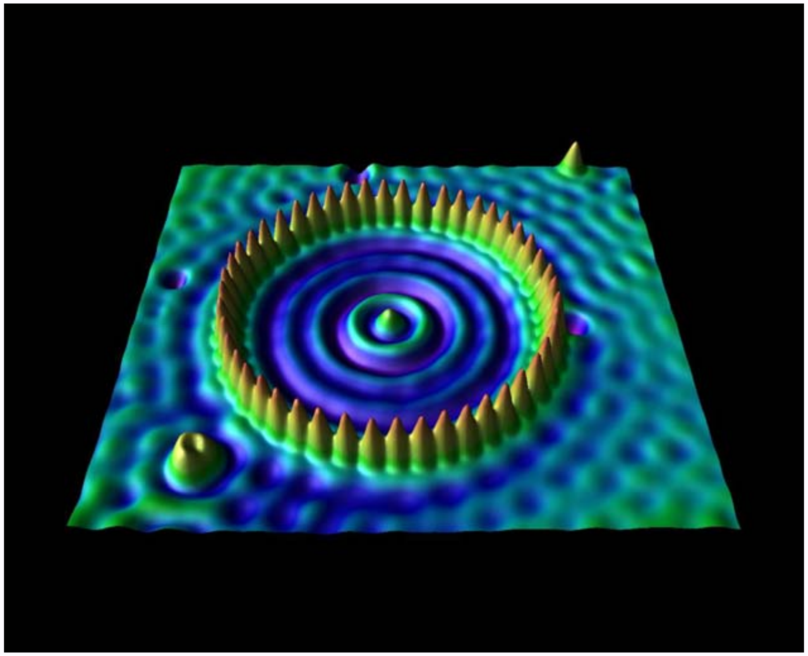
Lecture 25:
Surfaces –
Scanning Tunneling Microscope



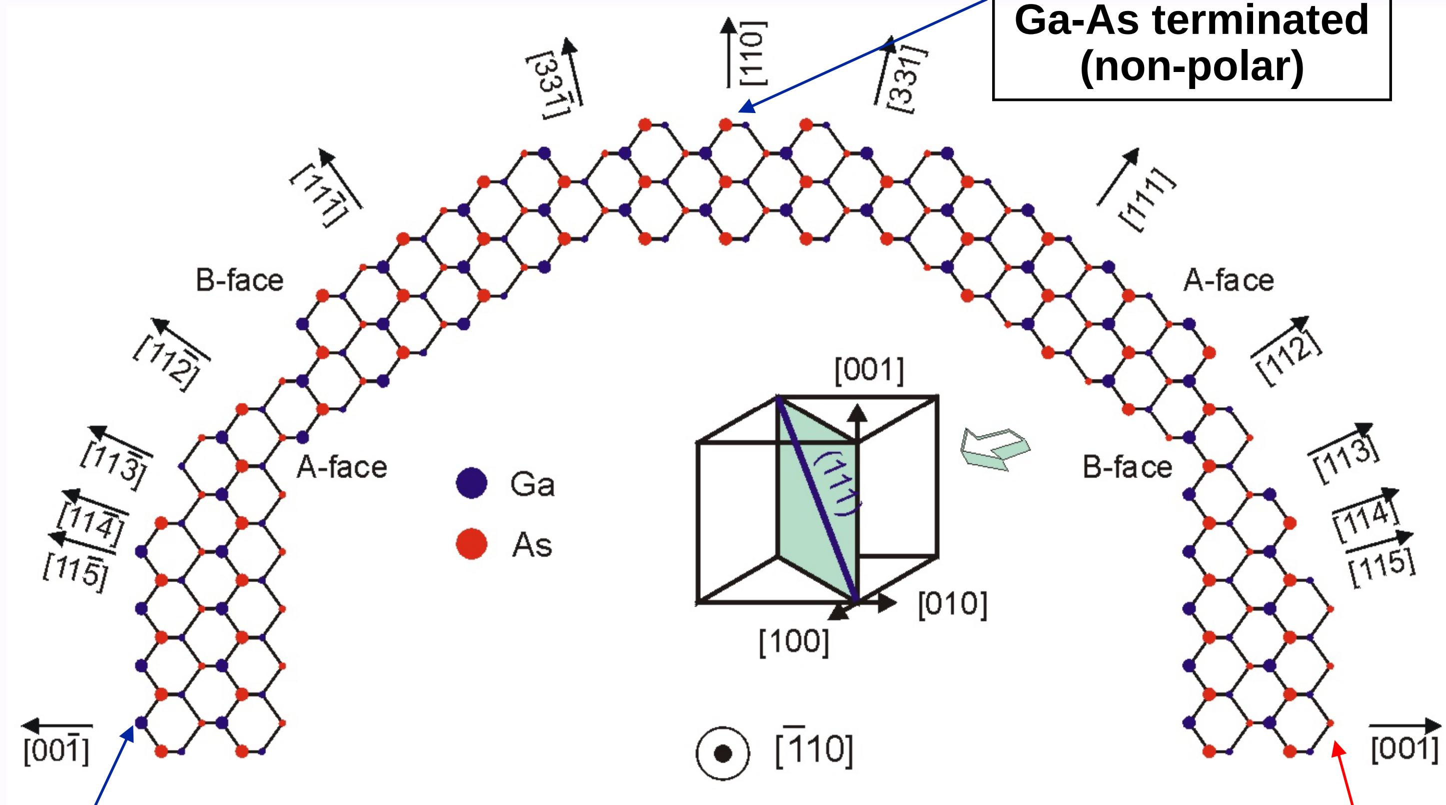
Special Presentation Today by Prof. Raffi BUdakian
On
Magnetic Resonance Force Microscopy

Outline

- Surfaces of crystals
- Example – surfaces of semiconductors –
  GaAs
- Tunneling in quantum mechanics
  Particles can tunnel through barriers
- Scanning tunneling microscope -- STM
- Examples of GaAs, Mn on GaAs, adatoms on Cu, atoms on GaN surface that illustrate growth, ….
- AFM – very brief

