超导电性与磁性

李晓光
合肥微尺度物质科学国家实验室(筹)
中国科学技术大学

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内容提要

一、超导材料的应用

二、超导电性的发现

三、两种类型的超导体及磁通行为

四、超导机理/BCS模型

五、Josephson 效应

六、高温超导材料的发现

七、自旋电子材料

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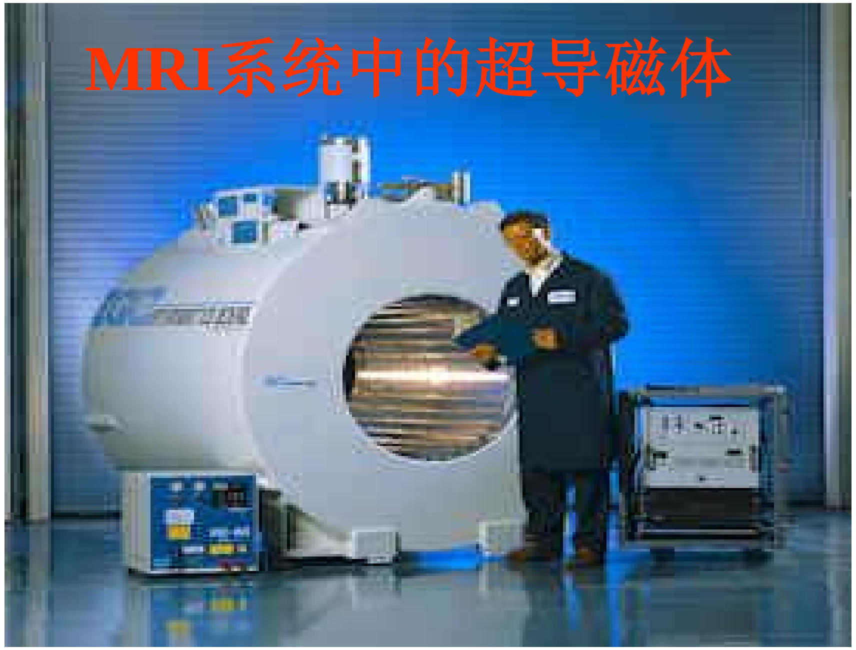
一、超导材料的应用

一）医疗设备：磁共振人体成像仪(MRI)


MRI系统中的超导磁体

IGC Magnet Business Group

A Division of Intermagnetics General Corporation

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二）科学研究装置：高能粒子加速器

加速器其要求四极磁体：
1. 磁场强, ~7T
2. 体积小,
3. 能耗低.
± 超导磁体最为理想.

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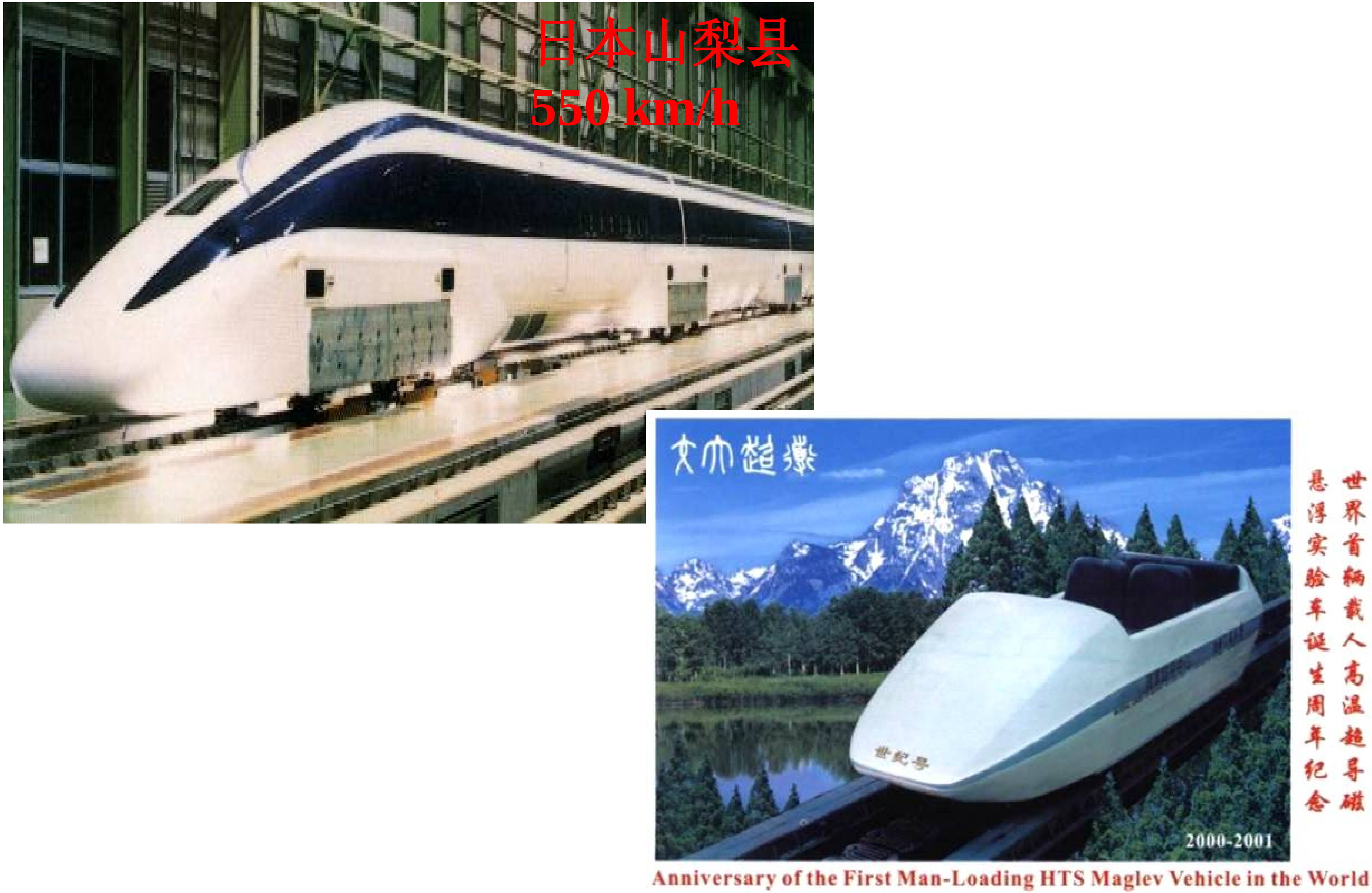
三）交通运输：超导磁悬浮列车



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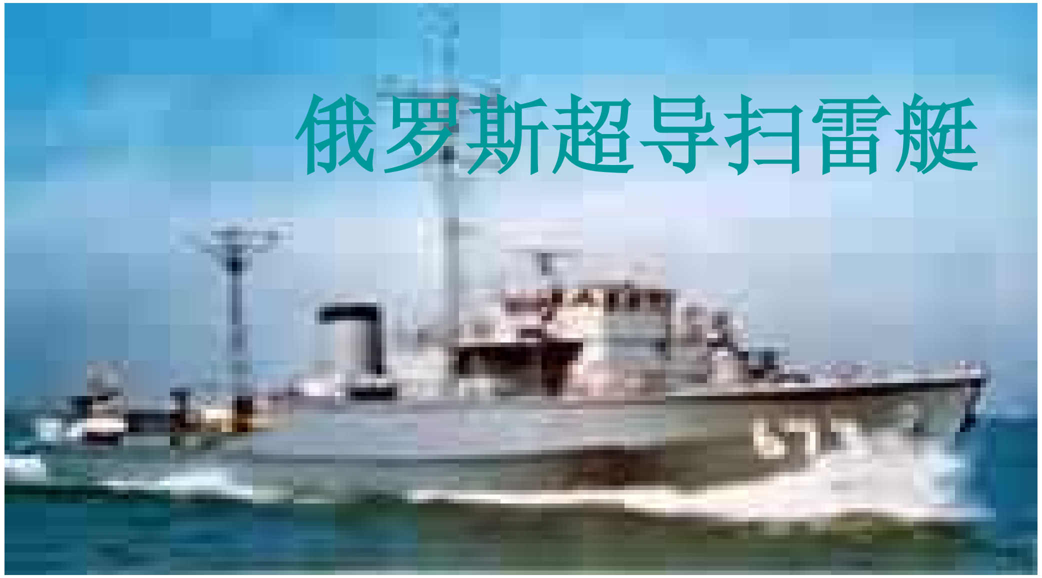
四）军事应用



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五）国际热核聚变反应堆 (ITER）

- 利用地球上海水中的重氢和超重氢，进行核聚变发电。危险小且无污染，是未来能源的希望！

•参加国：加拿大，欧盟，日本、俄罗斯 、美国和中国

ITER 计划共需要

铌钛线材 240吨

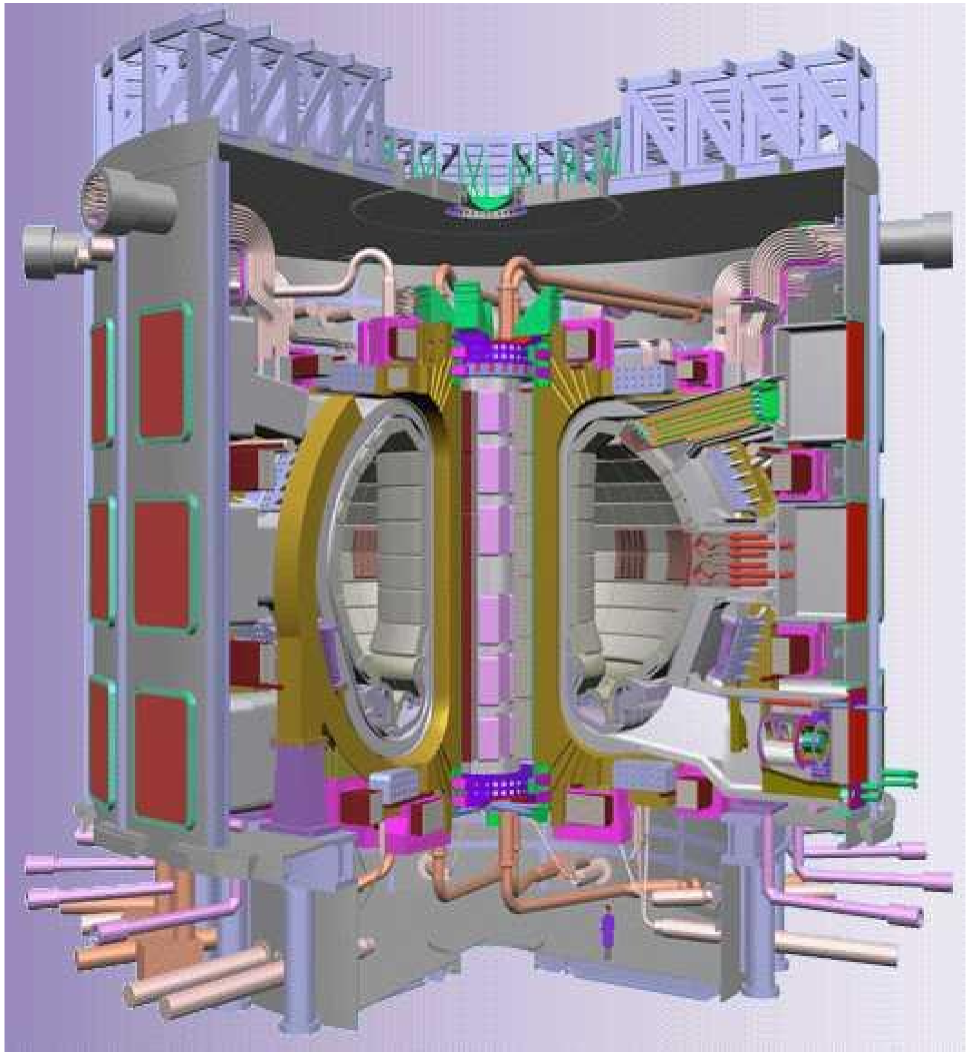
Nb3Sn线材 480吨

我国将出资4亿美元，超导线材作为首选

铌钛线材: 200吨

Nb3Sn线材: 100吨

价值：6亿元人民币



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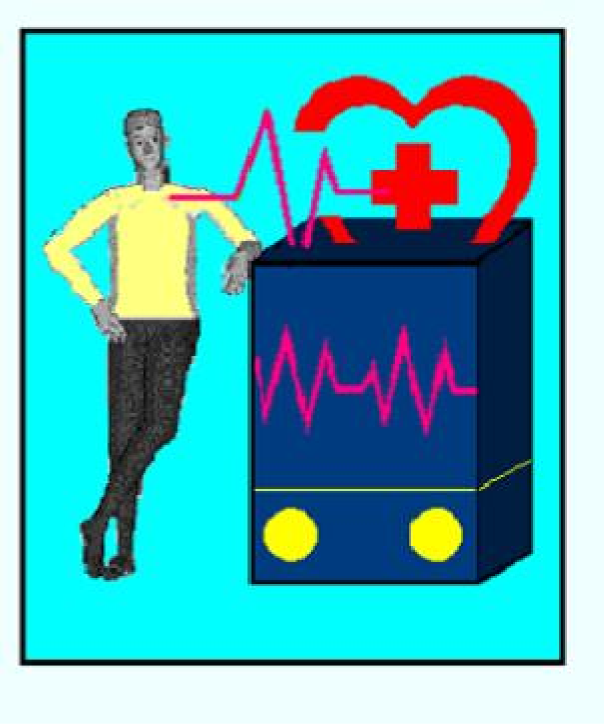
六）弱电应用

可测地球磁场的十亿分之一

超导量子干涉器(SQUID)

- 军事
- 勘探
- 医学

……



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二、超导电性的发现

奇异的低温世界

μ 大自然中的千里冰封，万里雪飘，雪球激战，白雪老人……

μ 1983年7月21日：南极 -89.2℃

μ 物理学家 ® 低温下的物性是如何变化的?

向更低的温度进军：热力学、物性

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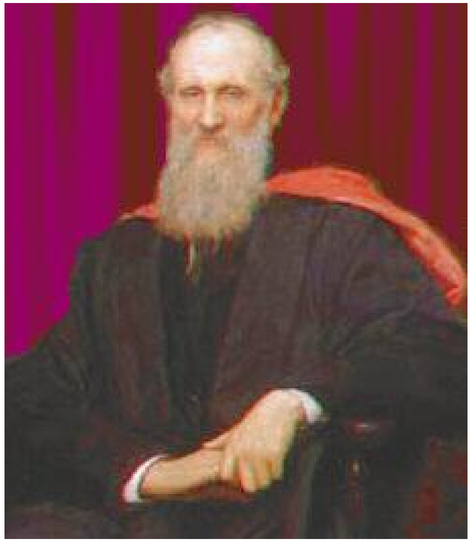
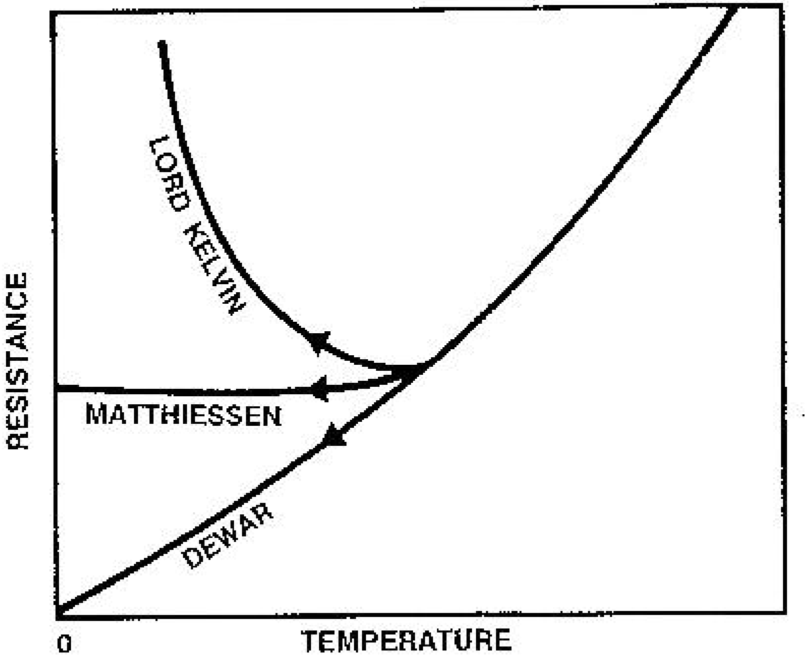
一）电阻的可能变化

Three different hypotheses existed on how resistance would respond as temperature approaches 0 K:

- Resistance would increase (Kelvin)
- Resistance would plateau (Matthiessen)
- Resistance would continue to drop gradually to 0 W and 0 K (Dewar).



