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SPRING COLLEGE IN CONDENSED MATTER
ON
"THE INTERACTION OF ATOMS & MOLECULES WITH SOLID SURFACES"
(25 April - 17 June 1988)

SCANNING TUNNELING MICROSCOPY

Randall M. FEENSTRA
IBM Thomas J. Watson Research Center
P.O. Box 218
Yorktown Heights, New York 10598
U.S.A.

1988 ICTP Spring College in Condensed Matter Physics

Scanning Tunneling Microscopy

R. M. Feenstra

IBM Yorktown Heights

1. Historical Review
2. Apparatus
3. Microscopy
   (a) image interpretation (metal vs. semiconductors)
   (b) surface buckling - GaAs(110)
   (c) surface reconstruction - Si(111)2x1
4. Spectroscopy
   (a) tunneling theory
   (b) ordered surface states - Si(111)2x1
   (c) semiconductor effects - GaAs(110)
   (d) charge of adsorbates - O/GaAs(110)
   (e) disordered surface states - Sb/GaAs(110)
5. Other Applications/Techniques

Pre-STM Related Work (partial list):

A. Solid Barrier Tunneling:

1. L. Esaki, "New phenomena in narrow Germanium p-n junctions", Phys. Rev. ***109***, 603 (1958).

2. I. Giaver, "Energy gap in superconductors measured by electron tunneling", Phys. Rev. Lett. ***5***, 147 (1960).

3. R. C. Jaklevic and J. Lambe, "Molecular Vibration Spectra by Electron Tunneling", Phys. Rev. Lett. ***17***, 1139 (1966).

B. Squeeze Tunneling:

1. J. Moreland and P. K. Hansma, "Electromagnetic squeezer for compressing squeezable electron tunneling junction", Rev. Sci. Instr. ***55***, 399 (1984).

C. Measurement of Surface Forces:

1. J. N. Israelachvili and D. Tabor, "The measurement of van der Waals dispersion forces in the range 1.5 to 130 nm", Proc. Roy. Soc. A***331***, 19 (1972).

D. Vacuum Tunneling:

1. R. Young, J. Ward, and F. Scire, "Observation of Metal-Vacuum-Metal Tunneling, Field Emission, and the Transition Regime, Phys. Rev. Lett. ***27***, 922 (1971).

2. W. A. Thompson and S. F. Hanrahan, "Thermal drive apparatus for direct vacuum tunneling experiments", Rev. Sci. Instr. ***47***, 1303 (1976).

3. E. C. Teague, "Room-Temperature Gold-Vacuum-Gold Tunneling Experiments", Bull. Amer. Phys. Soc. ***23***, 290 (1978).

E. Fowler-Nordheim Tunneling & Scanning:

1. R. D. Young, "Surface Microtopography" Physics Today, ***24***, 42 (1971).

1. R. D. Young, J. Ward, and F. Scire, "The Topografiner: An Instrument for Measuring Surface Microtopography", Rev. Sci. Instr. ***43***, 999 (1972).

Early Papers:

1. G. Binnig, H. Rohrer, Ch. Gerber, E. Weibel, "Tunneling through a controllable vacuum gap", Appl. Phys. Lett. ***40***, 179 (1982).

2. G. Binnig, H. Rohrer, Ch. Gerber, and E. Weibel, "Surface Studies by Scanning Tunneling Microscopy", Phys. Rev. Lett. ***49***, 57 (1982).

3. G. Binnig, H. Rohrer, Ch. Gerber, and E. Weibel, "7x7 Reconstruction on Si(111) Resolved in Real Space", Phys. Rev. Lett. ***50***, 120 (1983).

Reviews:

1. G. Binnig and H. Rohrer, Helv. Phys. Acta ***55***, 726 (1982).

2. G. Binnig and H. Rohrer, Surf. Sci. ***152/153***, 17 (1985).

3. G. Binnig and H. Rohrer, IBM J. Res. Devel. ***30***, 355 (1986).

4. P. K. Hansma and J. Tersoff, J. Appl. Phys. ***61***, R1 (1987).

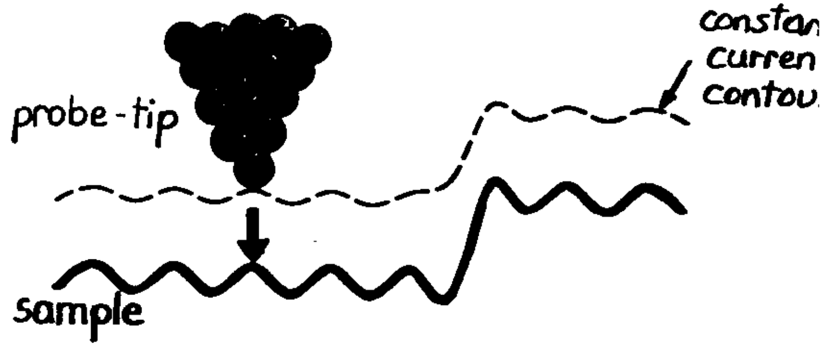
Conference Proceedings:

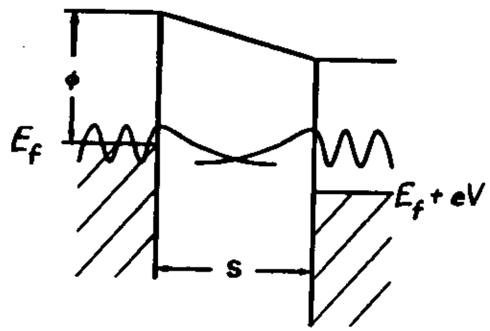
1. IBM Journal of Research and Development, Vol. 30, No. 4 & 5 (1986).

2. Surface Science, Vol. 181, No. 1 & 2 (1987).

3. Journal of Vacuum Science and Technology A, March/April (1988).

STM - G. Binnig, H. Rohrer, Ch. Gerber, E. Weibel, Phys. Rev. Lett. 49, 57 (1982).





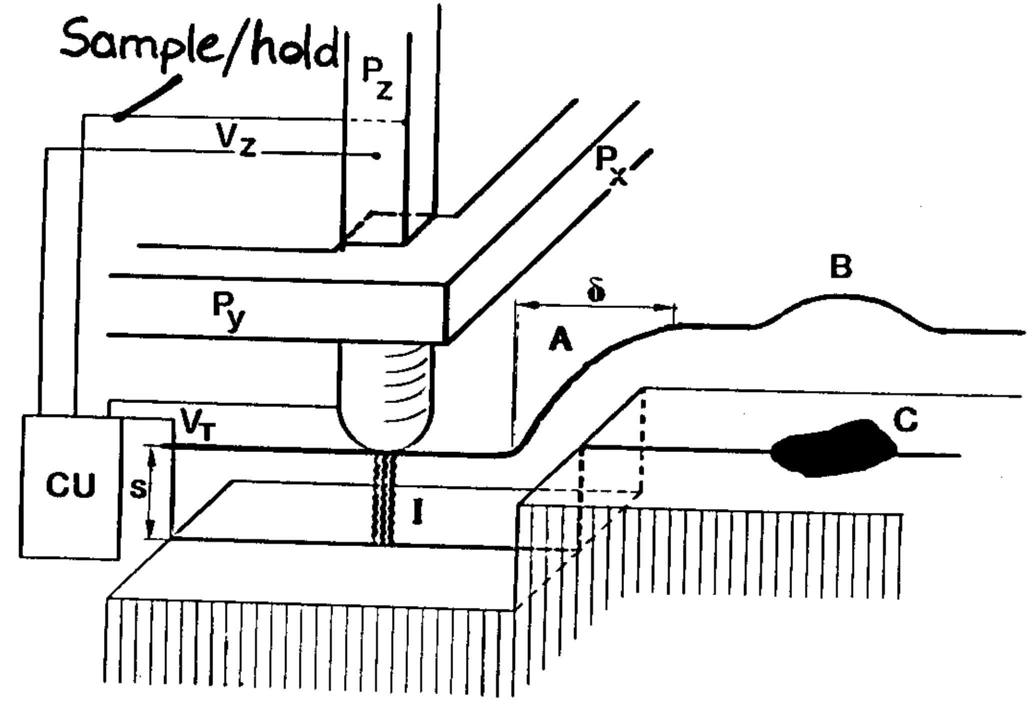
$$\frac{I}{V} \propto \rho\, e^{-2\kappa s}$$

$$\kappa = \frac{\sqrt{2m\phi}}{\hbar} \simeq 1.1\ \text{Å}^{-1}$$

ρ = density-of-states

(Tersoff + Hamann, PRL 50, 1998 (198:

STM G. Binnig, H. Rohrer, Ch. Gerber, E. Weibel, Phys. Rev. Lett. 49, 57 (1982).



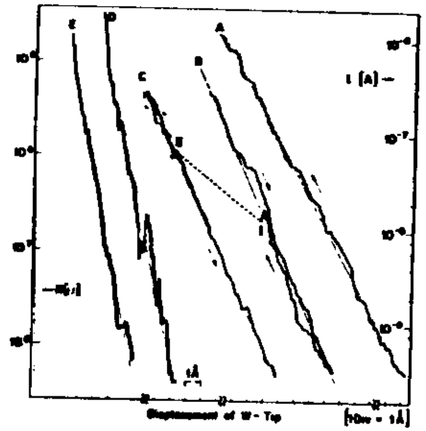
P_x, P_y, P_z – Piezo-electric elements

CU – Feedback control unit

Sample/hold – spectroscopic measurements

Exponential dependance of tunneling current:

(Binnig, Rohrer, Gerber, Weibel, Appl. Phys. Lett. 40, 178 (1982)



I (A)

S (Å)

previous work:

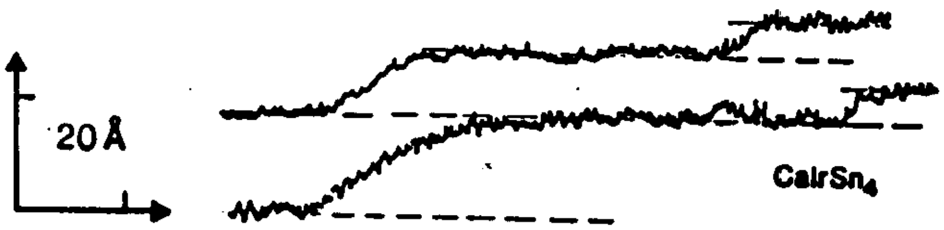
Young, Ward, Scire, Rev. Sci. Instr. 43, 999 (1972

Thompson, Hanrahan, Rev. Sci. Instr. 47, 1303 (1976

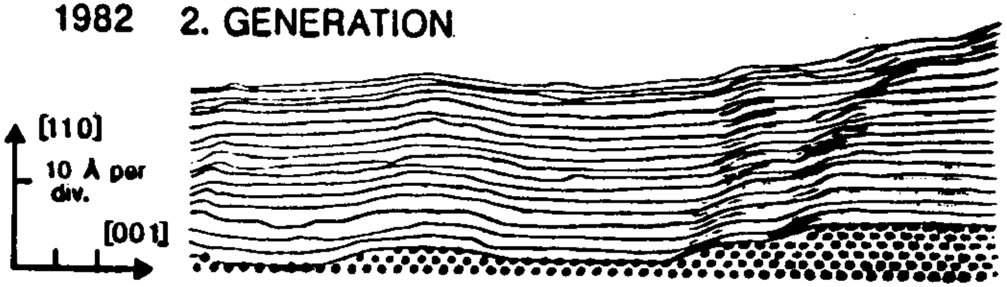
Binnig, Rohrer, Gerber, Weibel - IBM Zürich

EVOLUTION OF STM

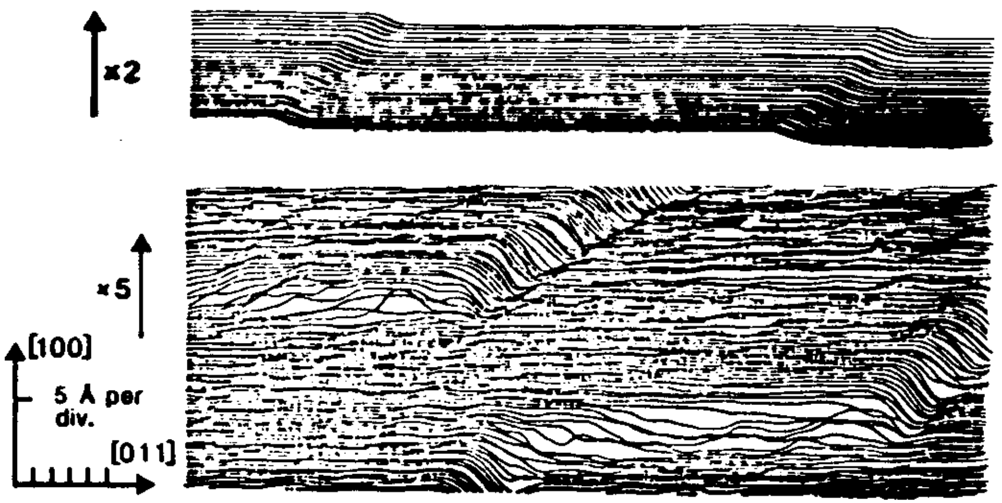
1981 1. GENERATION



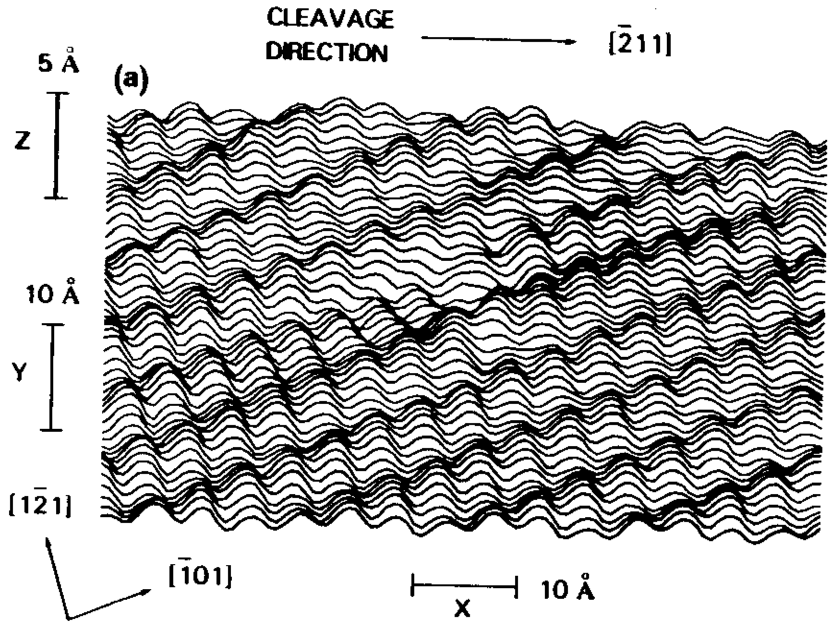
1982 2. GENERATION



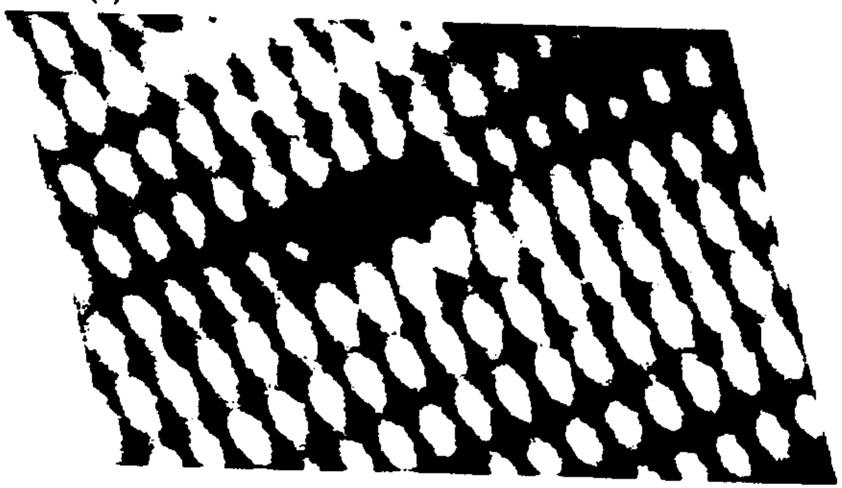
1983 3. GENERATION



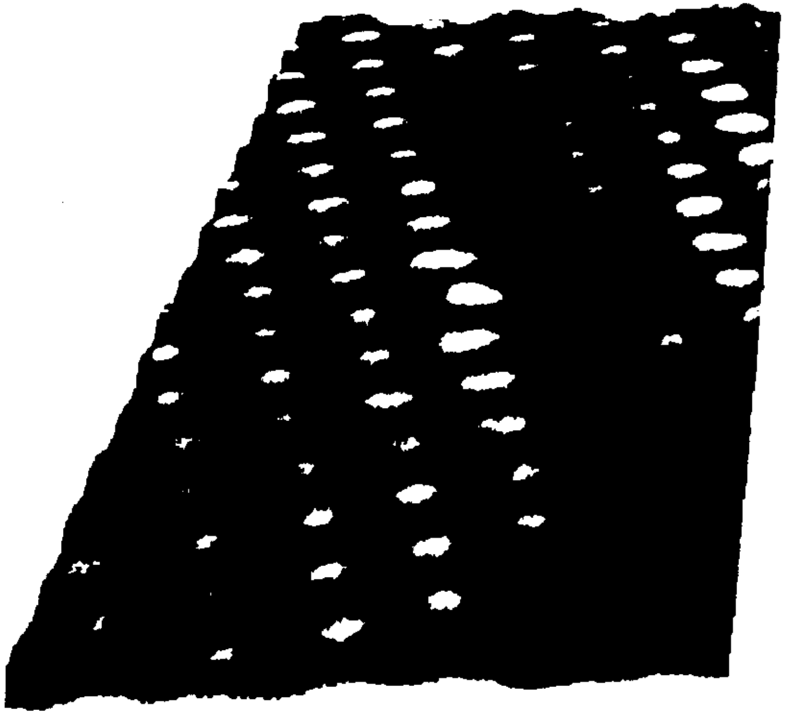
Si(111) 2×1



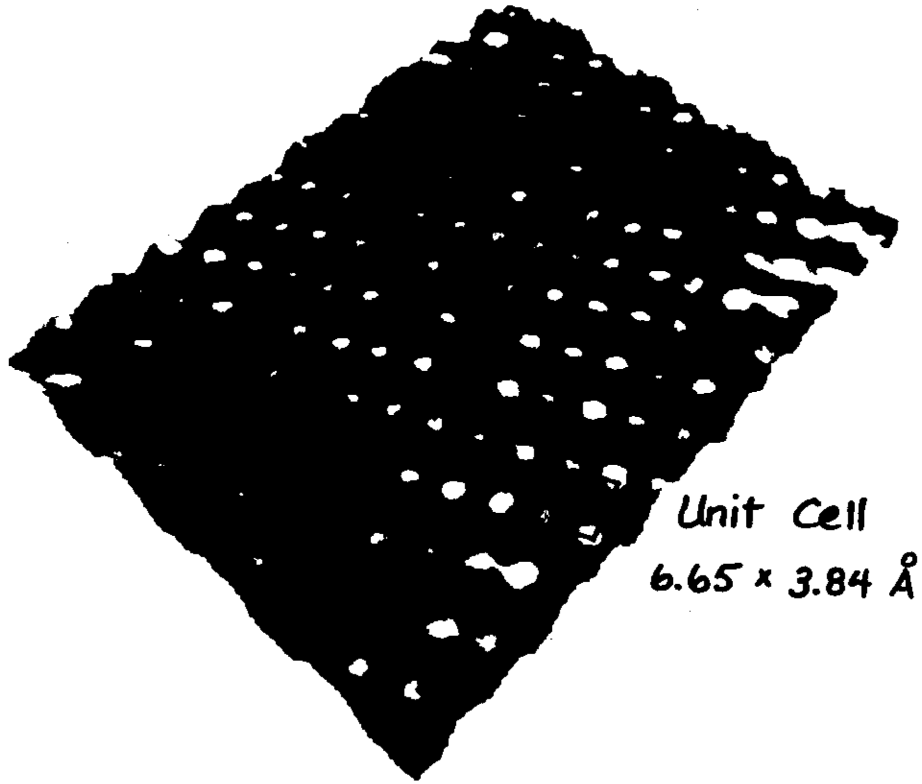
(b)



