

Chapter 2

Magnetism and Magnetic Materials

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量子材料科学中心

2017年9月29日

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

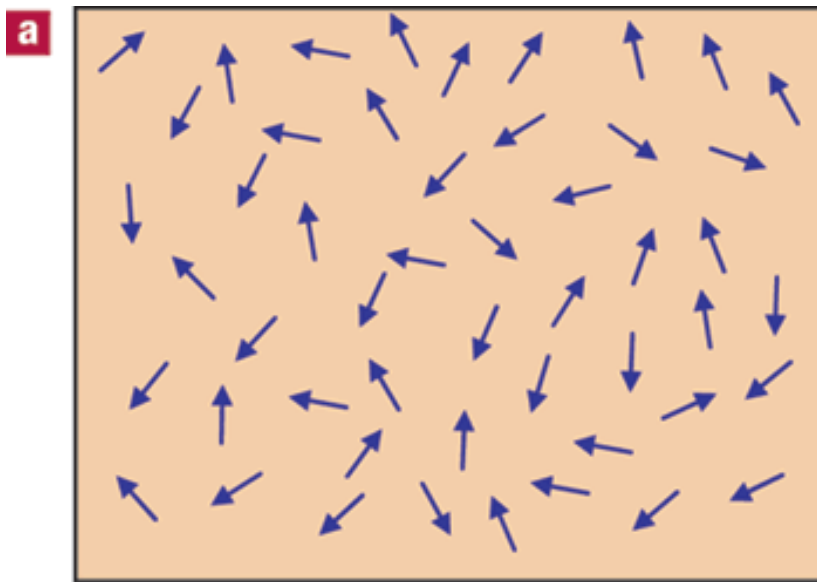
提纲

2. How to induce magnetic moment

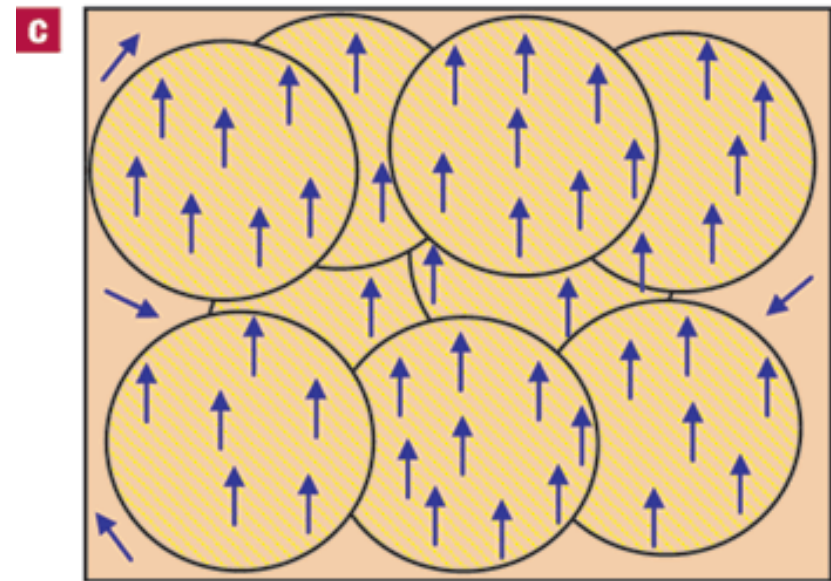
Mainly two methods

1) Impurity doping

Mn impurity in GaMnAs



Low doping

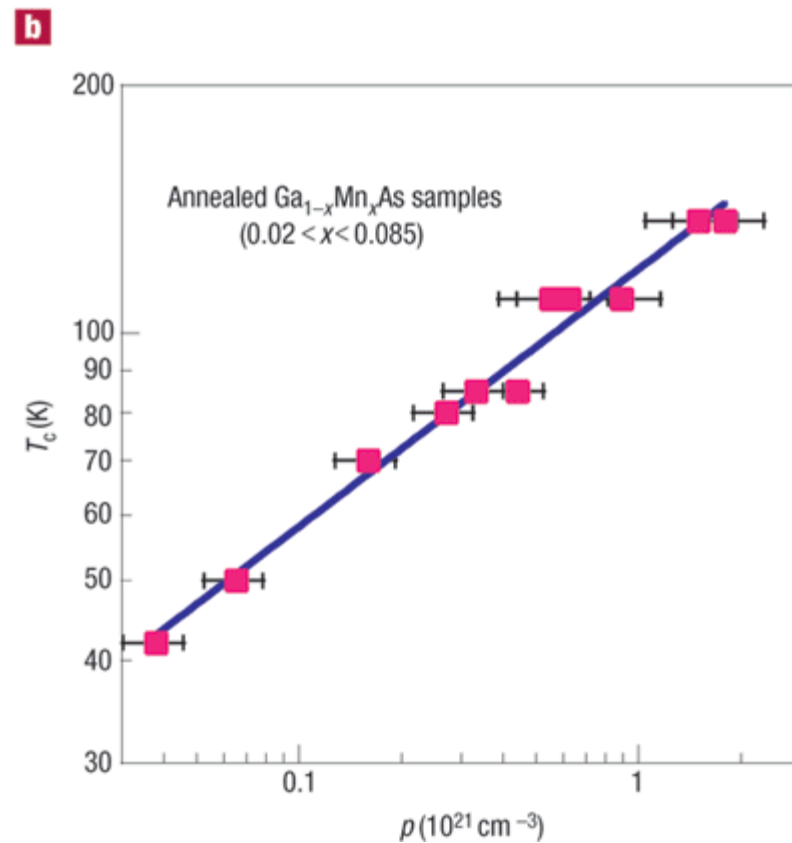
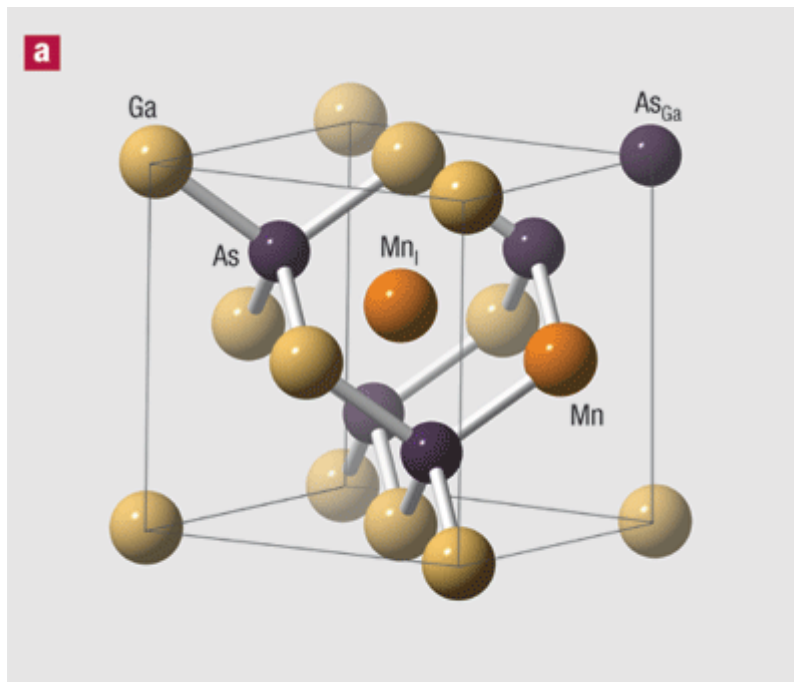


High doping

MacDonald, et al, Nature Mater. (2005)

Mainly two methods

1) Impurity doping

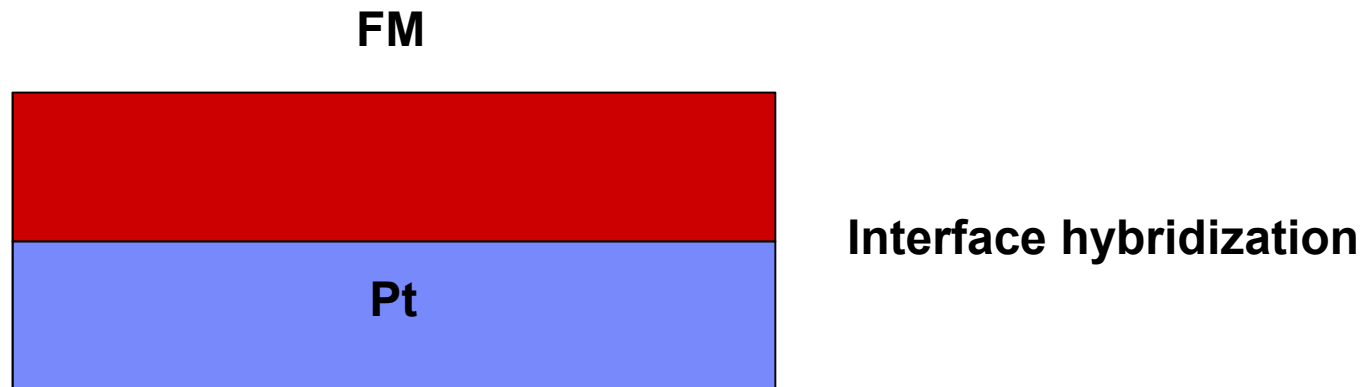


MacDonald, et al, Nature Mater. (2005)

Mainly two methods

2) Proximity effect

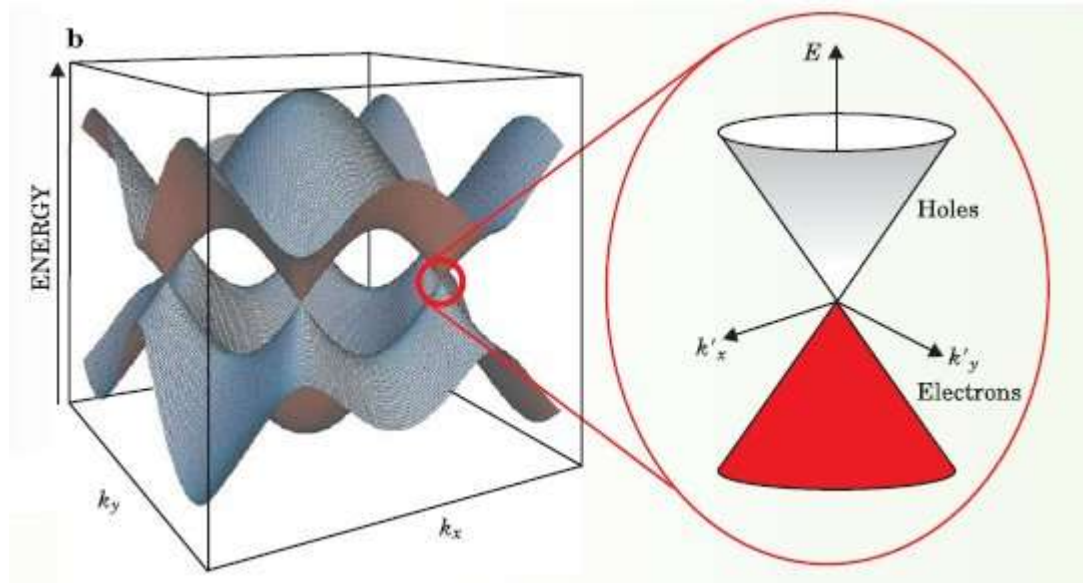
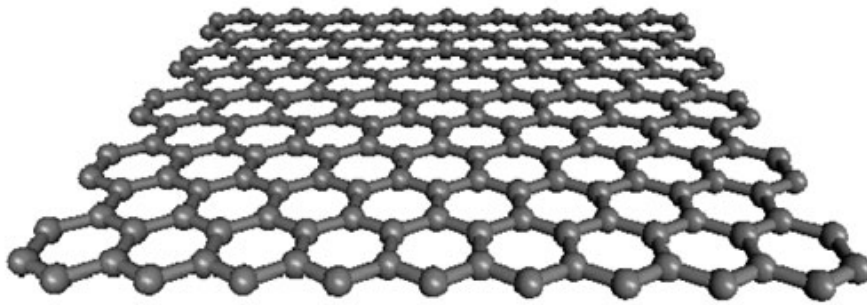
At the atomic level, when two atoms come into proximity, the highest energy, or valence, orbitals of the atoms change substantially and the electrons on the two atoms reorganize.



Induce M in two Quantum Materials

Two Dirac Materials

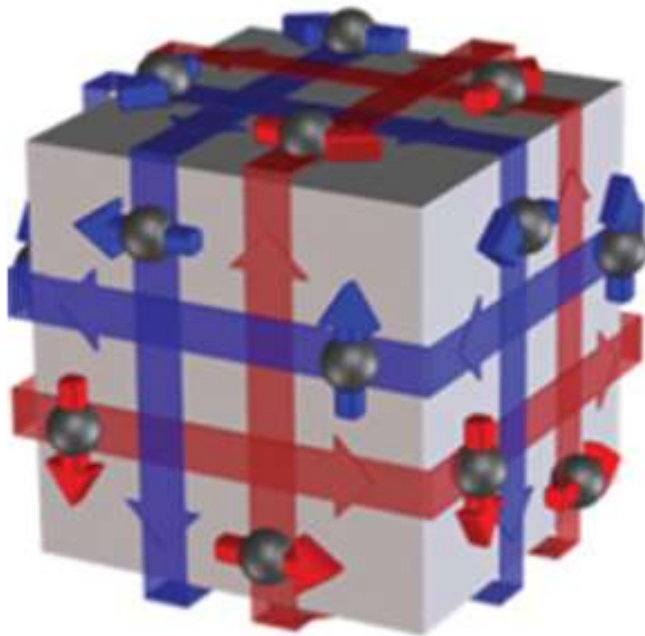
Graphene



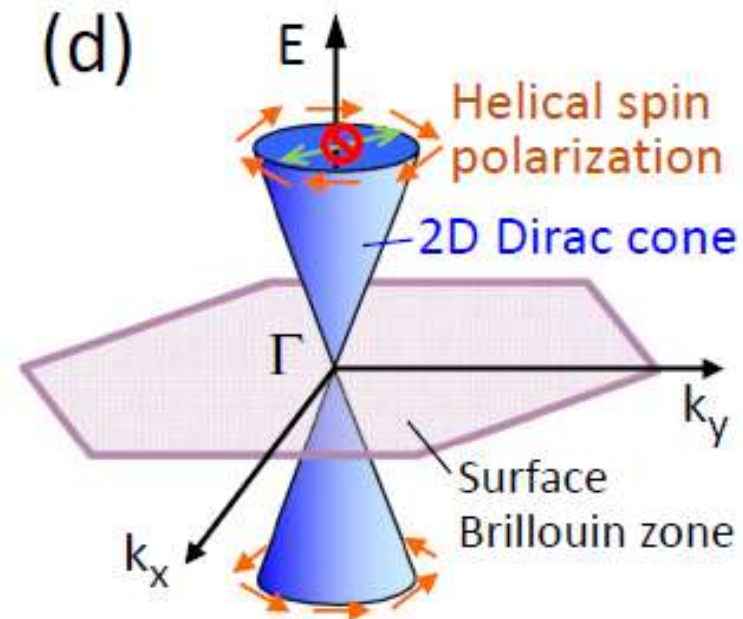
Induce M in two Quantum Materials

Two Dirac Materials

Topological Insulator

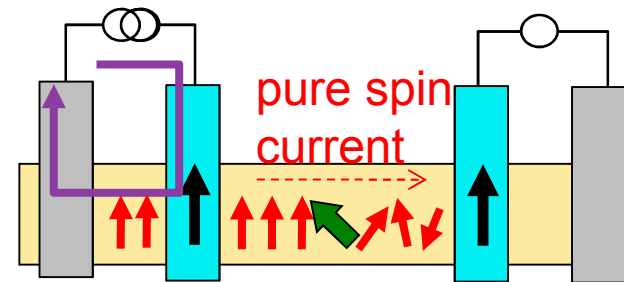
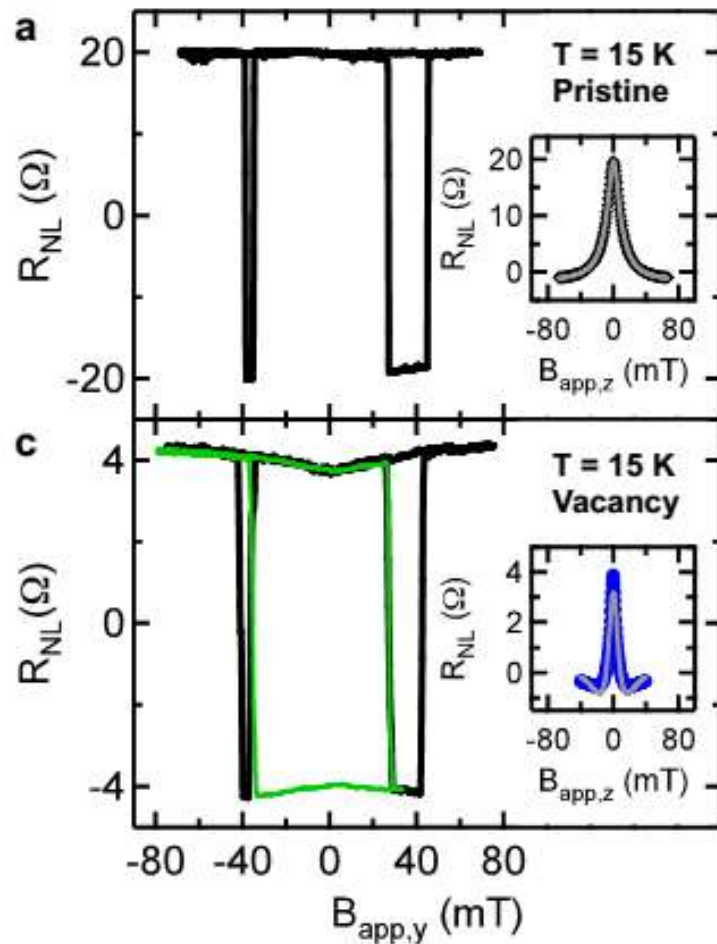


3D Topological insulator



Vacancies Defects

Using the spin current approach



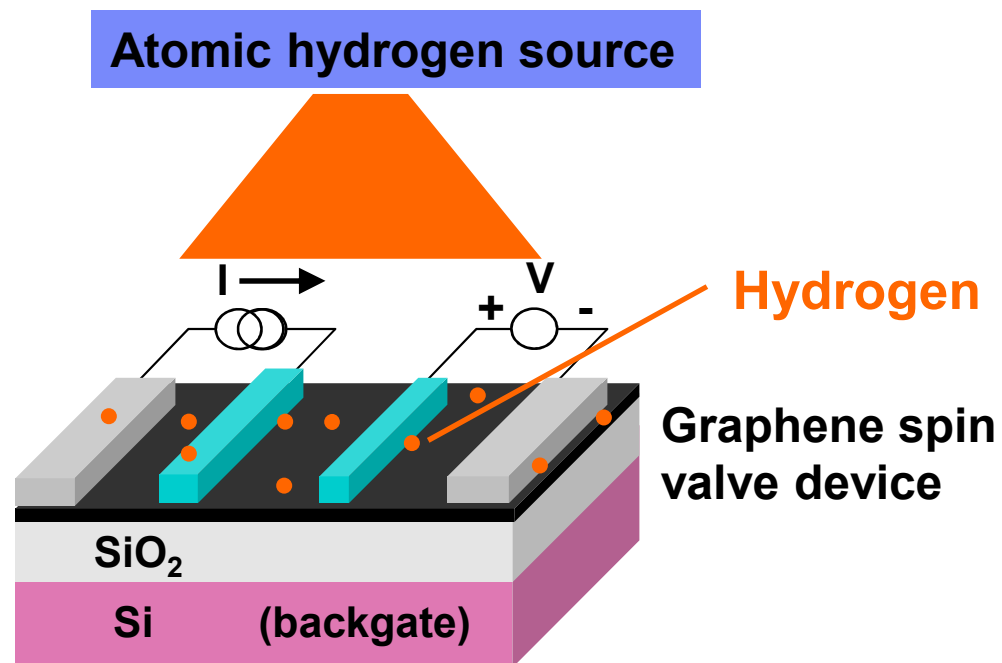
At high field

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

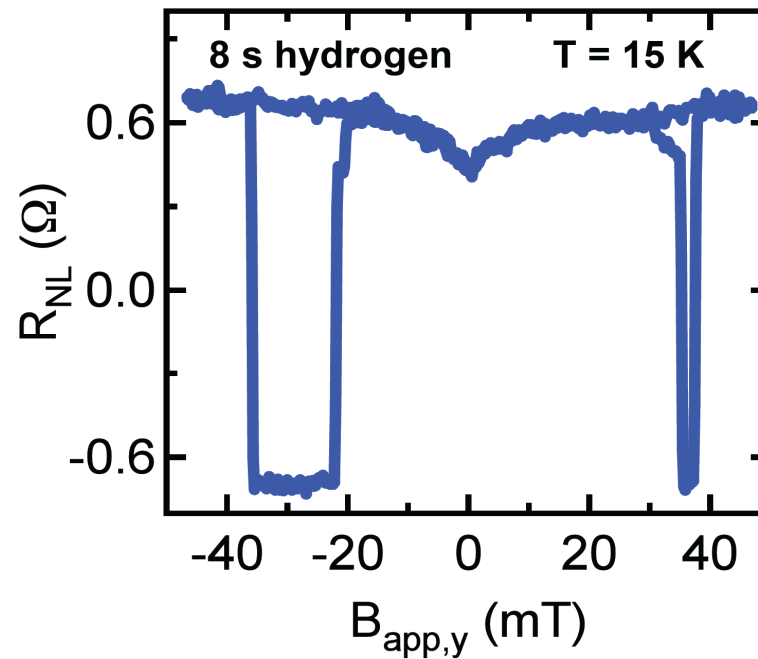
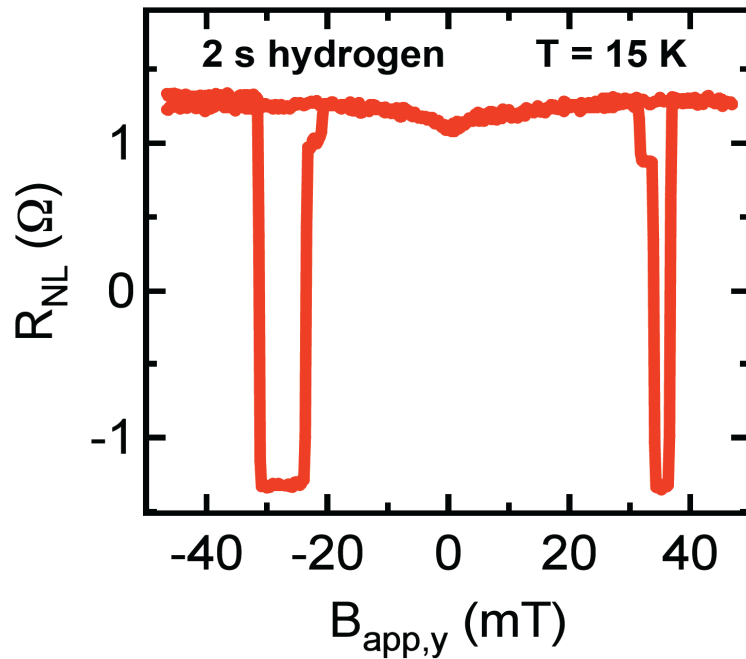
Scattering by exchange coupling is suppressed

➡ More spins at detector

Hydrogen Doping



Hydrogen Doping

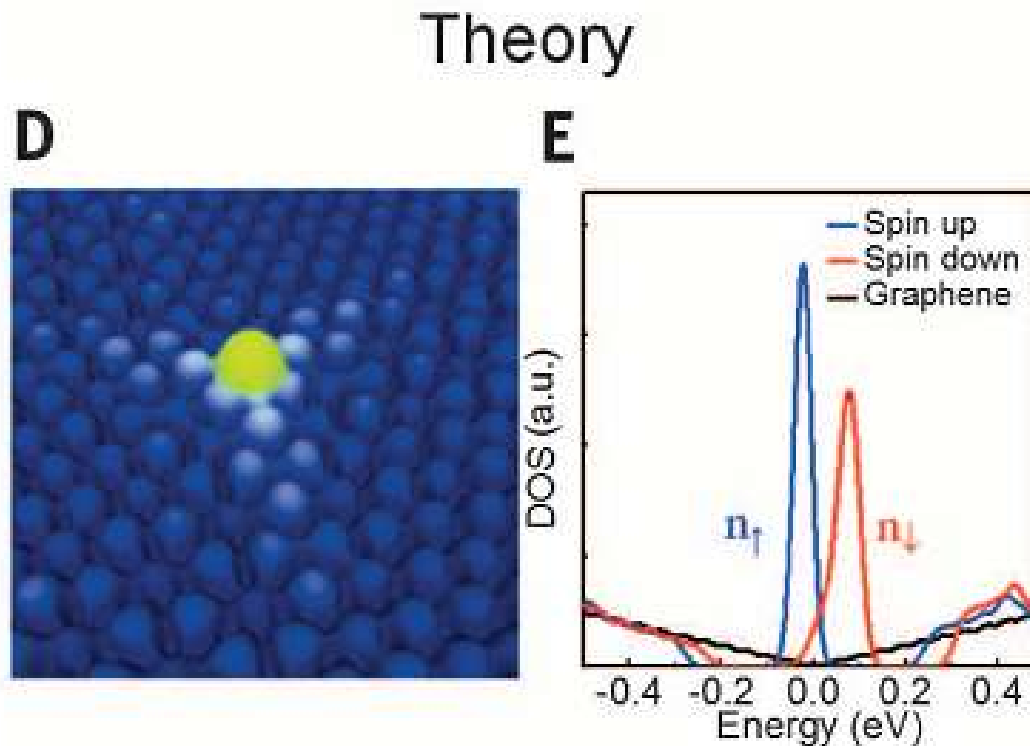


Paramagnetic at 15 K!

