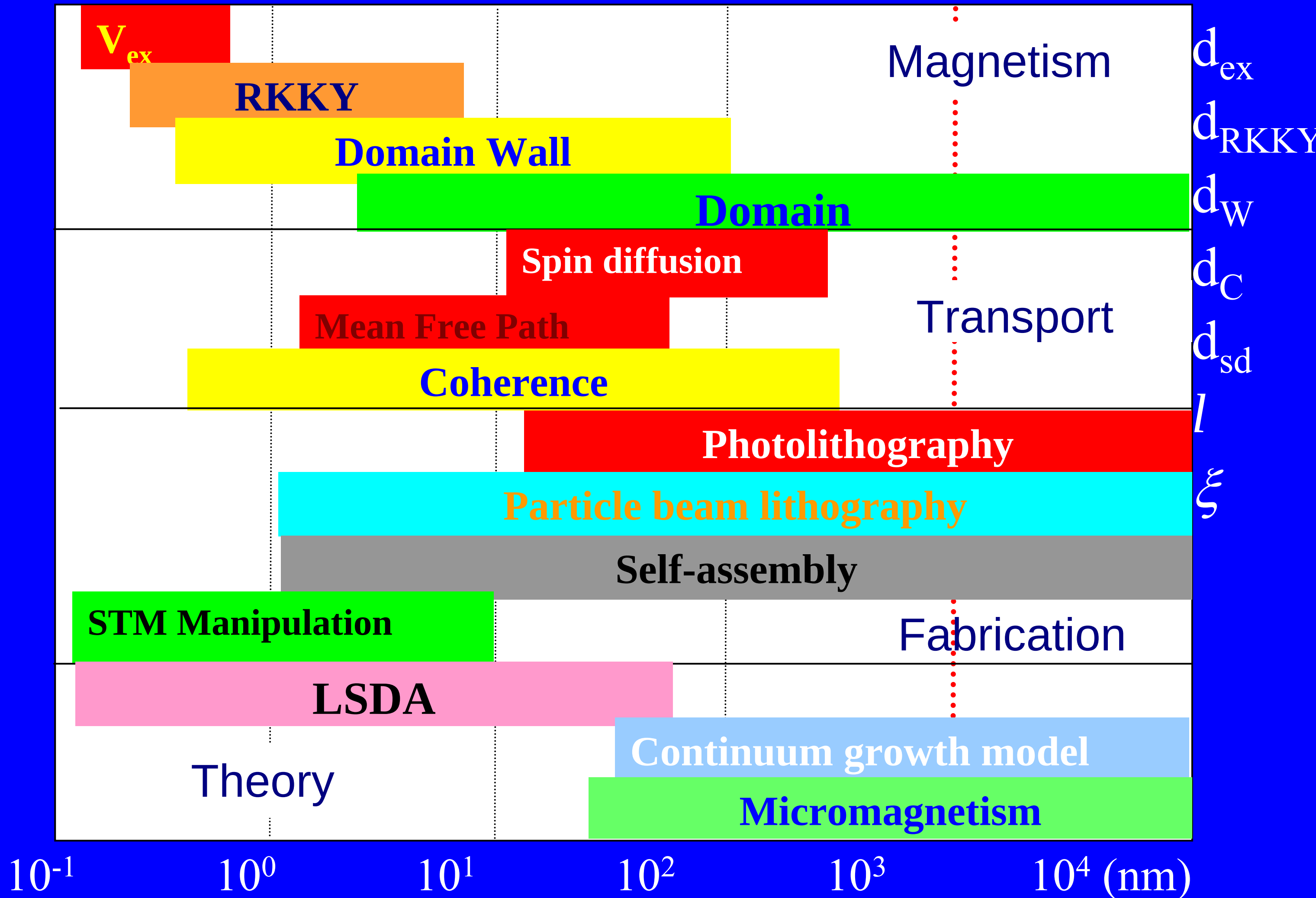
磁性纳米结构的可控生长与磁性调控

成昭华

中国科学院物理研究所磁学国家重点实验室

特征物理长度



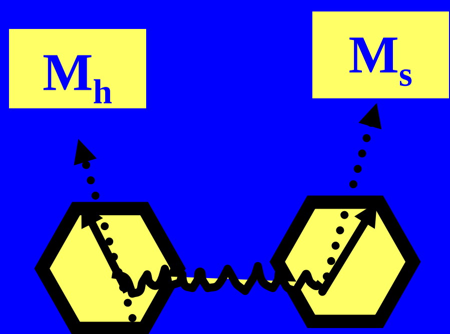
V_{ex}
RKKY
Domain Wall
Domain
Magnetism
Spin diffusion
Mean Free Path
Coherence
Transport
Photolithography
Particle beam lithography
Self-assembly
STM Manipulation
Fabrication
LSDA
Continuum growth model
Micromagnetism
Theory
d_{ex}
d_{RKKY}
d_{W}
d_{C}
d_{sd}
l
ξ
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4} (nm)

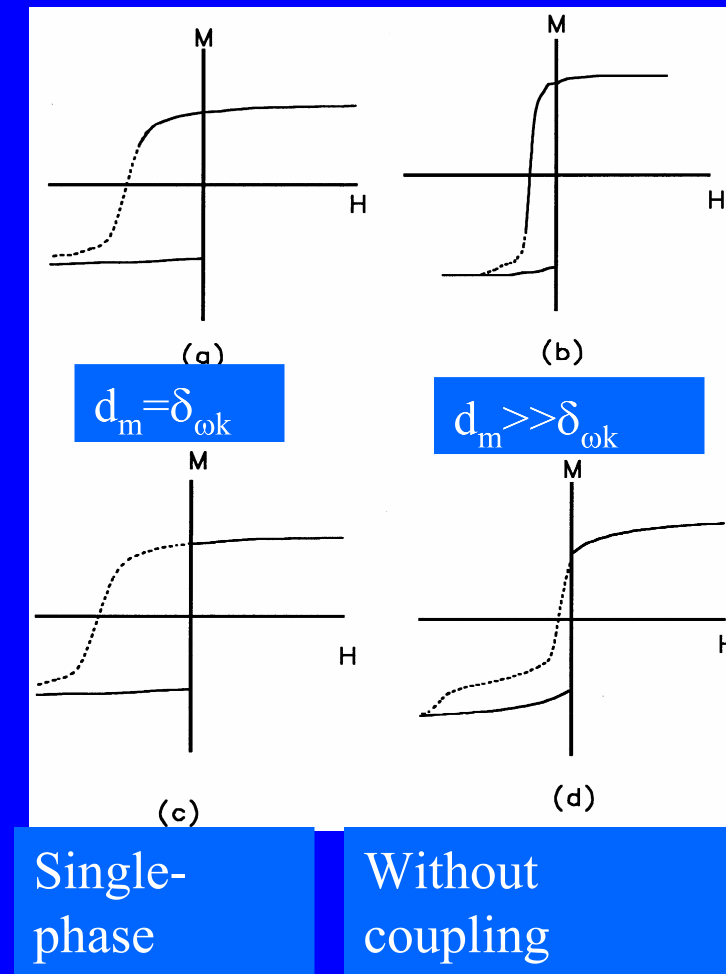
Exchange-spring magnets

交换弹性耦合与剩磁增强

晶粒尺寸 20 nm ～ 30 nm

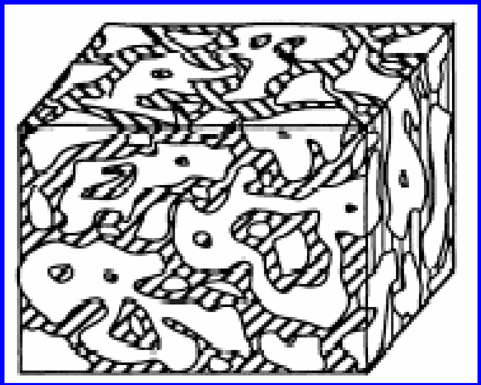
交换弹性耦合 ➡ 剩磁增强

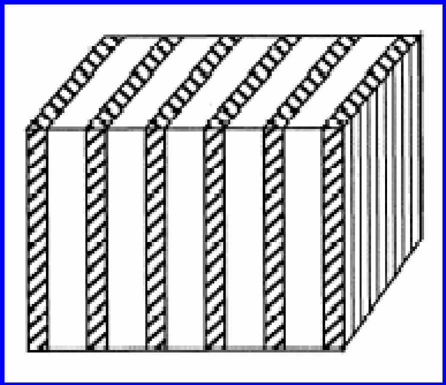




磁硬化机制不同于单相永磁

典型永磁材料性能实验与理论比较





$$M_r = f_h M_h + f_s M_s$$

$$H_n = 2\frac{f_s K_s + f_h K_H}{\mu_0 (f_s M_s + f_h M_h)}$$

$$(BH)_{\max} = \frac{1}{4}\mu_0 M_s^2 [1 - \frac{\mu_0 (M_s - M_h) M_s}{2K_h}]$$

实验值远远低于理论极限

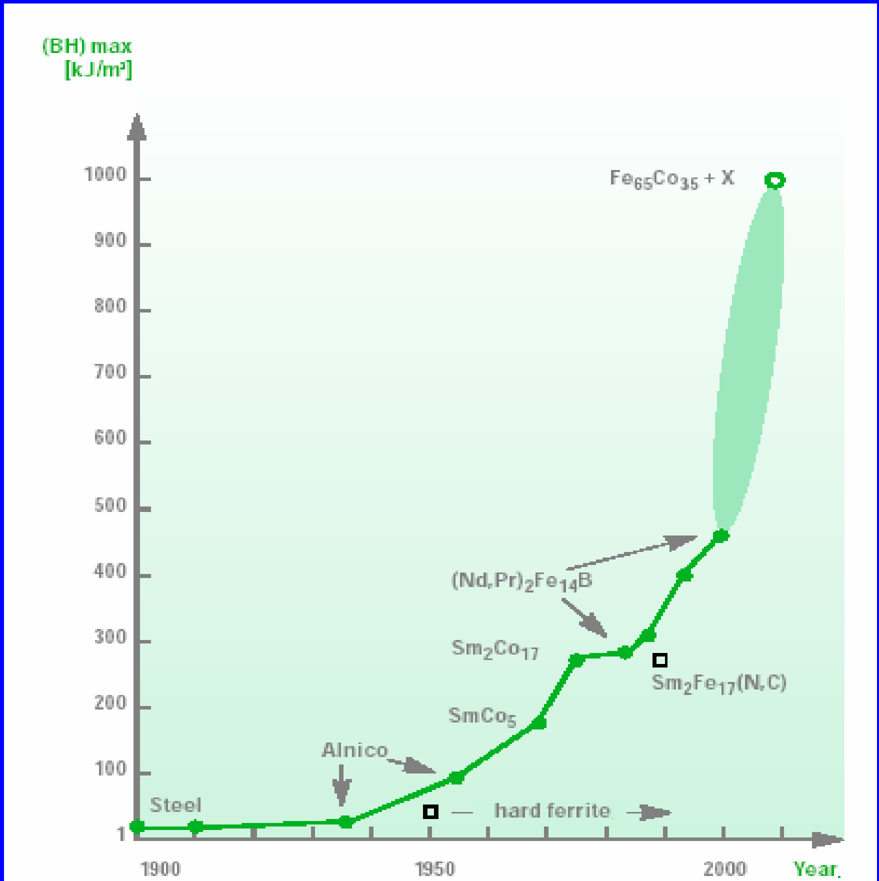
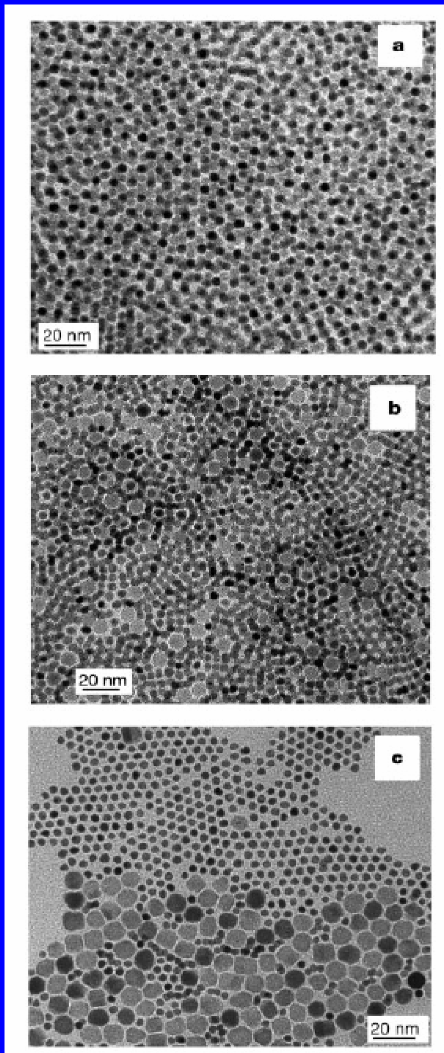
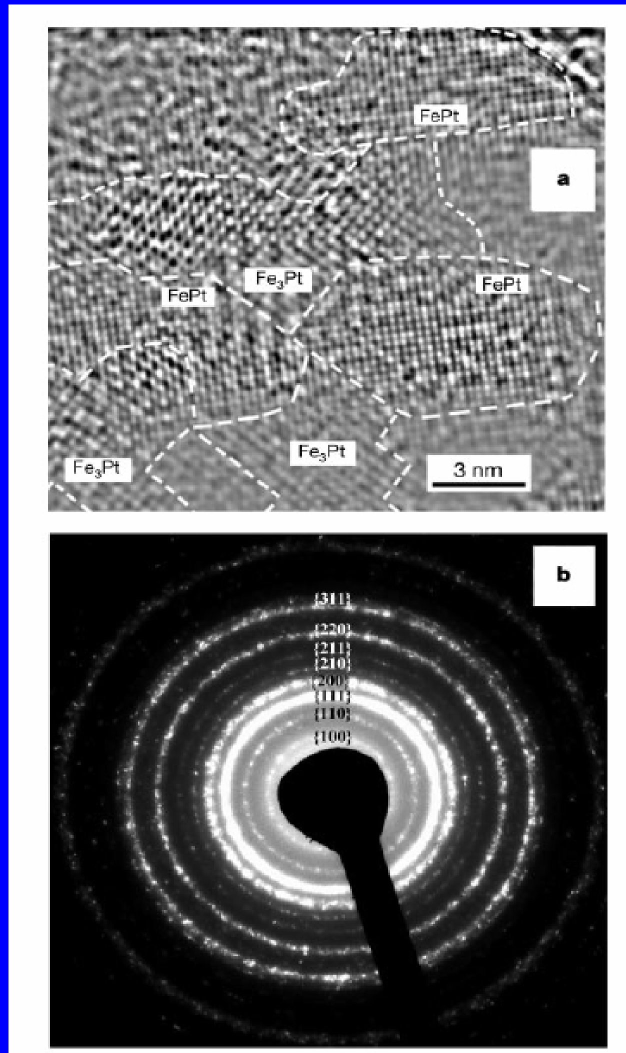
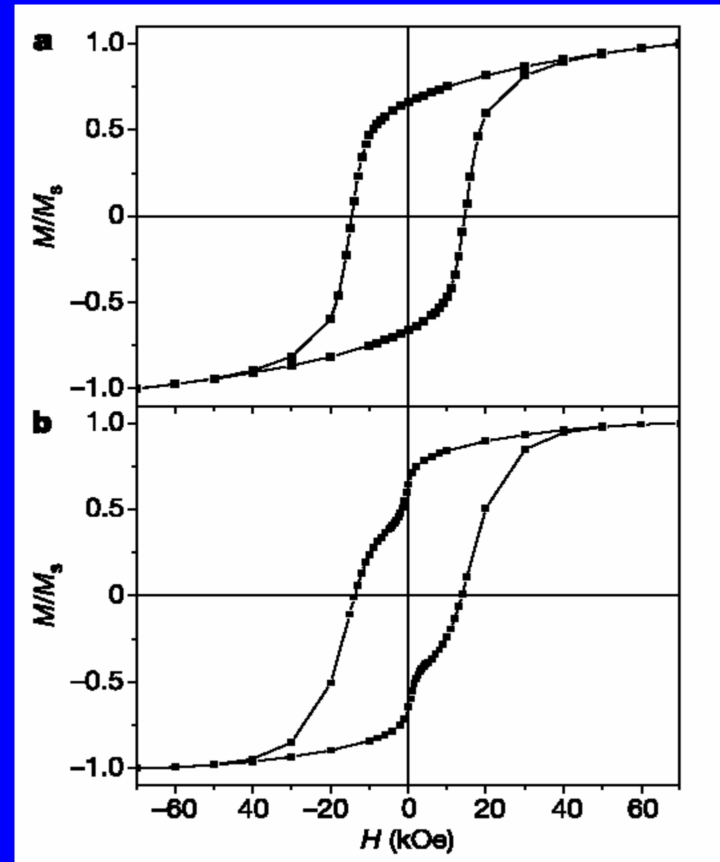


Fig. 2.15. Progress in improving $(BH)_{max}$ over the last century. The shaded region covers hypothetical FeCo-based alloys, which are magnetically hardened by additives X.

Self-assembly (particles)







(BH)max=20.1MG Oe

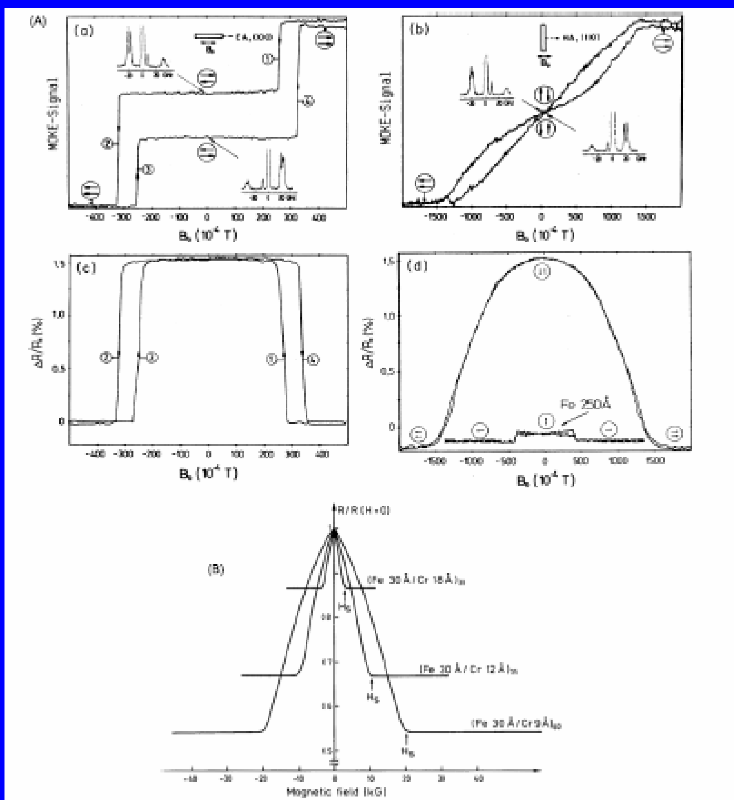
H. Zeng et al., Nature 420(2002)395

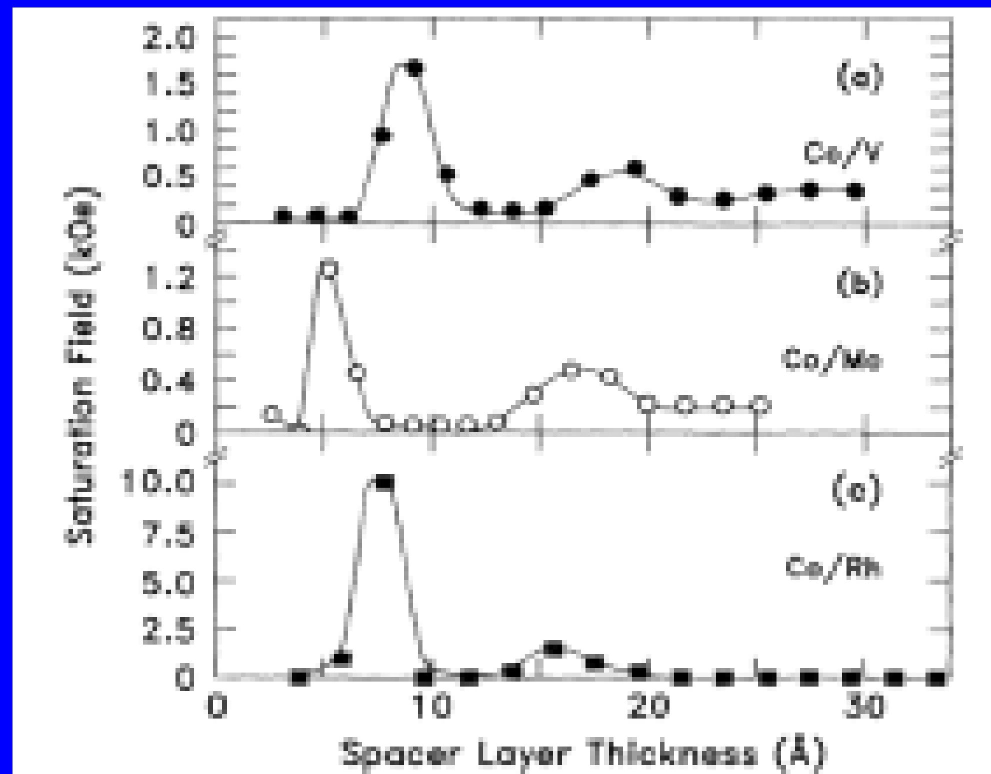
IOP Publishing Journal of Physics D: Applied Physics
J. Phys. D: Appl. Phys. 41 (2008) 093001 (20pp) doi:10.1088/0022-3727/41/9/093001

TOPICAL REVIEW

The discovery, development and future of GMR: The Nobel Prize 2007

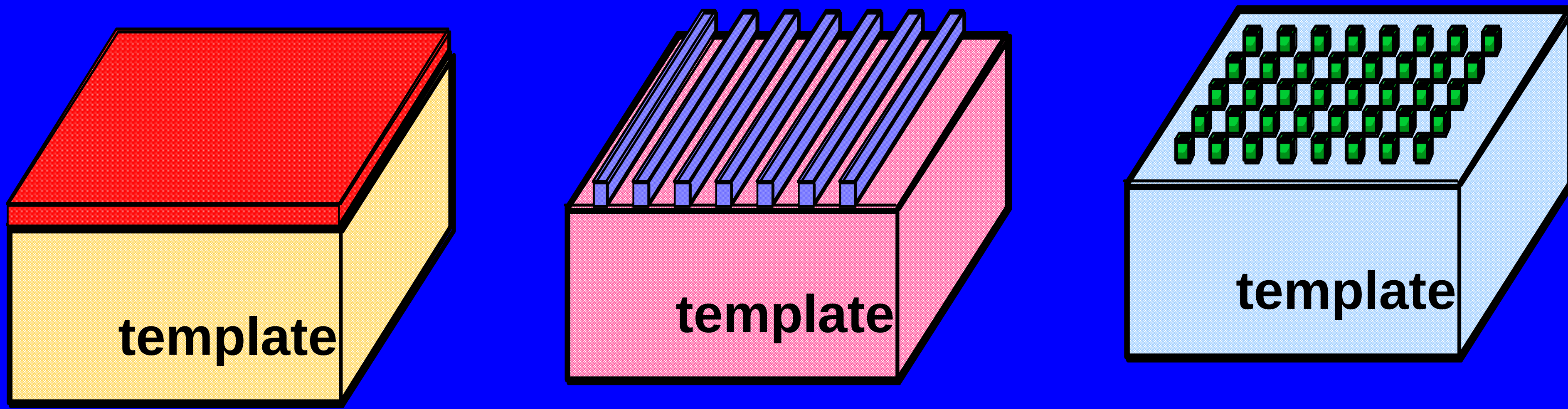
Sarah M Thompson





State Key Lab. of Magnetism, IPCAS; http://maglab.iphy.ac.cn

• 维度与磁性的关系


template
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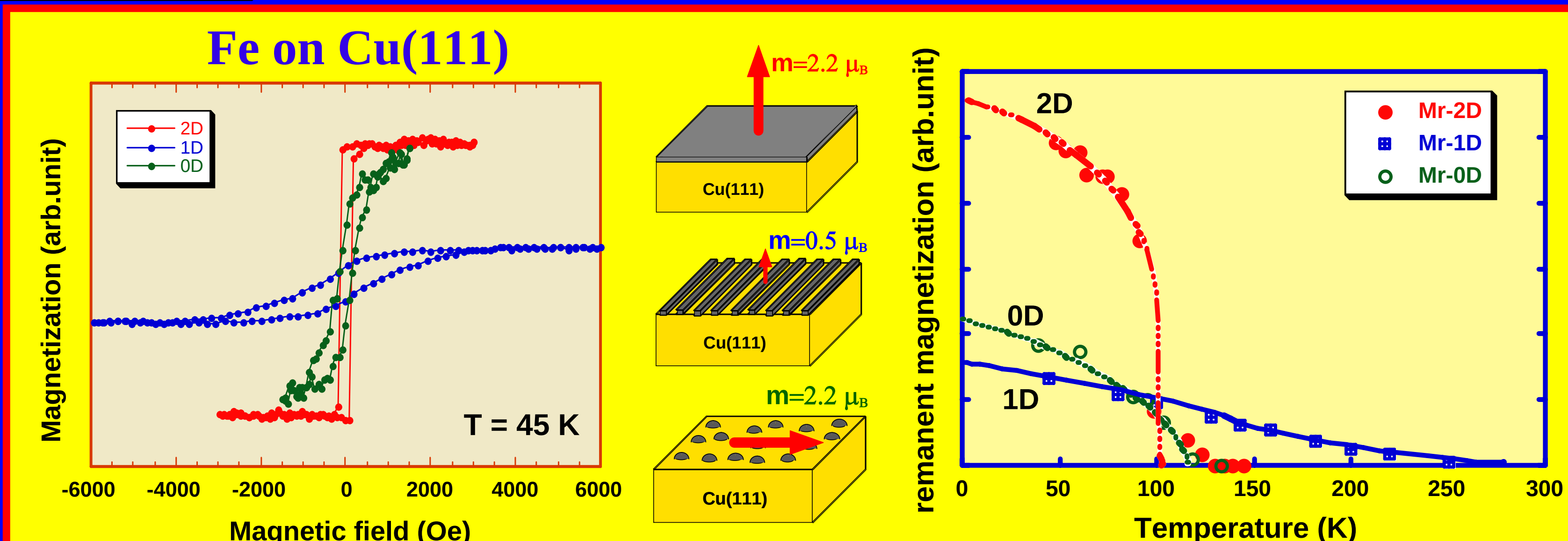
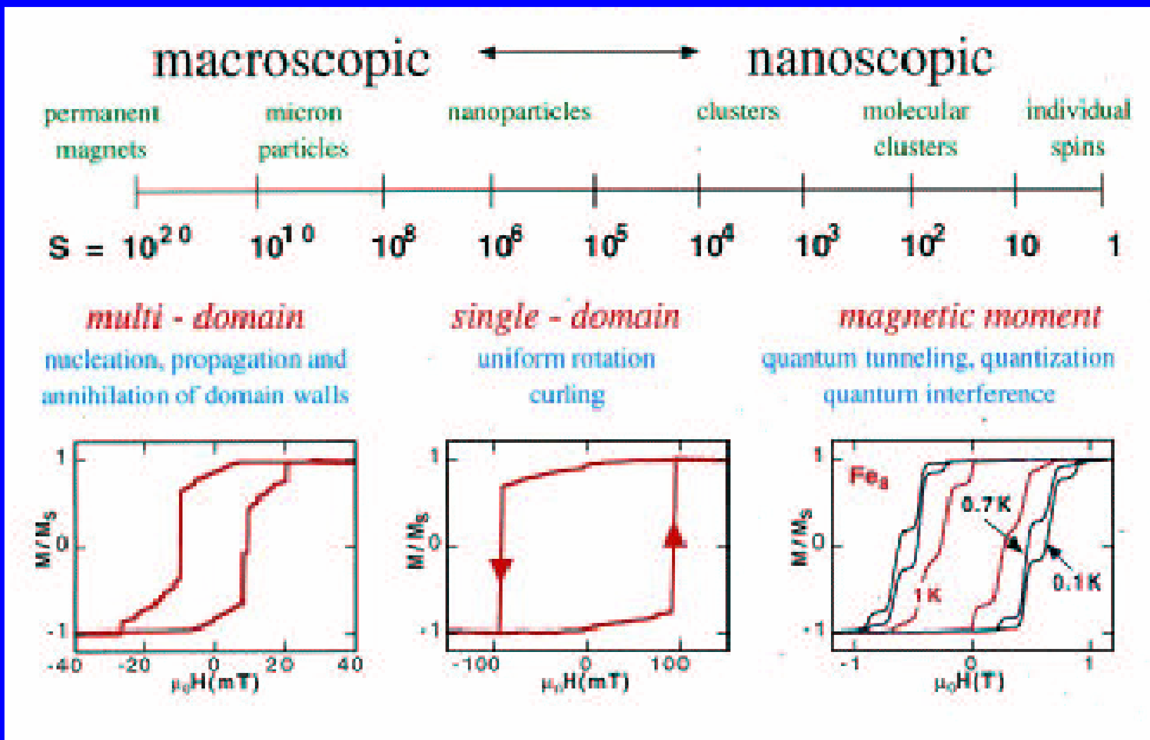
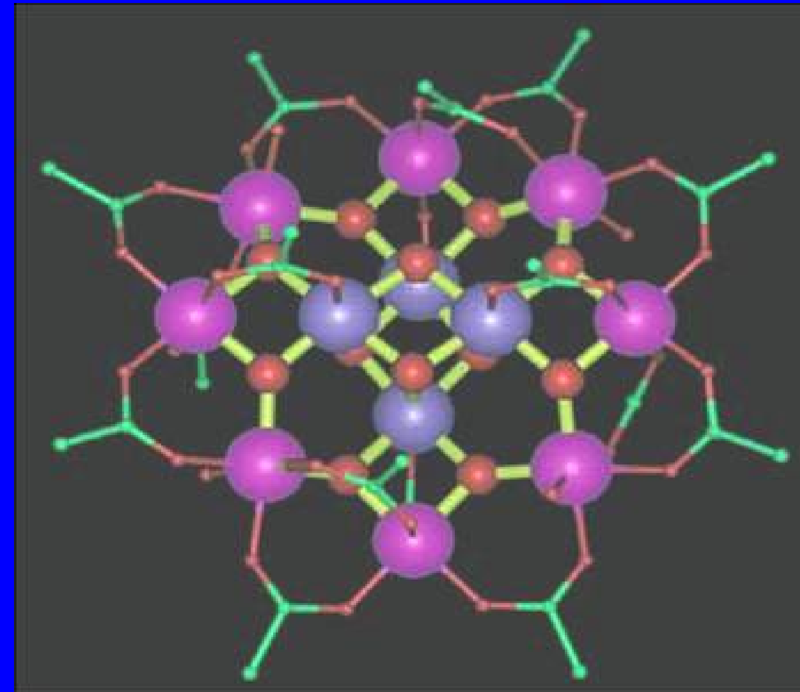
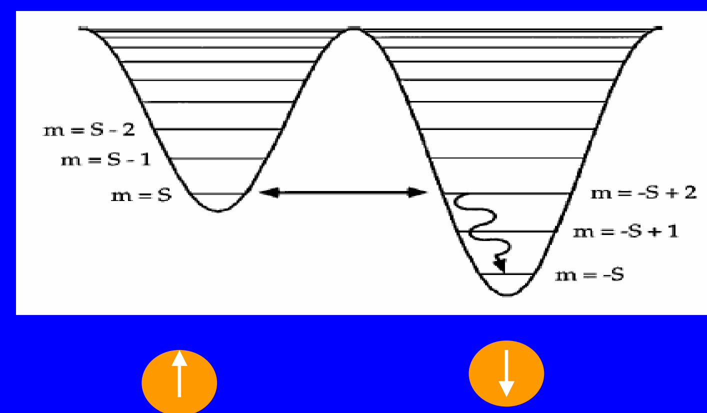