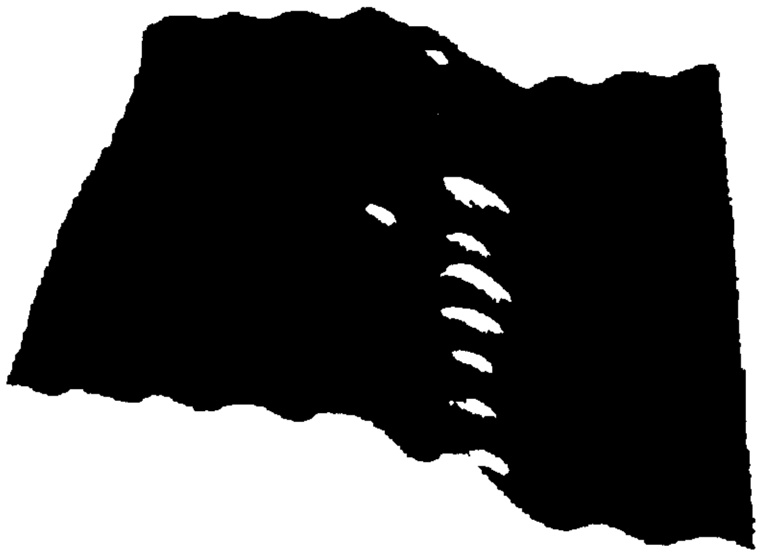
Si(111) 2×1



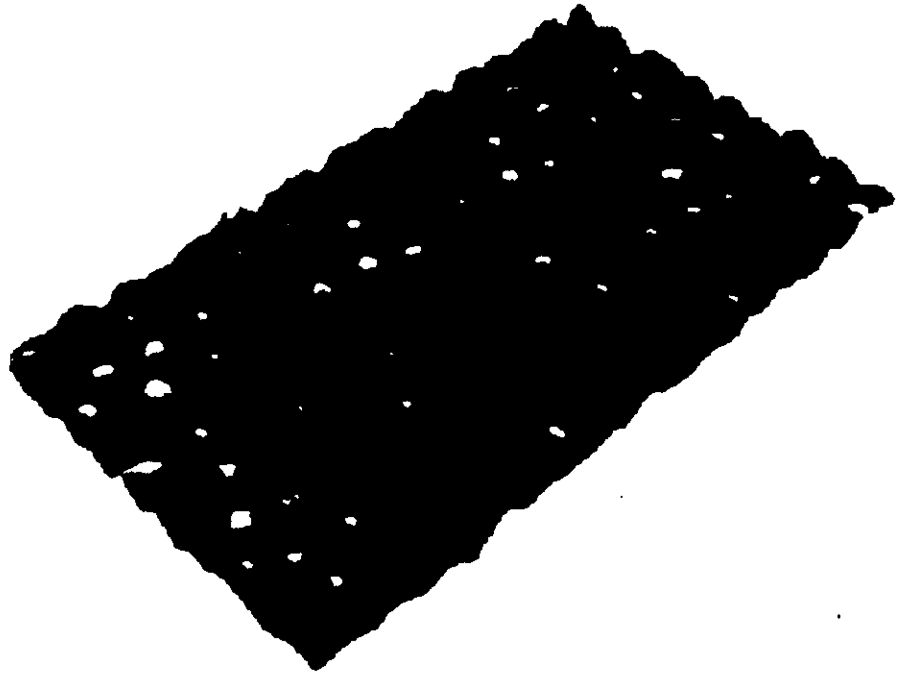
Si(111) 2×1



Si (111) 2×1 mono-atomic step



Si (111) 7×7



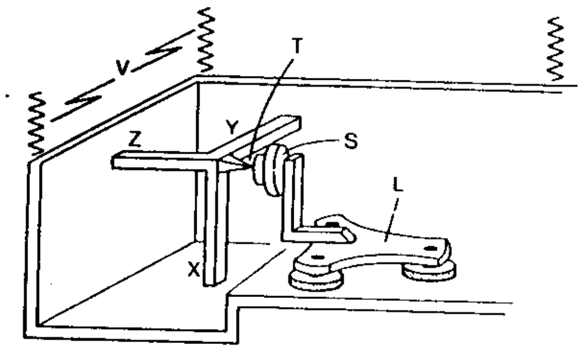
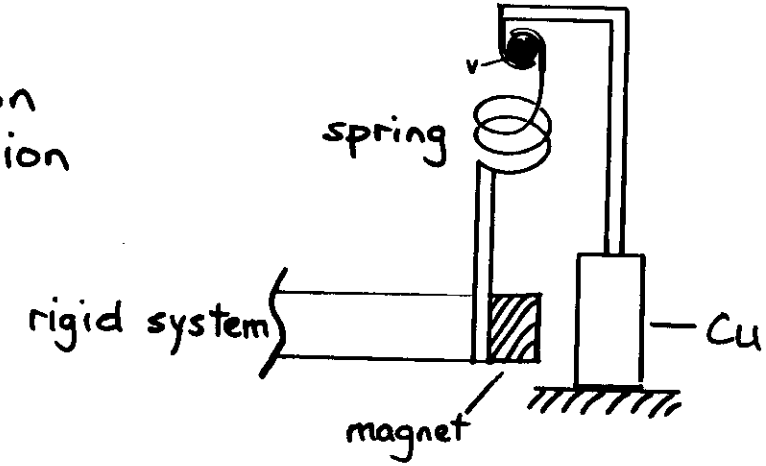


FIG. 1. Schematic of a STM using a piezotripod, (X-Y-Z) for fine positioning of the tunnel tip T and a piezomotor L for rough positioning of the sample S. Vibration isolation is achieved with coil spring V and eddy-current damping (not shown).

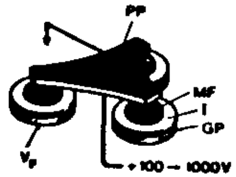
Ch. Gerber, G. Binnig, H. Fuchs, O. Marti, H. Rohrer, Rev. Sci. Instr. 57, 221 (1986).

Components of STM: (Binnig, et. al.)

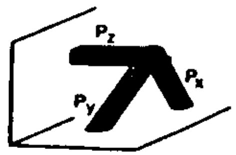
a) vibration isolation

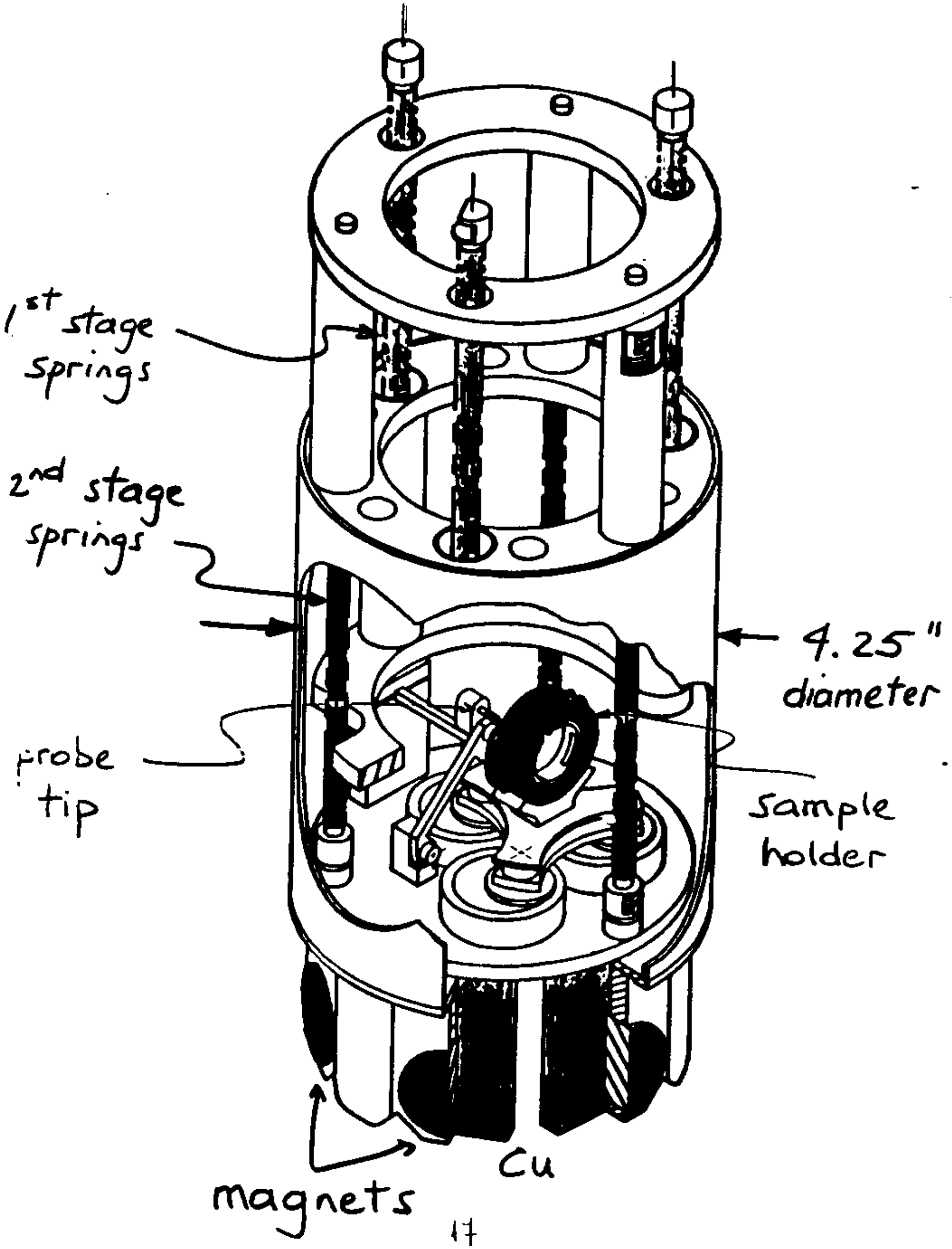


b) coarse motion "louse" (1 μm - 1 cm)

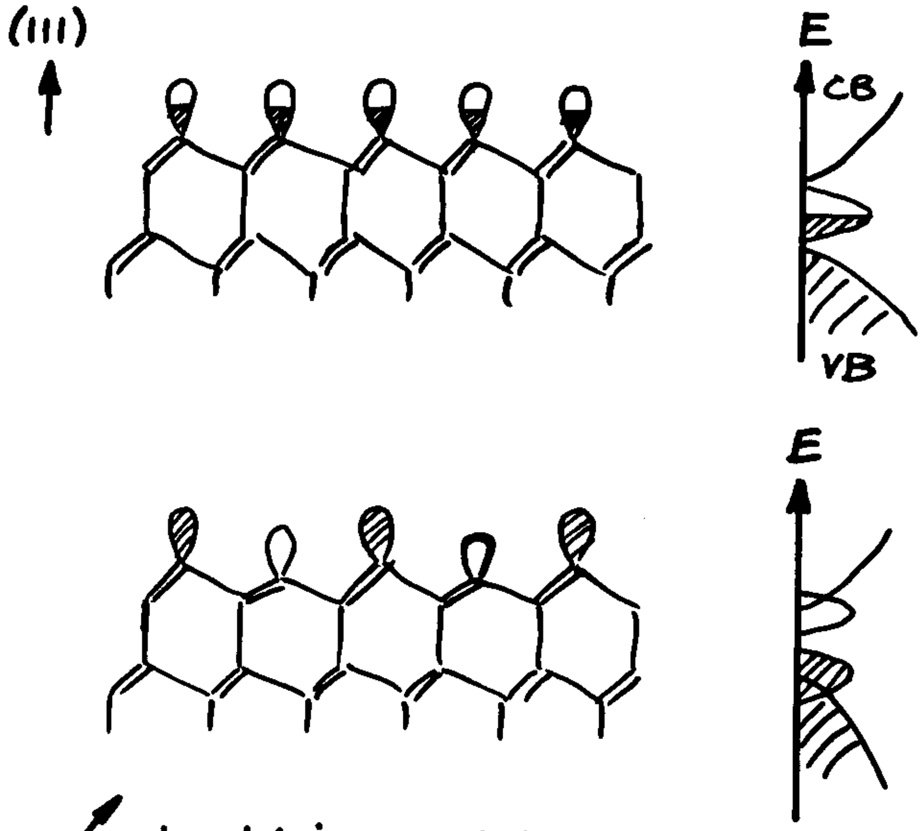


c) fine motion piezo - tripod (0.1 Å - 1 μm)





Surface Reconstructions:



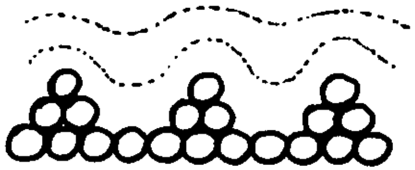
↙ buckling model

Where are the atoms ?

Where are the electrons ?

Interpretation of Images

Metals - state-density follows atoms

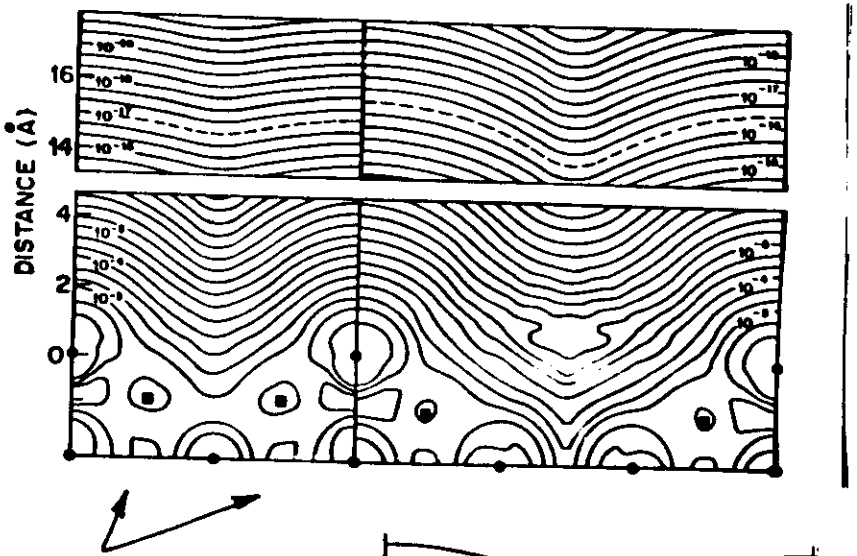


→ place ball of charge $\rho_i \sim e^{-\beta(r-R_i)}$
around each atom,
and sum $\rho_{tot} = \sum_i \rho_i$,
Search for contour of constant ρ.
"CHARGE SUPERPOSITION"

Semiconductors -
state-density does <u>not</u> follow atoms

→ Charge superposition usually not applicable, even to lowest order.
→ Look at electronic band-structure.

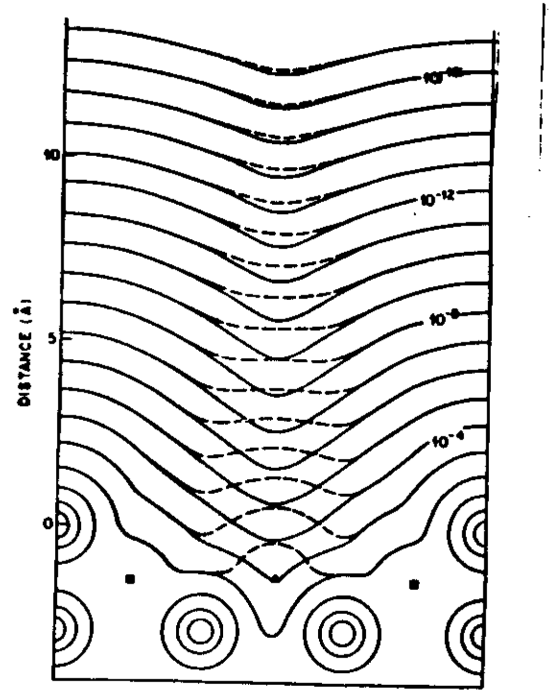
J. Tersoff + D.R. Hamann, Phys. Rev. B31, 805 (1985).



Au(110) 2×1, 3×1
$\rho(\vec{r}, E_f)$ by LAPW
• in-plane atom
■ out-of-plane atom

Au (110) 2×1 →
charge-superposition

— atoms as shown
--- extra atom ▲

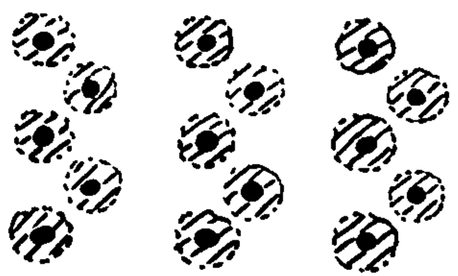


STM images of semiconductors:

tight-binding $\quad \psi_j \sim \sum_i a_{ij}\, \phi_i (r - R_i)$

(a_{ij}: energy dependent; ϕ_i: dangling bond on i^{th} atom)

lateral position: (x, y)

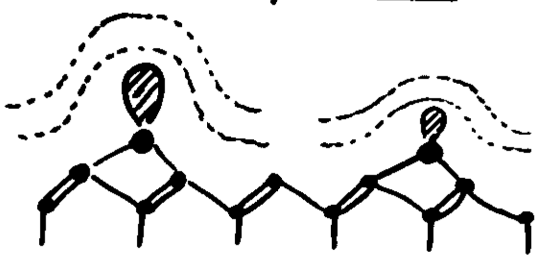


STM sees atoms with dangling bonds, but <u>not</u> all atoms are seen equally.

$\Delta(x,y) \sim 1$ Å

voltage-dependence

vertical position: (z)



difficult to distinguis between atomic height and magnitude of state-density.

Δz large!

"normalization" of data

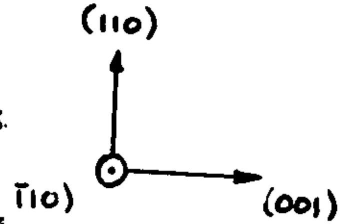
Tersoff and Hamann

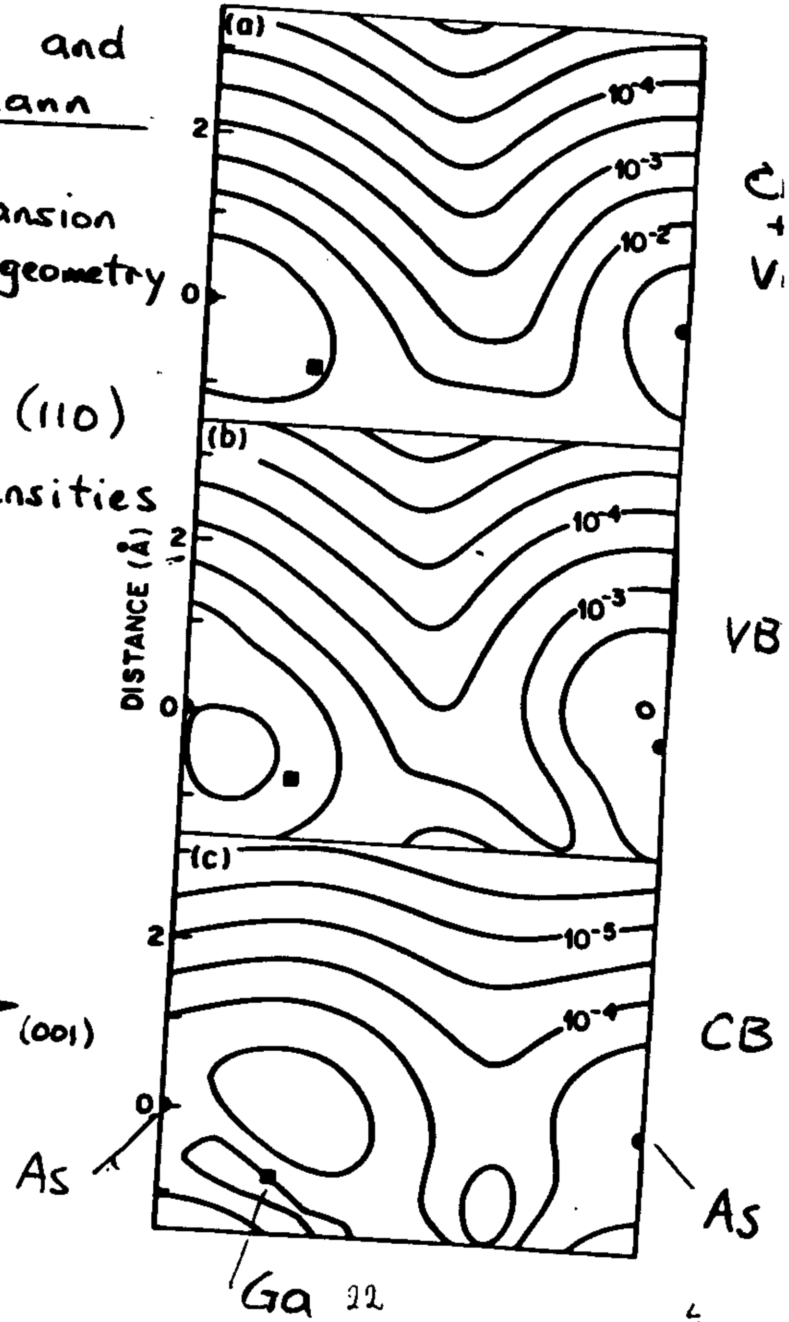
LAPW expansion

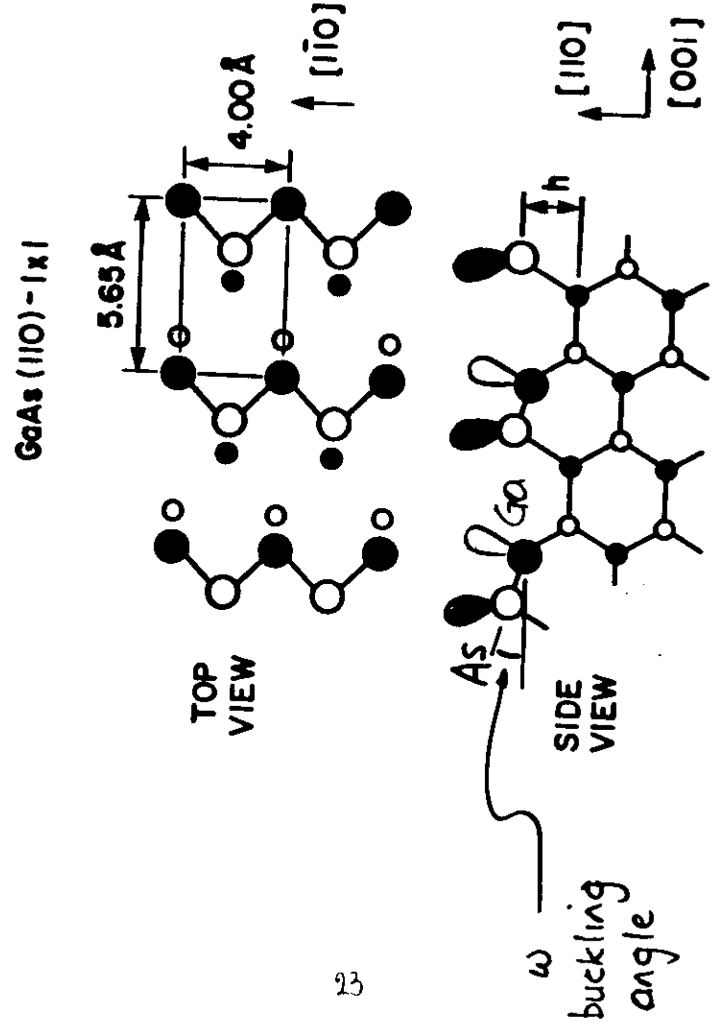
thin-slab geometry

GaAs (110)