Kelvin



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J1895：空气被液化 -192℃ （81K）
J1898：氢气被液化 -253℃ （20K）
J1908：氦气被液化 4.25K

K. Onnes教授(1853-1926年)

荷兰莱登实验室:

J1913年获诺贝尔物理学奖（60岁）
J29岁：莱登大学教授
J30岁：阿姆斯特丹皇家科学院院士
J“绝对零度先生”

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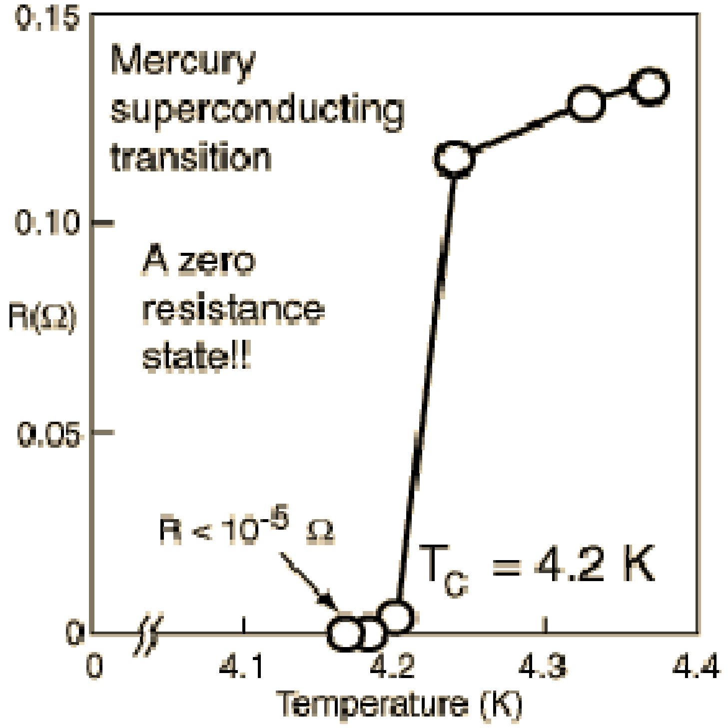
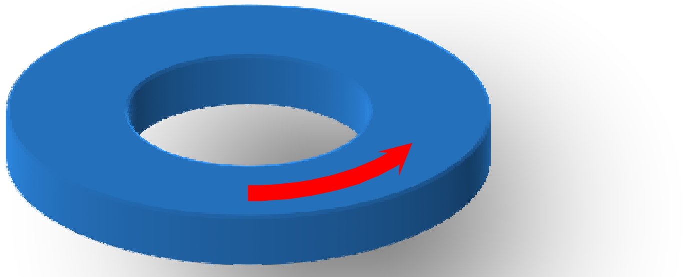
二）廿世纪的重要发现——超导电性



Perfect conductor



$$\rho = 0$$

$$\frac{I}{dI/dt} > 10^5 \text{ yrs}$$

K. Omnes, Commun. Phys. Lab. (1911).

- 1911年，Hg在4.2K下，电阻率完全消失

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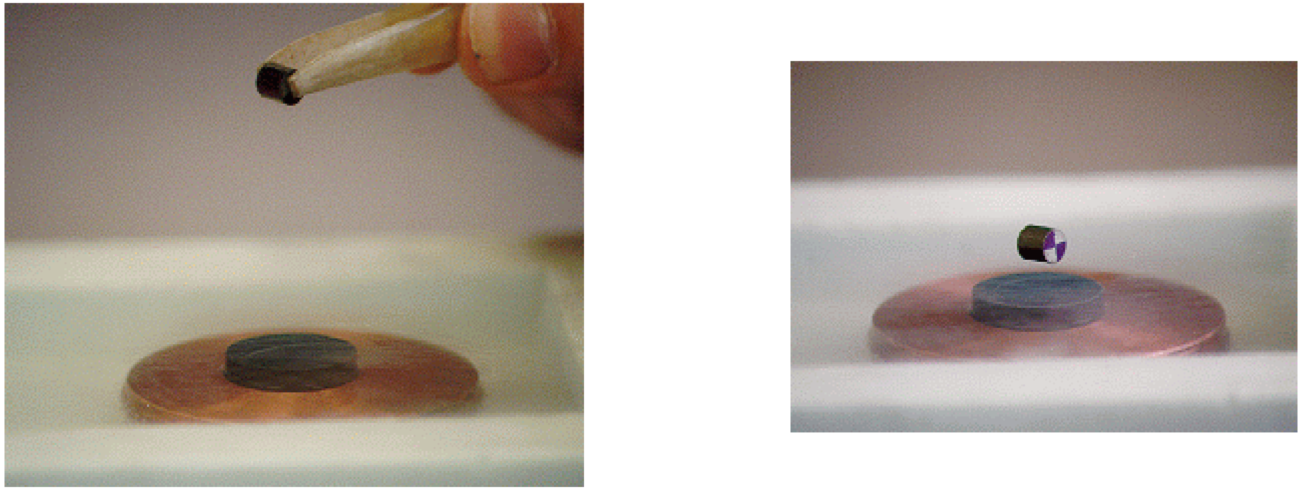
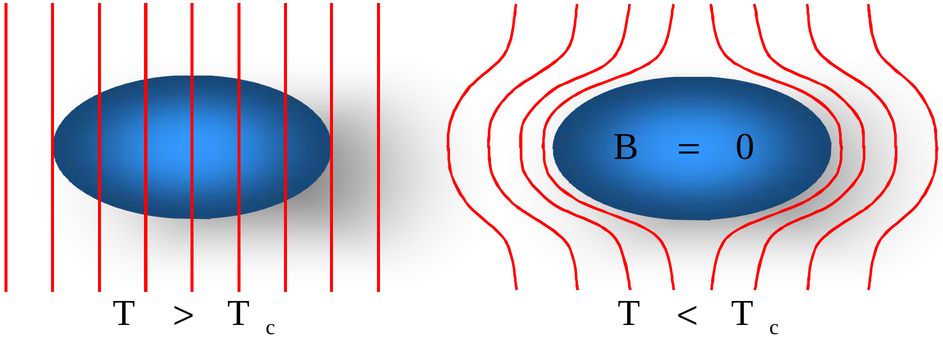
抗磁性



A superconductor can pin a magnet in free space was first characterized by Meissner and Ochsenfeld in 1933. This phenomenom is now known as the “Meissner effect.”

Meissner effect



There are TWO distinct properties.

- **They have ZERO resistance**
- **They exhibit DIAMAGNETISM**

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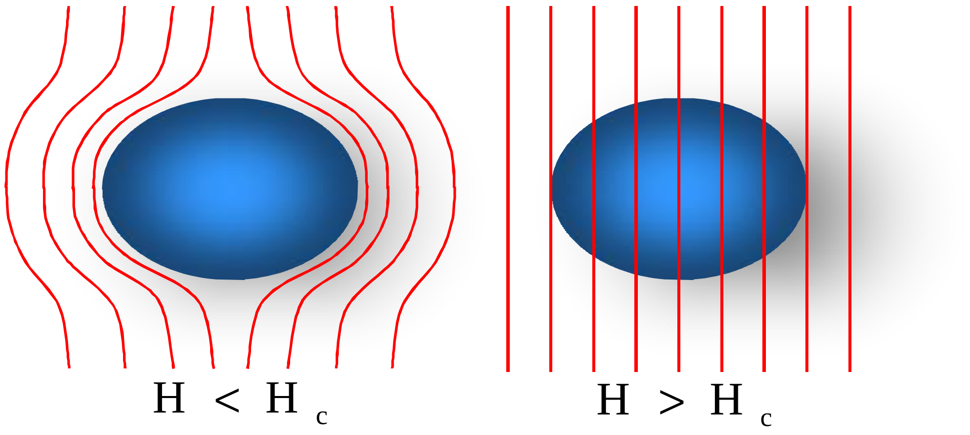
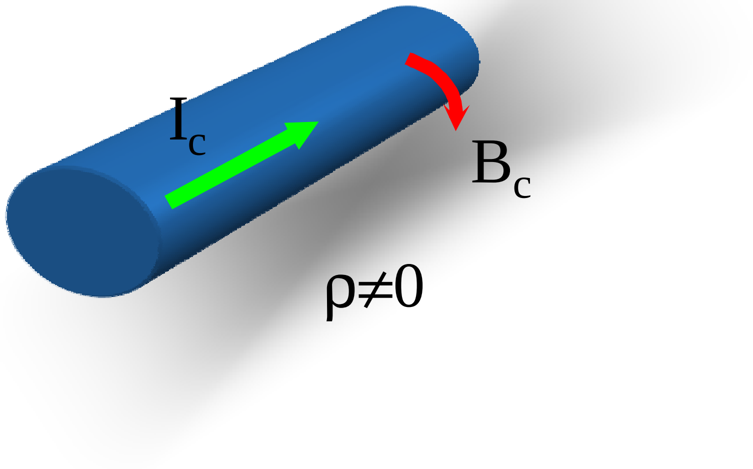
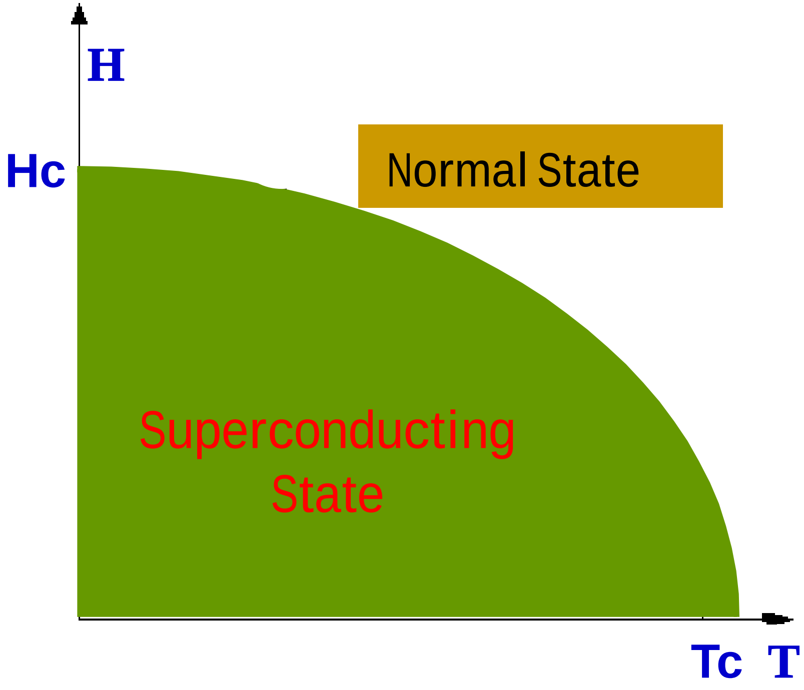
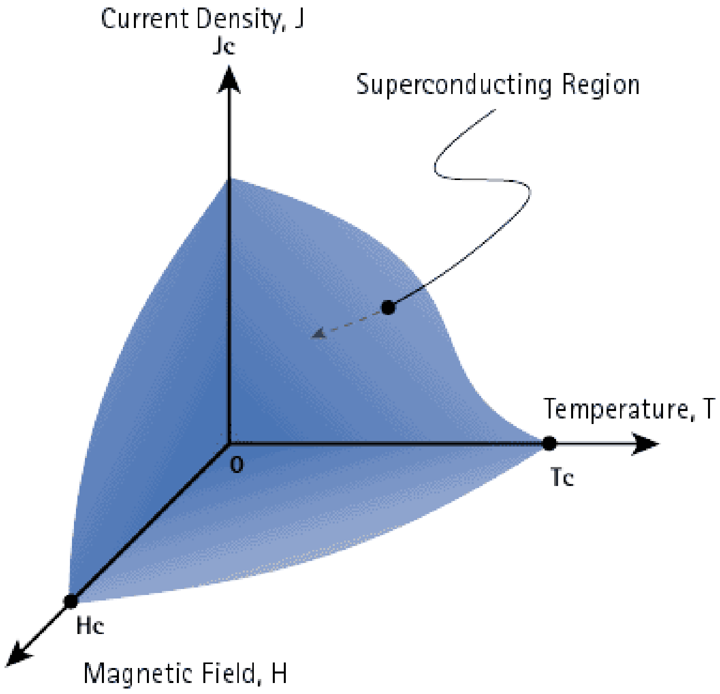
Magnetic field destroys s/c



Electric current destroys s/c







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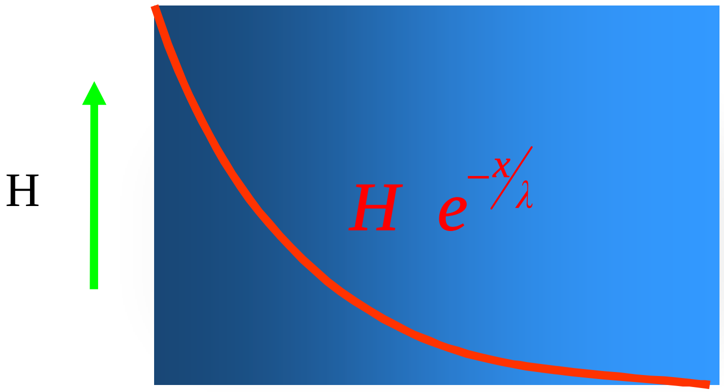
三）Theories of Superconductivity

- **London Equation**

$$\boxed{\vec{J} = -\frac{c}{4\pi\lambda_L^2}\vec{A}}$$

$$\boxed{\nabla^2 B = B/\lambda_L^2}$$



- **Ginzburg-Landau Theory**

$$F = F_n + \alpha|\Psi|^2 + \frac{\beta}{2}|\Psi|^4 + \frac{1}{2m}\left|\left(-i\hbar\nabla + \frac{2e}{c}\vec{A}\right)\Psi\right|^2 + \frac{H^2}{8\pi}$$

$$\alpha(T) = \alpha_0\frac{T - T_c}{T_c}$$

$$|\Psi|^2 = \frac{\alpha(T)}{\beta}, \qquad H_c = \left[\frac{4\pi|\alpha(T)|^2}{\beta}\right]^{1/2}$$

$$\boxed{\begin{aligned} &\frac{1}{2m}\left(\frac{\hbar}{i}\nabla + \frac{2e}{c}\vec{A}\right)\Psi + \alpha\Psi + \beta|\Psi|^2\Psi = 0 \\ &\vec{j}_s \equiv \frac{c}{4\pi}\nabla\times\vec{B} = \frac{i\hbar e}{m}\left[\Psi^*\nabla\Psi - \Psi\nabla\Psi^*\right] - \frac{4e^2}{mc}|\Psi|^2\vec{A} \end{aligned}}$$

$$\xi(T) = \left[\frac{\hbar^2}{2m|\alpha(T)|}\right]^{1/2}$$

$$\lambda(T) = \left[\frac{mc^2\beta}{4\pi(2e)^2|\alpha(T)|}\right]^{1/2}$$

$\kappa = \lambda/\xi$ GL parameter

$\kappa < 1/\sqrt{2}$ → type I

$\kappa > 1/\sqrt{2}$ → type II

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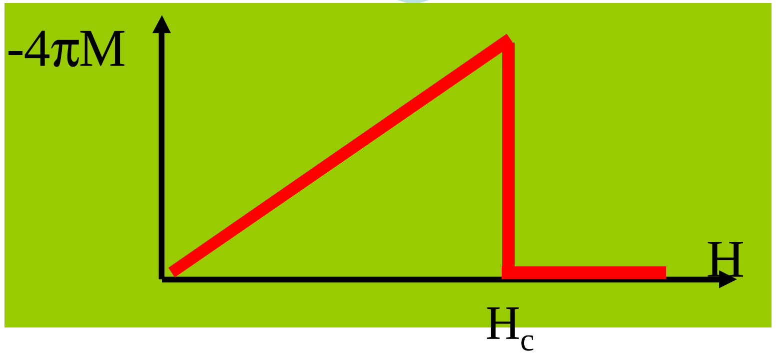
三、两种类型的超导体及磁通行为

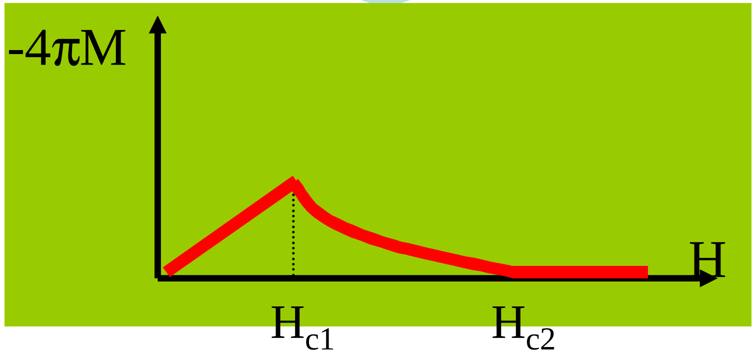
一）两种类型的超导体

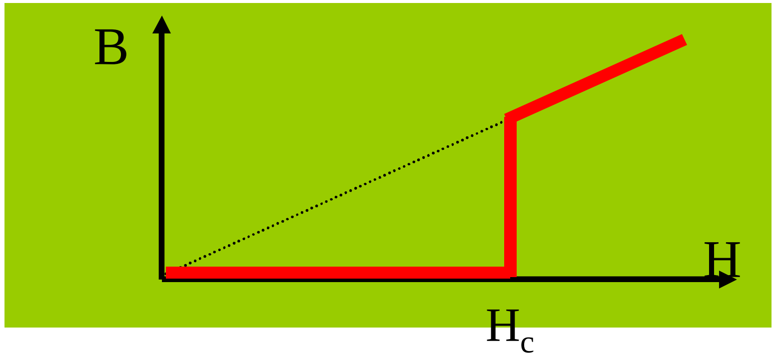
Type I

Type II

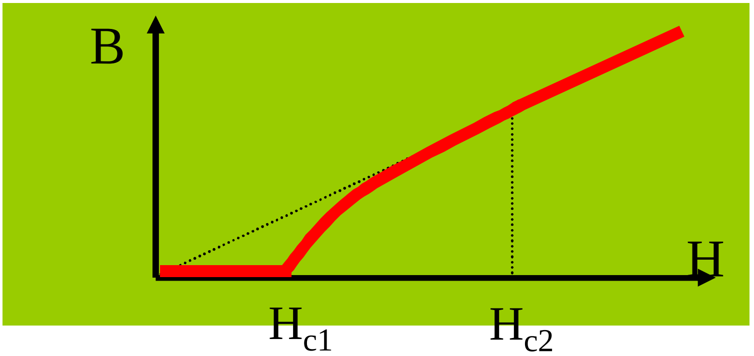


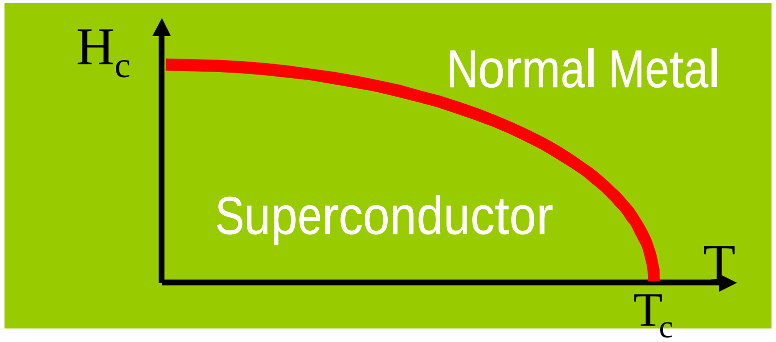
Magnetization



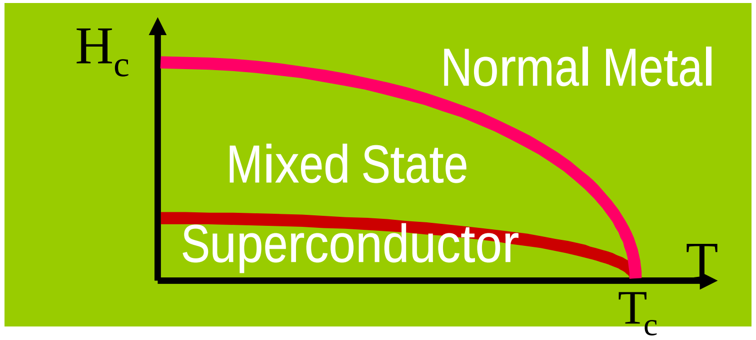


Magnetic Field





Critical Field



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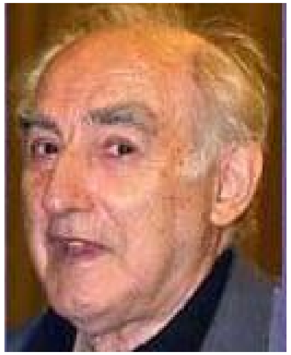
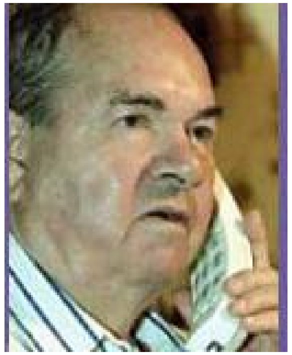
二）第二类超导体的磁通行为