Surface structure – example: GaAs

[110]
Ga-As terminated
(non-polar)



[100] Ga terminated

[100] As terminated

Figure from
w3.rz-berlin.mpg.de/pc/ElecSpec/MBE/mbe.html

Surface structure – example: GaAs

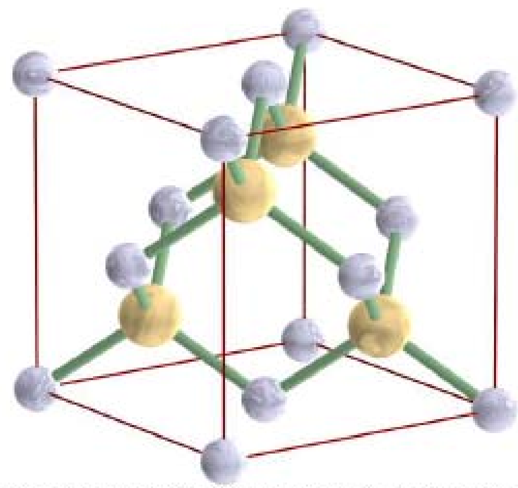
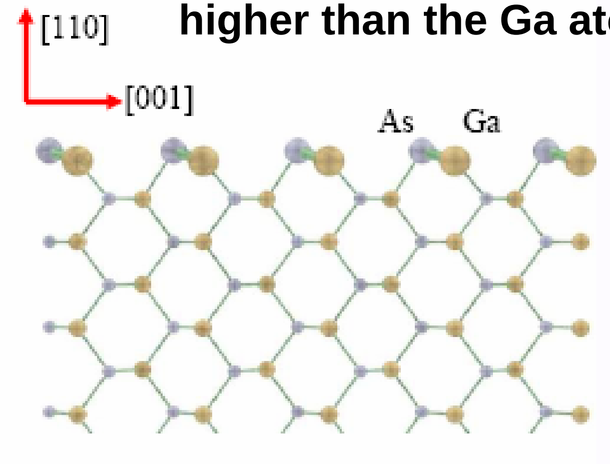


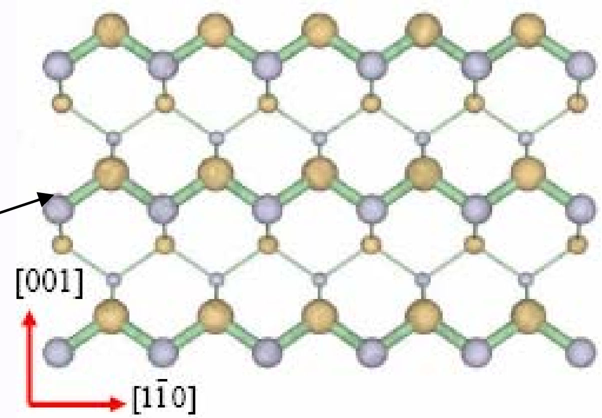
Figure 2.1: The unit cell of GaAs in a Zinc Blende structure

Conventional Cubic Cell in the bulk crystal

(110) surface -Ga-As terminated
Note the As atoms are slightly higher than the Ga atoms



Top view of (110) surface
Note zig-zag chains of Ga and As atoms



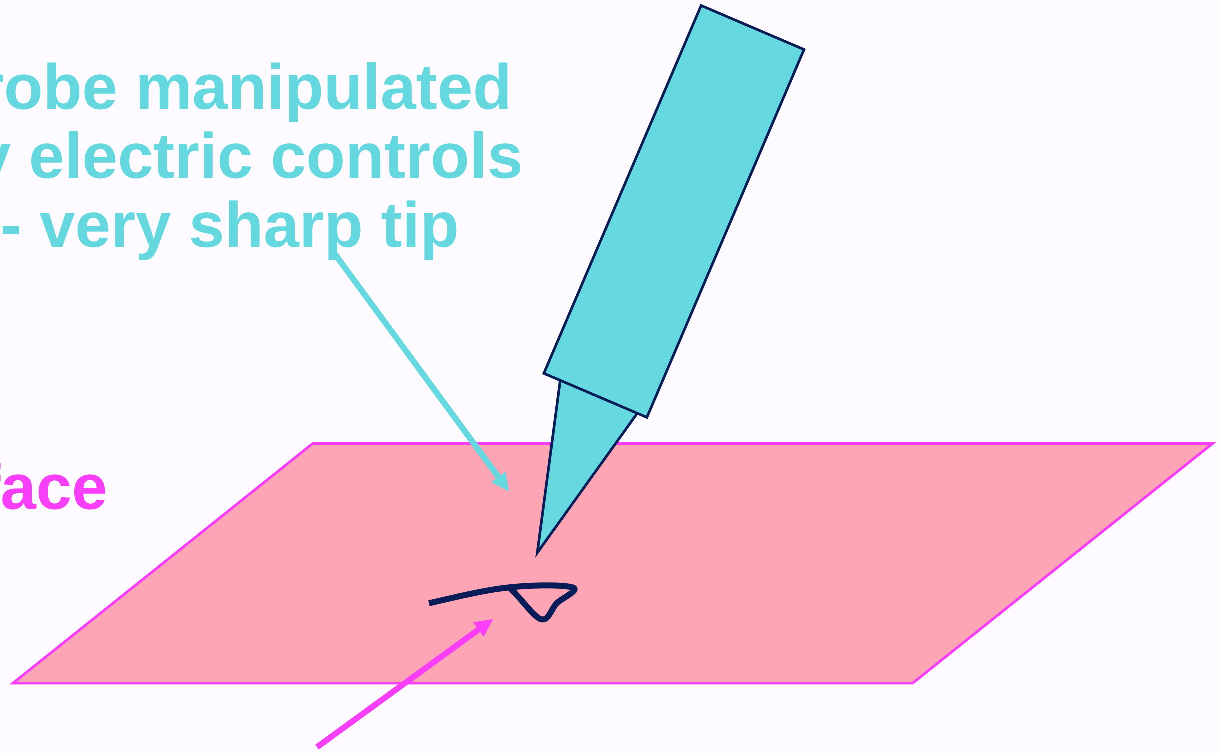
Figures from PhD thesis of Dale Kitchen, U of Illinois, 2006

