Chapter 2

Magnetism and Magnetic Materials

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上节课总结

本课程介绍自旋电子学基础知识以及其最新进展。

1） 介绍自旋电子学的基础知识，包括铁磁、反铁磁性、磁阻等。

2） 着重介绍自旋电子学的最近进展，包括自旋阀、自旋转移力矩、热自旋电子学、拓扑自旋、反铁磁自旋电子学等。

上节课总结

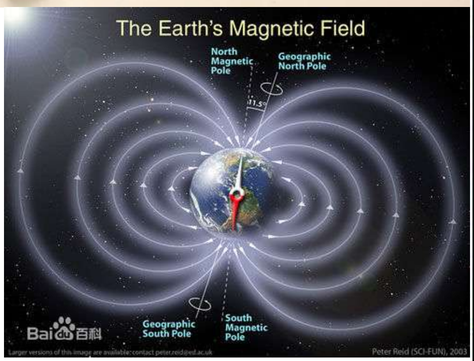
从宏观（指南针）到微观（原子内部的电子自旋：Bohr Magneton）

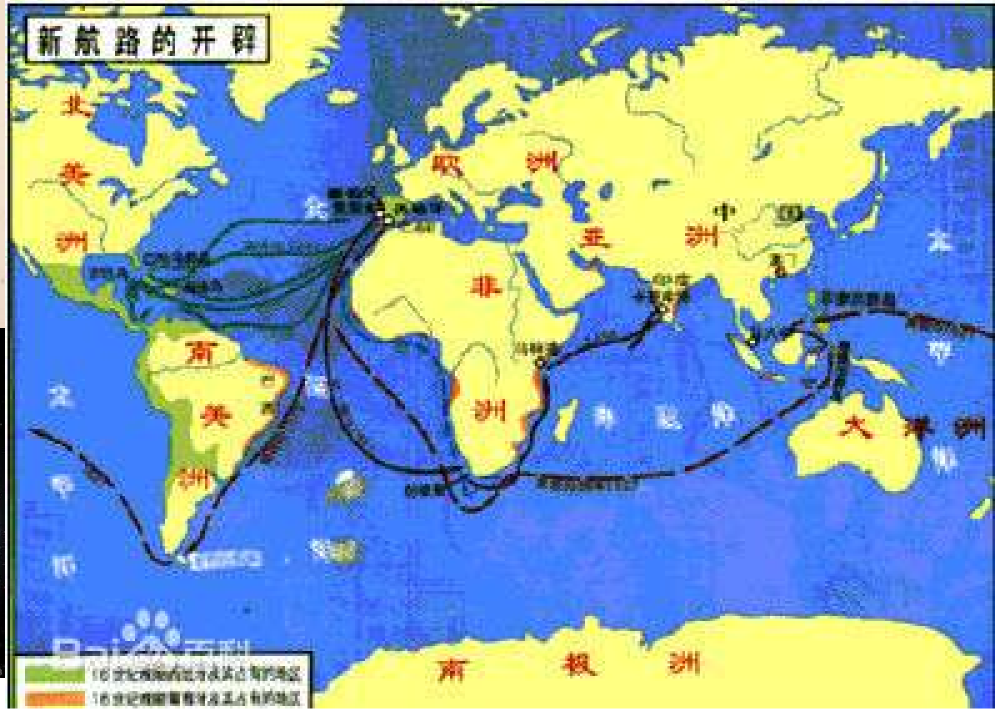
自旋—量子数

自旋—利用自旋并操控自旋

自旋—物理机制

上节课总结


The Earth's Magnetic Field
North Magnetic Pole
Geographic North Pole
Geographic South Pole
South Magnetic Pole


新航路的开辟
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提纲

1. Introduction to magnetism

2. How to induce magnetic moment

3. How to control magnetization

提纲

1. Introduction to magnetism

Introduction to Magnetism

- **Magnetism of Electrons**

- **Spin orbit Coupling**

- **Magnetism**

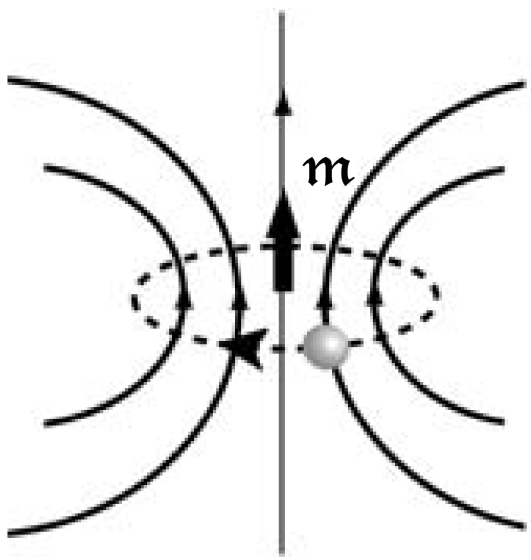
  Diamangetism, Paramagnetism,
  FM, AFM, Ferrimagnet, Half metallic

- **Magnetic resonance**

- **Magnetic domains**

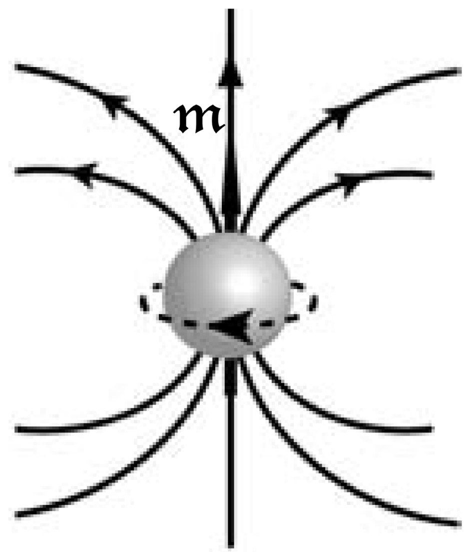
Magnetism of Electrons

Orbital moment



(a)

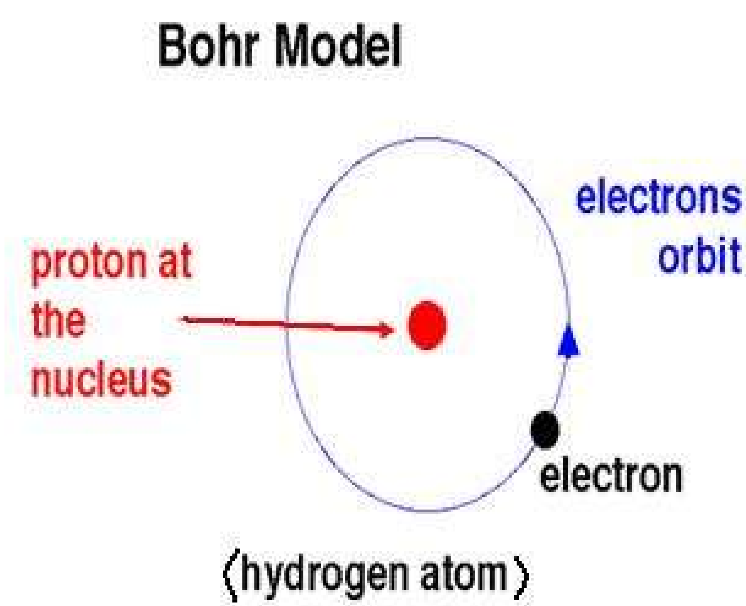
Spin moment



(b)

Orbital moment

Bohr Atom



Speed of the electron: *v*

Period of rotation:

$$\tau = 2\pi r / v$$

The equivalent current:

$$I = -e / \tau$$

The magnetic moment:

$$m = IA = -\tfrac{1}{2} e\vec{r} \times \vec{v}$$

Angular momentum:

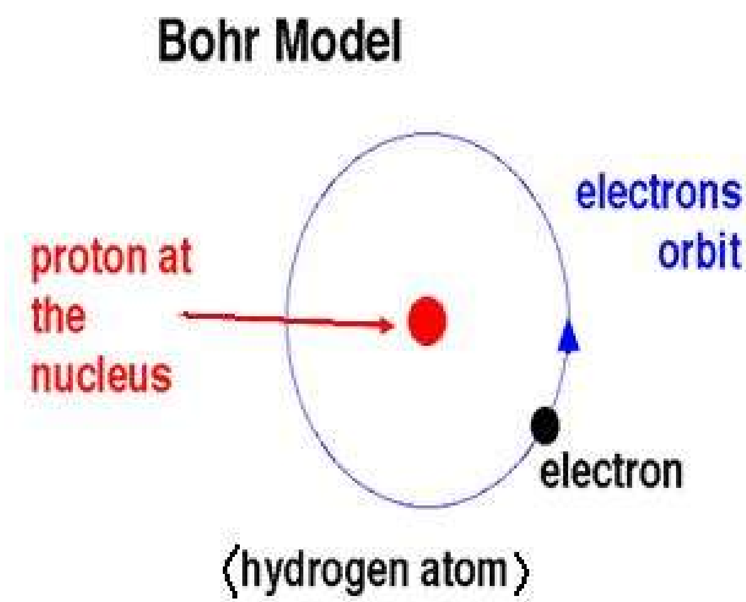
$$\vec{l} = m_e \vec{r} \times \vec{v}$$

The moment:

$$m = -\frac{e}{2m_e}\vec{l}$$

Orbital moment

Bohr Atom



The moment:

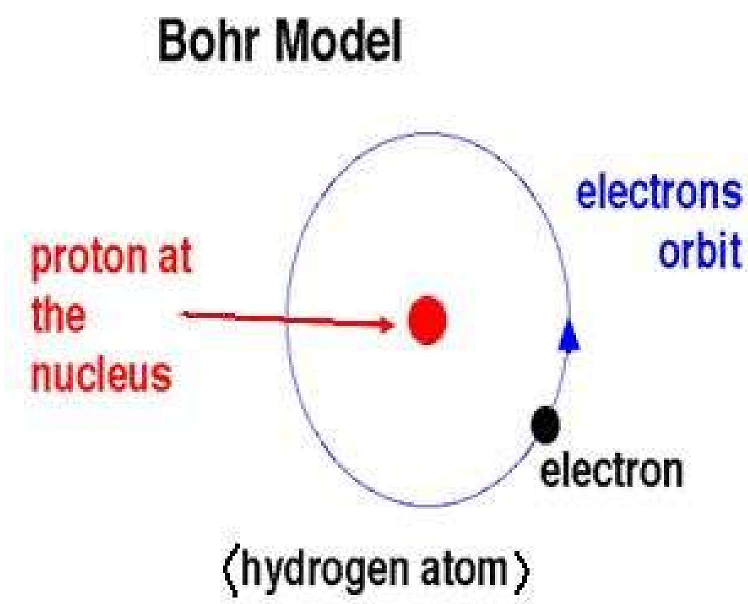
$$\vec{m} = \boxed{-\frac{e}{2m_e}}\vec{l}$$

gyromagnetic ratio

$$m_z = -\frac{e}{2m_e} m_l \hbar, m_l = 0, \pm 1, \pm 2, \ldots$$

Orbital moment

Bohr Atom



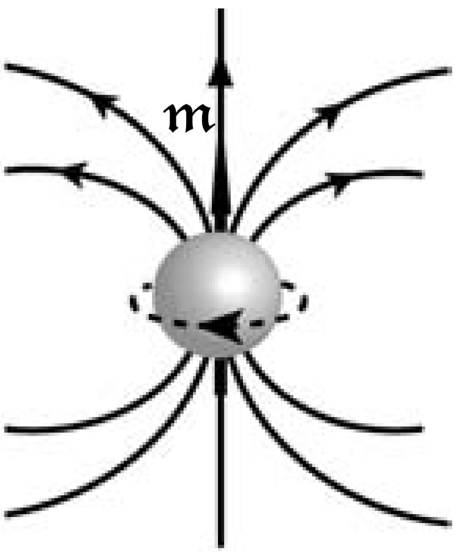
Bohr Magneton:

$$\mu_B = \frac{e\hbar}{2m_e}$$

$$1\ \mu_B = 9.274 \times 10^{-24}\ \mathrm{A\ m^2}$$

Spin moment

Bohr Atom



(b)

The spin moment:

$$m = -\frac{e}{m_e}\vec{s}$$

$$m_z = -\frac{e}{m_e} m_s \hbar, m_s = \pm\frac{1}{2}$$

Magnetism of Electrons

Table 3.1. Properties of the electron

Mass	m_e	9.109×10^{-31} kg
Charge	$-e$	-1.6022×10^{-19} C
Spin quantum number	s	$1/2$
Spin angular momentum	$\frac{1}{2}\hbar$	5.273×10^{-34} J s
Spin g-factor	g	2.0023
Spin magnetic moment	m	-9.285×10^{-24} A m^2
Classical radius $\mu_0 e^2/4\pi m_e$	r_e	2.818×10^{-15} m

Gyromagnetic ratio

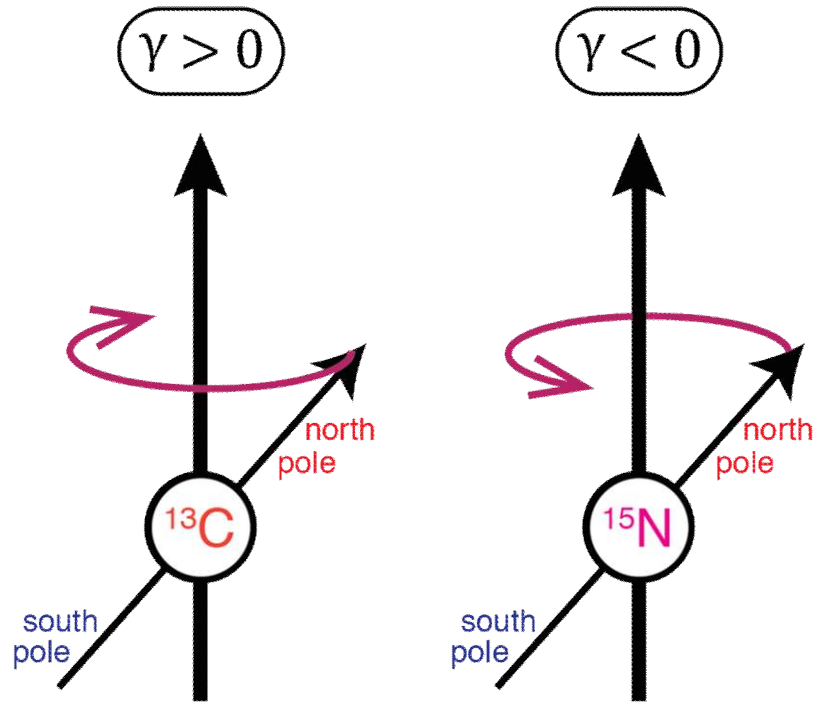
$$\gamma = -\frac{q}{2m}$$

For a free electron:

$$\gamma = -\frac{e}{2m_e} g_e = 1.760 \times 10^{11} \frac{rad}{s * T}$$

Gyromagnetic ratio

$$\gamma = -\frac{q}{2m}$$



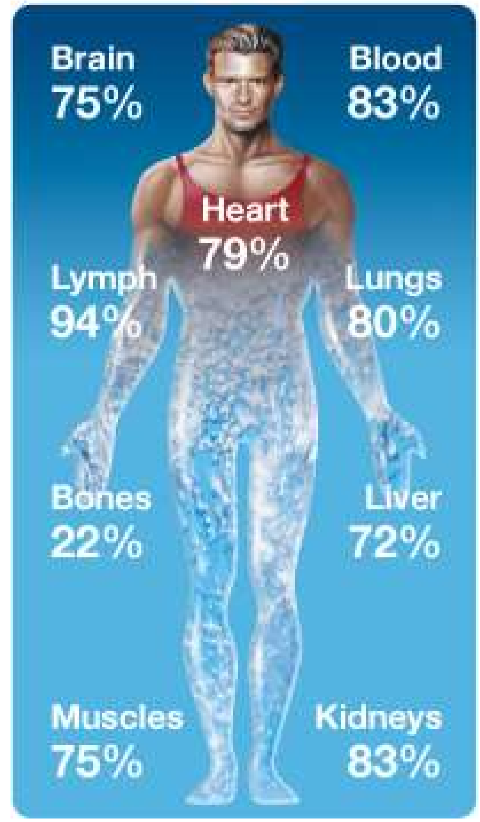
For a nucleus:

$$\gamma_n = -\frac{e}{2m_p} g_n = g_n \mu_n / \hbar$$

Gyromagnetic ratio

Nucleus	γ (10^6 rad s^{-1} T^{-1})
^1H	267.513
^2H	41.065
^3He	−203.789
^{13}C	67.262
^{14}N	19.331
^{15}N	−27.116
^{17}O	−36.264
^{29}Si	−53.190
^{31}P	108.291

Gyromagnetic ratio



H_2O

Hund’s Rule

(1) First maximize S for the configuration.
(2) Then maximize L consistent with S.
(3) Finally couple L and S to form J: $J = L - S$ if the shell is less than half full, and $J = L + S$ if the shell is more than half full. When the shell is exactly half full, $L = 0$ and $J = S$.

