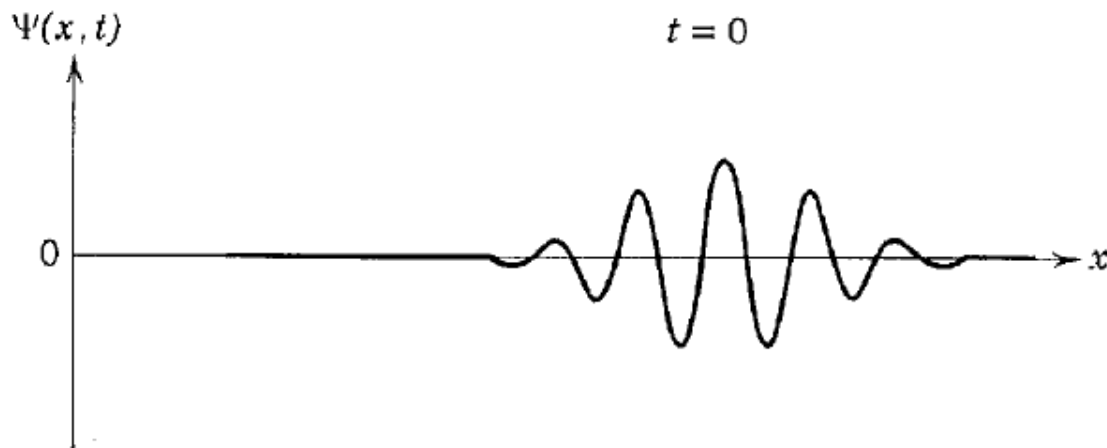
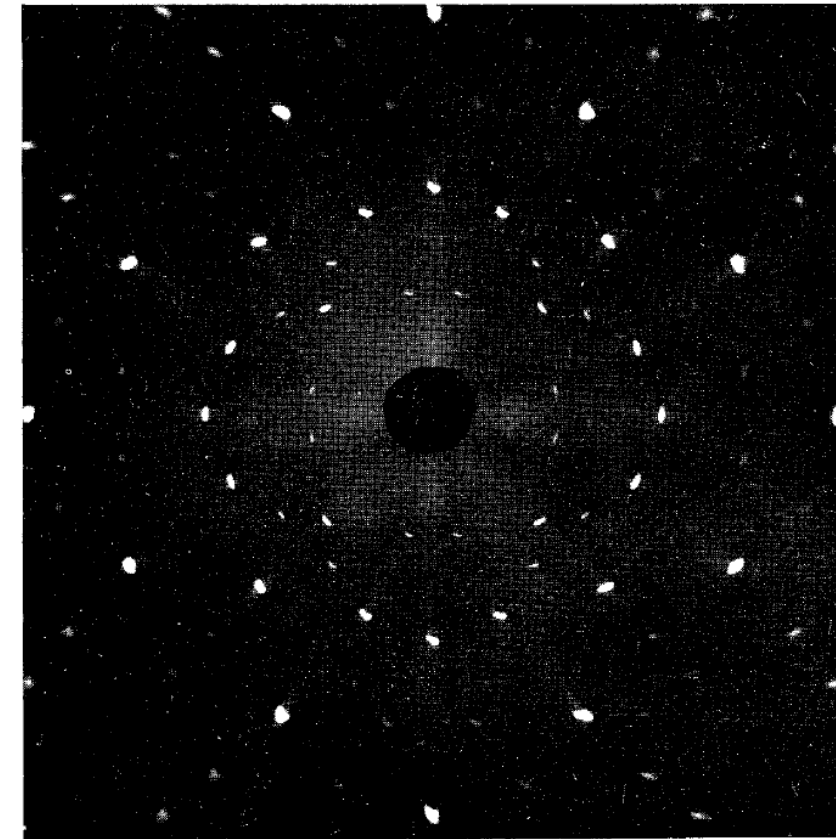
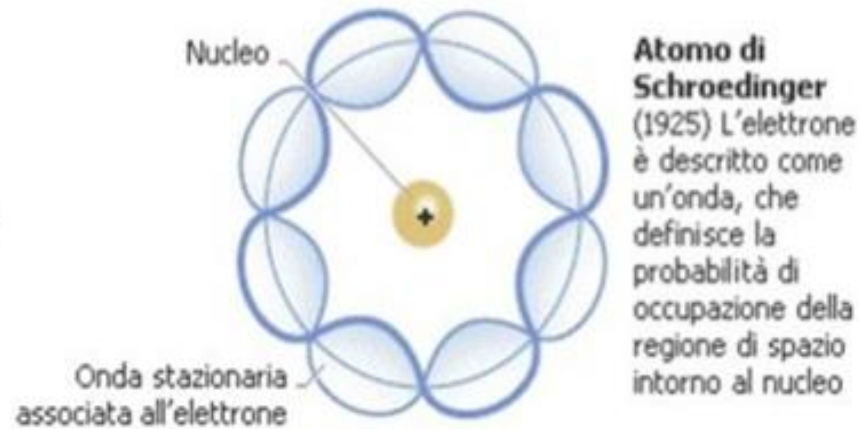
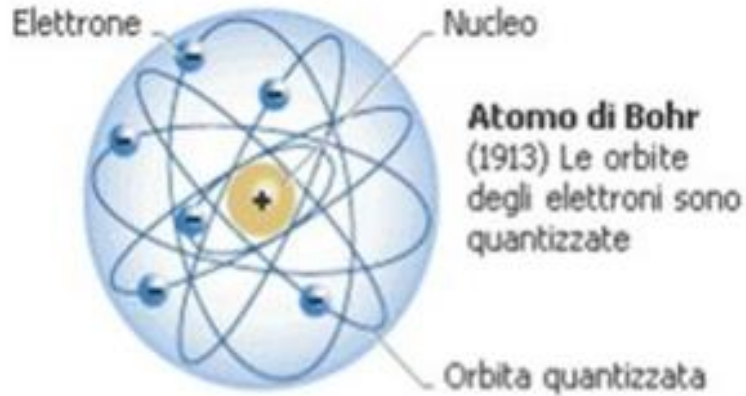




**Conferenza Internazionale Solvay (Brussels, Belgium) 1927**

# Riassunto lezione n.1



A de Broglie wave for a particle.

Diffraction from X-rays, electrons, neutrons  
Bragg's Law, existence of ordered lattice  
in solids

$$\Delta p_x \Delta x \geq \hbar/2$$

**Heisenberg's uncertainty principle:** The position and momentum of a particle cannot be simultaneously measured with arbitrarily high precision

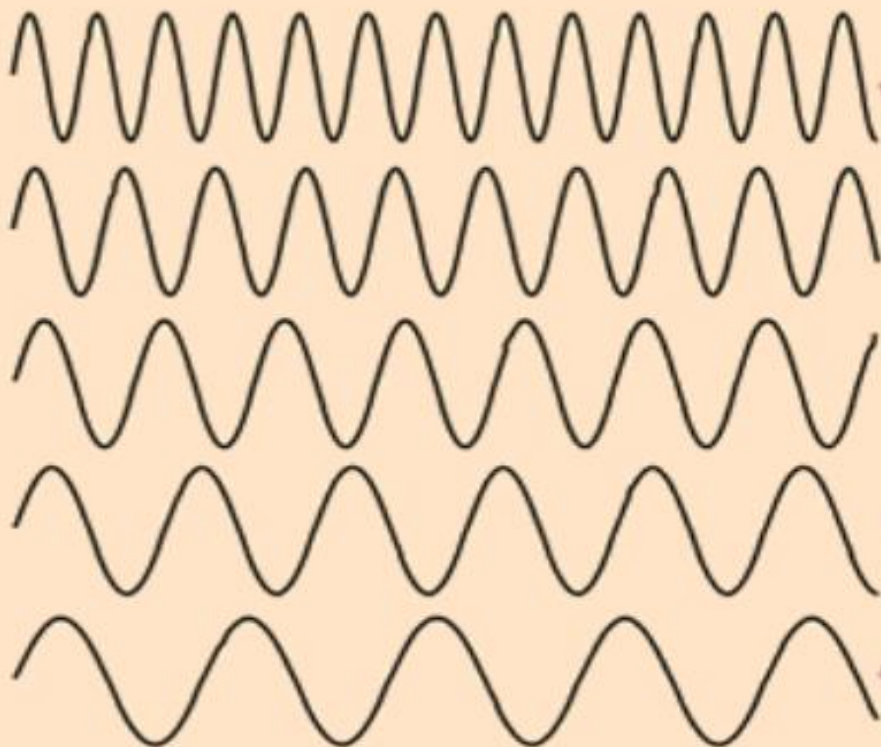
### Precisely determined momentum



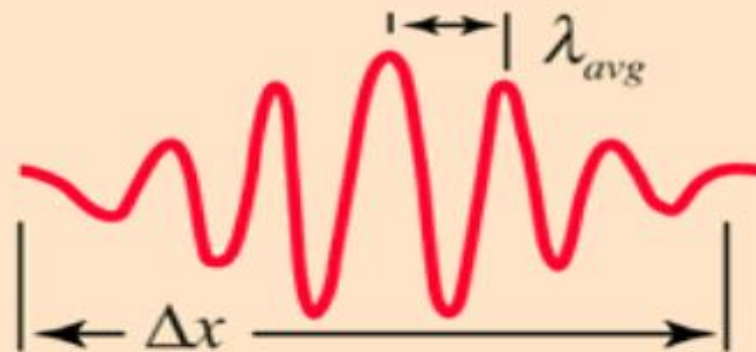
A sine wave of wavelength  $\lambda$  implies that the momentum is precisely known. But the wavefunction and the probability of finding the particle  $\Psi^* \Psi$  is spread over all of space!

$$p = \frac{h}{\lambda}$$

p precise  
x unknown

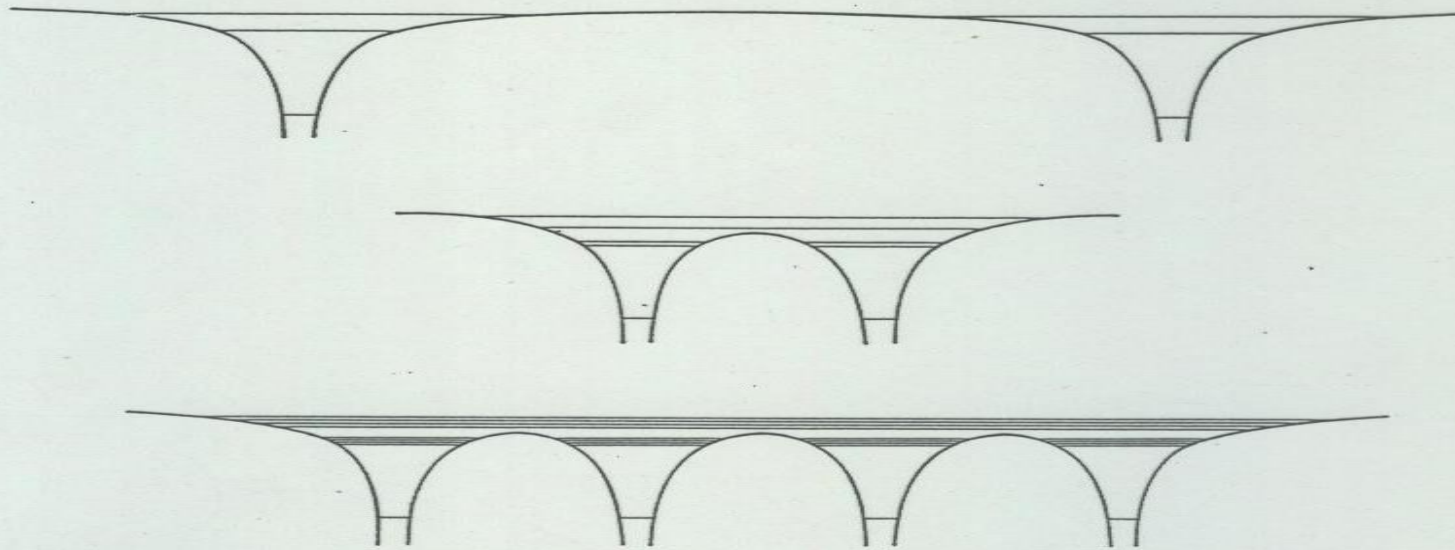


Adding several waves of different wavelength together will produce an interference pattern which begins to localize the wave.

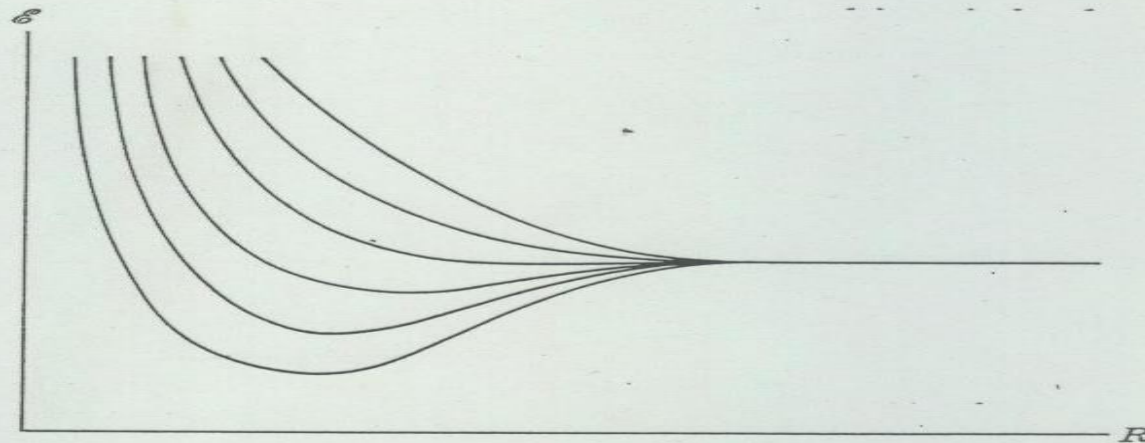


But that process spreads the momentum values and makes it more uncertain. This is an inherent and inescapable increase in the uncertainty  $\Delta p$  when  $\Delta x$  is decreased.

$$\Delta x \Delta p > \frac{\hbar}{2}$$

**FIGURE 13-2**

*Top:* Energy-level scheme for two isolated atoms. *Middle:* Energy-level scheme for the same two atoms in a diatomic molecule. *Bottom:* Energy-level scheme for four of the same atoms in a rudimentary one-dimensional crystal. Note that the lowest lying levels are not split appreciably because the atomic eigenfunctions for these levels do not overlap significantly.

**FIGURE 13-1**

Schematic drawing of the splitting of an energy level in a system of six atoms, as a function of the separation distance  $R$  between adjacent atoms.

**10.2.1 Hamiltoniana del sistema.** In questo paragrafo scriveremo un'hamiltoniana per il sistema di nuclei ed elettroni cercando di tradurre in modo ragionevolmente completo gli aspetti fisici del problema. A rigore ci si dovrebbe porre nell'ambito delle teorie quantistico-relativistiche (v. cap. 8.7) e scrivere l'equazione del sistema in forma relativisticamente covariante; tuttavia ciò non sembra possibile. Rinunciando però al carattere relativistico della formulazione generale, è possibile scrivere formalmente l'equazione di Schrödinger che descrive esattamente il sistema:

$$H_{\text{tot}} \psi_{\text{tot}} \{r, R\} = E_{\text{tot}} \psi_{\text{tot}} \{r, R\}, \quad (10.182)$$

dove  $H_{\text{tot}}$  è l'hamiltoniana del cristallo,  $\psi_{\text{tot}}$  una sua particolare autofunzione ed  $E_{\text{tot}}$  il corrispondente autovalore;  $\{r\}$  ed  $\{R\}$  denotano l'insieme delle coordinate, spaziali e di spin, per gli  $N_T$  elettroni e gli  $M$  nuclei costituenti il sistema, rispettivamente. Alcuni effetti relativistici che non possono venire trascurati, soprattutto in cristalli contenenti atomi pesanti, possono essere introdotti nella (10.182) mediante un termine  $H_{\text{rel}}$ , dipendente dagli spin; in particolare, l'interazione spin-orbita può venire correttamente trattata con questo approccio. L'hamiltoniana del sistema è allora:

$$H_{\text{tot}} = \sum_{i=1}^{N_T} -\frac{\hbar^2}{2m_e} \nabla_i^2 + \sum_{I=1}^M -\frac{\hbar^2}{2M_I} \nabla_I^2 + \sum_{i<j} \frac{e^2}{r_{ij}} - \sum_{i,I} \sum \frac{Z_I e^2}{|R_I - r_i|} + \\ + \sum_{I<J} \sum \frac{Z_I Z_J e^2}{R_{IJ}} + H_{\text{rel}} + H_{\text{ext}}, \quad (10.183)$$

nella quale gli indici  $i$  e  $I$  si riferiscono all' $i$ -esimo elettrone e all' $I$ -esimo nucleo, rispettivamente;  $m_e$  ed  $e$  sono la massa e la carica dell'elettrone;  $M_I$  e  $Z_I e$  la massa e la carica dell' $I$ -esimo nucleo;  $r_{ij}$  ed  $R_{IJ}$  denotano rispettivamente le distanze tra gli elettroni  $i$  e  $j$ , e tra i nuclei  $I$  e  $J$ .  $H_{\text{rel}}$  è un termine, dipendente dagli spin, che include gli effetti relativistici, e  $H_{\text{ext}}$  traduce l'interazione del sistema con campi esterni. Gli operatori  $\nabla^2$  agiscono solo sulle parti spaziali delle funzioni d'onda. Nella (10.183) il primo termine al secondo membro rappresenta l'energia cinetica totale del sistema elettronico, il secondo termine l'energia cinetica totale del sistema dei nuclei; i termini successivi denotano, nell'ordine, l'energia potenziale di repulsione elettronica, di attrazione nuclei-elettroni e di repulsione nucleare.

L'equazione (10.182), con l'hamiltoniana (10.183), è considerata una base adeguata per trattare qualunque problema di fisica dello stato solido. In pratica è però troppo complessa per poter venire risolta; si introducono allora, a seconda del tipo di problema, vari tipi di approssimazioni che

la semplificano, spesso drasticamente, in modo da renderla un po' più trattabile.

Una prima approssimazione consiste nel supporre che soltanto gli elettroni di valenza degli atomi costituenti il cristallo prendano parte al legame cristallino, così che i loro orbitali vengano più o meno profondamente modificati. Al contrario gli elettroni delle shell più interne (v. par. 9.1.5), che hanno la configurazione dei gas inerti, non partecipando al legame cristallino, mantengono pressoché inalterati gli orbitali che avevano nell'atomo isolato. È allora possibile separare i primi dai secondi, e considerare il cristallo come composto da  $N$  elettroni di valenza e da  $M$  noccioli ionici (*core*), ciascuno costituito da un nucleo e dagli elettroni delle shell interne a esso associate.

L'hamiltoniana (10.183) può allora venire riformulata così:

$$H_{\text{tot}} = - \sum_{i=1}^N \frac{\hbar^2}{2m_e} \nabla_i^2 - \sum_{I=1}^M \frac{\hbar^2}{2M_I} \nabla_I^2 + \sum_{i < j} \frac{e^2}{r_{ij}} - \sum_{i,j} V_{eN}(r_i, R_j) + \\ + \sum_{I < J} V_{NN}(R_I, R_J) + H_{\text{rel}} + H_{\text{ext}}, \quad (10.184)$$

dove gli indici  $i$  e  $I$ , questa volta, si riferiscono agli elettroni di valenza e ai noccioli ionici, rispettivamente. Il primo termine al secondo membro rappresenta l'energia cinetica totale  $K_e$  degli elettroni di valenza, il secondo l'energia cinetica  $K_N$  dei noccioli ionici, il terzo l'energia di repulsione coulombiana  $V_{ee}$  tra gli elettroni di valenza, il quarto l'energia di interazione  $V_{eN}$  (non più puramente coulombiana) tra gli elettroni di valenza e i noccioli ionici e il quinto, infine, l'energia di repulsione  $V_{NN}$ .

In generale si pone, in prima approssimazione,  $H_{\text{rel}} = 0$  e  $H_{\text{ext}} = 0$ , cosicché la (10.184) si riduce a

$$H_{\text{tot}} = K_e + K_N + V_{ee}\{r\} + V_{eN}\{r, R\} + V_{NN}\{R\}; \quad (10.185)$$

gli effetti di  $H_{\text{rel}}$  e  $H_{\text{ext}}$  possono eventualmente venire reintrodotti come perturbazioni sulle soluzioni  $\psi^0\{r, R\}$  dell'equazione di Schrödinger con l'hamiltoniana (10.185).

**10.2.2 Approssimazione adiabatica.** L'hamiltoniana (10.185) descrive il sistema di  $N$  elettroni di valenza e quello di  $M$  noccioli ionici, accoppiati tra loro dal termine  $V_{eN}\{r, R\}$ ; un'importante semplificazione, a questo punto, si ottiene mediante l'approssimazione adiabatica, o di Born-Oppenheimer, già nota in fisica molecolare (v. par. 9.2.2). In questa approssimazione si suppone che la funzione d'onda totale  $\psi^0\{r, R\}$  possa venire espressa come:

$$\psi^0\{r, R\} = \Phi_R\{r\} \theta_r\{R\}, \quad (10.186)$$

in cui  $\Phi_R\{r\}$ , che è una funzione delle coordinate elettroniche  $\{r\}$ , dipende

$$E_{\text{TOT}} = E_T + E_{\text{Nuclei}}$$

$$E_T^{\text{rot}} - E_T = \sum_{\text{Nuclei}}$$

parametricamente da  $\{R\}$ , e  $\theta_r\{R\}$ , che è funzione delle coordinate ioniche, dipende parametricamente da  $\{r\}$ .

Si può dimostrare che, per soluzioni stazionarie, l'equazione di Schrödinger con hamiltoniana (10.185) e autofunzione (10.186) è equivalente alle equazioni

$$[K_e + V_{ee}\{r\} + V_{eN}\{r, R\}] \Phi_R\{r\} = \varepsilon_T\{R\} \Phi_R\{r\}, \quad (10.187)$$

$$[K_N + V_{NN}\{R\} + \varepsilon_T\{R\}] \theta_r\{R\} = \mathcal{E}_r \theta_r\{R\}. \quad (10.188)$$

Le equazioni (10.187) e (10.188) mostrano che, a ogni configurazione ionica  $\{R\}$  corrisponde uno stato elettronico stazionario  $\Phi_R\{r\}$ , con autovalore  $\varepsilon_T\{R\}$ , mentre, d'altro canto, il moto ionico avviene in un potenziale che risente, attraverso  $\varepsilon_T\{R\}$ , della configurazione elettronica media corrispondente a  $\{R\}$ . Si ammette che, a causa delle masse molto maggiori, i noccioli ionici si muovano così lentamente rispetto agli elettroni, che questi ultimi riescono, in ogni istante, ad assumere la configurazione d'equilibrio corrispondente alla particolare configurazione ionica in quell'istante; in altre parole, il sistema elettronico segue "adiabaticamente" il movimento degli ioni. Si trascura invece l'interazione *elettrone-fonone*, in particolare la possibilità che il moto degli ioni possa indurre transizioni tra i livelli del sistema elettronico. L'approssimazione adiabatica è considerata appropriata per la maggior parte dei problemi della fisica dello stato solido, con le notevoli eccezioni della *superconduttività* (v. cap. 10.4) e del *polarone* (v. par. 10.2.6); essa consente in generale di trattare separatamente il problema elettronico e quello vibrazionale, per poi reintrodurre eventualmente l'interazione *elettrone-fonone* come perturbazione.

Il problema elettronico è generalmente trattato nell'*approssimazione statica*; si trascura cioè completamente, in prima approssimazione, il moto reticolare, e si studia soltanto l'equazione (10.187), supponendo i noccioli ionici fissi nella configurazione di equilibrio  $\{R_0\}$  in cui cristallizza la sostanza in esame. In linea di principio  $\{R_0\}$  potrebbe venire ottenuta dalla (10.188), minimizzando  $\mathcal{E}_r$ ; in pratica, tuttavia, essa viene determinata sperimentalmente mediante esperimenti di diffrazione di raggi X (v. par. 10.1.10 e cap. 13.3). Nota  $\{R_0\}$ , comunque, la (10.187) diviene:

$$\left[ -\frac{\hbar^2}{2m_e} \sum_{i=1}^N \nabla_i^2 + \sum_{i=1}^N V_{eN}(r_i) + \sum_{i<j} \sum \frac{e^2}{r_{ij}} \right] \Phi\{r\} = \varepsilon_T \Phi\{r\}. \quad (10.189)$$

Si noti che il potenziale  $V_{eN}(r_i)$  ha ora le proprietà di simmetria della configurazione di equilibrio  $\{R_0\}$  del cristallo in esame.

$$\nabla_R \nabla_R \bar{\Phi}_R(z) f_2(R) = f_2(R) \nabla_R^2 \bar{\Phi}_R(z) + 2 \nabla_R \bar{\Phi}_R(z) \nabla_R f_2(R) + \bar{\Phi}_R(z) \nabla_R^2 f_2(R)$$

$\nabla_R$  opera sulle coordinate dei nuclei

approssimazione B-0  $\nabla_R^2 \bar{\Phi}_R(z) = \nabla_R \bar{\Phi}_R(z) = 0$  le variabili di  $\bar{\Phi}_R(z)$  sono piccole

### 10.2.3 Approssimazione a un elettrone.

#### *Approssimazione di Hartree*

La (10.189) rappresenta una notevole semplificazione rispetto alla (10.185), e tuttavia il problema rimane eccezionalmente difficile in quanto, pur avendo eliminato il moto degli ioni, rimangono  $N \simeq 10^{23}$  elettroni interagenti, per cui la  $\Phi\{\mathbf{r}\}$  nella (10.189) è una funzione di  $N$  variabili. La principale difficoltà è rappresentata dal termine di *interazione coulombiana* che accoppia i moti degli  $N$  elettroni del sistema. Trascurando questo termine si potrebbe scrivere  $\Phi\{\mathbf{r}\}$  come un prodotto di  $N$  funzioni "a un elettrone" (cioè funzioni delle coordinate di un solo elettrone):

$$\Phi\{\mathbf{r}\} = \Phi(\mathbf{r}_1, \mathbf{r}_2, \dots, \mathbf{r}_N) = \varphi_1(\mathbf{r}_1) \varphi_2(\mathbf{r}_2) \dots \varphi_N(\mathbf{r}_N), \quad (10.190)$$

e la (10.189) si separerebbe in  $N$  equazioni a un elettrone del tipo

$$\left[ -\frac{\hbar^2}{2m_e} \nabla_i^2 + V(\mathbf{r}_i) \right] \varphi_i(\mathbf{r}_i) = \varepsilon_i \varphi_i(\mathbf{r}_i), \quad (10.191)$$

dove  $V(\mathbf{r}_i) = V_{eN}(\mathbf{r}_i)$ . L'energia totale del sistema sarebbe, in questo caso, uguale alla somma delle energie dei singoli elettroni

$$\varepsilon_T = \sum_{i=1}^N \varepsilon_i. \quad (10.192)$$

Ancor più drasticamente si può trascurare, oltre al termine di repulsione coulombiana, anche il potenziale degli elettroni nel campo dei noccioli ionici  $\sum_i V_{eN}(\mathbf{r}_i)$ , col che la (10.189), sempre usando l'autofunzione (10.190), si riduce a  $N$  equazioni a un elettrone del tipo

$$-\frac{\hbar^2}{2m_e} \nabla_i^2 \varphi_i(\mathbf{r}_i) = \varepsilon_i \varphi_i(\mathbf{r}_i). \quad (10.193)$$

La (10.193) descrive il moto di una particella libera, ed è alla base dell'*approssimazione degli elettroni liberi, o modello di Sommerfeld* (par. 10.2.4). Nonostante la sua drasticità, questa approssimazione può spiegare, in modo relativamente soddisfacente, diverse proprietà elettroniche dei metalli. La (10.191) descrive invece il moto di una particella nel potenziale simmetrico dei noccioli ionici, ed è alla base della *teoria delle bande* (par. 10.2.5).

