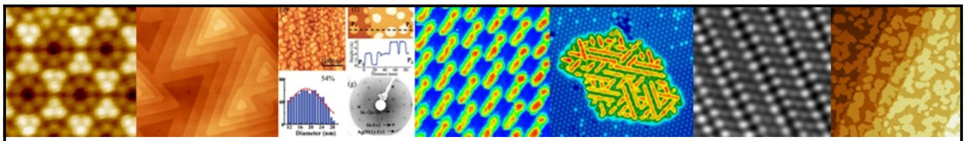


中科院物理研究所, 研究生专业学位课程

基于扫描探针显微镜的分析方法

Scanning probe microscopy: analytical methods

主讲：吴克辉、陆兴华、孟胜

时间：9月16日开始、共计40课时
每周二、四上午8：30pm-10:30pm
地点：D楼210

中国科学院物理研究所 INSTITUTE OF PHYSICS CHINESE ACADEMY OF SCIENCES | 北京凝聚态物理国家实验室 BEIJING NATIONAL LABORATORY FOR CONDENSED MATTER PHYSICS

主要内容

第一章：扫描探针显微镜概述（4）（吴克辉）
§1.1与扫描隧道显微镜有关的历史概述
§1.2 STM仪器原理、设计及和制作
§1.3 STM的基本理论
§1.4 STM的基本应用实例

第二章：扫描隧道谱与非弹性隧道谱（4）（吴克辉）
§1.1扫描隧道谱理论和技术
§1.2扫描隧道谱应用实例
§1.3非弹性隧道谱
§1.4非弹性隧道谱应用实例
§1.5傅立叶变换扫描隧道像及应用实例
§1.6其他隧道谱技术及实例

原子搬运技术和应用（5）
原子搬运技术的原理
金属原子的人工结构：量子围栏等
分子的操控和结构裁剪
STM操控表面的化学反应

化学组分的探测（4）
共振隧穿
半导体-悬挂键
金属-表面态和镜像态
针尖态的影响

自旋信号探测（6）
铁磁-超导自旋极化隧穿
磁性-磁性自旋极化隧穿
自旋极化针尖的制备
自旋极化扫描隧道显微镜
单自旋反转的隧道谱探测
电子自旋共振显微镜

光耦合扫描隧道显微镜技术（6）
光耦合扫描隧道显微镜设计及仪器
光与隧穿结的相互作用：热效应、光电效应、非线性信号的产生、距离控制
光电效应的应用：时间分辨、光诱导隧穿电流
非线性信号的应用：光驱动扫描隧道显微镜、表面等离子体的激发与探测、交流扫描隧道显微镜
光耦合扫描隧道谱

原子力显微镜(AFM)技术（5）
原子力显微镜的设计及仪器
接触原子力显微镜
非接触原子力显微镜
原子力显微镜在分子化学组分探测方面的应用

磁共振力显微镜技术（简介）（2）
磁共振力显微镜的设计及仪器
磁共振力显微镜的应用

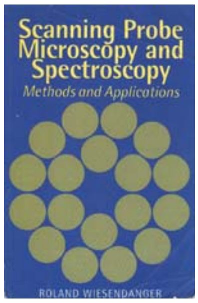
近场光学显微镜技术（简介）（3）
近场光学显微镜的设计及仪器
近场光学显微像的对比
近场光学显微谱及应用

课程学习目的：

1. 深入了解以**STM/STS**为代表的分析技术
2. 从实例入手，理解和掌握**STM**在研究中的应用
3. 讨论交流、学习分析问题、解决问题的思路和方法

参考书：

Roland Wiesendanger "Scanning probe microscopy and spectroscopy: Methods and applications",Cambridge University press, 1994



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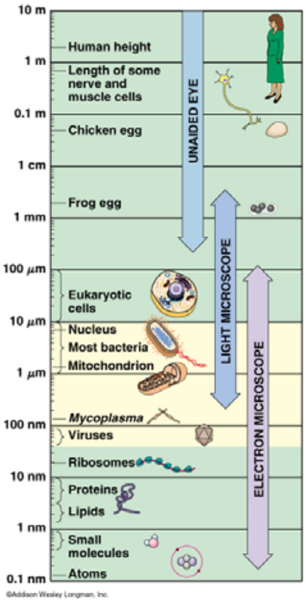
第一章：扫描探针显微镜概述（4课时）

§ 1.1 显微镜发展简史
§ 1.2 STM的基本原理和应用
§ 1.3 STM仪器设计及和制作
} 2课时

§ 1.4 STM的基本理论
§ 1.5 STM的基本应用实例
} 2课时



§ 1.1 扫描隧道显微镜发展简史

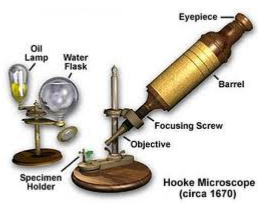
人类探索微观世界的最重要的两类工具：

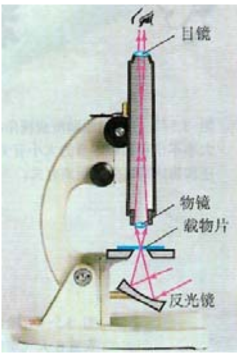
显微技术（microscopy）　和　谱学技术(spectroscopy)

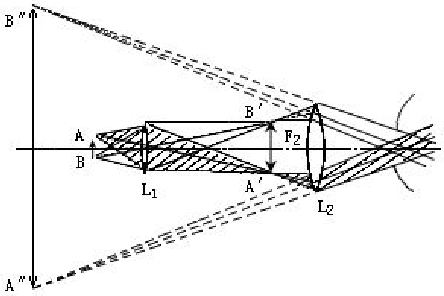
显微镜是用于观察微观结构的技术，属于广义上的成像技术的一种。

最早的显微镜 ---光学显微镜

1610年前后 ： 伽利略和开普勒在望远镜的基础上提出显微镜的工作原理。
伽利略用显微镜观察到昆虫的复眼结构。
1663年：罗伯特.虎克(Robert Hooke)大幅改进，制作复式显微镜。







显微镜系统成像原理图

光学显微镜：放大倍率1000-1500倍。主要局限：光的衍射极限。

可见光波长：400 -760 nm，分辨极限: λ/2= 200 nm

200 nm x 1500倍 = 0.3 mm ~ 人眼分辨极限

电子波的波长取决于加速电压和电子的质量，即

$$\lambda = \frac{h}{\sqrt{2emU}}$$

，式中 h为普朗克常数，m为电子的质量；e为电子所带的电荷，U为加速电压。

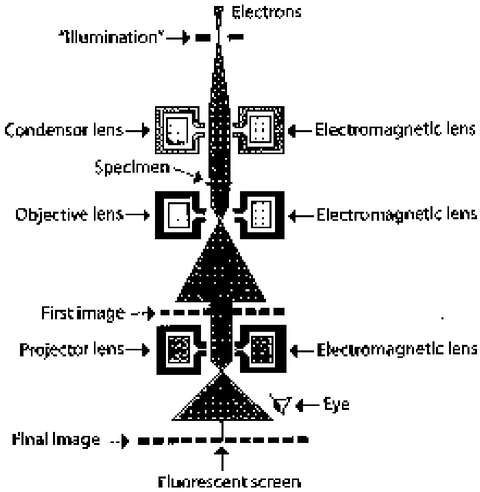
如果电子速度较低，则它的质量和静止质量相近，即m≈m_0。如果加速电压很高，使电子具有极高的速度，则必须经过相对论校正，此时

$$\lambda = \frac{h}{\sqrt{2em_0U(1+eU/2m_0c^2)}}$$

表 7-1 不同加速电压下电子波的波长(经相对论校正)

加速电压/kV	电子波波长/Å	加速电压/kV	电子波波长/Å
1	0.388	40	0.060 1
2	0.274	50	0.053 6
3	0.224	60	0.048 7
4	0.194	80	0.041 8
5	0.713	100	0.037 0
10	0.122	200	0.025 1
20	0.085 9	500	0.014 2
30	0.069 8	1 000	0.008 7

TEM



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透射电子显微镜：基于电子光学成像原理的显微镜

1920年：法国德布罗意提出电子的波粒二象性

1926年：德国H. Busch提出电子透镜理论

1932年：德国Max Knoll与Ernst Ruska制作第一台电子显微镜（放大率12倍）。

1933年： Ernst Ruska制作成放大率1万倍透射电子显微镜

1939年：德国西门子公司制作出第一批商用透射电镜 （分辨率3 nm）

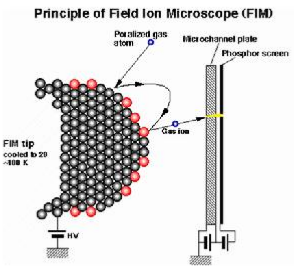
1970年：芝加哥大学 Albert V. Crewe等人首次用TEM实现原子分辨 (*Science* 1970, *168*, 1338)

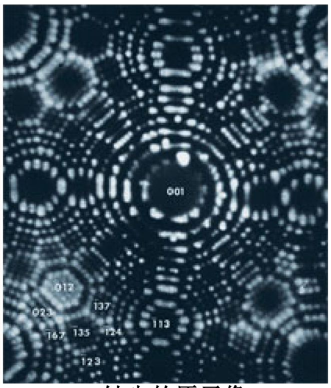
20世纪末：球差矫正技术使TEM分辨率达到达到~1Å

场离子显微镜(Field Ion Microscopy)：最早实现原子分辨的显微镜

1955年，美国宾州大学Erwin W. Mueller(1911-1977) 发明场离子显微镜
1967： 元素分辨场离子显微镜

场离子显微镜-原理





W(001)针尖的原子像

放大倍数:

$\eta = D/(R\beta)$

D=10cm, R=50nm

η=100万

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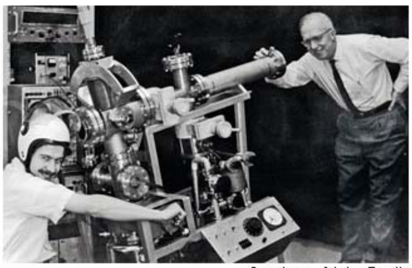
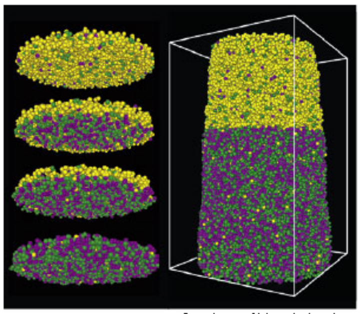
元素分辨场离子显微镜(atom-probe field ion microscope)



Courtesy of John Panitz

LINE OF FIRE Wielding the first all-metal atom-probe field ion microscope as though it were a weapon, Panitz (at the gunner's position) "fires" a friendly shot at Müller, who is holding the instrument's time-of-flight mass spectrometer tube in this 1969 photo.