Fe on Cu(111)
2D
1D
0D
T = 45 K
Magnetization (arb.unit)
Magnetic field (Oe)
-6000
-4000
-2000
0
2000
4000
6000
m=2.2 μB
Cu(111)
m=0.5 μB
Cu(111)
m=2.2 μB
Cu(111)
remanent magnetization (arb.unit)
2D
0D
1D
Mr-2D
Mr-1D
Mr-0D
0
50
100
150
200
250
300
Temperature (K)

宏观量子效应和量子隧穿

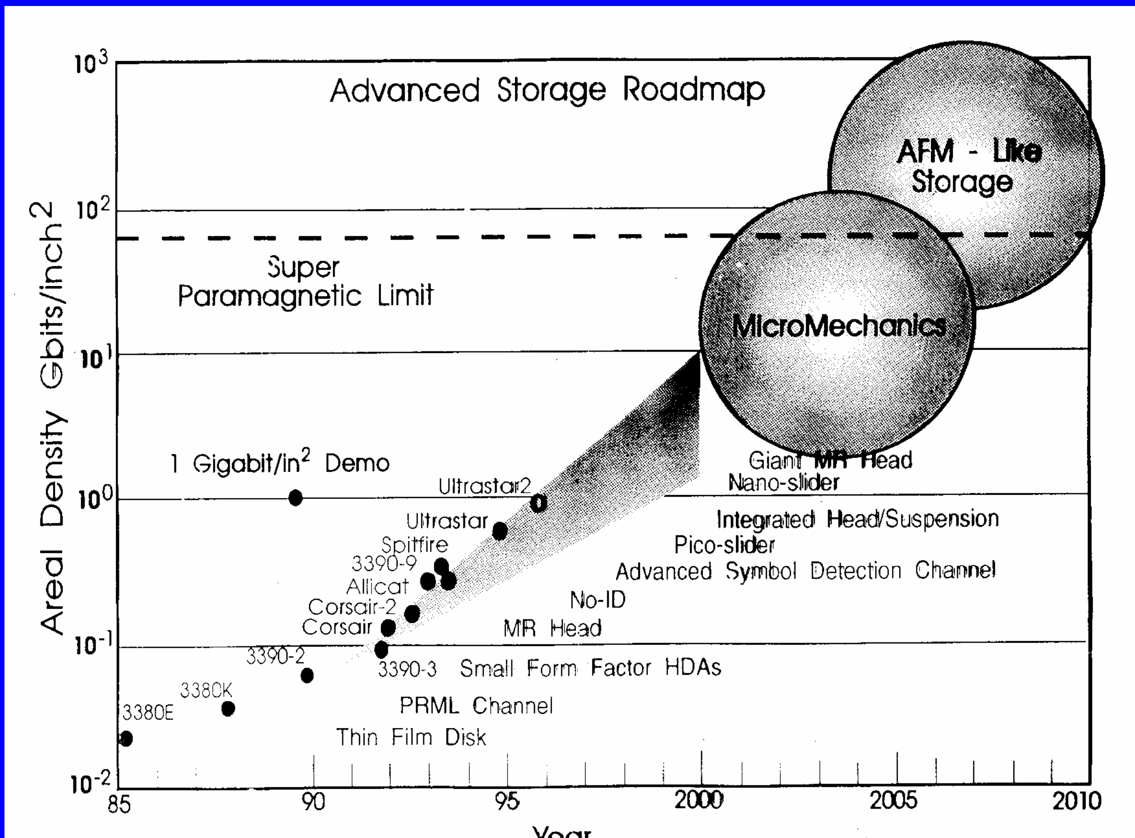


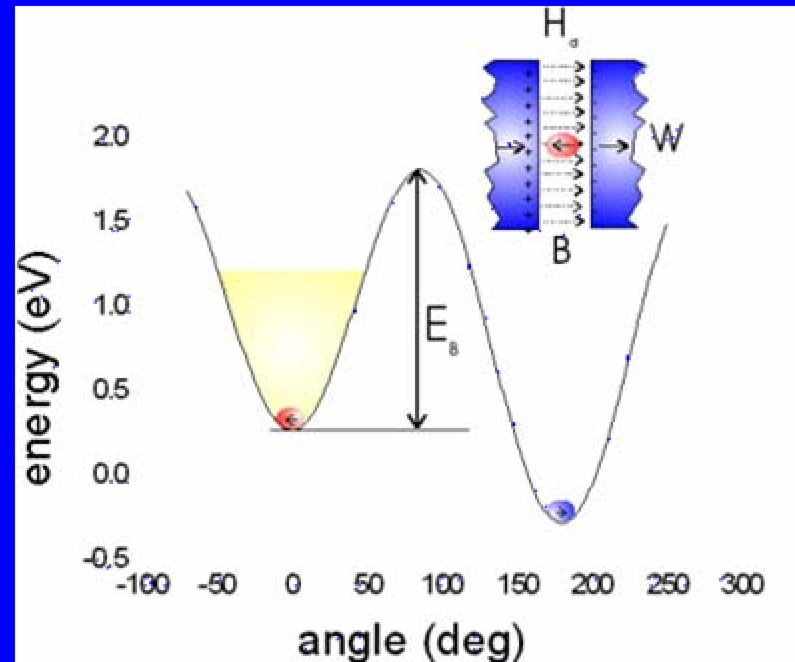




quantum bit

超高密度磁存储与超顺磁极限





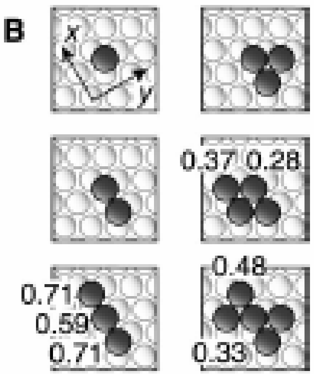
$$t = 10 \quad \text{year}$$

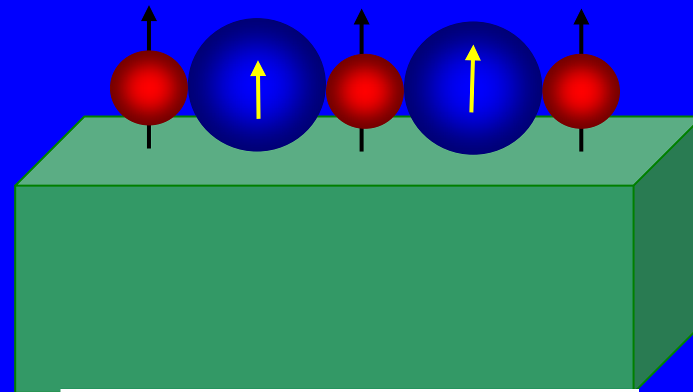
$$\frac{KV}{k_B T} > 40$$

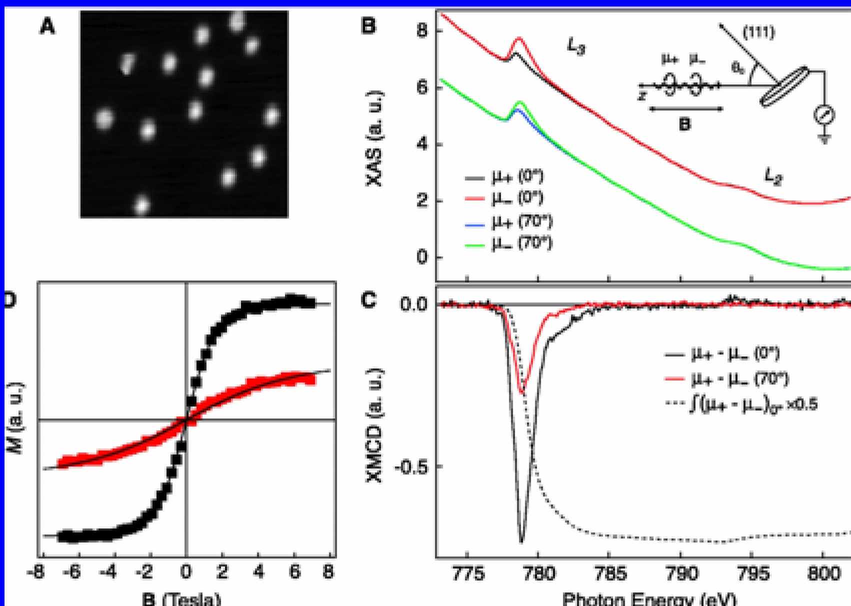
• 巨大磁矩与磁各向异性

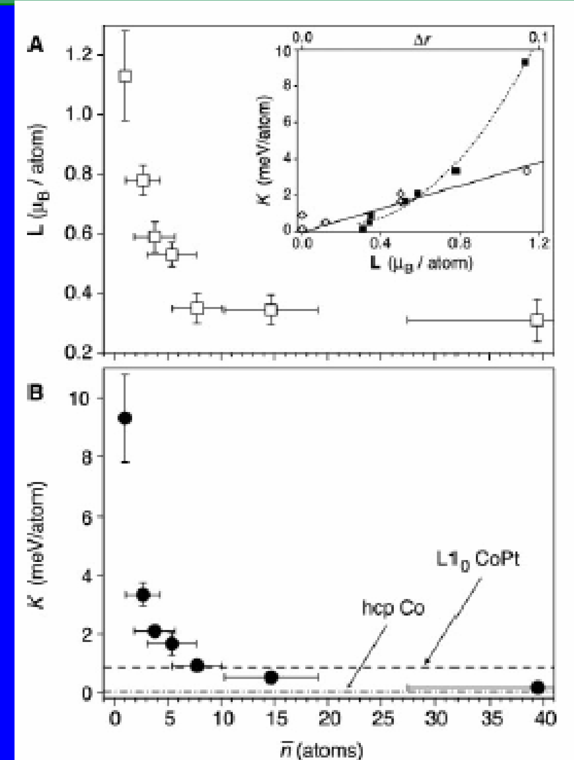
A

n	S	L	$\Delta L_{x\text{-}z}$	$K_{x\text{-}z}$
1	2.14	0.60 (1.50)	- 0.25	+ 18.45
2	2.11	0.38 (0.74)	- 0.11	+ 4.11
3 chain	2.08	0.34 (0.67)	- 0.06	+ 3.69
3 triangle	2.10	0.25 (0.43)	- 0.05	+ 2.22
4	2.08	0.22 (0.33)	- 0.01	+ 0.75
5	2.08	0.27 (0.45)	- 0.09	+ 1.81





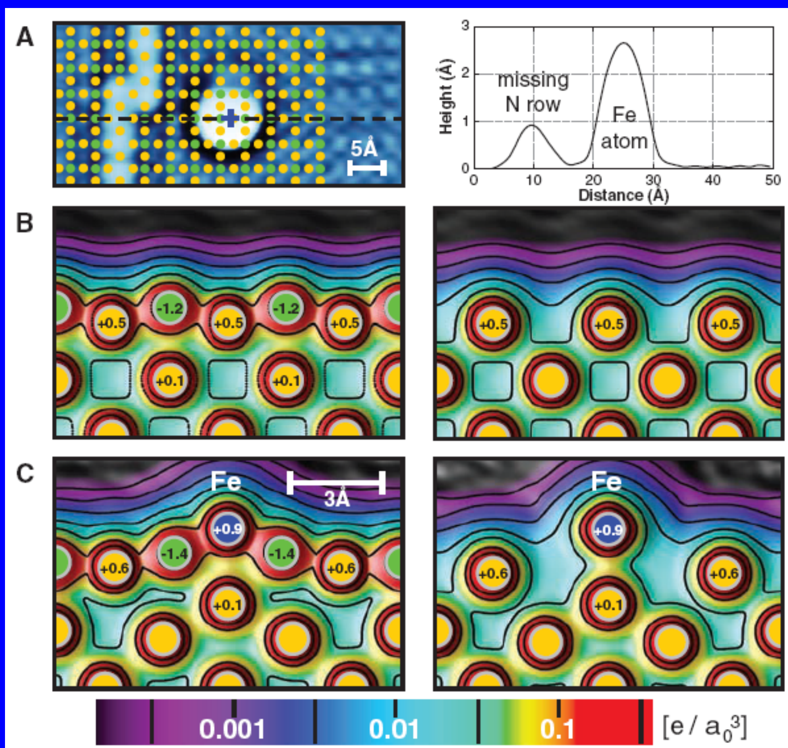


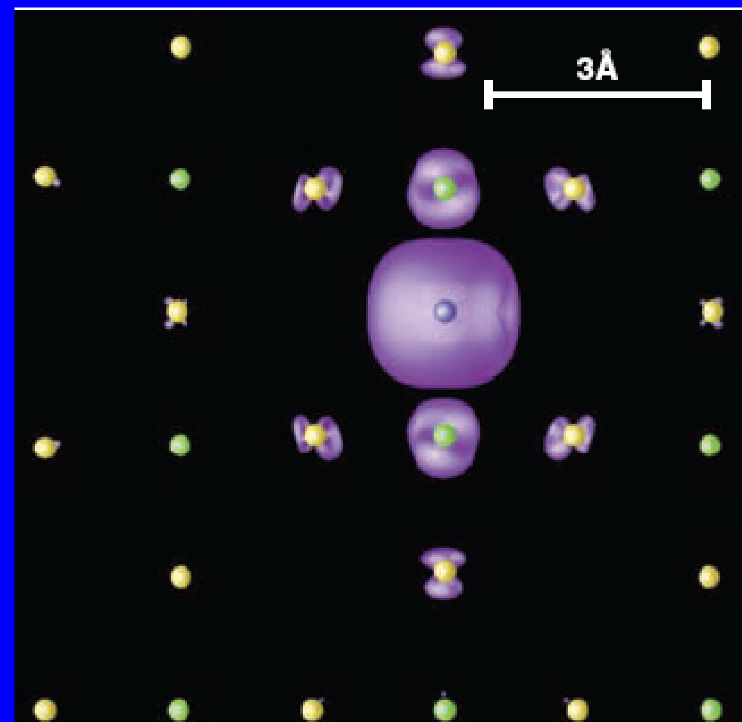


P. Gambardella et al., Science, 300,1130(2003)

Large Magnetic Anisotropy of a Single Atomic Spin Embedded in a Surface Molecular Network

Cyrus F. Hirjibehedin,[1] Chiung-Yuan Lin,[1,2] Alexander F. Otte,[1,3] Markus Ternes,[1,4] Christopher P. Lutz,[1] Barbara A. Jones,[1] Andreas J. Heinrich[1]





磁性纳米结构与磁共振　实验条件

单晶生长炉(2002)

电化学实验室（**2003)**

MBE/SPM/SMOKE/MS(2004)

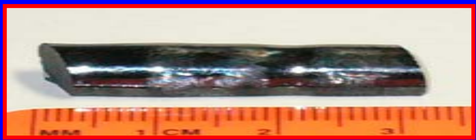
多电极磁输运（**2002)**

穆斯堡尔谱仪(2003)

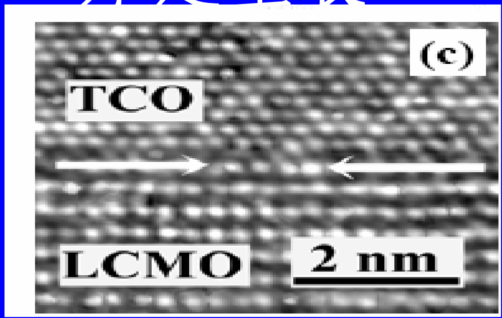
电子自旋共振**(2006)**

磁性纳米结构与磁共振

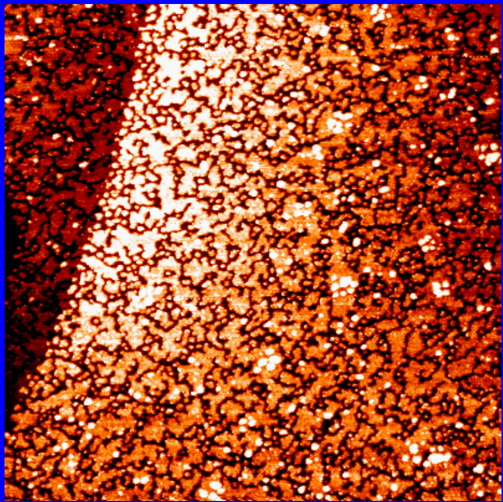
单晶生长



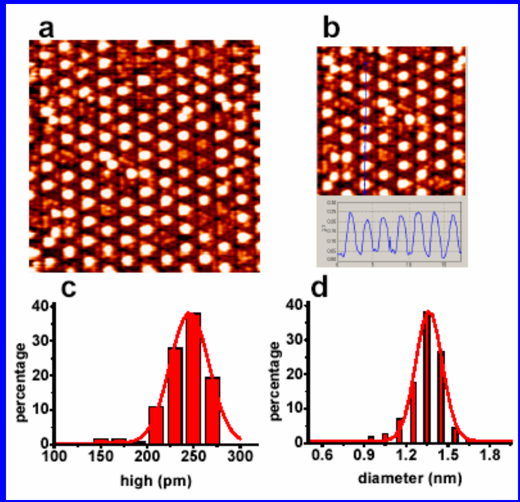
外延生长



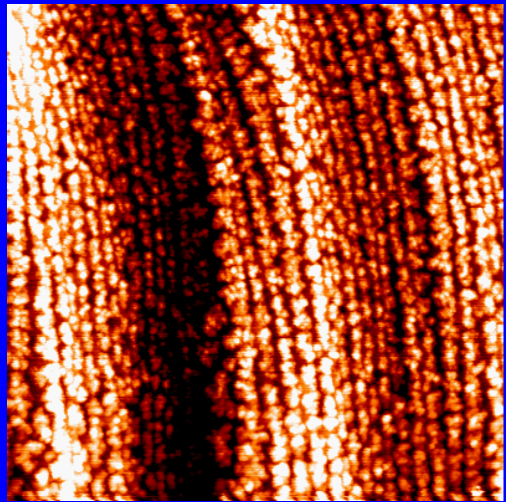
磁性超薄膜



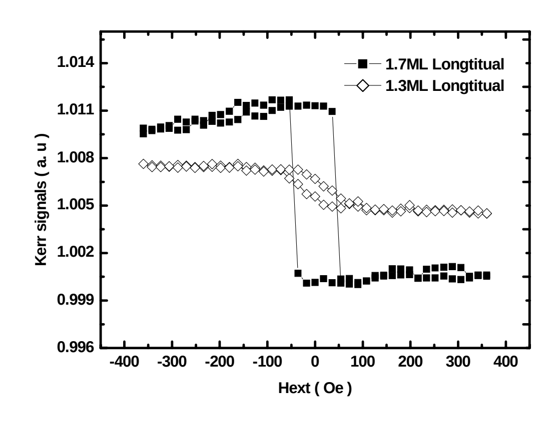
磁性纳米点



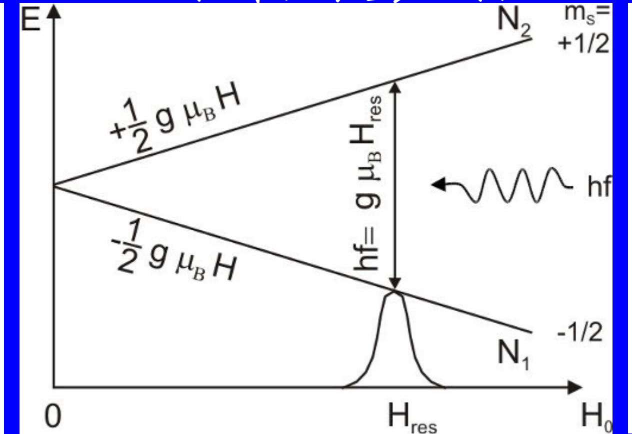
磁性纳米线



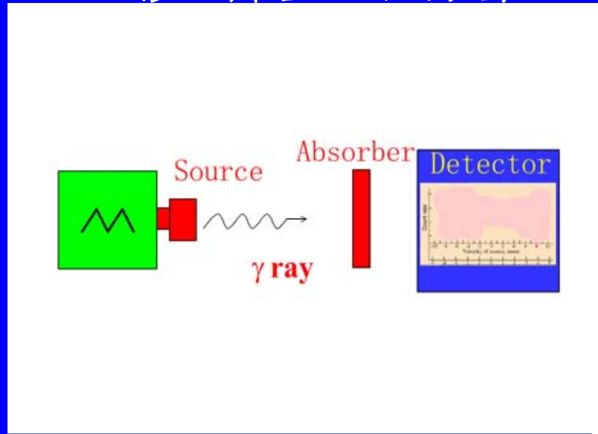
表面磁光科尔效应



电子自旋共振



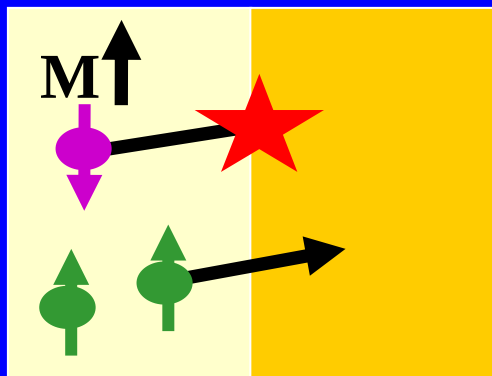
穆斯堡尔效应

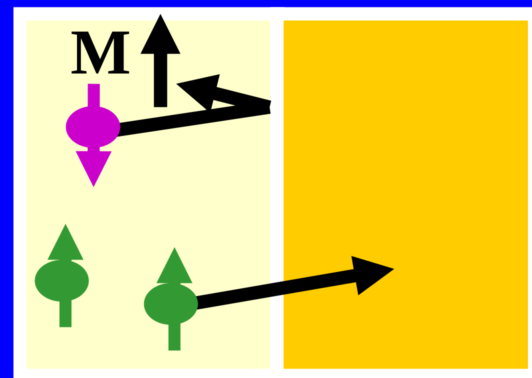


- MnSi磁性半导体超薄膜可控生长和磁性调控

- 磁性纳米线的磁各向异性调控

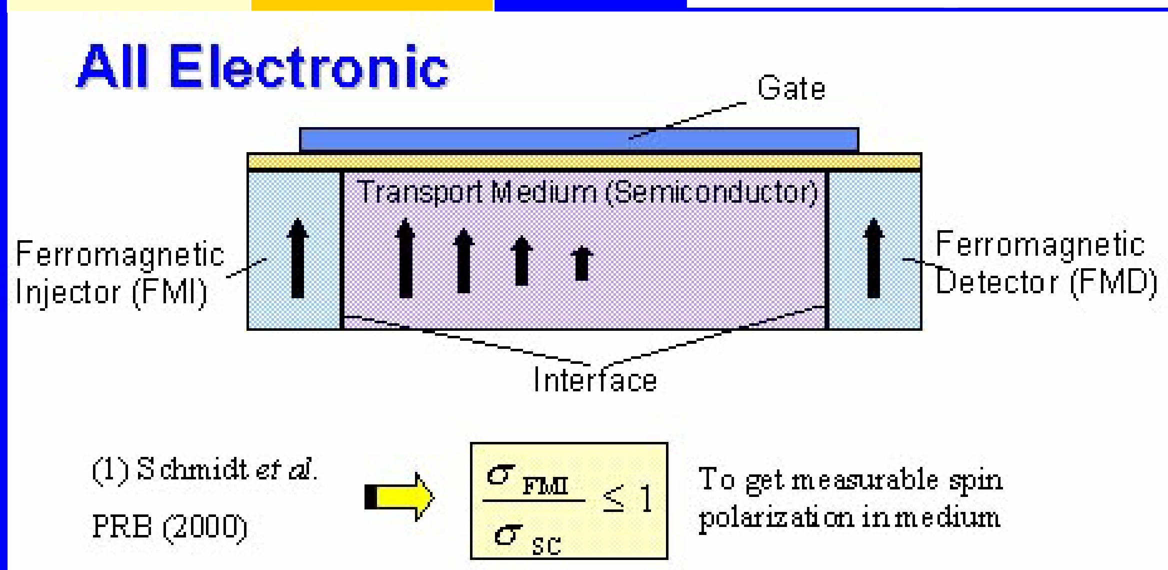
MnSi磁性半导体超薄膜的可控生长和磁性调控





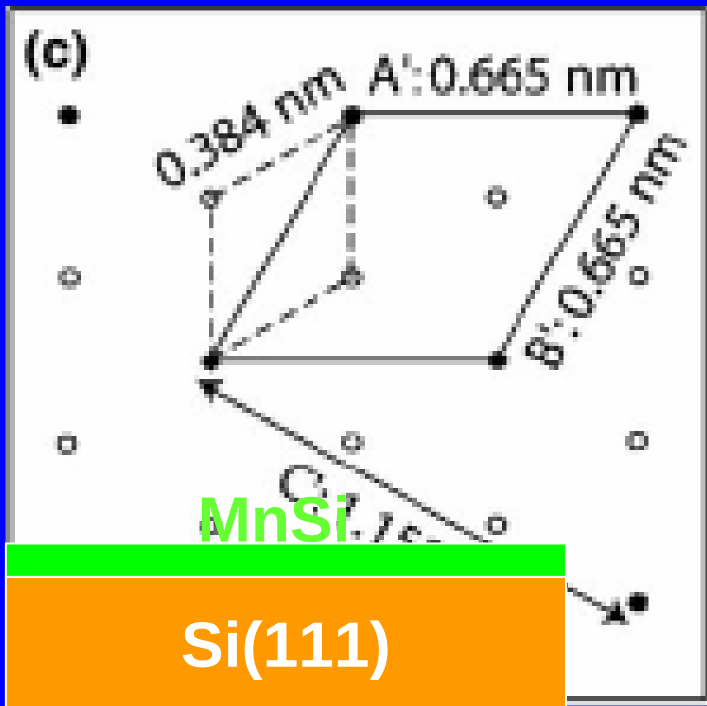
- 晶格失配
- 电导失配

自旋注入困难



Si表面外延生长金属和金属Si化物

FeSi, CoSi, NiSi　　弱磁或非磁



•MnSi　　铁磁性金属

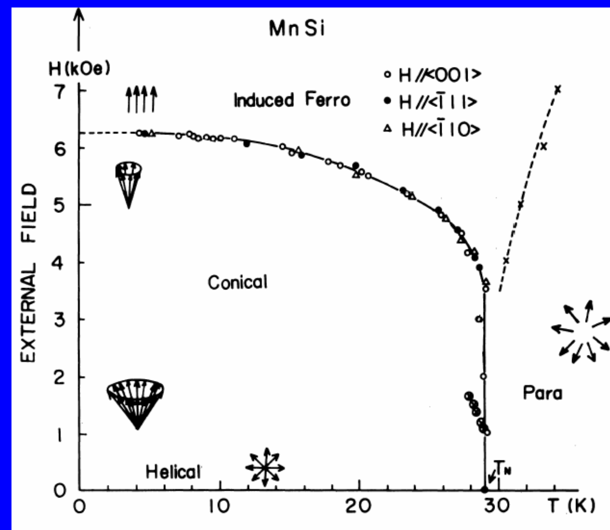
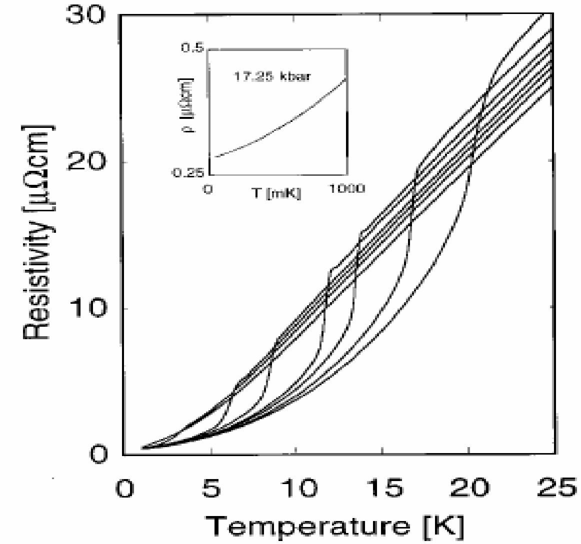


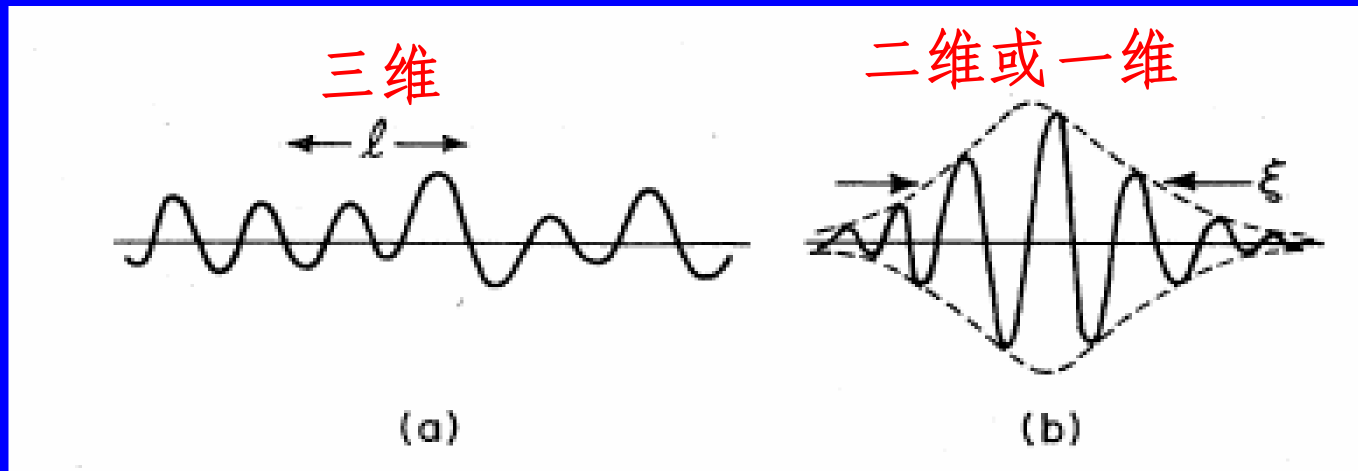
FIG. 1. Magnetic phase diagram of MnSi.