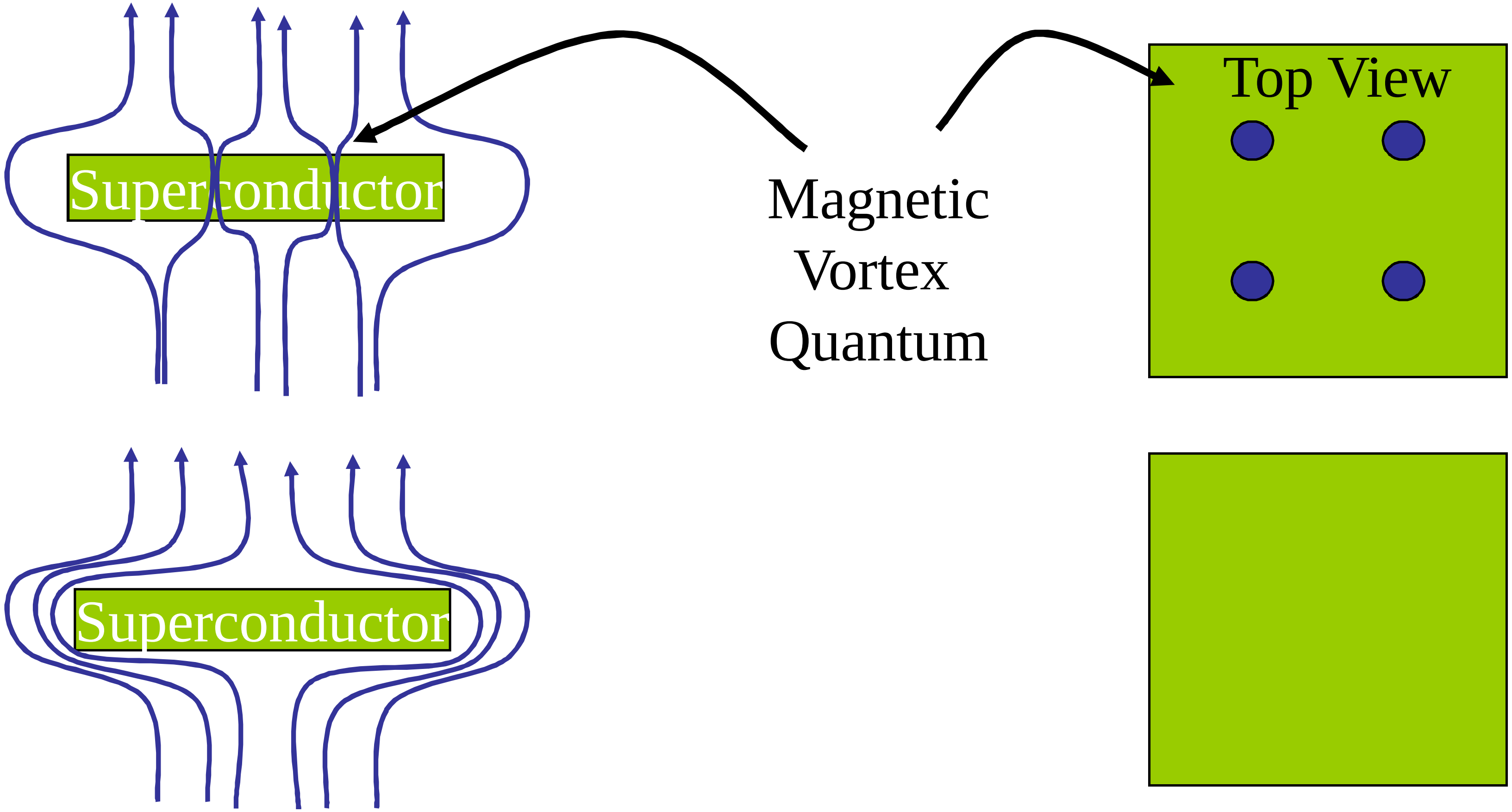
1950年，当时只有34岁的京茨堡和朗道提出了一个描述超导体特性的理论。阿布里科索夫在1953年的研究表明，还存在第二类超导体，这种超导体允许磁场穿过。2003年诺贝尔物理学奖。



V. L.Ginzburg



A A A Abrikosov



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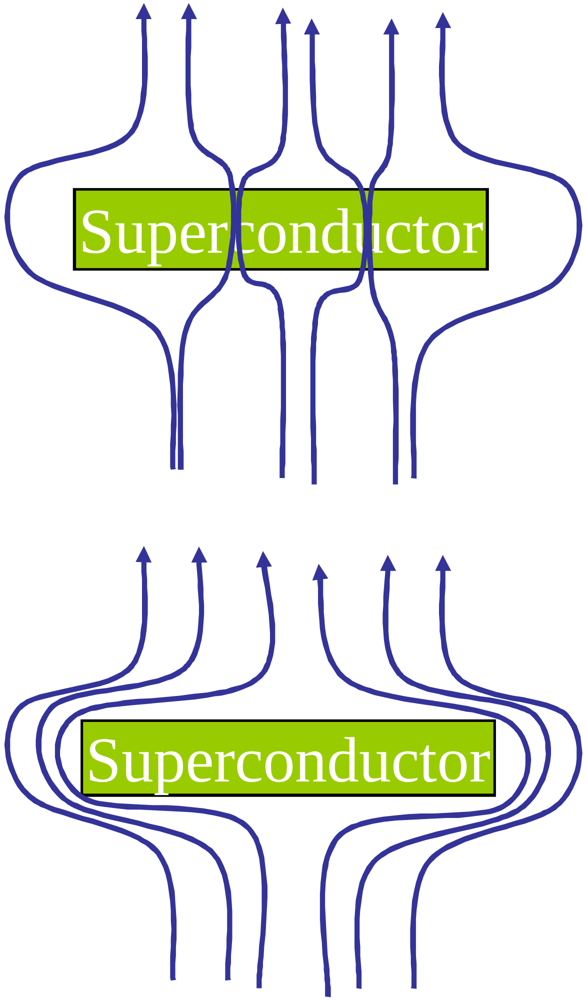

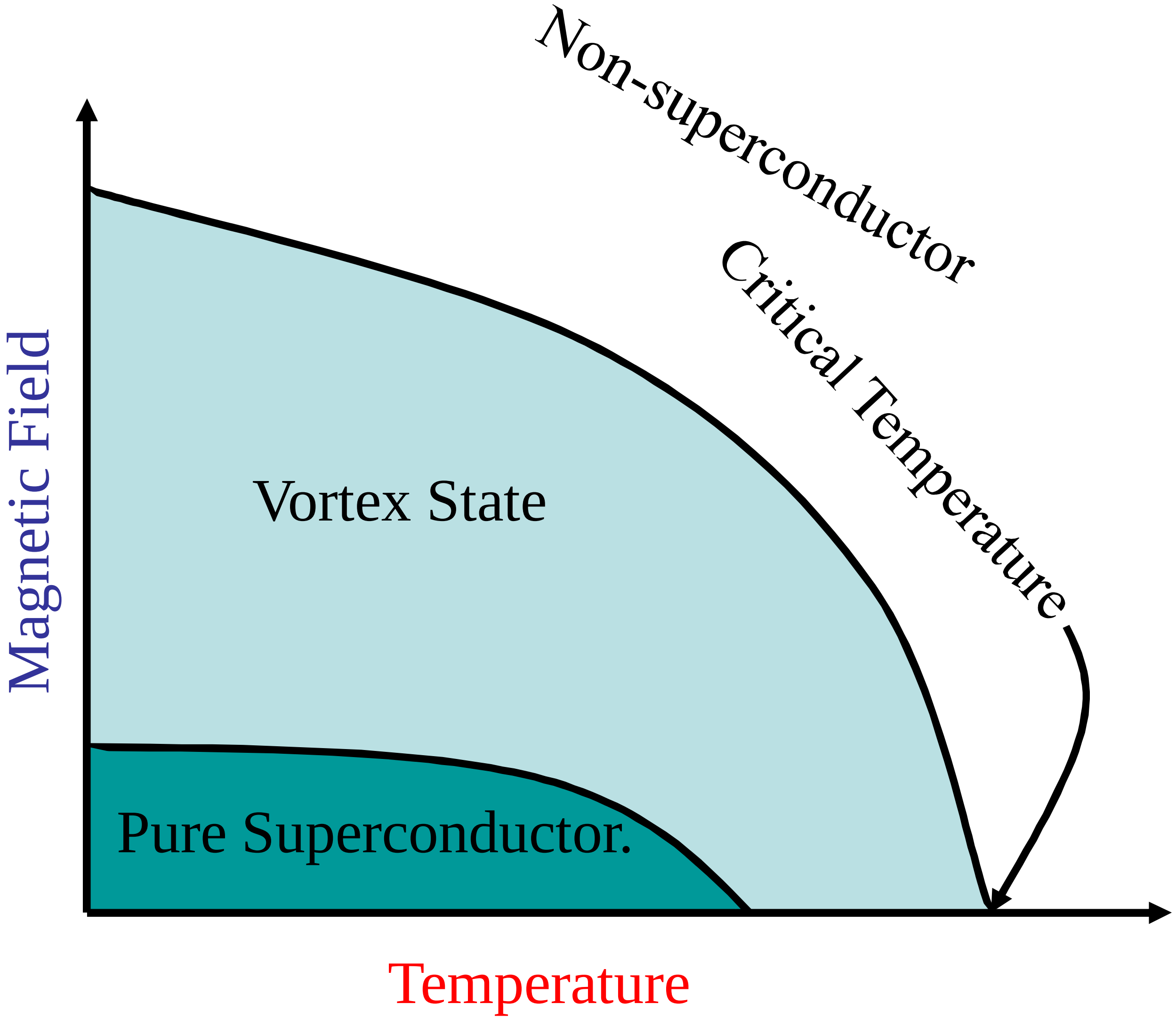

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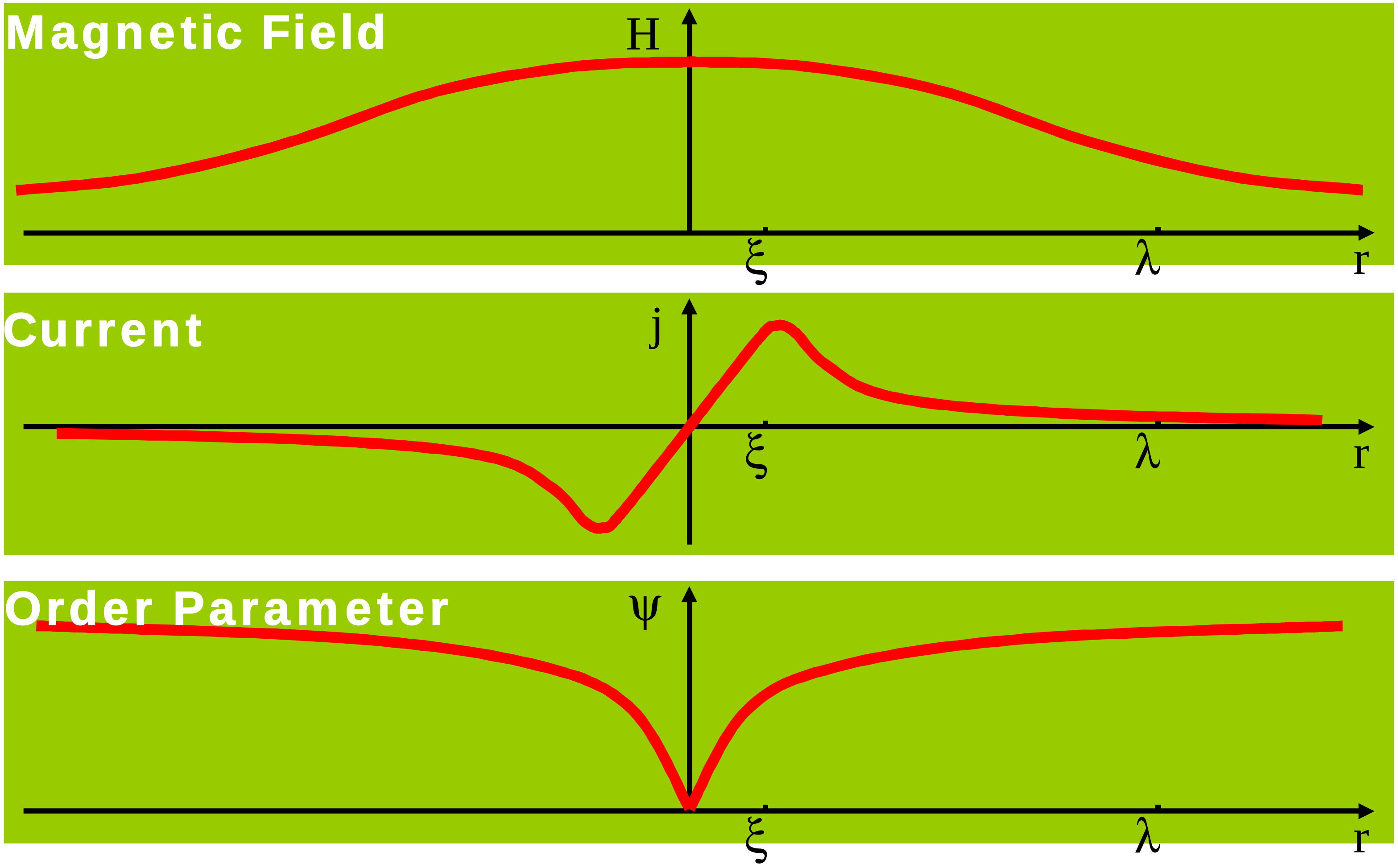
Vortices in Type II Superconductors

$$\vec{H} + \lambda^2 \nabla \times \left(\nabla \times \vec{H}\right) = \hat{z}\,\Phi_0\,\delta_2(\vec{r}), \qquad \Phi_0 = \frac{hc}{2e} \quad \text{flux quantum}$$

$$\boxed{H = \frac{\Phi_0}{2\pi\lambda^2} K_0\left(\frac{r}{\lambda}\right)}$$

$$H = \frac{\Phi_0}{2\pi\lambda^2} \ln\frac{\lambda}{r}, \qquad \xi < r \ll \lambda$$

$$H = \frac{\Phi_0}{2\pi\lambda^2} \sqrt{\frac{\pi\lambda}{2r}}\, e^{-r/\lambda}, \qquad r \gg \lambda$$



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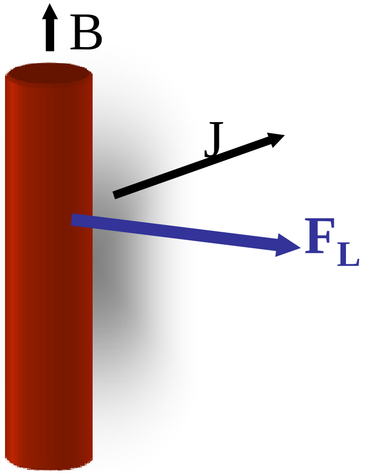
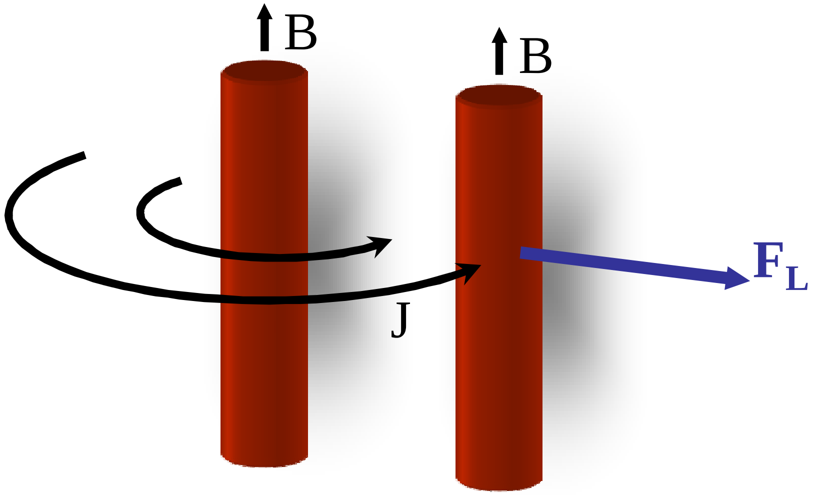
Interaction between Vortices





Lorenz type force

$$F_L = \frac{\Phi_0}{c} J$$

Repulsion

$$F_L = \frac{\Phi_0}{c} J = \frac{1}{2} h\, n_s v_s$$

$$\vec{H} + \lambda^2 \nabla \times \left(\nabla \times \vec{H}\right) = \hat{z}\, \Phi_0 \left[\delta_2\left(\vec{r} - \vec{r}_1\right) + \delta_2\left(\vec{r} - \vec{r}_2\right)\right]$$

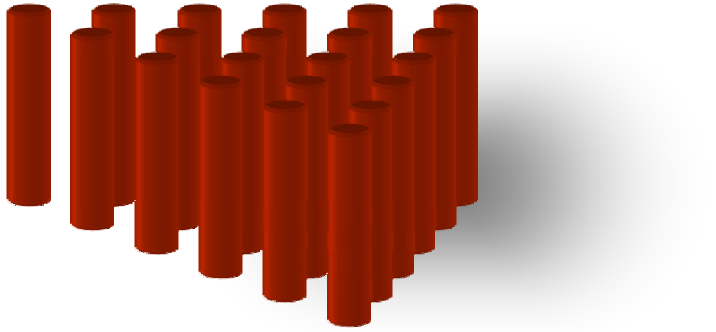
$$\vec{H}\left(\vec{r}\right) = \vec{H}_1\left(\vec{r}\right) + \vec{H}_2\left(\vec{r}\right)$$

$$F = \frac{\lambda^2}{8\pi} \int \left(\vec{H}_1 + \vec{H}_2\right) \times \left(\nabla \times \vec{H}_1 + \nabla \times \vec{H}_2\right)\left(d\vec{\sigma}_1 + d\vec{\sigma}_2\right)$$

$$U_{12} = \frac{\lambda^2}{8\pi} \int \left(\vec{H}_1 \times \left(\nabla \times \vec{H}_2\right) d\vec{\sigma}_2 + \vec{H}_2 \times \left(\nabla \times \vec{H}_1\right) d\vec{\sigma}_1\right)$$

$$U_{12} = \frac{\Phi_0 H_{12}}{4\pi}, \qquad H_{12} = \frac{\Phi_0}{2\pi\lambda^2} K_0\left(\frac{\left|\vec{r}_1 - \vec{r}_2\right|}{\lambda}\right)$$

Triangular lattice



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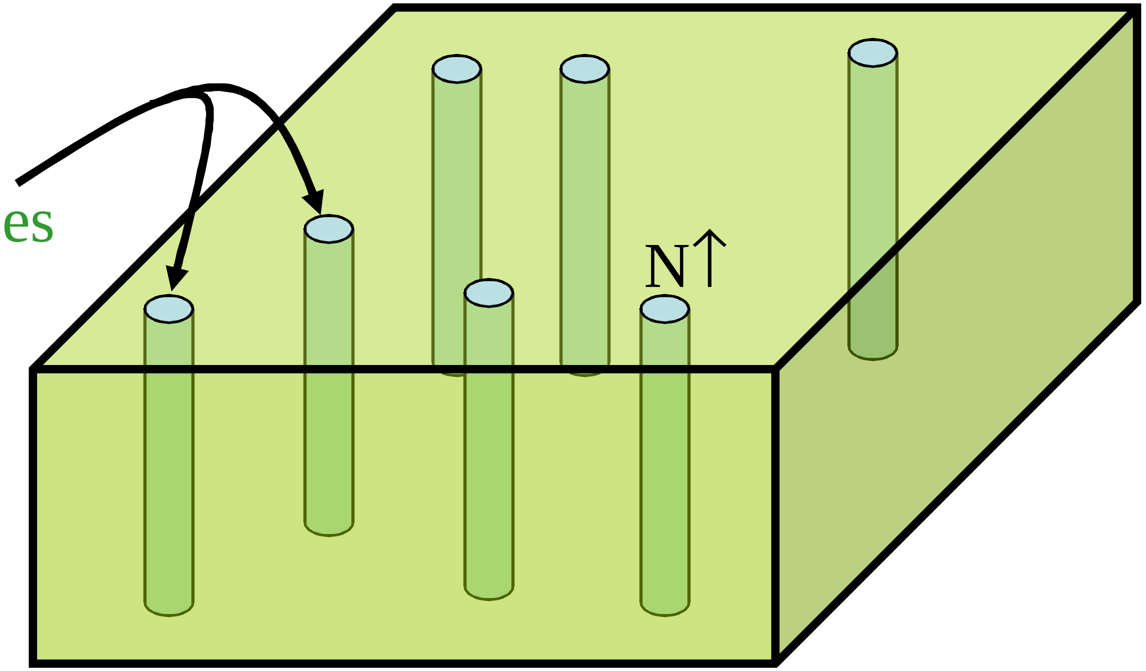
三） Superconductors Can Have ~~No~~ Resistance

