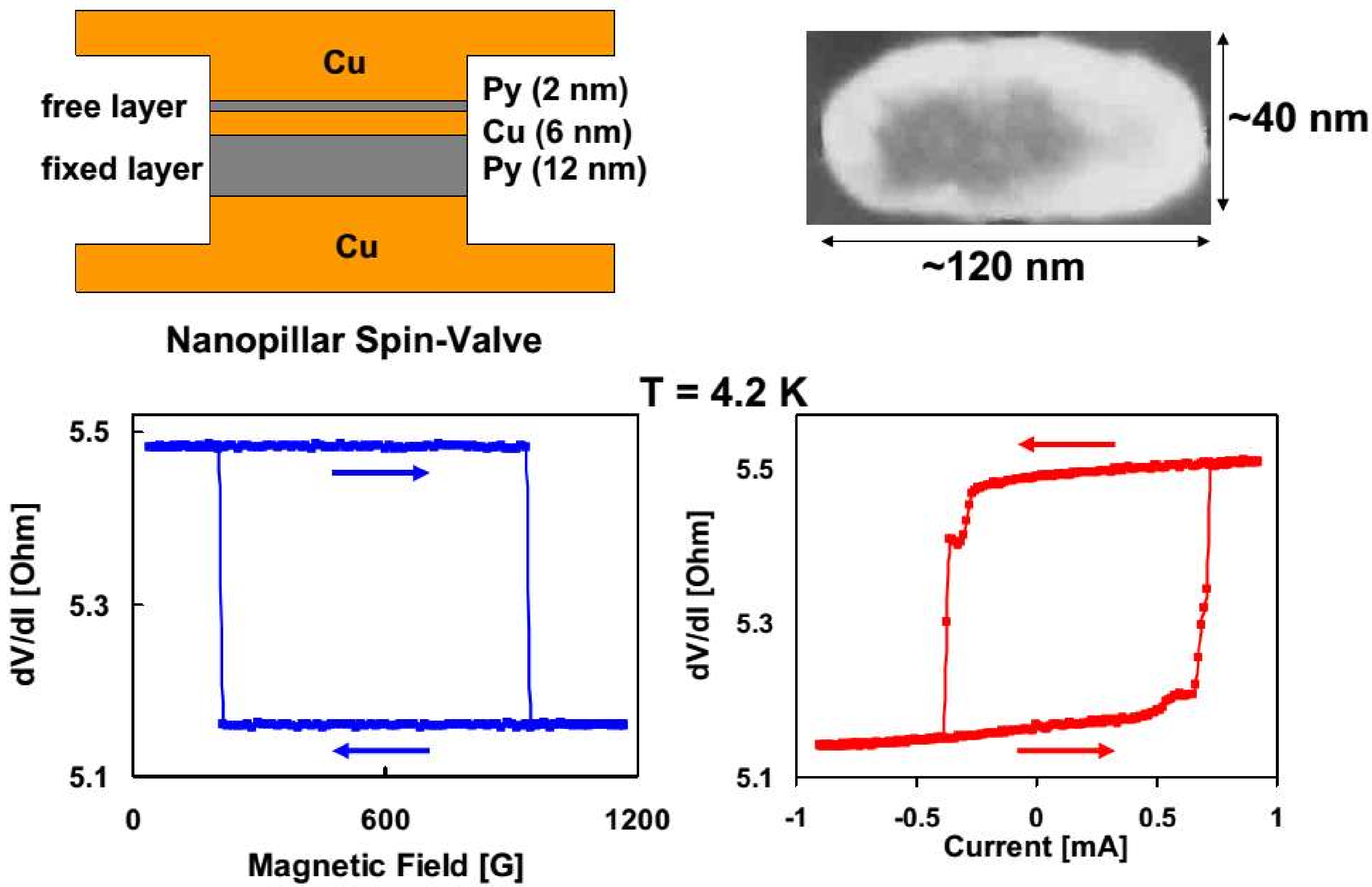
# FM by Spin transfer torque

Spin transfer torque



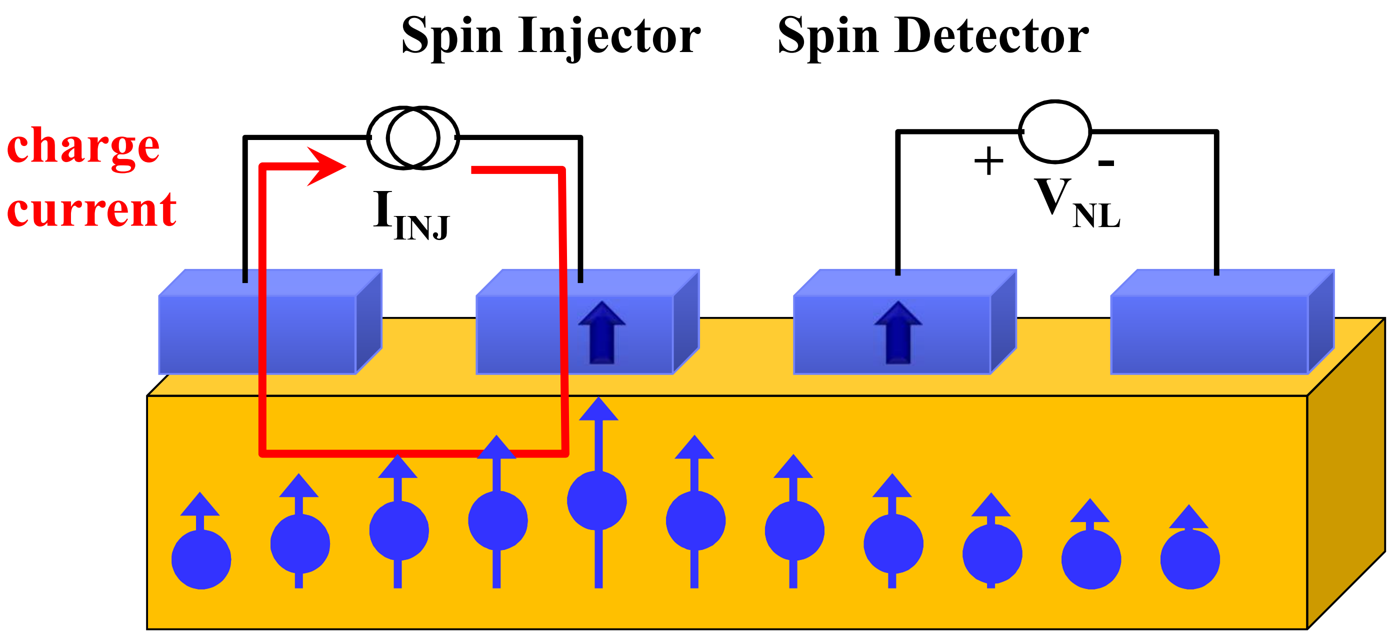

Brataas, et al. Nature Mater. (2012)

# Spin transfer torque

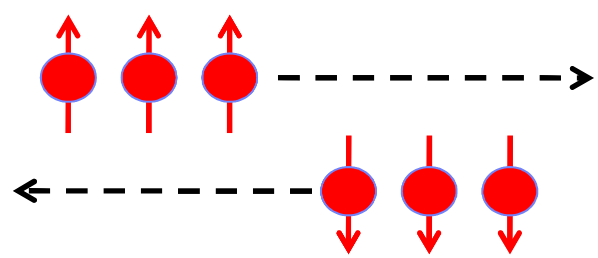



Ralph & Stiles, JMMM (2008)