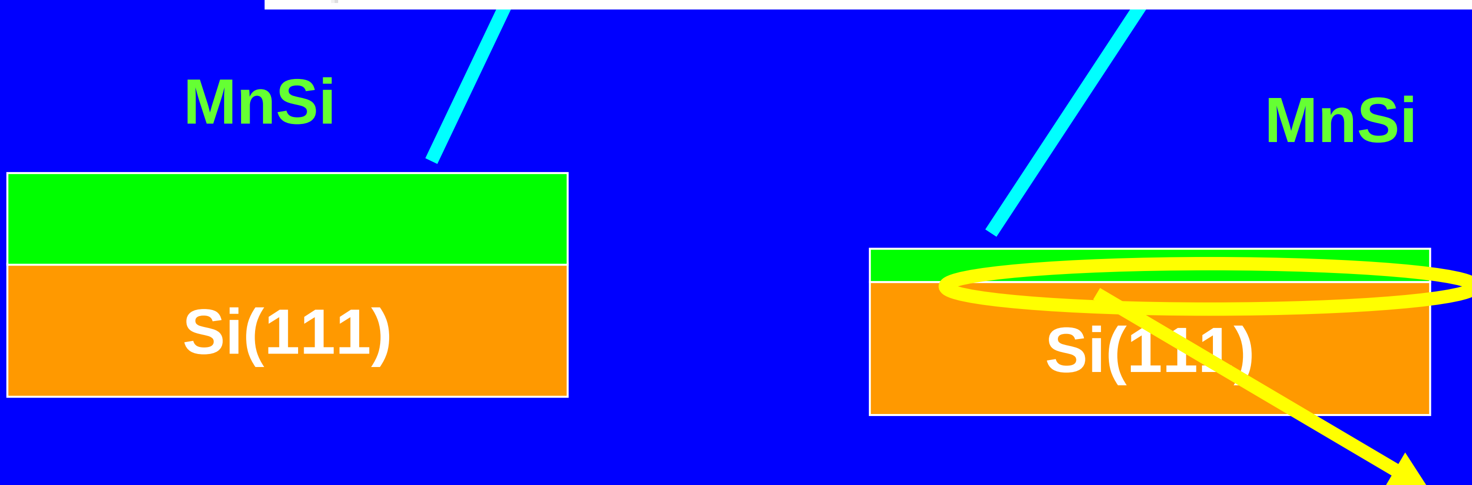


C. Pfleider, PRB,55,8330(1997)

MnSi超薄膜的磁性与电性调控

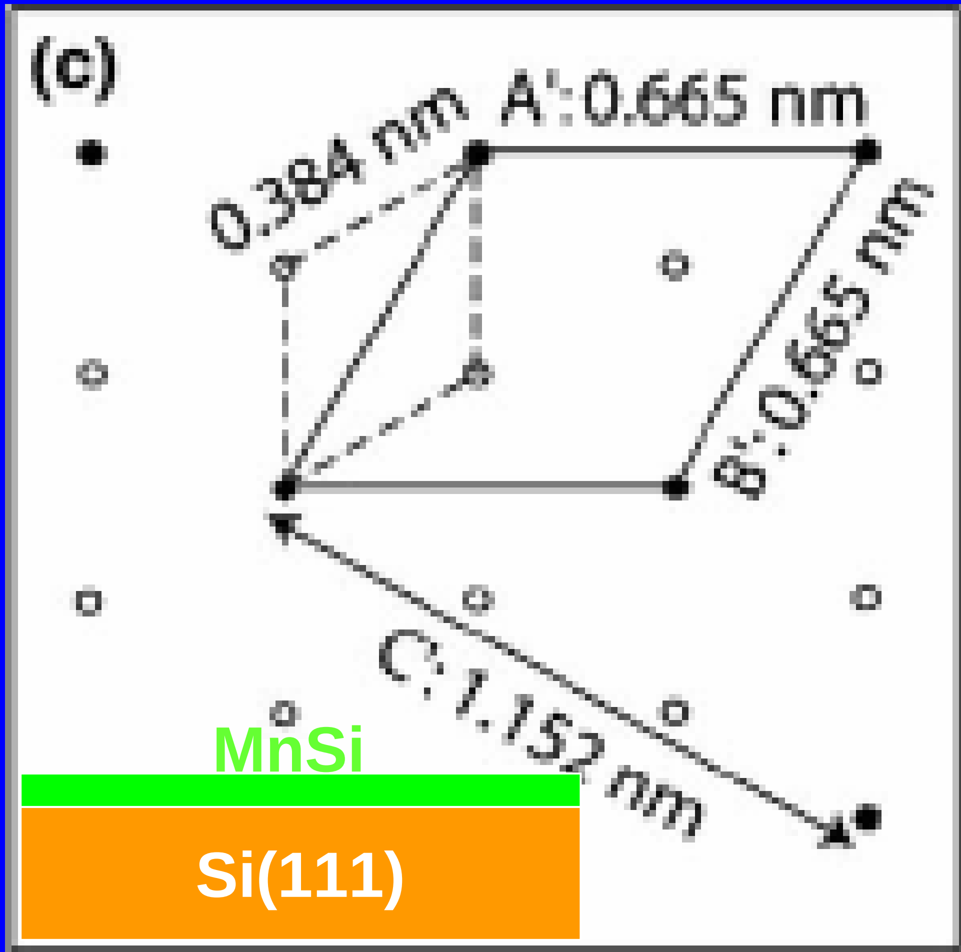
- 维度？

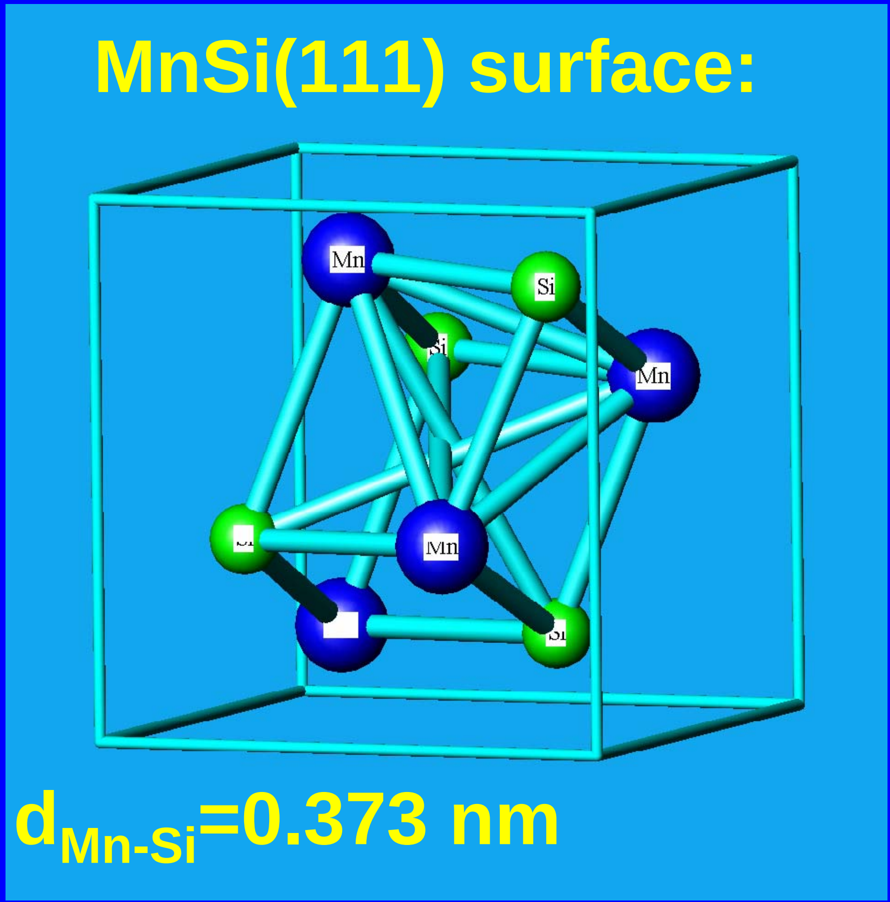




- 应力？

Epitaxial Growth of metal or metal Silicides on Si





MnSi(111) surface:A=B=0.645nm,C=1.17nm

Ferromagnetic and Metallic Properties of MnSi bulk intermetallic Compounds

FeSi, CoSi, NiSi   weak, or non-magnetic

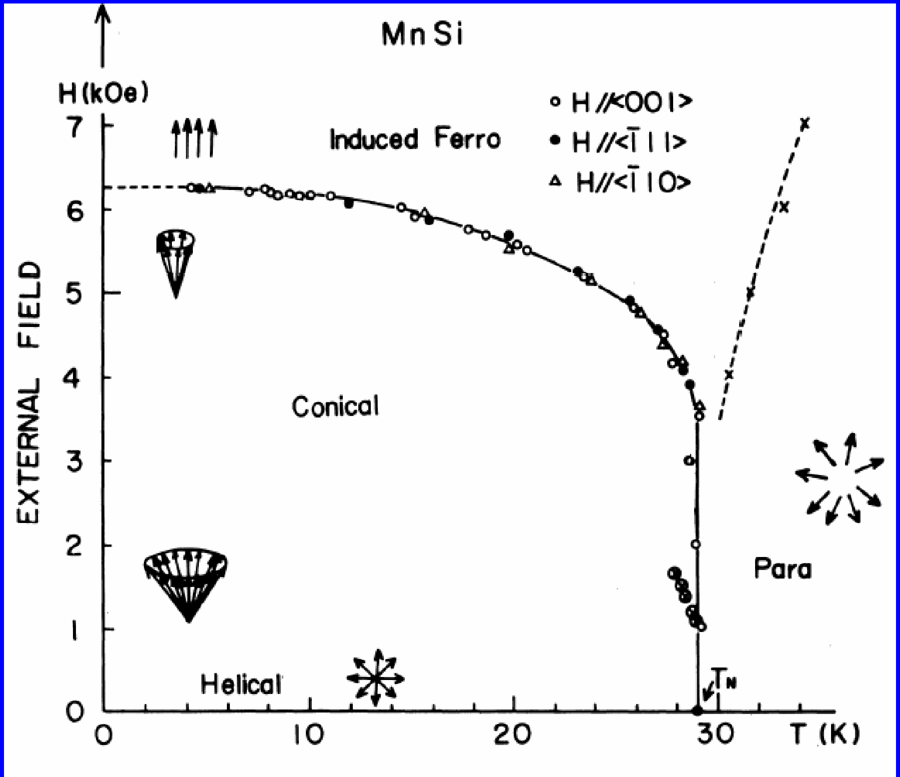
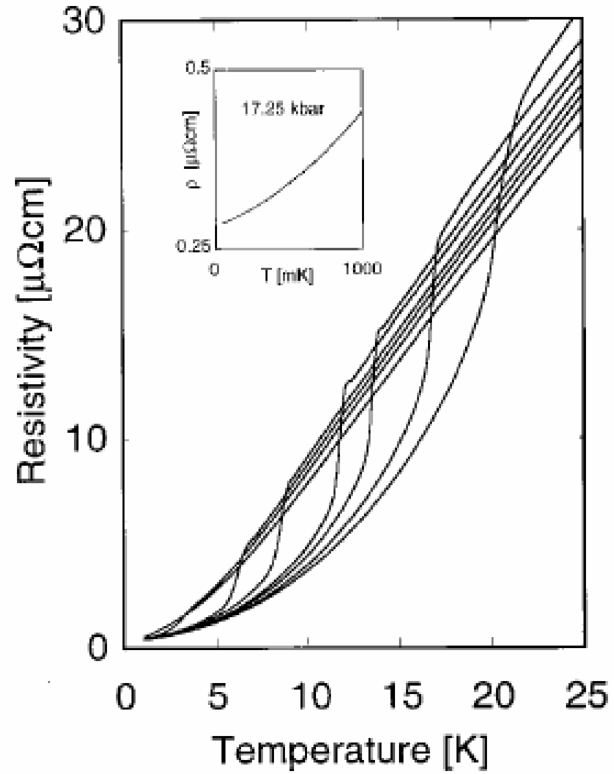


FIG. 1. Magnetic phase diagram of MnSi.



C. Pfleider, PRB,55,8330(1997)

Scaling Theory of Localization

$$g = G/(e^2/\hbar)$$

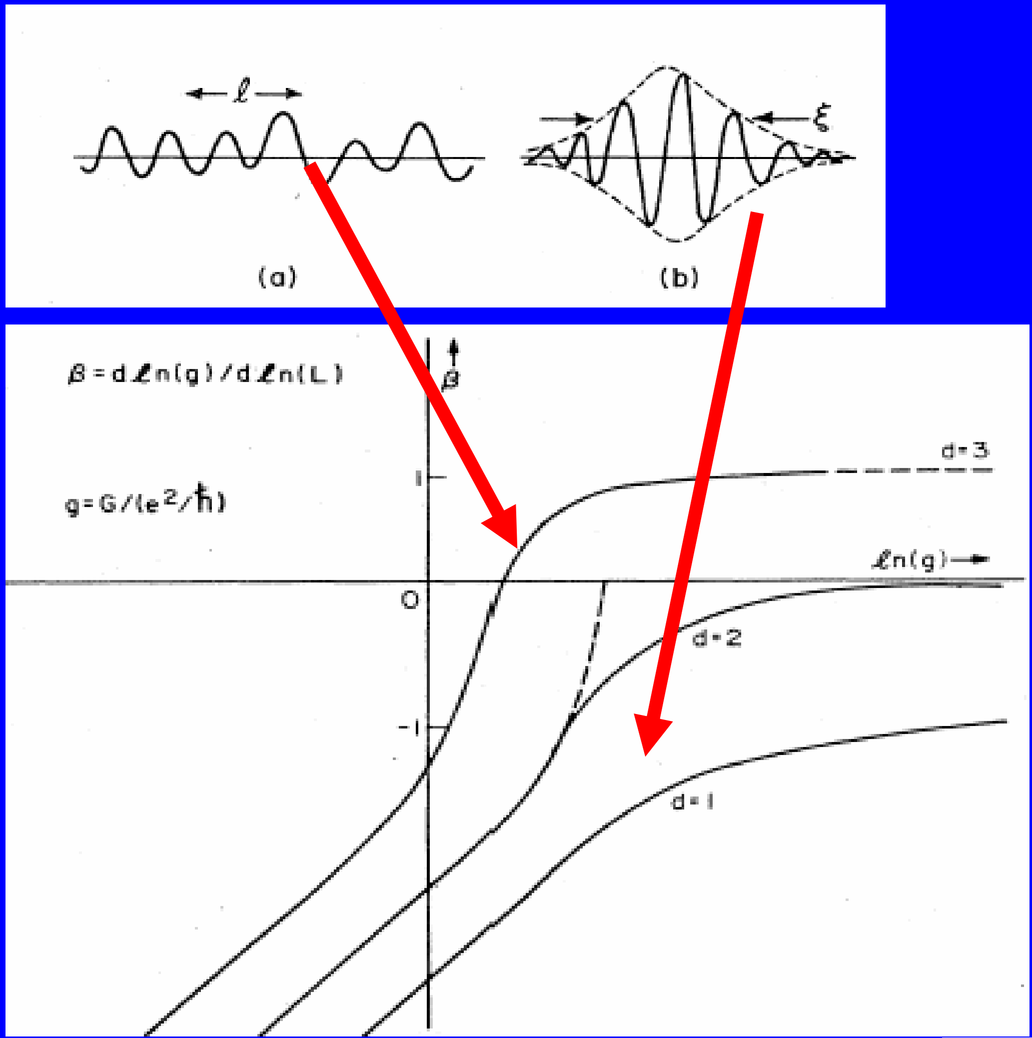
$$\beta(g) = \frac{d\ln g}{d\ln L} = \frac{L}{g}\frac{dg}{dL}$$

$\beta(g) = 1$ Ohm's-law

$\beta(g) > 0$ Extended state

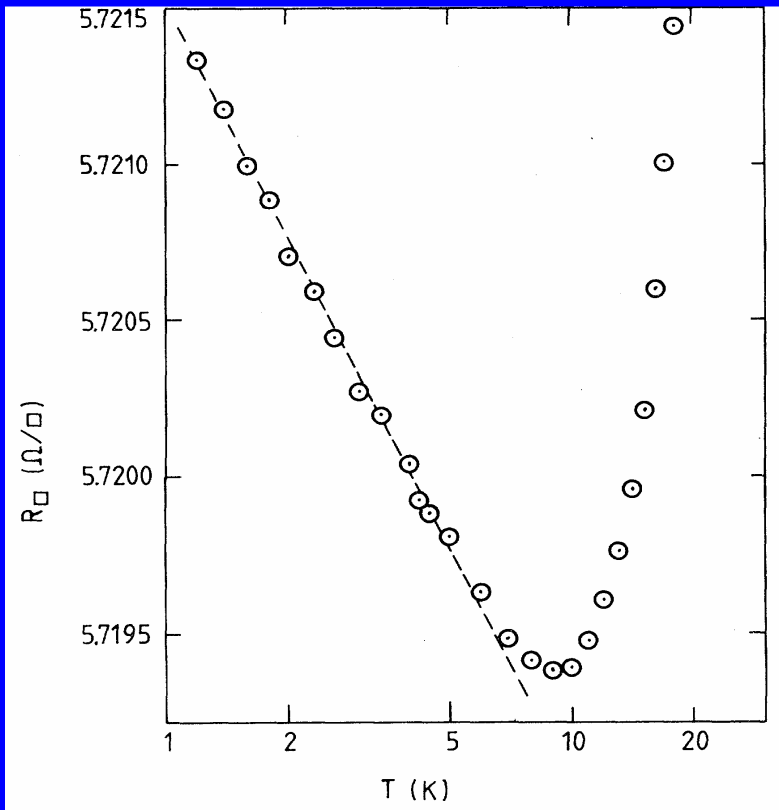
$\beta(g) < 0$ Localized state

D.J. Thouless, PRL,39,1167(1977)
P.W. Anderson, PRL,43,718(1979)

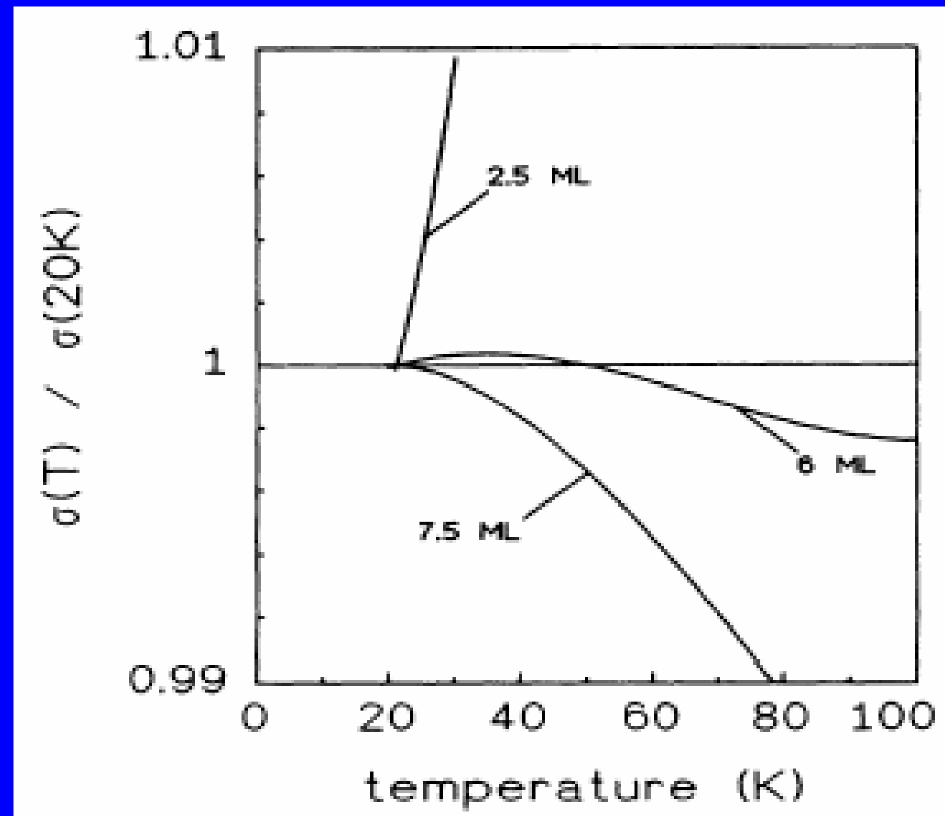


Experimental Studies of Localization

Cu on glass 11.9nm



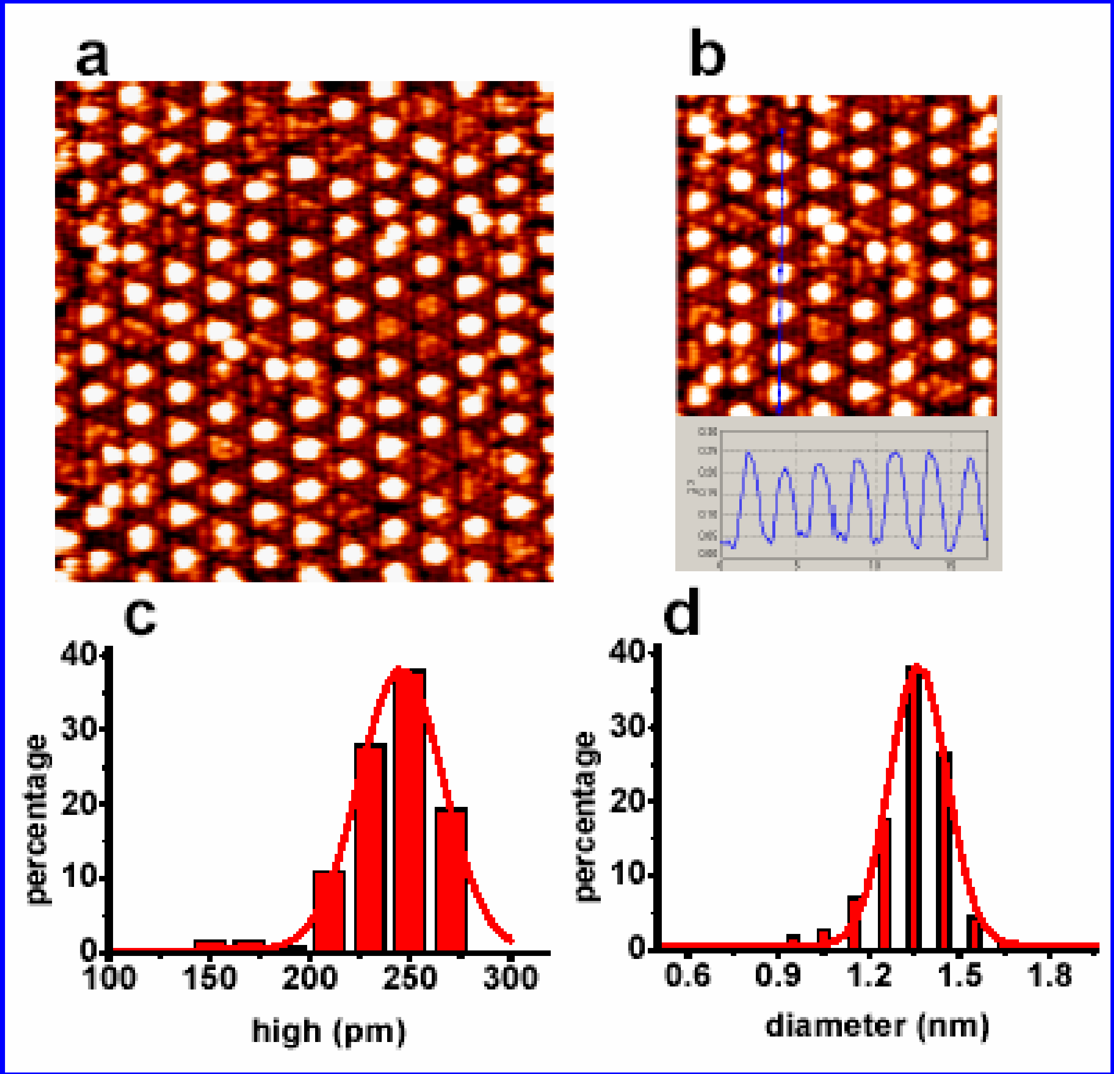
Ag/Si(111)-7×7



L. Van de dries, PRL 46, 565(1981)

PRB 45 11430

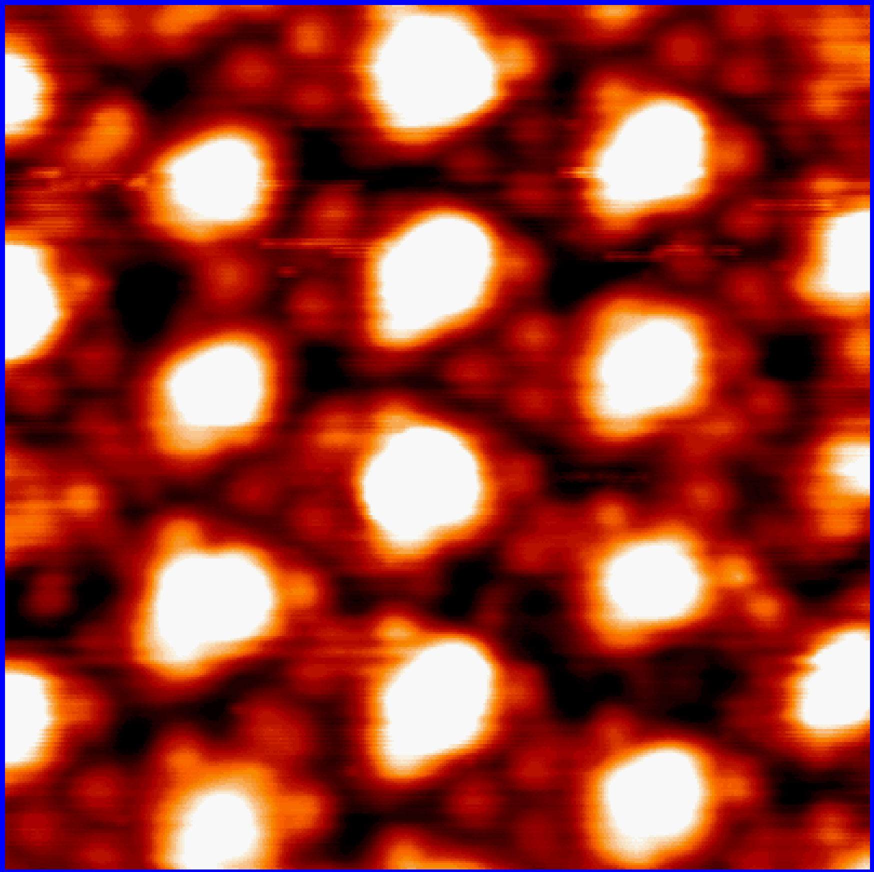
Uniform Mn nanodots on Si(111)



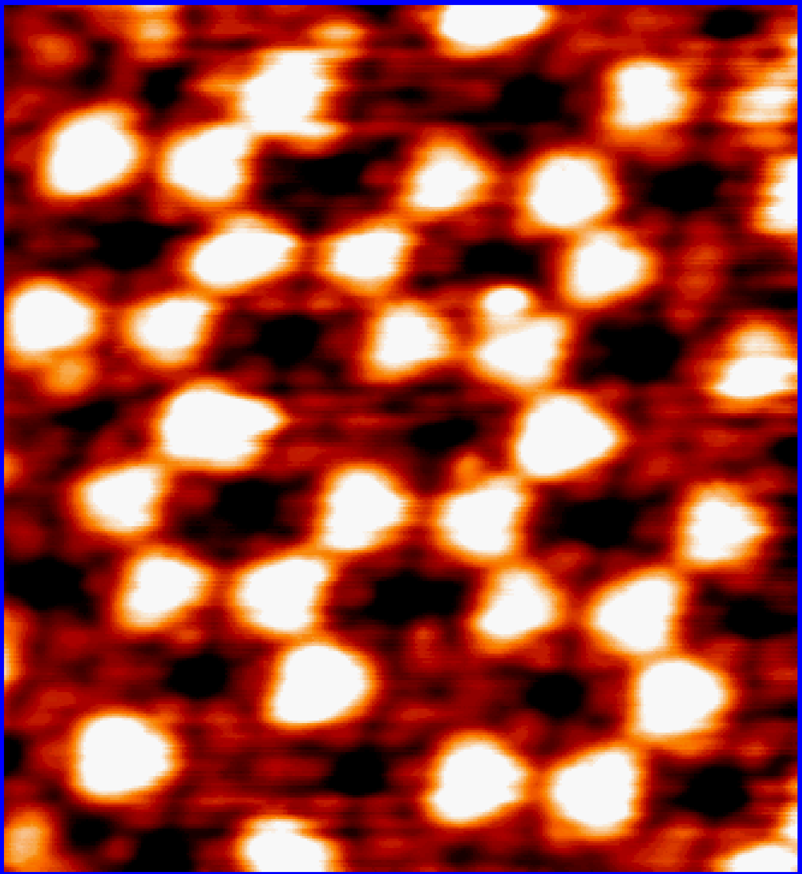
II. Preferential arrangement and Controllable Growth of Mn Nanodots

Triangular structure

Honeycomb structure

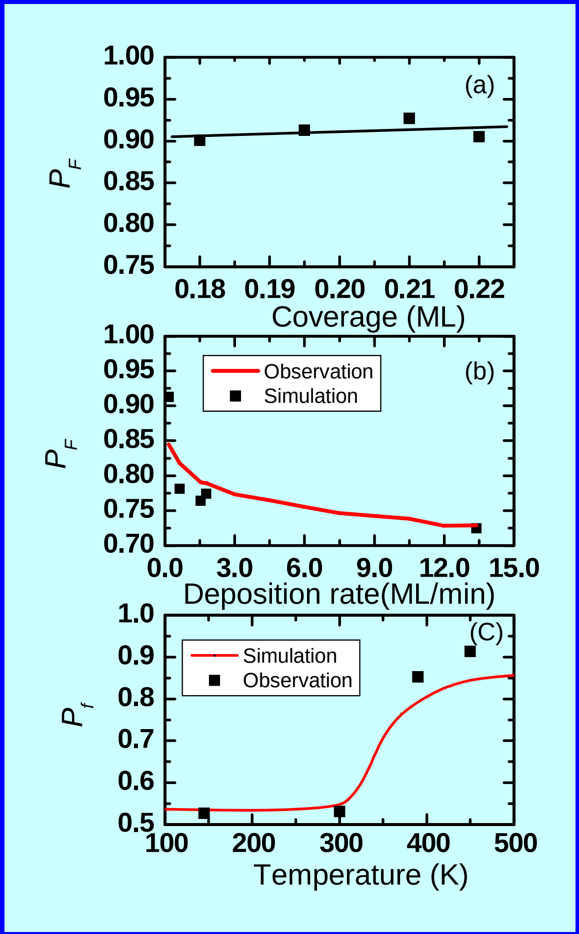


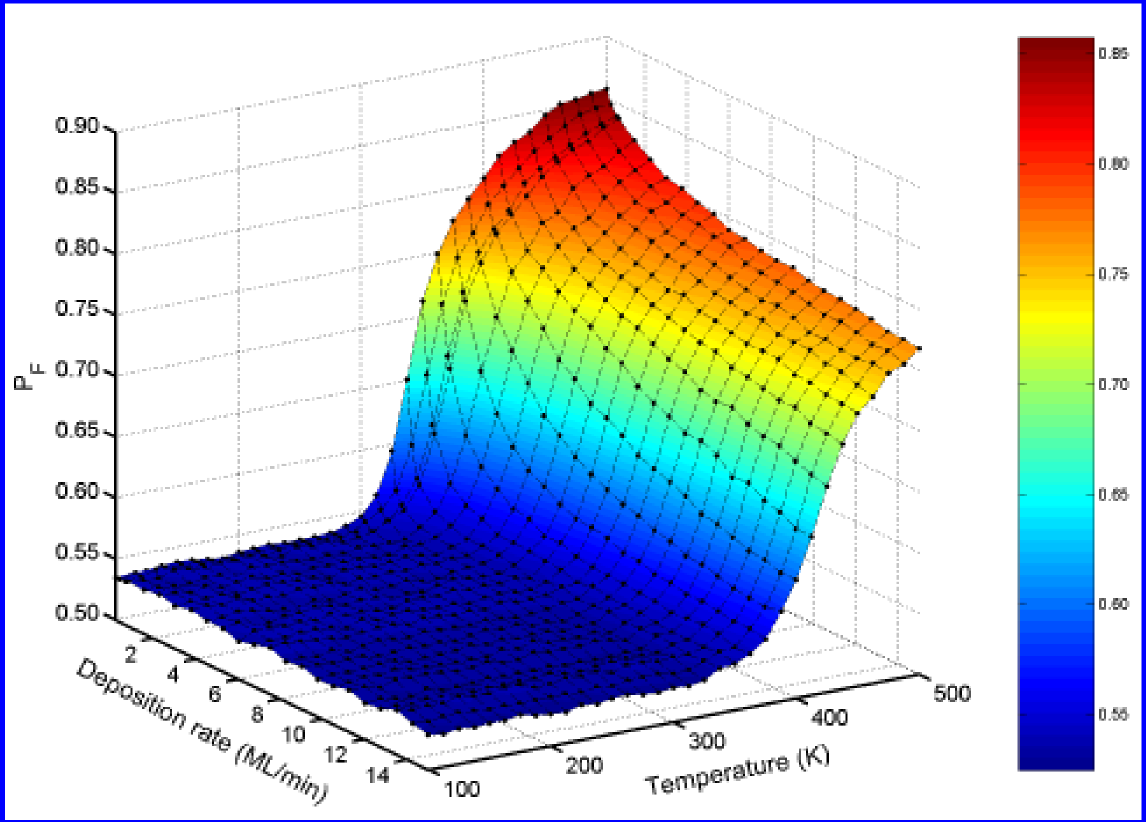
Deposition Rate



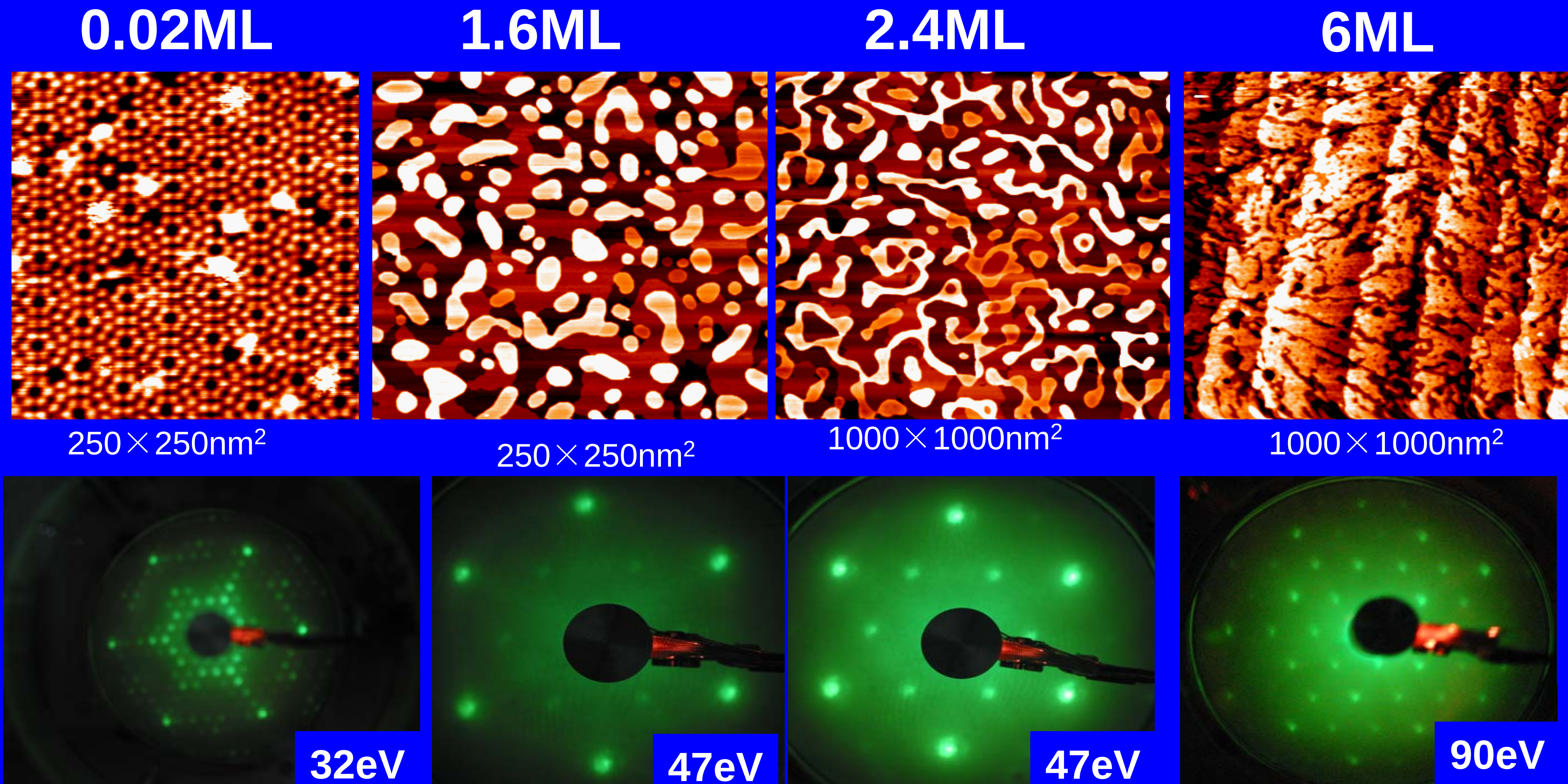
II. Preferential arrangement and Controllable Growth of Mn Nanodots