三） Superconductors Have No Resistance

- Resistance is friction
- Magnetic field vortices



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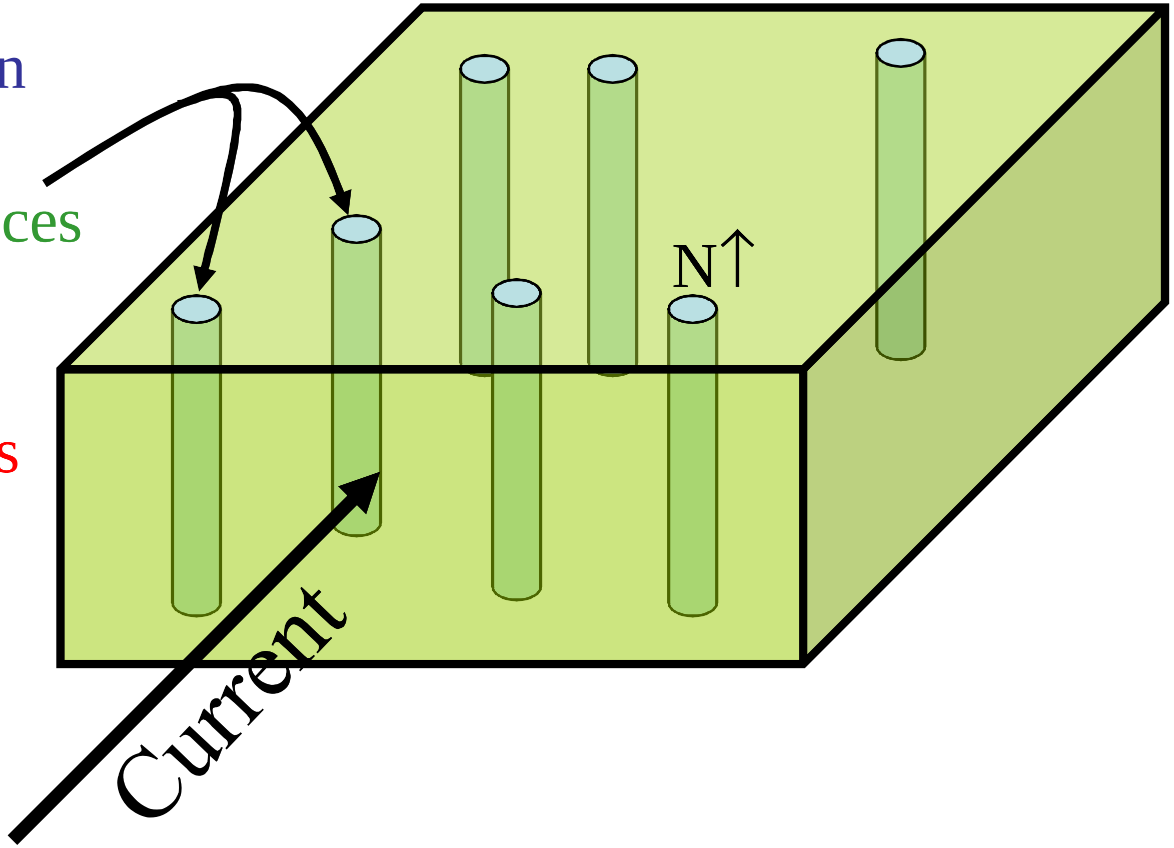
三） Superconductors Can Have ~~No~~ Resistance

- Resistance is friction
- Magnetic field vortices
- Current puts a force on the vortices



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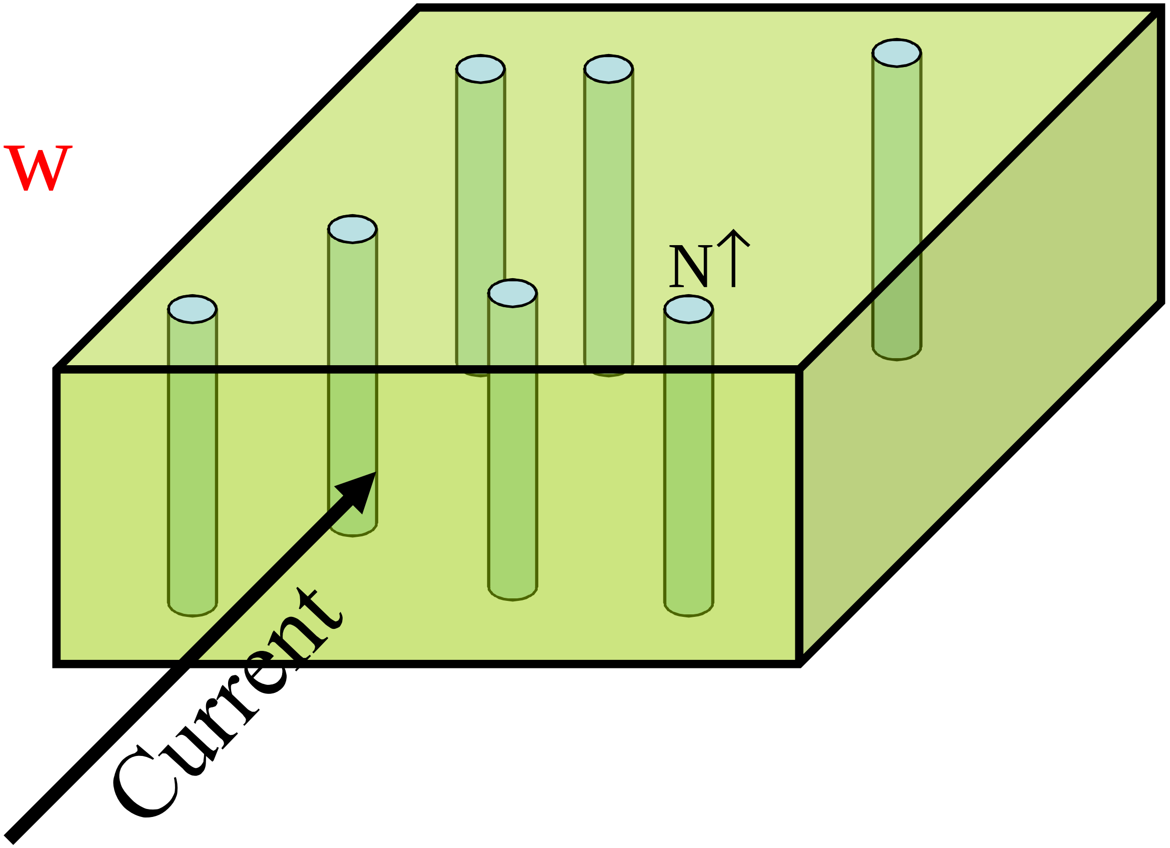
三） Superconductors Have ~~No~~ Resistance

Can

Vortices can flow



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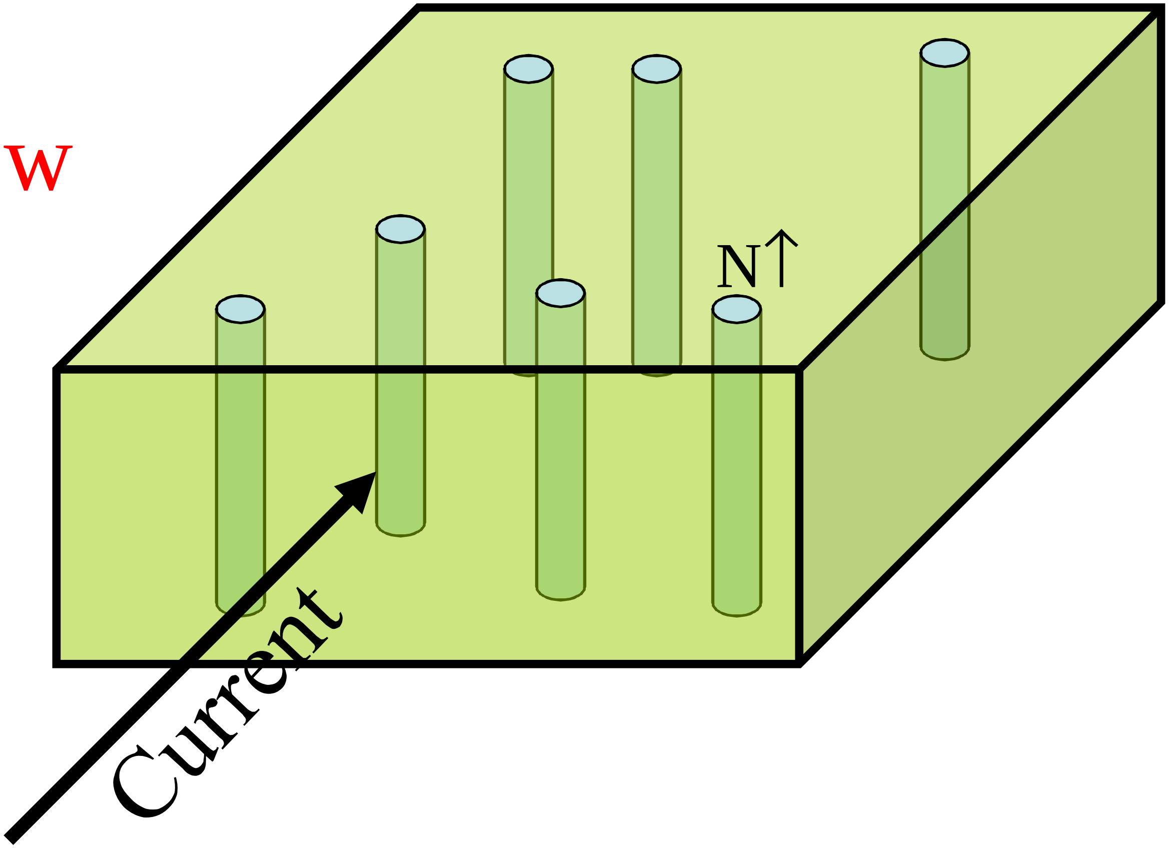
三） Superconductors Have ~~No~~ Resistance

Can

Vortices can flow



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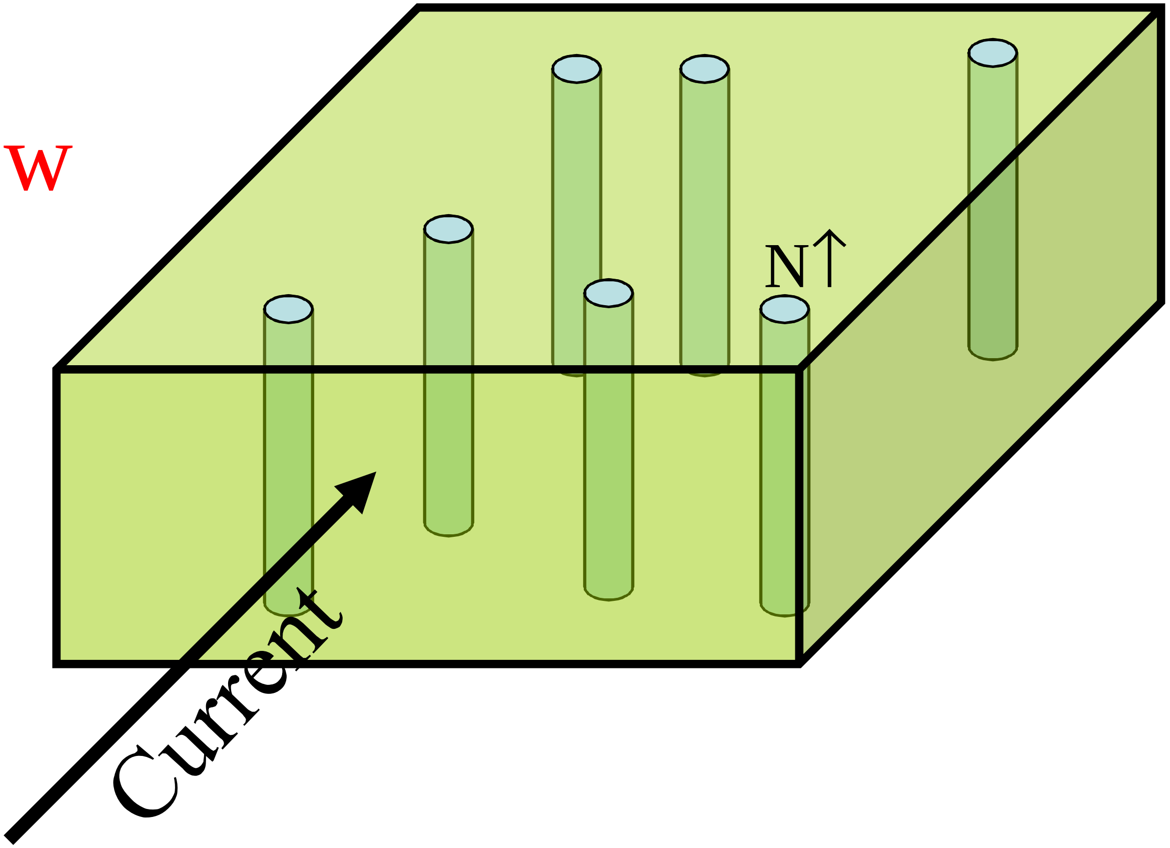
三） Superconductors Have ~~No~~ Resistance

Can

Vortices can flow



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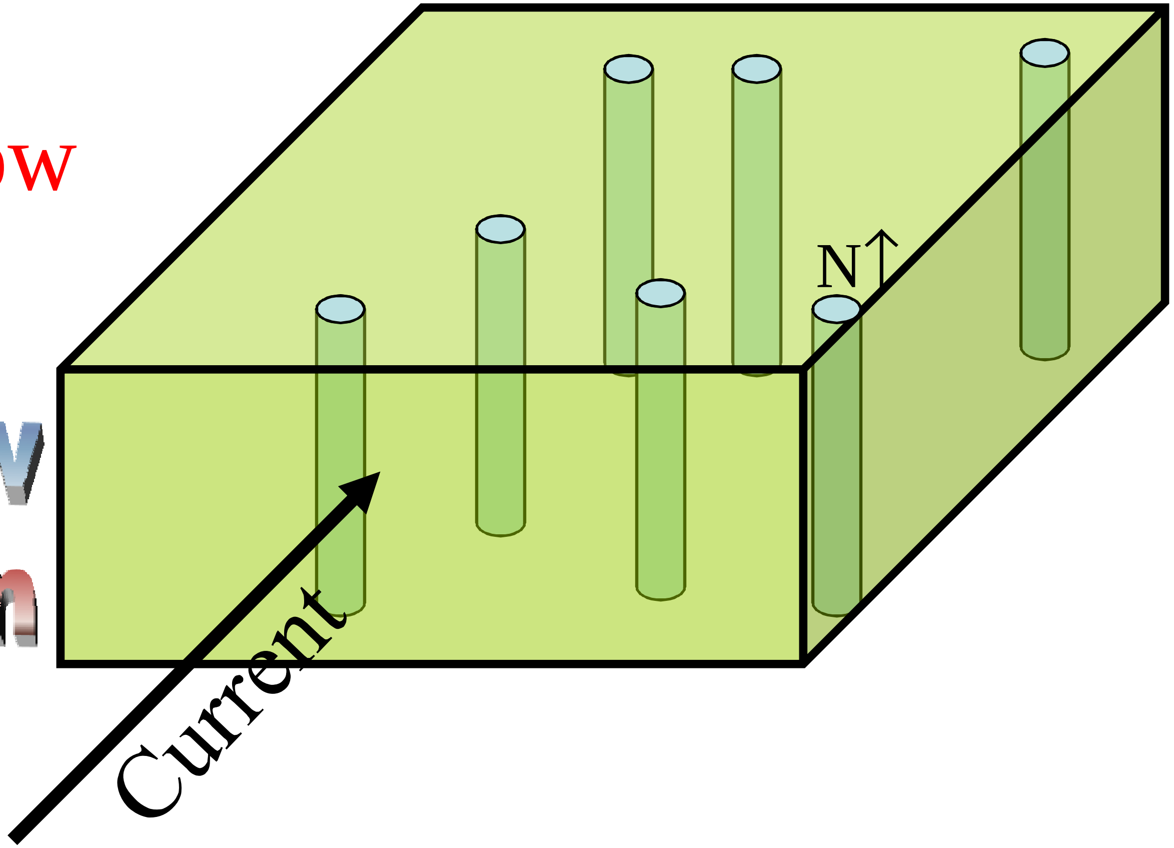
三） Superconductors Have ~~No~~ Resistance

Can

Vortices can flow

Vortex Flow

→ Friction



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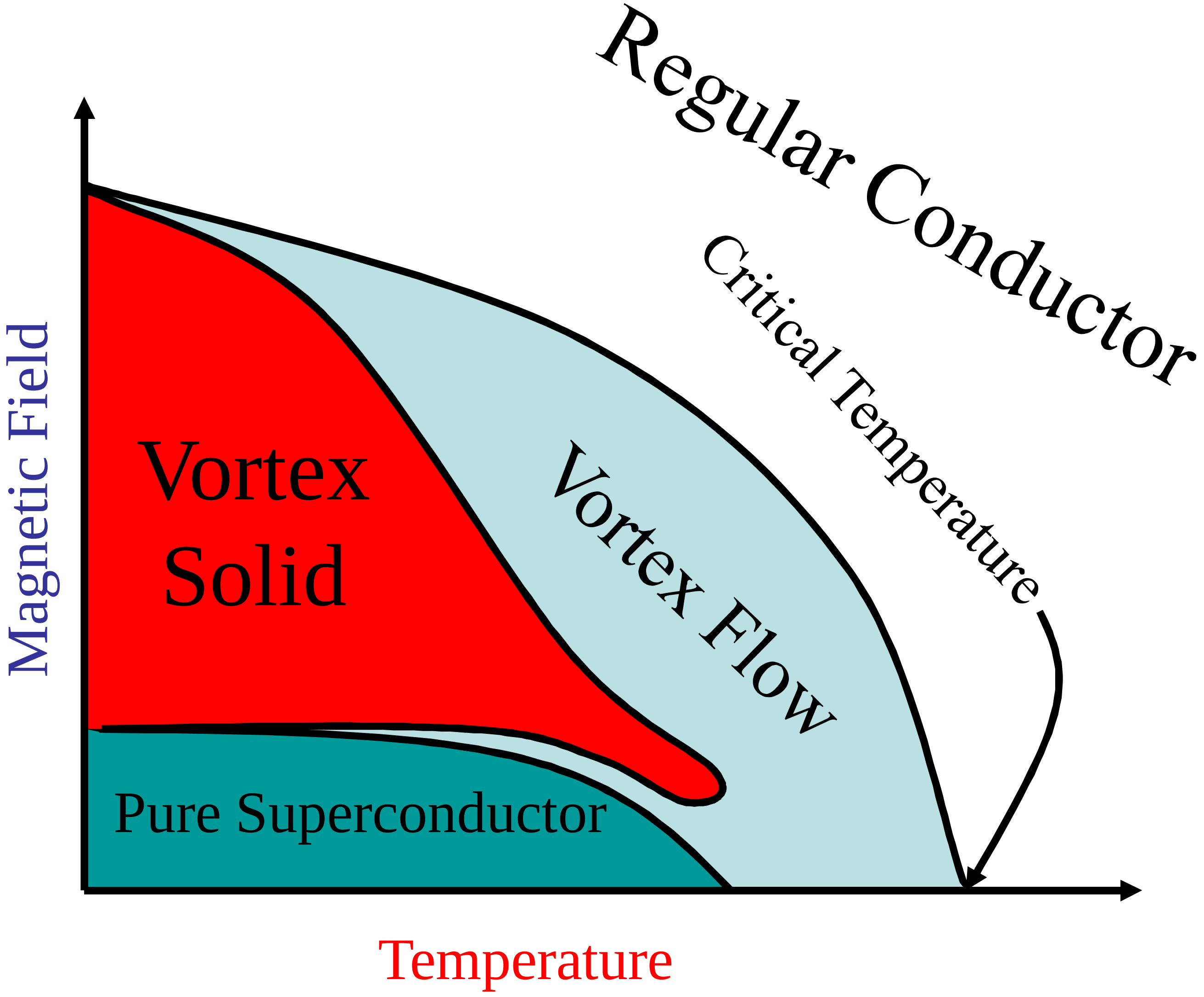
When do superconductors have resistance?



