

Scanning Tunneling Microscopy & Spectroscopy of Correlated Electronic Systems

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Boulder Summer School on Condensed Matter Physics



Why do we need local measurements?

- Conventional wisdom in solid state physics: band theory
- Past: Understanding things in momentum space is enough!
- New wisdom?: for correlated or nanoscale systems this may not be enough

Examples:

- Randomly doped systems are not spatially homogenous
- Systems close to a transition may segregate in to different phases (ex: last conducting link in a metal-insulator transition)
- Can learn about correlated system by study of their response to defects (impurities, vortices, boundaries)
- “Fluctuating order”--search for “propensity” for organization of electrons
- Complimenting spatially average measurements is also critical

Length Scales:

- Inter-atomic distances: few Å
- Electron wavelength: depending on density; “good metals” few Å, “Unconventional metals” about 10–15 Å, semiconductors 100–200 Å
- Correlation lengths: conventional superconductors 100–1000 Å; unconventional one below 20 typically (size of a vortex or a defect state)
- “Phase separation lengths”: depends on the model from 10s of Å to 1000 Å

Plan for Lectures

Lecture I

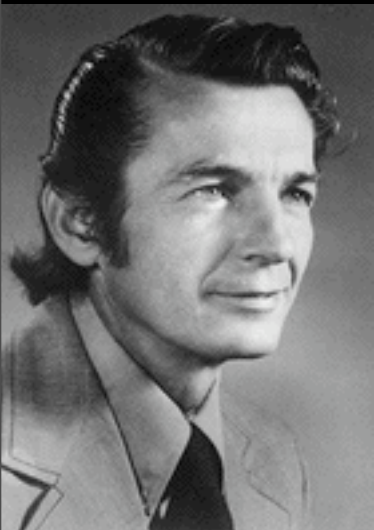
- Brief history of tunneling: tunneling through insulating barriers
- Basics of scanning tunneling microscopy
- Some comments on construction of an STM
- STM on simple metals--quantum interference of electronic states
- STM on semiconductors--imaging and probing single dopants
- STM on conventional superconductors--impurity effects in a BCS superconductor

Lecture II

- STM on high- T_c superconductors
- Local signatures of d-wave pairing
- Quasi-particle Interference
- Local Pairing above T_c and the phase diagram
- Clues on the mechanism: electron-boson or not?



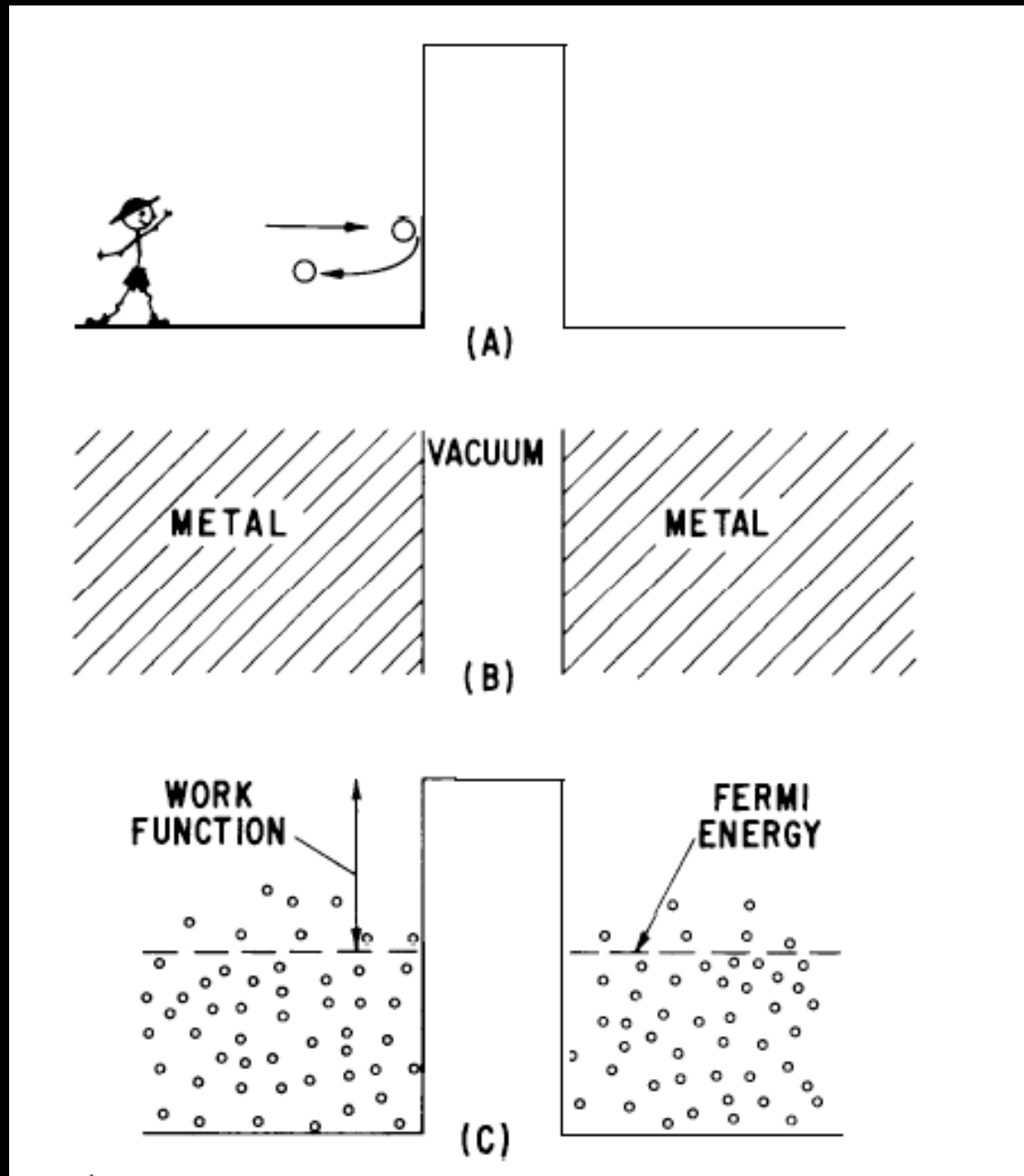
Leo Esaki



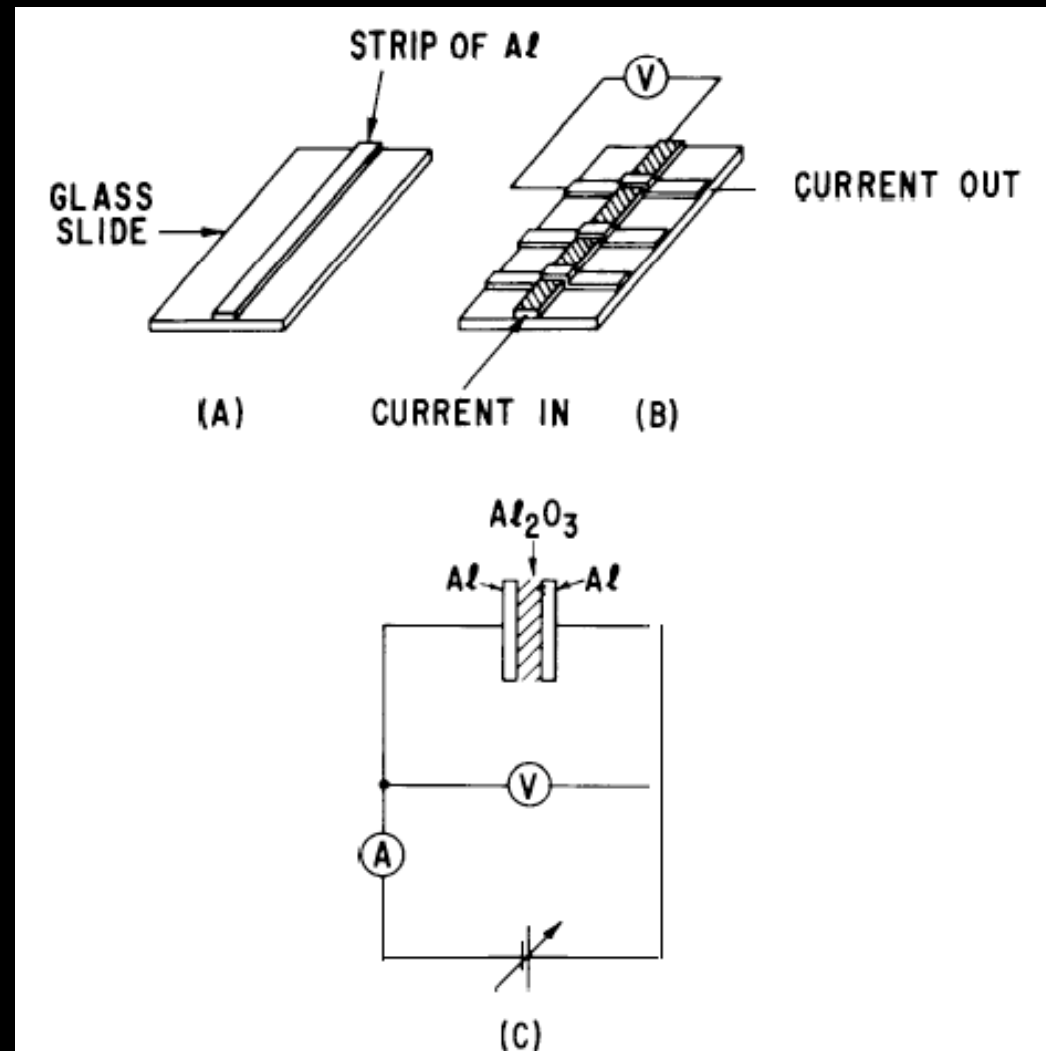
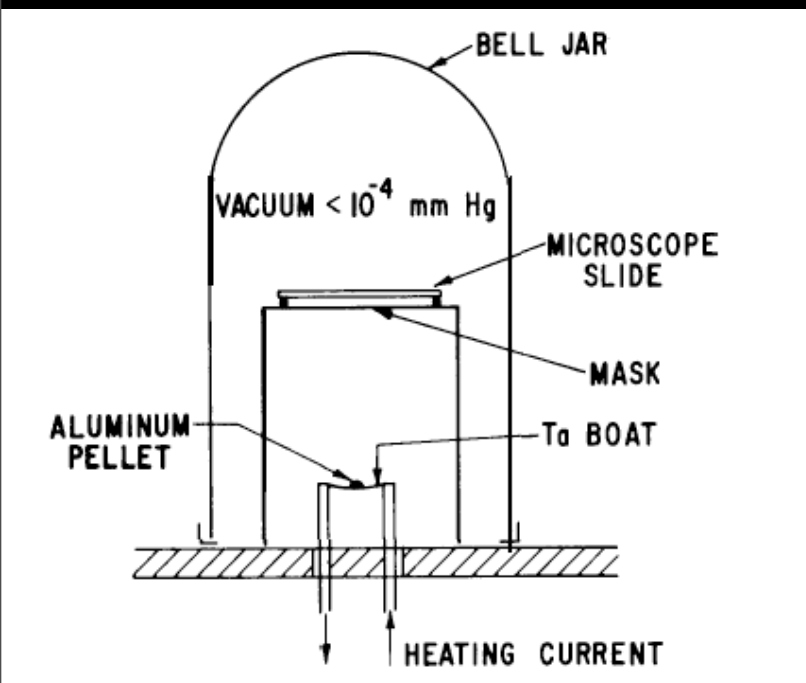
Ivar Giaever

Shared Nobel Prize in Physics
(with B. Josephson 1973)

Yazdani-Boulder 08 lectures

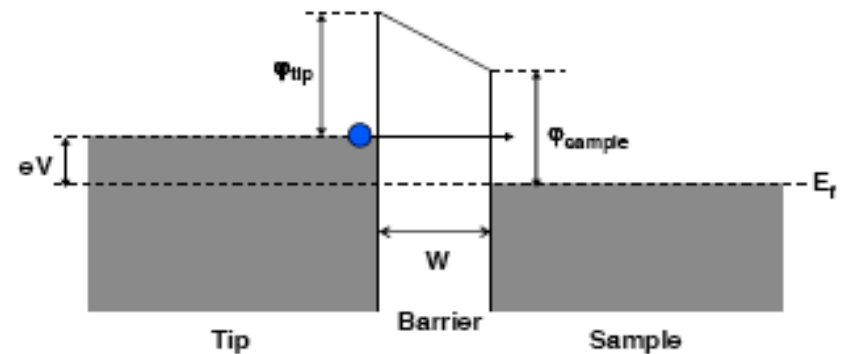
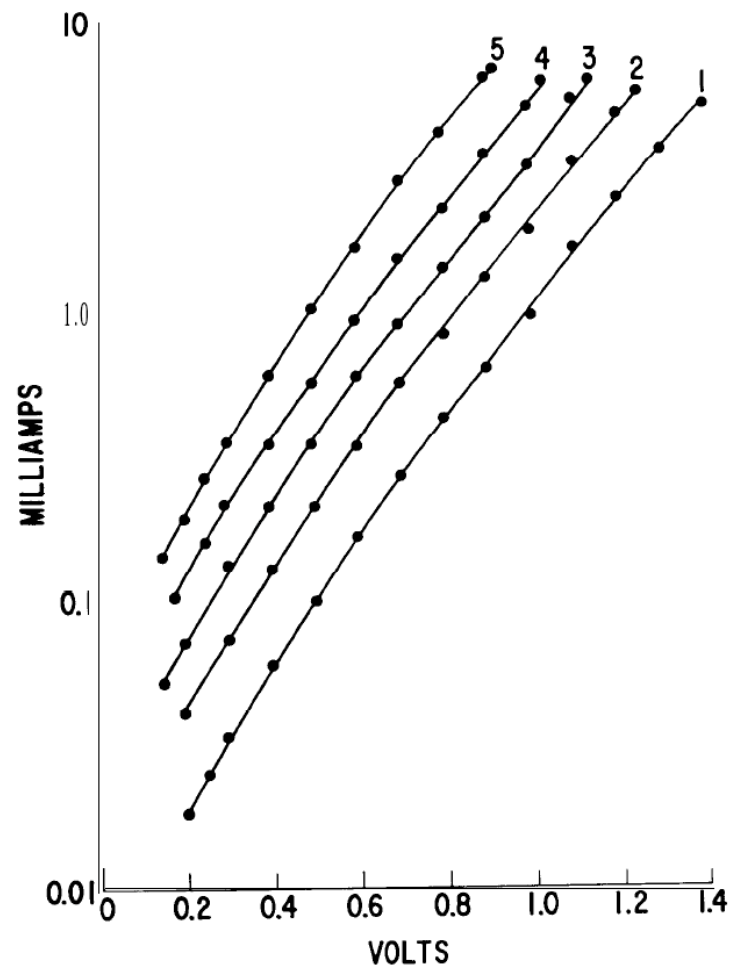


Giaever Tunneling: Aluminum-oxide the key to tunneling 1963

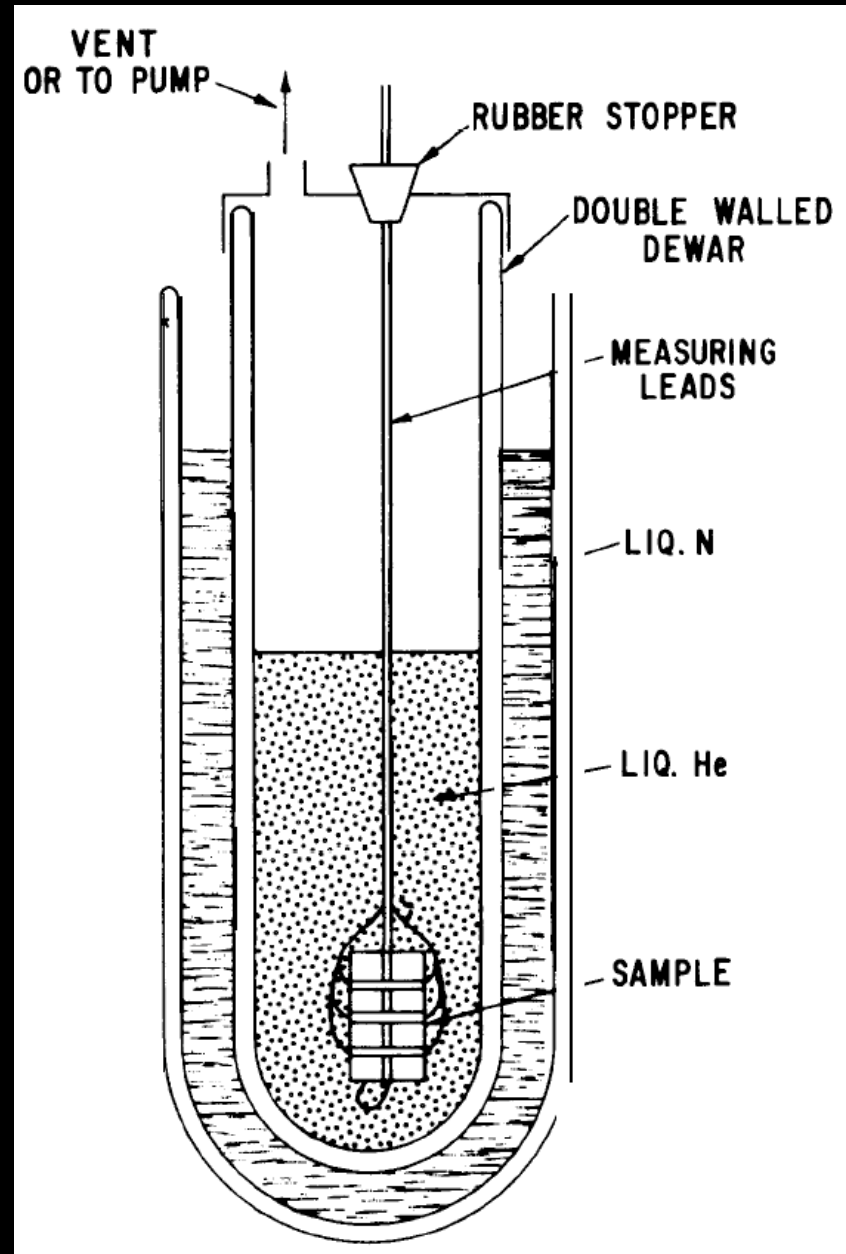
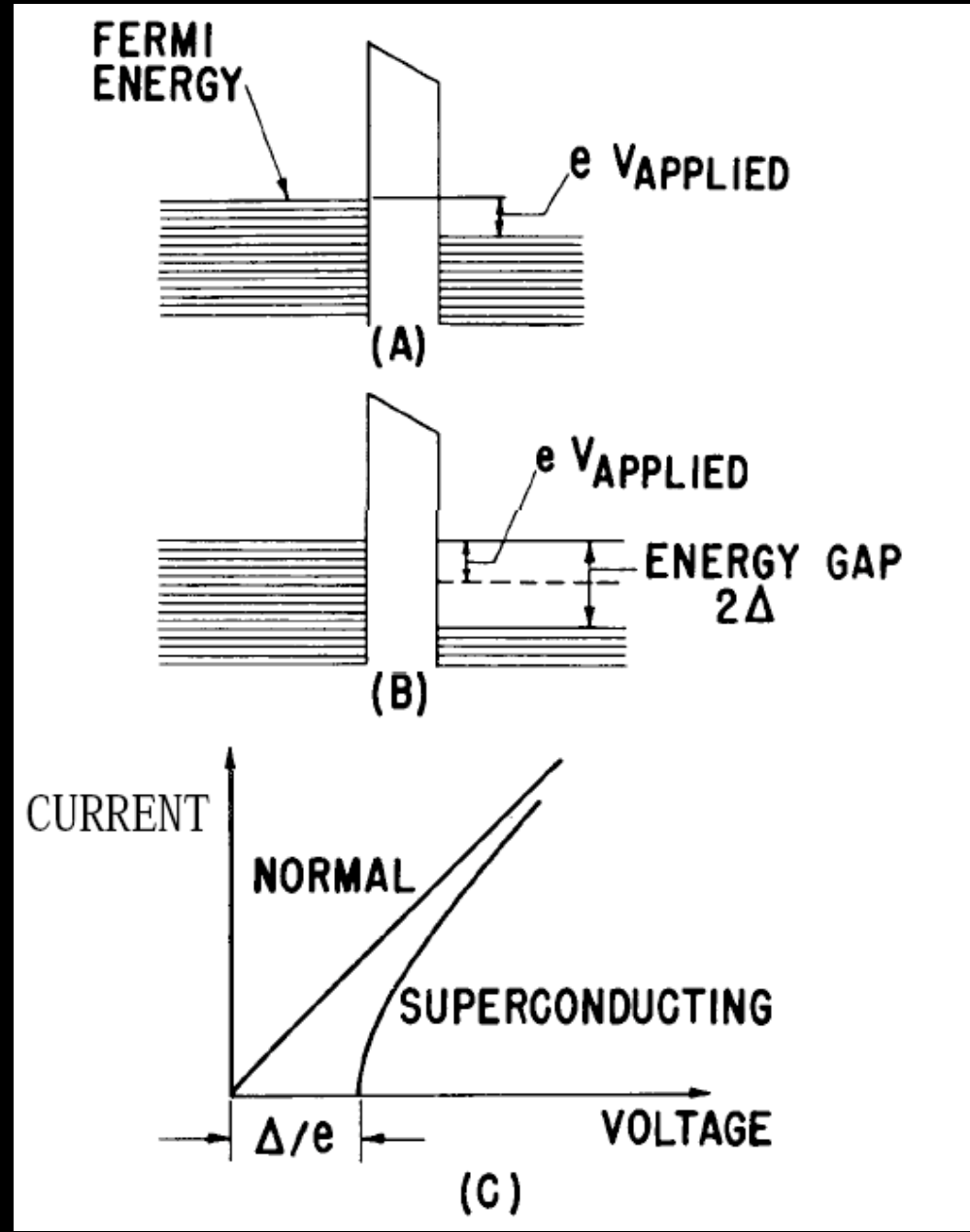


Giaever Tunneling: Aluminum-oxide the key to tunneling

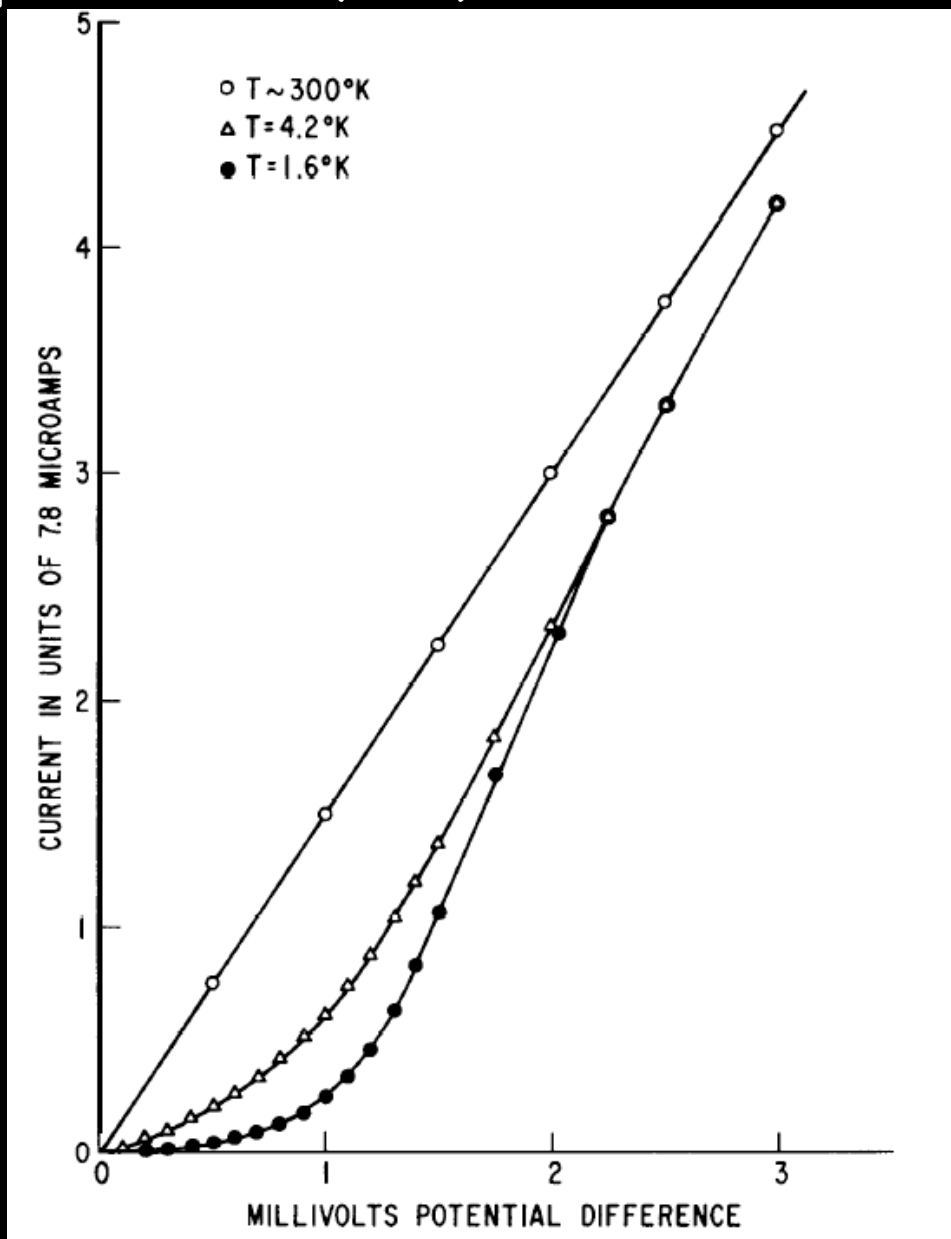
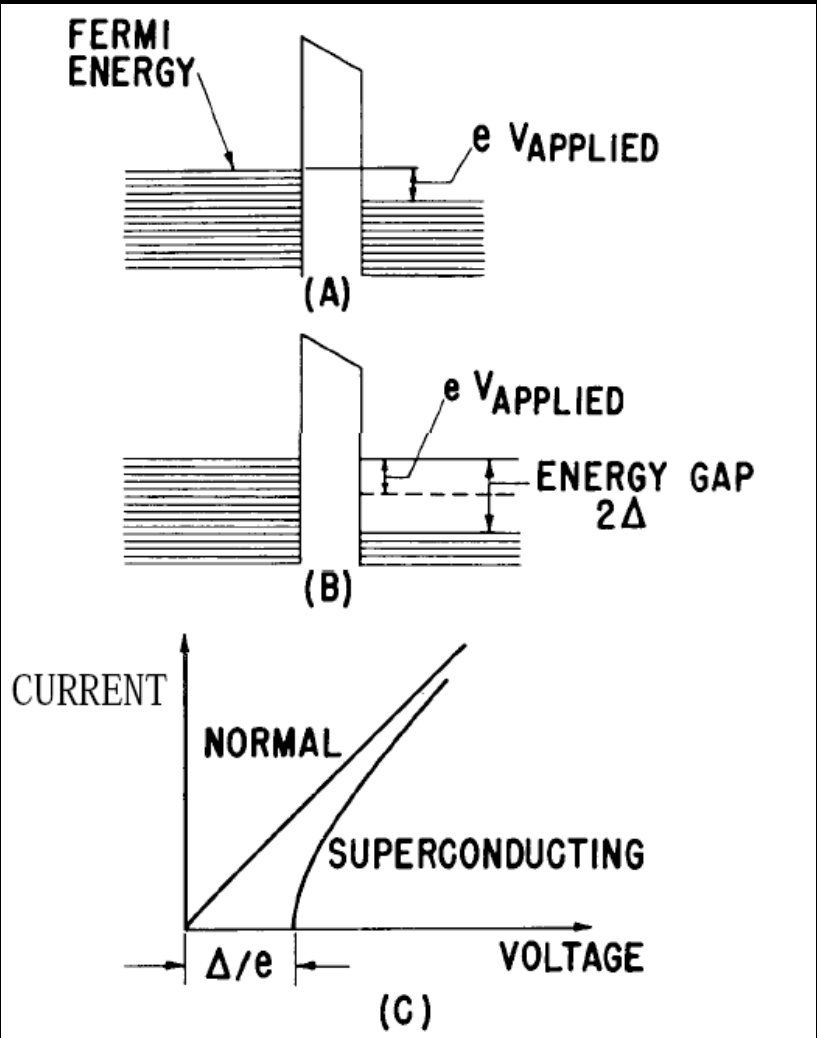
Pinhole free tunnel barrier



Giaever Tunneling: Tunneling into a superconductor

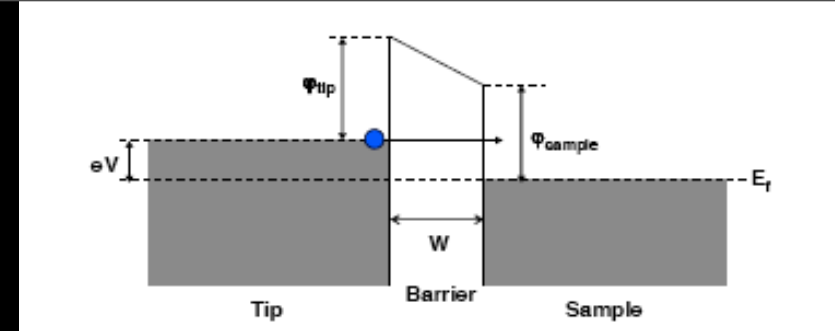


Giaever Tunneling: Tunneling into a superconductor (1963)



Al-AlOx-Pb junction: Pb goes superconducting at 7.2K

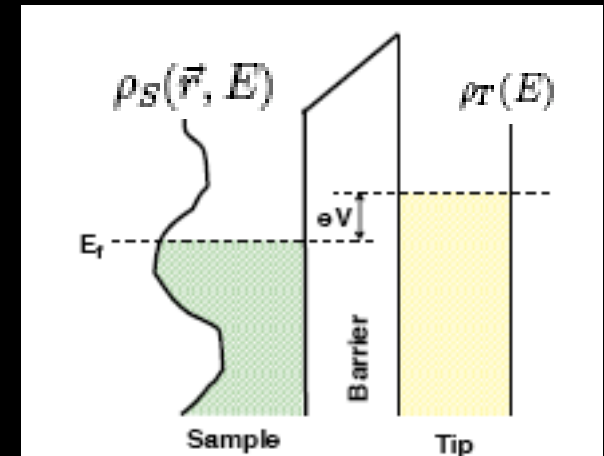
Basics of Tunneling



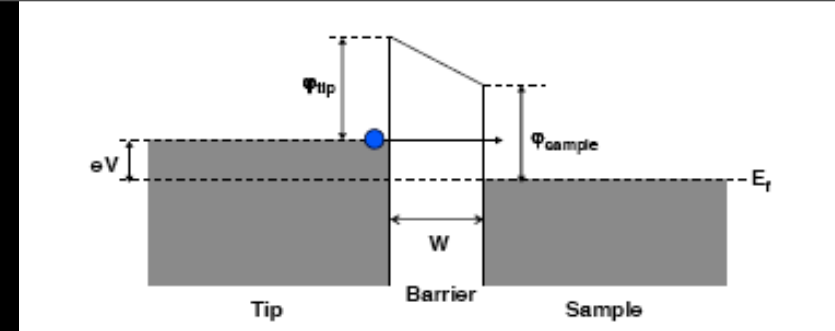
- Giaever tunneling: conducting electrodes separated by an insulating barrier
- Apply a voltage bias across the barrier to get a net tunneling current I
- First consider elastic tunneling: electrons get across without change in E
- Tunneling current depends on density of states (DOS) of the electrodes
- If one of the electrodes has a simple DOS, we can use this technique to measure the unknown DOS. (Except can not forget the influence of T)

$$I(V, \vec{r}) = \frac{4\pi}{\hbar^2} \int_{-\infty}^{+\infty} dE |M(E)|^2 \begin{bmatrix} \rho_{tip}(E) f(E) \rho_{sample}(E - eV, \vec{r}) (1 - f(E - eV)) \\ -\rho_{tip}(E) (1 - f(E)) \rho_{sample}(E - eV, \vec{r}) f(E - eV) \end{bmatrix}$$

$$|M|^2 \propto e^{-z/z_0}$$



Basics of Tunneling

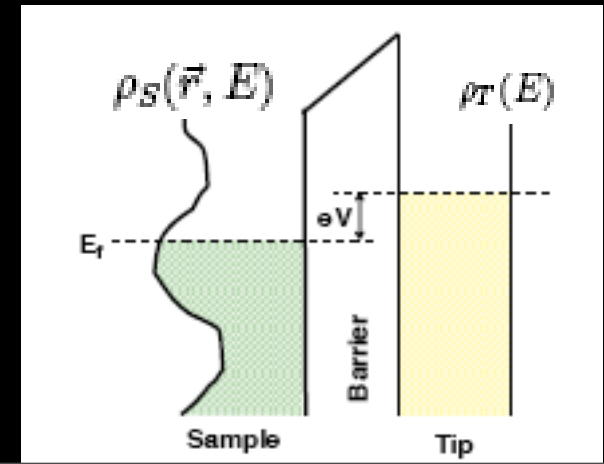


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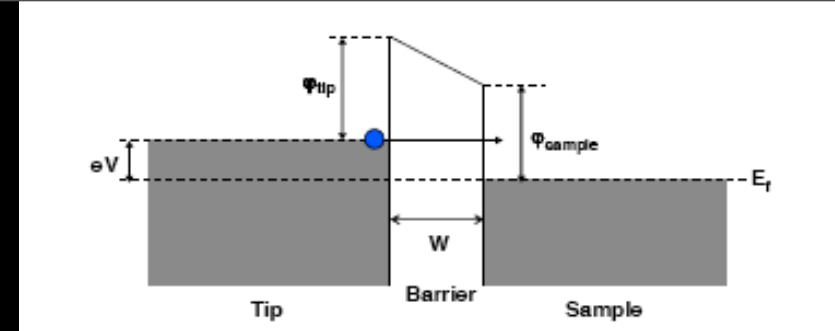
$$I(V, \vec{r}) = \frac{4\pi}{\hbar^2} \int_{-\infty}^{+\infty} dE |M(E)|^2 \begin{bmatrix} \rho_{tip}(E) f(E) \rho_{sample}(E - eV, \vec{r}) (1 - f(E - eV)) \\ -\rho_{tip}(E) (1 - f(E)) \rho_{sample}(E - eV, \vec{r}) f(E - eV) \end{bmatrix}$$

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Basics of Tunneling

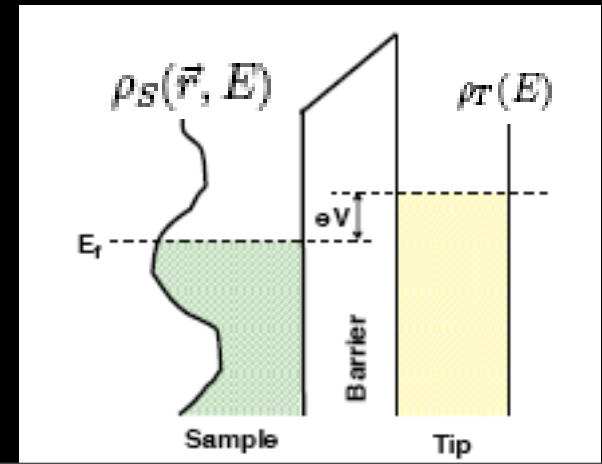


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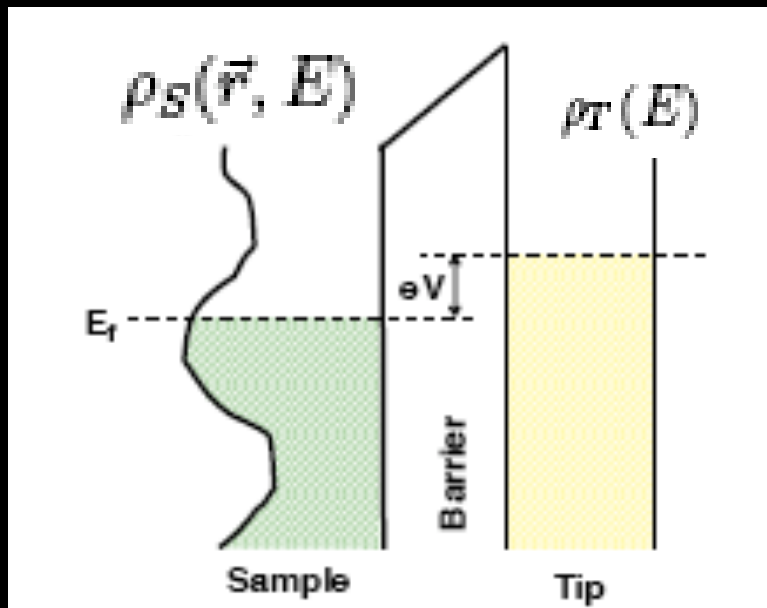


$$I(V, \vec{r}) \propto |M|^2 \int_{E_F}^{E_F + V} dE \rho_{tip}(E) \rho_{sample}(E_F - eV, \vec{r})$$

Principles of Tunneling Spectroscopy

A la J. Bardeen, Phys. Rev. Lett. 6, 57 (1960).

$$I(V, \vec{r}) \propto |M|^2 \rho_{tip} \int_{E_F}^{E_F + V} dE \rho_{sample}(E_F - eV, \vec{r})$$



In the limit of low temperature, the Fermi functions can be replaced by step functions. If the tip DOS and the tunneling matrix $\mathbf{M}$ are constant in the energy range of interest, then this expression reduces to:

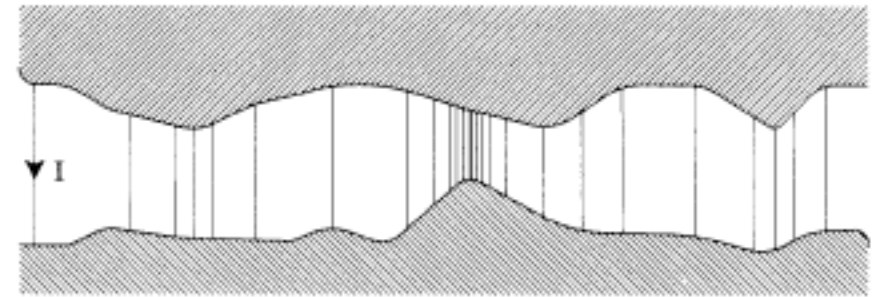
$$\frac{dI}{dV}(V, \vec{r}) \propto |M|^2 \rho_{tip} \rho_{sample}(E_F - eV, \vec{r})$$

So far consider elastic tunneling only!