McCreary, et al, PRL (2012)

Hydrogen Doping

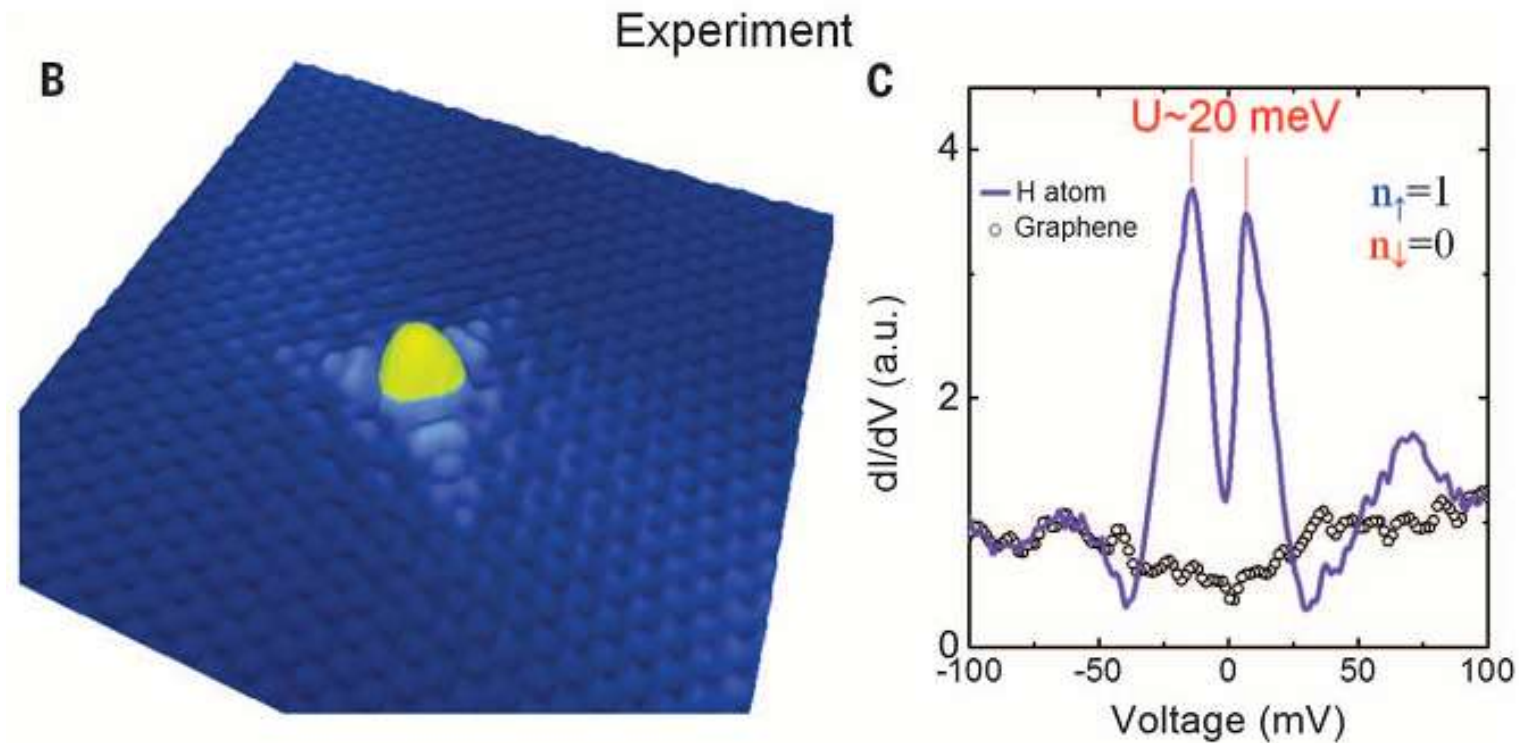
STM probe of H-graphene



González-Herrero, et al, Science (2016)

Hydrogen Doping

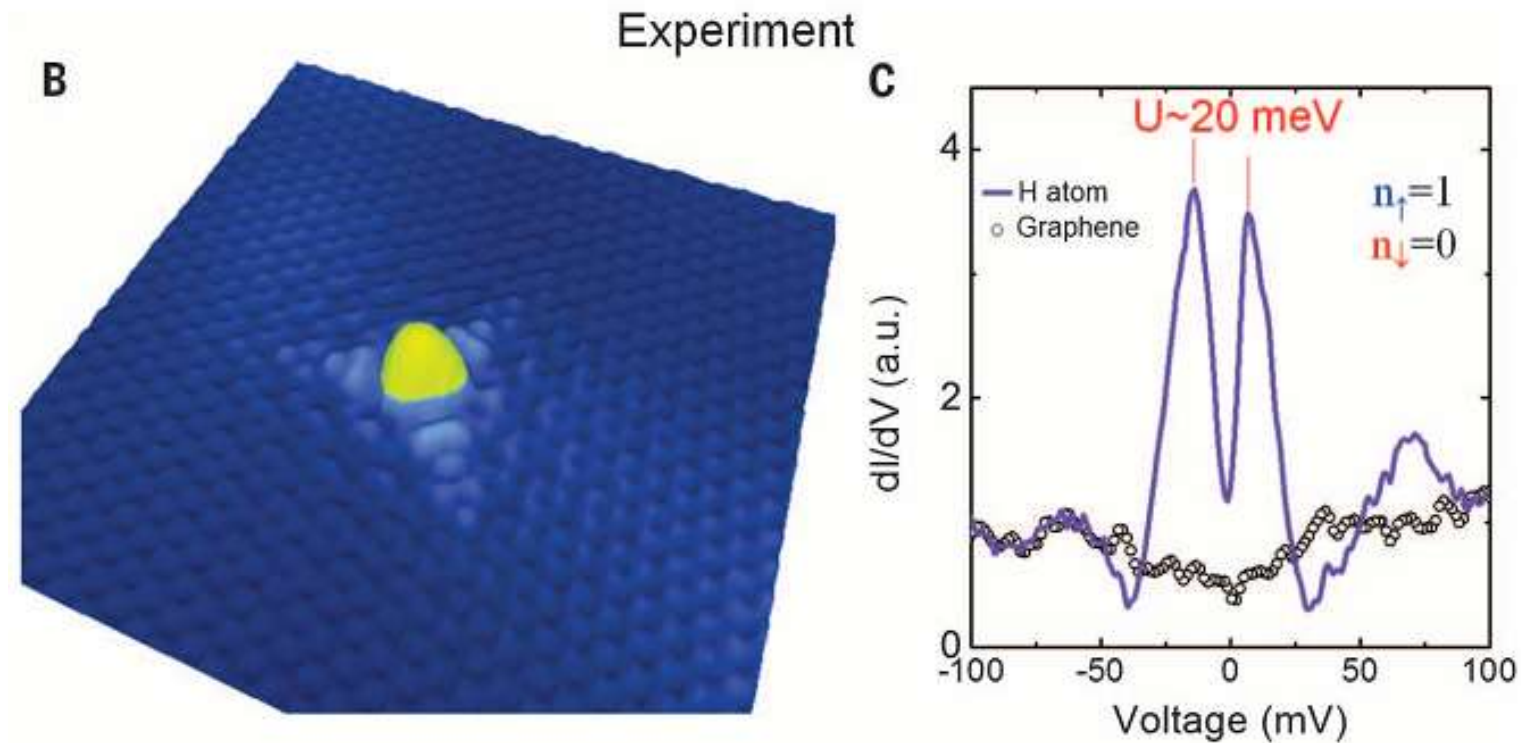
STM probe of H-graphene



González-Herrero, et al, Science (2016)

Hydrogen Doping

STM probe of H-graphene

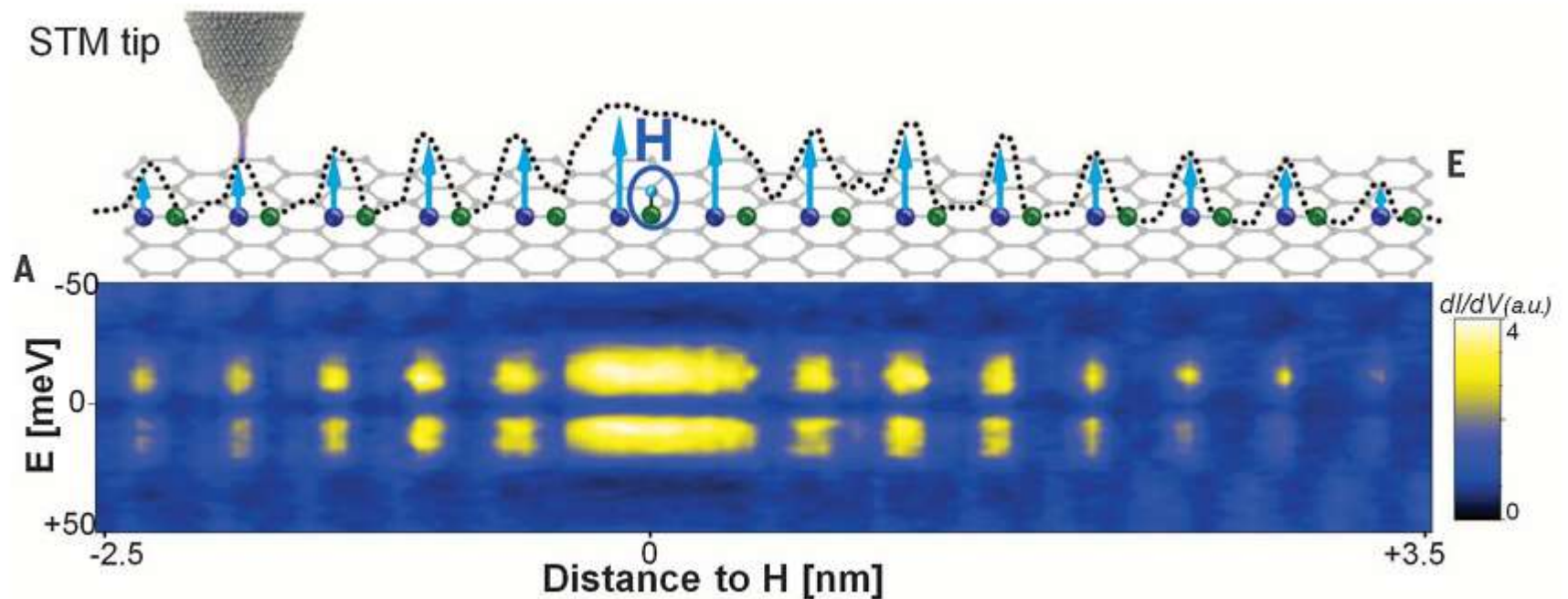


$T = 5 \text{ K}$

González-Herrero, et al, Science (2016)

Hydrogen Doping

STM probe of H-graphene

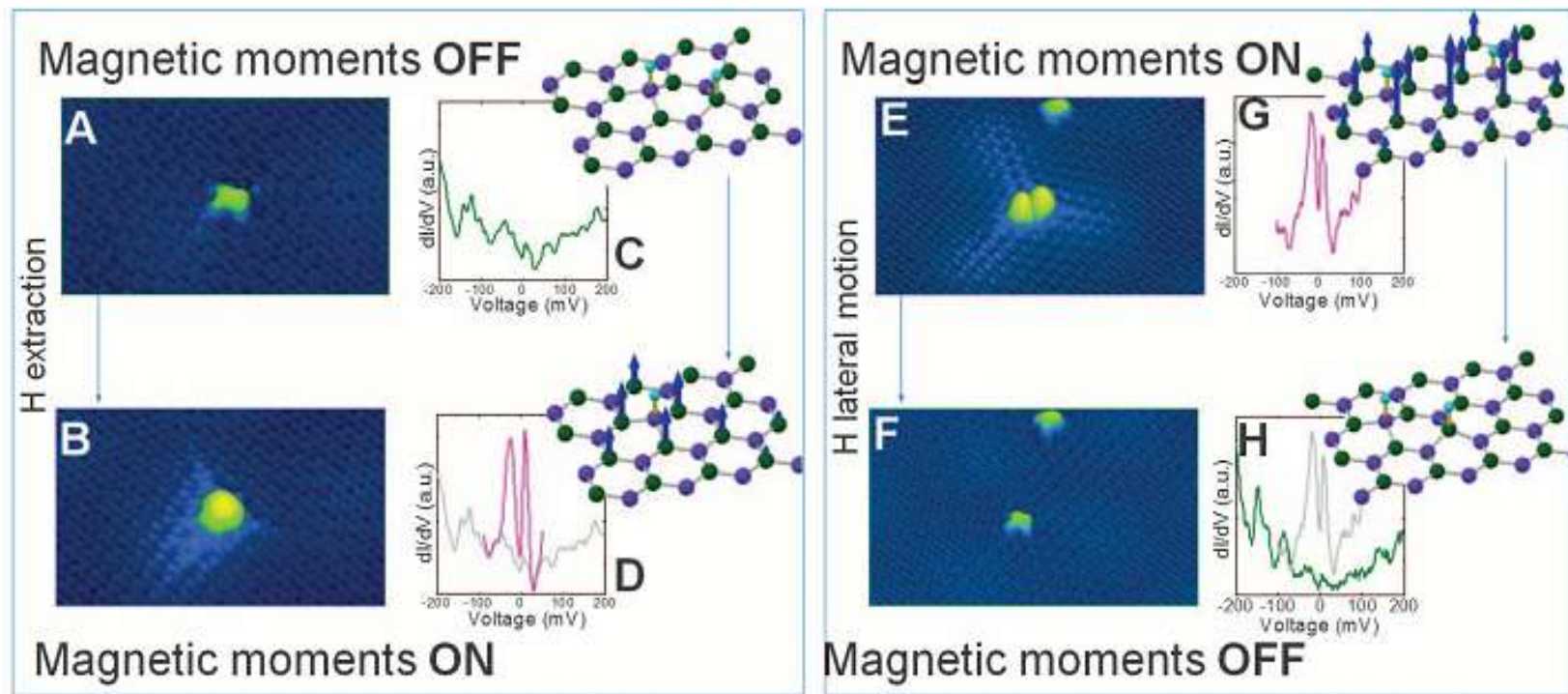


$T = 5 \text{ K}$

González-Herrero, et al, Science (2016)

Hydrogen Doping

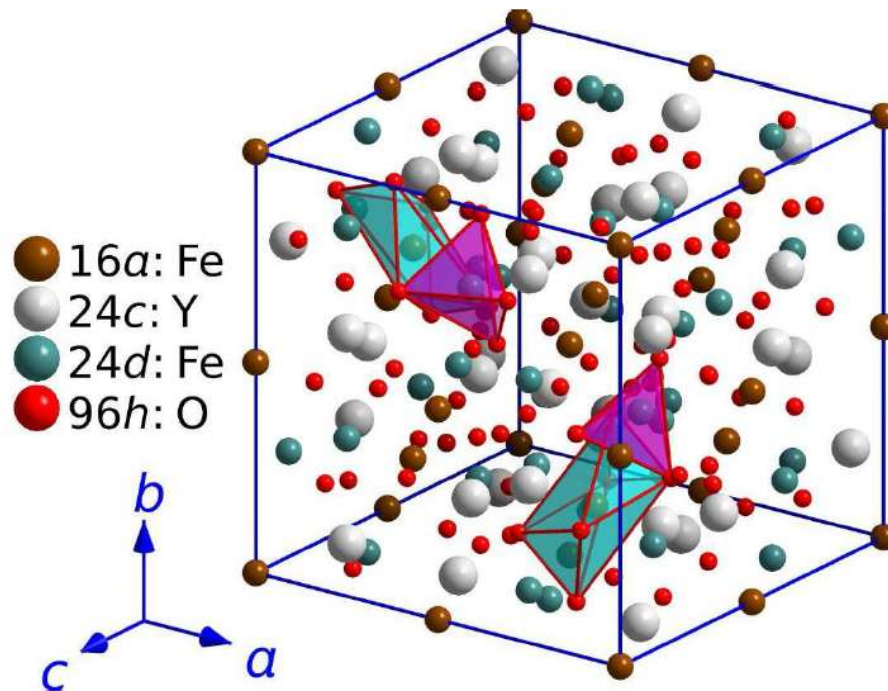
STM probe of H-graphene



González-Herrero, et al, Science (2016)

Proximity effect

Graphene on YIG



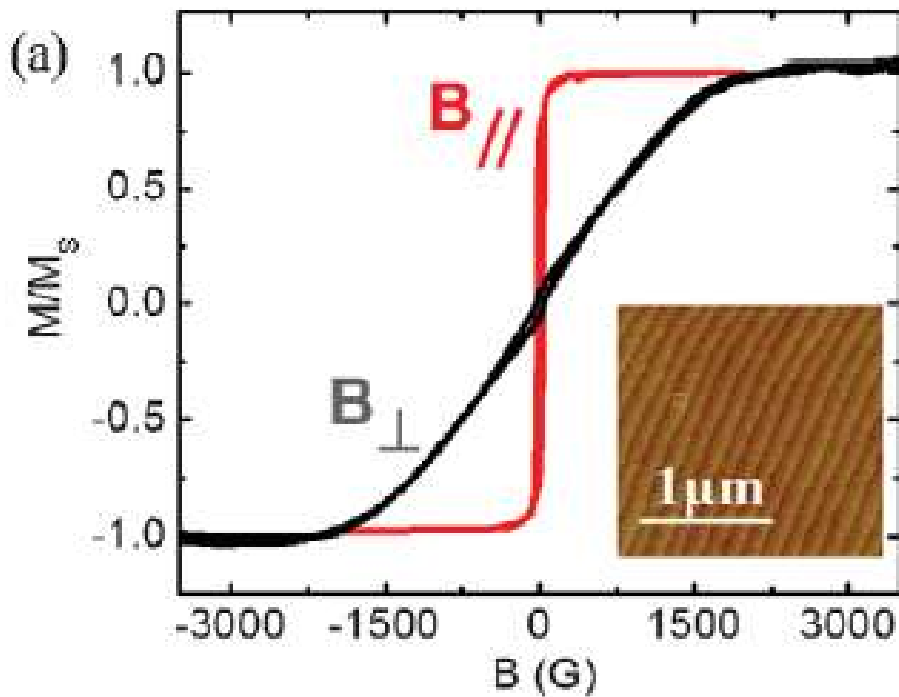
yttrium iron garnet (YIG):

- high $T_c \sim 550\text{K}$;
- Extremely small intrinsic damping constant (3×10^{-5});
- Insulating behavior;
- In-plane magnetic anisotropy.

$\text{Y}_3\text{Fe}_5\text{O}_{12}$, YIG: A FM insulator

Proximity effect

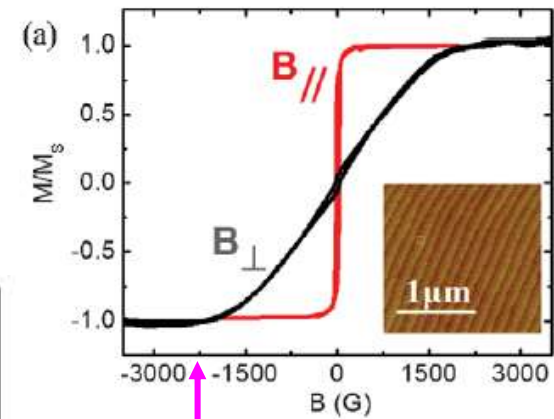
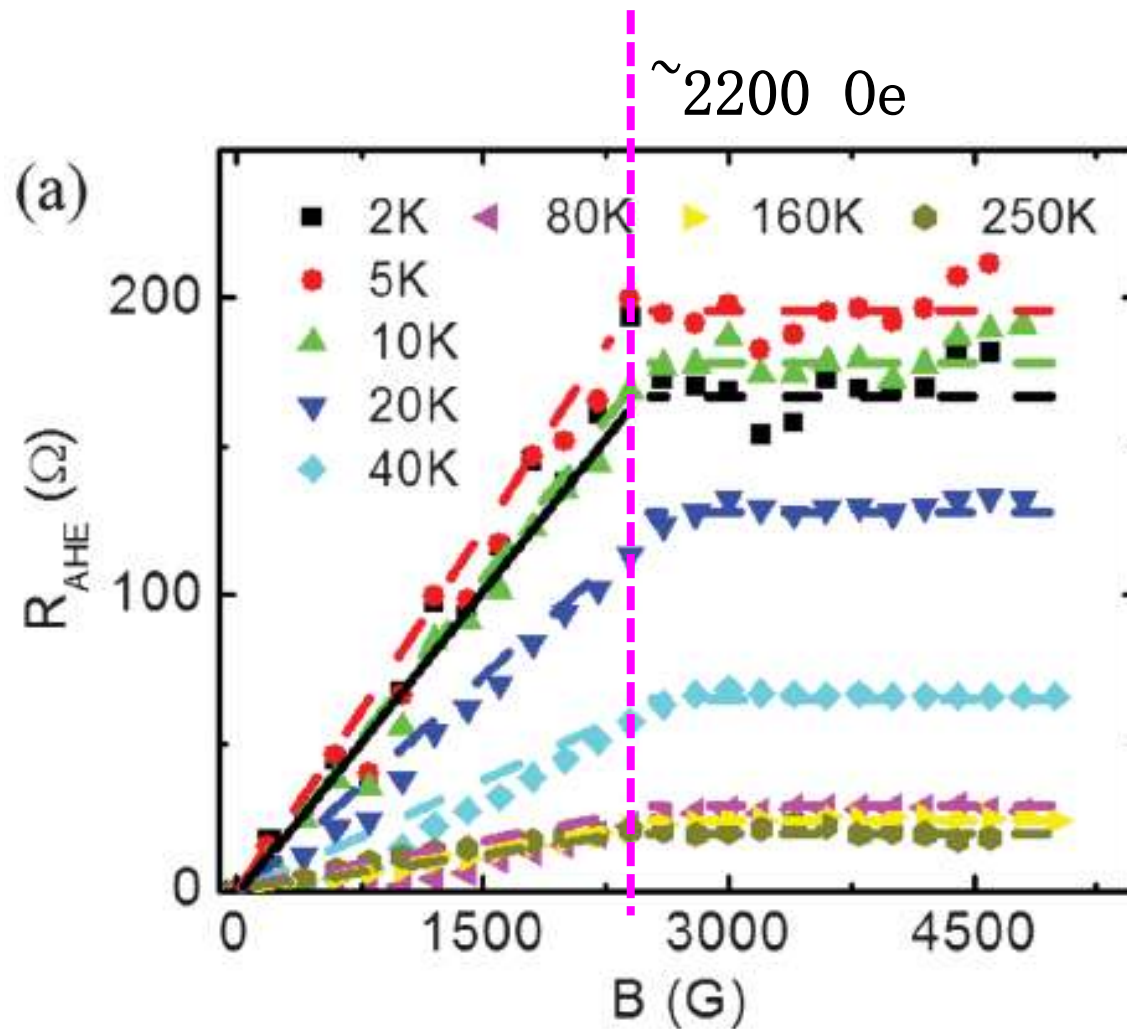
Graphene on YIG



Wang, et al, PRL (2015)

Proximity effect

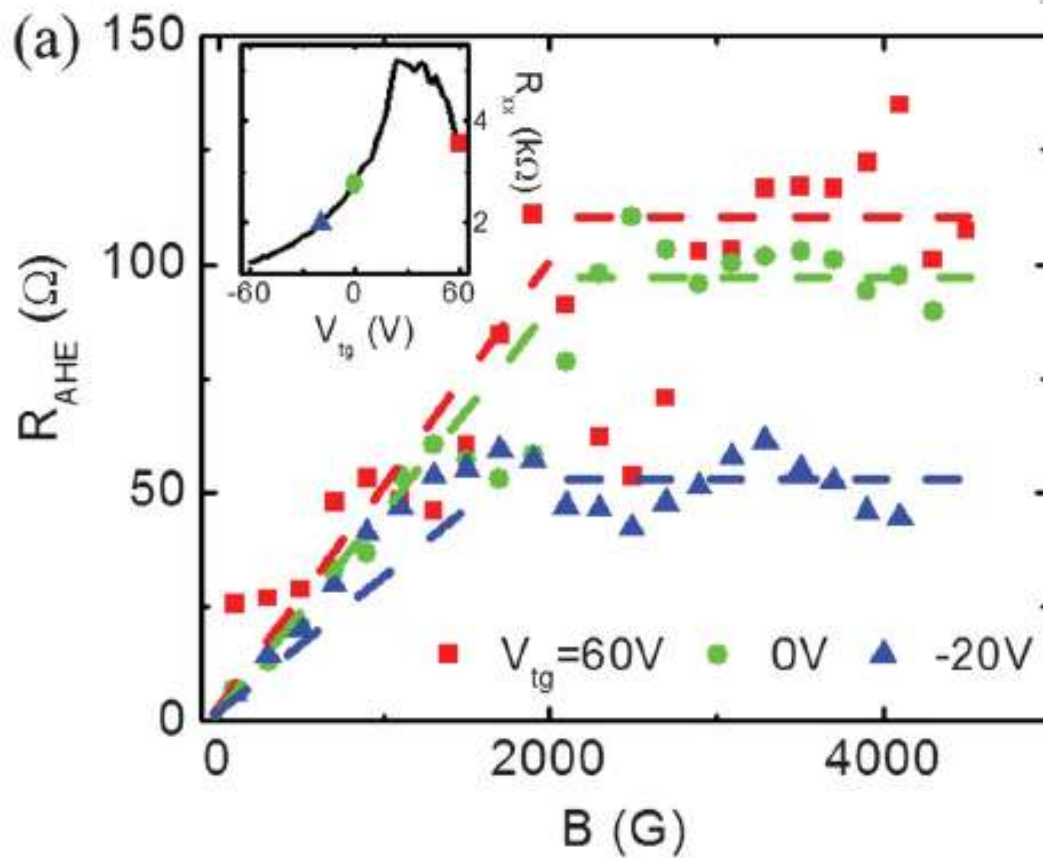
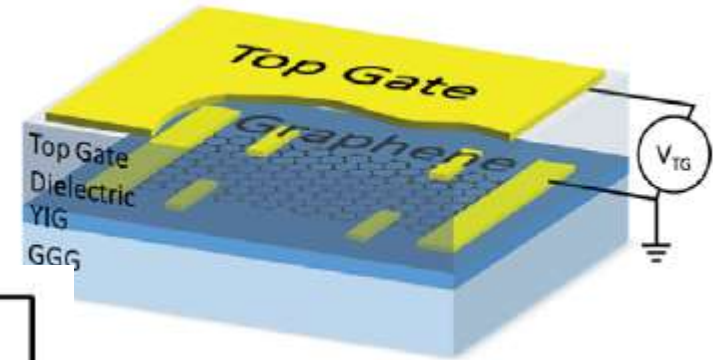
Graphene on YIG



$\sim 2200 \text{ Oe}$

Proximity effect

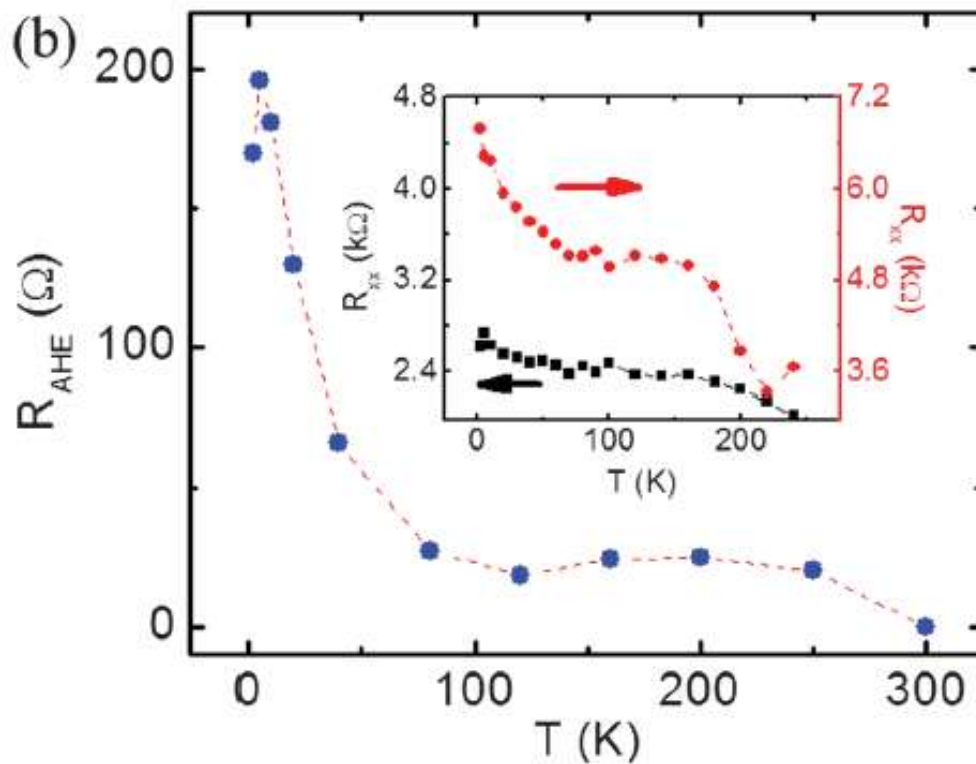
Graphene on YIG



Wang, et al, PRL (2015)

