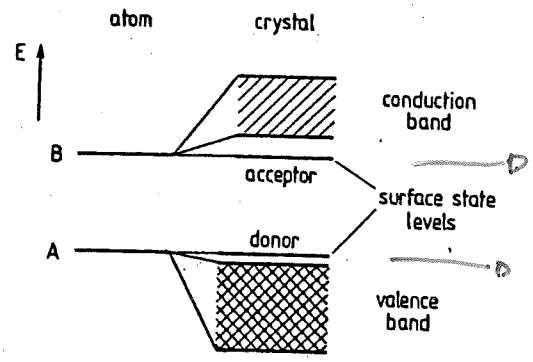
STATI DI SUPERFICIE

$Q_{ss} = - Q_{sc}$

↑ densità di carica superficiale (stati di superficie)

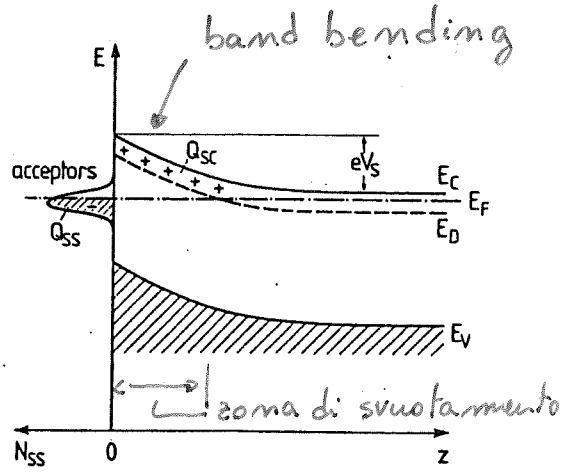
↳ densità di carica spaziale



occupato —
vuoto ∅ → neutro (senza elettrone)

occupato ∅ → neutro (con elettrone)
vuoto +

Fig. 6.5. Qualitative explanation of the origin of surface states in the tight-binding picture. Two atomic levels A and B form the bulk valence and conduction bands, respectively. Surface atoms have fewer bonding partners than bulk atoms and thus give rise to electronic energy levels that are closer to those of the free atoms, i.e. surface state levels are split off from the bulk bands. Depending on their origin, these states have acceptor- or donor-like charging character



a) distanza ss – E_C fissata

b) Se non c'è bending, tutti gli stati di superficie $< E_F$ → occupati

c) Per neutralità di carica → bending

$Q_{ss} = -Q_{sc}$

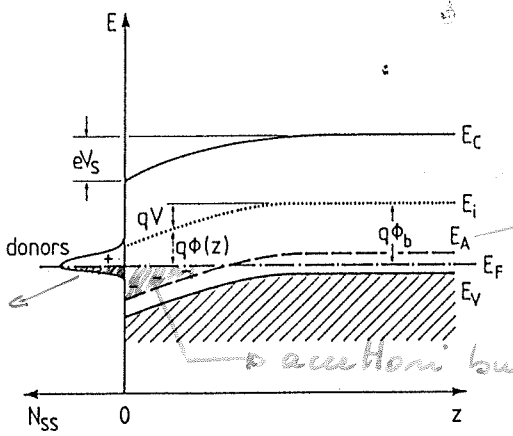
↓

posizione E_F → eV_s

d) zona di svuotamento → no cariche libere!

Fig. 7.1. Band scheme (band energy E versus z coordinate normal to the surface z = 0), for an n-doped semiconductor with depletion space-charge layer at low temperature (bulk donors not ionized). Partially occupied acceptor type surface states (density N_{ss}) are also indicated. Their charge Q_{ss} is compensated by the space charge Q_{sc}. E_F is Fermi energy, E_C and E_V conduction- and valence-band edges, respectively, and E_D the energy of the bulk donors. The band bending at the surface is eV_s with e being the positive elementary charge

p-type



livelli accettori non ionizzati

centro pieno

accettori bulk pieni → sotto E_F

Fig.7.3. Band scheme of a hole depletion space-charge layer on a p-doped semiconductor at low temperature (bulk acceptors not ionized). eV_s is the band bending at the surface, eV(z) the local band bending, $\phi(z)$ the local potential and ϕ_b the potential in the bulk. E_i is the intrinsic energy, E_F the Fermi energy, E_A the energy of bulk acceptors and E_C and E_V as in Fig.7.1

