Nanostructures – density of states

Faculty of Physics UW

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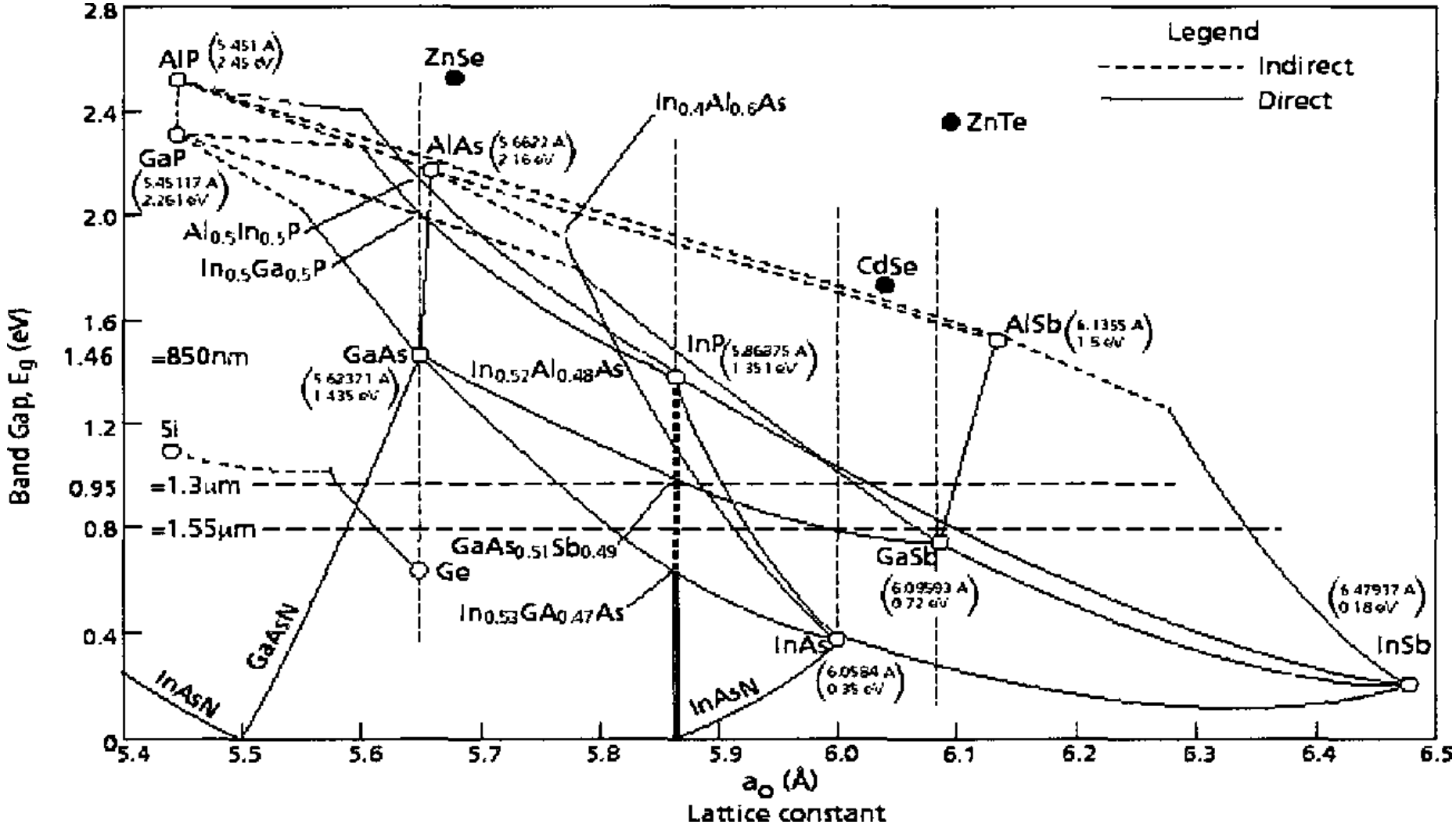
inżynieria nanostruktur

Semiconductor heterostructures



Investigation of high antimony-content gallium arsenic nitride-gallium arsenic antimonide heterostructures for long wavelength application

Bandgap enginee

Valence band offset

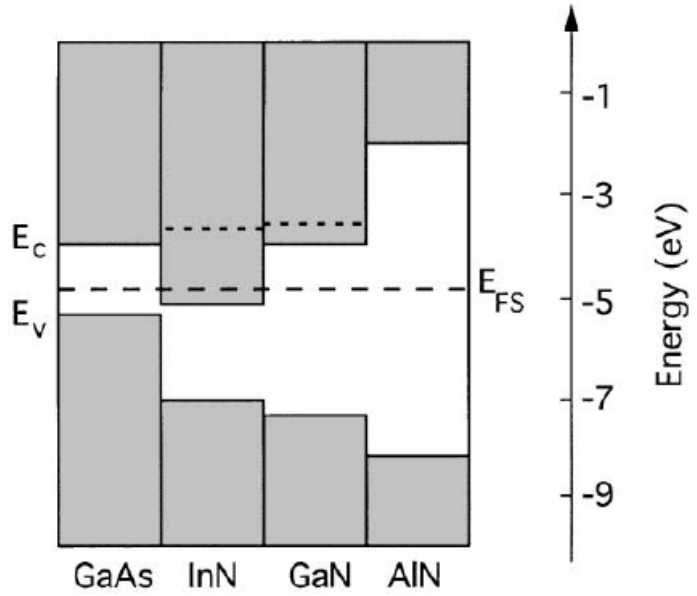


Fig. 4. Band offsets for group III-Nitrides. The dashed lines represent the Fermi energy for the maximum achievable free electron concentration in GaN and InN.