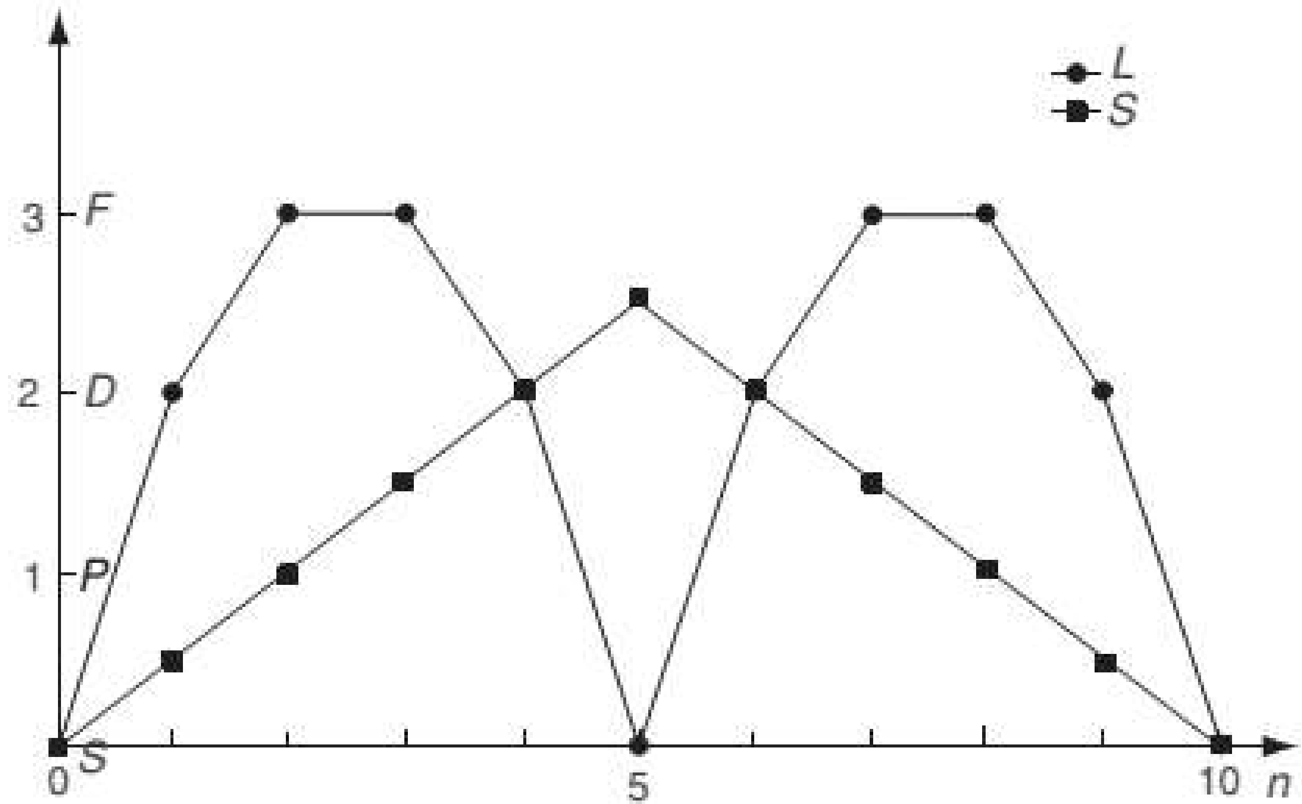
Fe^{3+} $\quad 3d^5 \quad \uparrow\uparrow\uparrow\uparrow\uparrow \,|\, ooooo$

$S = 5/2 \qquad L = 0 \qquad J = 5/2$

Ni^{2+} $\quad 3d^8 \quad \uparrow\uparrow\uparrow\uparrow\uparrow \,|\, \downarrow\downarrow\downarrow oo$

$S = 1 \qquad L = 3 \qquad J = 4$

Hund’s Rule



(a)

Hund's Rule

Table 4.7. The 3*d* ions. m_{eff} is in units of μ_B

$3d^n$		S	L	J	g	$m_{eff} = g\sqrt{J(J+1)}$	$m_{eff} = g\sqrt{S(S+1)}$	m_{eff}^{exp}
1	Ti^{3+}, V^{4+}	$\frac{1}{2}$	2	$\frac{3}{2}$	$\frac{4}{5}$	1.55	1.73	1.7
2	Ti^{2+}, V^{3+}	1	3	2	$\frac{2}{3}$	1.63	2.83	2.8
3	V^{2+}, Cr^{3+}	$\frac{3}{2}$	3	$\frac{3}{2}$	$\frac{2}{5}$	0.78	3.87	3.8
4	Cr^{2+}, Mn^{3+}	2	2	0			4.90	4.9
5	Mn^{2+}, Fe^{3+}	$\frac{5}{2}$	0	$\frac{5}{2}$	2	5.92	5.92	5.9
6	Fe^{2+}, Co^{3+}	2	2	4	$\frac{3}{2}$	6.71	4.90	5.4
7	Co^{2+}, Ni^{3+}	$\frac{3}{2}$	3	$\frac{9}{2}$	$\frac{4}{3}$	6.63	3.87	4.8

3d metals: magnetism mainly due to spin moment

Spin orbit coupling

4f metals: orbit moment is large

$$H_{SO} = \lambda \vec{l} * \vec{s}$$

$$J = L + S$$

Spin orbit coupling

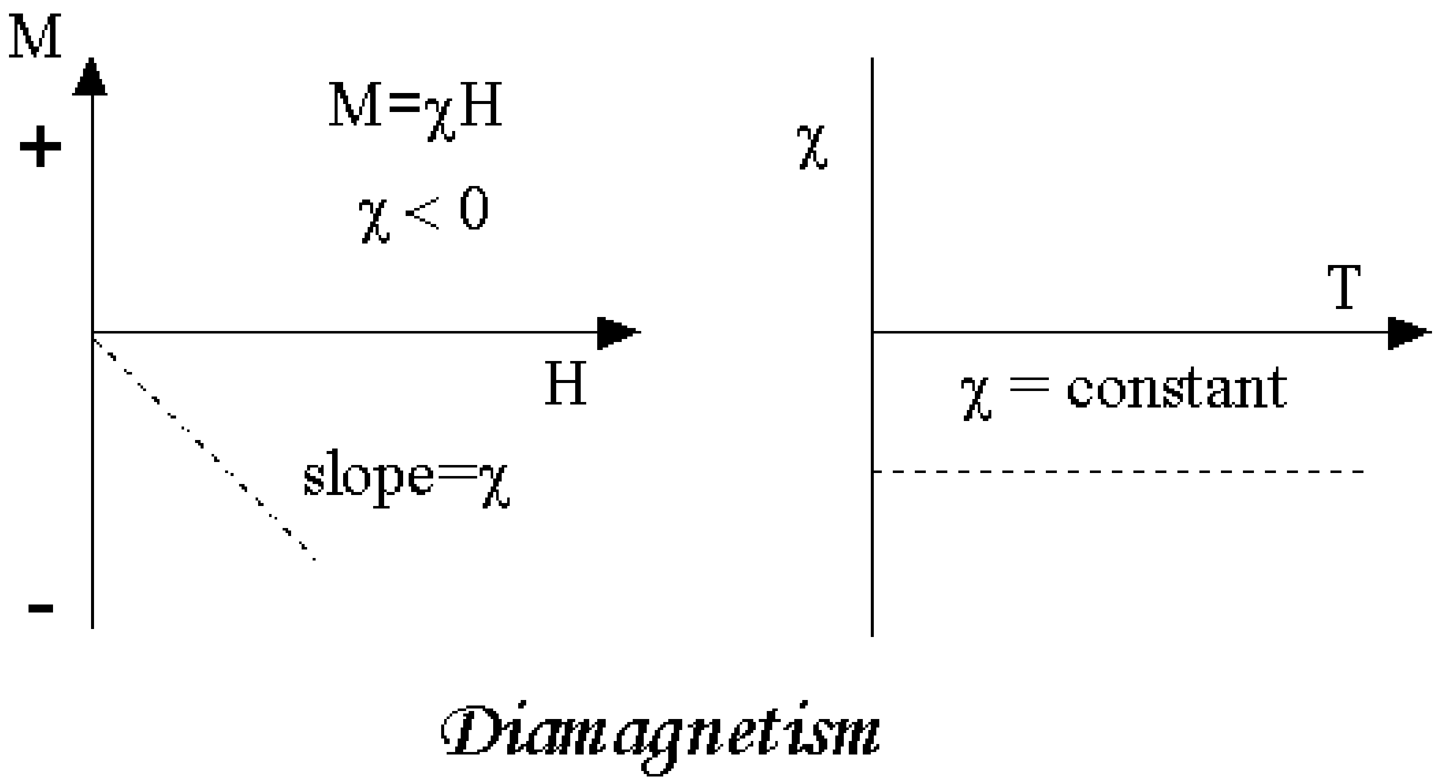
Table 4.6. The 4 f ions. The paramagnetic moment m_{eff} and the saturation moment m_0 are in units of μ_B

$4f^n$		S	L	J	g	$m_0 = gJ$	$m_{eff} = g\sqrt{J(J+1)}$	m_{eff}^{exp}
1	Ce^{3+}	$\frac{1}{2}$	3	$\frac{5}{2}$	$\frac{6}{7}$	2.14	2.54	2.5
2	Pr^{3+}	1	5	4	$\frac{4}{5}$	3.20	3.58	3.5
3	Nd^{3+}	$\frac{3}{2}$	6	$\frac{9}{2}$	$\frac{8}{11}$	3.27	3.52	3.4
4	Pm^{3+}	2	6	4	$\frac{3}{5}$	2.40	2.68	
5	Sm^{3+}	$\frac{5}{2}$	5	$\frac{5}{2}$	$\frac{2}{7}$	0.71	0.85	1.7
6	Eu^{3+}	3	3	0	0	0	0	3.4
7	Gd^{3+}	$\frac{7}{2}$	0	$\frac{7}{2}$	2	7.0	7.94	8.9
8	Tb^{3+}	3	3	6	$\frac{3}{2}$	9.0	9.72	9.8
9	Dy^{3+}	$\frac{5}{2}$	5	$\frac{15}{2}$	$\frac{4}{3}$	10.0	10.65	10.6
10	Ho^{3+}	2	6	8	$\frac{5}{4}$	10.0	10.61	10.4
11	Er^{3+}	$\frac{3}{2}$	6	$\frac{15}{2}$	$\frac{6}{5}$	9.0	9.58	9.5
12	Tm^{3+}	1	5	6	$\frac{7}{6}$	7.0	7.56	7.6
13	Yb^{3+}	$\frac{1}{2}$	3	$\frac{7}{2}$	$\frac{8}{7}$	4.0	4.53	4.5

4f metals: magnetism described better by "J"

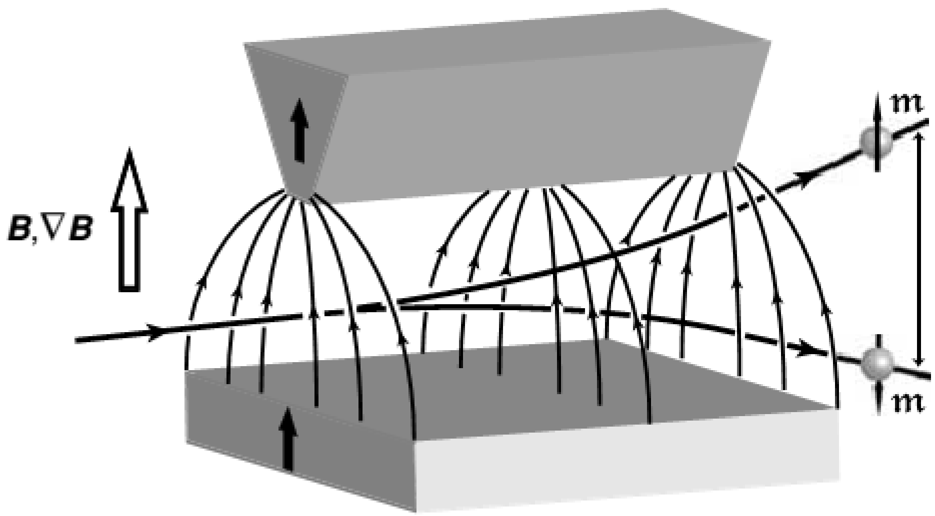
Diamagnetism

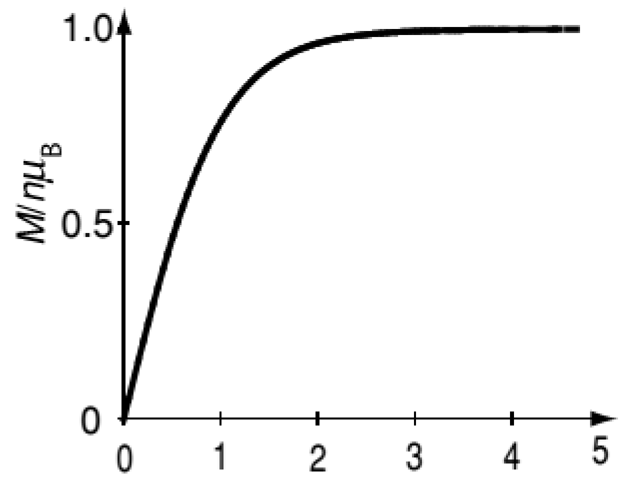
Curie's Law: localized electron



Paramagnetism

Curie's Law: localized electron





$$(\mu_B B / k_B T)$$

$$M = n\mu_B \tanh(\mu_B B / k_B T)$$

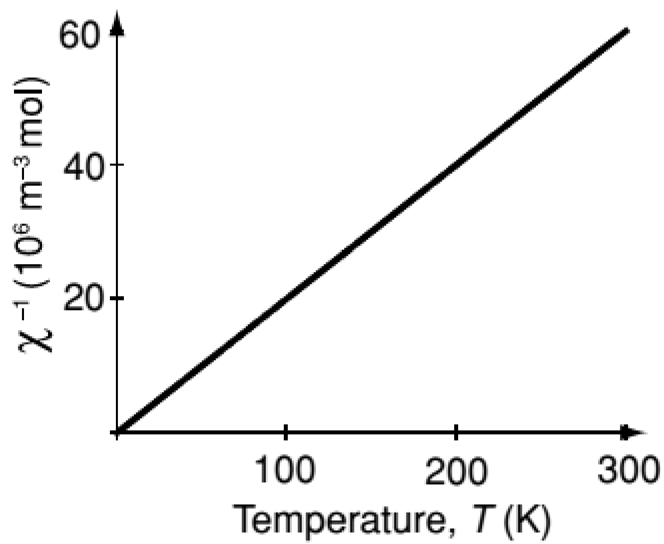
Curie-law paramagnetism

Curie's Law: localized electron

$$M = n\mu_B \tanh(\mu_B B / k_B T)$$

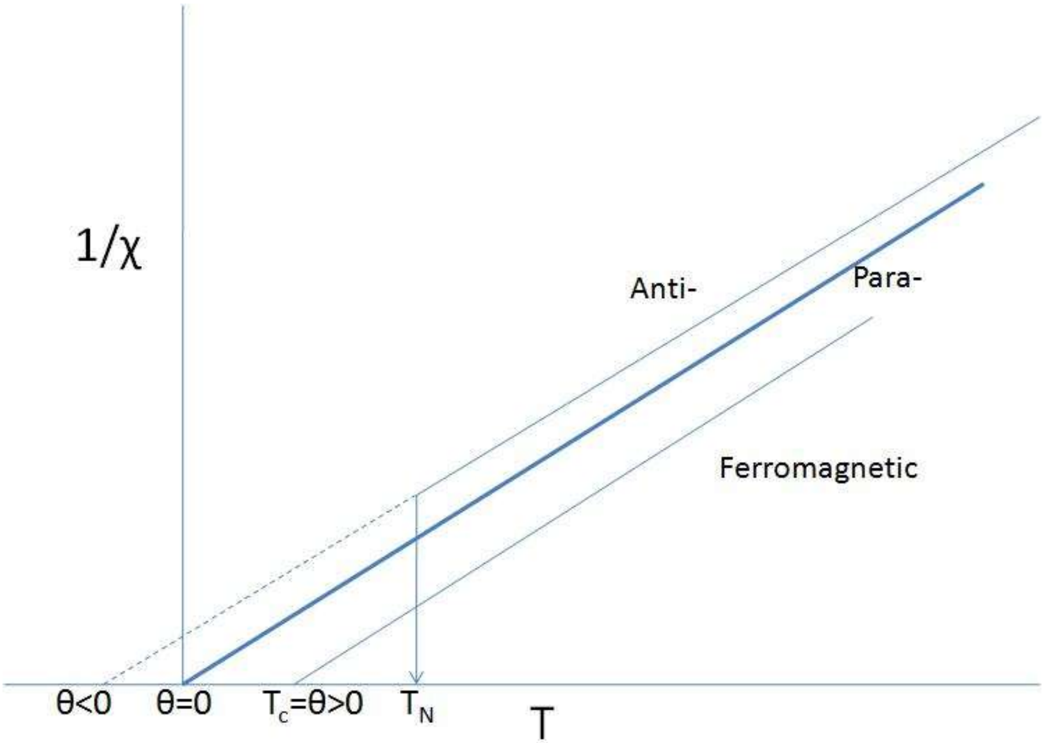
$$\chi = \mu_0 M / B = C / nT$$

$$C = n\mu_0\mu_B{}^2 / k_B$$



FM and AFM

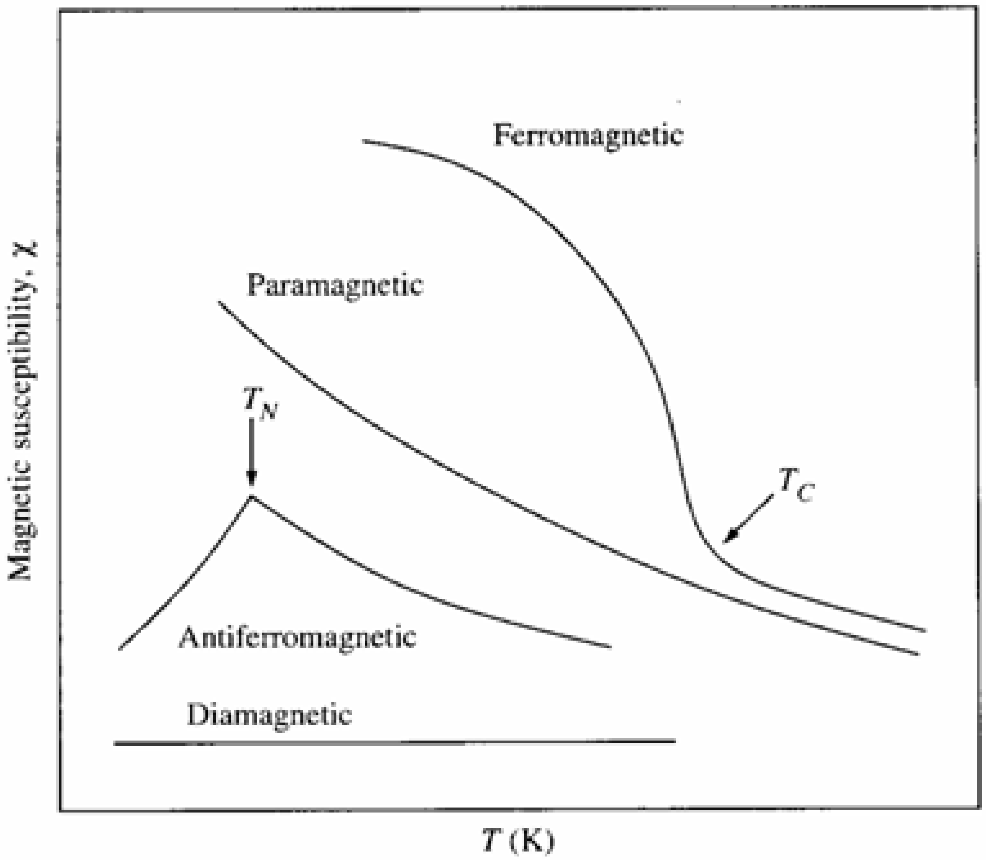
Curie-Weiss Law for FM



$$\chi = C/(T-\theta_p)$$

FM and AFM

Susceptibility



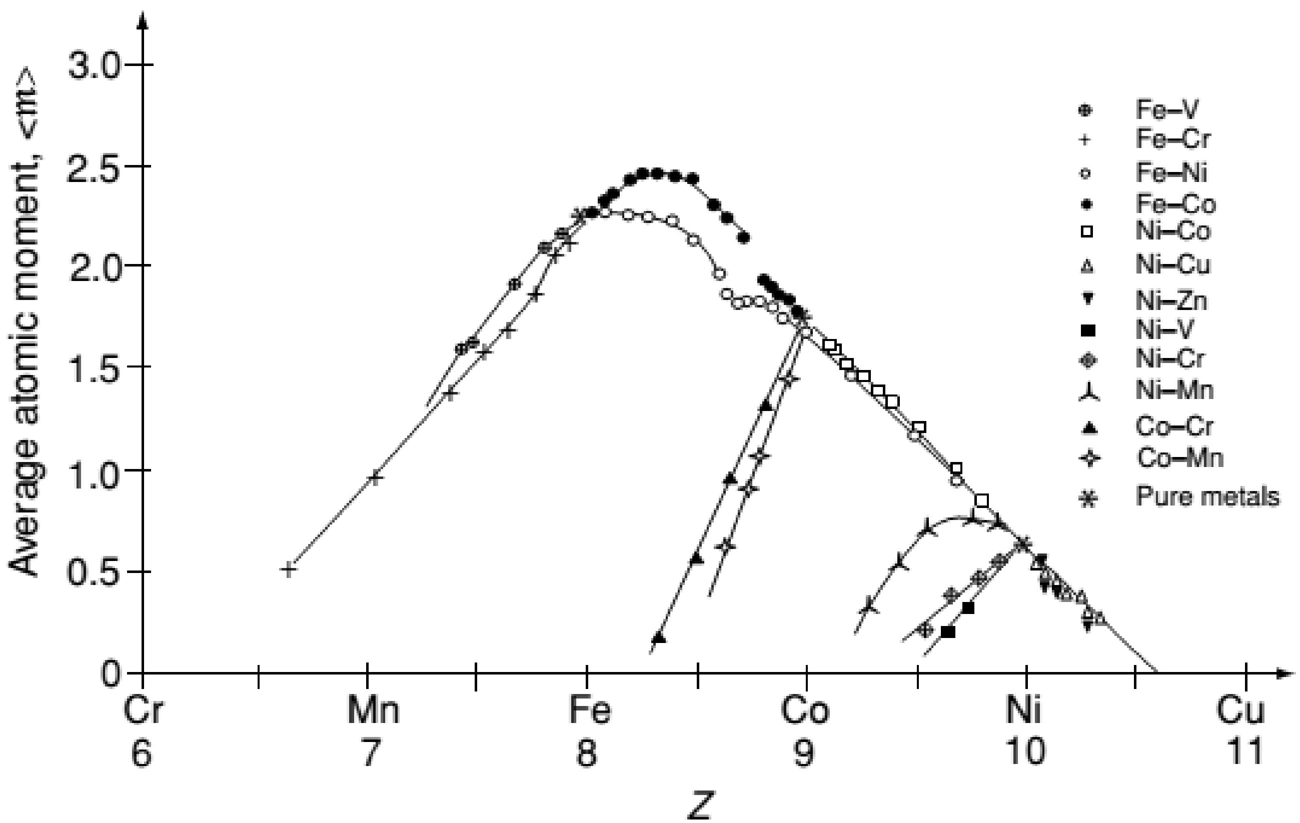
FM

Typical FM

	T_C (K)	d ($kg\ m^{-3}$)	σ_s ($A\ m^2\ kg^{-1}$)	M_s ($kA\ m^{-1}$)
Fe	1044	7874	217	1710
Co	1360(ε)	8920	162(ε)	1440
Ni	628	8902	54.8	488