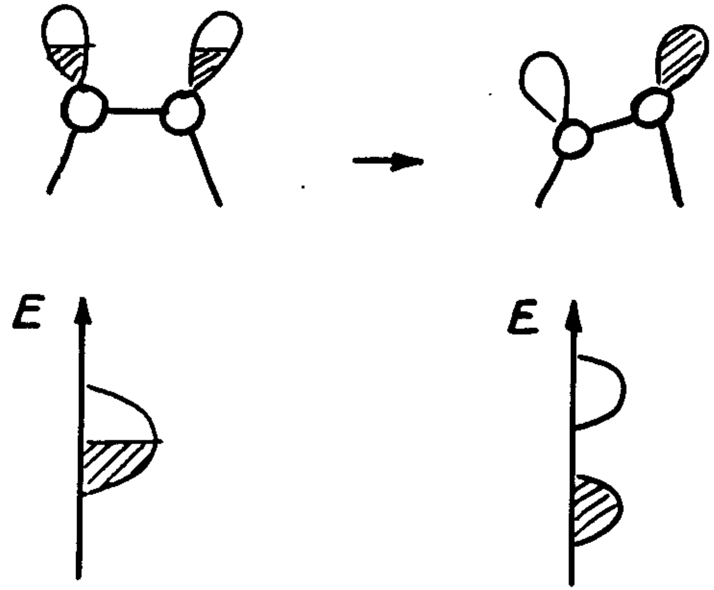
charge densities







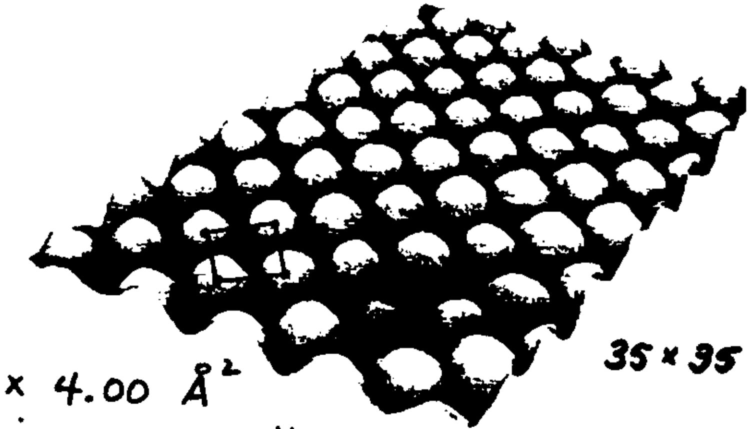
Buckling: charge transfer between equivalent *or* inequivalent atoms



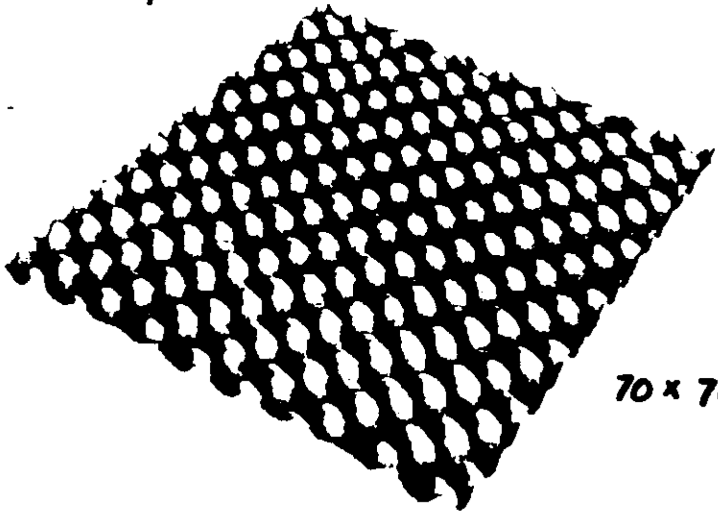
Energy is lowered.

Filled states on *up* atoms,
Empty states on *down* atoms.

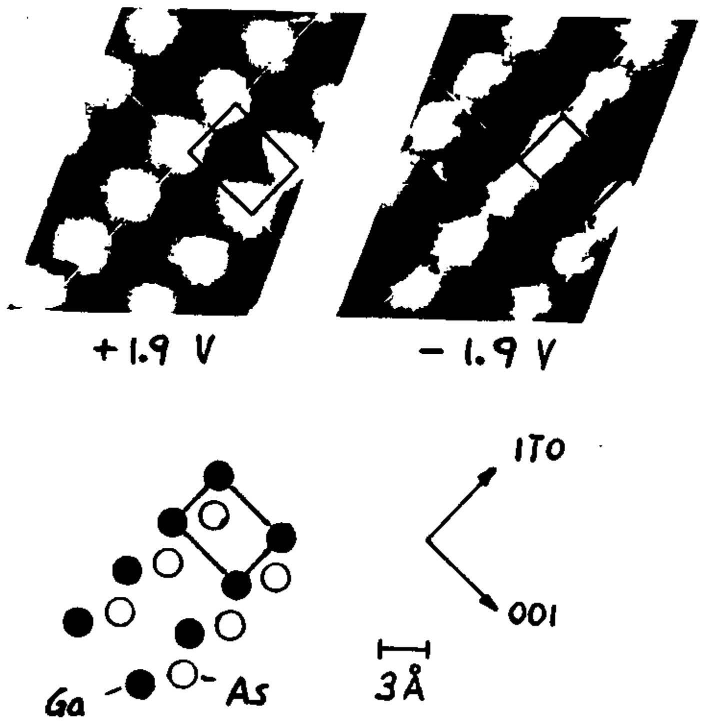
GaAs (110) - 1×1



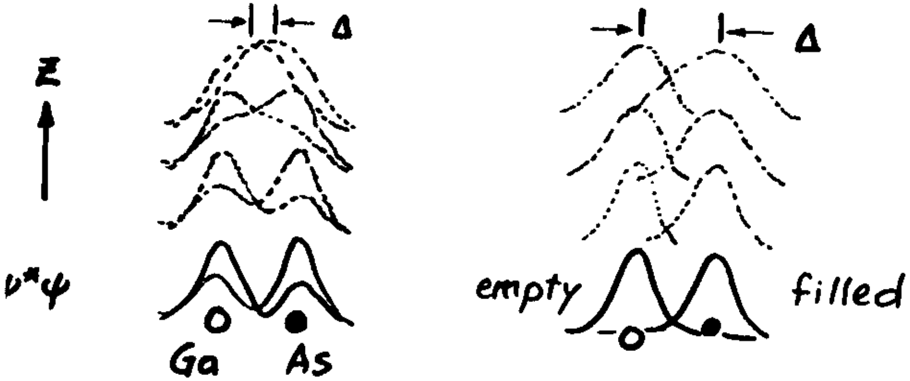
Unit Cell:
5.65 × 4.00 Å²
one maxima per cell



GaAs (110)



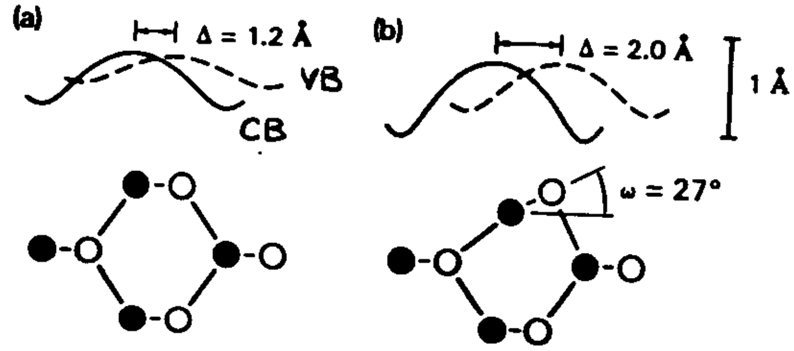
Lateral Shift between Empty and Filled States



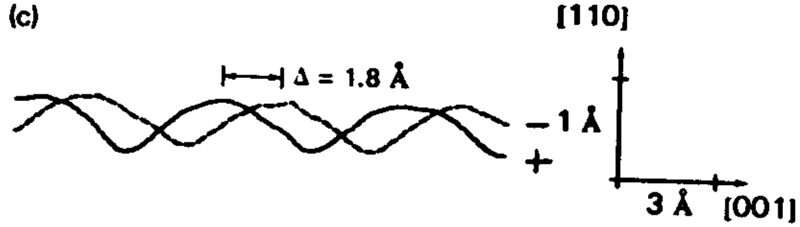
non-buckled   buckled

GaAs(110) - Structural Dependence of State-Density

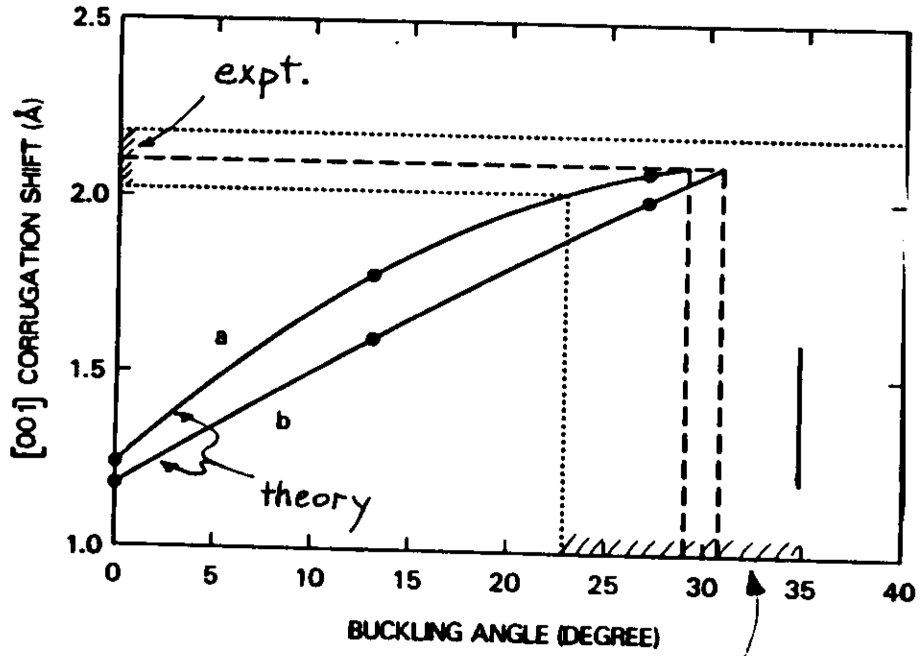
THEORY:



EXPERIMENT:



$\overline{\Delta} = 2.10\ \text{Å} \quad , \quad \frac{\sigma}{\sqrt{N}} = 0.08\ \text{Å}$



a) $s = 5.7$ Å
b) $s = 7.5$ Å

determined range of buckling

GaAs (110) images:

- chemical difference : large effect
  Ga. vs. As
  electronegativity
- determination of structural paramete
  (buckling) : small effect

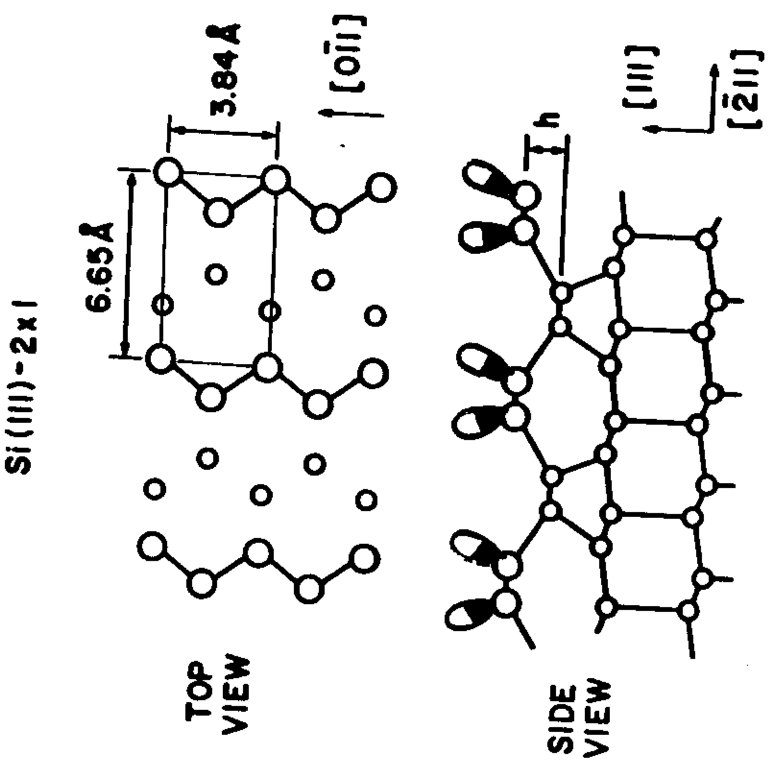


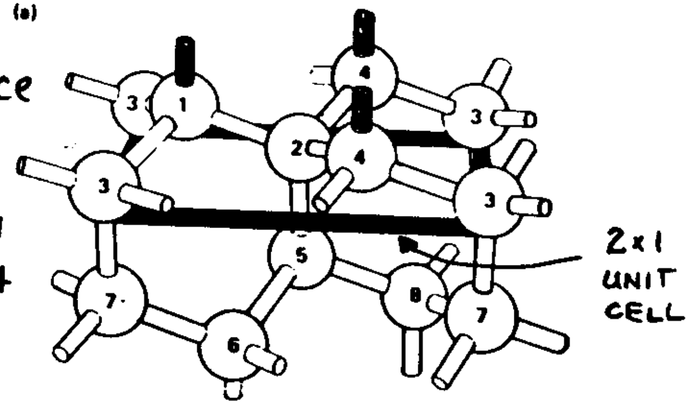
Figure from Nielsen, Martin, Chadi and Kunc, JVST B1, 714 (1983):

(a)

Ideal (111) Surface

Buckled { lower 1, raise 4 }

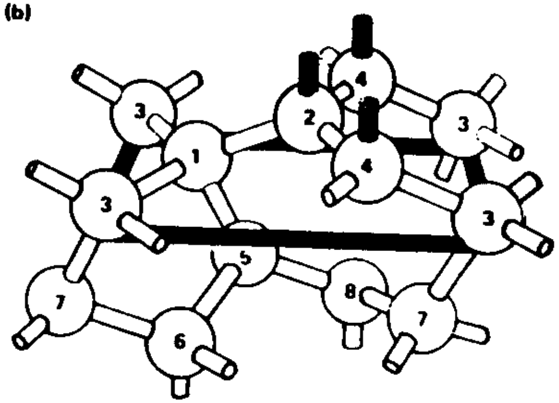
Haneman (1961)



(b)

π-bonded chain

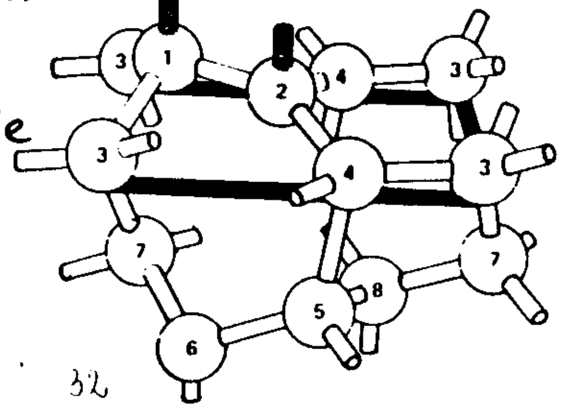
Pandey (1981)



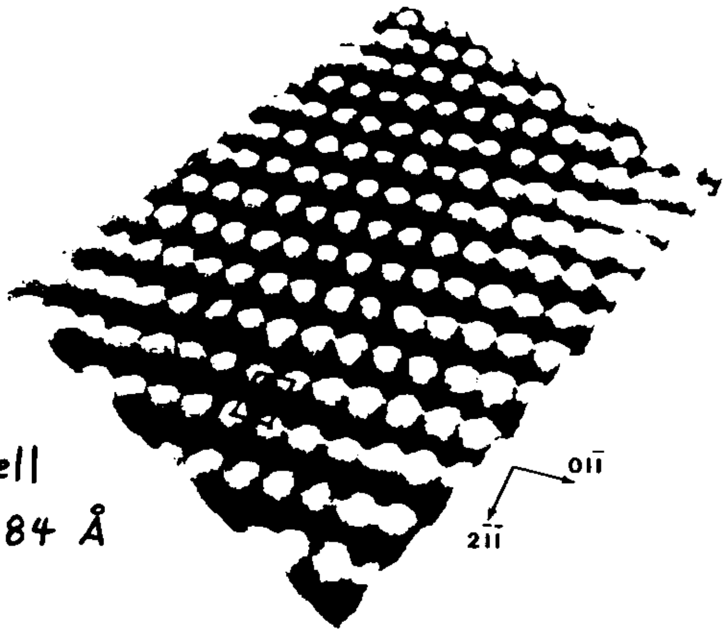
(c)

π-bonded molecule

Chadi (1982)