Senza voler adottare in partenza queste semplificazioni, ci si può chiedere se è possibile determinare un sistema di equazioni a un elettrone che risulti in qualche modo equivalente alla (10.189) (*approssimazione a un elettrone*). In altre parole, si tratta di determinare un potenziale a un elettrone  $V_C(\mathbf{r}_i)$  tale che la (10.189) si separi in  $N$  equazioni del tipo:



si noti che, mentre nel caso del gas di elettroni liberi la densità elettronica  $n$  è uniforme su tutto il cristallo, nella (10.203)  $n$  è invece da considerarsi come densità locale di elettroni, così che  $\bar{V}_\infty$  è funzione della posizione; esso mantiene, comunque, la simmetria del cristallo. Con l'introduzione della (10.203), la (10.200) viene ricondotta alla forma (10.191) con

$$V(r_i) = V_{eN}(r_i) + V_C^H(r_i) + \bar{V}_\infty(r_i). \quad (10.204)$$

**10.2.4 Approssimazione degli elettroni liberi.** In questo paragrafo si introduce *l'approssimazione degli elettroni liberi* che è la più drastica delle approssimazioni a un elettrone in quanto tratta il sistema di elettroni del solido trascurando sia la loro repulsione coulombiana, sia la loro interazione col potenziale periodico dei noccioli ionici. Tuttavia già il lavoro di *P. Drude* e *H. A. Lorentz*, all'inizio del secolo, aveva mostrato come si potesse rendere conto in modo relativamente soddisfacente di alcune proprietà dei metalli applicando a certi elettroni (*elettroni di conduzione*), considerati come costituenti un gas di particelle cariche indipendenti, i metodi della *teoria cinetica dei gas* (v. cap. 5.9) (*modello classico*). Successivamente l'introduzione, per opera di Sommerfeld, della statistica di Fermi-Dirac (v. par. 5.4.3) (*modello di Sommerfeld*) aveva permesso di rimuovere alcune delle più serie difficoltà incontrate nel modello classico.

Ci si soffermerà sul modello di Sommerfeld per due ragioni: da un lato esso fornisce la terminologia e molti dei concetti in uso nella trattazione semiclassica delle proprietà elettroniche; dall'altro esso è il punto di partenza per trattare gli effetti dell'interazione coulombiana tra gli elettroni coi metodi della teoria a molti corpi.

#### *Modello di Sommerfeld. Energia di Fermi*

Nel modello di Sommerfeld l'energia potenziale di ciascun elettrone nel potenziale dei noccioli ionici e degli altri elettroni è rappresentata da un termine negativo e costante  $-W$ ; (10.189) si separa allora in  $N$  equazioni del tipo

$$\left[ -\frac{\hbar^2}{2m_e} \nabla^2 - W \right] \varphi(r) = \varepsilon \varphi(r). \quad (10.205)$$

Il valore di  $W$  è chiaramente importante nel calcolo dell'energia di coesione o nello studio di effetti di superficie, quali l'emissione termoionica ecc. Nella maggior parte delle proprietà elettroniche dei solidi, però, ciò che interessa non è tanto l'energia assoluta dello stato fondamentale del cristallo, quando la distribuzione dei vari livelli energetici rispetto al livello fondamentale. Si può allora supporre nullo il potenziale  $W$  all'interno del cristallo e, con un'ulteriore approssimazione, si può porre  $W$  uguale a infinito il potenziale esterno. Il problema è così ricondotto a un noto caso di meccanica quantistica elementare, la *buccia di potenziale*

*infinito* (v. par. 8.1.4). Considerando per semplicità il cristallo nella forma di un cubetto macroscopico di lato  $L$ , i cui spigoli, nel seguito, assumeremo come assi di riferimento di un sistema cartesiano, la (10.205) diviene:

$$-\frac{\hbar^2}{2m_e} \nabla^2 \varphi(\mathbf{r}) = \varepsilon \varphi(\mathbf{r}), \quad (10.206)$$

con la condizione al contorno che le  $\varphi$  si annullino sulle facce del cubo. Come è noto (v. par. 8.1.4), le  $\varphi$  hanno allora la forma di onde stazionarie, per le quali il valor medio del momento si annulla. Nella descrizione dei *fenomeni di trasporto* è invece più conveniente disporre di autofunzioni in forma di onde progressive, che descrivono il moto di un elettrone in una direzione determinata. Si può dimostrare facilmente che onde di questo tipo possono ottenersi modificando opportunamente le condizioni al contorno della (10.206). In particolare, scegliendo le cosiddette *condizioni al contorno periodiche*, o di *Born-von Kàrmàn*, date da:

$$\varphi(x, y, z) = \varphi(x + L, y, z) = \varphi(x, y + L, z) = \varphi(x, y, z + L), \quad (10.207)$$

si ricava che le autofunzioni della (10.206) assumono la forma

$$\varphi_{\mathbf{k}}(\mathbf{r}) = (\Omega)^{-1/2} \exp(i \mathbf{k} \cdot \mathbf{r}), \quad (10.208)$$

dove  $\Omega$  è il volume del cristallo e  $\mathbf{k}$  può assumere *soltanto valori discreti* dati da

$$|\mathbf{k}| = \frac{2\pi}{|\mathbf{n}|}, \quad (10.209)$$

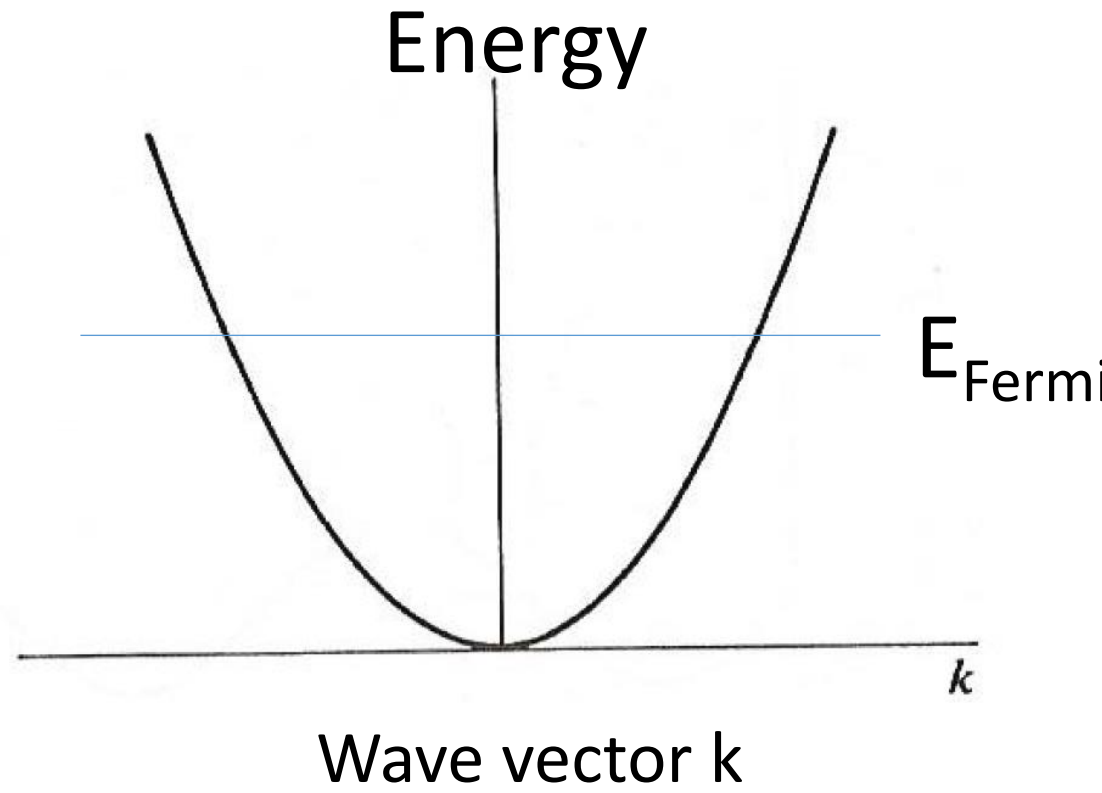
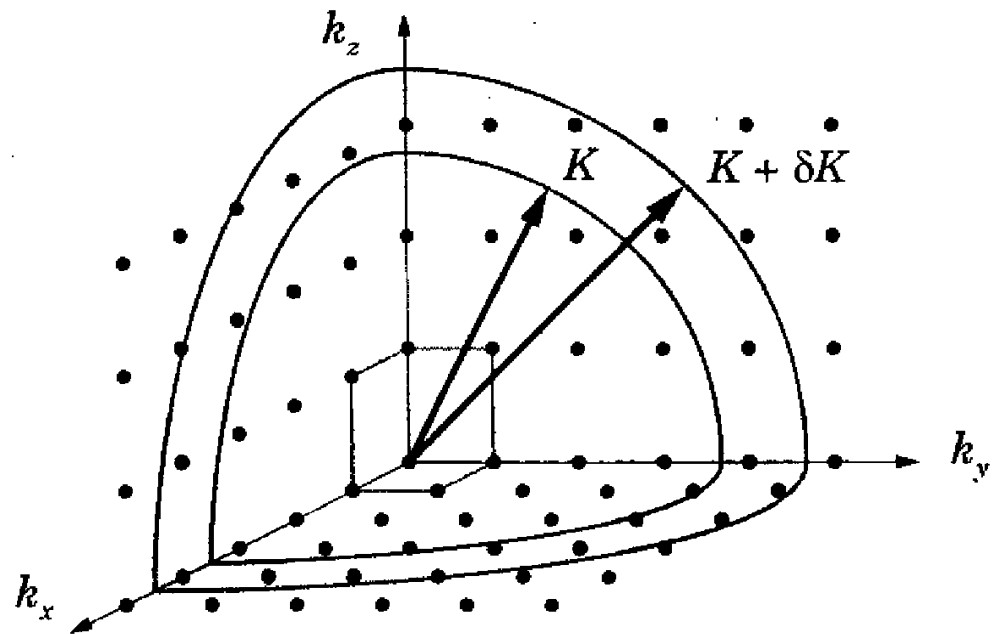
dove  $\mathbf{n}$  denota un vettore a componenti intere arbitrarie  $n_1, n_2, n_3$ . La (10.208) rappresenta un'onda piana che descrive il moto di un elettrone di momento  $\hbar\mathbf{k}$  e di energia

$$E(\mathbf{k}) = \frac{\hbar^2 k^2}{2m_e} \quad (10.210)$$

o, per la (10.209)

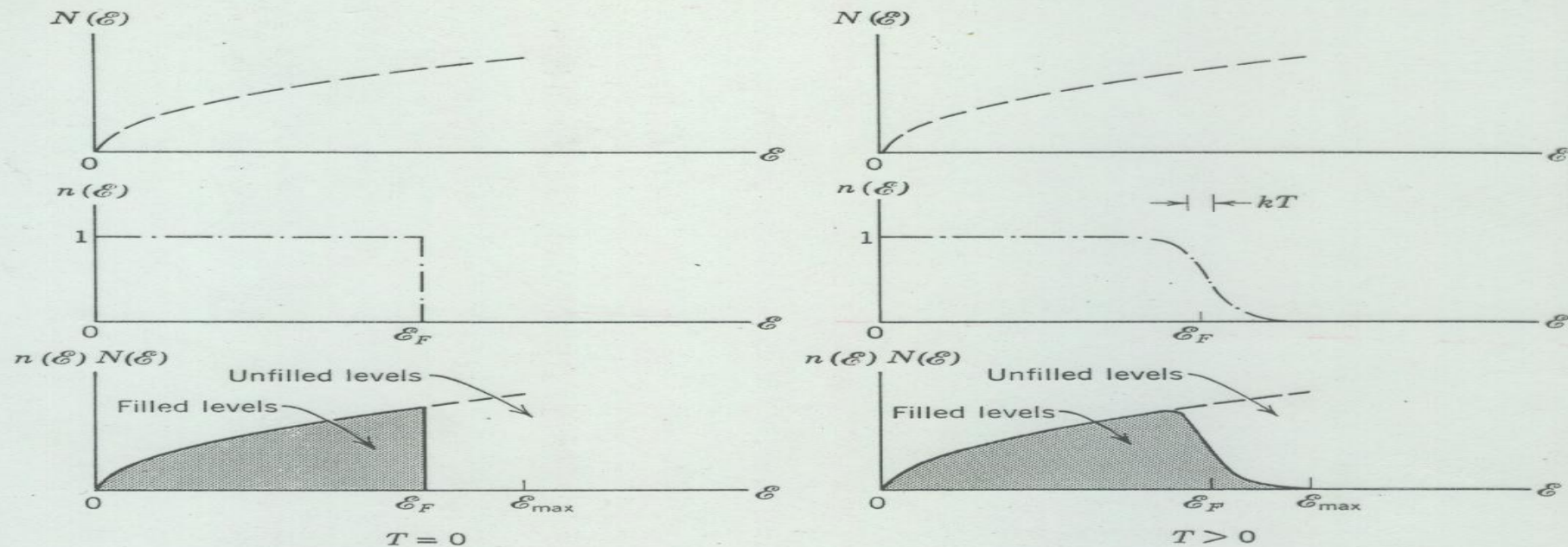
$$E_{n_1 n_2 n_3} = \frac{2\pi^2 \hbar^2}{m_e L^2} (n_1^2 + n_2^2 + n_3^2). \quad (10.211)$$

Lo spettro energetico degli elettroni di conduzione è dunque discreto; ogni stato è rappresentato da una terna di interi  $n_1, n_2, n_3$  o, equivalentemente, da un punto nello spazio del vettore  $\mathbf{k}$ , o *spazio- $\mathbf{k}$* . La (10.209) mostra che questi punti sono distribuiti uniformemente nello spazio- $\mathbf{k}$ ; questa distribuzione, dal momento che la separazione energetica tra i livelli (10.211), per un campione macroscopico, è così piccola (inferiore



**FIGURE 1.8.** Construction in **K**-space to calculate the density of states for free electrons in three dimensions. The shells have radii  $K$  and  $K + \delta K$ , corresponding to energies  $\epsilon$  and  $\epsilon + \delta\epsilon$ .

$$n_{3D}(E) = \frac{mK}{\pi^2 \hbar^2} = \frac{m}{\pi^2 \hbar^3} \sqrt{2mE}.$$

**FIGURE 13-4**

*Left:* The distribution with energy of conduction electrons in an unfilled band of width  $\mathcal{E}_{\max}$  in a solid at  $T = 0$ , according to the free electron model. *Right:* The same at a higher temperature.

**Example 13-1.** The Fermi energy,  $\mathcal{E}_F$ , for lithium is 4.72 eV at  $T = 0$ . Calculate the number of conduction electrons per unit volume in lithium.

From (11-53) we have

$$\mathcal{E}_F = \frac{h^2}{8m} \left( \frac{3\mathcal{N}}{\pi V} \right)^{2/3} \quad \text{for } kT \ll \mathcal{E}_F \quad (13-5)$$

so that the number of free electrons per unit volume is

$$n = \frac{\mathcal{N}}{V} = \left( \frac{8m}{h^2} \right)^{3/2} \mathcal{E}_F^{3/2} \frac{\pi}{3}$$

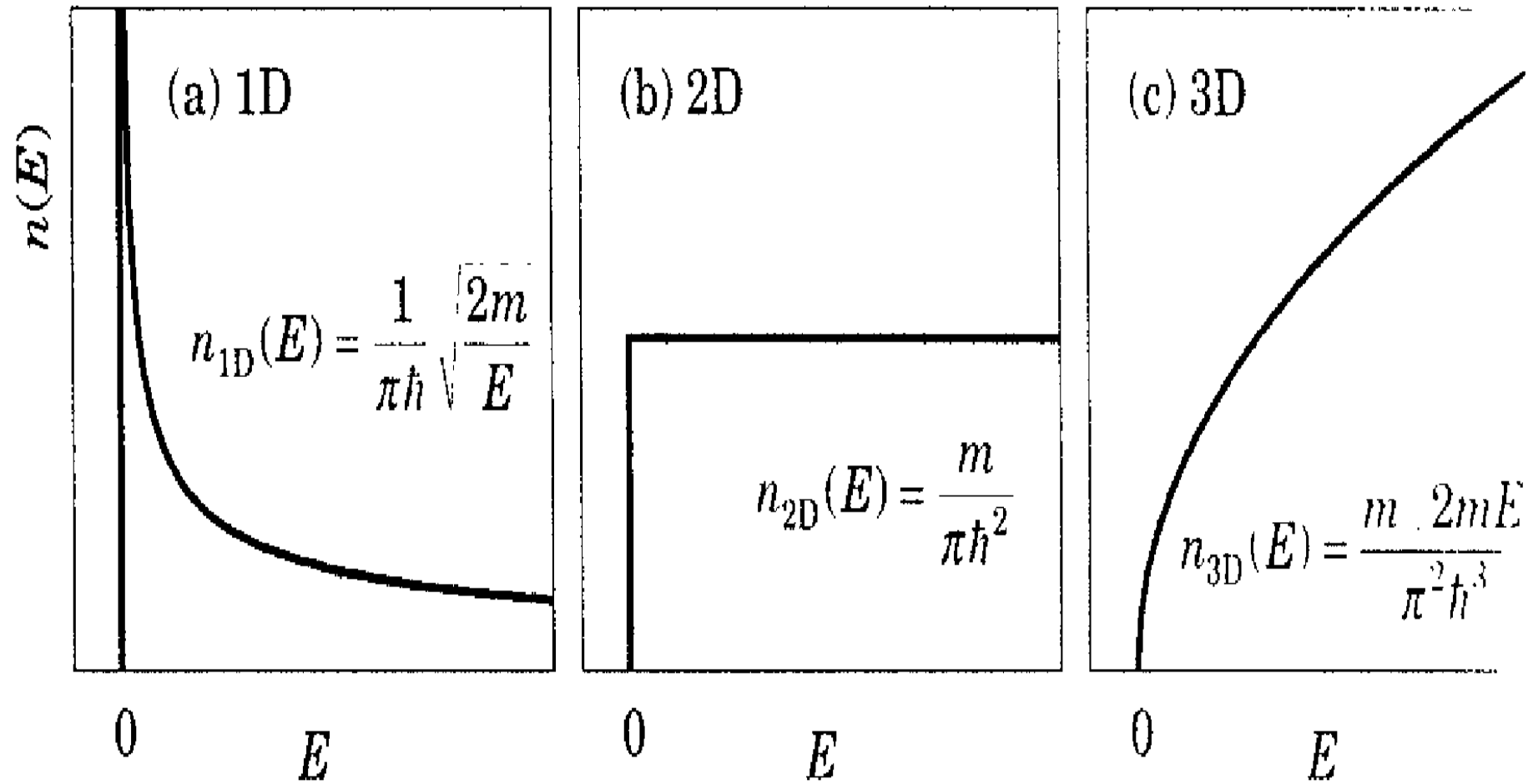
in which  $m$  is the mass of the electron. Then, with  $\mathcal{E}_F = 4.72$  eV, we have

$$\begin{aligned} n &= \frac{\mathcal{N}}{V} = \left[ \frac{8 \times 9.11 \times 10^{-31} \text{ kg}}{(6.63 \times 10^{-34} \text{ joule-sec})^2} \right]^{3/2} \frac{(4.72 \times 1.60 \times 10^{-19} \text{ joule})^{3/2}}{3} \pi \\ &= 4.64 \times 10^{28} / \text{m}^3 = 4.64 \times 10^{22} / \text{cm}^3 \end{aligned}$$

as the number of conduction electrons per unit volume in lithium.

This corresponds exactly to one free electron per lithium atom, since the number of lithium atoms per unit volume, in solid lithium of density 0.534 g/cm<sup>3</sup>, is

$$0.534 \frac{\text{g}}{\text{cm}^3} \times \frac{1 \text{ mole}}{6.94 \text{ g}} \times 6.02 \times 10^{23} \frac{\text{atom}}{\text{mole}} = 4.64 \times 10^{22} \text{ atom/cm}^3$$



Densities of states for free electrons in one, two, and three dimensions.

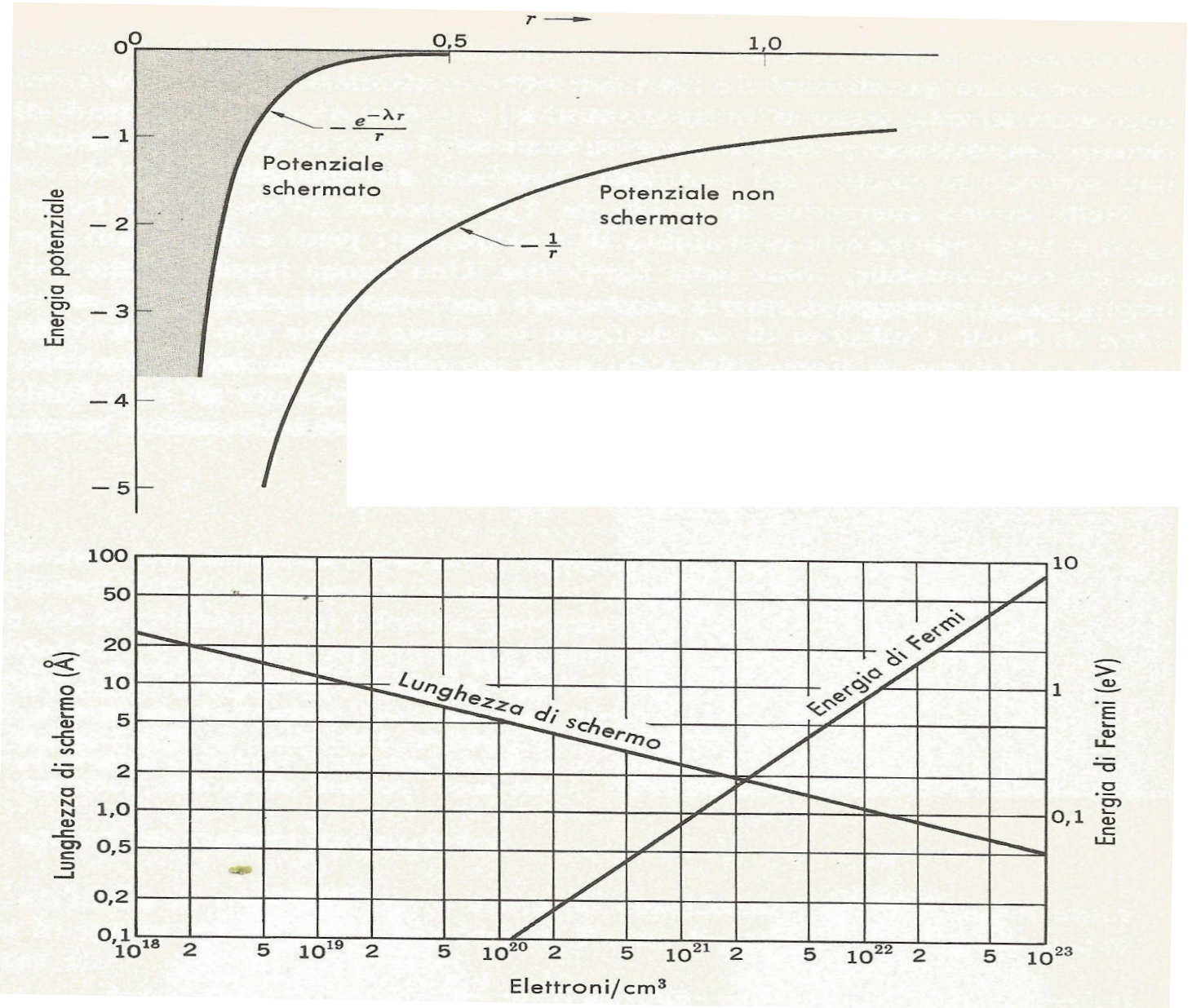
Table 1 Calculated free electron Fermi surface parameters for metals at room temperature  
(Except for Na, K, Rb, Cs at 5 K and Li at 78 K)

Valency	Metal	Electron concentration, in $\text{cm}^{-3}$	Radius <sup>a</sup> parameter $r_s$	Fermi wavevector, in $\text{cm}^{-1}$	Fermi velocity, in $\text{cm s}^{-1}$	Fermi energy, in eV	Fermi temperature $T_F = \epsilon_F/k_B$ , in deg K
1	Li	$4.70 \times 10^{22}$	3.25	$1.11 \times 10^8$	$1.29 \times 10^8$	4.72	$5.48 \times 10^4$
	Na	2.65	3.93	0.92	1.07	3.23	3.75
	K	1.40	4.86	0.75	0.86	2.12	2.46
	Rb	1.15	5.20	0.70	0.81	1.85	2.15
	Cs	0.91	5.63	0.64	0.75	1.58	1.83
	Cu	8.45	2.67	1.36	1.57	7.00	8.12
	Ag	5.85	3.02	1.20	1.39	5.48	6.36
	Au	5.90	3.01	1.20	1.39	5.51	6.39
	2	Be	24.2	1.88	1.93	2.23	14.14
Mg		8.60	2.65	1.37	1.58	7.13	8.27
Ca		4.60	3.27	1.11	1.28	4.68	5.43
Sr		3.56	3.56	1.02	1.18	3.95	4.58
Ba		3.20	3.69	0.98	1.13	3.65	4.24
Zn		13.10	2.31	1.57	1.82	9.39	10.90
Cd		9.28	2.59	1.40	1.62	7.46	8.66
3	Al	18.06	2.07	1.75	2.02	11.63	13.49
	Ga	15.30	2.19	1.65	1.91	10.35	12.01
	In	11.49	2.41	1.50	1.74	8.60	9.98
4	Pb	13.20	2.30	1.57	1.82	9.37	10.87
	Sn( <i>w</i> )	14.48	2.23	1.62	1.88	10.03	11.64

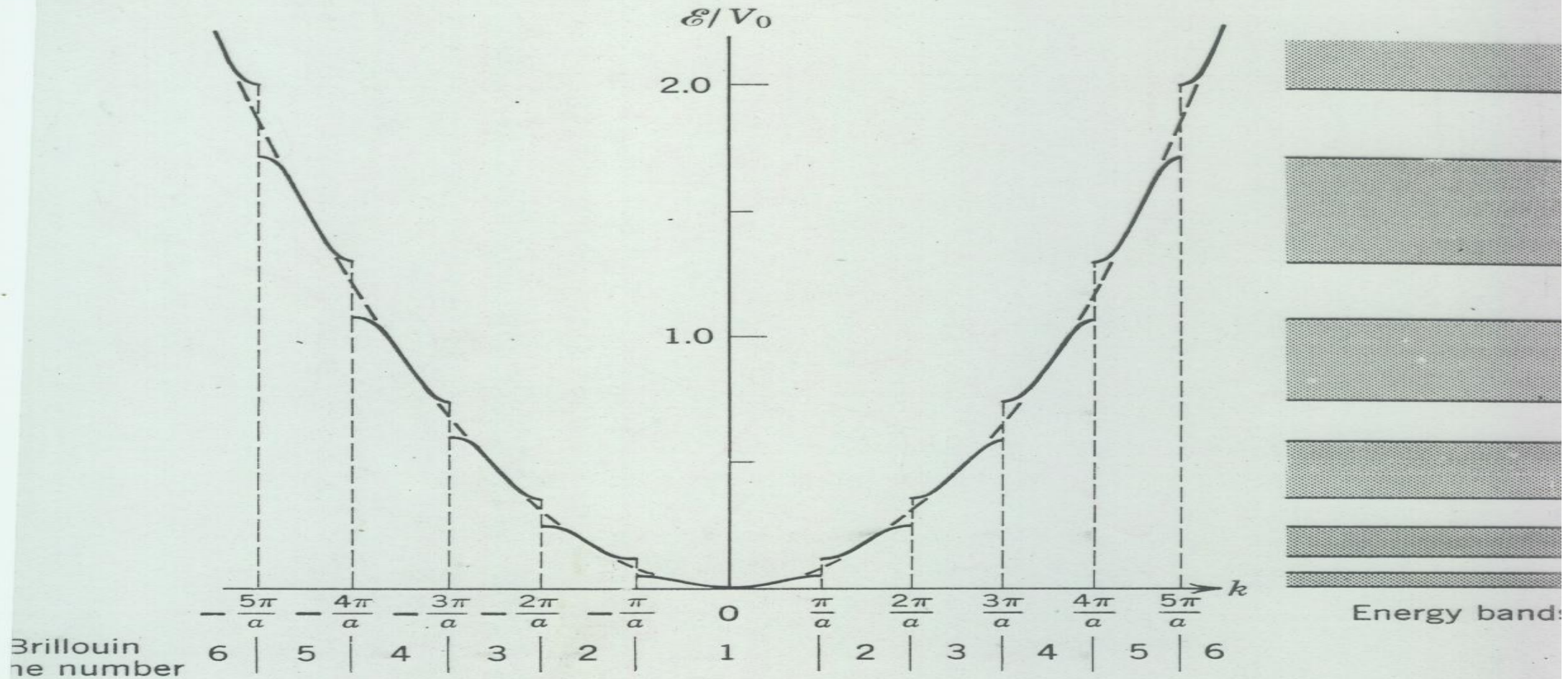
<sup>a</sup>The dimensionless radius parameter is defined as  $r_s = r_0/a_H$ , where  $a_H$  is the first Bohr radius and  $r_0$  is the radius of a sphere that contains one electron.