Proximity effect

Graphene on YIG

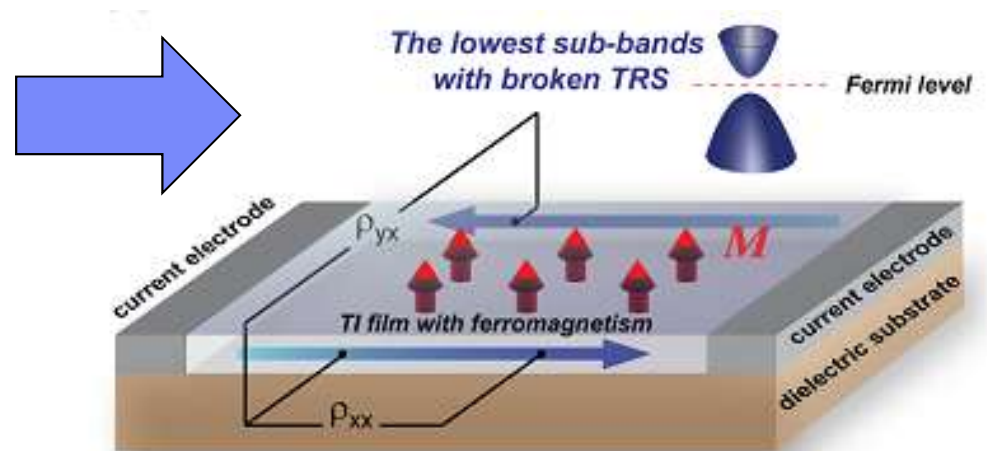
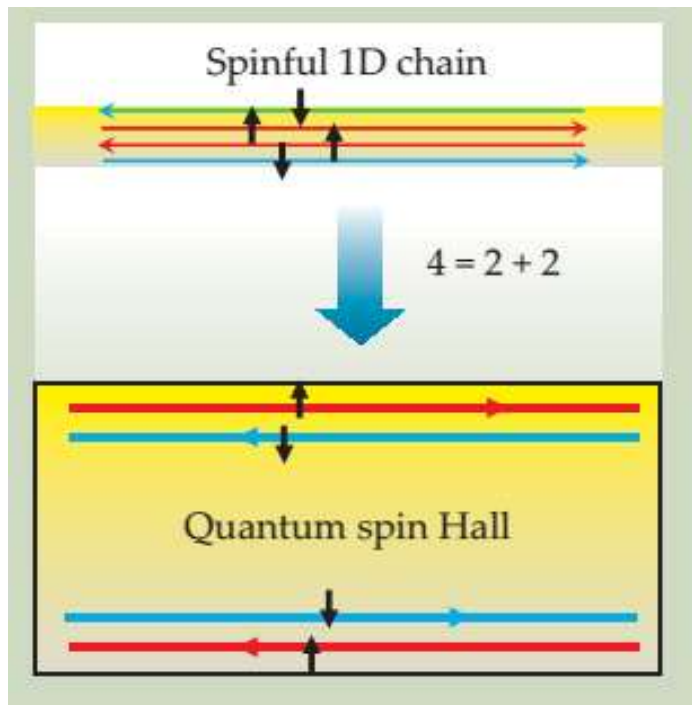


$$R_{xy} = R_H(B) + R_{\text{AHE}}(M) = \alpha B + \beta M$$

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

Induce M in Topological Insulator

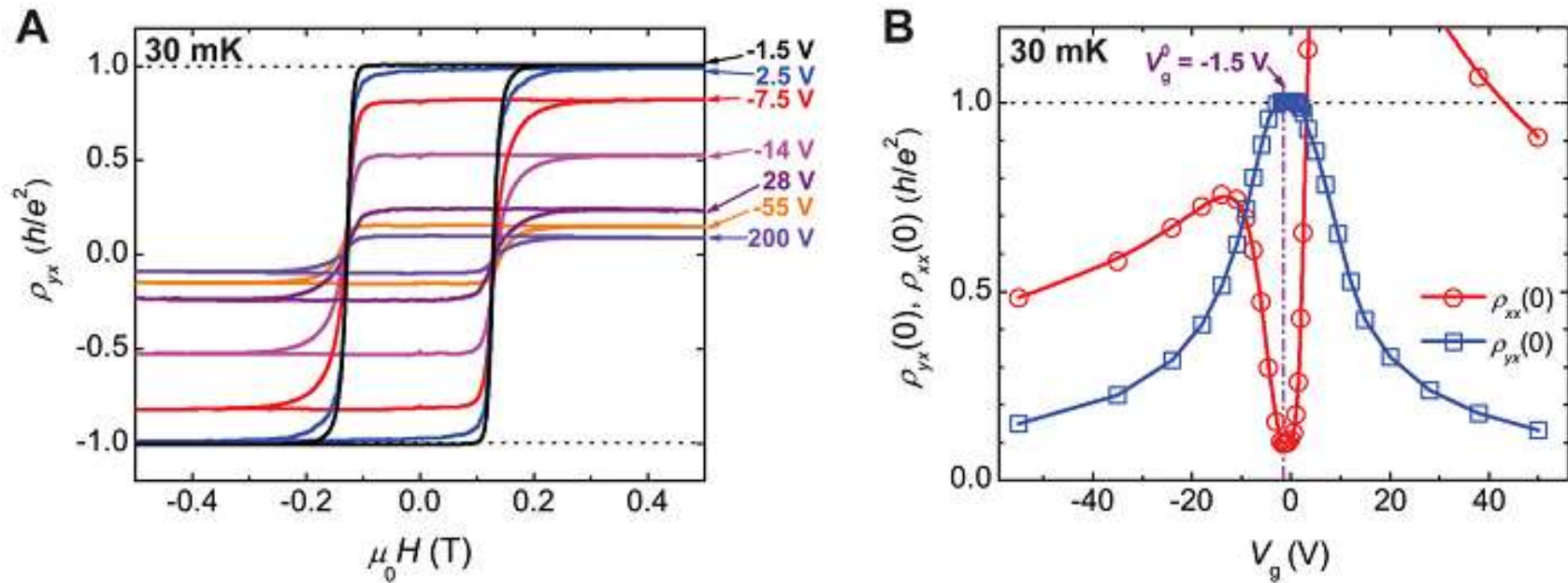
Why making TI magnetic



Quantum Anomalous Hall effect

Doping of Magnetic impurity

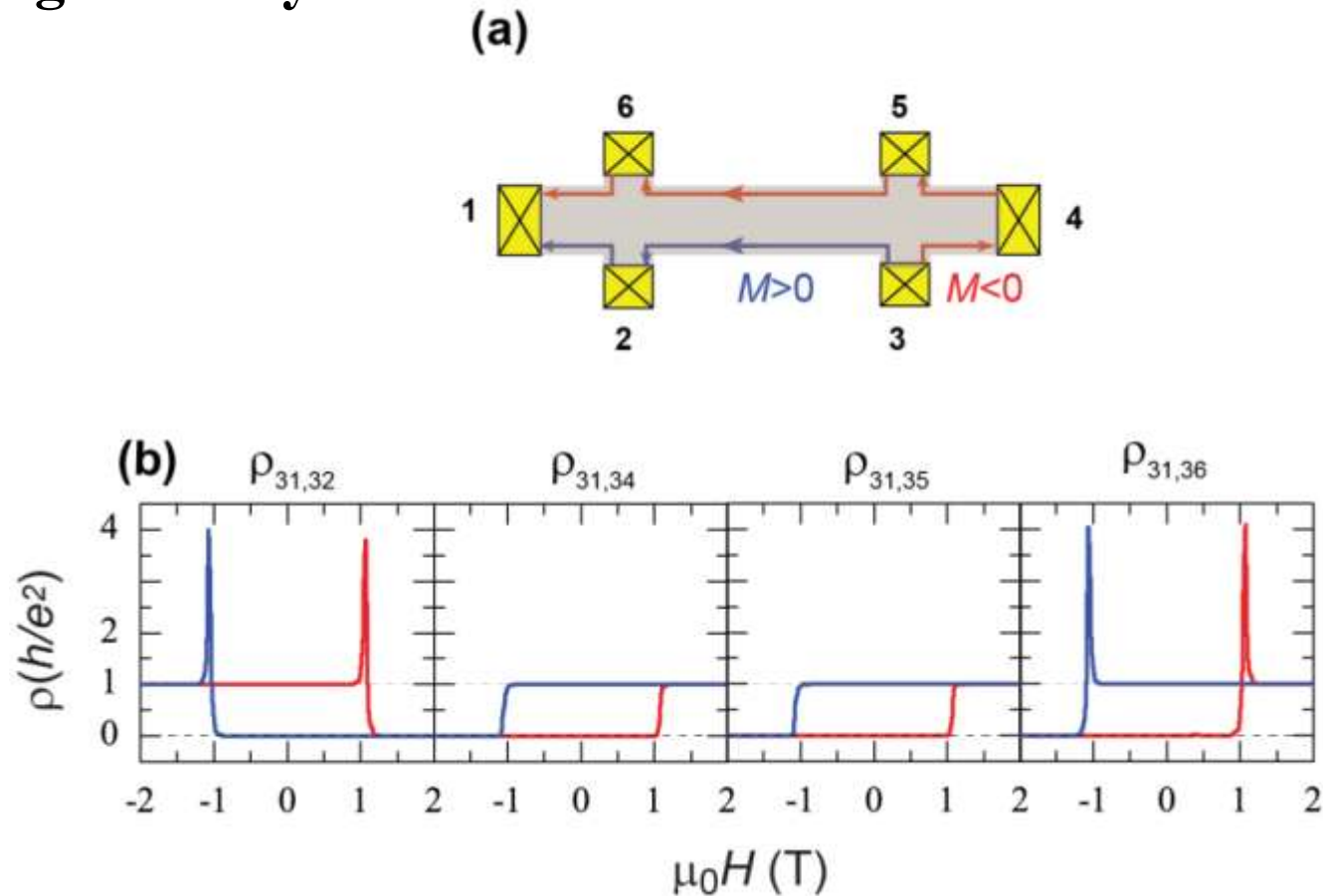
Doping effect by Cr



Chang, et al, Science (2013)

Doping of Magnetic impurity

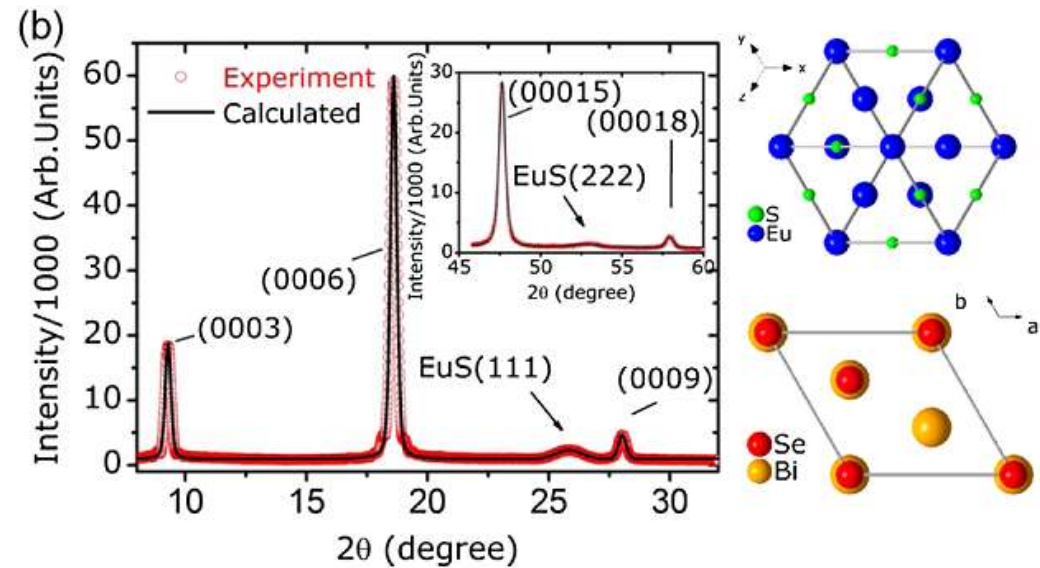
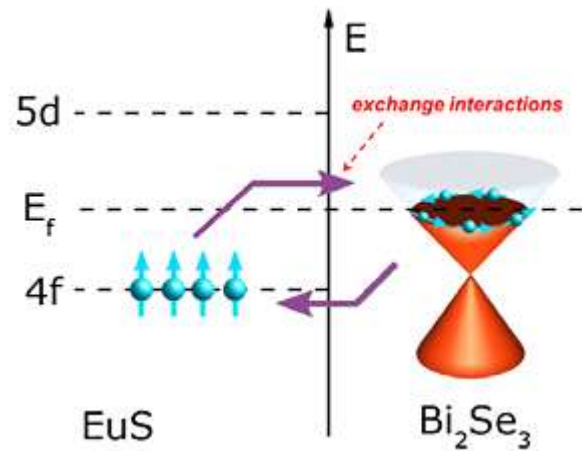
Doping effect by V



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

Proximity effect

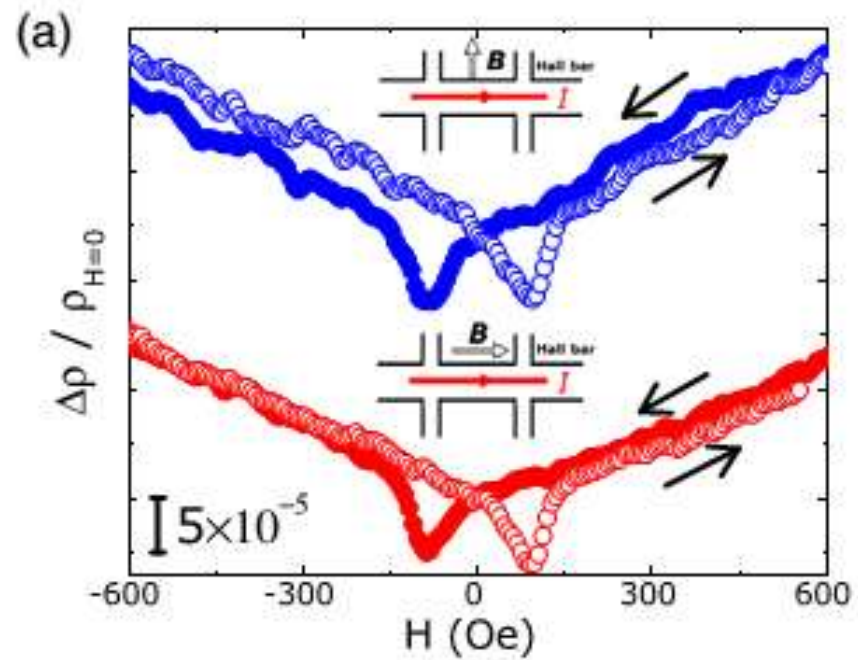
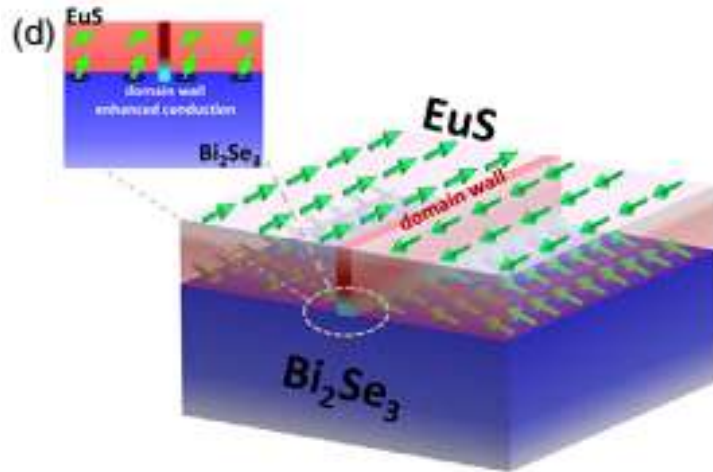
EuS: magnetic insulator



Wei, et al, PRL (2013)

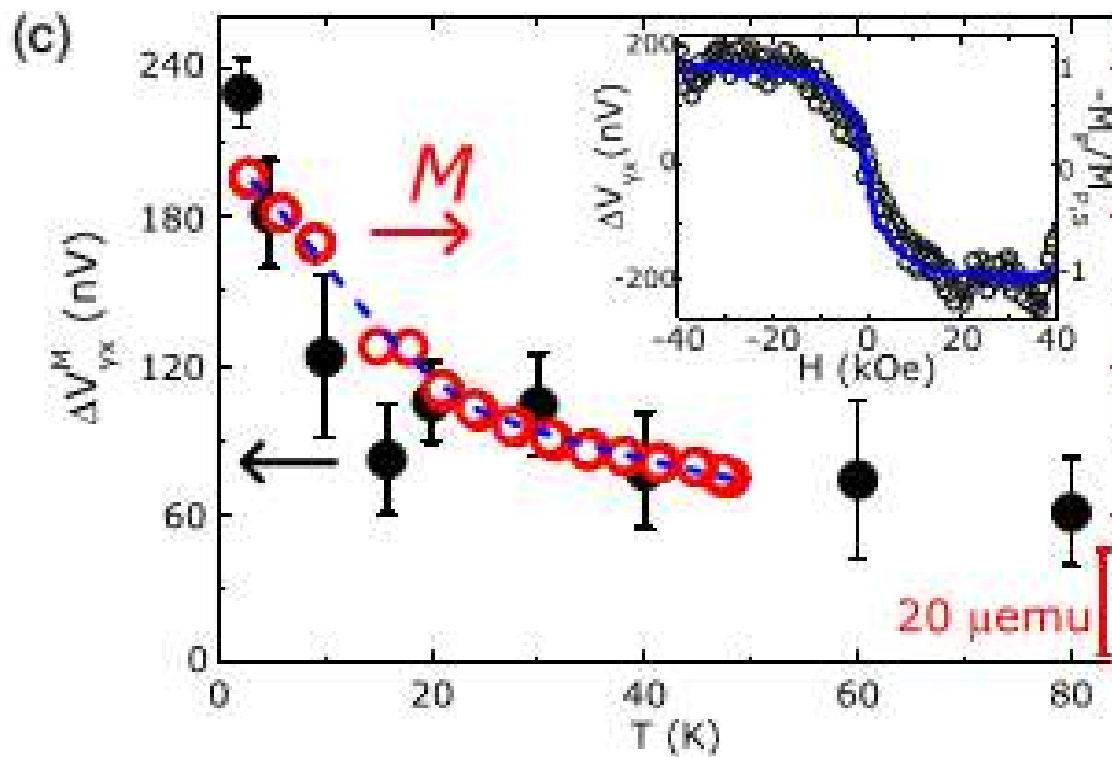
Proximity effect

EuS: magnetic insulator



Proximity effect

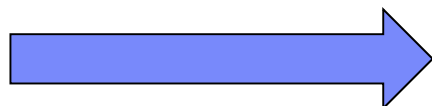
EuS: magnetic insulator



Wei, et al, PRL (2013)

Proximity effect

TIG, a magnetic insulator with perpendicular easy axis



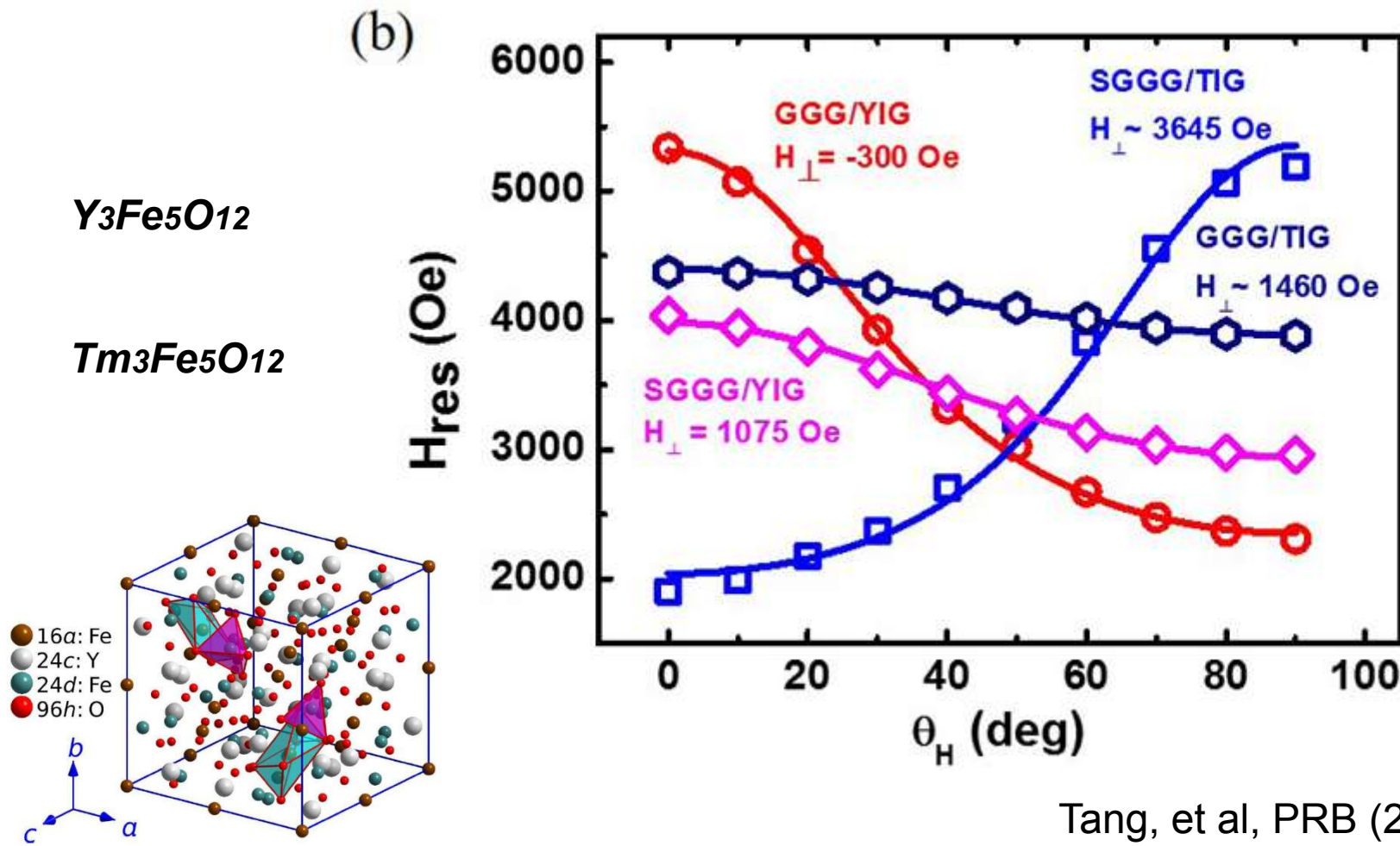
1A	2A	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Na	Mg	III B	IV B	V B	VI B	VII B	VIII	VIII	VIII	IB	IIB	Al	Si	P	S	Cl	Ar
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.88	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.933	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.39	31 Ga Gallium 69.723	32 Ge Germanium 72.61	33 As Arsenic 74.922	34 Se Selenium 78.09	35 Br Bromine 79.904	36 Kr Krypton 84.80
37 Rb Rubidium 84.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.94	43 Tc Technetium 98.907	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.71	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.904	54 Xe Xenon 131.29
55 Cs Cesium 132.905	56 Ba Barium 137.327	57-71	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.85	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.22	78 Pt Platinum 195.08	79 Au Gold 196.967	80 Hg Mercury 200.59	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium [208.982]	85 At Astatine 209.987	86 Rn Radon 222.018
87 Fr Francium 223.020	88 Ra Radium 226.025	89-103	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [268]	110 Ds Darmstadtium [269]	111 Rg Roentgenium [272]	112 Cn Copernicium [277]	113 Uut Ununtrium unknown	114 Fl Flerovium [289]	115 Uup Ununpentium unknown	116 Lv Livermorium [293]	117 Uus Ununseptium unknown	118 Uuo Ununoctium unknown

Lanthanide Series	57 La Lanthanum 138.906	58 Ce Cerium 140.115	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.24	61 Pm Promethium 144.913	62 Sm Samarium 150.36	63 Eu Europium 151.966	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.50	67 Ho Holmium 164.930	68 Er Erbium 167.26	69 Tm Thulium 168.934	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.967
Actinide Series	89 Ac Actinium 227.028	90 Th Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.029	93 Np Neptunium 237.048	94 Pu Plutonium 244.064	95 Am Americium 243.061	96 Cm Curium 247.070	97 Bk Berkelium 247.070	98 Cf Californium 251.080	99 Es Einsteinium [254]	100 Fm Fermium 257.095	101 Md Mendelevium 258.1	102 No Nobelium 259.101	103 Lr Lawrencium [262]

Alkali Metal	Alkaline Earth	Transition Metal	Semimetal	Nonmetal	Basic Metal	Halogen	Noble Gas	Lanthanide	Actinide
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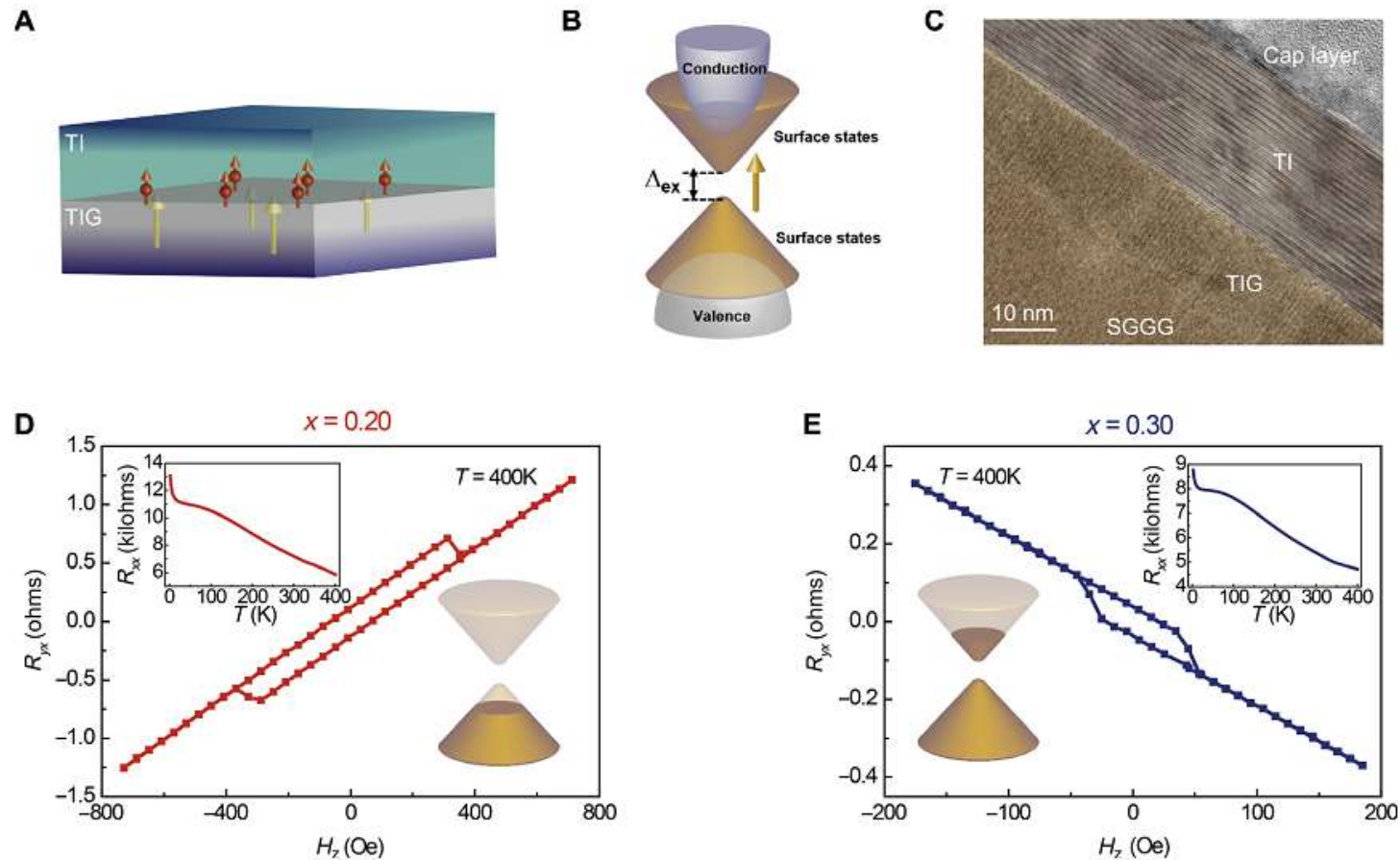
Proximity effect