“Seeing” atomic scale features

“Scanning Tunneling Microscope”
Measures electric current from tip to surface as tip is moved

Probe manipulated by electric controls ---- very sharp tip

Surface



Feature on surface

Scanning Tunneling Microscope

Nobel Prize 1985

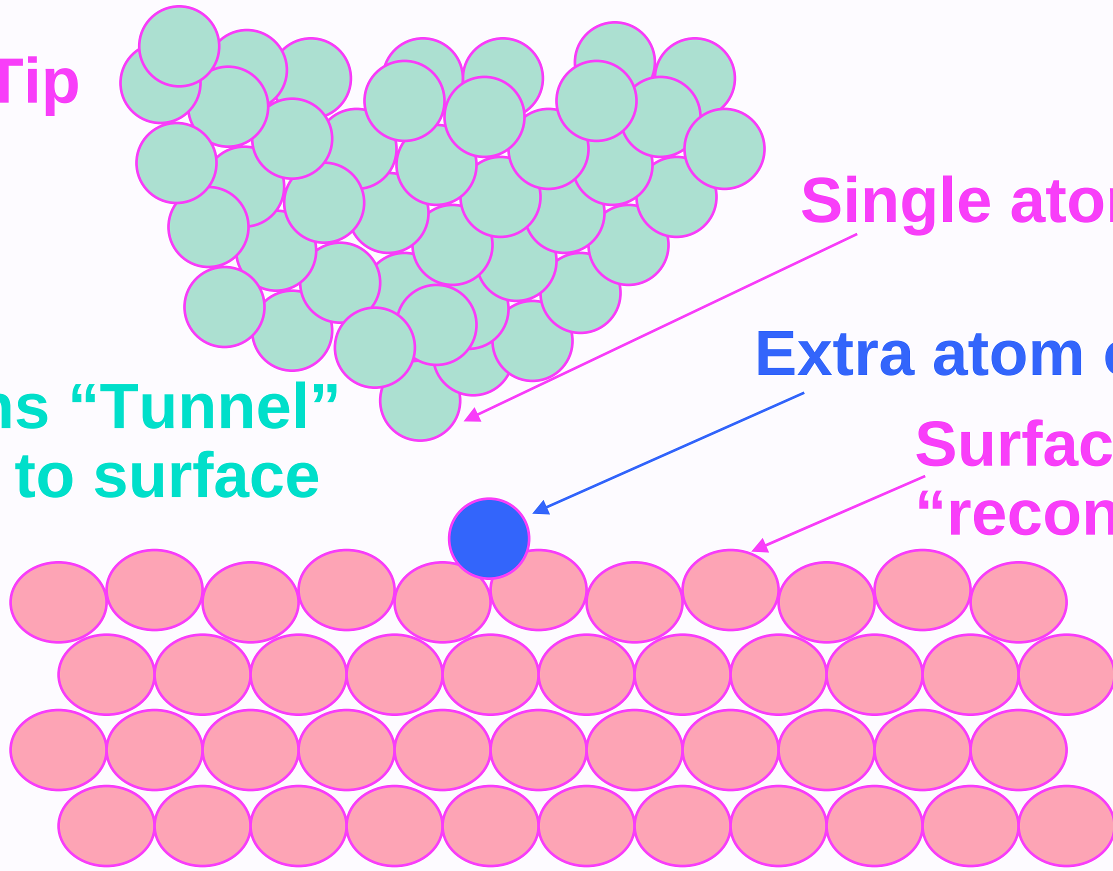
Tip

Single atom at tip

Extra atom on surface

Electrons "Tunnel"
from tip to surface

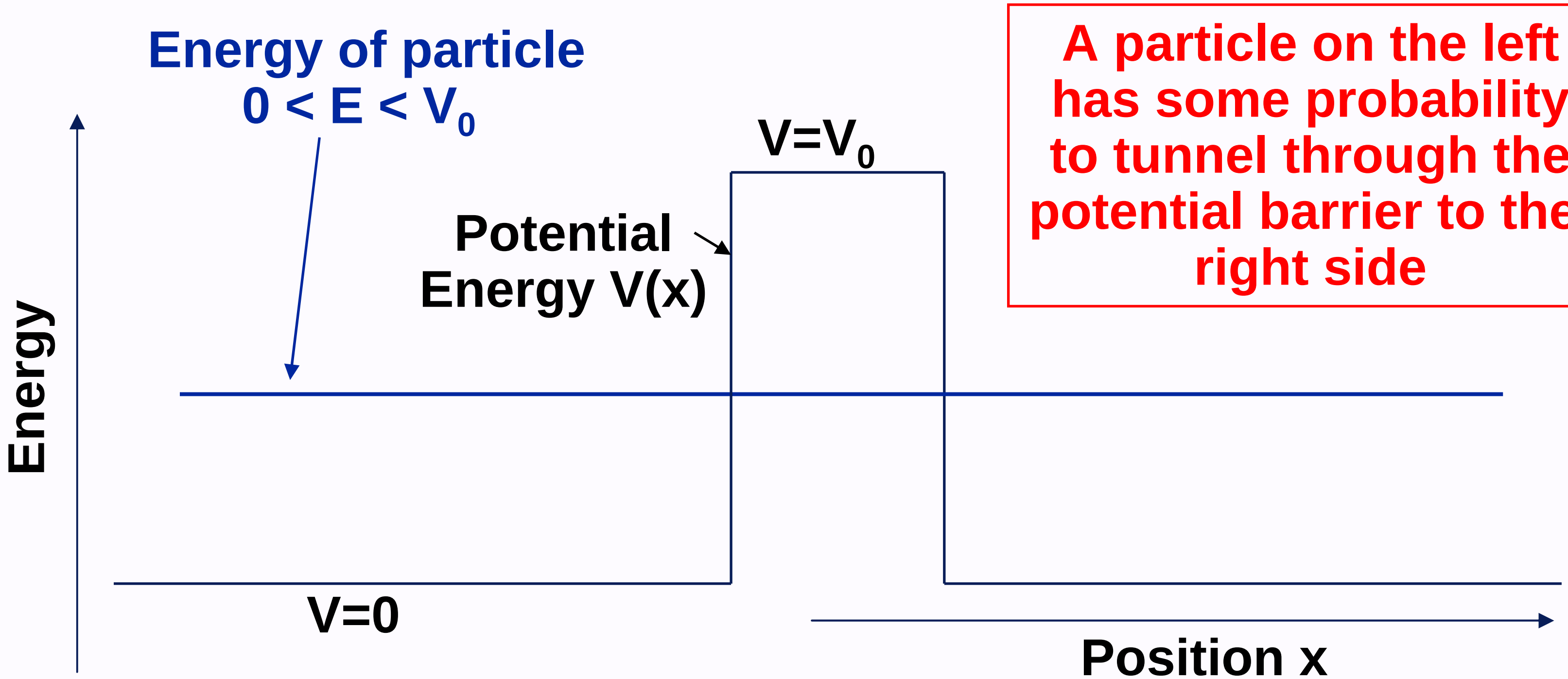
Surface
"reconstruction"