Perche' funziona «bene»  
il modello dell'elettrone libero?

Effetto di schermo di  
Thomas e Fermi



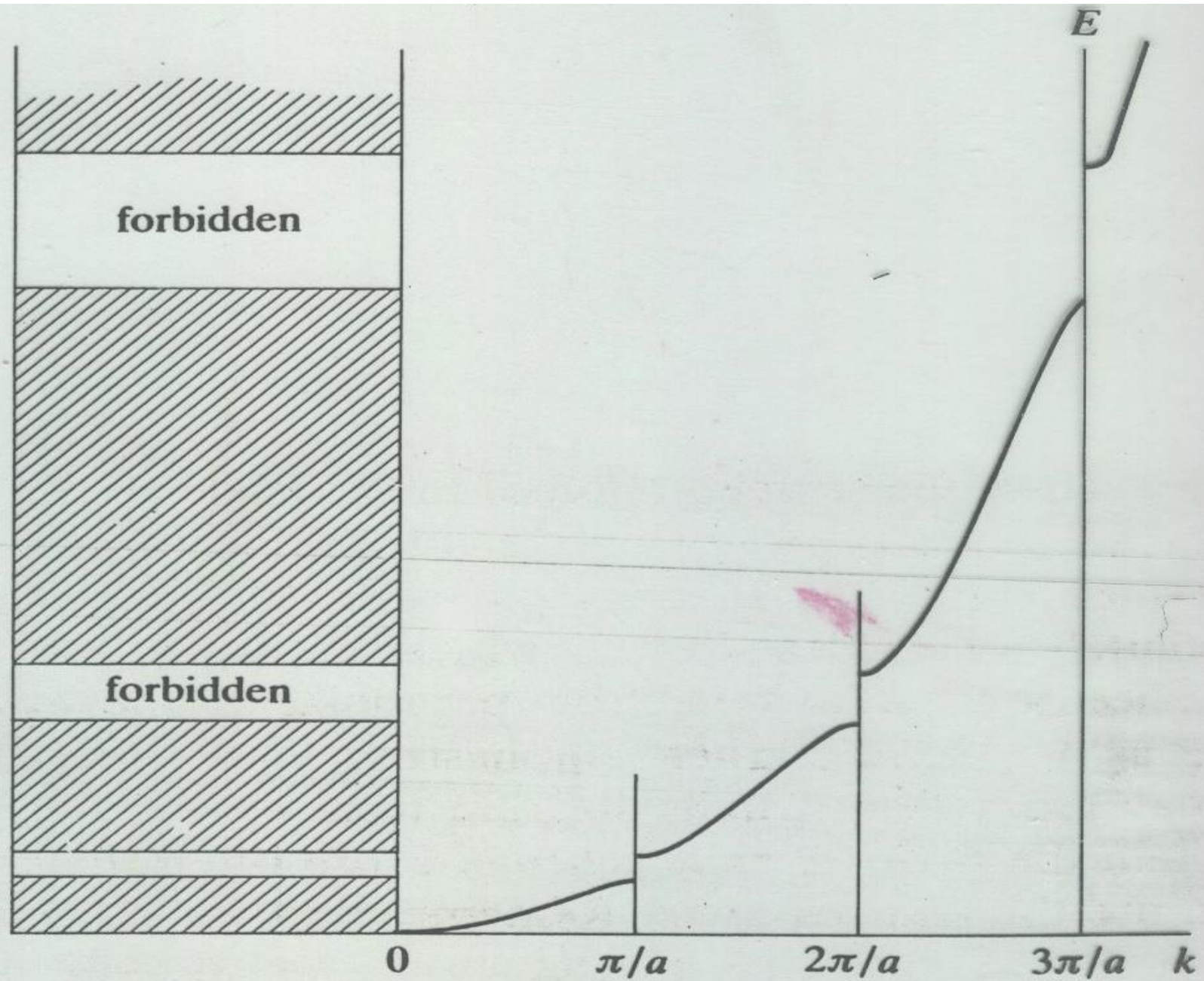
SOLIDS—CONDUCTORS AND SEMICONDUCTORS



**FIGURE 13-10**

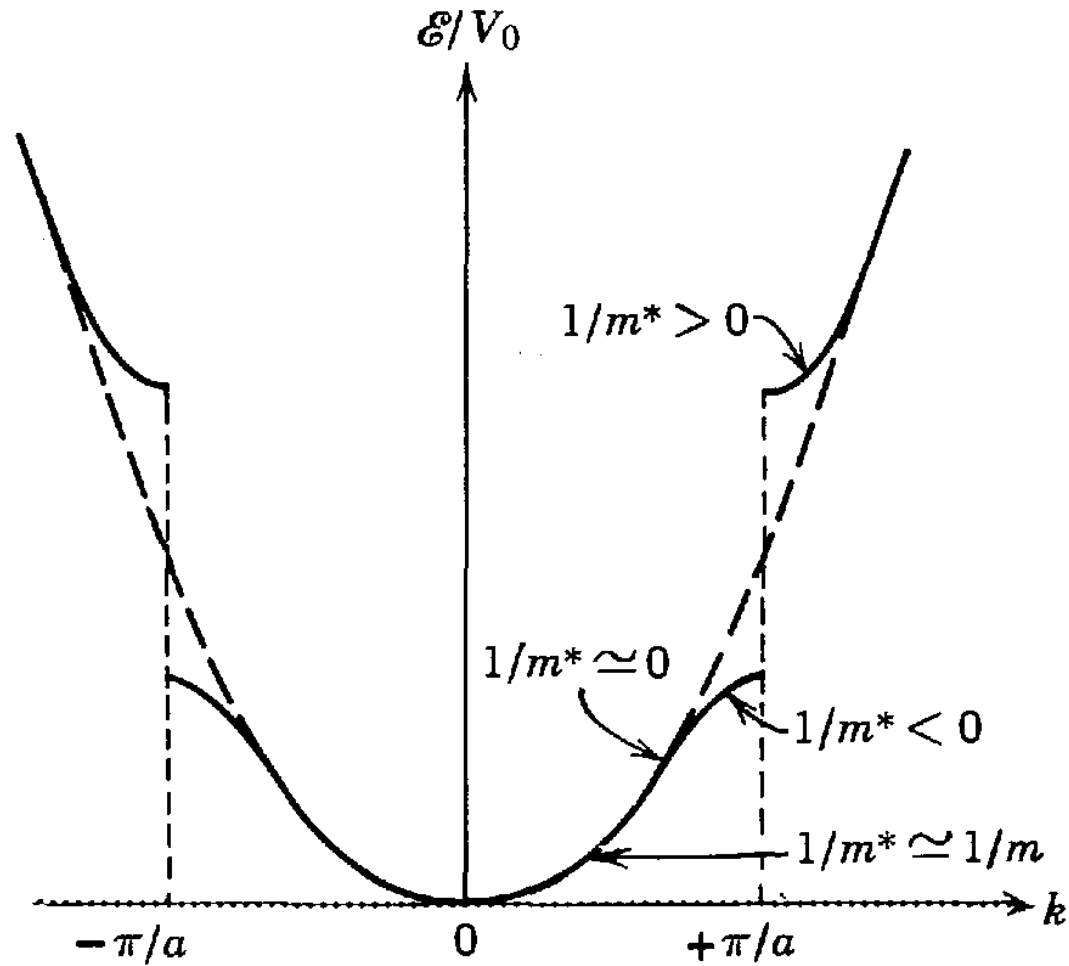
Allowed energies in a one-dimensional lattice of periodicity  $a$ , as a function of the wave number  $k$ . The dashed curve gives the free electron model result, for comparison. The allowed and forbidden energy bands that result are shown on the right.

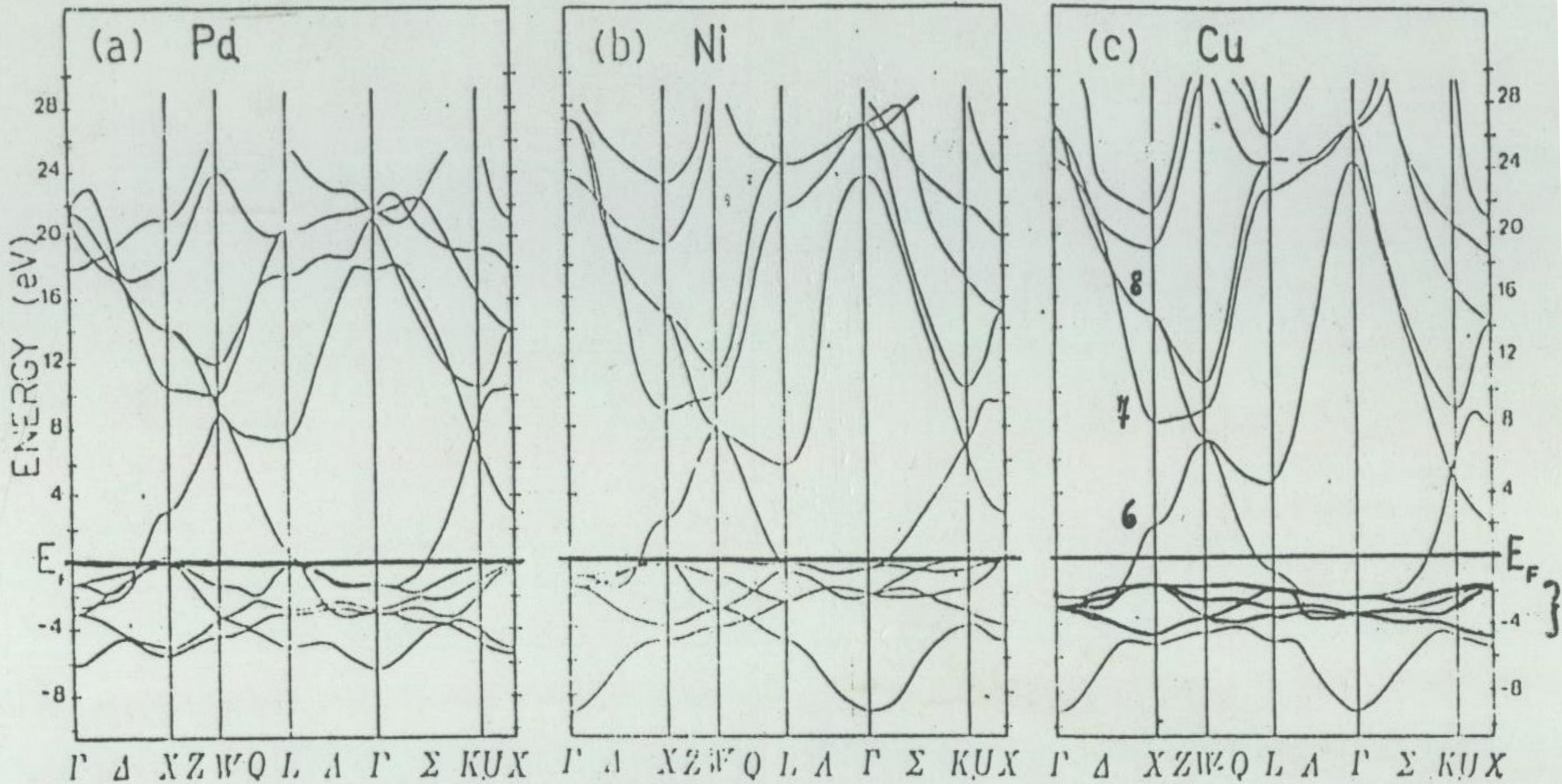


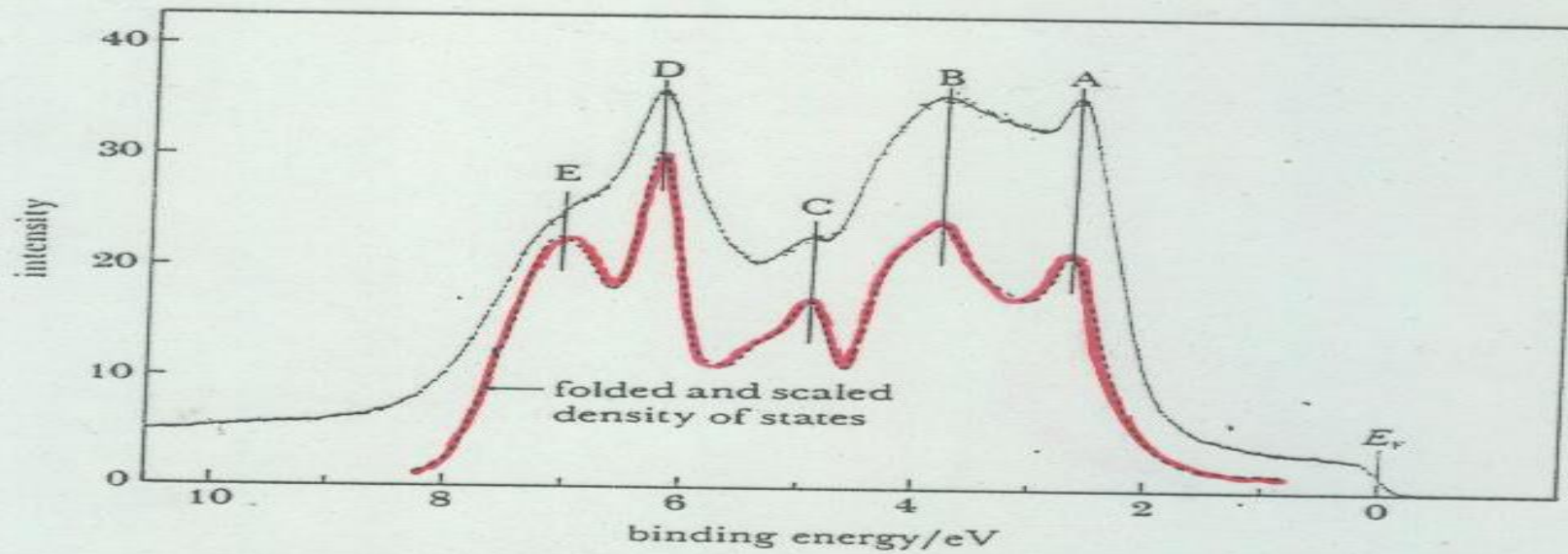


# Massa efficace di un elettrone in un potenziale periodico

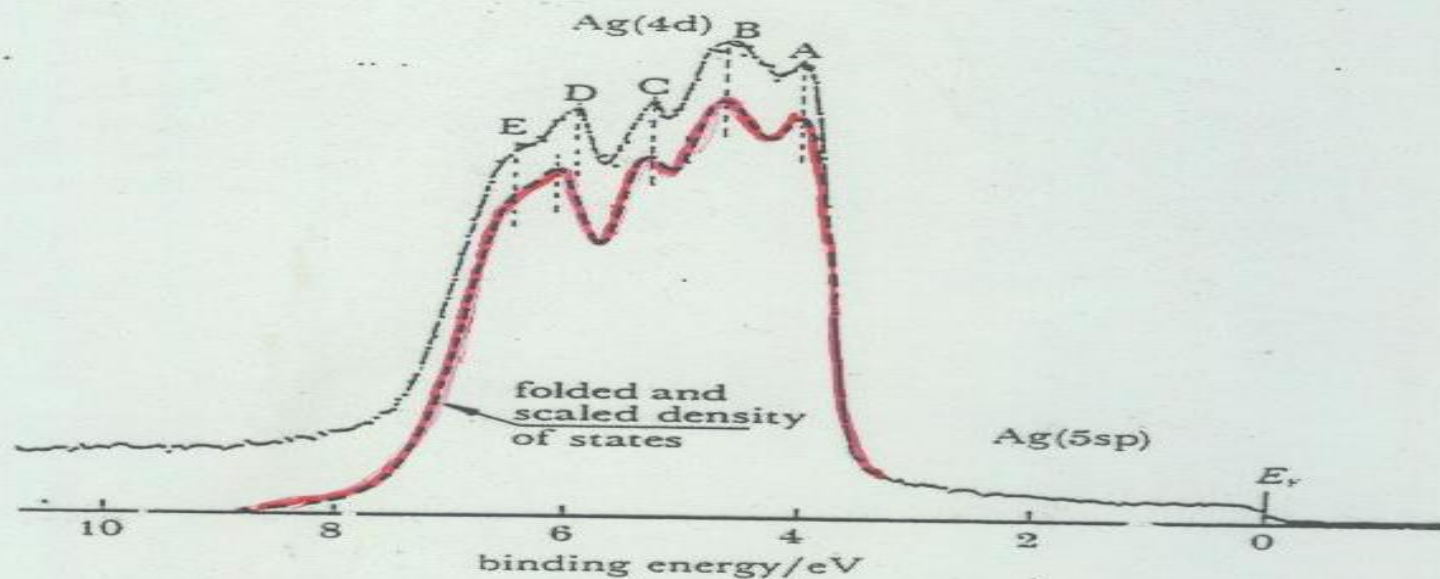
$$\frac{1}{m^*} \equiv \frac{1}{\hbar^2} \frac{d^2 \mathcal{E}}{dk^2}$$







The gold conduction-electron band spectrum for  $h\nu = 1486.7$  eV



The silver conduction-electron band spectrum for  $h\nu = 1486$  eV.

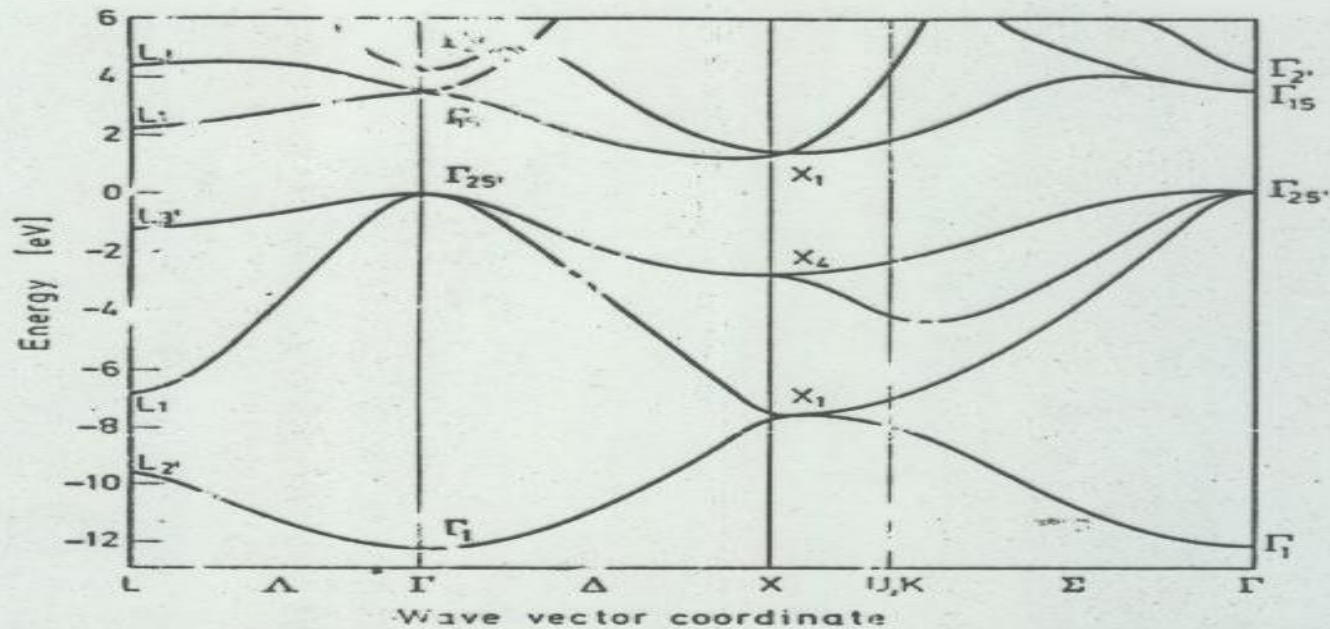


Fig. 2.31. Band structure of silicon along the most important axes of symmetry in the Brillouin zone. For an explanation of the symmetry symbols also shown see Section 2.2.14 [from J. R. Chelikowski, M. L. Cohen: Phys. Rev. B 14, 556 (1976)]

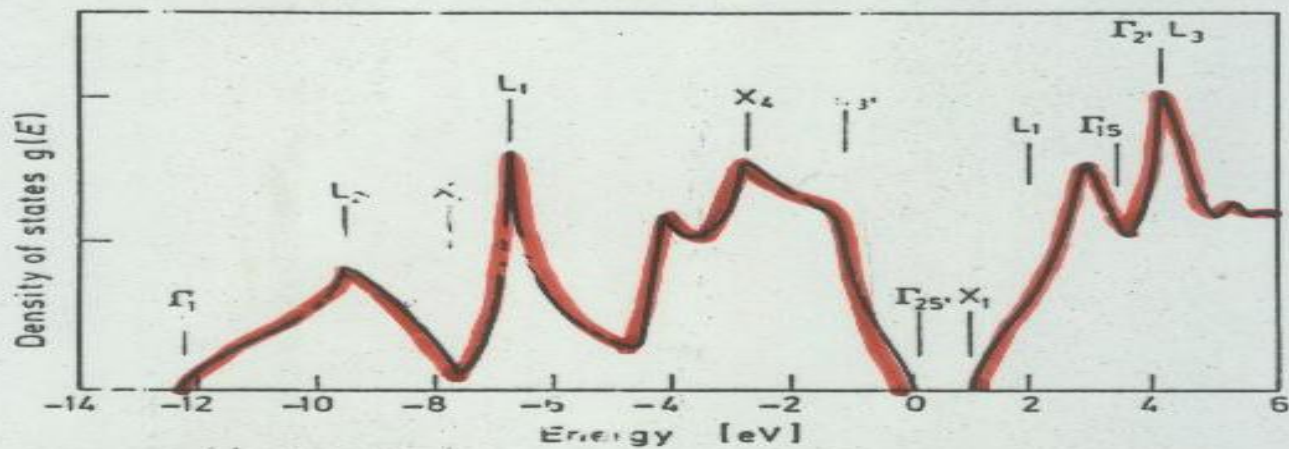
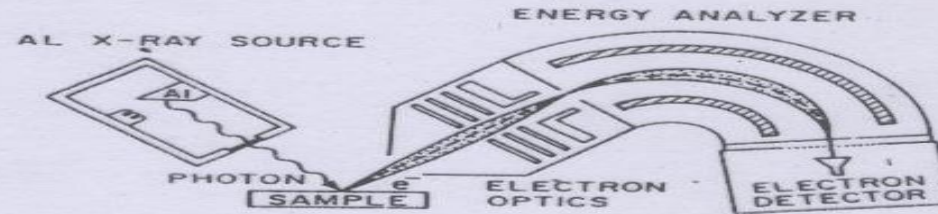


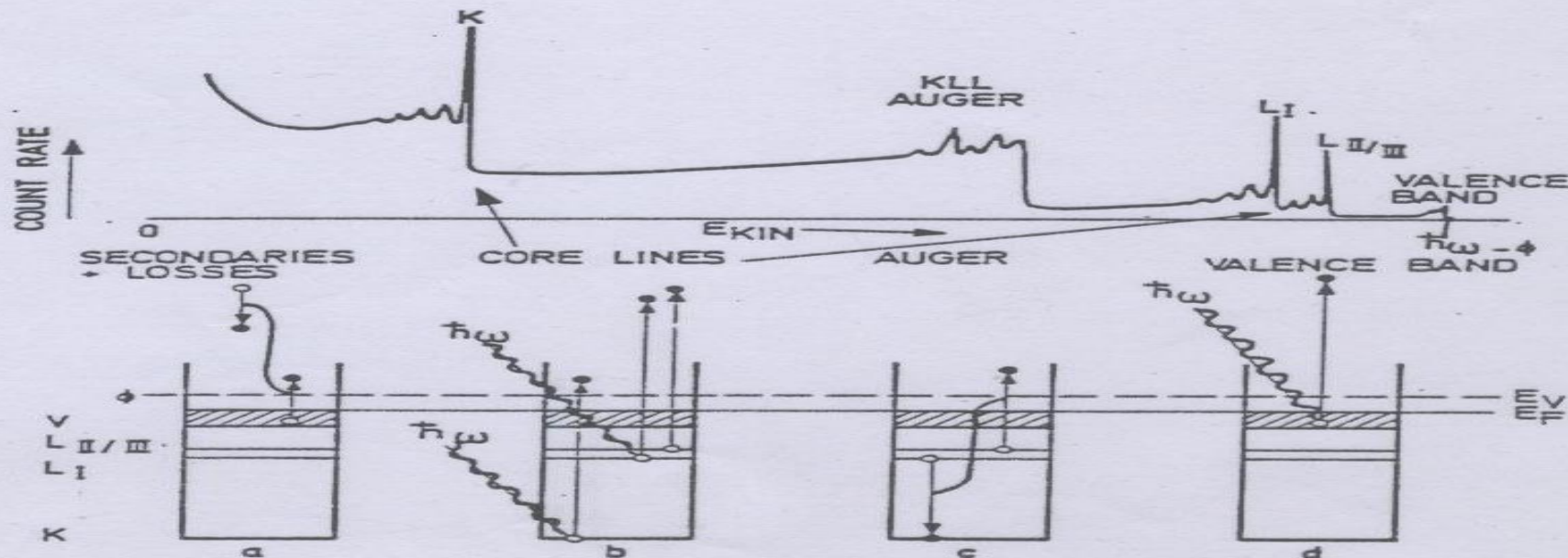
Fig. 2.32. Density of states in the valence and conduction bands of silicon. For an easier comparison with Fig. 2.31 the symbols of the high symmetry points of the band structure are insetted. [from J. R. Chelikowski, D. J. Chadi, M. L. Cohen: Phys. Rev. B 8, 2786 (1973)]

# Spettroscopia XPS

(X-ray Photoelectron Spectroscopy)



$$E_K = h\omega - E_B - e\Phi$$



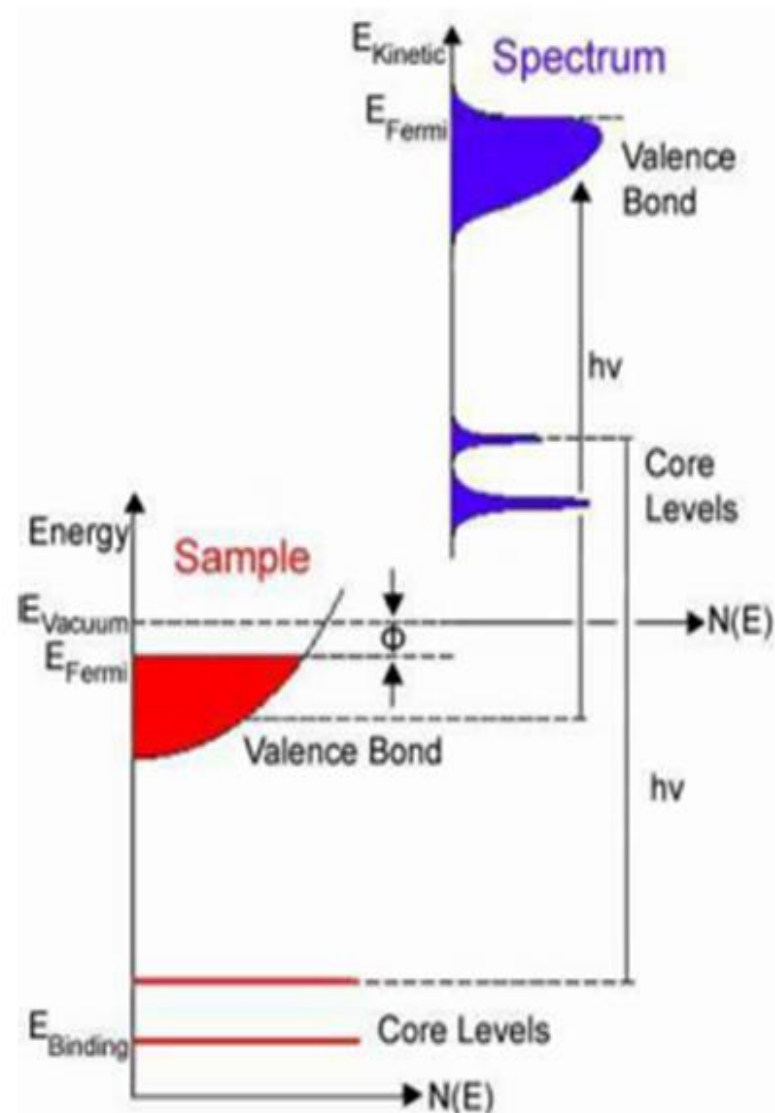


Figure 2.20. Scheme of the energy diagram for the photoelectron emission process: electronic bands of a sample are related to the signals in the XPS spectrum.