TIG, a magnetic insulator with perpendicular easy axis



Proximity effect

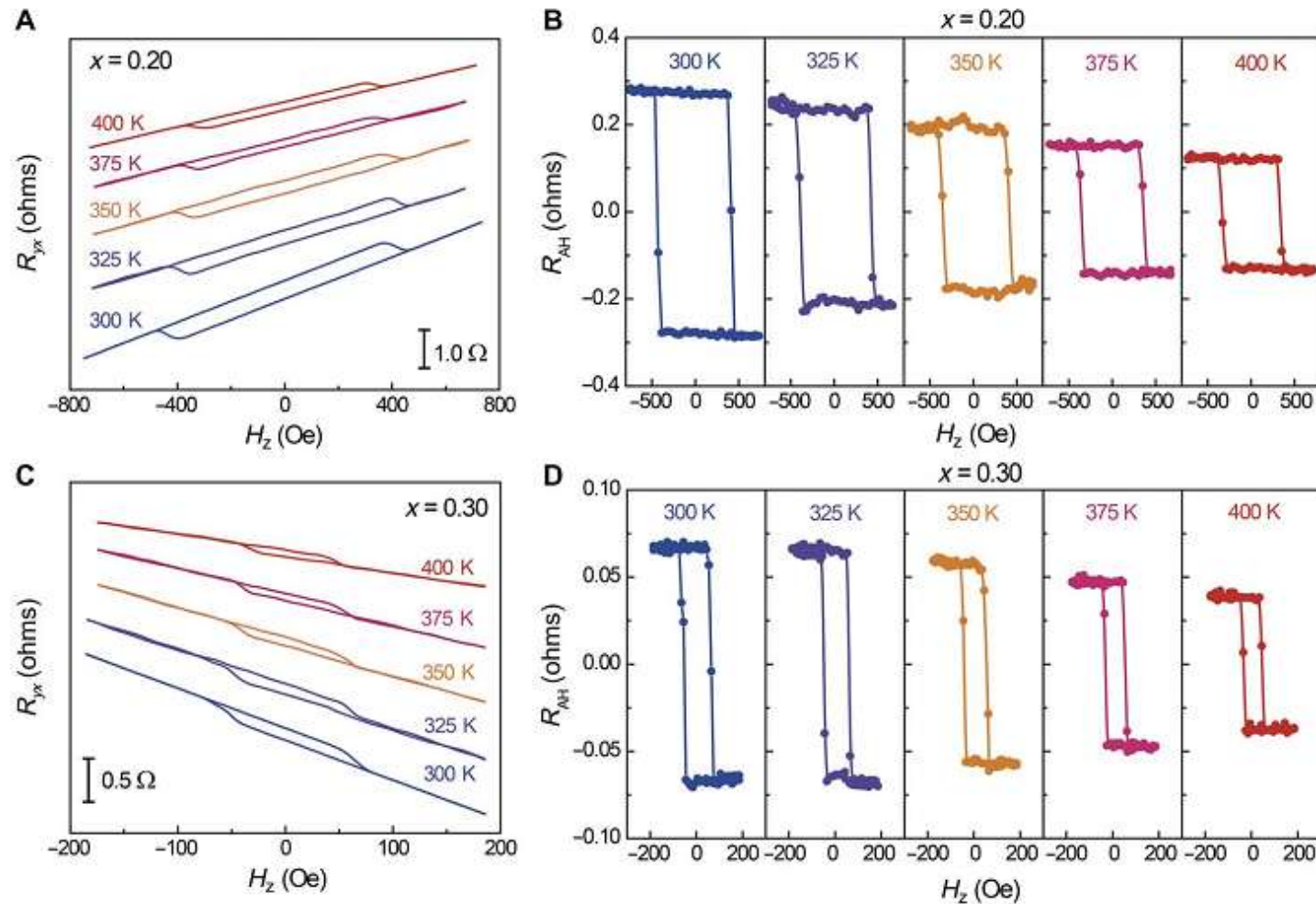
TIG, a magnetic insulator with perpendicular easy axis



Tang, et al, Science Advances (2017)

Proximity effect

TIG, a magnetic insulator with perpendicular easy axis

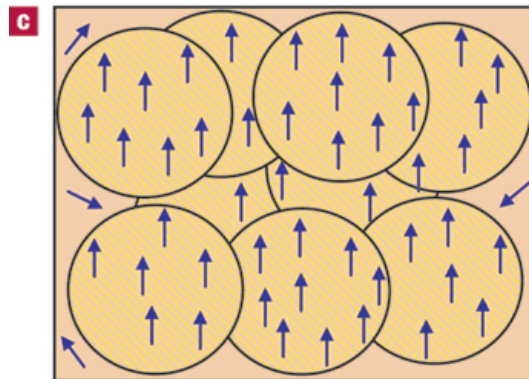


Tang, et al, Science Advances (2017) ³²

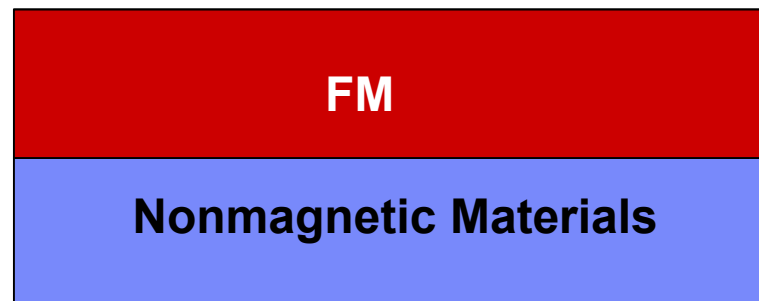
Summary

How to induce magnetic moment

Doping



Proximity effect



Interface hybridization

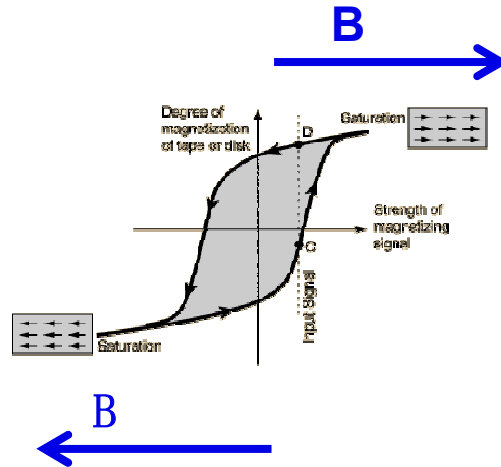
休息10分钟

提纲

3. How to control magnetization

How to control the magnetization

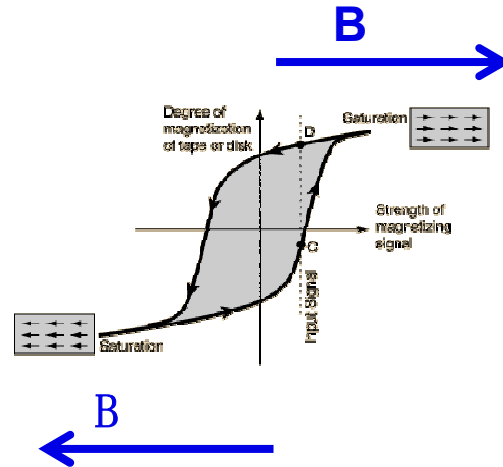
Magnetic field



Without B
???

How to control the magnetization

Magnetic field



Without B
???

Control??

Electric field

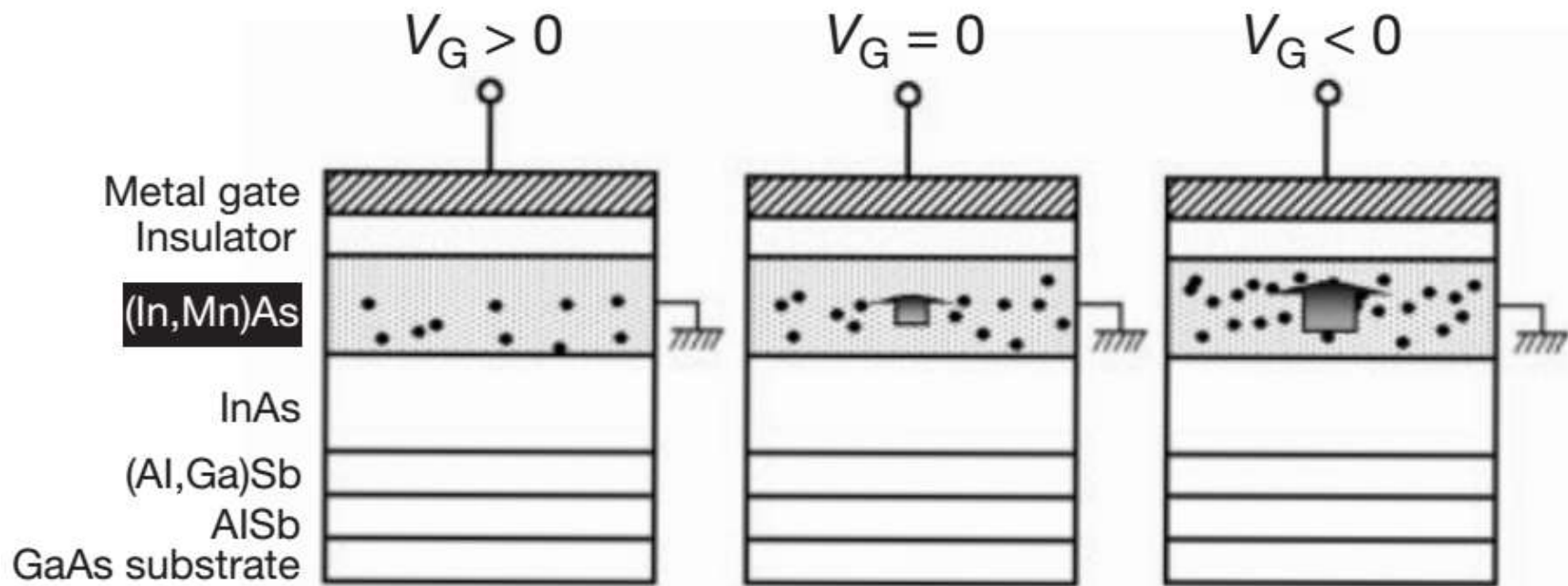
Spin torque

Ultrafast Laser

Interface Strain

Electric field control the magnetization

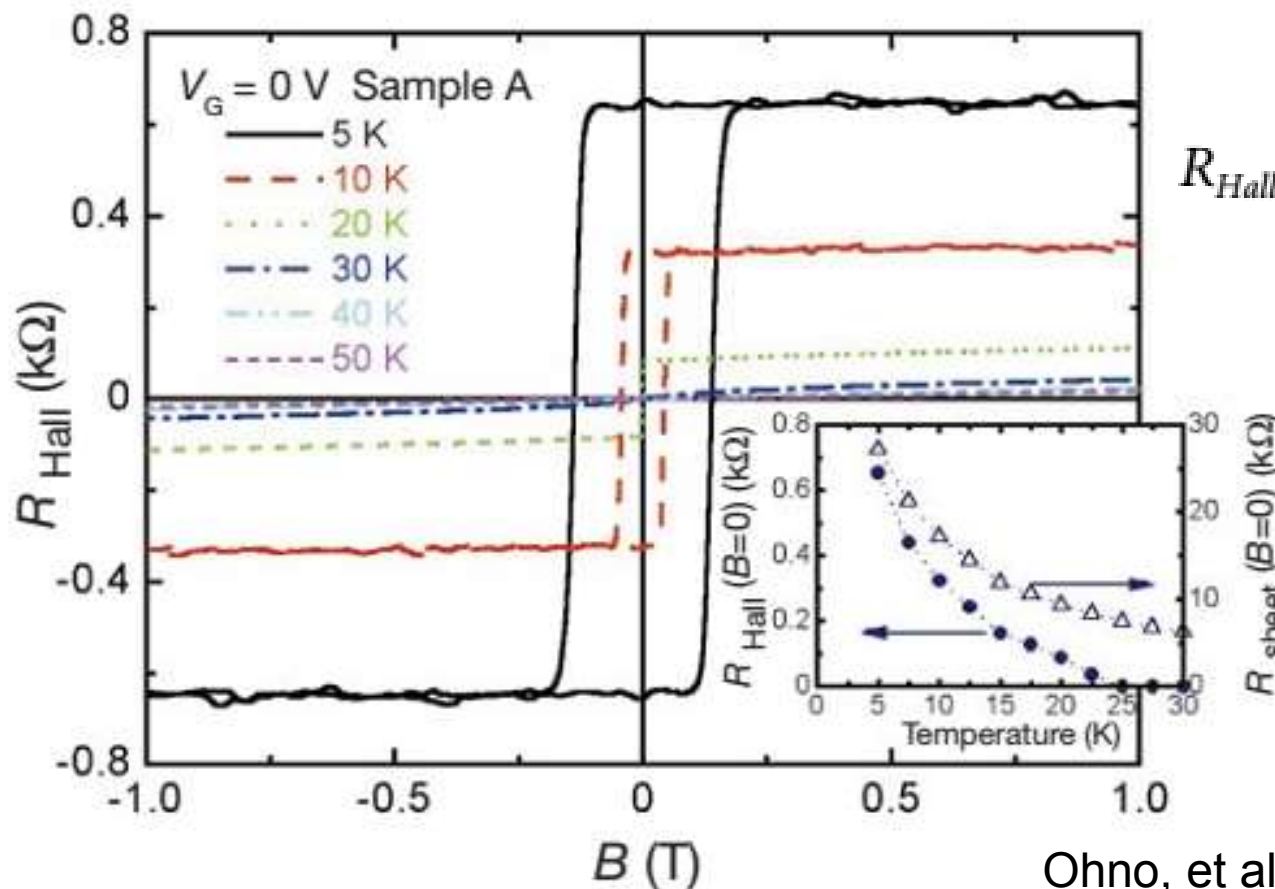
Electrical field effect in magnetic semiconductor



Ohno, et al, Nature (2000)

Electric field control the magnetization

Magnetic properties of InMnAs (AHE)

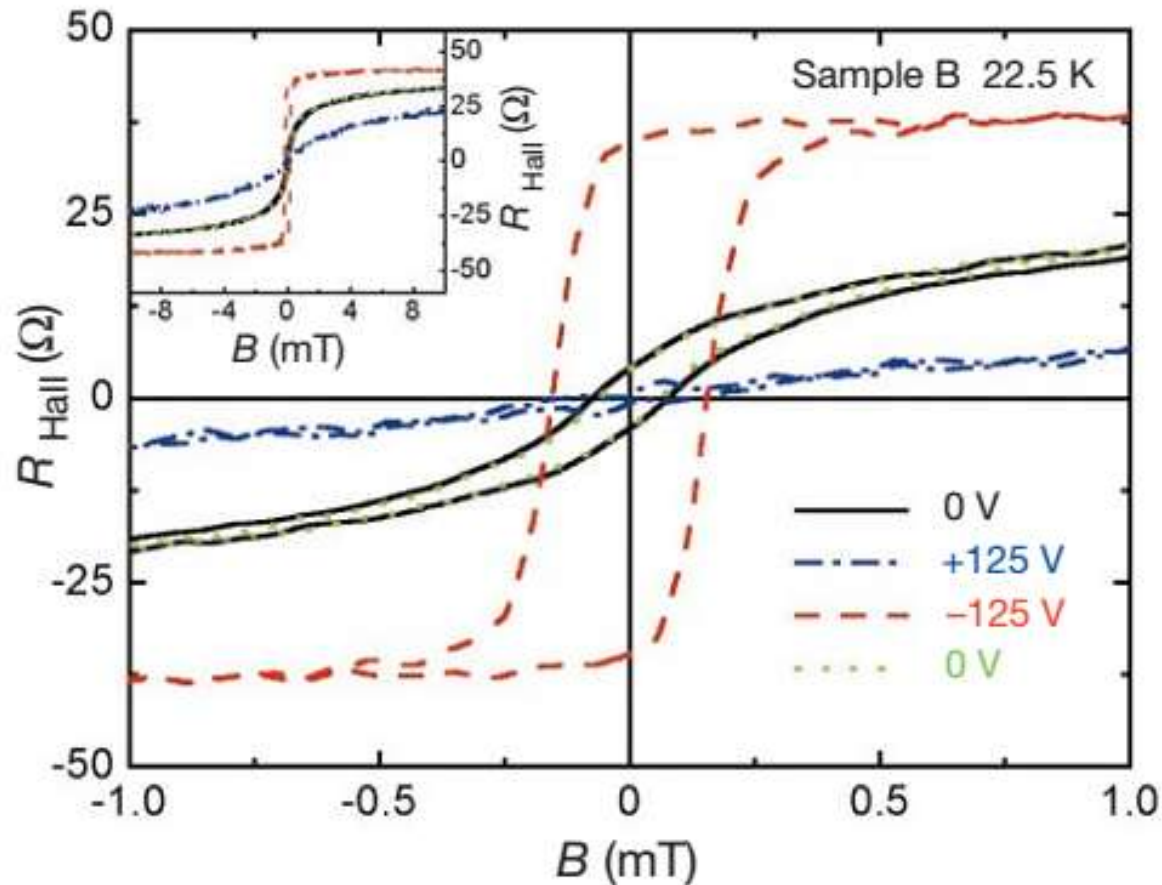


$$R_{Hall} = \frac{R_0}{d} B + \frac{R_s}{d} M$$

Ohno, et al, Nature (2000)

Electric field control the magnetization

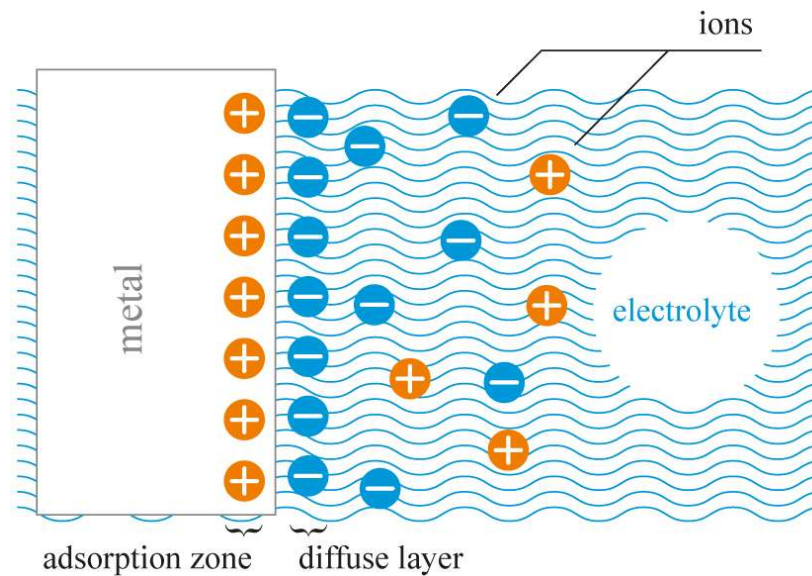
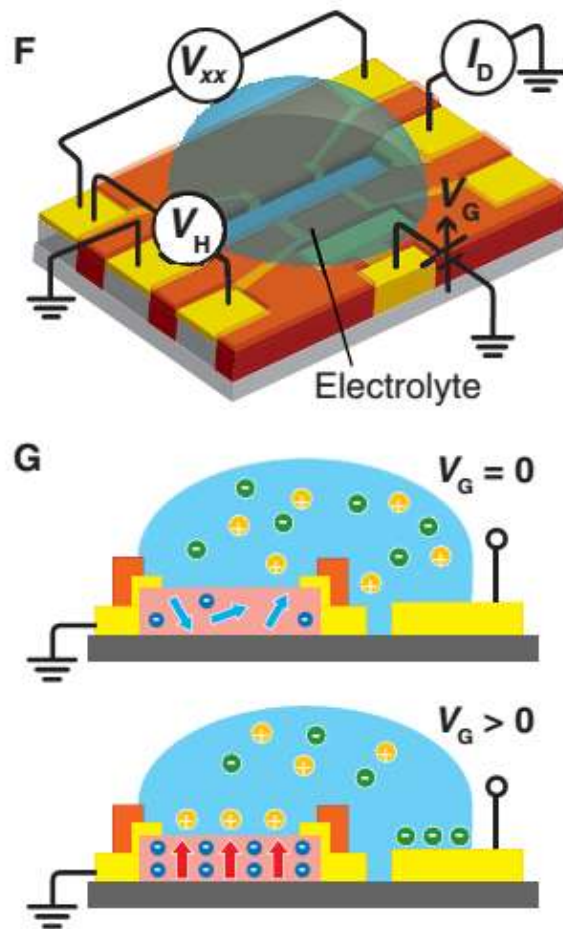
Electrical field effect on InMnAs



Ohno, et al, Nature (2000)

Electric field control the magnetization

Ionic liquid gate control



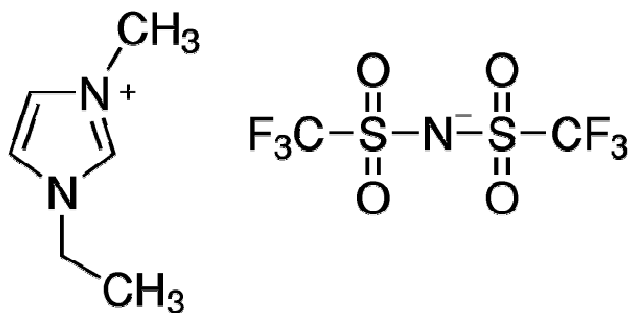
Large electric field on the surface

Yamada, et al, Science (2011)

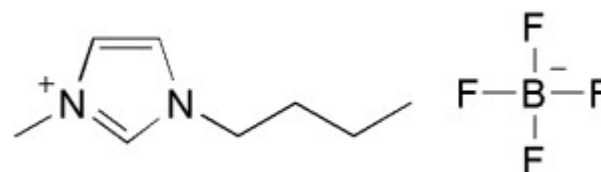
Electric field control the magnetization

Ionic liquid

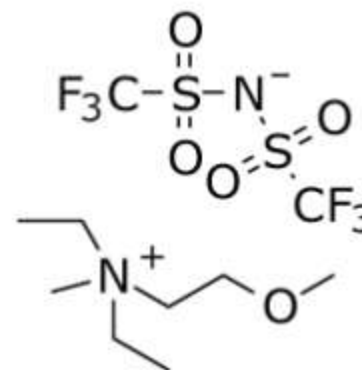
EMIM TFSI



HMIM BF₄

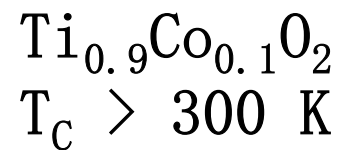
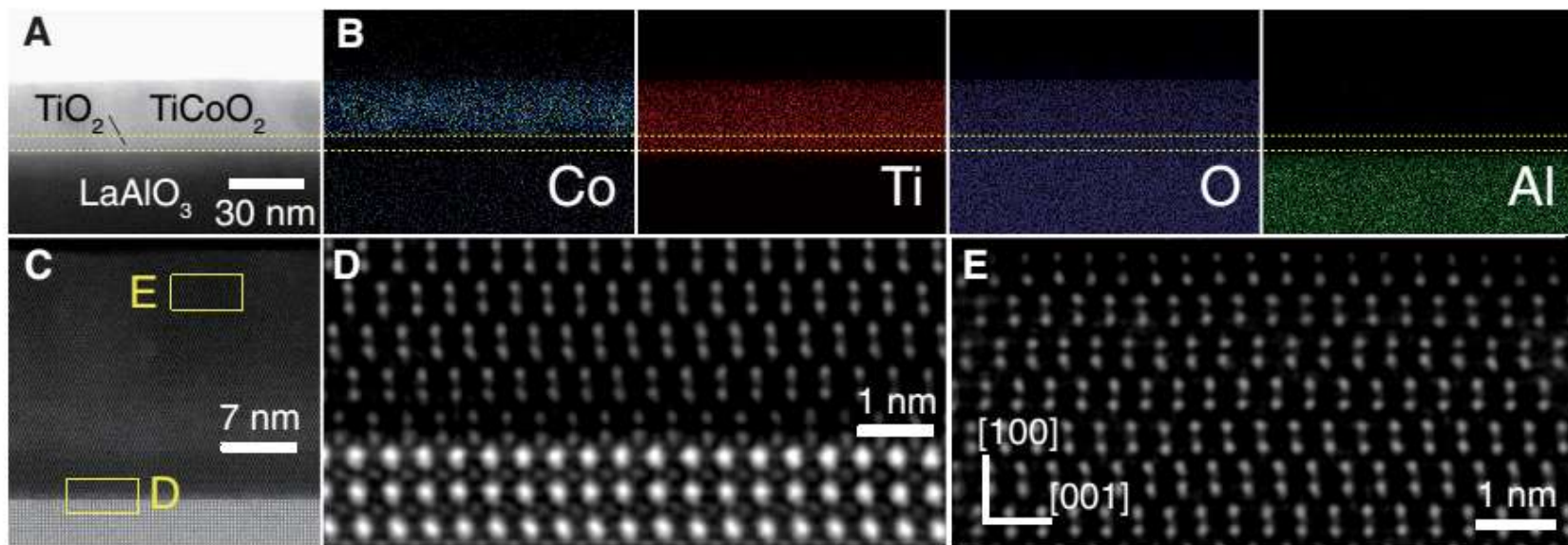


DEME TFSI



Electric field control the magnetization

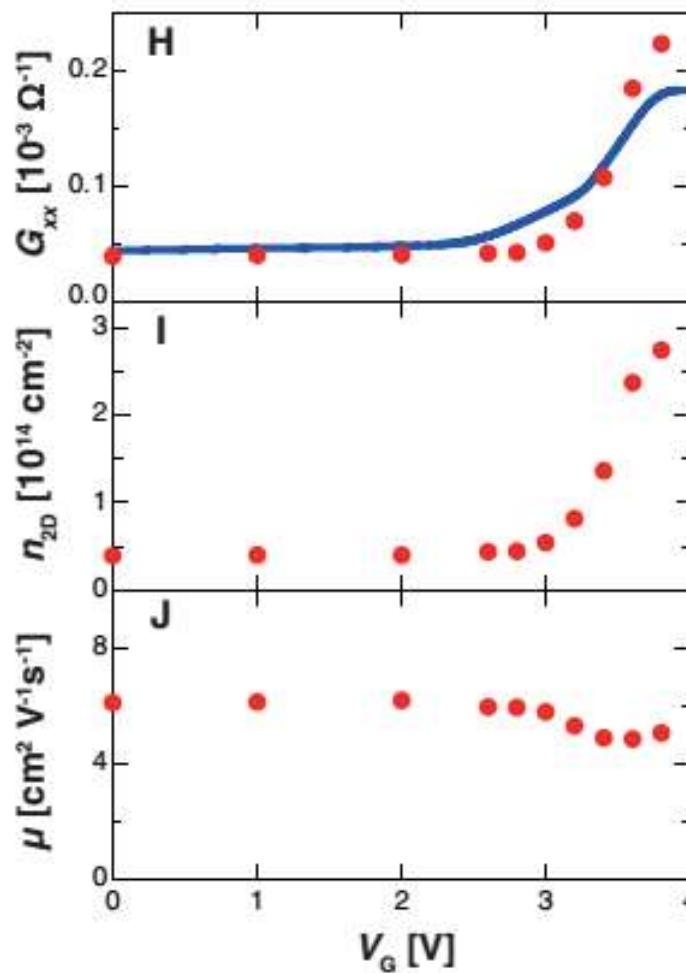
Ionic liquid gate control



Yamada, et al, Science (2011)