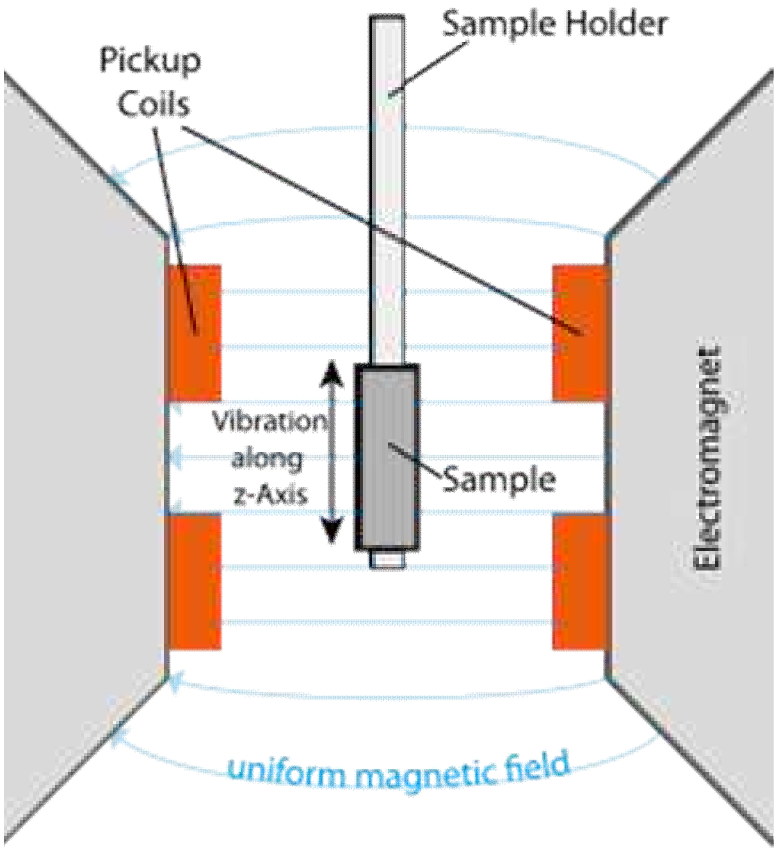
FM

The Slater－Pauling curve



Characterization of FM

Vibrating sample magnetometer

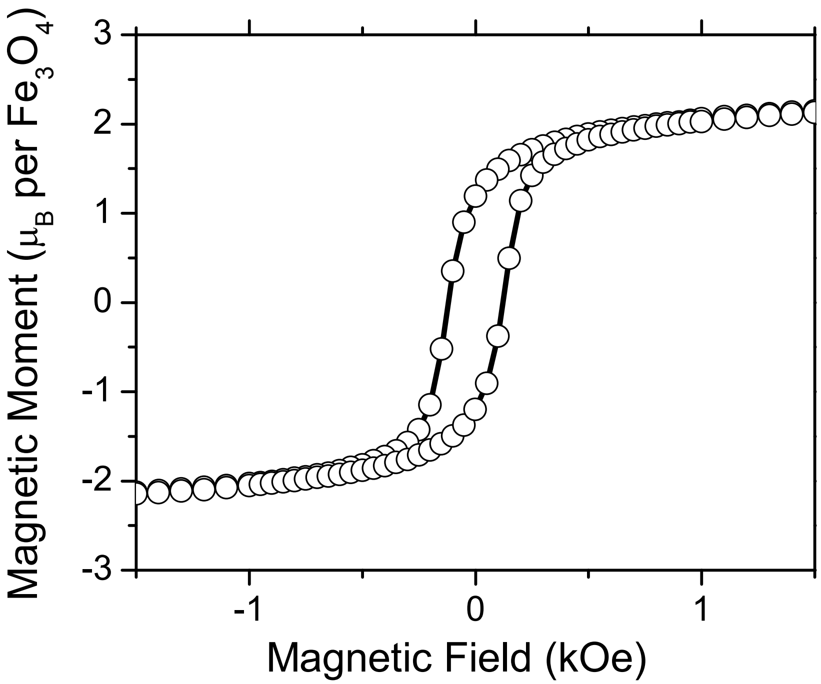


Sensitivity: 10^{-6} emu

Characterization of FM

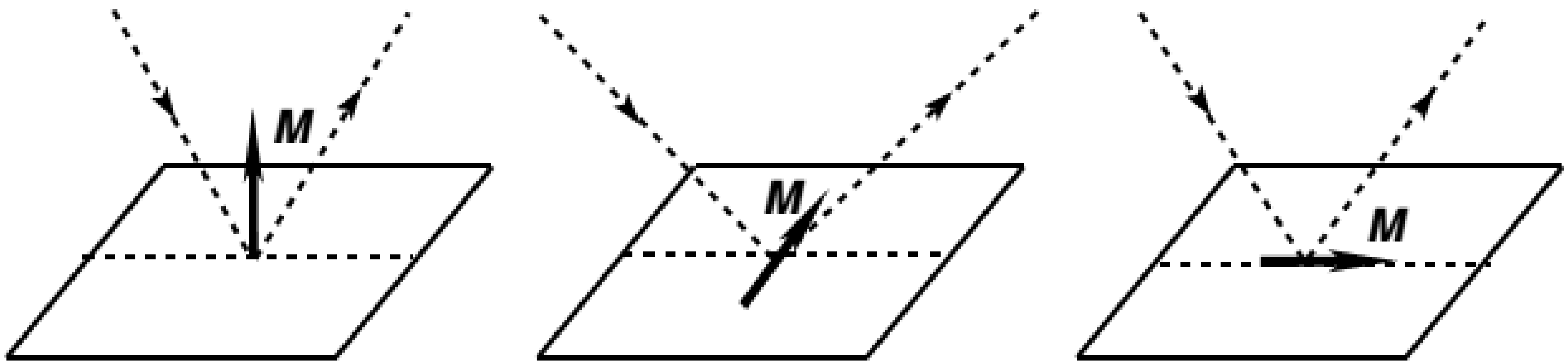
SQUID Magnetometry

Sensitivity: 5 x 10^{-8} emu



Characterization of FM

MOKE: Surface sensitive



(a) (b) (c)

Table 5.13. Kerr rotation in ferromagnetic metals at 830 nm (1.5 eV)

	θ_K (°)		θ_K (°)
Fe	−0.53	CoPd	−0.17
FePt	−0.39	CoPt	−0.36
FeCo	−0.60	Ni	−0.09
Co	−0.36	PtMnSb	−1.3

AFM

Typical AFM

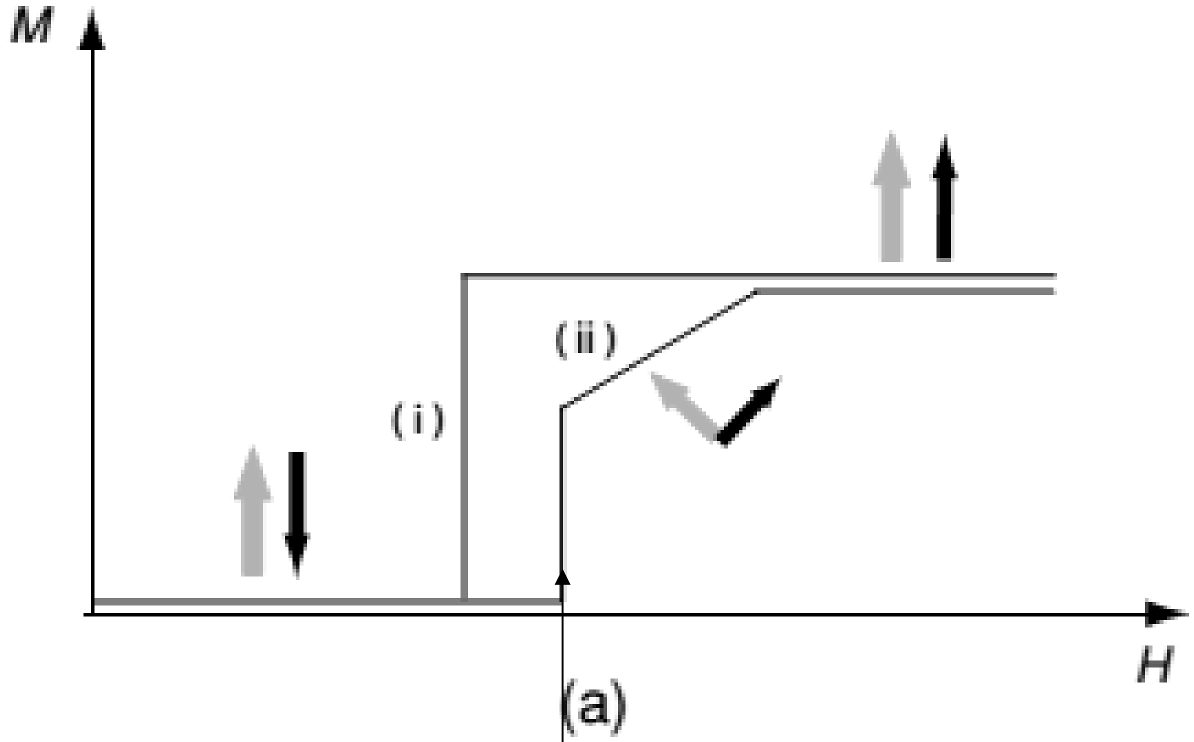
Table 6.1. Some common antiferromagnets

	Structure	T_N (K)	θ_p (K)	$\mu_0 M_\alpha$ (T)
Cr	sdw	311		0.20
Mn	Complex	96	~ -2000	0.20
NiO	Néel	524	-1310	0.54
αFe_2O_3	Canted	958	-2000	0.92
MnF_2	Néel	67	-80	0.78
FeMn	Néel	510		0.53
$IrMn_3$	Néel	690		0.50

sdw – spin density wave; Néel – two collinear sublattices.

AFM

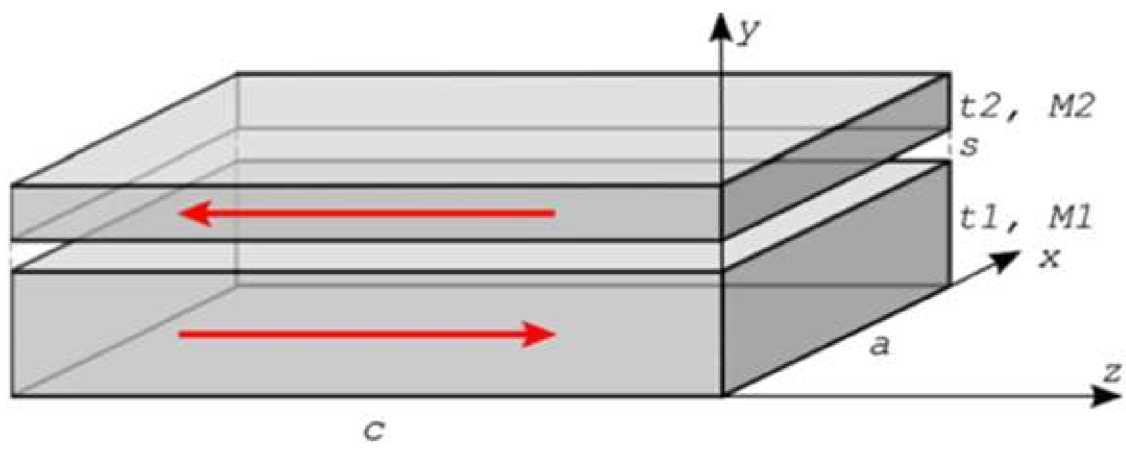
M vs. H loop



Spin flop field

AFM

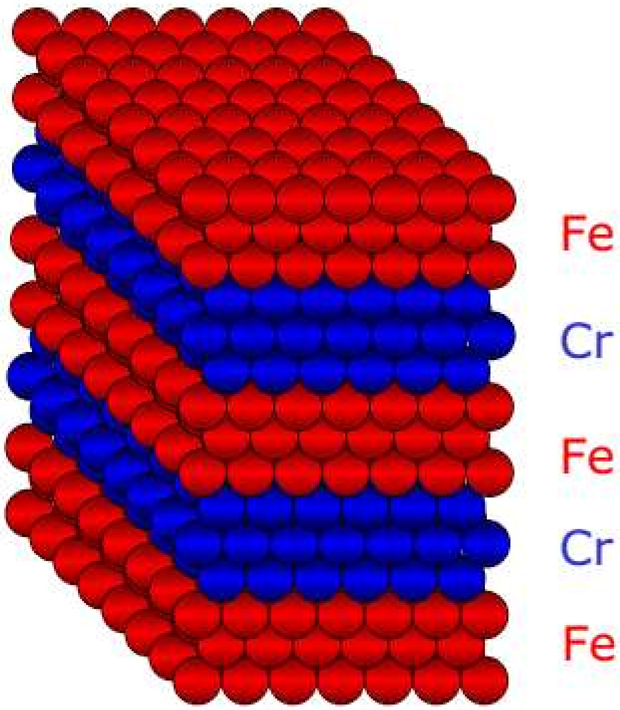
SAF: Synthetic antiferromagnets

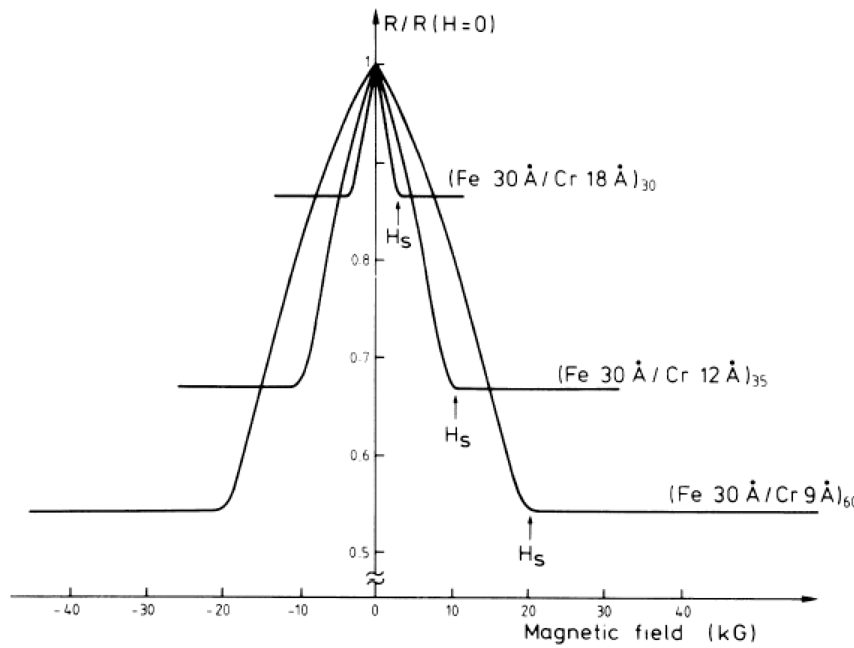


Antiferromagnetic exchange coupling between two FM layers

AFM

SAF：Synthetic antiferromagnets

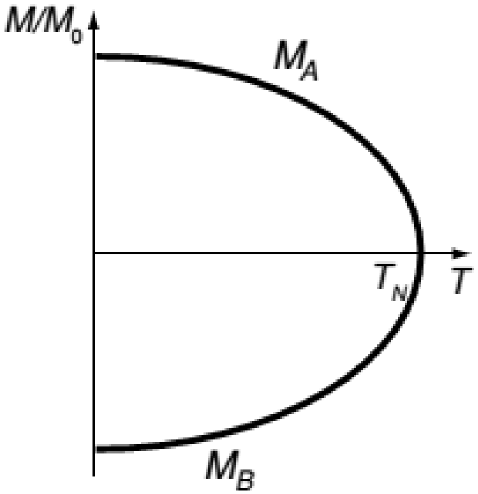


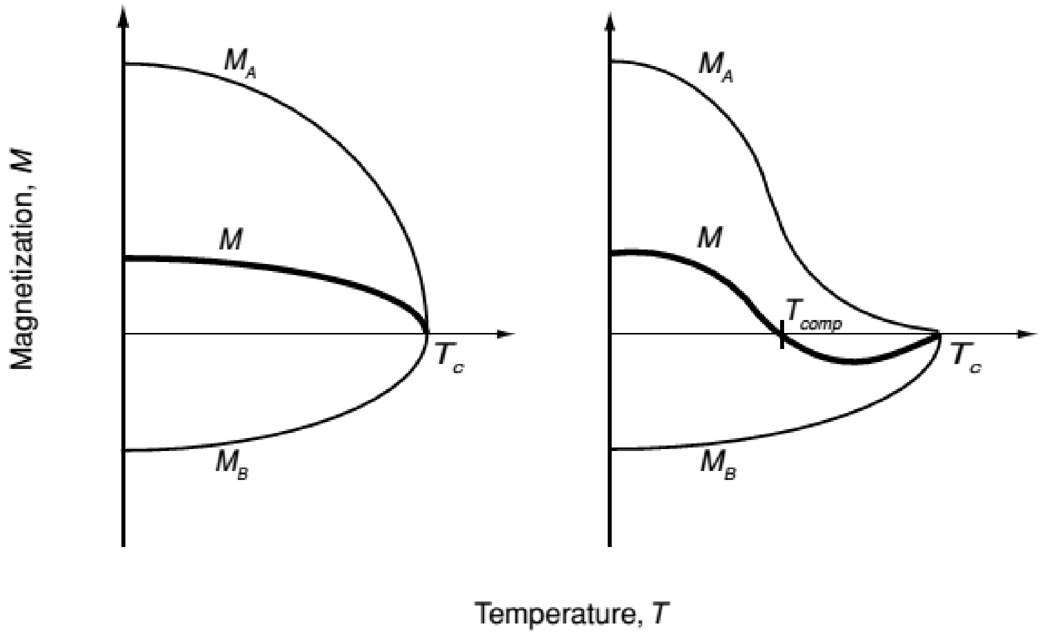


Baibich, et al, PRL (1988)
Fert, Rev. Mod. Phys. (2007)