Courtesy of Lincoln Lauhon

SLICE AND DICE In addition to mapping the atoms in an indium arsenide nanowire capped with a gold catalyst (right), modern atom probes can quickly reveal compositional variations in the interior of ultrathin slices (left) made on either side of the interface. Indium is green; arsenic, purple; gold, yellow.

50th Anniversary of Atomic Resolution Microscopy (on June 15-17, 2005 at PSU)

In front of Osmond Building

for Penn State's 150th Anniversary in 2005

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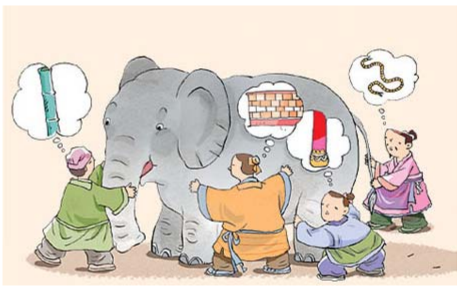
盲人摸象

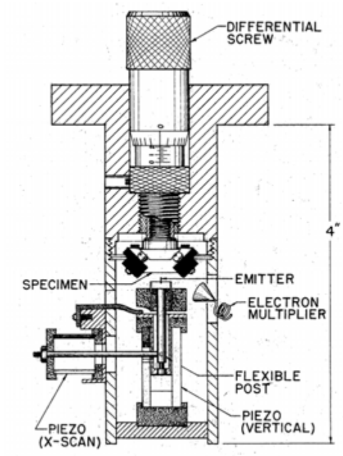


“扫描”、“以局部构筑整体”的概念，是贯穿许多仪器工作的核心思想

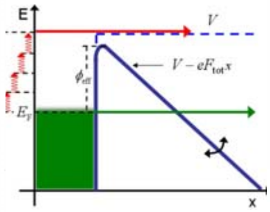
如：扫描电子显微镜（1952年）\电视机（电子显像管）

STM 的原型：场发射扫描形貌仪

] R. Young, J. Ward, and F. Scire. The topographiner: An instrument for measuring surface microtopography. Review of Scientific Instruments, 43(7):999–1011, July 1972.



针尖距离： 100nm
电压： 几个KV
分辨率： 400nm



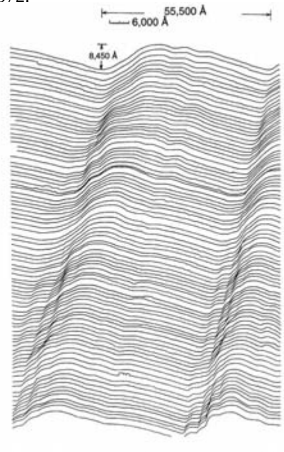
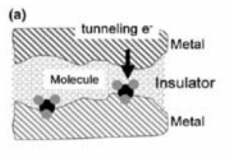


Fig. 4. Topographic map of ruled diffraction grating with the Topografiner. Labeled distances are in ångströms. 1 Å = 0.1 nm.

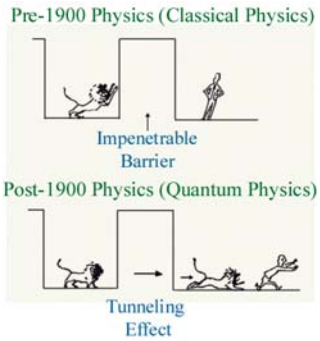
量子隧穿效应的研究历史

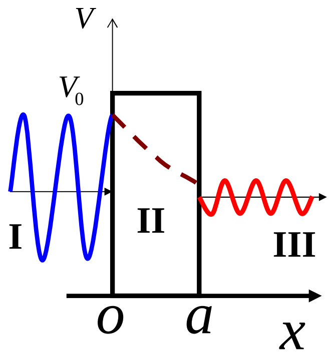


Landmarks in the science of tunneling (Roy, 1986)

	Phenomena	Investigators	Year
1	Observation of field emission from metals	Lilienfeld	1922
2	Ionization of hydrogen atoms by electron tunneling	Oppenheimer	1928
3	Explanation of field emission	Fowler and Nordheim	1928
4	Alpha-decay theory	Gamov Gurney and Condon	1928 1928
5	Theory of interband tunneling in solids	Zener	1934
6	Field-emission microscope (FEM)	Müller	1937
7	Observation of Zener breakdown	Chynoweth and Mckay	1957
8	Tunneling in degenerate p–n junctions	Esaki	1958
9	Extension of Zener's theory to tunnel diodes	Keldysh Price and Radcliffe Kane	1958 1959 1961
10	Measurement of energy gap of superconductors	Giaever	1960
11	Perturbation treatment of tunneling	Bardeen	1961
12	Tunneling of Cooper particles	Josephson	1962
13	Experimental verification of the Josephson effect	Anderson and Powell Rowell Fiske	1963 1963 1964
14	Inelastic tunneling spectroscopy (IETS)	Jaklevic and Lambe	1966
15	Point contact tunneling	Levinstein and Kunzler von Molnar *et al.*	1966 1967
16	Experimental observation of Coulomb blockade	Zeller and Giaever	1969
17	Observation of tunneling tails	Lea and Gomer Gadzuk and Plummer	1970 1971
18	Spin-polarized tunneling	Tedrow and Meservey	1971
19	Vacuum tunneling and topografiner	Young *et al.*	1971
20	Development of scanning tunneling microscope (STM)	Binnig *et al.*	1982
21	Theory of traversal time for tunneling	Büttiker and Landauer	1982
22	Theory of Coulomb blockade	Ben-Jacob and Gefen Averin and Likharev	1985 1986

量子隧穿效应





穿透几率 $\propto e^{-\frac{2a}{\hbar}\sqrt{2m(V-E)}}$

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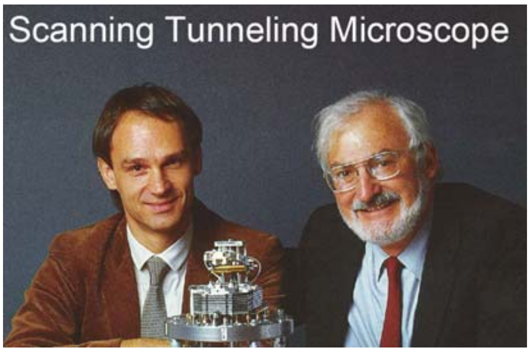
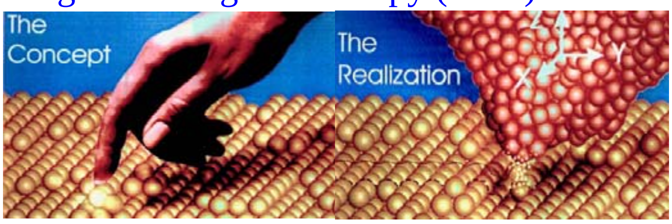


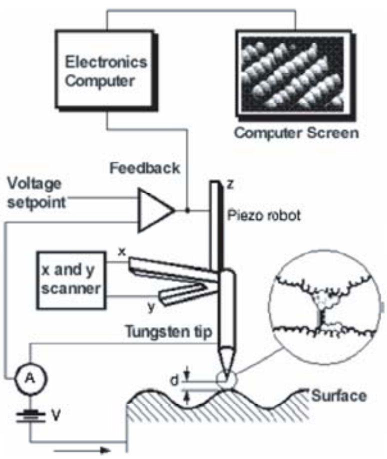
Gerd Binnig and
Heinrich Rohrer,
IBM Research Division

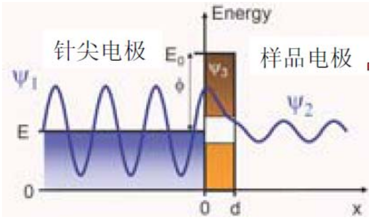
Scanning Tunneling Microscopy (STM)



Binnig and Rohrer, *Rev. Mod. Phys.* ***71***, *S324 (1999)*

The expermental setup:





解一维薛定谔方程

$$-\frac{\hbar^2}{2m}\frac{d^2\psi}{dx^2}+E(x)\psi=E_\psi\psi$$

指数变化

$$I \sim \exp(-2\kappa d)$$

其中 $\kappa=\sqrt{\frac{2m(E_0-E)}{\hbar^2}}$

扫描隧道显微镜的工作模式

(1) 通常的形貌图：

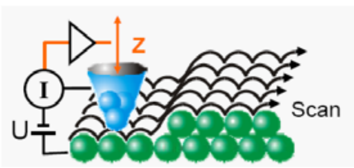
扫描图象时常保持**V**恒定。

恒流模式**(V,I)=const. (x,y)/z,**测量电子态的空间分布

等高模式**(V,Z)=const. (x,y)/I,**测量态的分布与贡献

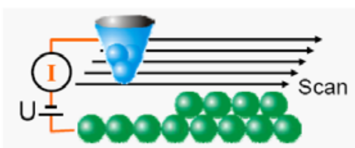
恒流模式

a) I constant, feedback loop active, Z variation measured



恒高模式

b) Z constant, feedback loop idle, I variation measured



STM实验中有(x,y,z,V,I)五个可以独立控制的变量。

其中(x,y)面内扫描定位使用。

而(z, V, I) 之间可以以多种不同的方式组合，或者通过增加调制，产生多种工作模式。

（1）通常的形貌图：

扫描图象时常保持**V**恒定。

恒流模式**(V,I)=const. (x,y)/z,**测量电子态的空间分布

等高模式**(V,Z)=const. (x,y)/I,**测量态的分布与贡献

（2）扫描隧道谱

单点扫描隧道谱：

固定（x,y,z）于一点，测量 I- V、dI/dV(扫描隧道谱)、或 d^2I/dV^2 (非弹性隧道谱)。

扫描隧道像：

(V,I)=const. (x,y)/ dI/dV(扫描隧道像)

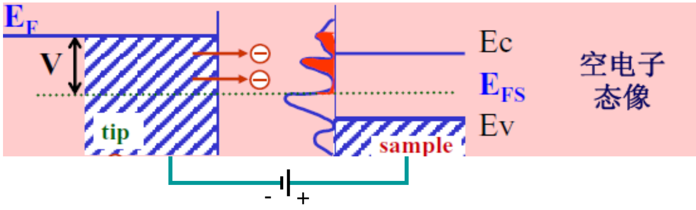
(V,I)=const. (x,y)/ d^2I/dV^2(非弹性隧道像)

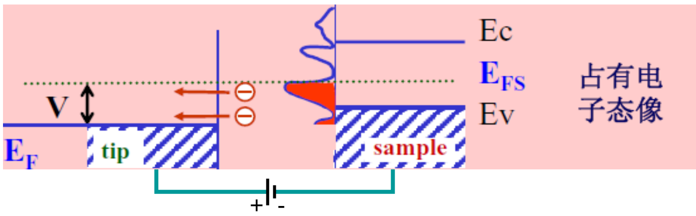
（3）功函数谱

(V,I)=const. (x,y)/ dI/dz

采用锁相放大技术直接测量

占有态电子像和空态电子像





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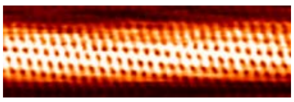
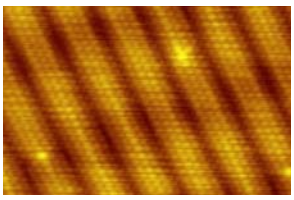
扫描电子显微镜的基本功能：原子分辨形貌像

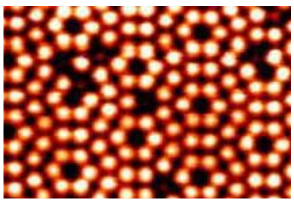


特点：

1. 实空间成像
2. 原子分辨（面内: 0.2nm, 垂直：0.01nm）
3. 工作环境： 超高真空、大气、溶液
4. 非周期结构

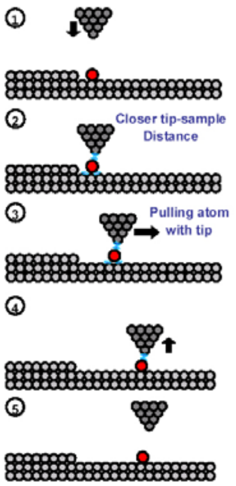
Au(100)



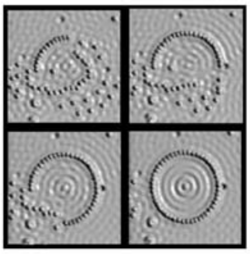


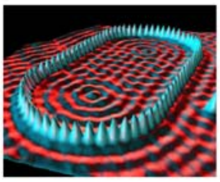
扫描电子显微镜的基本功能（2）：单原子操纵

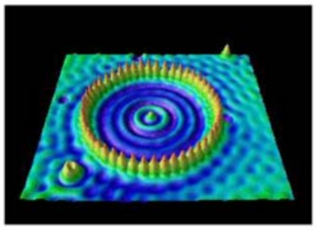
开辟了“自下而上”的制造技术



Nanomanipulation and electron density waves by STM: Quantum Corrals
(Don Eigler IBM)



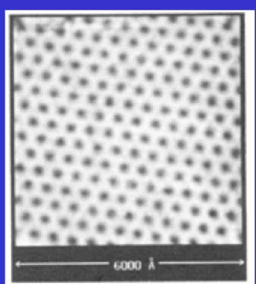




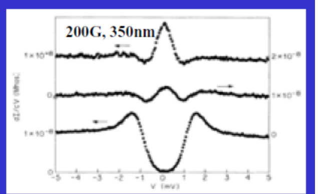
扫描电子显微镜的基本功能（3）：扫描隧道谱（STS）
揭示表面电子态及其分布、超导能隙、**Kondo**效应、分子轨道。。。。

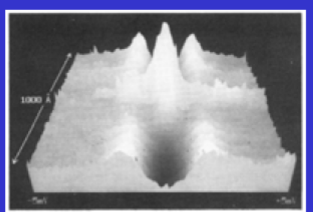
超导Vortex state成像

$2H-NbSe_2$ at T = 1.8K and 1 Tesla, dI/dV at 1.3mV



T_c=7.2K, Δ=1meV, $\xi_{\|}$=8nm, $\kappa_{\|}$=30

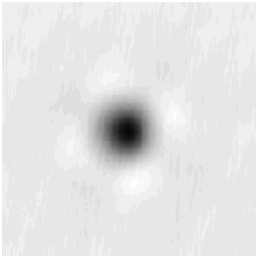




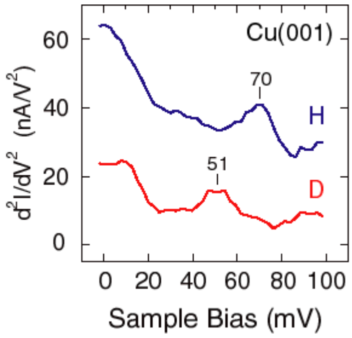
Ref.: H. F. Hess et.al., Phys. Rev. Lett. 62, 214–216 (1989)

扫描电子显微镜的基本功能（**4**）：非弹性隧道谱（**IETS**）
（对应原子/分子的特征振动）

Single H Atom



15 x 15 Å^2



By Wilson Ho et al.

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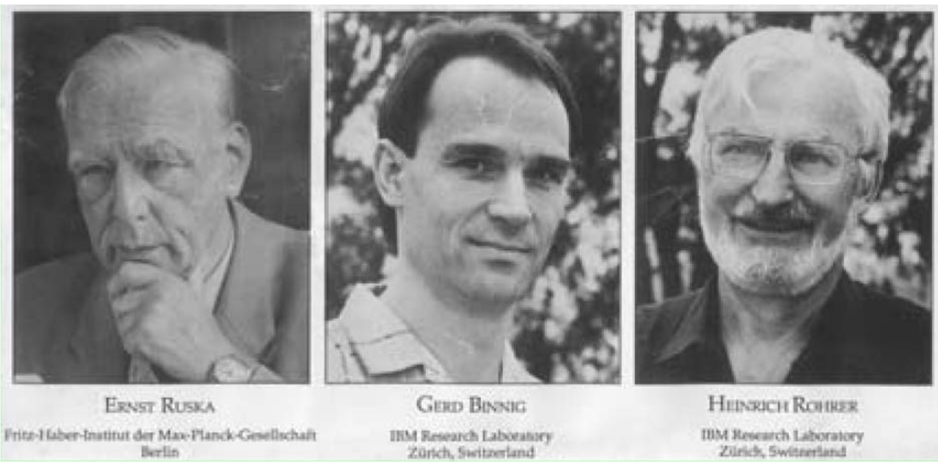
诺贝尔物理学奖—**1986**
透射电子显微镜与扫描隧道显微镜的发明
Atomic resolution images of surfaces



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STM 发展大事记

1982: Binnig, Rohrer 和Gerber发明扫描隧道显微镜
1983: 利用STM获得第一个表面, Si(111)-7x7的原子分辨图.
1984: Tersoff and Hamann发展了基本的STM理论.
1984: 近场光学显微镜发明 (D. W. Pohl)
1985: 原子力显微镜发明(Bining, Gerber, Quate)
1986: Binnig & Rohrer 获得诺贝尔物理奖
1987: 非接触式AFM出现，并获得首个原子分辨像

1989: D. Eigler利用STM实现单原子操控
1993: Y.Hasegawa 和D. Eigler利用STM/STS观察金属表面驻波
1998: 利用傅立叶变换STM技术实现对二维电子态的观察
1999: Wilson Ho利用非弹性隧道谱实现对分子振动的观察
2009: 低温STM发展到10mK低温，15T强磁场(美国NIST)

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Family of local probes

Binnig & Rohrer, Rev. Modern Phys. 71, S324 (1999)

Scanning Near-field Optical Microscopy (近场光学显微镜)
Photo Scanning Tunneling Microscopy Microscopy
Scanning Force Microscopy (SPM)
Atomic Force Microscopy (AFM) （原子力显微镜）
Magnetic Force Microscopy (MFM) （磁力显微镜）
Electrostatic Force Microscopy (EFM) （静电力显微镜）
Lateral Fiction Force Microscopy (LFM) （摩擦力显微镜）
Scanning Thermal Microscopy (STHM) (热电势显微镜)
Ballistic Electron Emission Microscopy (BEEM)
(弹道电子发射显微镜)

Instruments with Atomic Resolution
(达到原子分辨的三种科学仪器)

Transmission Electron Microscope (TEM)
透射电子显微镜**(Ruska, 1931)**

Field Ion Microscope (FIM)
场离子显微镜**(Muller, 1955)**

Scanning Tunneling Microscope (STM)
扫描隧道显微镜**(Binnig & Rohrer, 1981)**

思考：TEM和FIM出现的历史都远远早于STM，但其主要应用都在材料科学领域。而STM的出现直接导致了纳米科学的兴起，其影响力深入到基础物理学、纳米材料科学、生物学等多种学科，其深度和广度仍在不断发展。STM究竟有哪些特质使其有别于同样具有原子分辨的TEM和FIM?