Rate of tunneling extremely sensitive to distance of tip from surface due to quantum effects

"Tunneling" in quantum mechanics

- In Quantum Mechanics has a non-zero probability to be in region that is "classically forbidden"
- A particle can tunnel through a barrier even though it does not have enough energy to get over the barrier



A particle on the left has some probability to tunnel through the potential barrier to the right side

Schrodinger Equation

- Basic equation of Quantum Mechanics

$$[- (\hbar^2/2m)d^2/dx^2 + V(x)] \Psi (x) = E \Psi (x)$$

where we consider only one dimension

m = mass of particle
$V(x)$ = potential energy at point x
E = eigenvalue = energy of quantum state
$\Psi (x)$ = wavefunction
$n (x) = | \Psi (x) |^2$ = probability density

•Key issue for tunneling: What happens if the energy E is less than the potential V at some point x

Schrodinger Equation II

- Consider the case where V = constant = V_0

$$[- (\hbar^2/2m)(d^2/dx^2)+ V_0]\, \Psi (x) = E\, \Psi (x)$$

which can be written

or $$(\hbar^2/2m))(d^2/dx^2)\, \Psi (x) = [V_0 - E]\, \Psi (x)$$

$$(d^2/dx^2)\Psi (x) = - k^2\, \Psi (x), \qquad k^2 = (E - V_0)(2m/\hbar^2)$$

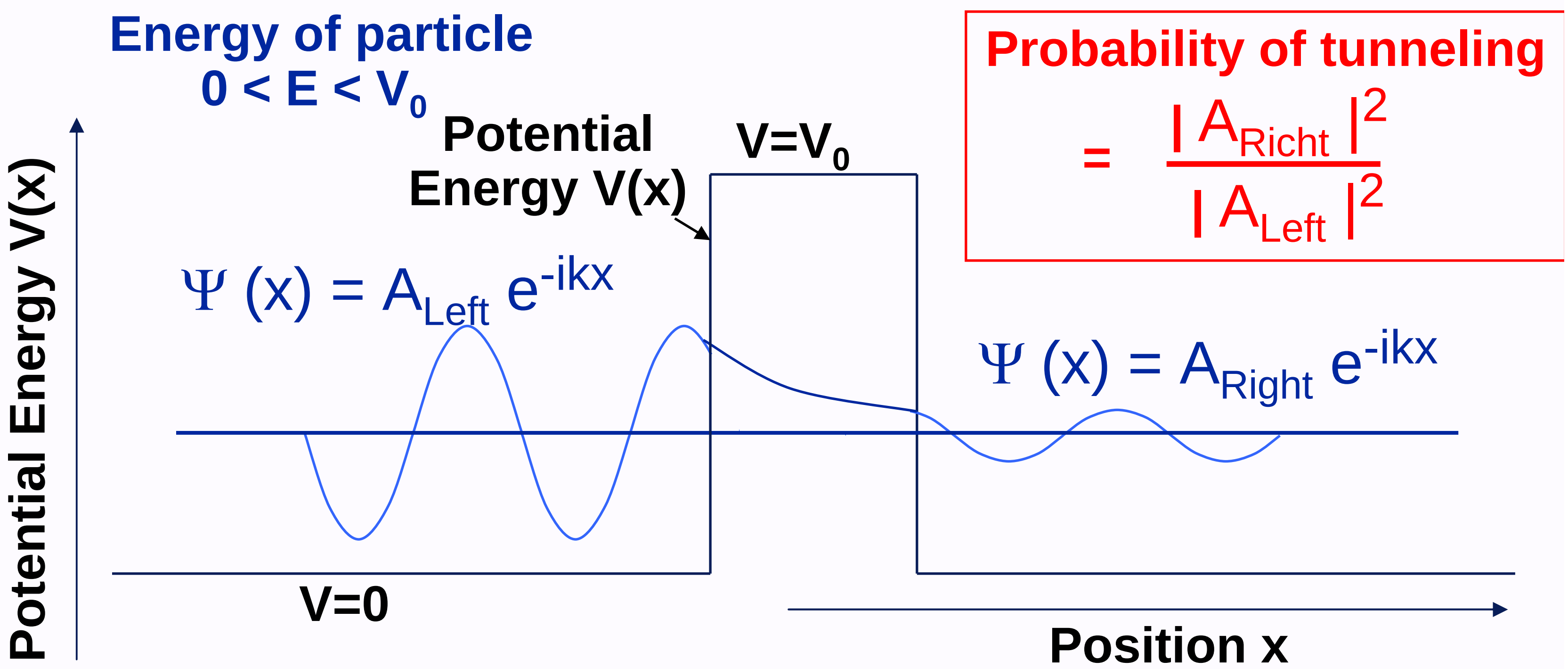
•If $E > V_0$, $\Psi (x) \sim e^{-ikx}$ (the same as before)