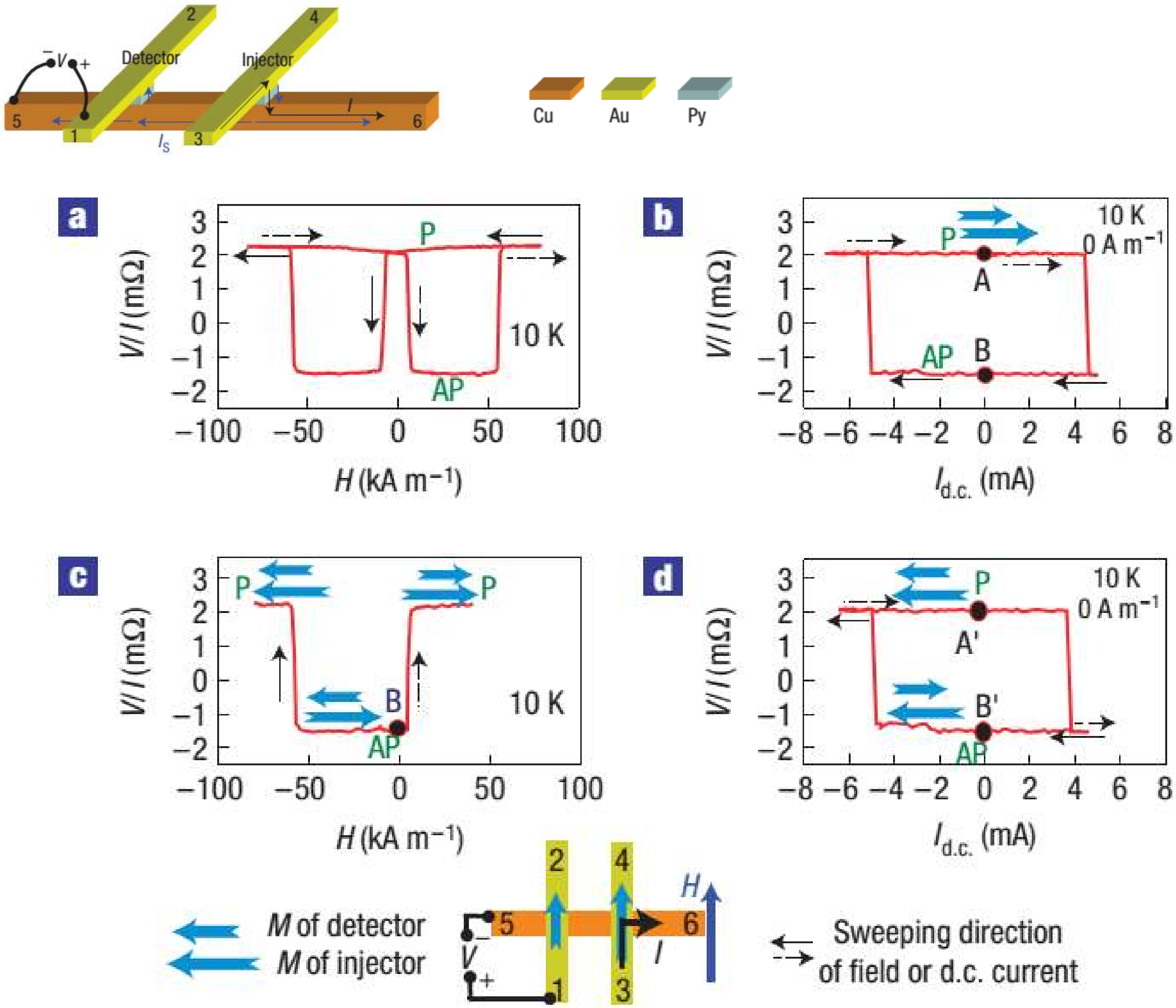
# Pure Spin current torque




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

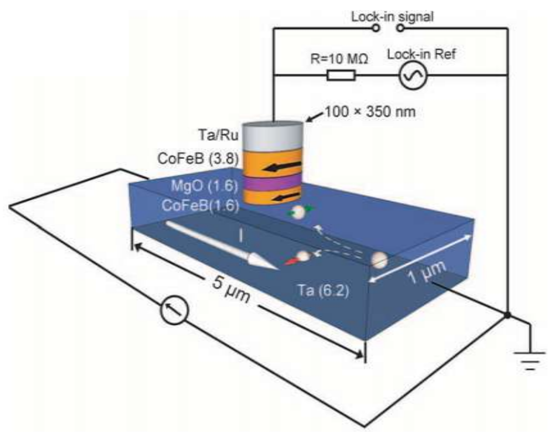


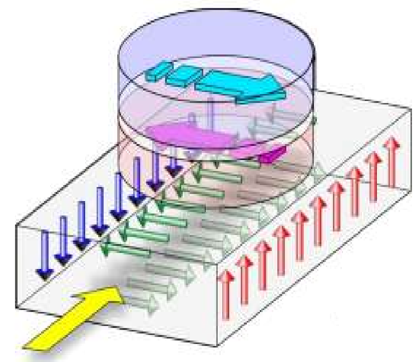