Electric field control the magnetization

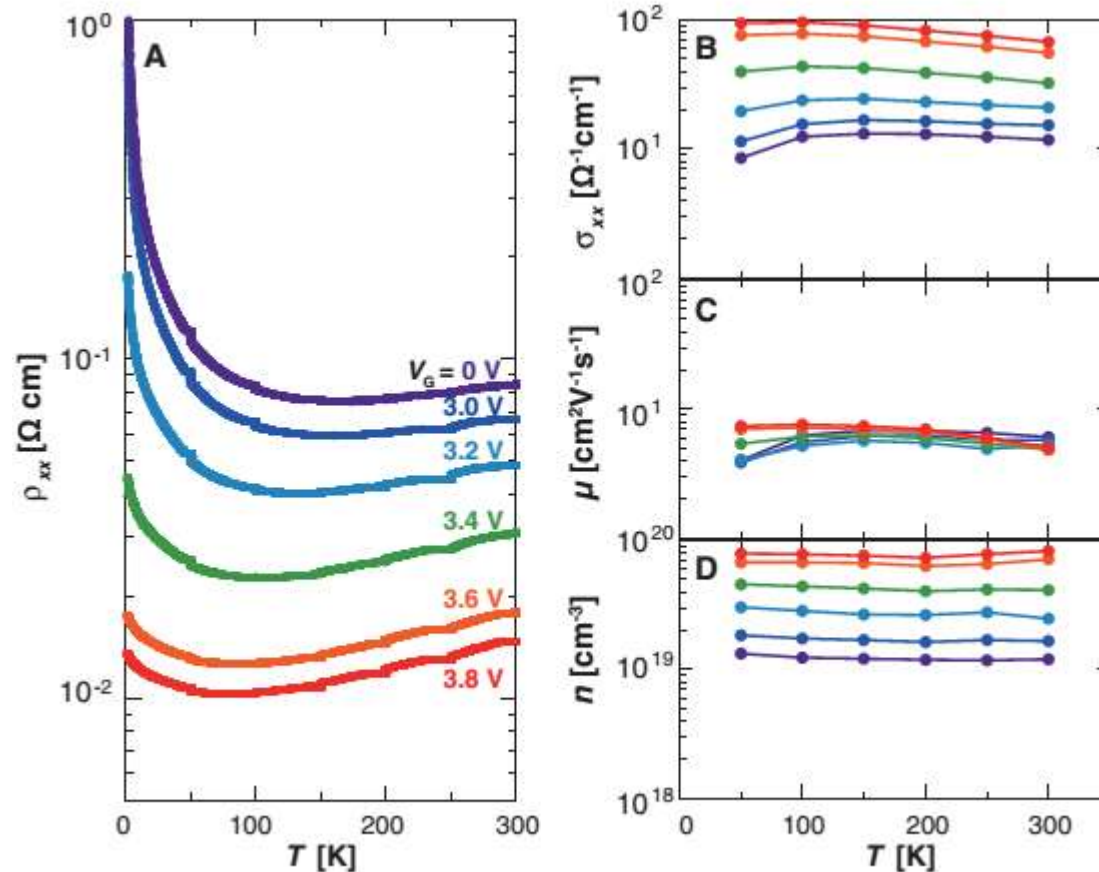
Ionic liquid gate control electronic properties



Yamada, et al, Science (2011)

Electric field control the magnetization

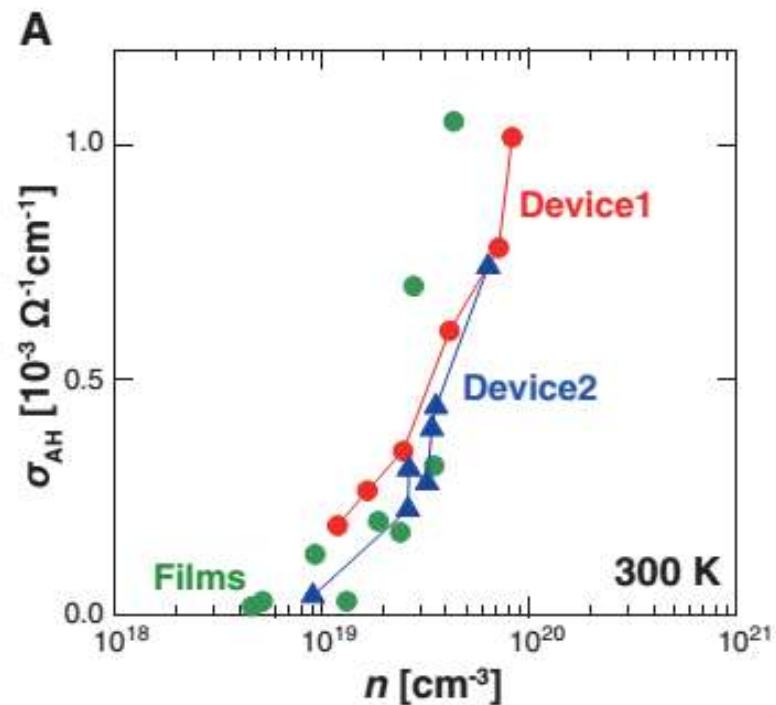
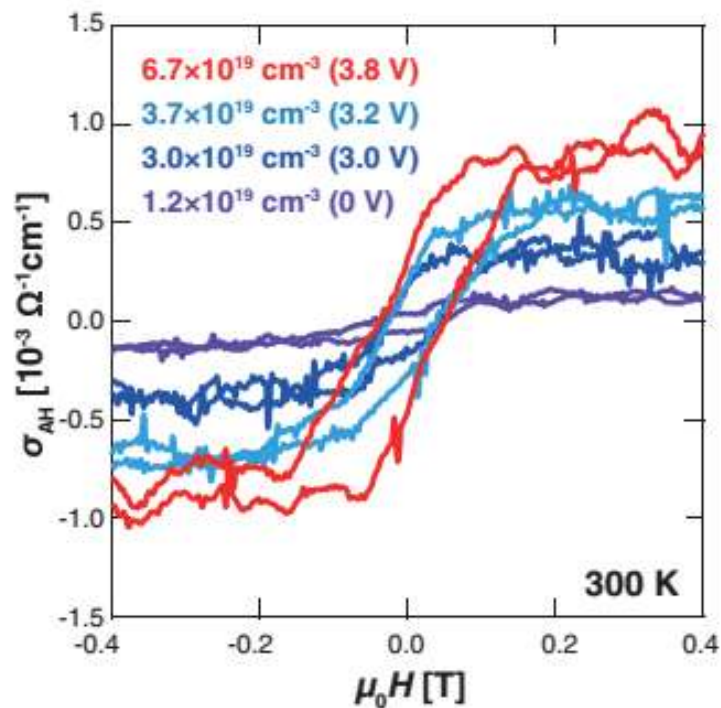
Ionic liquid gate control electronic properties



Yamada, et al, Science (2011)

Electric field control the magnetization

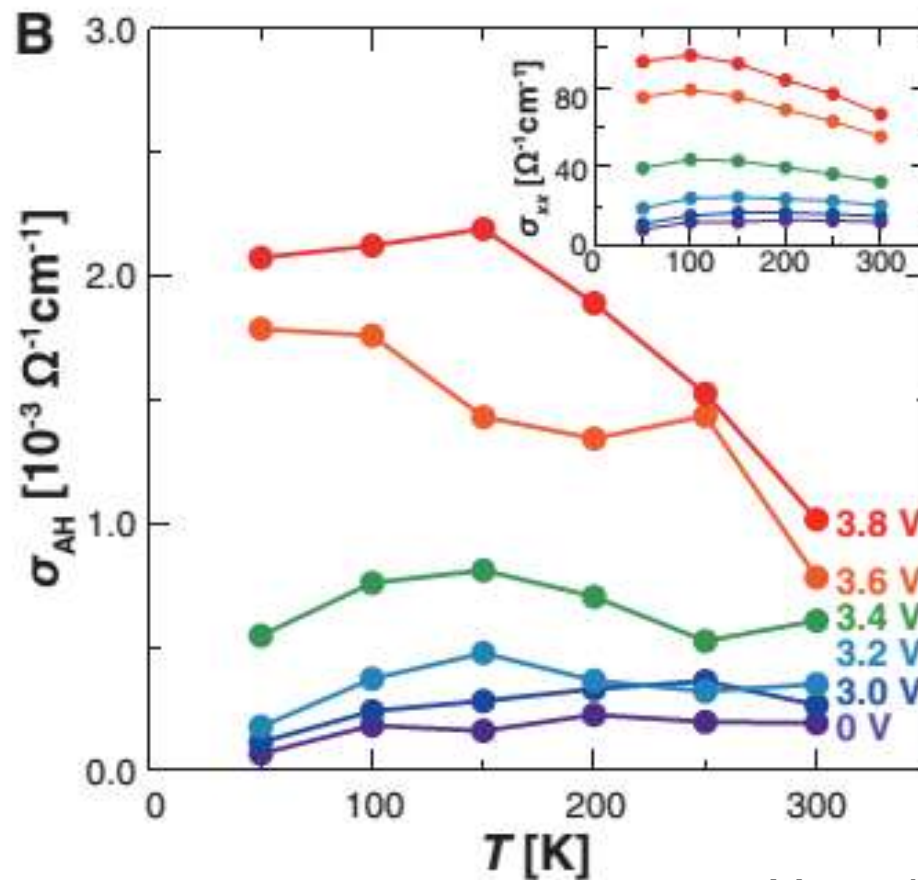
Ionic liquid gate control magnetic properties



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

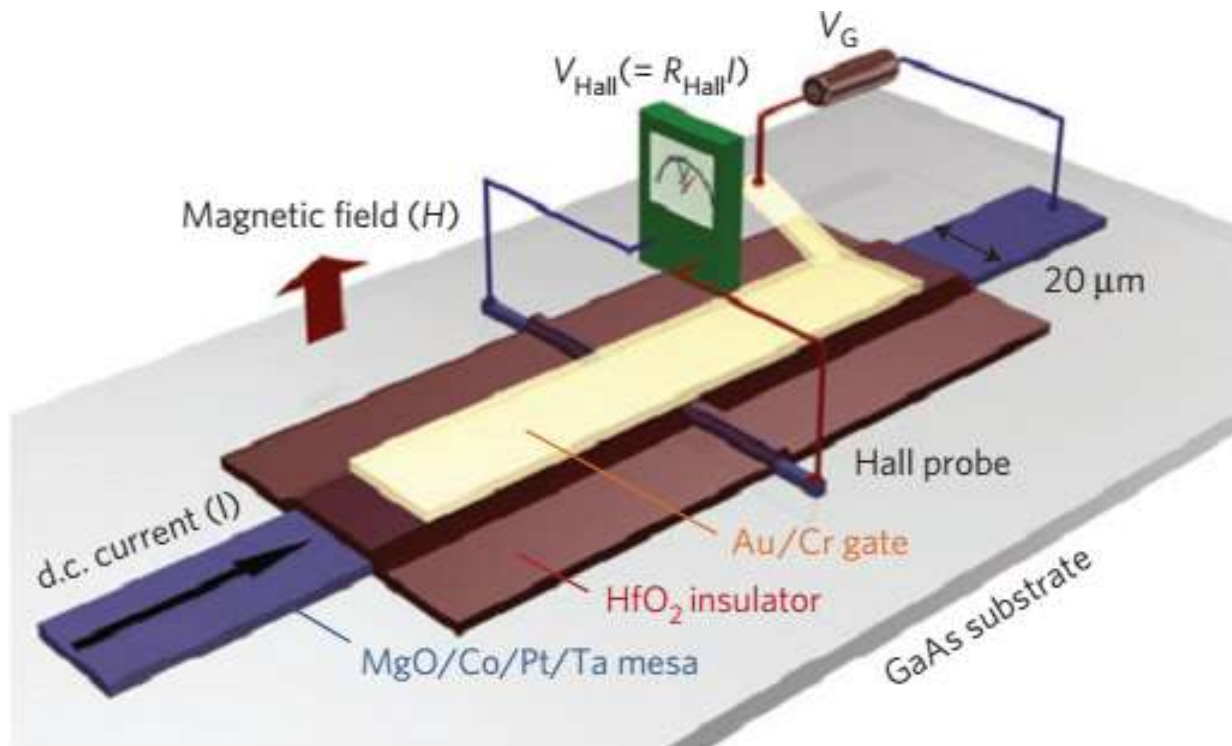
PUBLISHED ONLINE: 2 OCTOBER 2011 | DOI: 10.1038/NMAT3130

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

D. Chiba^{1,2★}, S. Fukami³, K. Shimamura¹, N. Ishiwata³, K. Kobayashi¹ and T. Ono¹

Electric field control the magnetization

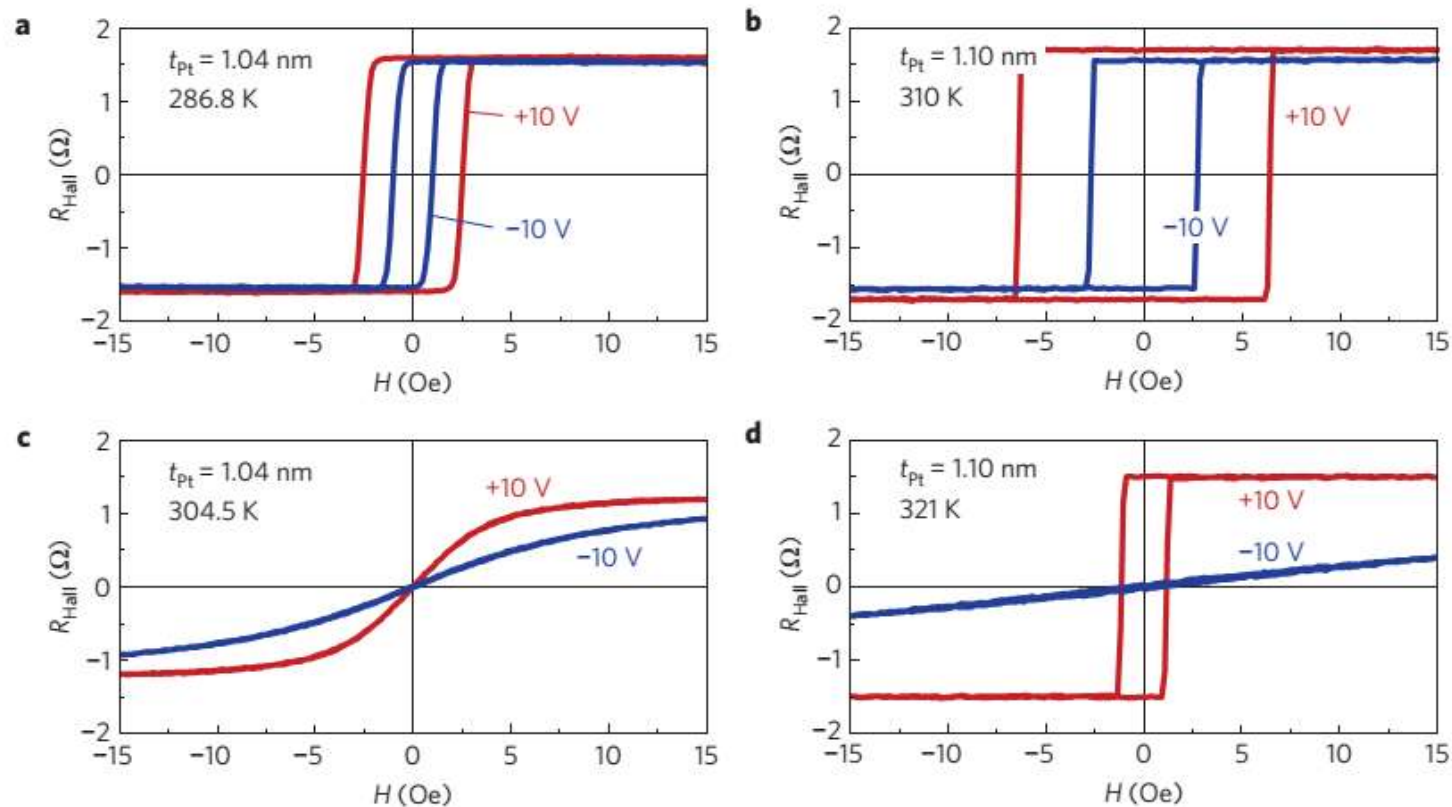
Electric field control in Metallic FM



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

Electric field control the magnetization

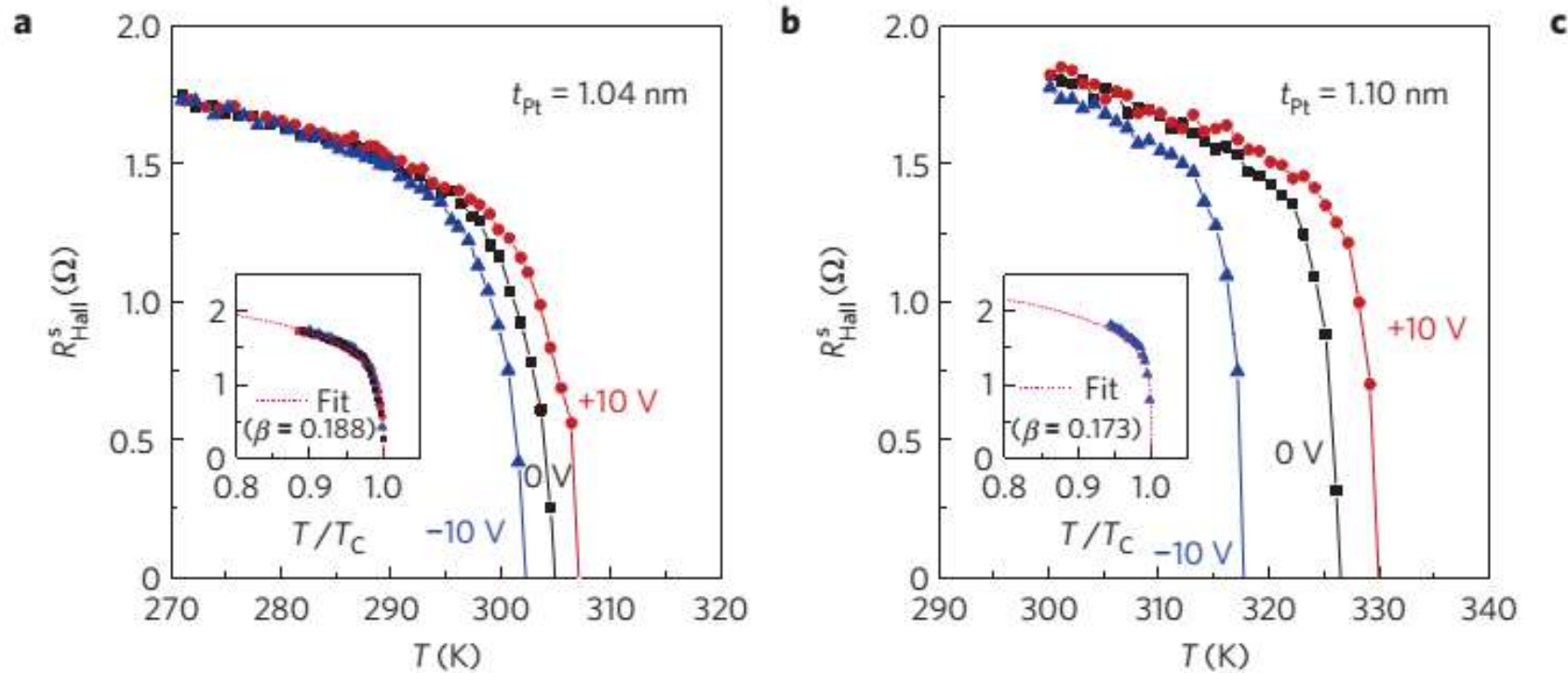
Electric field control in Metallic FM



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

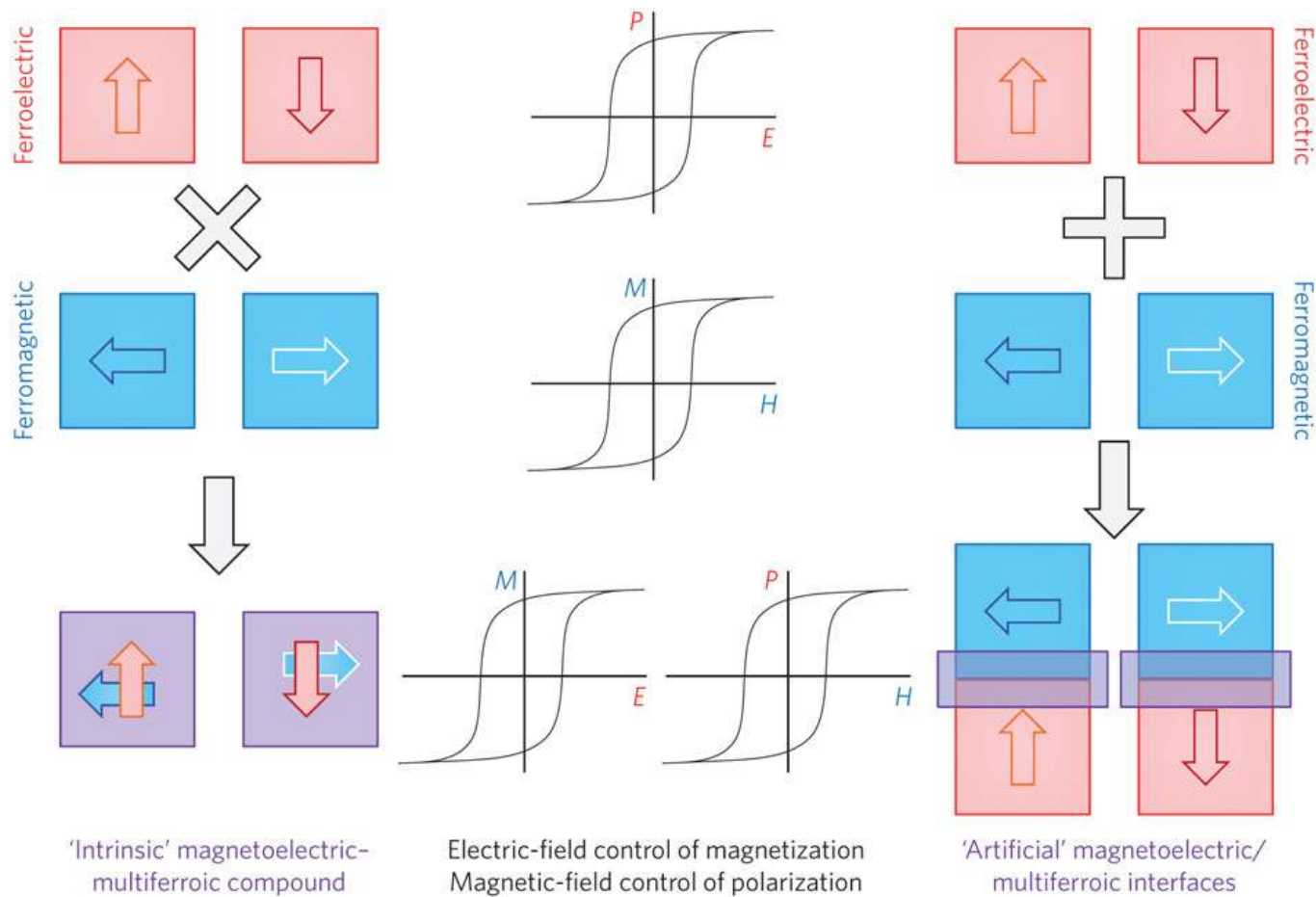
Electric field control the magnetization

Electric field control in Metallic FM



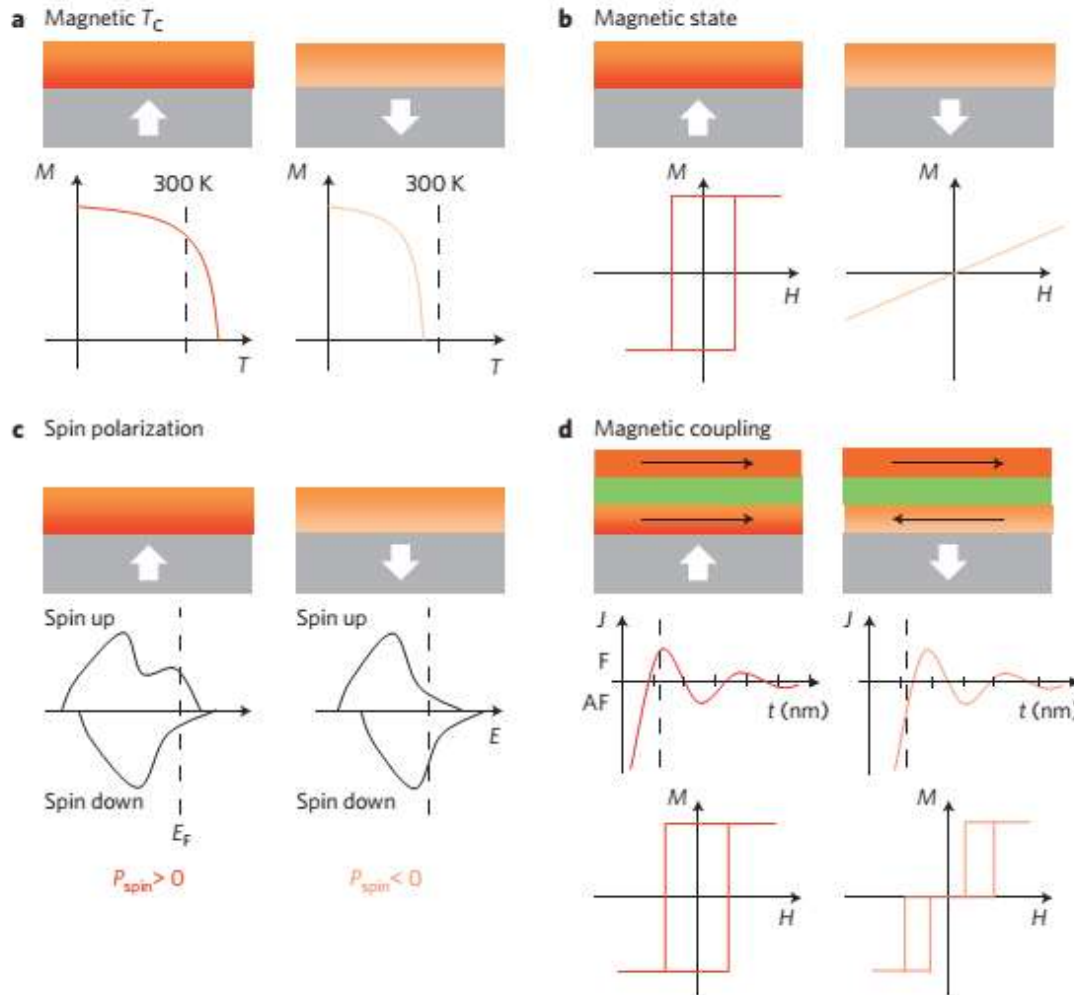
Chiba, et al, Nat. Mater. (2011)