Kinetic Monte Carlo Simulation



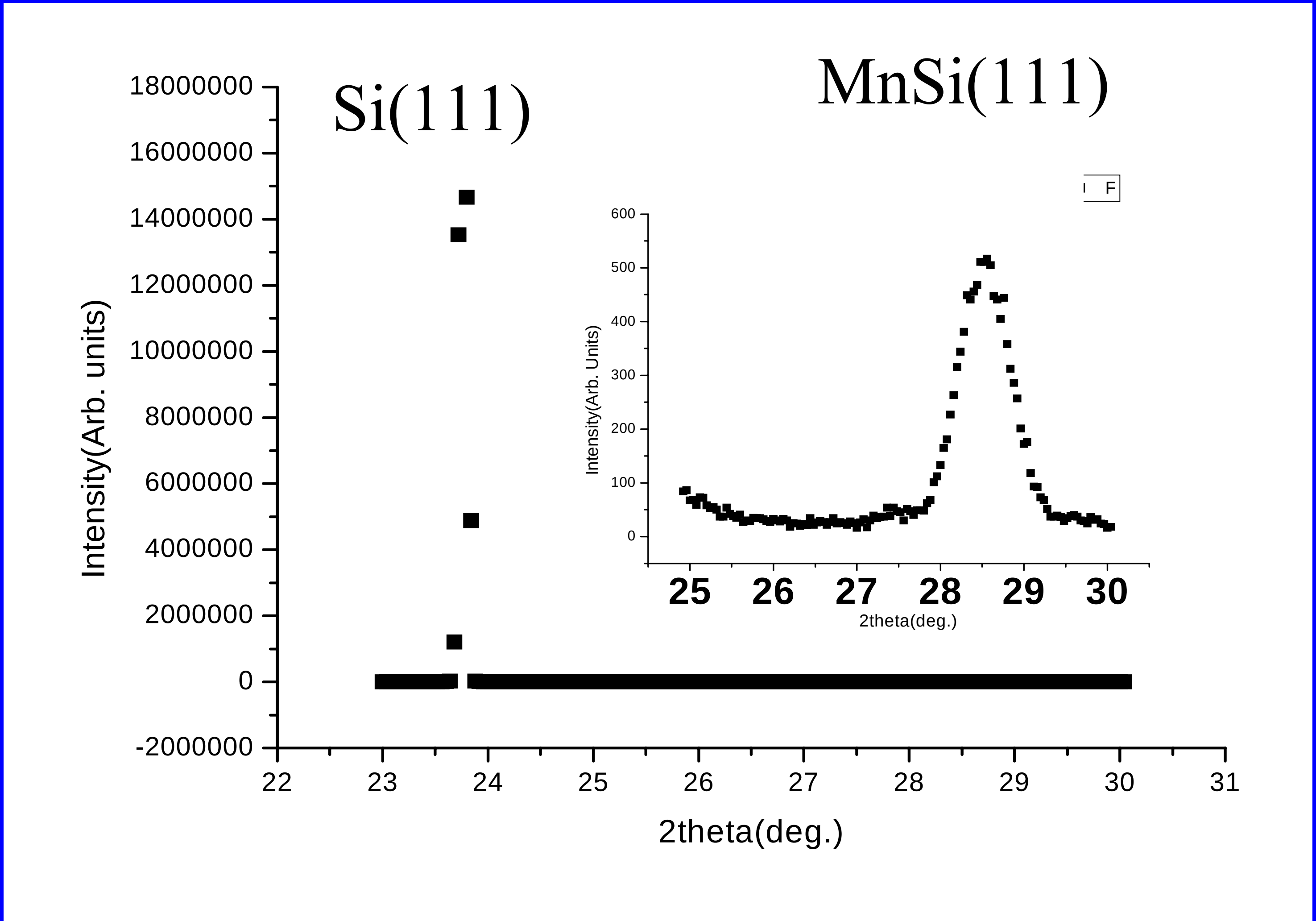


III. Fabrication of MnSi ultrathin film on Si(111)



III. Fabrication of MnSi ultrathin film on Si(111)

同步辐射 XRD 确定成分和结构



Growth model of MnSi

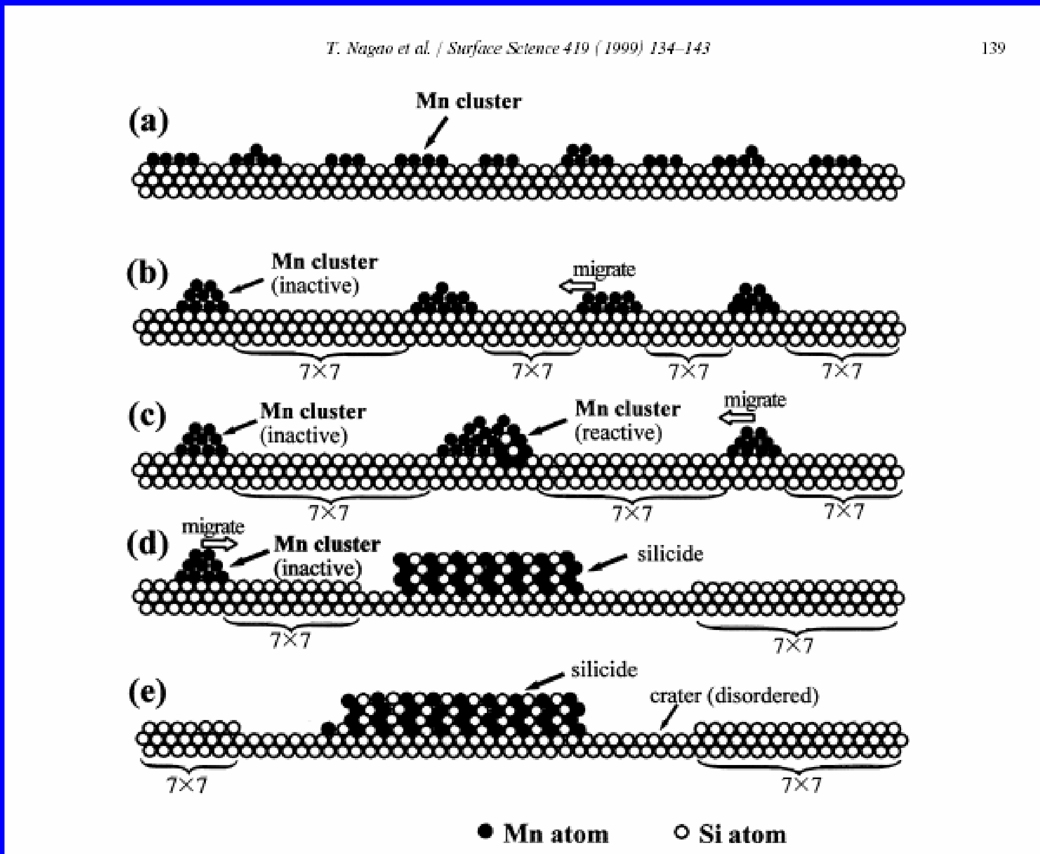
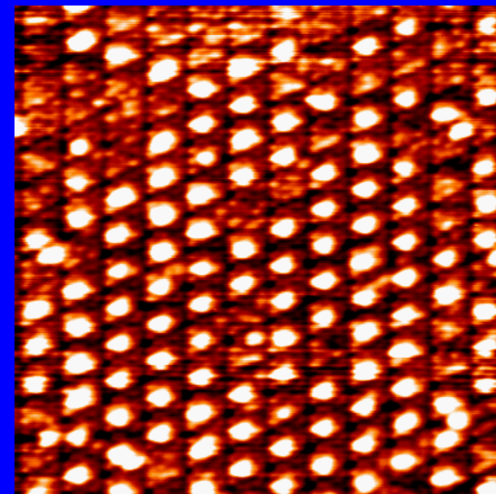


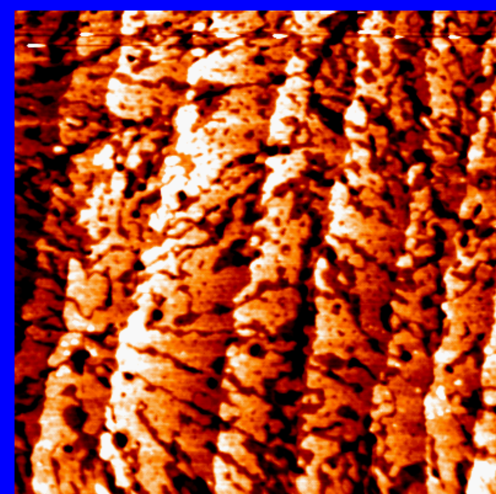
Fig. 3. Schematic illustrations for explaining the mechanism of Mn silicide formation on the Si(111)-(7×7) surface. ●, Mn atoms; ○, Si atoms.

T. Nagao et al., Surf. Sci. 419(1999), 134



As-deposited

30×30nm^2

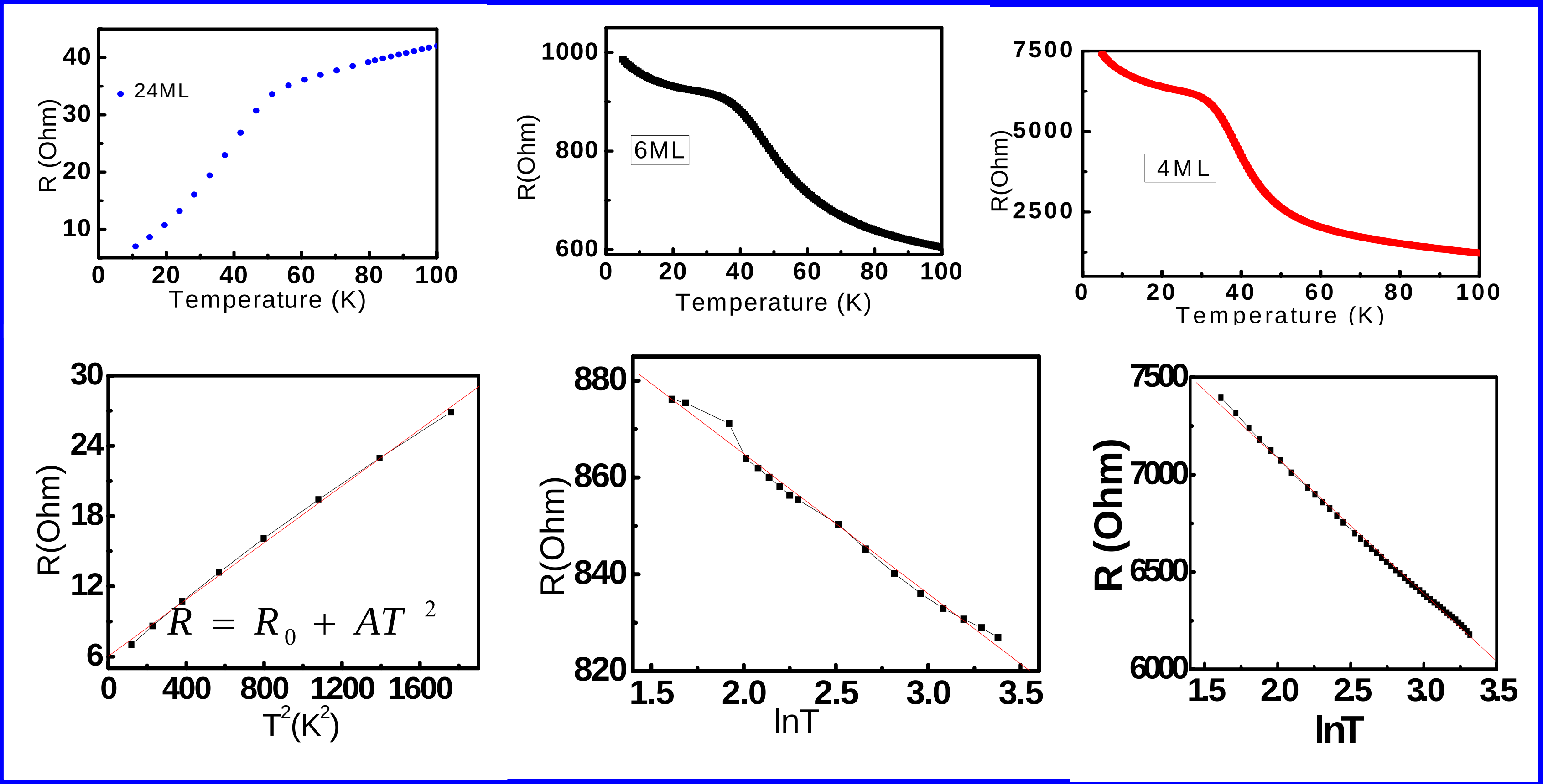


Post-annealed

1000×1000nm^2

厚度度诱导的金属-半导体转变

24ML **6ML** **4ML**

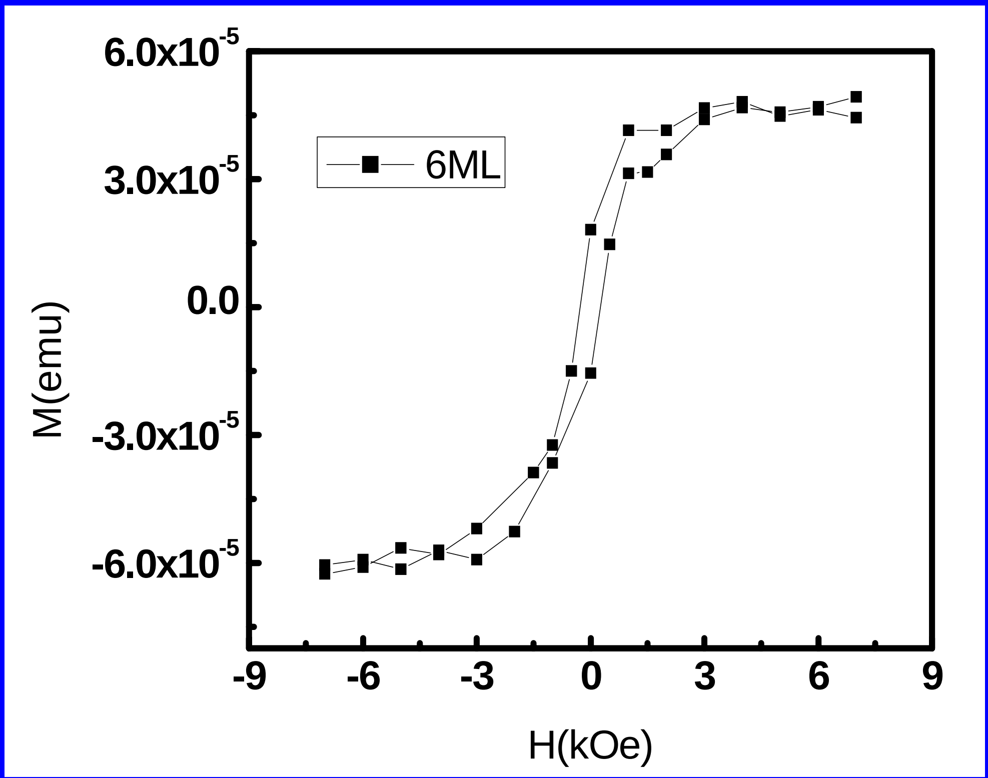


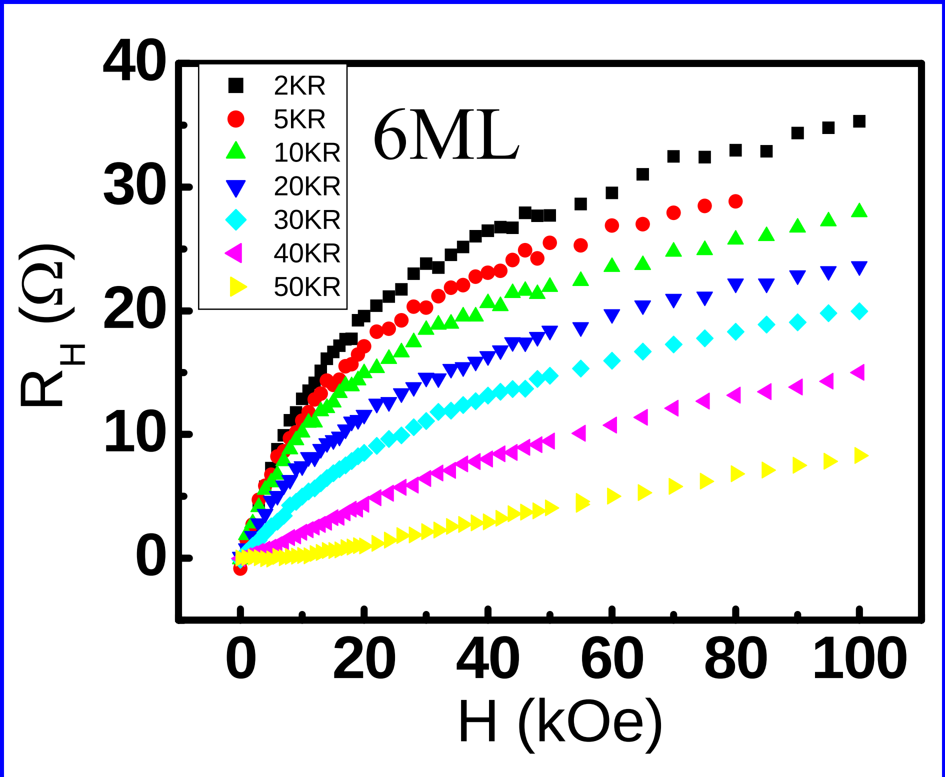
弱巡游电子铁磁性

二维弱局域化

合成同时具有铁磁性和半导体特性的磁性超薄膜材料

Hall Effect

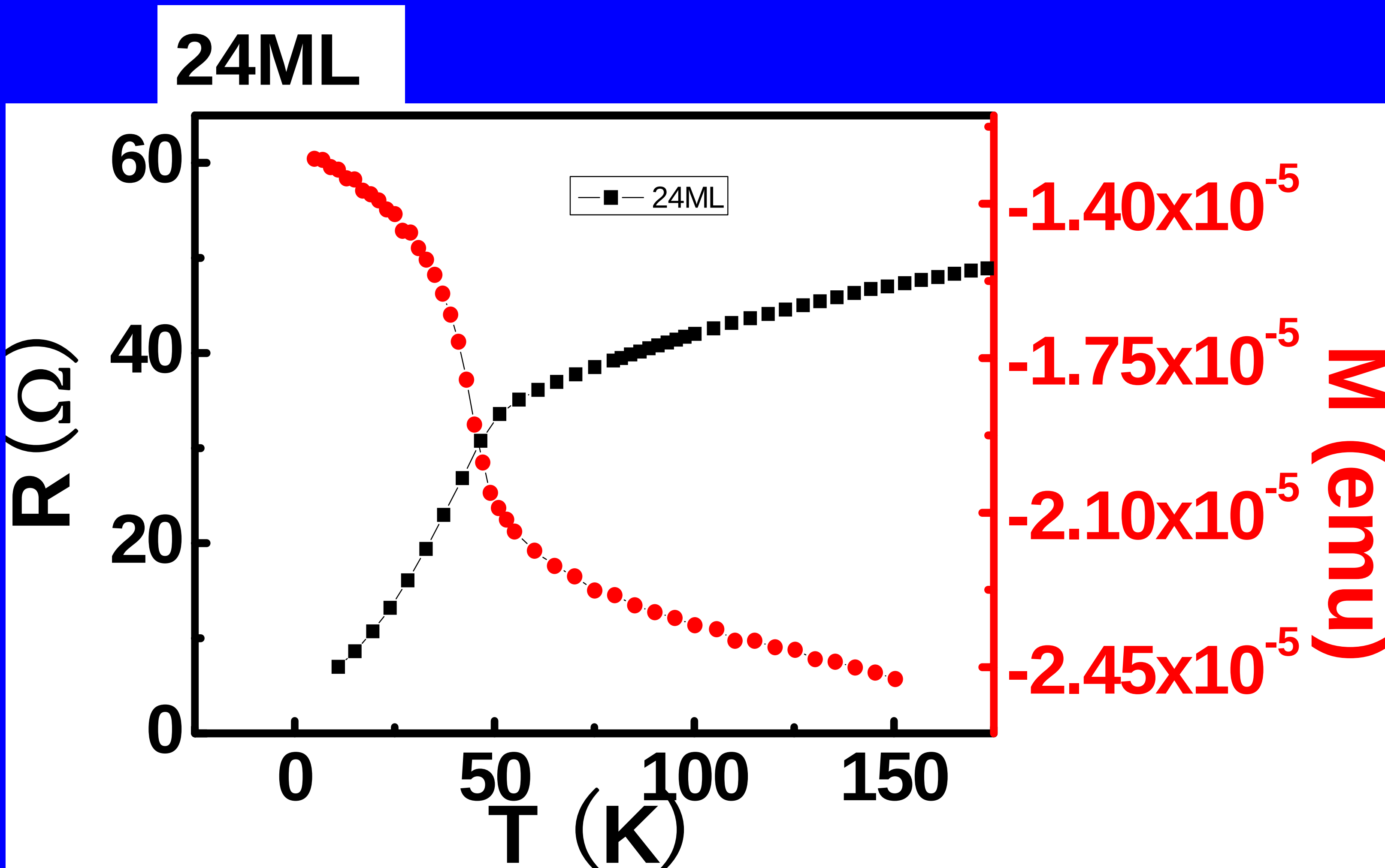




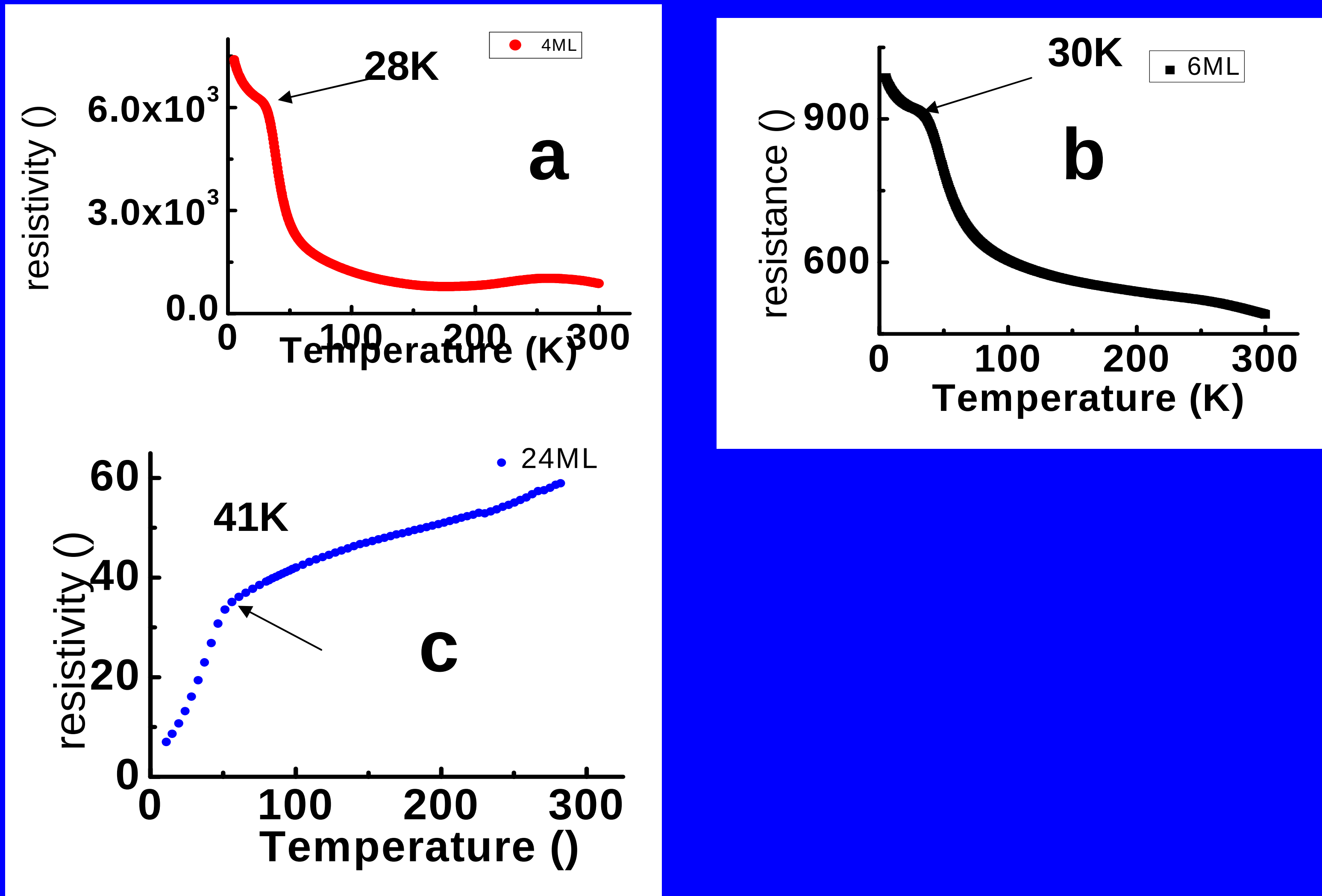
$$R_H = R_0 H + R_S M$$

Si: n-type, MnSi P-type

IV. Magnetic and Magnetotransport Properties of MnSi Ultrathin films

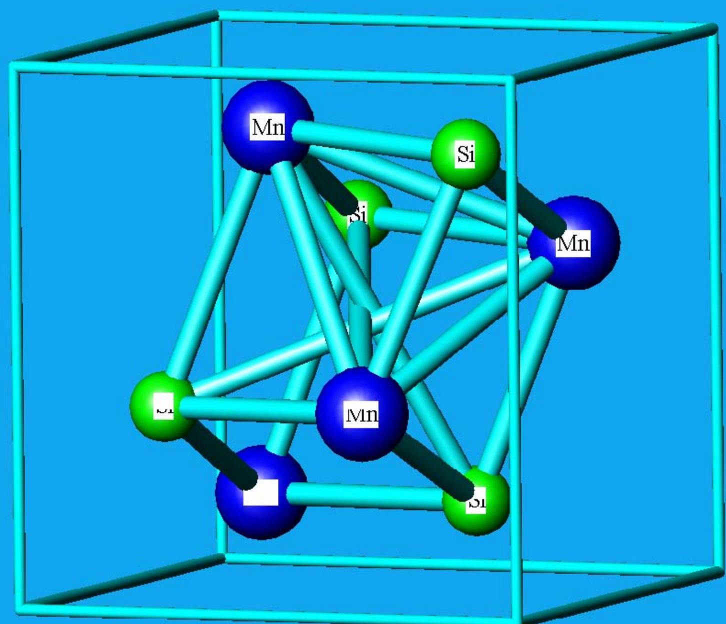


Enhancement of Tc

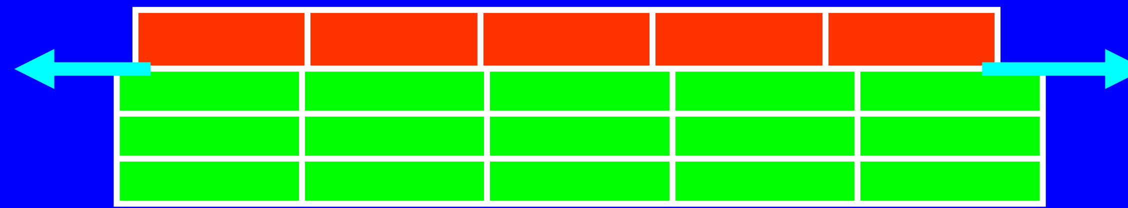


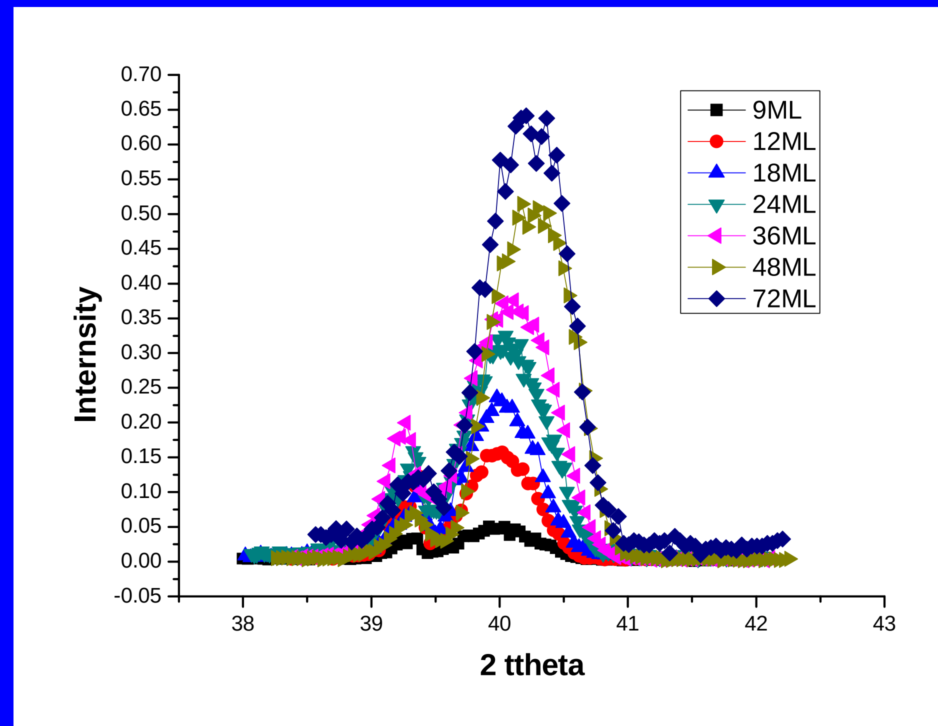
应力诱导居里温度的提高

MnSi(111) surface:



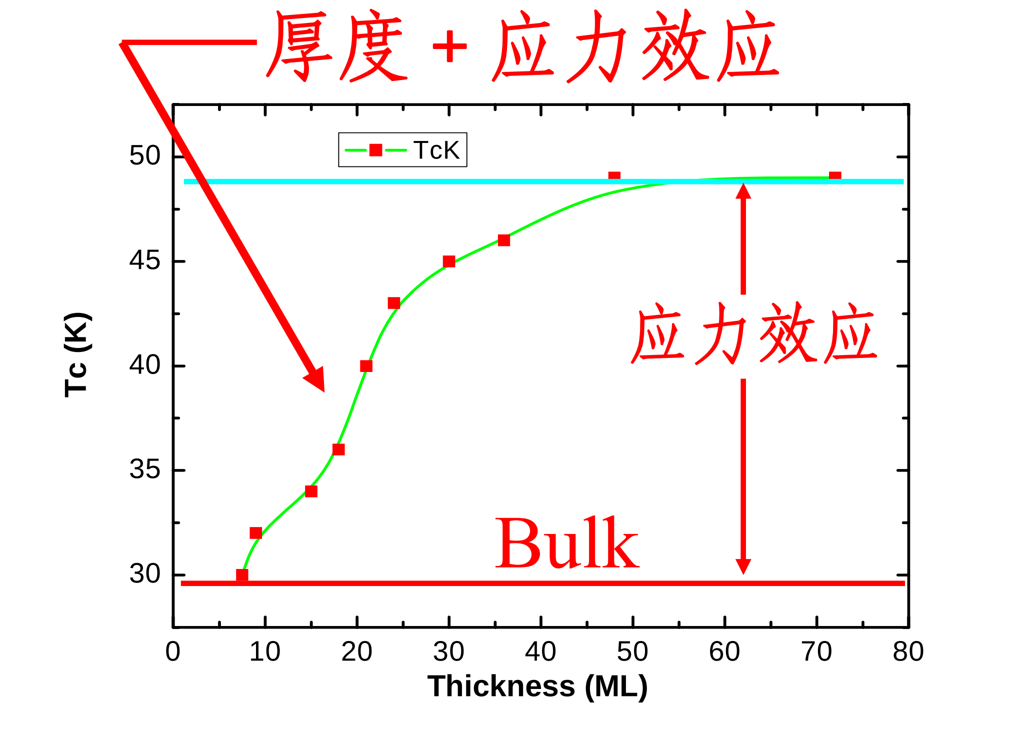
$d_{Mn\text{-}Si}$=0.373 nm



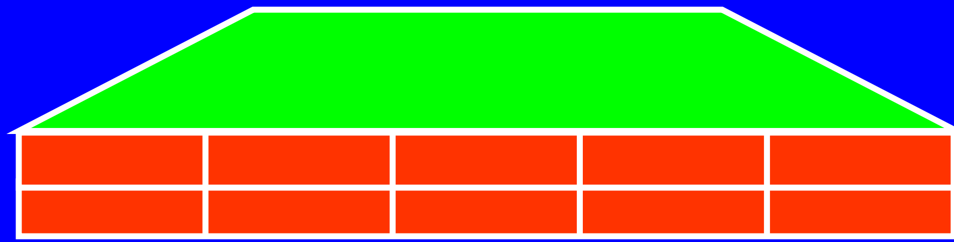


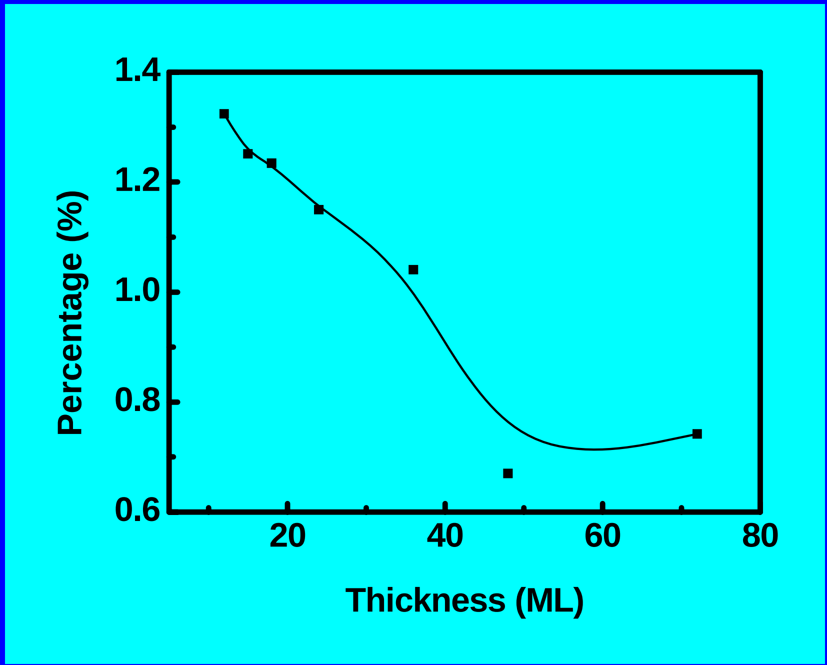
Si(111) dSi-Si=0.384 nm

应力诱导居里温度的提高



Strain relaxation





- Thickness

$$[T_c(\infty) - T_c(d)]/T_c(\infty) = (c/d)^{\lambda},$$

- Strain

应力诱导居里温度的提高

压力效应

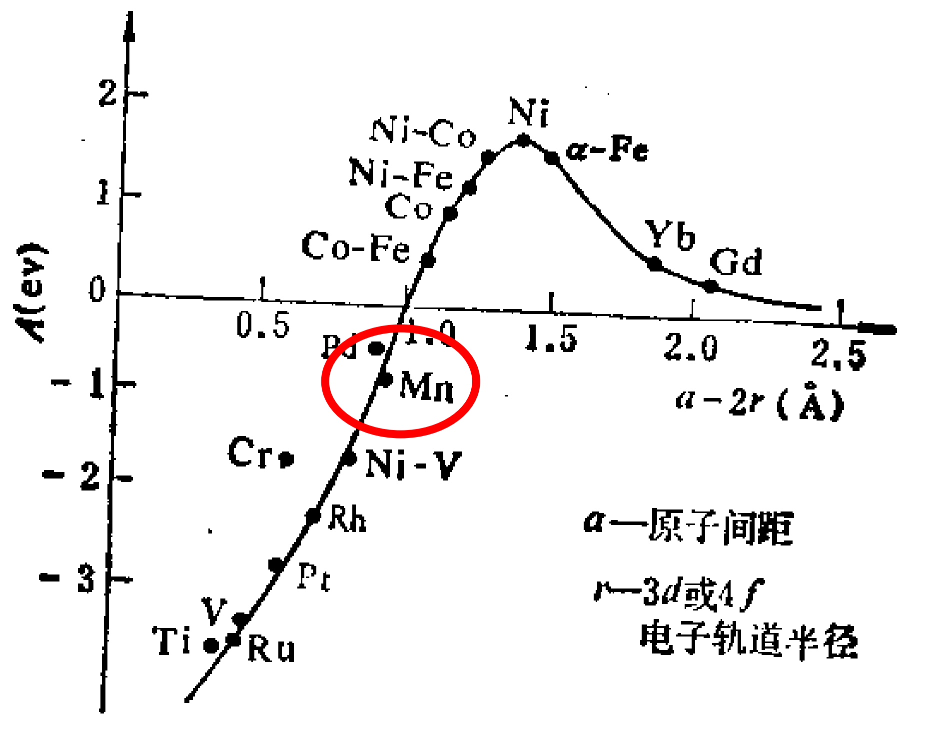
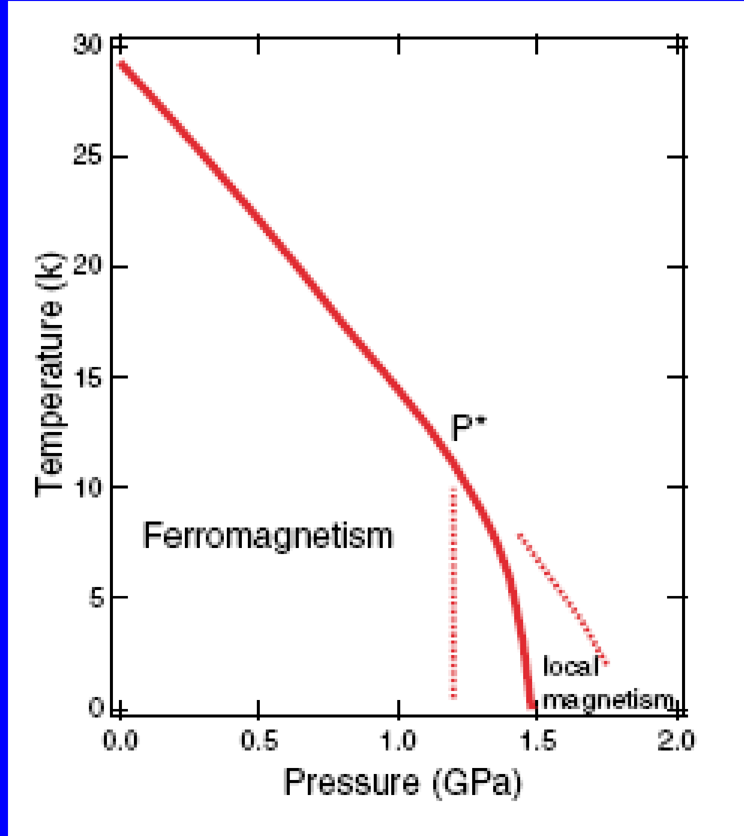


图 3.3 奈耳给出的交换能与($a-2r$)的关系曲线。



W. Yu et al., PRL, 92,086403(2004)

小 结

1. 在MnSi 超薄膜中发现维度诱导的金属－绝缘体转变。
2. 电阻率温度依赖性表明MnSi 超薄膜是一个弱局域的二维电子系统
3. MnSi超薄膜同时具有铁磁性和半导体特性
4. 维度调控金属－绝缘体转变现象的发现可为自旋电子器件研制和应用提供一个新的途径。

磁性纳米线的磁各向异性调控

磁各向异性的重要性

1. 低维体系中长程磁有序的来源

2. 磁性材料的主要参数

- 高矫顽力
- 高频特性
- 磁记录
- …………….

磁性纳米线的磁各向异性调控

Long Range Magnetic Order low-dimensional System

Mermin-Wagner Theorem

An infinite *d* dimensional lattice of localized spins cannot have LRO at any finite temperature for $d<3$ if the effective exchange interactions among spins are isotropic in spin space and of finite range

T=0 K, **FM LRO, No AFM LRO**

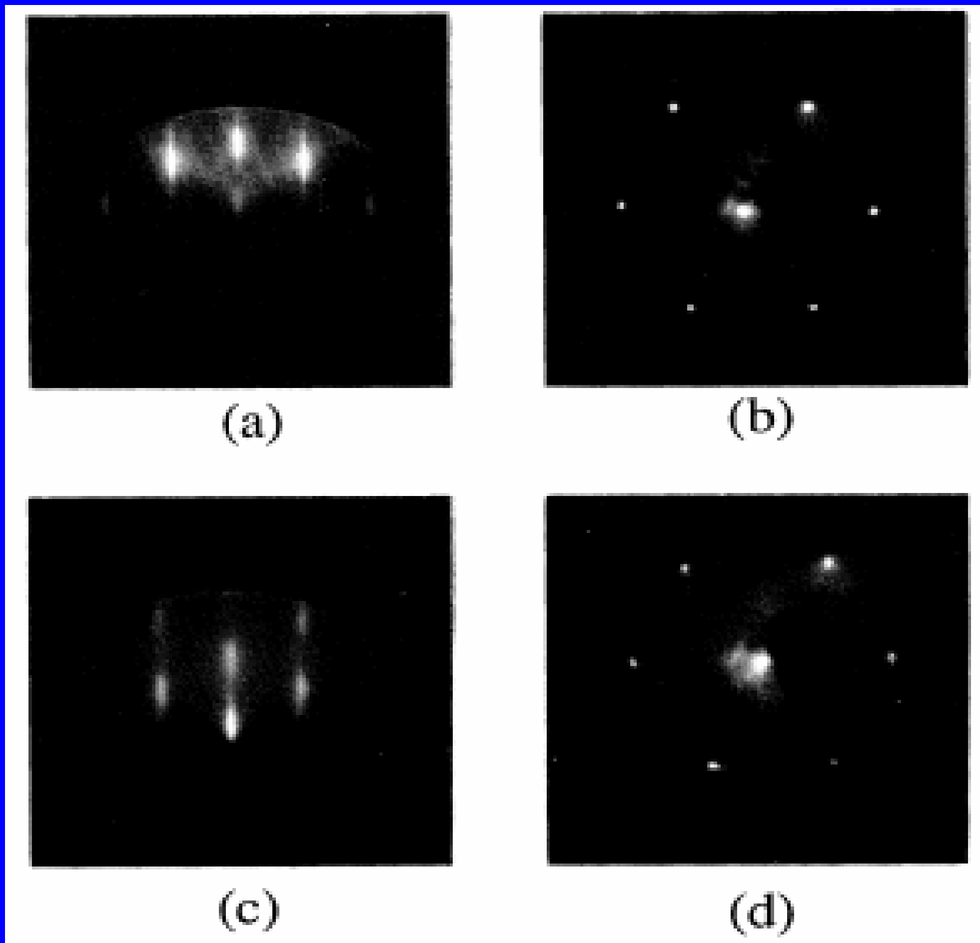
FM LRMO at T>0 if

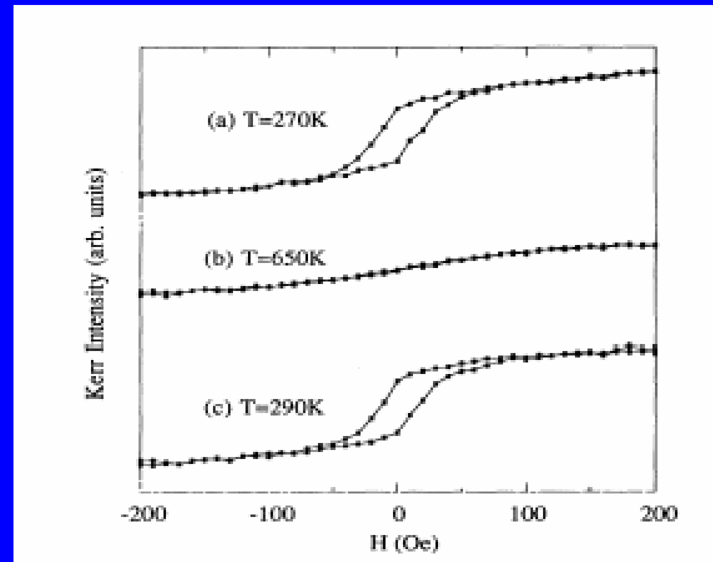
- **Anisotropy (exchange,dipolar or single-ion anisotropy)**
- **Dipolar or RKKY interactions**

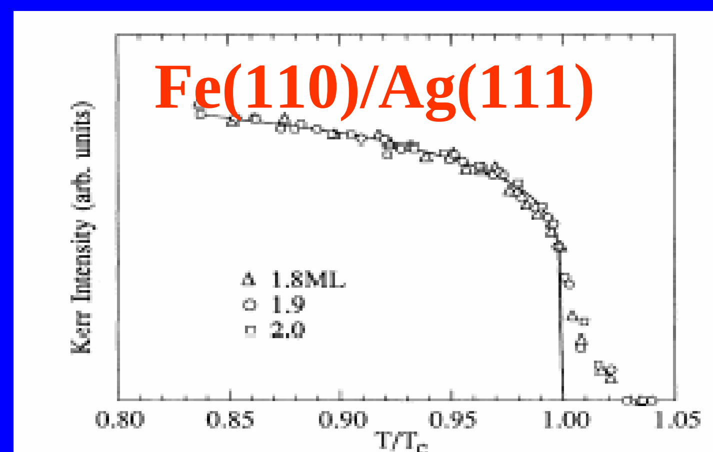
Mermin and Wagner, PRL 17(1966),1133; M. Bander and D.L. Mills, Phys. Rev. B. 38(1988)

Importance of Magnetic anisotropy

- Origin of Long range Magnetic order in low dimensional system



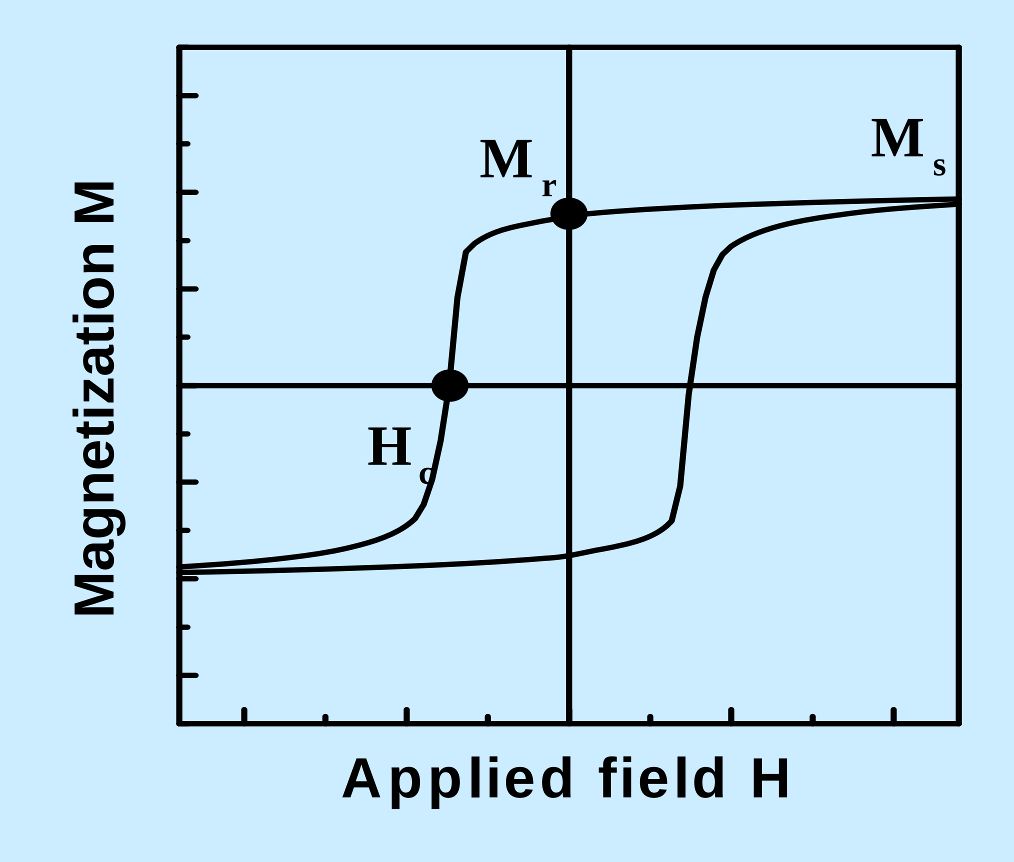




Z.Q. Qiu et al., PRL 67(1991),1133

Importance of Magnetic anisotropy

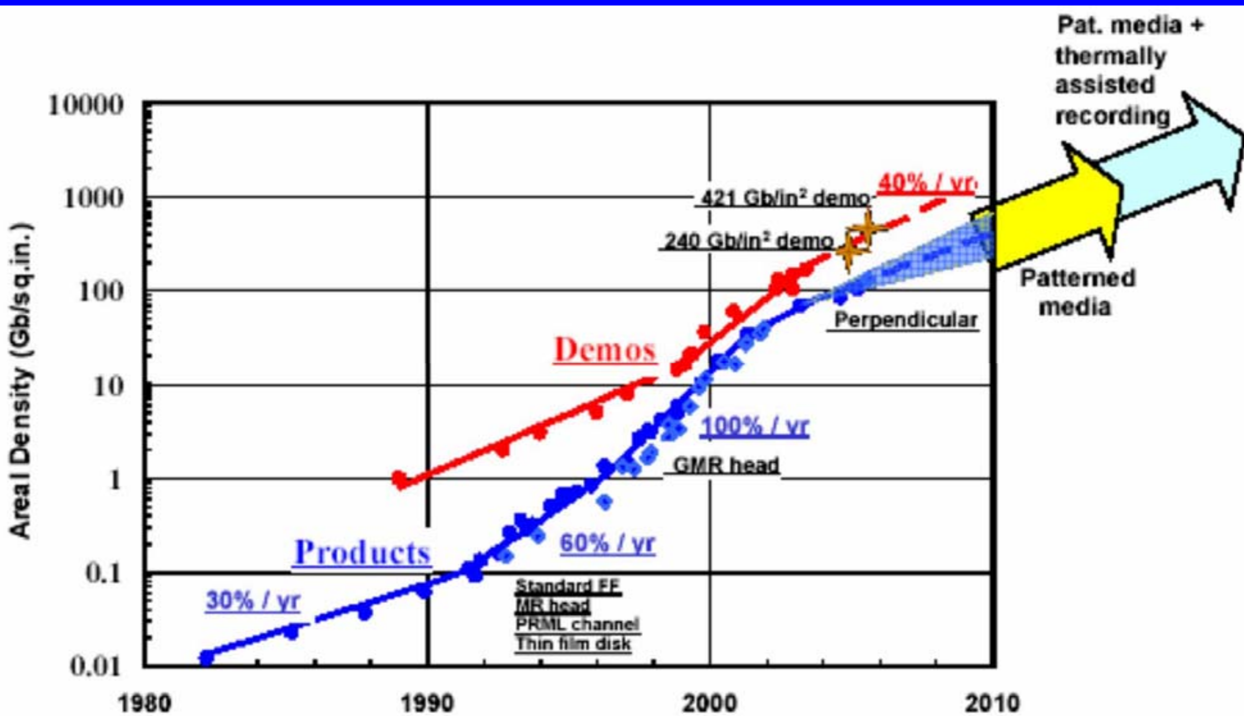
•Strong permanent magnet

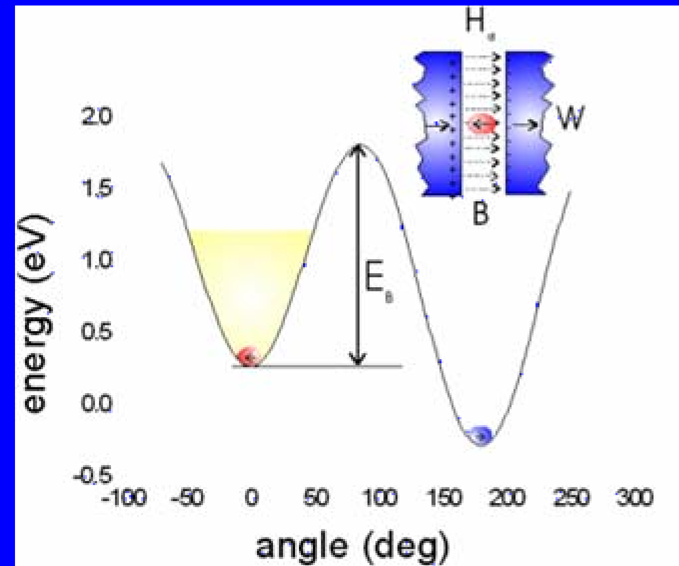


$$H_0 = \alpha \cdot \frac{2 \cdot K_u}{M_S} - N_{eff} \cdot M_S$$

Importance of Magnetic anisotropy

- Ultrahigh density of magnetic media and superparamagnetism limit





$$t = 10 \quad \text{year}$$

$$\frac{KV}{k_B T} > 40 - 60$$

E. A. Dobisz, et al., Proceedings of the IEEE 96,(2008), 1836

Importance of Magnetic anisotropy

•High frequency of magnetic materials

•For cubic symmetry

Natural Resonance frequency

$$f_r = \frac{\gamma K_u}{\pi M_s}$$

×

Peamibility of strong magnet

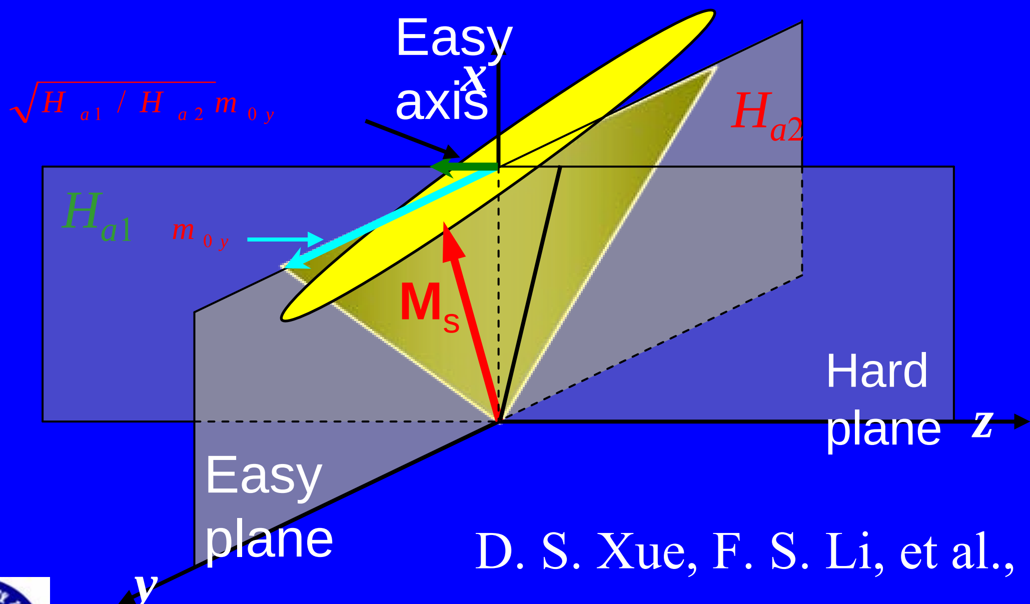
$$\overline{\mu} = \frac{M_s^2}{3\mu_0 K_u}$$

=

Limit of Snoek

$$f_r \cdot \overline{\mu} = \frac{\gamma M_s}{3\mu_0}$$

•For in-plane uniaxial anisotropy

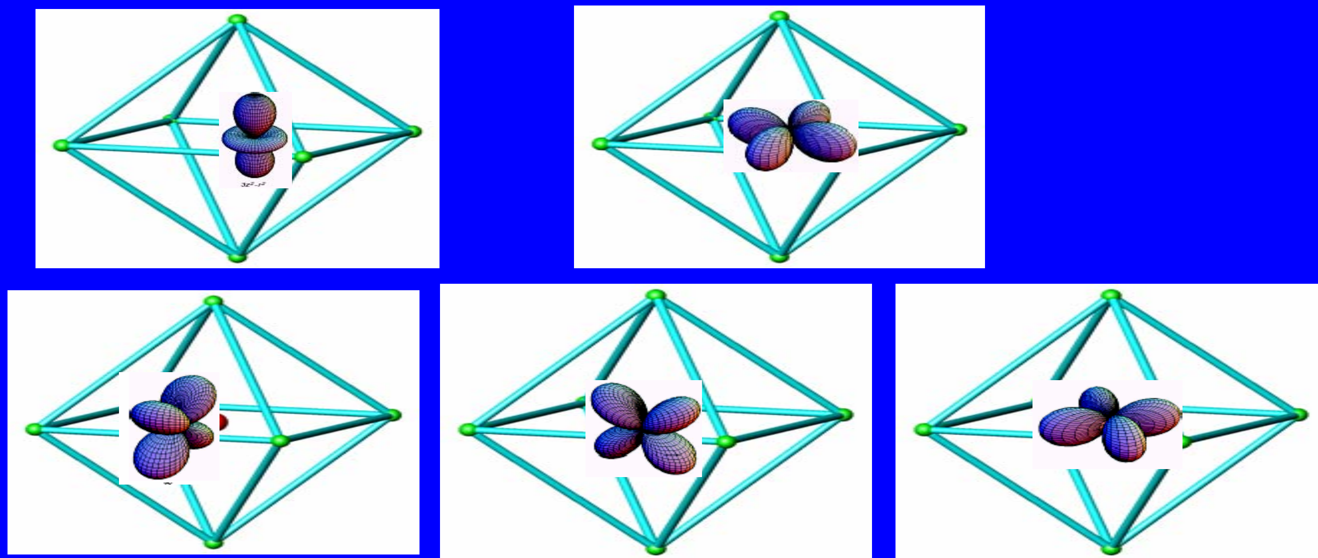


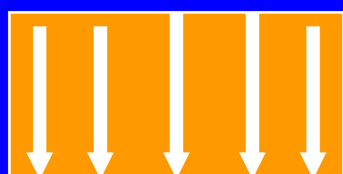
$$(\mu_s - 1) f_r = \frac{\gamma}{2\pi}\sqrt{\frac{H_{a1}}{H_{a2}}} M_s$$