Ferrimagnet

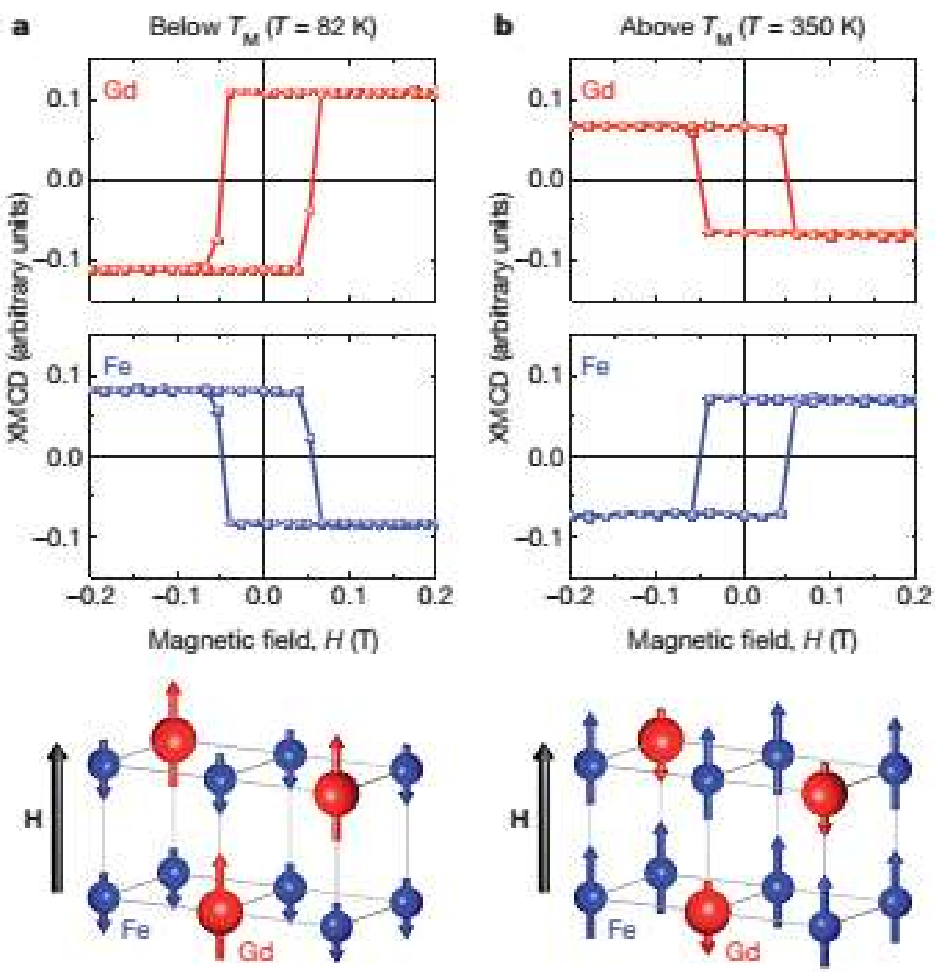
AFM → Ferrimagnet





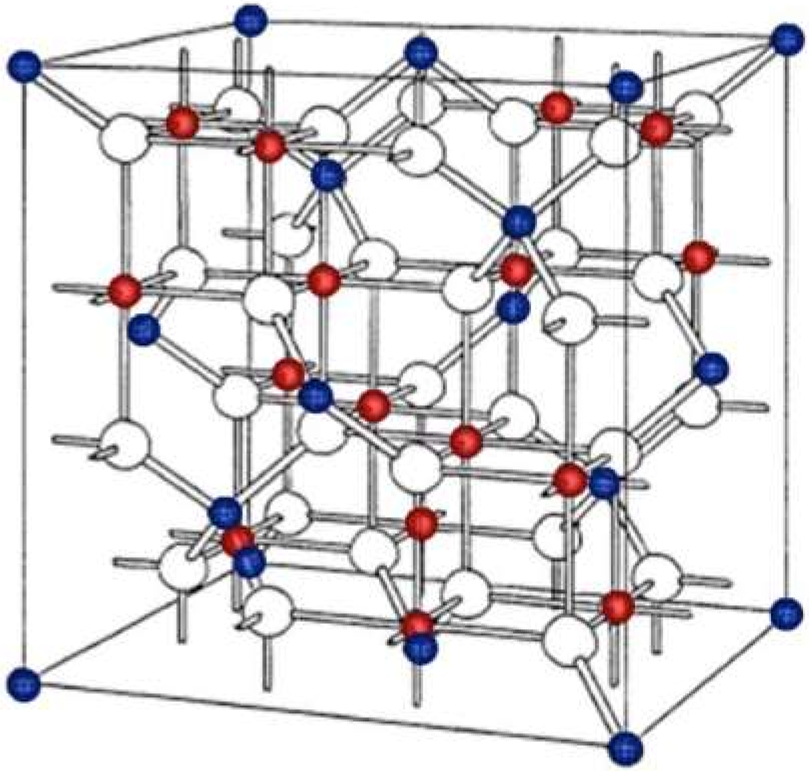
Ferrimagnet

FM-Gd alloys



Ferrimagnet

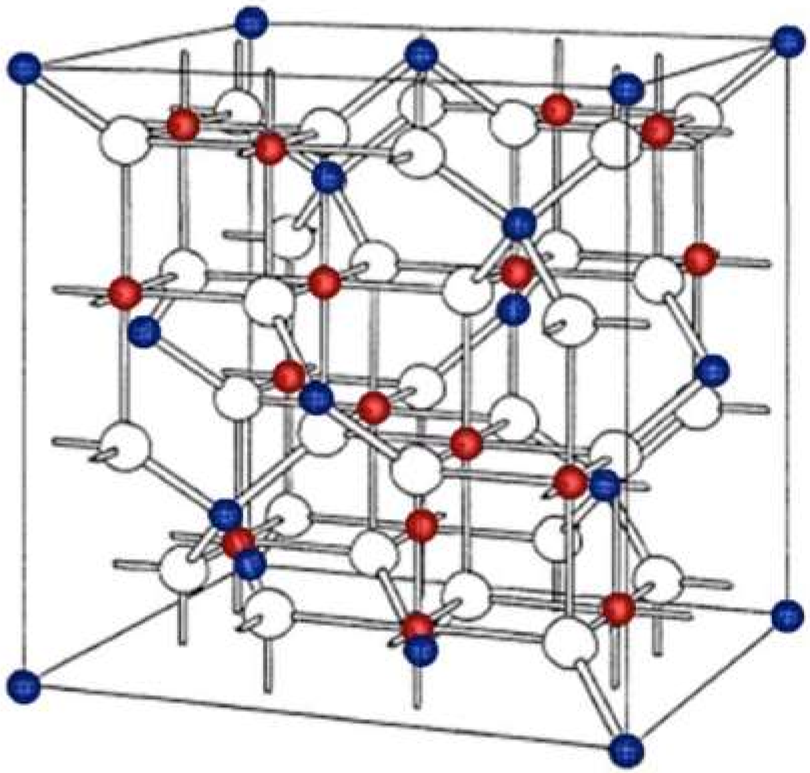
Fe_3O_4



white: O^{2-}, form a fcc sublattice
(He, $2s^2$, $2p^4$)
blue: A site, tetrahedral, Fe^{3+} only
(Ar, $4s^2$, $3d\downarrow^5$)
red: B site, octahedral, half Fe^{3+},
half Fe^{2+}
(Ar, $4s^2$, $3d\uparrow^5$, $3d\downarrow^{0.5}$)

Ferrimagnet

Fe_3O_4



Blue: Fe^{3+}

Red: Fe^{3+} and Fe^{2+}

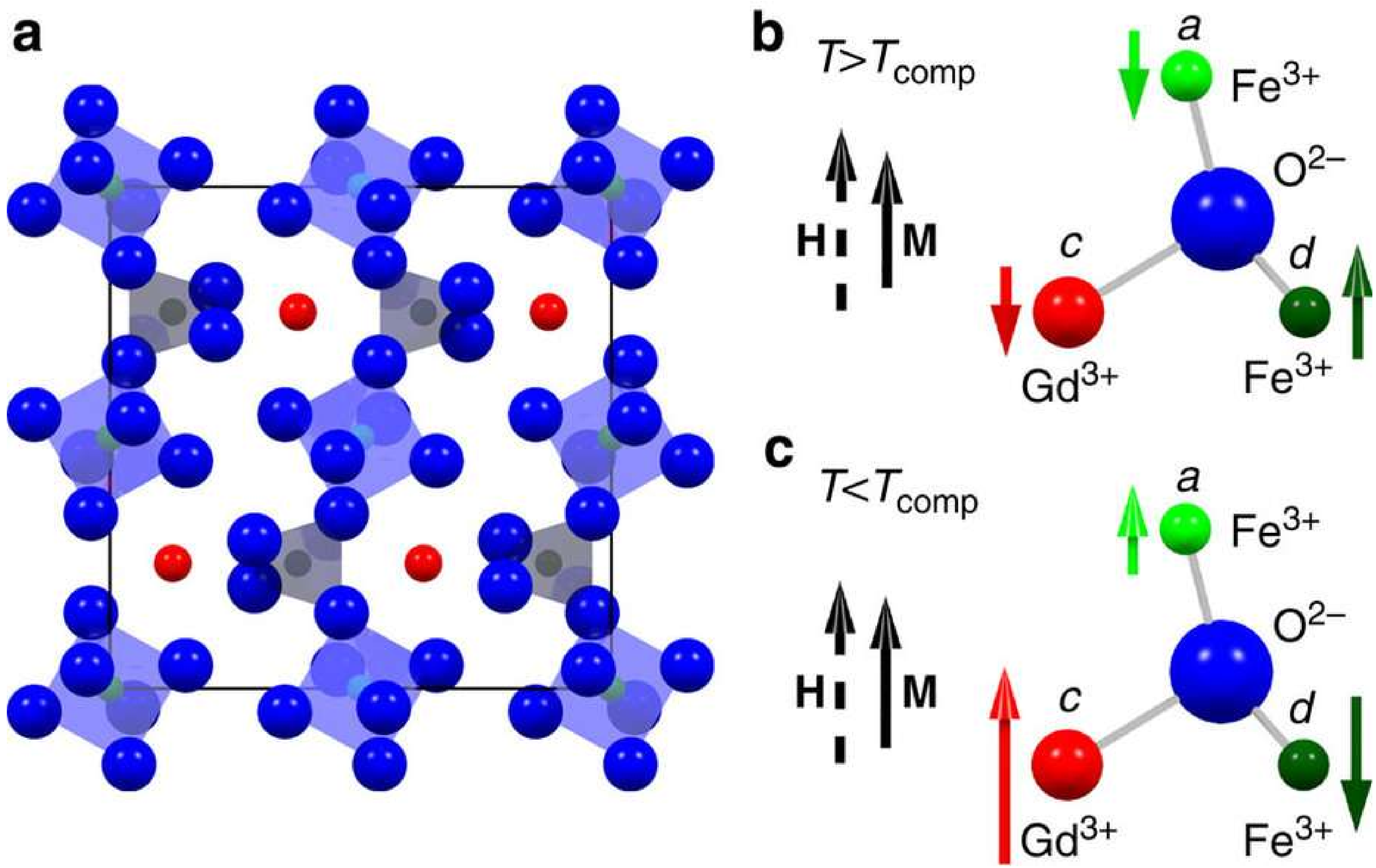
Fe^{3+} : $5\mu_B$

Fe^{2+} :$4\mu_B$

Total moment: $4\mu_B$ /Fe_3O_4

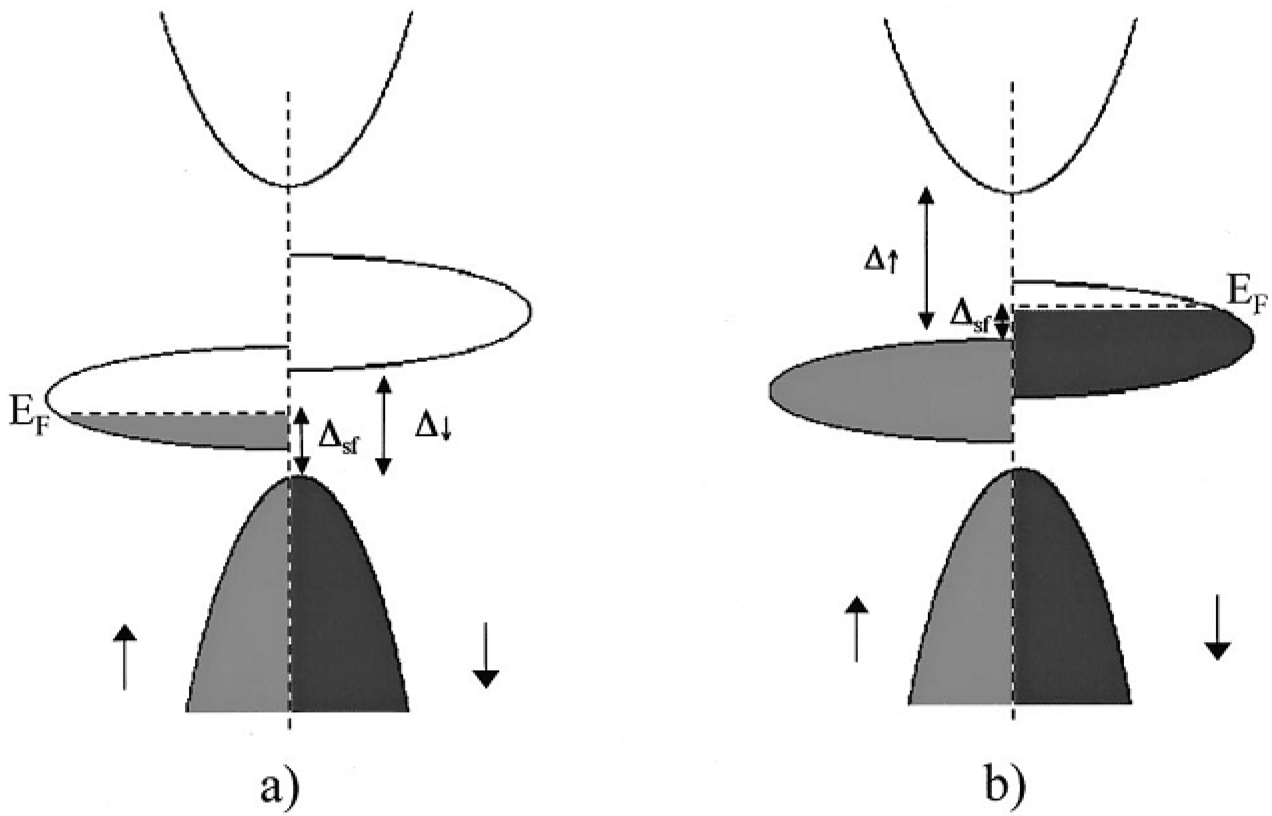
Ferrimagnet

YIG: $Gd_3Fe_5O_{12}$



Half Metallic

Density of states

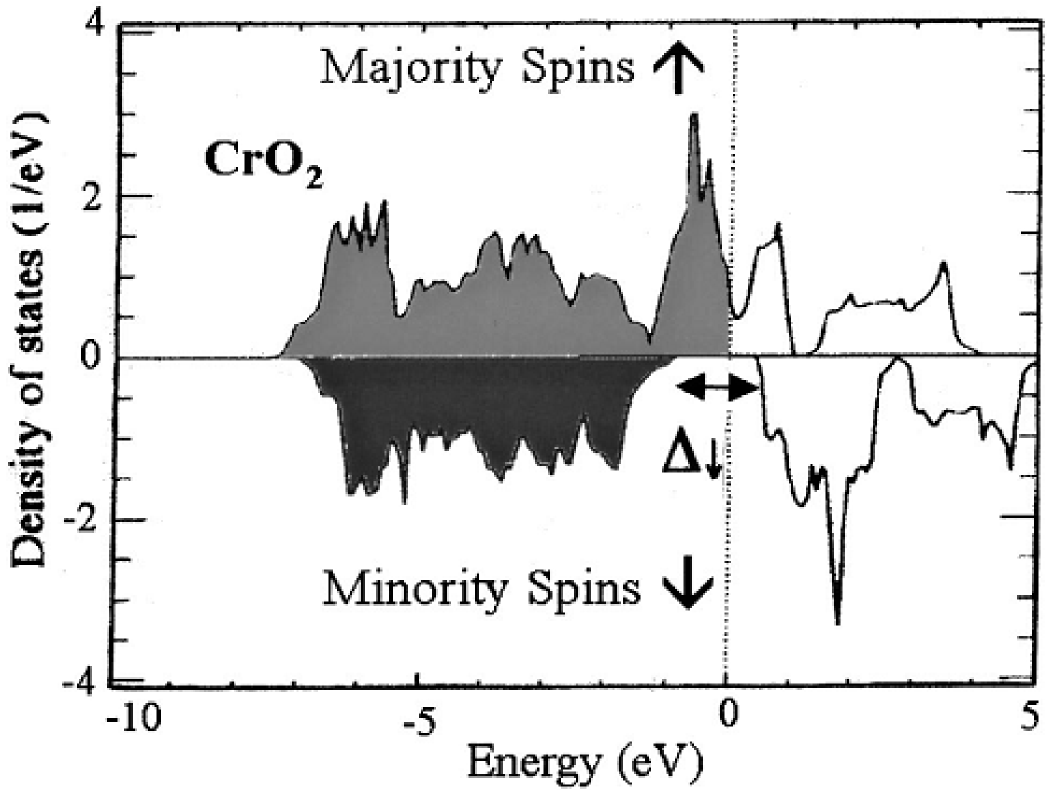


Coey & Venkatesan, JAP (2002)