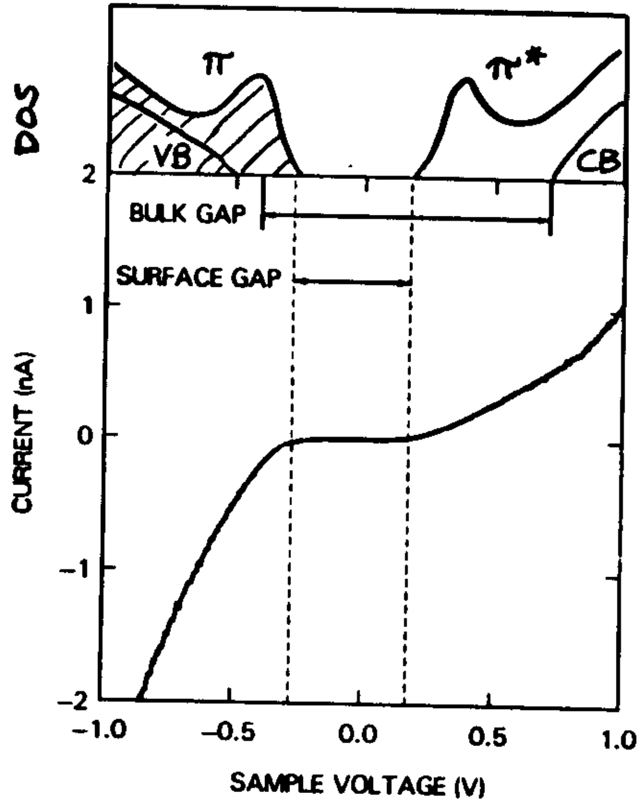


Si(111) 2×1



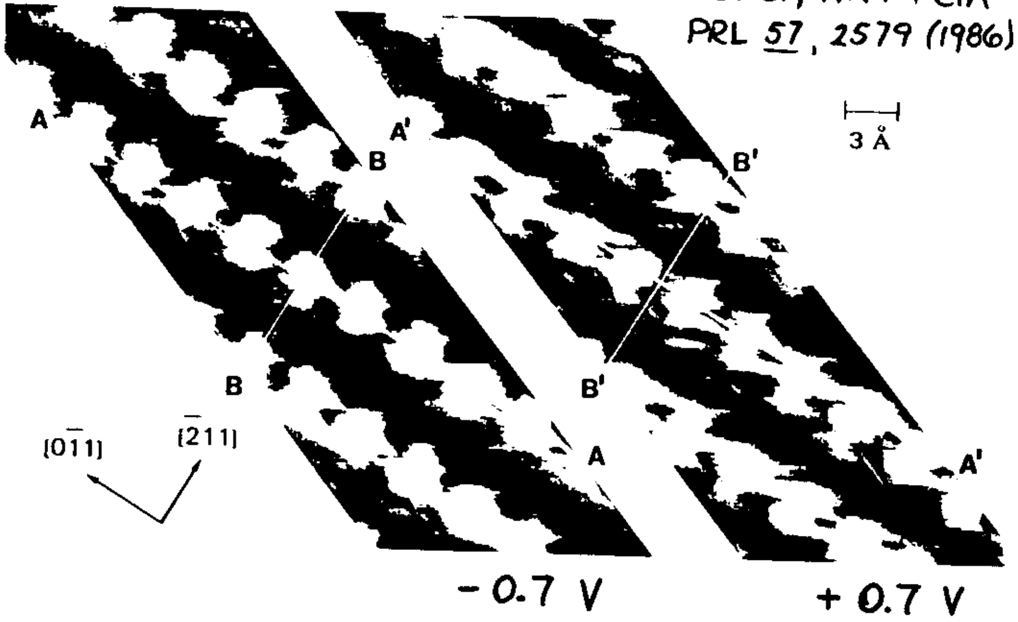
Unit Cell
6.65 × 3.84 Å

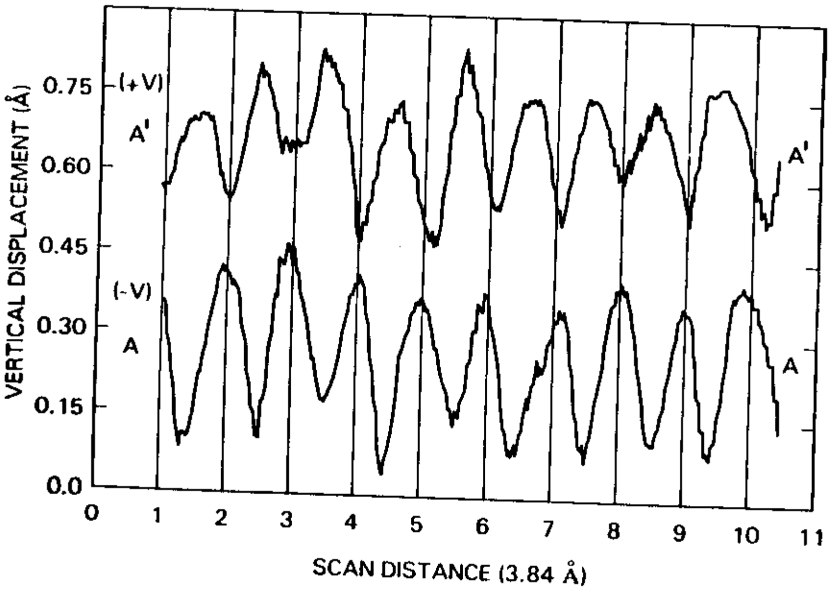
Si(111) 2×1



Si(111) 2×1

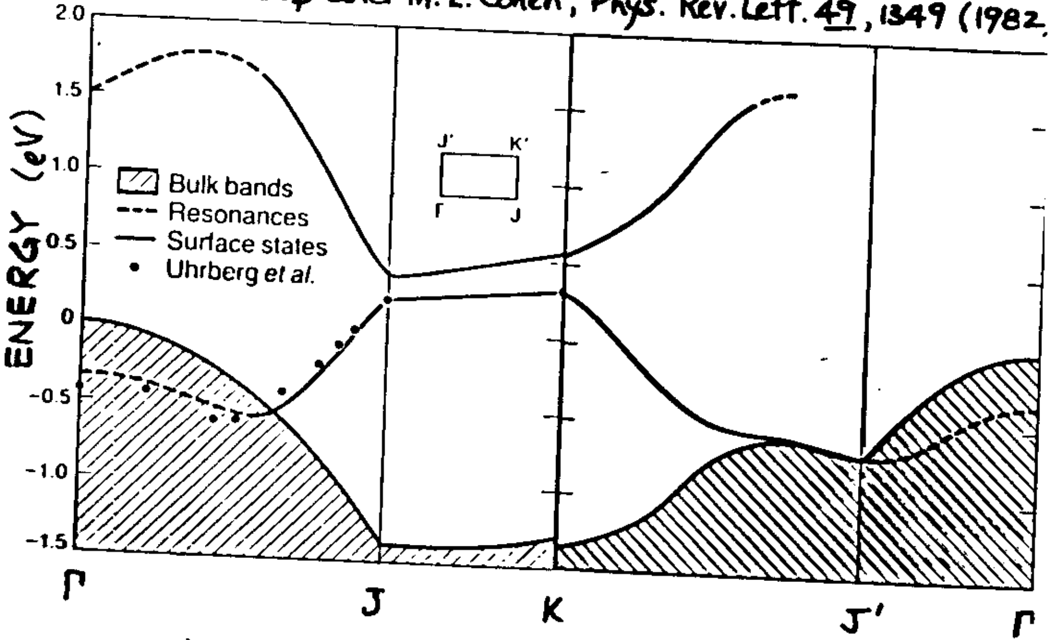
J. A. Stroscio, R. M. Feenstra, A. P. Fein
PRL 57, 2579 (1986)

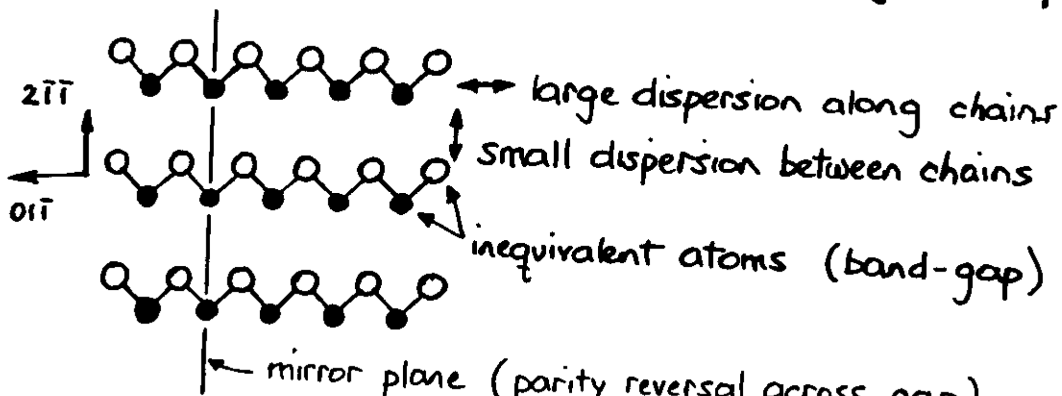




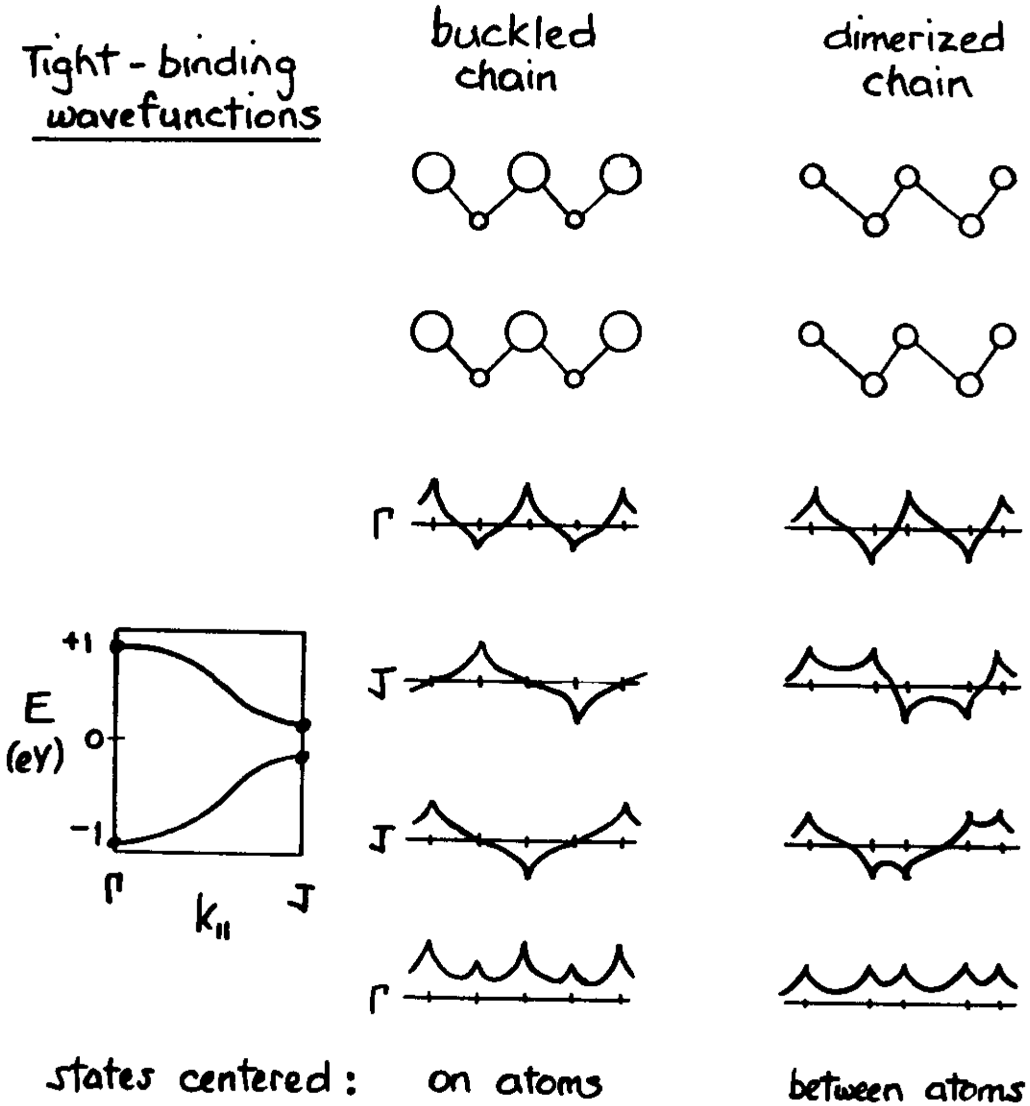
Surface-state Bands for π-bonded chains:

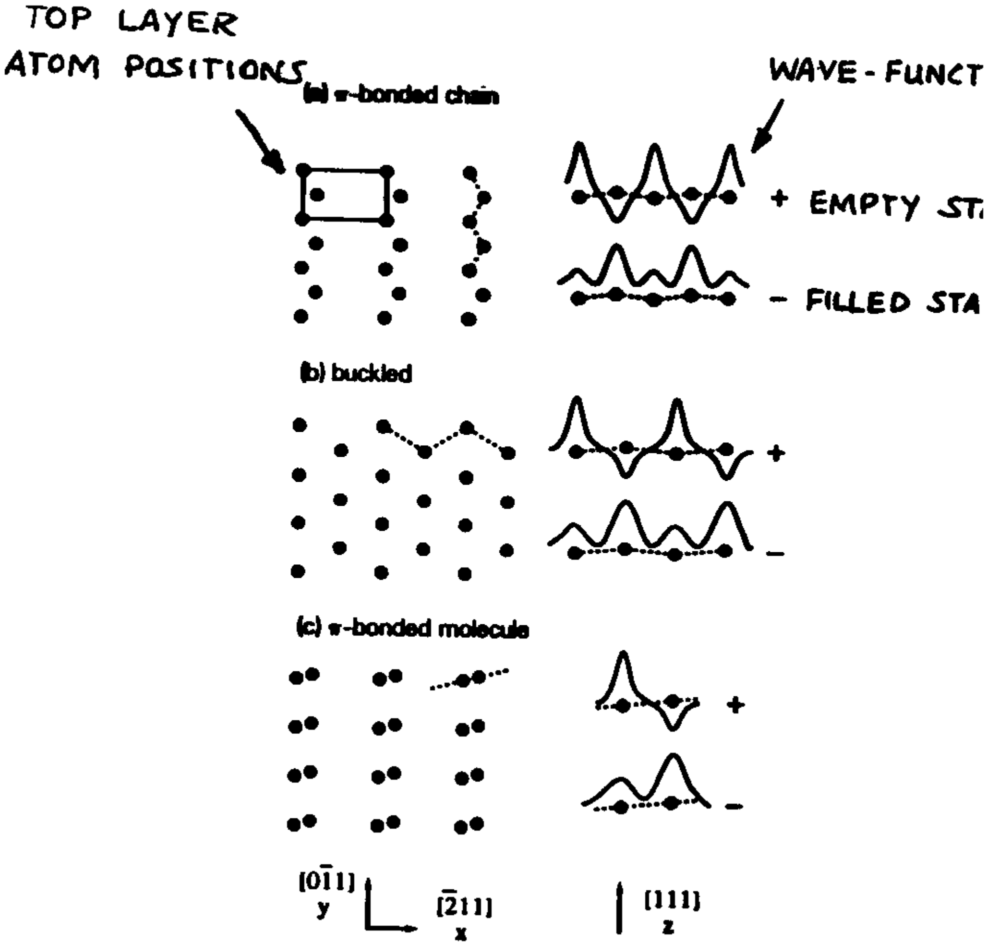
K. C. Pandey, Phys. Rev. Lett. 47, 1913 (1981)
J. E. Northrop and M. L. Cohen, Phys. Rev. Lett. 49, 1349 (1982)



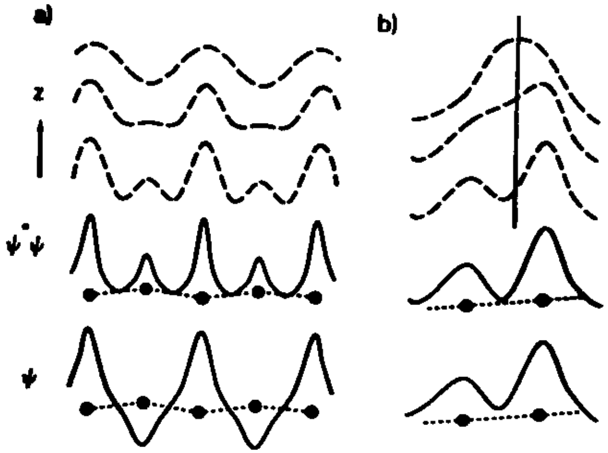


Tight-binding wavefunctions





Decay of State-Density ($\psi^*\psi$) with Separation from Surface

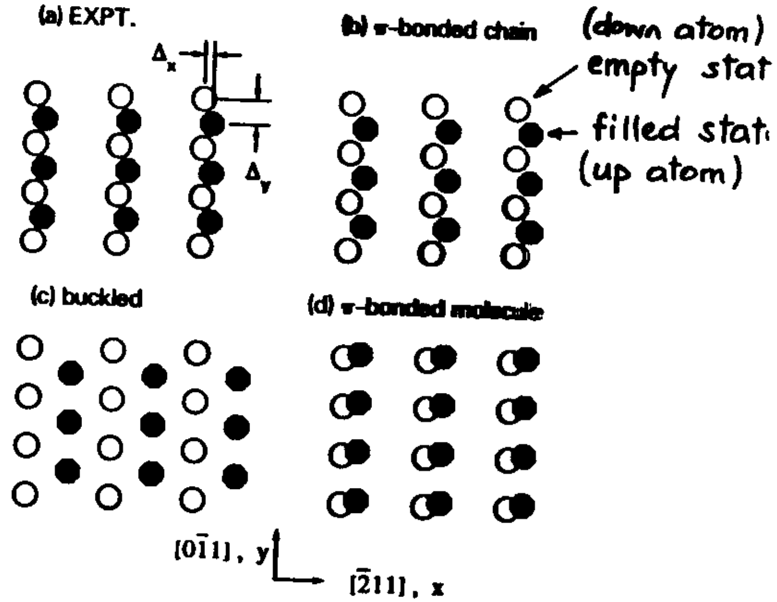


Spatial location of states

observe:

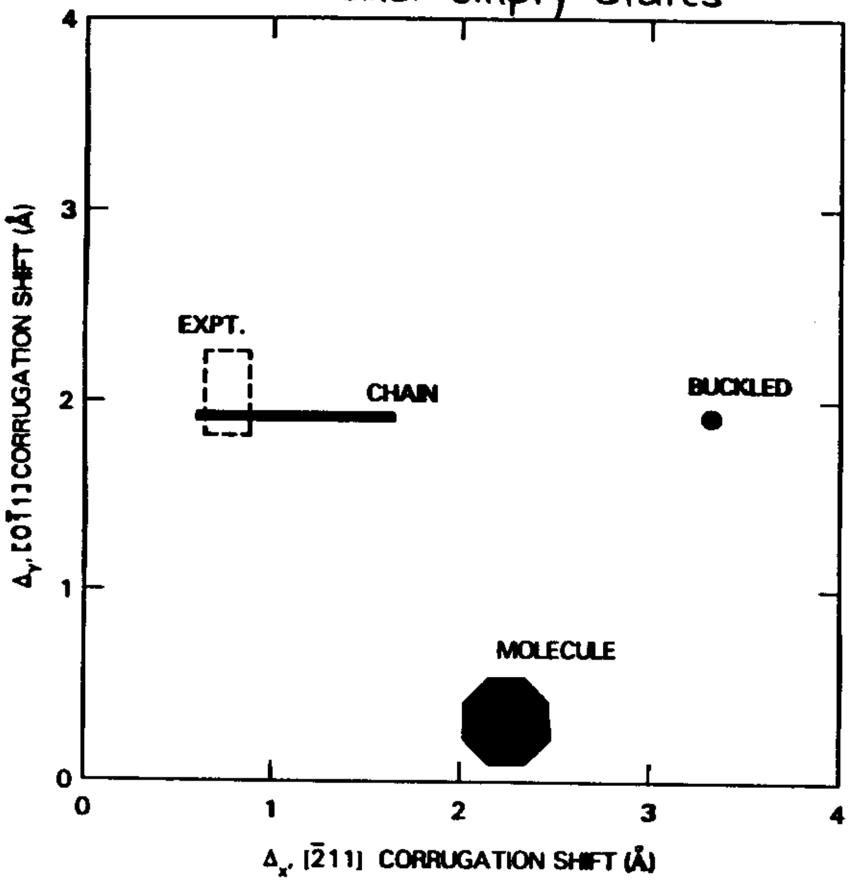
$\Delta_x \approx 0.7$ Å

$\Delta_y \approx 3.3$ Å



STM images yield structure directly

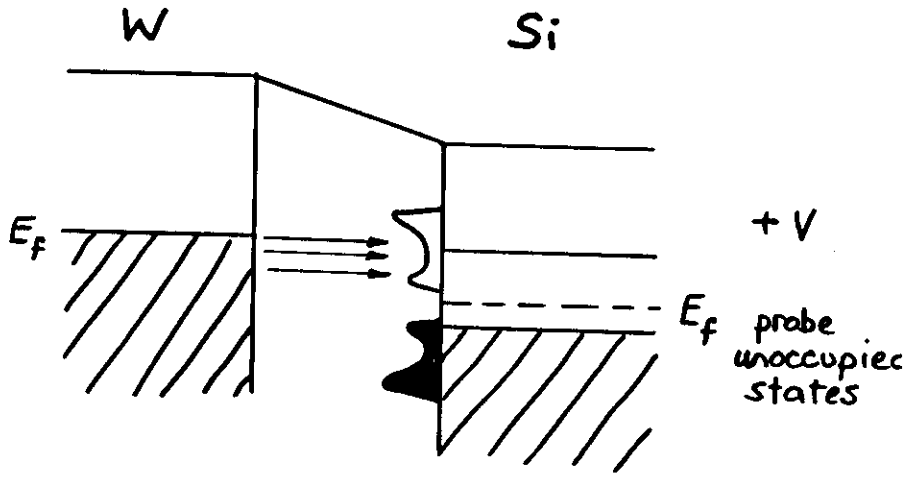
Si(111)2×1 - Spatial shift between filled and empty states

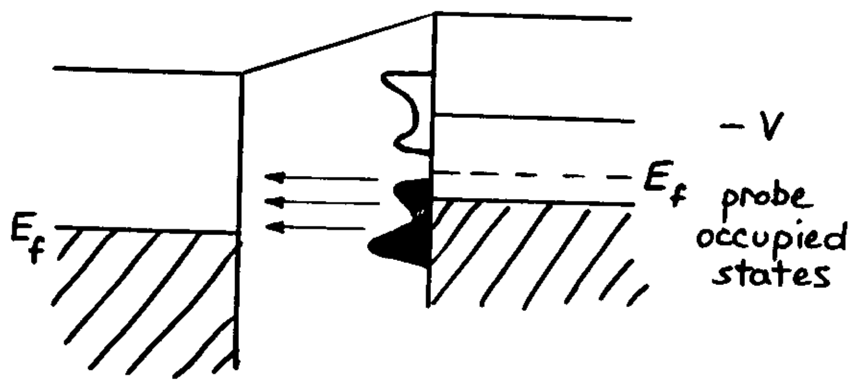


Summary:

- STM measures the electronic properties of a surface
- view surface states as linear combinati[ons] of dangling bonds
- attach dangling bonds to atoms
  → connection to geometric structure

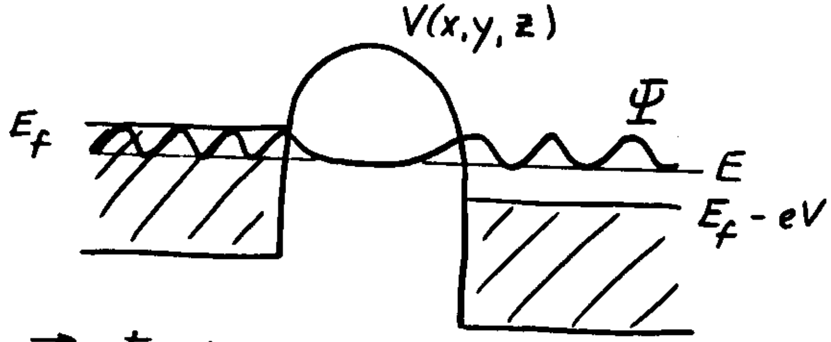
Tunneling Spectroscopy:





$$I \propto \int_0^{eV} \sum_\nu \psi_\nu^* \psi_\nu \, \delta(E_\nu - E)\, dE$$

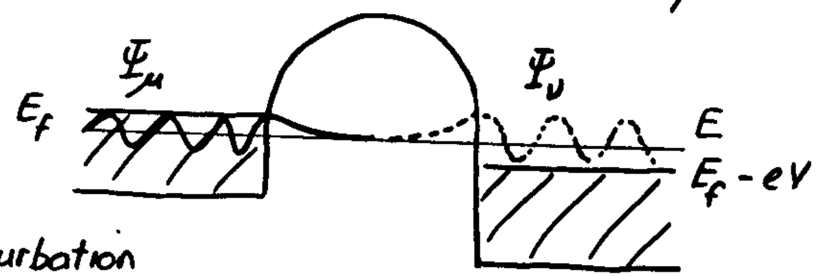
Current through Barrier



$$\vec{j} = \frac{\hbar}{2mi}\left(\Psi^* \nabla \Psi - \Psi \nabla \Psi^*\right)$$

integrate over separating surface, sum over states
(eg. Stoll, Baratoff, Selloni, Carnevali, J. Phys. C. 17, 3073 (1984), for free-electron model with corrugated boundaries).

Bardeen: Ψ_R, Ψ_L known separately.