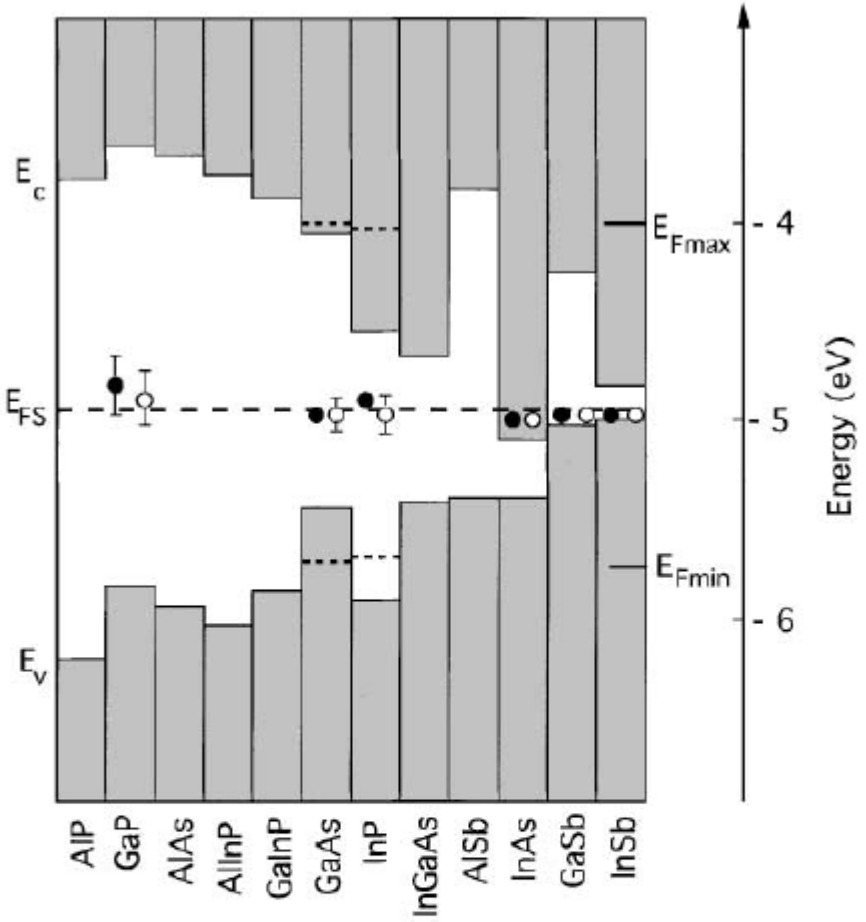


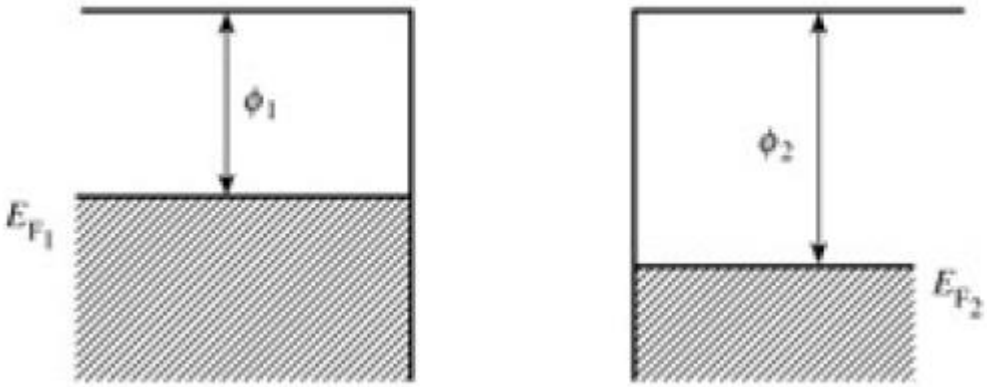
Fig. 1. Band offsets and the Fermi level stabilization energy (E_{FS}) in III–V compounds. The energy is measured relative to the vacuum level. The filled circles represent stabilized Fermi energies in heavily damaged materials, exposed to high energy radiation. The open circles correspond to the location of the Fermi energy on pinned semiconductor surfaces and at metal/semiconductor interfaces. The dashed lines show the location of the Fermi energy for a maximum equilibrium n- and p-type doping in GaAs and InP.

Walukiewicz Physica B 302–303 (2001) 123–134

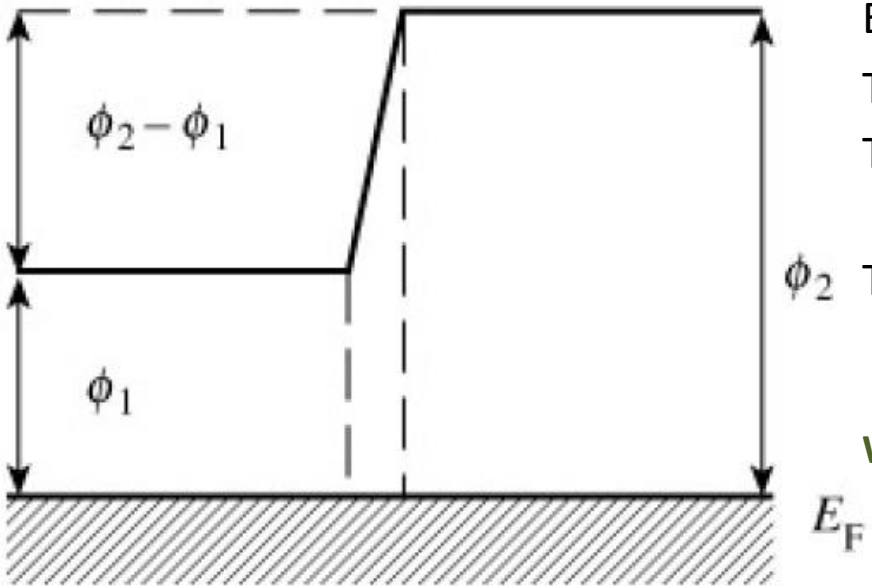
The construction of energy band diagrams

metal-metal junction

Anderson's rule



Suppose, that $\phi_2 - \phi_1 \approx 1\ eV$
Estimate the number of electrons that pass from one metal to another to create equilibrium potential difference. Assume that the distance between the metals is $5 \times 10^{-10} m$.



Electric field: $E = \frac{\Delta\phi}{d} = 2 \times 10^9 \frac{V}{m}$

The surface charge: $\sigma = \varepsilon_0 E$

The concentration: $n^{2D} = \frac{\sigma}{e} = 1.12 \times 10^{13} cm^{-2}$

The concnetration in metal

$$n^{3D} = 5 \times 10^{22} cm^{-3}$$

$$n^{2D} = 1.5 \times 10^{15} cm^{-2}$$

Within the width of 1 lattice parameter ~1% of charge

Electrical properties of materials Solymar, Walsh (6.11)
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The doping of semiconductors

Thus the electric field in the range $(x_p, 0)$:

$$\vec{E}_A = -\frac{dU}{dx} = \frac{1}{\epsilon} eN_A(x + C) = \frac{1}{\epsilon} eN_A(x - x_p)$$

Similarly for $(0, x_n)$:

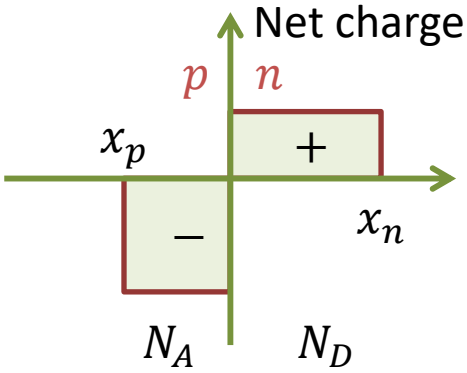
$$\vec{E}_D = -\frac{dU}{dx} = \frac{1}{\epsilon} eN_D(x + C) = \frac{1}{\epsilon} eN_D(x - x_n)$$

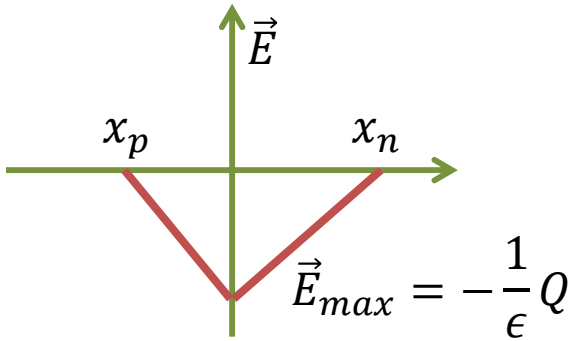
$$U = -\int_{x_p}^{0} E_A dx \qquad x < 0$$

$$U = -\int_{0_p}^{x_n} E_D dx \qquad x > 0$$

The built-in volatage in the pn-junction

$$U_0 = U(x_n) - U(x_p) = \frac{e}{2\varepsilon}(N_A x_P^2 + N_D x_n^2)$$





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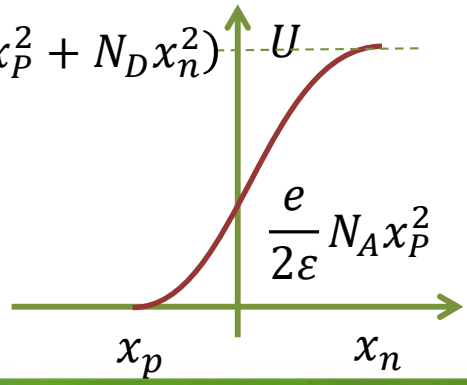