Three levels in our knowledge of condensed matter

IR, Raman — **Excitation spectrum** (optical property, plasmonic property…) — **IETS**

ARPES — **Electronic structure** (Conductivity, chemical property, reactivity Magnetism..) — **STS**

TEM, XRD, LEED — **Atomic structure** (Crystal structure, mechanical properties Hardness…) — **STM**

STM can do everything, locally, with atomic resolution

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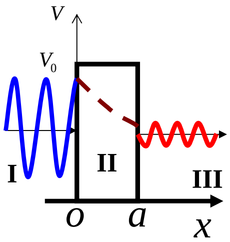
附录a)：一维势垒散射问题

a.1 方势垒的穿透（隧道效应）

$$V(x)=0, \qquad x<0, x>a$$
$$V(x)=V_0, \qquad 0\le x\le a$$



按经典力学观点，当一个粒子能量**E**＜**V$_0$**时，此粒子是不能越过此势垒的。 **E>V$_0$**时，此粒子全部越过势垒，不会部分被反射的。

按量子力学观点，无论一个粒子能量**E**＜**V$_0$**或**E**＞**V$_0$**时，此粒子都将有一定几率越过此势垒，也将有一定几率被反射回去。

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附录a)：一维势垒散射问题

I 区的解： $\varphi_1(x)=\mathrm{R}'\mathrm{e}^{ikx}+\mathrm{R}\mathrm{e}^{-ikx}, \qquad x\le 0$

III 区的解： $\varphi_3(x)=Se^{ikx}+S'e^{-ikx}, \qquad x\ge a$

考虑粒子是从 **I** 区入射，在 **I** 区中有入射波、反射波；在**III**区只有透射波。故得：

$$\varphi_1(x)=e^{ikx}+\mathrm{R}e^{-ikx}, \qquad x\le 0$$
$$\varphi_3(x)=Se^{ikx}, \qquad x\ge a$$

其中， $e^{ikx}, \mathrm{R}e^{-ikx}, Se^{ikx}$

分别代表入射波，反射波与透射波。

反射系数＝

$$j_r / j_i = |R|^2$$

透射系数**T**＝

$$j_t / j_i = |S|^2$$

附录a)：一维势垒散射问题

II区定态薛定谔方程为：

$$-\frac{\hbar^2}{2m}\frac{d^2\varphi_2(x)}{dx^2}+V_0\varphi_2(x)=E\varphi_2(x),\qquad 0\le x\le a$$

$$\frac{d^2\varphi_2(x)}{dx^2}-k_2^2\varphi_2(x)=0,\qquad (0\le x\le a)$$

$$k_2=\sqrt{\frac{2m(V_0-E)}{\hbar^2}}$$

得， $\varphi_2 = Ae^{k_2x}+Be^{-k_2x}, (0\le x\le a)$

与 $\varphi_1(x)=e^{ikx}+\mathrm{R}e^{-ikx},\qquad (x\le 0)$

$\varphi_3(x)=Se^{ikx},\qquad (x\ge a)$，一起，

在$x=0$，a处波函数与一阶导数要 连续：

附录a)：一维势垒散射问题

根据连续条件，可求得4个系数R，S，A，B：

$$\varphi_1(0)=\varphi_2(0)\qquad \frac{d\varphi_1(x)}{dx}\Big|_{x=0}=\frac{d\varphi_2(x)}{dx}\Big|_{x=0}$$

$$\varphi_2(a)=\varphi_3(a)\qquad \frac{d\varphi_2(x)}{dx}\Big|_{x=a}=\frac{d\varphi_3(x)}{dx}\Big|_{x=a}$$

解之得，（**11**）、（**12**）式。

（**11**）式：$A=\frac{1}{2}\left[(1+\frac{ik}{k_2})+R(1-\frac{ik}{k_2})\right]\qquad B=\frac{1}{2}\left[(1-\frac{ik}{k_2})+R(1+\frac{ik}{k_2})\right]$

（**12**）式：$A=\frac{S}{2}\left[1+\frac{ik}{k_2}\right]e^{ika-k_2a}\qquad B=\frac{S}{2}\left[1-\frac{ik}{k_2}\right]e^{ika+k_2a}$

附录a)：一维势垒散射问题

由（11）与（12），消去A、B，得（13）

（13）式：

$$(1+\frac{ik}{k_2})+R(1-\frac{ik}{k_2})=S(1+\frac{ik}{k_2})e^{ika-k_2a}$$

$$(1-\frac{ik}{k_2})+R(1+\frac{ik}{k_2})=S(1-\frac{ik}{k_2})e^{ika+k_2a}$$

由（13）式，消去R，得S，（15）式：

（15）式：

$$Se^{ika}=\frac{-2ik/k_2}{[1-(k/k_2)^2]shk_2a-2i\frac{k}{k_2}chk_2a}$$

附录a)：一维势垒散射问题

由（15）式得透射系数T：

$$T=\left[1+\frac{1}{\frac{E}{V_0}(1-\frac{E}{V_0})}sh^2k_2a\right]^{-1},\ (16)$$

由（13）式消去S，得R，得反射系数：

$$|R|^2=\frac{(k^2+k_2^2)^2sh^2k_2a}{(k^2+k_2^2)^2sh^2k_2a+4k^2k_2^2},(17)$$

$$|R|^2+|S|^2=1$$

由（12）式与S，

得A、B，从而得波函数：Φ$_1$、Φ$_2$、Φ$_3$。

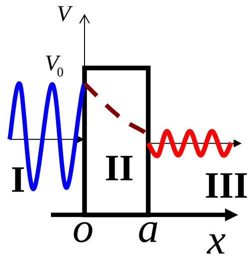
附录a)：一维势垒散射问题

由（15）式得透射系数T：$T=\left[1+\dfrac{1}{\dfrac{E}{V_0}(1-\dfrac{E}{V_0})}sh^2k_2a\right]^{-1}$，(16)

估算. 设 $\kappa a\gg1$，此时 $\mathrm{sh}\kappa a\approx\frac{1}{2}e^{\kappa a}\gg1$

$$T\approx\frac{16k^2\kappa^2}{(k^2+\kappa^2)^2}e^{-2\kappa a}$$

$$=\frac{16E(V_0-E)}{V_0}\exp\left[-\frac{2a}{\hbar}\sqrt{2m(V_0-E)}\right]$$



附录a)：一维势垒散射问题

对任意形状的势垒(见图)，势垒贯穿几率公式推广为：

$$D=D_0e^{-\frac{2}{\hbar}\int_a^b\sqrt{2m[U(x)-E]}dx}$$

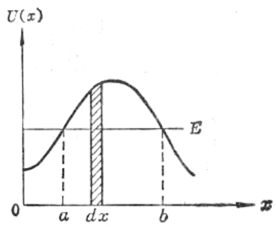
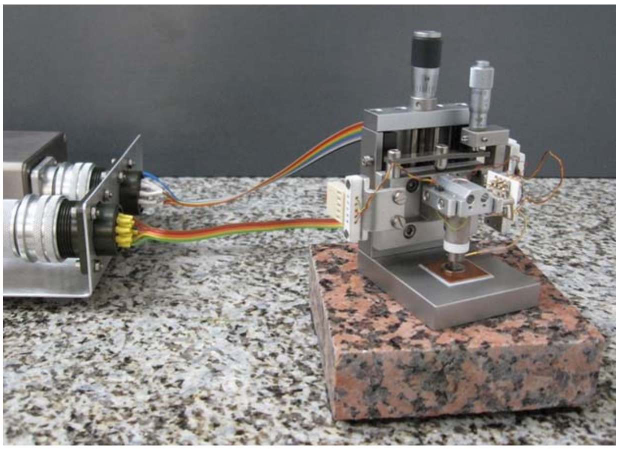


图 17　任意形状的势垒

§1.2 STM的技术实现

一个简单的大气下**STM**装置



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大气下的STM系统

某德国业余爱好者自制STM系统

STM
a project by Jürgen Müller

What's new?
Overview
Mechanics
Electronics
Software
Applications
References
Budget
Questions

Mechanics

The mechanical components of an STM should do three things: Bring the tip into tunneling distance from the sample (coarse approach), keep it there in a stable position (undisturbed by vibrations and thermal drifts), and scan it across the sample with sub-nanometer resolution. This page tries to address all relevant topics, beginning at the center of the STM: Piezo element for scanning motion, approach mechanisms and materials for the scanning head, and vibration isolation systems. In most sub-sections, I'll try to give a brief overview of design options described in the literature, followed by some details of my own implementation.

click on picture to enlarge

Piezos

Piezo elements are apparently used universally to produce the small motions (on the nanometer scale) of the tip in scanning probe microscopy. Piezoelectric materials - most notably some types of ceramics that have been polarized by letting them cool down in the presence of an electric field - exhibit a mechanical deformation when a voltage is applied across them. The exact amount of deformation depends on the material and its geometry (some more details will follow below); typically, excursions of a few nanometer/Volt may be obtained from handy piezo elements, say 1 inch in length.