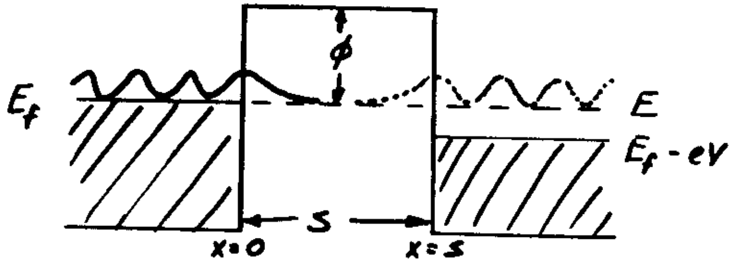


perturbation

$$I = \frac{2\pi e}{\hbar} \sum_{\mu\nu} f(E_\mu)[1 - f(E_\nu)]\, |M_{\mu\nu}|^2 \, \delta(E_\mu - E_\nu)$$

$$M_{\mu\nu} = \frac{\hbar^2}{2m}\int d\vec{S}\cdot\left(\psi_\mu^* \nabla \psi_\nu - \psi_\nu \nabla \psi_\mu^*\right)$$

example:



$\psi_\mu \sim a_\mu e^{ikx}$ $\quad b_\mu e^{-Kx}$ $\quad b_\nu e^{+K(x-s)}$ $\quad \psi_\nu \sim a_\nu e^{ikx}$

$k = \sqrt{\frac{2mE}{\hbar}}$

$K = \sqrt{\frac{2m\phi}{\hbar^2}}$

$$\rightarrow M_{\mu\nu} = \frac{\hbar^2}{2m}\int d\vec{S}\cdot\left(b_\mu^* e^{-Kx} b_\nu K e^{K(x-s)} - b_\nu e^{K(x-s)} b_\mu^*(-K) e^{-Kx}\right),$$

$$\underbrace{\qquad\qquad}_{2K\, b_\mu^* b_\nu\, e^{-Ks}}$$

$$I \propto |b_\mu|^2 |b_\nu|^2 e^{-2Ks}$$

{ observe overlap of wave-function }

$|b_\mu|^2 |b_\nu|^2$ ← surface wave-functions

e^{-2Ks} ← wave-function tails

Baratoff, Physica 127B, 143 (1984)

Tersoff and Hamann, Phys. Rev. Lett. 50, 1998 (1983).
Phys. Rev. B 31, 805 (1985).

point probe: ψ_μ very localized, at $\vec{r_0}$

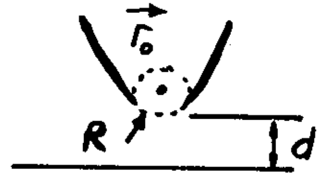
$\Rightarrow M_{\mu\nu} \propto \psi_\nu$

$$I \propto \underbrace{\sum_\nu |\psi_\nu(r_0)|^2 \delta(E_\nu - E_\mu)}$$

$\equiv \rho$ · local-density-of-states.

* just consider ρ of sample, extending into vacuum.

spherical probe



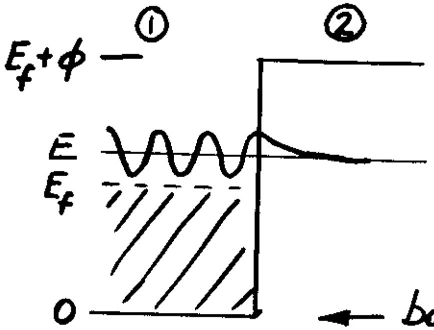
$\psi_{tip} = \psi_\mu$ = spherical waves

$$\Rightarrow I \propto \sum_\nu |\psi_\nu(r_0)|^2 \delta(E_\nu - E_f) \qquad \text{low } T,\ \text{low } V.$$

$$= \rho(\vec{r_0}, E_f).$$

STM measures ρ at point corresponding to center of radius-of-curvature of tip.

1-Dimensional Barrier Penetration



vacuum level

E_f = Fermi energy

ϕ = Work function

← bottom of valence band

$$-\frac{\hbar^2}{2m}\frac{d^2\psi}{dx^2} + V\psi = E\psi$$

region ① $V = 0$, $-\frac{\hbar^2}{2m}\frac{d^2\psi}{dx^2} = E\psi$.

try $\psi = Ae^{ikx}$ $\Rightarrow$ $+\frac{\hbar^2}{2m}Ak^2e^{ikx} = EAe^{ikx}$

$$\Rightarrow \quad k = \sqrt{\frac{2mE}{\hbar^2}}$$

region ② $V = E_f + \phi$, $-\frac{\hbar^2}{2m}\frac{d^2\psi}{dx^2} + (E_f+\phi)\psi = E\psi$

try $\psi = Be^{-Kx}$ $\Rightarrow$ $-\frac{\hbar^2}{2m}K^2Be^{-Kx} = (E-E_f-\phi)Be^{-Kx}$

$\Rightarrow$ $\boxed{K = \sqrt{\frac{2m}{\hbar^2}(\phi - E')}}$ * $E' = E - E_f$ = energy relative to E_f

Numbers: take $E' = 0$

$$K = \sqrt{\frac{2m\phi}{\hbar^2}} = \left(\frac{2 \times .511\times10^6\,eV \times 4.5\,eV}{(1973\,eV\cdot Å)^2}\right)^{1/2} = 1.1\ Å^{-1}$$

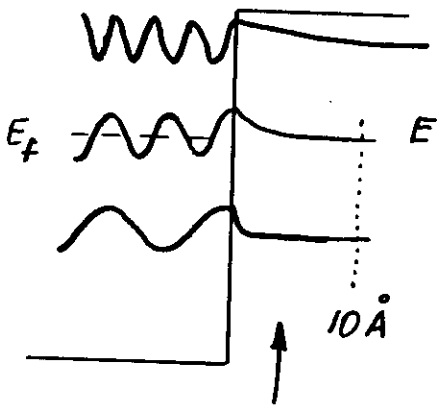
ρ = state-density = $\psi^*\psi \sim e^{-2Kx}$

$$\Delta x = 1\,Å \Rightarrow \frac{\rho_{new}}{\rho_{old}} = \frac{e^{-2K(x+\Delta x)}}{e^{-2Kx}} = e^{-2K(1Å)} \approx 0.1$$

an order-of-magnitude change for each Å.

Energy dependence: $E' \neq 0$

$$K = \sqrt{\frac{2m}{\hbar^2}(\phi - E')}$$



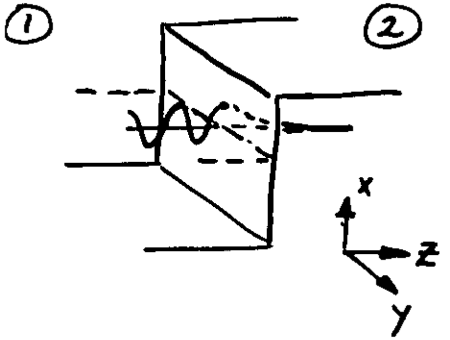
$E' = 0$, $\rho \sim e^{-2Kx} = 4\times10^{-10}$

$E' = -1$ eV , $\rho = 4\times10^{-11}$

$E' = -2$ eV , $\rho = 4\times10^{-12}$

faster decay for lower energy

3-Dimensional Planar Barrier Penetration



$$V = V(z)$$

$$\Psi = \psi_{\parallel}(x,y)\,\psi_{\perp}(z)$$

$$-\frac{\hbar^2}{2m}\left[\psi_{\perp}\left(\frac{\partial^2\psi_{\parallel}}{\partial x^2} + \frac{\partial^2\psi_{\parallel}}{\partial y^2}\right) + \psi_{\parallel}\frac{\partial^2\psi_{\perp}}{\partial z^2}\right]$$

$$+ V(z)\,\psi_{\parallel}\psi_{\perp} = E\,\psi_{\parallel}\psi_{\perp}$$

write $E = E_{\parallel} + E_{\perp}$

$$\Rightarrow -\frac{\hbar^2}{2m}\left(\frac{\partial^2\psi_{\parallel}}{\partial x^2} + \frac{\partial^2\psi_{\parallel}}{\partial y^2}\right) = E_{\parallel}\psi_{\parallel} \quad \Rightarrow \quad \psi_{\parallel} = A e^{i\vec{k}_{\parallel}\cdot\vec{(x,y)}}$$

$$k_{\parallel} = \sqrt{\frac{2mE_{\parallel}}{\hbar^2}}$$

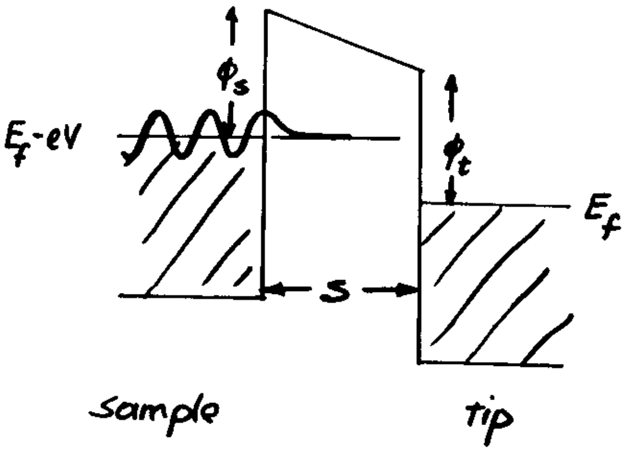
and $-\dfrac{\hbar^2}{2m}\dfrac{\partial^2\psi_{\perp}}{\partial z^2} + V(z)\psi_{\perp} = E_{\perp}\psi_{\perp}$

$$E_{\perp} = E - E_{\parallel} = E - \frac{\hbar^2 k_{\parallel}^2}{2m}$$

<u>region ②</u> $\psi_{\perp} = Ae^{-\kappa z}$ $\boxed{\kappa = \sqrt{\frac{2m}{\hbar^2}\left(\phi - E' + \frac{\hbar^2 k_{\parallel}^2}{2m}\right)}}$ *

states with large $k_{\parallel}$ decay faster (for E = const.)

Trapezoidal Barrier (finite voltage)



V = voltage on samp
$V > 0 \Rightarrow$ empty sta
$V < 0 \Rightarrow$ filled sta

$(k_{\parallel} = 0)$

$$I \propto \int \rho_s(E)\,dE \qquad \rho_s \propto e^{-2\kappa z} = e^{-2\kappa s}$$

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

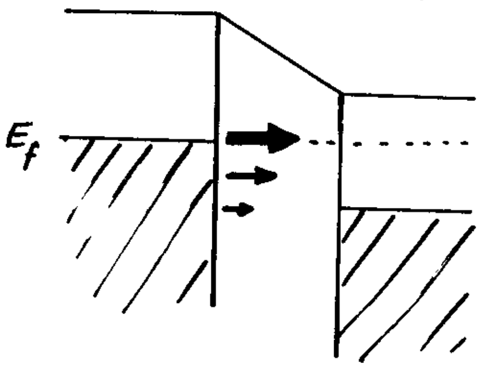
trap. barrier $\phi \rightarrow \bar{\phi} = \dfrac{\phi_s + \phi_t + eV}{2} = \phi_{st} + \dfrac{eV}{2}$ (WKB)

for $E' = 0$.

$\therefore$ $\boxed{\kappa = \sqrt{\frac{2m}{\hbar^2}\left(\phi_{st} - E' + \frac{eV}{2}\right)}}$ * ϕ_{st} = average work-fcn betw tip + sample

Effect of energy + voltage dependence

tip sample (V > 0, empty states)



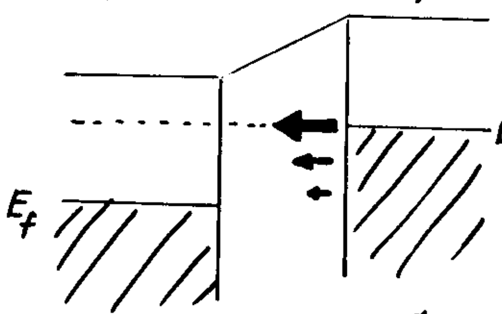
← max I, $E' = eV$

← min I, $E' = 0$

at maximum, $-E' + \frac{eV}{2} = -\frac{|eV|}{2}$

tip sample

(V < 0, filled states)



← max I, $E' = 0$

← min I, $E' = eV$

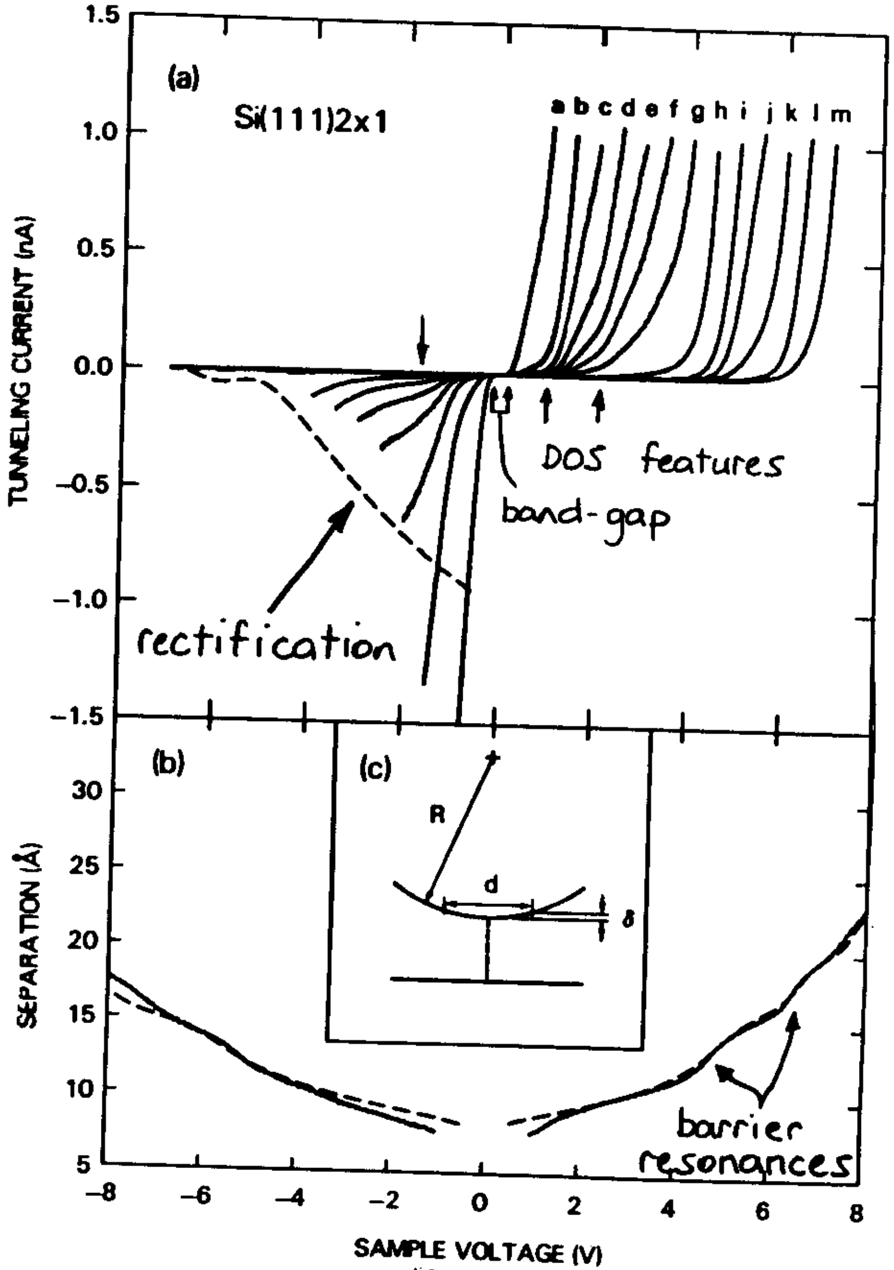
at maximum, $-E' + \frac{eV}{2} = -\frac{|eV|}{2}$

$$I \propto \int \rho_s(E, z=s)\, dE = \int \rho_0(E)\, e^{-2\kappa s}\, dE$$

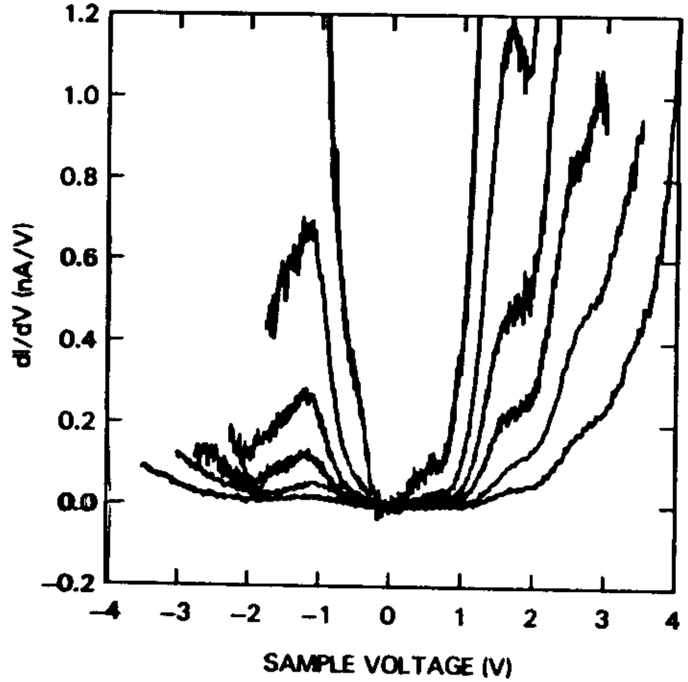
$$\rightarrow \begin{cases} \rho_0(eV)\, e^{-2\kappa s}, & V > 0 \\ \rho_0(E'=0)\, e^{-2\kappa s}, & V < 0 \end{cases}$$

$$\boxed{\kappa = \sqrt{\frac{2m}{\hbar^2}\left(\phi_{st} - \frac{|eV|}{2}\right)}}$$

Cannot observe low-lying occupied states!