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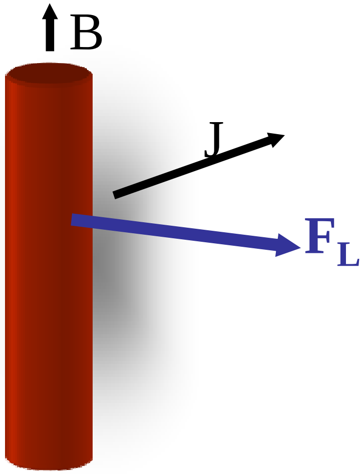
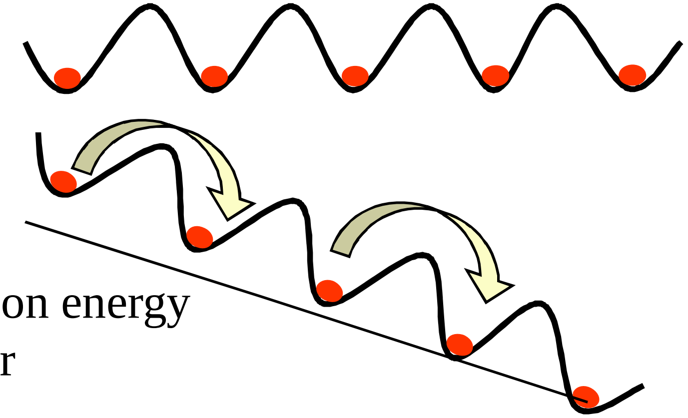
Interaction with Defects



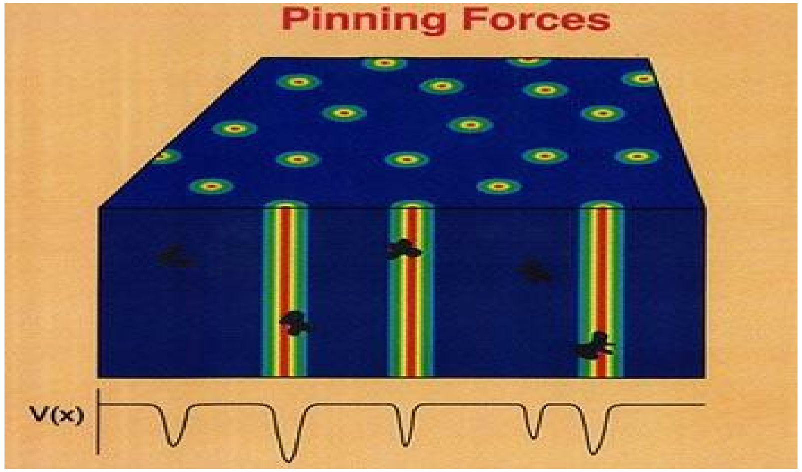
$$F_L = \frac{\Phi_0}{c} J$$

Flux Creep



Activation energy behavior

Pinning



- Vacancies, voids, inhomogeneities, where superconductivity is weak
- Pinning decreases energy losses caused by flux creep

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四、超导机理/BCS模型

Then, in 1957, William Bardeen, Leon Cooper, and Robert Schrieffer proposed a theory now known as BCS theory

1972年，诺贝尔物理学奖：超导机理——BCS理论

巴丁（美国）64岁

库柏 42岁：27岁，提出超导理论模型，36岁任教授

施里弗 41岁：26岁解决超导理论问题，33岁任教授

无序

有序

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一）建立BCS理论的实验基础

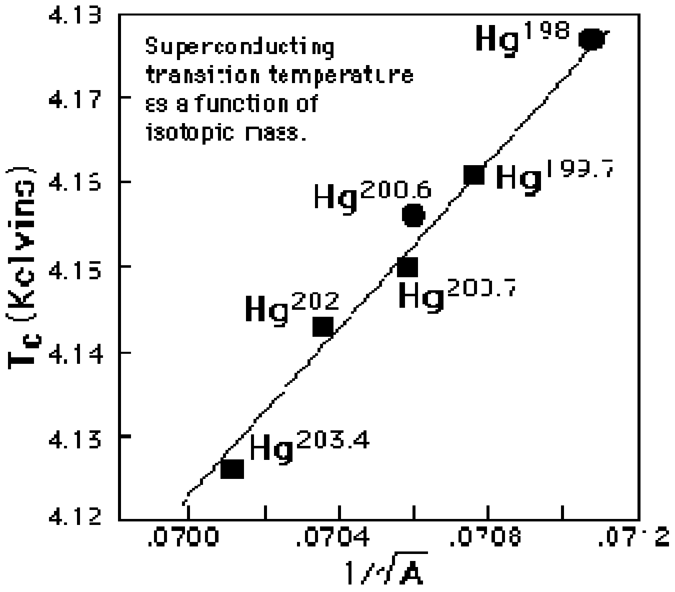
1、超导相变前后材料的结构，点阵及振动谱不变

2、超导能隙：比热 $C_{es} = a\exp(-1.50T_C / T)$

3、同位素效应

Smoking gun: Isotope effect

$$T_c \propto M^{-1/2}$$



E. Maxwell, Phys. Rev. (1950)

C.A. Reynolds et al., Phys. Rev. 78 (1950).

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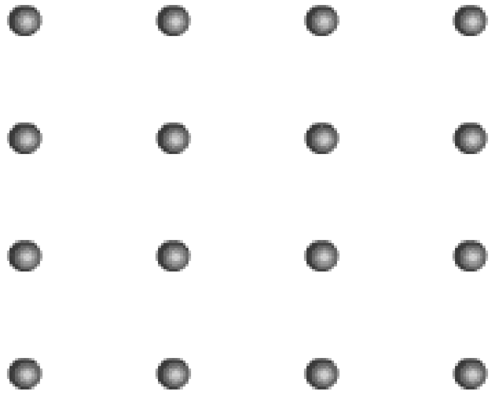
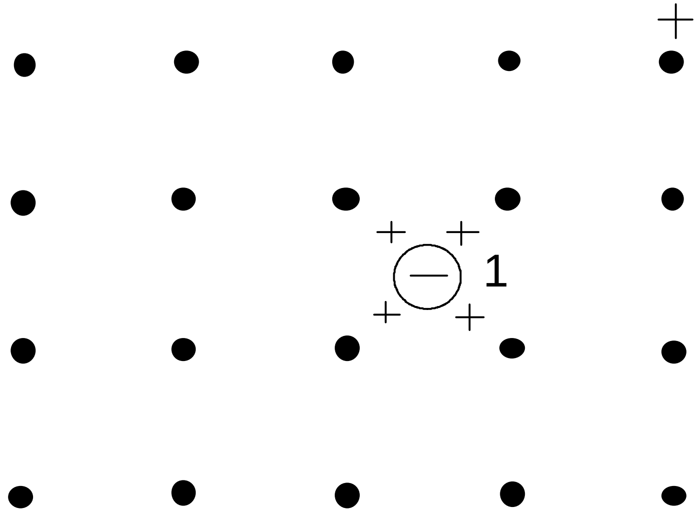
二）电声子相互作用模型

电子—声子相互作用能把两个电子耦合在一起，这种耦合就好象两个电子之间有相互吸引作用一样。





Electron-Phone interaction to form Cooper Pairs

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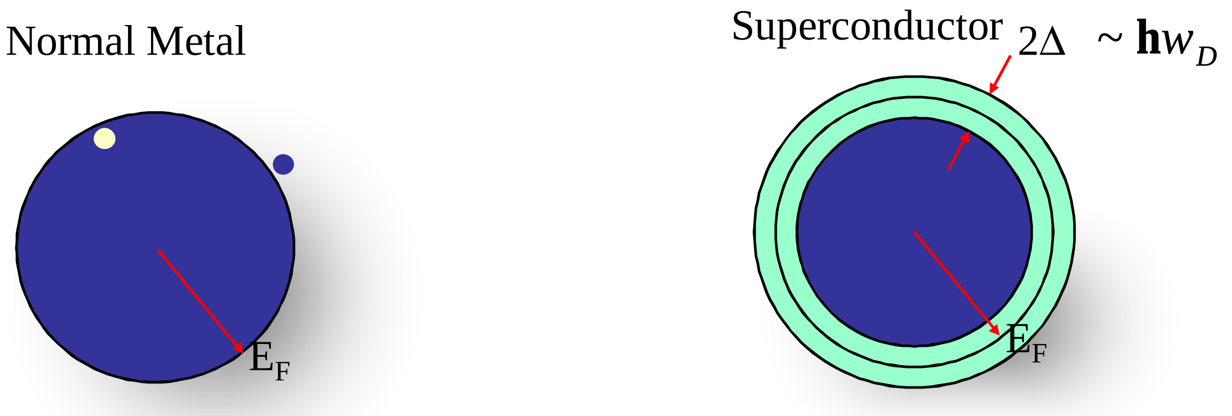
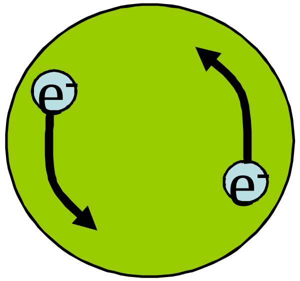
三）Cooper对

Bardeen, Cooper, Schrieffer 著名BCS的理论

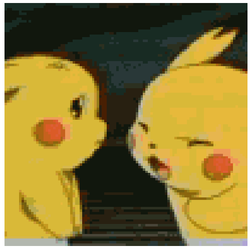


- **Electrons can attract via phonons**
- **Attraction leads to energy gap $\Delta \approx 1.76T_c$**

在Fermi面附近,能量在 hw_D 范围之内的自旋和动量都相反的一对电子——Cooper对



能量守恒
动量守恒
电子——声子相互作用能
泡利不相容原理



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五、Josephson 效应

1973年，诺贝尔物理学奖。约瑟夫森（英国）33岁，贾埃佛 44岁（机械工程师）

约瑟夫森22岁时解决理论问题，34岁 任教授

贾埃佛 33岁解决实验问题。“物理学几乎不及格的台球和桥牌能手”

电子隧道效应

弱电应用 →

可测地球磁场的十亿分之一

- 军事
- 勘探
- 医学

……

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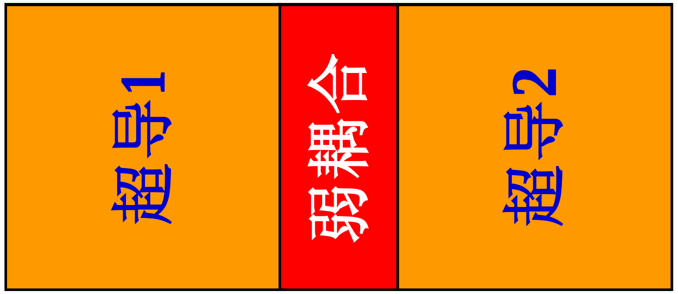

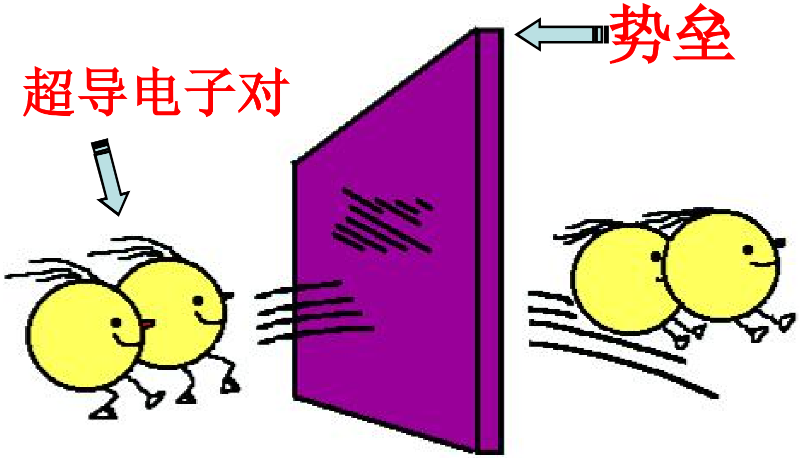

超导电子隧道效应

弱电应用

心脏磁图的测量

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六、高温超导材料的发现

一）液氮温区以上的超导材料的探索

- **1986年瑞士科学家Muller和Bednorz发现。**
- **LaBaCuO超导体：$T_c \sim 36K$。**
- **1983年开始，在瑞士苏黎世实验室研究氧化物超导电性。**
- **1987年，诺贝尔物理学奖**
- **氧化物高温超导体的发现**
- **柏诺兹（德国）37岁**
- **缪勒（瑞士）60岁**

K.A.Muller,
1927——，
瑞士物理学家

J.G.Bednorz,
1950——，
德国籍

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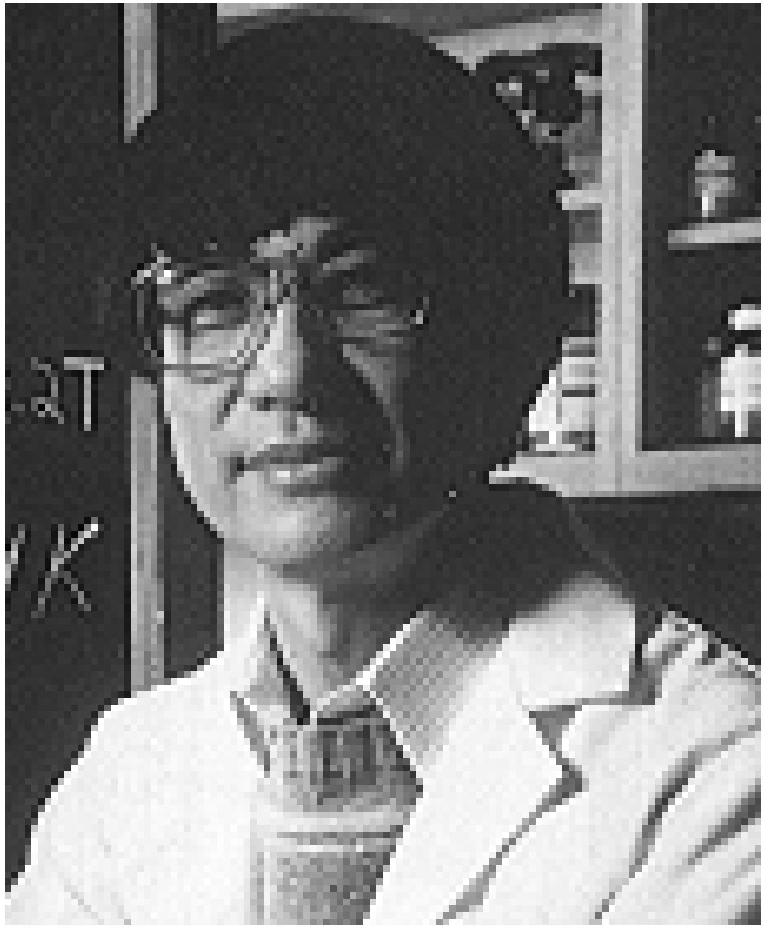
赵忠贤



朱经武

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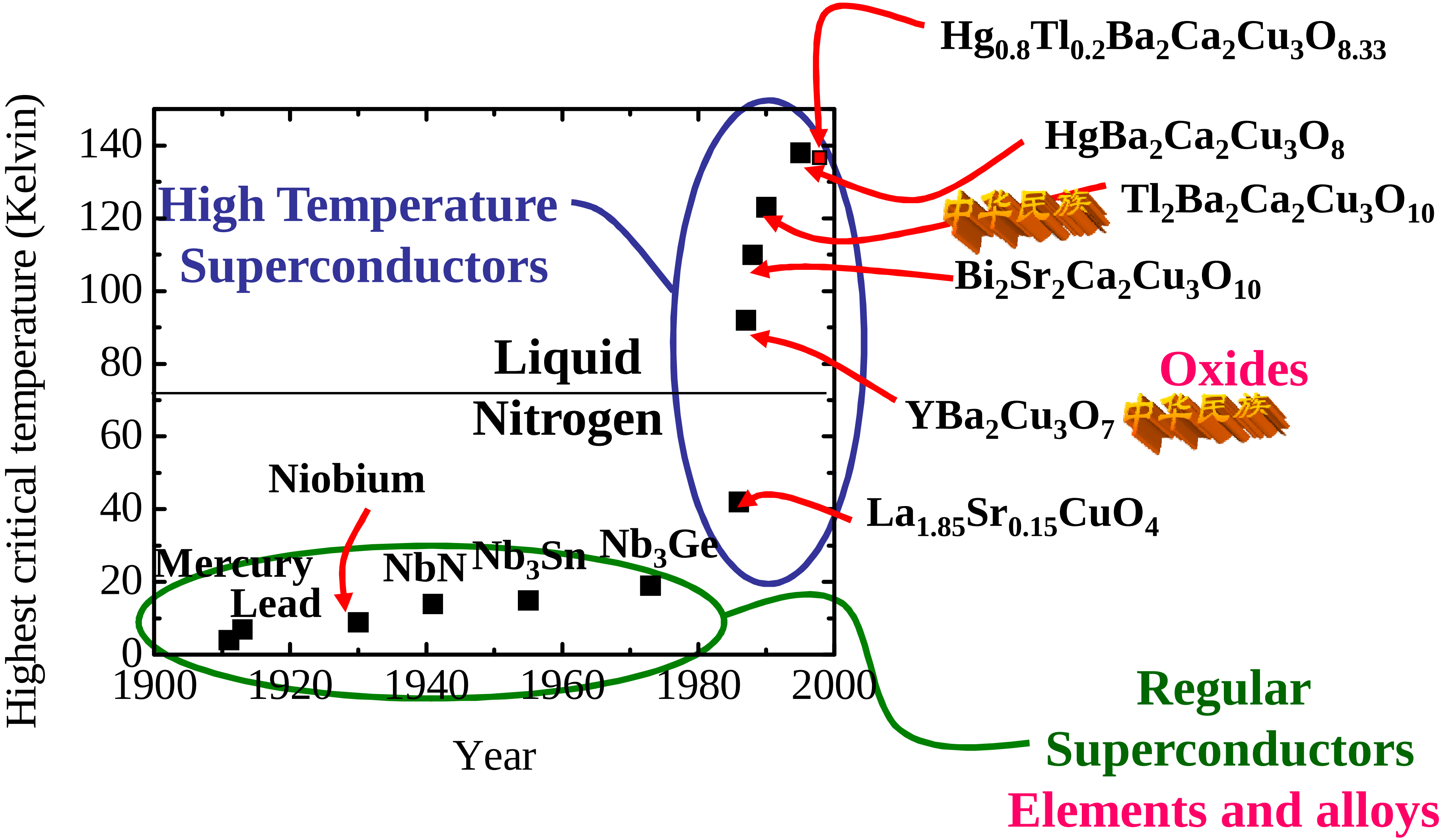