Once you know what you want, the piezo scanner may well be the easiest part of the whole STM project: I just bought a piezo tube, complete with the desired electrode configuration, via mail-order; it wasn't even expensive.

Piezo scanner geometries

In all designs I have seen, piezos are used both for the X/Y scanning motion and for the Z height tracking. There are, however, a number of different geometries commonly used:

- Tripod – the original STM by Binnig and Rohrer, and its early successors, used tripods assembled from three pieces of piezo-electric material, with their polarization (i.e. stretching) axes oriented in three orthogonal directions. Since only the un-amplified stretching motion of the piezos is used, they need to be rather long and thin, making the assembly not as rigid as is desirable.
- Tube – a very elegant design, also proposed by Binnig and Smith a few years later (Rev. Sci. Instrum. 57 (8), p. 1688, 1986). A single piezo tube is used, with one electrode on the inside, and for electrode stripes running the length of the tube on the outside. When a voltage is applied between inner electrode and one outer electrode, the material between the electrodes stretches/contracts in the tube's longitudinal direction. By applying the same voltage to all four outer electrodes, the whole tube can be stretched, for Z tracking. But the tube can also be bent, by applying some voltage to one outer segment only (and optionally the opposite voltage to the opposing electrode segment, for symmetrical deformation). If the tube is mounted on one end, bending will move the other end sideways for the X/Y scanning motion. By far the most common scanner design today: tubes in the described electrode configuration are readily available. Since

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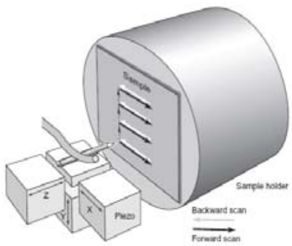
大气下的STM系统

瑞士Nanosurf公司的STM系统

easyScan 2 STM system

Placing the sample holder in the scan head

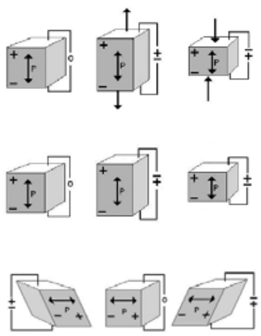


大气下的STM系统

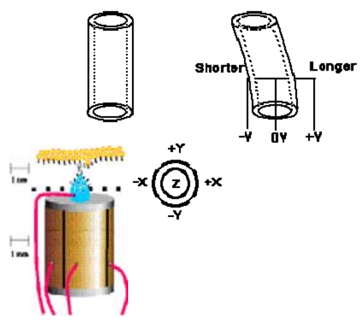
某国内公司生产的大气SPM系统

STM的关键零件：压电陶瓷

压电陶瓷片



压电陶瓷管



压电陶瓷片的形变方向与其极化方向有关

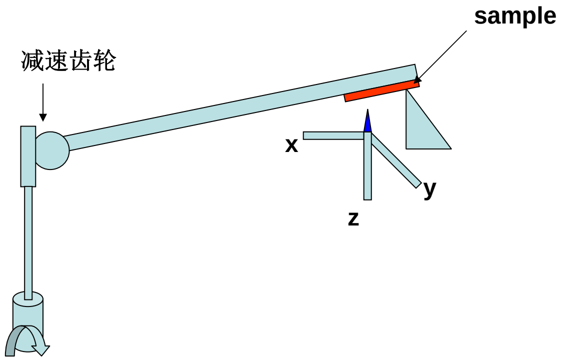
当压电陶瓷管的内壁与外壁之间存在电压差时，管会发生轴向伸缩，并产生径向长度的变化（Z向）。四分电极的压电陶瓷管还可以产生XYZ三维运动。

STM的核心-coarse approaching mechanics

STM的核心并不是扫描机构，而是逼近机构

----如何将针尖安全地从厘米逼近到纳米的距离？

方法**1**：机械式：
Sakurai type STM head

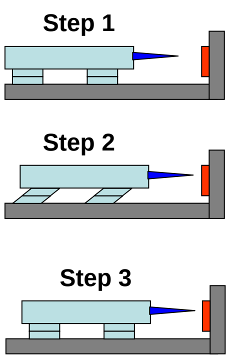


STM的核心-coarse approaching mechanics

STM的核心并不是扫描机构，而是逼近机构
----如何将针尖安全地从厘米逼近到纳米的距离？

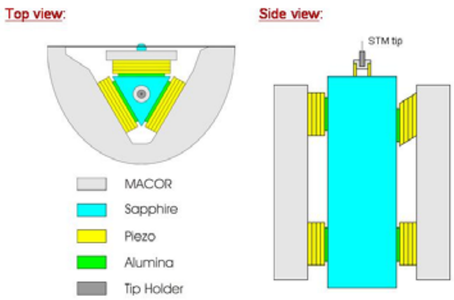
方法**2**：**Inchworm**

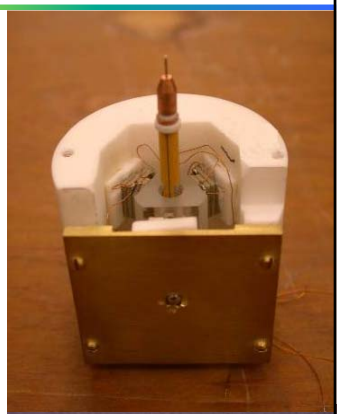
Inchworm

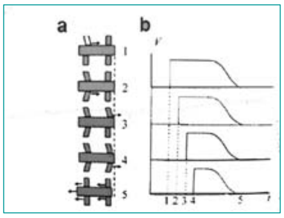


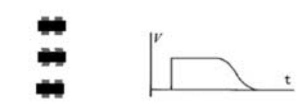
Nanosurf 公司

方法3： Pan –type STM scanner









图十四 粗逼近原理示意图　　图十五 电压信号（图中只画出了一个周期）

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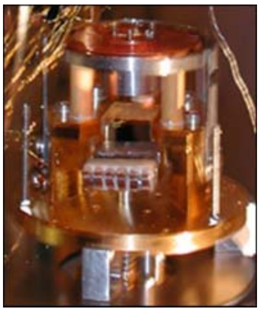
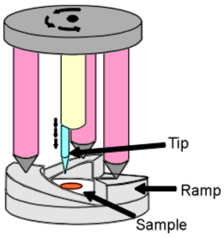
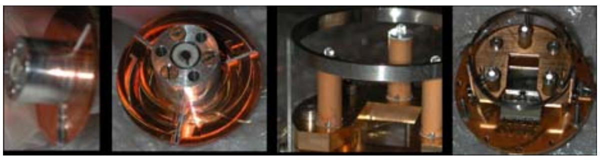
方法4： "Besocke-Beetle" type scanner







reaTec's LTSTM uses a variation of the Besocke Beetle STM scanner. Due to its rigidity and compactness, the Besocke Beetle has low mechanical noise and little drift. CreaTec's Beetle consists of a plate called the ramp that on its bottom side has three equal-angled ramps. Three tubular piezoelectric transducers have a sapphire ball on its top end and on these balls rests the ramp. In the center of the ramp is a metal cylindrical tube that holds another tubular piezoelectric transducer. The sample is brought underneath the middle of the ramp and the STM tip is mounted to the inner piezoelectric tube by a magnet.

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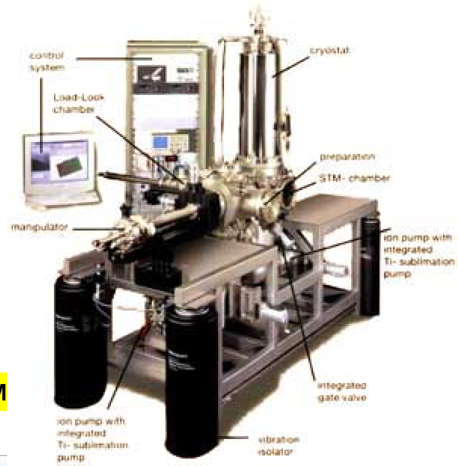
低温STM

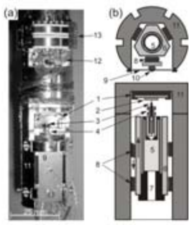
- 超高真空&样品传递
- 样品处理制备装置
- 低温冷却系统
- 机械减震系统
- STM探头
- STM控制电子学系统