Half Metallic

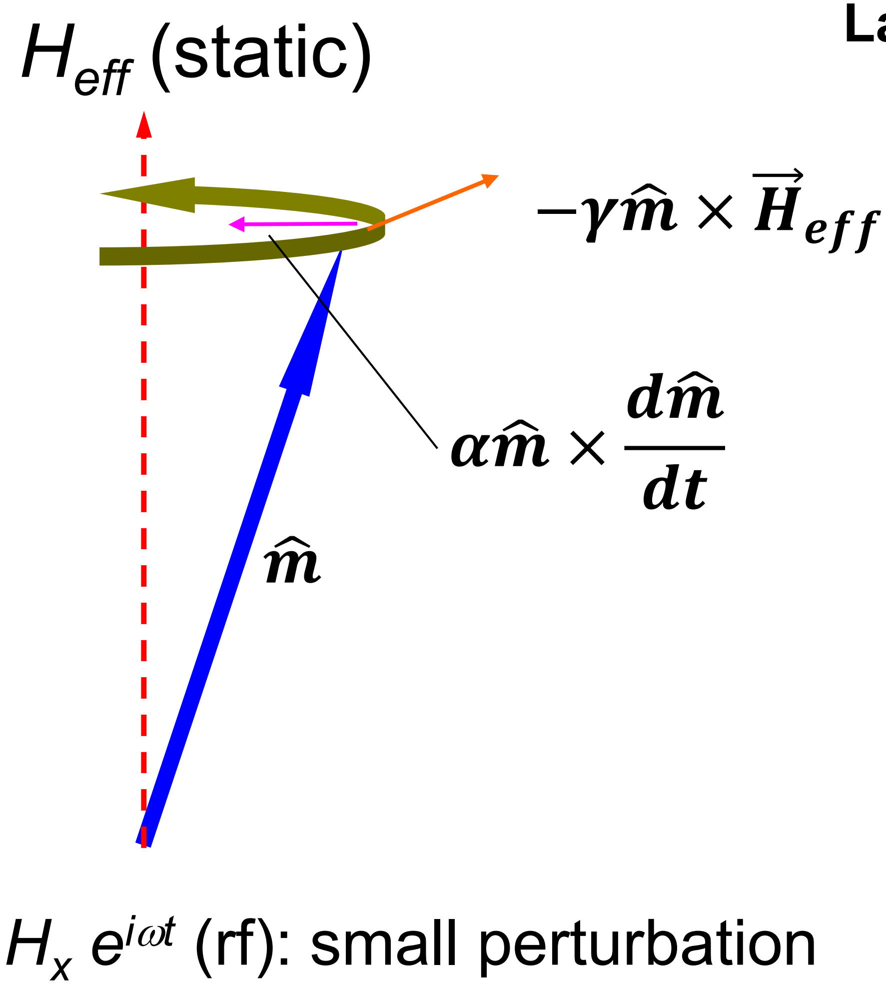
CrO_2

Spin polarization: 100%



Coey & Venkatesan, JAP (2002)

Magnetic resonance



Landau-Lifshitz-Gilbert equation

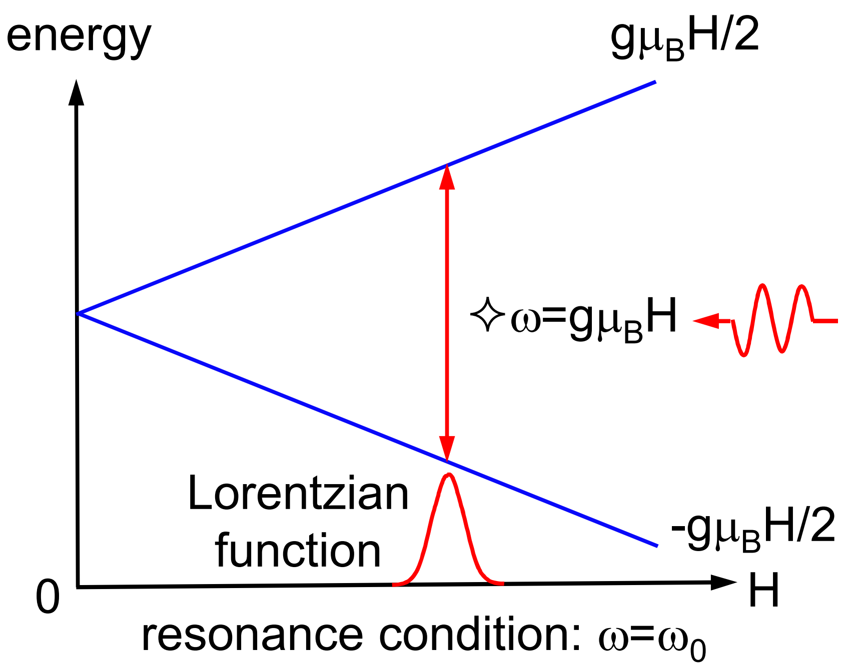
$$\frac{d\hat{m}}{dt} = -\gamma\hat{m}\times\vec{H}_{eff} + \alpha\hat{m}\times\frac{d\hat{m}}{dt}$$

$\gamma = \frac{g\,e}{2\,m_e c}$ is gyromagnetic ratio

α is the Gilbert damping

Magnetic resonance

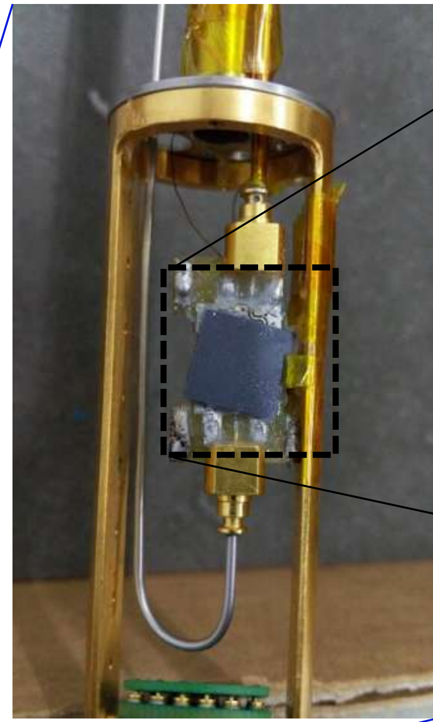
FMR

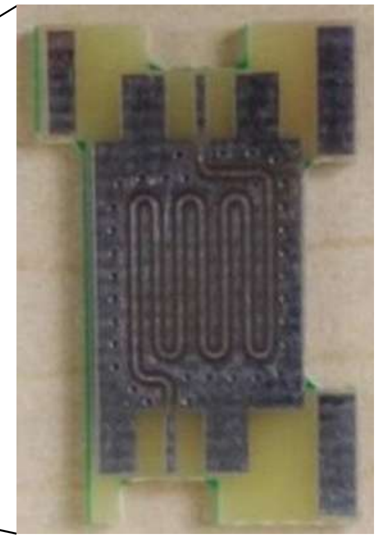


Magnetic resonance

FMR system

PPMS
T: 2 K - 300 K
B: 9T

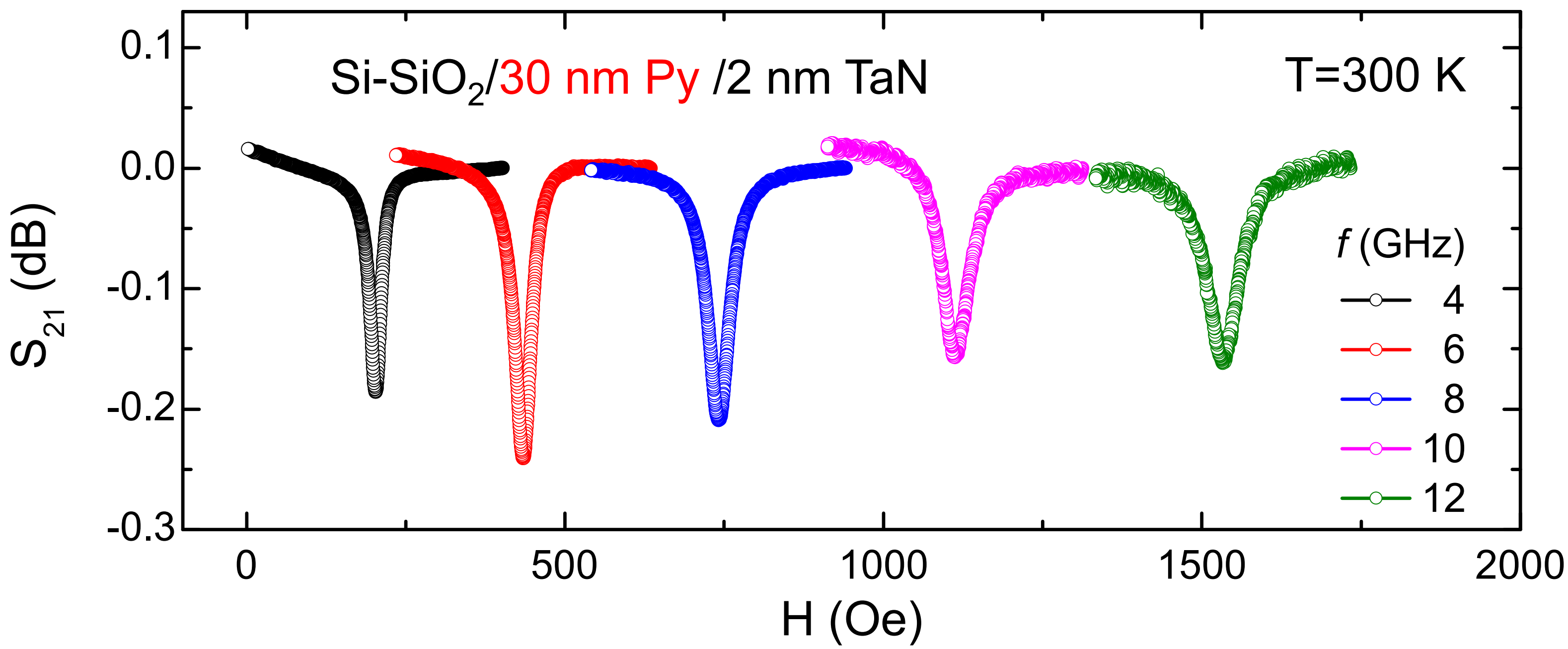




Coplanar Waveguide

Magnetic resonance

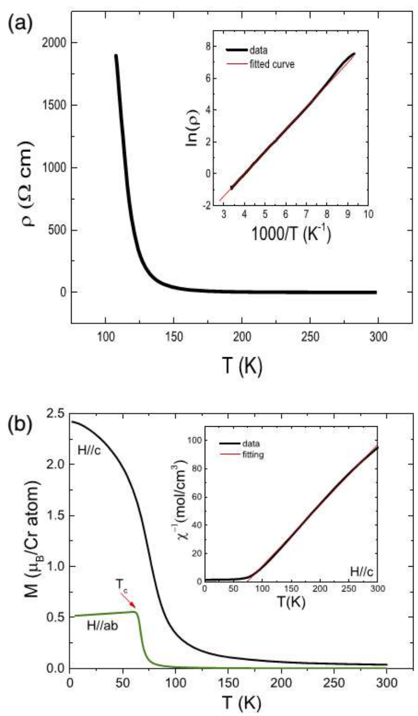
Metallic FM– Py (NiFe)

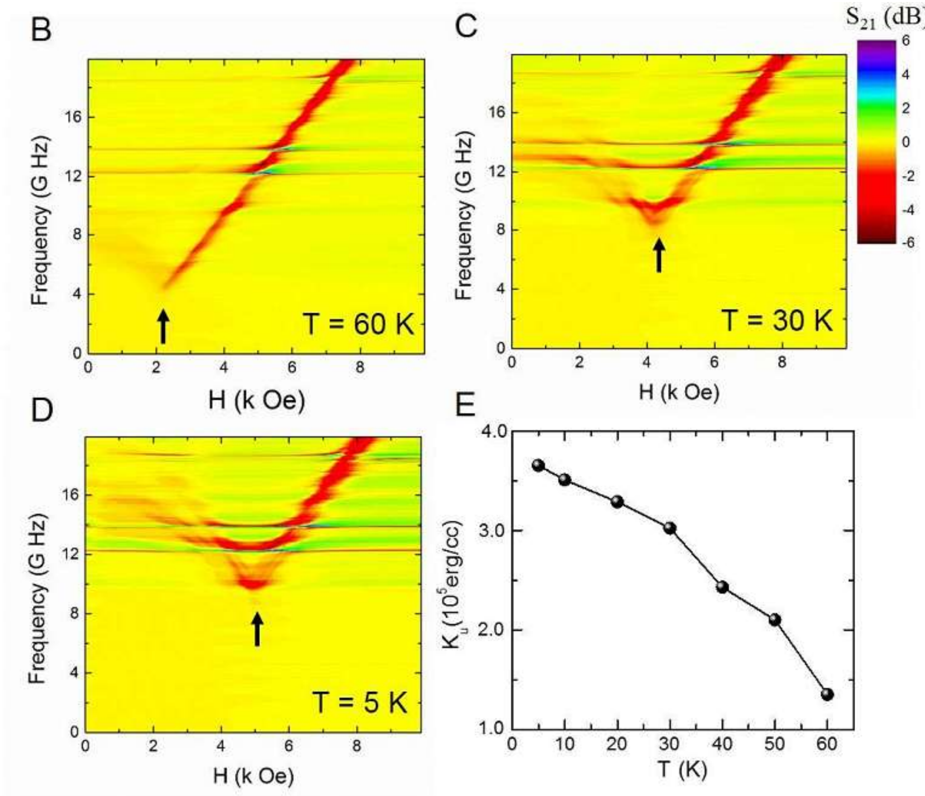


Zhao, et al, Scientific Reports (2016)

Magnetic resonance

Semiconducting FM—Cr2Ge2Te6

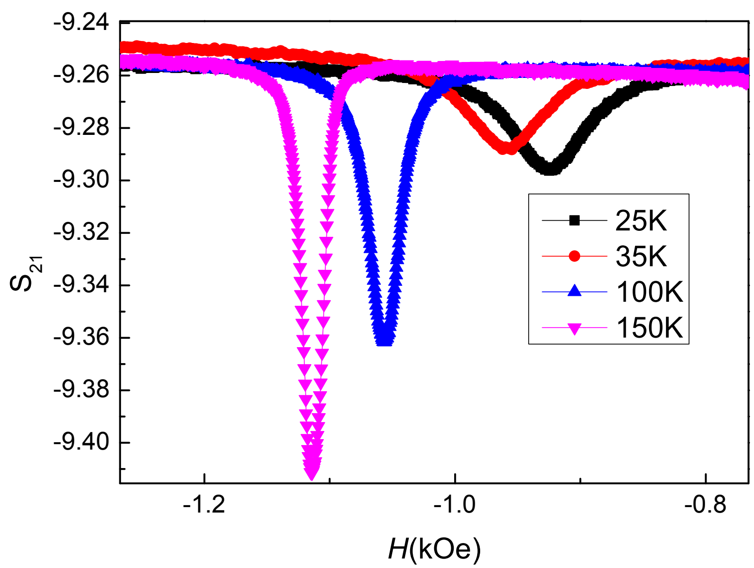


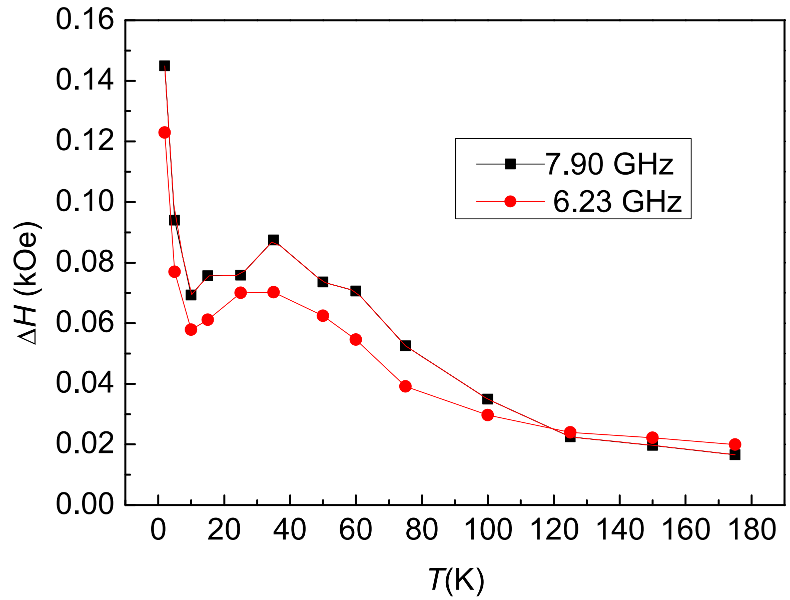


Zhang, et al, JJAP (2016)