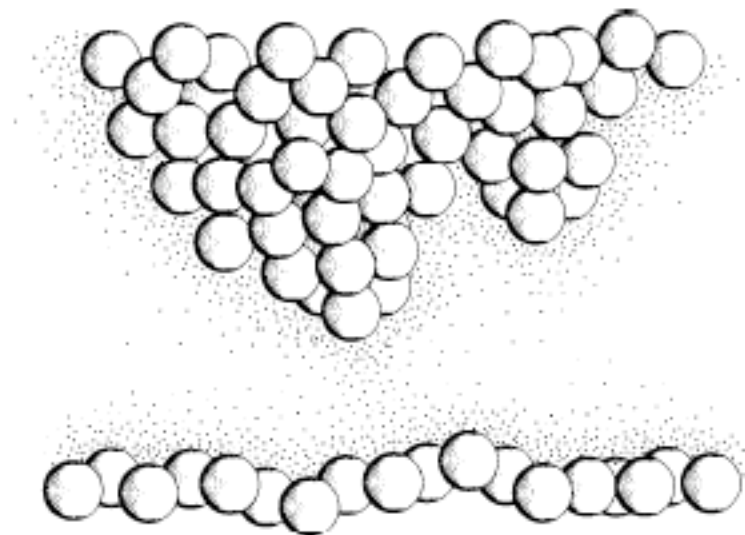
Vacuum Tunneling: Binnig & Rohrer (IBM-1980)

- Tunneling exponential with distance
- In vacuum: order of magnitude $1/\text{\AA}$
- With a tip perform local tunneling
- First idea was to do local spectroscopy
- Imaging was a secondary realization

Oxide Junction



Tunnel Tip



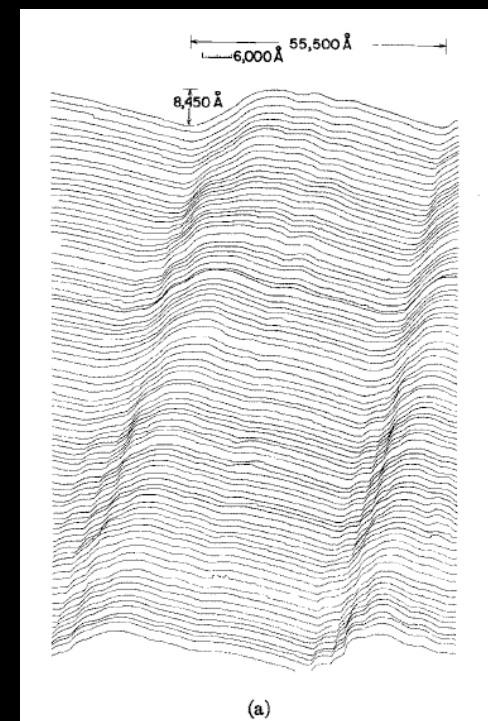
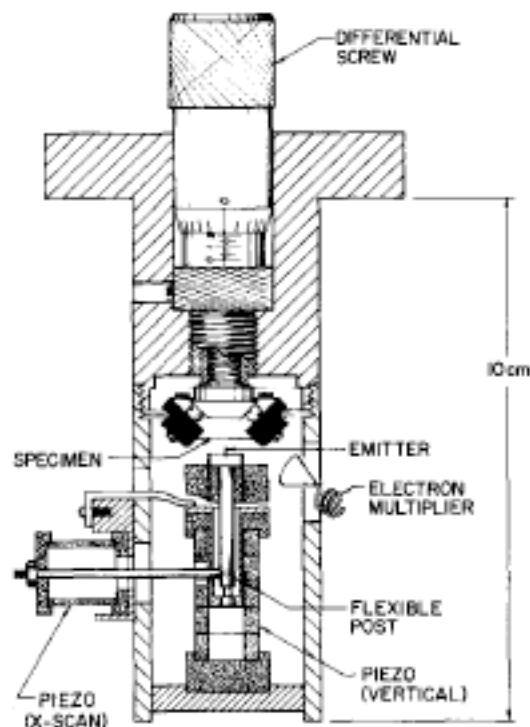
The Topografiner: An Instrument for Measuring Surface Microtopography

RUSSELL YOUNG, JOHN WARD, AND FREDRIC SCIRE

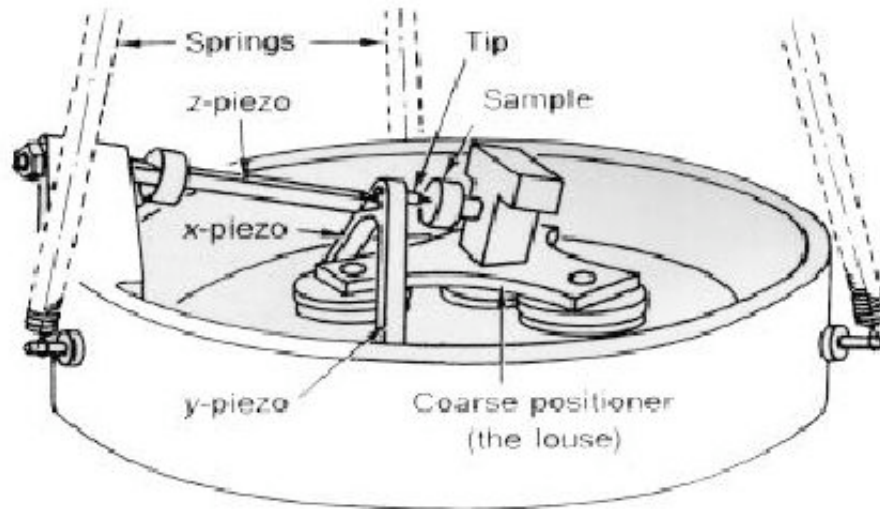
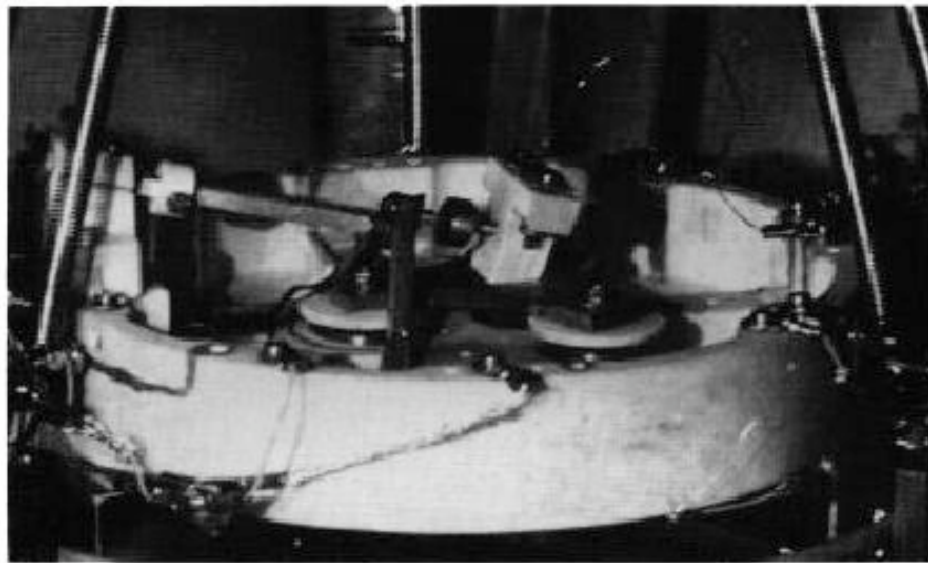
National Bureau of Standards, Washington, D. C. 20234

(Received 1 February 1972; and in final form, 29 March 1972)

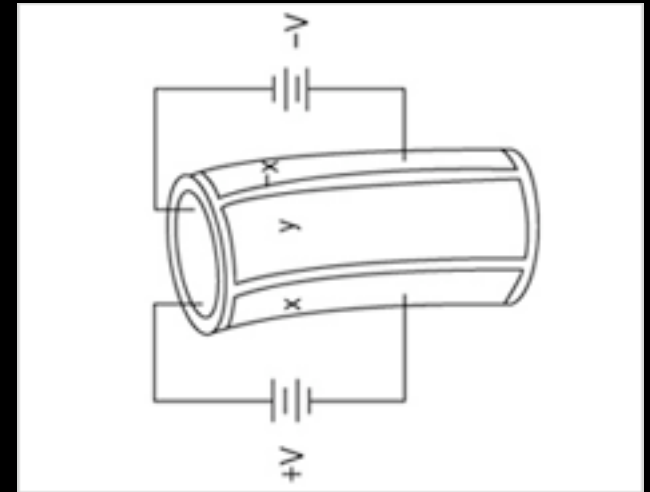
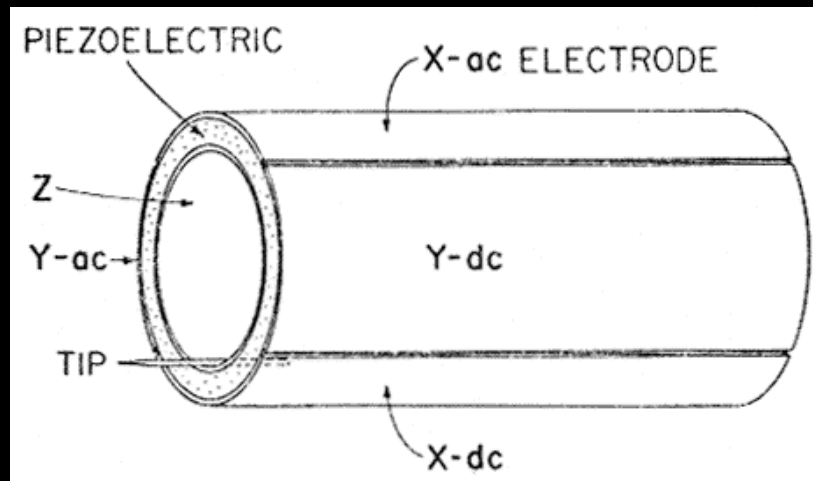
A noncontacting instrument for measuring the microtopography of metallic surfaces has been developed to the point where the feasibility of constructing a prototype instrument has been demonstrated. The resolution of the preprototype unit is $30 \text{ \AA}$ perpendicular to the surface and $4000 \text{ \AA}$ in the plane of the surface. Inherent noise in the perpendicular direction corresponds to $3 \text{ \AA}$ or one atomic layer. By using a typical field emitter with radius of $100 \text{ \AA}$, an ultimate limit of $200 \text{ \AA}$ would be expected for the horizontal resolution. Topographic maps of an infrared diffraction grating have been measured in order to demonstrate the performance of the instrument in measuring a well characterized surface. The instrument has been shown to conform to the Fowler-Nordheim description of field emission while spaced at the usual operating distances from the surface. When moved to within $30 \text{ \AA}$ of the surface, its performance is compatible with Simmons' theory of MVM tunneling. In the MVM mode, the instrument is capable of performing a noncontacting measurement of the position of a surface to within about $3 \text{ \AA}$. The instrument can be used in surface science experiments to study the density of single and multiple atom steps on single crystal surfaces, adsorption of gases, and processes involving electronic excitations at surfaces.



The First Scanning Tunneling Microscope

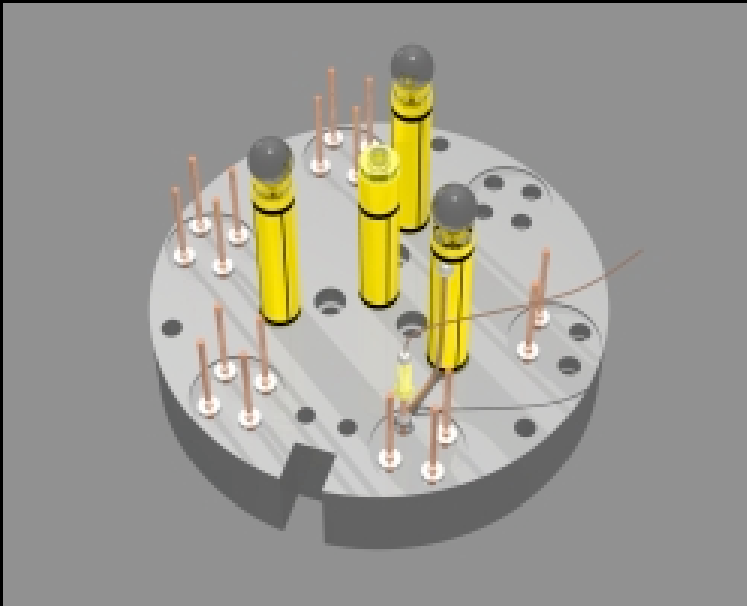


Commonly used piezo-electric element for an STM Scan Head

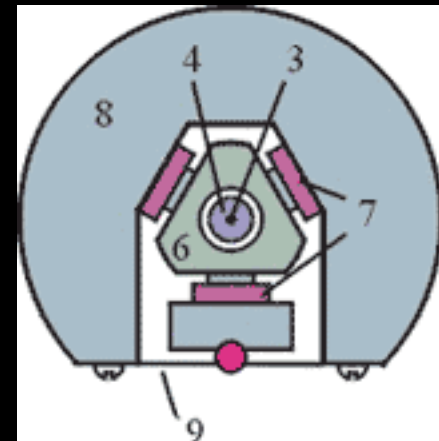
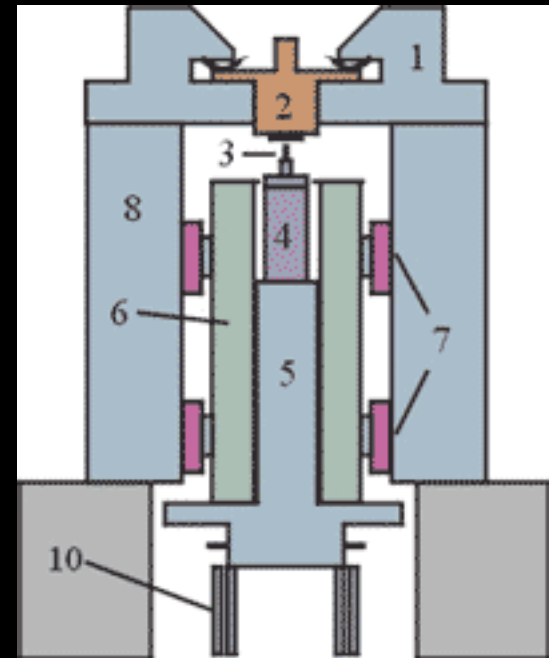


Various Coarse Approach Mechanism

Besoke/Bettle Walker

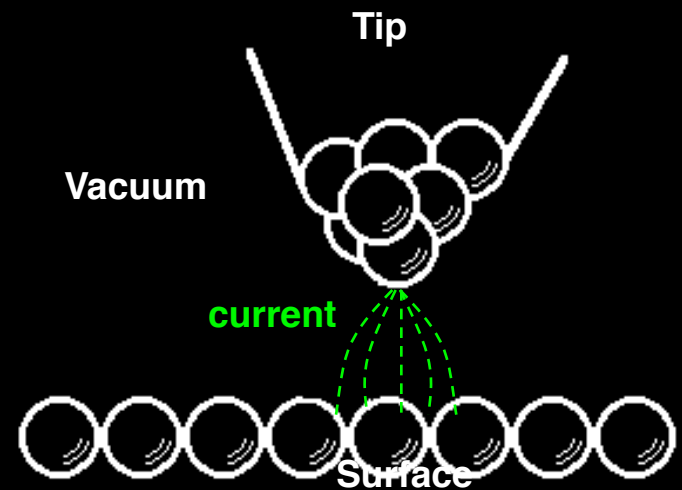


Pan Walker

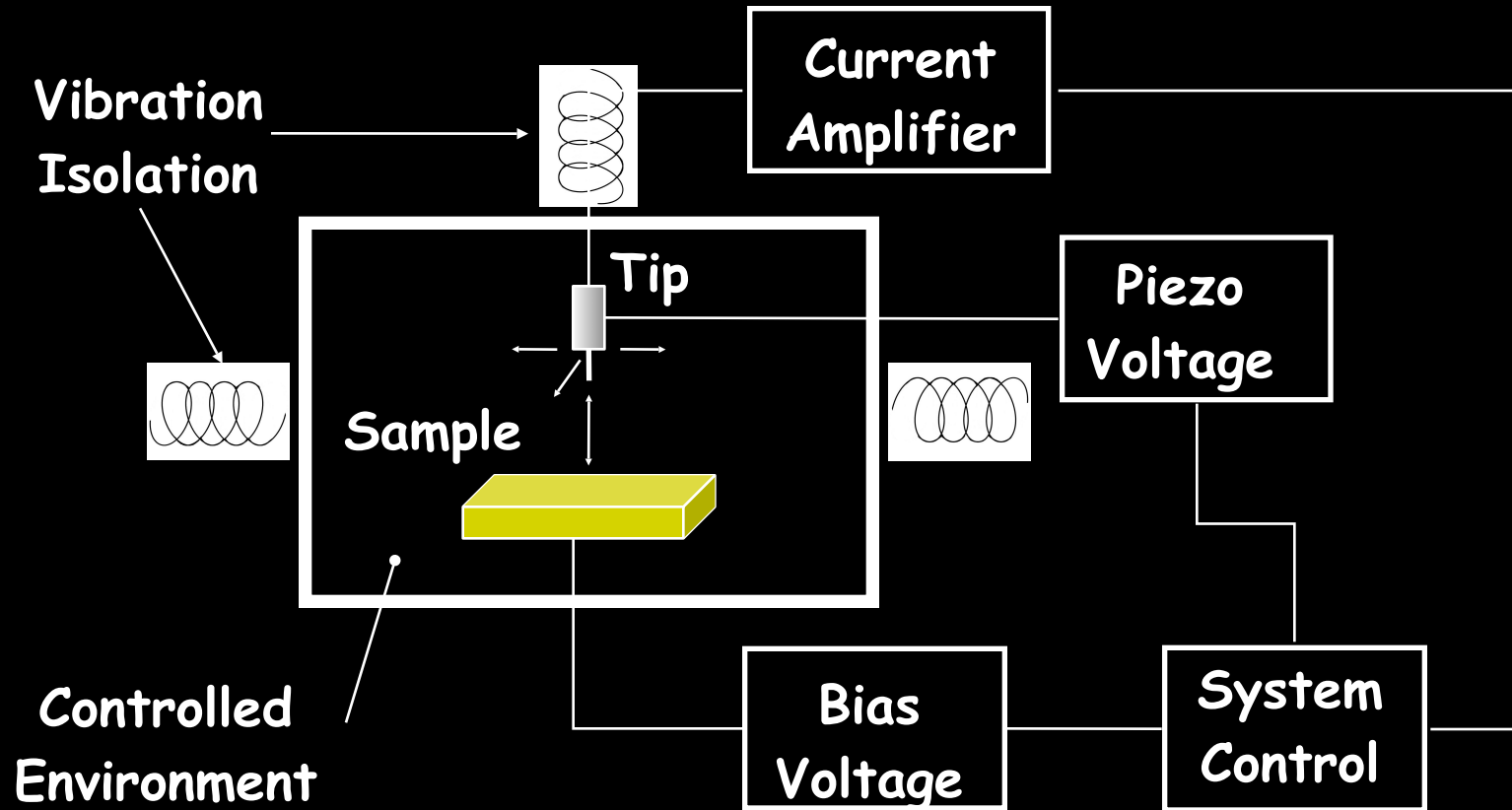


Basics of STM:

- Tunnel not from a macroscopic electrode but from a sharp tip
- The barrier is vacuum
- Since tunneling is exponential in distance--all current happens with a tunneling cone under the tip
- If the tip is sharp, the spatial extent is roughly the height of the tip
- Typical condition: 5-6 Å, 1V, you get a 1 nano-Amp of current (easy to measure with room temp electrometer)

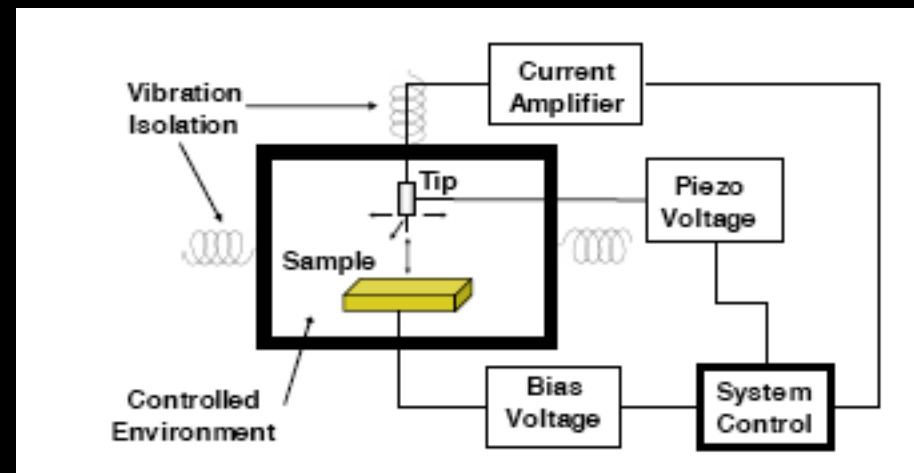
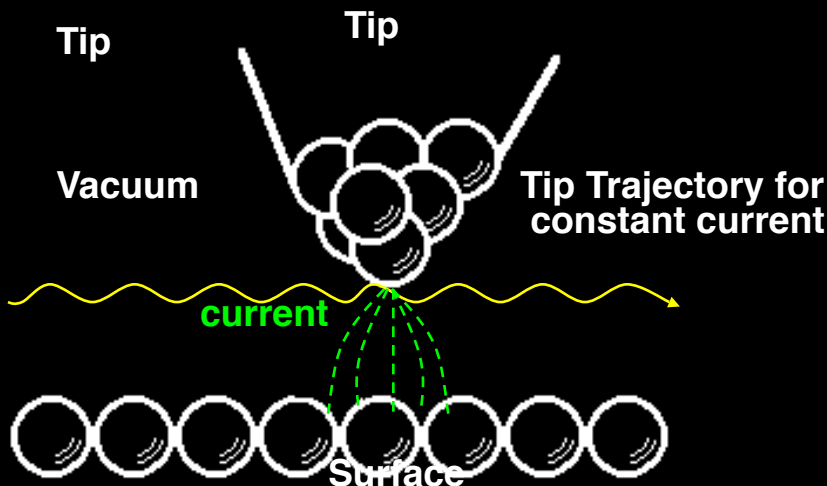


Block Diagram of an STM



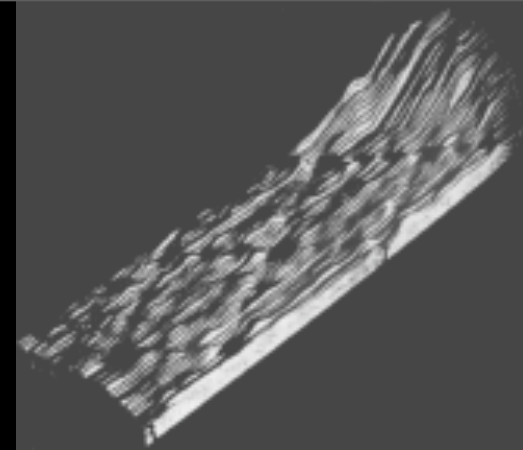
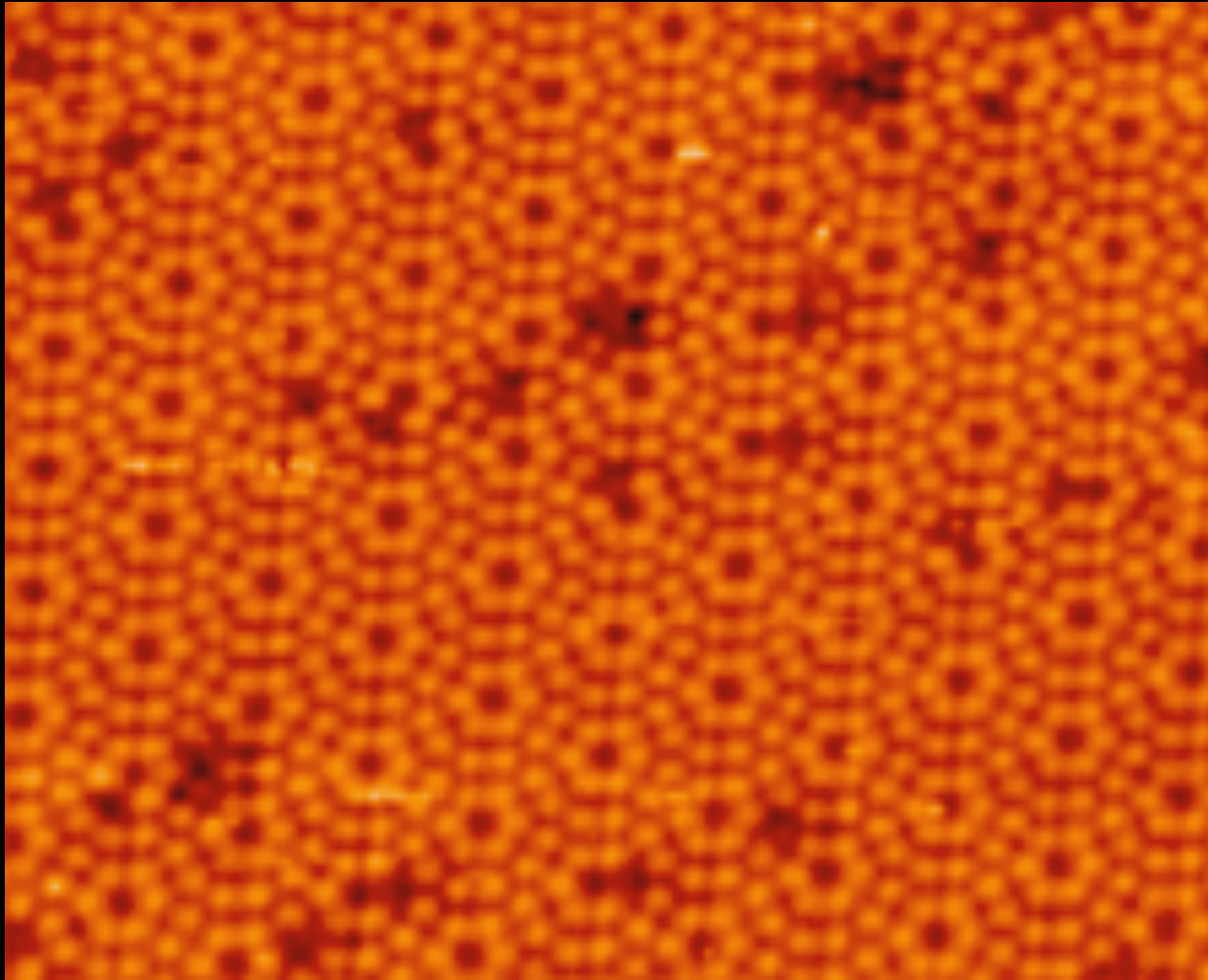
Basics II: STM topography

- The most typical use of the STM is to record a constant current image
- A feedback loop adjusts the height of the tip to keep I constant
- As another circuit scans the tip across an area (typically $100 \text{ \AA}$)
- Computer record and displays the trajectory of the tip
- Constant- I topograph is a map of contours of constant DOS in vacuum



Atomic Scale Imaging with STM

- Binnig & Rohrer realized how local tunneling can be used as an atomic scale imaging tool
- First example: Si 7X7 surface reconstruction



First "STM Topograph"--Binnig & Rohrer 1983

Si (111) Surface



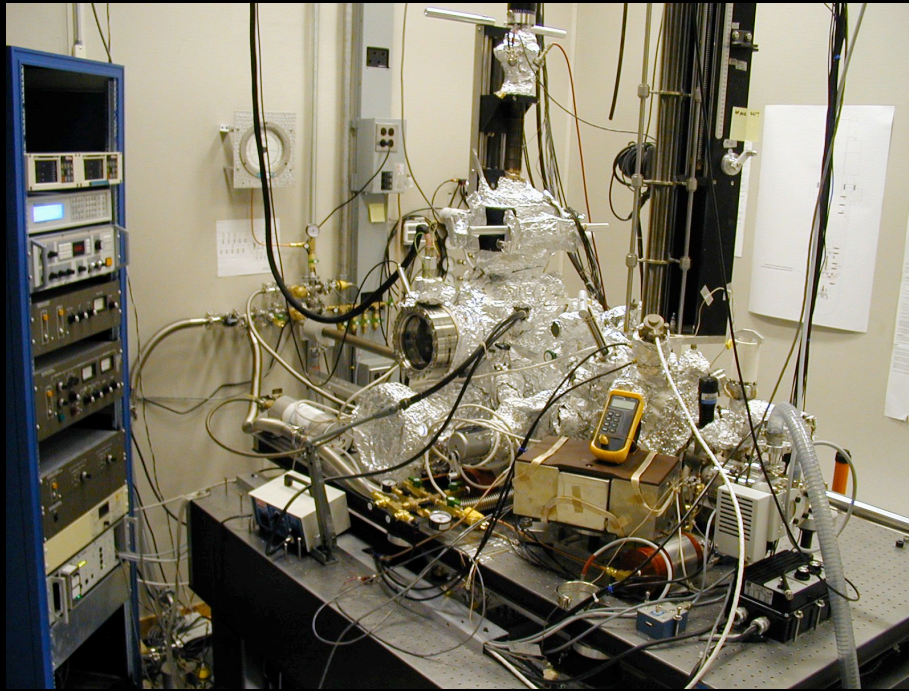
Rohrer & Binnig
IBM Lab in Zurich
Invented STM in 1981
Nobel Prize awarded 1986

Construction of an STM

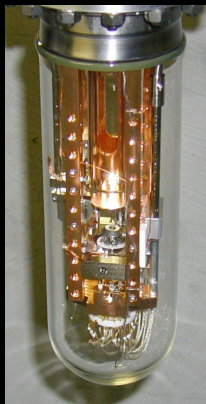
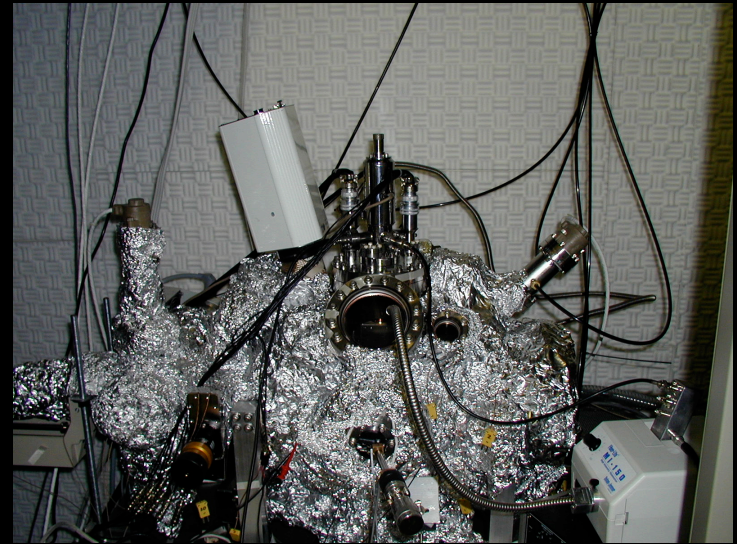
- Scanning with piezoelectric elements: 1A/V
- Tips: “hard” metals such as W, Pt, Ir
- Coarse (mm range) and fine motion (0.1 μ m range) are separate
- Need clean surfaces: UHV environment (10^{-6} Torr about 1 monolayer/sec)
- Need low vibrations: floating table, rigid construction, acoustic rooms
- Need low electrical noise: Rf shielding, low noise high voltage amplification
- Need to measure small currents: Large gain, low noise, electrometers
- Most important of all you need the sample surface to cooperate!
- It can be a pain to make all these work at the same time!

Scanning Tunneling Microscopy Laboratory:

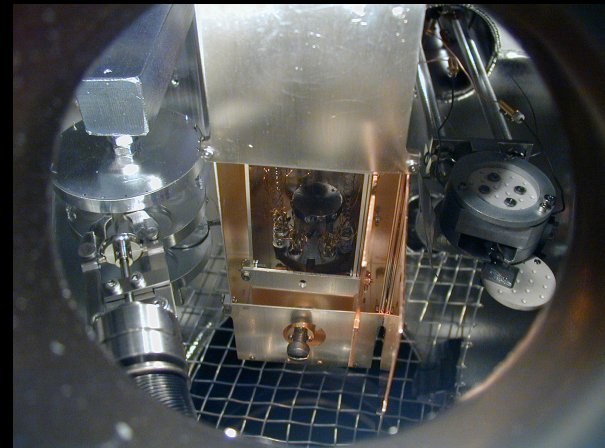
$(1.5\text{K} < T < 4.2\text{K})$



$(8\text{K} < T < 350\text{K})$

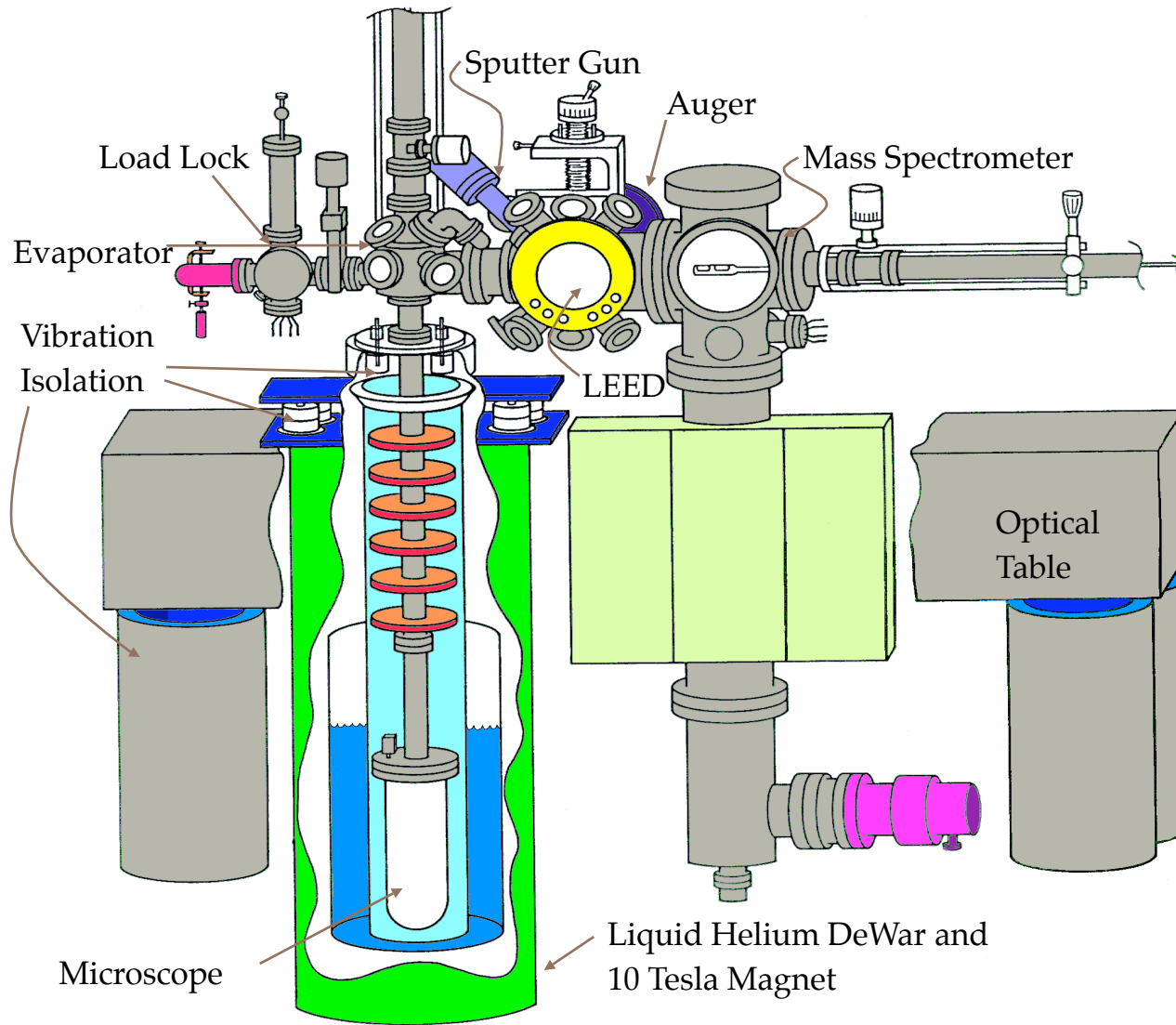


STM head

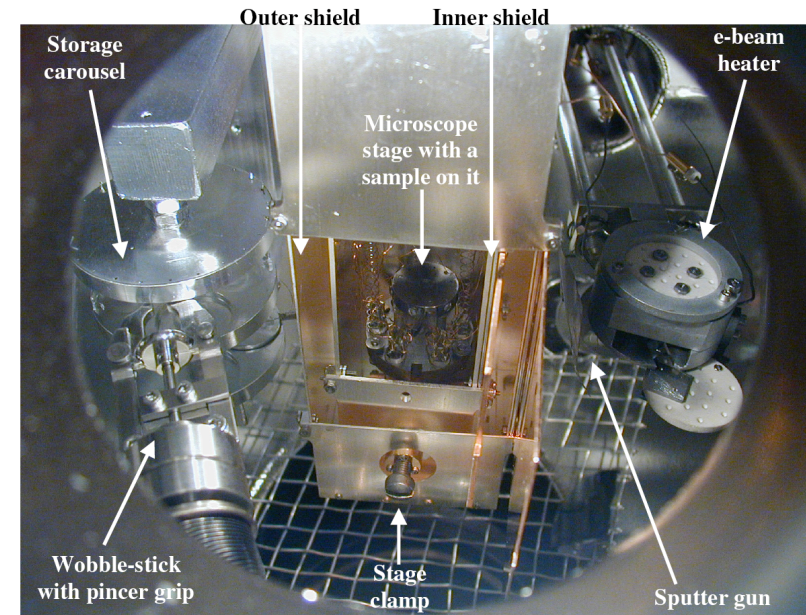
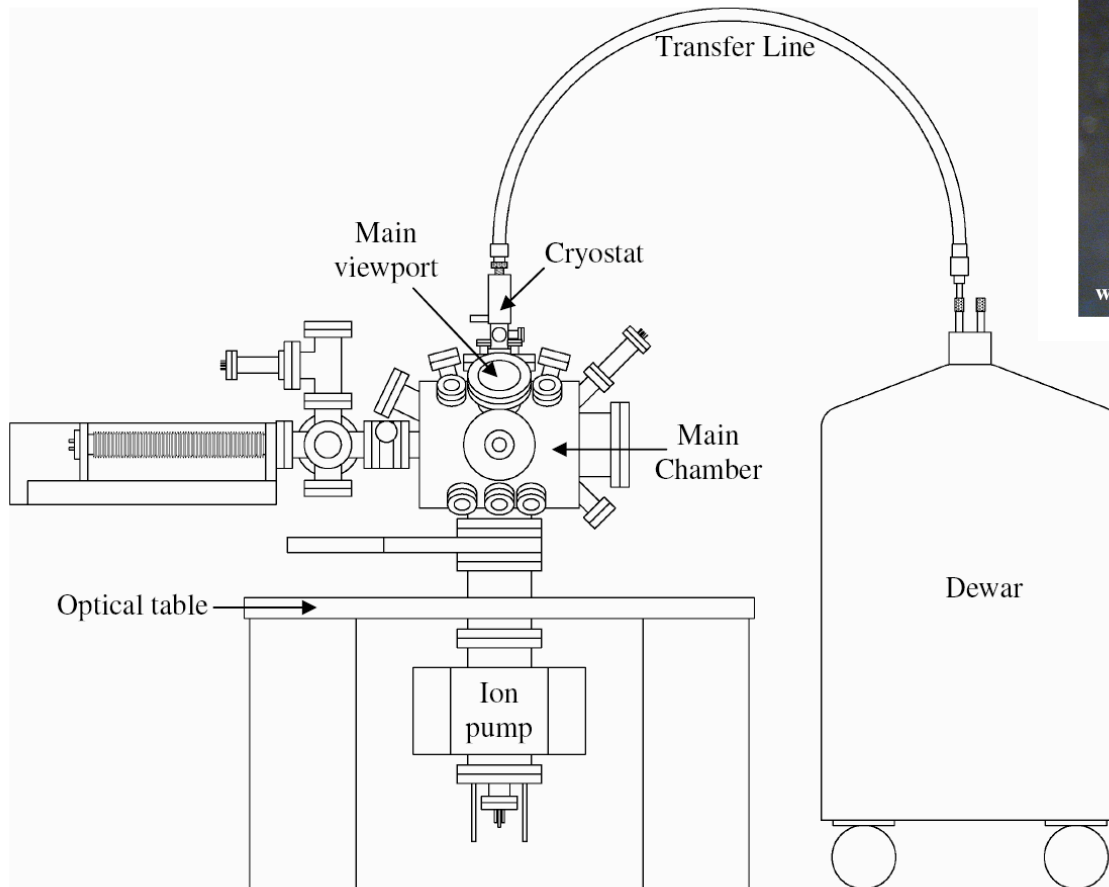