The doping of semiconductors

Charge conservation

$$eN_A x_p = eN_D x_n = Q$$

The total width of the depletion region w

$$w = x_n - x_p = \sqrt{\frac{2\varepsilon U_0}{e(N_A + N_D)}}\left(\sqrt{\frac{N_A}{N_D}} + \sqrt{\frac{N_D}{N_A}}\right)$$

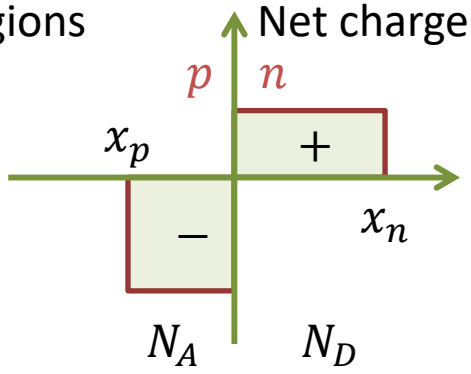
If, say, $N_A \gg N_D$ (p-type doping)
then:

$$w = \sqrt{\frac{2\varepsilon U_0}{eN_D}} \quad \text{i} \quad |x_n| > |x_p|$$

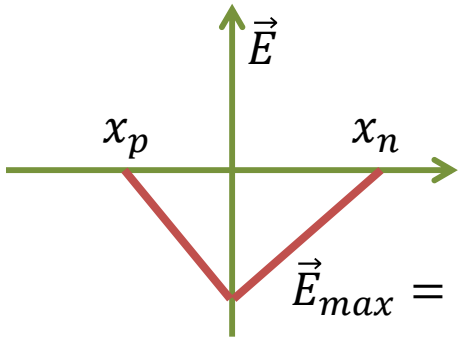
if the p-region is more highly doped, practically all of the potential drop is in the n-region. The less donors are the wider this region is.
(for $N_A \ll N_D$ is vice-versa!)

E.g. $N_D = 10^{15}\text{cm}^{-3}$ for typical $U_0 = 0.3$ V
We have $w \approx 180$ nm. If the change from acceptor impurities to donor impurities is gradual, then $w \approx 1\ \mu$m

Depletion regions

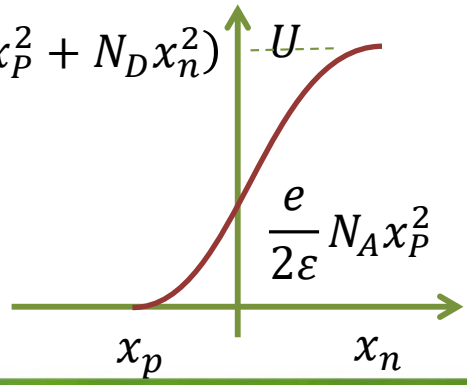


Net charge densities



$$\vec{E}_{max} = -\frac{1}{\epsilon}Q$$

$$U_0 = \frac{e}{2\varepsilon}(N_A x_P^2 + N_D x_n^2)$$



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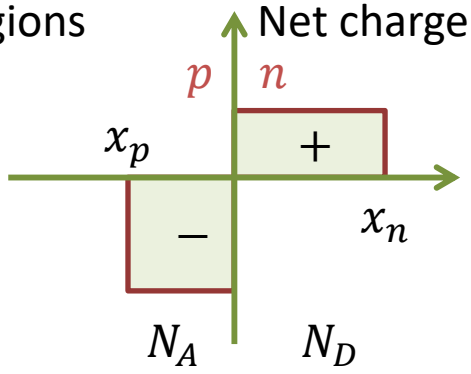
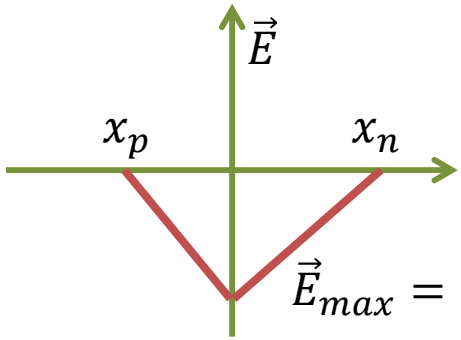


Net charge densities



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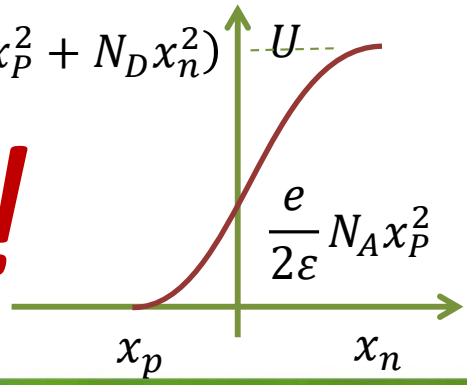
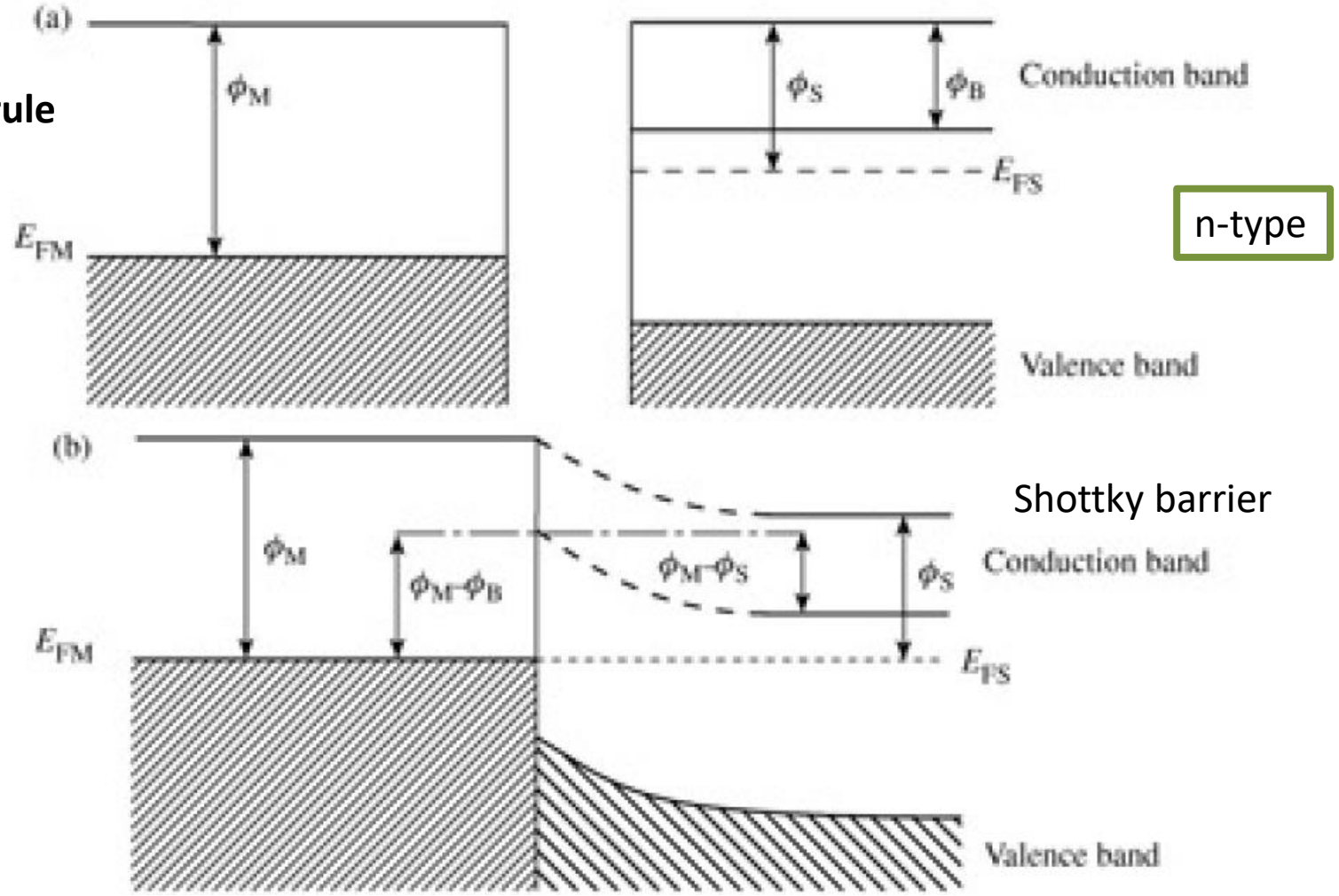