# Pure Spin current torque

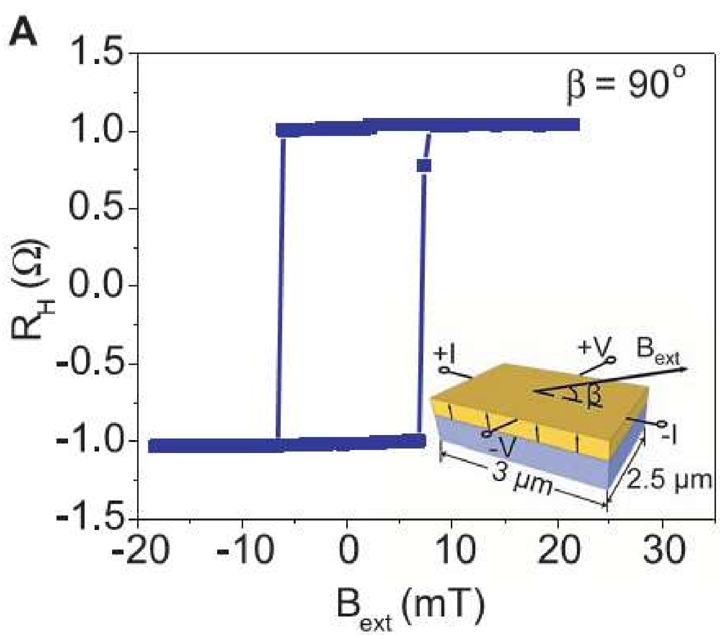


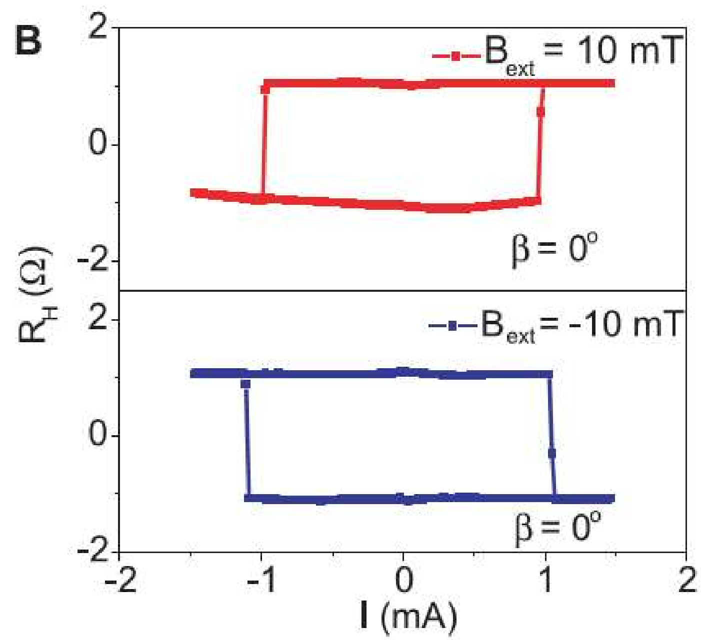

Yang et al, Nature Physics (2008)

# Spin Orbit torque






Liu et al, Science (2012)