D. S. Xue, F. S. Li, et al., Chin. Phys. Lett. **25**, 4120 (2008).

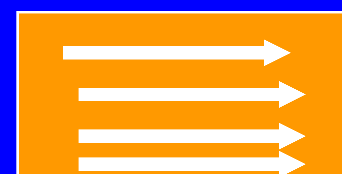
Magnetic Anisotropy

- **Magnetocrystalline anisotropy(MCA)**





$$E_{LS} = \lambda \vec{L} \bullet \vec{S}$$



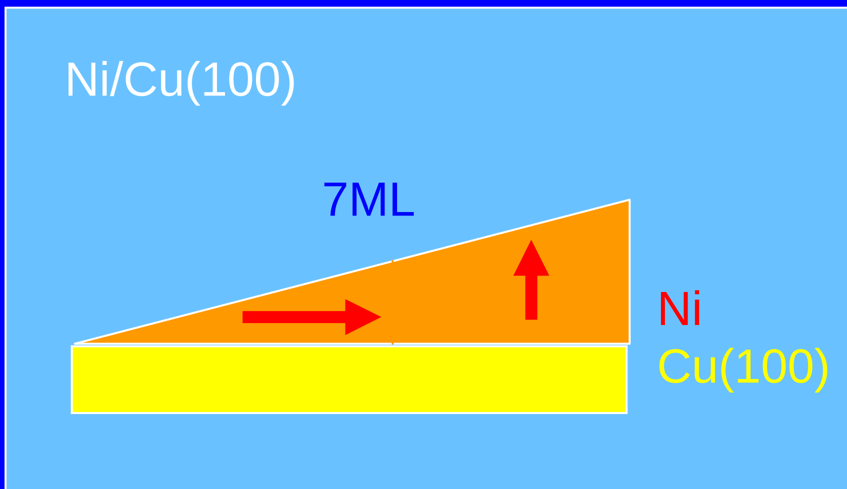
Single-Ion Model

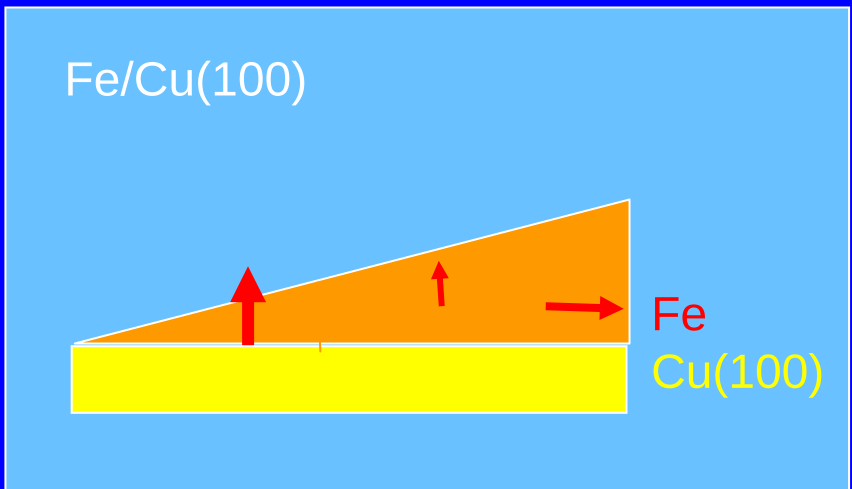
CEF → ***Orbital anisotropy*** —***LS***→ ***MCA***

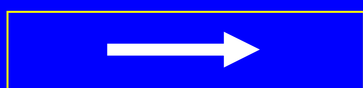
Magnetic Anisotropy

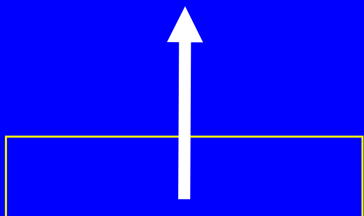
Surface magnetic anisotropy

Fe/Cu(100) SRT=5ML





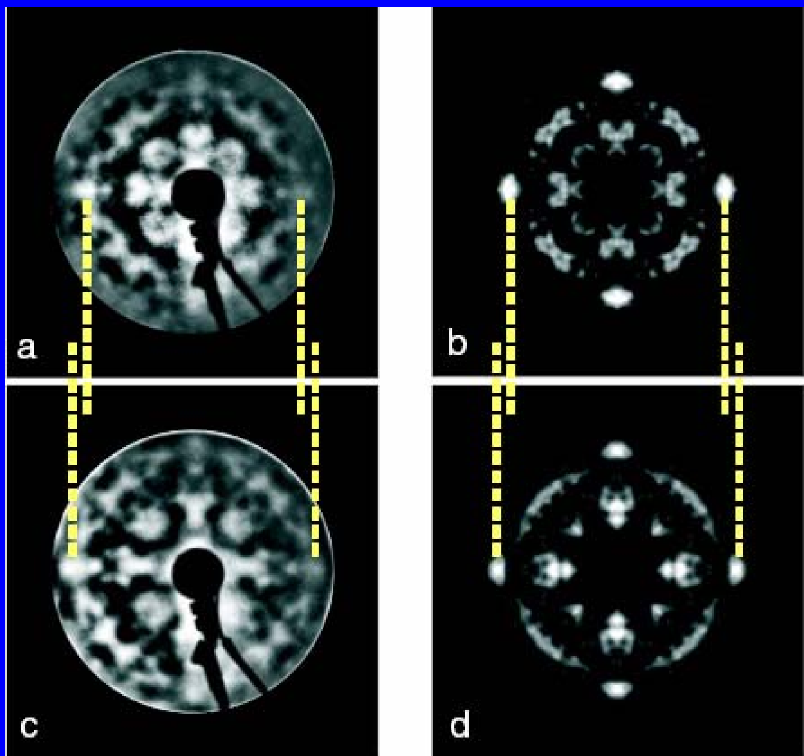


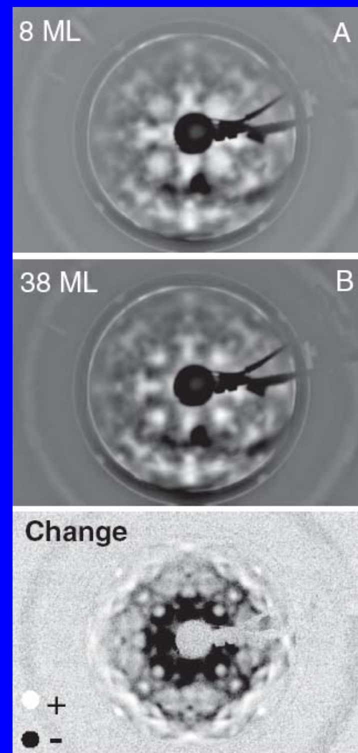


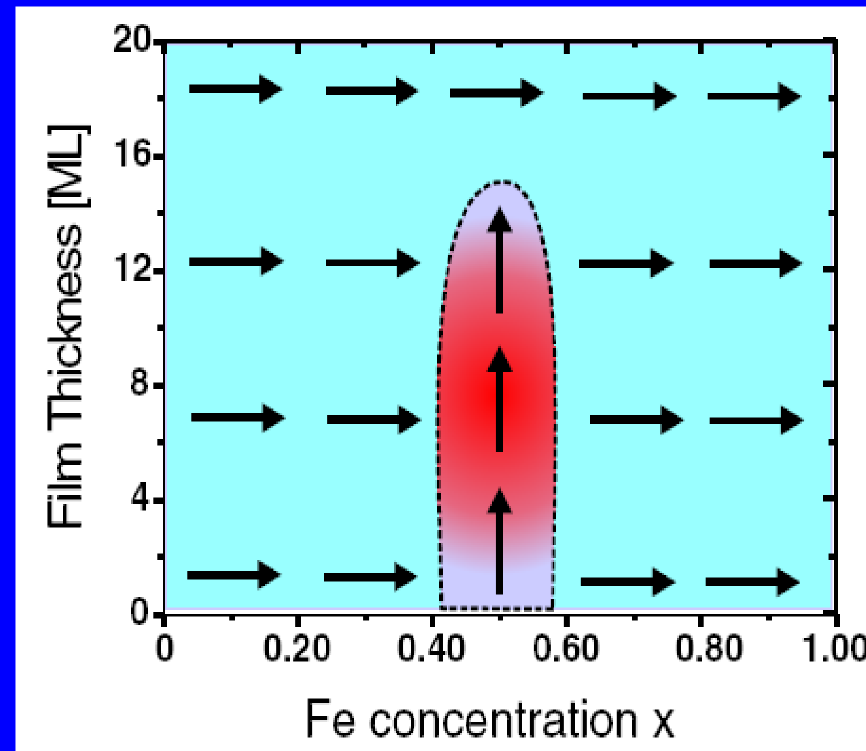
Ks < 0

Ks > 0

Perpendicular Magnetic Anisotropy Induced by Tetragonal Distortion of FeCo Alloy Films Grown on Pd(001)

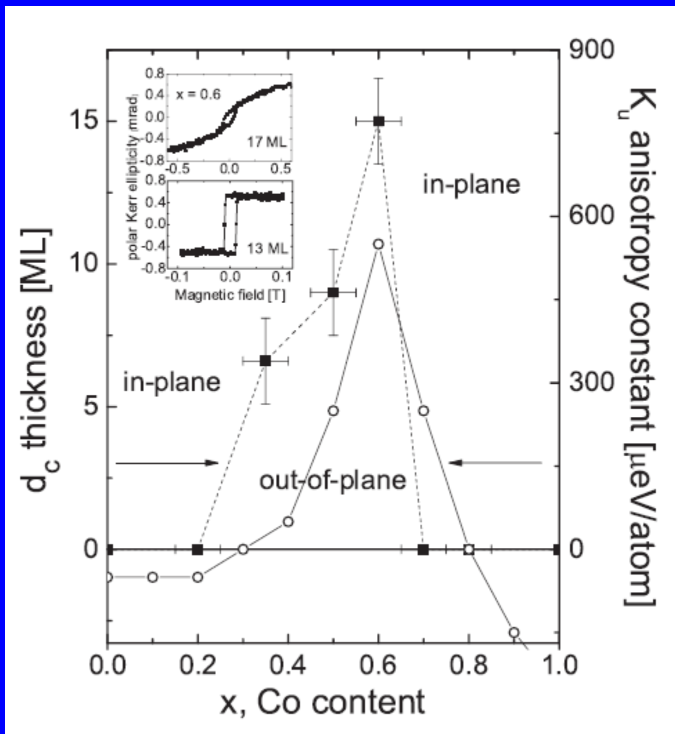


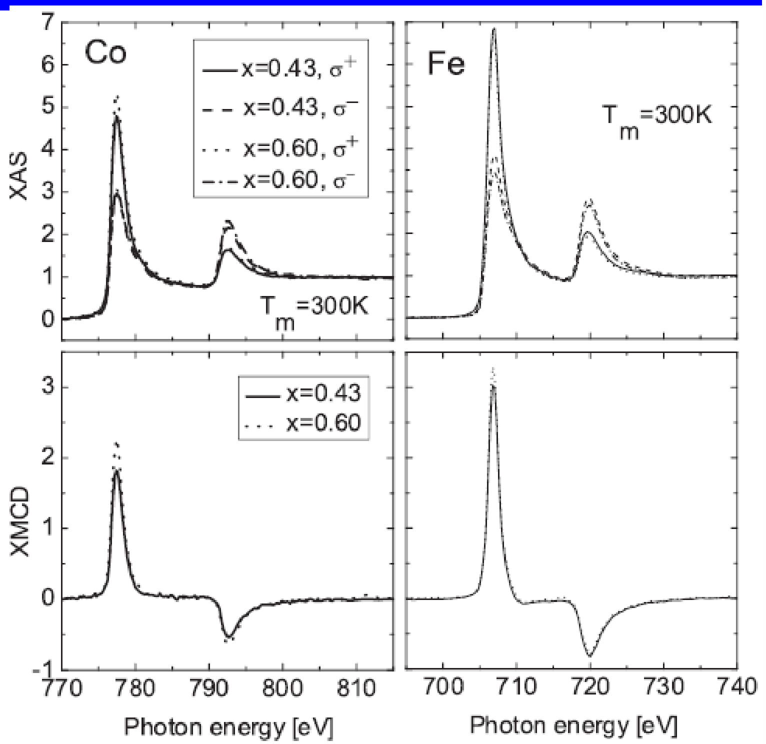


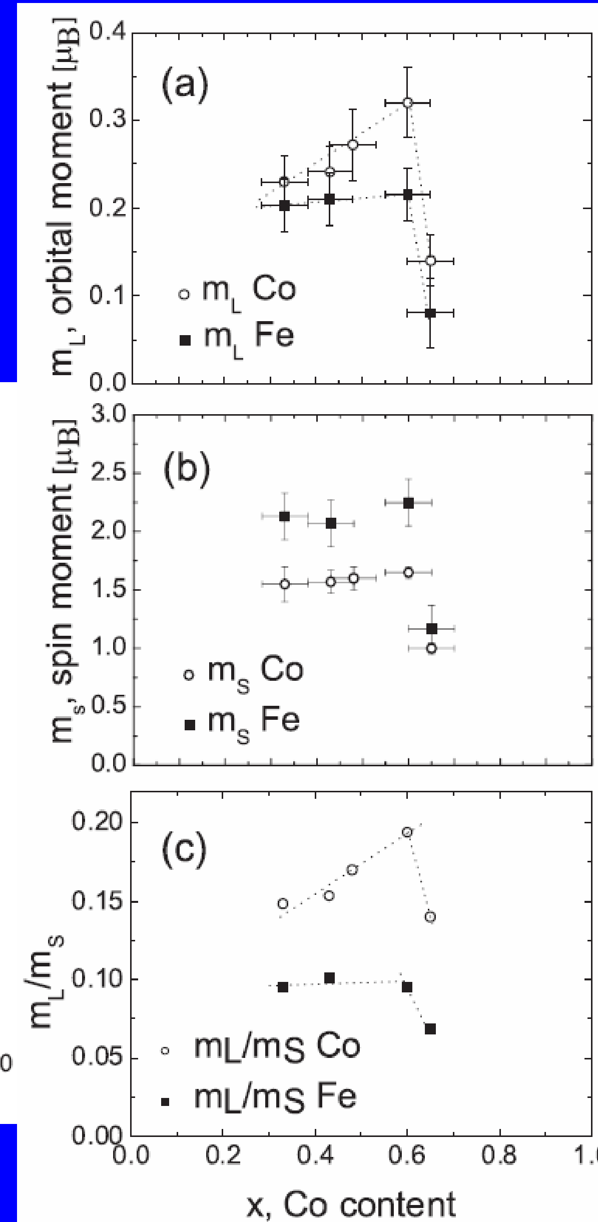


A.Winkelmann et al, PRL,96,257206(2006)

Strongly Enhanced Orbital Moment by Reduced Lattice Symmetry and varying Composition of Fe1-*x*Co*x* Alloy Films

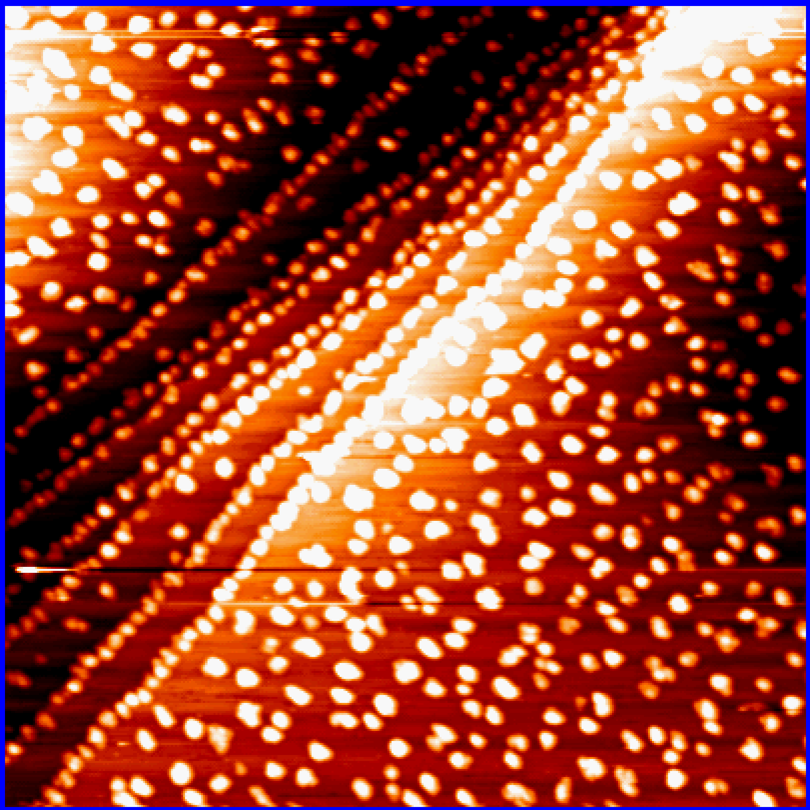




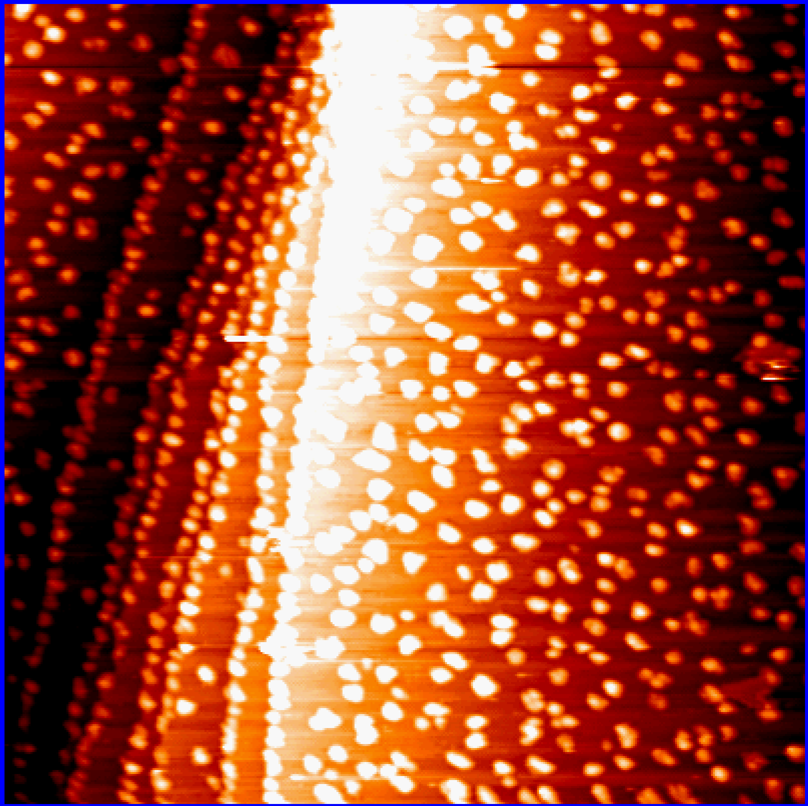


F. Yildiz et al, PRL,100,037205(2008)

Why chose Fe/Pb/Si(111)



200nm



200nm

Growth at Low temperature for 30 seconds Co

Why chose Fe/Pb/Si(111)

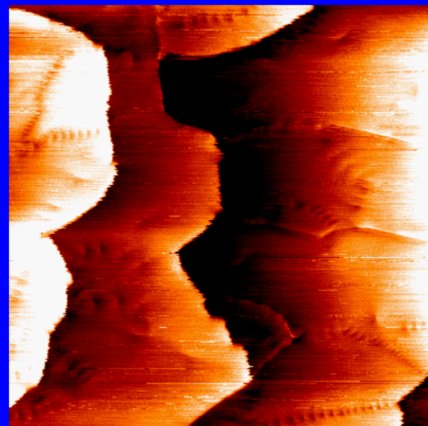
1. 直接用Pb基底不容易处理，而Si台阶容易获取和处理

2. Fe/Si 形成FeSi 化合物
   Fe/Pb/Si

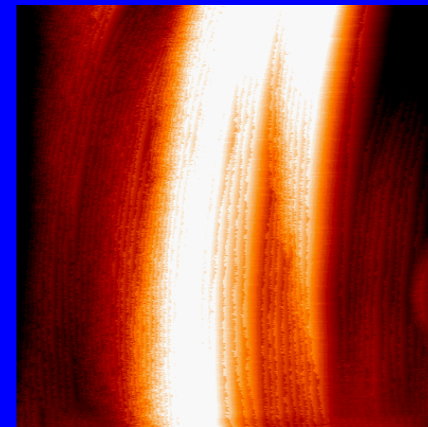
3. Fe表面自由能：2.48J/m^2, Pb表面自由能：0.5J/m^2
   Fe bcc 2.87A Fe(110) 2.49A
   Pb fcc 4.95A   Pb(111) 2.8435A
   0D: "V W" 直接成核模式
   1D: "Step-decoration"

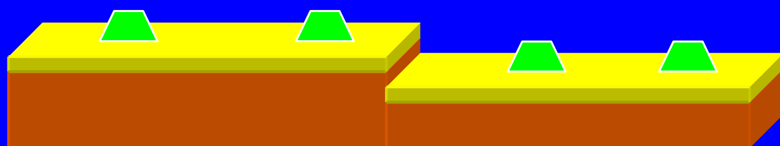
Pb膜上的Fe岛和Fe线

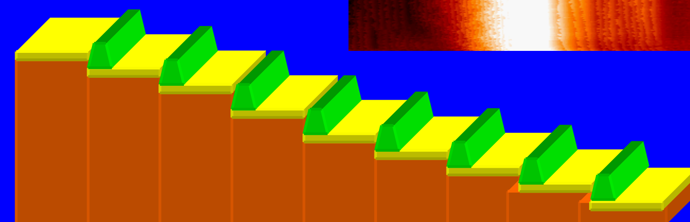
Pb / Si(111)
0.1度斜切
500×500

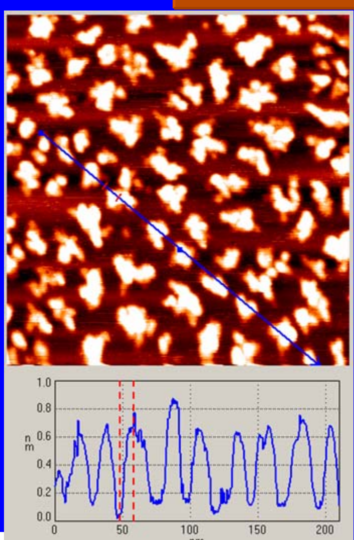


Pb / Si(111)
4度斜切
500×500

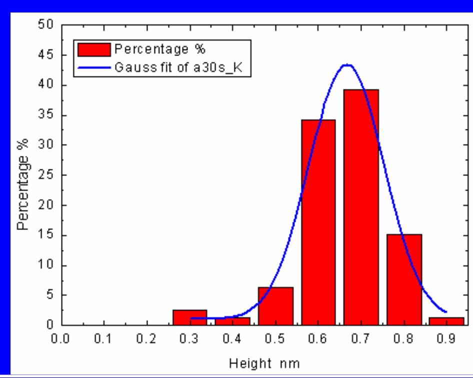




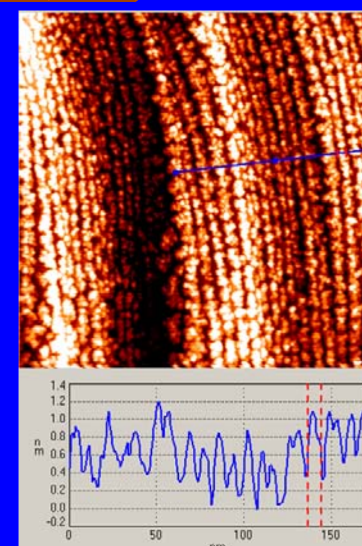




0.84ML
Fe islands on
Pb (18ML) / Si
(200nm × 200nm)

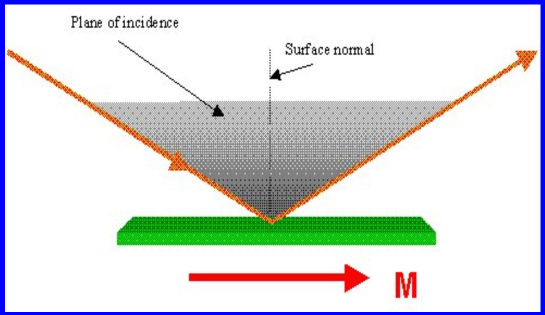


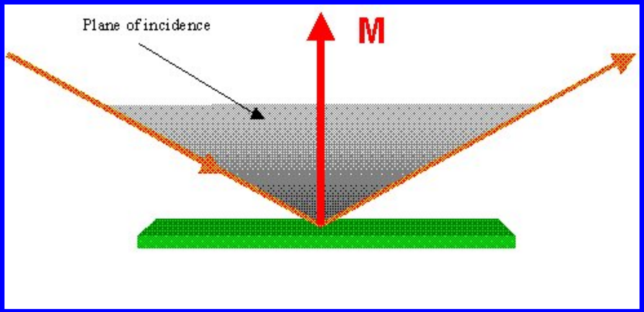
1.27ML
Fe wires on Pb (18ML) / Si
(300nm × 300nm)