ENERGIA POTENZIALE LOCALE

$$(e)\phi(z) = E_F - E_F^{i}(z)$$

↳ CARICA ELETTRICA > 0

$$e\phi_s = E_F - E_F^{i,s} \quad \text{superficie}$$

$$e\phi_b = E_F - E_F^{i,b} \quad \text{bulk}$$

"DEFORMAZIONE" LOCALE DELLA BANDA

$$V(z) = \phi(z) - \phi_b$$

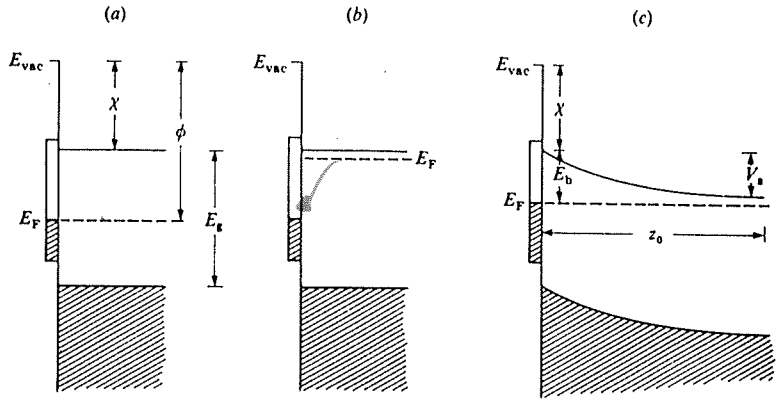
$V=0$ nel bulk, $\phi(z)=\phi_b$

$$V_s = \phi_s - \phi_b$$

POTENZIALE ALLA SUPERFICIE

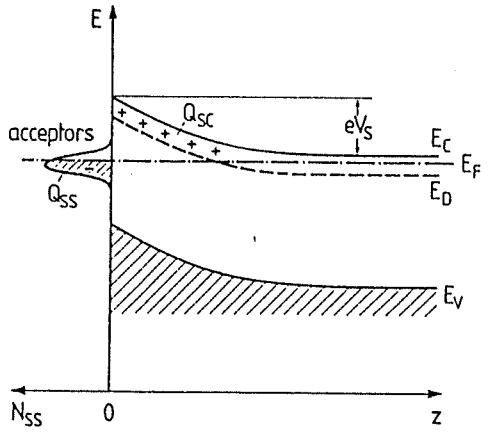
eV_s = band bending

Fig. 9.15. Electron energy levels near the surface of a clean semiconductor: (*a*) undoped sample; (*b*) disequilibrium between n-type bulk and its surface; (*c*) band bending and Fermi level pinning at equilibrium.



eV_s = BAND BENDING

χ = AFFINITA'



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Q_{ss} = densita' di carica superficiale

Q_{sc} = densita' di carica spaziale

NEUTRALITA' → $Q_{sc} = -Q_{ss}$

STRATO DI SVUOTAMENTO DI CARICA SPAZIALE DI SCHOTTKY

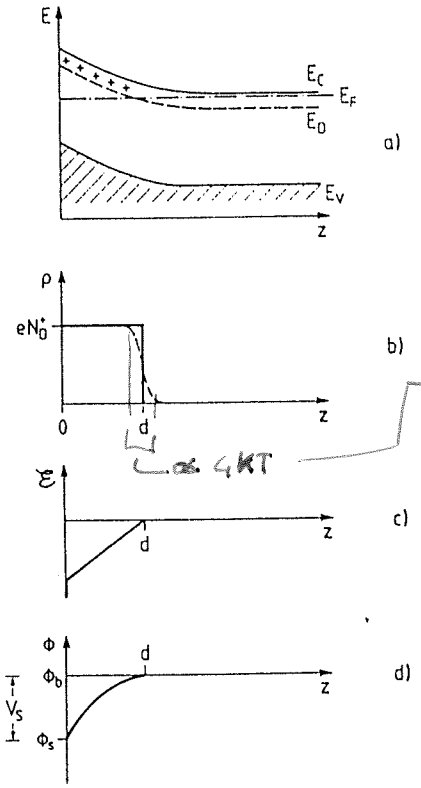


Fig.7.4a-d. A depletion layer on an n-type semiconductor in the Schottky approximation: (**a**) Band scheme with symbols as in Figs.7.1-3. (**b**) Volume density ρ. of the space charge, realistic density (*broken line*) and Schottky approximation (*full line*). d is the thickness of the space-charge layer and N_D^+ the density of the ionized bulk donors. (**c**) Electric field $\mathcal{E}(z)$ in the space charge layer. (**d**) Electric potential $\phi(z)$ with values ϕ_b and ϕ_s in the bulk and at the surface, respectively