Multiferroics



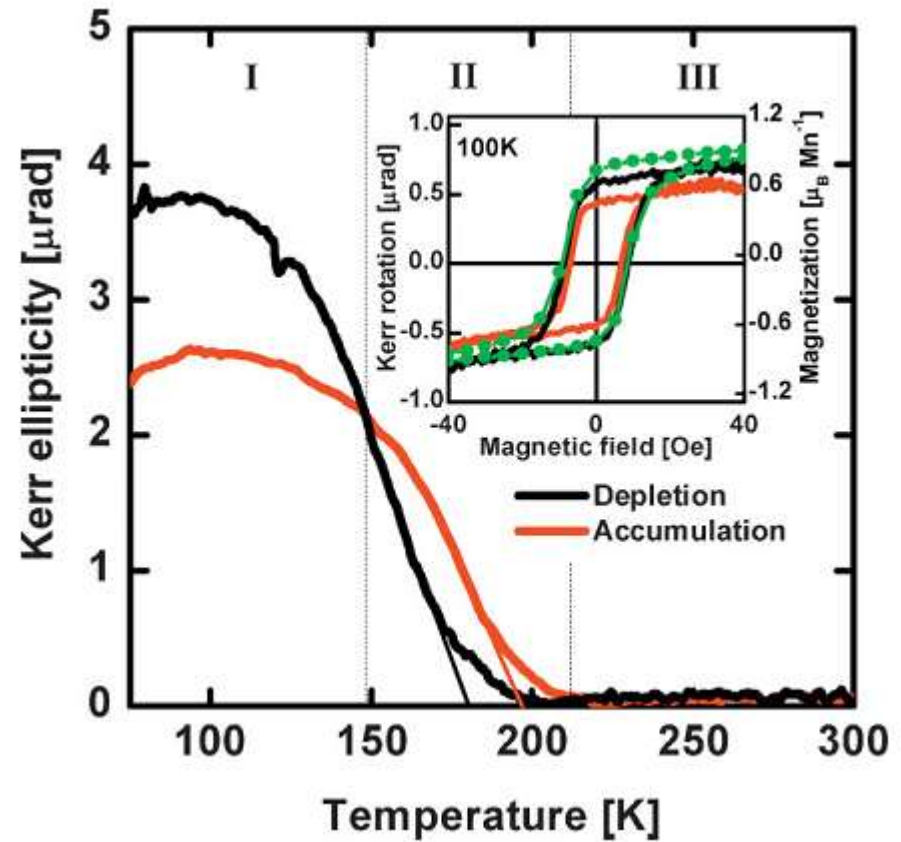
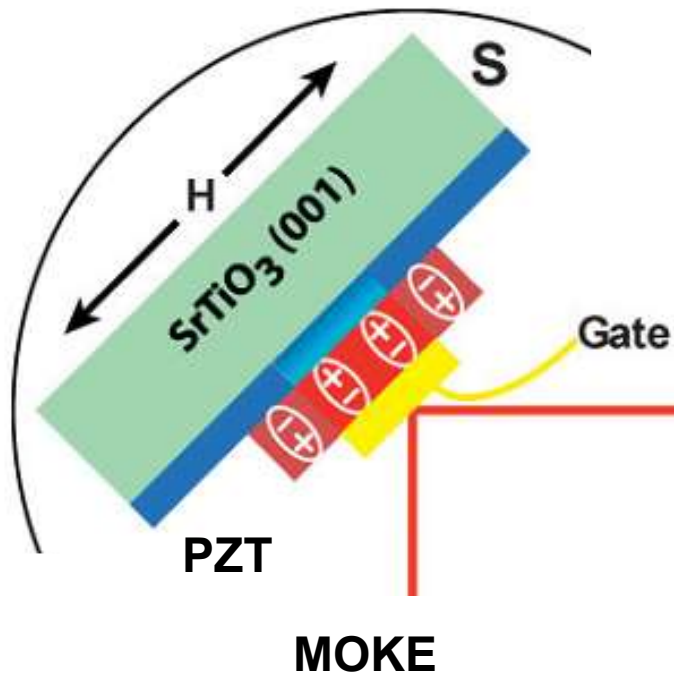
Bibes, Nat. Mater. (2012)

Multiferroics



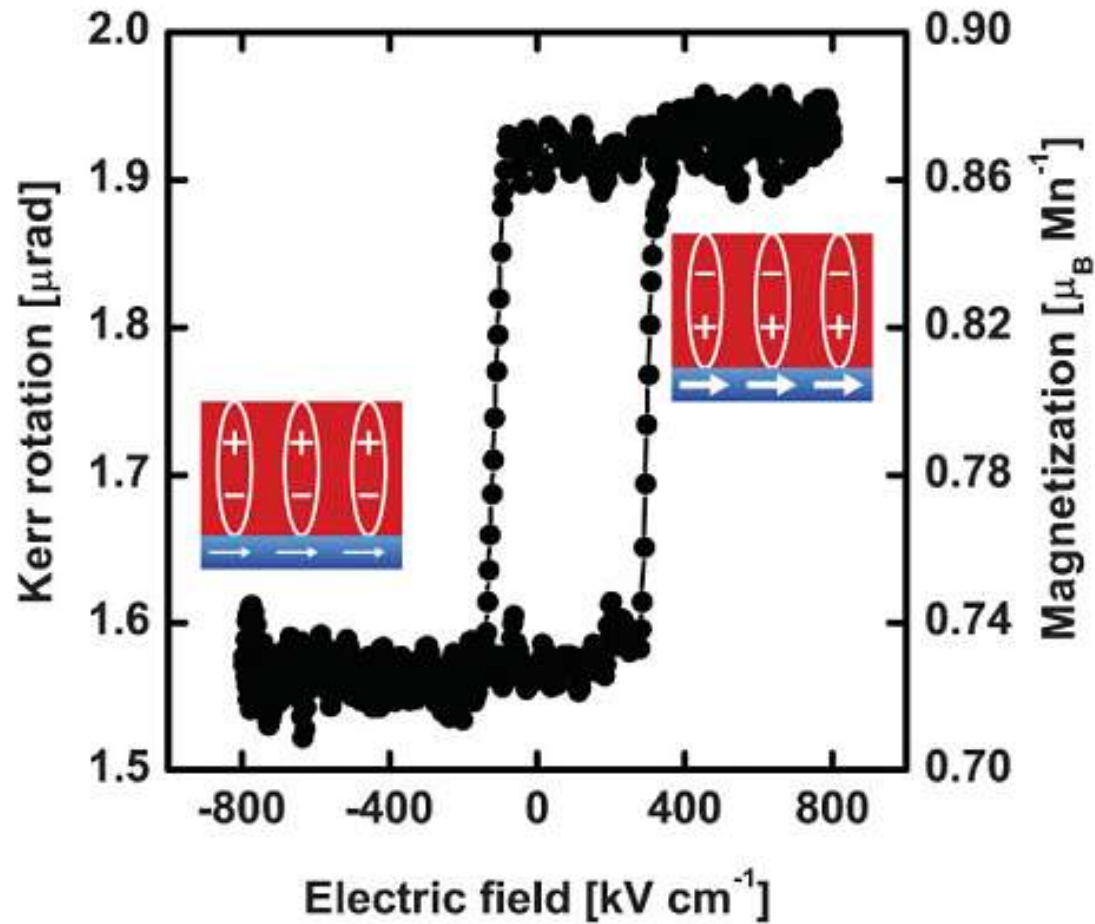
Bibes, Nat. Mater. (2012)

T_C by Multiferroics



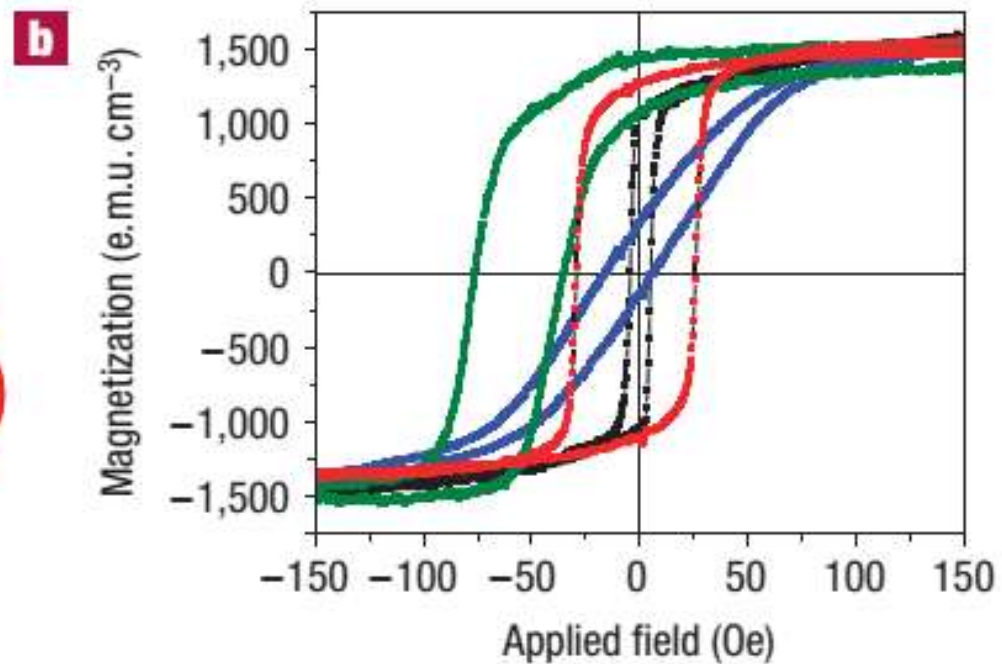
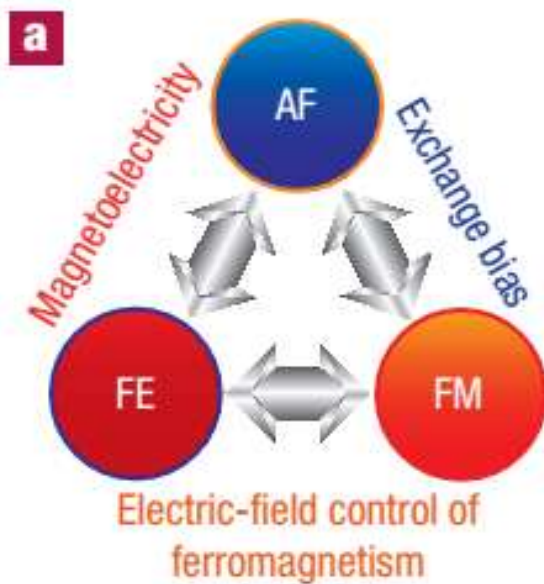
Molegraaf, et al, Adv. Mater. (2009)

T_C by Multiferroics



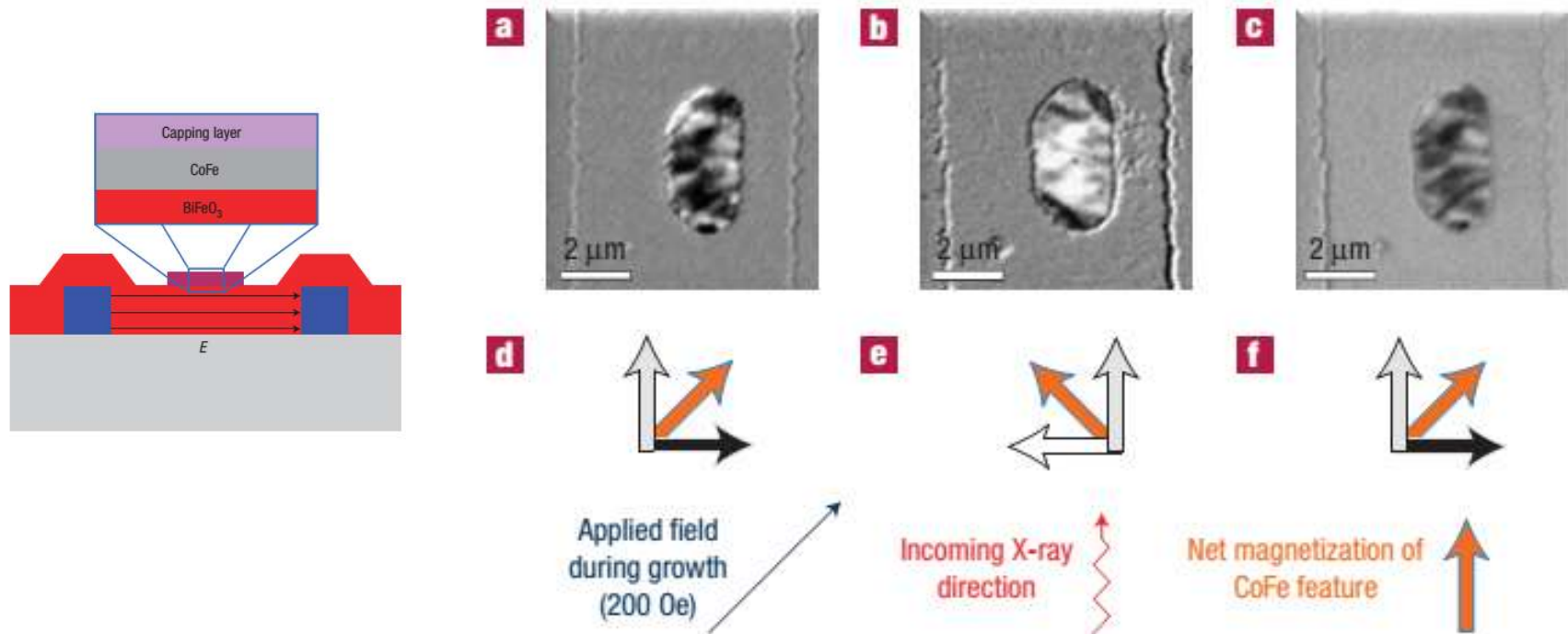
Molegraaf, et al, Adv. Mater. (2009)

FM magnetization by Multiferroics



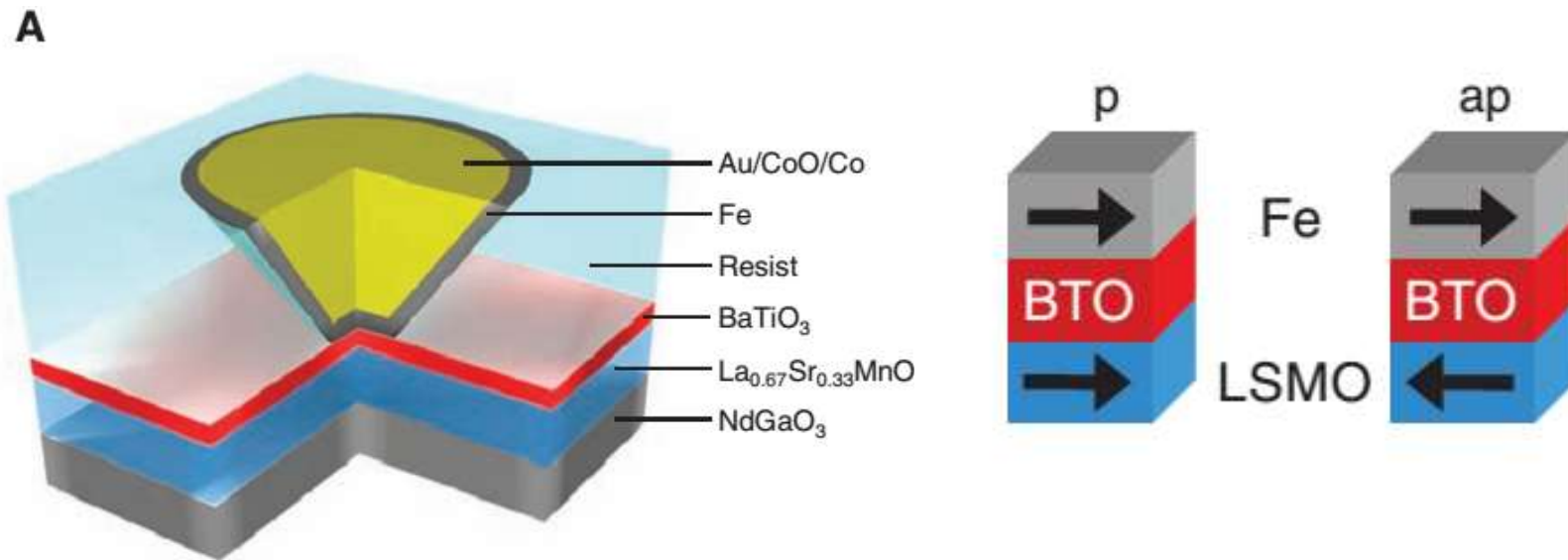
Chu, et al, Nat. Mater. (2008)

FM magnetization by Multiferroics



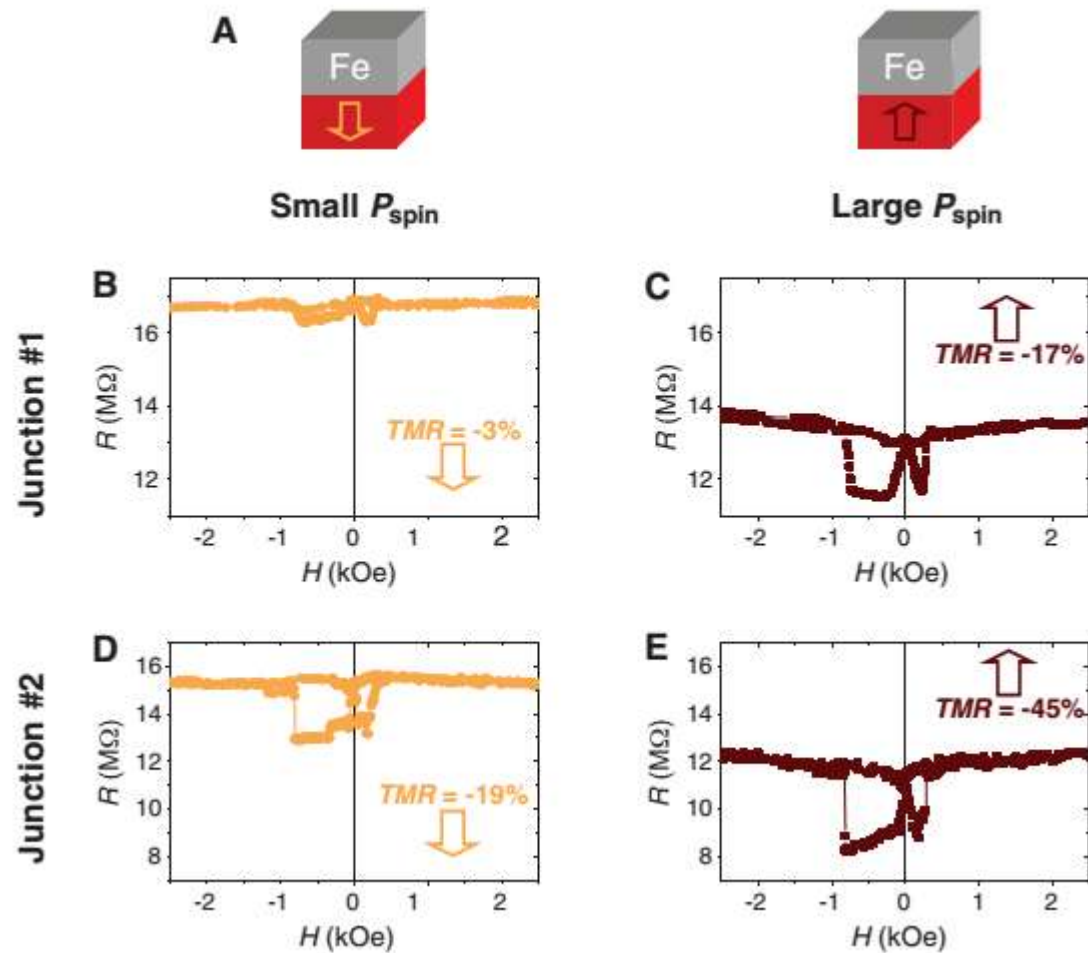
Chu, et al, Nat. Mater. (2008)

Spin polarization by Multiferroics



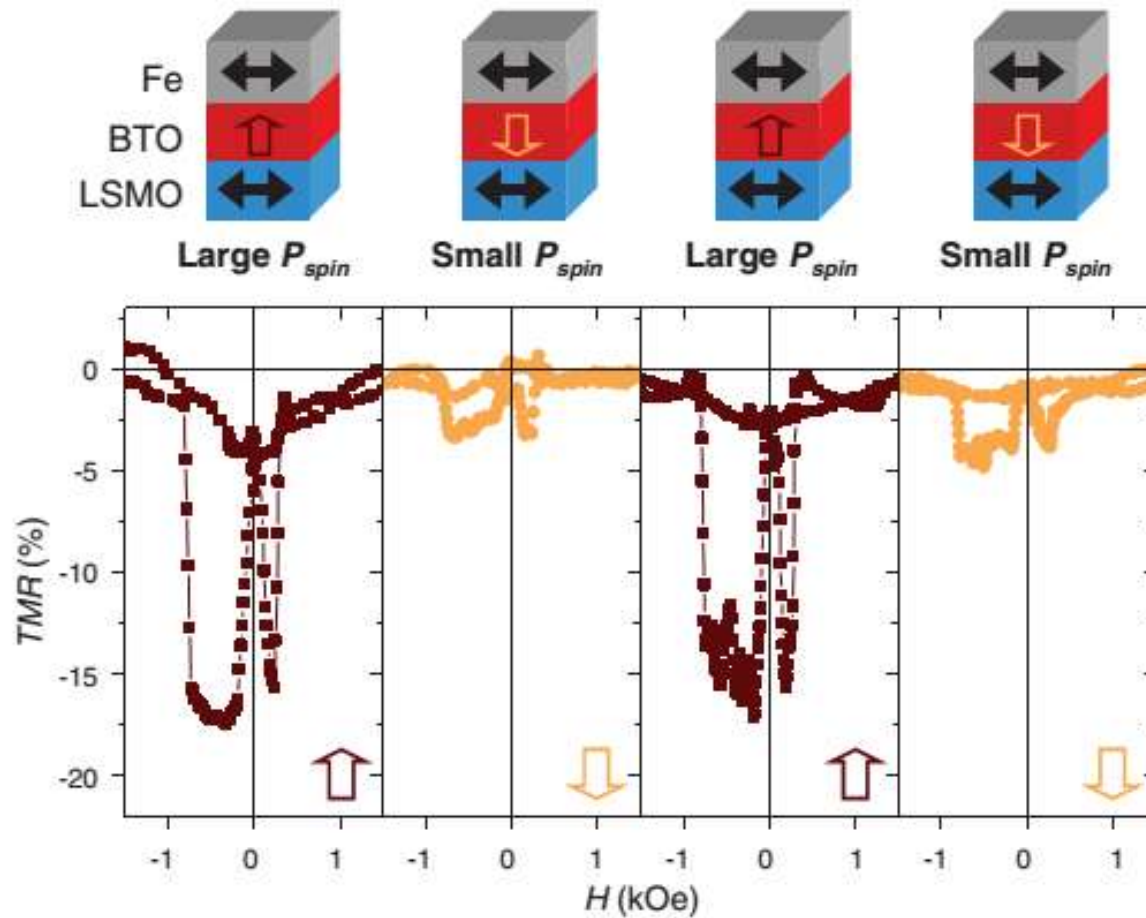
Garcia, et al, Science (2010)

Spin polarization by Multiferroics



Garcia, et al, Science (2010)

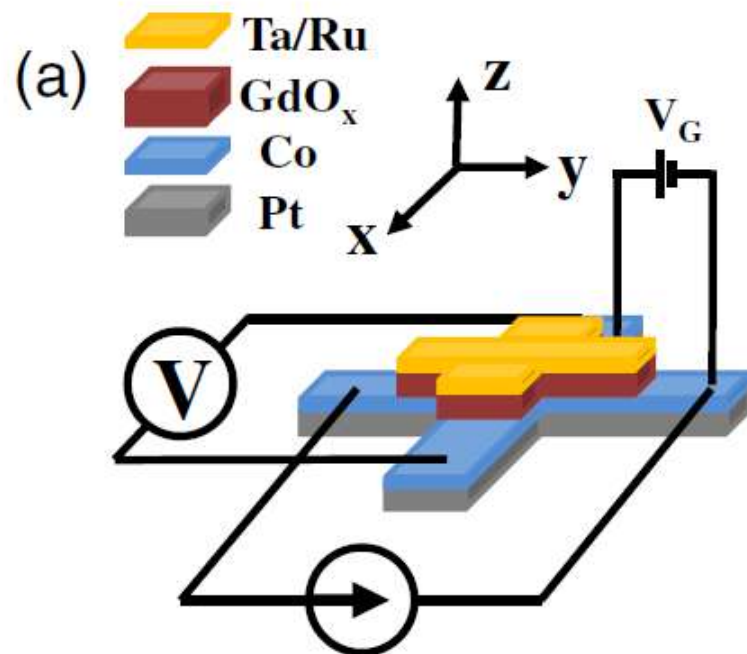
Spin polarization by Multiferroics



Garcia, et al, Science (2010)

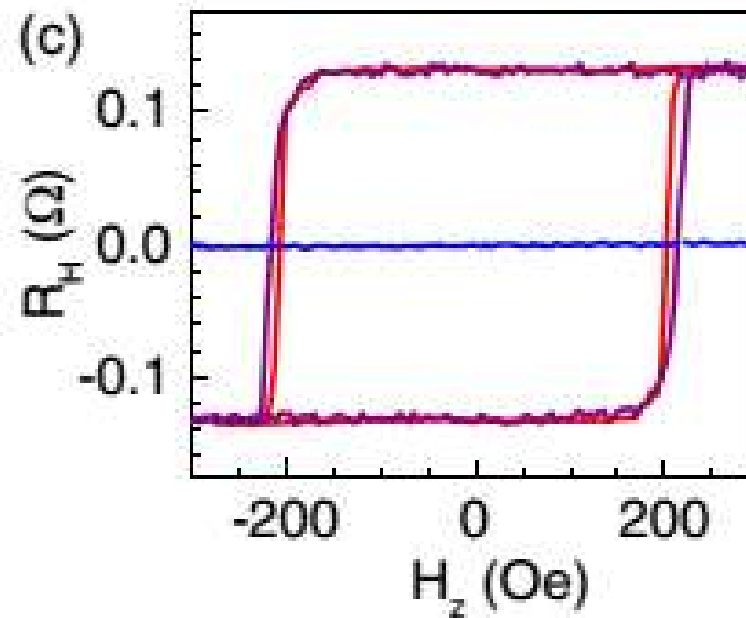
Ionics of Oxygen

Electric field via GdO_x/FM



Blue curve: Negative electrical field

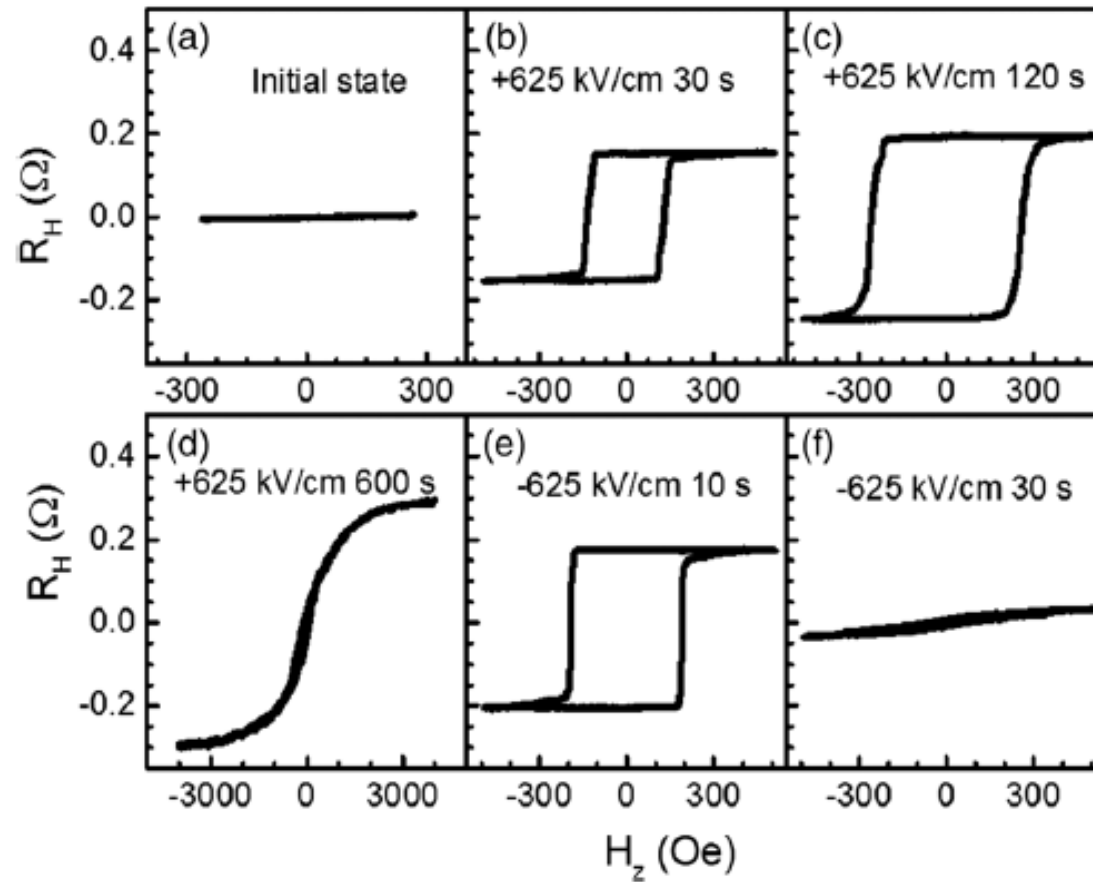
Purple curve: positive electrical field



Bi et al PRL (2014)