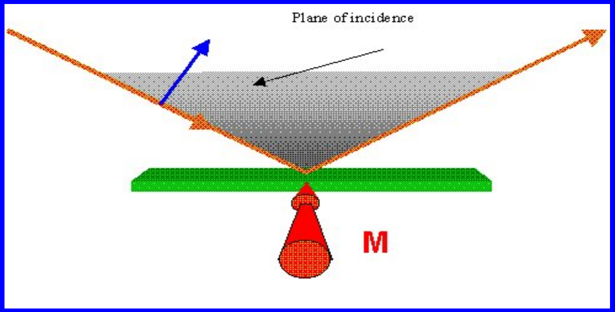


易磁化方向的确定

Three experimental geometries of SMOKE

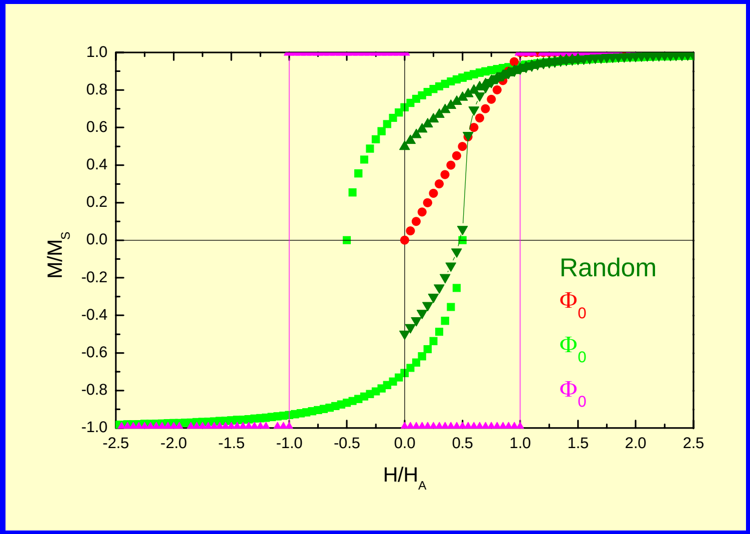




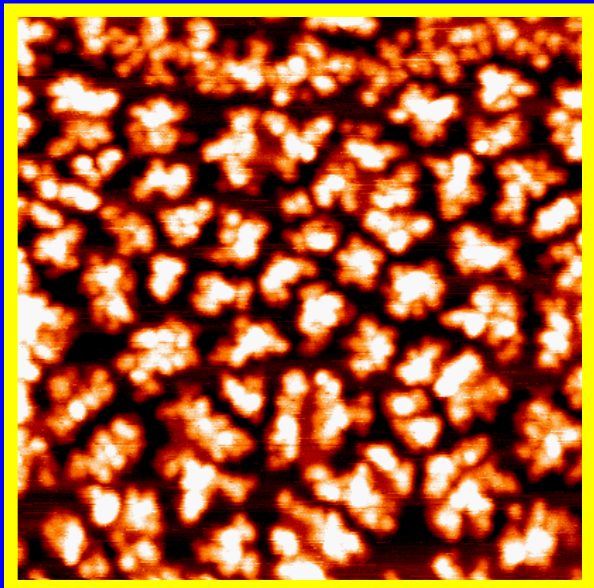


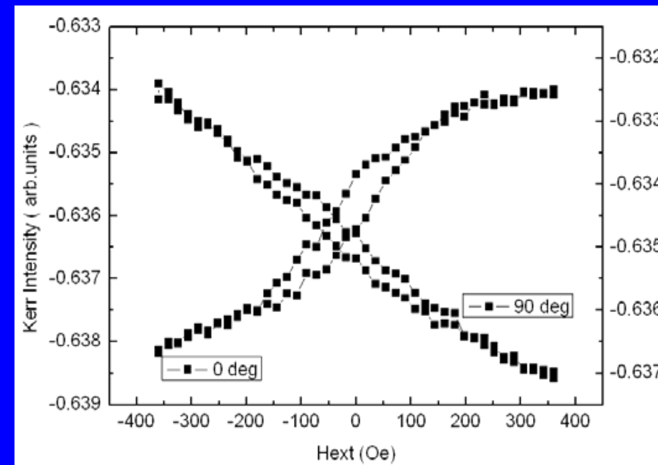
Longitudinal　　Polar　　transverse

磁场与易磁化轴不同角度的磁滞回线



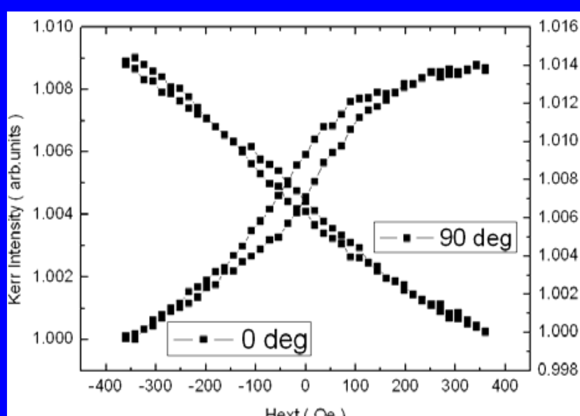
Pb膜面内不同方向的Fe岛磁性





SMOKE 信号 与线成60度角

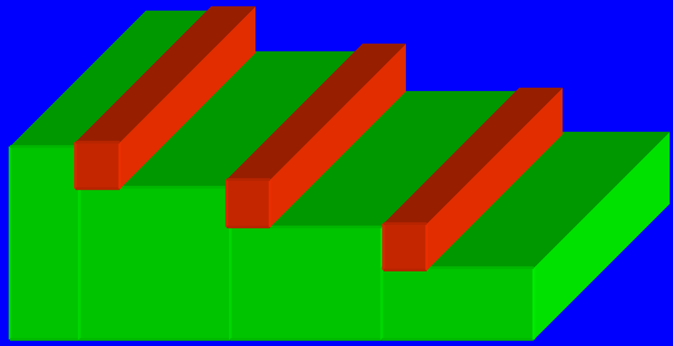
1.6 ML 300K

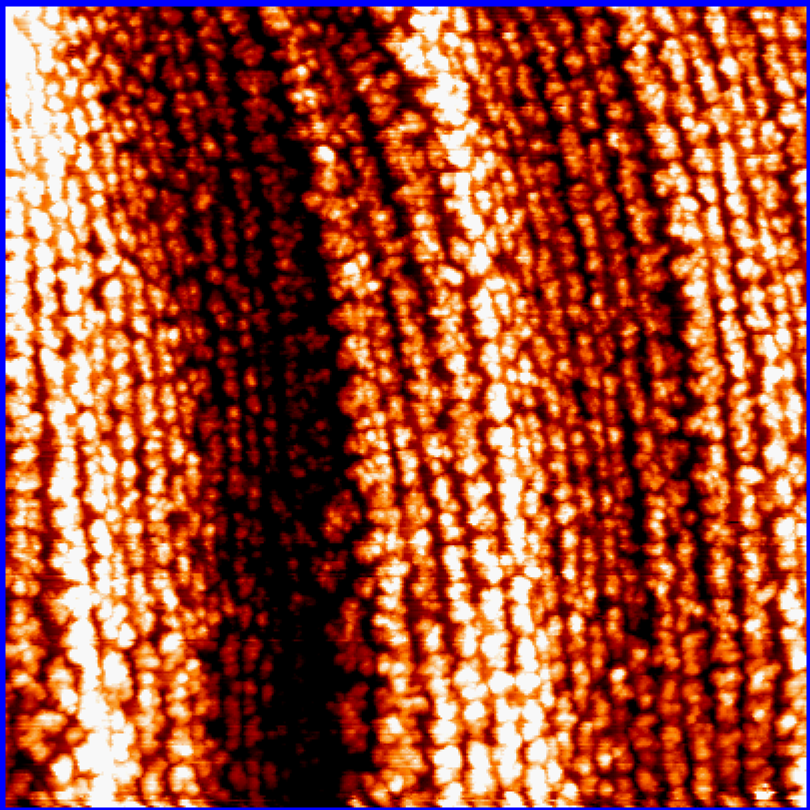


SMOKE 信号 与线成90度角

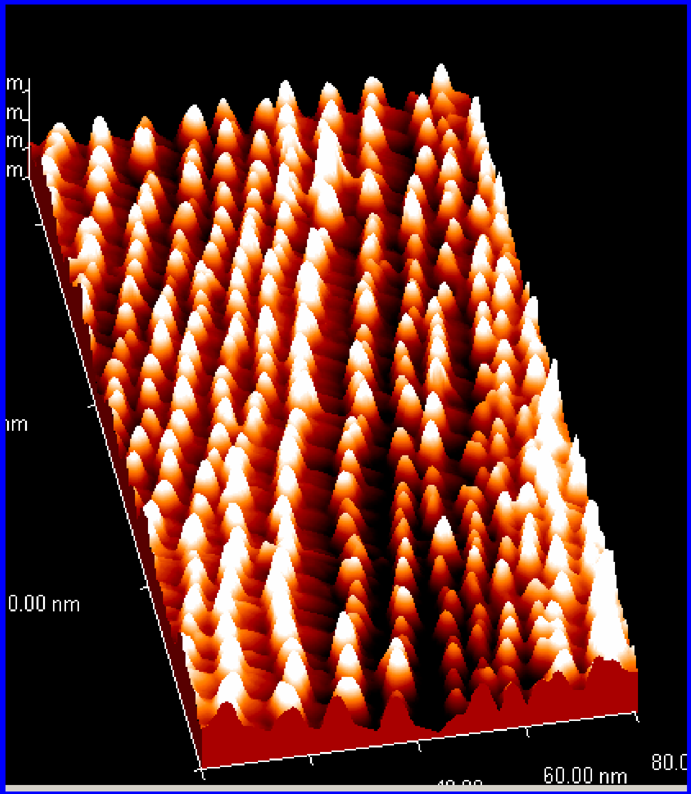
1.6 ML 300K

MBE-Step induced

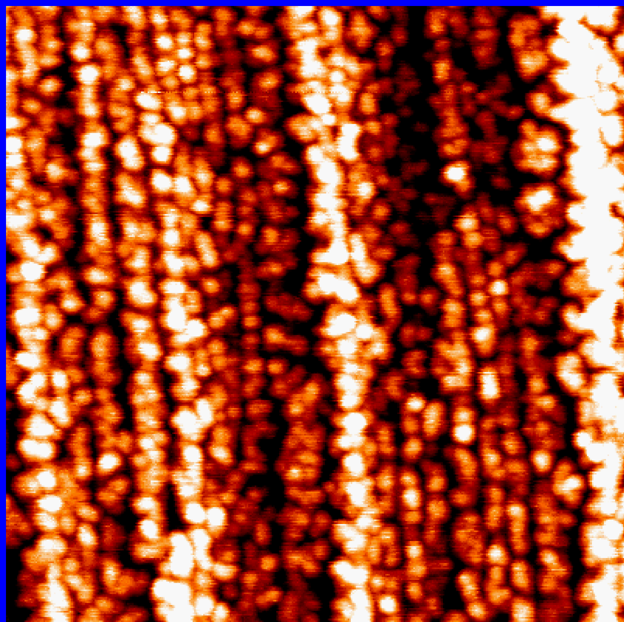




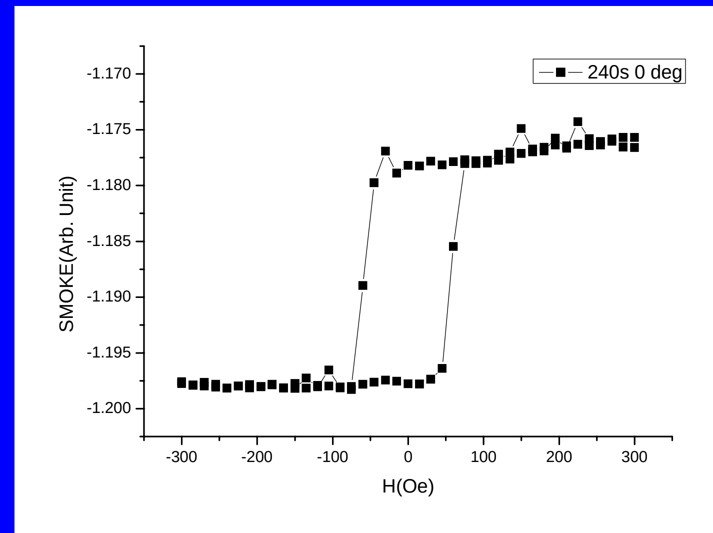
300 nm*300 nm



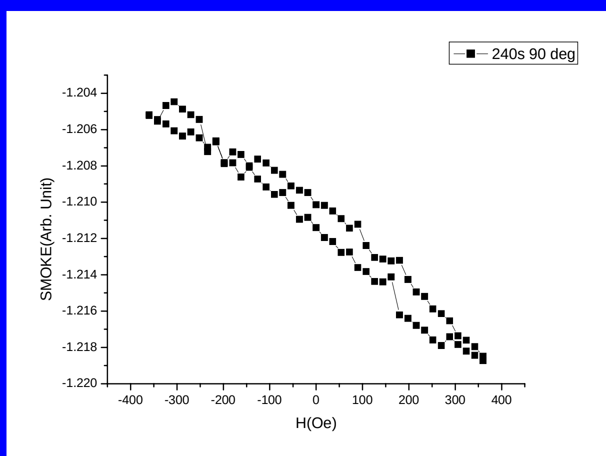
Uniaxial anisotropy of Fe on Si nanowires/chains



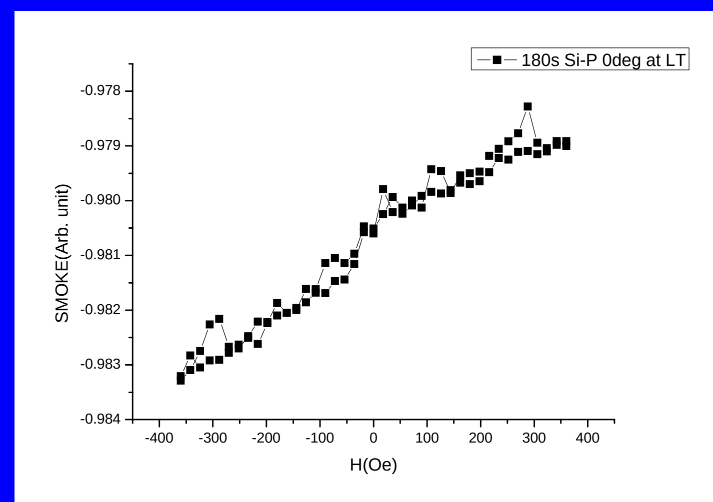
H



H

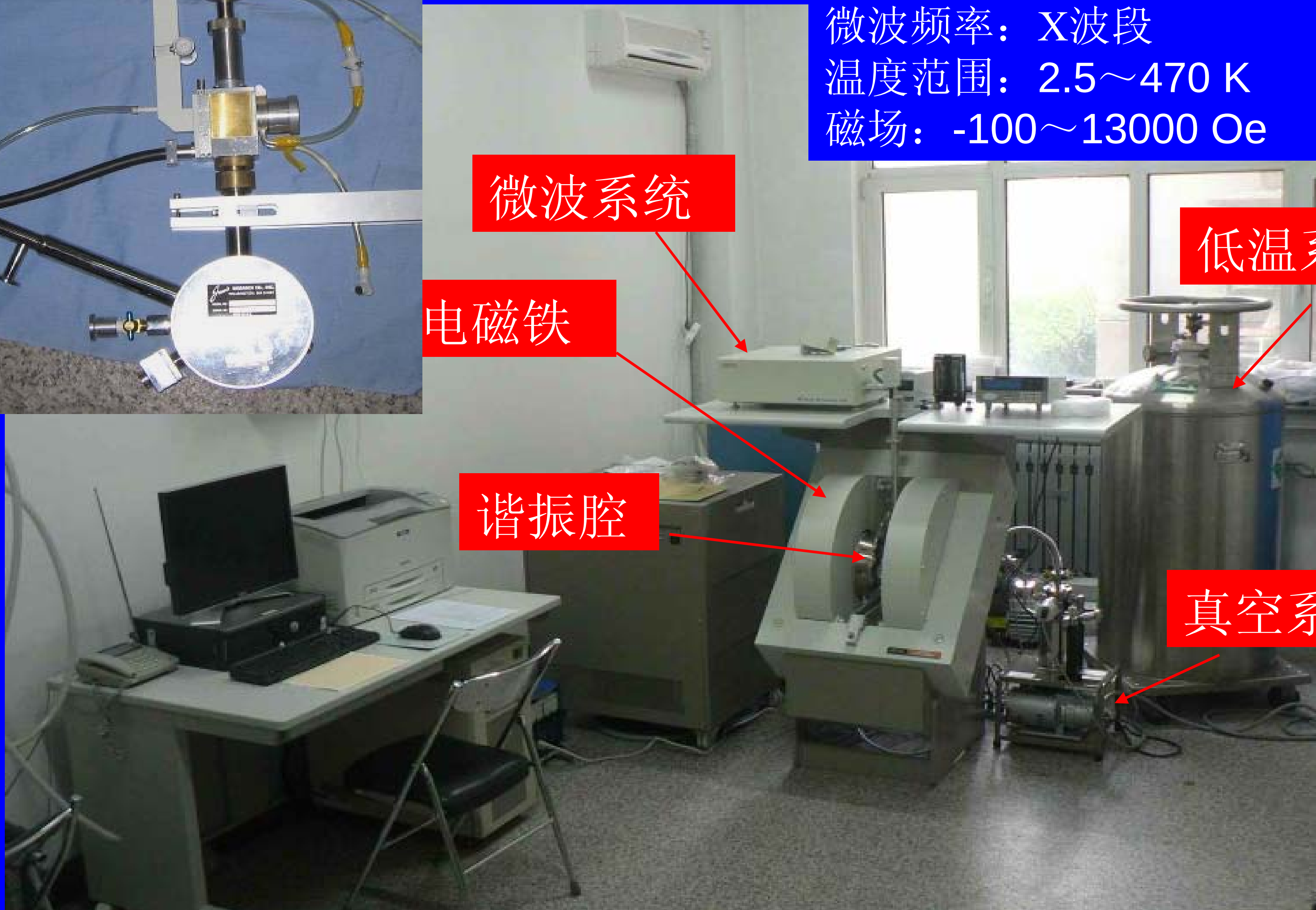


H



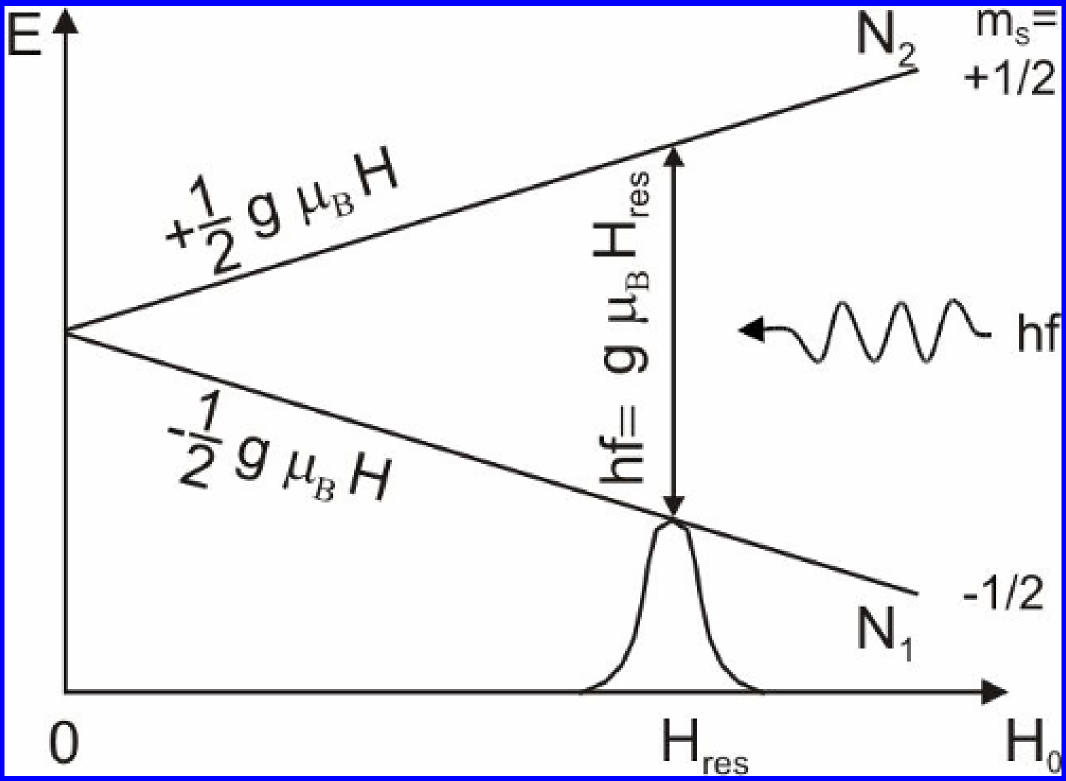
SR)

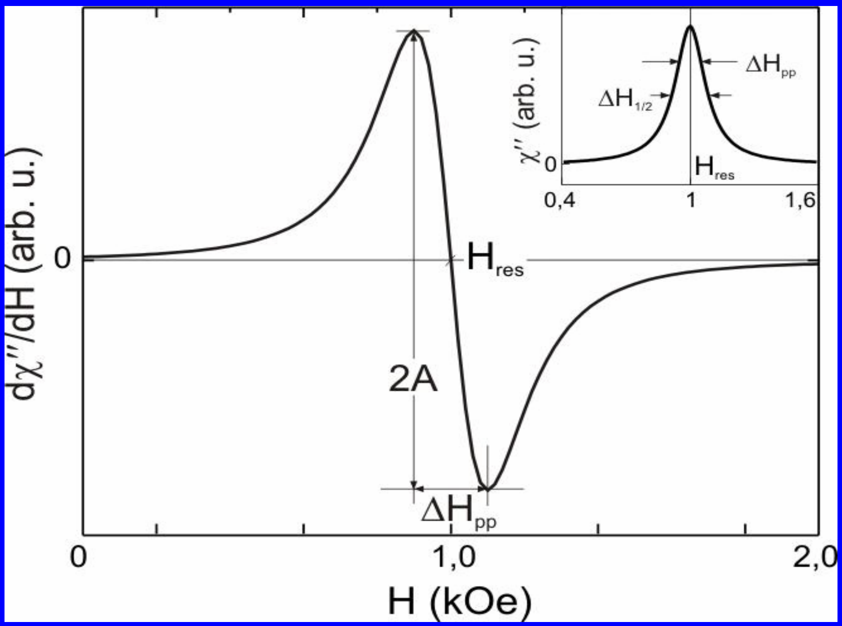
微波频率：X波段
温度范围：2.5～470 K
磁场：-100～13000 Oe



磁共振研究独特性

Short Time Scale



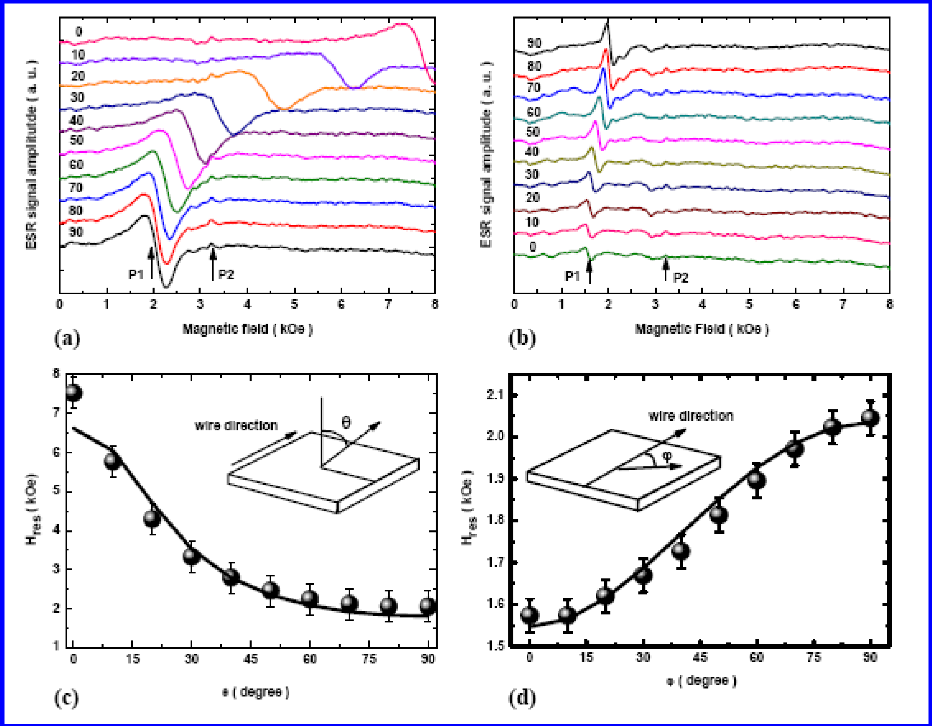


线宽 ΔH_{pp}: 自旋-晶格弛豫时间 T_1, 自旋-自旋弛豫时间 T_2;

g因子: 自旋角动量S和轨道角动量L对电子磁矩的贡献大小;

强度 *I*: 自旋磁化率

利用电子自旋共振确定磁各向异性



$$\left(\frac{\omega}{\gamma}\right)^2 = \left[H\cos(\varphi-\varphi_H)+4\pi M_{eff}+\frac{2K_u}{M_S}\cos^2\varphi\right]\times\left[H\cos(\varphi-\varphi_H)+\frac{4K_u}{M_S}\cos 2\varphi\right].$$

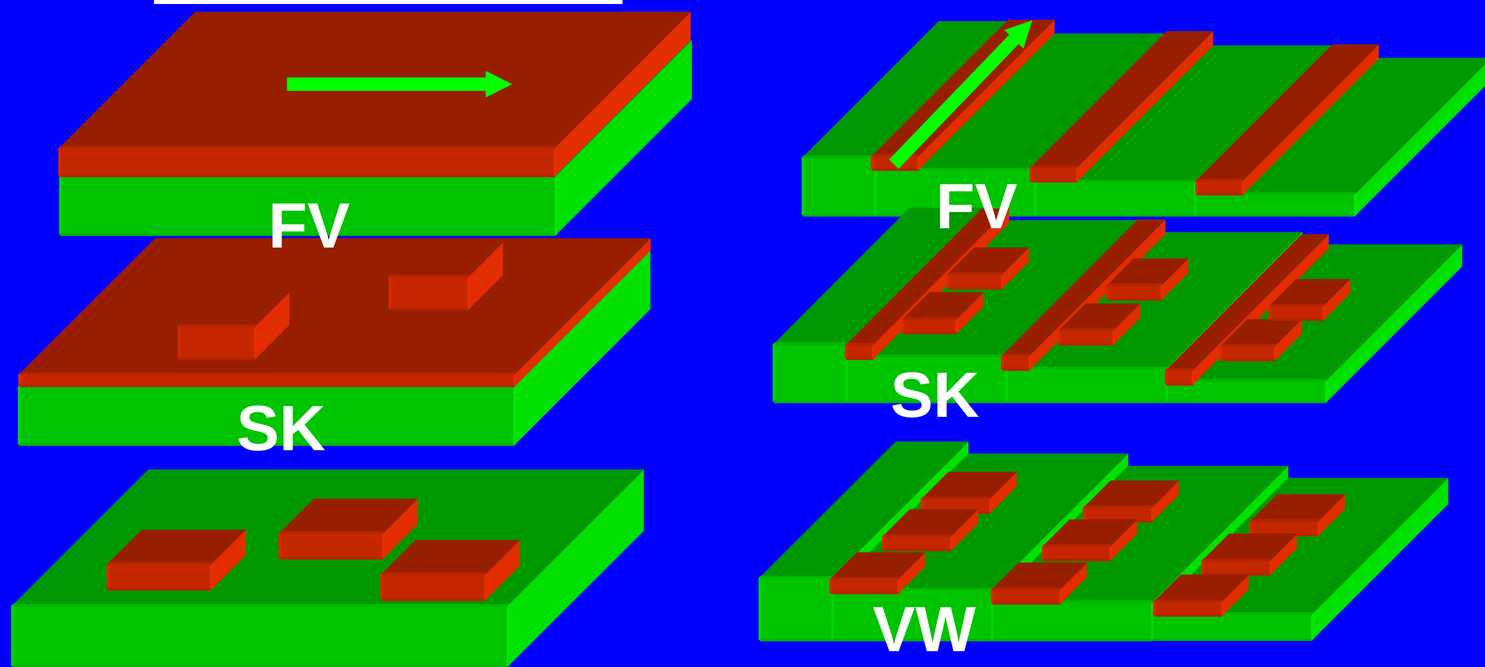
Magnetic Anisotropy

Shape anisotropy –Dipolar Interaction

$$E_d = -\frac{1}{2} I_s H_d = \frac{I_s^2}{2\mu_0}\left(N_x\alpha_1^2 + N_y\alpha_2^2 + N_z\alpha_3^2\right)$$

$$E_d = \frac{\mu_0 M^2}{2}\cos^2\theta$$

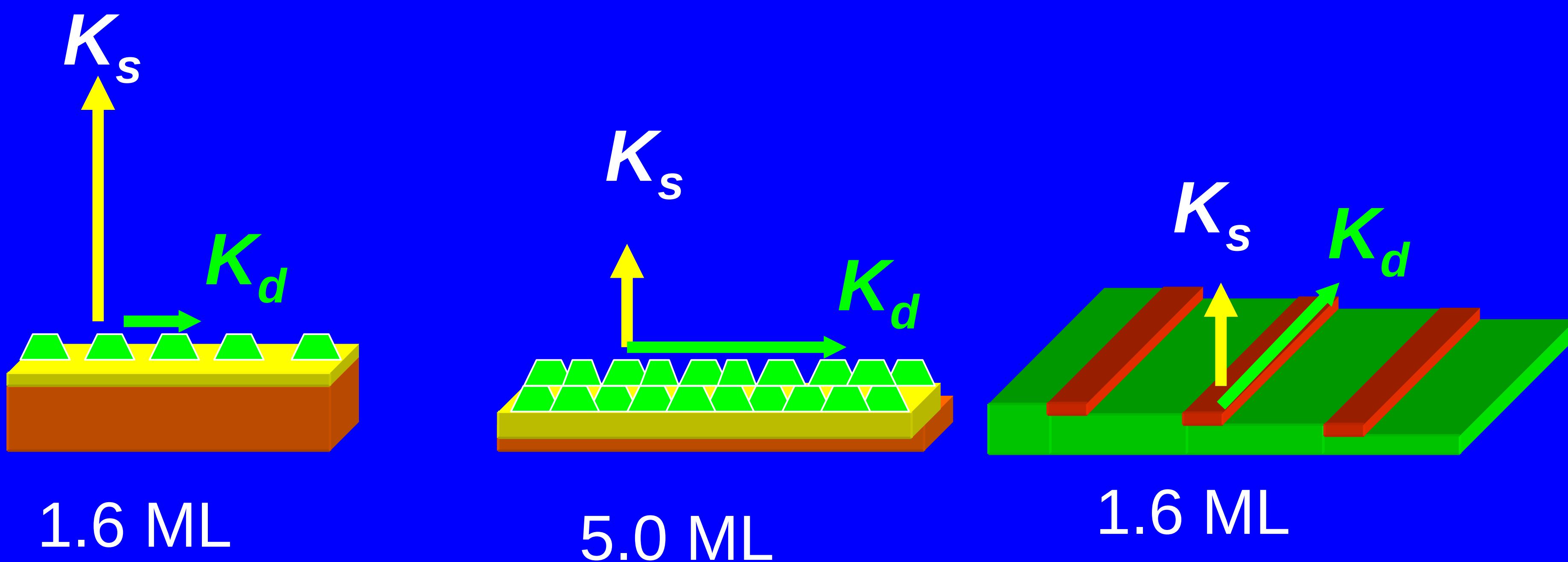
$$E_d == \frac{\mu_0 M^2}{4}\sin^2\varphi$$



Magnetic Anisotropy

$$K^{\text{eff}} = \frac{1}{d}\int_0^d (K^v + K^s\delta(z))dz$$

$$K_{eff} = (K_V - K_d) + 2K_s/d$$



小结

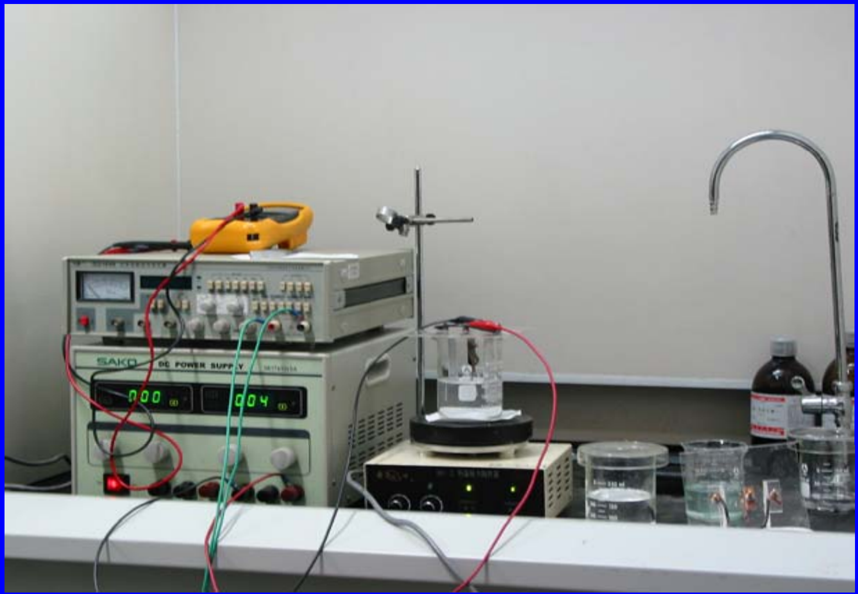
- 在低覆盖度时，Fe形成具有分形结构的岛状结构；表现出垂直磁各向异性;

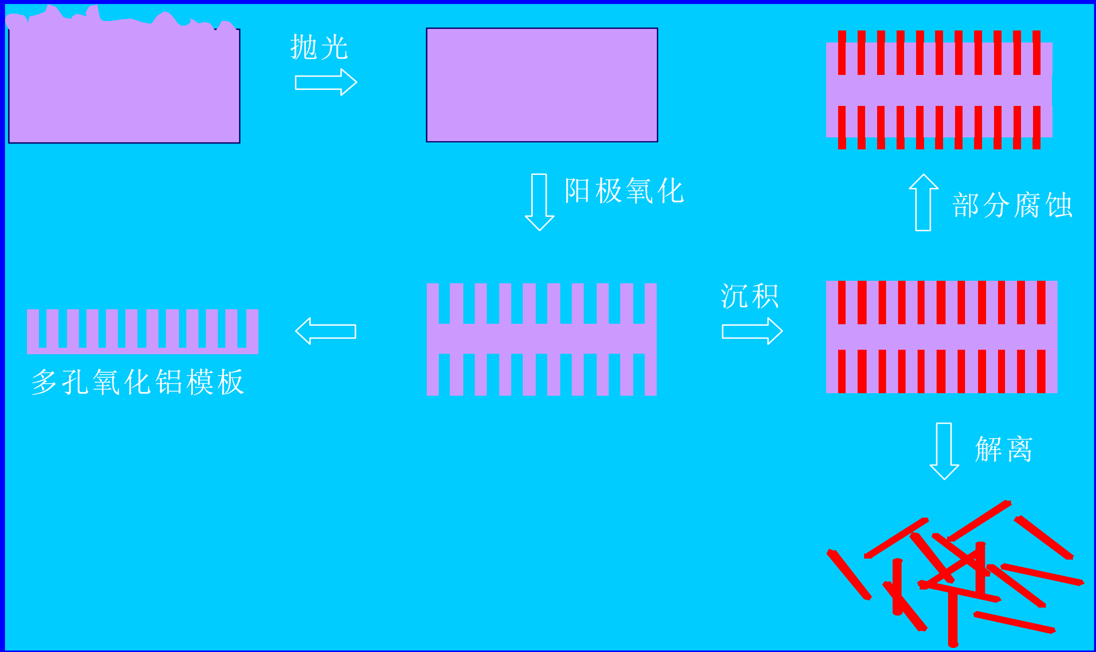
- 随着覆盖度的增加，在3.3 ML时在室温下可以观察Fe岛的平行于面内的各向同性的SMOKE信号