!

The construction of energy band diagrams

The metal-semiconductor junction ($\phi_M > \phi_S$) Work function ϕ_S, electron affinity ϕ_B

Anderson's rule



n-type

Shottky barrier

Electrical properties of materials Solymar, Walsh (9.16)
Pg. 257

The construction of energy band diagrams

The metal-semiconductor junction ($\phi_M > \phi_S$) Shottky barrier

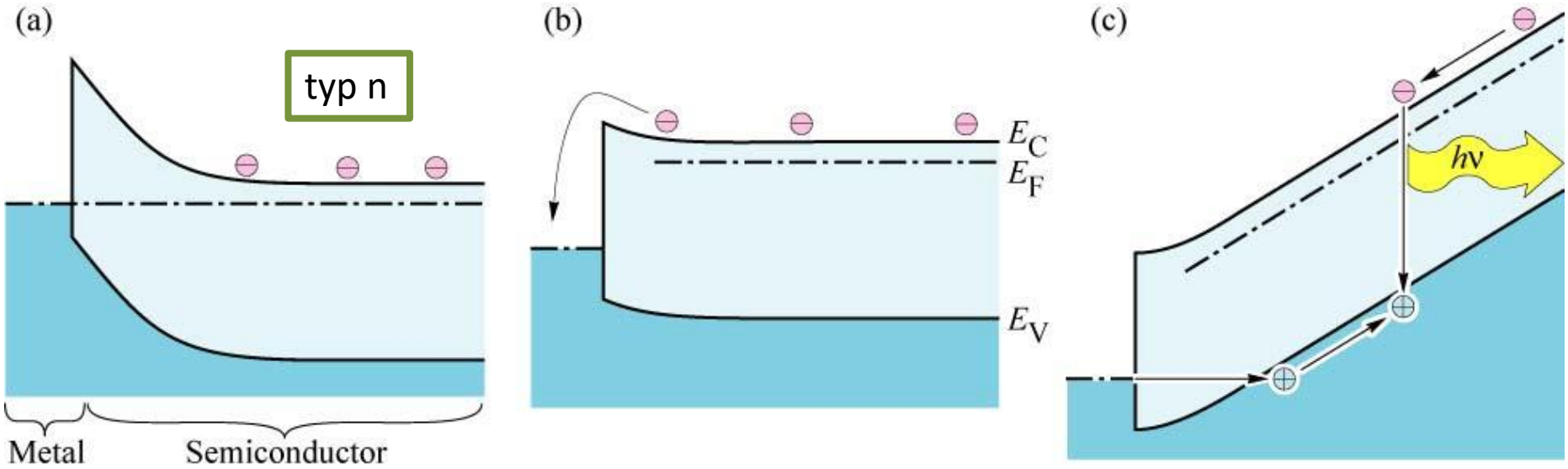
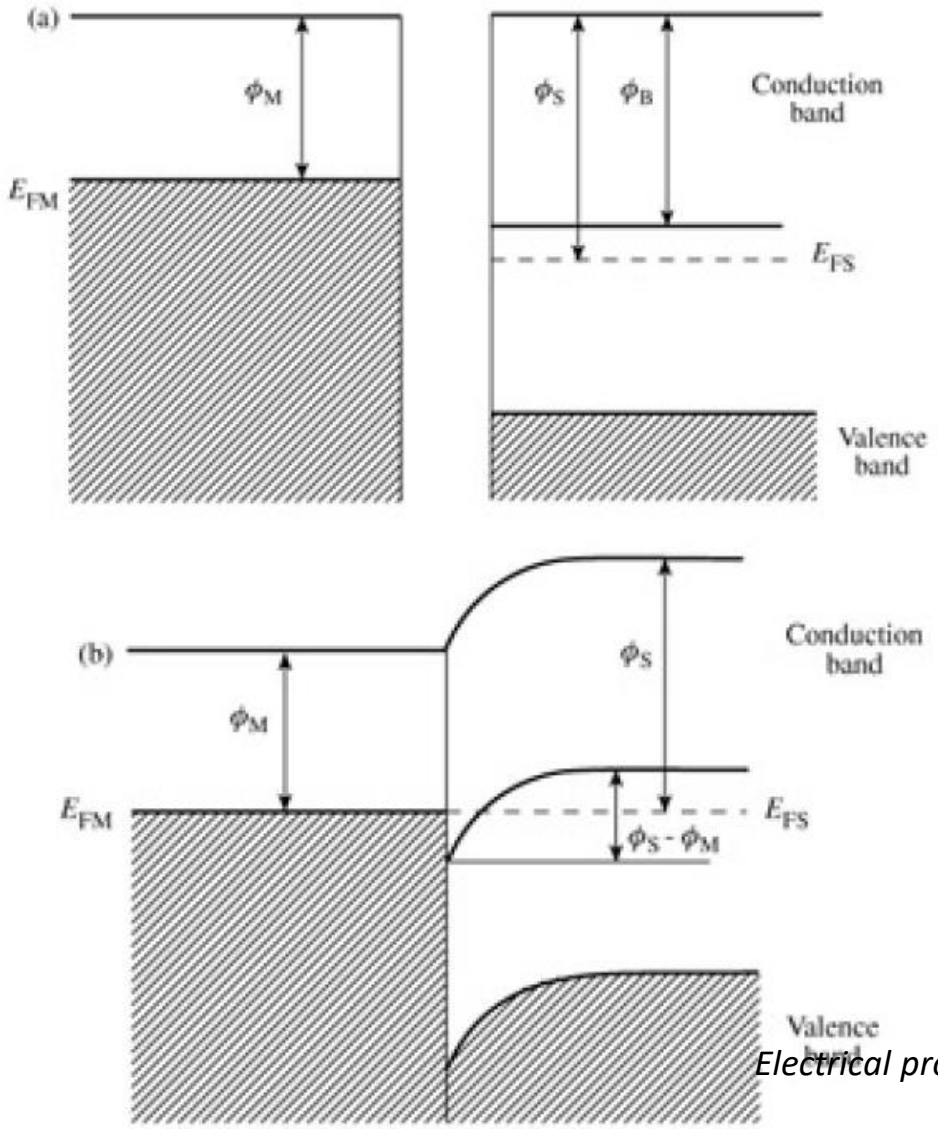


Fig. 1.2. Band diagram of a Schottky diode under (a) equilibrium conditions, (b) forward bias, and (c) strong forward bias. Under strong forward bias, minority carrier injection occurs making possible near-bandgap light emission.