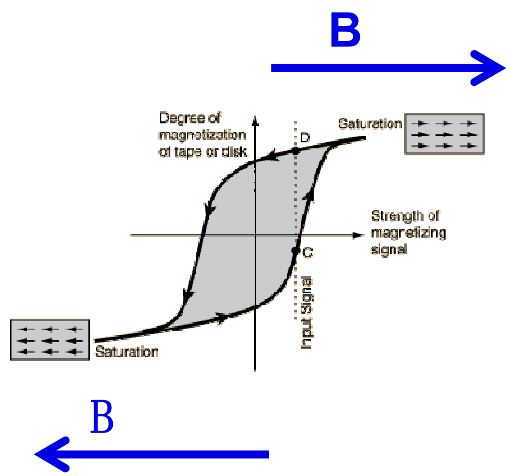
# Spin transfer torque

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**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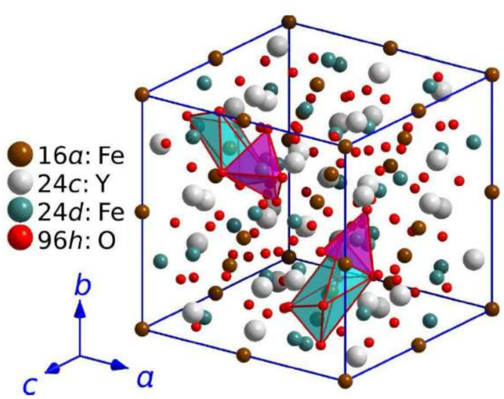
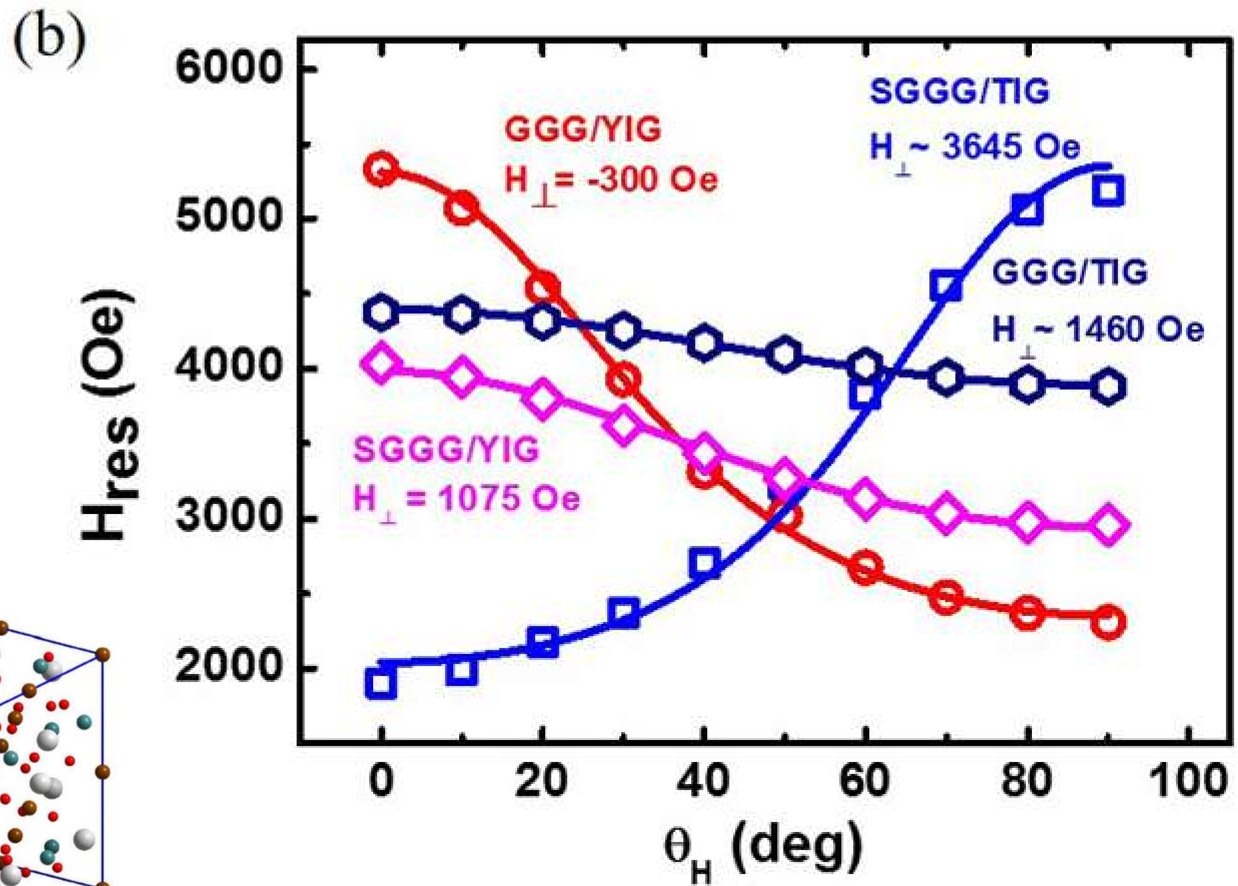
# Magnetization by Strain