- Si基底原子台阶诱导的Fe纳米线表现出具有沿着台阶方向的磁各向异性。

Fe基纳米线阵列的磁各向异性

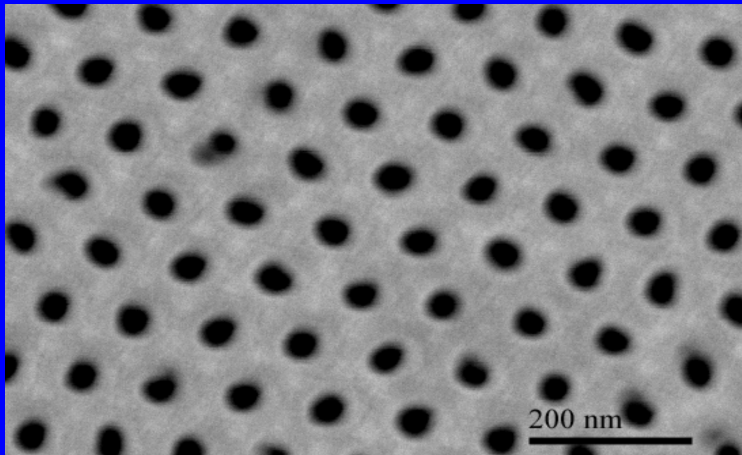
☞纳米线阵列的制备方法



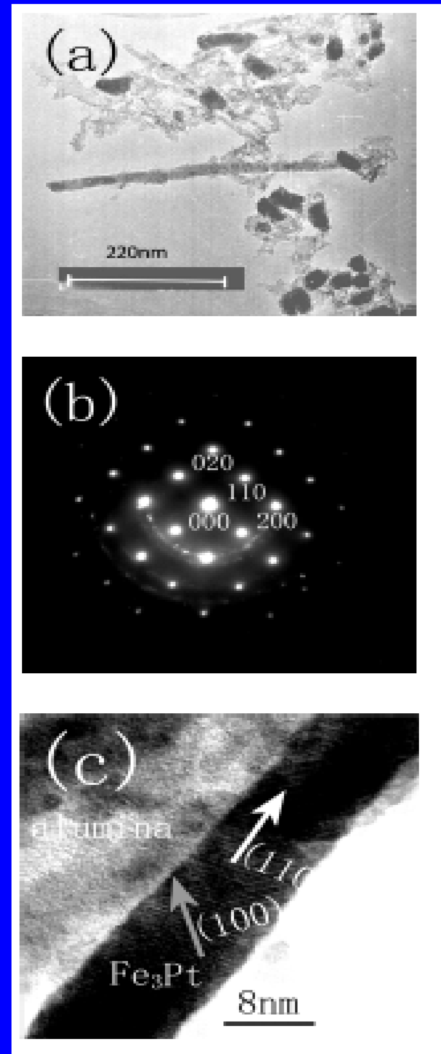


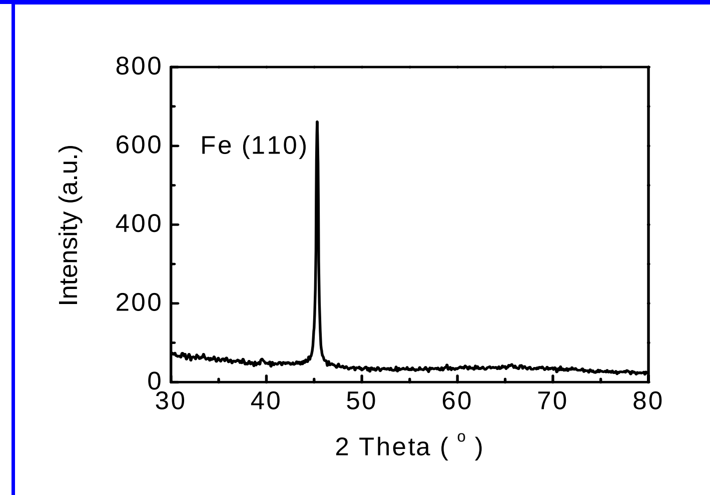
阳极氧化铝（AAO）模板法

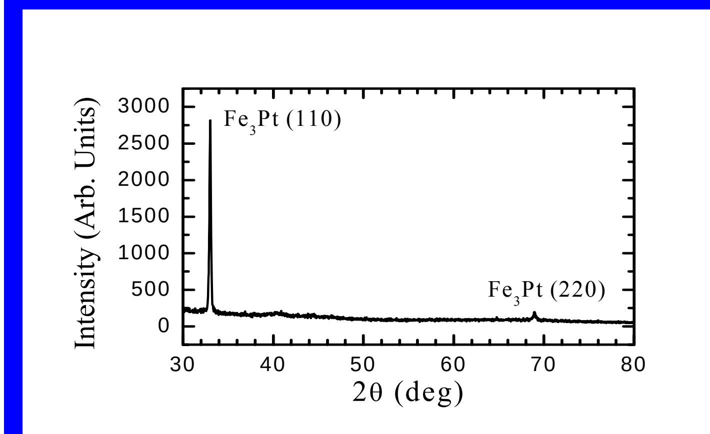
Fe3Pt nanowires



AAO template

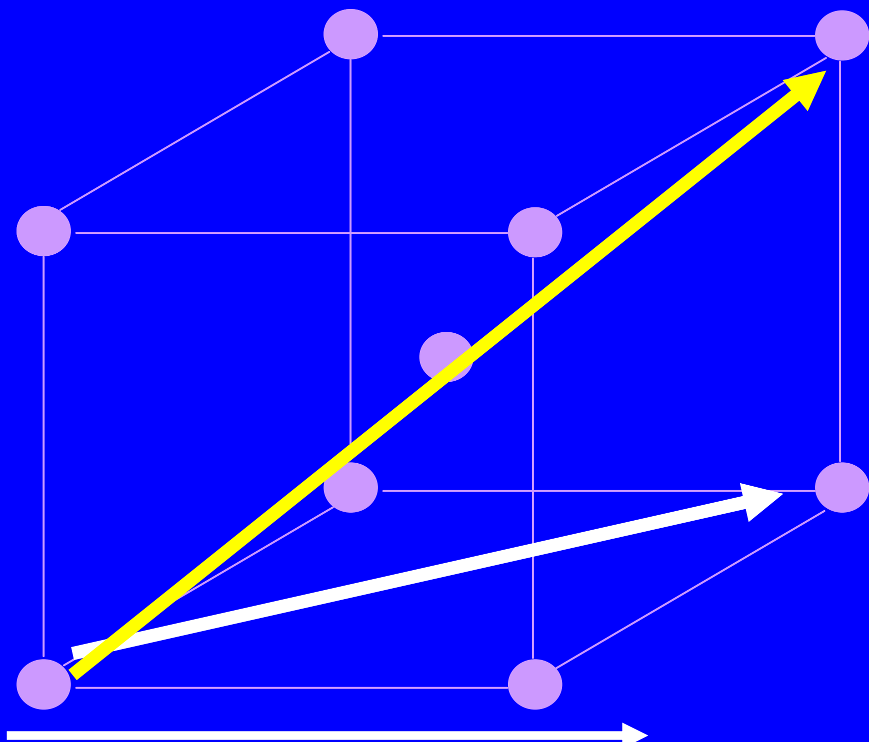




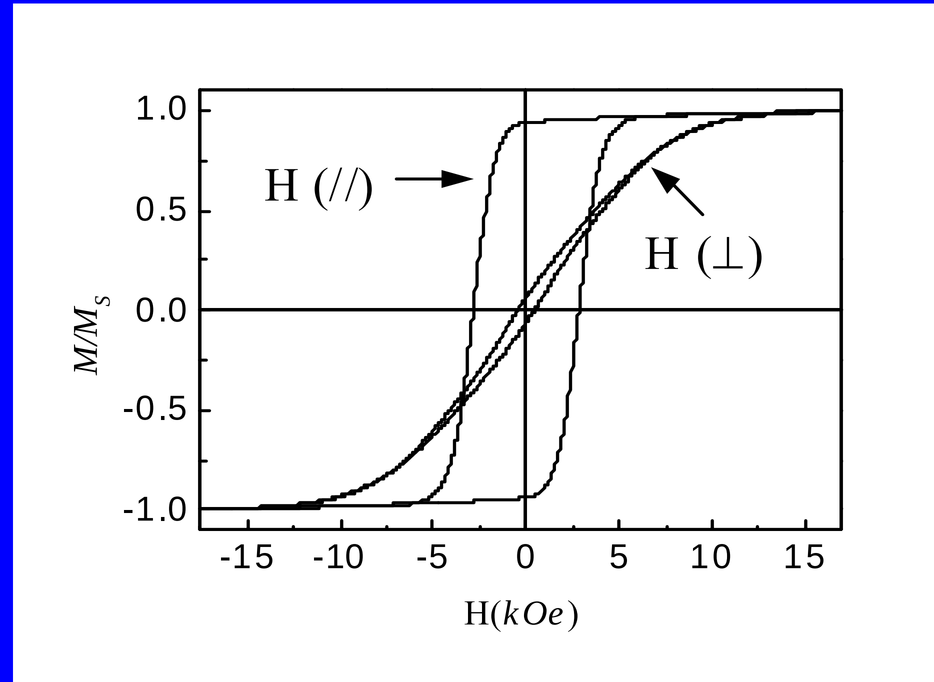


J.H. Gao, Appl. Phys. Lett. 86(2005)232506

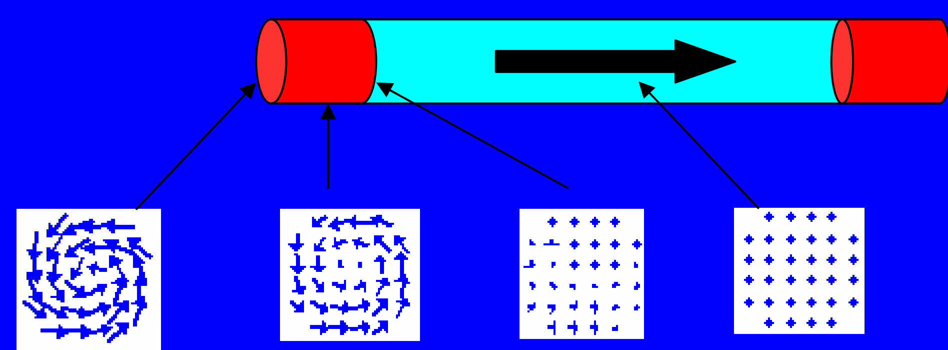
形状各向异性



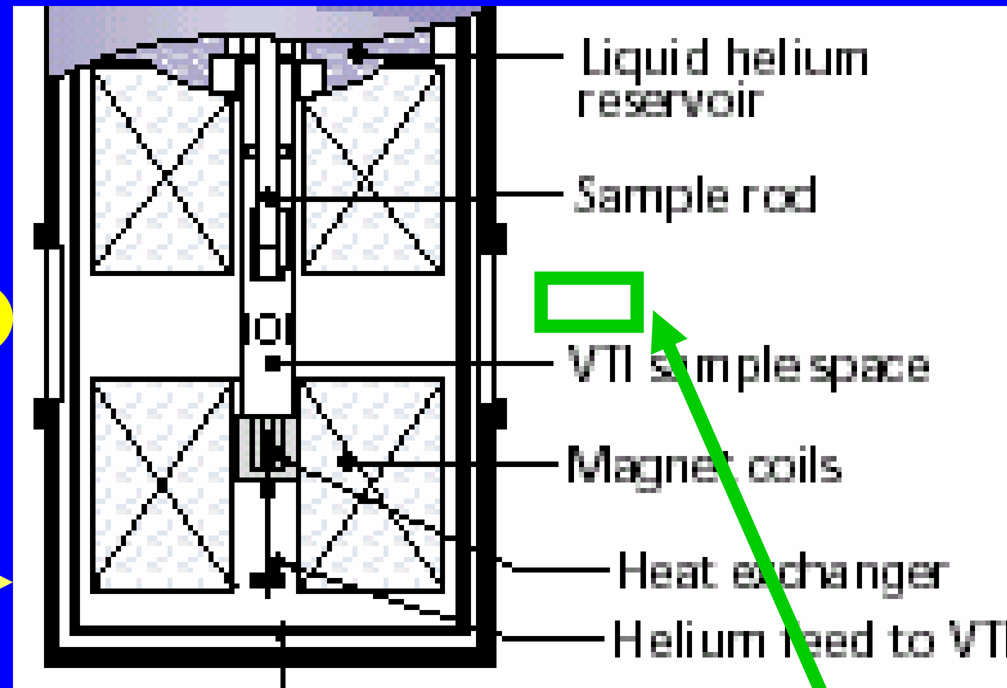
[100]: magnetic easy axis due to magnetocrystalline anisotropy



[110]: magnetic easy axis due to shape anisotropy



Low temperature and Superconducting Magnet for Mössbauer Spectrometer

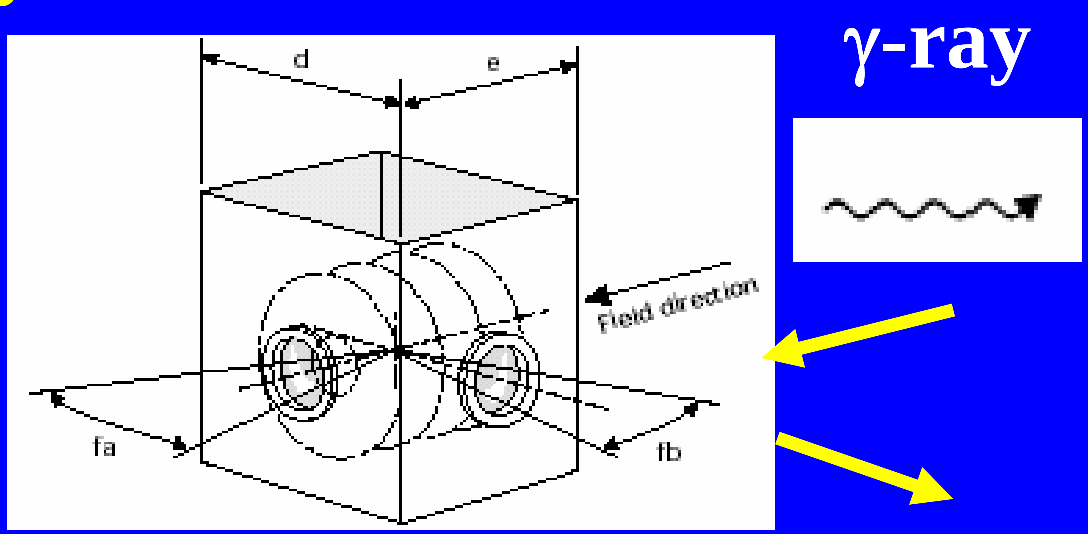


Source

Detector

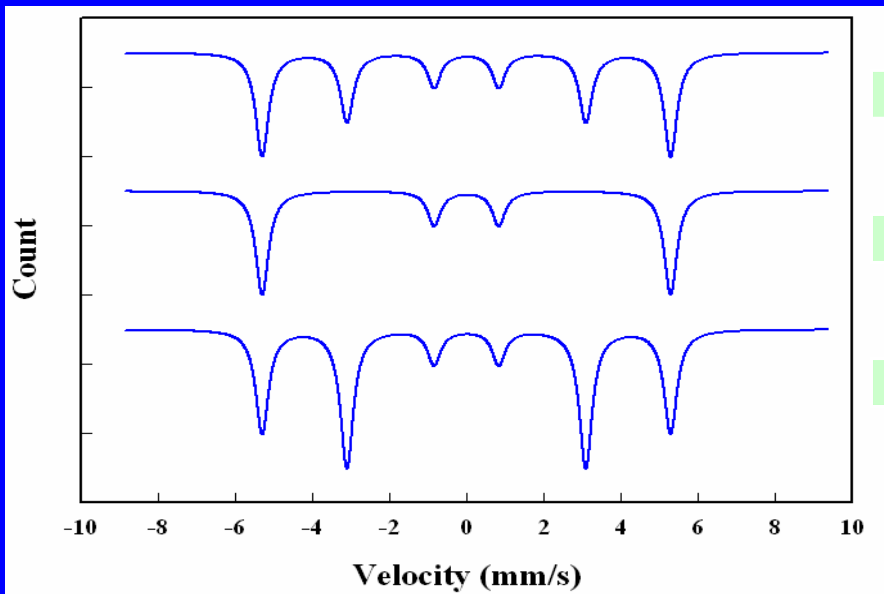
Applications of In-field Mössbauer Spectroscopy

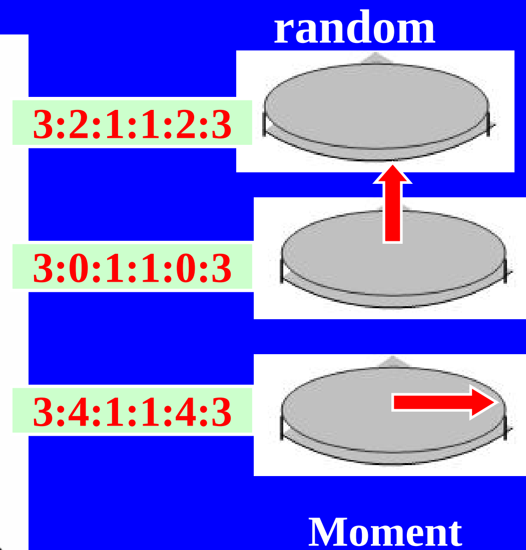
- Field-induced magnetic phase transition
- Magnetization processes of two phases individually from microscopic scale
- Magnetic anisotropy
- ………………

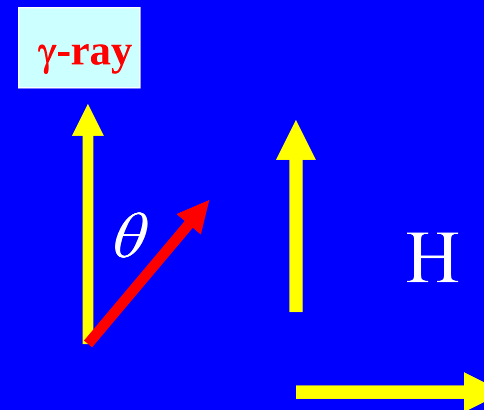


Magnetization processes

Intensities of the six lines





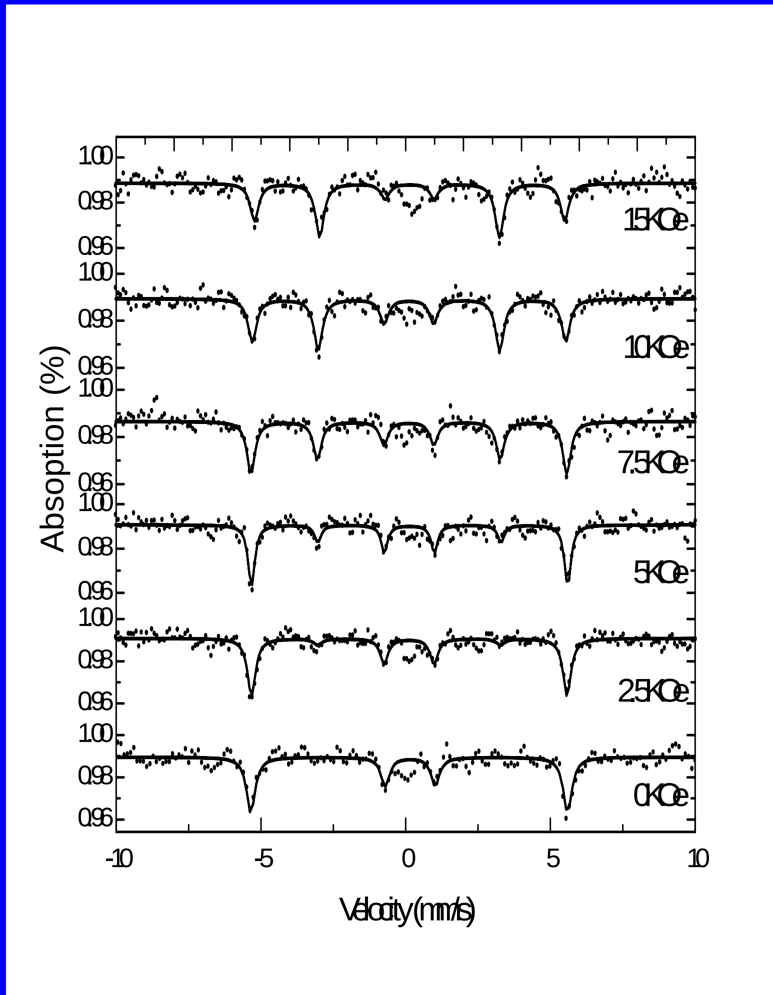


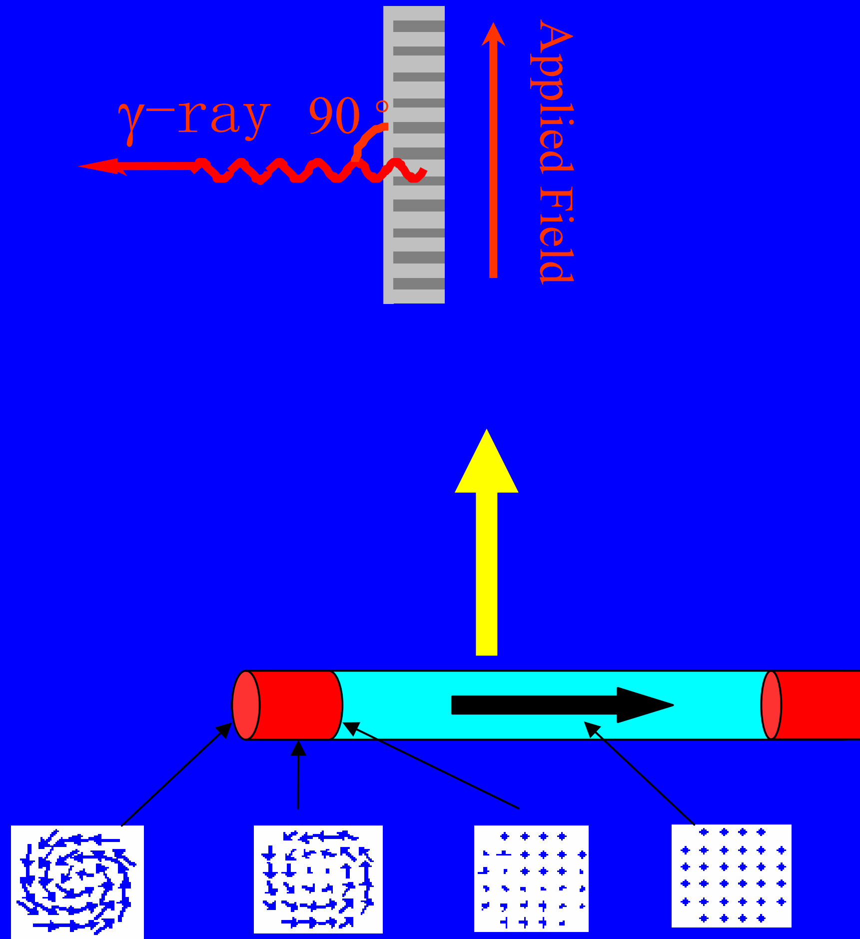
The intensity ratio among the six lines is $3:I_{2,5}:1:1:I_{2,5}:3$.

$$I_{2,5} = \frac{4\sin^2\theta}{1+\cos^2\theta}$$

θ *is the angle between Fe moment and* γ*-ray.*

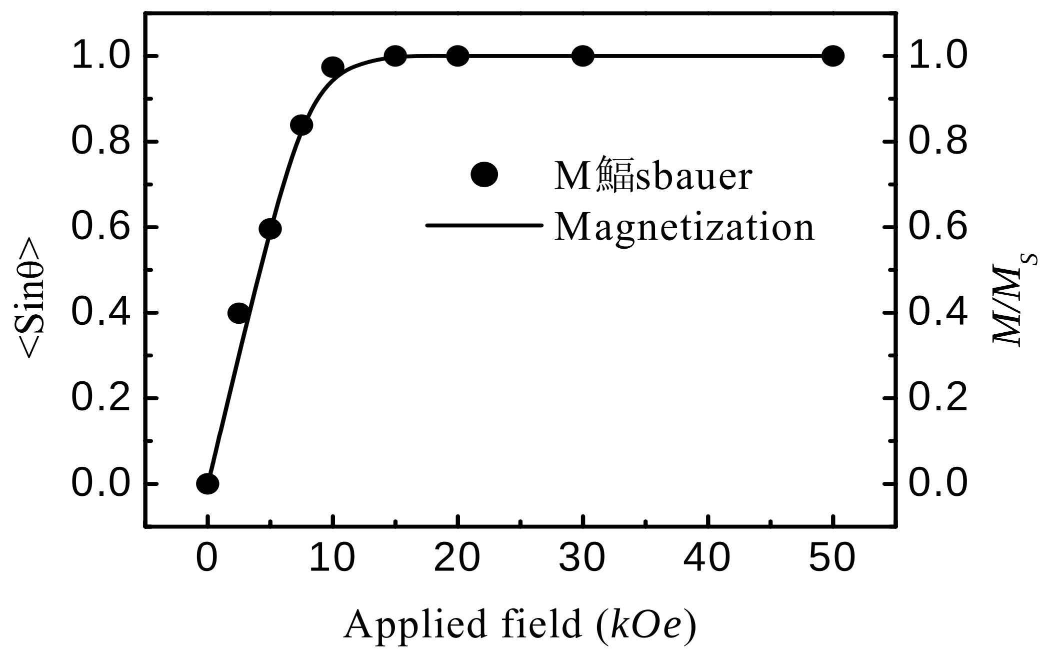
Magnetic shape anisotropy





Mössbauer spectra of Fe nanowire arrays in AAO films at 10 K in various magnetic fields applied perpendicular to the nanowire axis.

Magnetic shape anisotropy



θ : *the angle between Fe moment and* γ *-ray,*

$\pi/2 - \theta$: *the angle between Fe moment and applied field.*

$M/M_S = \langle \cos(\pi/2 - \theta) \rangle = \langle \sin\theta \rangle$

Magnetic shape anisotropy

$$W = K \sin^2\theta - \sum^{n} \mu_{Fe} H_{app} \cos\left(\frac{\pi}{2} - \theta\right)$$

$$K = \frac{M_S H_{app}}{2\sin\theta}$$

$0 < \theta < \pi/2$

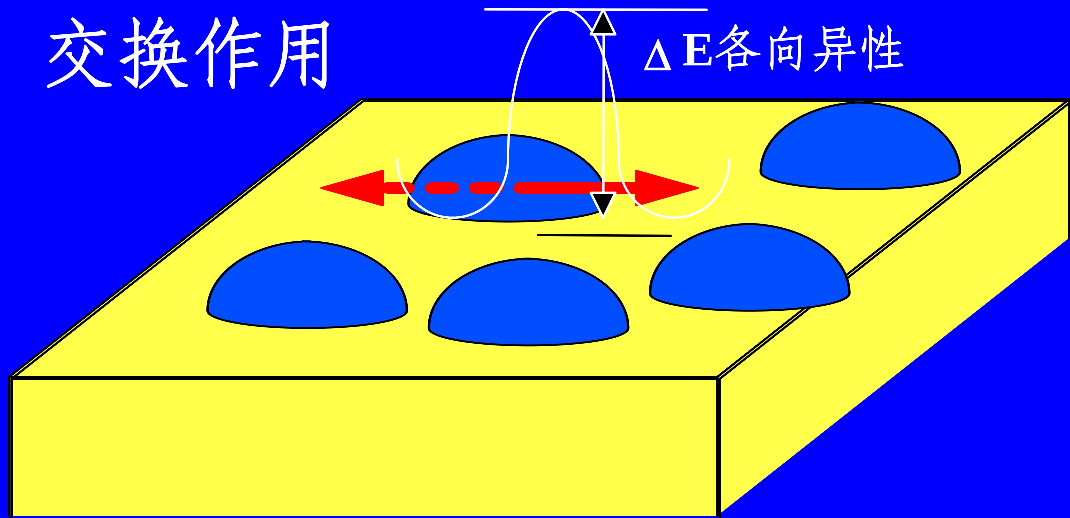
$$K \approx 7.3\times10^{6}\ (ergs/cm^{3})$$

$$K_1 \approx 5.21\times10^{5}\ (ergs/cm^{3})$$

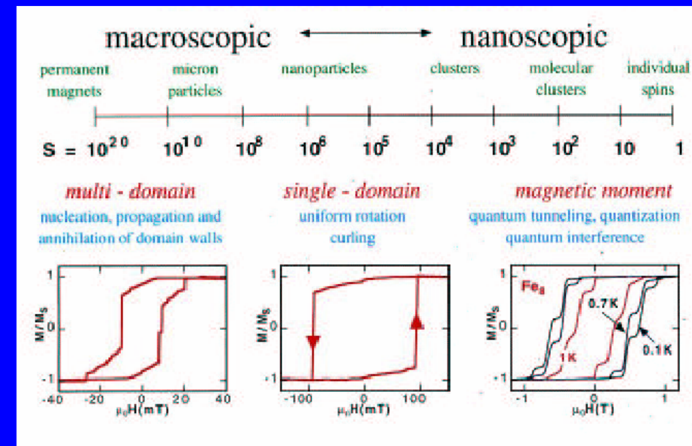
$$K \approx 14\ K_1$$

总　　结

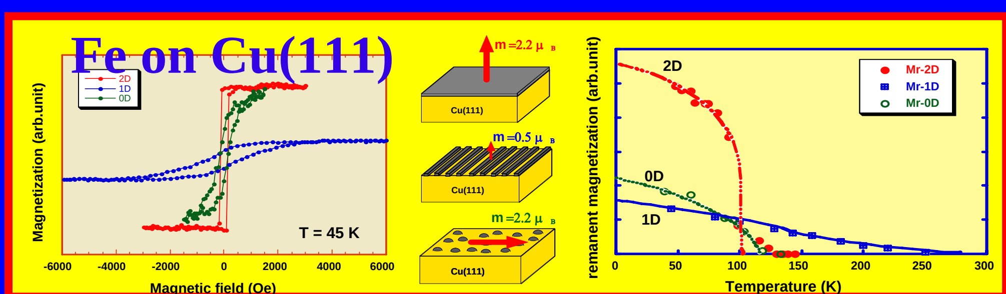
交换作用



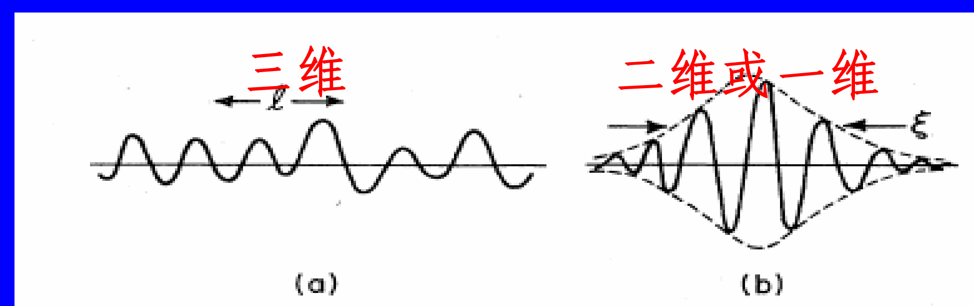
宏观量子效应和量子隧穿



维度与磁性的关系

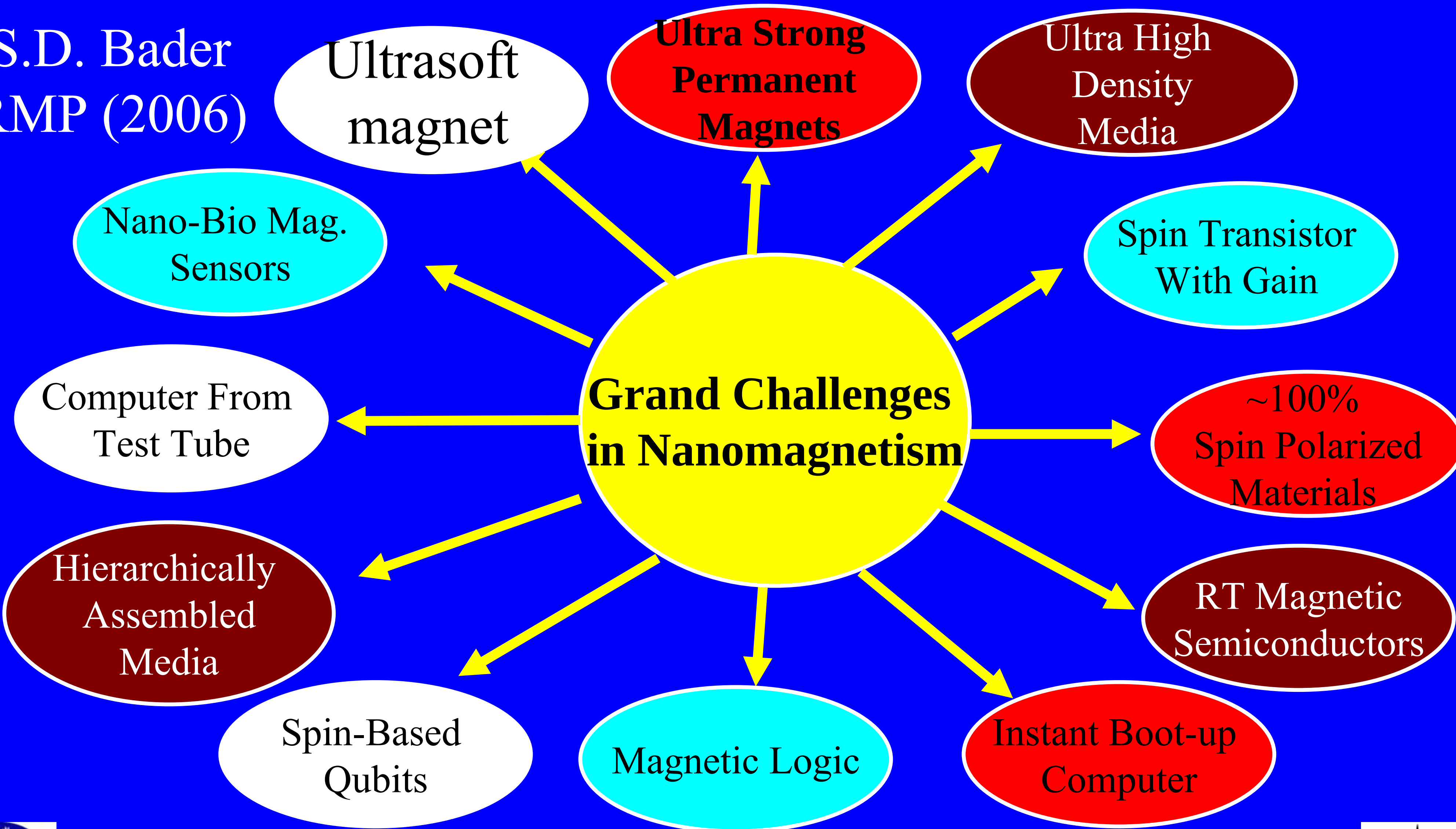


维度与电子态的关系



纳米磁性的机遇与挑战

S.D. Bader
RMP (2006)



致　谢

自课题组2001年成立以来，得到科技部，基金委，科学院和物理所的资助和支持，先后有40人为课题组的建设和发展做出了贡献，在此一并感谢！

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