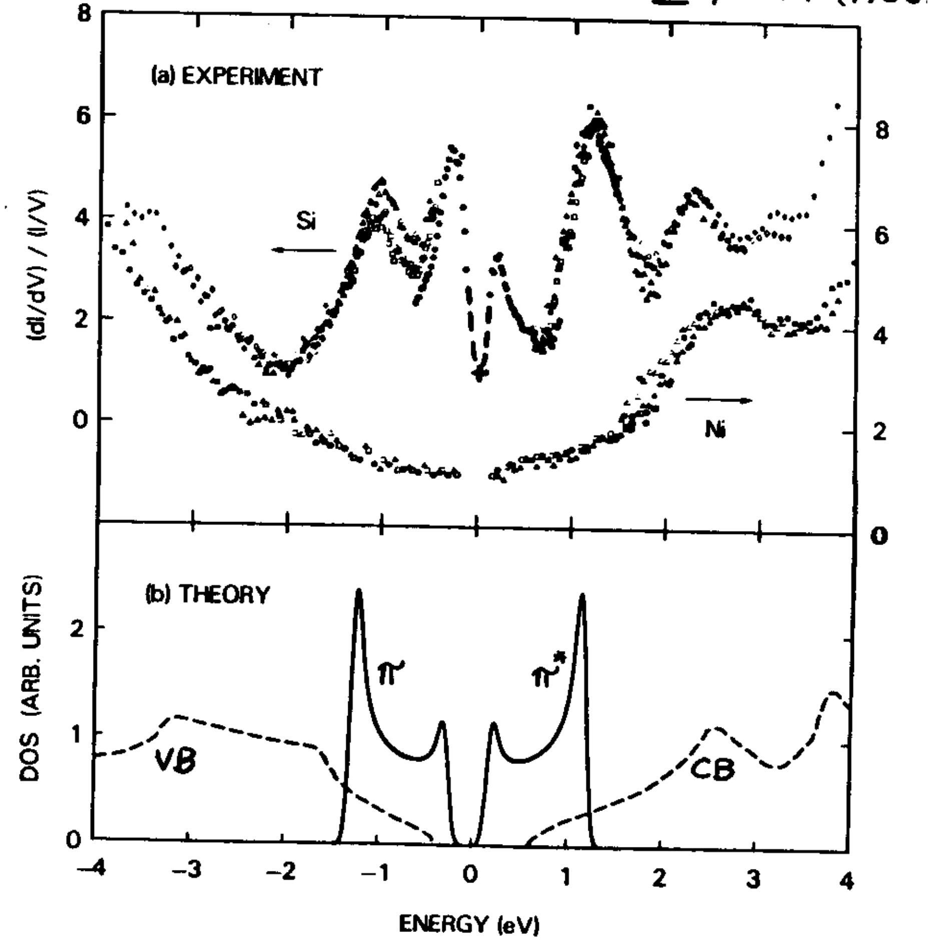


1^{st} - Derivative Spectra

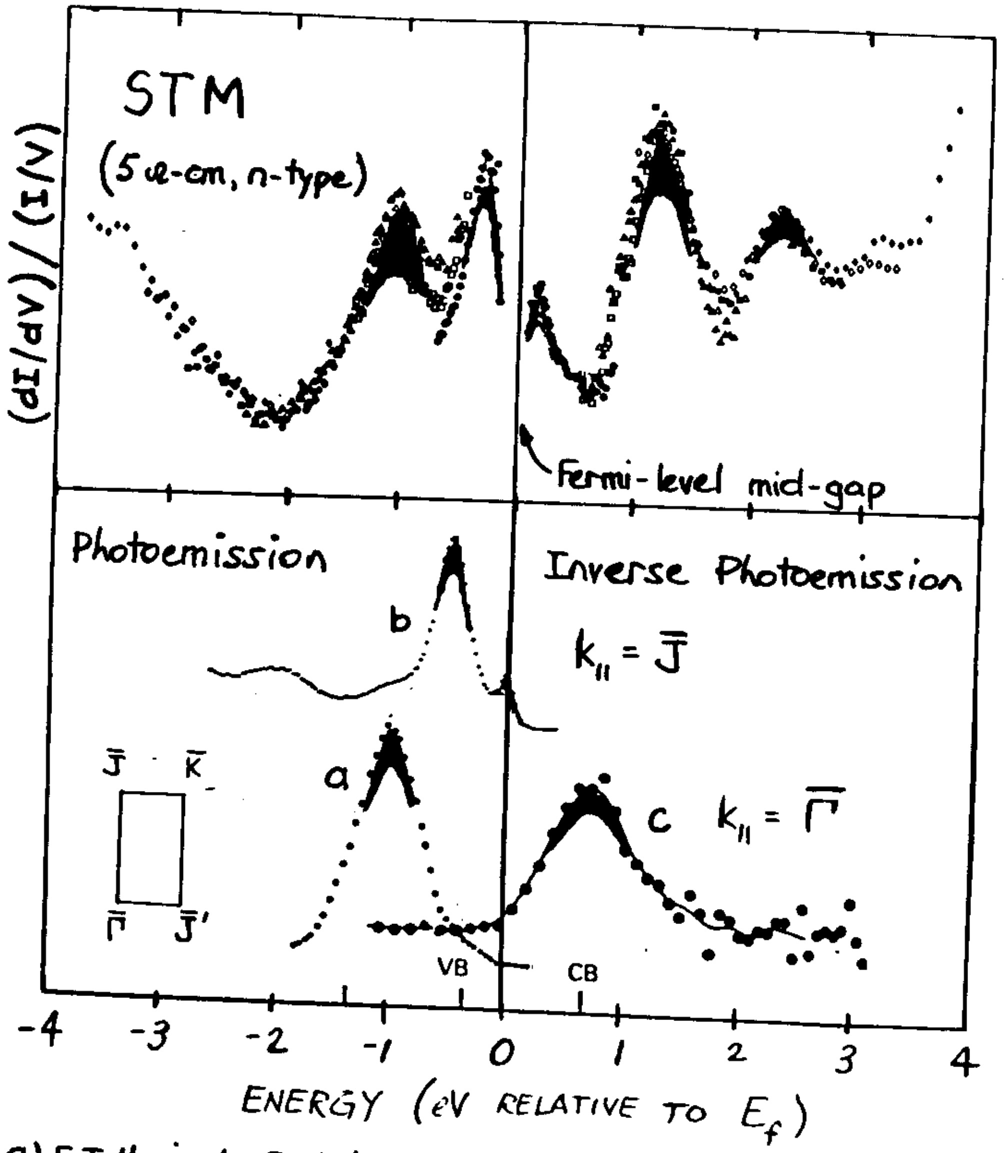


Si(111) - 2×1

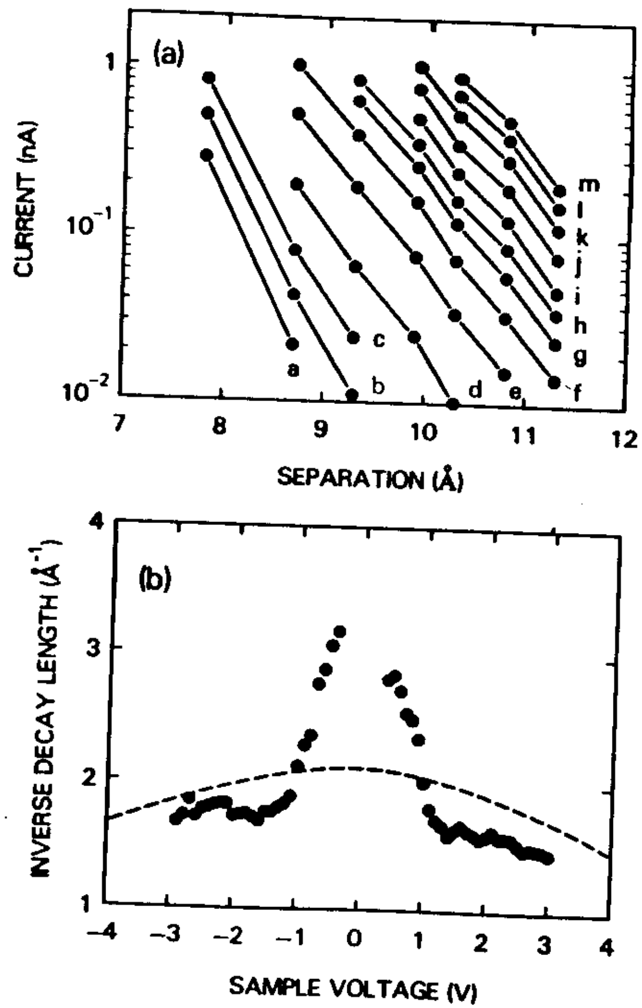
J. A. Stroscio, R. M. Feenstra, A. P. Fein
PRL 57, 2579 (1986.

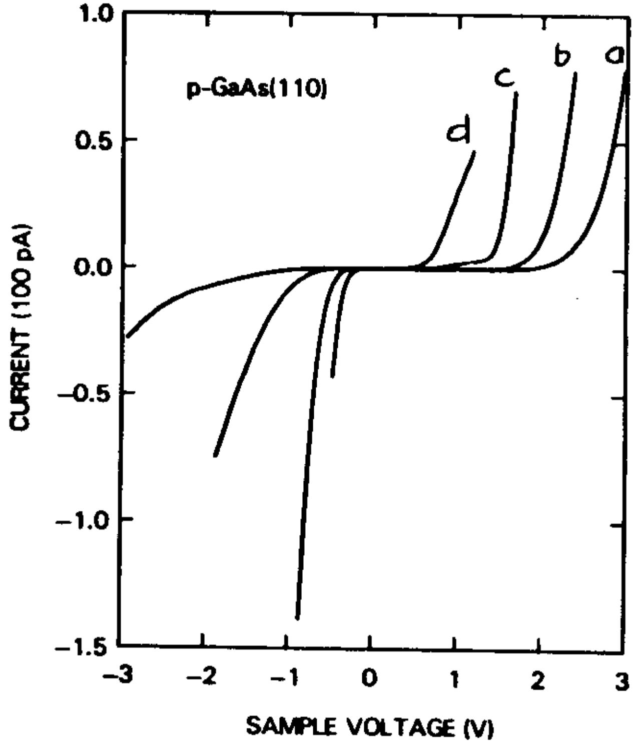


Surface bands - π, π* (1-D tight-binding model
Bulk bands - VB, CB (Chelikowsky and Cohe
Phys. Rev. B14, 556 (197



a) F.J. Himpsel, P. Heimann, D.E. Eastman, Phys. Rev. B 24, 2003 (1981
b) P. Mårtensson, A. Cricenti, G. Hansson, Phys. Rev. 32, 6959 (1985)
c) D. Straub, L. Ley, F.J. Himpsel, Phys. Rev. Lett. 54, 142 (1985)

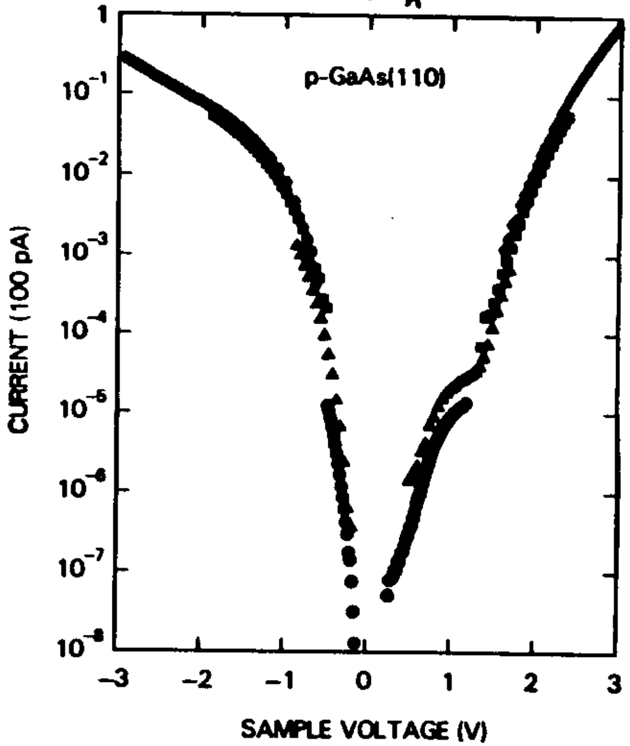




	ΔS (Å)
a	0
b	-1.2
c	-3.2
d	-4.8

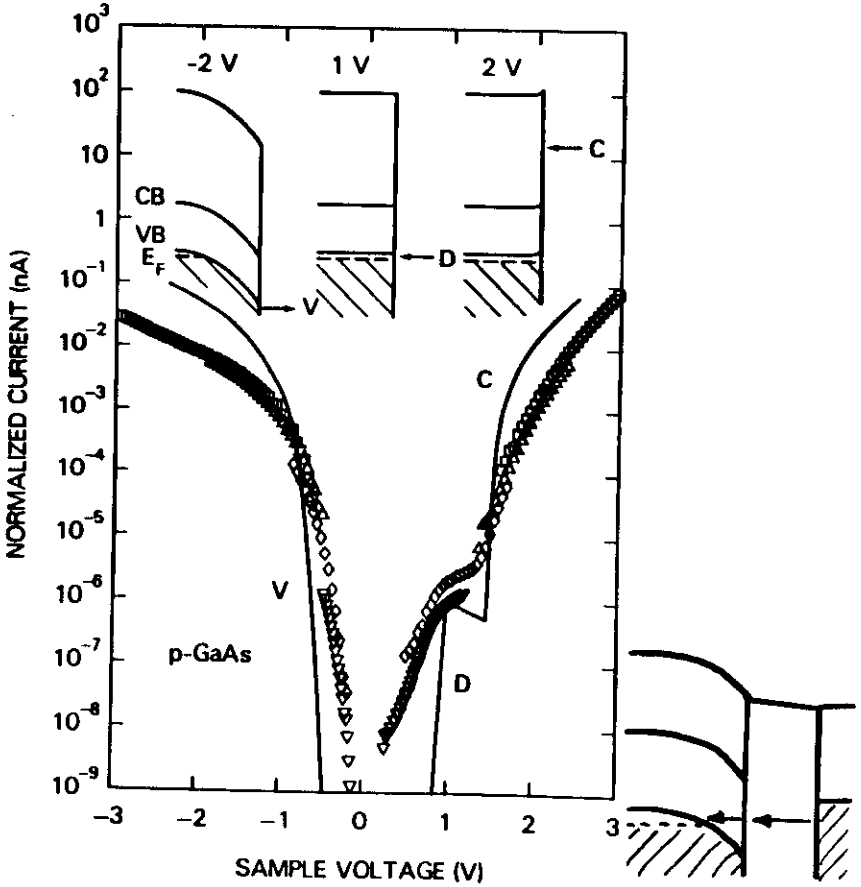
Normalized Current $= I\, e^{2\kappa \Delta S}$

$\kappa = \sqrt{\frac{2m\bar{\phi}}{\hbar^2}} = 1.1\ \text{Å}^{-1}, \quad \bar{\phi} = 4.5\ \text{eV}$

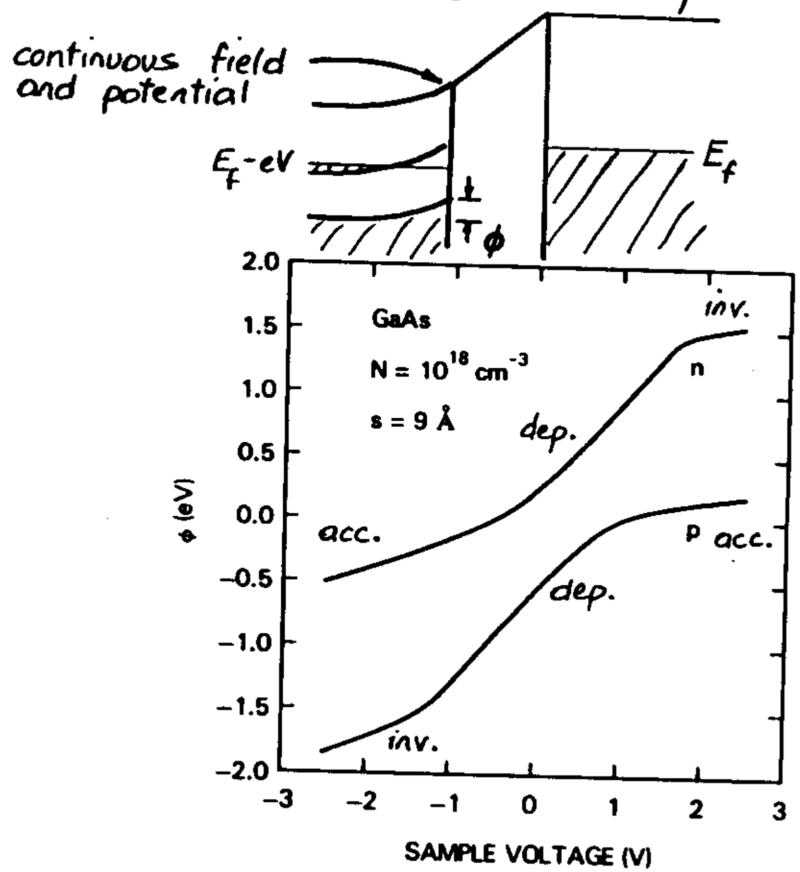


Feenstra + Stroscio, JVST B, Jul/Aug (1987).

p-GaAs (110) clean surface



Electrostatics: Schottky model

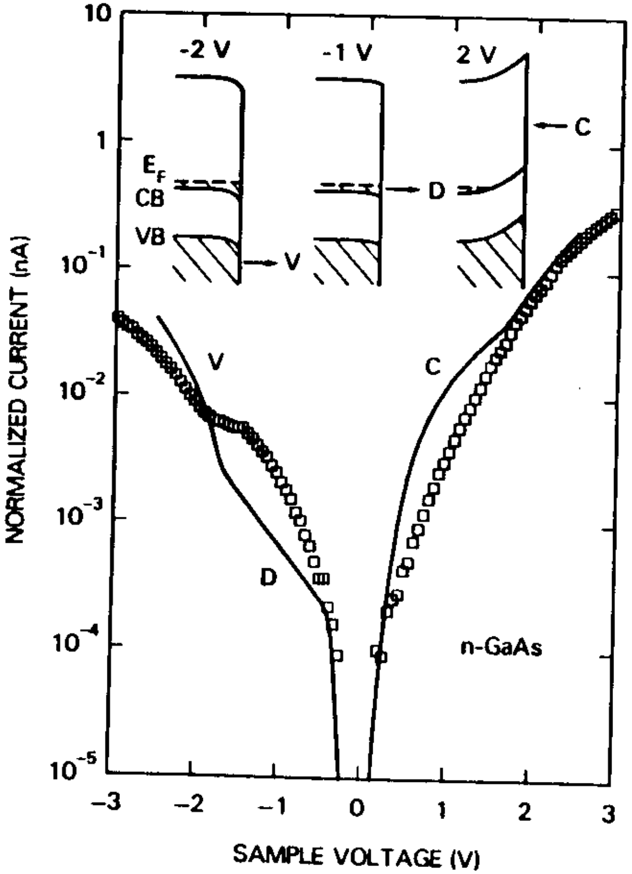


<u>Theory</u>: following Bono + Good, Surf. Sci. <u>175</u>, 415 (1986)

- parabolic bands, WKB

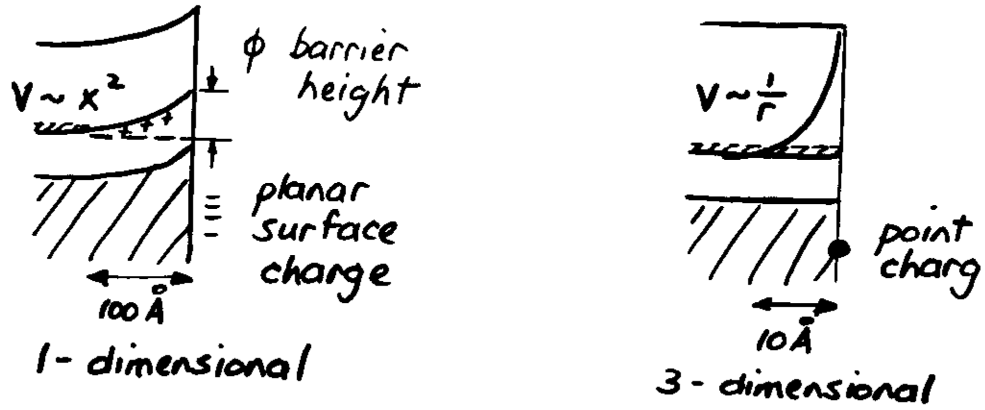
<u>plus</u>: band-bending in semiconductor,
(59) tunneling through semiconductor.