Ionics of Oxygen

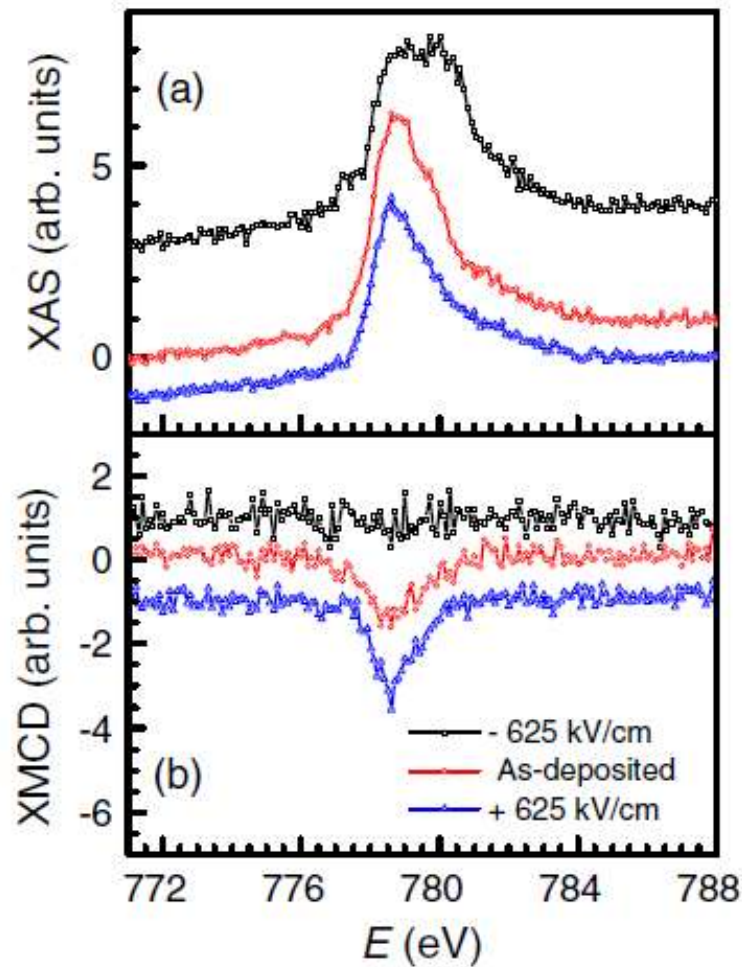
Electric field via GdO_x/FM



Bi et al PRL (2014)

Ionics of Oxygen

Electric field via GdO_x/FM



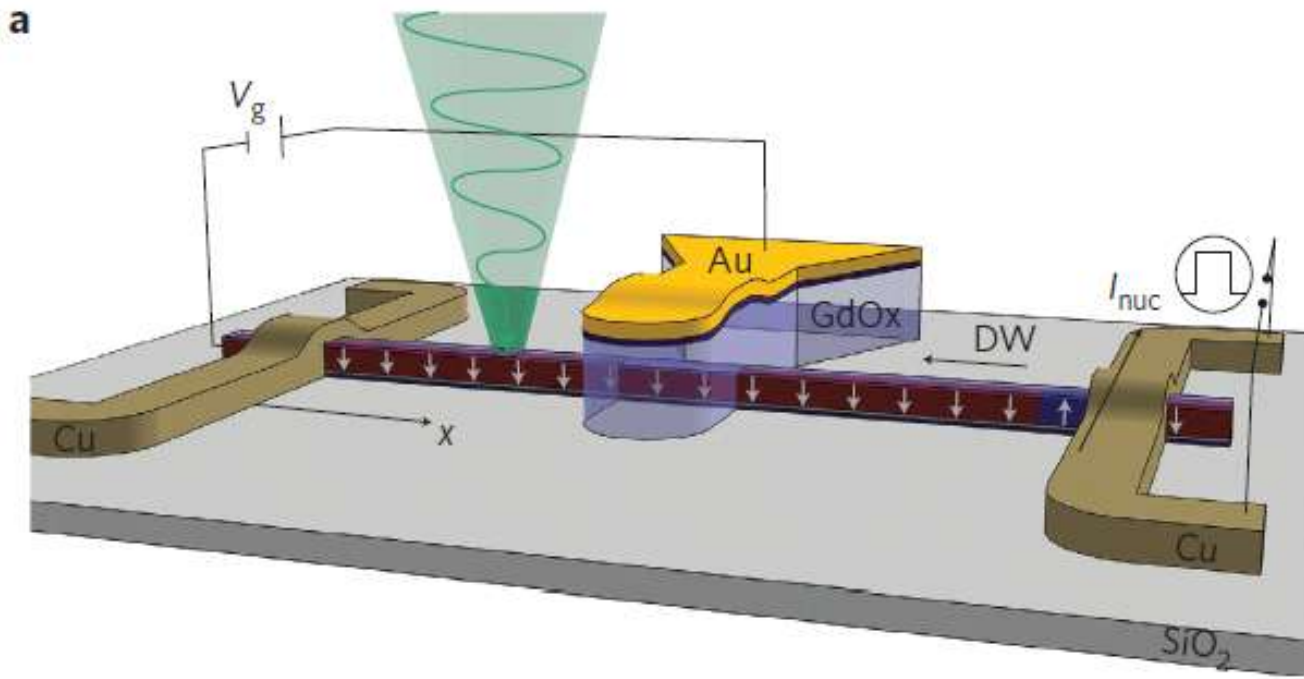
Co → CoO

CoO → Co

Bi et al PRL (2014)

Ionics of Oxygen

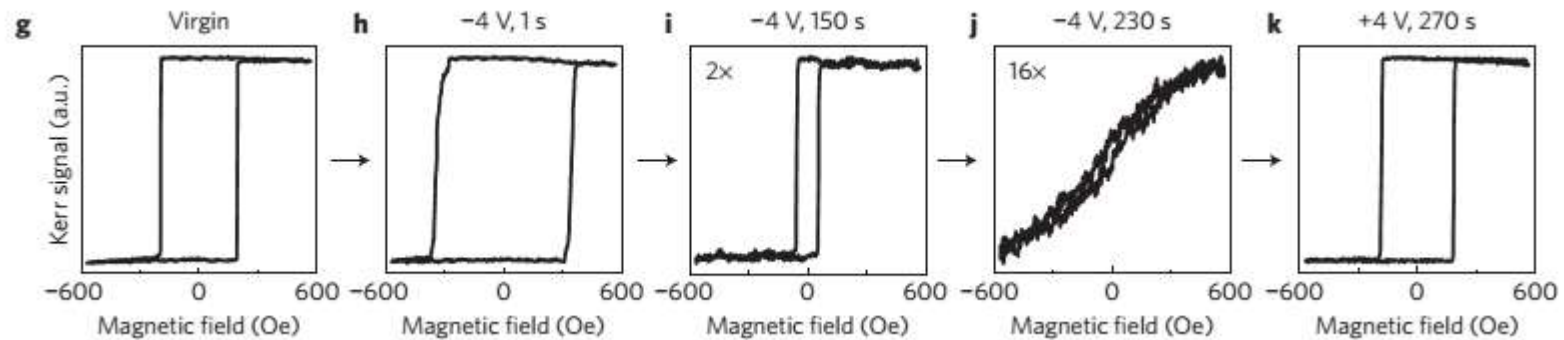
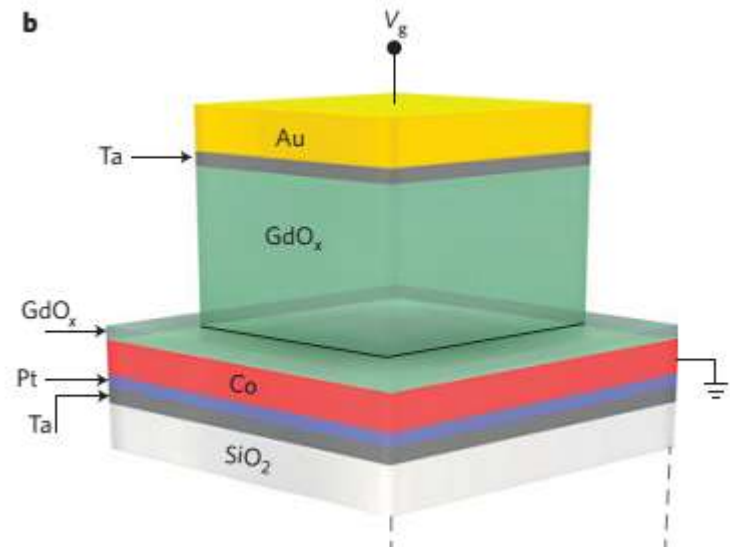
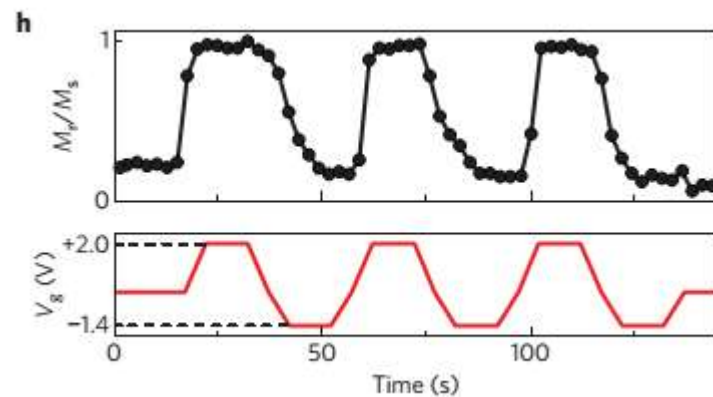
Electric field via GdO_x/FM



Bauer, et al Nat. Nano. (2014)

Ionics of Oxygen

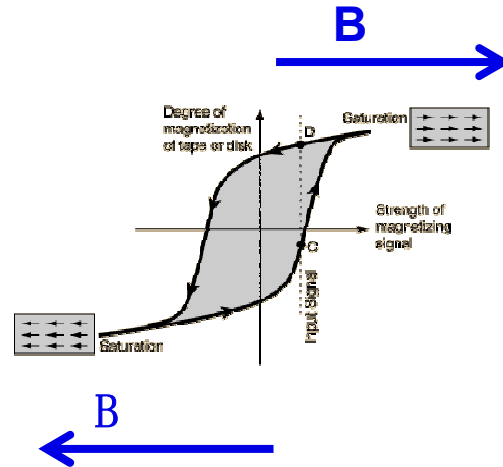
Electric field via GdO_x/FM



Bauer, et al Nat. Nano. (2014)

How to control the magnetization

Magnetic field



Without B
???

Control??

Electric field

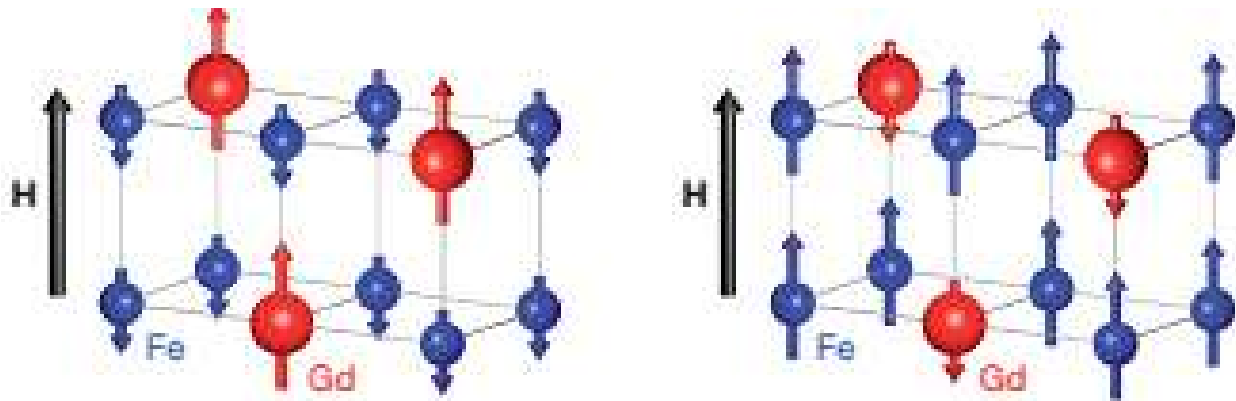
Spin torque

Ultrafast Laser

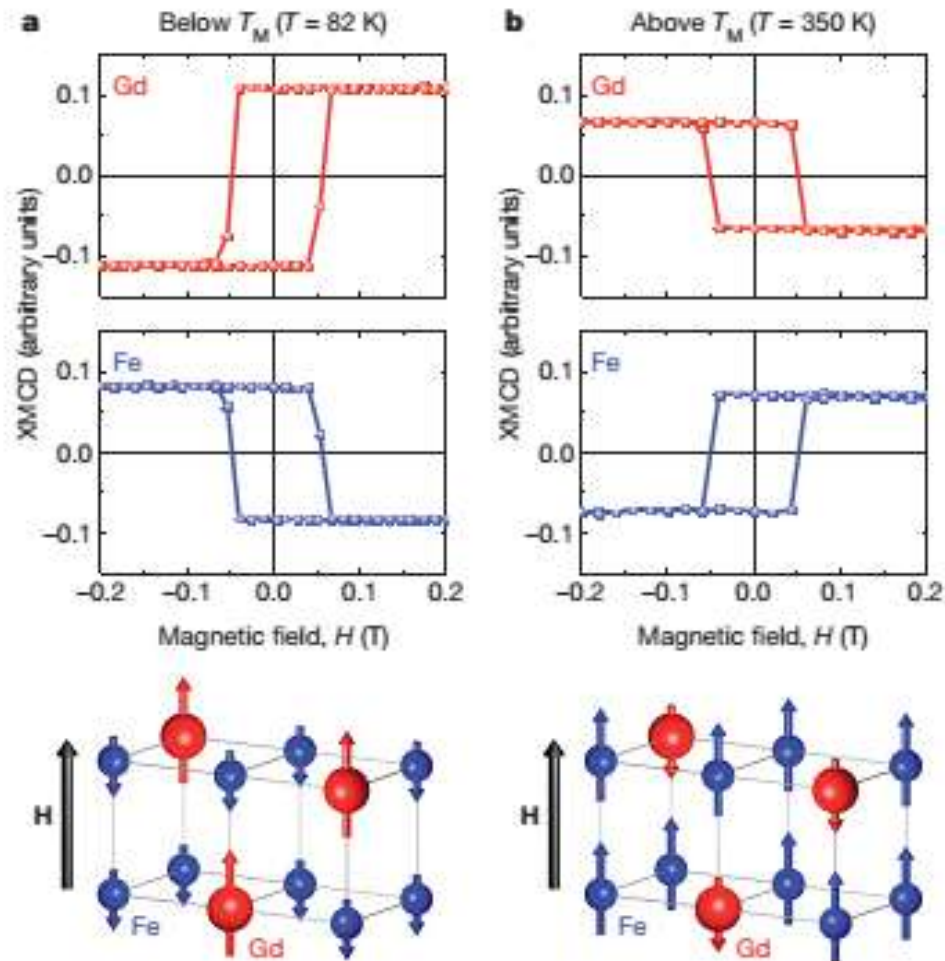
Interface Strain

FM by Ultrafast Laser

Ferrimagnet

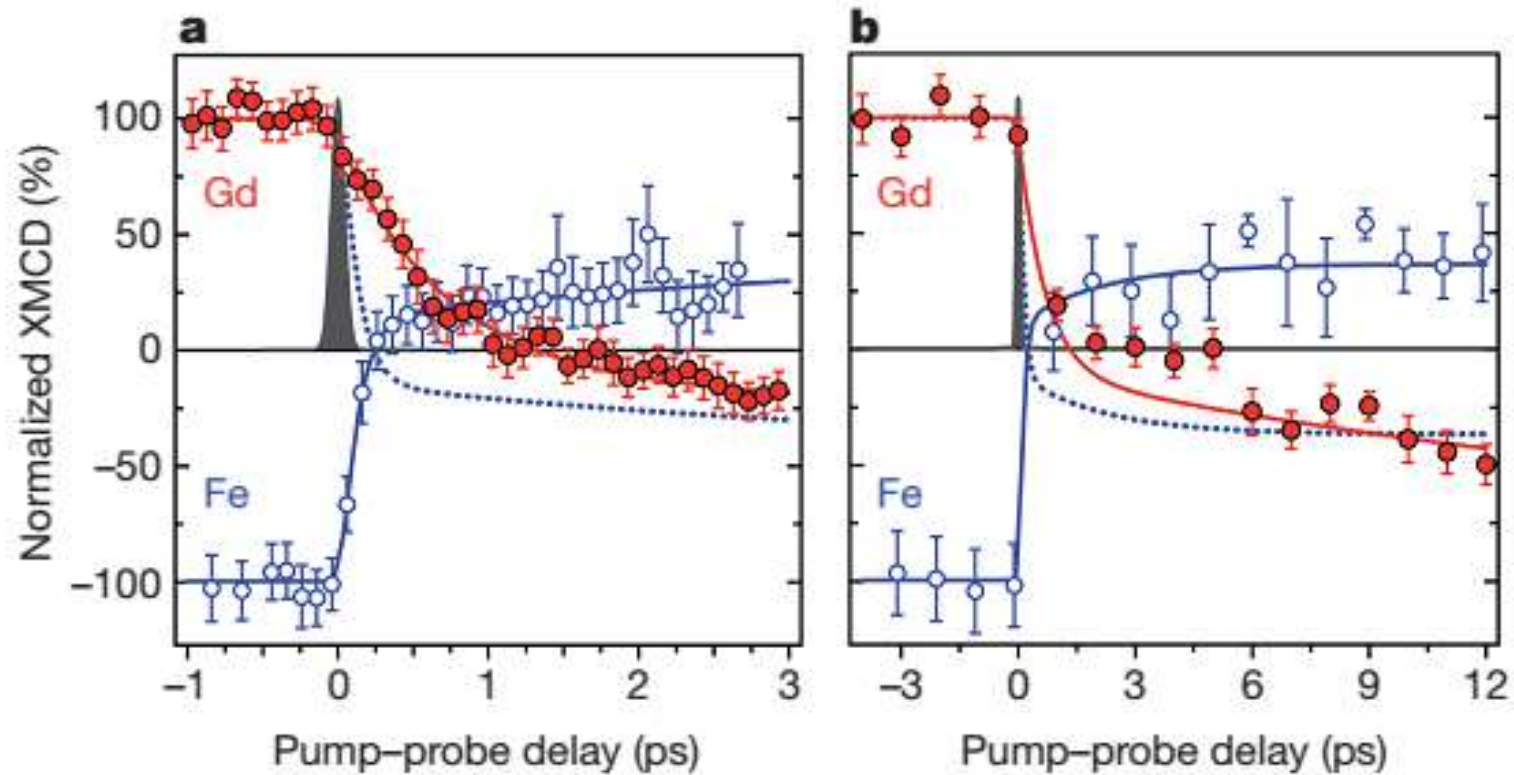


FM by Ultrafast Laser



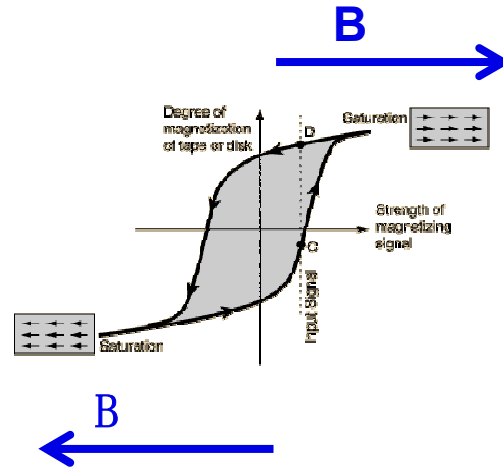
Radu, et al Nature (2011)

FM by Ultrafast Laser



How to control the magnetization

Magnetic field



Without B
???

Control??

Electric field

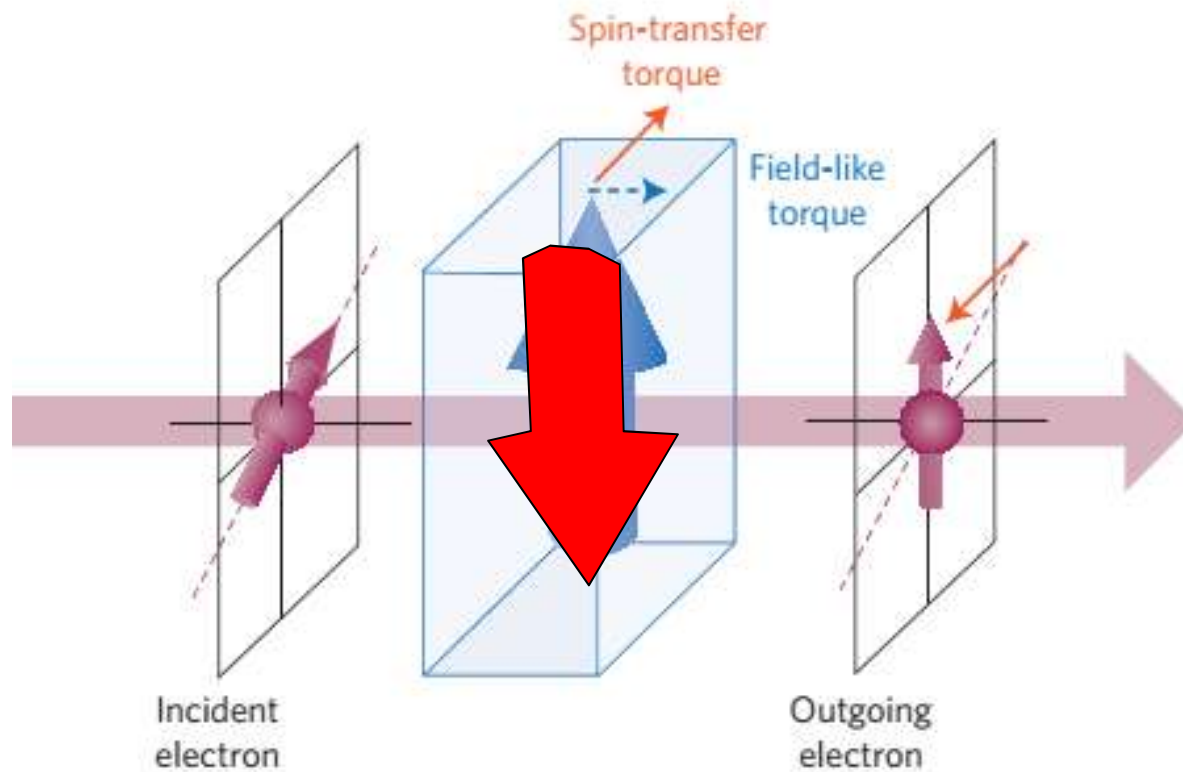
Spin torque

Ultrafast Laser

Interface Strain

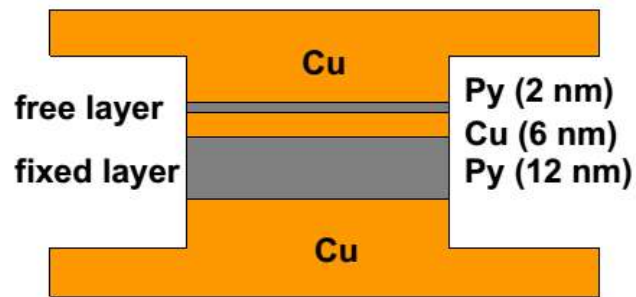
FM by Spin transfer torque

Spin transfer torque

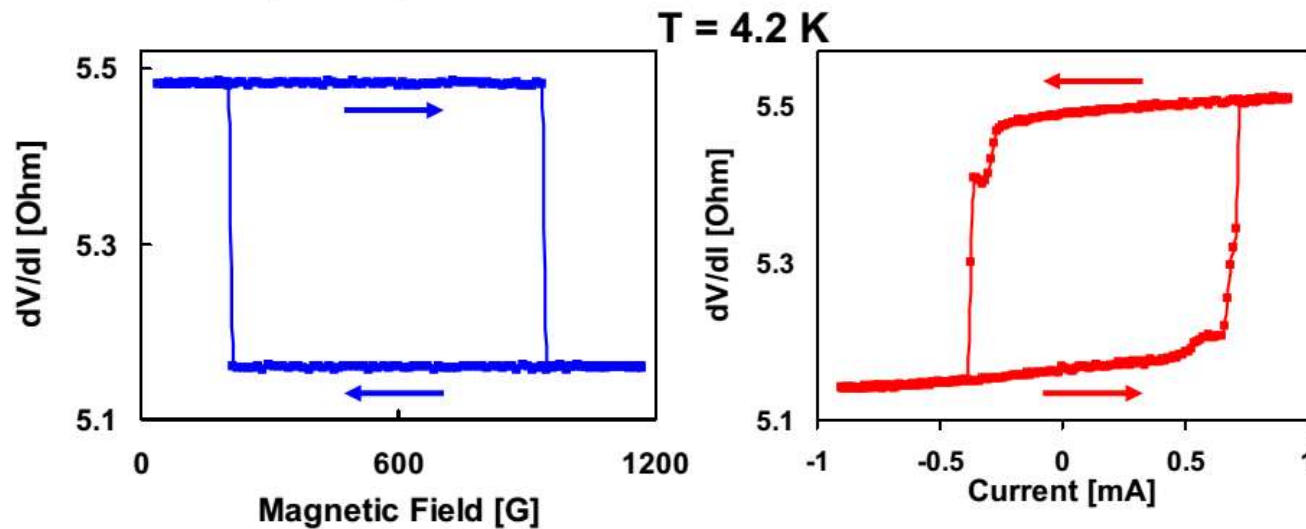
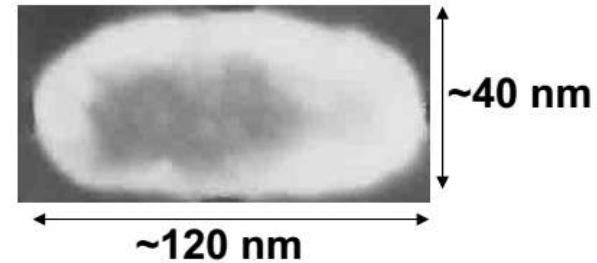