High Temperature Superconductors

$Hg_{0.8}Tl_{0.2}Ba_2Ca_2Cu_3O_{8.33}$

$HgBa_2Ca_2Cu_3O_8$

$Tl_2Ba_2Ca_2Cu_3O_{10}$

$Bi_2Sr_2Ca_2Cu_3O_{10}$

$YBa_2Cu_3O_7$

$La_{1.85}Sr_{0.15}CuO_4$

Oxides

Regular Superconductors

Elements and alloys

Two kinds of superconductors: Conventional and High Tc materials.
The more complex in the composition, the higher the T_c

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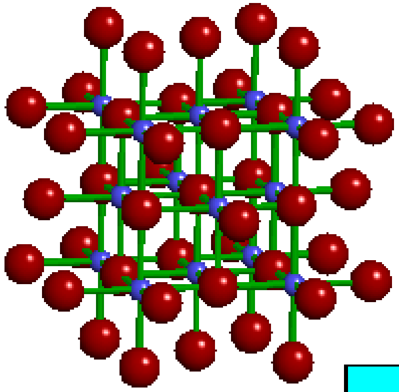
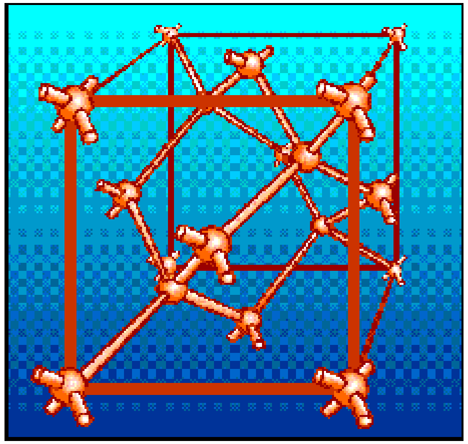
二） Difference Between Conventional and High T_c

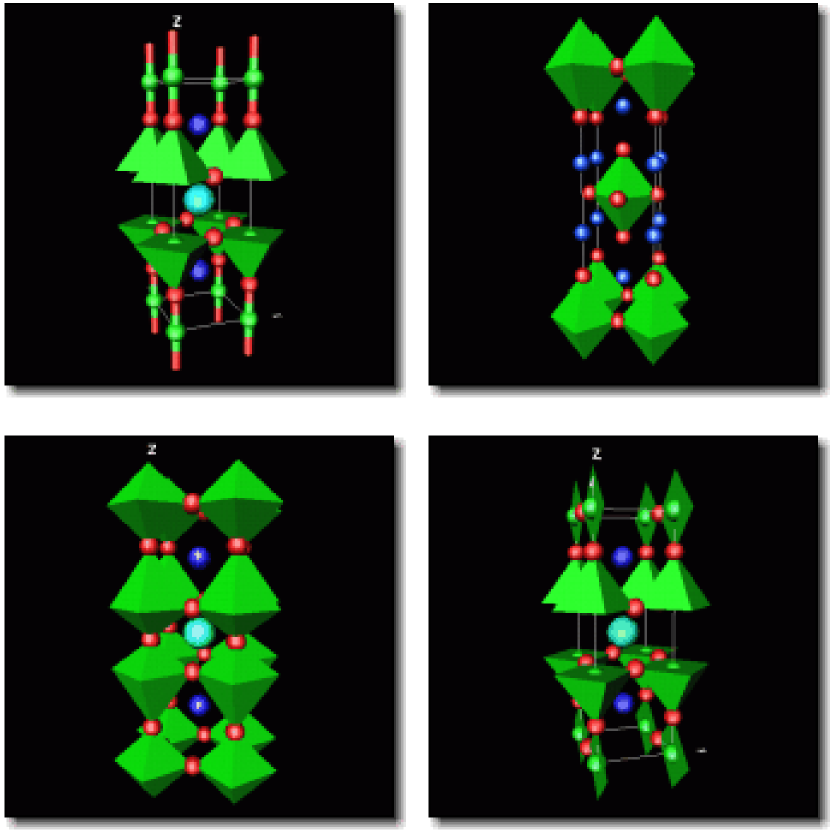
Difference in Structure for Conventional and High T_c

Regular Materials
3-Dimensional Structure





High-Temperature Superconductors:
Layered structures



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High Temperature Superconductors: Construction

High-Temperature Formulas

$HgBa_2Ca_2Cu_3O_8$

$Tl_2Ba_2Ca_2Cu_3O_{10}$

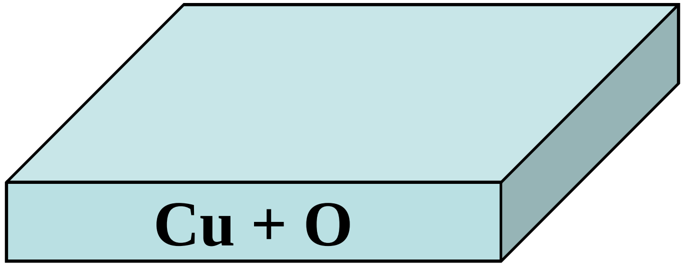
$Bi_2Sr_2Ca_2Cu_3O_{10}$

$La_{1.8}Sr_{0.2}CuO_4$

Cu = Copper

O = Oxygen

CuO = CopperOxide



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High Temperature Superconductors: Construction

High-Temperature Formulas

$HgBa_2Ca_2Cu_3O_8$

$Tl_2Ba_2Ca_2Cu_3O_{10}$

$Bi_2Sr_2Ca_2Cu_3O_{10}$

$La_{1.8}Sr_{0.2}CuO_4$

Cu = Copper
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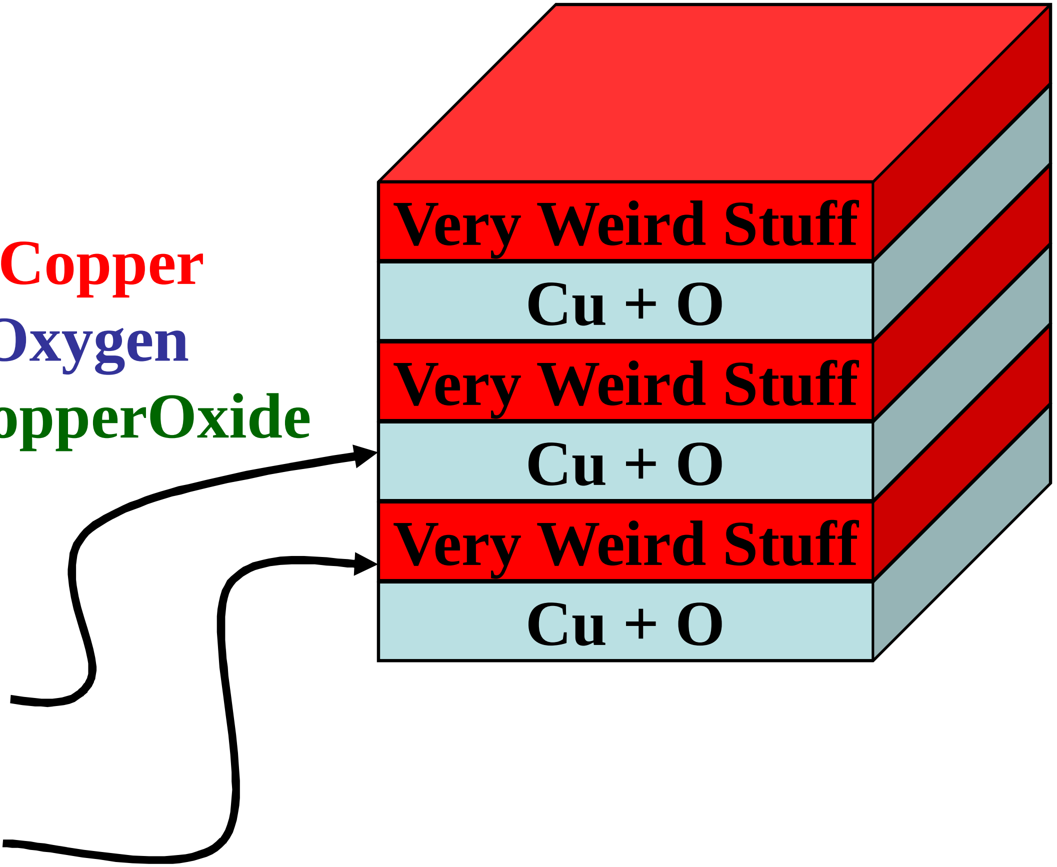

Superconductivity Here

Still Important!

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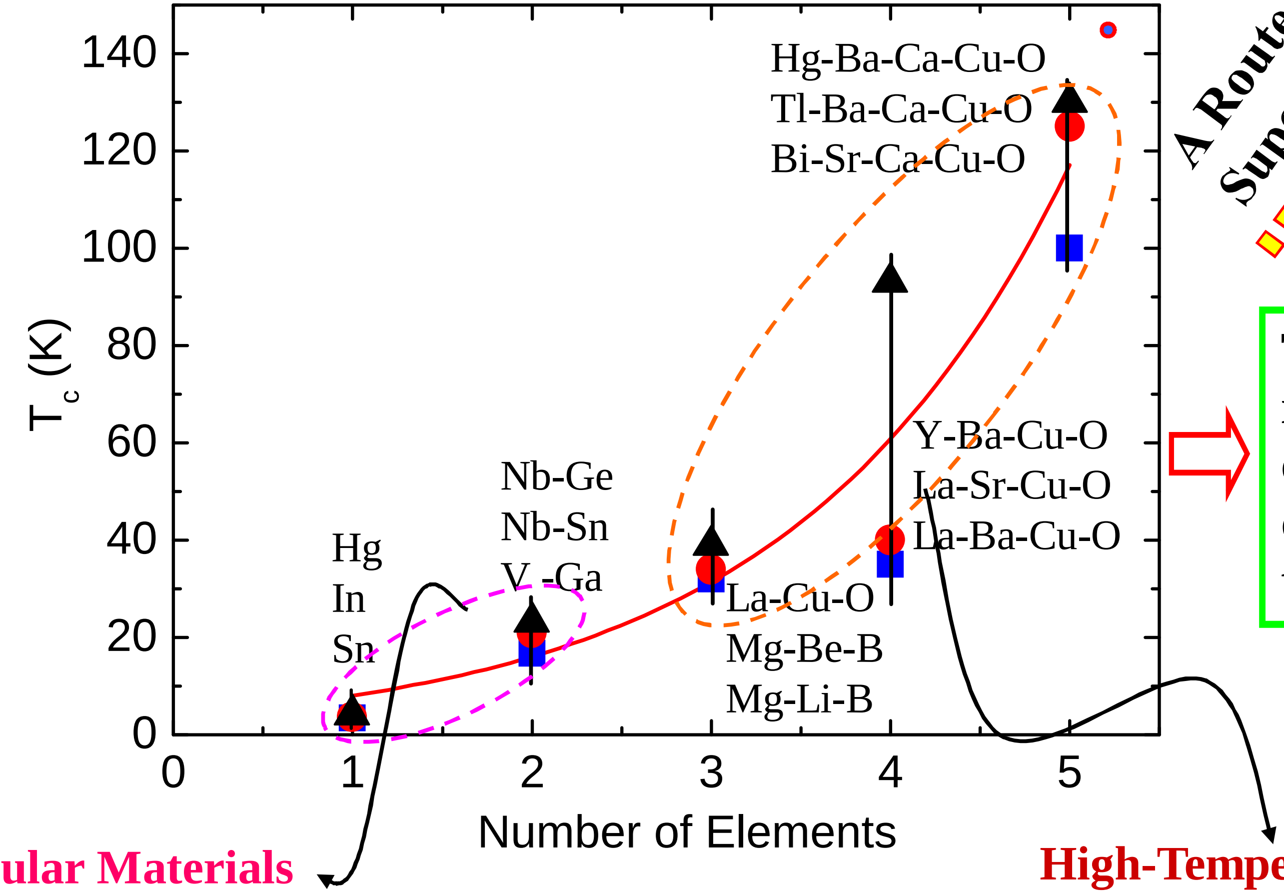
1、Motivation

1-Dimensional Structure
with multi-elements
RM-T_c??

Difference in Composition



A Route to RM-T_c Superconductivity?

Tc increases with increasing number of elements and decreasing dimentionality?

Regular Materials
3-Dimensional Structure

High-Temperature Superconductors: Layered structures

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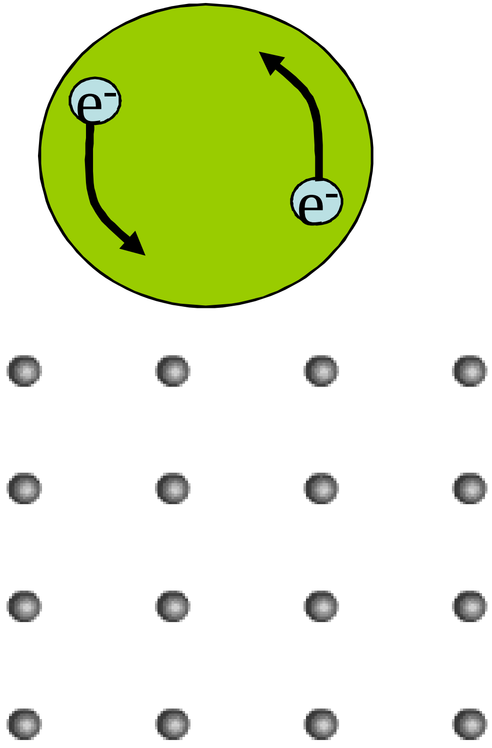
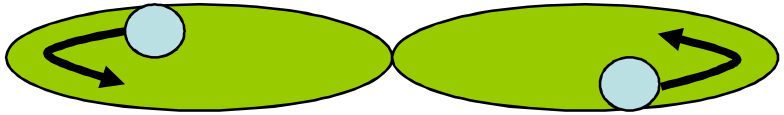
Difference in Mechanism

Regular Superconductors



Electron-Phone interaction to form Cooper Pairs

High-Temperature Superconductors



- A Magnetic Attraction ?
- Spin attraction ?
- The lattice after all ?
- Something else ?

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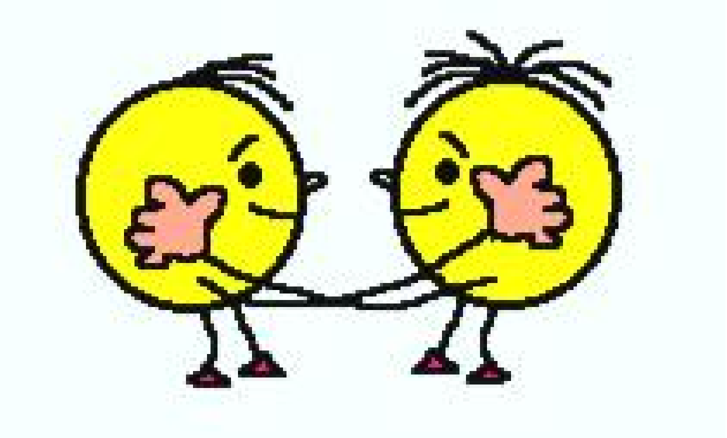
科学问题的发现及研究目的与意义

两个重大问题未从根本上解决

问题一：高温超导材料的超导机理悬而未决



探讨材料的导电机理——超导电子是如何配对的？

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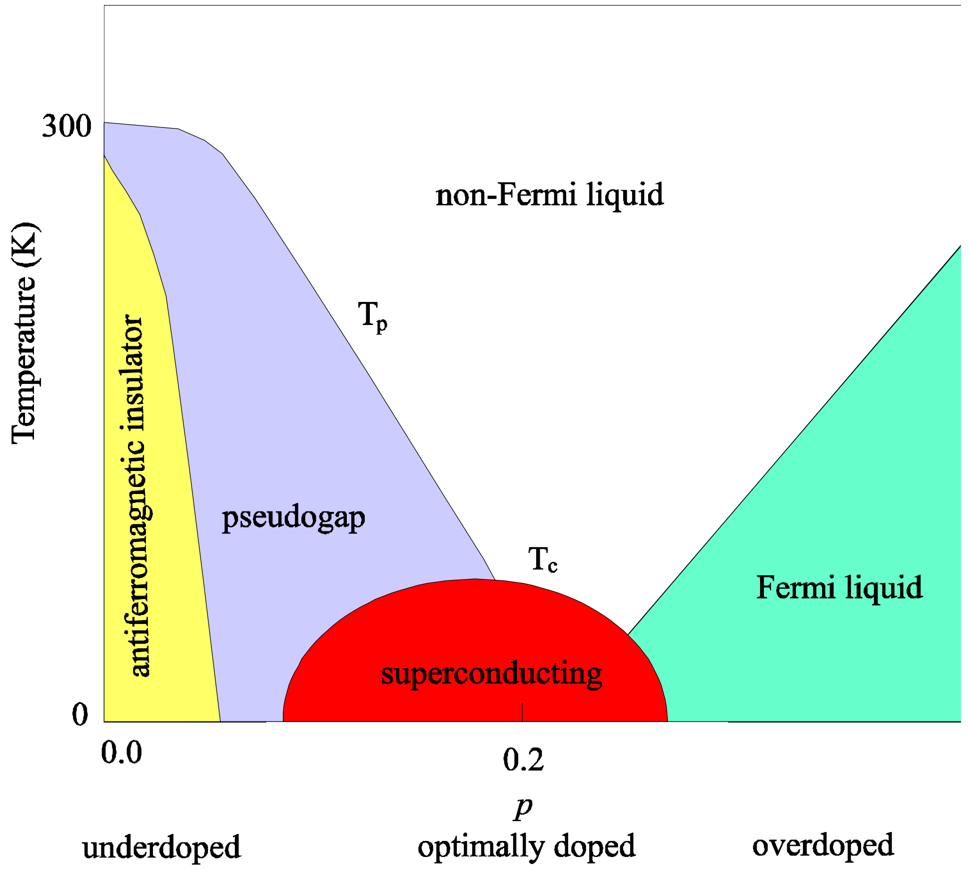
The Electronic Phase Diagram of the HTSC



All the pure Cu^{2+} compounds are antiferromagnetic insulators with high T_N. The Cu must be oxidised (hole doped) to achieve superconductivity i.e. by cation substitution or changing the oxygen content. Doping oxidises some Cu^{2+} to Cu^{3+} .

This frustrates the magnetic order which changes from long range to short range (p = 0.03). Then the system becomes metallic for p > 0.04 and superconductivity is found for p = 0.05 – 0.24. T_c max occurs for p = 0.16. Above p = 0.24 the HTSC behave as Fermi liquids.