STM head

The schematic of a UHV low temperature STM



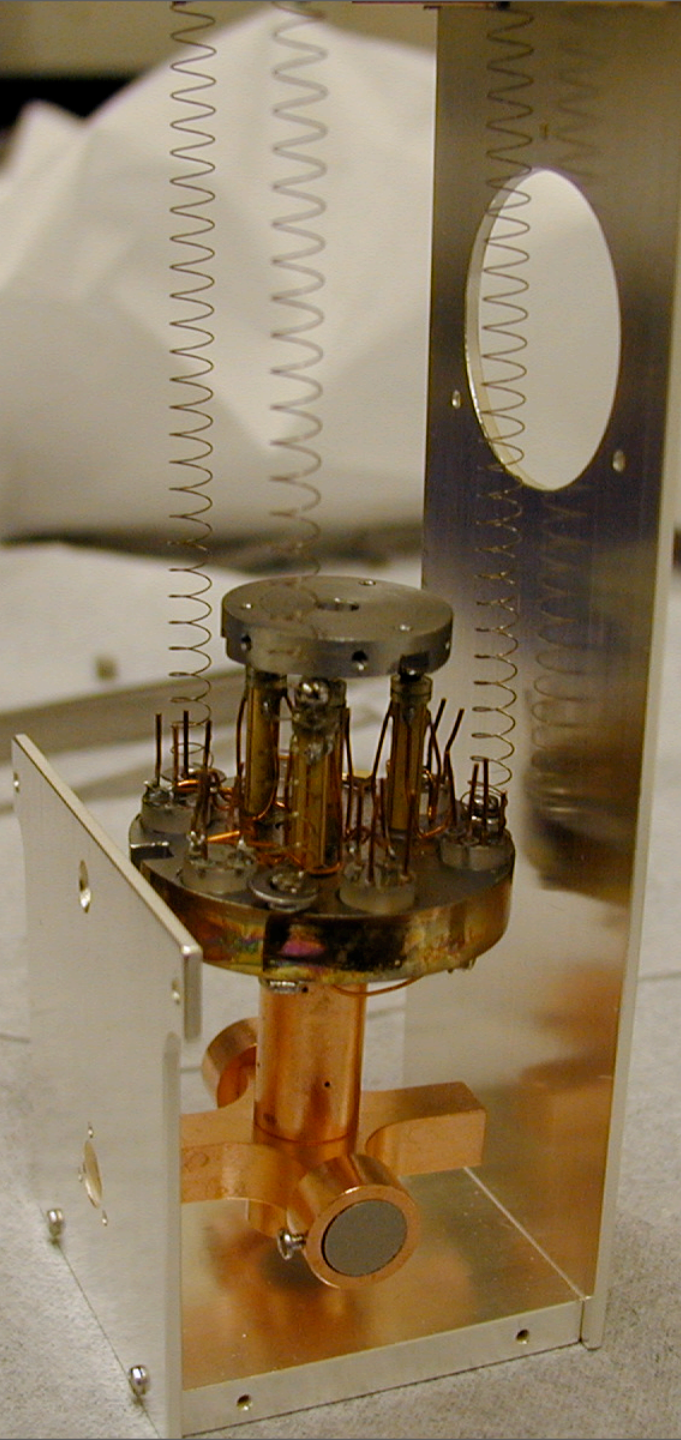
The schematic of a Variable Temperature UHV STM system



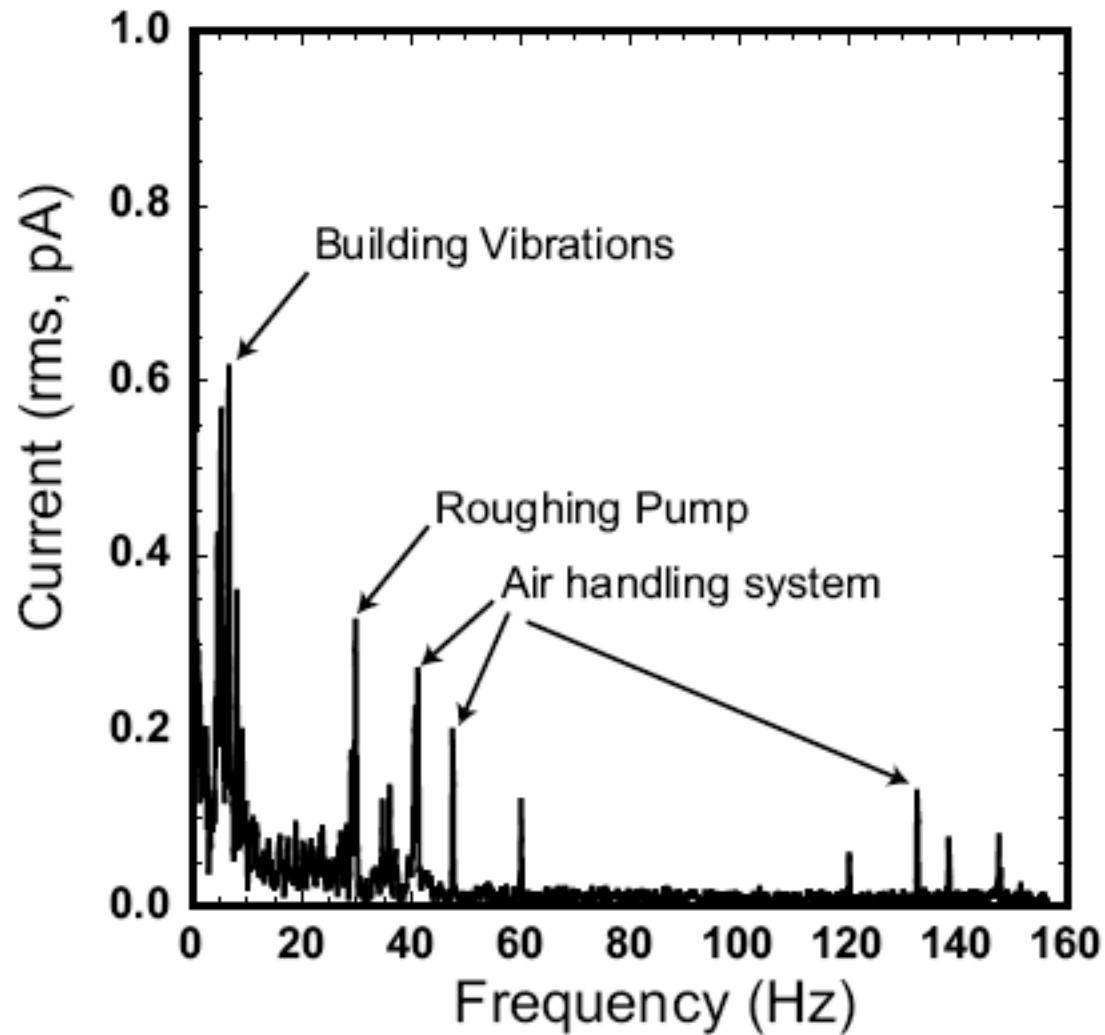
VT-STM Head

Designed for higher temperatures

- Thermal compensation
- Compact design
- Result :
- Extremely low drift at high temperatures

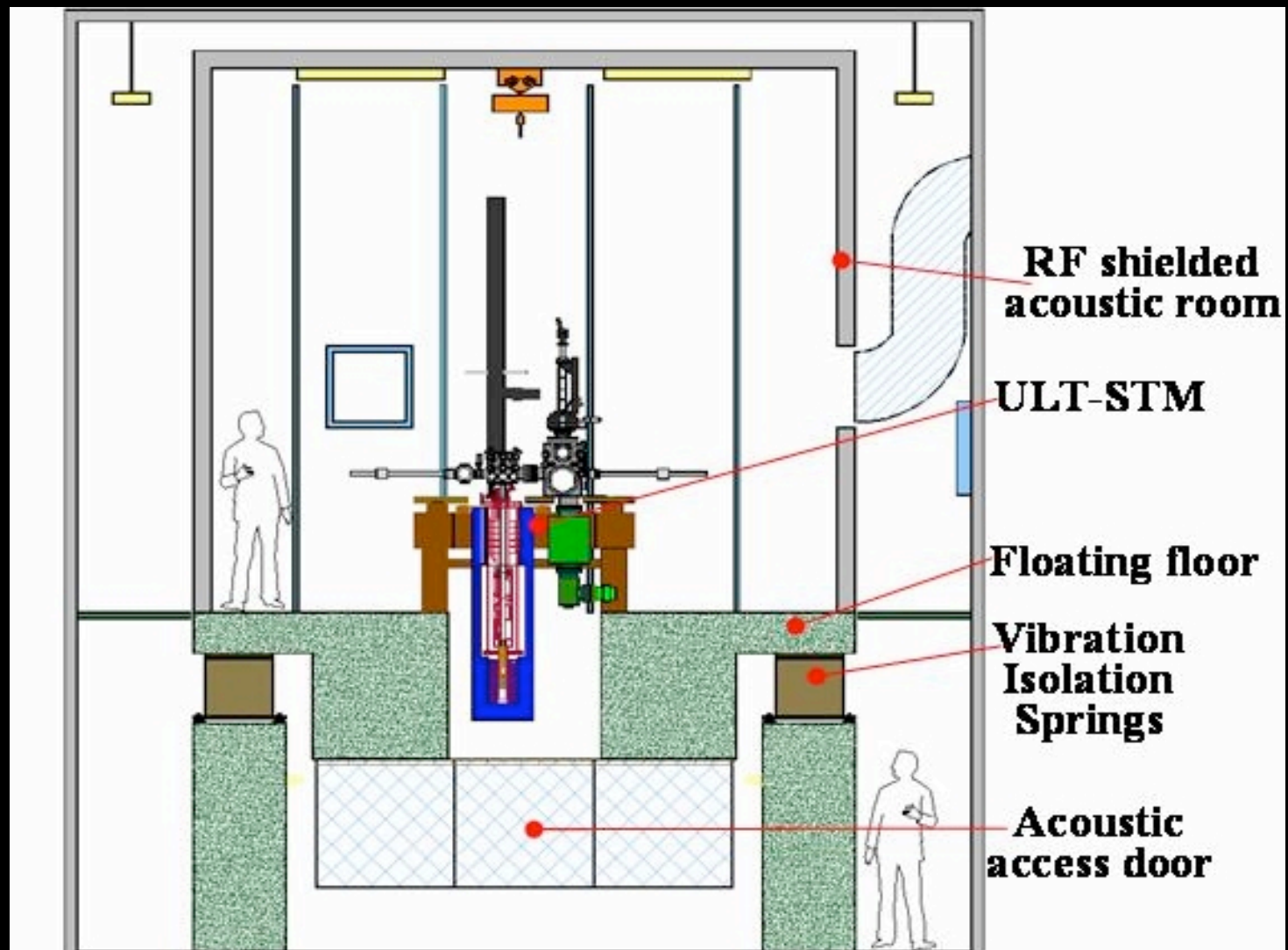


Trouble with a movable vacuum tunnel junction:



Princeton Nanoscale Microscopy Lab:

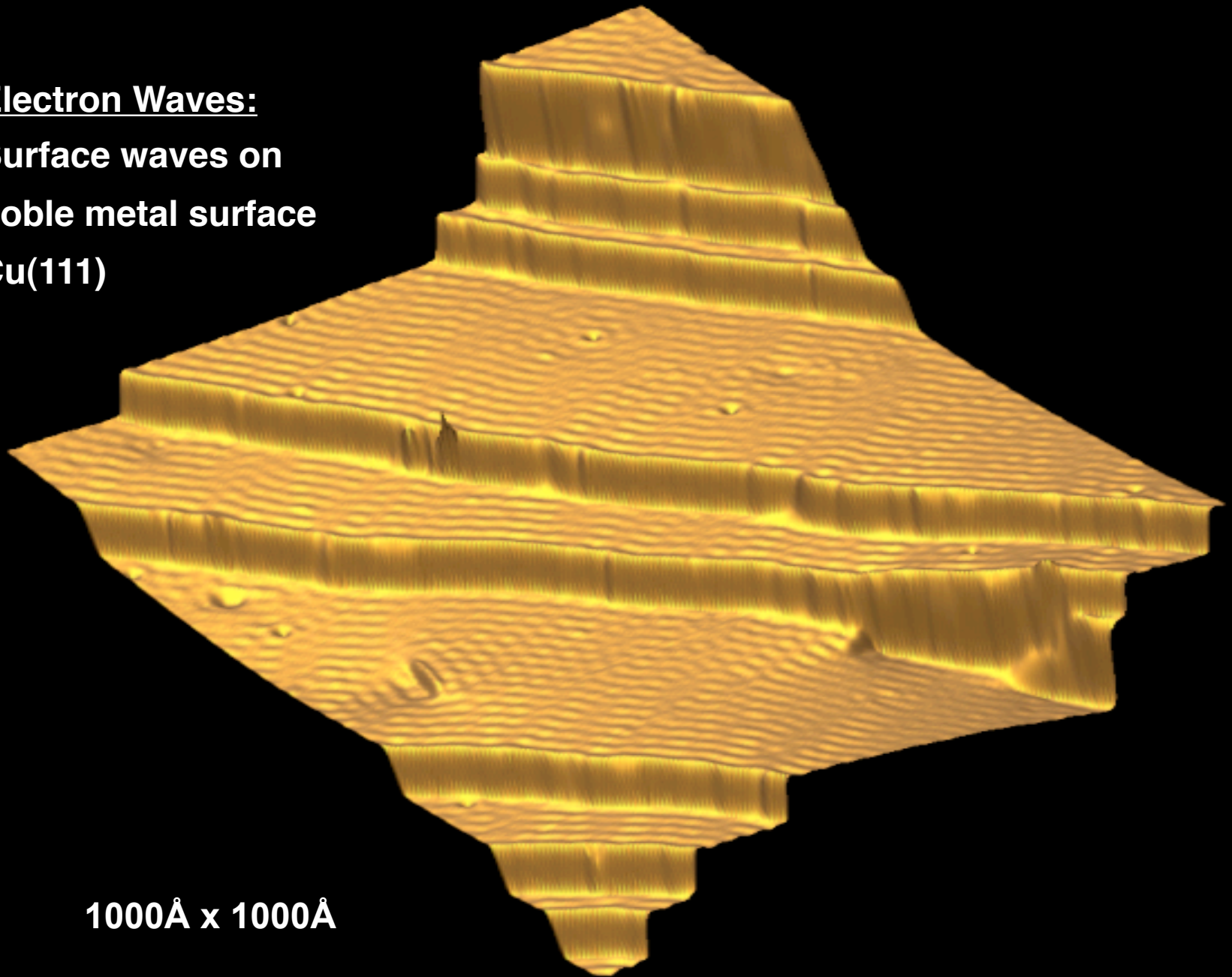
- Floating 30T slab of concrete supporting an acoustic/rf enclosure
- For operation high resolution scanning probe microscopes
- Outcome: better than 30ng of floor vibration



STM on Simple Metals

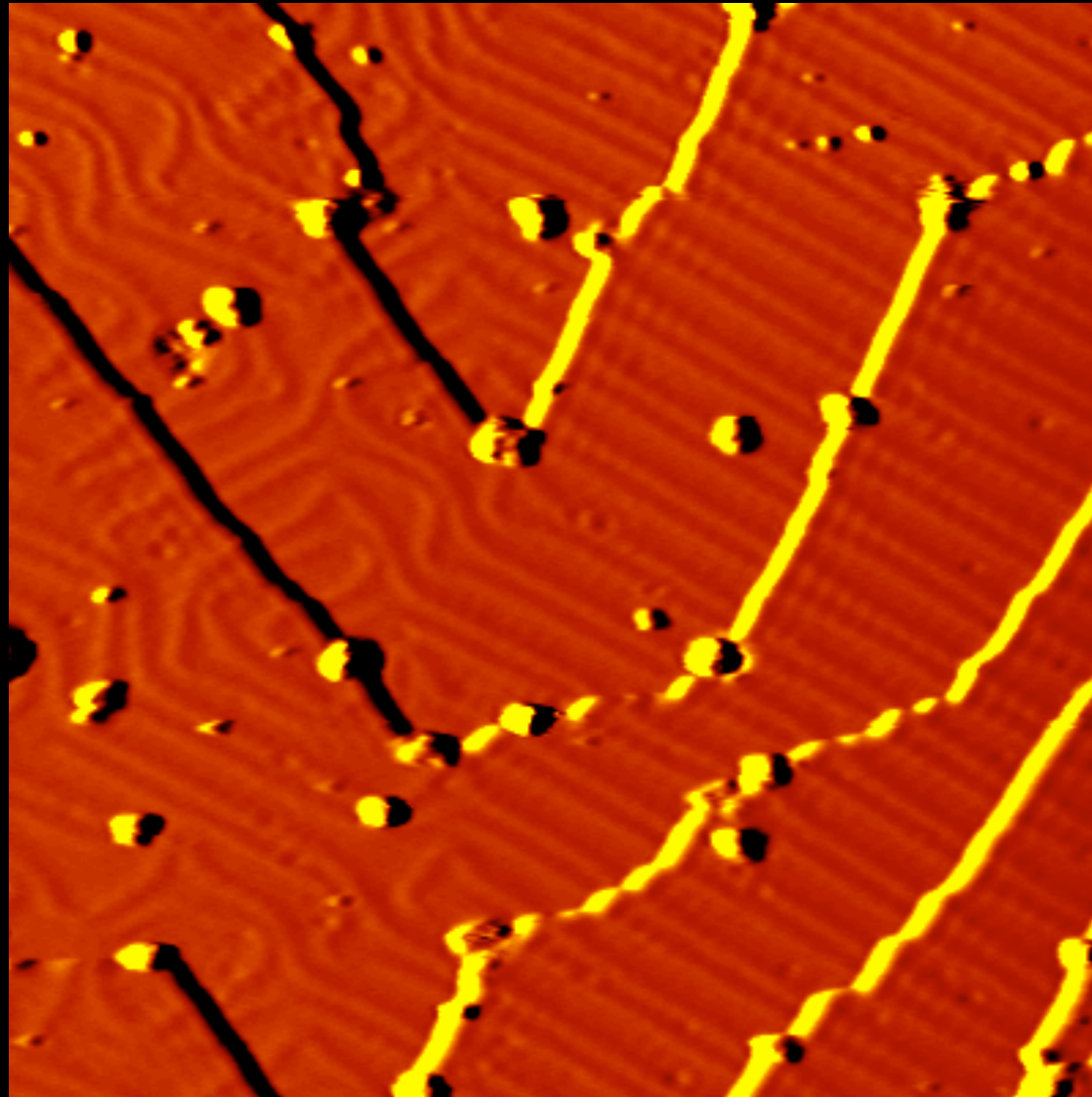
Electron Waves & Quantum Interference

Electron Waves:
Surface waves on
noble metal surface
Cu(111)



1000Å x 1000Å

Substrate: Au(111) on Mica



Reconstructed

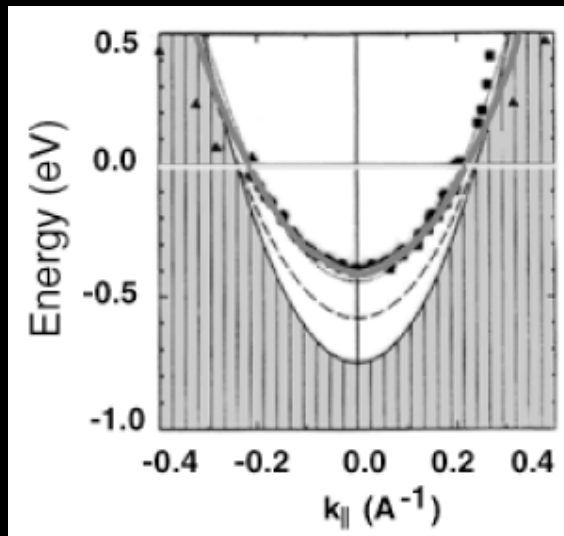
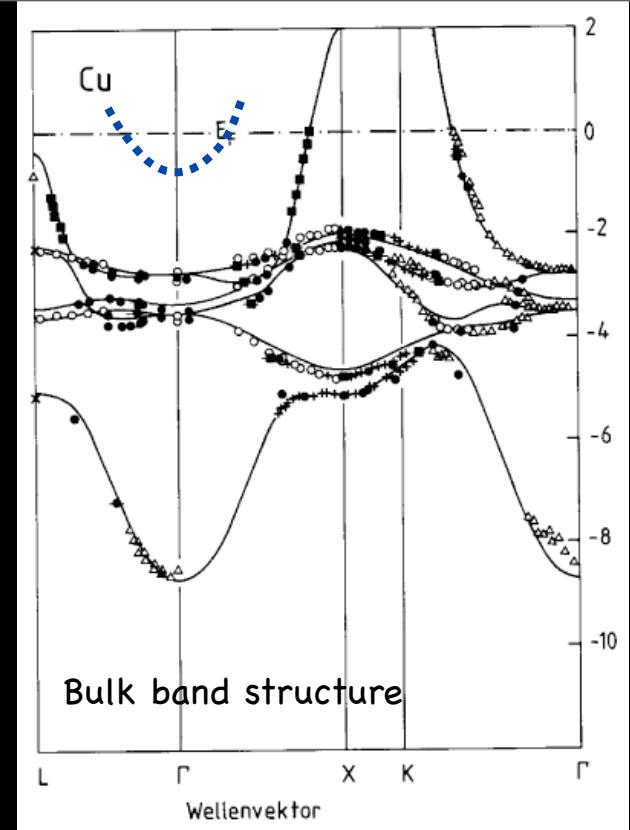
Surface &
adsorbates

Constant current image, $V=100$ mV, $I=90$ pA

1000 Å x 1000 Å

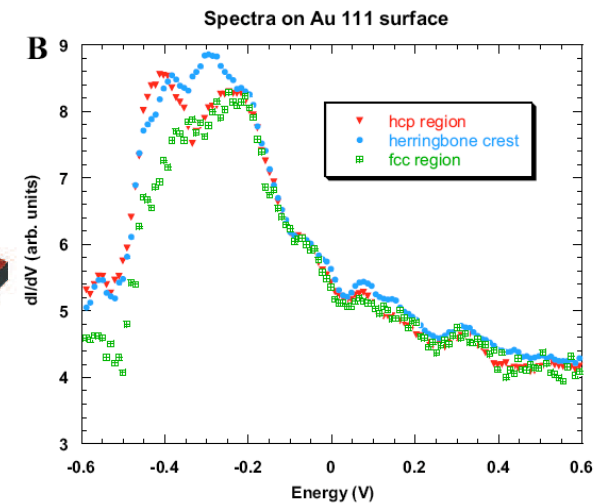
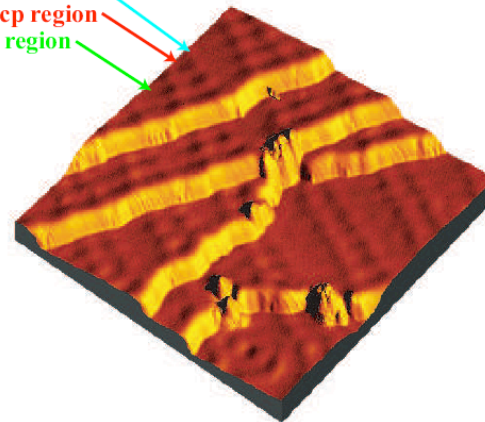
Simple Examples of Spectroscopy

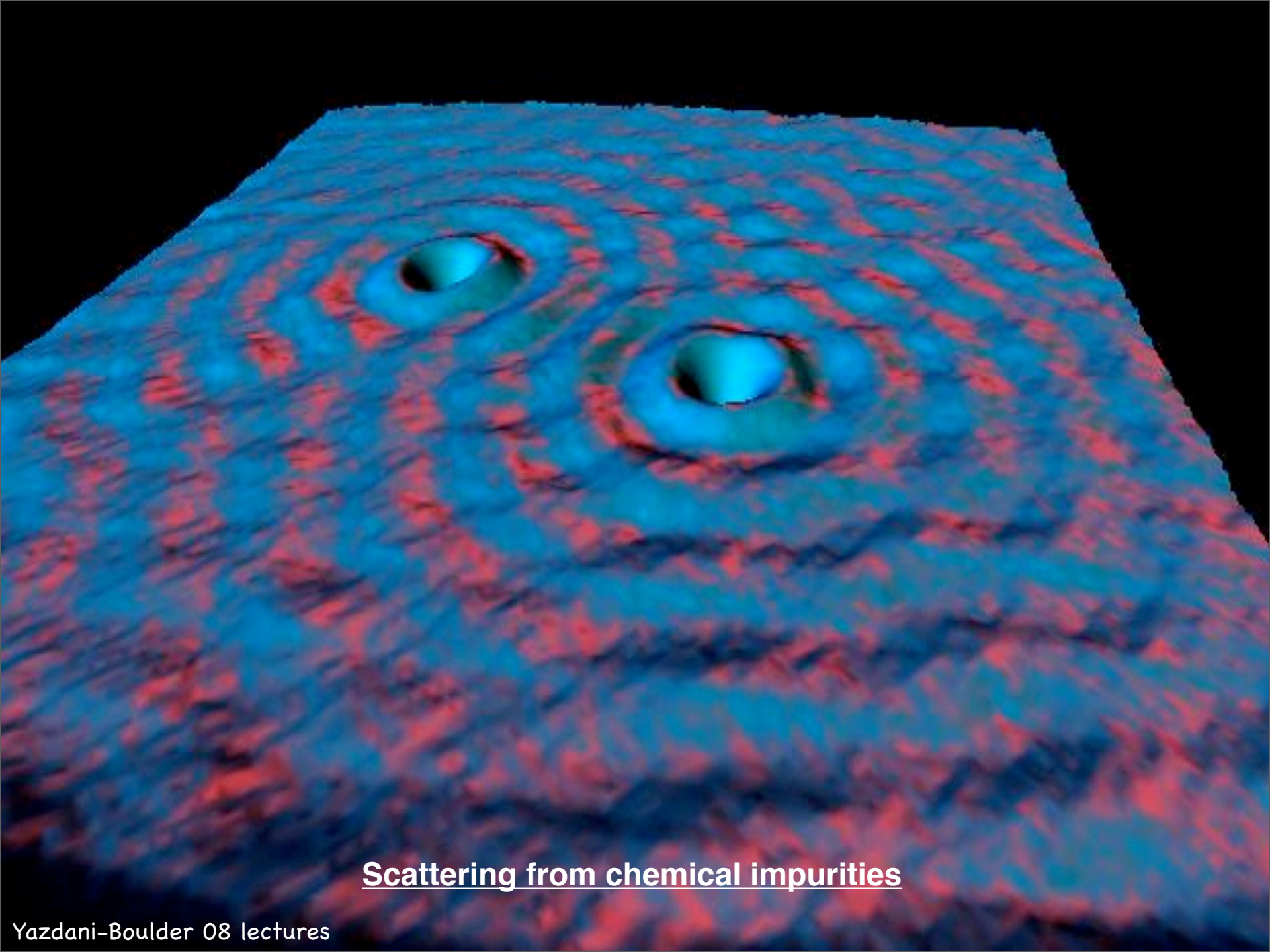
- Surface state on noble metal surfaces (Au, Cu, Ag); where bulk states are forbidden
- Au(111) surface has a two-dimensional surface state
- Measured previously with photoemission
- STM spectroscopy can probe these states



A herringbone crest

hcp region
fcc region





Scattering from chemical impurities

Standing Waves in Simple Metals

- Scattering from step edges and defect creates a situation for wave interference
- At each energy electrons have different wavelength and hence a satisfy slightly different interference condition

dI/dV maps Ag(111)



500Å x 500Å

500Å x 500Å

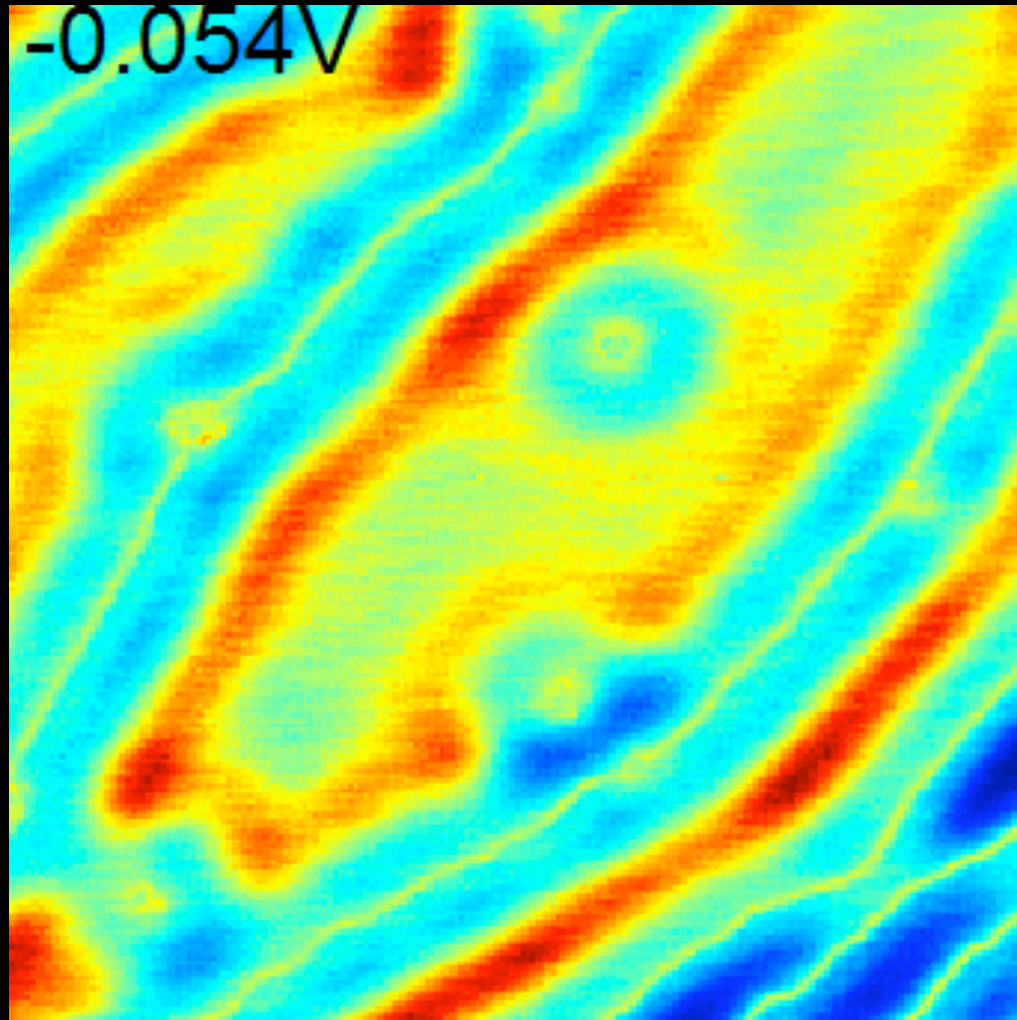
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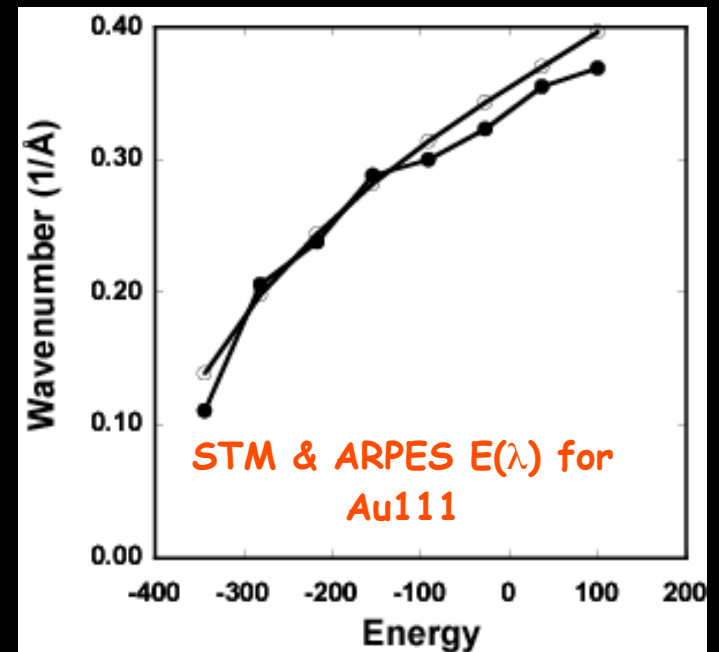
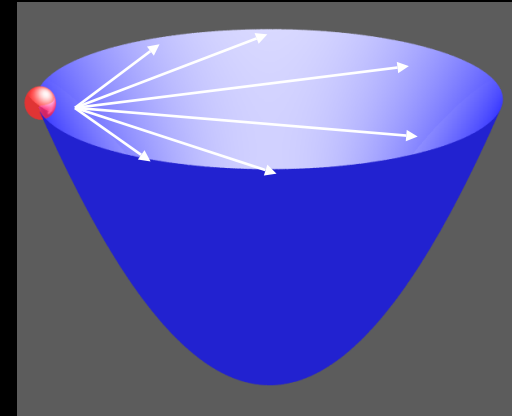


500Å x 500Å

Standing Waves in Simple Metals

- Elastic scattering electron from k_1 to k_2 allows mapping the Fermi Surface
- A standing wave occur with $Q=k_1 - k_2$
- At different energies different Q 's