→ Se $eV_s >> kT$ ⇒ $4kT \ll d \sim 0$

$|eV_s| >> kT$ $\quad f = \frac{1}{e^{(E-E_F)/kT} + 1}$

↓

$|\alpha_s| >> 1$

BANDA MOLTO PIEGATA → POCHI ELETTRONI LIBERI

funzione a step

$$\rho(z) = \frac{Q_{sc}}{d} = \frac{e N_D^+ d}{d} \sim e N_D$$

Tutti donori ionizzati

Q_{sc} → zona di svuotamento

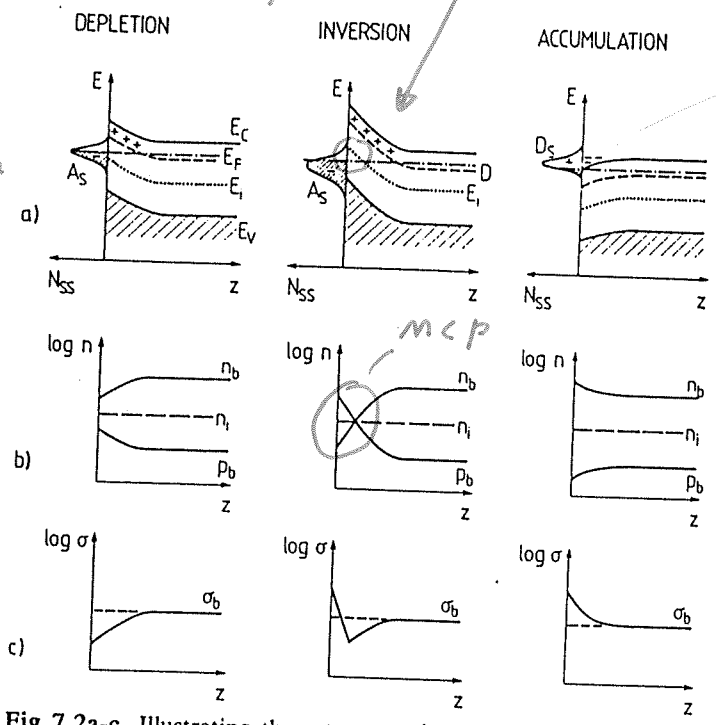
d → densità di cariche + per neutralizzare i Q_{ss} negativi (densità di carica per unità di area)

$$\frac{d^2V}{dz^2} = -\frac{\rho}{\varepsilon} = -\frac{e N_D}{\varepsilon}$$

n - type

(svuotamento)

$E_F < E_F^i$



Acceptor type

zona di accumulazione piccola (cariche mobili)

Donor - type

n c p

$n \cdot p = n_i^2$

$\sigma = n q \mu_e + p q \mu_h$

$\vec{v} = \mu \vec{E}$

Fig. 7.2a-c. Illustrating the n-type semiconductor: Schematic plots of band schemes (a), free carrier densities n and p on a logarithmic scale (b) and local conductivity σ (logarithmic scale) (c) for depletion, inversion and accumulation space charge layers at low temperature (bulk donors not ionized). E_C, E_V are the conduction- and valence-band edges, E_F the Fermi energy, E_i and n_i intrinsic energy and concentration, respectively. D denotes bulk donors, A_s and D_s surface acceptors and donors, respectively. The subscript b denotes bulk values

$$E_F^i = \frac{E_V + E_C}{2} + \frac{kT}{2} \ln \frac{N_V}{N_C}$$

E_F intrinseco

$$N_V = 2\left(\frac{2\pi m_h kT}{h^2}\right)^{3/2}$$

$$N_C = 2\left(\frac{2\pi m_e kT}{h^2}\right)^{3/2}$$

$$E_F - E_C = kT \ln \frac{N_D}{N_C}$$

per $n = N_D$, tutti i donori ionizzati

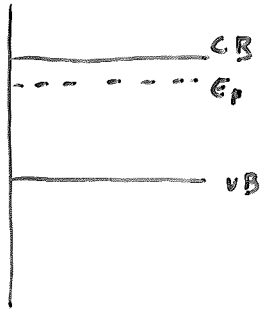
E_F per n - type

FERMI LEVEL PINNING (STABILIZZAZIONE)