E. F. Schubert
Light-Emitting Diodes (Cambridge Univ. Press)
www.LightEmittingDiodes.org

The construction of energy band diagrams

The metal-semiconductor junction ($\phi_M > \phi_S$)



n-type

Theoretically there should be no Shotky barrier

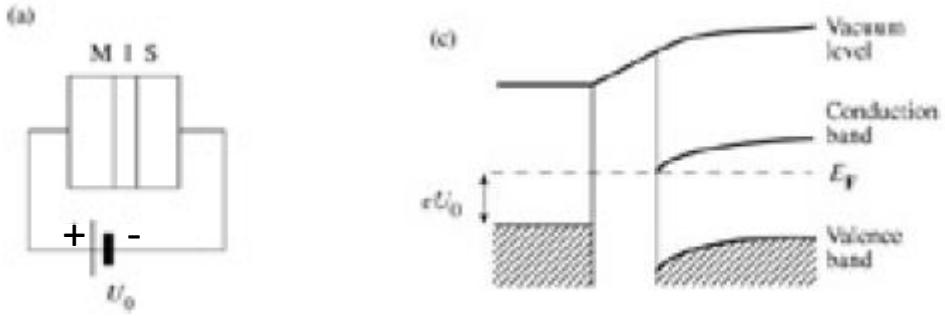
Electrical properties of materials Solymar, Walsh

The construction of energy band diagrams

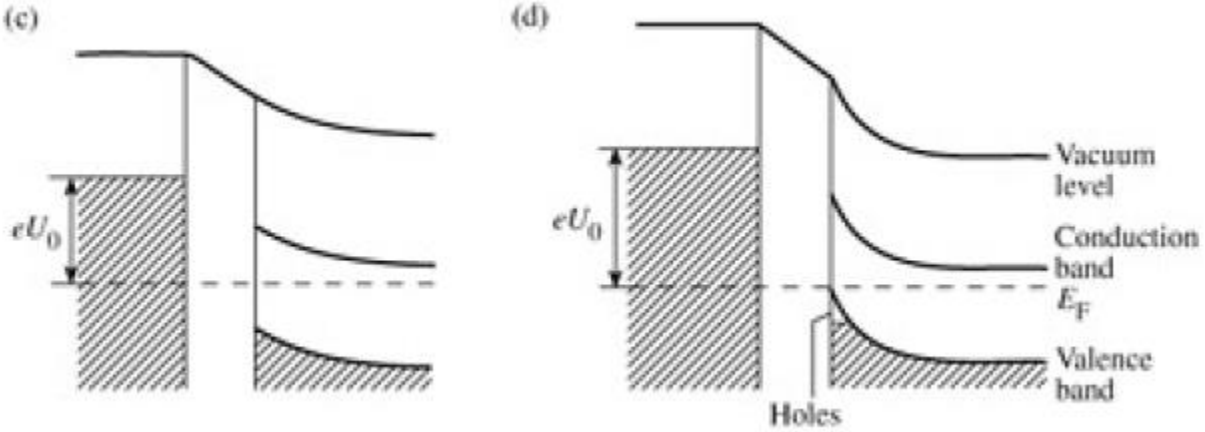
The metal-semiconductor junction ($\phi_M > \phi_S$)