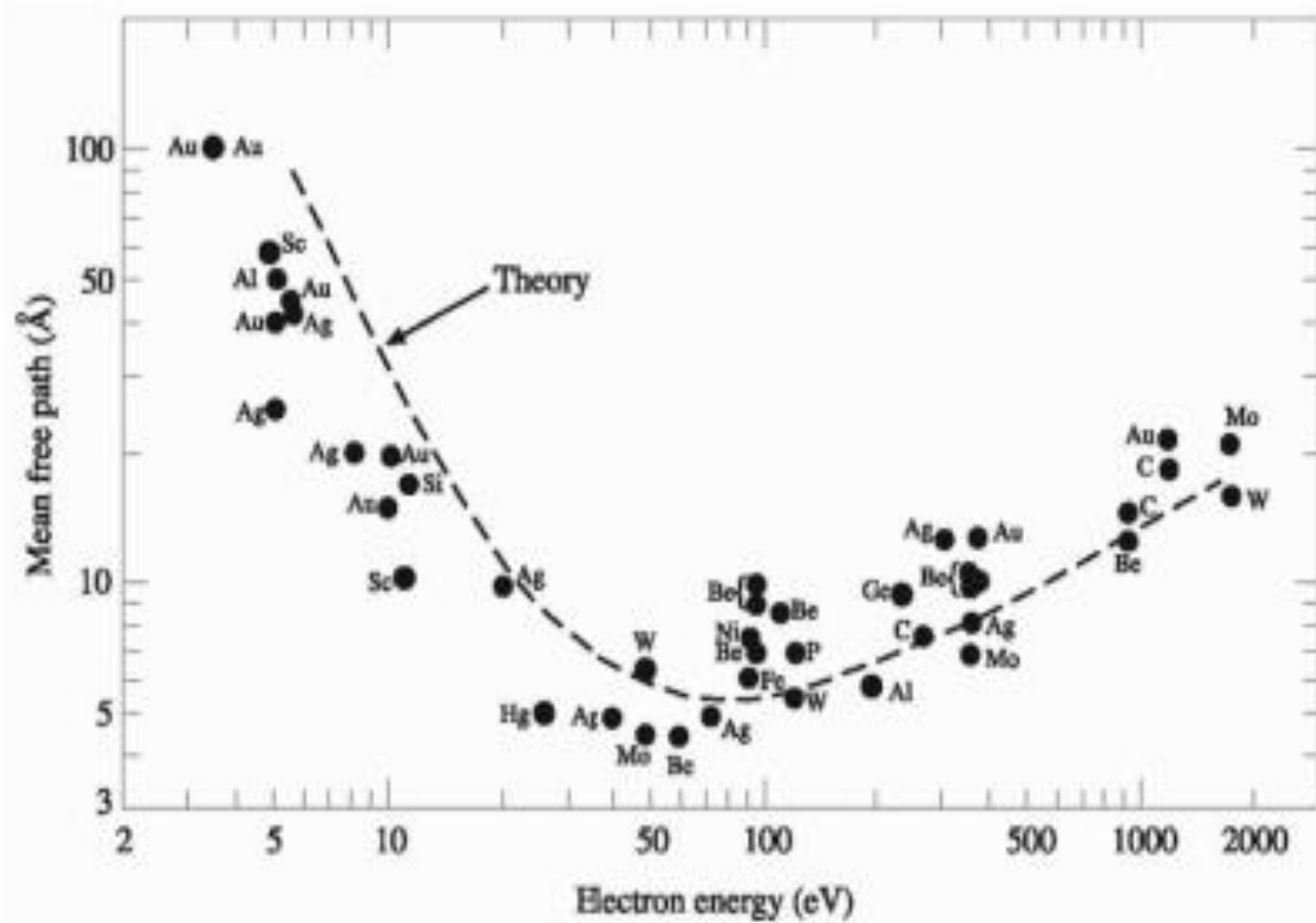
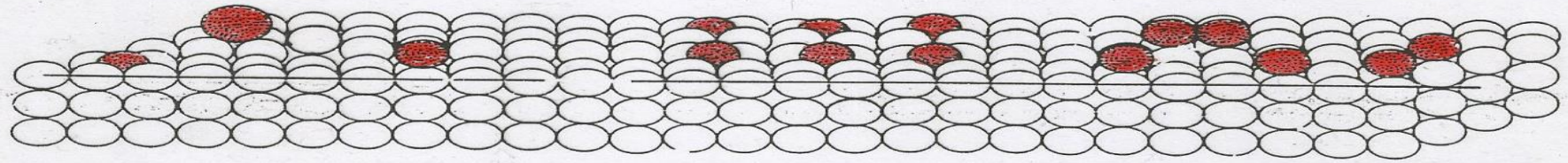


Figure 2.21. Universal curve of inelastic mean free path (IMFP) of electrons in matter as a function of the photoelectron kinetic energy.<sup>167</sup>

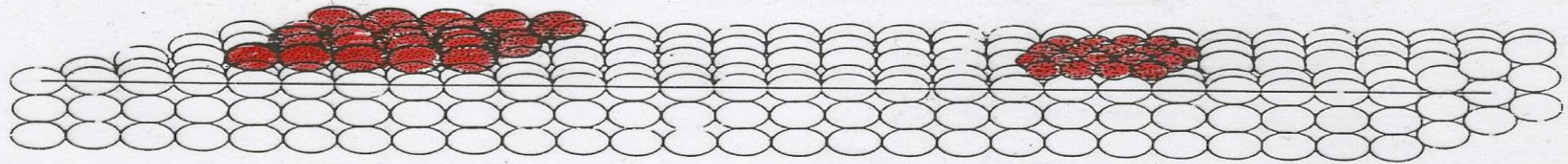




Isolated Adatoms

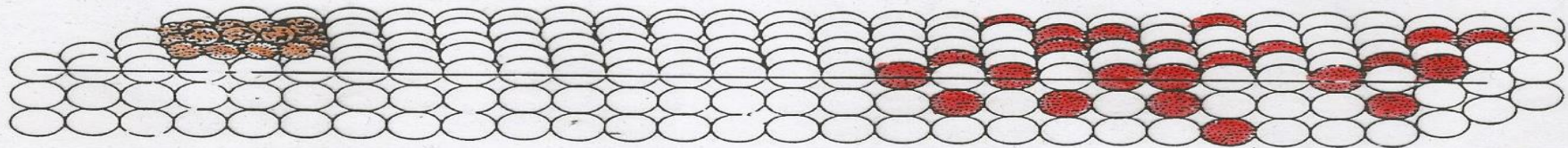
Ordered Adatoms

Disordered Adatoms



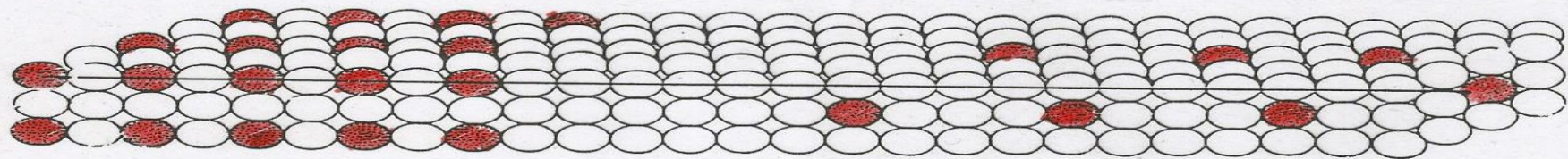
Epitaxial Overlayer

Non-epitaxial (patches)



Cluster Formation

Intermixed - Disordered



Intermixed - Long range order

Intermixed - Local order

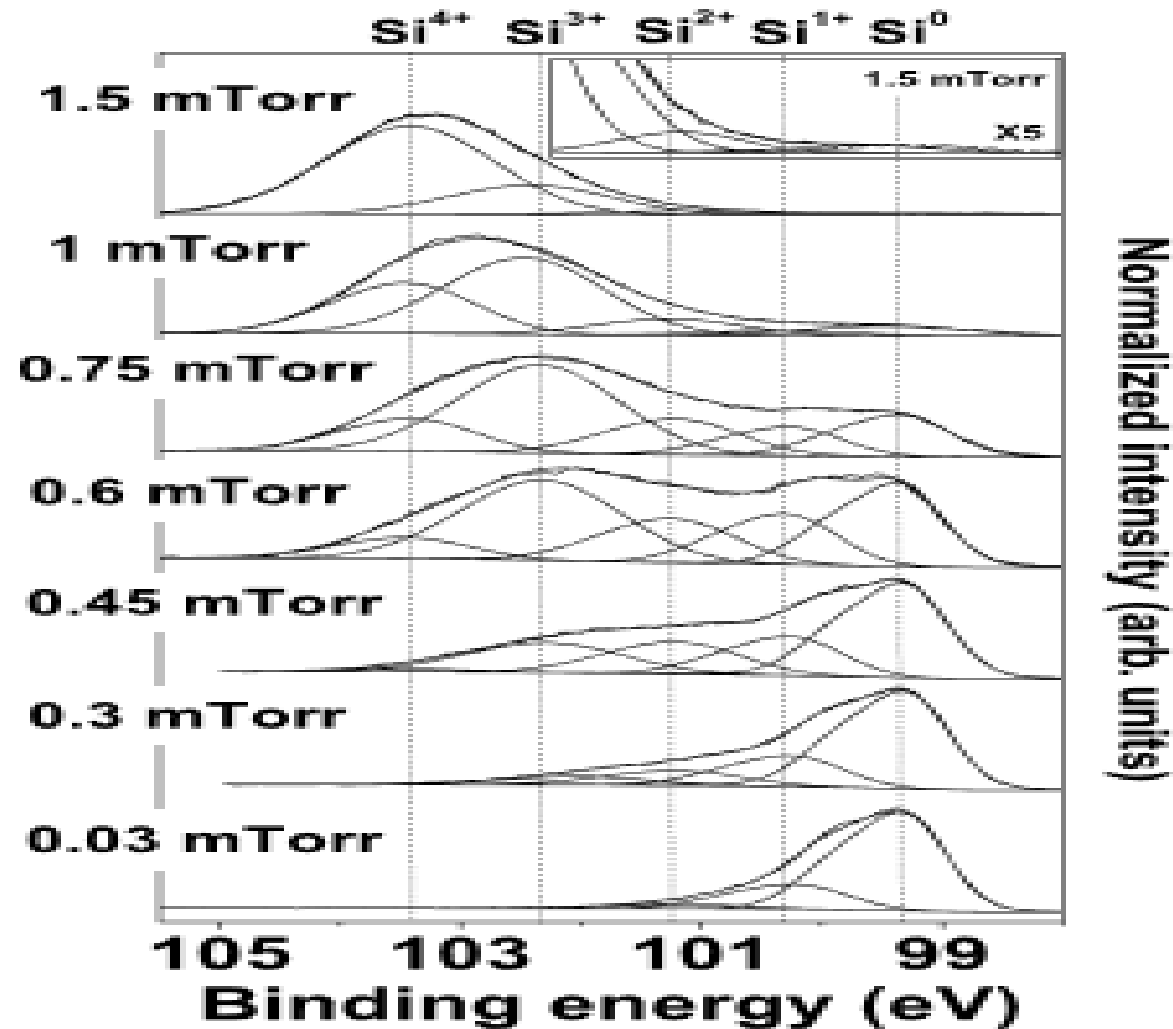
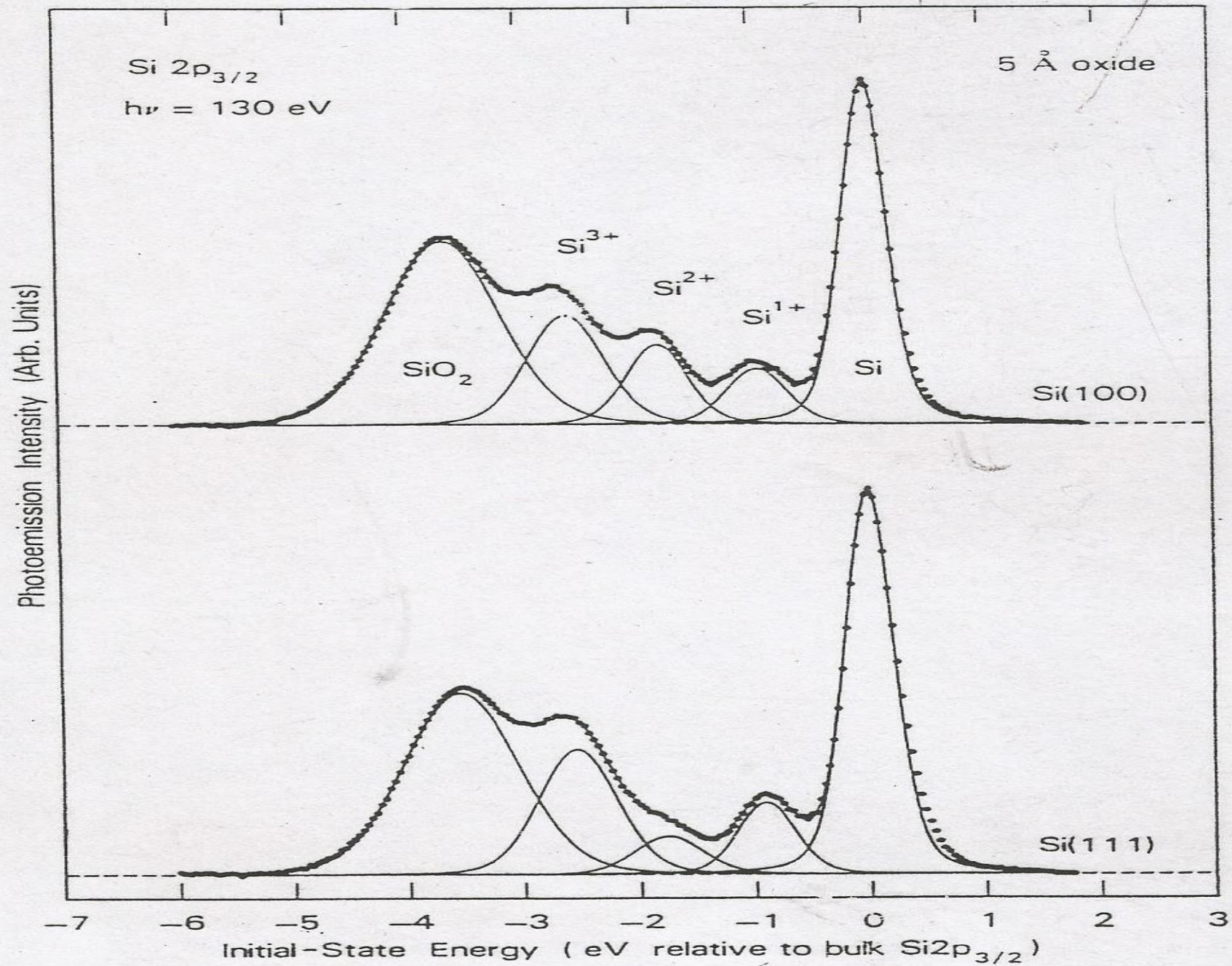


FIG. 1. Si  $2p$  XPS spectra of as-deposited films for oxygen pressures varied from 0.03 to 1.5 mTorr (in the inset, the enlargement of the 1.5 mTorr sample is shown). All spectra were fitted with five peaks corresponding to silicon ( $\text{Si}^0$ ), suboxide ( $\text{Si}^{1+}$ ,  $\text{Si}^{2+}$ , and  $\text{Si}^{3+}$ ), and  $\text{SiO}_2$  ( $\text{Si}^{4+}$ ) contributions.



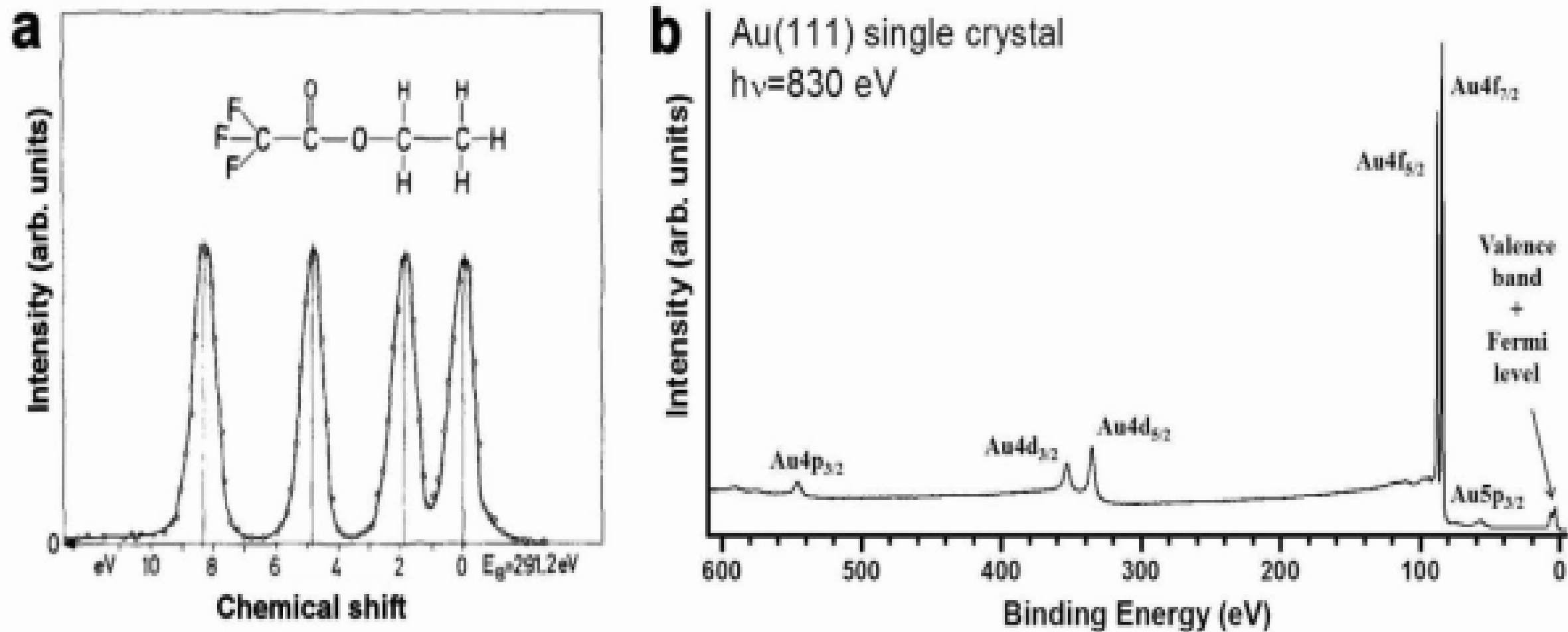


Figure 2.22. (a) XPS spectrum of ethyl trifluoroacetate. Chemical shift of C 1s core level is visible: different binding energies are found for carbon atoms with different chemical environment.<sup>168</sup> (b) XPS spectrum of clean Au(111) surface obtained using synchrotron radiation with 830 eV photon energy.

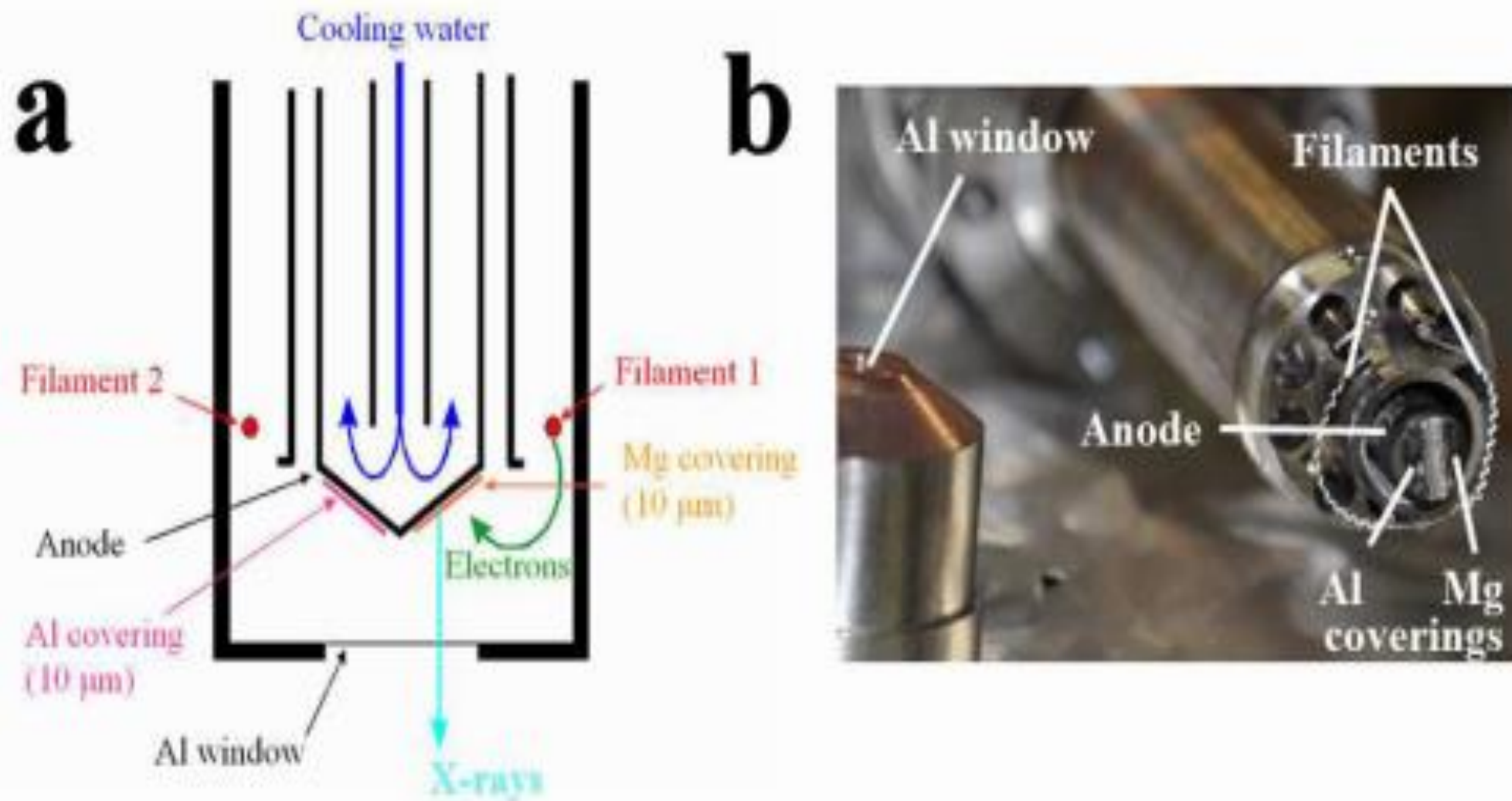


Figure 2.25. Scheme (a) and picture (b) of a laboratory X-ray source.

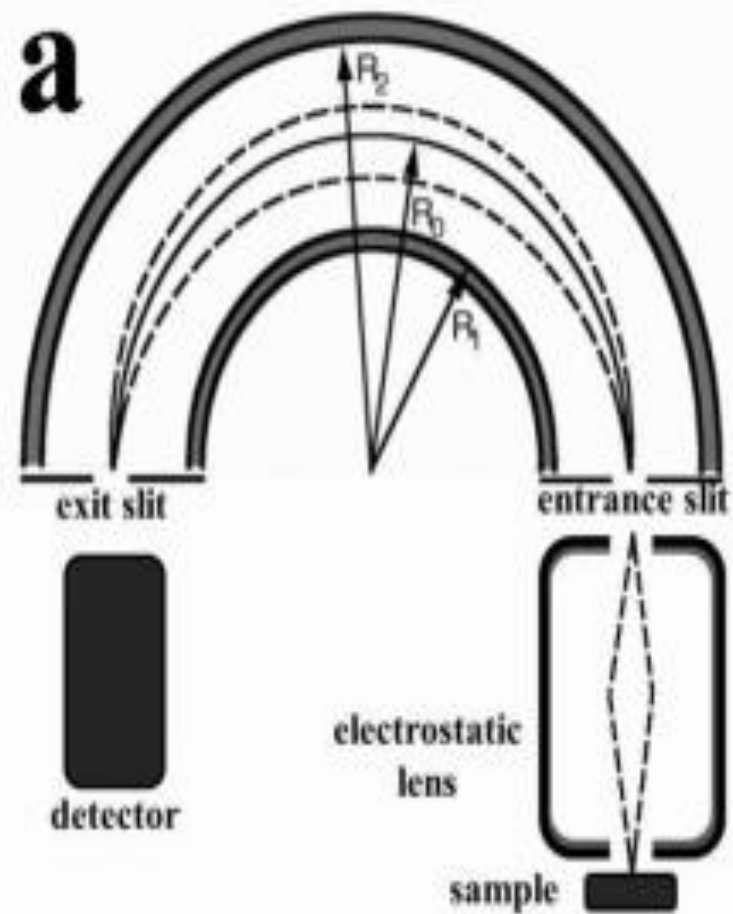


Figure 2.26. Scheme (a) and picture (b) of hemispherical electrons analyzer for XPS. Dotted lines in the scheme represent electron path.

# Scanning Tunneling Microscope

A **scanning tunneling microscope (STM)** is an instrument for imaging surfaces at the atomic level. Its development in 1981 earned its inventors, [Gerd Binnig](#) and [Heinrich Rohrer](#) (at [IBM](#) Zürich), the [Nobel Prize in Physics](#) in 1986.

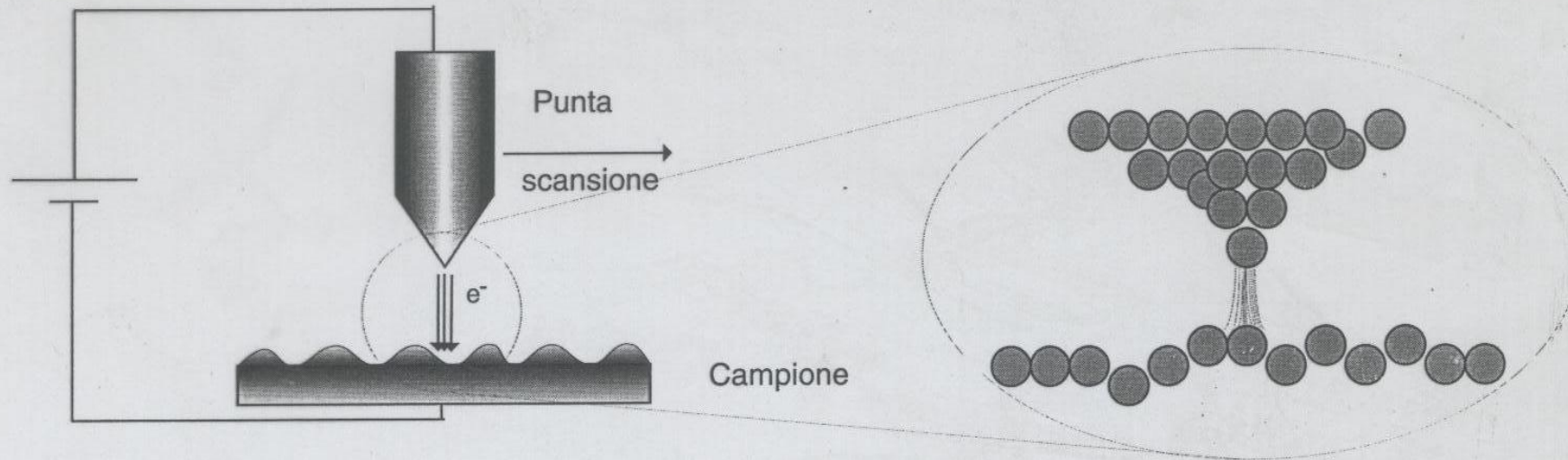
For an STM, good resolution is considered to be 0.1 [nm](#) lateral resolution and 0.01 nm depth resolution. With this resolution, individual atoms within materials are routinely imaged and manipulated. The STM can be used not only in ultra-high vacuum but also in air, water, and various other liquid or gas ambients, and at temperatures ranging from near [zero kelvin](#) to a few hundred degrees Celsius.