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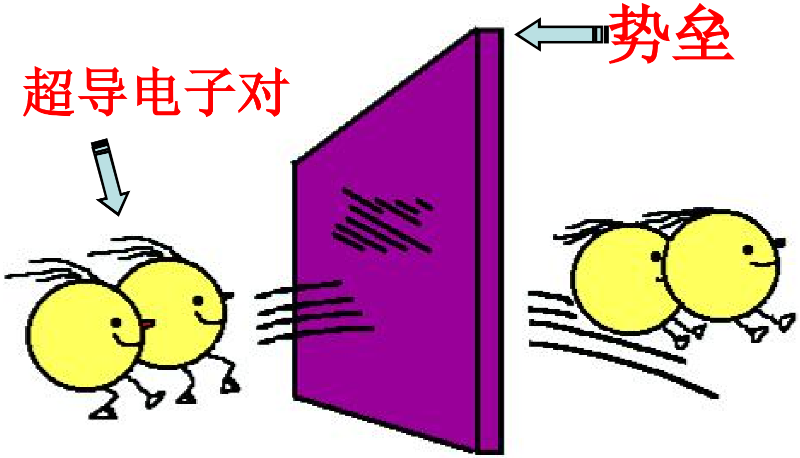
问题二：高温超导实际应用问题未根本解决



超导电子隧道效应

核心——如何控制和改善超导电子隧道效应？

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强电或强磁场下的应用

关键——如何提高磁场下的临界电流密度？

磁悬浮列车

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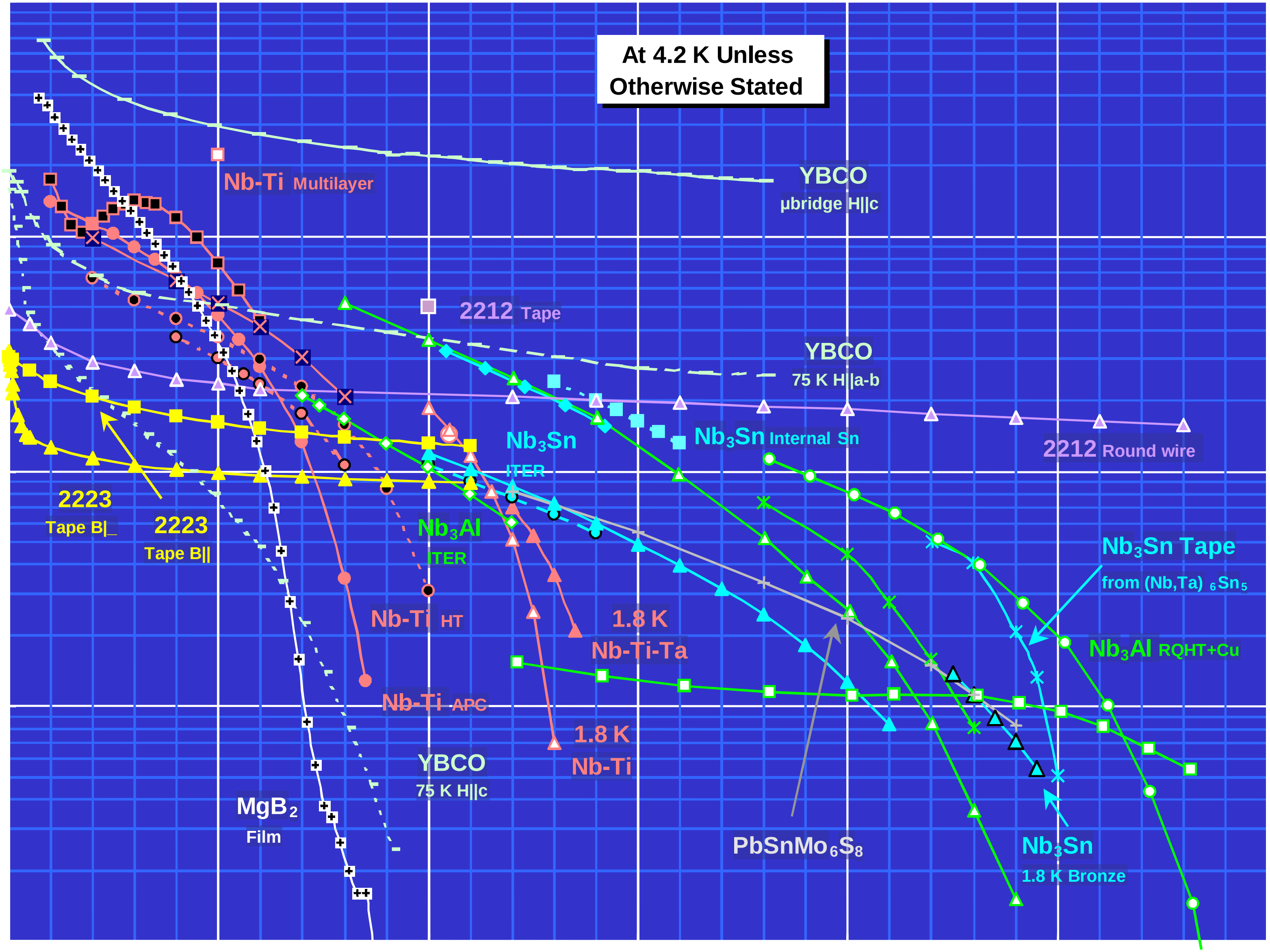

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七、自旋电子材料

材料中磁电阻效应

金属或合金在外磁场的作用下会产生电阻率的改变，其变化率称为磁致电阻(magnetoresistance，MR)。通常利用磁场引起的电阻率的相对变化量来度量磁电阻效应。

$$\frac{\Delta r}{r_0} = \frac{r_H - r_0}{r_0} \qquad \frac{\Delta r}{r_H} = \frac{r_H - r_0}{r_H}$$

这里r_0和 r_H分别表示无外加磁场和有外加磁场时的电阻率。

在大多数金属中，电阻的变化是正的；在大多数过渡金属的合金及铁磁体中，其变化是负的；对于半导体，磁电阻比较大。一般情况下，磁场的方向与电流的方向相互垂直时的磁电阻要明显大于相互平行时的磁电阻。

对非磁性金属来说，这是由于载流子受到洛伦兹力作用的结果，改变了载流子的漂移路径，导致电流分量的改变，从而影响电阻率的变化。

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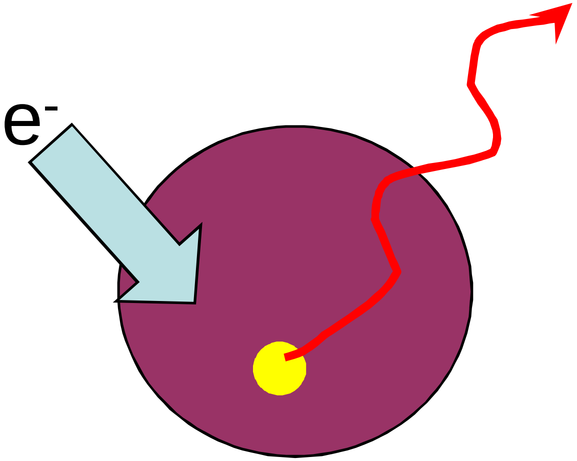
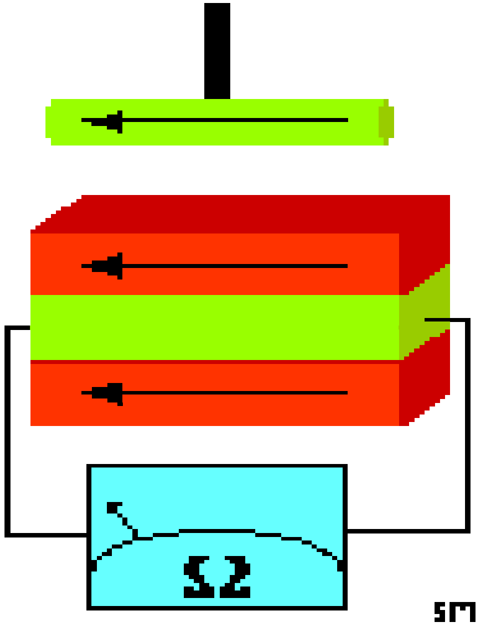
As for the advanced functional materials, the most important aspect is the behaviors of electrons

The behavior of an electron: Charge and Spin



Charge-Charge: 1eV



Spin-Spin: 10-100meV

The charge properties have been studied and used in many aspects. Recently, a lot of people pay much attention on the spin characteristics.

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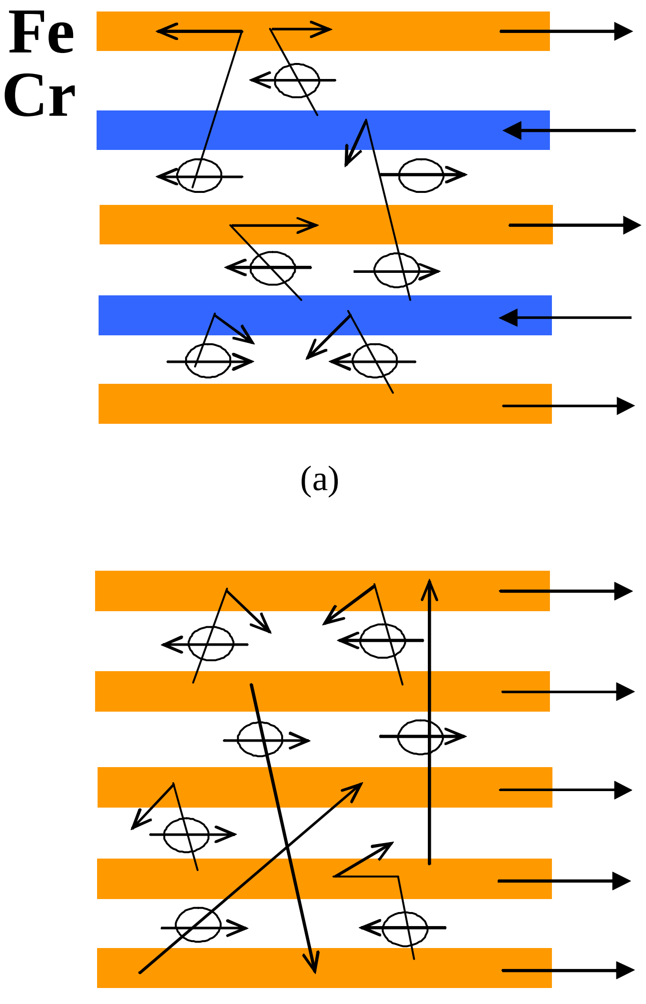
Spin

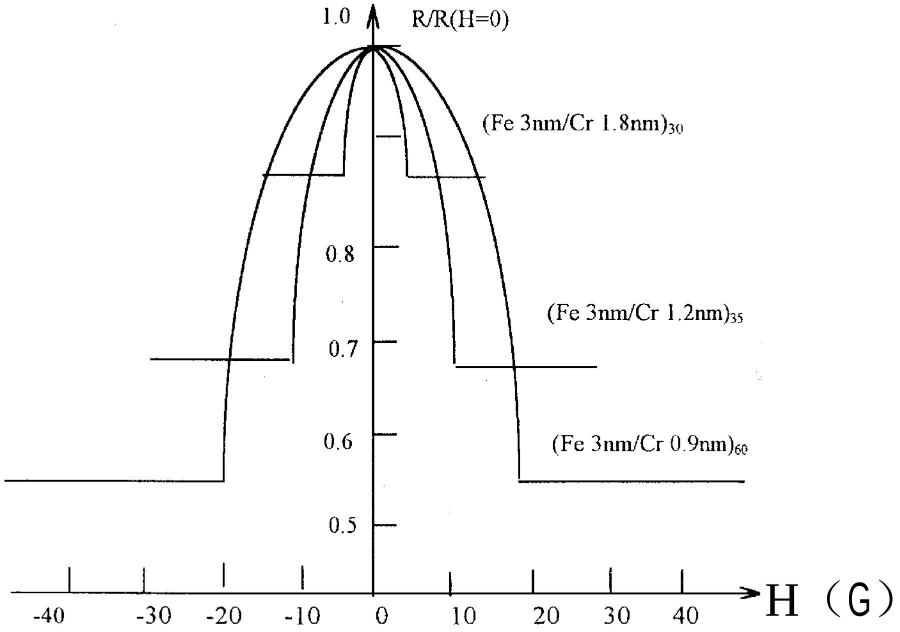
GMR



(a)

(b)

Multilayer



The magnetoresistance for Fe/Cr multilayers at 4.2K. The current and magnetic field direction is along (110)axis

M. N. Baibich et al., *Phys. Rev. Lett.* **61,** 2472 (1988).

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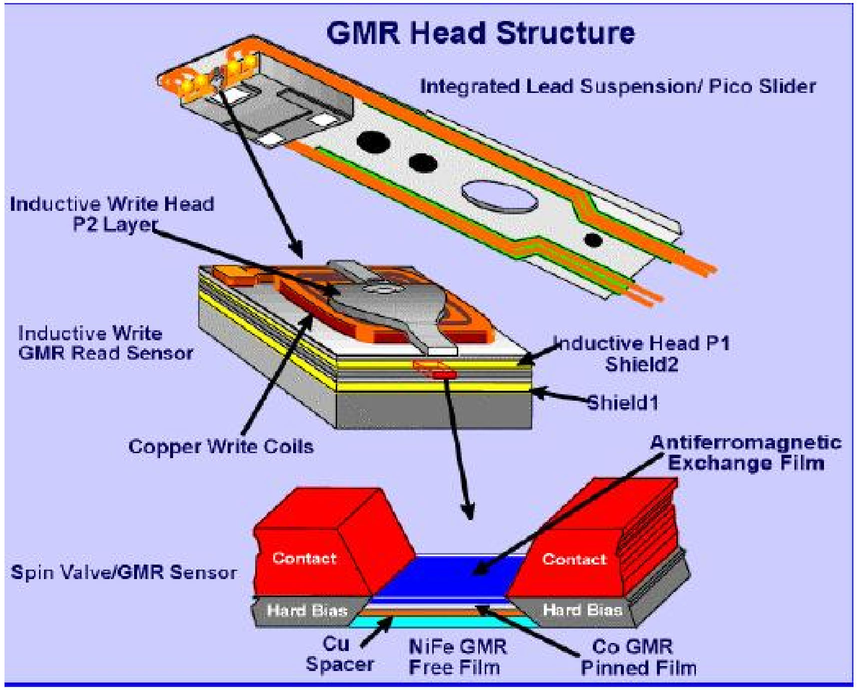
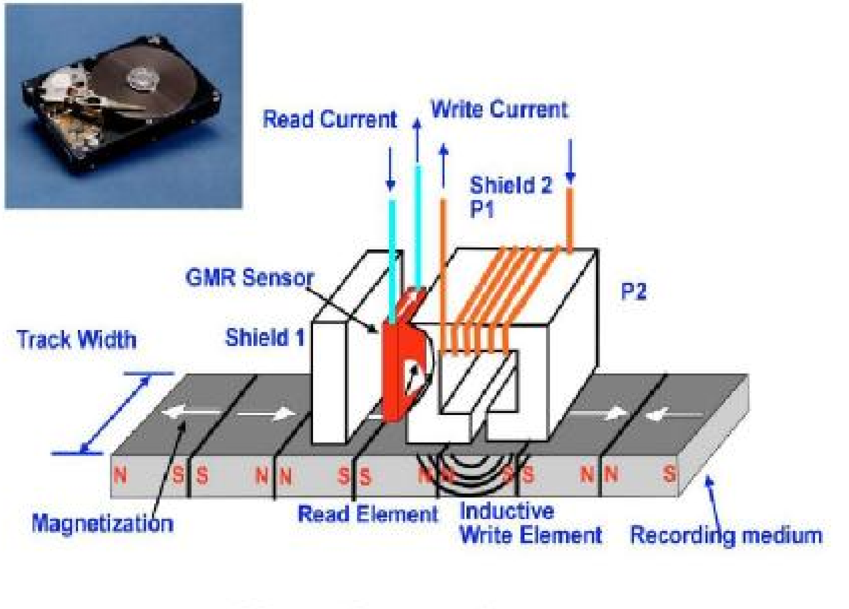


Commercial IBM giant magnetoresistance read head.



Magnetic recording process.

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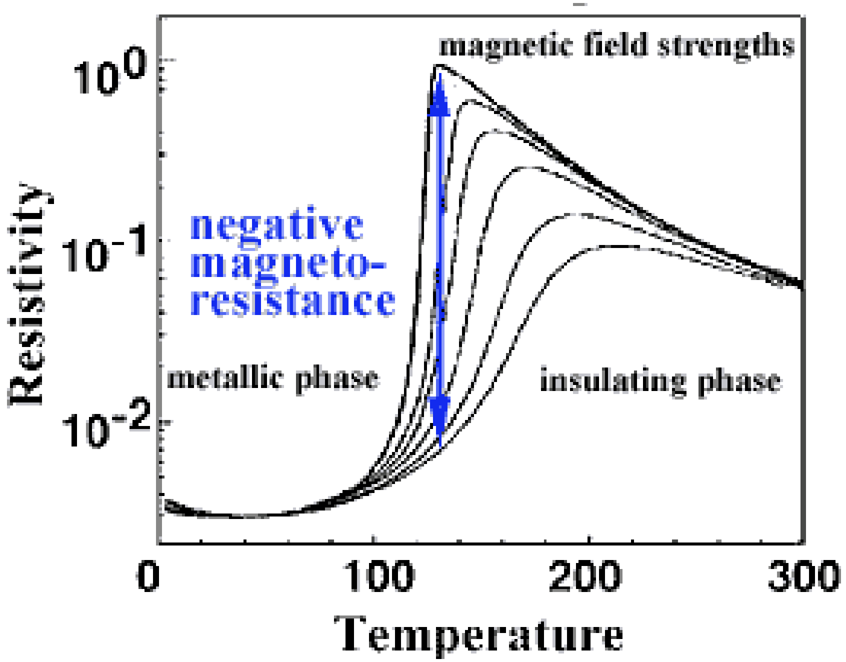
超大巨磁电阻效应
(Colossal Magnetoresistance effect, CMR)的发现

- 1993年，德国西门子公司的 Helmolt 等人在$La_{1/3}Ba_{2/3}MnO_3$中发现室温下 60％的 MR效应。
- 1994年，美国 IBM 公司的 Jin 等人在La-Ca-Mn-O薄膜中在6T下约 77K时观察到了 127000%的MR效应。



$$\mathrm{MR\%} = \frac{r(0) - r(H)}{r(H)}$$

Phys. Rev. Lett. 71, 2331 (1993) ; Science 264, 413 (1994)