n-GaAs - clean surface

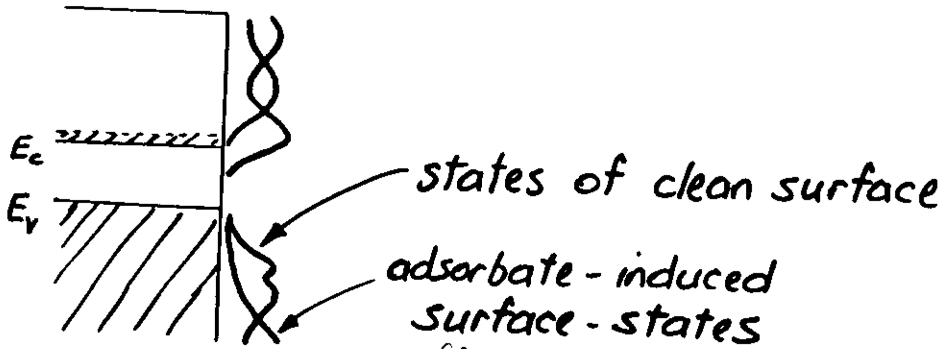


Spectroscopy of Adsorbates on Semiconducto

1. Electrostatics (band bending)

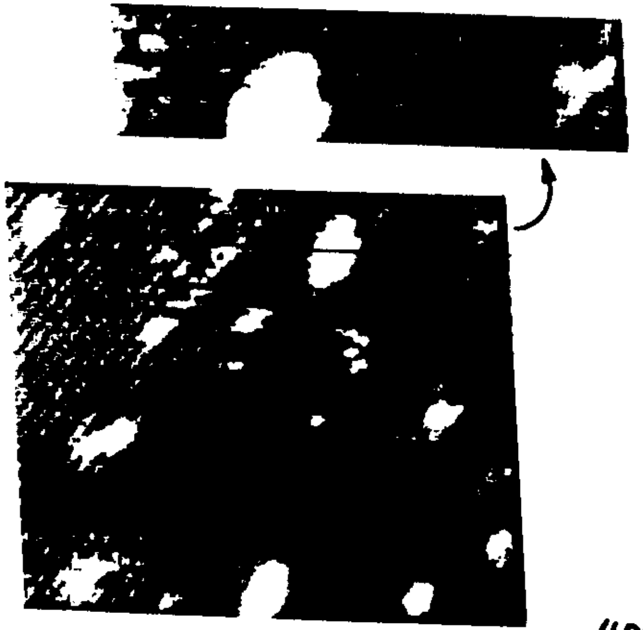


2. Changes in State-Density



O/ GaAs (110) 120 L

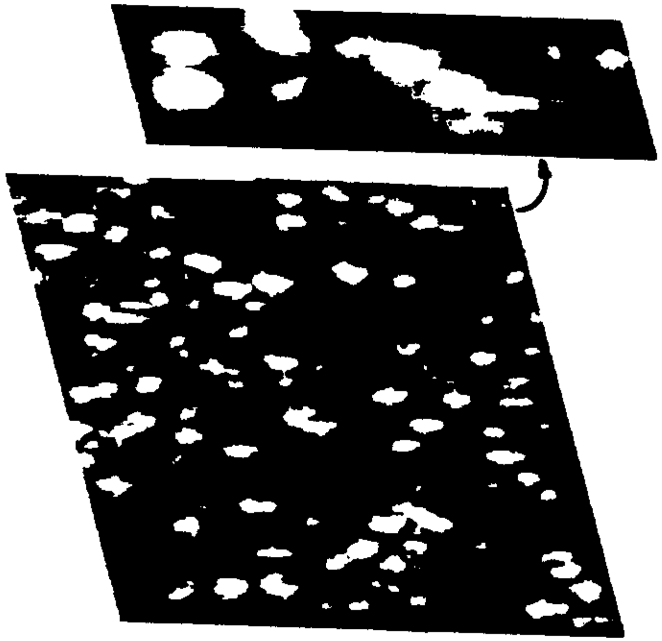
~.003 Monolayer



400 x 400 $Å^2$

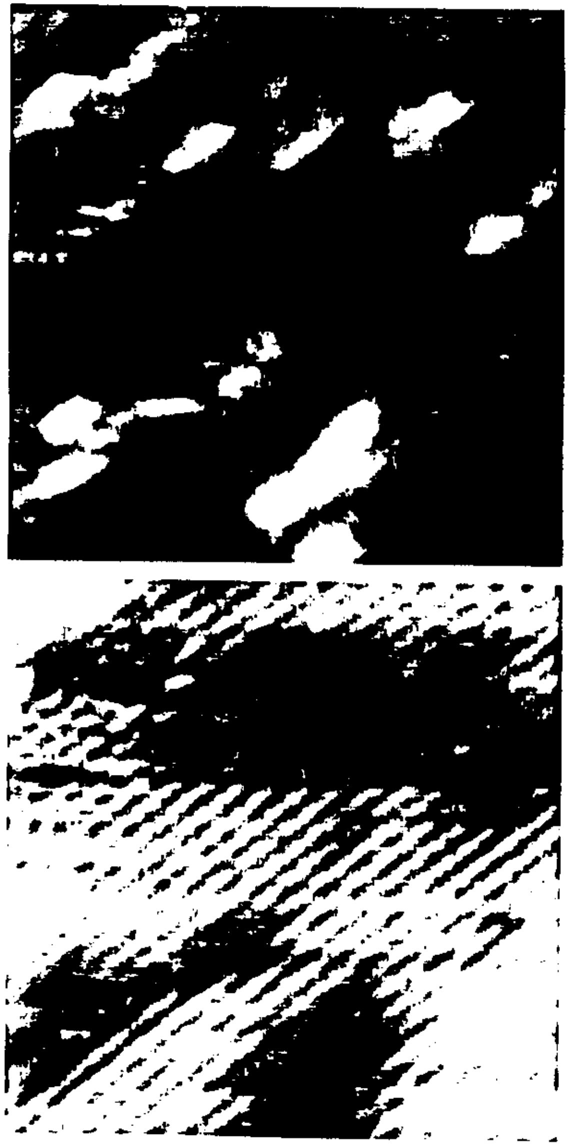
O/n-GaAs (110) 1480 L

~.01 Monolayer



400 x 400 $Å^2$

O/GaAs

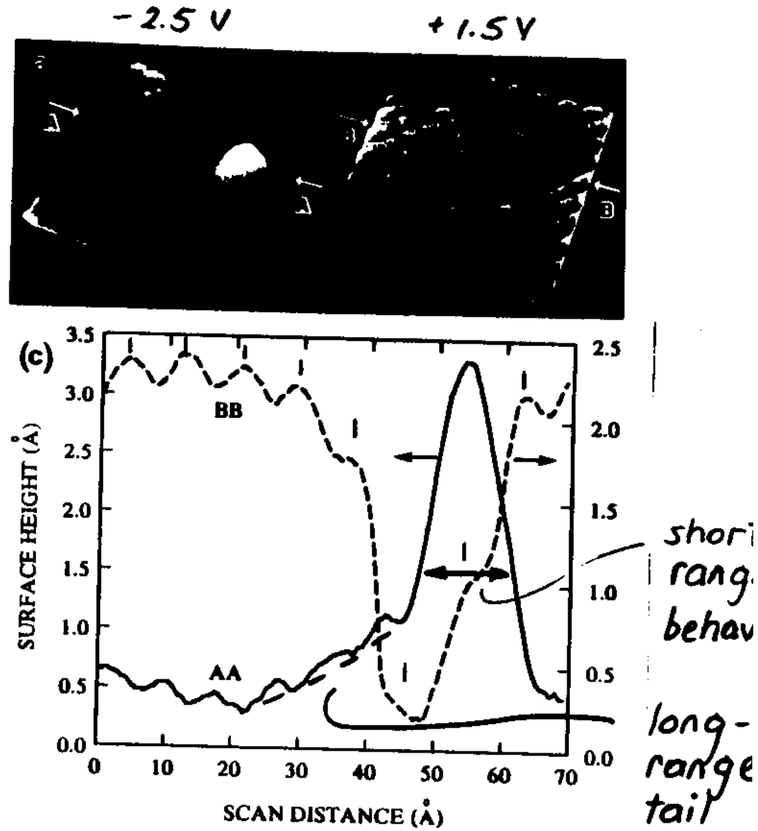


− 2.5 V

filled states

+ 1.5 V

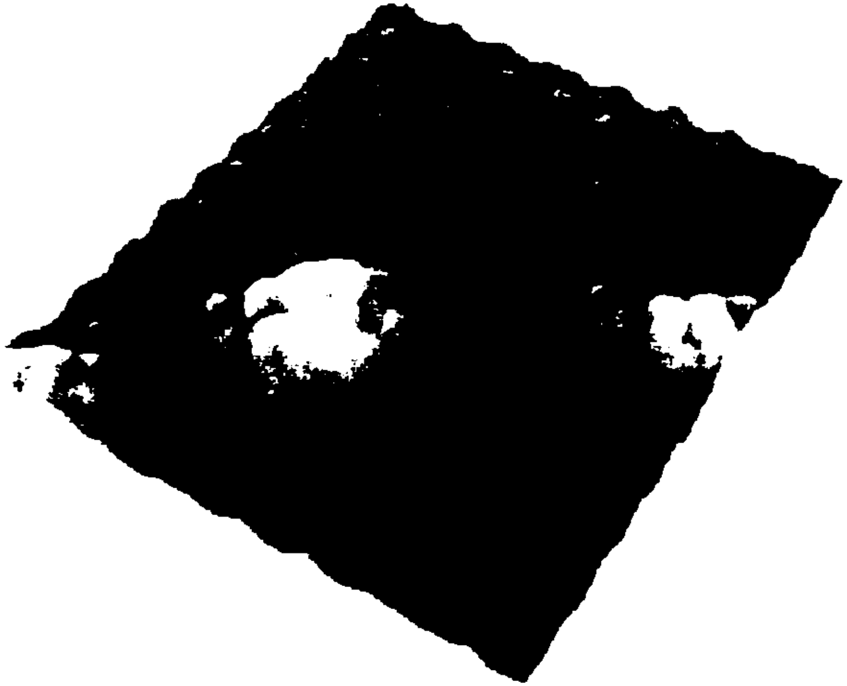
empty states



J. Stroscio, R. Feenstra, A. Fein, Phys. Rev. Lett 58, 1668 (1987).

Fig.

n - GaAs (110) - defect



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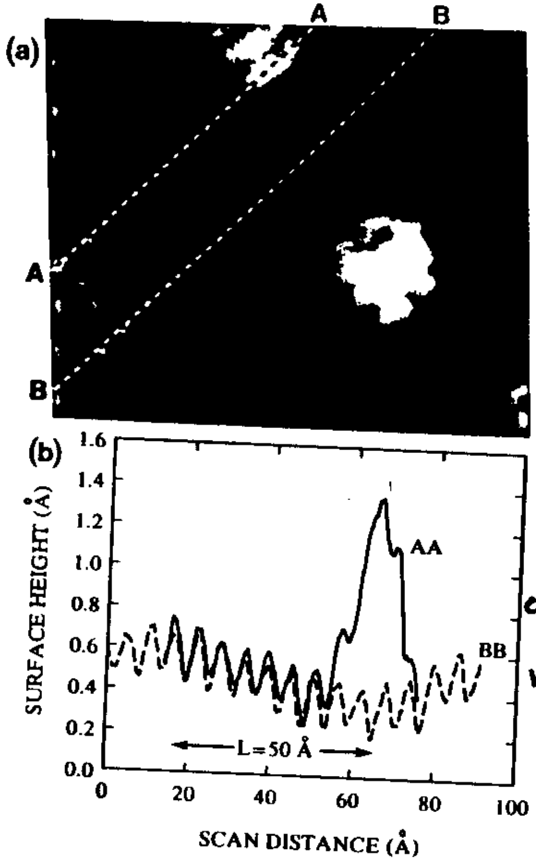
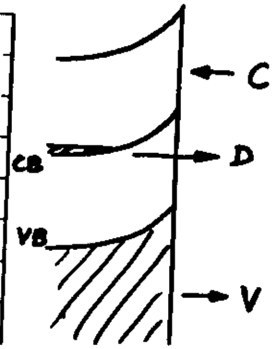
Long-range (electrostatic) effect:





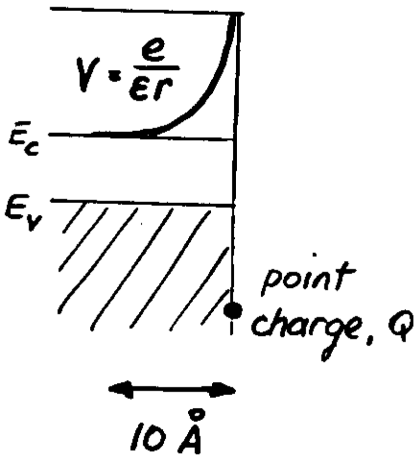
screened Coulomb potential: $\frac{e^{-r/L}}{r}$ $L = \frac{\epsilon kT}{ne^2} = 56$ Å

68 $n = 1 \times 10^{18}$ cm^{-3}

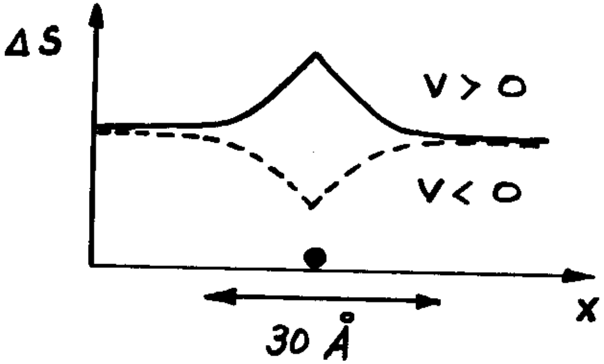
Fig 3

Observation of Charge with the STM

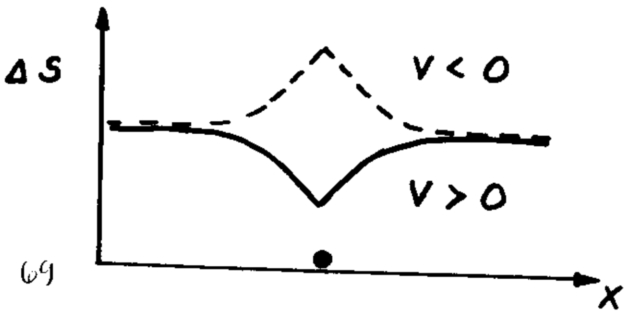
(Local band-bending)



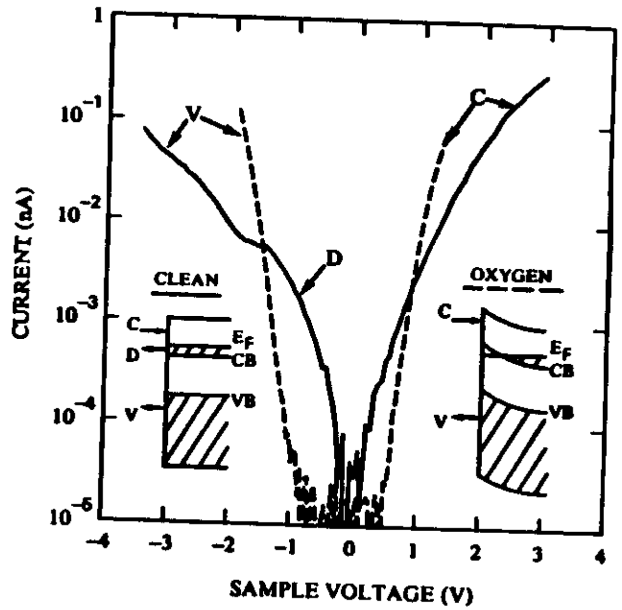
Q > 0 attracts electrons
repels holes



Q < 0 attracts holes
repels electrons



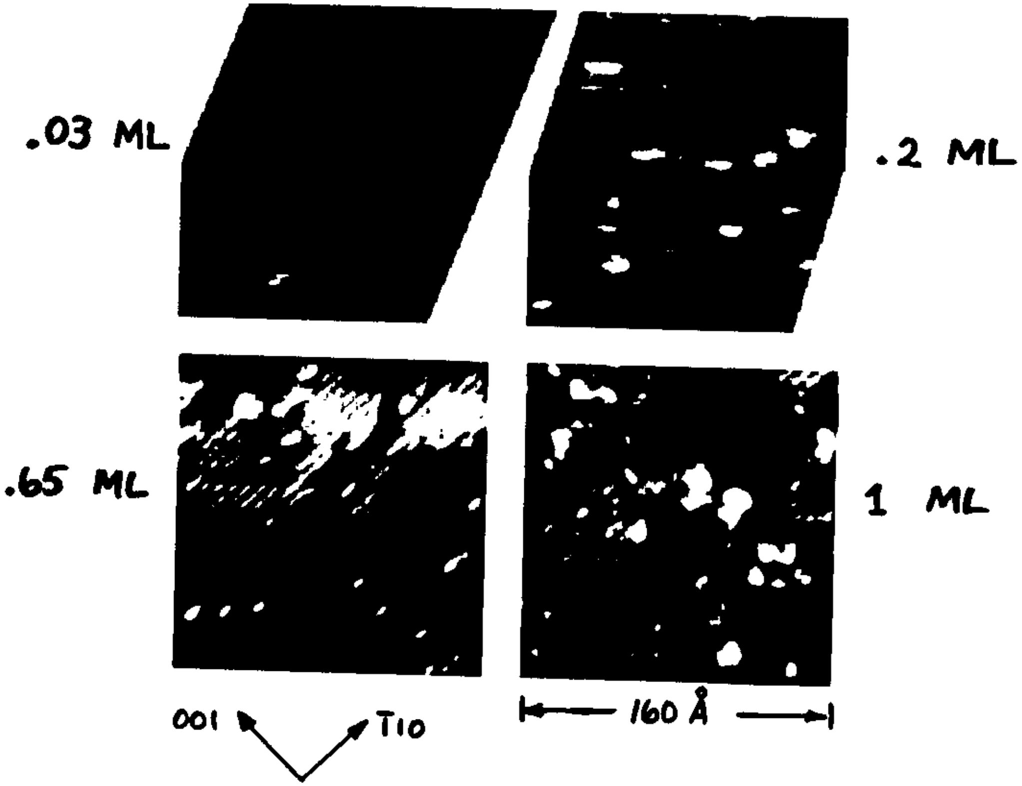
n-GaAs



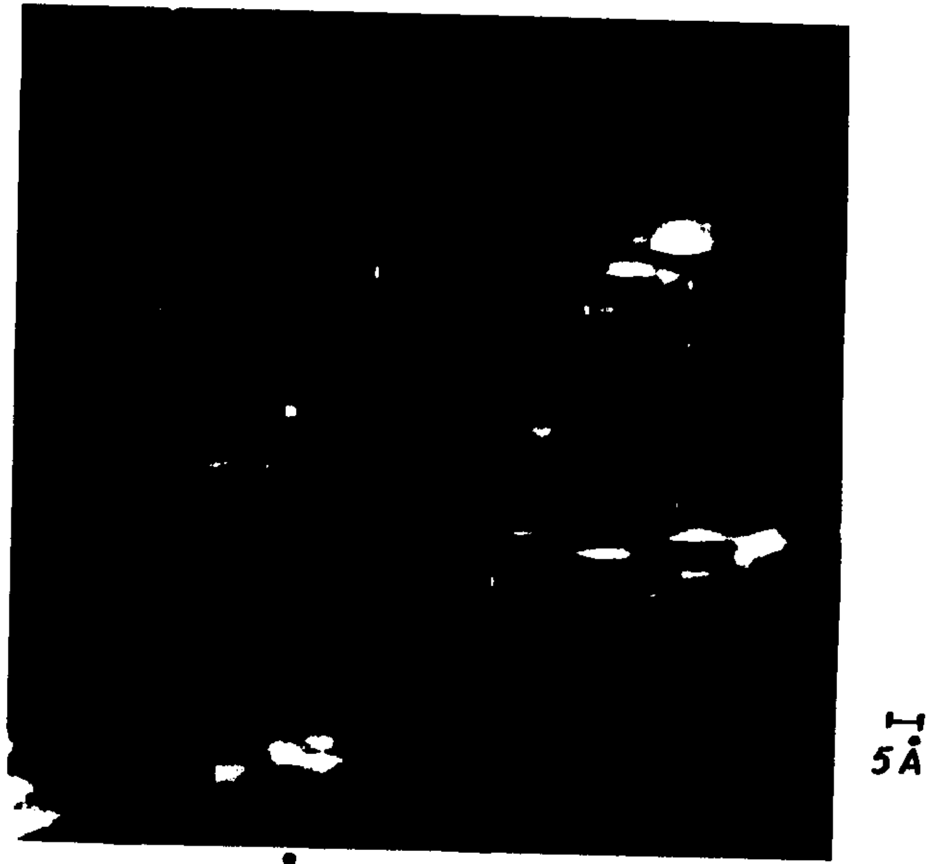
band-bending → increased VB density
decreased CB density
(negatively charged defects)

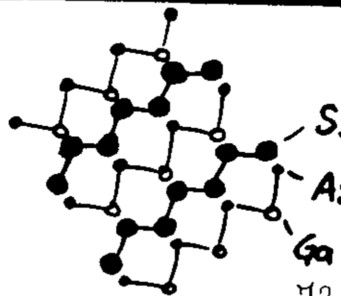
Sb/GaAs (110)

(ML = monolayer)



Sb/GaAs (110) - ordered cluster

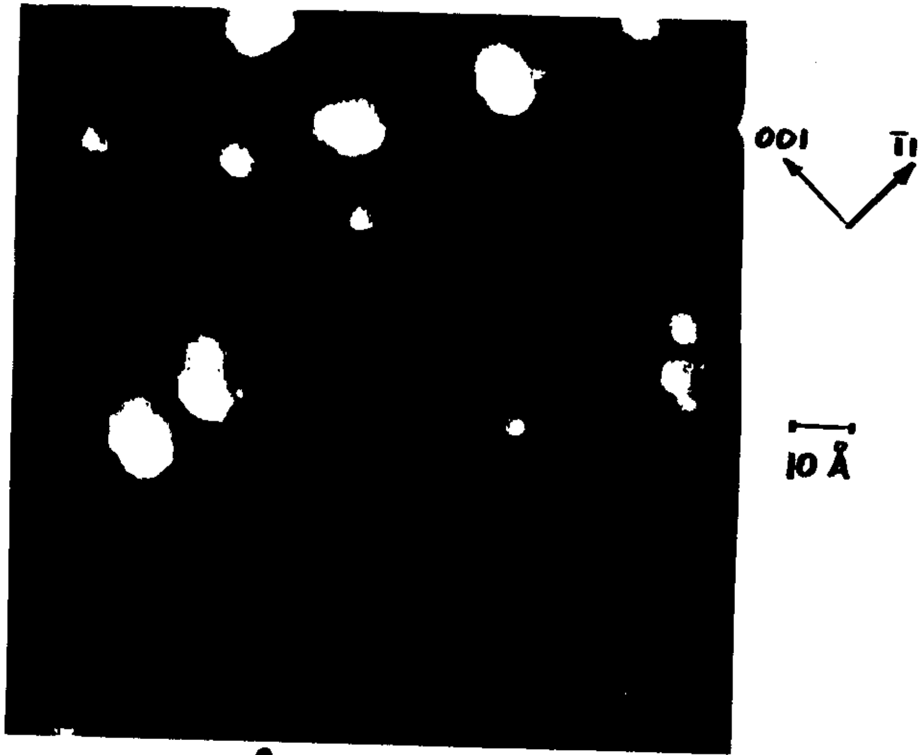




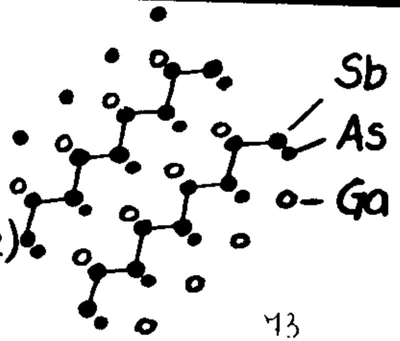
images are consistent with model

Sb/GaAs (110) 1×1 overlayer

1 ML



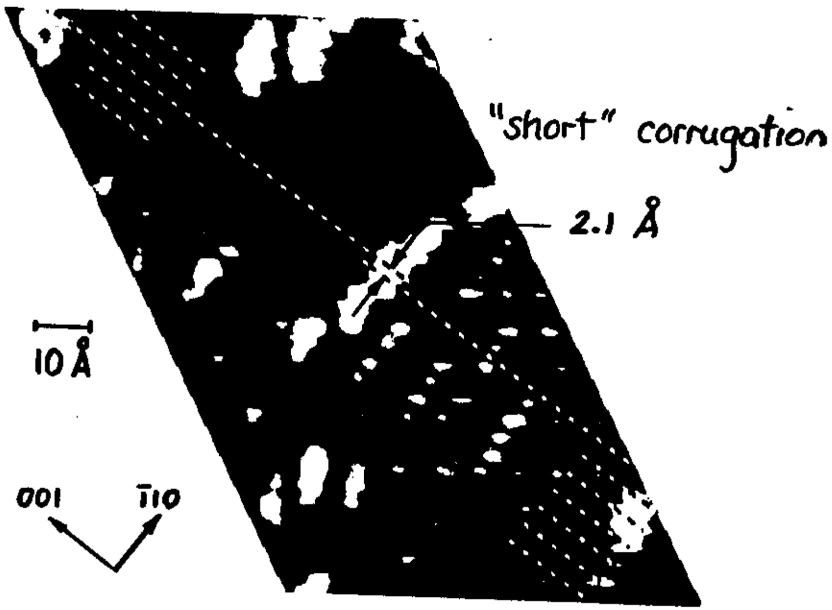
LEED:
Duke, et. al.
Phys. Rev. B
26, 803 (1982)



- two inequivalent Sb atom per cell
- filled dangling bonds.