N_{SS} = concentrazione (cm^{-2}) stati di superficie

E_{SS} = energia SS rispetto a CB

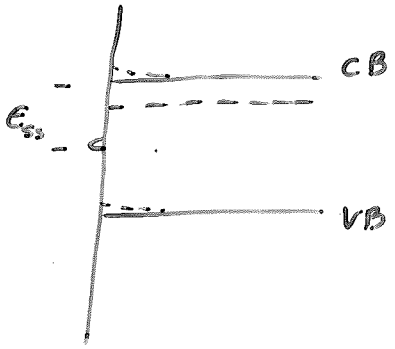
$N_{SS} = 0$



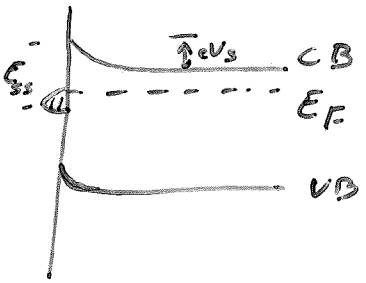
N_{SS} piccolo $\sim 10^{10}\ cm^{-2}$

N_{SS} pieni

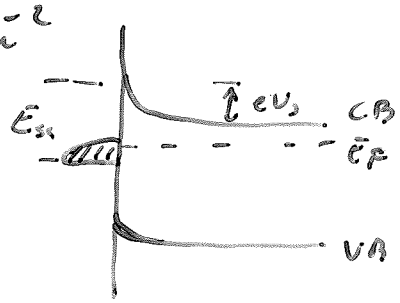
piccolo Band Bending



N_{SS} intermedi $\sim 10^{12}\ cm^{-2}$



N_{SS} Alto $\sim 10^{14}\ cm^{-2}$



Se N_{SS} cresce ancora → eV_S deve crescere, ma E_{SS} è fisso per cui i S.S. tendono ad uscire da E_F, cioè diminuiscono gli stati S.S. non occupati → eV_S non aumenta → E_F bloccato dagli S.S.

CASO NUMERICO su GaAs ($E_g = 1.4$ eV)

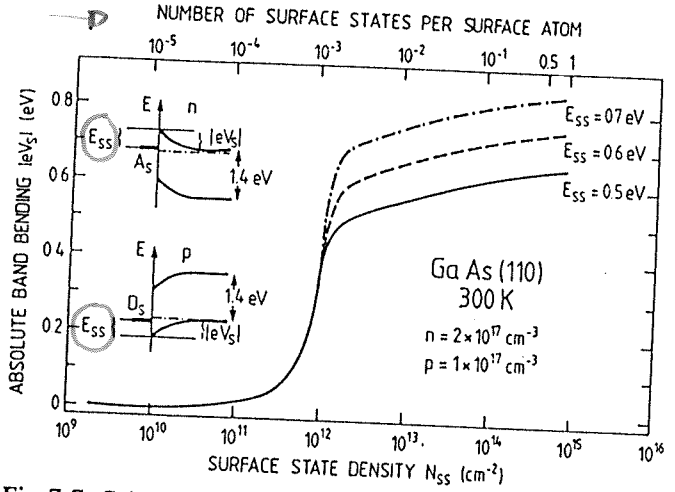


Fig. 7.7. Calculated absolute band bending $|V_s|$ due to an acceptor surface-state level A_s and a donor level D_s for n- and p-type GaAs. $|V_s|$ is plotted versus the surface state density N_{ss} (*lower scale*) and related to the number of surface states per surface atom (*upper scale*). With the different definition of the energetic position E_{ss} for n- and p-type crystals (insets) the calculated curves for n- and p-type material are not distinguishable on the scale used [7.3]

E_{ss} = distanza livello superficiale - CB, (o VB)

(Densità di atomi in superficie $\sim 10^{15} - 10^{16}$ cm^{-2})

Per $N_{ss} < 5 \cdot 10^{11}$ cm^{-2} $\quad |eV_s| \simeq 0$

$N_{ss} > 5 \cdot 10^{12}$ cm^{-2} $\quad |eV_s| \sim$ costante per E_{ss}

$\Downarrow$

$E_F \sim$ costante $\rightarrow$ PINNING di E_F

$E_F \sim$ sul livello di superficie

$\Downarrow$

normale concentrazione di stati di superficie

$\Downarrow$

sempre PINNING