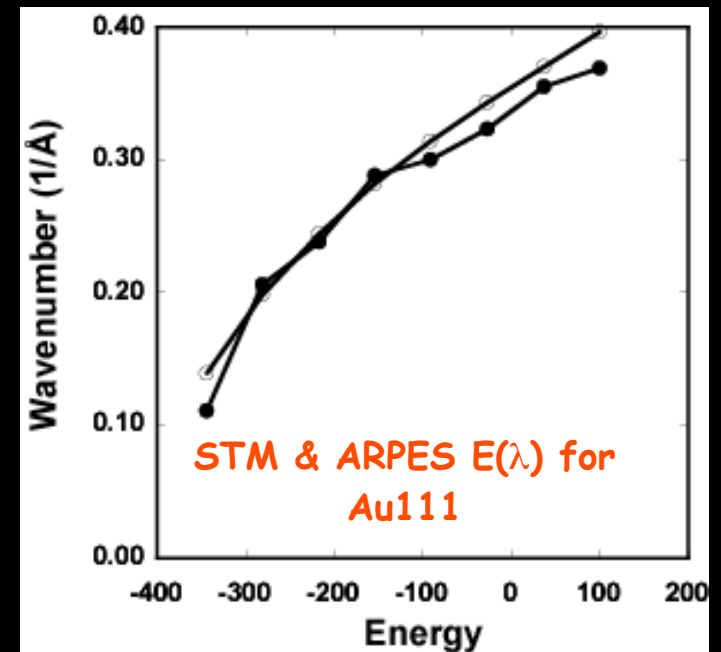
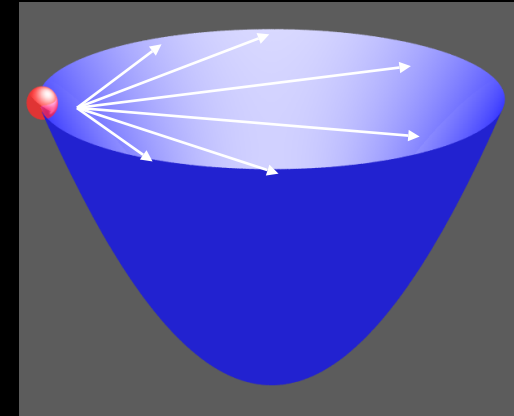
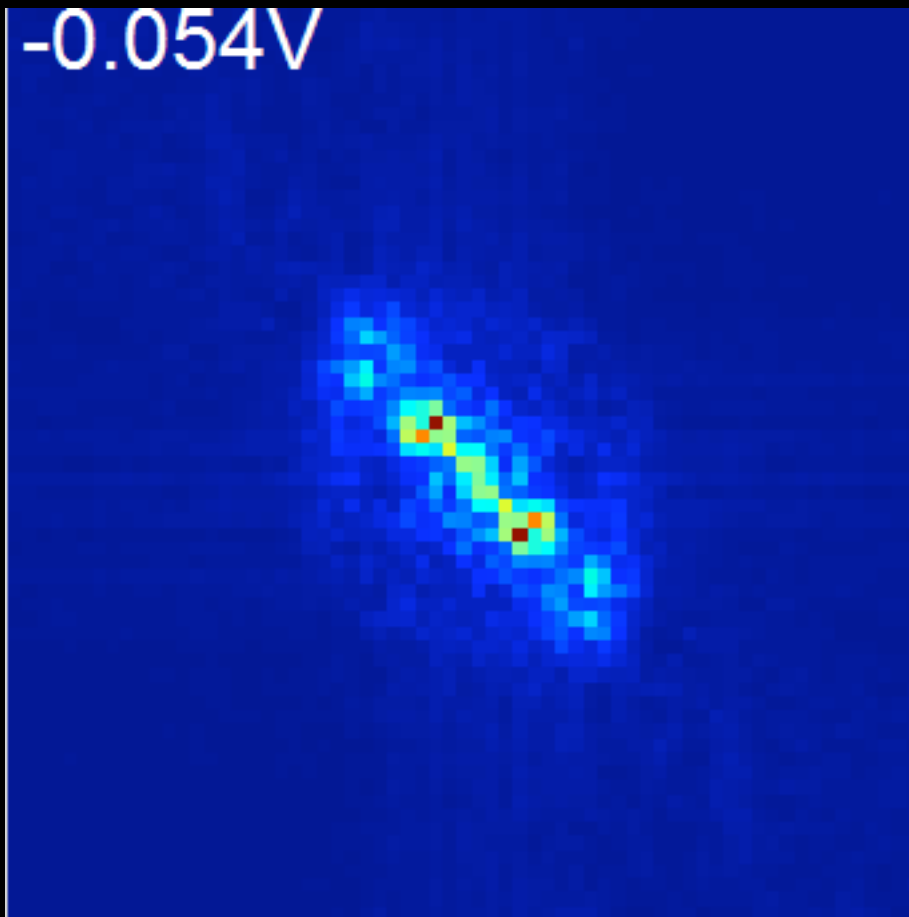
Fourier Transform of the dI/dV maps Ag(111)



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Fourier Transform of the dI/dV maps Ag(111)



Scattering of Electrons from a Hard Wall

VOLUME 82, NUMBER 22 PHYSICAL REVIEW LETTERS 31 MAY 1999

Probing Hot-Electron Dynamics at Surfaces with a Cold Scanning Tunneling Microscope

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²Max-Planck-Institut für Festkörperforschung, Heisenbergstrasse 1, D-70569 Stuttgart, Germany

(Received 11 January 1999)

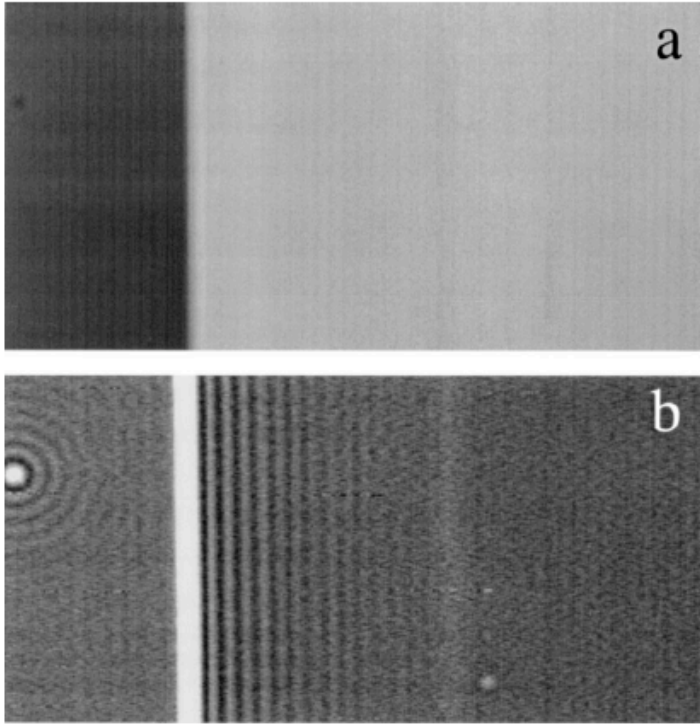


FIG. 1. (a) Constant current image of a Cu(111) step edge: $280 \text{ \AA} \times 138 \text{ \AA}$, $V = 1.4 \text{ V}$, $I = 7 \text{ nA}$. (b) dI/dV image taken simultaneously with (a) by lock-in technique ($\Delta V = 135 \text{ mV}$). Standing wave patterns at static scatterers as steps and impurities are clearly visible.

$$\rho_s(E, x) \approx \rho_b + L_0 [1 - r(k_E) e^{-2(x/L_\phi)} J_0(2k_E x)],$$

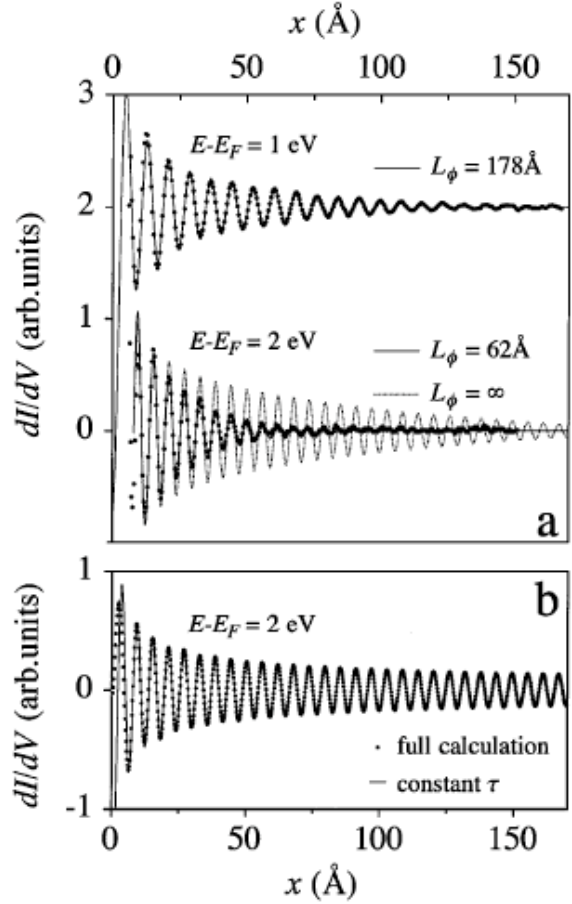


FIG. 2. (a) Typical dI/dV data perpendicular to a descending Cu(111) step obtained by averaging over several line scans of a dI/dV image as shown in Fig. 1(b). The data at 1 and 2 eV were taken with a stabilizing current of 5 and 10 nA and a ΔV of 119 and 156 mV, respectively. The solid lines depict the fits with Eqs. (4) and (5). The significance of the deduced L_ϕ is demonstrated by the dashed line: neglecting inelastic processes by setting $L_\phi = \infty$ leads to a much slower decay rate than observed. (b) Comparison between the full calculation of dI/dV with Eqs. (1) and (3) and the result obtained by setting T constant ($T \rightarrow 0$, $L_\phi \rightarrow \infty$, typical Cu(111) parameters: $W_s = W_t = 4.5 \text{ eV}$, $r = 0.5$ [23]).

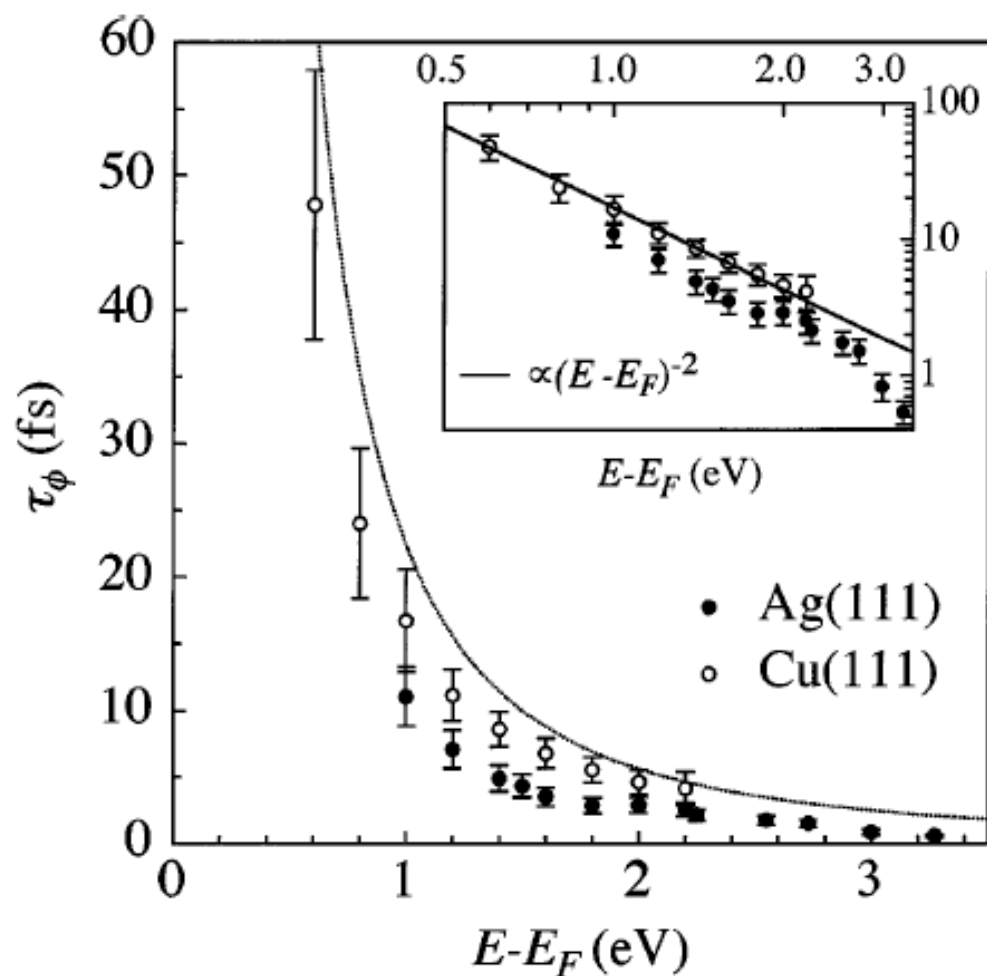
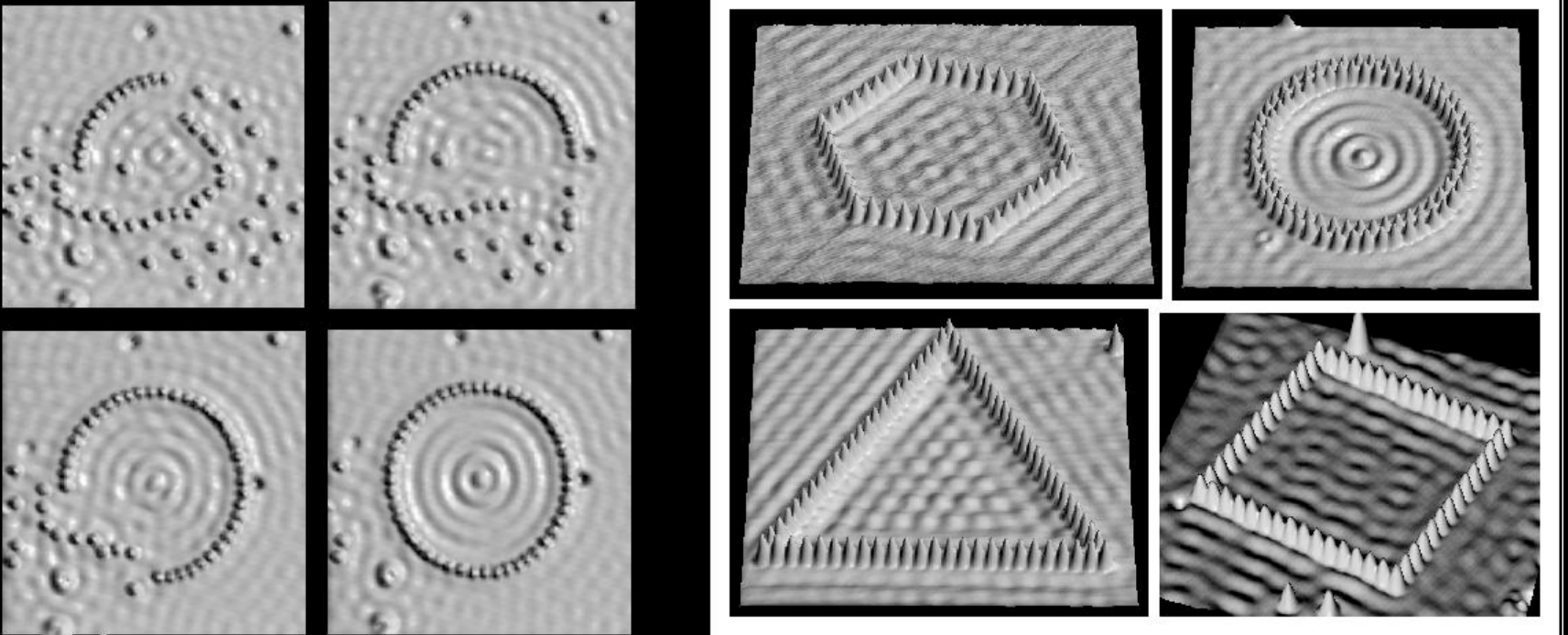


FIG. 3. Lifetimes of surface state electrons as a function of excess energy determined as described in the text. The dotted line depicts the lifetimes predicted by 3D FLT for Cu [25]: $\tau = (22.4 \text{ fs eV}^2)(E - E_F)^{-2}$. The inset shows the same data on a double logarithmic scale. The best inverse quadratic fit to the Cu data yields $\tau = (17.1 \text{ fs eV}^2)(E - E_F)^{-2}$ (full line).

Particle in a box

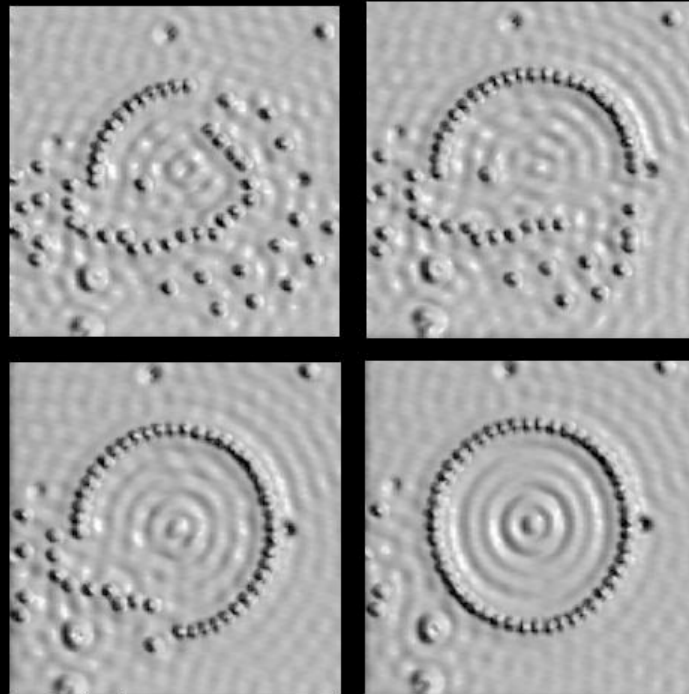
Surface waves : states that decay into the bulk of the sample

Adsorbates at 4K can be used to confine these states into artificial boxes



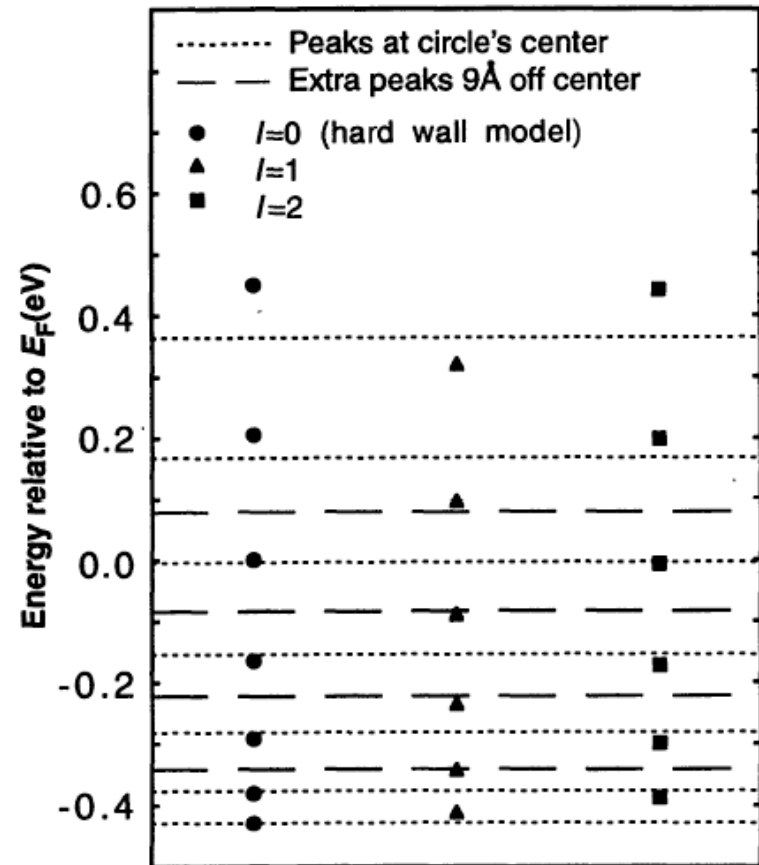
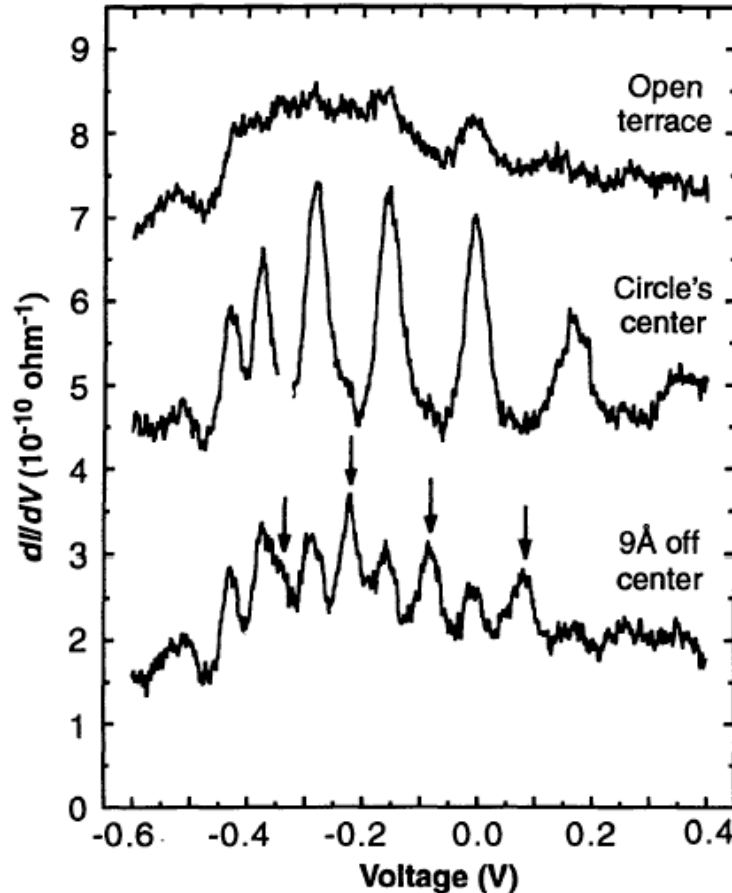
Example: Iron atom corrals on
Cu(111) Crommie and Eigler
1992-3

Spectroscopy of particle in a box states



Crommie and Eigler- 1992-93

Spectroscopy of particle in a box states



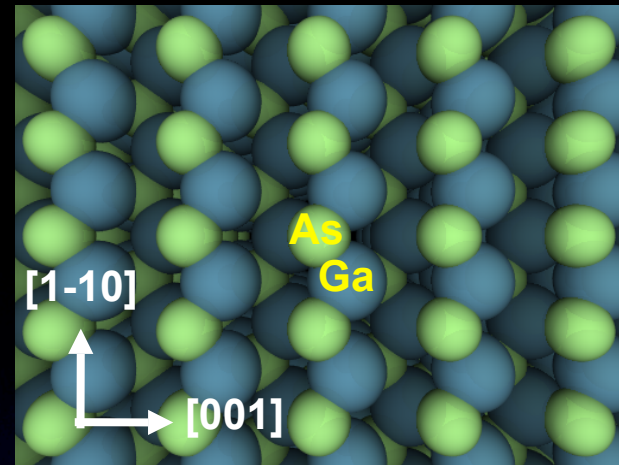
Crommie and Eigler- 1992-93

STM on Semiconductors

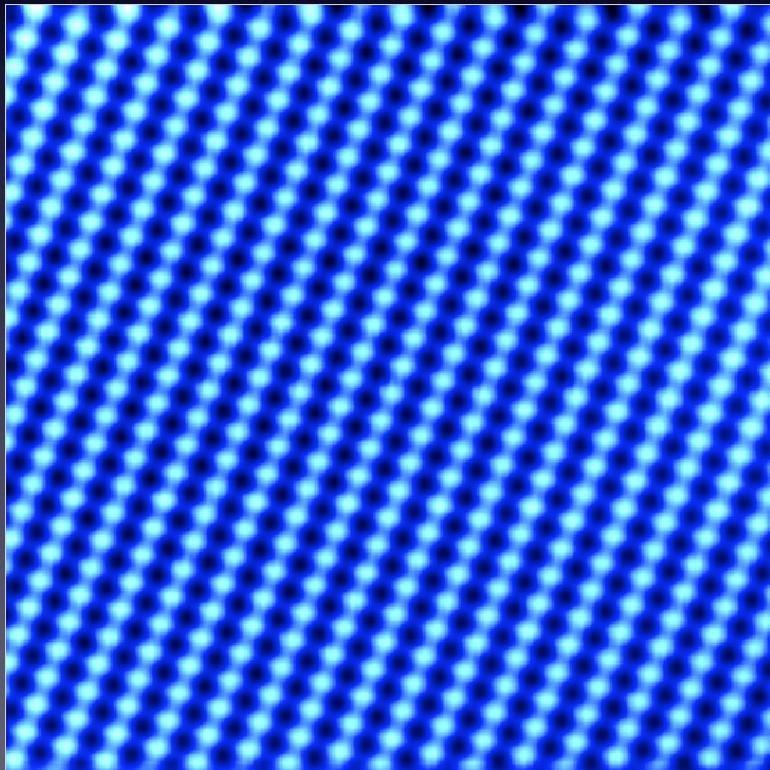
Imaging Single Dopants

STM on GaAs (110) surface

- Easily cleaved (110) surface—exposed in UHV
- Simple buckling of the surface bonds
- Ga or As atoms via empty or filled states
- STM can be used to image individual acceptors &

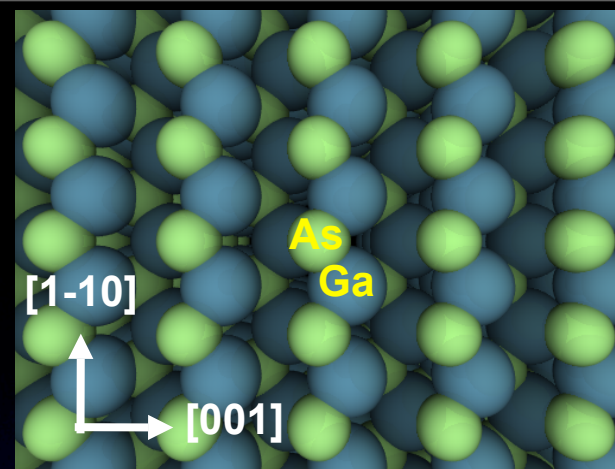


donors Ga atoms on GaAs surface
Empty states, +1.6V
100Å x 100Å

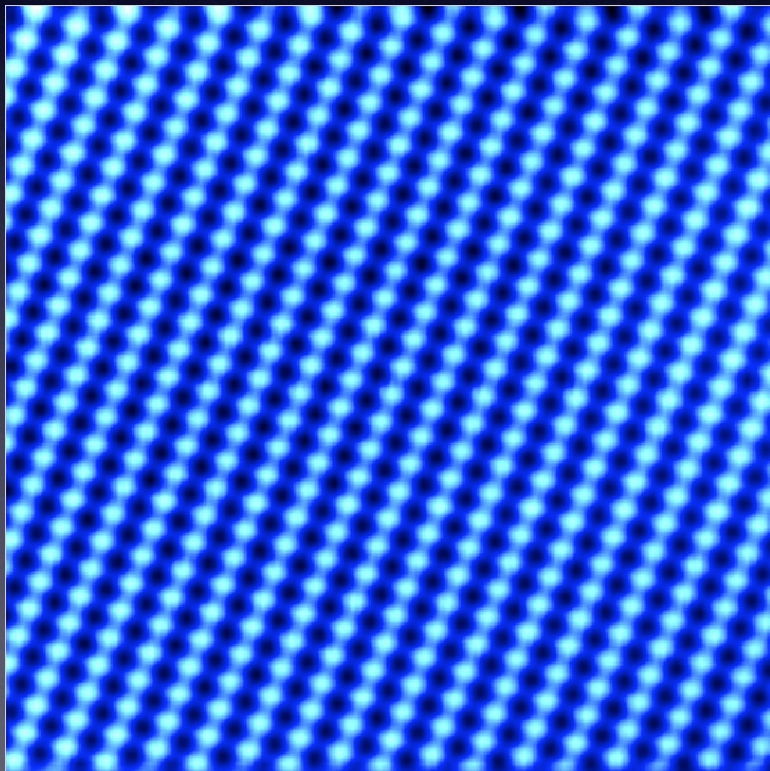


STM on GaAs (110) surface

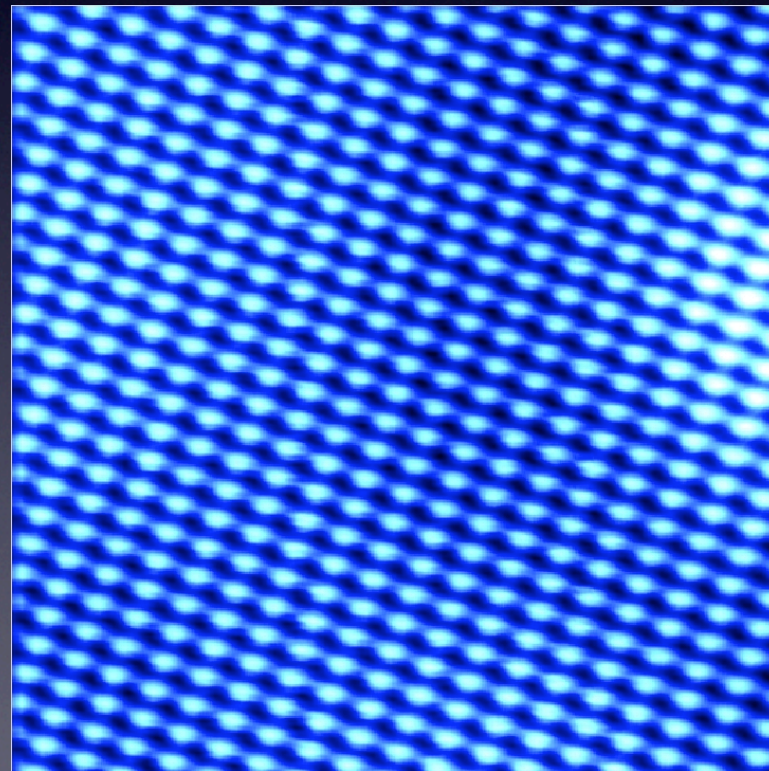
- Easily cleaved (110) surface—exposed in UHV
- Simple buckling of the surface bonds
- Ga or As atoms via empty or filled states
- STM can be used to image individual acceptors &



donors Ga atoms on GaAs surface
Empty states, $+1.6V$
 $100\text{\AA} \times 100\text{\AA}$

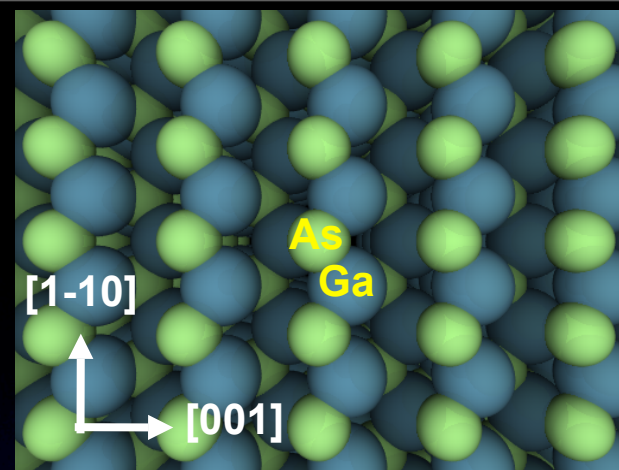


As atoms on GaAs surface
Filled States, $-1.6V$
 $100\text{\AA} \times 100\text{\AA}$



STM on GaAs (110) surface

- Easily cleaved (110) surface—exposed in UHV
- Simple buckling of the surface bonds
- Ga or As atoms via empty or filled states
- STM can be used to image individual acceptors &

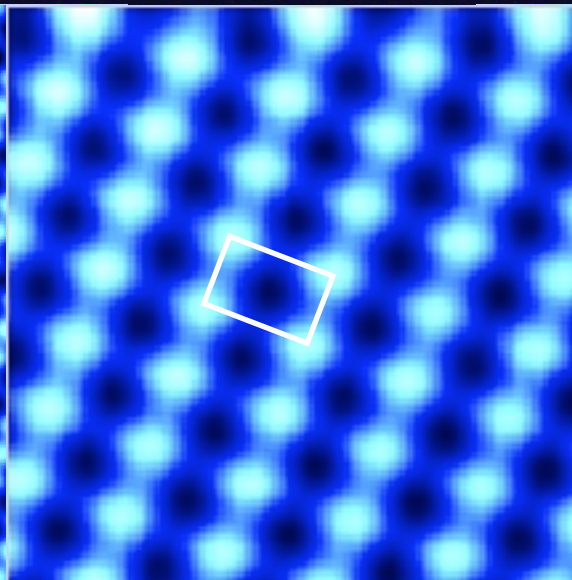
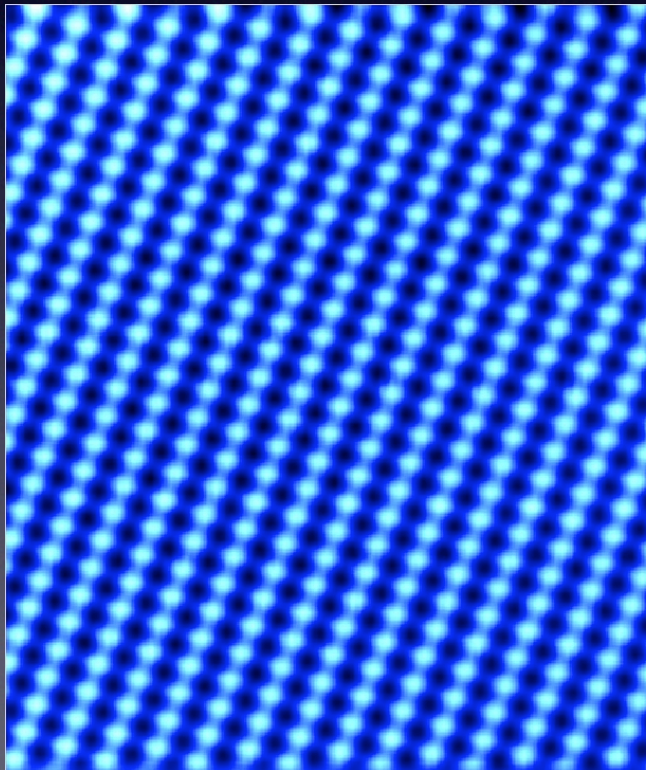


donors

Ga atoms on GaAs surface
Empty states, +1.6V
100Å × 100Å

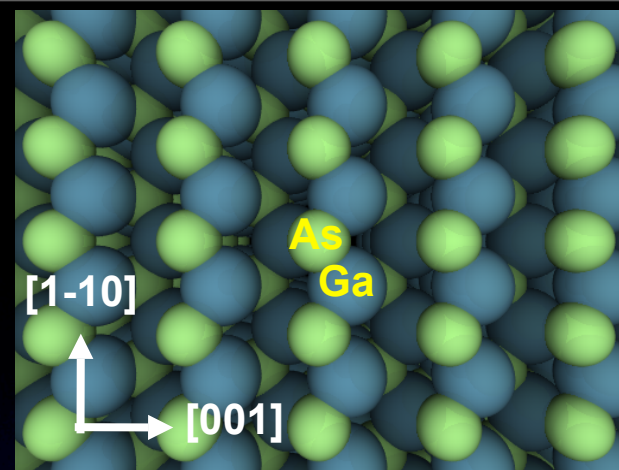
Ga atoms on GaAs surface
Empty states, +1.6V
30Å × 30Å

As atoms on GaAs surface
Filled States, -1.6V
100Å × 100Å



STM on GaAs (110) surface

- Easily cleaved (110) surface—exposed in UHV
- Simple buckling of the surface bonds
- Ga or As atoms via empty or filled states
- STM can be used to image individual acceptors &

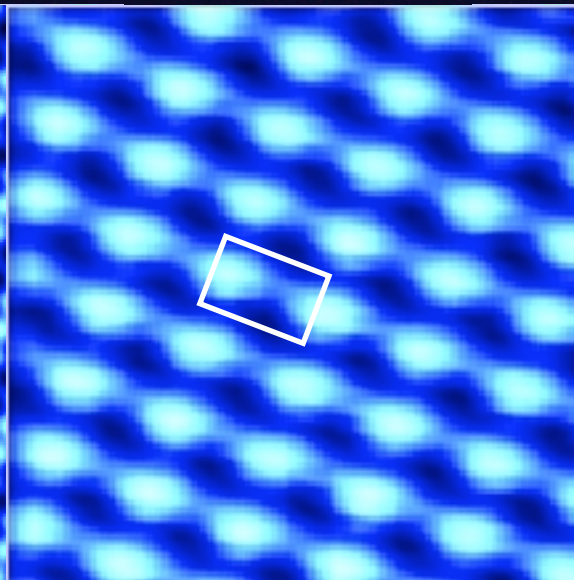
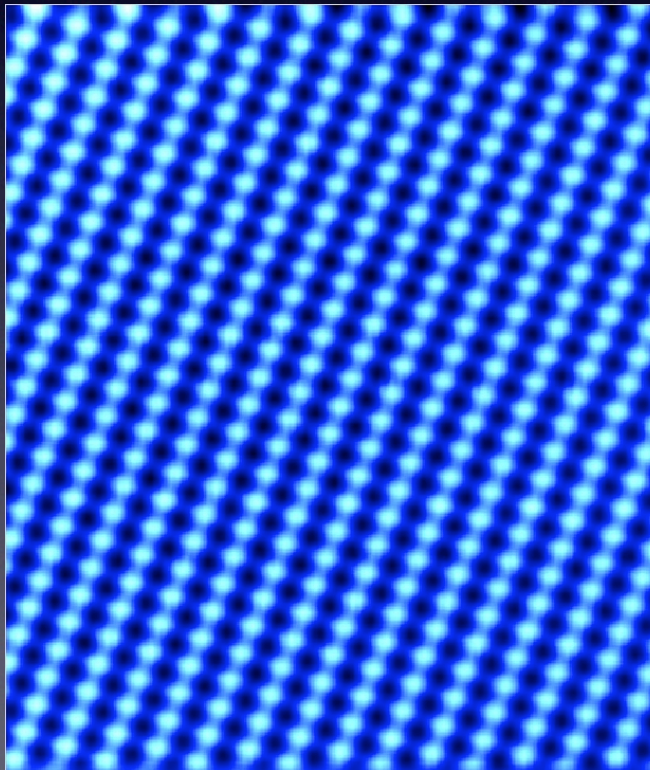


donors

Ga atoms on GaAs surface
Empty states, +1.6V
100Å × 100Å

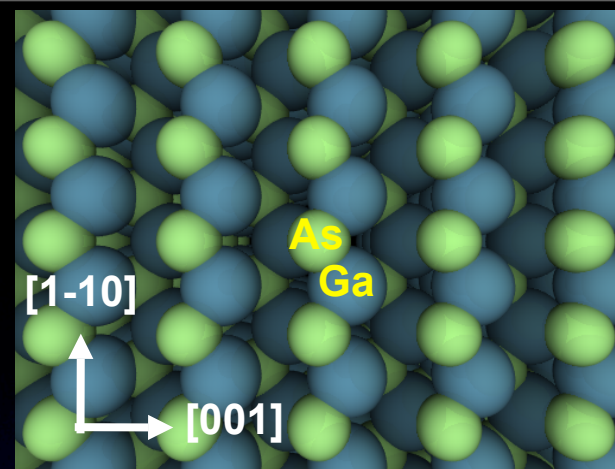
As atoms on GaAs surface
Filled States, -1.6V
30Å × 30Å