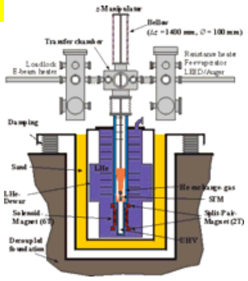
besocke type STM

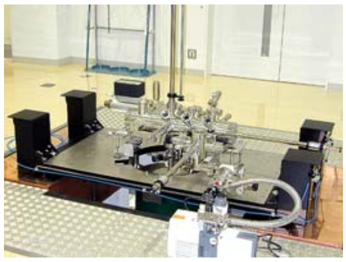


德国Createc公司产品

Pan（潘）式低温STM







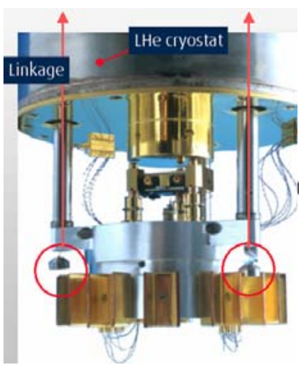
日本Unisoku公司低温STM

德国Omicron 公司低温STM

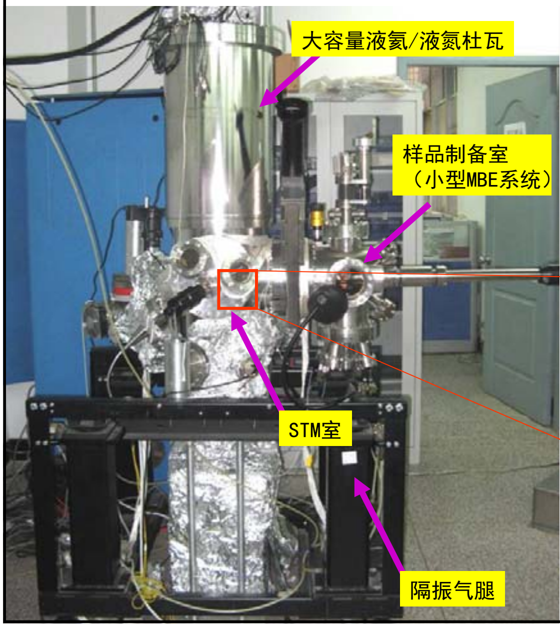
介于 Inchworm和Pan-type STM之间的外购模块

Omicron 低温 STM

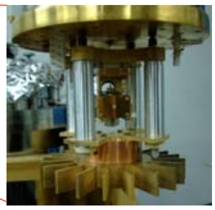
• XYZ位移台为外购模块



SF09组自制低温（4K）扫描隧道显微镜系统



Pan type
With optical accessibility

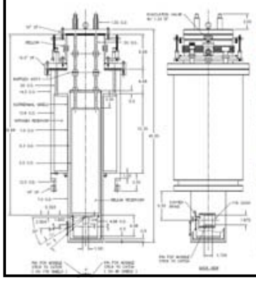


已与国内匡泰公司合作，**2011**年推出产品

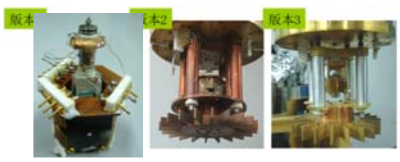
Our home-made LTSTM (4K)

Parameters	Our home-made system (4K)
LHe dewar hold time	〉70 h
Electronic noise	0.1 pA
Vibrational noise	< 0.1pm （3rd floor, without airleg ）
Thermal drift	no drift in continuous scanning for > 8 h

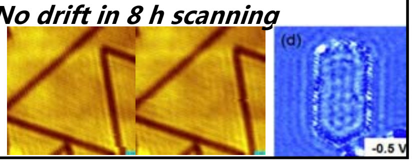
Home-designed LHe dewar

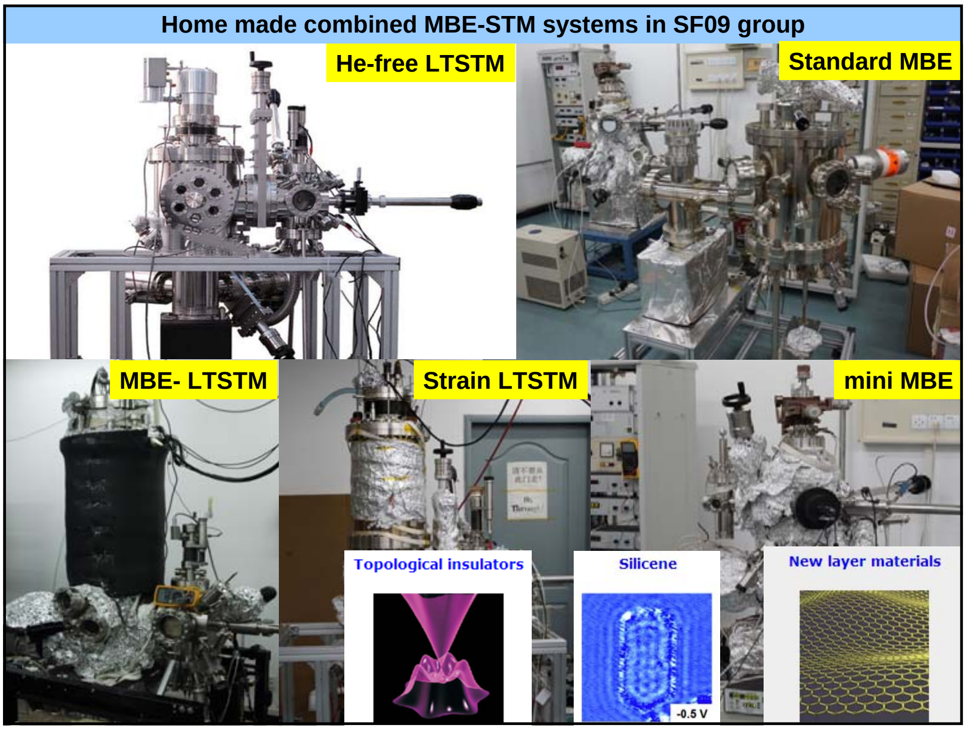


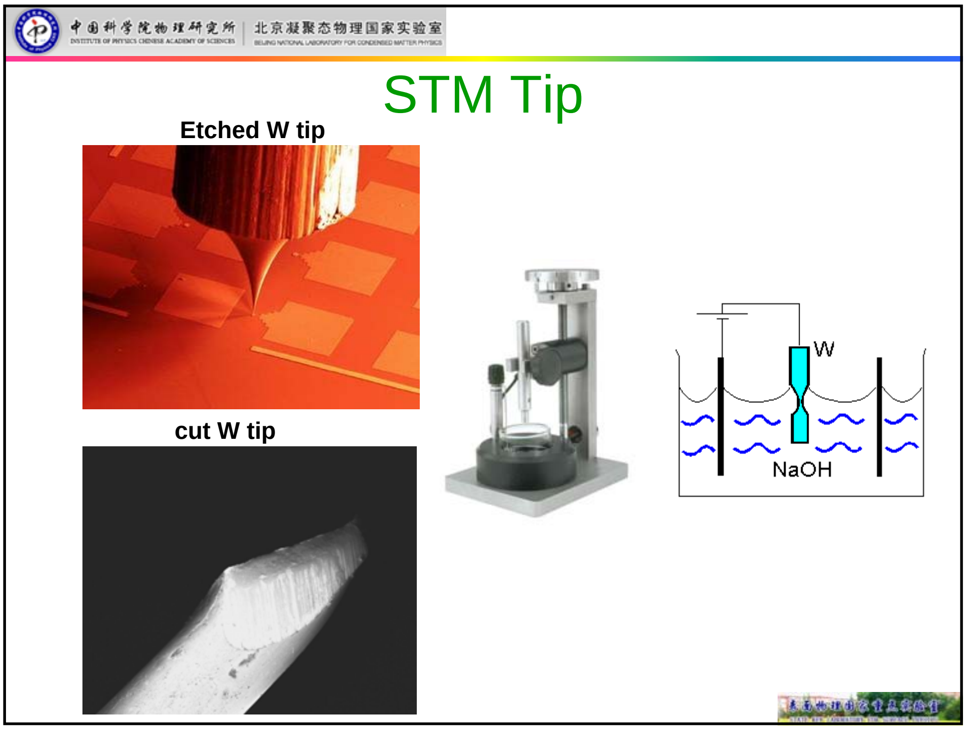
Hand-made STM heads



No drift in 8 h scanning




Home made combined MBE-STM systems in SF09 group
He-free LTSTM
Standard MBE
MBE- LTSTM
Strain LTSTM
mini MBE
Topological insulators
Silicene
-0.5 V
New layer materials


中国科学院物理研究所
北京凝聚态物理国家实验室
STM Tip
Etched W tip
cut W tip
W
NaOH

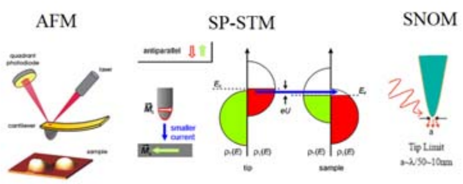
§ 1.2 基于STM的技术发展方向

基于STM的新技术的发展思路

STM包含探针和样品一体两面，同样重要

探测

针尖特性改变



- AFM/nc-AFM
- SP-STM/ ECR-SPSTM
- Scanning Microwave Impedance Microscopy (sMIM)
- STM中的光学集成

调控

样品外场调控

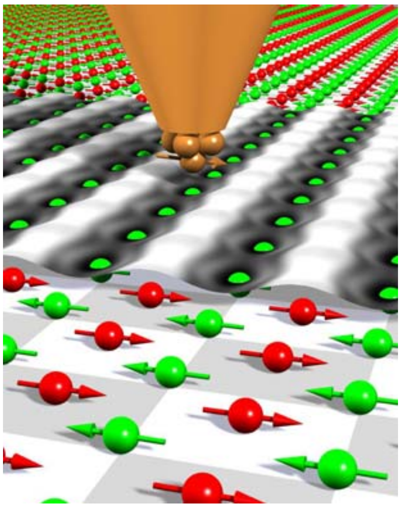
温度　低温/高温/变温STM

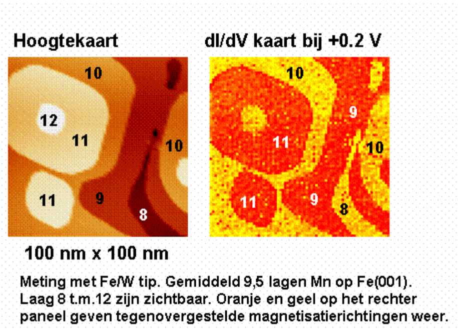
磁场　强磁场STM

应力　应力调控STM

- 低温STM
- 强磁场STM
- 应力调控STM

自旋极化STM

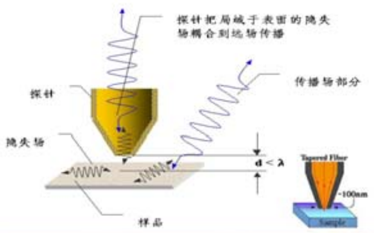




Measurement with a iron covered tip

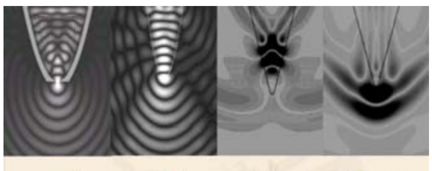
By Herman van Kempen.