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巨磁电阻材料的研究意义

- 广泛的应用前景

  磁存储，磁传感器件，自旋阀，自旋晶体管，磁制冷，红外成像等。

- 丰富的物理内容

  电荷，自旋，轨道，晶格强关联体系，凝聚态物理领域基本问题。

  绝缘体-金属转变，巨磁阻，巨压阻，巨磁熵变，巨磁致伸缩，自旋有序，电荷有序，轨道有序，场致（光致）绝缘体-金属转变等。

  双交换作用，Jahn-Teller效应，极化子，相分离等。

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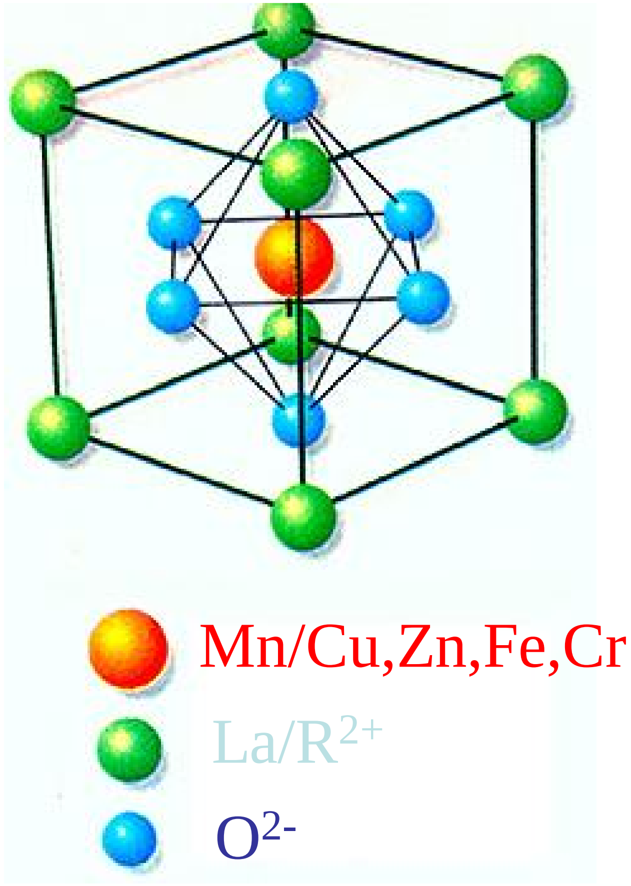
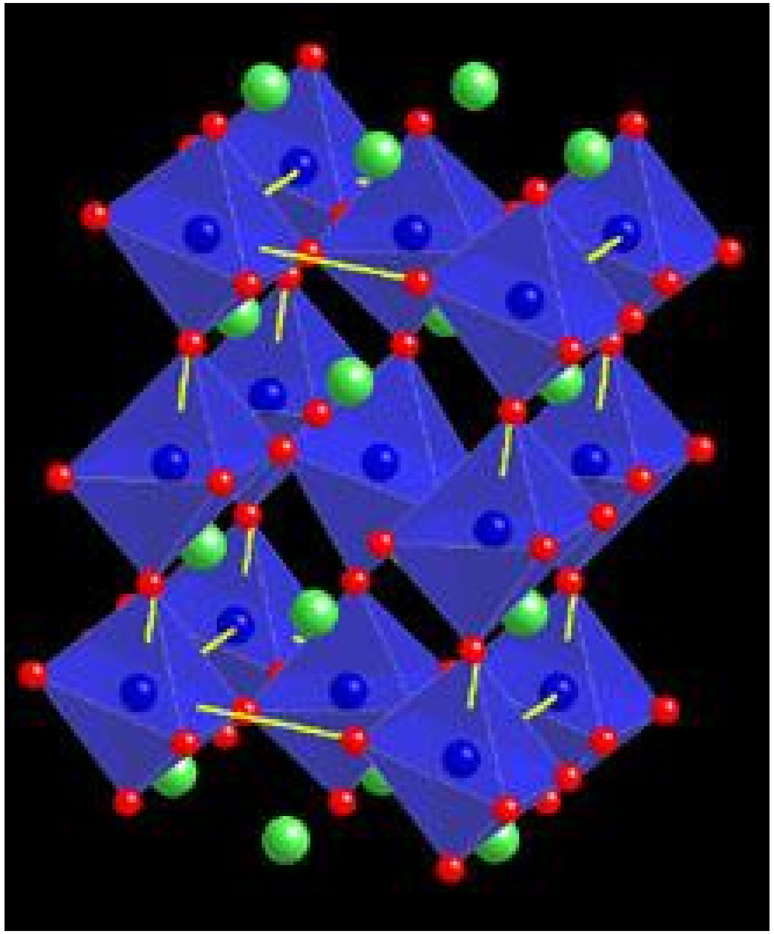
锰氧化物的晶体结构



钙钛矿ABO$_3$晶体结构



MnO$_6$在三维空间的排列

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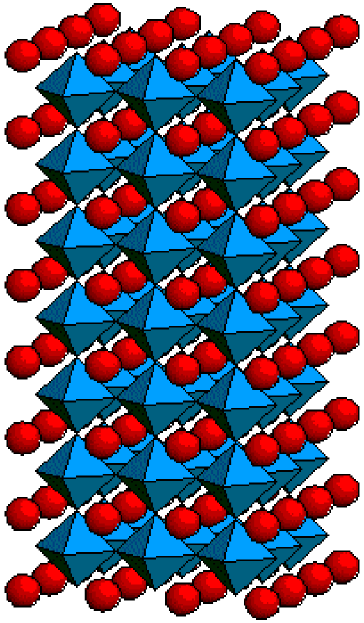
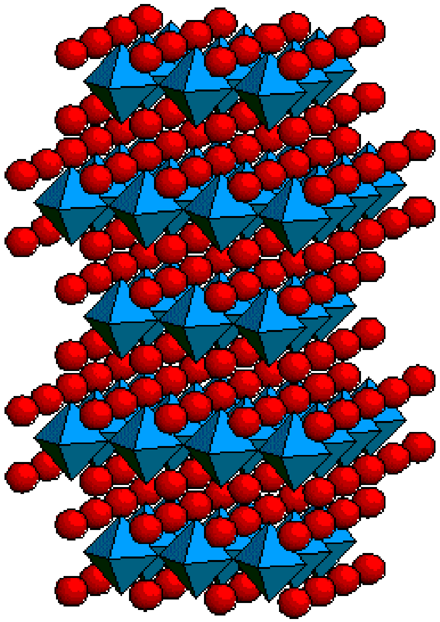
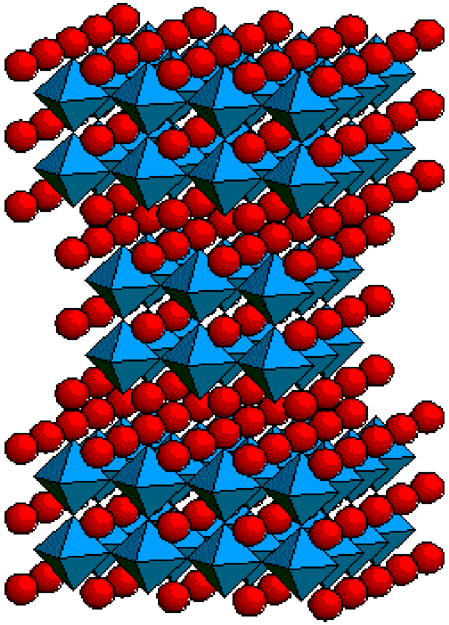
层状钙钛矿锰氧化物的晶体结构



n = ∞
ABO_3
perovskite



n = 1
A_2BO_4
K_2NiF_4



n = 2
$A_3B_2O_7$
bilayer

无限层MnO_2面　　一层MnO_2面　　二层MnO_2面

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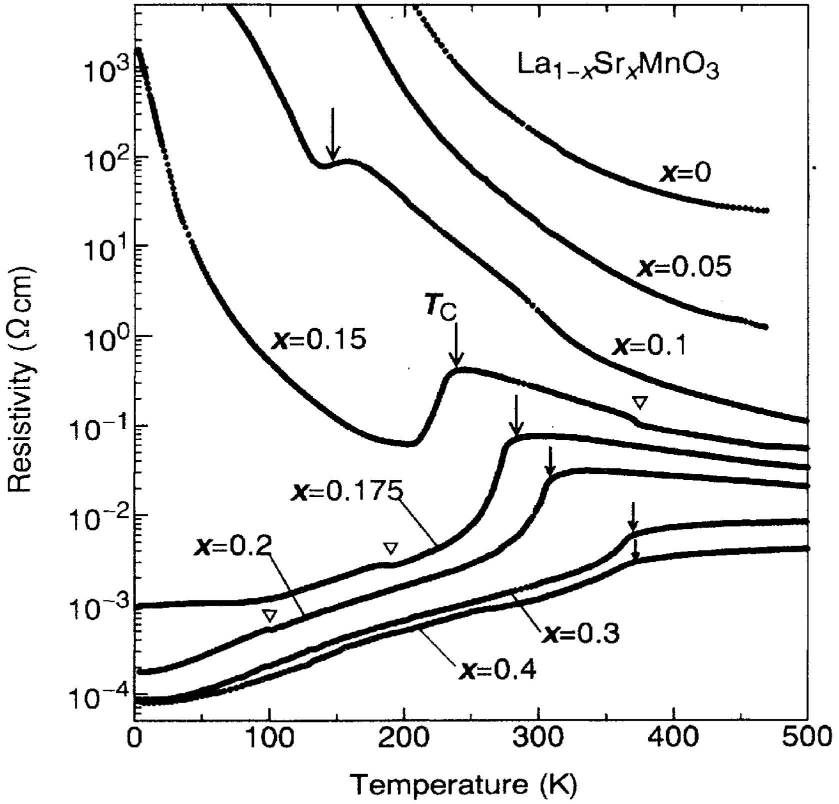
空穴掺杂导致金属绝缘体（MI）转变

$La_{1-x}Sr_xMnO_3$



当 $x < 0.1$，样品在整个温度区间内都表现出绝缘特性。随着 Sr 掺杂的增加，在刚好低于 T_C 时表现出金属性。但进一步降低温度，样品再次局域化。当 $0.15 < x < 0.30$，样品在 T_C 以下表现出金属性，但在 T_C 以上仍为绝缘体。当 x ³ 0.30，样品在整个温度范围内都表现出金属性。

箭头表示居里转变温度 T_C

三角形表示菱形到正交的结构转变

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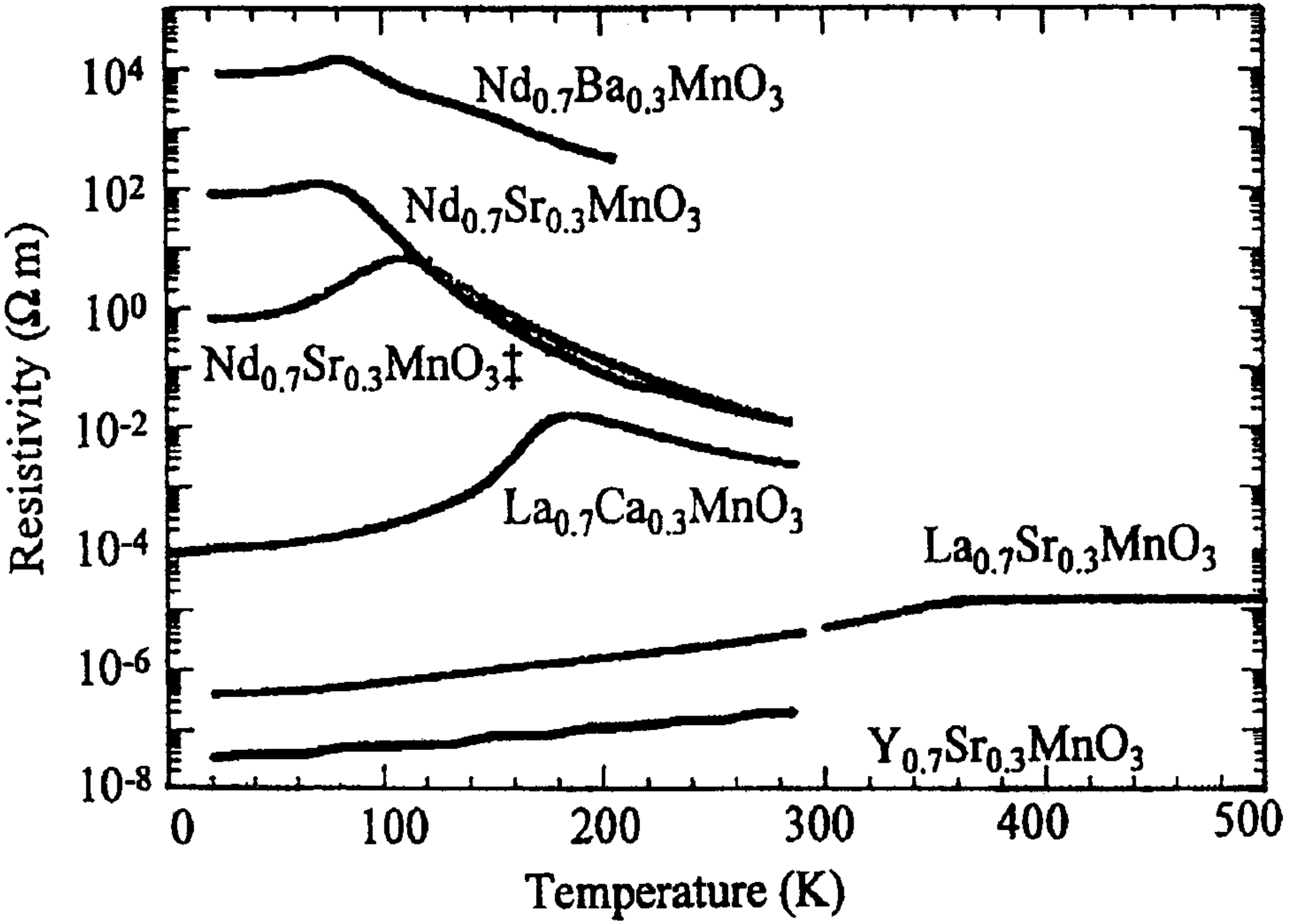

系列$R_{0.7}A_{0.3}MnO_3$在不同的温度下的电阻率

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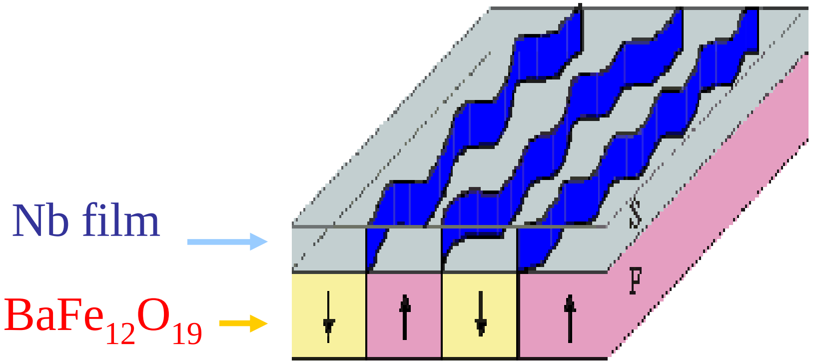
不同物理性能组装和调控的实现

铁磁与超导不相容？

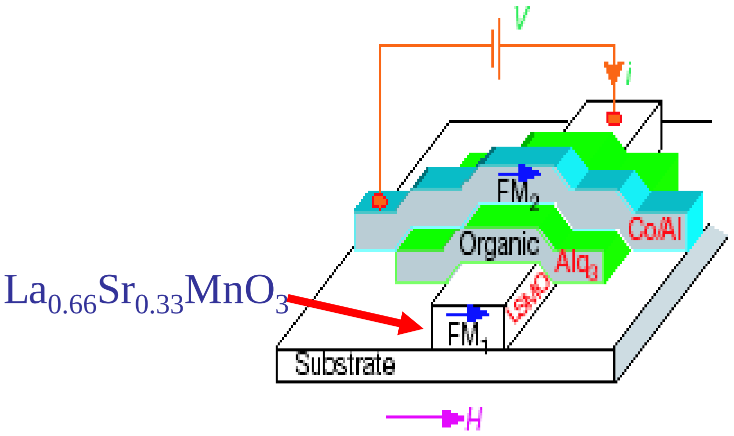
性能组装和调控：铁磁/超导杂化结构使得超导与磁性共存。

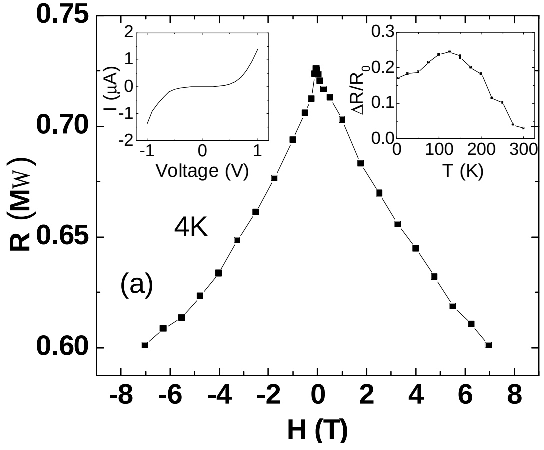


- 铁磁/超导杂化结构使得超导电子元件和磁存储元件耦合在同一个器件上成为可能。
- 人工控制超导电性。

自旋调控：

磁性/有机材料界面的自旋、载流子注入—改变磁电和光性能





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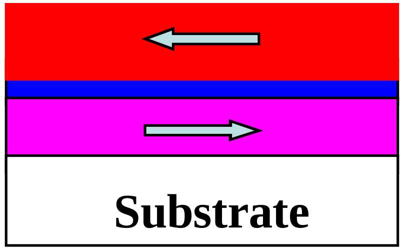
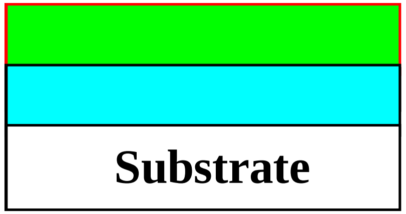
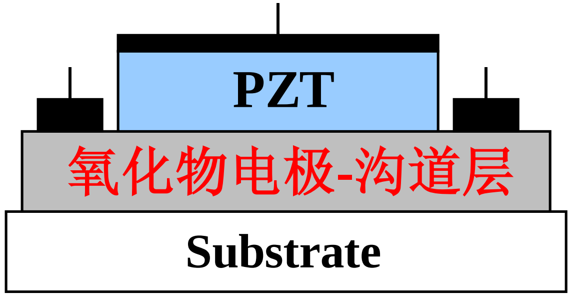
自旋阀



P—N结





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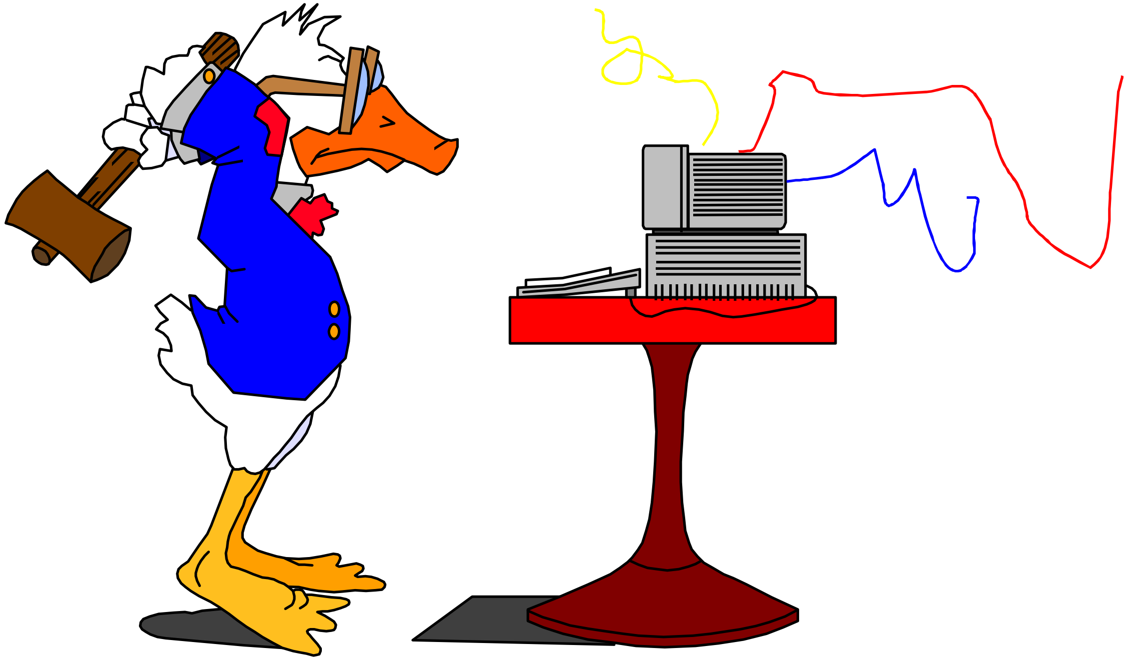

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