As atoms on GaAs surface
Filled States, -1.6V
100Å × 100Å

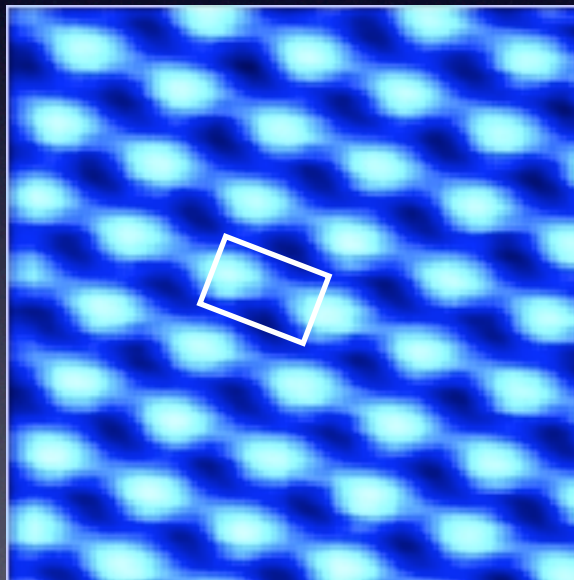


STM on GaAs (110) surface

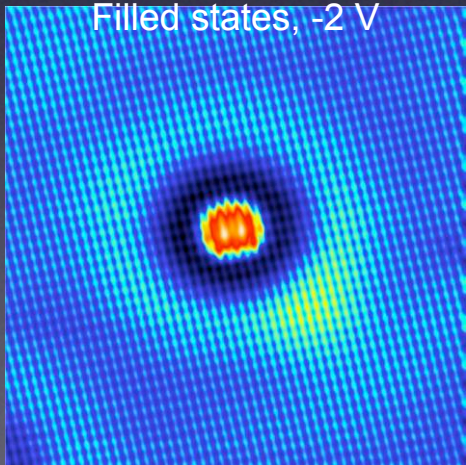
- Easily cleaved (110) surface—exposed in UHV
- Simple buckling of the surface bonds
- Ga or As atoms via empty or filled states
- STM can be used to image individual acceptors & donors



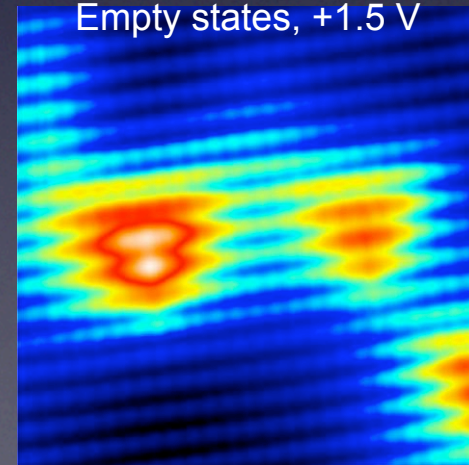
As atoms on GaAs surface
Filled States, -1.6V
 $30\text{\AA} \times 30\text{\AA}$



Si dopant in n-type
GaAs
Filled states, -2 V



Zn dopants in p-type
GaAs
Empty states, +1.5 V



Substrate: n-type GaAs(110) Single Si-donors

Feesntra et al 2002

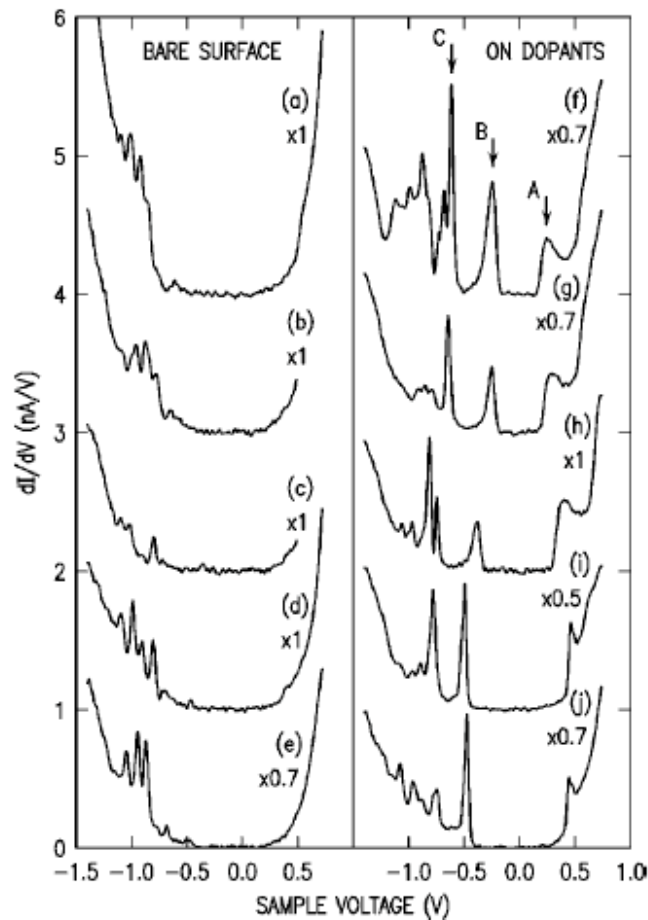


FIG. 3. Tunneling spectra acquired at the surface locations indicated in Fig. 1. Spectra *a*–*e* were acquired at locations far from dopant atoms, and spectra *f*–*j* were acquired directly on top of dopant atoms. Each spectrum is multiplied by the factor indicated prior to plotting, for ease of viewing. Successive spectra are shifted by one unit along the vertical axis. Discrete spectral lines observed at the dopant atoms are indicated by A, B, and C.

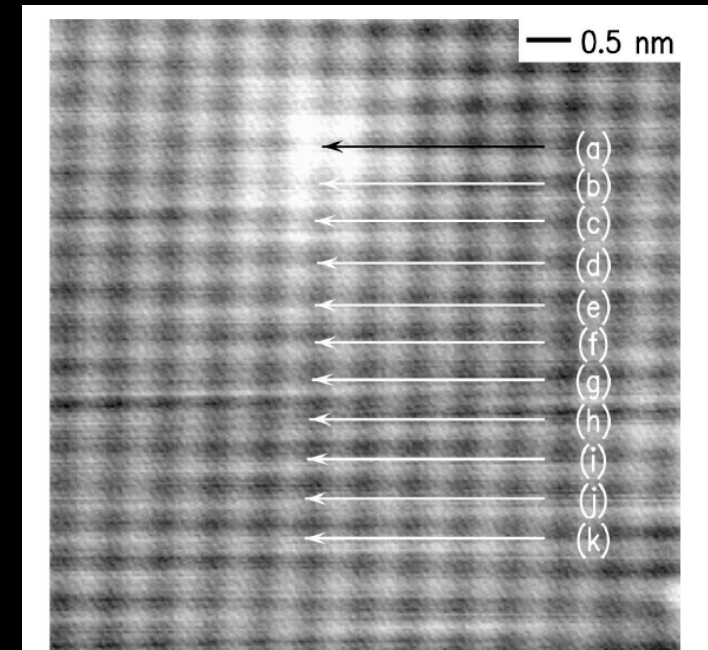
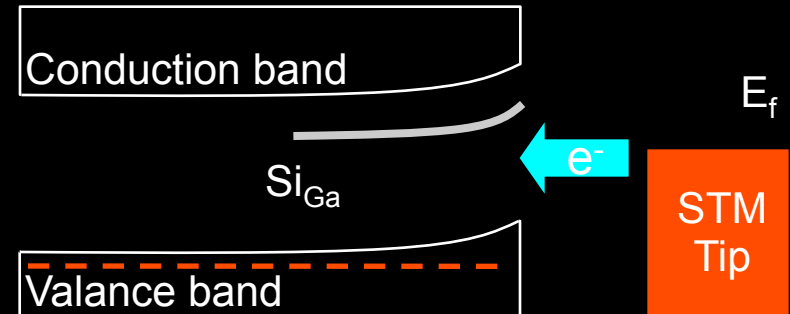


FIG. 4. Constant-current STM image of dopant atom, acquired with a sample voltage of +1.8 V and displayed with gray scale of 0.17 Å. Locations at which spectra were acquired are indicated.

Substrate: n-type GaAs(110) Single Si-donors

Feesntra et al 2002

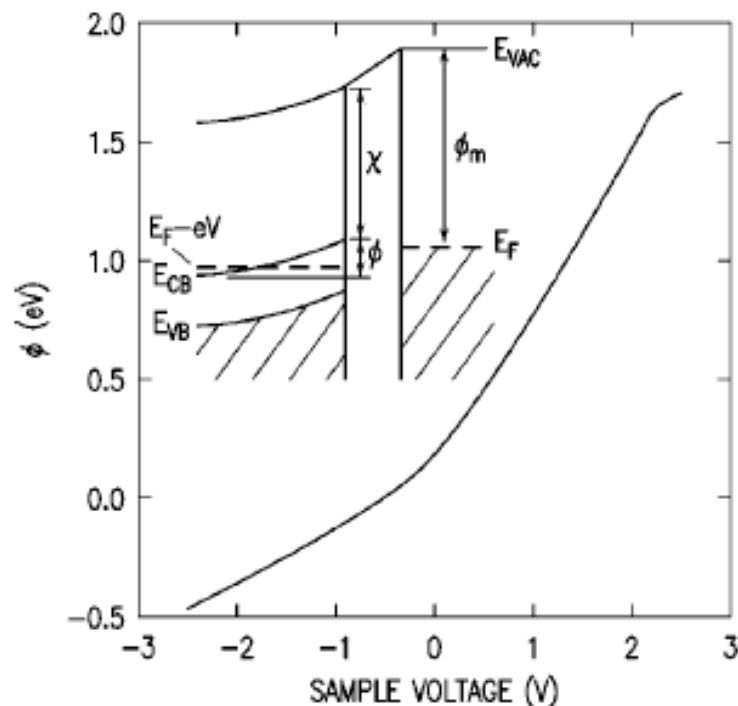


FIG. 7. Theoretical results for surface band bending ϕ as a function of sample-tip voltage. Computations are performed with tip work function $\phi_m = 4.5$ eV, sample electron affinity $\chi = 4.07$ eV, sample-tip separation of $9 \text{ \AA}$, n-GaAs doping density of $2 \times 10^{18} \text{ cm}^{-3}$, and at a temperature of 10 K.

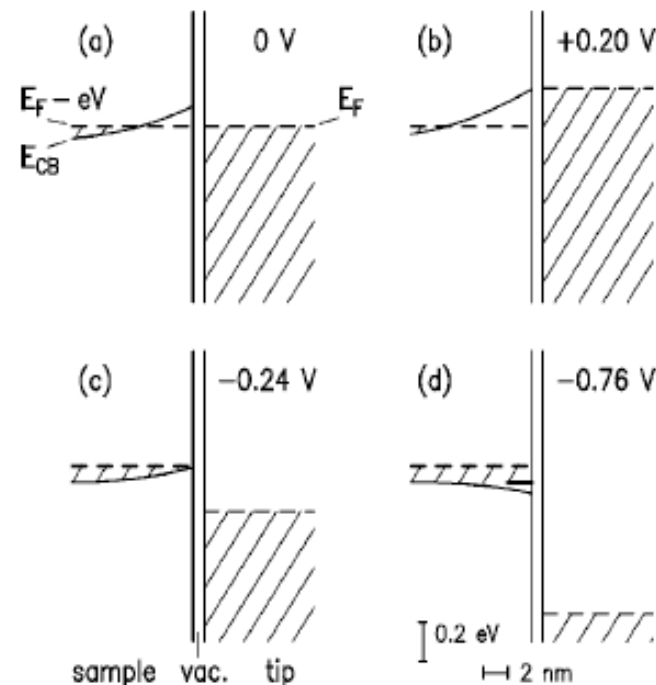
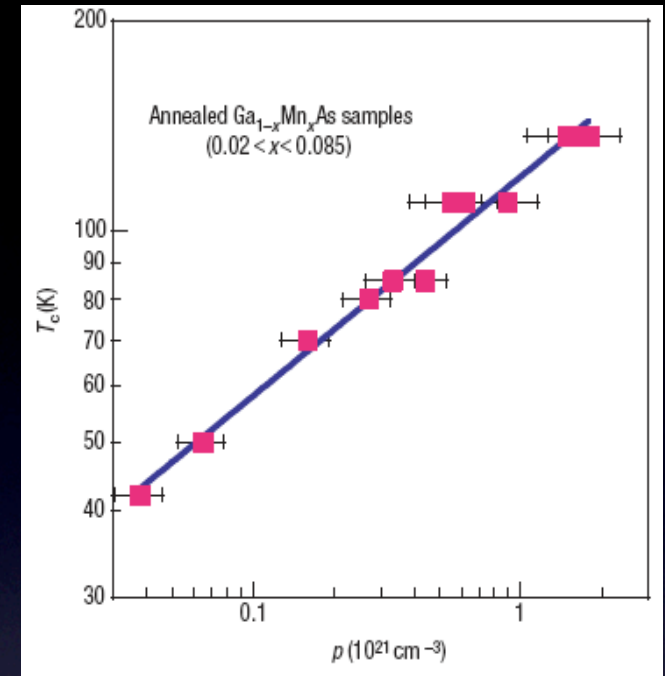


FIG. 8. Theoretical band profiles at energies near the Fermi levels of the metal probe tip and the semiconductor sample. Profiles are drawn to scale in both energy and distance. Case (a) shows the band profile for zero voltage between the sample and the tip. Cases (b)–(d) show cases that correspond to the observed spectral lines A–C, respectively. The heavy line in case (d) indicates a localized accumulation layer state, just forming at that energy.

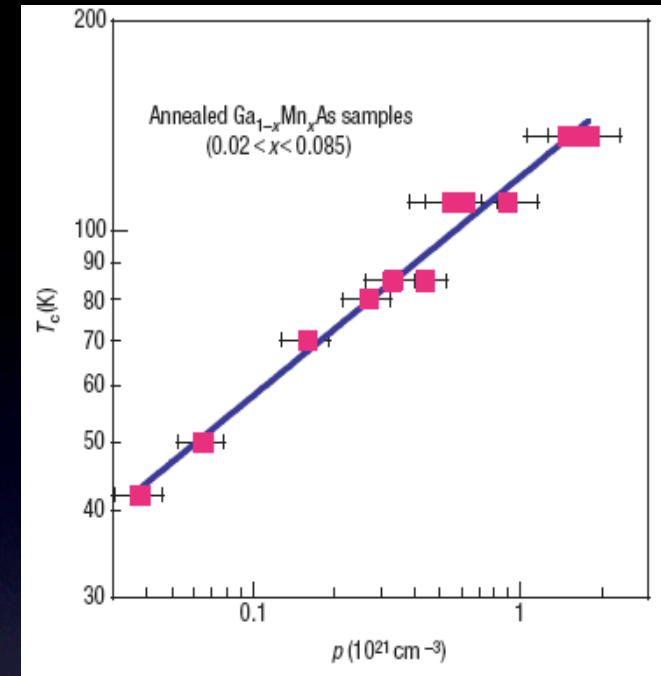
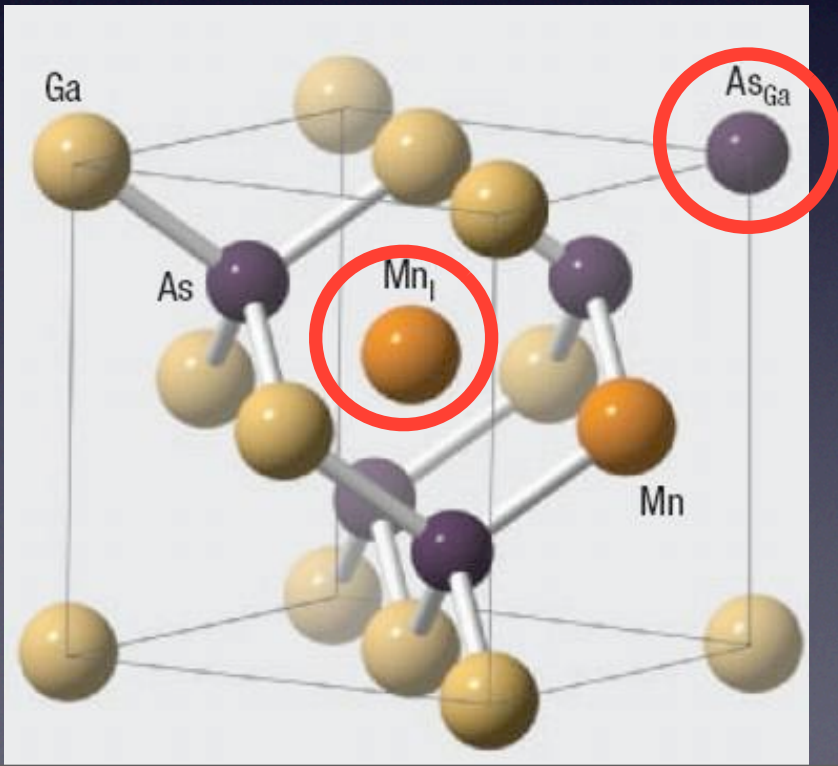
High-Temperature Ferromagnetism in GaAs with Mn doping

- Mn-doping makes GaAs ferromagnetic
- Mn contributed spins & holes
- Mn in Ga site an acceptor
- Holes make GaAs both conducting and couples the spins
- Low T-MBE various defects present



High-Temperature Ferromagnetism in GaAs with Mn doping

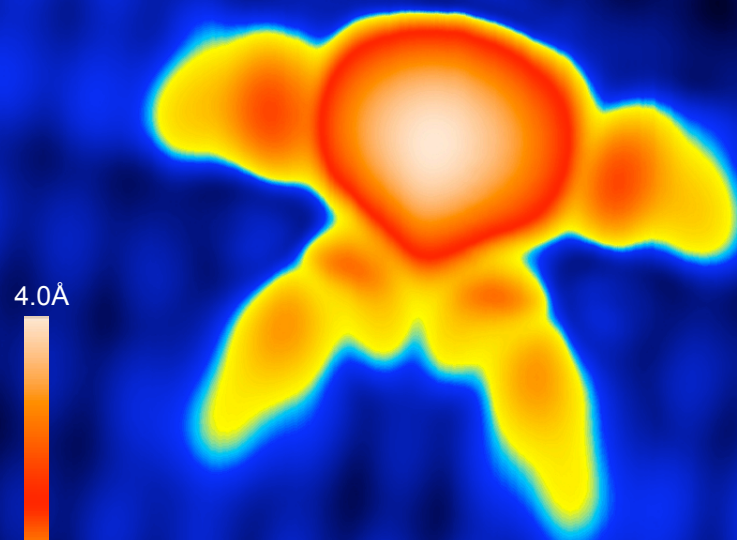
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- Holes make GaAs both conducting and couples the spins
- Low T-MBE various defects present



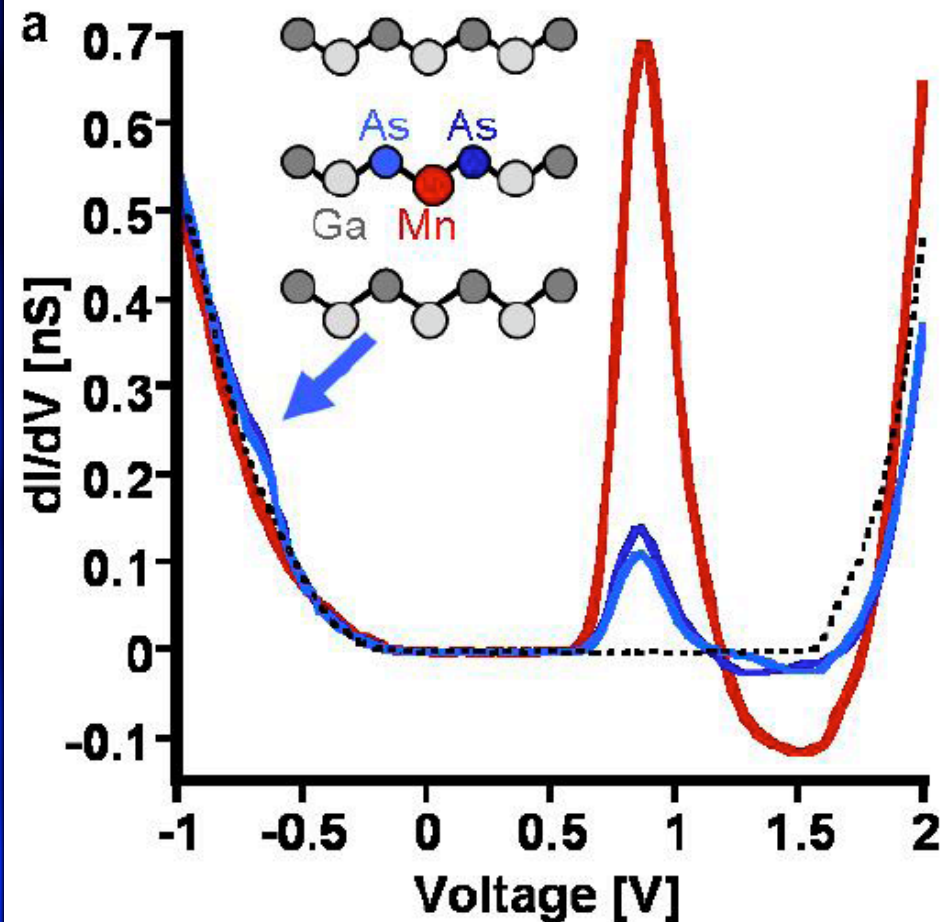
Mn-Acceptor State in GaAs (Kitchen et al. 2006)

- Mn modifies DOS of neighboring atoms inducing changes to valence band
- Modifications are anisotropic, modifying strongly along $\langle 110 \rangle$ directions
- Large in-gap acceptor level shows wavefunction of highly anisotropic character

Image of Mn's acceptor state



Empty states, $40\text{\AA}^2$

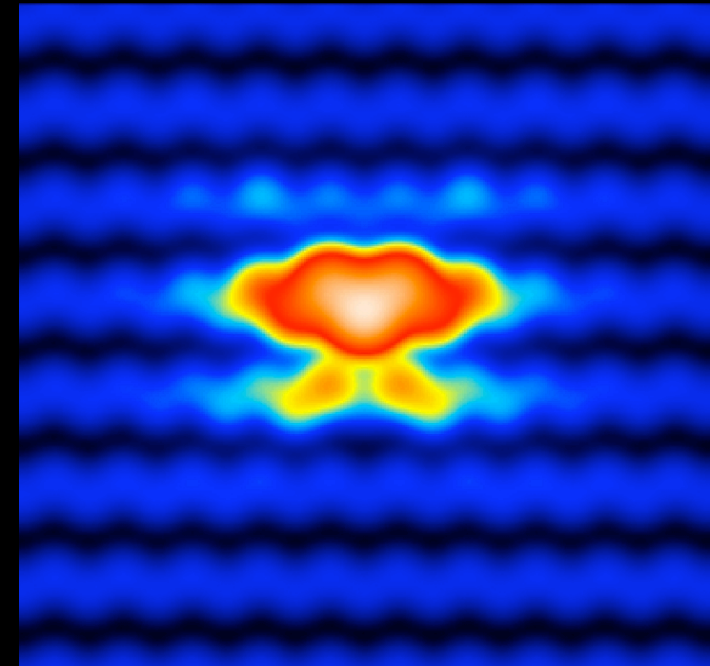
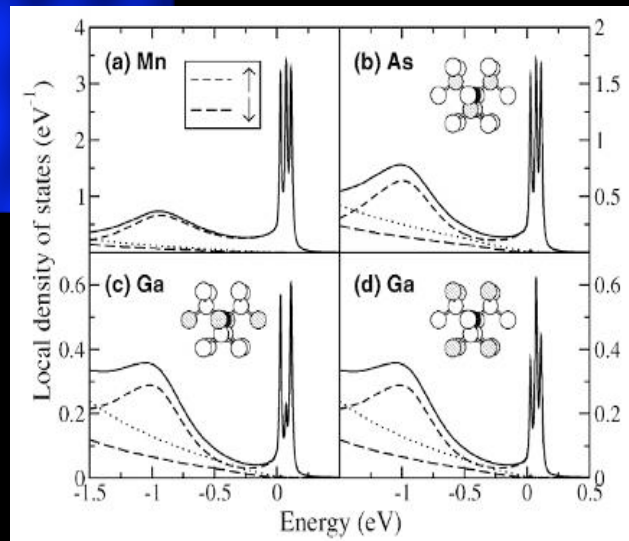
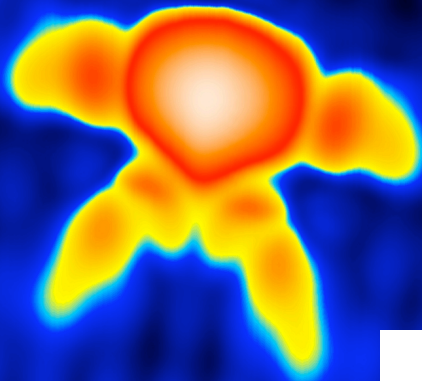


Mn-Acceptor State in GaAs

- Mn modifies DOS of neighboring atoms inducing changes to valence band
- Modifications are anisotropic, modifying strongly along $\langle 110 \rangle$ directions
- Large in-gap acceptor level shows wavefunction of highly anisotropic character

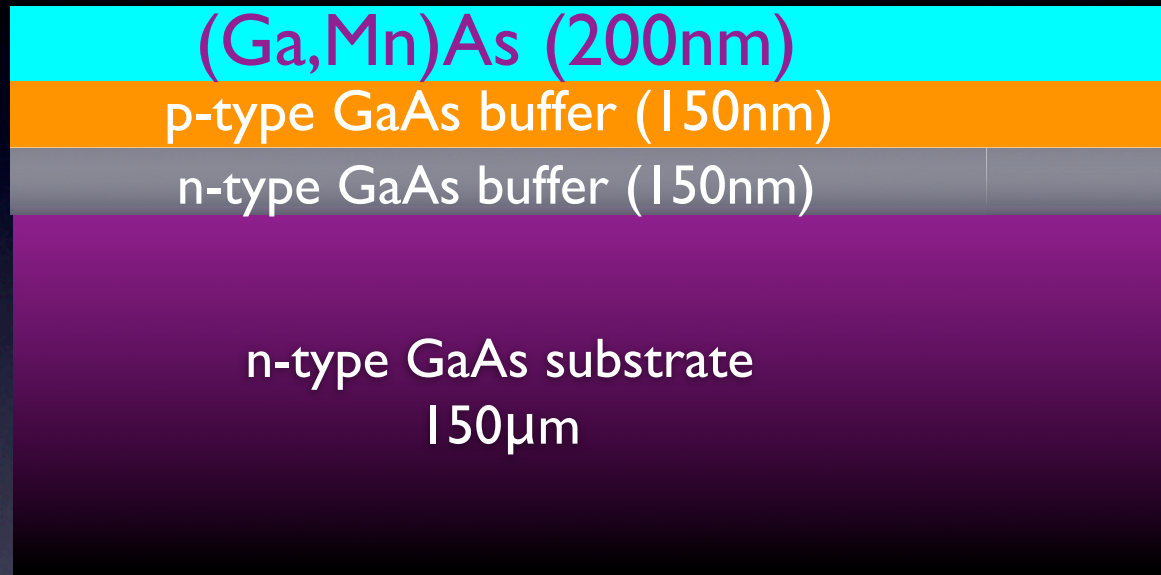
$$H = H_0 + V$$

$$V = U_0 \sum_{\ell, s} c_{\ell s}^\dagger(\mathbf{R}_0) c_{\ell s}(\mathbf{R}_0) + U_1 \sum_{j=1}^4 \sum_{\ell} c_{\ell 1}^\dagger(\mathbf{R}_j) c_{\ell 1}(\mathbf{R}_j)$$

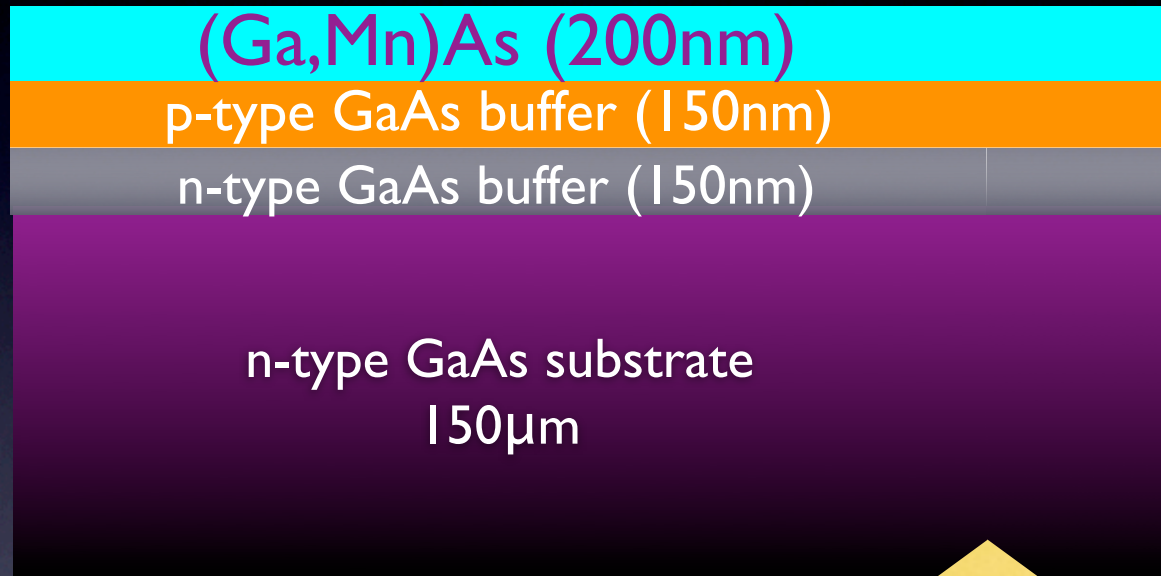


- Bulk calculation viewed in the 110 direction
- Tang et al PRL (2004)

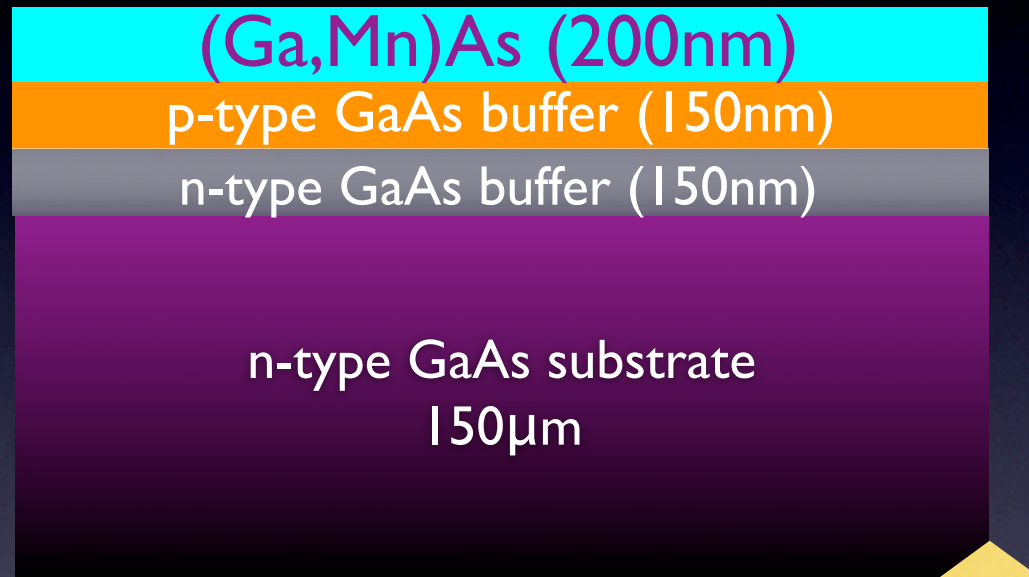
X-STM of $\text{Ga}_{1-x}\text{Mn}_x\text{As}$ Heterostructures



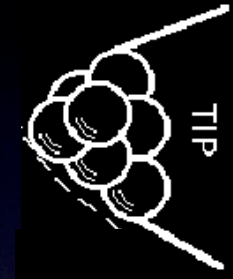
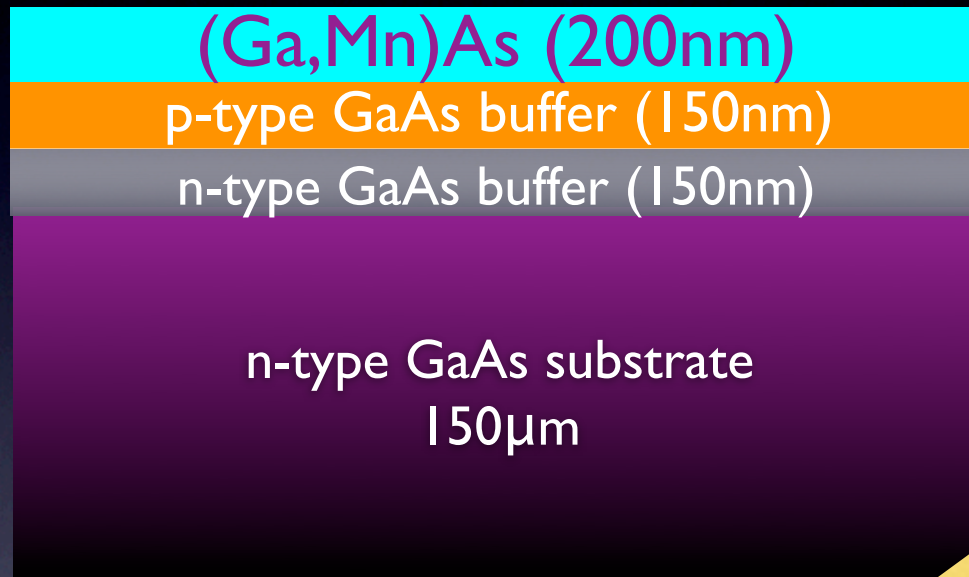
X-STM of $\text{Ga}_{1-x}\text{Mn}_x\text{As}$ Heterostructures



X-STM of $\text{Ga}_{1-x}\text{Mn}_x\text{As}$ Heterostructures



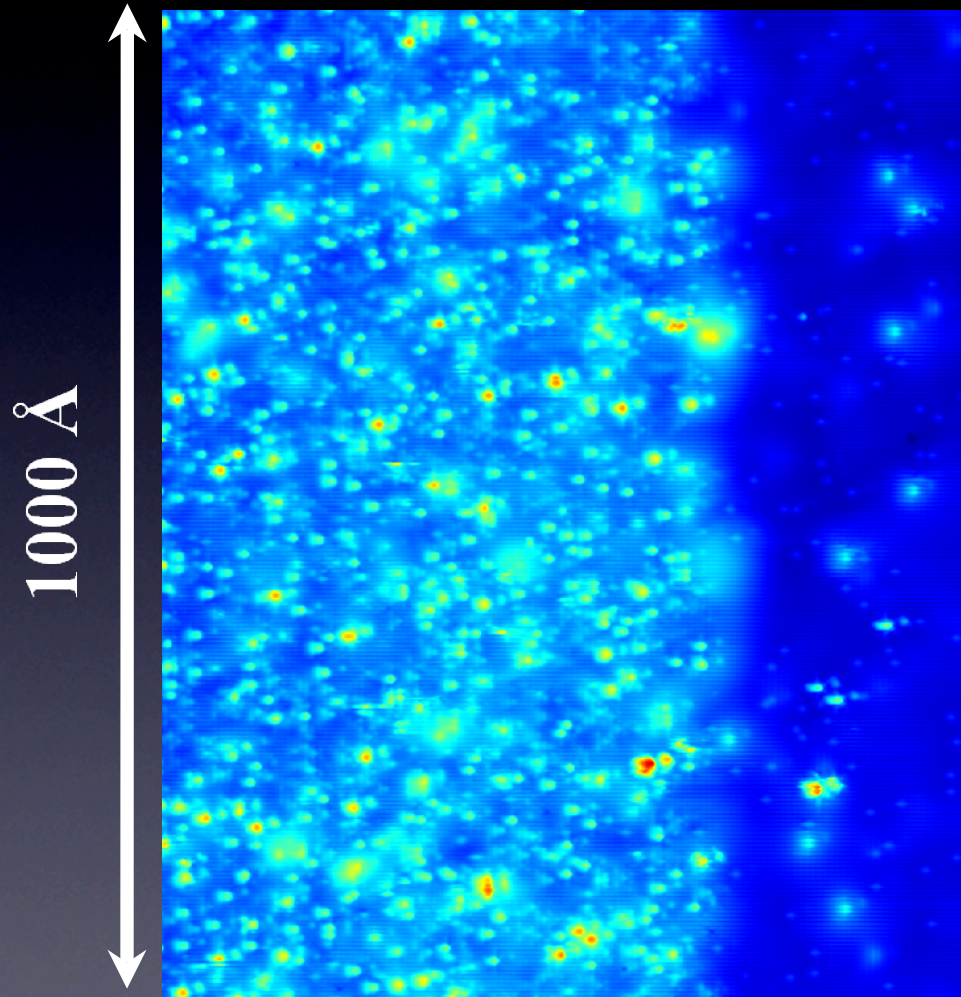
X-STM of $\text{Ga}_{1-x}\text{Mn}_x\text{As}$ Heterostructures