扫描近场光学显微镜（SNOM）

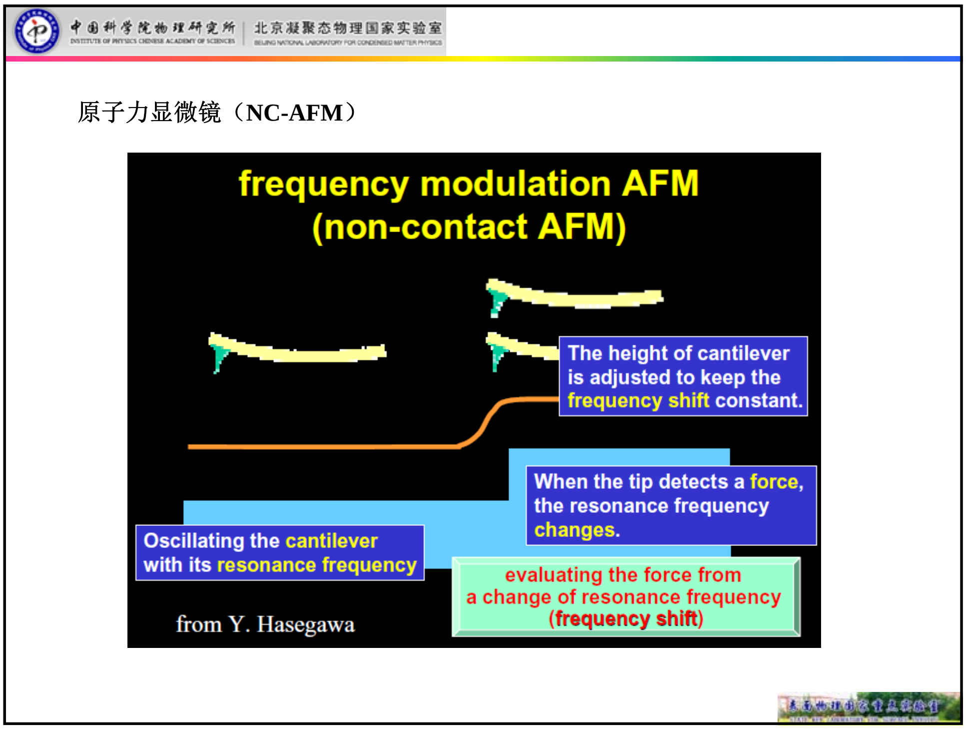


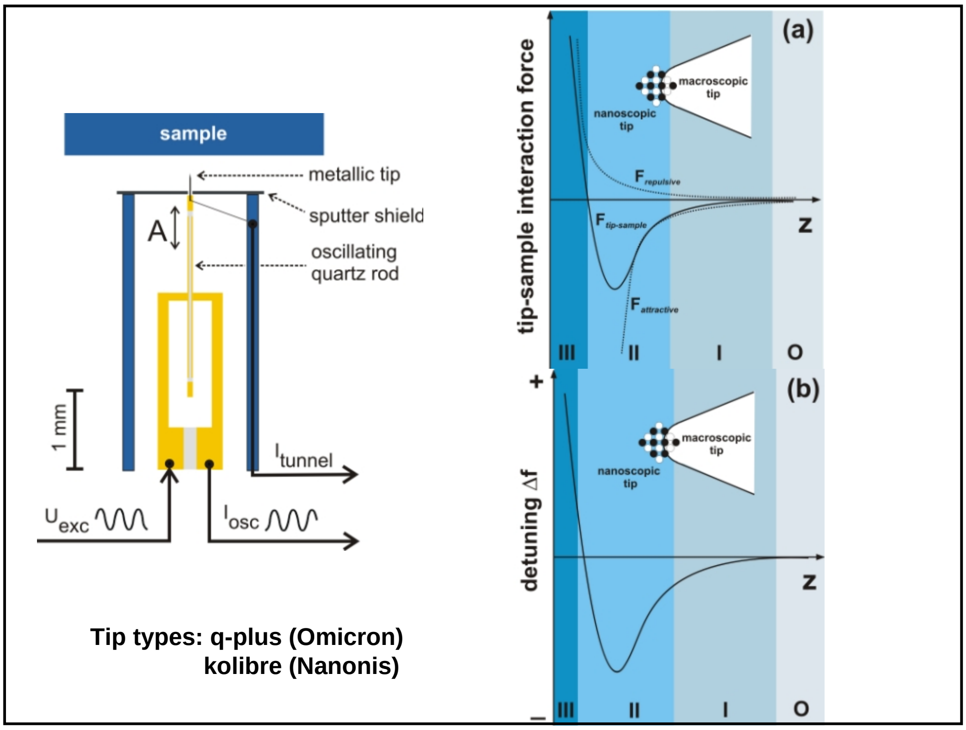
近场光学显微探针示意图

1991年Betzig AT&T Bell Lab
镀上金属铝的光纤针尖得到
λ/20的光学分辨率, 突破了
光学显微镜的衍射极限

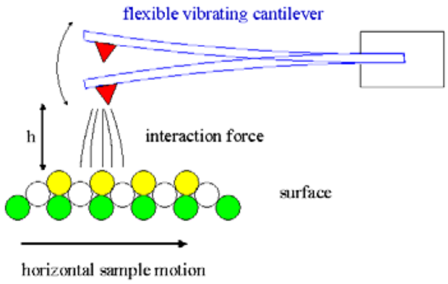


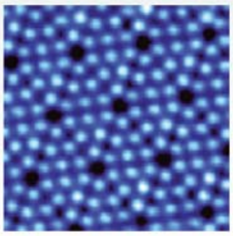
Instantaneous electromagnetic wave propagation of fiber Probes with coated(a), defective(b), femtosecond pulse (c) and (d)


中国科学院物理研究所
北京凝聚态物理国家实验室
原子力显微镜（NC-AFM）
frequency modulation AFM
(non-contact AFM)
The height of cantilever is adjusted to keep the frequency shift constant.
When the tip detects a force, the resonance frequency changes.
Oscillating the cantilever with its resonance frequency
evaluating the force from a change of resonance frequency (frequency shift)
from Y. Hasegawa

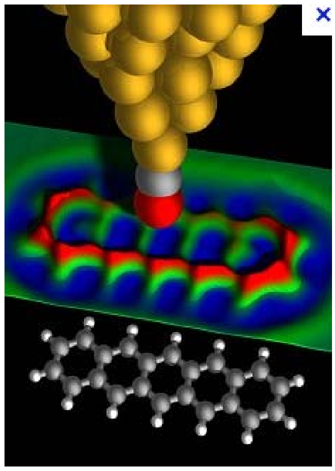

sample
metallic tip
sputter shield
A
oscillating quartz rod
1 mm
I_{tunnel}
U_{exc}
I_{osc}
Tip types: q-plus (Omicron)
kolibre (Nanonis)
(a)
tip-sample interaction force
macroscopic tip
nanoscopic tip
$F_{repulsive}$
$F_{tip-sample}$
$F_{attractive}$
z
III II I O
(b)
detuning Δf
+
–
macroscopic tip
nanoscopic tip
z
III II I O

非接触式原子力显微镜（nc-AFM）





nc-AFM image of Si7x7 at low temperature
T = 2.4 K; A = 69 pm;
Q = 80000; Δf = -1.3 Hz
Courtesy of Toshu An, group of Prof. Hasegawa, The University of Tokyo