•If $E < V_0$, define $\kappa^2 = - k^2$,
$\Psi (x) \sim e^{- \kappa x}$

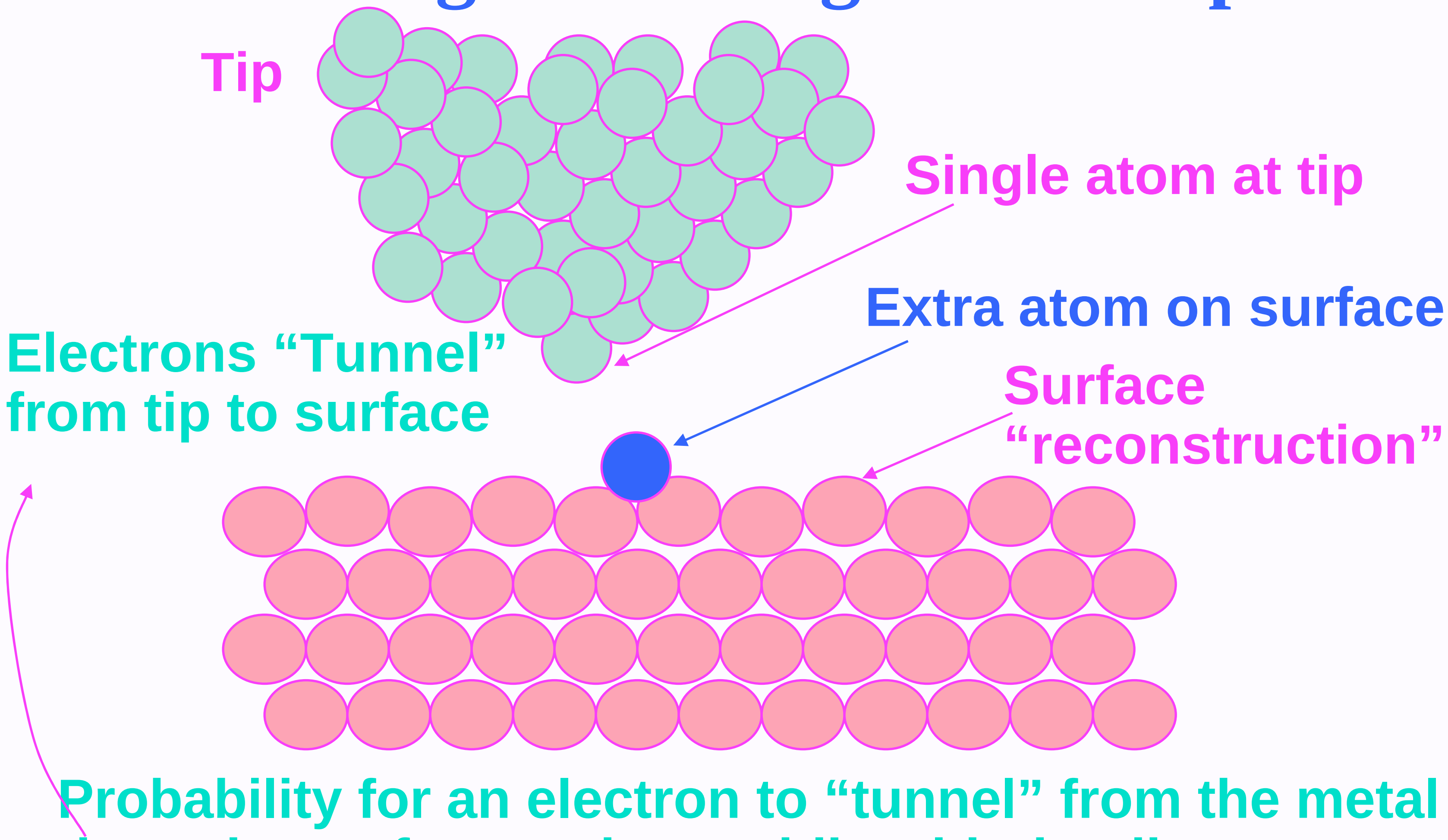
•The wavefuntion decays exponentially in the region where E < V

"Tunneling" in quantum mechanics

- In Quantum Mechanics has a non-zero probability to be in region that is "classically forbidden"
- A particle can tunnel through a barrier even though it does not have enough energy to get over the barrier



Scanning Tunneling Microscope



Probability for an electron to "tunnel" from the metal tip to the surface varies rapidly with the distance

STM images – example: GaAs

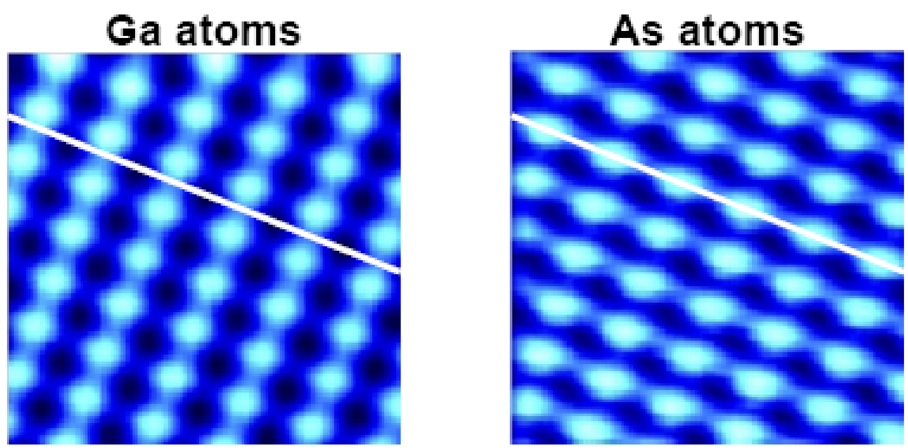
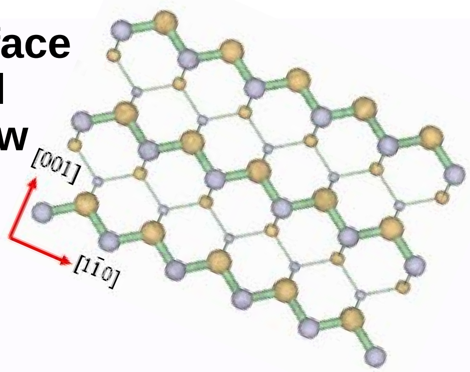


Figure 4.4: The empty states image (left) shows the Ga atoms at +2 V. The filled states image (right) sho~ the As atoms at -2 V. White lines are to guide eye to identical locations.