GaAs/Ga_{1-x}Mn_xAs Hetrostructures

- 1.5% doped sample
- T_c ~ 25K as grown

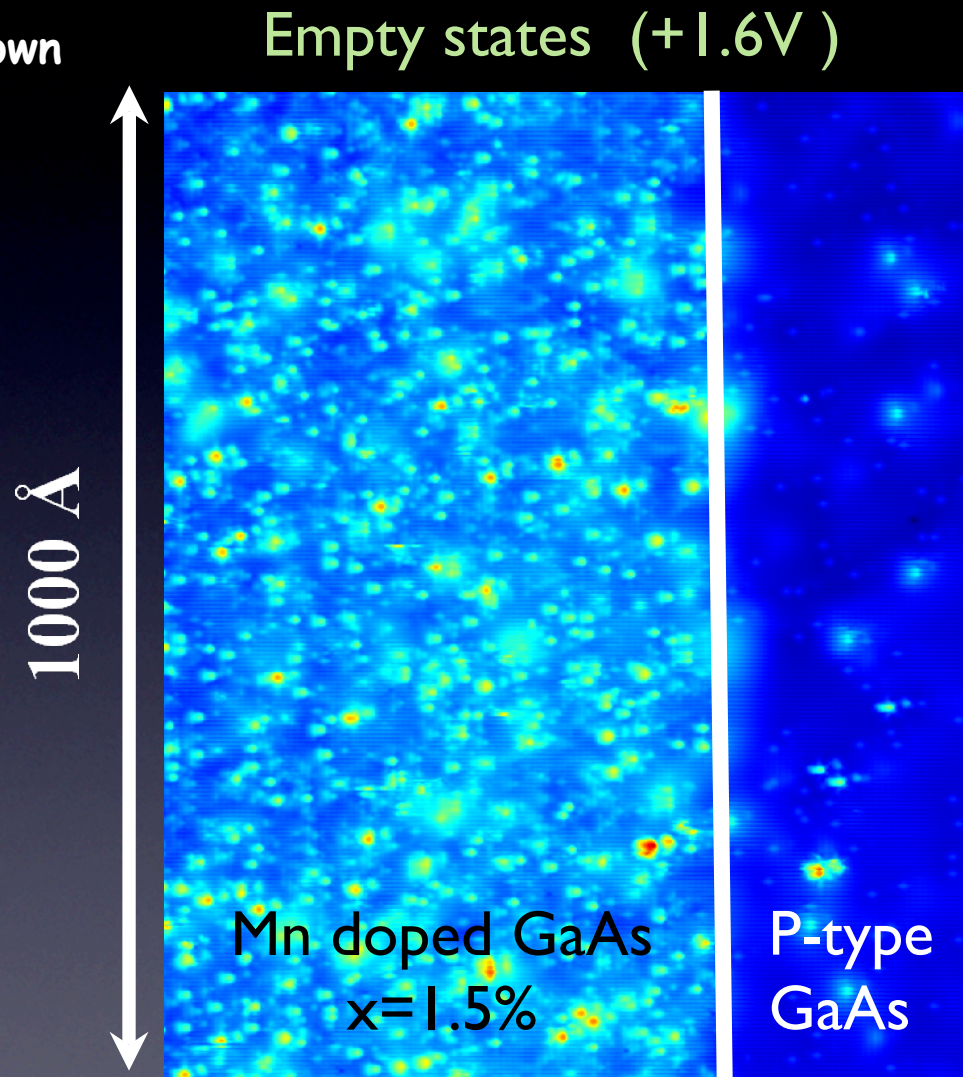
Empty states (+1.6V)



Grown at UCSB

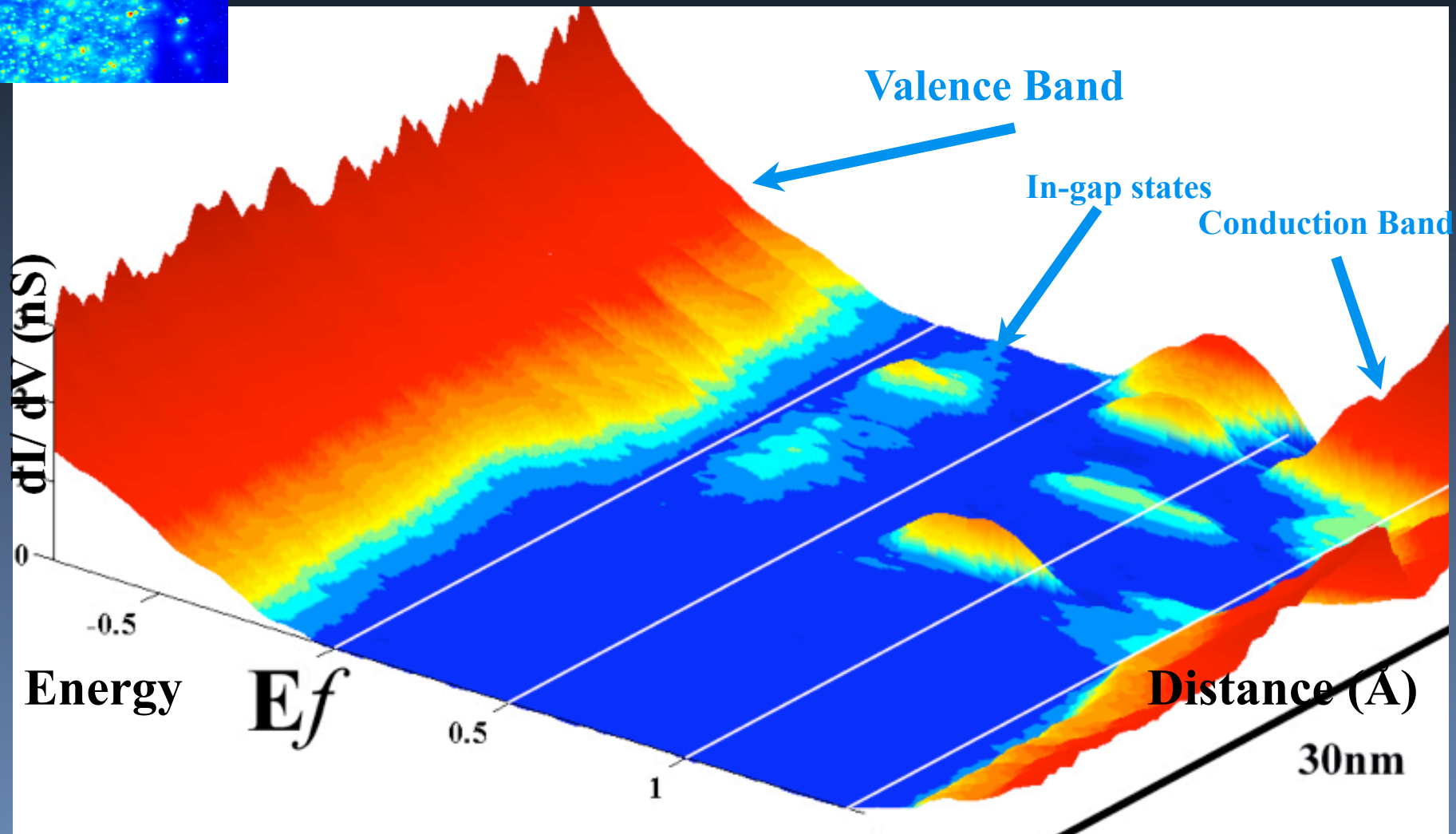
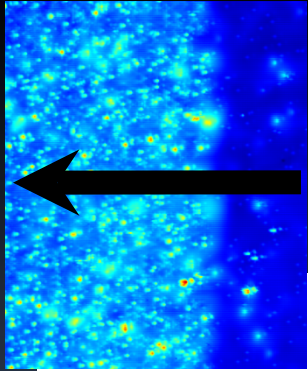
GaAs/Ga_{1-x}Mn_xAs Hetrostructures

- 1.5% doped sample
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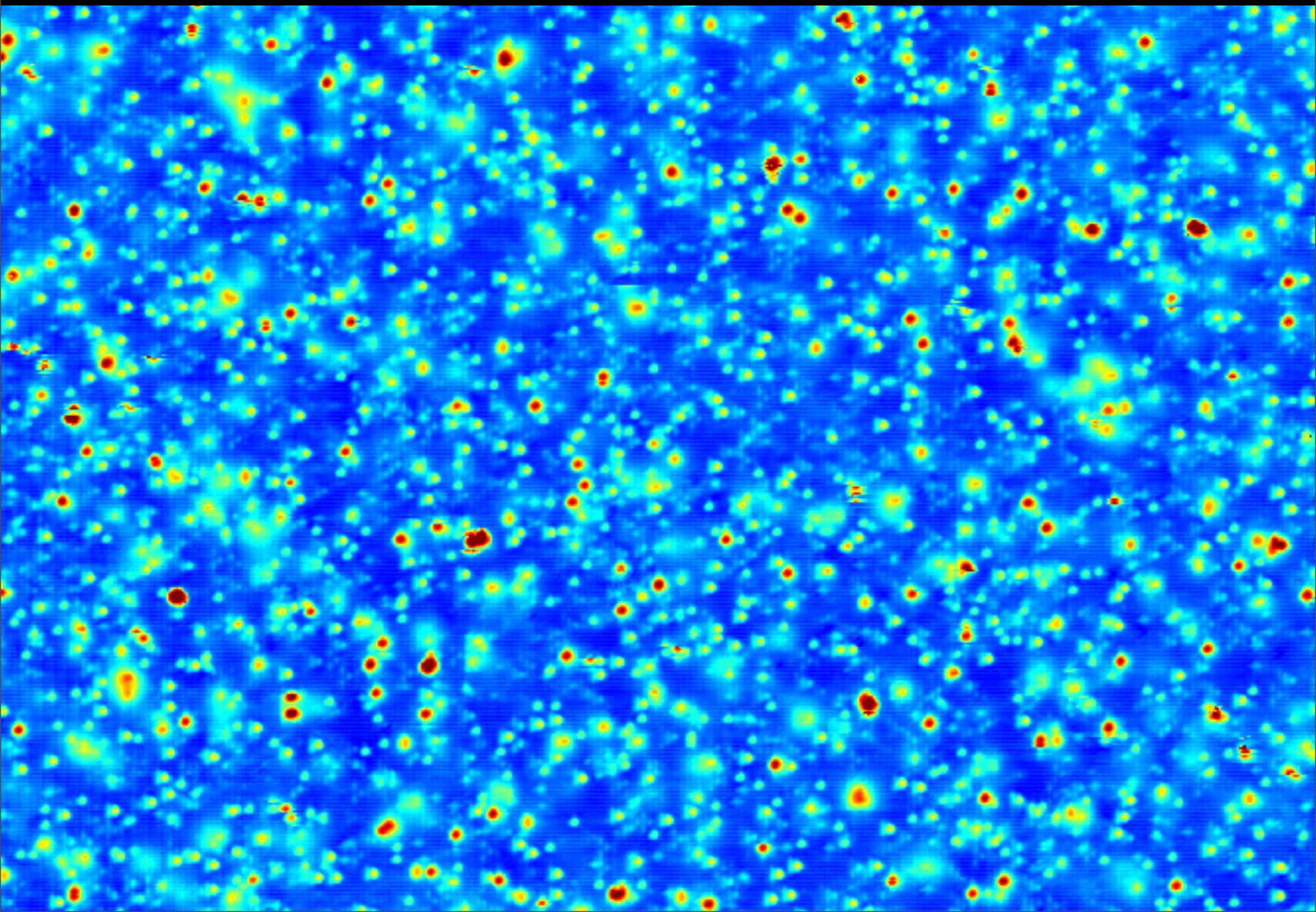


Grown at UCSB

dI / dV measurements across GaAs / $\text{Mn}_{0.015}\text{Ga}_{0.985}\text{As}$ Junction

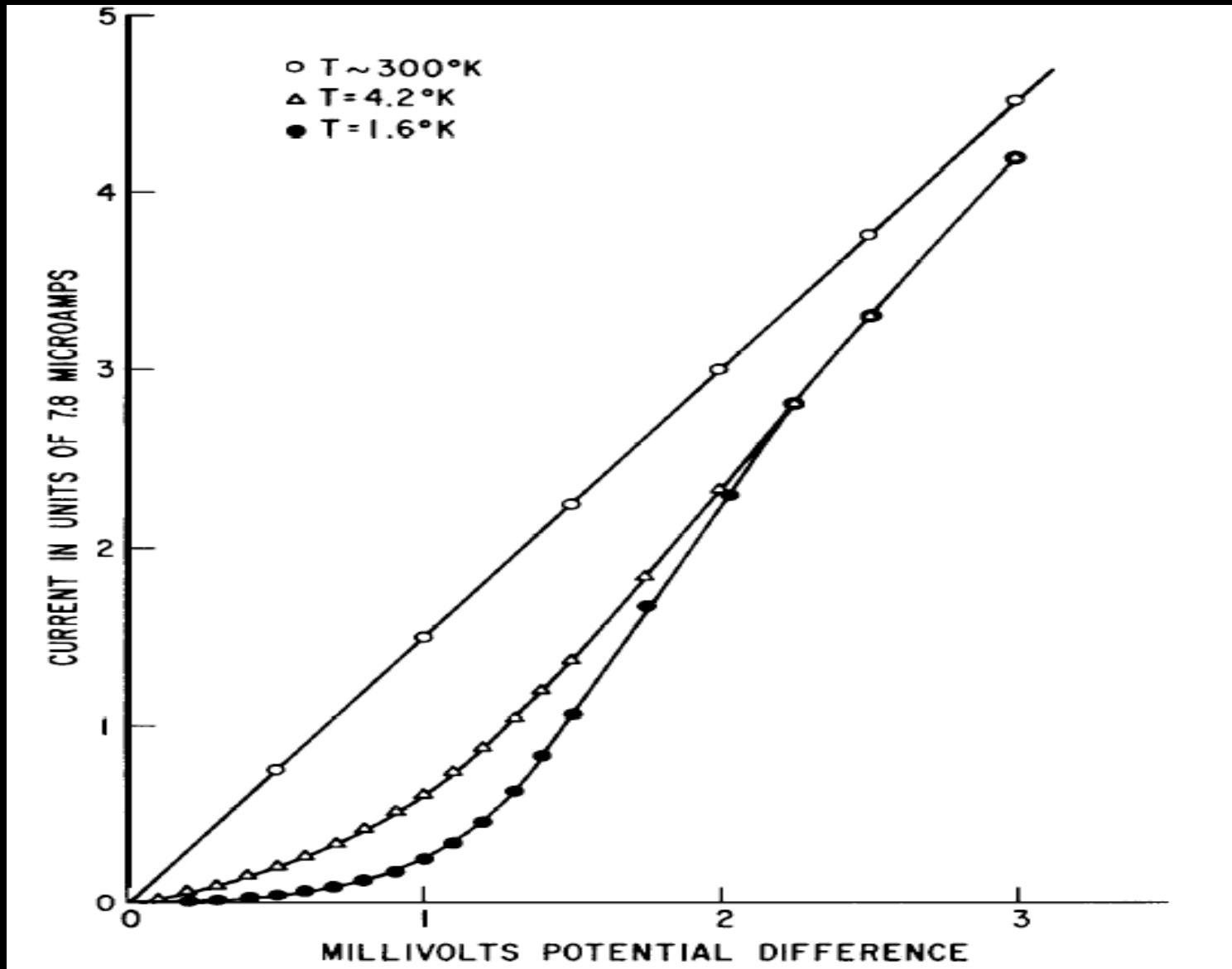


← 1300Å →



STM on Superconductors

Giaever Tunneling: Planar Tunneling into a superconductor (1963)



BCS Density of States

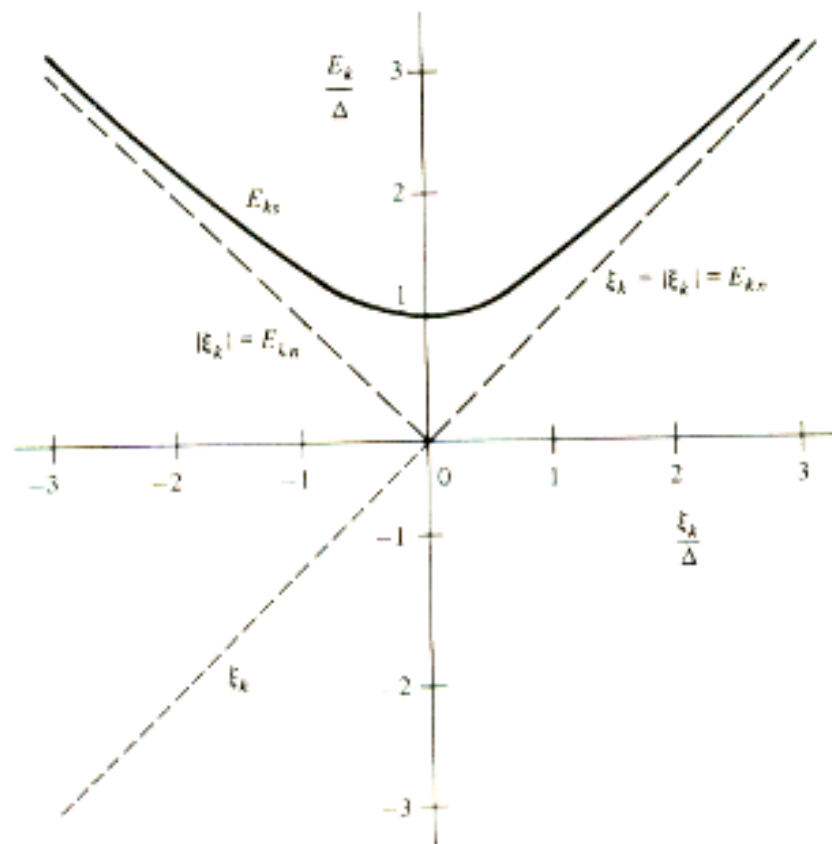


FIGURE 2-5
Energies of elementary excitations in the normal and superconducting states as functions of ξ_k , the independent-particle kinetic energy relative to the Fermi energy.

BCS Density of States

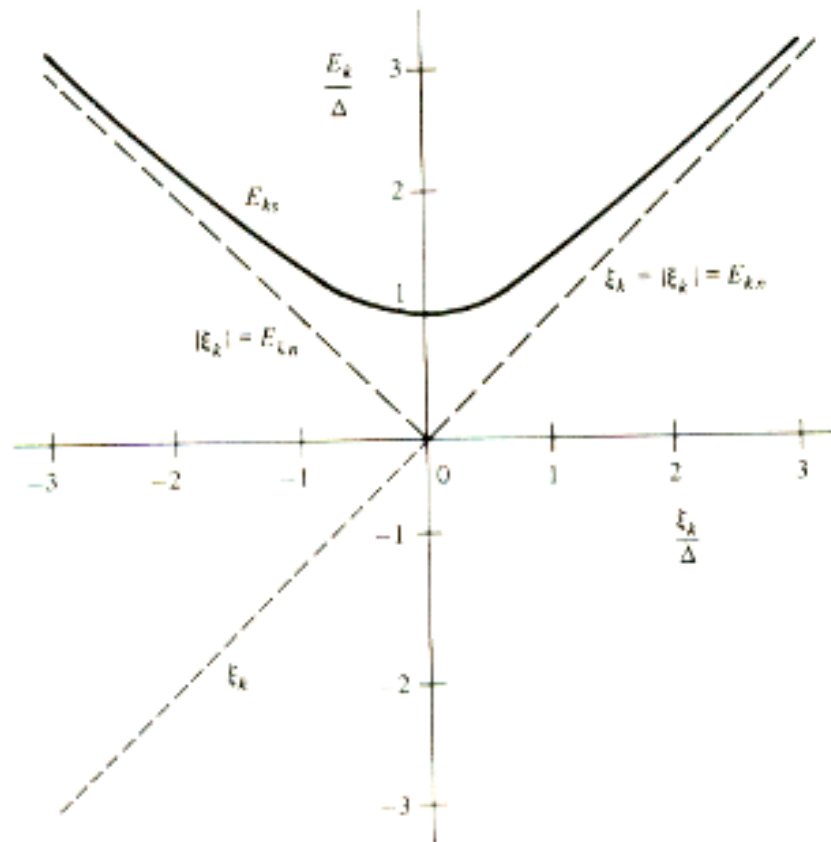
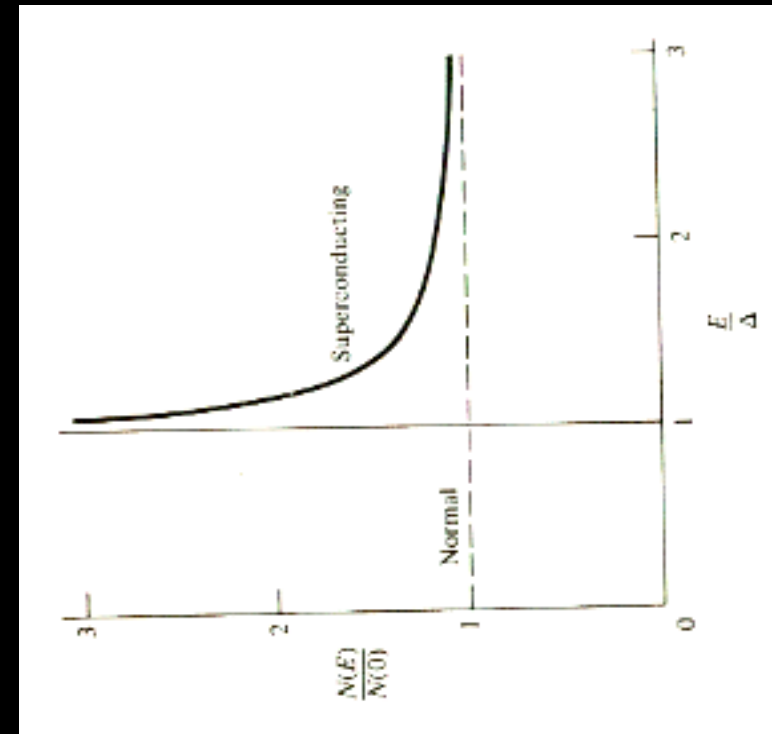


FIGURE 2-5
Energies of elementary excitations in the normal and superconducting states as functions of ξ_k , the independent-particle kinetic energy relative to the Fermi energy.



Quantum Tunneling of Electrons as a probe of superconductivity & pairing:

Planar Tunneling into a superconductor Giaever (1963)

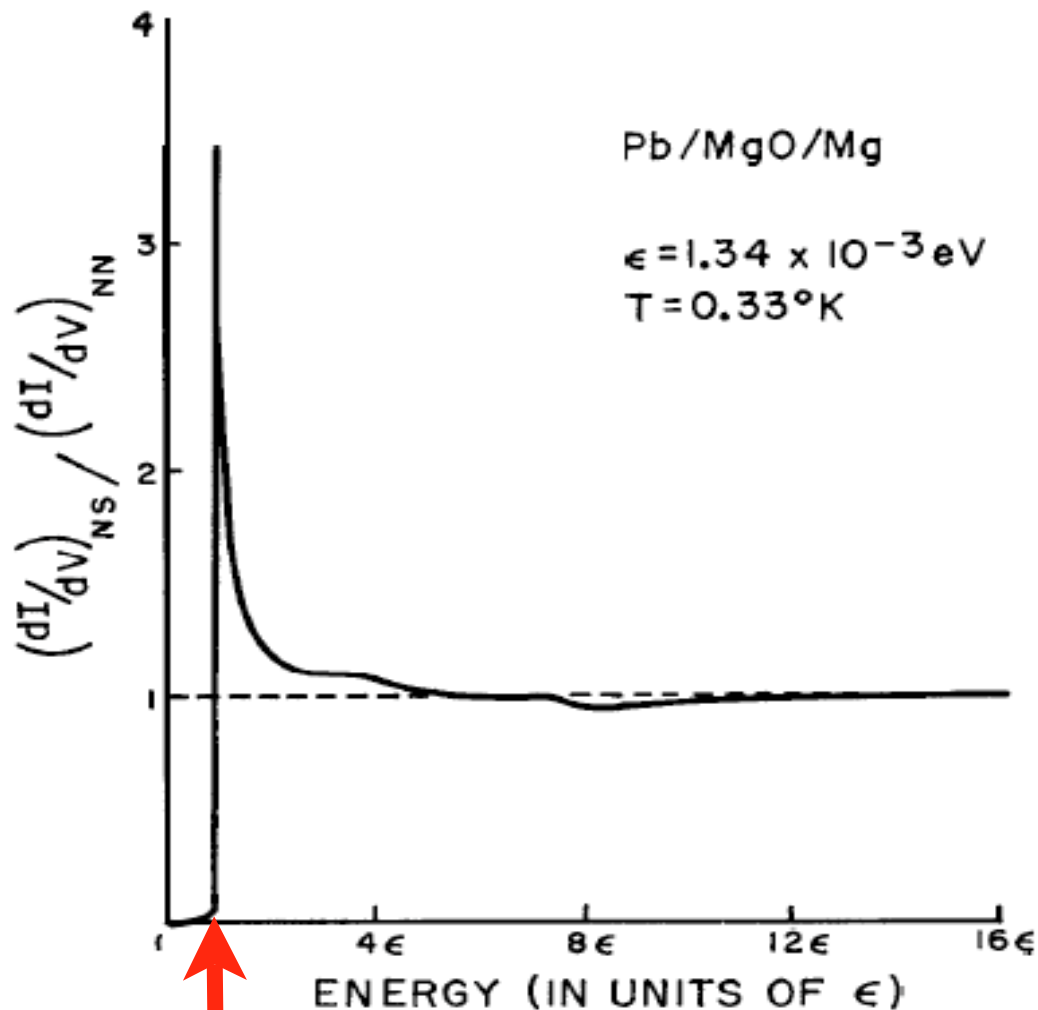
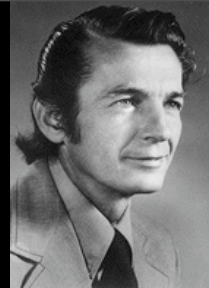
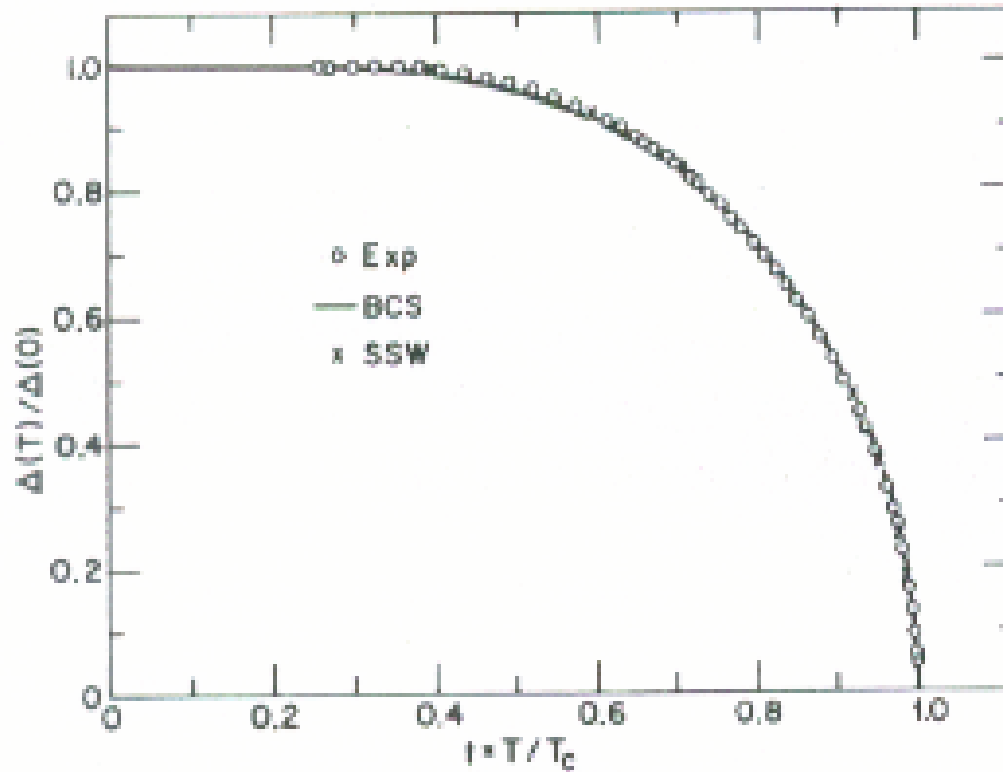
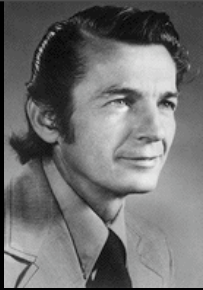


Fig. 2.

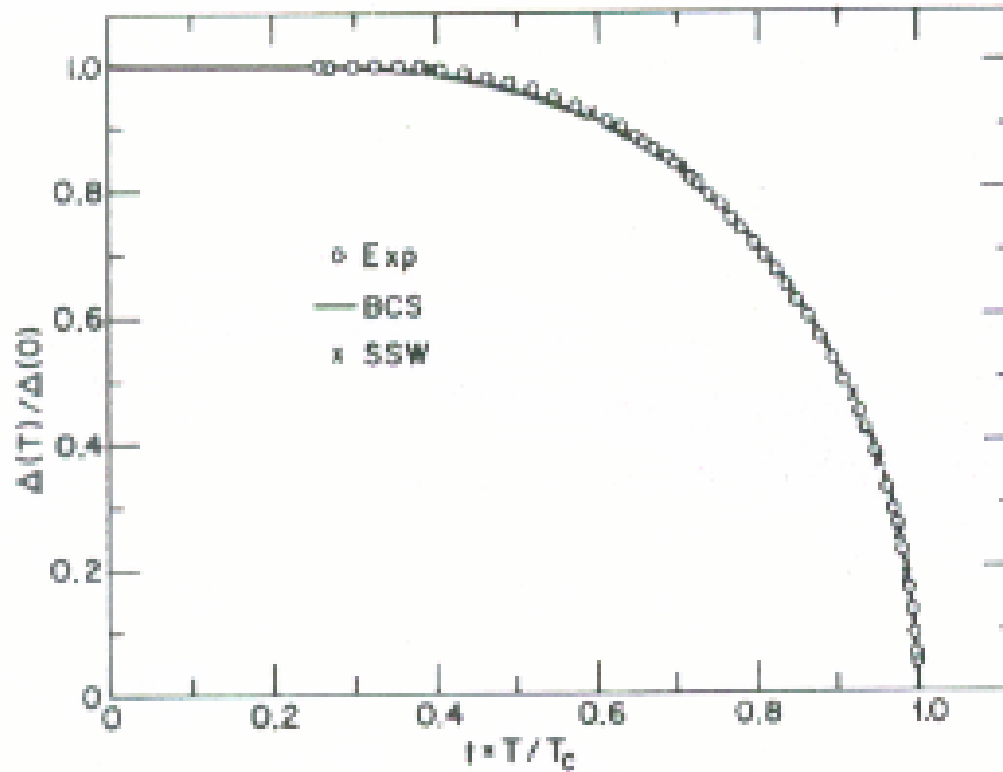
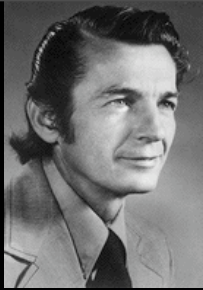
Conductance of a Pb-Mg junction as a function of applied voltage (from reference 24).

Quantum Tunneling of Electrons as a probe of superconductivity & pairing: Planar Tunneling into a superconductor Giaever (1963)



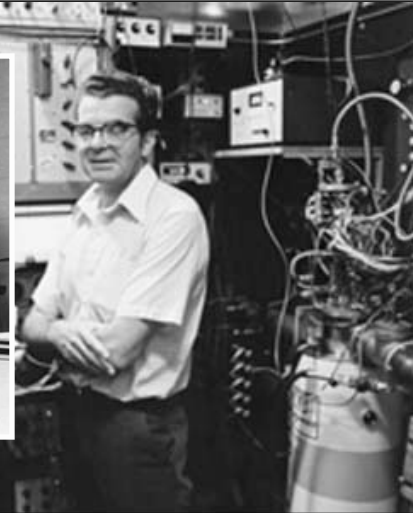
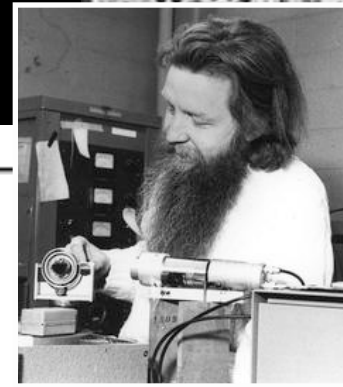
Quantum Tunneling of Electrons as a probe of superconductivity & pairing:

Planar Tunneling into a superconductor Giaever (1963)



$$\frac{2\Delta(0)}{k_B T_C} = 3.5 - 4.3$$

Tunneling Spectroscopy and the Pairing Interaction



Scanned at the American
Institute of Physics

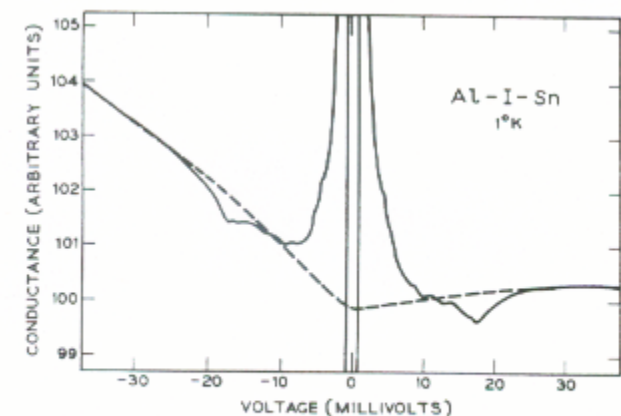
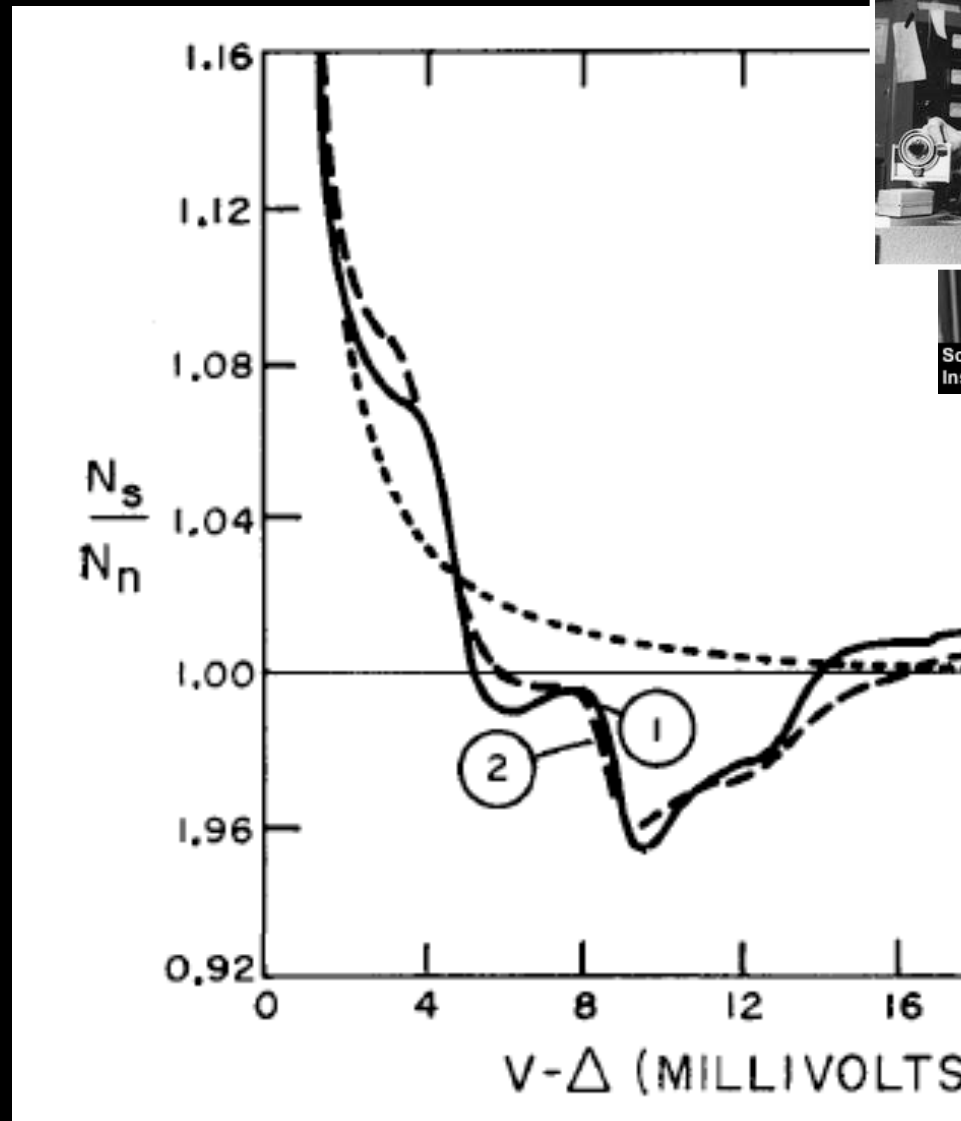


Fig. 17. Conductance of an Al-I-Sn junction in the normal (----) and superconducting (—) states.