**TIG, a magnetic insulator with perpendicular easy axis**

*$Y_3Fe_5O_{12}$*

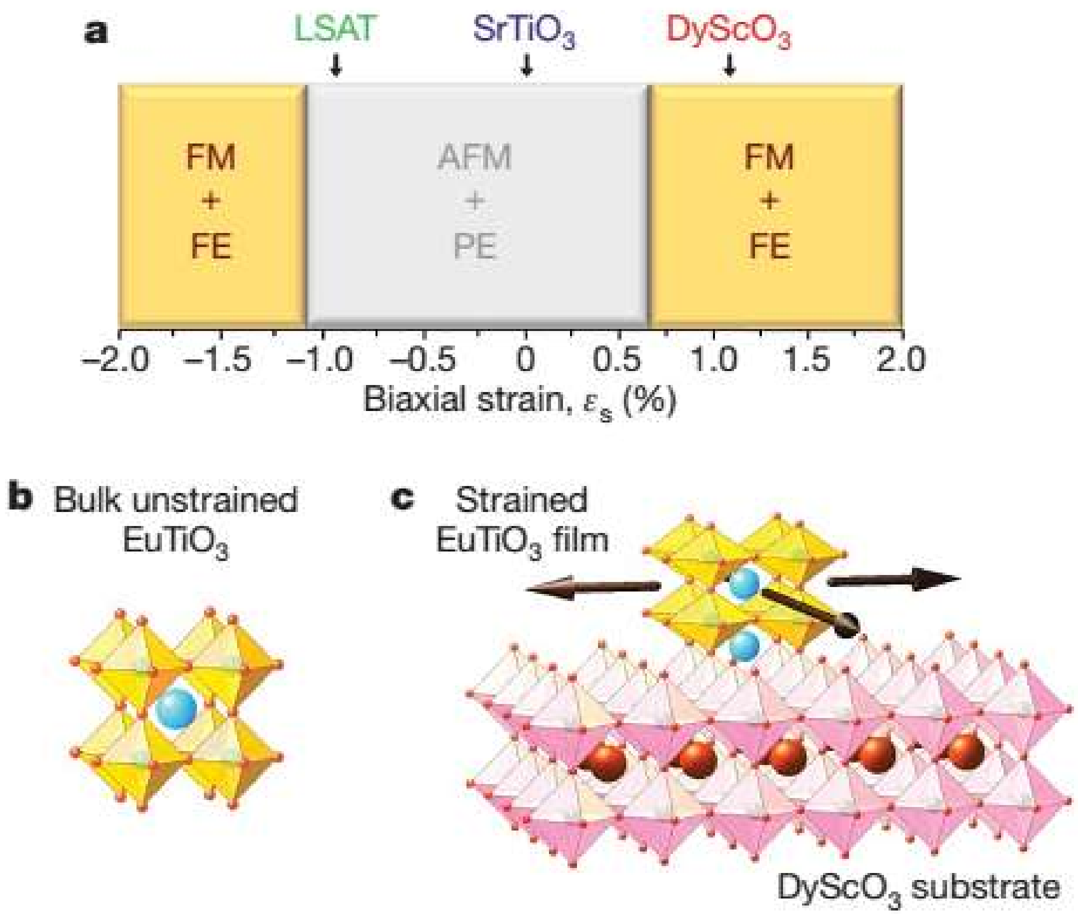
*$Tm_3Fe_5O_{12}$*



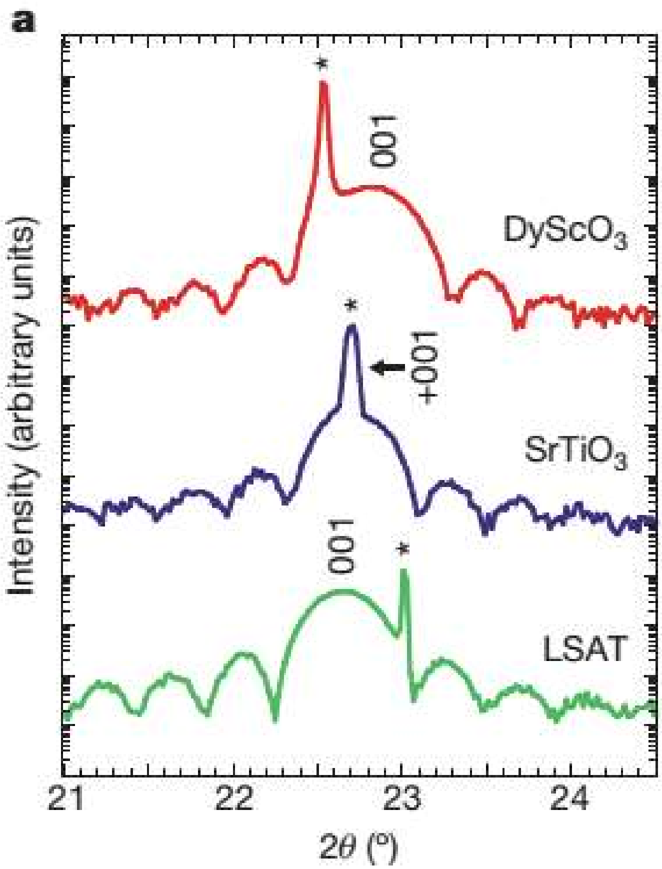

Tang, et al, PRB (2017)