The STM is based on the concept of [quantum tunneling](#).

When a conducting tip is brought very near to the surface to be examined, a [bias](#) (voltage difference) applied between the two can allow electrons to tunnel through the vacuum between them. The resulting *tunneling current* is a function of tip position, applied voltage, and the [local density of states](#) (LDOS) of the sample.

Information is acquired by monitoring the current as the tip's position scans across the surface, and is usually displayed in image form. STM can be a challenging technique, as it requires extremely clean and stable surfaces, sharp tips, excellent [vibration control](#), and sophisticated electronics, but nonetheless many hobbyists have built their own.

# STM- principio di funzionamento



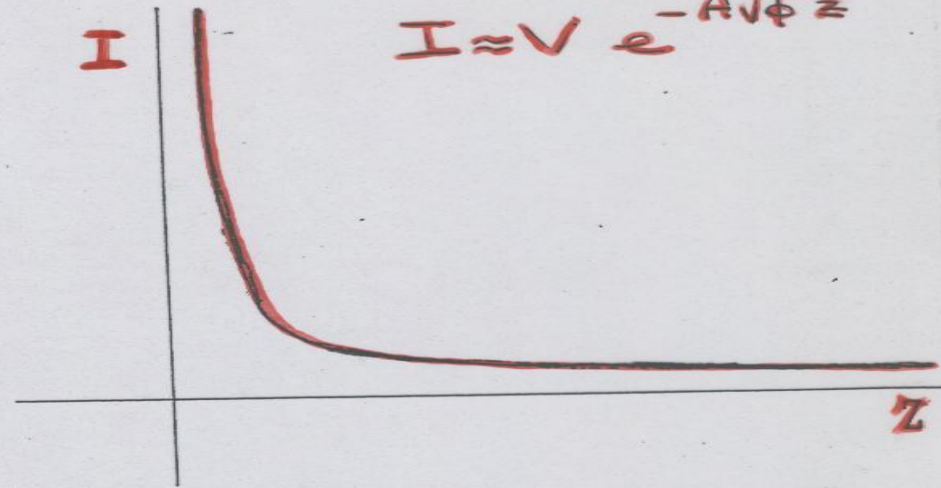
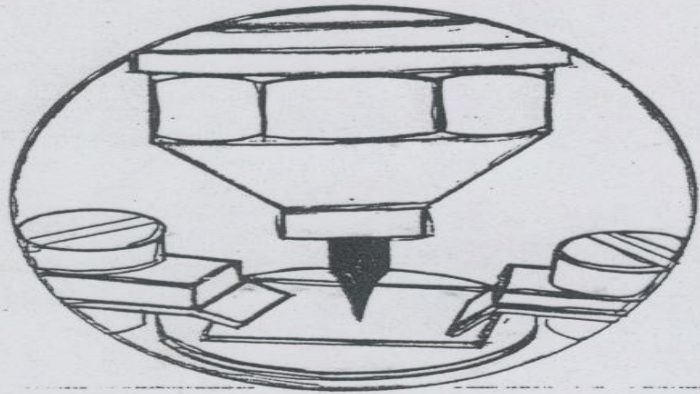
- ◆ Avvicinando una punta di W o altro metallo alla superficie e applicando una ddp (0.02 - 5 V) si determina il passaggio di elettroni attraverso il vuoto per effetto tunnel (sovrapposizione delle funzioni d'onda attraverso il vuoto).
- ◆ L'effetto può essere sfruttato per visualizzare gli atomi della superficie poiché l'andamento della corrente di tunnel in funzione della distanza  $s$  è esponenziale

$$I = Ve^{-A\sqrt{\phi}s}$$

quindi il flusso di elettroni rimane limitato ad una piccolissima area



# STM SCANNING TUNNELING MICROSCOPE



## INFORMAZIONI LOCALI

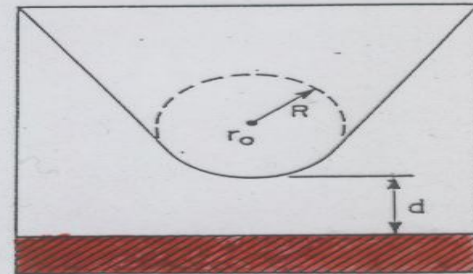
### TOPOGRAFIA

PUNTA = POTENZIALE SFERICO

$$I \approx \sum_v |\phi(r_0)|^2 \delta(E_v - E_F)$$

### SPETTROSCOPIA

$$\frac{(dI/dV)}{(I/V)} \propto \rho_s(r, E)$$



### CHIMICA

PICCOLE DISTANZE

$$-\frac{1}{I} \frac{dI}{dz} = \sqrt{\phi}$$

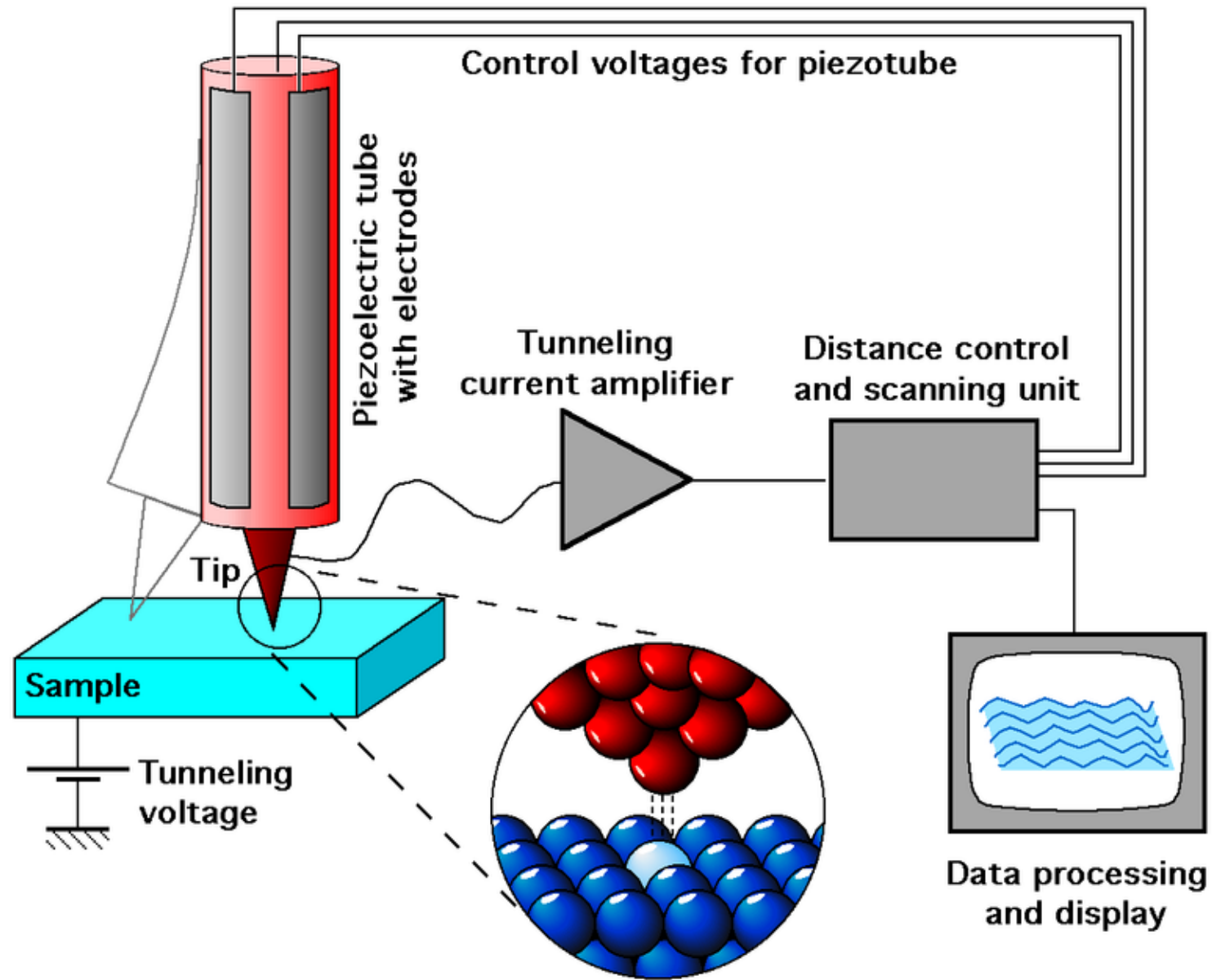
## Instrumentation

The components of an STM include scanning tip, piezoelectric controlled height and x,y scanner, coarse sample-to-tip control, vibration isolation system, and computer.

The [resolution](#) of an image is limited by the [radius of curvature](#) of the scanning tip of the STM. Additionally, image artifacts can occur if the tip has two tips at the end rather than a single atom; this leads to “double-tip imaging,” a situation in which both tips contribute to the tunneling. Therefore it has been essential to develop processes for consistently obtaining sharp, usable tips. Recently, [carbon nanotubes](#) have been used in this instance.

The tip is often made of [tungsten](#) or platinum-iridium, though [gold](#) is also used. Tungsten tips are usually made by electrochemical etching, and platinum-iridium tips by mechanical shearing.

Due to the extreme sensitivity of tunnel current to height, proper vibration isolation or an extremely rigid STM body is imperative for obtaining usable results. In the first STM by Binnig and Rohrer, [magnetic levitation](#) was used to keep the STM free from vibrations; now mechanical spring or [gas spring](#) systems are often used.



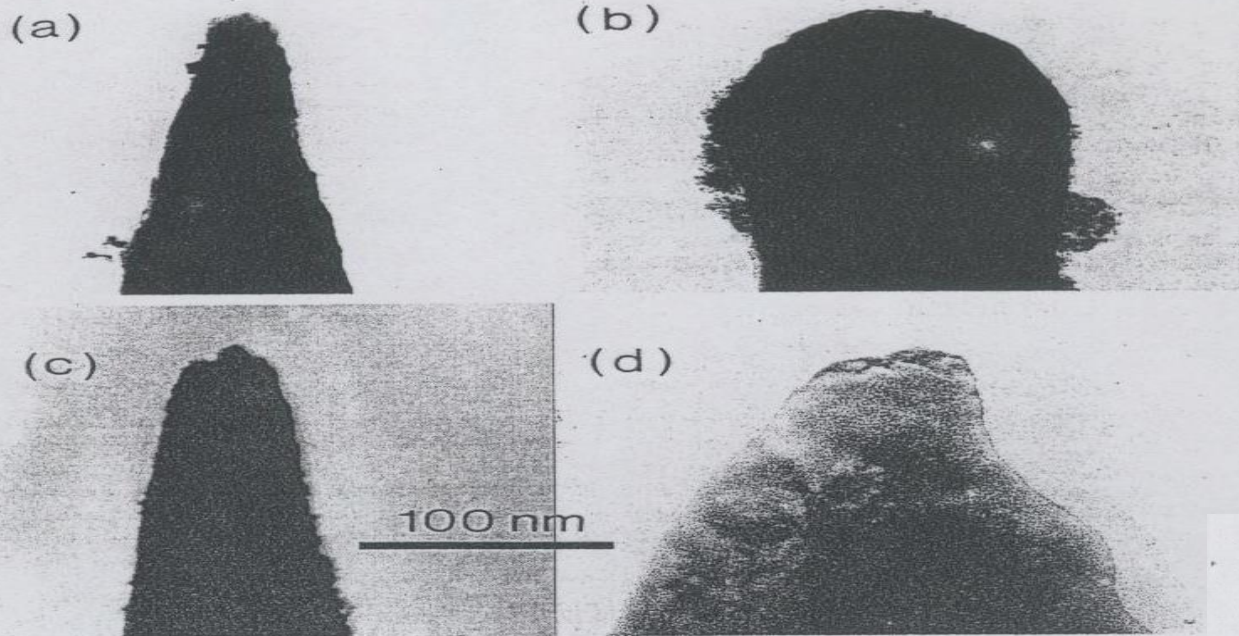


FIG. 5. TEM micrograph of electropolished Pt-Ir tips. (a) An example of a successfully electropolished and clean Pt-Ir tip. The other micrographs show the problems in making fine tips of Pt-Ir. In (b) the tip is shaped like a drop, and in (c) the tip has fractured, (d) shows an unevenly ion milled Pt-Ir tip.

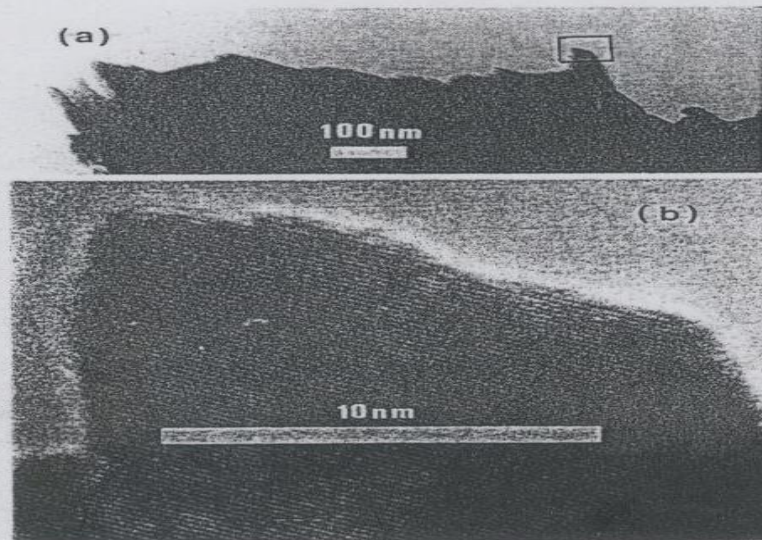


FIG. 6. TEM micrograph of Pt-Ir tip. This tip is prepared by cutting a wire with an ordinary pair of tongs. The jagged surface of (a) is further magnified in (b). No oxide is visible.

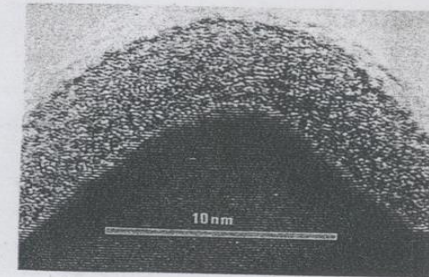


FIG. 1. TEM micrograph of an oxide-covered tungsten tip.

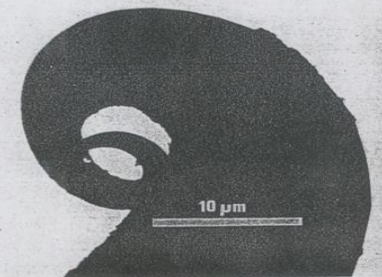


FIG. 2. TEM micrograph of an oxide-covered tungsten tip severely bent into a ring shape in the STM. The substrate was made of platinum.

### 7 × 7 Reconstruction on Si(111) Resolved in Real Space

G. Binnig, H. Rohrer, Ch. Gerber, and E. Weibel  
 IBM Zurich Research Laboratory, 8803 Rüschlikon-ZH, Switzerland  
 (Received 17 November 1982)

The 7 × 7 reconstruction on Si(111) was observed in real space by scanning tunneling microscopy. The experiment strongly favors a modified adatom model with 12 adatoms per unit cell and an inhomogeneously relaxed underlying top layer.

PACS numbers: 68.20.+t, 73.40.Gk

The 7 × 7 reconstruction of the Si(111) surface is one of the most intriguing problems in surface science. In recent years, most impressive experimental and theoretical efforts have dealt with the structure of this reconstruction.<sup>1,2</sup> However, the complexity of the large basic unit cell with 49 atoms is a serious handicap to deriving a structural model unambiguously even from an abundant set of experiments. Models in accordance with one class of experiments are in conflict with others.<sup>1</sup> The ever-increasing number of models and their variations appear to confuse rather than clarify the issue. In order to make significant progress, some basically new approach is required. Such a new approach is the *scanning tunneling microscopy* recently introduced by the authors.<sup>3</sup>

In the following, we report on the first *real-space* determination of the Si(111) 7 × 7 reconstruction. The scanning tunneling micrographs yield the principal structural features of the 7 × 7 unit cell.

The principle of the scanning tunneling microscope (STM) is explained in Ref. 3. It consists essentially in scanning a metal tip at constant tunnel current over the surface to be investigated. The corrugation monitored by the vertical motion of the tunnel tip reflects qualitatively the topography of the surface.

The 7 × 7 reconstruction was generated as follows. After etching the oxide with an HF solution the Si wafer was immediately transferred to the STM in the UHV chamber. Repeated heating to 900 °C in a vacuum not exceeding  $3 \times 10^{-8}$  Pa effects sublimation of the SiO layer grown during the transfer. This procedure is known to give fairly clean surfaces,<sup>4</sup> e.g., less than  $\frac{1}{25}$  of a monolayer of carbon. However, the condition of the surface could not yet be tested by another contamination-sensitive method.

The micrographs were taken at 2.9 V (tip positive) since tunnel voltages below 2.5 V lead to direct contact between tip and sample. The voltage drop across the vacuum gap is smaller by an un-

known amount because of band bending in the semiconductor. Only unidirectional scans (3 deg off the [211] direction) were recorded to avoid small but noticeable hysteresis effects of the scanning piezodrives.

The original recordings of two complete 7 × 7 unit cells are presented in Fig. 1 in relief form. The rhombohedral 7 × 7 unit cell is clearly bounded by the lines of minima with deep corners. Inside each cell, twelve maxima appear. The diagonals are  $46 \pm 1$  and  $29 \pm 4$  Å, in agreement with the crystallographic values of 46.56 and 26.88 Å, respectively. The short diagonal is less accurately determined since thermal drifts are more noticeable (scanning along the long diagonal with 2 sec/scan). For comparison with models, the cell size is adjusted to its proper value. Figure 2, a top view of Fig. 1, shows the sixfold rotational symmetry of the positions of the maxima around each corner. The minima pattern, however, ap-

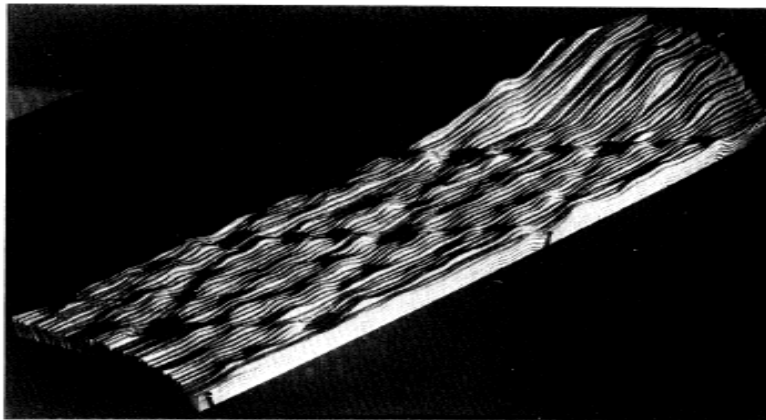
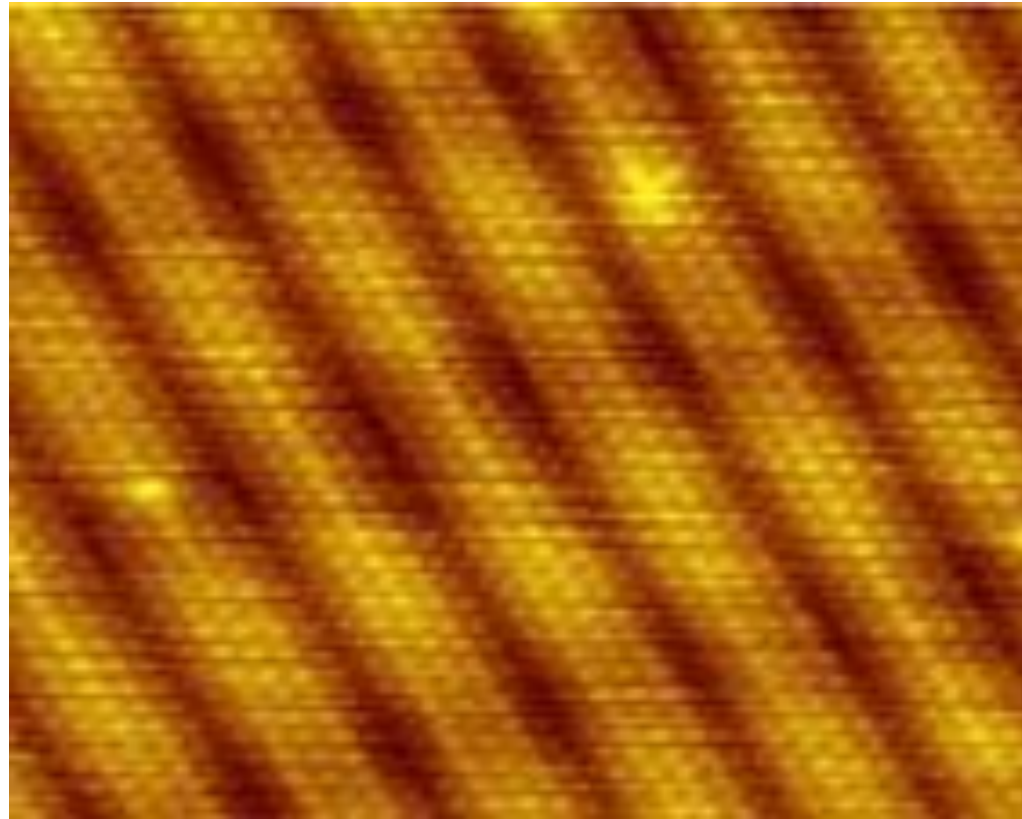
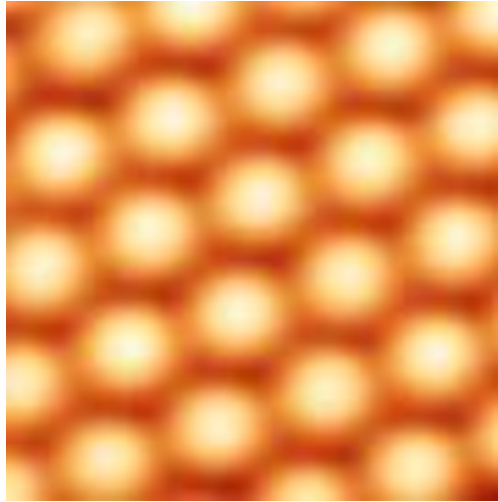
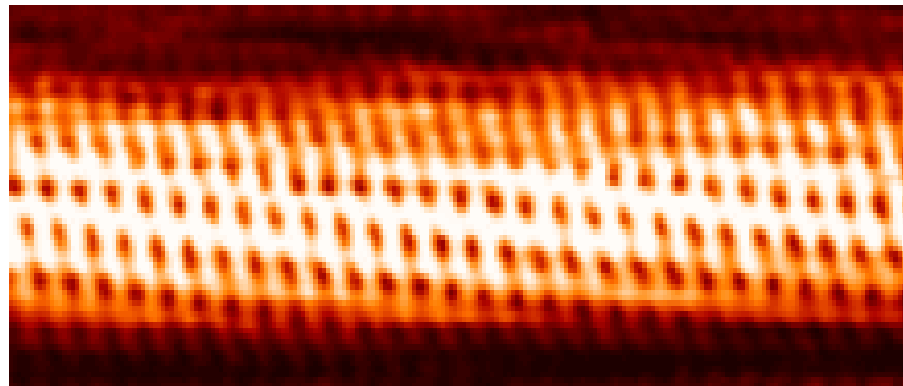


FIG. 1. Relief of two complete 7 × 7 unit cells, with nine minima and twelve maxima each, taken at 300 °C. Heights are enhanced by 55%; the hill at the right grows to a maximal height of 15 Å. The [211] direction points from right to left, along the long diagonal.

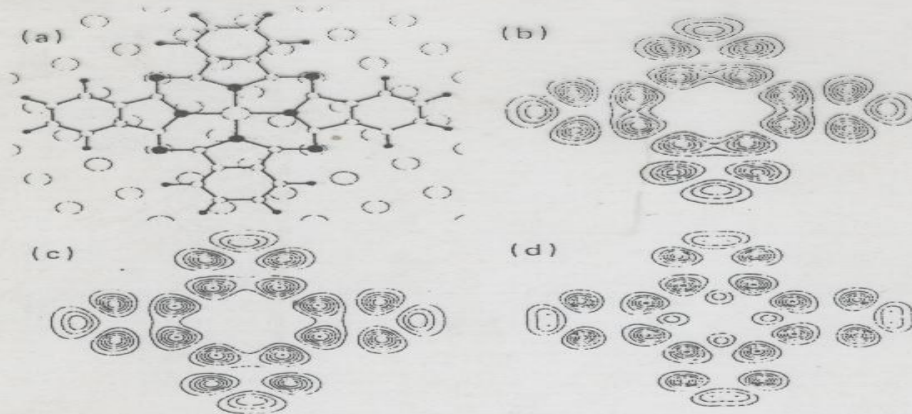
SiC Silicon Carbide



Au  
reconstructed  
surface



Carbon Nanotube



(a) Model of the Cu-phth molecule above a Cu(100) surface. Small (large) open circles are C (Cu) atoms and small (large) filled circles are H (N) atoms. The Cu(100) lattice is shown rotated by  $26.5^\circ$  (Ref. 5). (b) and (c) Contour plots of the charge densities of the highest occupied molecular orbital (HOMO) and lowest unoccupied molecular orbital (LUMO)  $2 \text{ \AA}$  above the molecular plane. (d) Charge density of the HOMO,

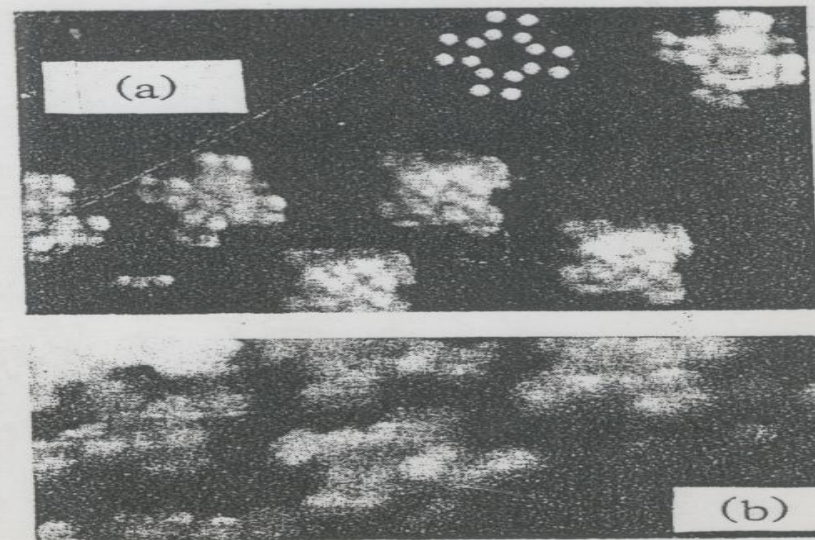


FIG. 4. (a) High-resolution image at submonolayer coverage for ( $-0.15 \text{ V}$ ,  $2 \text{ nA}$ ). Fine structure has been emphasized by baseline subtraction, and a gray scale representation of the  $\psi_{\text{HOMO}}$ , evaluated  $2 \text{ \AA}$  above the molecular plane, has been embedded in the image. (b) High-resolution image near 1-ML coverage with ( $-0.07 \text{ V}$ ,  $6 \text{ nA}$ ).