(110) Surface

(110) Surface model top view



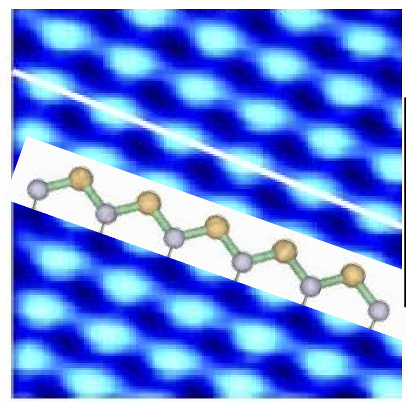


Image of As atoms Model showing Ga and As zig-zag chains

Figures from PhD thesis of Dale Kitchen, U of Illinois, 2006

STM image - Mn atom on GaAs

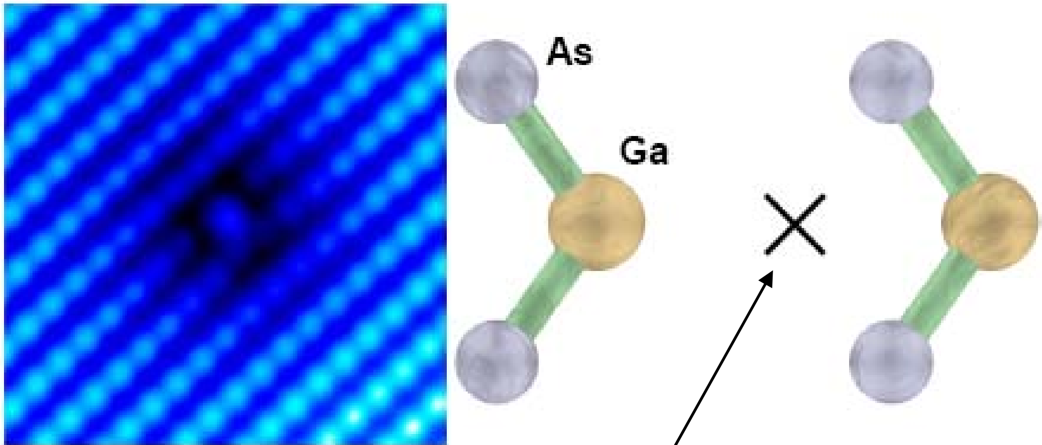


Figure 5.6: A Mn adatom is seen on the As sublattice (Filled states, -1.5 V) in a 50x50 Å area. The Mn adatom is positioned between two of the As rows. The Mn sits between two Ga sites.

GaAs (110) Surface with one added Mn atom at position indicated by x

Figures from PhD thesis of Dale Kitchen, U of Illinois, 2006

STM image – subsurface atoms

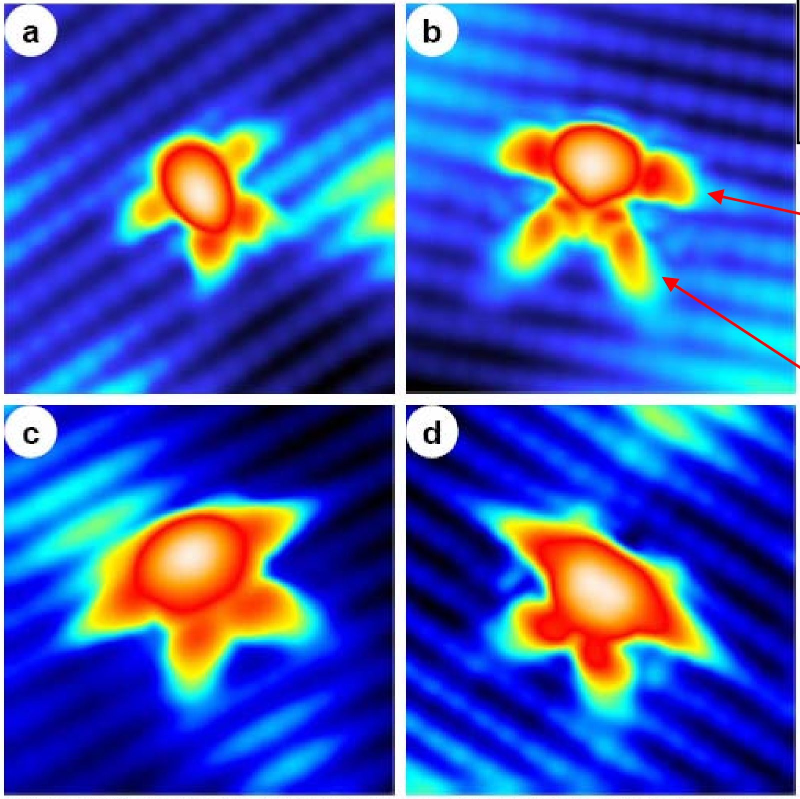


Figure 5.16: Empty states topography (50x50 Å) at conduction band bottom (+1.5 V) captures the in-gap resonances. The isolated impurities are (a) Zn, (b) Mn, (c) Fe, and (d) Co acceptors.