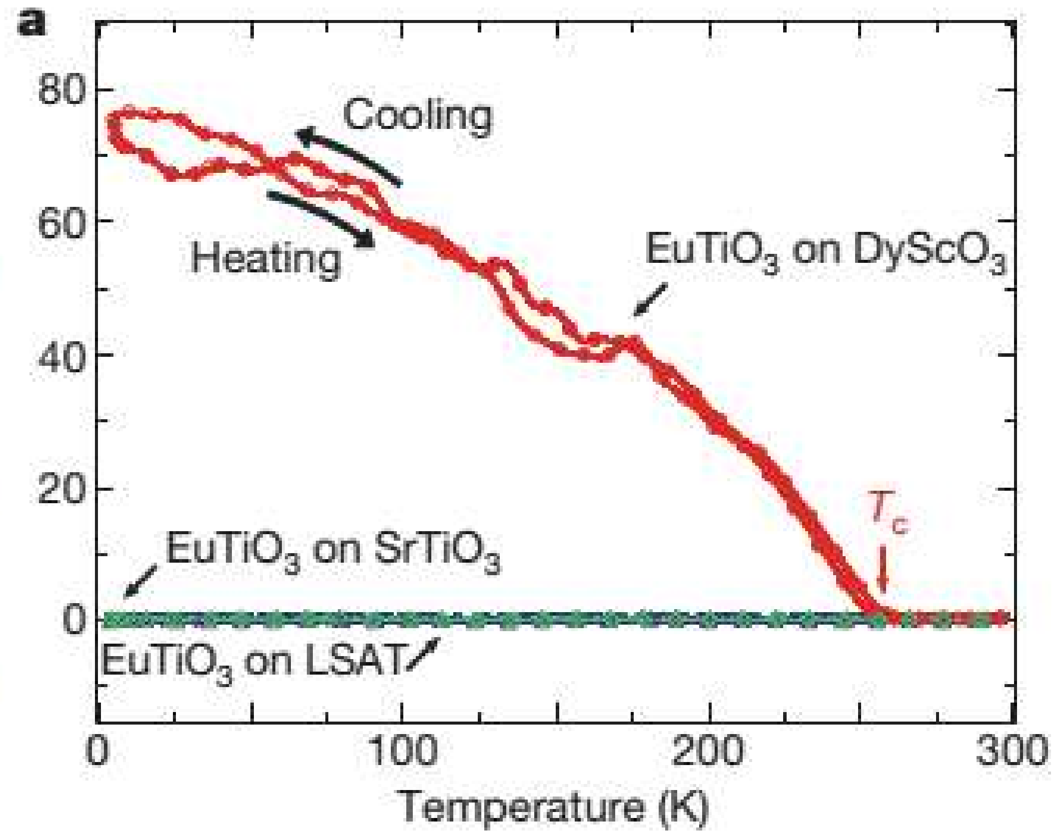
# Magnetization by Strain




Lee 2010, et al. Nature (2011)

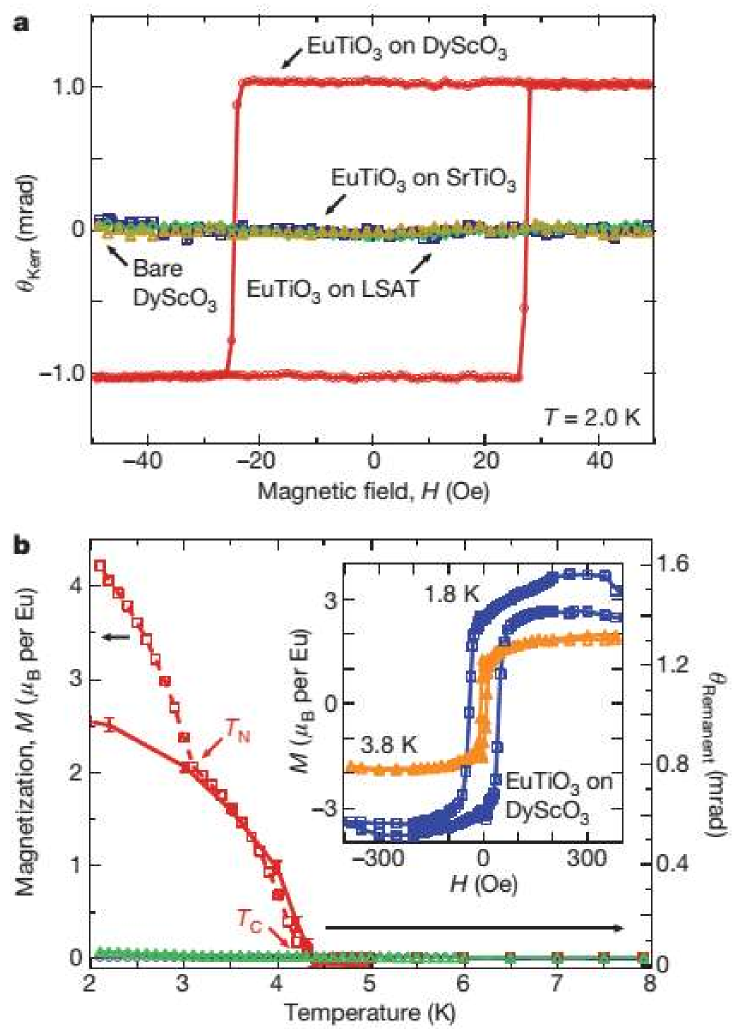
# Magnetization by Strain




Lee 2010, et al. Nature (2011)

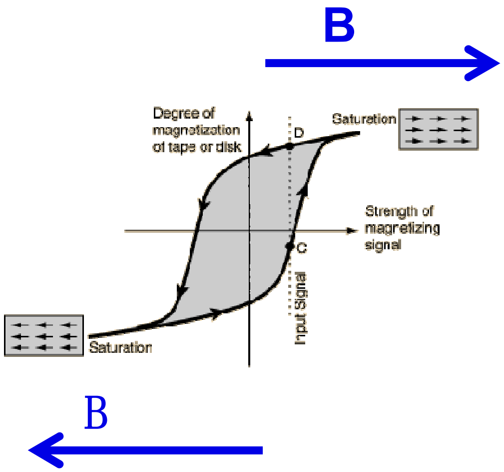
# Magnetization by Strain




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. 19th

# Chapter 3: Magnetoresistance

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