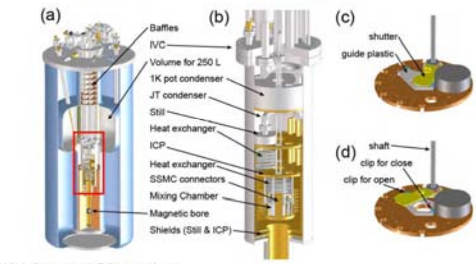
低温强磁场STM

- Tunneling resolution ≈3kT
  - 300K, ΔE= 85 meV
  - 4K, ΔE= 1 meV
  - 10 mK, ΔE= 10 μeV
- Figure of merit for high resolution

$$\mu_B B / k_B T$$

- NIST, 10 mK at 15 T

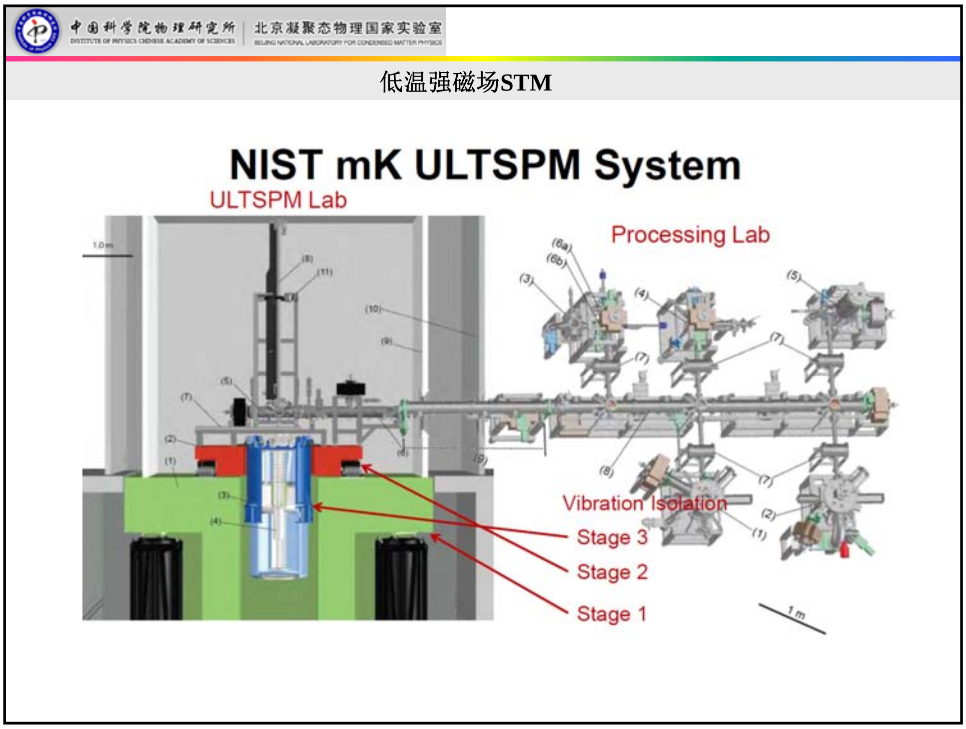
NIST mK ULTSPM System

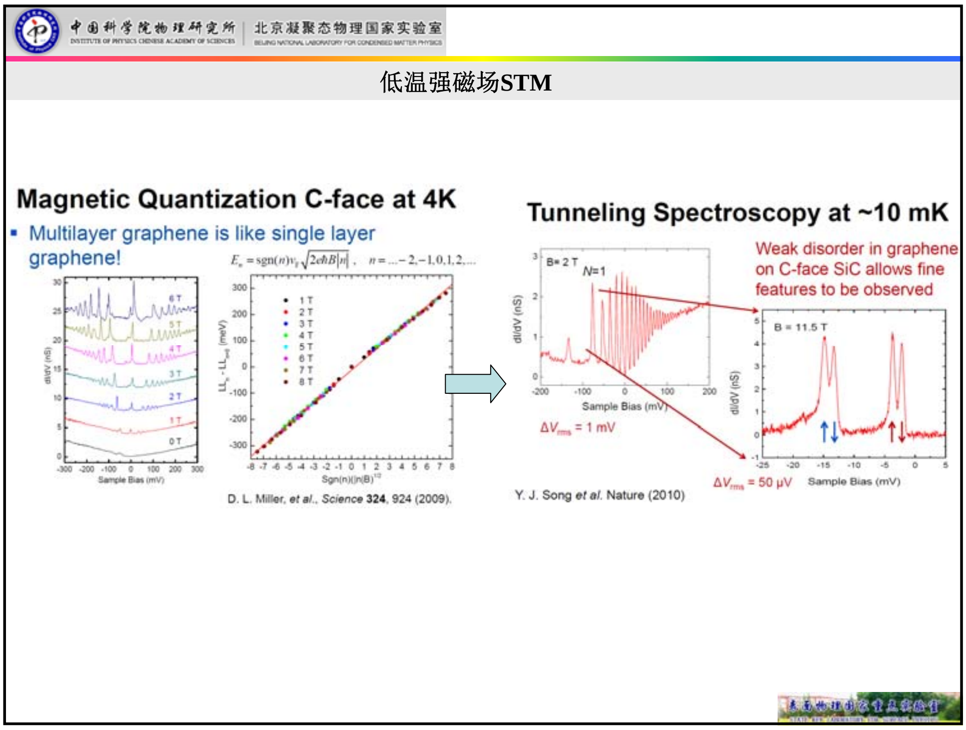


Y. J. Song *et al.* RSI submitted

Brief History of Cryogenic SPMs

1981 invention of STM – Binnig and Rohrer
1985 low temperature STM – de Lozzane et al.
1990s 4 K STMs, Eigler, Hug, Wiesendager…
2000s sub-K STMs, Heinrich, Wiebe…
Challenges in combining coarse movement, UHV, cryogenics, vibration isolation
Sub-K STMs more challenging since “fridges” can be noisy and vibration isolation can be difficult


中国科学院物理研究所 | 北京凝聚态物理国家实验室
INSTITUTE OF PHYSICS CHINESE ACADEMY OF SCIENCES
低温强磁场STM
NIST mK ULTSPM System
ULTSPM Lab
Processing Lab
Vibration Isolation
Stage 3
Stage 2
Stage 1
1 m


中国科学院物理研究所 | 北京凝聚态物理国家实验室
INSTITUTE OF PHYSICS CHINESE ACADEMY OF SCIENCES
低温强磁场STM
Magnetic Quantization C-face at 4K
▪ Multilayer graphene is like single layer graphene!
$E_n = \mathrm{sgn}(n) v_F \sqrt{2e\hbar B|n|}$, $n = \ldots -2, -1, 0, 1, 2, \ldots$
Sample Bias (mV)
Sgn(n)(|n|B)^1/2
D. L. Miller, et al., Science 324, 924 (2009).
Tunneling Spectroscopy at ~10 mK
Weak disorder in graphene on C-face SiC allows fine features to be observed
B= 2 T
N=1
Sample Bias (mV)
ΔV_rms = 1 mV
B = 11.5 T
ΔV_rms = 50 μV
Sample Bias (mV)
Y. J. Song et al. Nature (2010)

光耦合STM

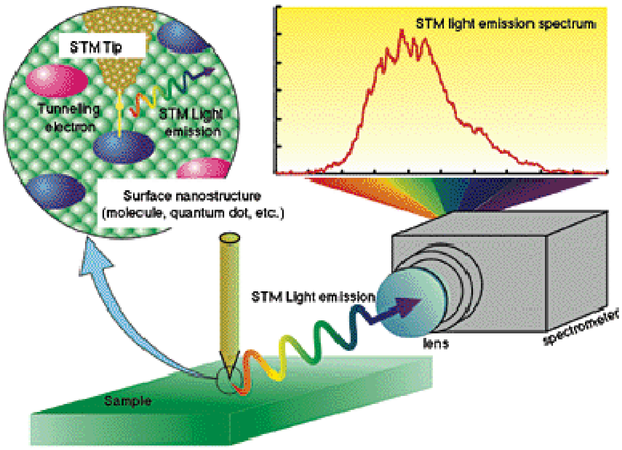
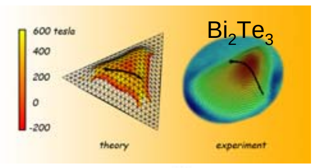
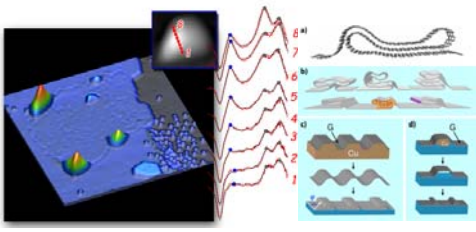


Figure 1. Experimental concept of STM light emission.

应力调制STM

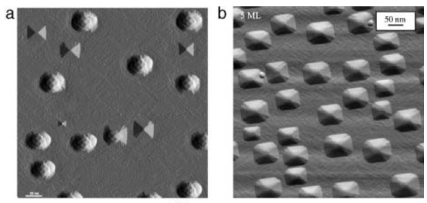
石墨烯巨大赝磁场



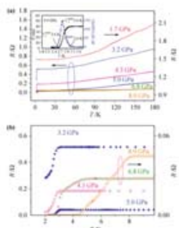


M. Crommie et al. Science 2010

Ge/Si量子点的生长



拓扑绝缘体 → 超导体

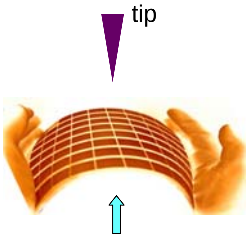


J. L. Zhang et al. Front. Phys. **7**, 193(2012)

应力调制STM

低温STM/STS

tip



对样品原位施加应力

拉伸/压缩
弯折/剪切

原位观察应力作用下的物理效应

- 晶格形变
- 结构相变
- 金属-绝缘体转变
- 磁相变
- 超导相变
- 量子点生长
- 催化性质
- 电子态变化
- 等效电场

为什么需要低温STM?

高分辨、高稳定性（高分辨STM）
弹性/非弹性隧道谱（电子结构研究）

总结

1. STM发展历史：和光学显微镜的比较、和其他两种原子分别仪器（TEM、FIM）的比较。

2. STM的基本概念：隧穿、扫描、基本功能及其衍生功能

3. STM的基本构造、典型探头结构、系统构造、针尖制作

4. 基于STM的技术的新发展