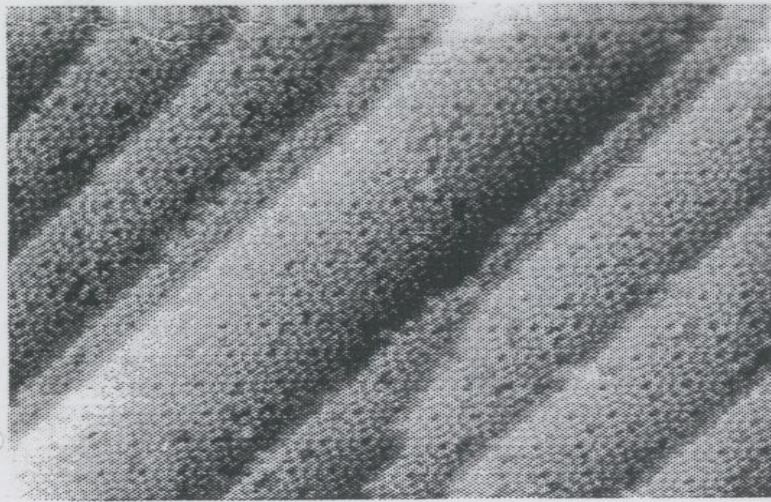


Fig 1. STM image of Si 7x7 (500x500 Å) bias 1.5V.

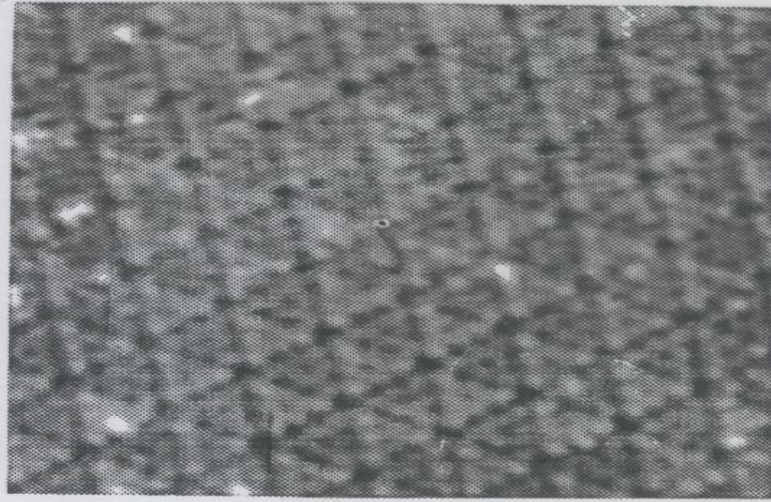


Fig 2. STM image of Si 7x7 (200x200 Å) bias -1.5V

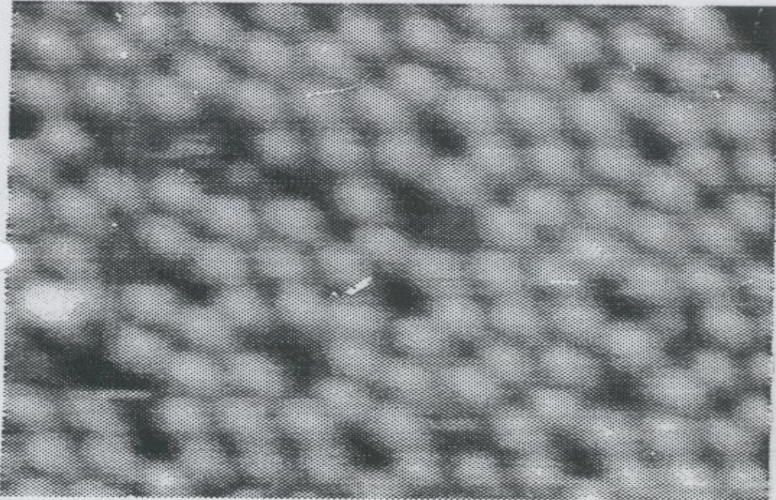


Fig 3. STM image of Si 7x7 (80x80 Å) bias 1.5V.

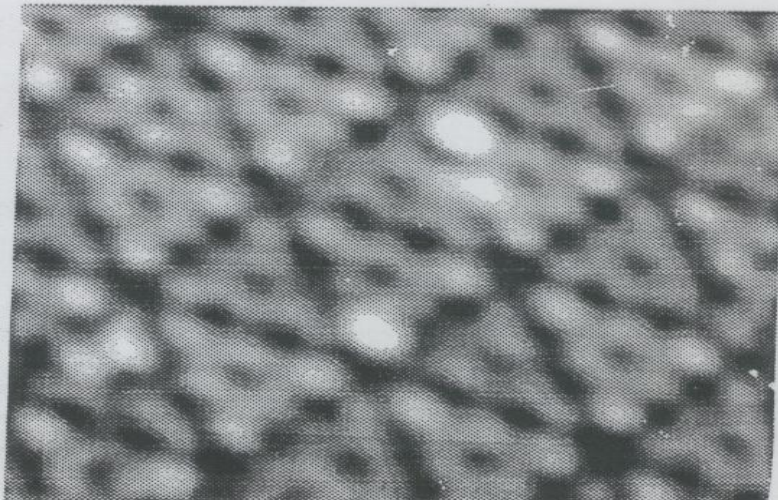
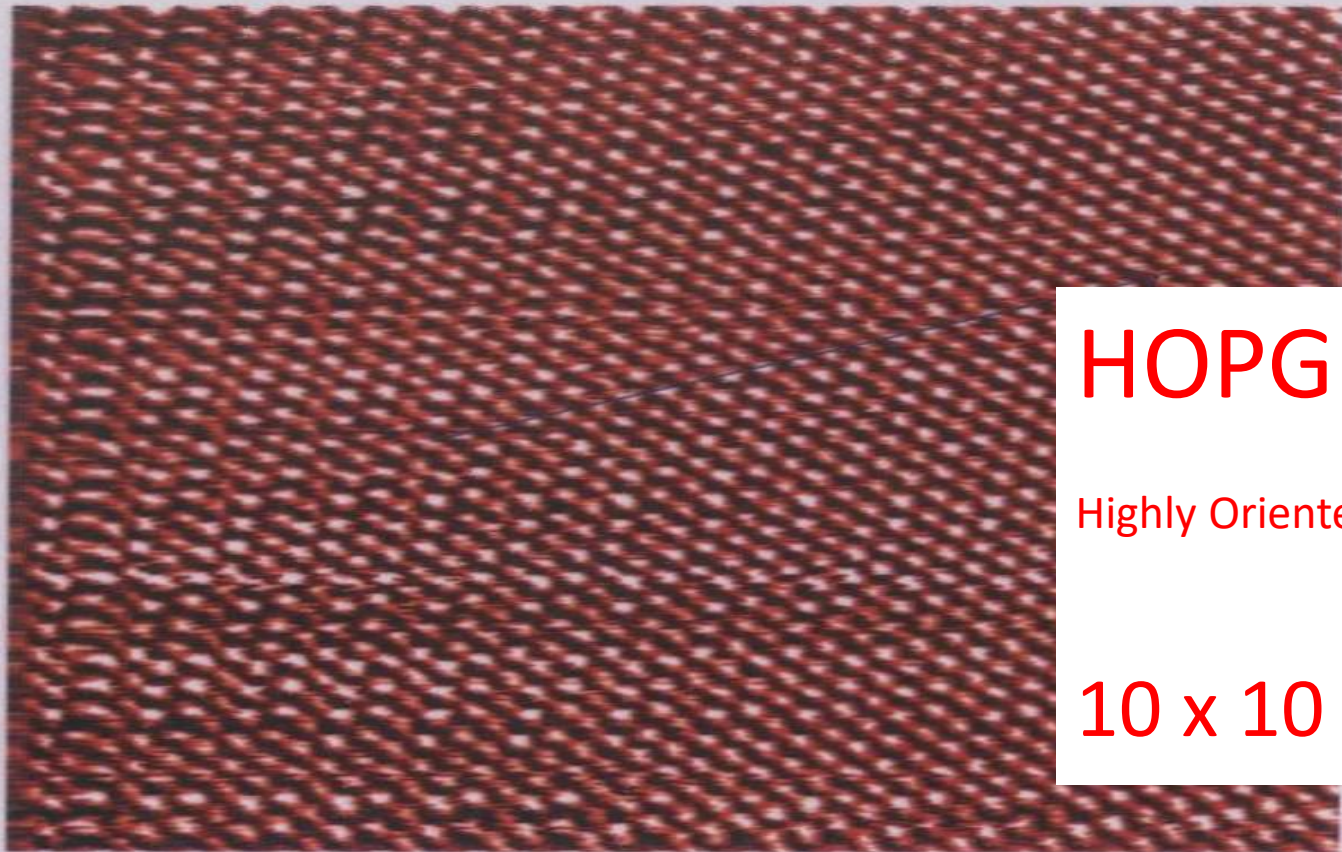


Fig 4. STM image of Si 7x7 (80x80 Å) bias -1.5V.

*N. MOTTA, M. DE CRESCENZI  
DIPARTIMENTO DI FISICA,*

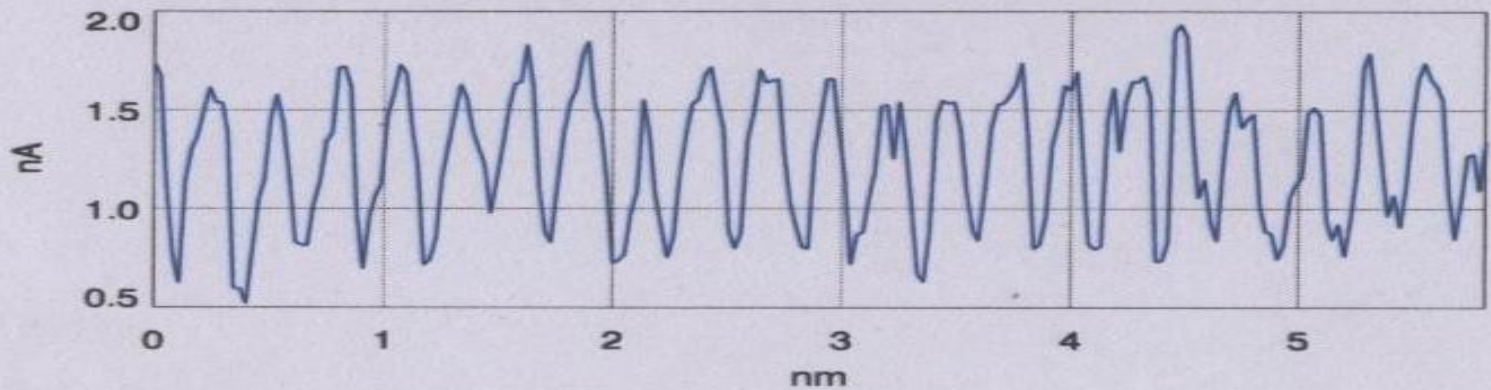




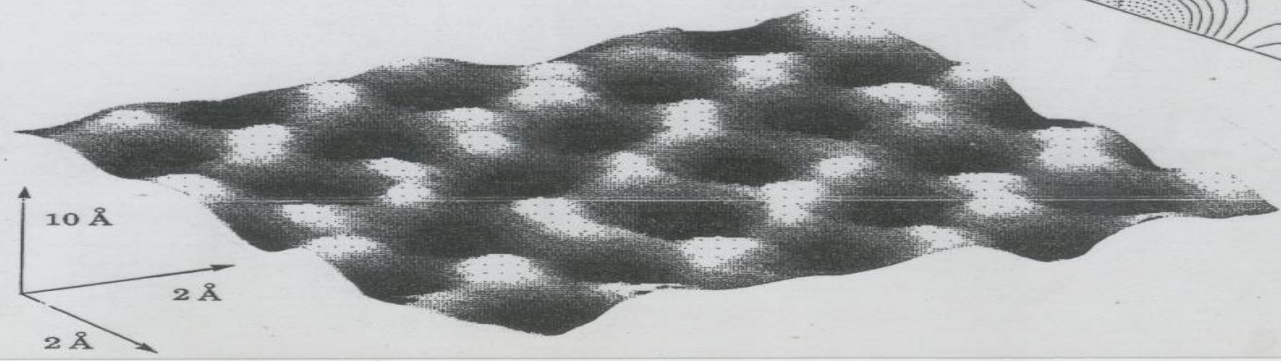
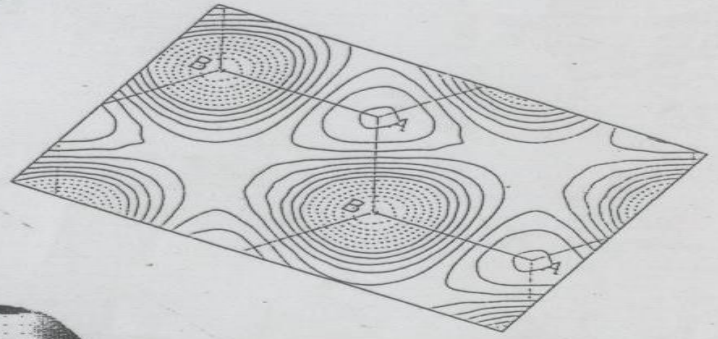
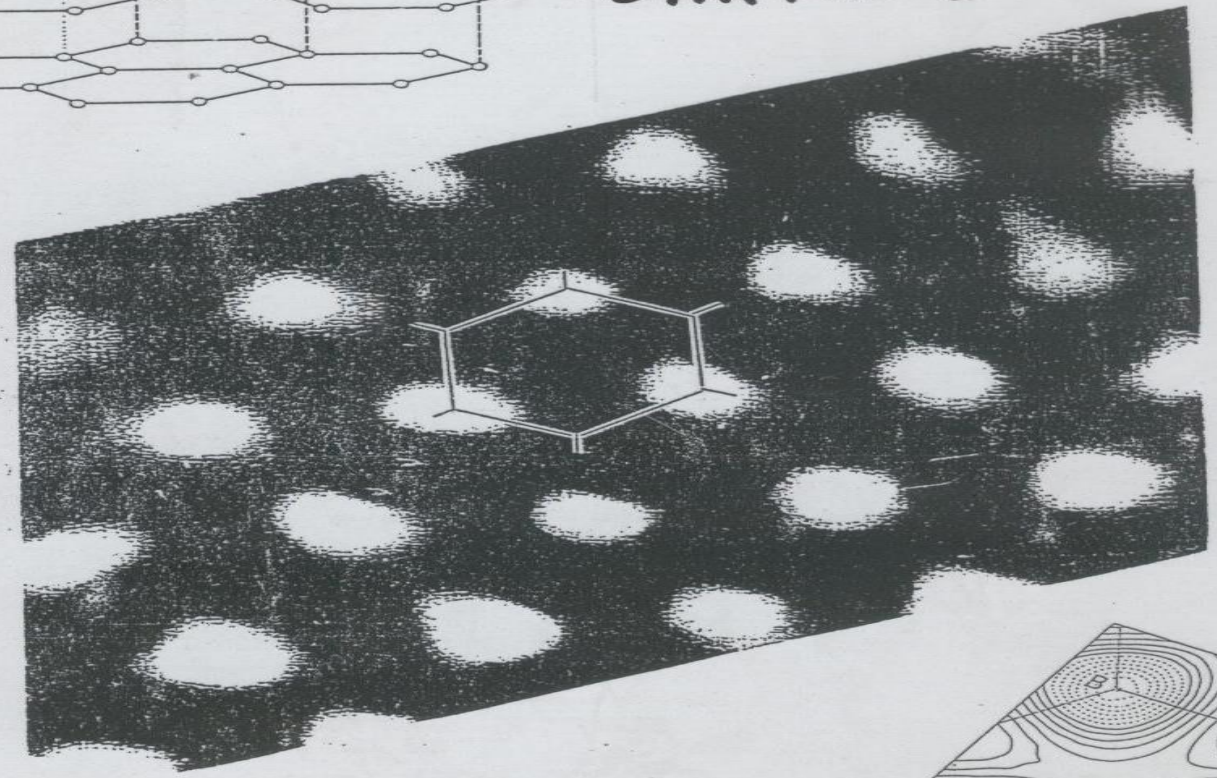
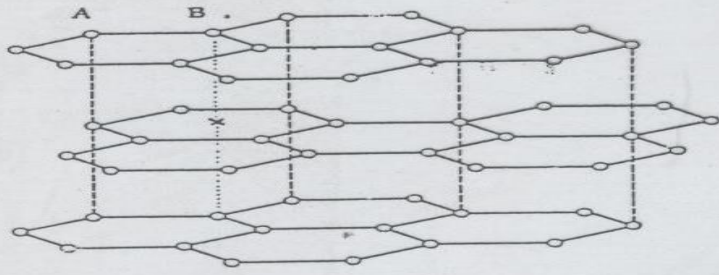
**HOPG**

Highly Oriented Pyrolytic Graphite

**10 x 10 nm<sup>2</sup>**

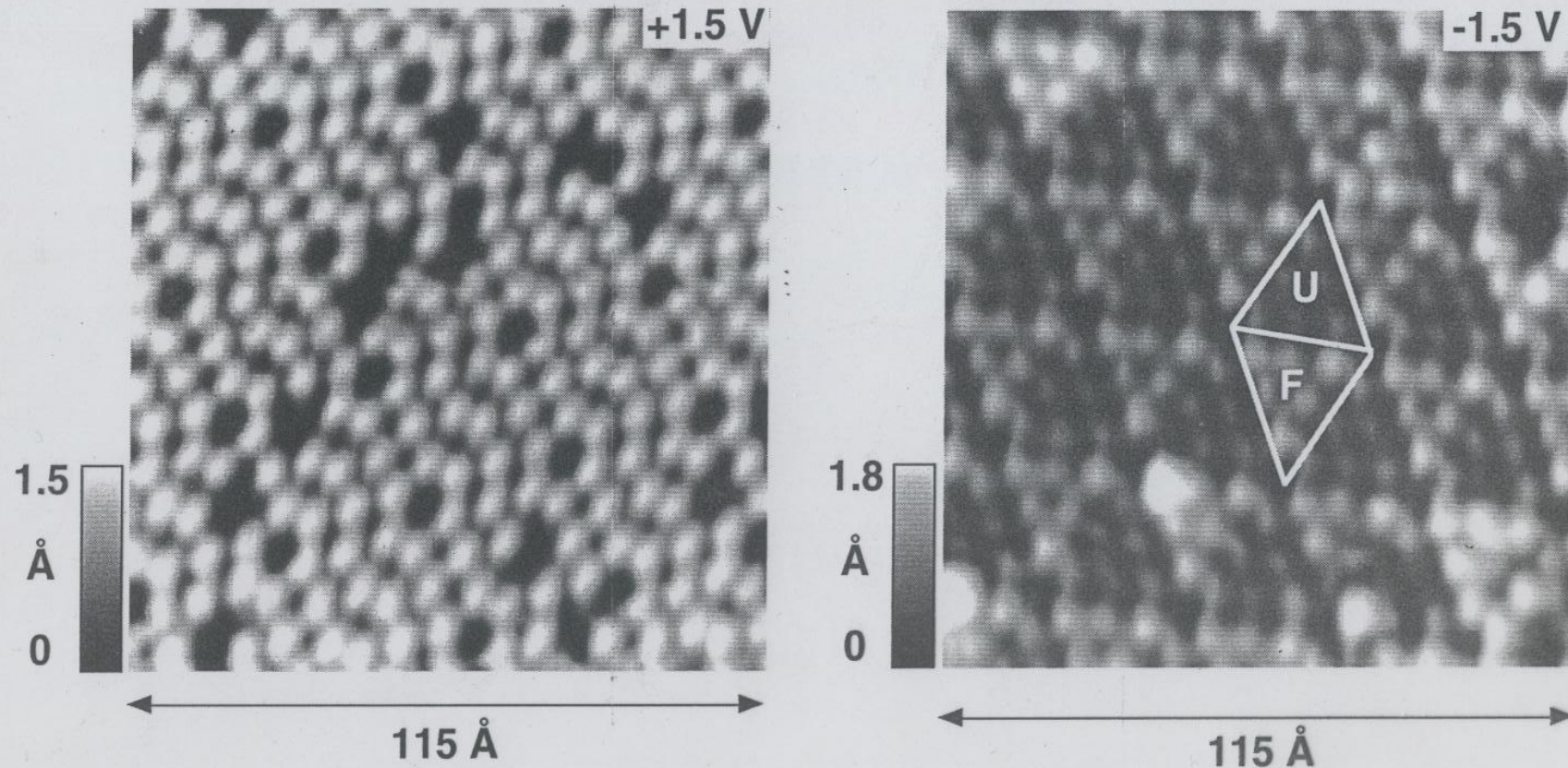


# HOPG HIGHLY ORIENTED PYROLITIC GRAPHITE



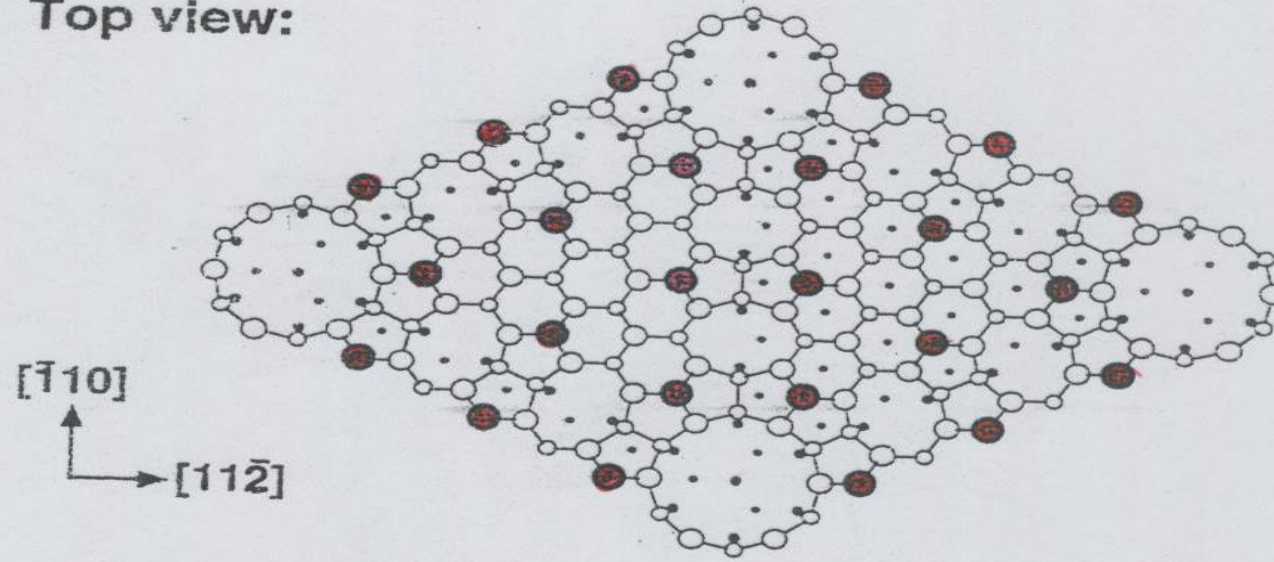
# Si(111) 7x7

Le superfici dei solidi visualizzate tramite l'STM mostrano protuberanze di dimensioni atomiche legate non solo alla posizione degli atomi, ma anche alla densità di carica. Con differenti tensioni di polarizzazione tra punta e campione si ottiene la visualizzazione delle nuvole elettroniche appartenenti a orbitali di diversa energia. Orbitali vuoti per polarizzazione positiva. Orbitali di legame per polarizzazione negativa.



# Reconstruction model of 7x7 surface of Si(111) surface

Top view:



Side view:

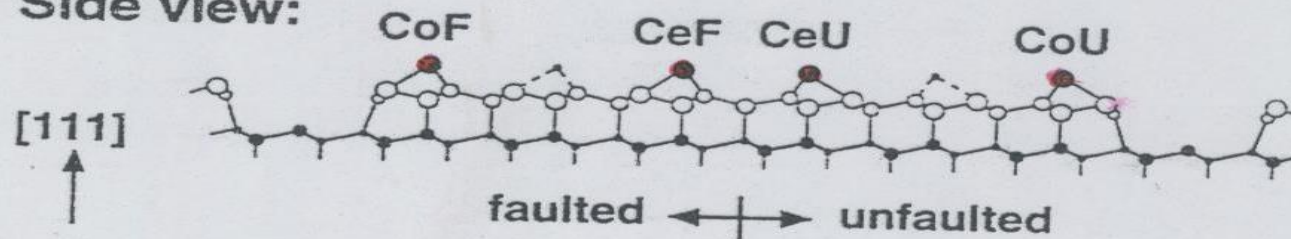
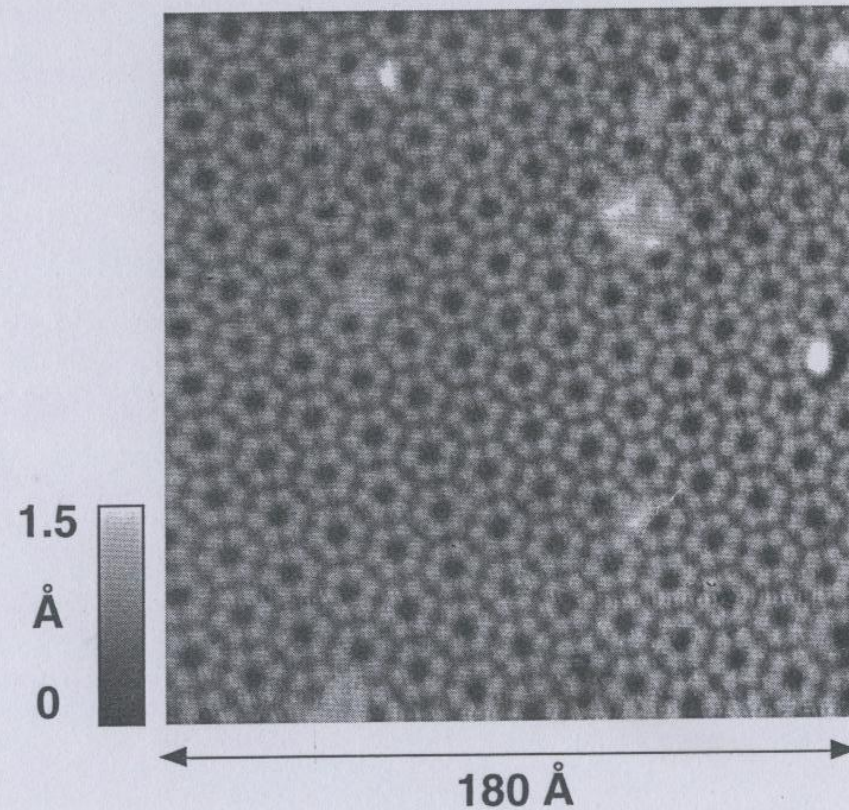
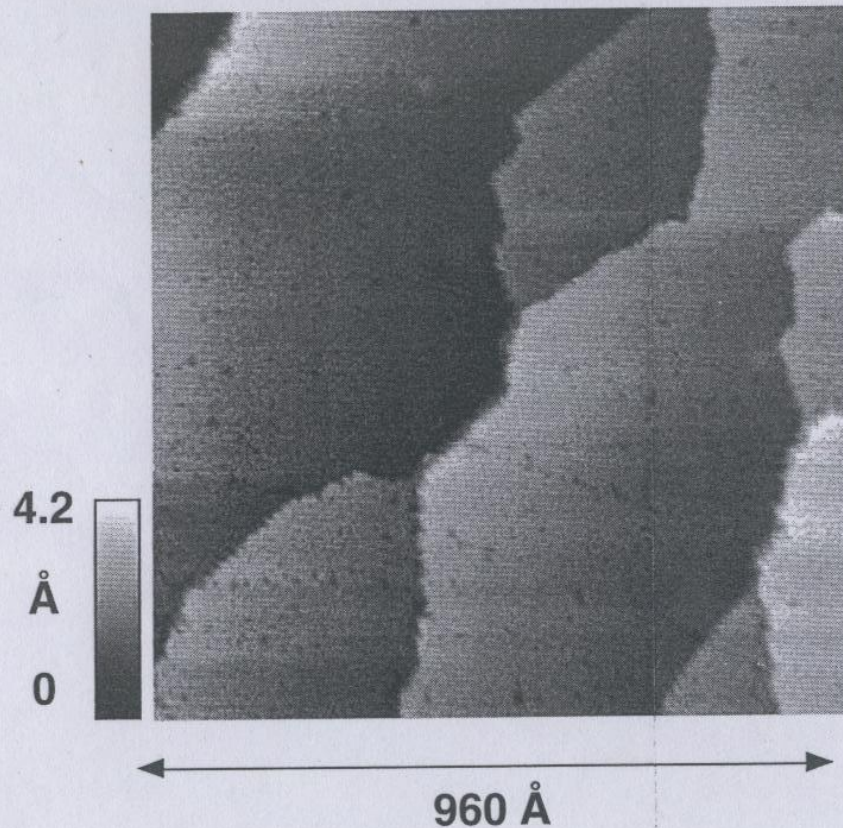


FIG. 1. Top and side views of the Si(111)  $7 \times 7$  reconstruction as described by the DAS model. The adatoms occupy four equivalent sites denoted: CoF, corner faulted; CeF, center faulted; CeU, center unfaulted; and CoU, corner unfaulted.