Magnetic resonance

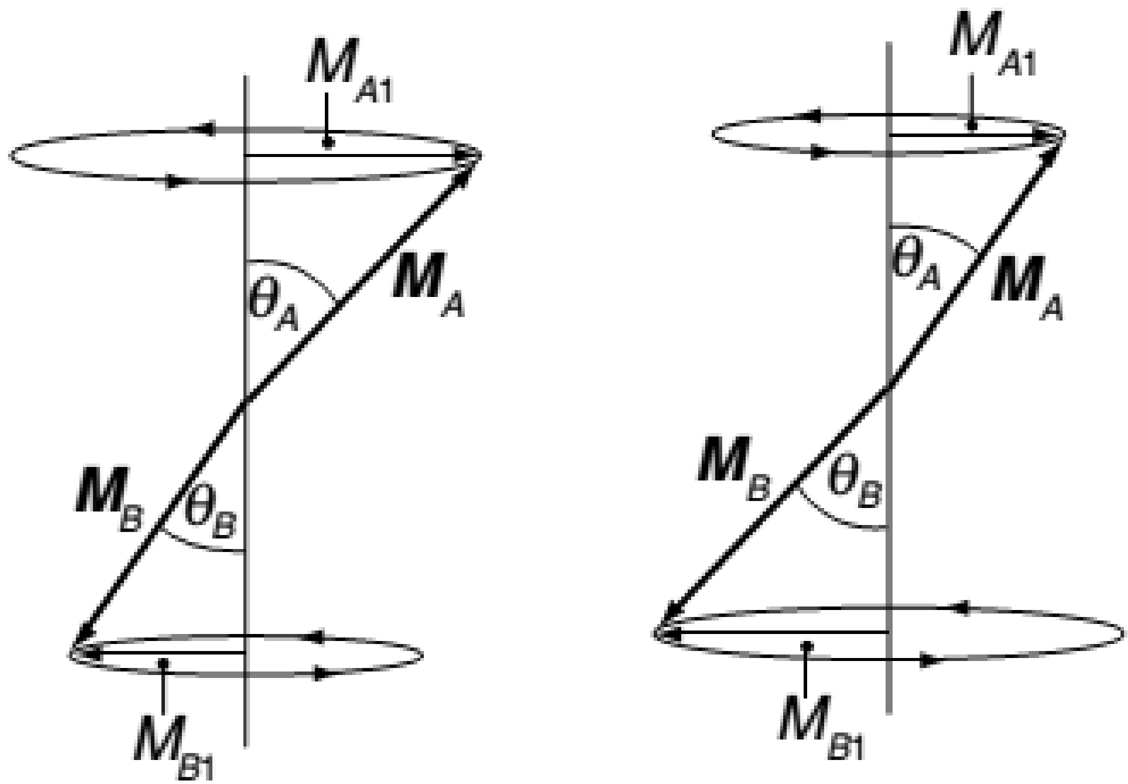
Insulating FM-- YIG





Antiferromagnetic resonance

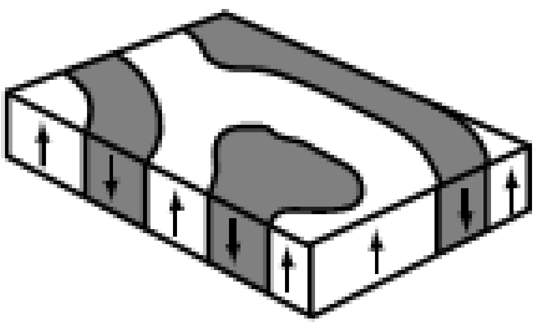
Precessing Modes

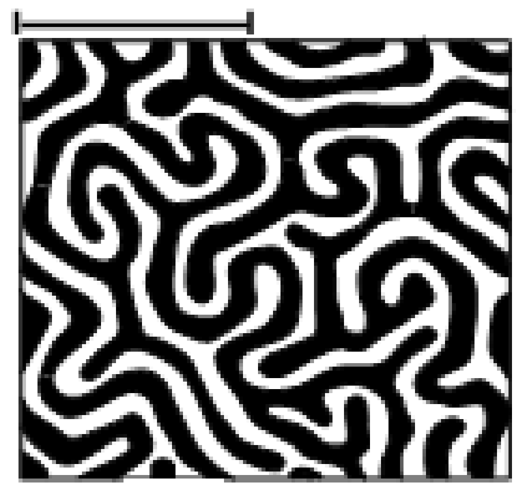


$$\omega_0 = \gamma \mu_0 [H_a(H_a + 2H_{ex})]^{\frac{1}{2}}.$$

Magnetic domains

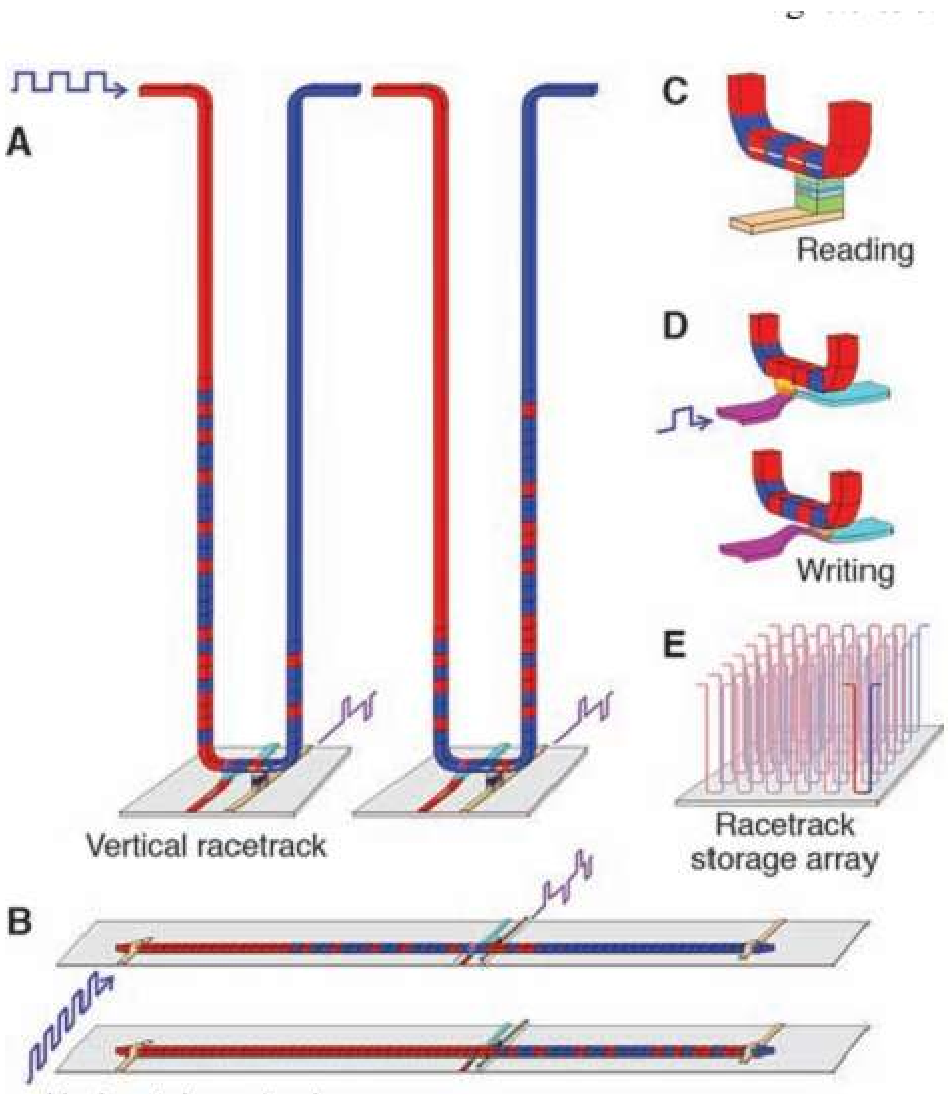
FM domains





Magnetic domains

Racetrack memory



Summary

- Magnetism of Electrons
- Spin orbit Coupling
- Magnetism

    Diamangetism, Paramagnetism,
    FM, AFM, Ferrimagnet, Half metallic

- Magnetic resonance
- Magnetic domains

休息10分钟

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**

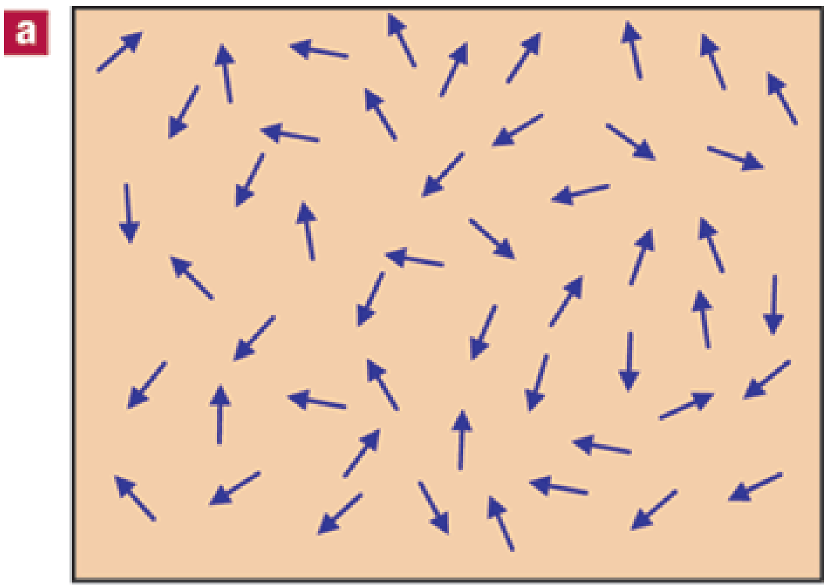
  Diamangetism, Paramagnetism,
  FM, AFM, Ferrimagnet, Half metallic
- **Magnetic resonance**
- **Magnetic domains**

2. How to induce magnetic moment

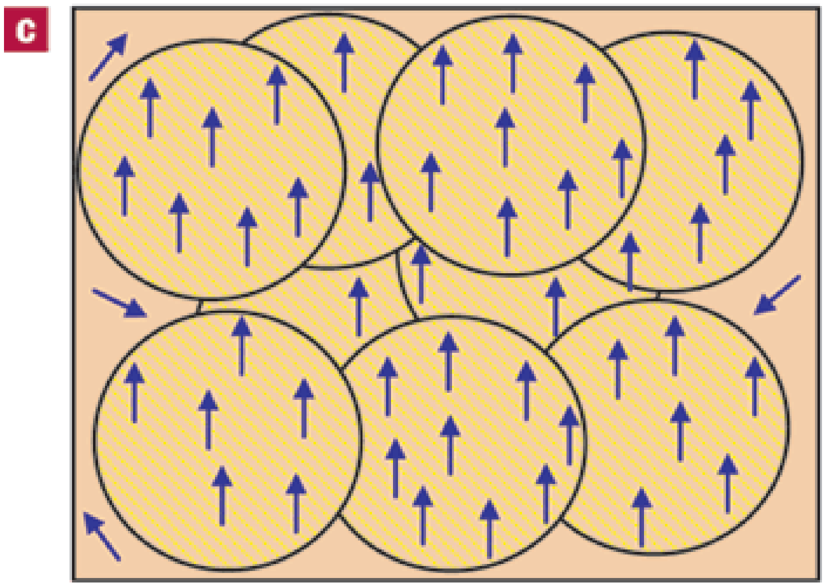
Mainly two methods

1) Impurity doping

Mn impurity in GaMnAs



Low doping

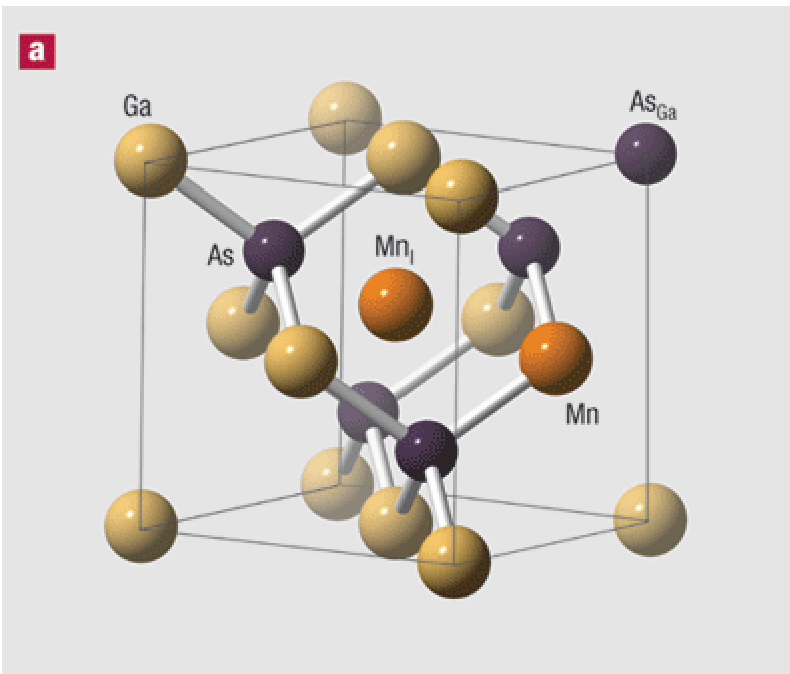


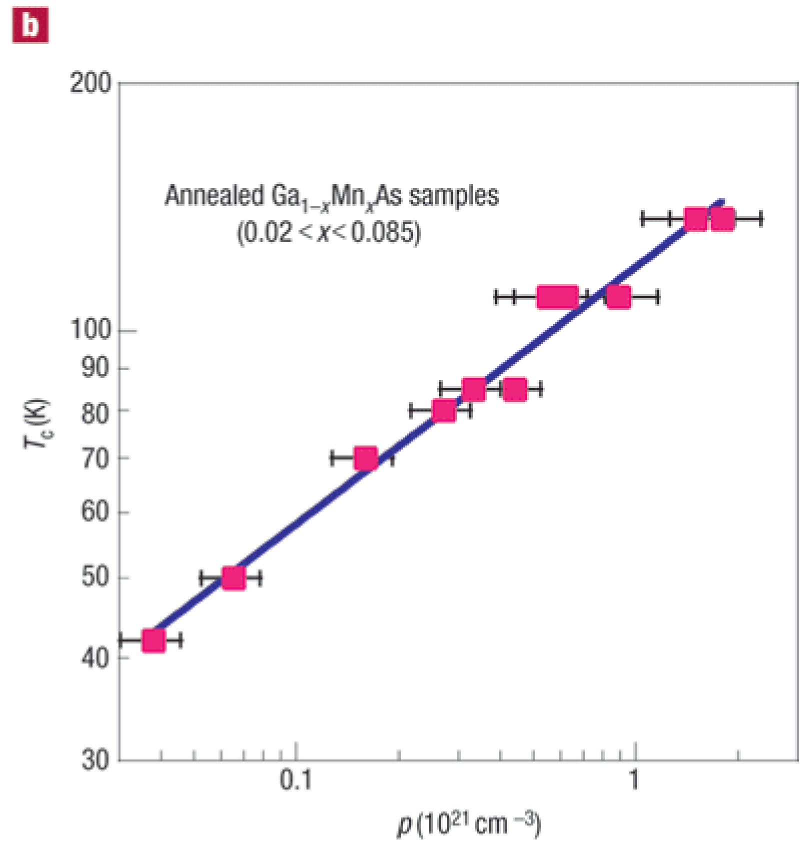
High doping

MacDonald, et al, Nature Mater. (2005)

Mainly two methods

1) Impurity doping



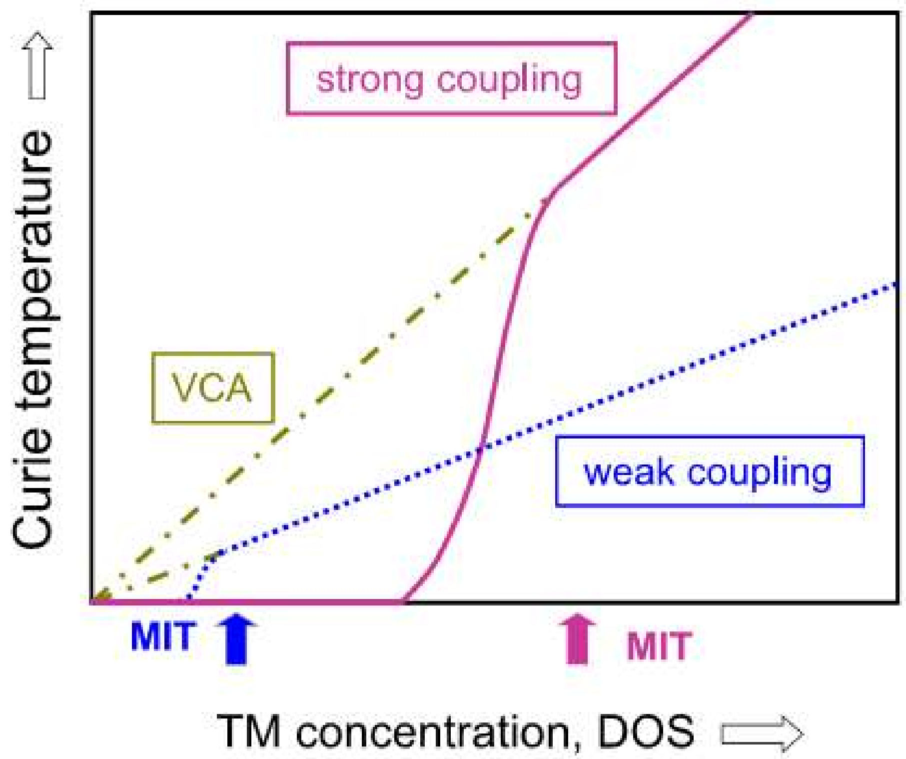


MacDonald, et al, Nature Mater. (2005)

Mainly two methods

1) Impurity doping

p-d Zener mode



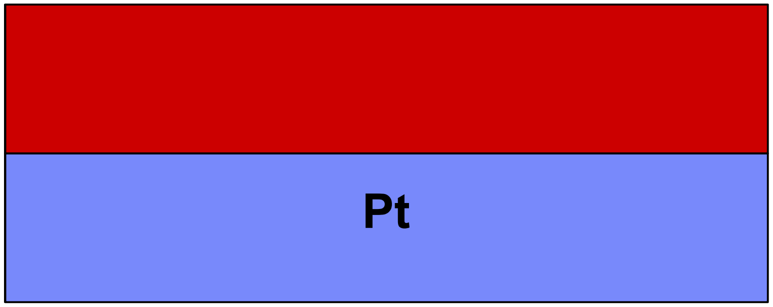
Dietl, et al, Science (2010)

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.