Shape indicates the directions of the electron bonds

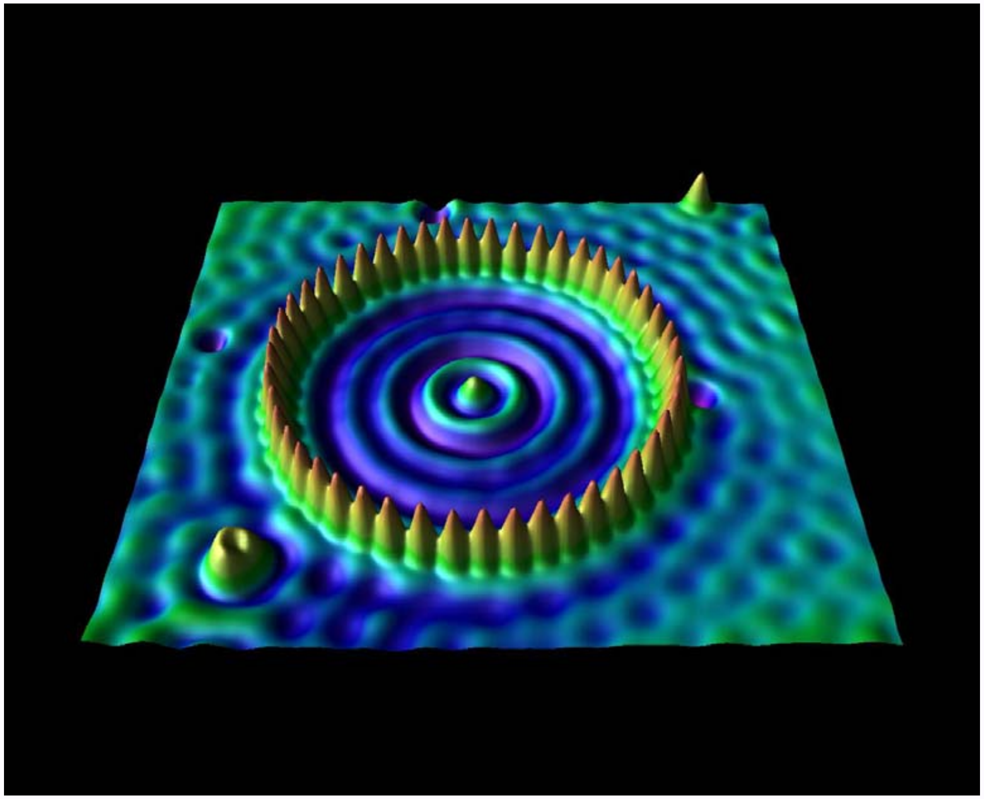
Bonds to surface atoms

Bonds to the other neighbors

GaAs (110) surface with Zn, Mn, Fe or Co atoms substituted for Ga in the first layer below the surface

Figures from PhD thesis of Dale Kitchen, U of Illinois, 2006

Observation of atoms, electron waves with Scanning Tunneling Microscope



Observation of atoms, electron waves with Scanning Tunneling Microscope

Corral of atoms placed one at the time
by maneuvering atoms with STM

Electron standing waves inside the “corral”

Extra atom

Surface Atoms

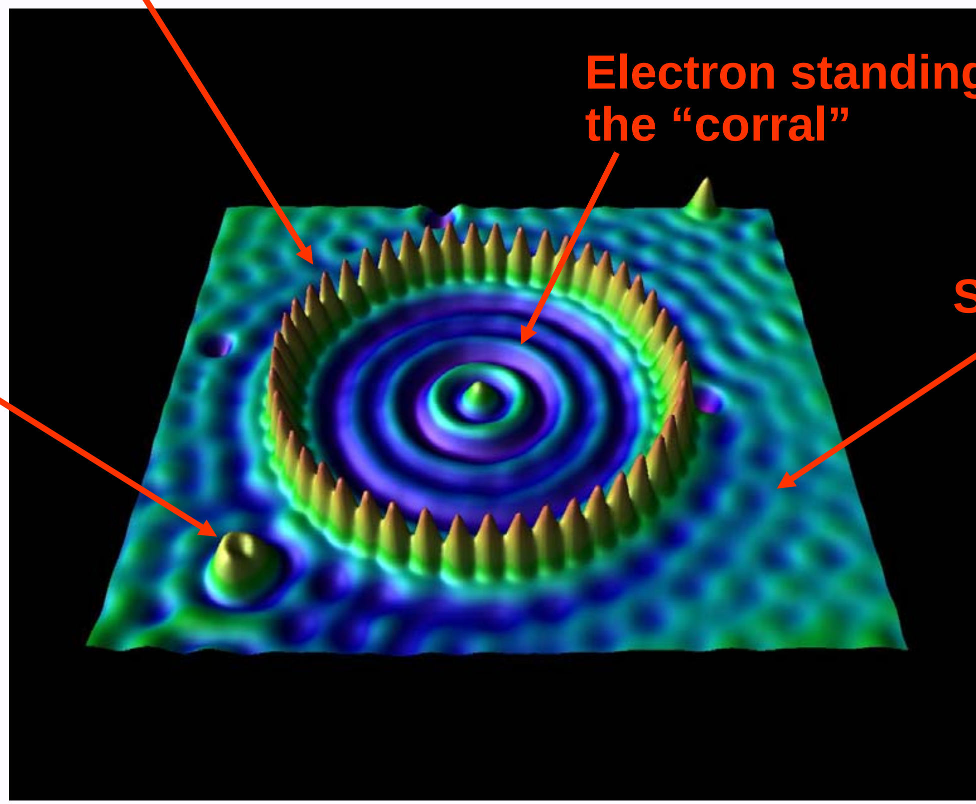
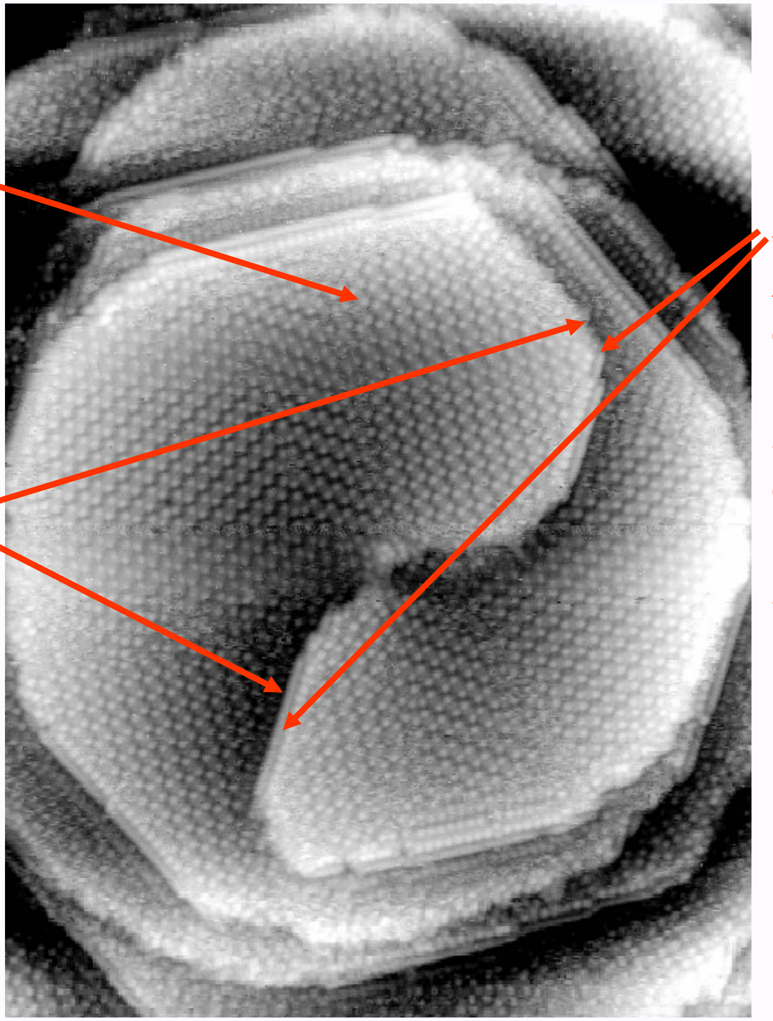