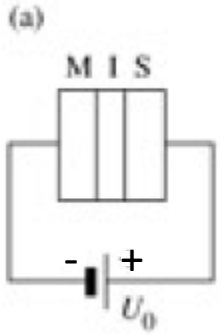
n-type

isolator



forward bias
napięcie przewodzenia



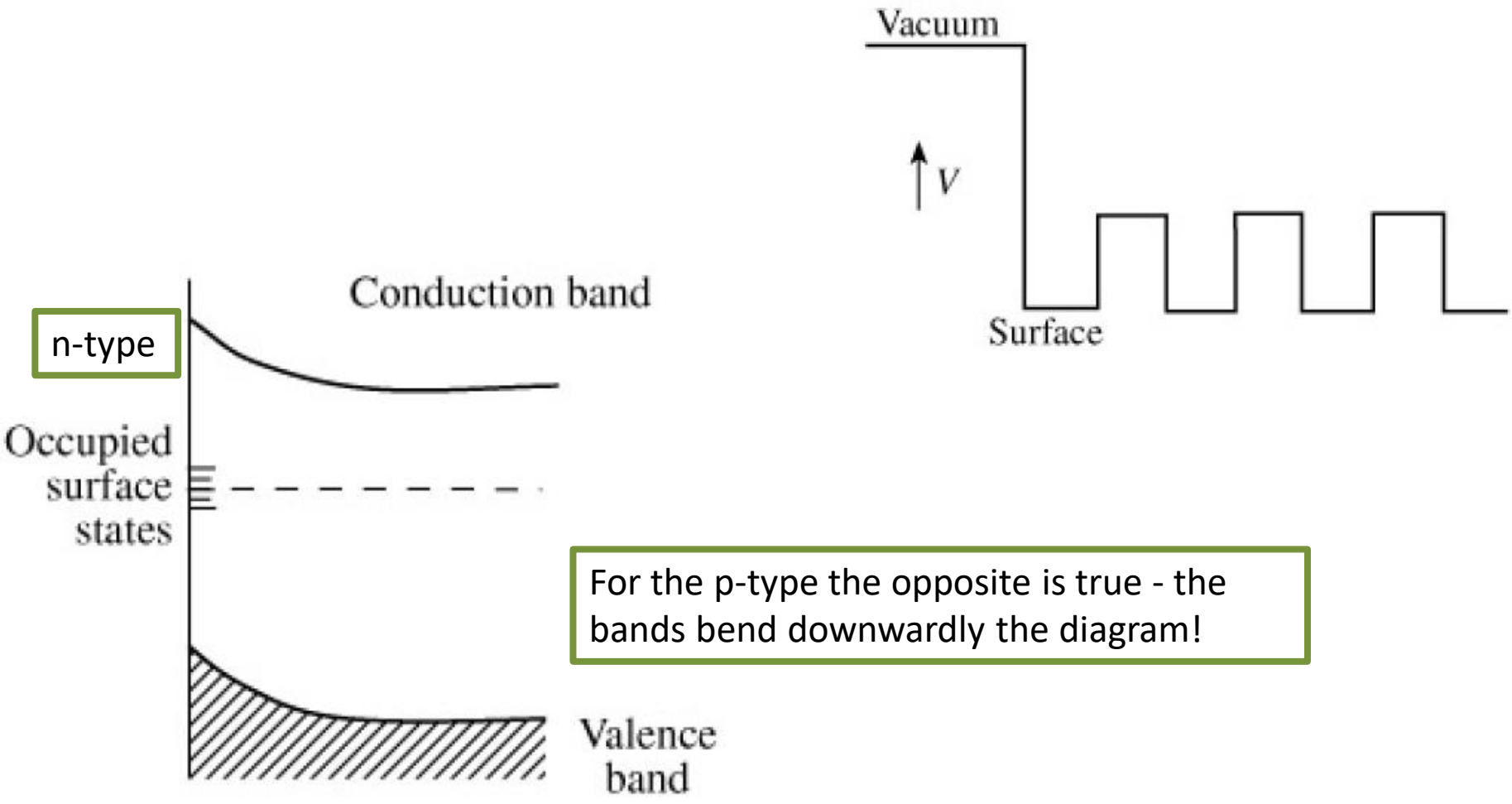


reverse bias
napięcie zaporowe

Electrical properties of materials Solymar, Walsh

The construction of energy band diagrams

The surface of the semiconductor is usually charged



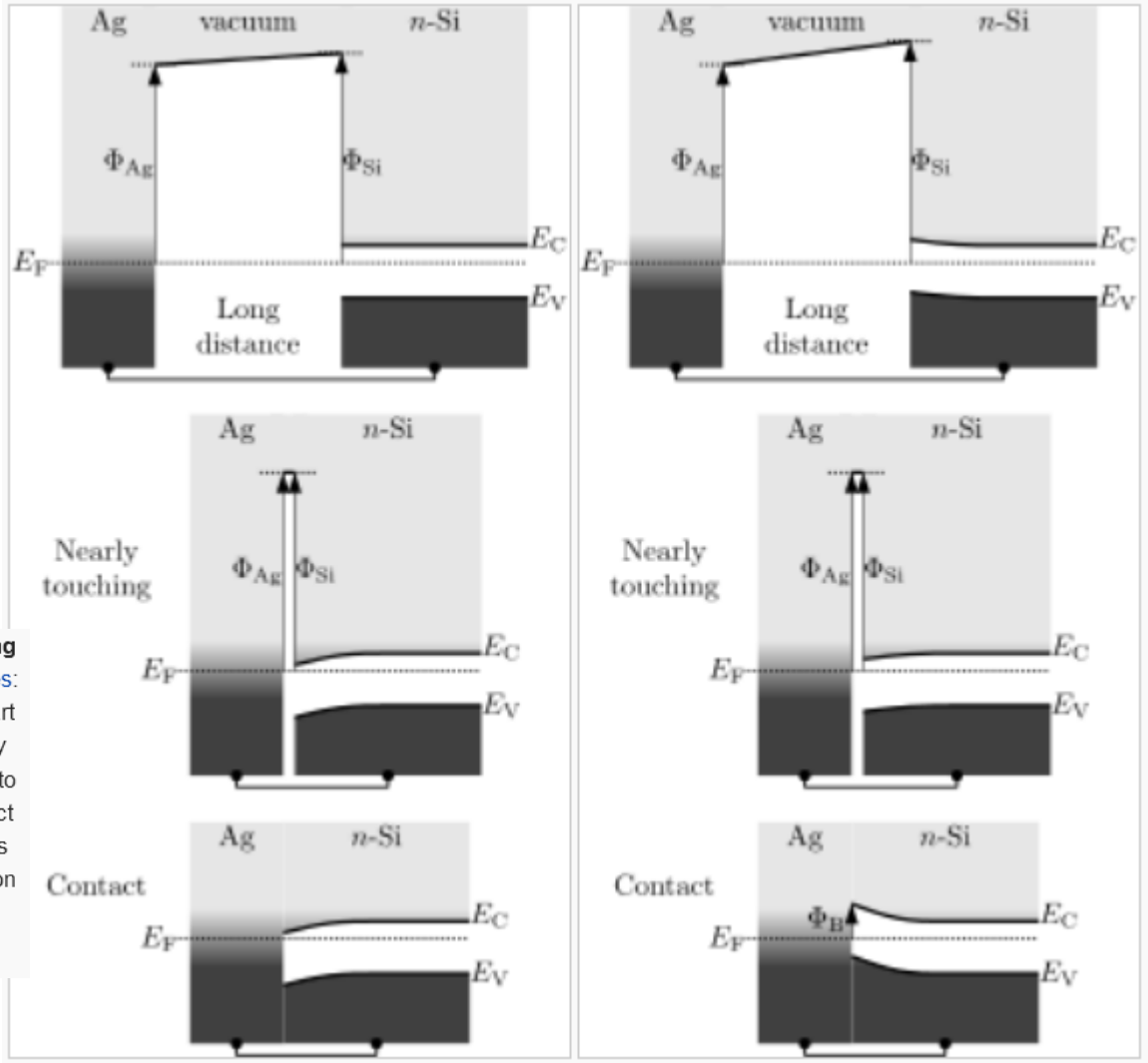
For the p-type the opposite is true - the bands bend downwardly the diagram!

Electrical properties of materials Solymar, Walsh

The construction of energy band diagrams

The metal-semiconductor junction ($\phi_{\cdot\cdot} > \phi_{\cdot}$)

n-type



Schottky–Mott rule: As the materials are brought together, the bands in the silicon bend such that the silicon's work function Φ matches the silver's. The bands retain their bending upon contact. This model predicts silver to have a very low Schottky barrier to *n*-doped silicon, making an excellent ohmic contact.

Picture showing **Fermi level pinning** effect from metal-induced gap states: The bands in the silicon already start out bent due to surface states. They are bent again just before contact (to match work functions). Upon contact however, the band bending changes completely, in a way that depends on the chemistry of the Ag-Si bonding.[4]

https://en.wikipedia.org/wiki/Metal%E2%80%93semiconductor_junction

WKB approximation

$$V(x) = V_b\left[1 - \left(\frac{x}{d}\right)^2\right]$$

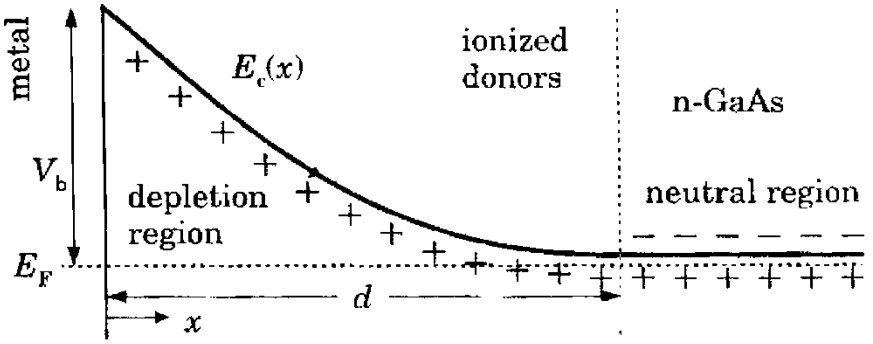


FIGURE 7.7. Schottky barrier in the conduction band $E_c(x)$ between a metal and n-GaAs. The potential is parabolic with height V_b and thickness d.

$$k_n(x) = \frac{1}{\hbar}\sqrt{2mV(x)} = \frac{1}{\hbar}\sqrt{2mV_b\left[1 - \left(\frac{x}{d}\right)^2\right]}$$