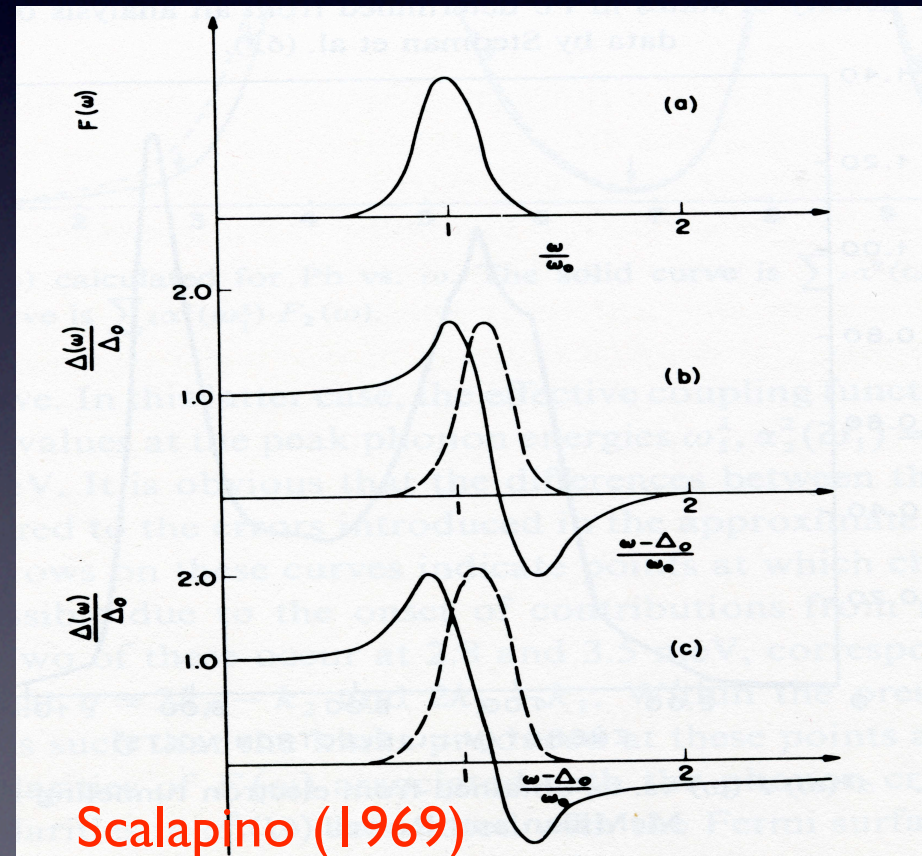
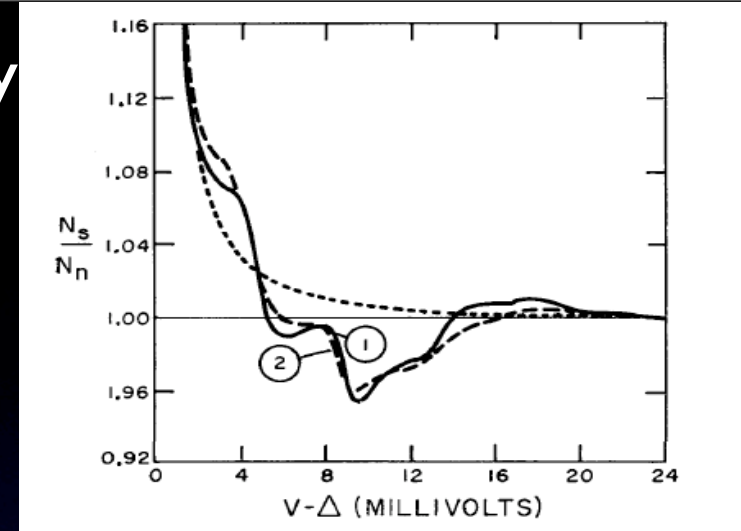
Electron Boson Coupling & Frequency Dependent of the Pairing Interaction:

$$\frac{N_s(\omega)}{N(0)} = \text{Re} \left\{ \frac{|\omega|}{[\omega^2 - \Delta^2(\omega)]^{1/2}} \right\},$$

$N_s(V)/N_n$ is a function of V
and can be less than 1

A simple model:

- Δ must have some ω dependence
- $\Delta(\omega) = \Delta_R(\omega) + i \Delta_I(\omega)$



Scalapino (1969)

IMAGE OF THE PHONON SPECTRUM IN THE TUNNELING CHARACTERISTIC
BETWEEN SUPERCONDUCTORS

J. M. Rowell, P. W. Anderson, and D. E. Thomas
Bell Telephone Laboratories, Murray Hill, New Jersey
(Received 14 March 1963)

EFFECTIVE TUNNELING DENSITY OF STATES IN SUPERCONDUCTORS*

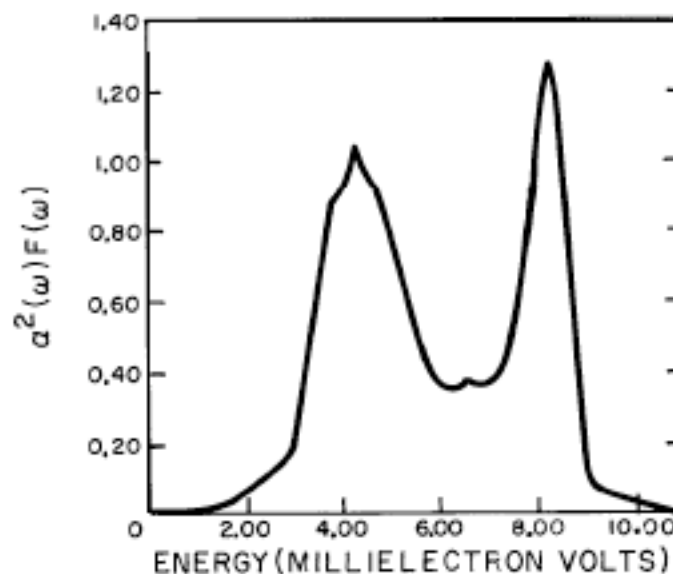
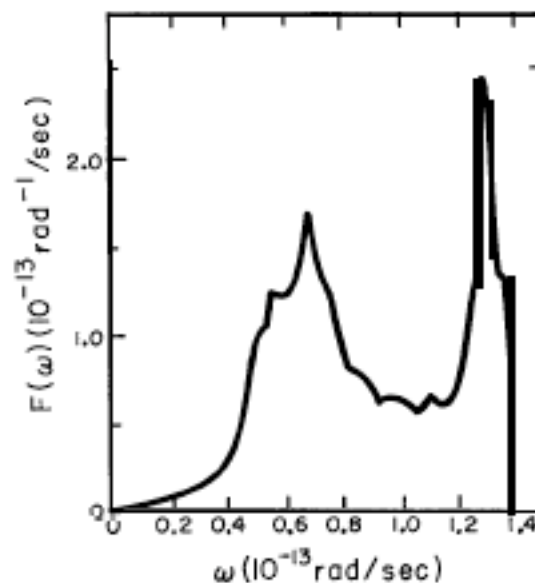
J. R. Schrieffer, D. J. Scalapino, and J. W. Wilkins
University of Pennsylvania, Philadelphia, Pennsylvania
(Received 15 March 1963)

LEAD PHONON SPECTRUM CALCULATED FROM SUPERCONDUCTING DENSITY OF STATES

W. L. McMillan and J. M. Rowell
Bell Telephone Laboratories, Murray Hill, New Jersey
(Received 18 December 1964)

$$\frac{N_s(\omega)}{N(0)} = \text{Re} \left\{ \frac{|\omega|}{[\omega^2 - \Delta^2(\omega)]^{1/2}} \right\},$$

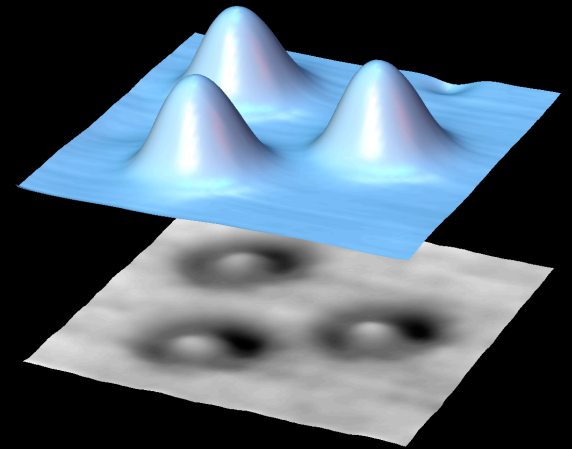
$$\Delta(\omega) = \frac{1}{Z(\omega)} \int_{\Delta_0}^{\omega_c} d\omega' \text{Re} \left[\frac{\Delta'}{(\omega'^2 - \Delta'^2)^{1/2}} \right] \left\{ \sum_{\lambda} \int d\omega_q \alpha_{\lambda}^2(\omega_q) \right. \\ \left. \times F_{\lambda}(\omega_q) [D_q(\omega' + \omega) + D_q(\omega' - \omega)] - U \right\}, \quad (9)$$



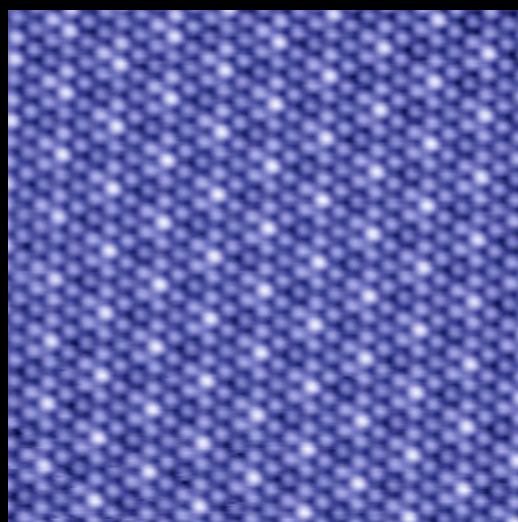
Comparison of $\alpha^2 F(\omega)$ and $F(\omega)$ for Pb (after McMillan and Rowell)

Application of STM to Superconductors

- Probing superconductivity on the nanoscale
- Imaging defects and vortices
- Can we detect the influence of a single impurity?
- Impurities in conventional s-wave superconductors
- High-T_c Superconductors: defects, inhomogeneity, phase diagram, clues to the mechanism



STM Spectroscopy of a Superconductor



Niobium Diselenide
(NbSe₂)

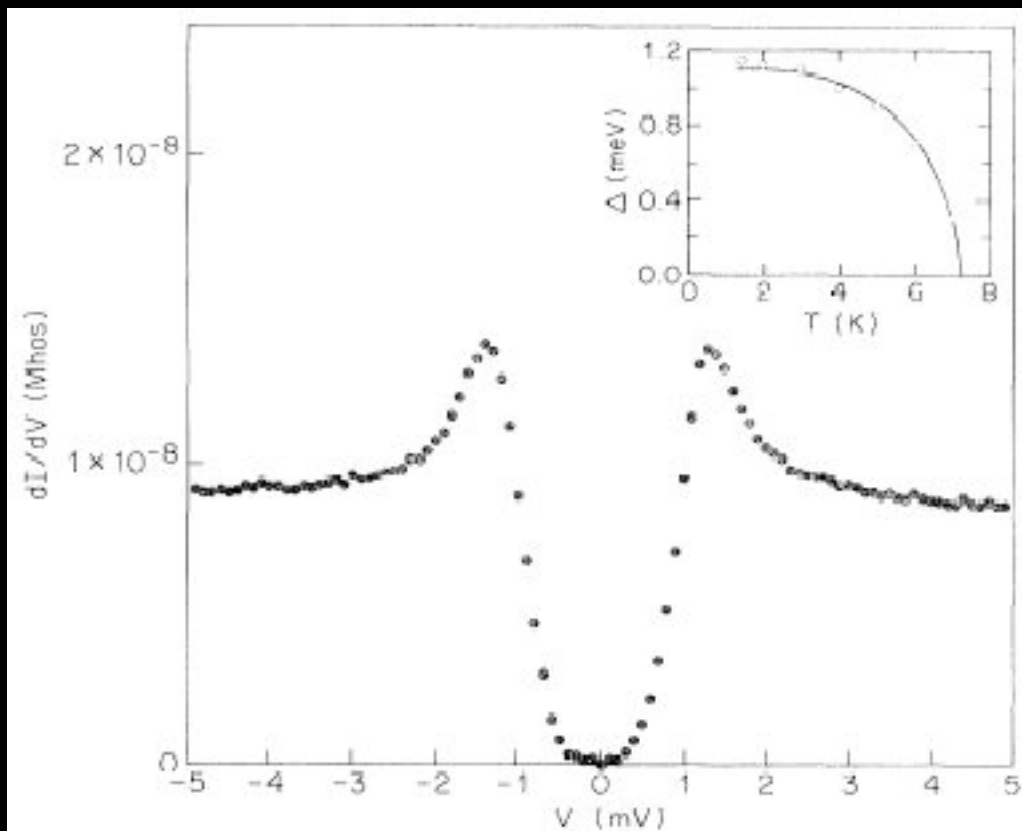


FIG. 1. dI/dV vs V for NbSe₂ and 0-T applied magnetic field used to determine the gap at 1.45 K. Inset: The gap vs temperature and the corresponding BCS fit.

STM Spectroscopy of Flux Vortices in NbSe₂

H.F. Hess *et al.* *Phys. Rev. Lett.* **64**, 2711 (1990).

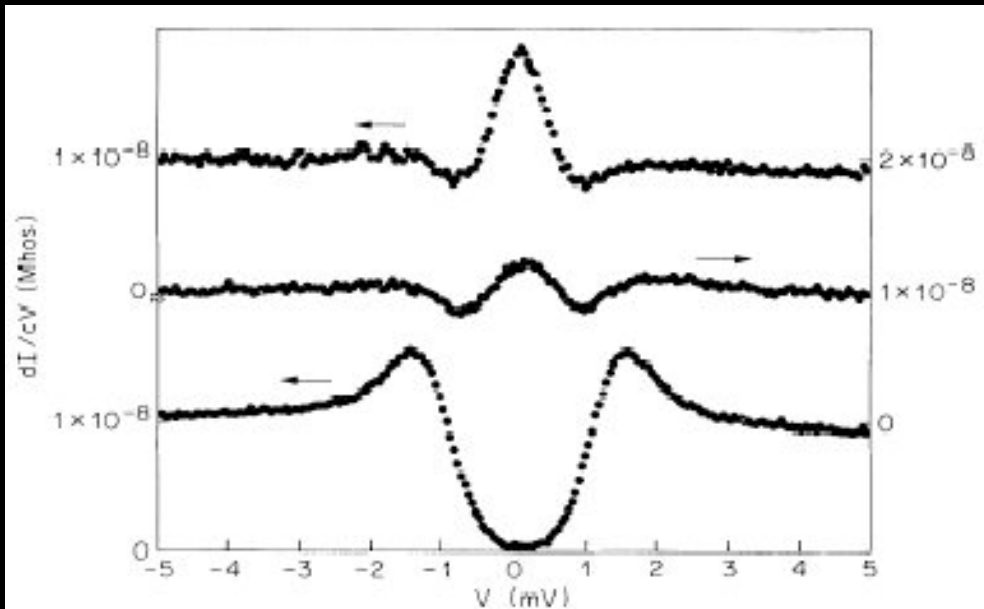


FIG. 3. dI/dV vs V for NbSe₂ at 1.85 K and a 0.02-T field, taken at three positions: on a vortex, about 75 Å from a vortex, and 2000 Å from a vortex. The zero of each successive curve is shifted up by one quarter of the vertical scale.

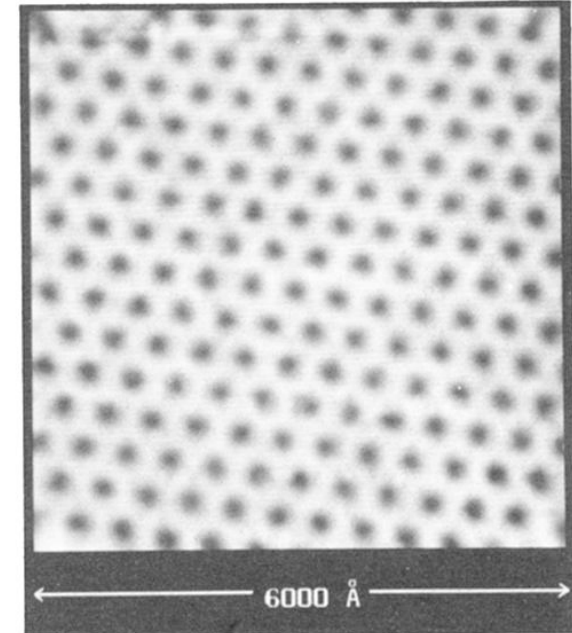
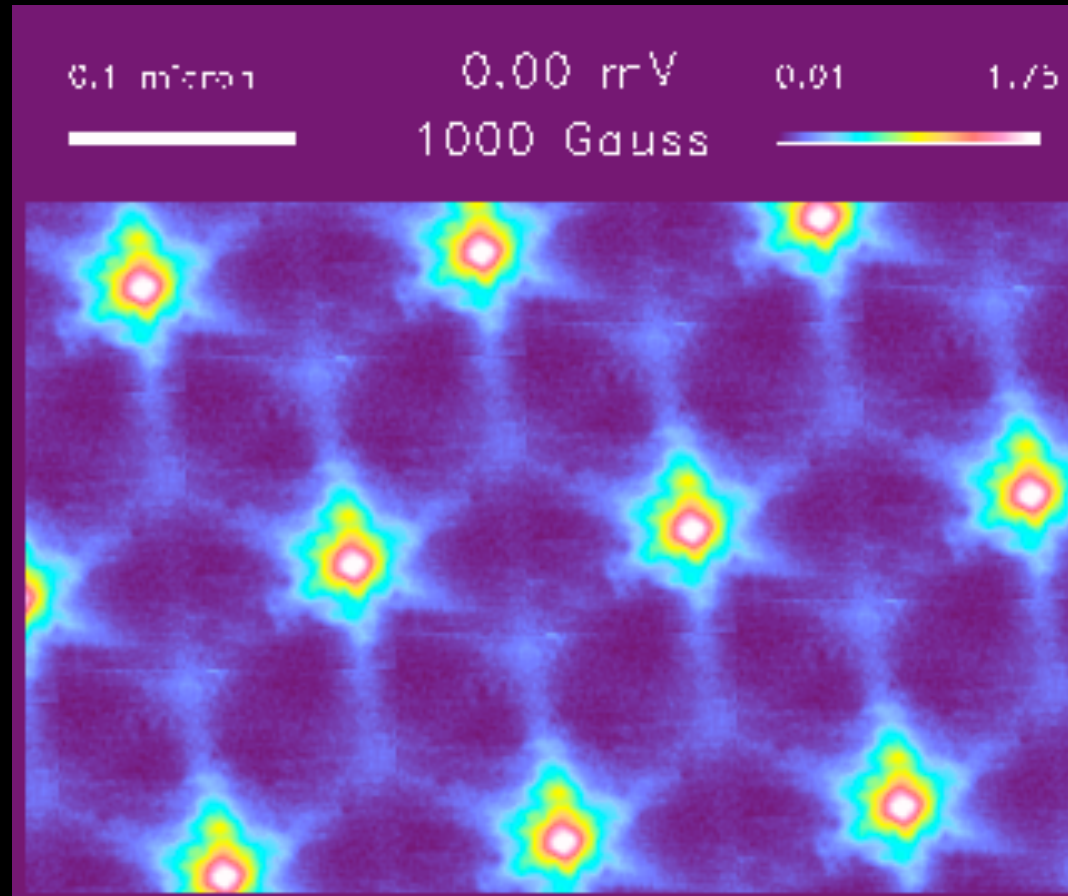


FIG. 2. Abrikosov flux lattice produced by a 1-T magnetic field in NbSe₂ at 1.8 K. The scan range is about 6000 Å. The gray scale corresponds to dI/dV ranging from approximately 1×10^{-8} mho (black) to 1.5×10^{-9} mho (white).

Localized states are observed at the center of vortices in spectroscopy measurements



H.F. Hess *et al.*

Electronic tunneling into an isolated vortex in a clean type-II superconductor

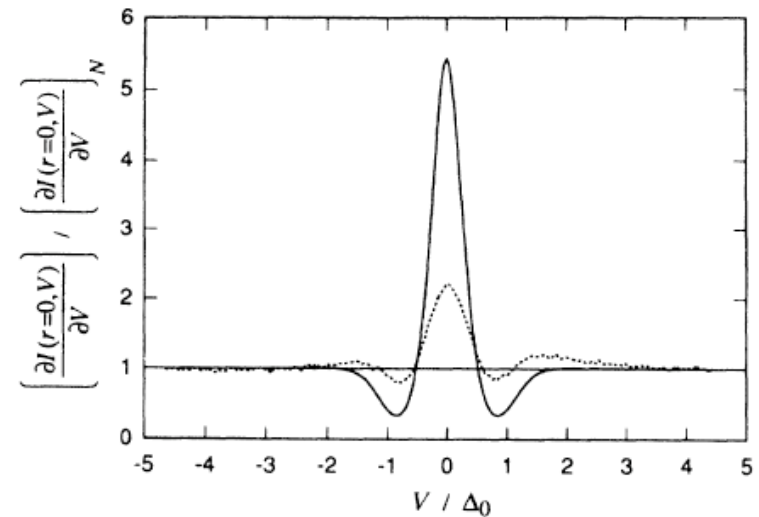
François Gygi and Michael Schluter

AT&T Bell Laboratories, 600 Mountain Avenue, Murray Hill, New Jersey 07974

(Received 11 July 1989)

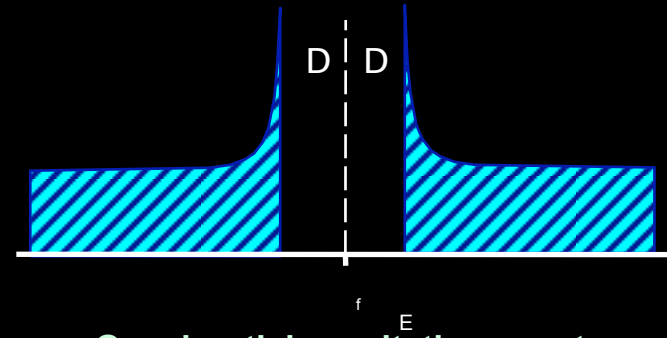
$$\begin{aligned}
 -\frac{\partial^2}{\partial r^2} u_{\mu n k_z}(r) - \frac{1}{r} \frac{\partial}{\partial r} u_{\mu n k_z}(r) + \left[\frac{(\mu - \frac{1}{2})^2}{r^2} - \left(E_F - \frac{k_z^2}{m_z} + E_{\mu n k_z} \right) \right] u_{\mu n k_z}(r) + \Delta(r) v_{\mu n k_z}(r) &= 0, \\
 -\frac{\partial^2}{\partial r^2} v_{\mu n k_z}(r) - \frac{1}{r} \frac{\partial}{\partial r} v_{\mu n k_z}(r) + \left[\frac{(\mu + \frac{1}{2})^2}{r^2} - \left(E_F - \frac{k_z^2}{m_z} - E_{\mu n k_z} \right) \right] v_{\mu n k_z}(r) - \Delta(r) u_{\mu n k_z}(r) &= 0.
 \end{aligned}$$

$$\begin{aligned}
 \frac{\partial I(r, V)}{\partial V} \propto - \sum_{\mu n k_z} [u_{\mu n k_z}^2(r) f'(E_{\mu n k_z} - eV) \\
 + v_{\mu n k_z}^2(r) f'(E_{\mu n k_z} + eV)],
 \end{aligned}$$



PURE S-WAVE BCS SUPERCONDUCTOR

Cooper pair

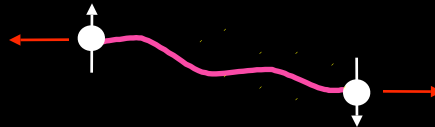
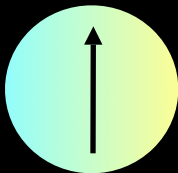


Quasiparticle excitation spectrum

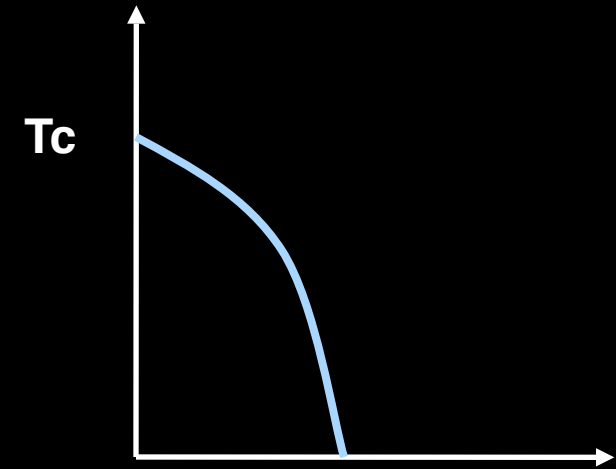
S-WAVE SUPERCONDUCTOR WITH MAGNETIC IMPURITY

$$E_{\text{exchange}} = -J \vec{S}_{\text{impurity}} \cdot \vec{s}_{\text{conduction electron}}$$

Weak and static magnetic impurity



Exchange interaction breaks pairs!

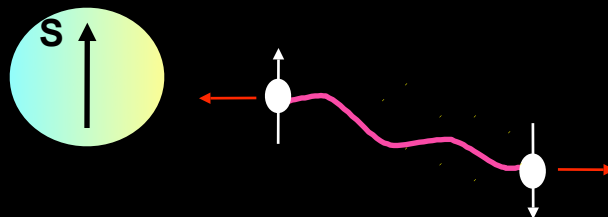


Impurity Concentration

Impurity-Induced States in Superconductors

Shiba 1968, Yu 1965, Rusinov 1969

S-wave Superconductor



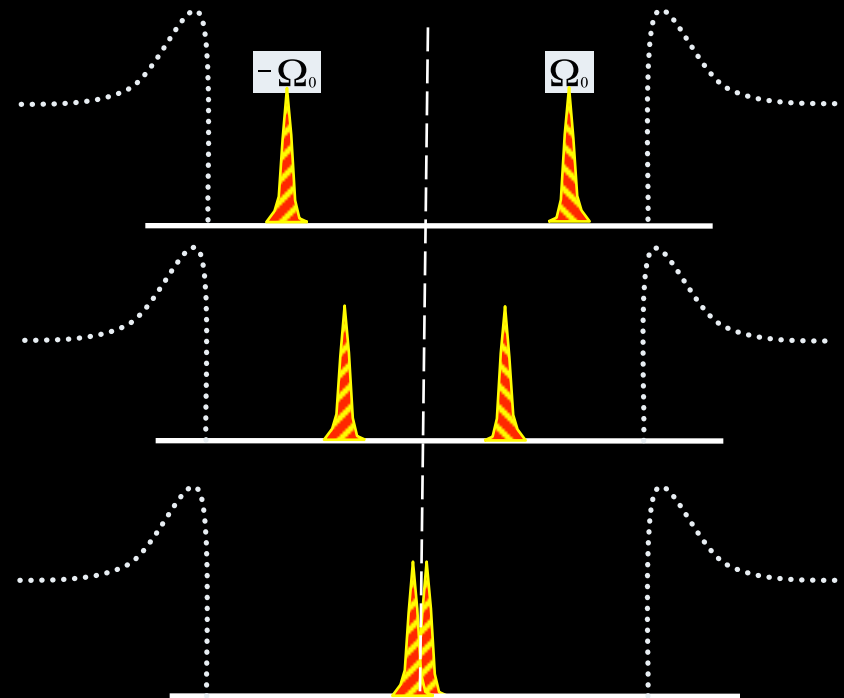
● Energy

$$\Omega_0 \approx \Delta_0 \frac{1 - (\pi N_F JS)^2}{1 + (\pi N_F JS)^2}$$

See Review by Balatsky et al.

arXiv:cond-mat/0409474

Yazdani-Boulder 08 lectures

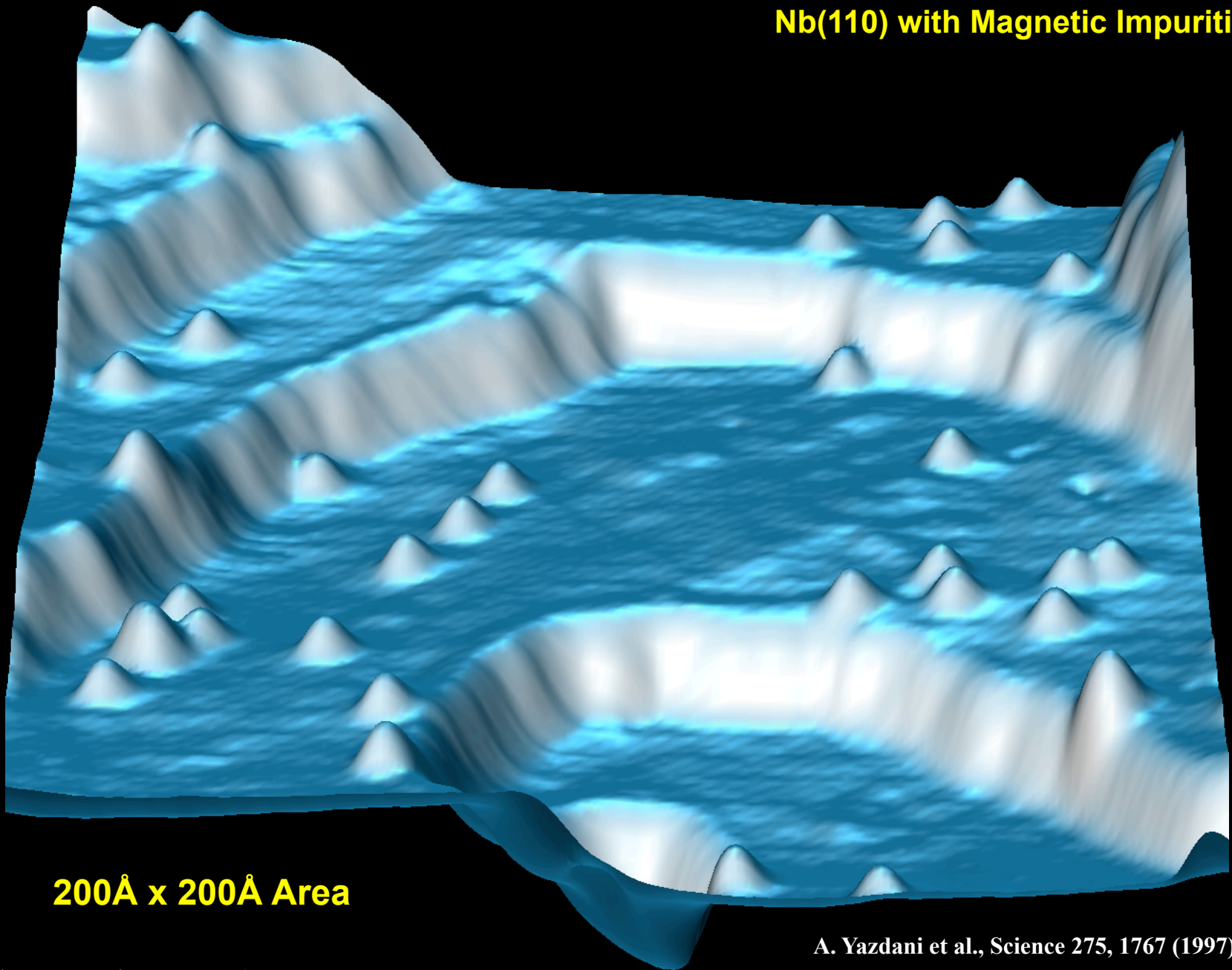


Total (Not Local) Density of Electronic States

Evidence for these states from Thermodynamic and Tunneling Measurements:

D. Ginsburg in the 80's.

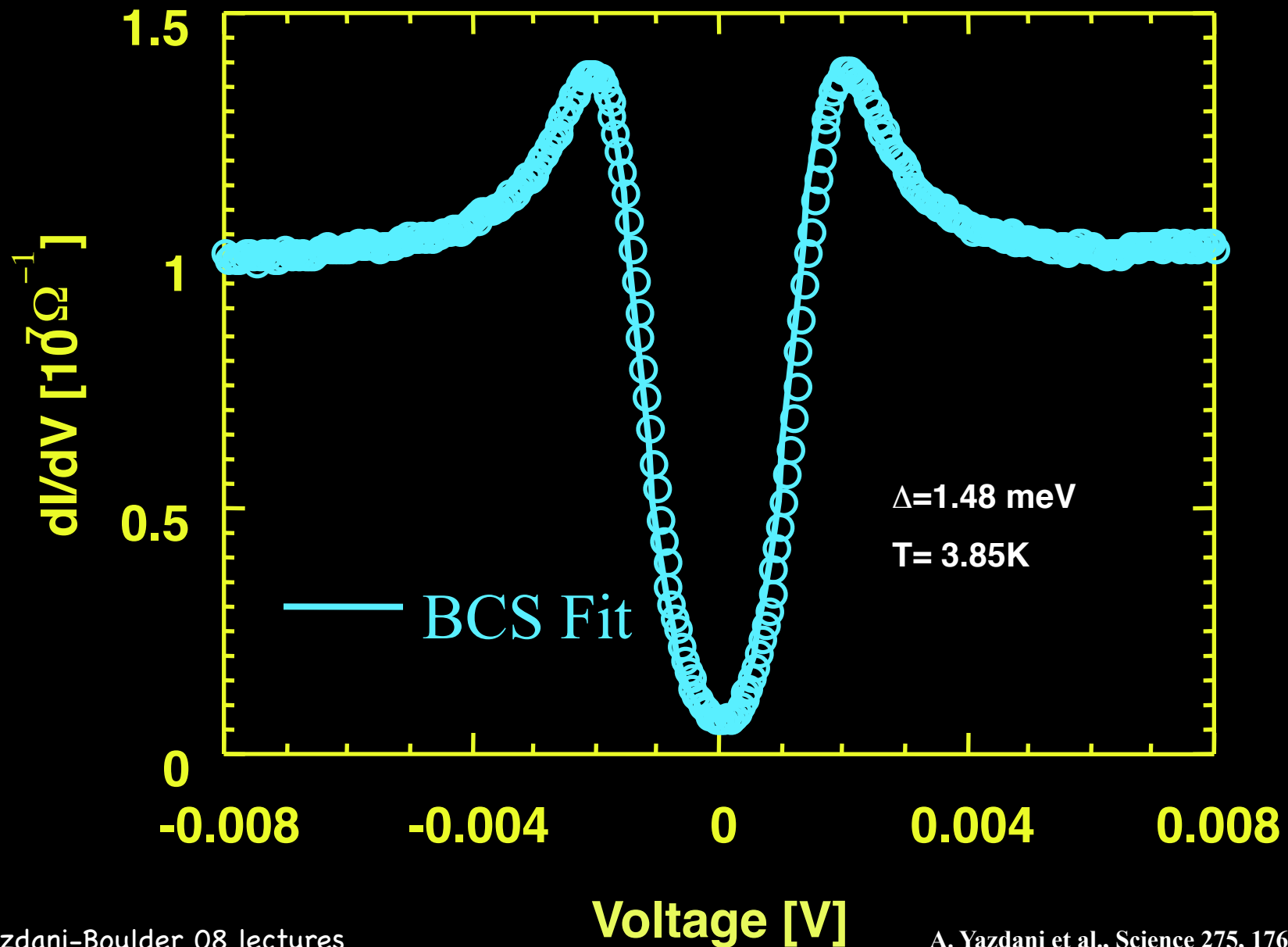
Nb(110) with Magnetic Impurities



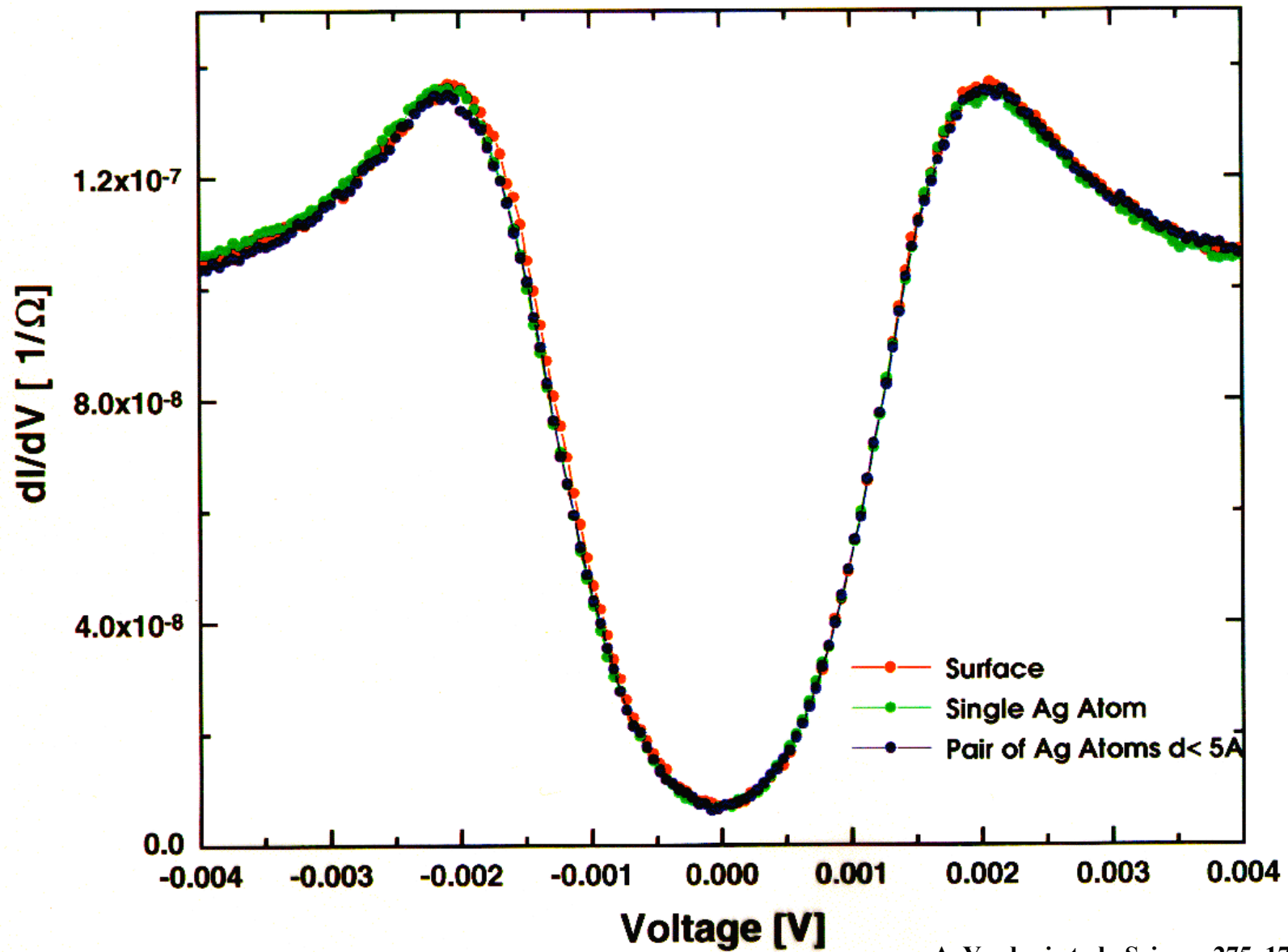
200Å x 200Å Area

A. Yazdani et al., Science 275, 1767 (1997)

STM Spectra: Resolution limited by temperature

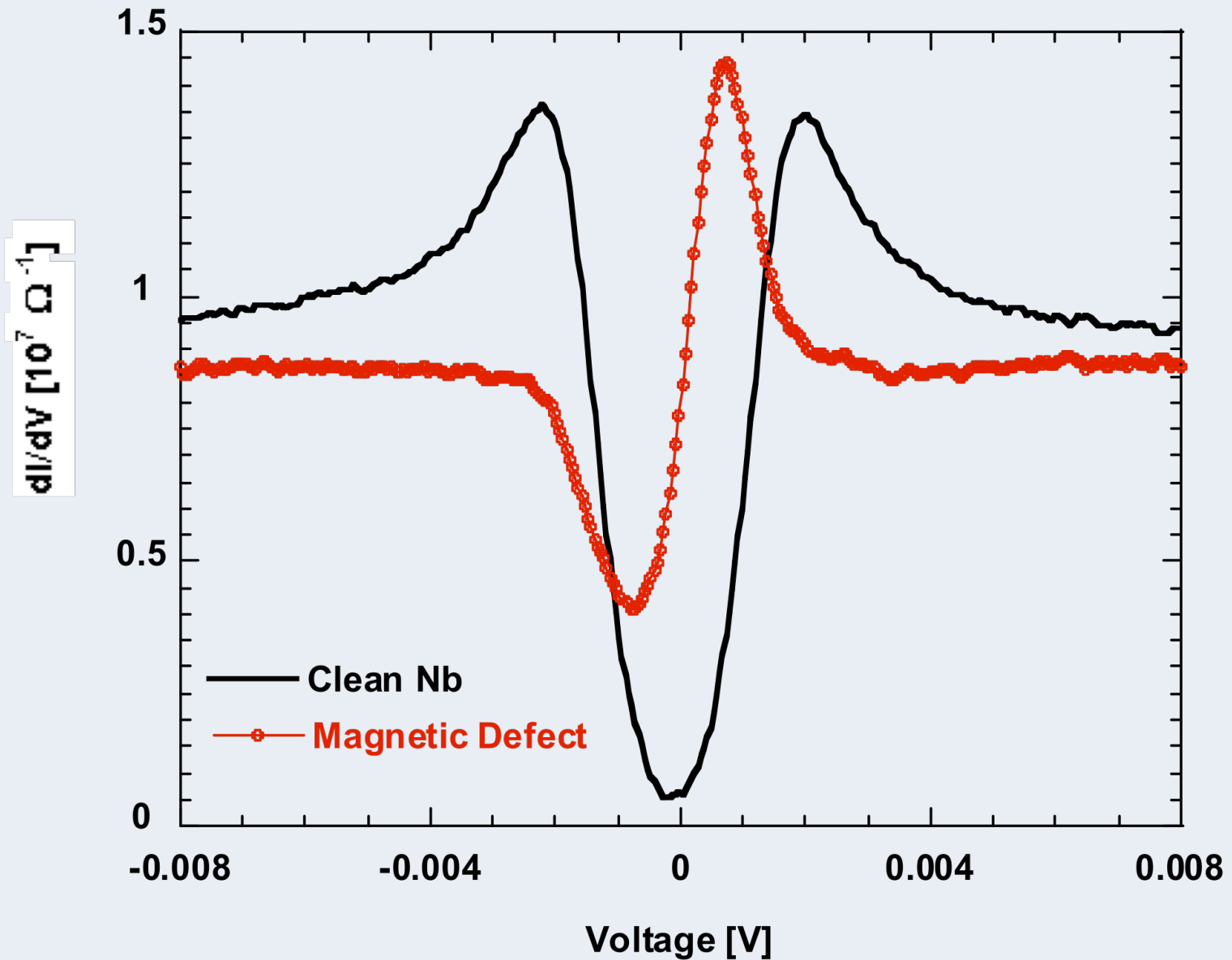


Spectra Measured Near Ag Atoms

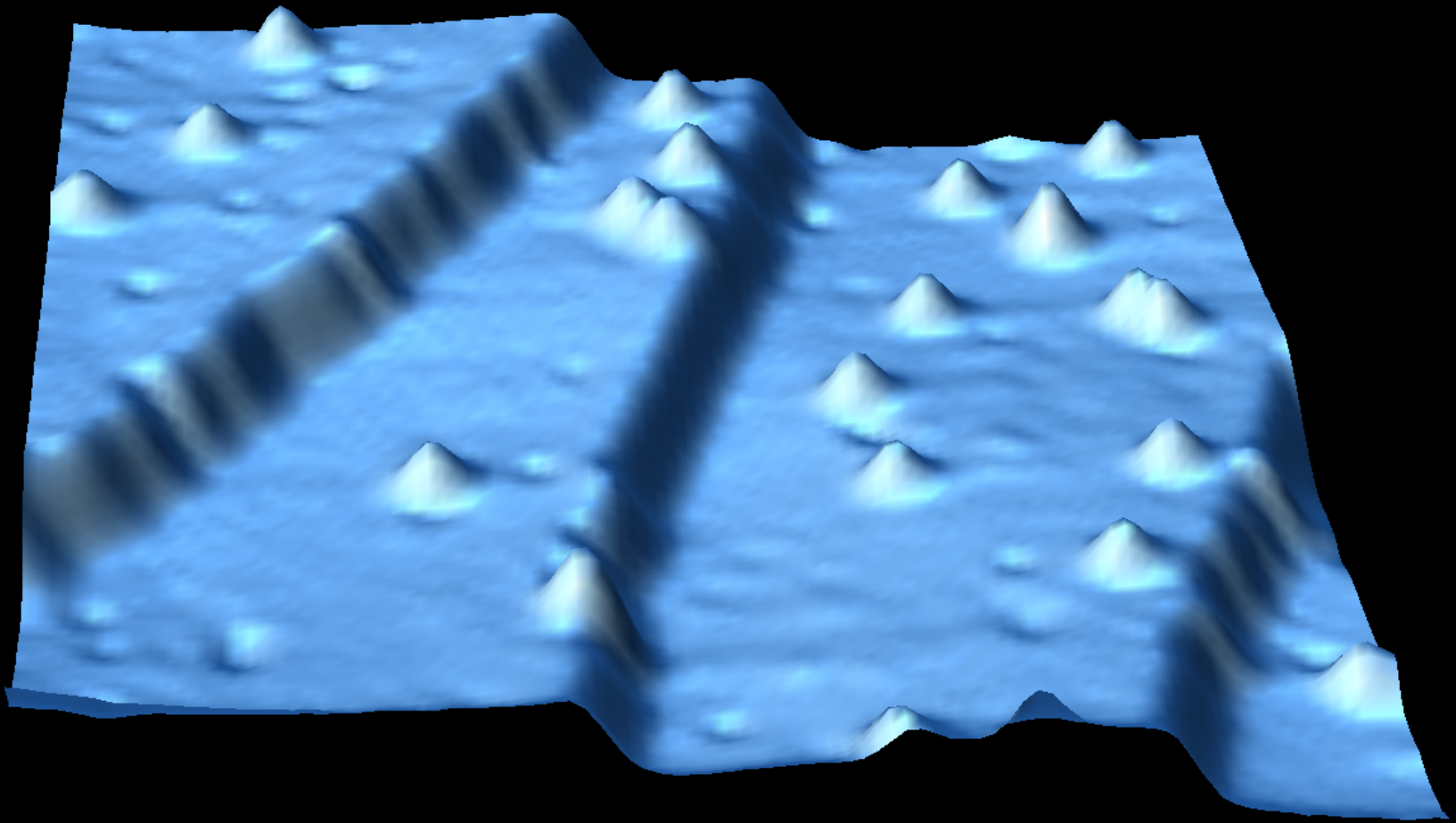


A. Yazdani et al., Science 275, 1767 (1997)

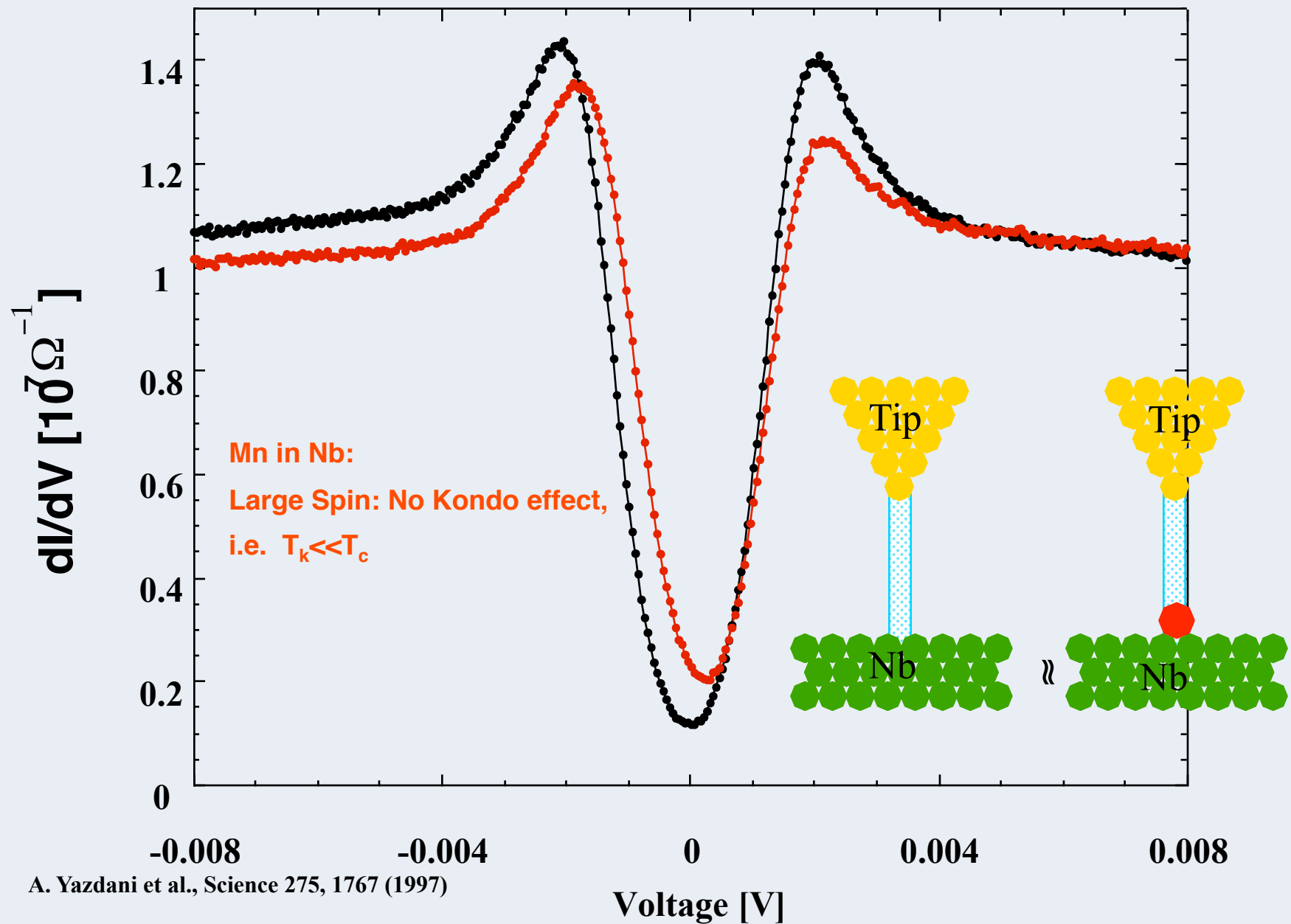
Tunneling Spectra on Nb near a magnetic defects



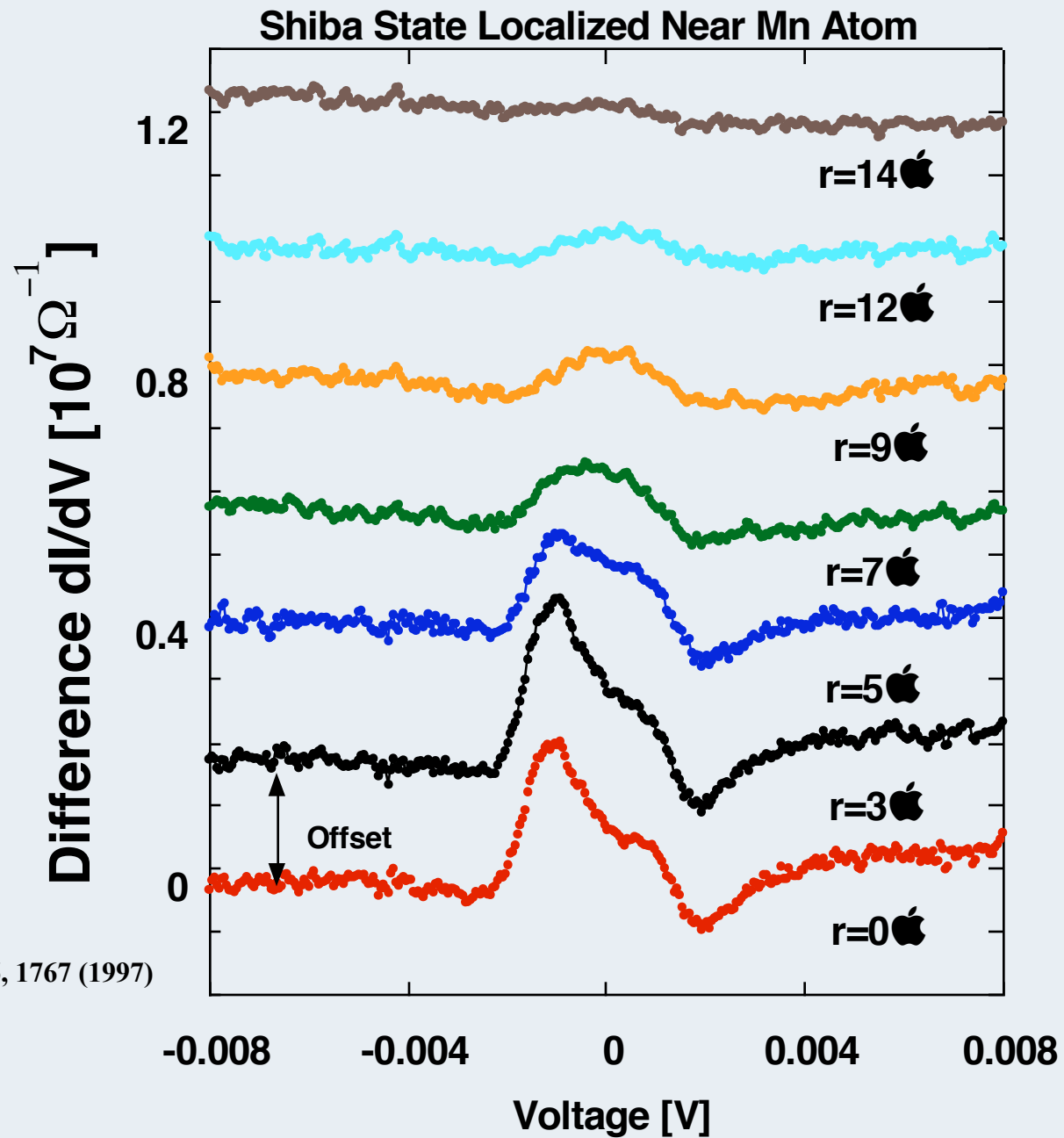
Mn on Nb(110)



STM Spectra on&off the Mn Atom

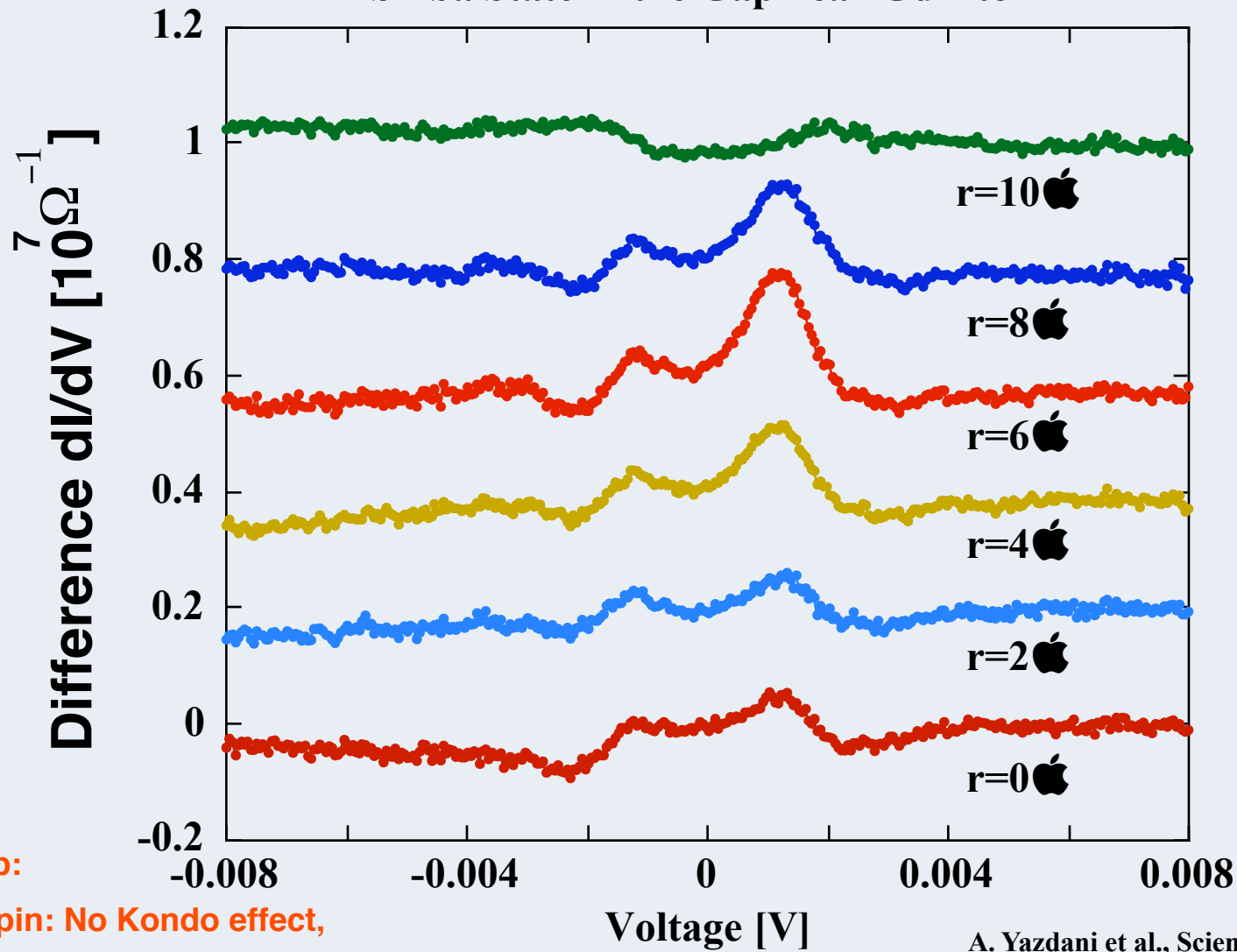


A. Yazdani et al., Science 275, 1767 (1997)



A. Yazdani et al., Science 275, 1767 (1997)

Shiba State in the Gap near Gd Atom

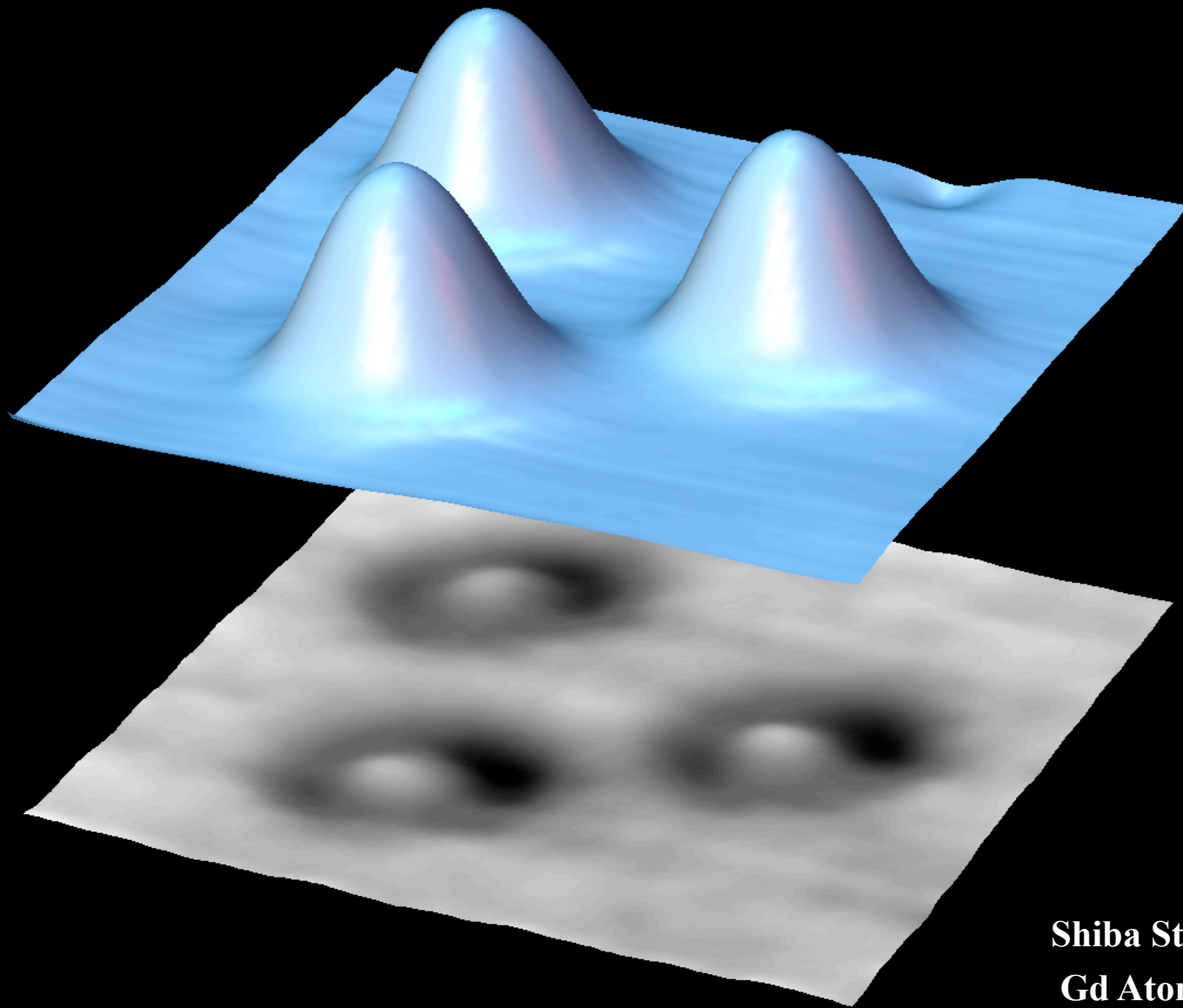


Gd in Nb:

Large Spin: No Kondo effect,

i.e. $T_k \ll T_c$

A. Yazdani et al., Science 275, 1767 (1997)



**Shiba State near
Gd Atoms on Nb**

Model Calculation

Short range suppression of Δ

(Schlottmann '76, Kummel '72)

Spin dependent potential J

Bogoliubov-de Gennes equations

$$\left[\frac{-\hbar^2 \nabla^2}{2m} + J(r) \right] u_{n\uparrow}(r) + \Delta(r) v_{n\downarrow}(r) = (E_F + E_n) u_{n\uparrow}(r)$$

$$\left[\frac{-\hbar^2 \nabla^2}{2m} - J(r) \right] v_{n\downarrow}(r) - \Delta(r) u_{n\uparrow}(r) = (E_F - E_n) v_{n\downarrow}(r)$$

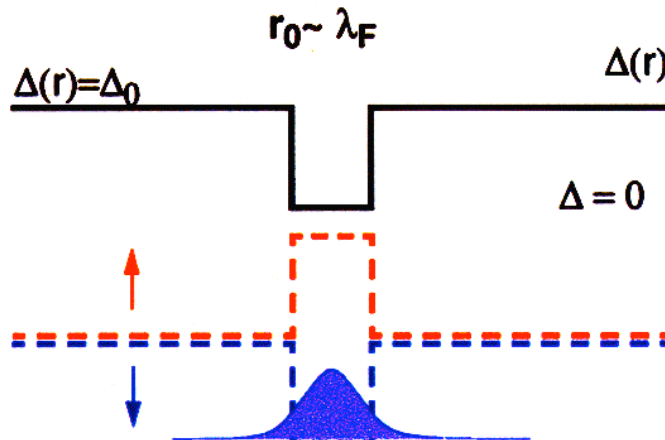
.....two more coupled equations

Differential Conductivity:

$$\frac{dI}{dV}(r, V) \propto \sum_{n\sigma} \left[u_{n\sigma}^2 \delta(\omega_n - eV) - v_{n\sigma}^2 \delta(\omega_n + eV) \right]$$

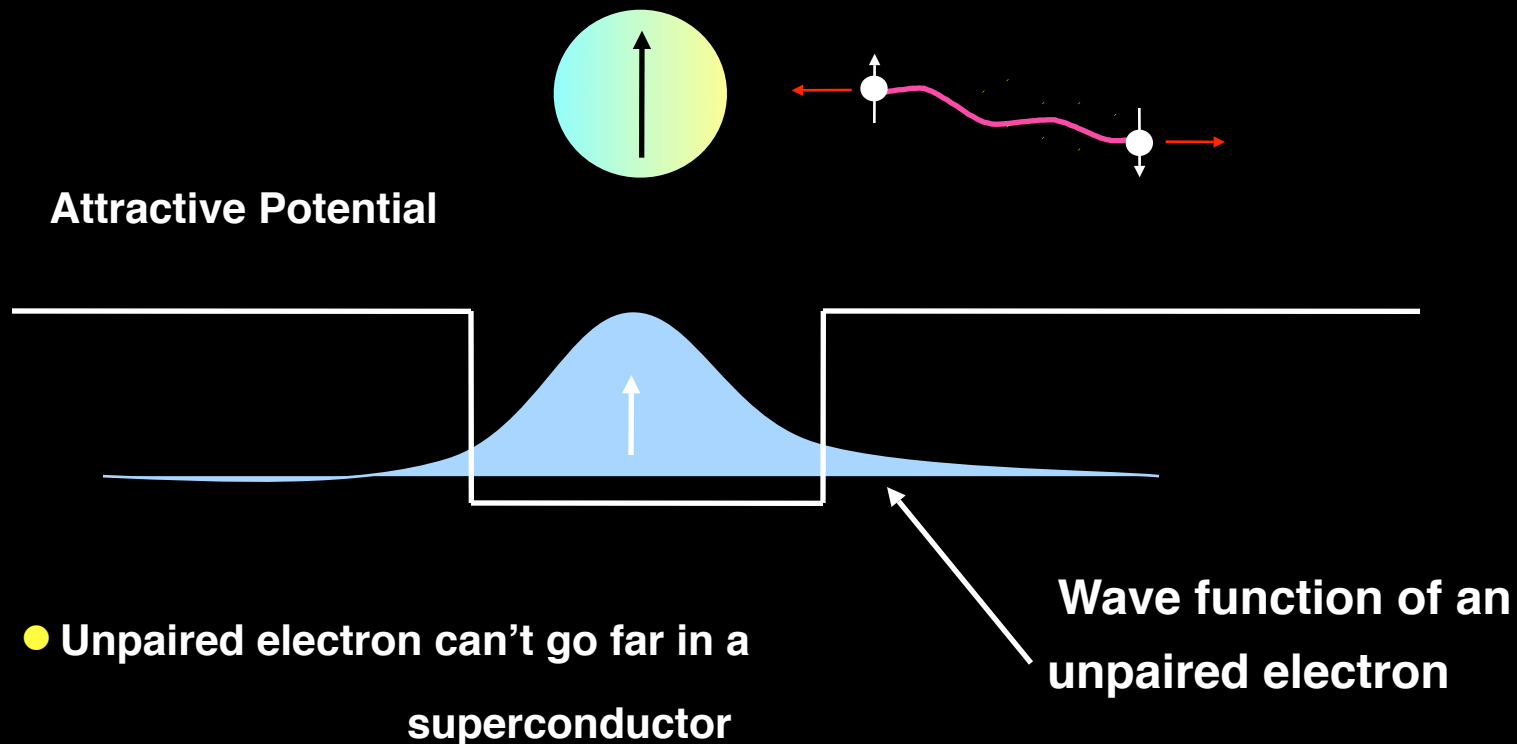
Tunneling Electrons In

Tunneling Electrons Out



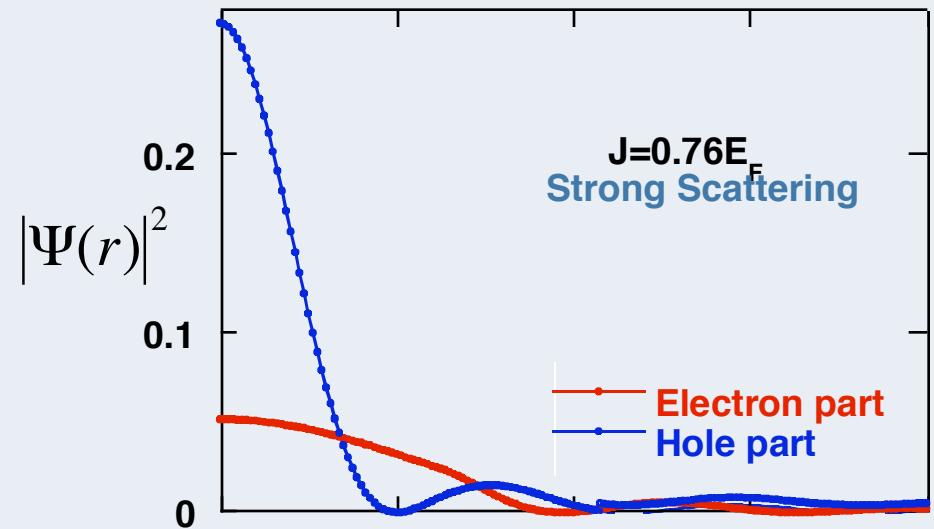
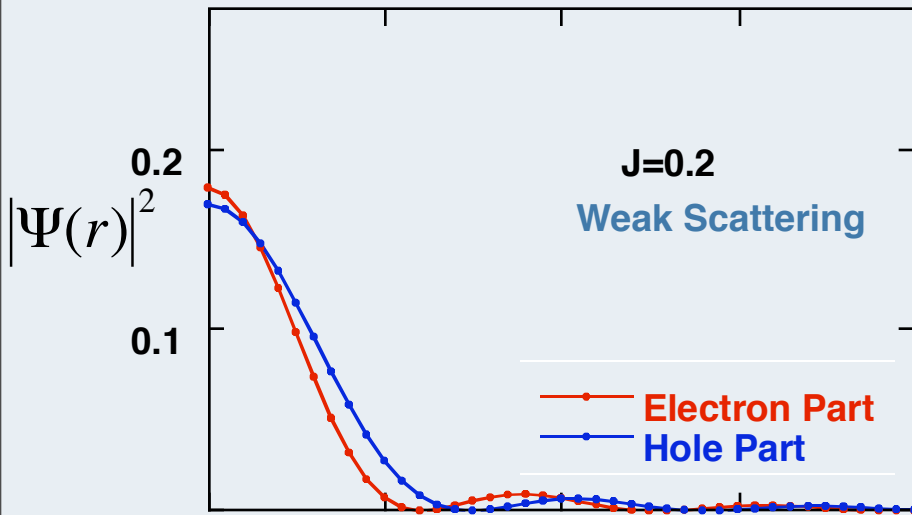
What happens near a magnetic atom?

- A Simple View

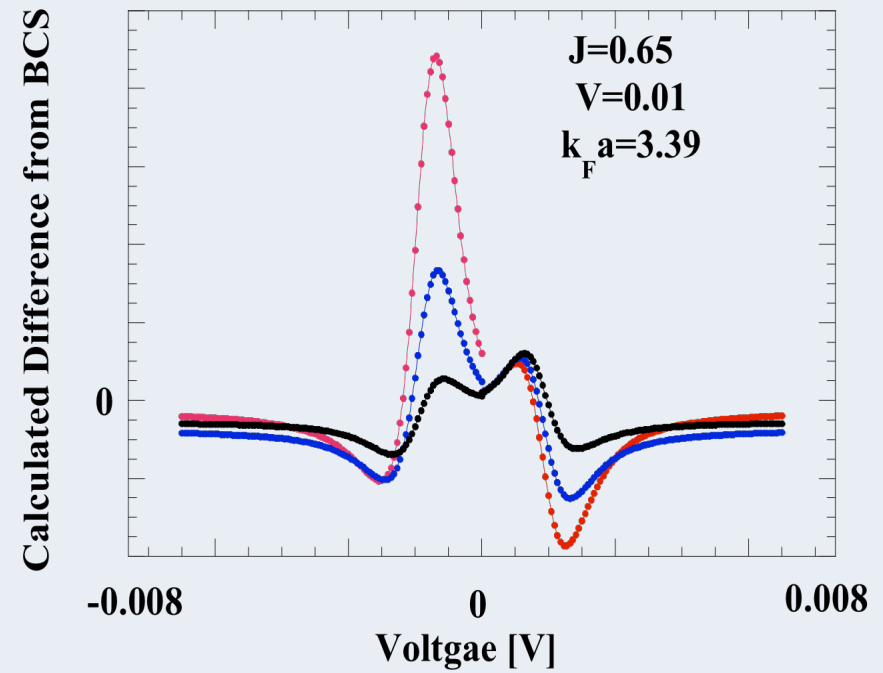
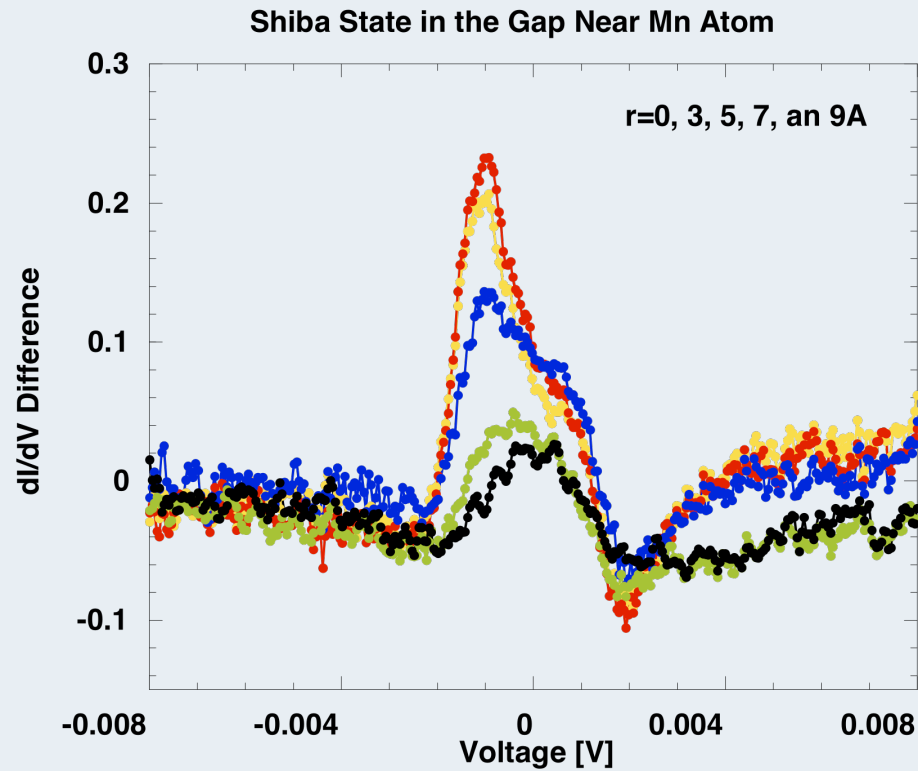


Local Theory of Shiba state in s-wave superconductors:
Flatte and Byers, PRL 78, 3761 (1997); PRB 56, 11213 (1997)
Solkola, Balatsky, and Shrieffer, PRB 55, 12648 (1997)

Bound state wavefunction



A. Yazdani et al., Science 275, 1767 (1997)



A. Yazdani et al., Science 275, 1767 (1997)

Summary

Lecture I

- Brief history of tunneling: tunneling through insulating barriers
- Basics of scanning tunneling microscopy
- Some comments on construction of an STM
- STM on simple metals--quantum interference of electronic states
- STM on semiconductors--imaging and probing single dopants
- STM on conventional superconductors--impurity effects in a BCS superconductor

Other basic things I could have talk about:
spin polarized measurements
Inelastic Tunneling Spectroscopy