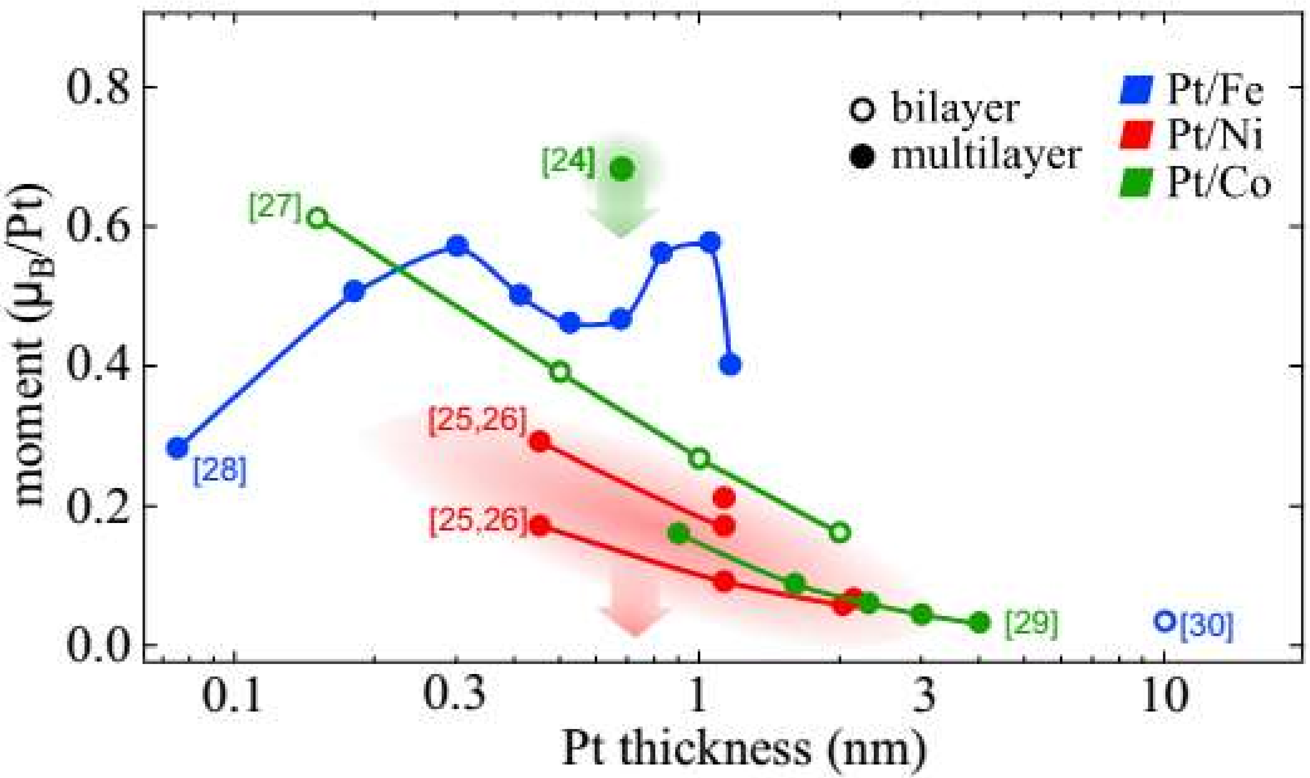
FM



Interface hybridization

Mainly two methods

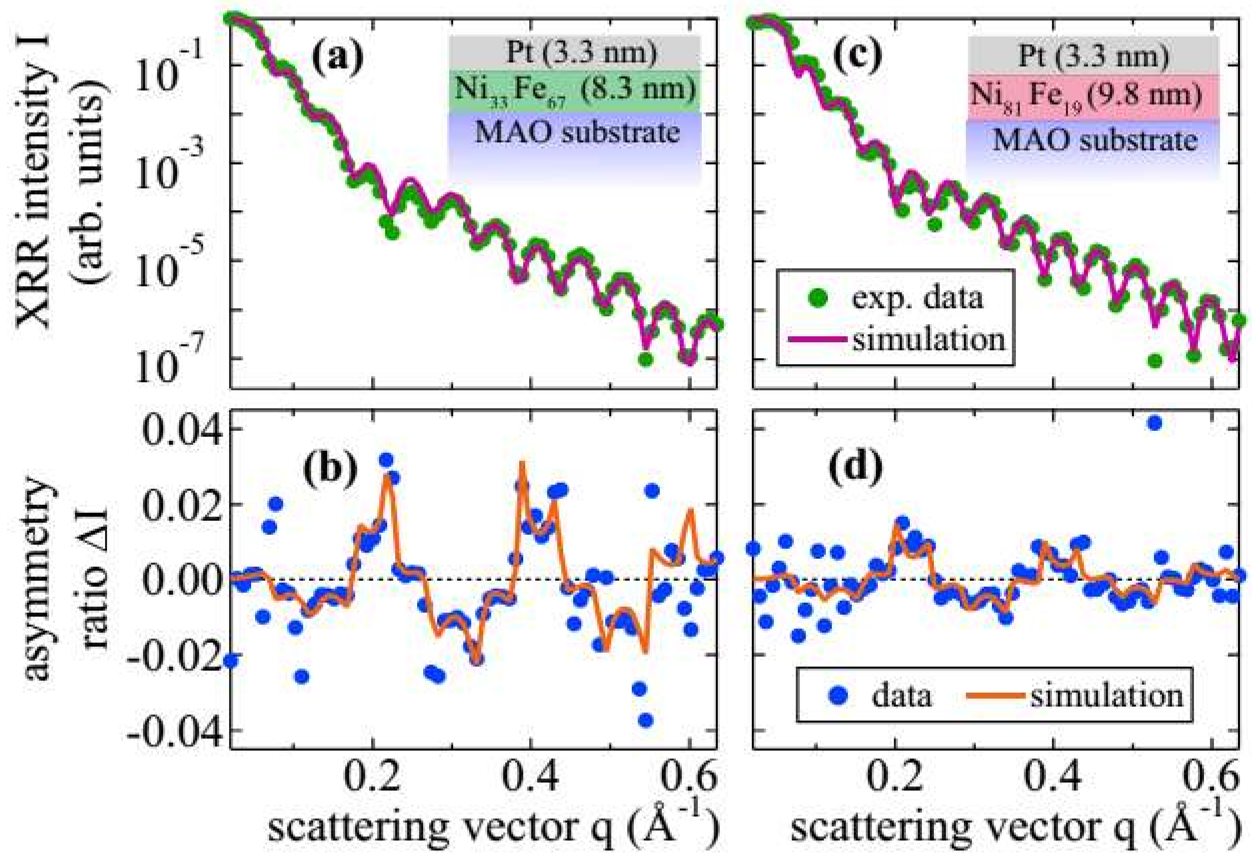
2) Proximity effect



Klewe, et al, PRB (2016)

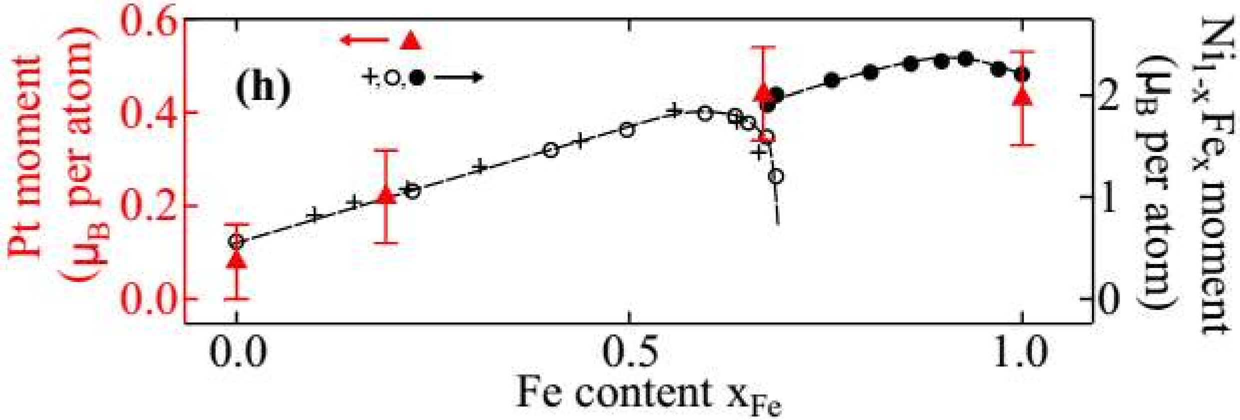
Mainly two methods

2) Proximity effect



Mainly two methods

2) Proximity effect

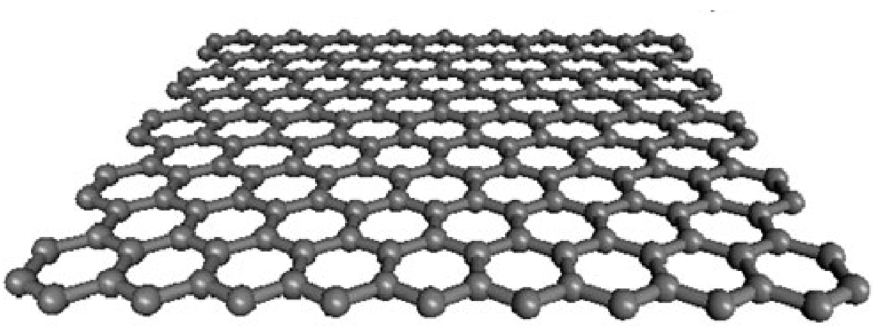


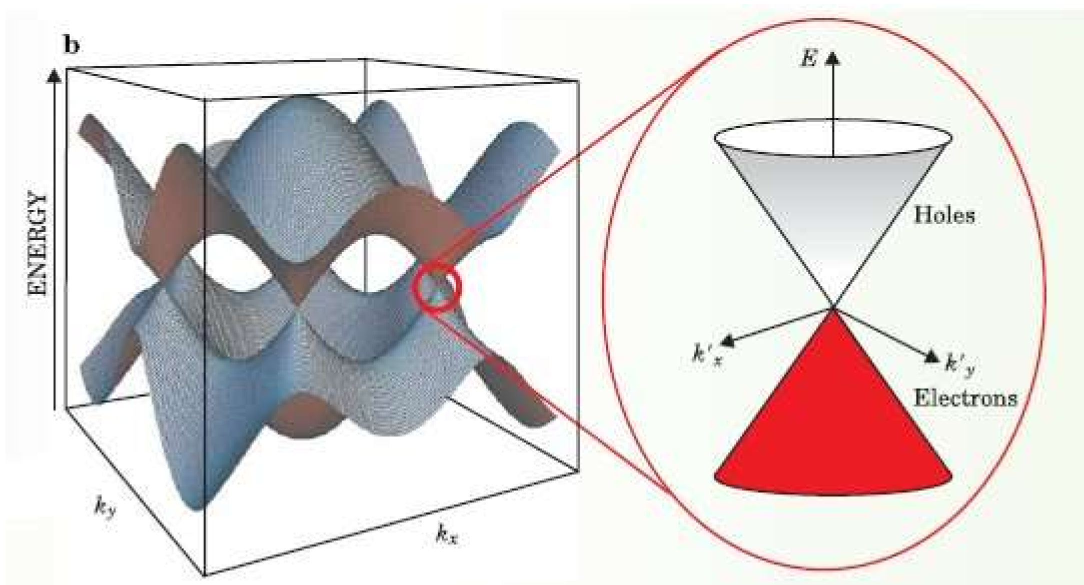
Composition	Pt thickness (nm)	FM thickness (nm)	Magnetic moment (μ_B per atom)
Pt/Fe	1.8	9.8	0.2 ± 0.1[a]
	3.4	9.2	0.6 ± 0.1[a]
	5.9	9.8	0.6 ± 0.1[a]
	20.0	9.8	0.6 ± 0.1[a]
	3.4	9.2	0.43 ± 0.08[b]
Pt/$Ni_{33}Fe_{67}$	3.3	8.3	0.44 ± 0.10[b]
Pt/$Ni_{81}Fe_{19}$	3.3	9.8	0.22 ± 0.10[b]
Pt/Ni	3.2	9.8	0.08 ± 0.08[b]

Induce M in two Quantum Materials

Two Dirac Materials

Graphene

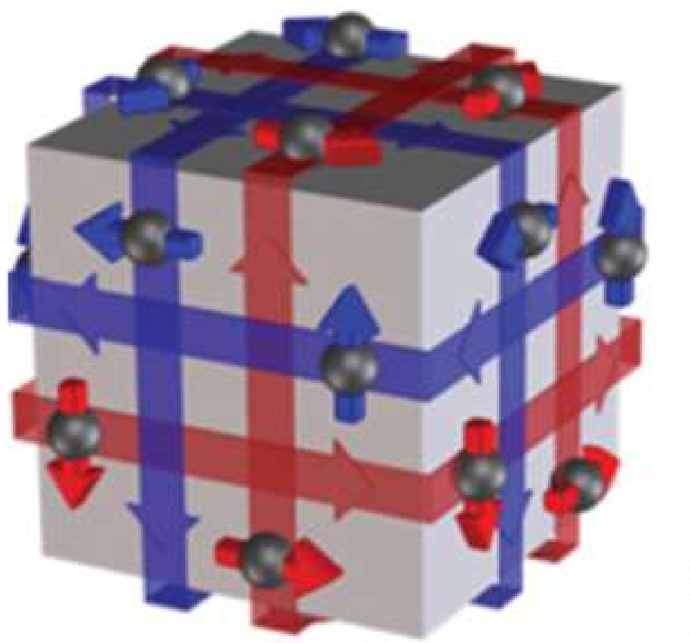




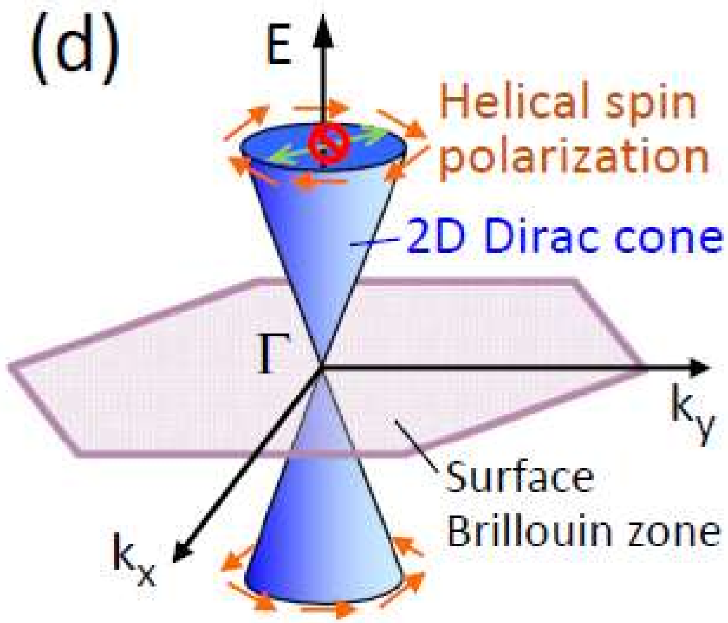
Induce M in two Quantum Materials

Two Dirac Materials

Topological Insulator



3D Topological insulator



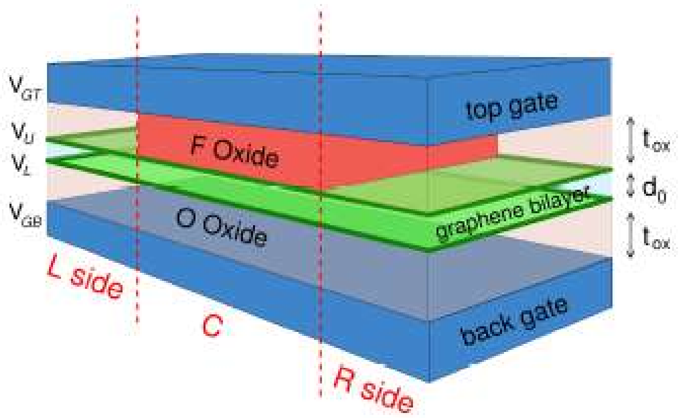
Induce M in graphene

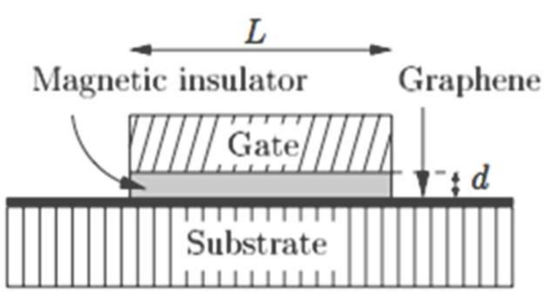
Why making graphene magnetic

PHYSICAL REVIEW B **83**, 155447 (2011)

Quantum anomalous Hall effect in single-layer and bilayer graphene

Wang-Kong Tse,[1] Zhenhua Qiao,[1] Yugui Yao,[1,2] A. H. MacDonald,[1] and Qian Niu[1,3,*]





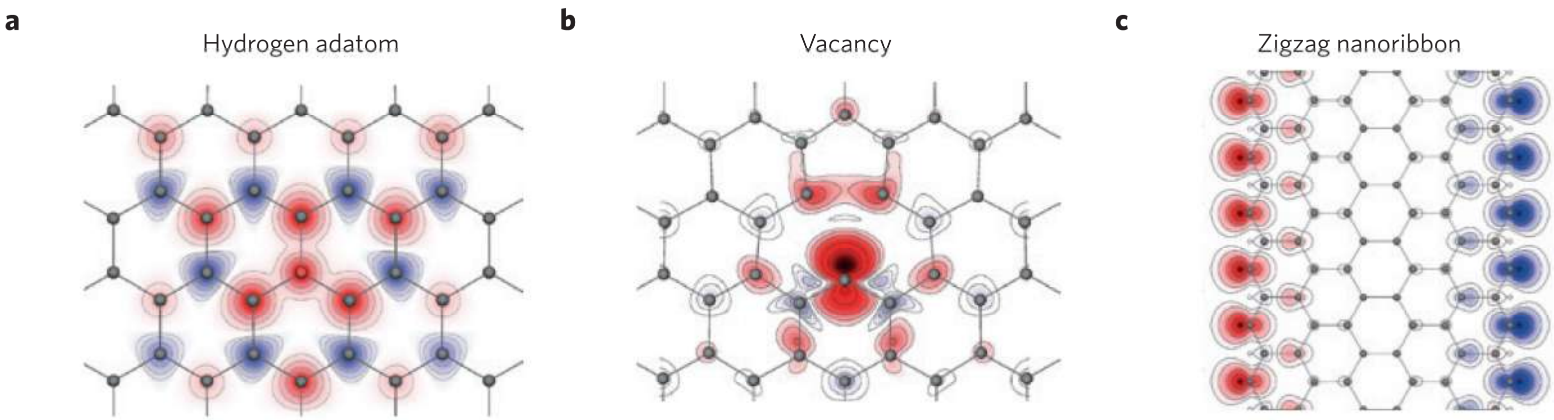
PHYSICAL REVIEW B 77, 115406 (2008)

Spin transport in proximity-induced ferromagnetic graphene

Håvard Haugen,* Daniel Huertas-Hernando, and Arne Brataas
Department of Physics, Norwegian University of Science and Technology, N-7491 Trondheim, Norway

Induce M in graphene

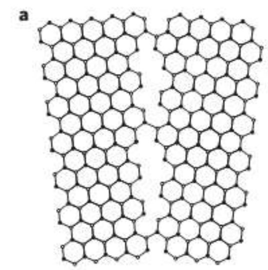
How to make graphene magnetic

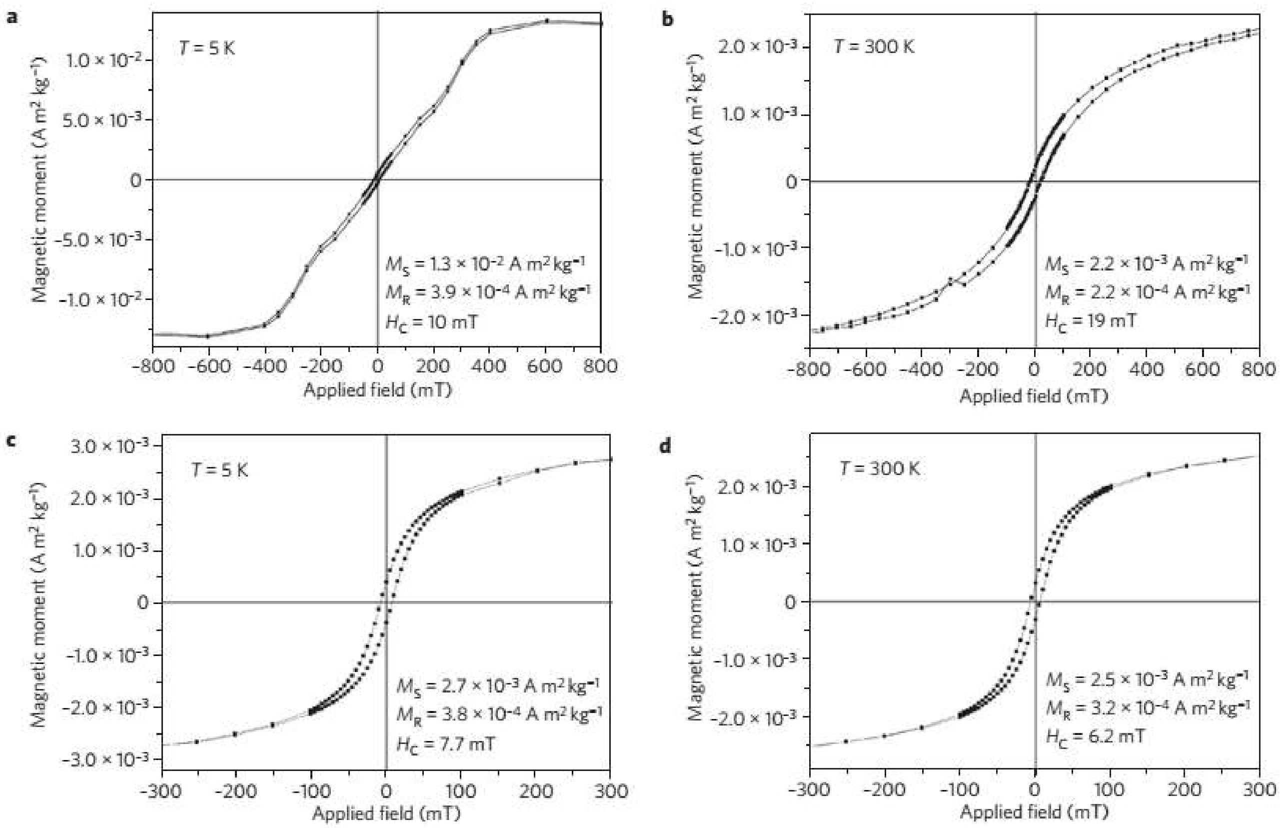


Yazyev and Helm, PRB (2007)
Han, et al, Nature Nanotech (2014)