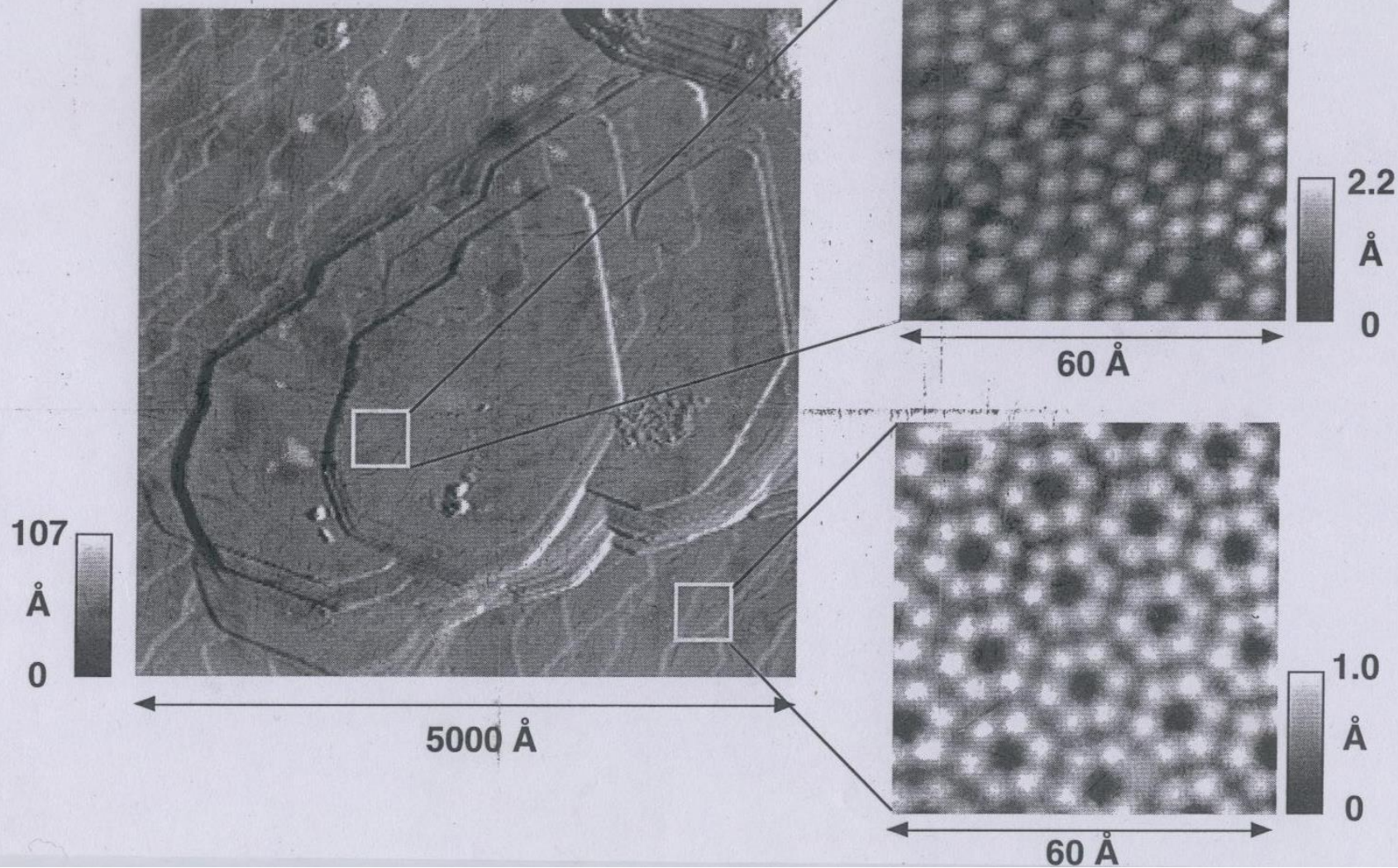
# 10Å Ge / Si(111) T=500 °C

Interessanti risultati sono stati ottenuti crescendo strati di Ge su Si a T=500 C in ultra alto vuoto. Tra 7 e 10 Å si ha la formazione di strati bidimensionali di lega Ge-Si, a causa della reazione chimica e dell'interdiffusione che avviene tra i due elementi. La ricostruzione di superficie ha una simmetria 5x5.



# 20Å Ge/Si(111) T=500 °C

Visualizzazione di isole tridimensionali di Ge su Si(111)



# Principle of operation

Tunneling is a functioning concept that arises from quantum mechanics. Classically, an object hitting an impenetrable barrier will not pass through. In contrast, objects with a very small mass, such as the electron, have wavelike characteristics which permit such an event, referred to as tunneling.

Electrons behave as beams of energy, and in the presence of a potential  $U(z)$ , assuming 1-dimensional case, the energy levels  $\psi_n(z)$  of the electrons are given by solutions to Schrödinger's equation,

$$-\frac{\hbar^2}{2m} \frac{\partial^2 \psi_n(z)}{\partial z^2} + U(z) \psi_n(z) = E \psi_n(z)$$

where  $\hbar$  is the reduced Planck's constant,  $z$  is the position, and  $m$  is the mass of an electron<sup>[4]</sup>. If an electron of energy  $E$  is incident upon an energy barrier of height  $U(z)$ , the electron wave function is a traveling wave solution,

$$\psi_n(z) = \psi_n(0)e^{\pm ikz}$$

where

$$k = \frac{\sqrt{2m(E - U(z))}}{\hbar}$$

if  $E > U(z)$ , which is true for a wave function inside the tip or inside the sample<sup>[4]</sup>. Inside a barrier,  $E < U(z)$  so the wave functions which satisfy this are decaying waves,

$$\psi_n(z) = \psi_n(0)e^{\pm \kappa z}$$

where

$$\kappa = \frac{\sqrt{2m(U - E)}}{\hbar}$$

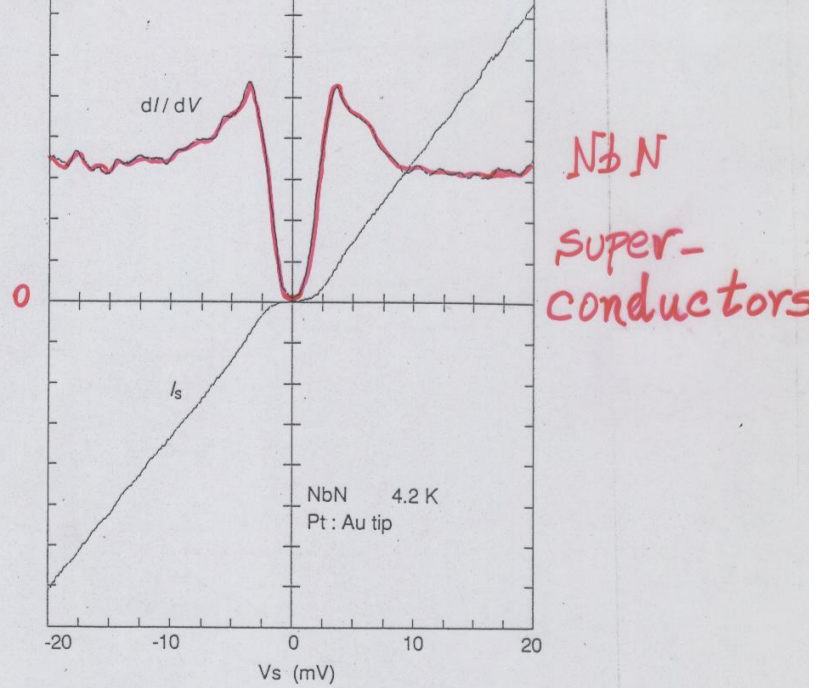
quantifies the decay of the wave inside the barrier, with the barrier in the  $+z$  direction for  $-\kappa$ <sup>[4]</sup>.



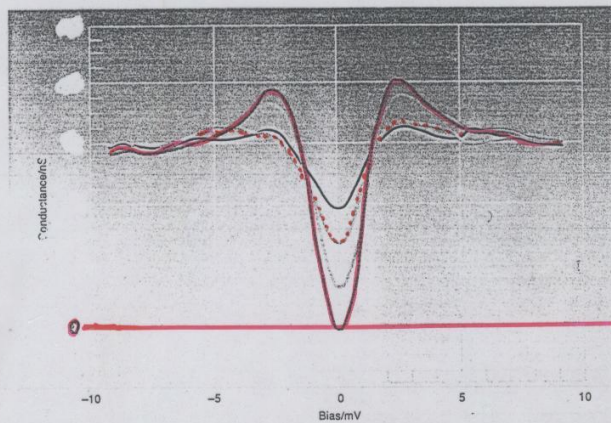
Knowing the wave function allows one to calculate the probability density for that electron to be found at some location. In the case of tunneling, the tip and sample wave functions overlap such that when under a bias, there is some finite probability to find the electron in the barrier region and even on the other side of the barrier<sup>[4]</sup>. Let us assume the bias is  $V$  and the barrier width is  $W$ . This probability,  $P$ , that an electron at  $z=0$  (left edge of barrier) can be found at  $z=W$  (right edge of barrier) is proportional to the wave function squared,

$$P \propto |\psi_n(0)|^2 e^{-2\kappa W} \text{ [4]}.$$

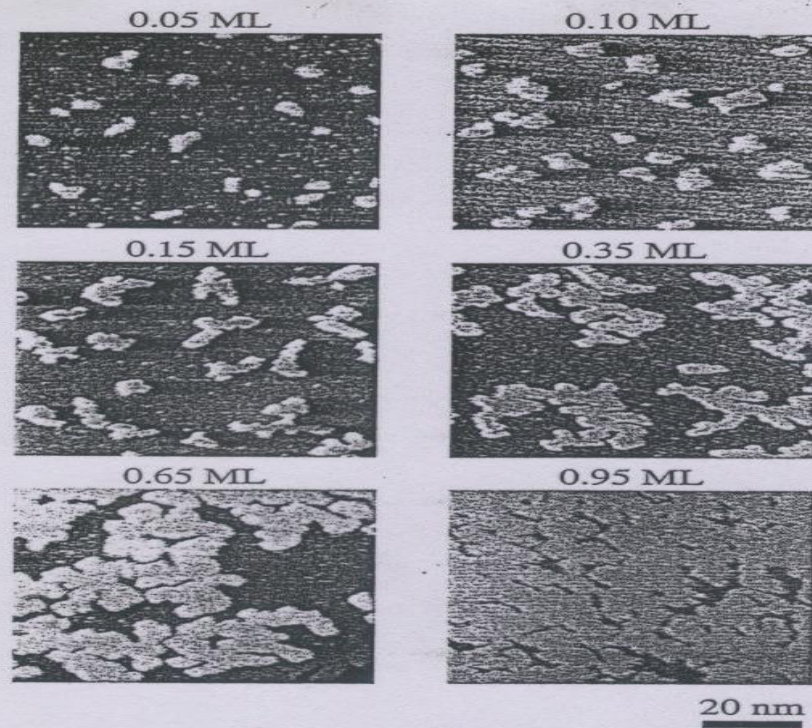
If the bias is small, we can let  $U - E \approx \phi M$  in the expression for  $\kappa$ , where  $\phi M$ , the work function, gives the minimum energy needed to bring an electron from an occupied level, the highest of which is at the Fermi level (for metals at  $T=0$  kelvins), to vacuum level. When a small bias  $V$  is applied to the system, only electronic states very near the Fermi level, within  $eV$  (a product of electron charge and voltage, not to be confused here with electronvolt unit), are excited<sup>[4]</sup>. These excited electrons can tunnel across the barrier. In other words, tunneling occurs mainly with electrons of energies near the Fermi level.



Current-voltage characteristics and differential conductance of a NbN film measured at 4.2 K.



Spectra taken from superconducting lead at various temperatures below its transition temperature (7.18 K) illustrate the changing density of states and the increase in the characteristic peak on either side of the energy gap.



STM images showing the evolution of the area density of copper islands on Ni(100) with coverage at a substrate temperature of 345 K and a deposition rate of  $6 \times 10^{-3}$  monolayers/s. The different submonolayer coverages are indicated. The copper islands are always of monolayer thickness. The larger islands exhibit a ramified shape.

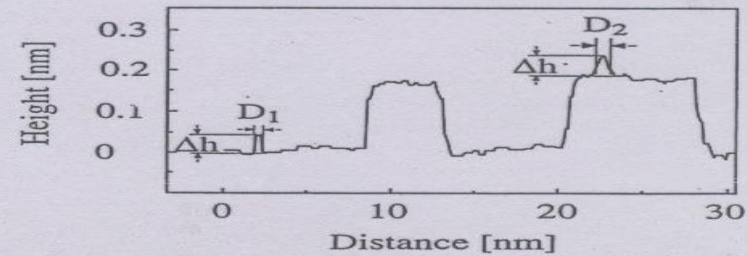
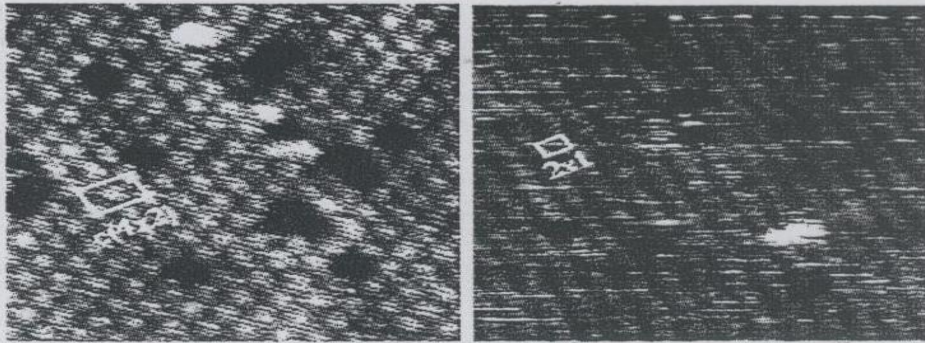
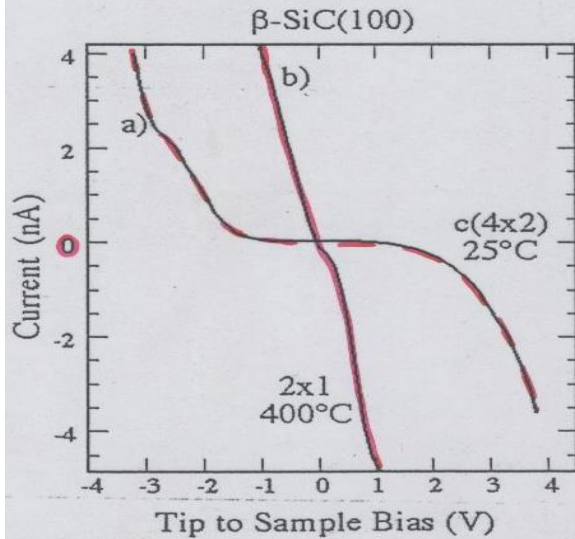


Fig. 23. Formation of the second copper layer

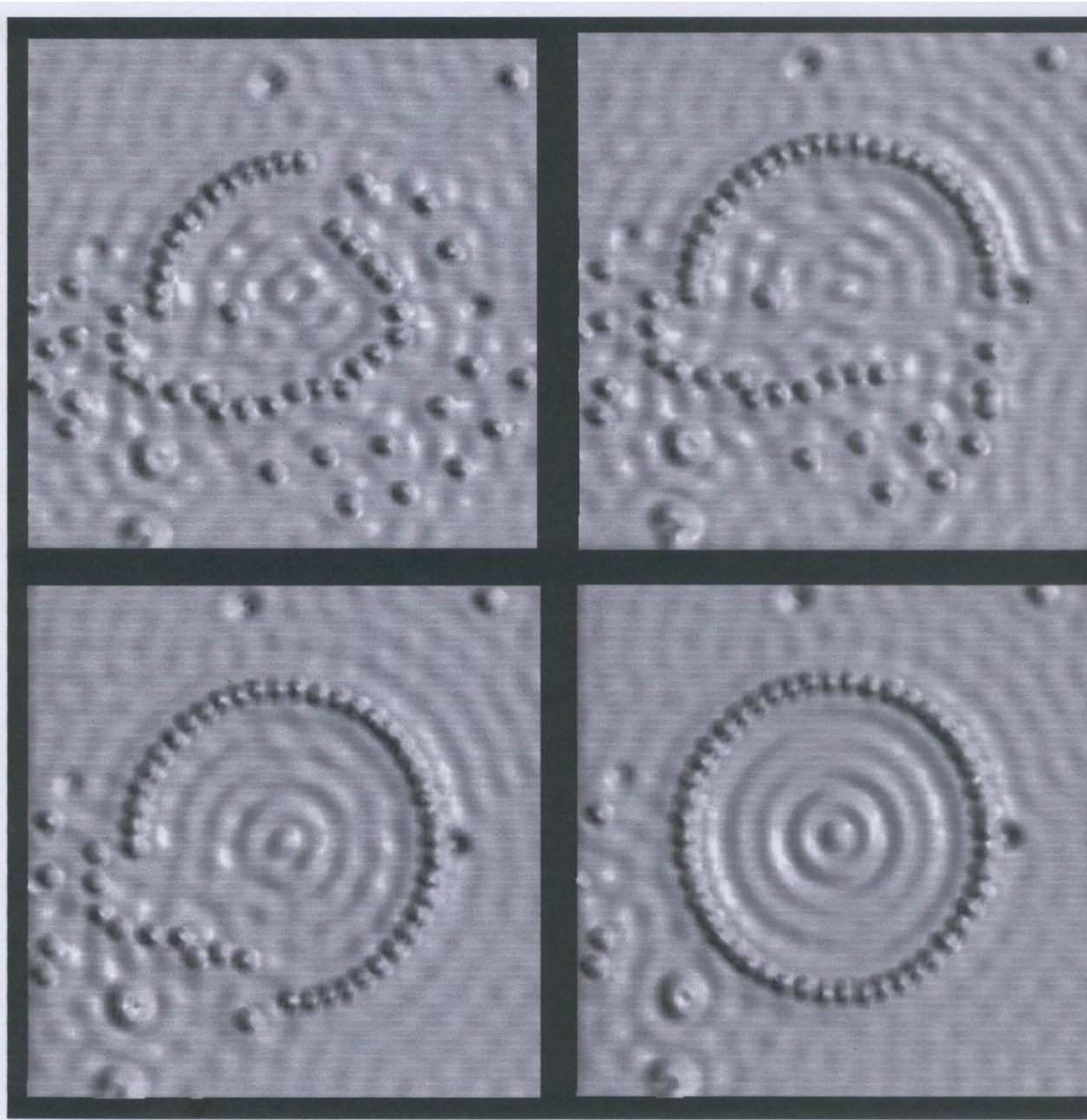


**Figure 1: STM topographs (filled states) of:**  
 a)  $\beta$ -SiC(100)c(4x2) at RT and  
 b)  $\beta$ -SiC(100)2x1 at 700 K.  
 The tip bias was +3.2 eV at a 0.12 nA tunneling current. The corresponding surface unit cells are also shown (100Å x 100Å).



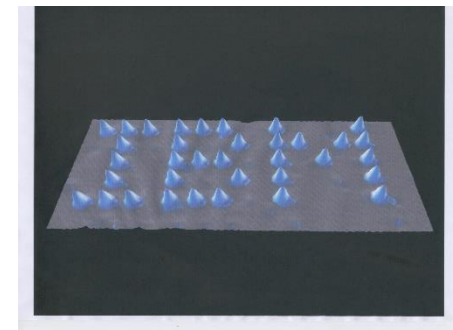
**Figure 2:**  
 Tunneling current vs. gap voltage STS (I-V) for:  
 a)  $\beta$ -SiC(100) c(4x2) at RT,  
 b)  $\beta$ -SiC(100) 2x1 at 700 K.  
 Both curves were recorded using the same tip to sample distance.

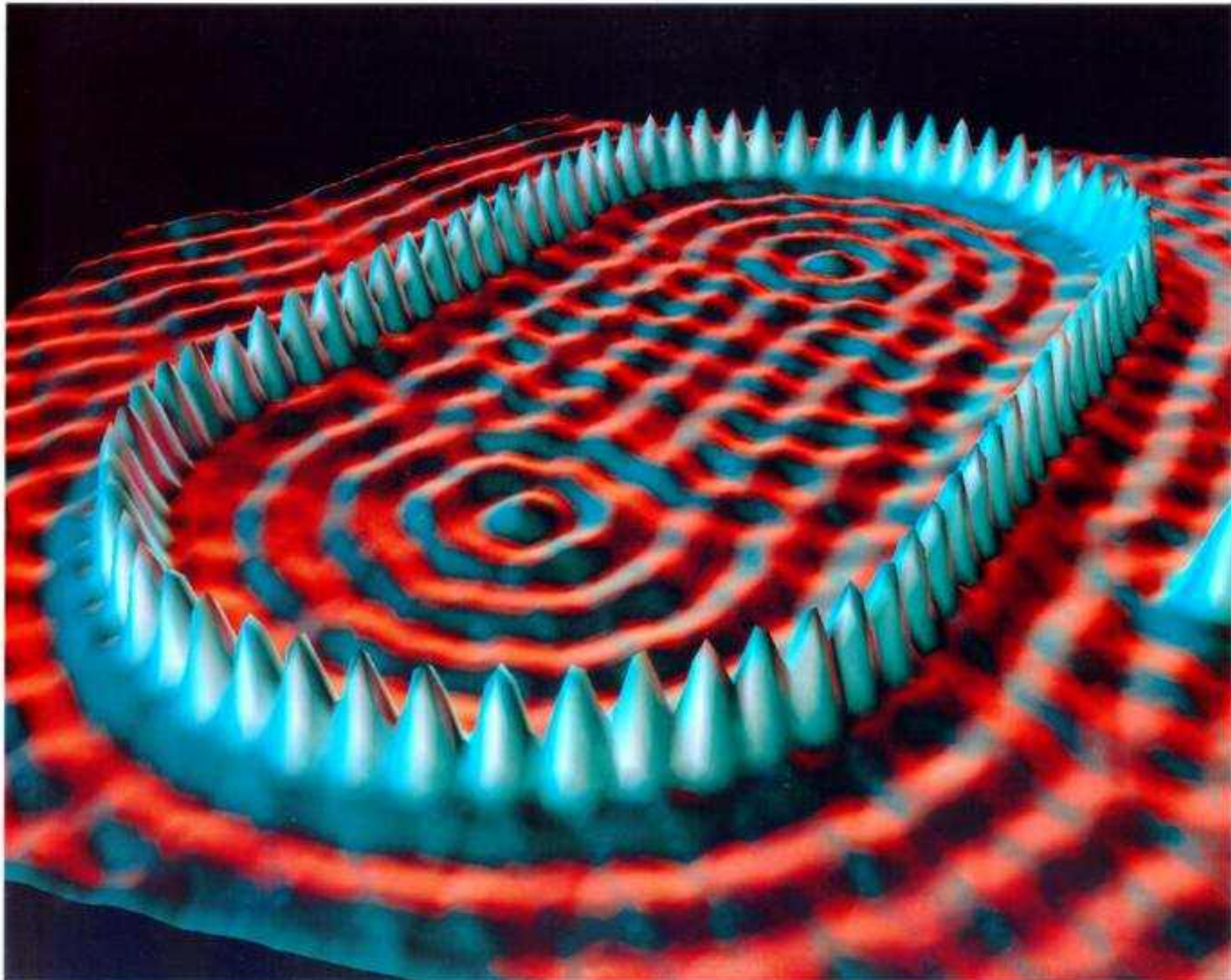
P. Soukiassian et al. PRL 78, 907 (1997)

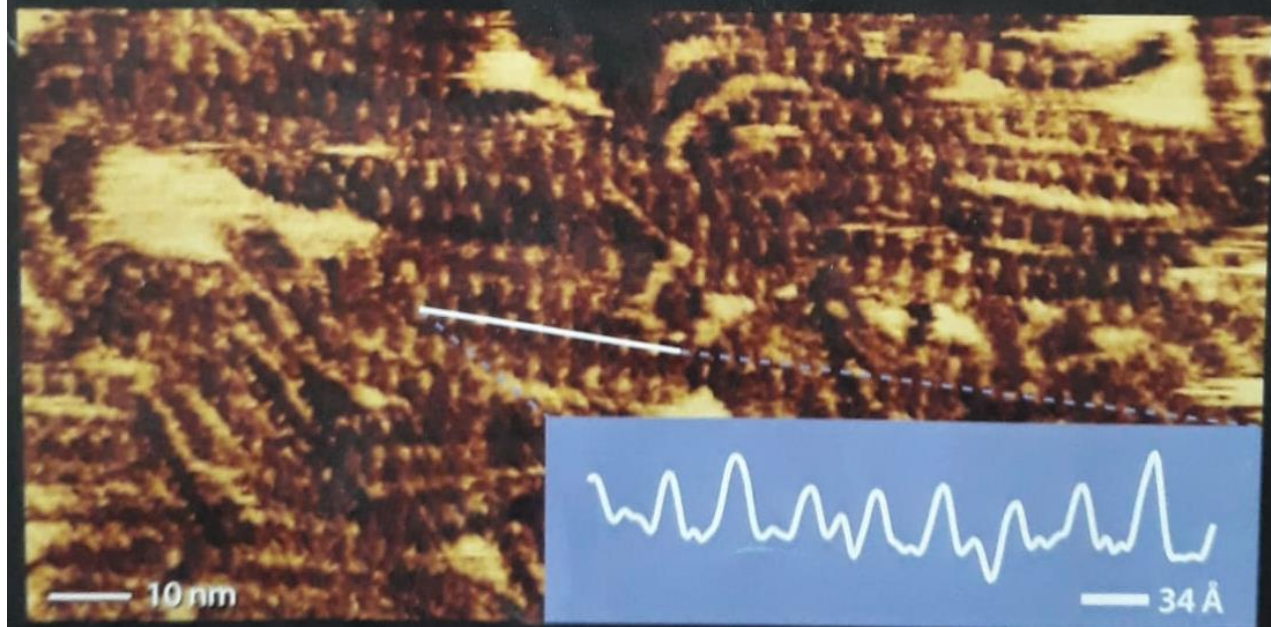
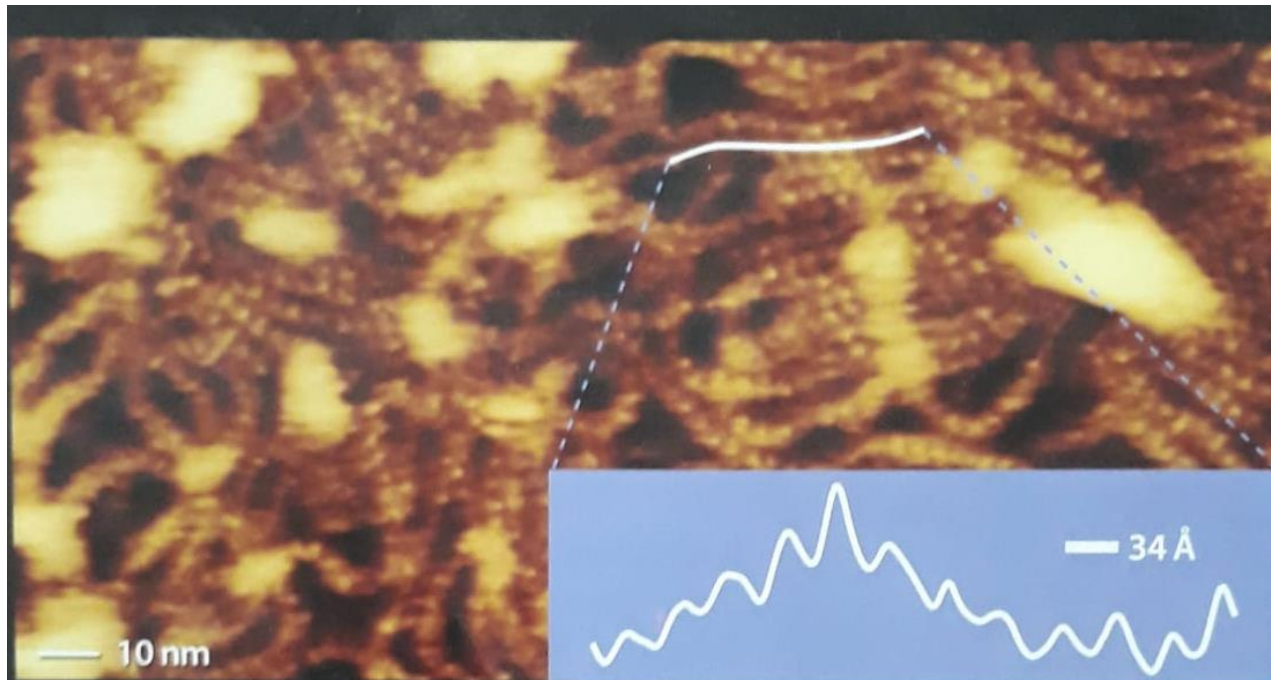