Sb/GaAs registration

Sb/GaAs registration



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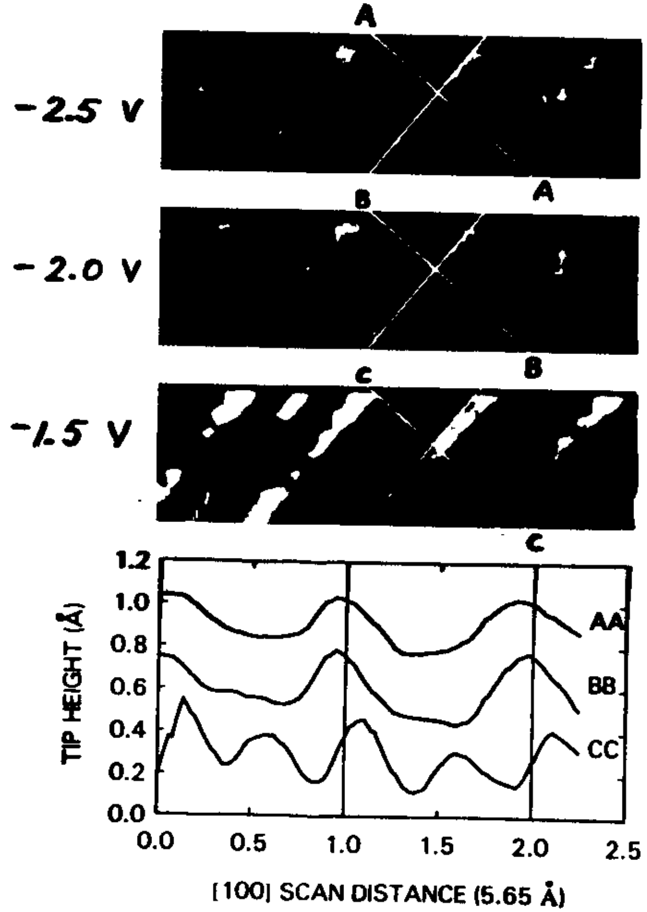
Sb/GaAs (110) - voltage dependence



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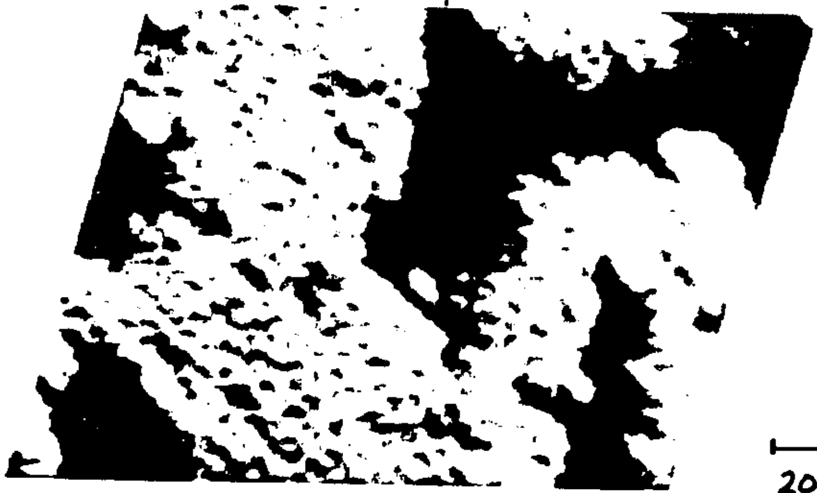
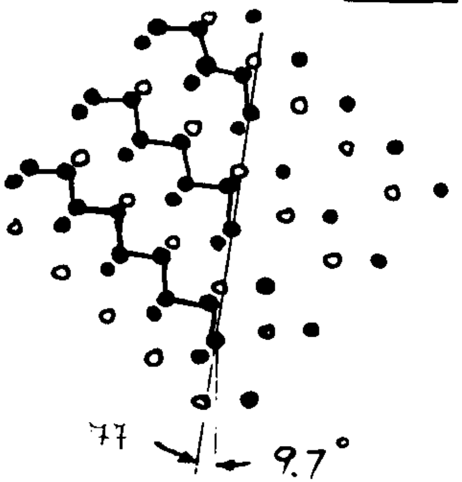
Sb/GaAs(110)

drift corrected

0.6 monolayer

9°

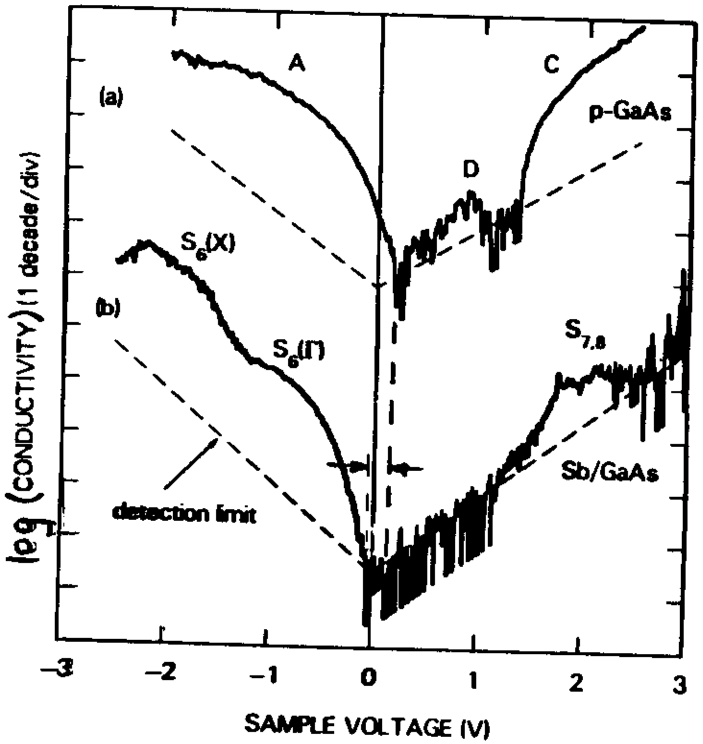


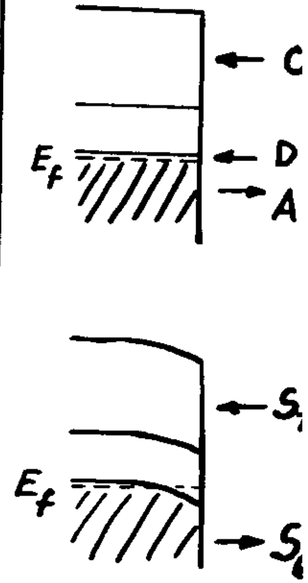


ordered kinks

77 9.7°

Conductivity at constant z (log scale)





0.25 eV band-bending on terrace

Photoemission: 0.3 eV on annealed layer

Schäffler, et al. 0.6 eV on unannealed layer

JVST B5, 1048 (1987)

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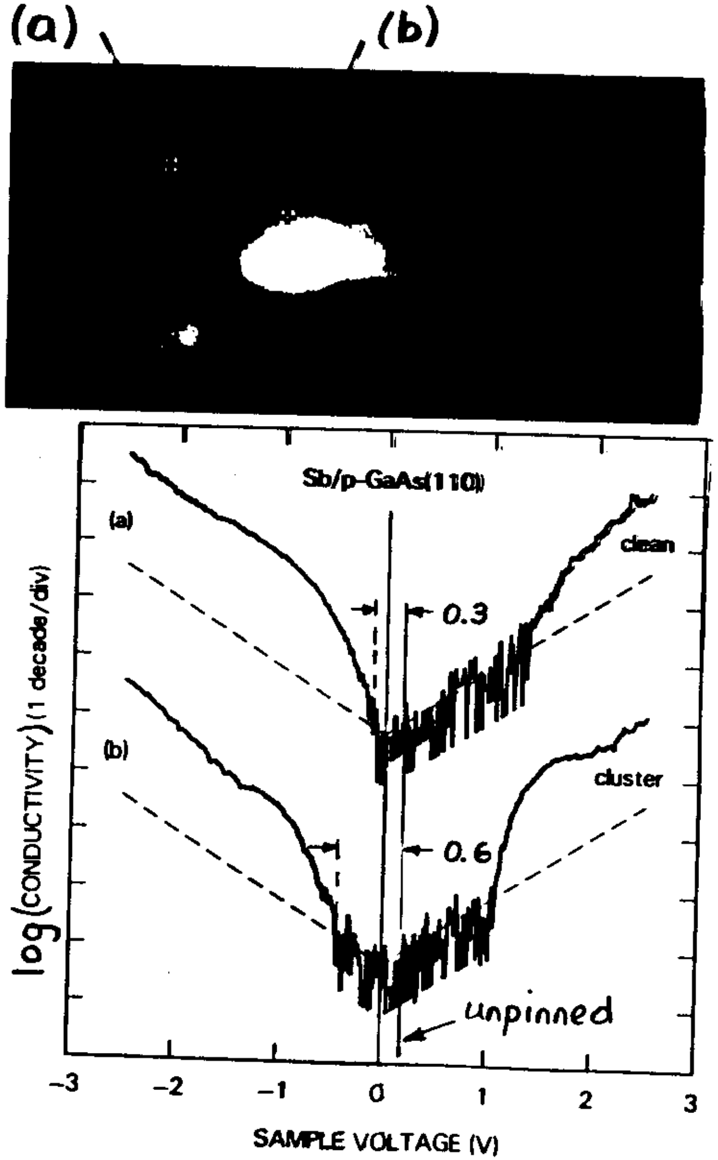
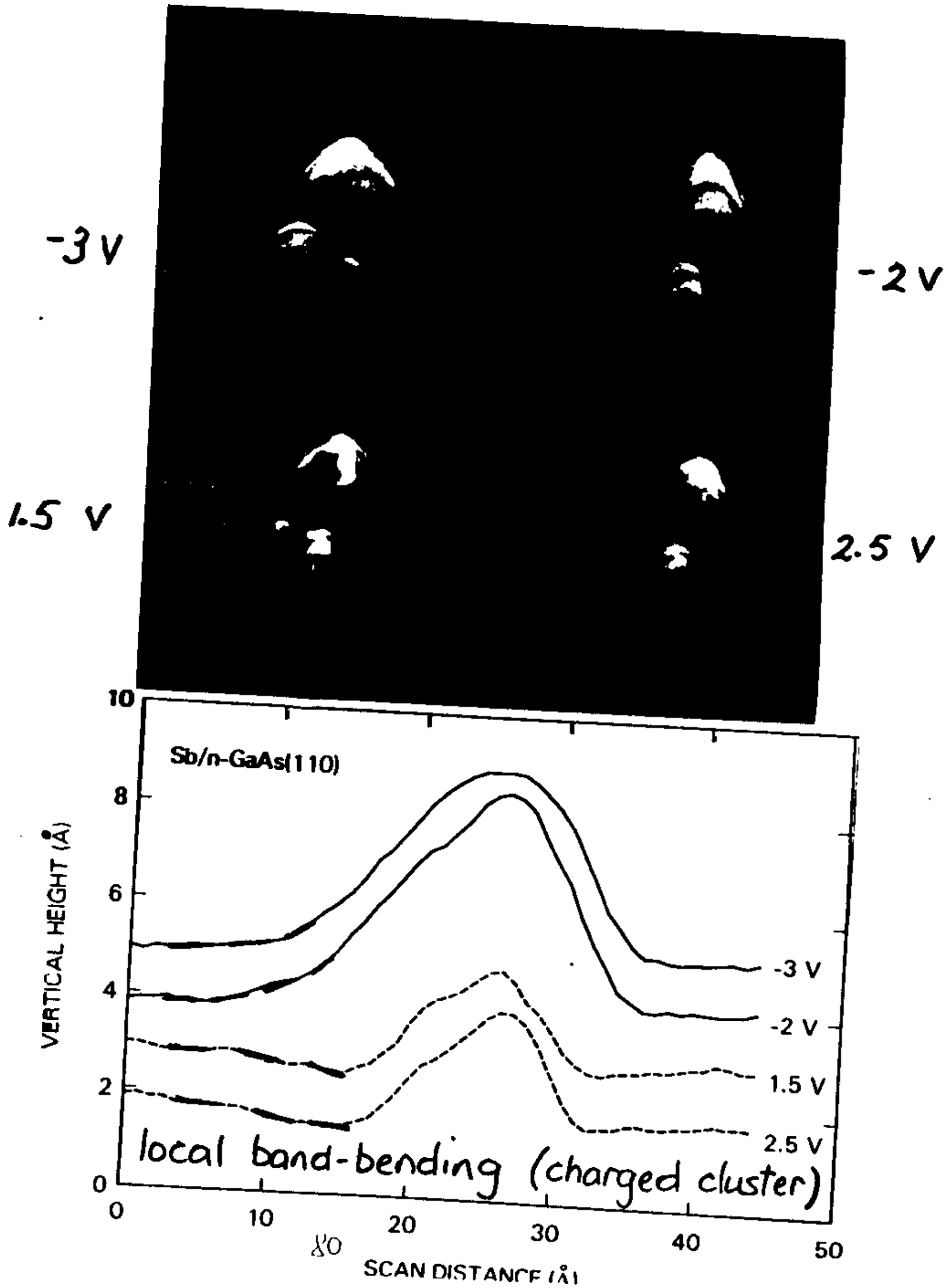
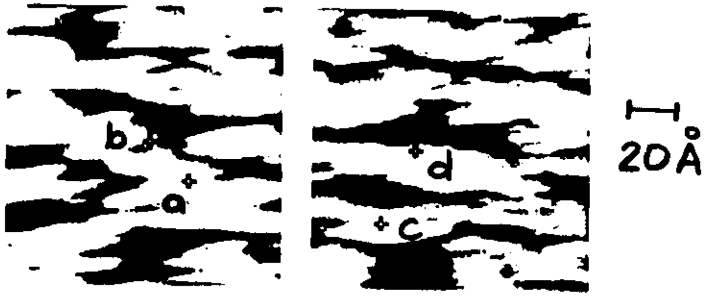
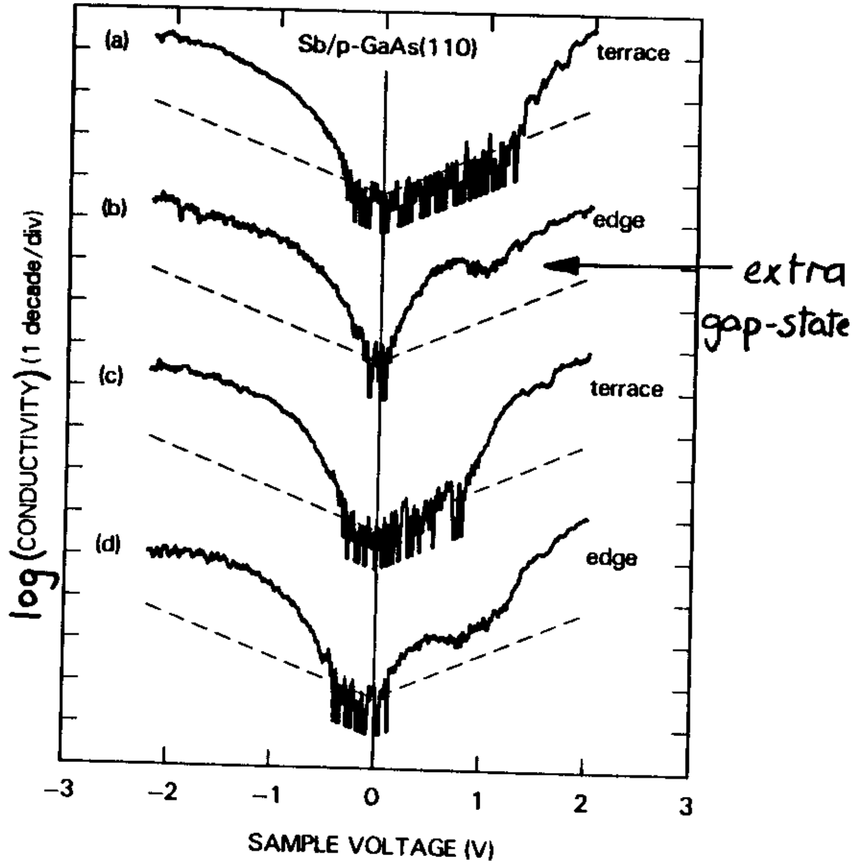

(a)
(b)
.02 ML
10 Å
Sb/p-GaAs(110)
(a)
clean
0.3
(b)
cluster
0.6
unpinned
log(CONDUCTIVITY) (1 decade/div)
−3 −2 −1 0 1 2 3
SAMPLE VOLTAGE (V)


-3 V
-2 V
1.5 V
2.5 V
Sb/n-GaAs(110)
VERTICAL HEIGHT (Å)
0 2 4 6 8 10
-3 V
-2 V
1.5 V
2.5 V
local band-bending (charged cluster)
0 10 20 30 40 50
SCAN DISTANCE (Å)

Sb/GaAs

.7 ML





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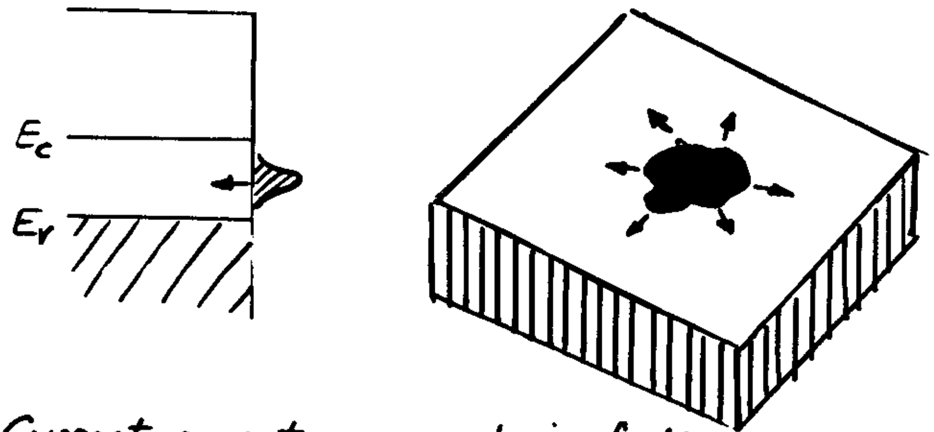
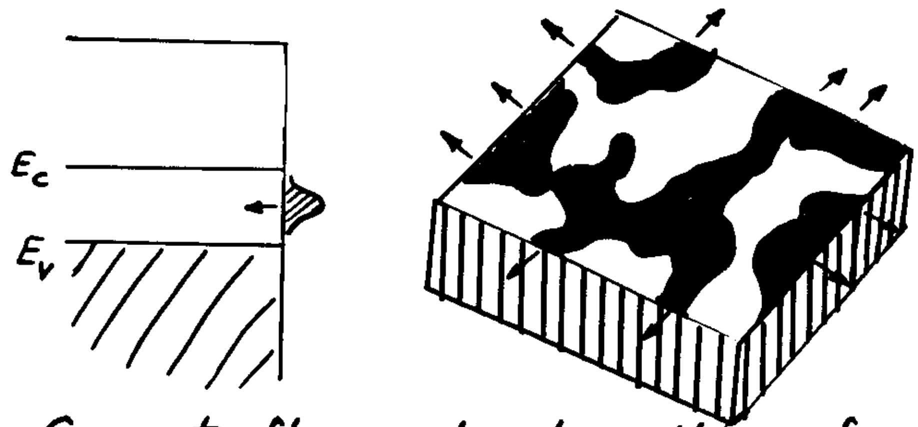
Isolated Clusters - Charging Effects



Current cannot propagate in forbidden energy g

Connected Islands



Current flows only along the surface.

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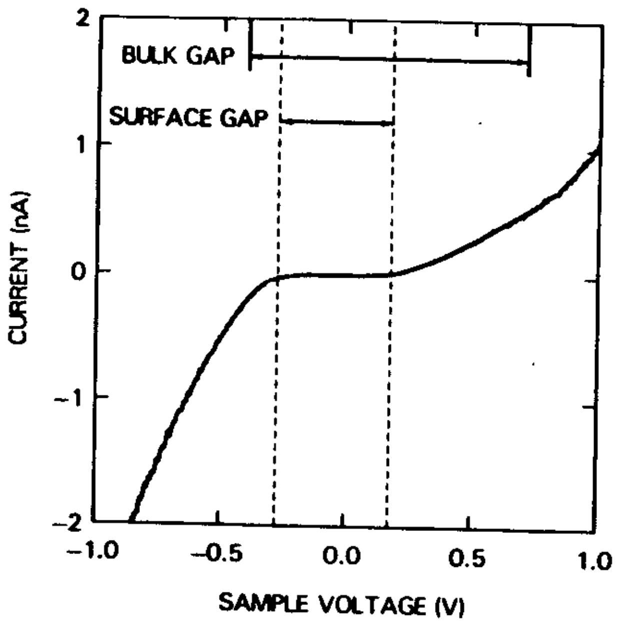
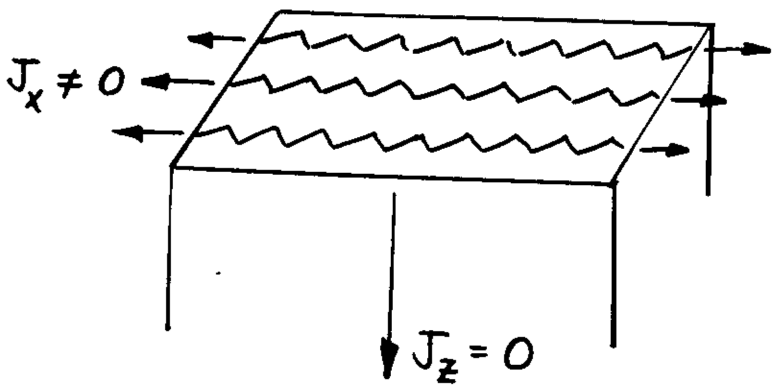
Si(111) 2×1





Summary

- Geometric Structure,
  STM images dangling bonds,
  bonds are connected to the surface atoms.
  (only!)
- Surface State Density & Band-bending,
  Observed directly in spectroscopy.
  (both empty and filled states).
- Charge of Adsorbates and Clusters,
  Observed as ~20 Å tails in images.
- Current Transport,
  Believed to occur along surface.