We will return discussing the transport

Heterojunction

Charge conservation

$$eN_A x_p = eN_D x_n = Q$$

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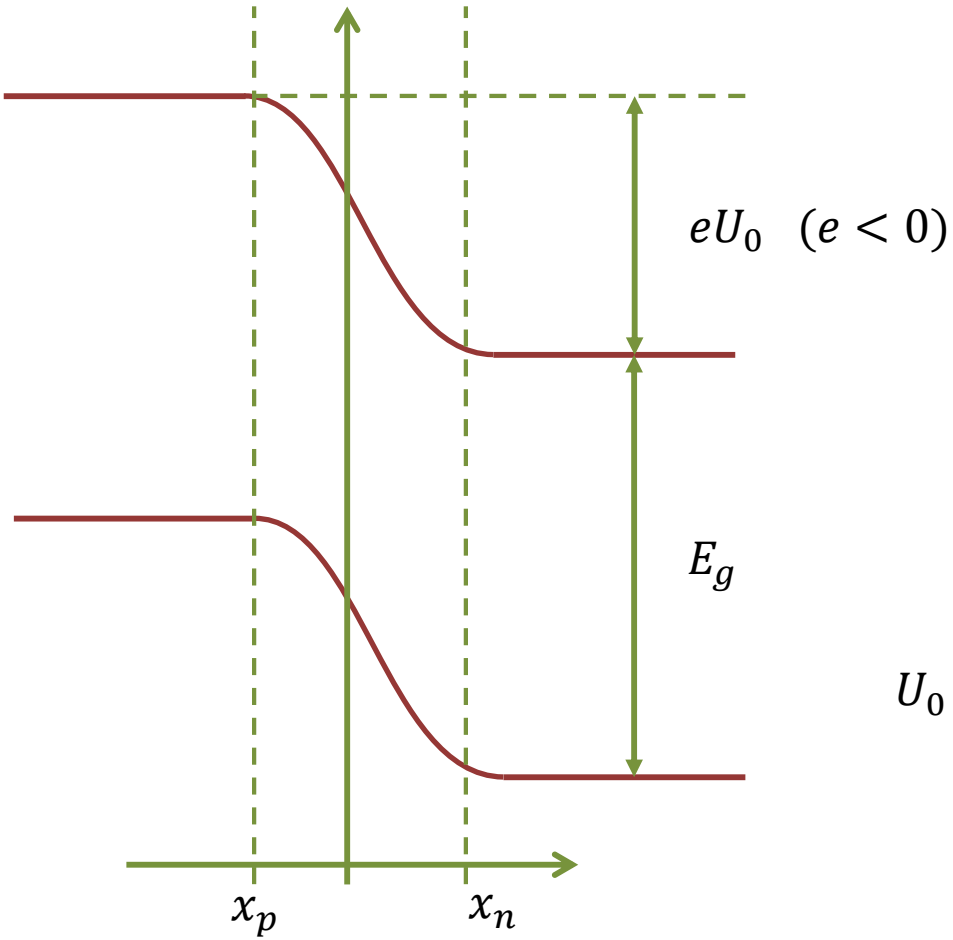
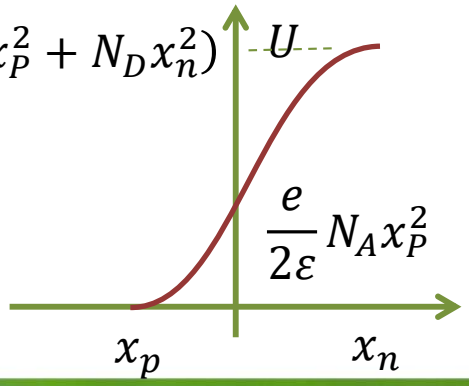


$$U_0 = \frac{e}{2\varepsilon}(N_A x_P^2 + N_D x_n^2)$$



Heterojunction

Heterozłącze (heterojunction)

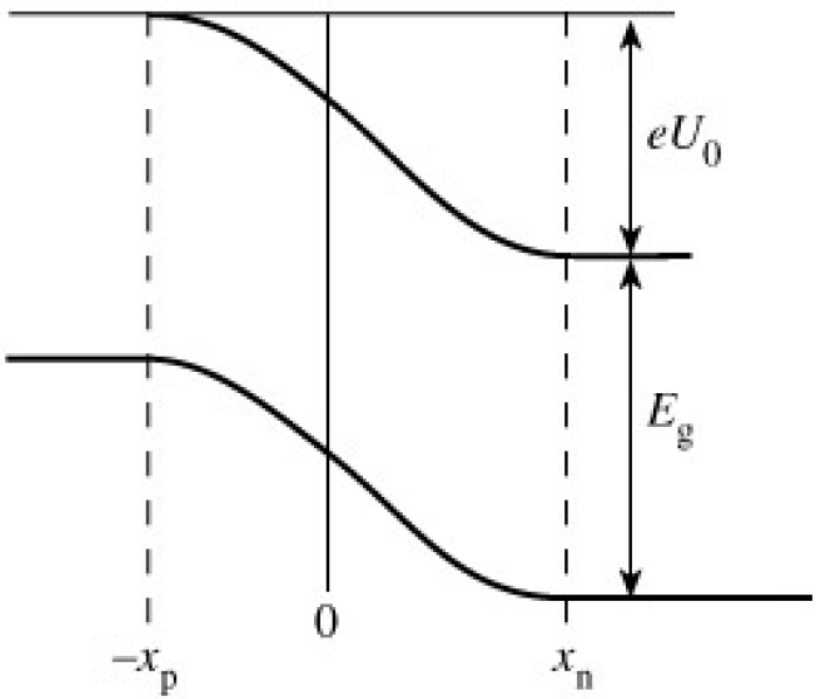
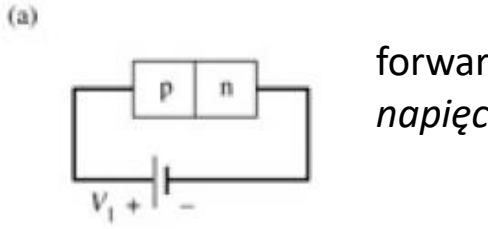
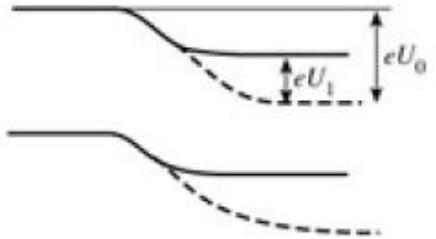
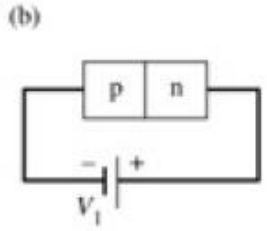


Figure 9.3: The energy diagram for the transition region of a p-n junction.