STM

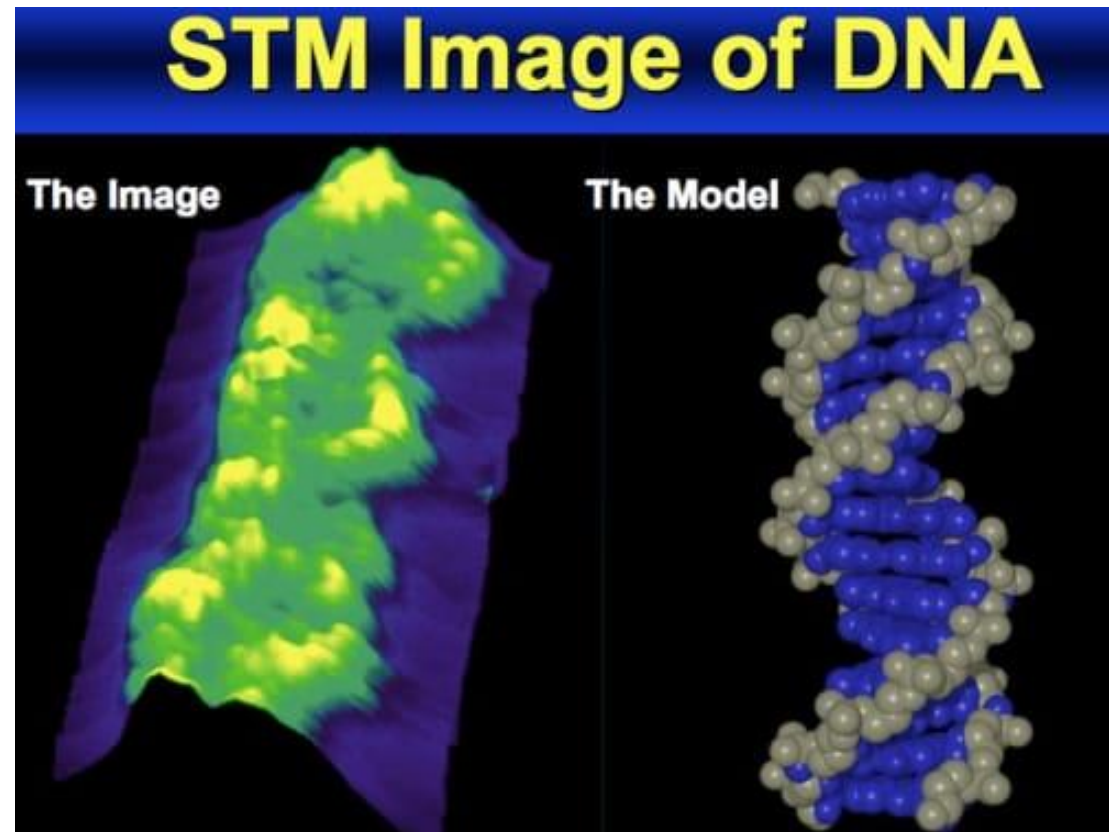
Fe atoms  
on Cu at 5K

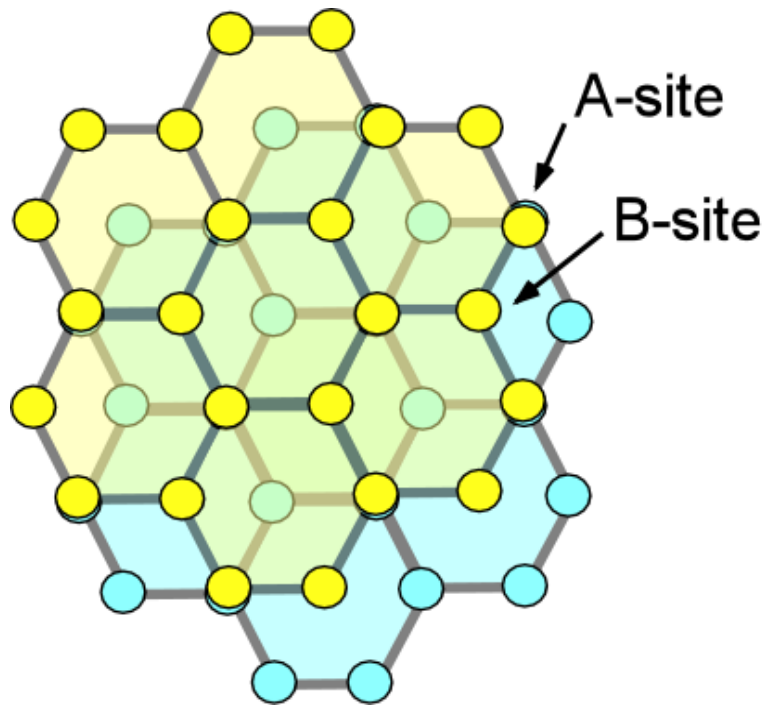






**DNA double helix resolved -**





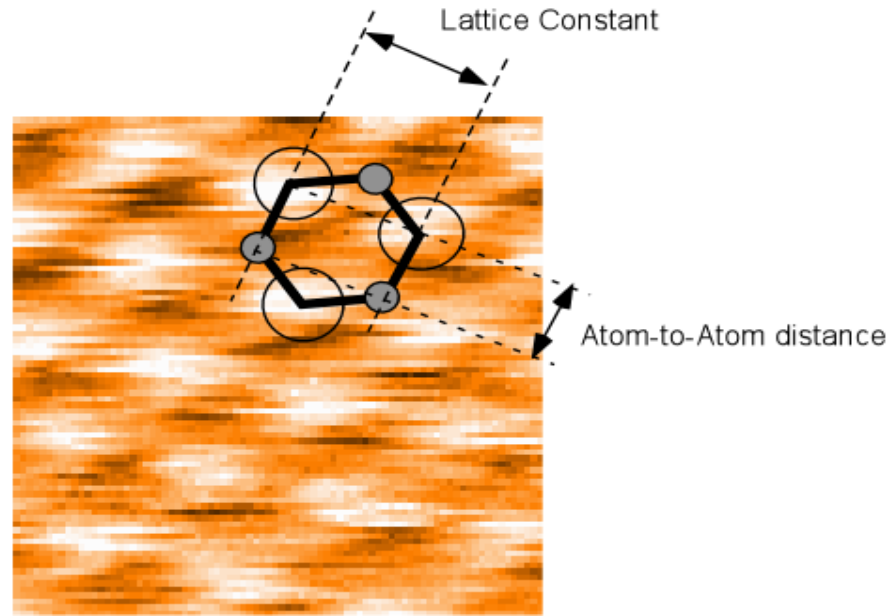
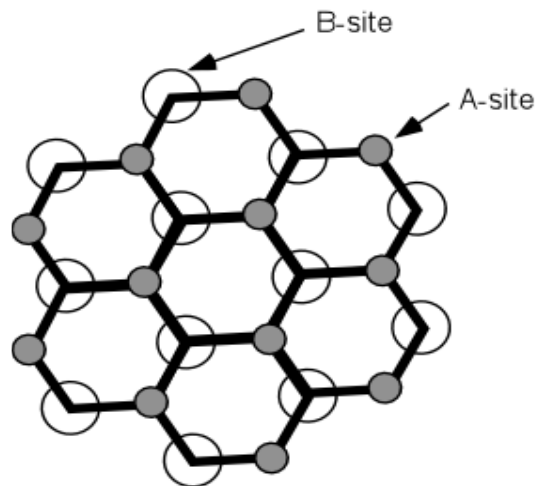
### Layered structure of HOPG

- Carbon on the first layer
- Carbon on the second layer

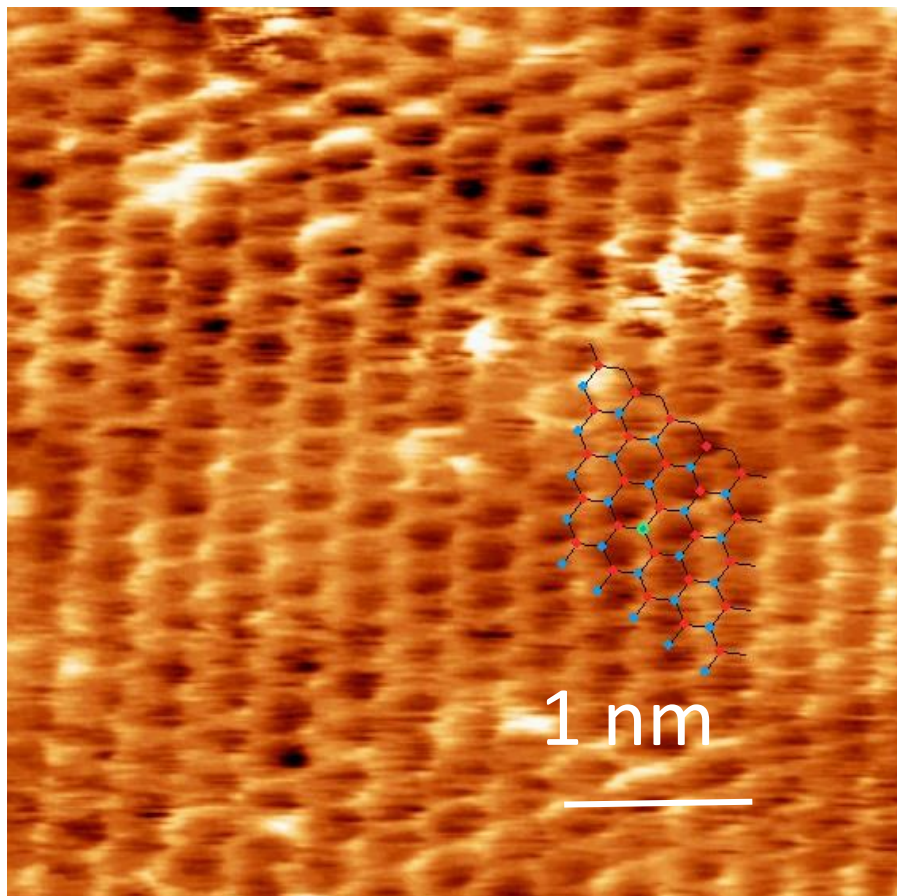
**A-site** Carbons that are right above a carbon in the second layer

**B-site** Carbons that do not have a carbon directly below.

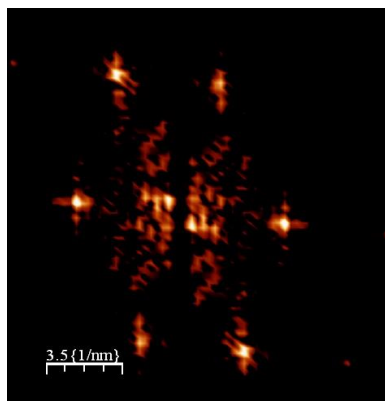
Interpretation of HOPG's three-fold-hexagon pattern of STM images



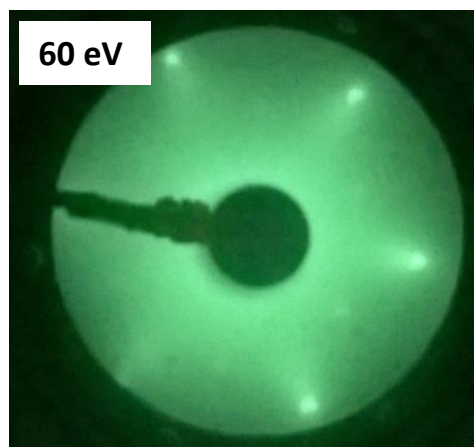
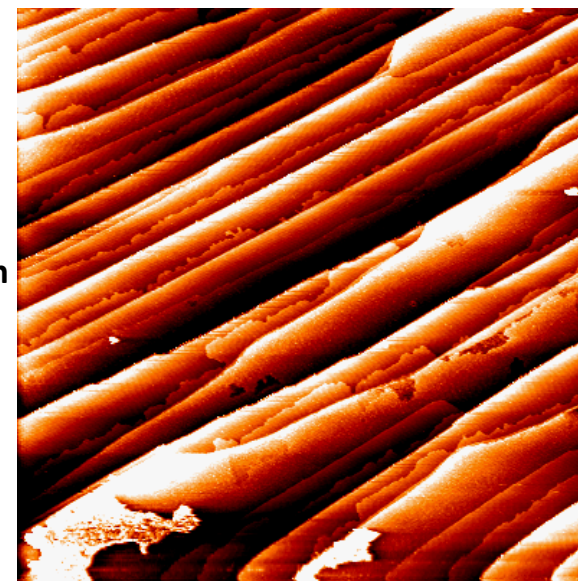




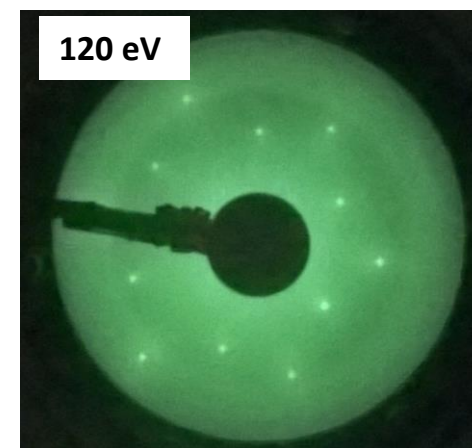
STM image of graphene/SiC(0001) surface geometry with stick & ball model (with a lattice  $a = 0.25$  nm and a distance between atoms of 0.14 nm)



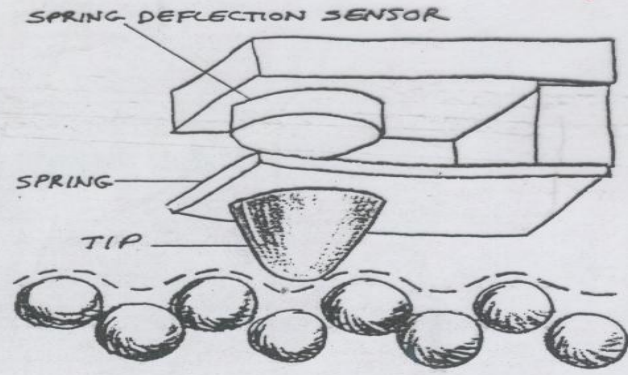
STM  
1.5  $\mu\text{m}$  x 1.5  $\mu\text{m}$



LEED pattern Si/Graphene/SiC(0001)



# ATOMIC FORCE MICROSCOPE



Scheme for an atomic force microscope. The tip is fastened to a cantilever spring that has a lower spring constant than the effective spring between two atoms. With sufficient sensitivity in the spring deflection sensor, the tip can reveal surface profiles with atomic resolution.

Binnig, Quate, Gerber,  
*Phys. Rev. Lett.* 56, 930 (1986)

$$\omega^2 m = K$$

the cantilever. This problem has now been solved by using either a fiberoptic technique that places a reference reflector within microns of the cantilever or by using a two-beam differential technique.

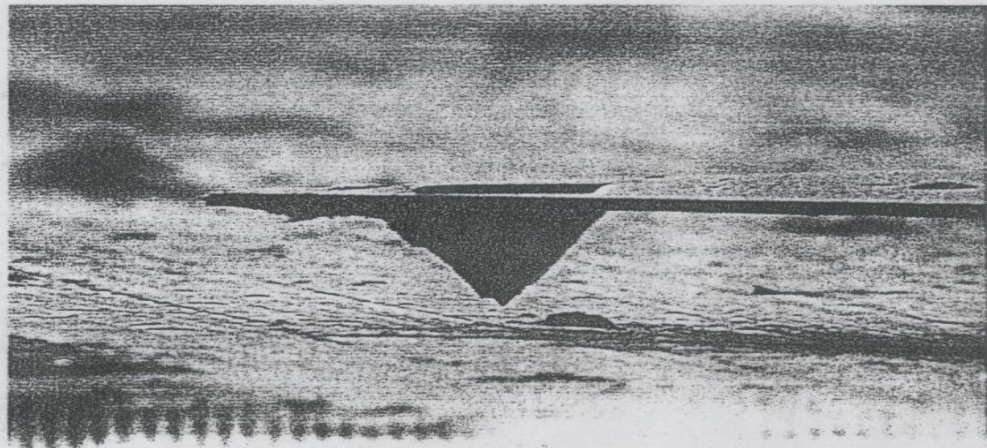
Because the AFM is such a sensitive instrument, care must be taken to ensure that external vibrations, such as from the laboratory building, do not limit its performance. The effect of external vibration is to cause unwanted motion of the tip with respect to the sample and the deflection sensor. The immunity of the AFM to external vibration depends on the frequency  $\nu$  of the vibration relative to the lowest resonant frequency  $\nu_0$  of the mechanical system. The mechanical system includes both the cantilever and the rest of the AFM. The amplitude of relative tip motion is attenuated by a factor  $(\nu/\nu_0)^2$  in the limit  $\nu \ll \nu_0$ . Thus, if the lowest resonant frequency is greater than 20 kHz, a typical 20-Hz building vibration of amplitude 1 micron results in relative tip motion of less than 0.01 Å, a nearly harmless level. Because cantilevers can be readily made with high resonant frequencies, the limiting factor is usually the rest of the AFM. Good AFM designers focus on making the mechanical components of

the AFM rigid and compact, especially in the path from the cantilever to the sample.

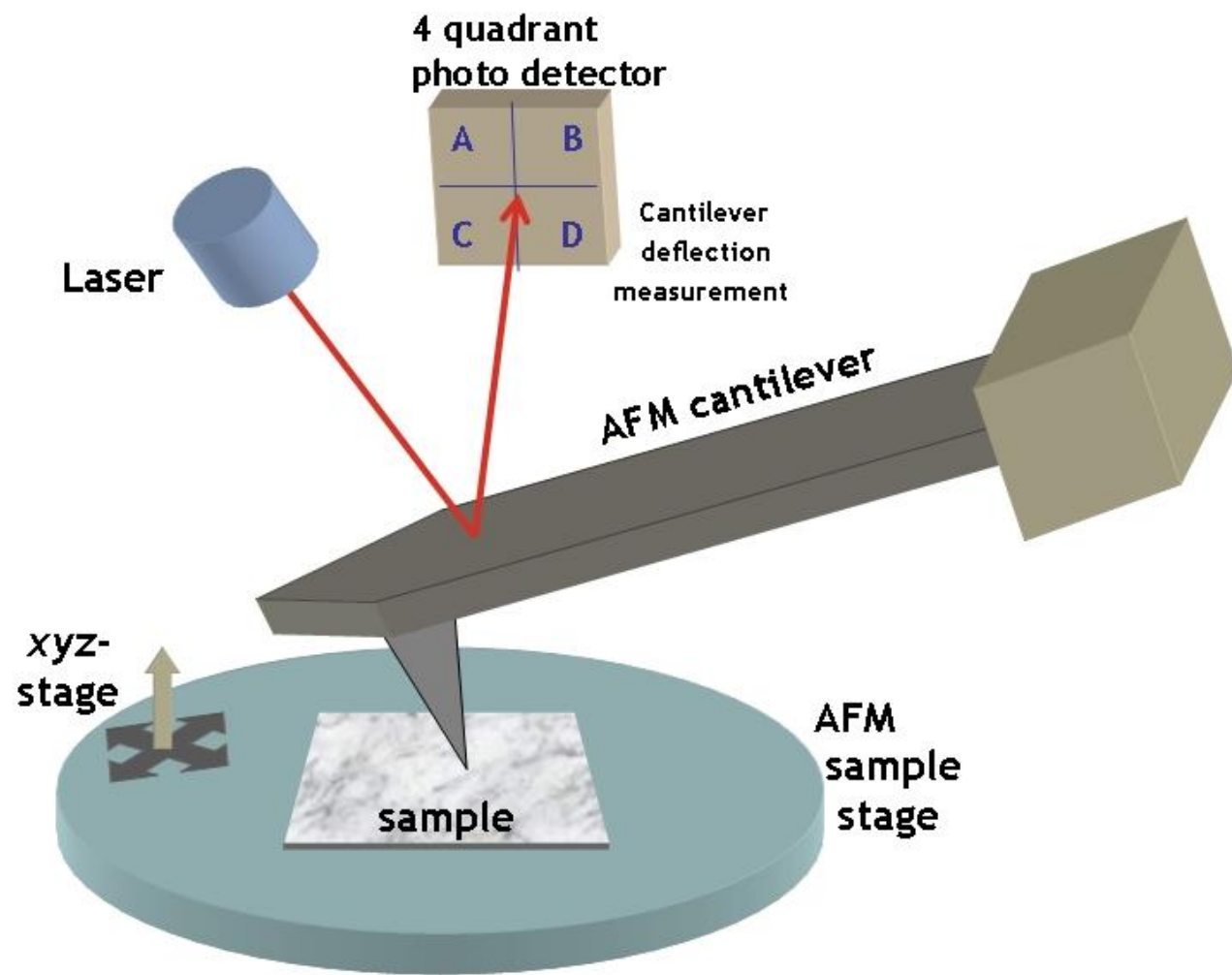
## Atomic resolution

One of the most exciting results from atomic force microscopy has been the discovery that atomic resolution can be achieved when the tip is in contact with the sample while scanning.<sup>8</sup> Conceptually, this "contact mode" of imaging is like using a stylus profilometer to measure the topography of surface atoms. At first, this idea may seem implausible, especially when one considers the macroscopic size of typical AFM tips. The AFM achieves such high resolution by using a very small loading force on the tip—typically  $10^{-7}$  to  $10^{-11}$  N—which makes the area of contact between the tip and sample exceedingly small. This small and well-controlled loading force is the essential difference between the contact-mode AFM and earlier stylus profilometers,<sup>9</sup> which typically used loading forces on the order of  $10^{-4}$  N.

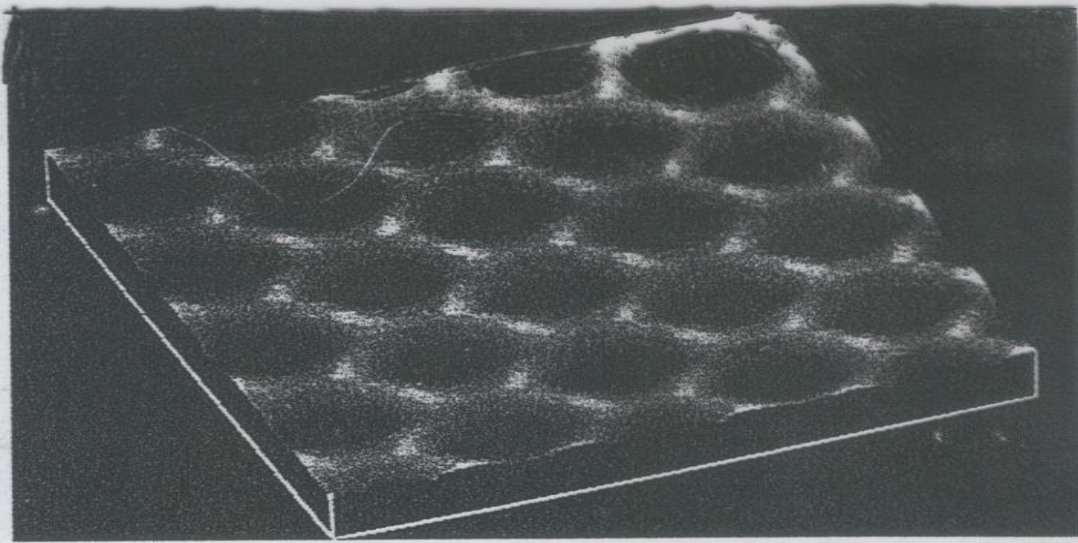
Atomic resolution has been achieved on a number of different materials, including both insulators and conductors. The first materials that showed atomic corrugations



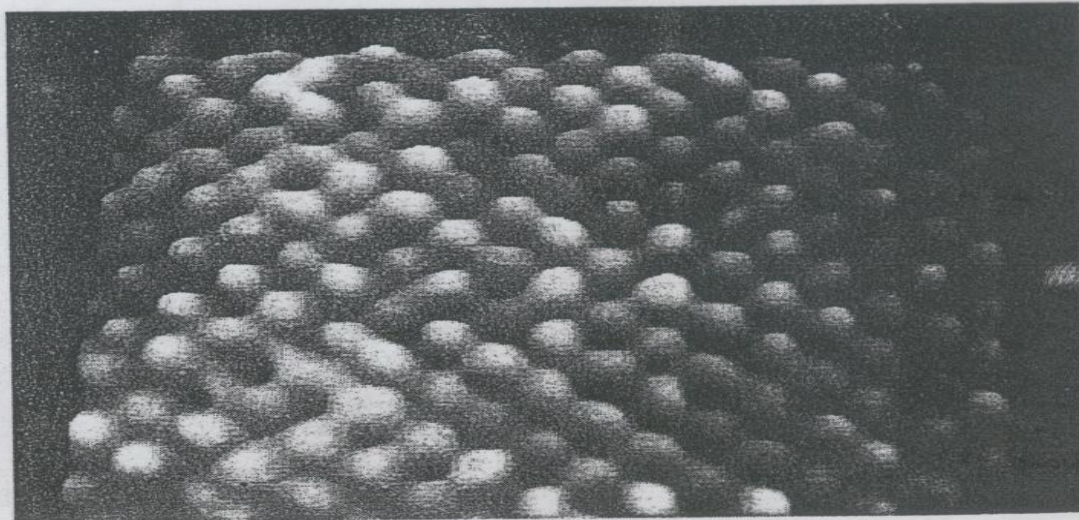
Microcantilever with microfabricated tip for a contact-mode atomic force microscope. This silicon nitride cantilever was manufactured by Park Scientific Instruments, Mountain View, California. (Photograph by Greg Klimek)



AFM



**Individual carbon atoms** in graphite. The atoms are only  $1.5 \text{ \AA}$  apart, but can be imaged with an unusually good tip. (From Srinivas Manne and Scot Gould, University of California, Santa Barbara.)



**Sodium chloride** crystal surface, at atomic resolution. (From G. Meyer and N. M. Amer, reference 10).

# ‘Current-Driven Spin Dynamics of Artificially Constructed Quantum Magnets’

A. A. Khajetoorians, Roland Wiesendanger et al. *Science* 339, 55 (2013)

The power of “spin-polarized” scanning tunneling microscope (SP-STM) relies on an atomically sharp magnetic needle which can be freely positioned above single atoms, move it and sense their magnetic orientation.