Figure by D. Eigler, et. al, IBM Research

Surface of GaN observed by STM



Atomic scale structure of surface

"Step" on surface where the surface height changes by one layer

Step

Side view

Spiral growth -- A common way that crystals grow -- by adding atoms at a step, the higher layer grows over the lower layer – continues in a spiral

Adding atoms at step makes step move to cover lower layer

Step

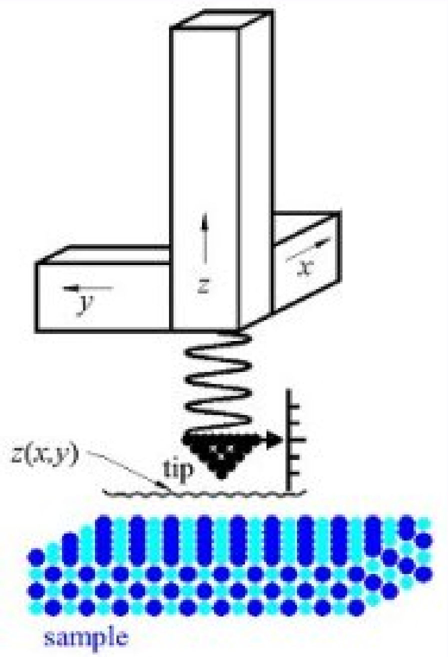
Side view

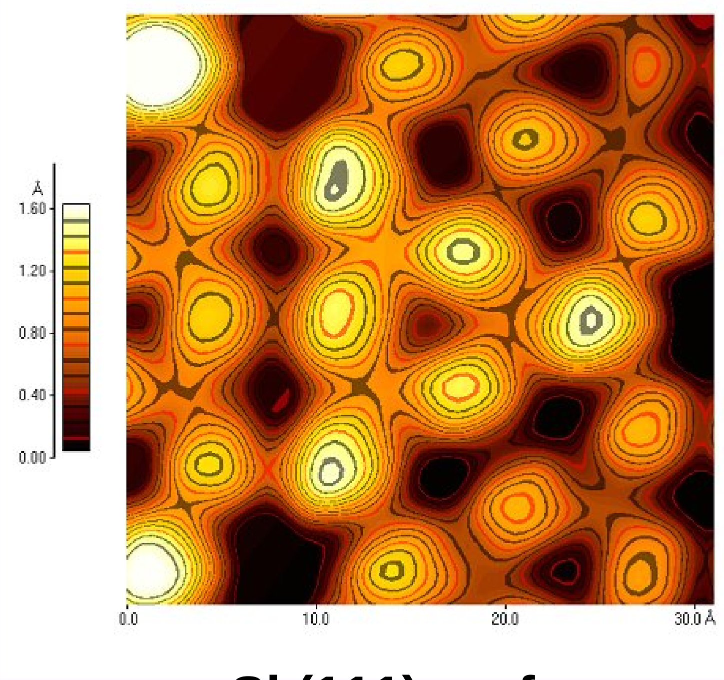
Figure by D. Smith, reproduced in Electronic Structure", by R. M. Martin, Cambridge University Press 2004

Atomic Force Microscope

Article in Physics Today, December, 2006

Works for insulators, ….





Si (111) surface

From http://www.physik.uni-augsburg.de/exp6/research/sxm/sxm_e.shtml

Summary

- Surfaces of crystals
- Example – surfaces of semiconductors – GaAs
- Tunneling in quantum mechanics
  Particles can tunnel through barriers
  Exponential decay where E < V
- STM – electrons tunnel through space between tip and sample
  Leads to the extreme sensitivity of tunneling current to the distanceof tip to sample
  Dominated by a single atom on tip
- Examples of GaAs, Mn on GaAs, adatoms on Cu, atoms on GaN surface that illustrate growth, ….
- AFM – very brief

Next Lecture

- **Nanostructures**

  Magnetic, superconducting

- **Final lecture ---- Summary of course**