Brataas, et al. Nature Mater. (2012)

Spin transfer torque

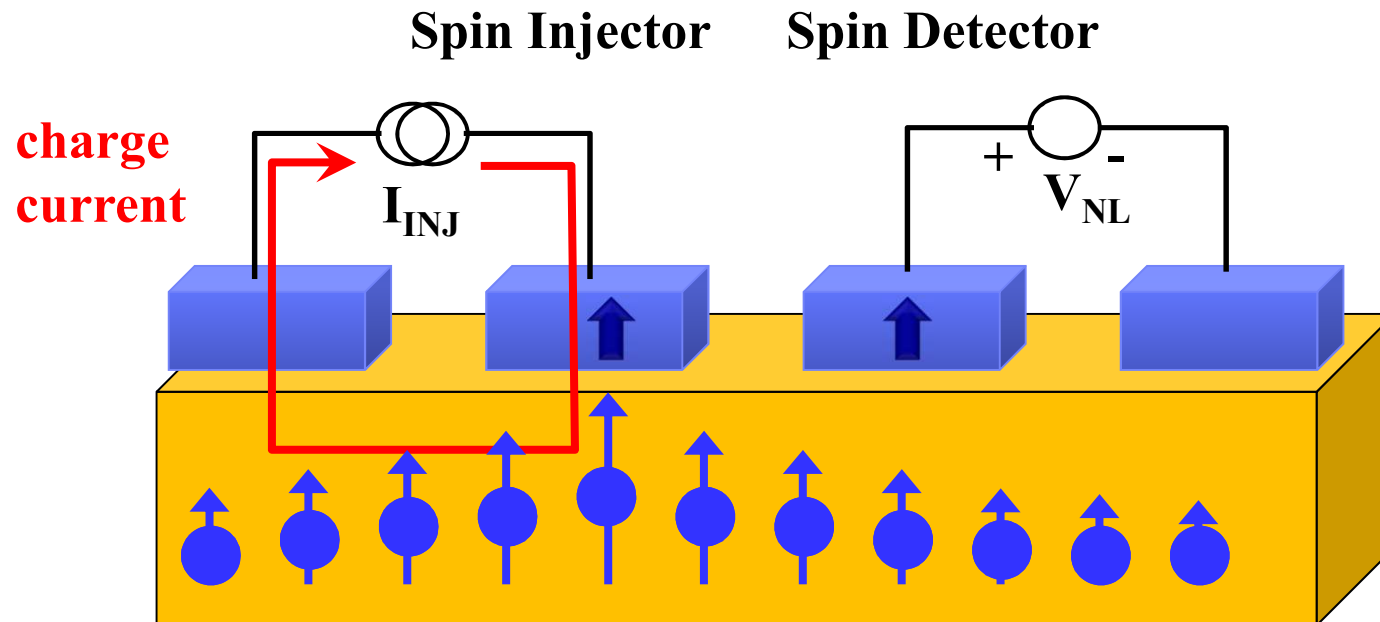


Nanopillar Spin-Valve

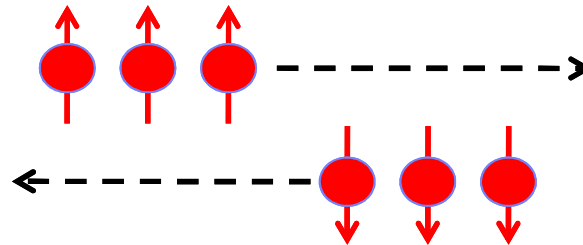


Ralph & Stiles, JMMM (2008)

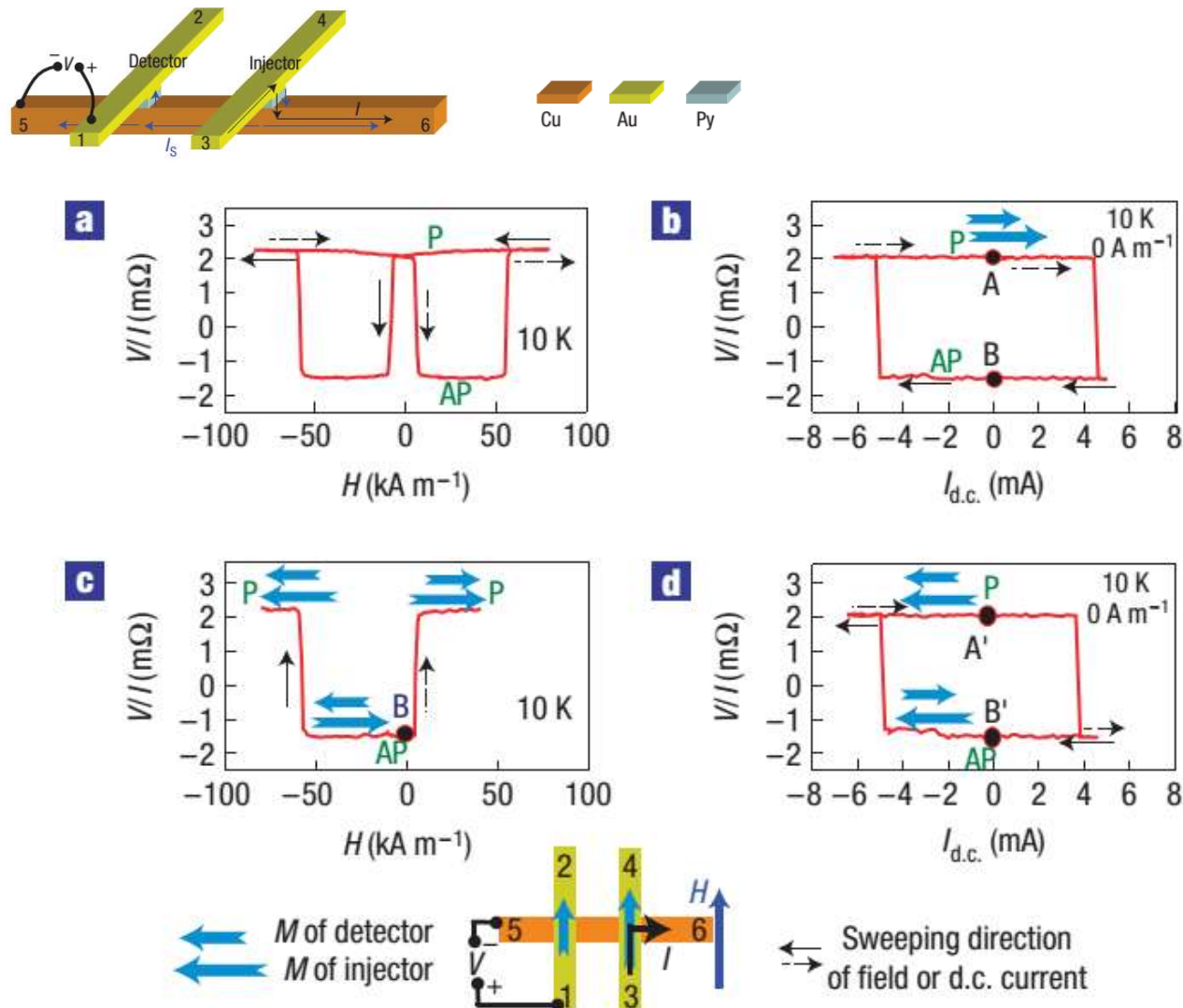
Pure Spin current torque



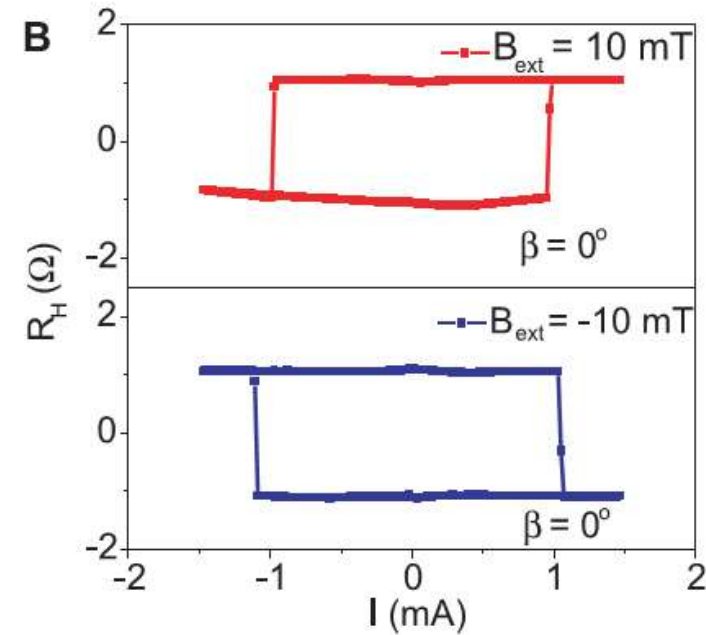
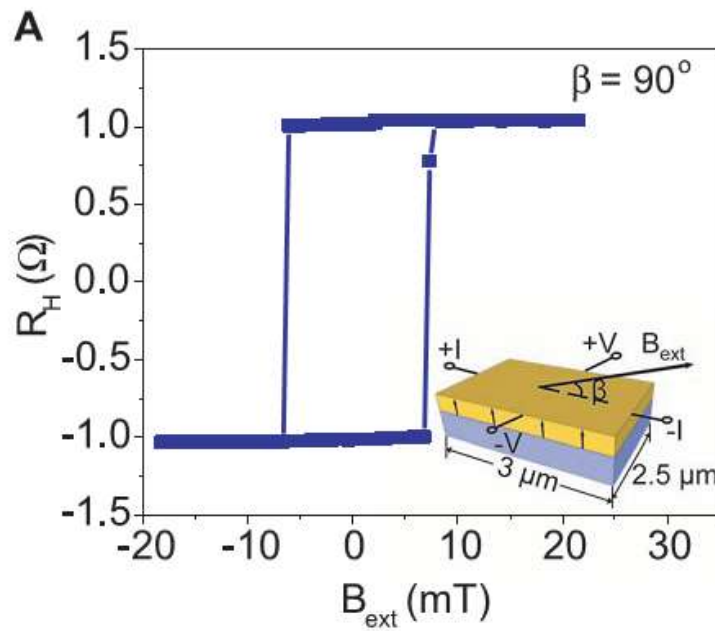
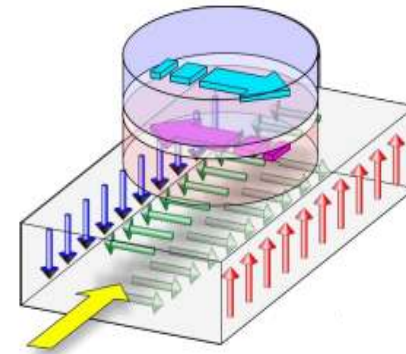
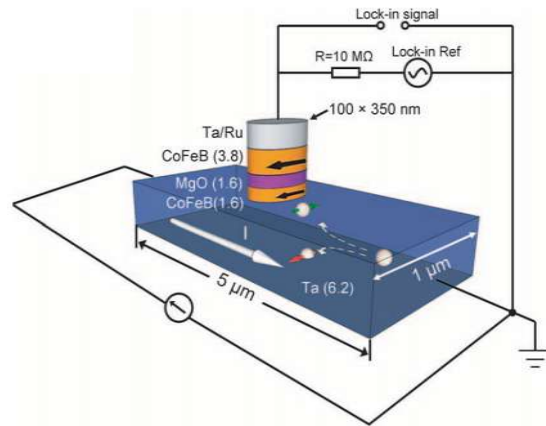
Pure spin current: Flow of spin without net flow of charge



Pure Spin current torque



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

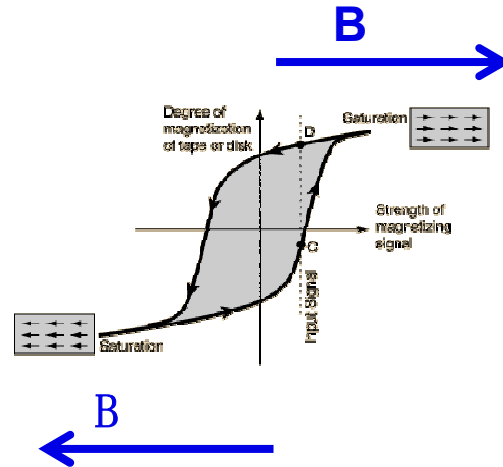
六、热自旋电子学

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

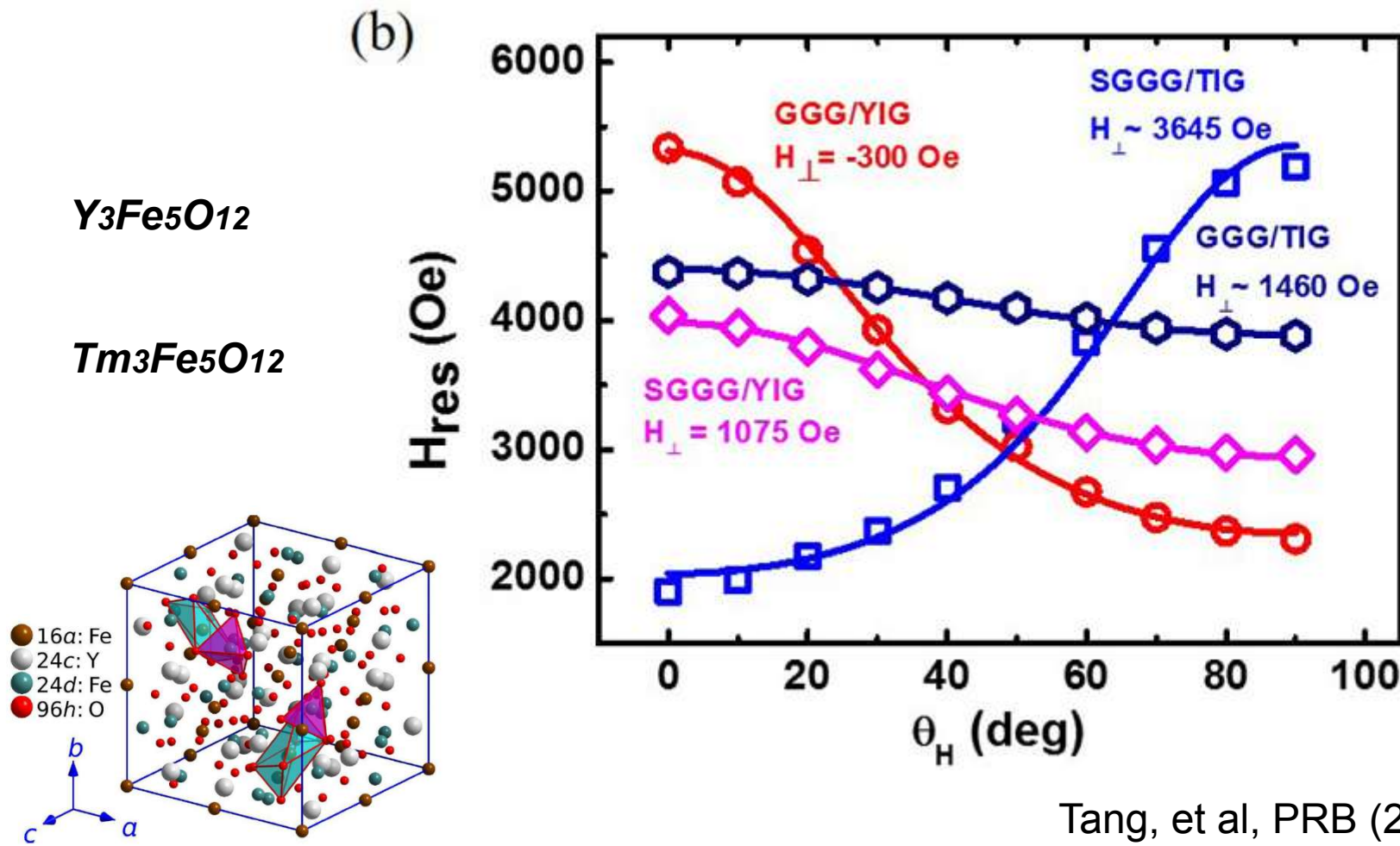
Spin torque

Ultrafast Laser

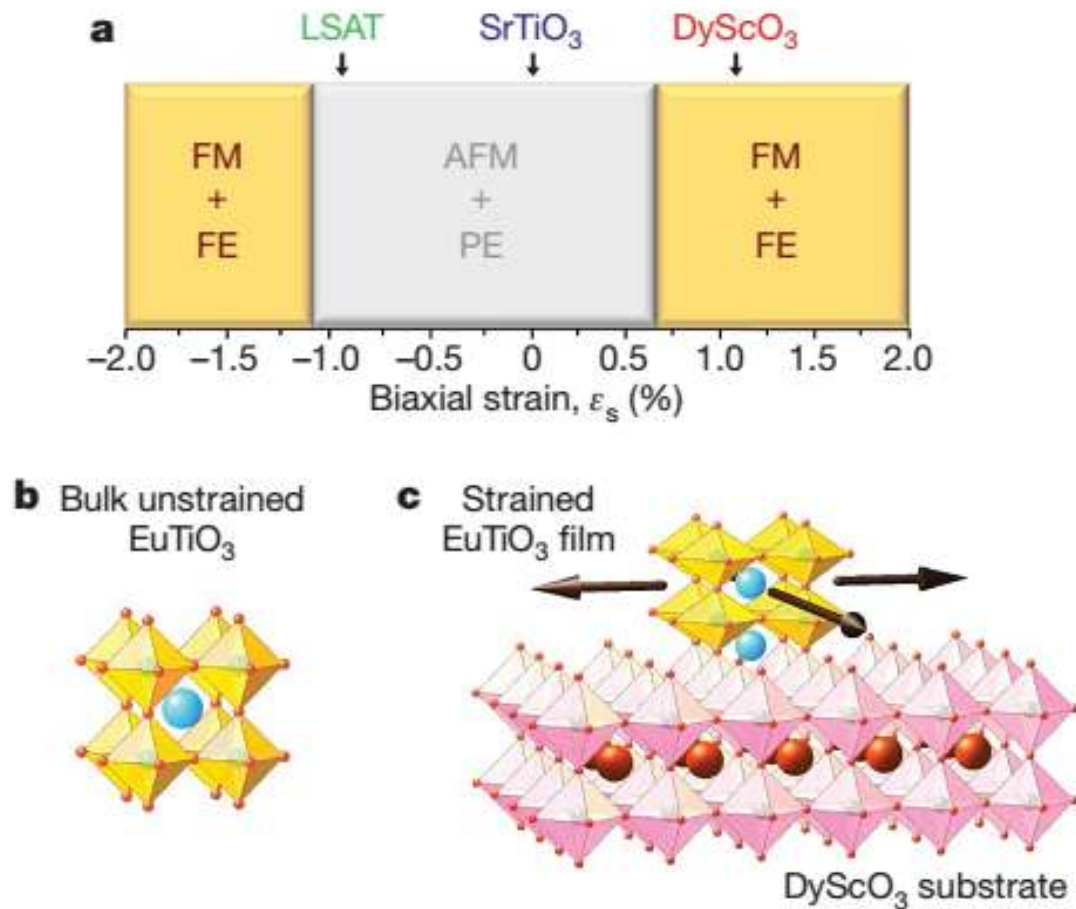
Interface Strain

Magnetization by Strain

TIG, a magnetic insulator with perpendicular easy axis

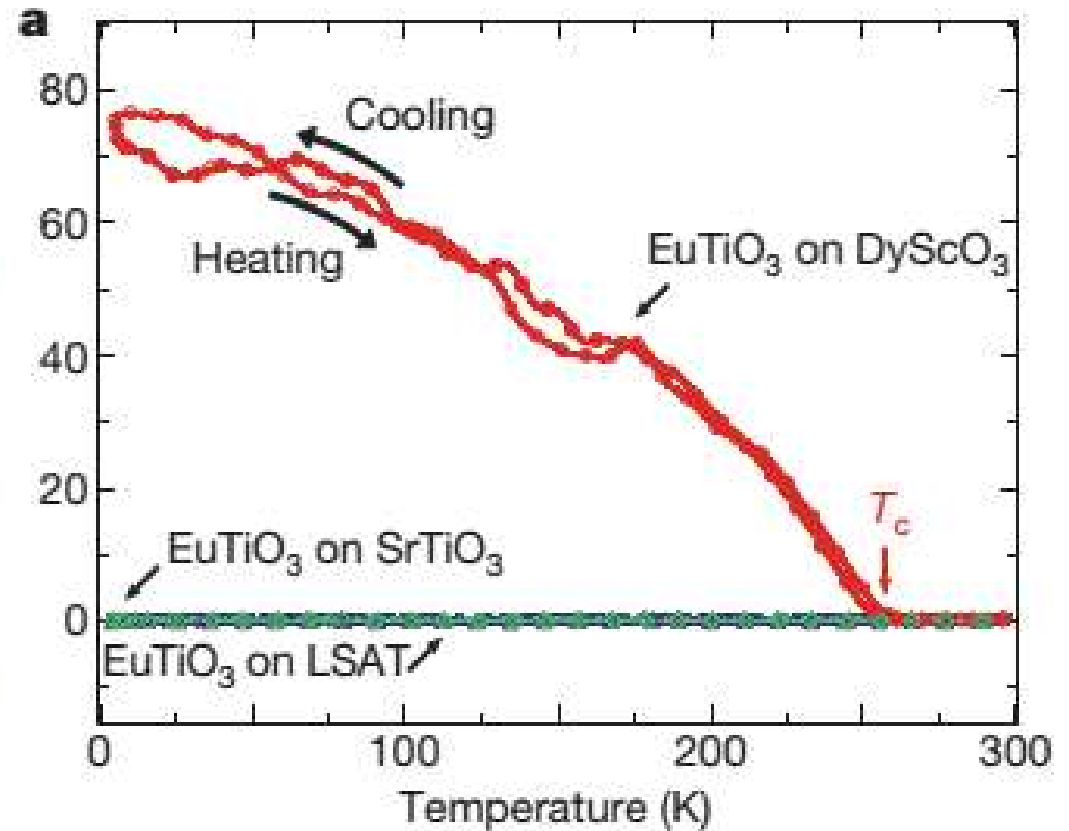
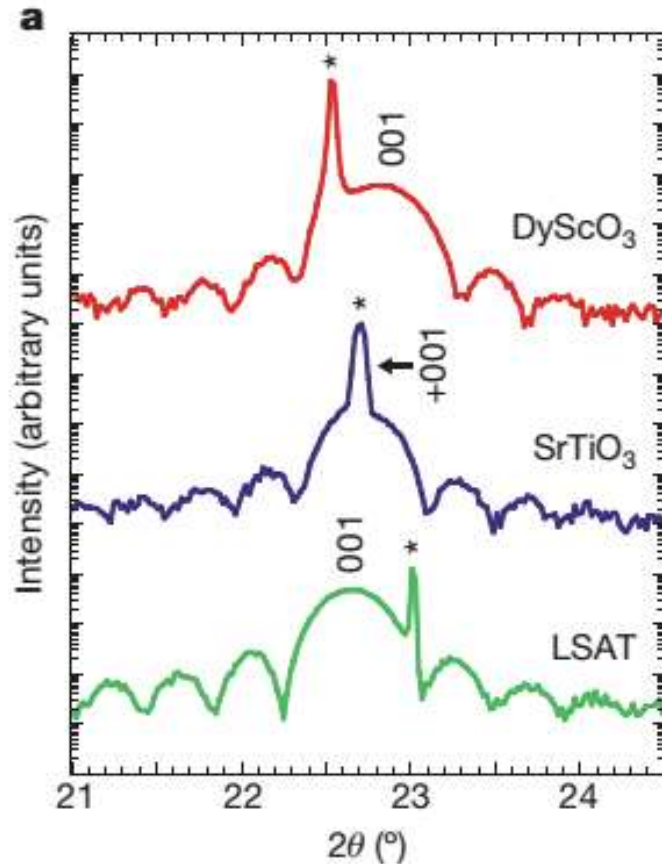


Magnetization by Strain



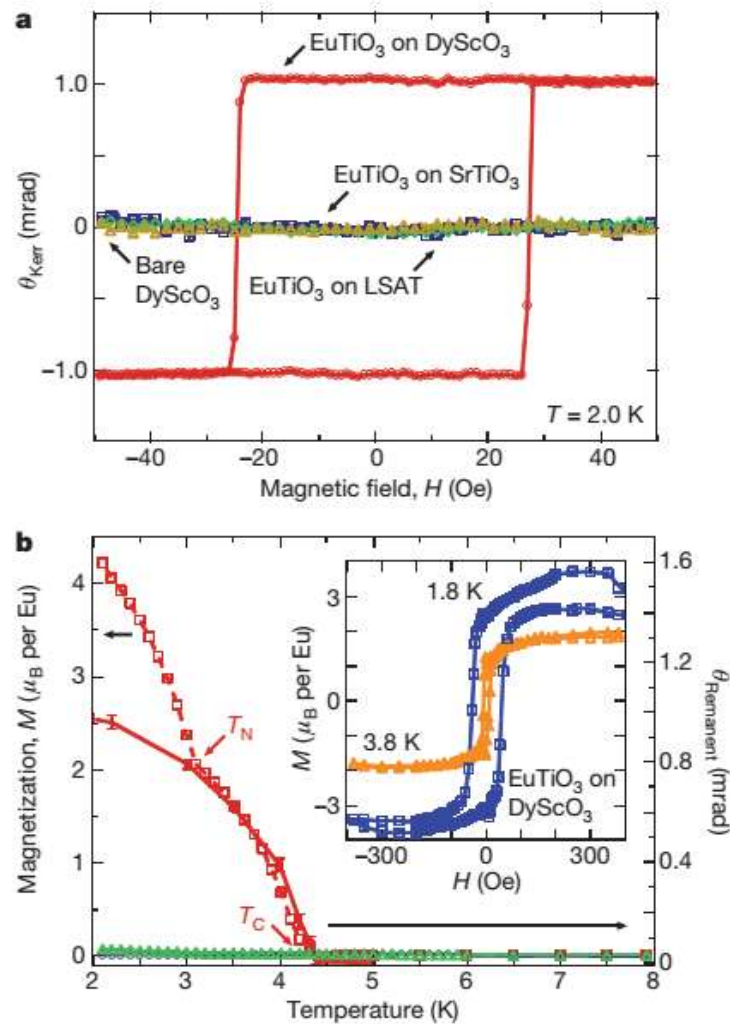
Lee 2010, et al. Nature (2011)

Magnetization by Strain



Lee 2010, et al. Nature (2011)

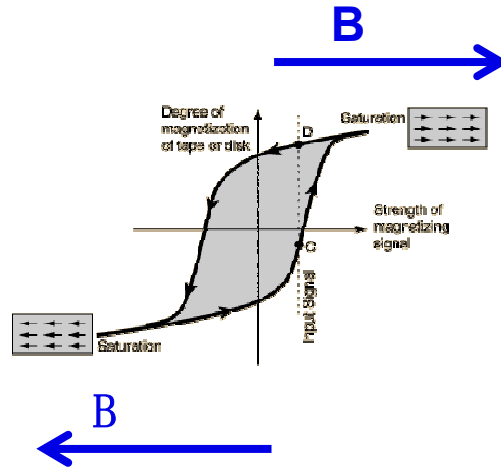
Magnetization by Strain



Lee 2010, et al. Nature (2011)

Summary

Magnetic field



Without B
???

Control

Electric field

Spin torque

Ultrafast Laser

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！