Vacancies Defects

Vacancies Defects→ FM



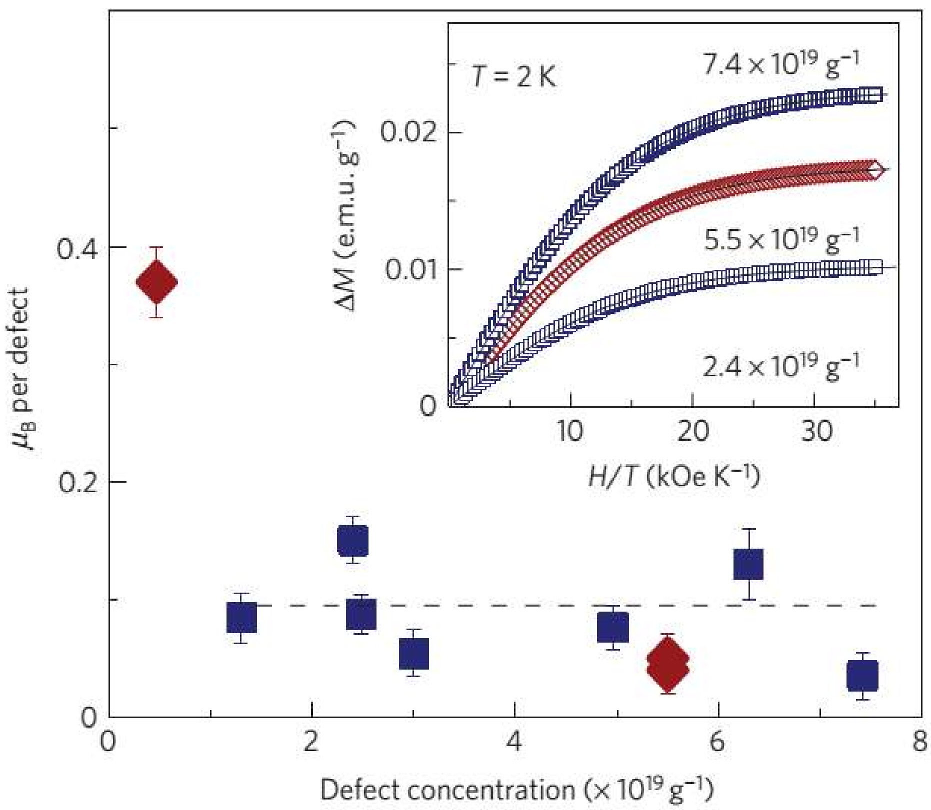


Cervenka, et al, Nature Phy. (2009)

Vacancies Defects

Vacancies Defects→ PM

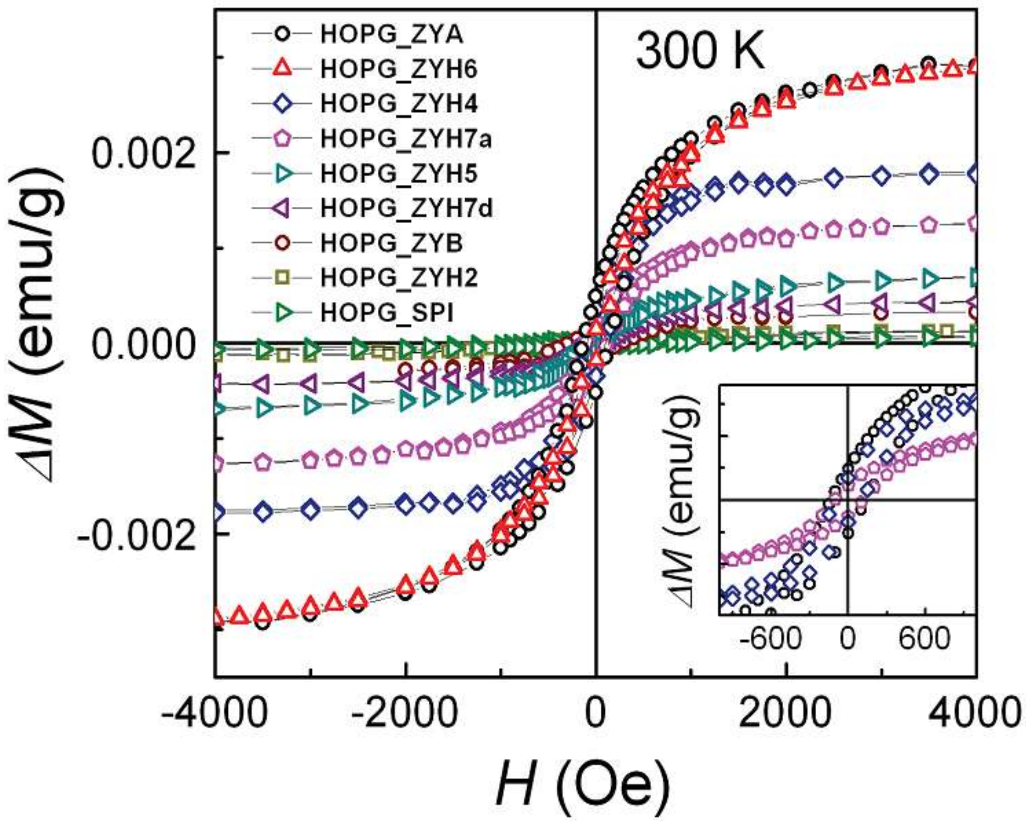
$$M = NgJ\mu_B \left[\frac{2J}{2J+1} \operatorname{ctnh}\left(\frac{(2J+1)z}{2J}\right) - \frac{1}{2J} \operatorname{ctnh}\left(\frac{z}{2J}\right) \right]$$



Nair, et al, Nature Phy. (2012)

Vacancies Defects

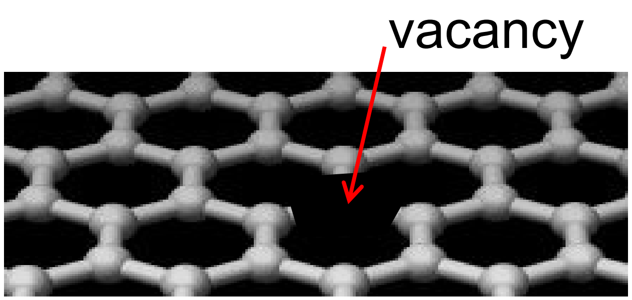
Vacancies Defects→ PM



Nair, et al, Nature Phy. (2012)

Vacancies Defects

Question?

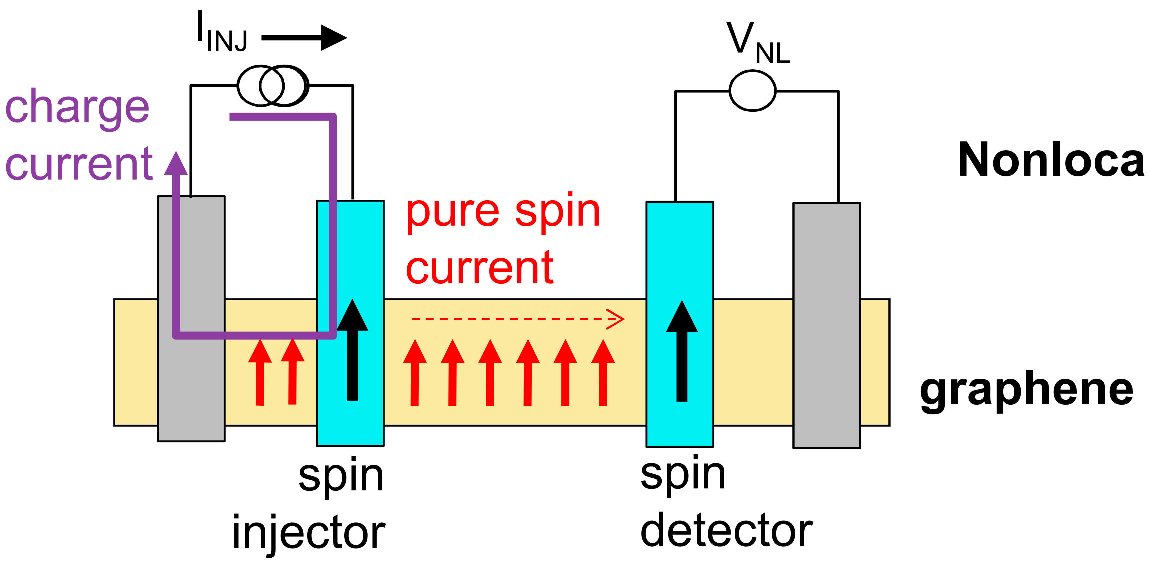


Ferromagnetic ??

Paramagnetic ??

Vacancies Defects

Using the spin current approach

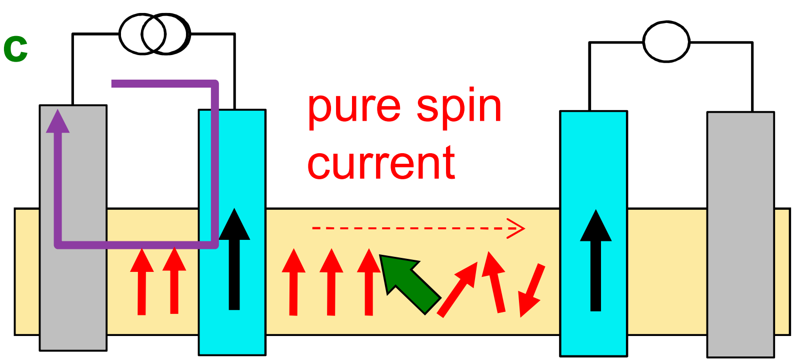


Nonlocal spin transport geometry

Vacancies Defects

Using the spin current approach

With magnetic moment



Magnetic moment could scatter pure spin current through exchange interaction:

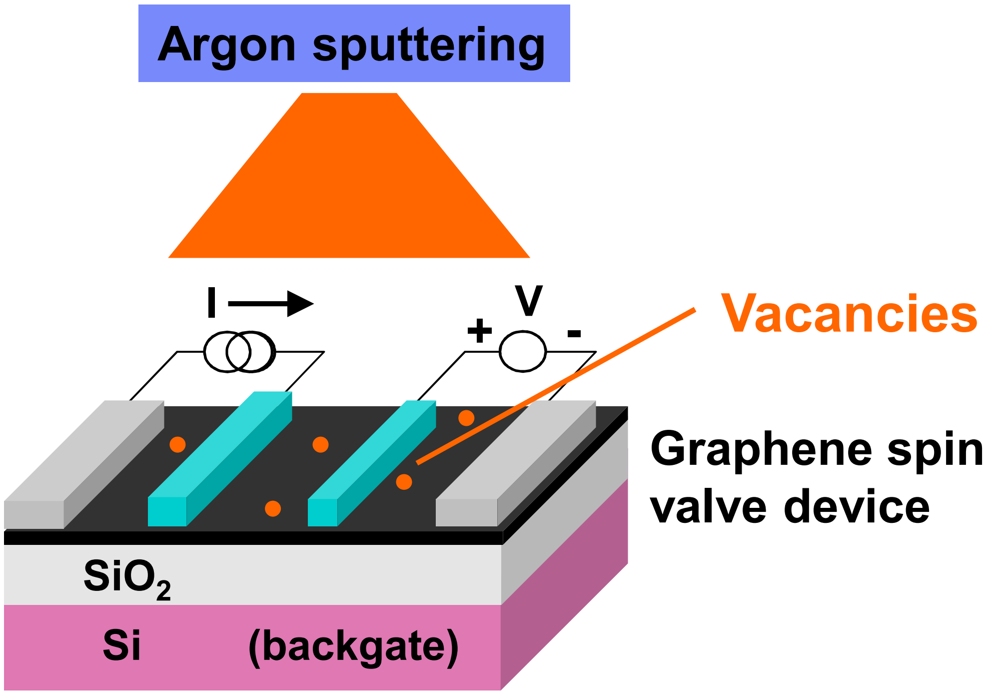
$$\mathcal{H}_{ex} = A_{ex}\, \vec{S}_e \cdot \vec{S}_M$$

- Localized measurement
- Direct coupling of spin to magnetic moment

Vacancies Defects

Using the spin current approach

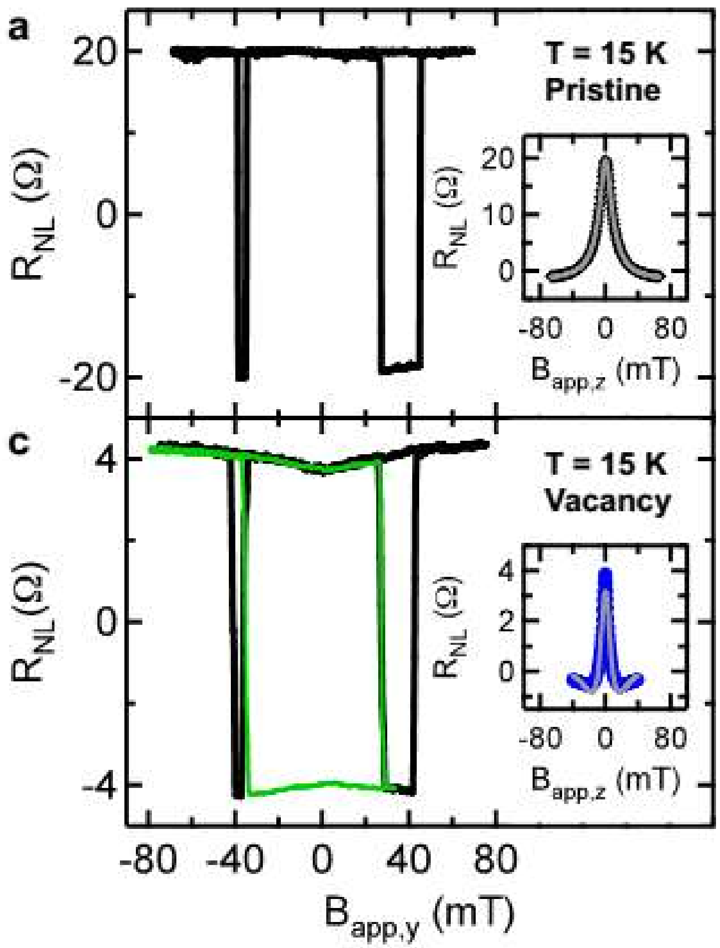
- **All measurements done in ultrahigh vacuum (UHV)**
- **Compare immediately before and after hydrogen doping**

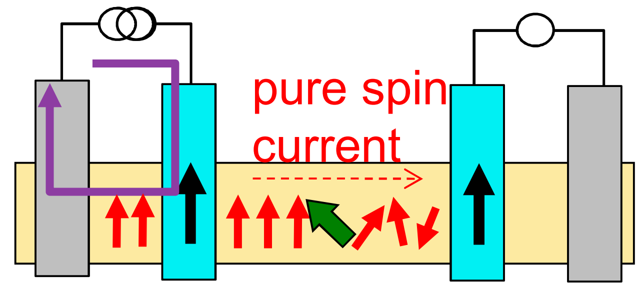


McCreary, et al, PRL (2012)

Vacancies Defects

Using the spin current approach





At zero field

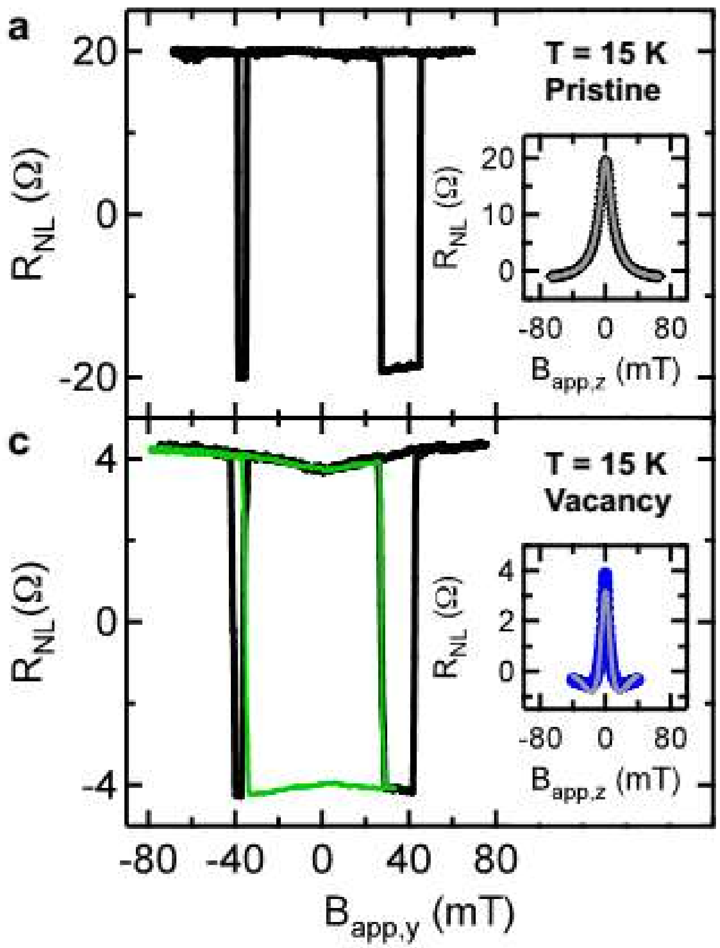
$$H_{ex} = A_{ex}\,\vec{S}_e \cdot \vec{S}_M$$

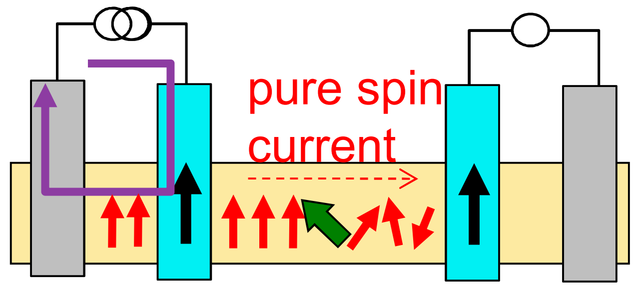
Due to exchange coupling, pure spin current is scattered by magnetic moment

Fewer spins at detector

Vacancies Defects

Using the spin current approach





At high field

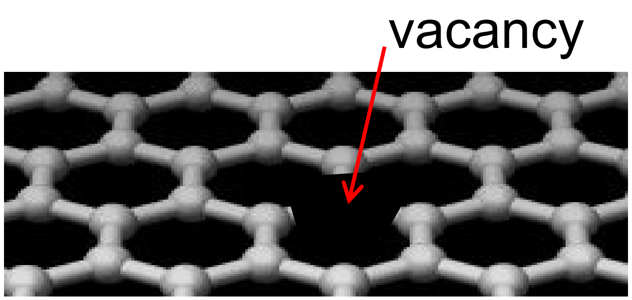
$\vec{S}_e$ and $\vec{S}_M$ decouple!

Scattering by exchange coupling is suppressed

More spins at detector

Vacancies Defects

Question?



Ferromagnetic ??

Paramagnetic > 15 K

下一节课: Sept. 27 th

1. Introduction to magnetism

2. How to induce magnetic moment

3. How to control magnetization

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

谢谢！