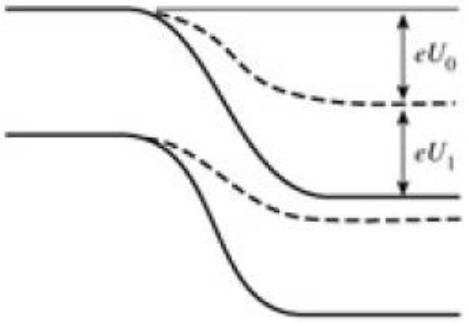


forward bias
napięcie przewodzenia



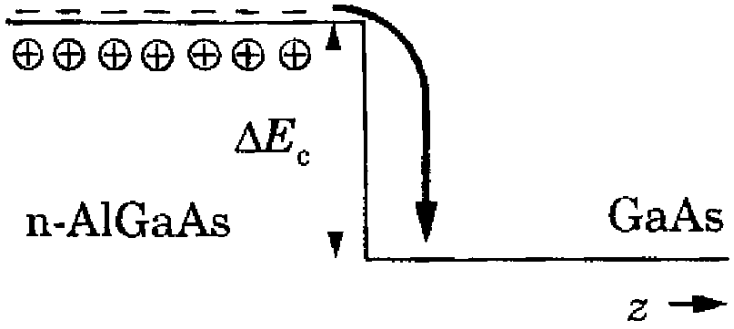


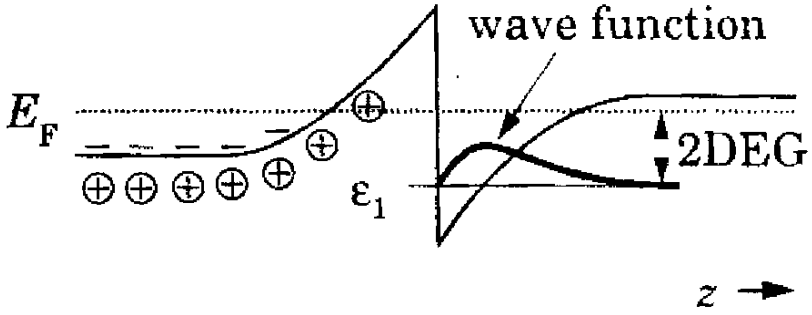
reverse bias
napięcie zaporowe



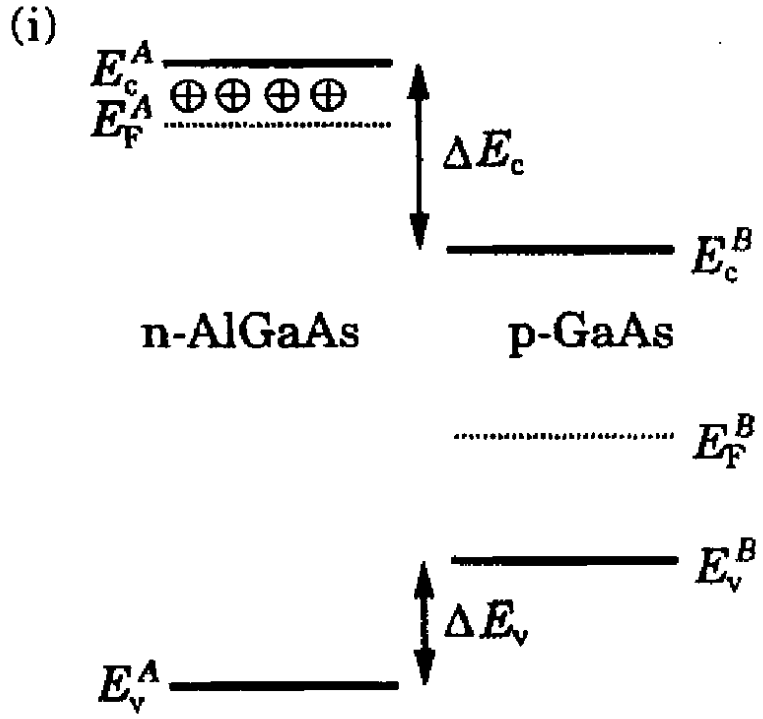
The construction of energy band diagrams

Heterozłącze (heterojunction)





The construction of energy band diagrams



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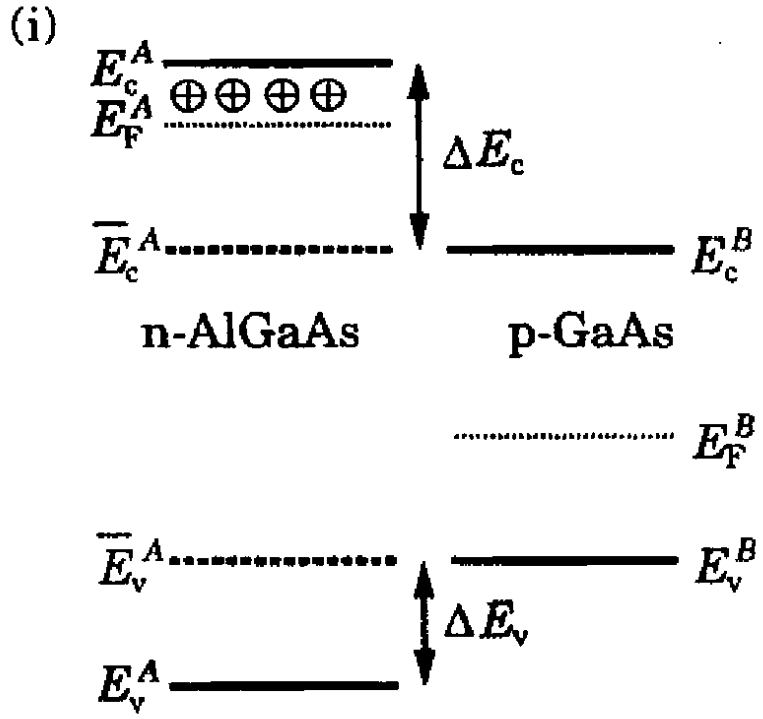
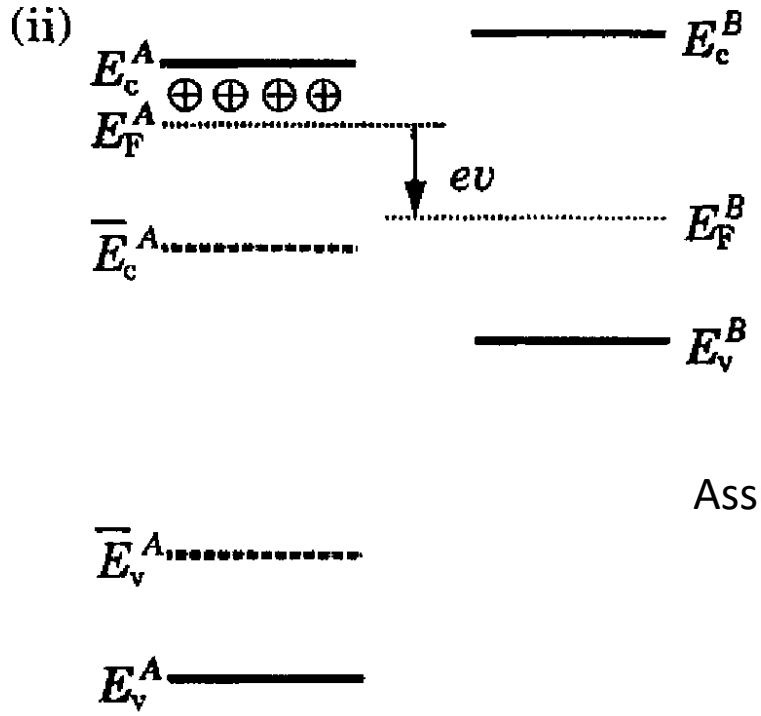


We add $\bar{E}_c^A$ i$\bar{E}_v^A$

The construction of energy band diagrams

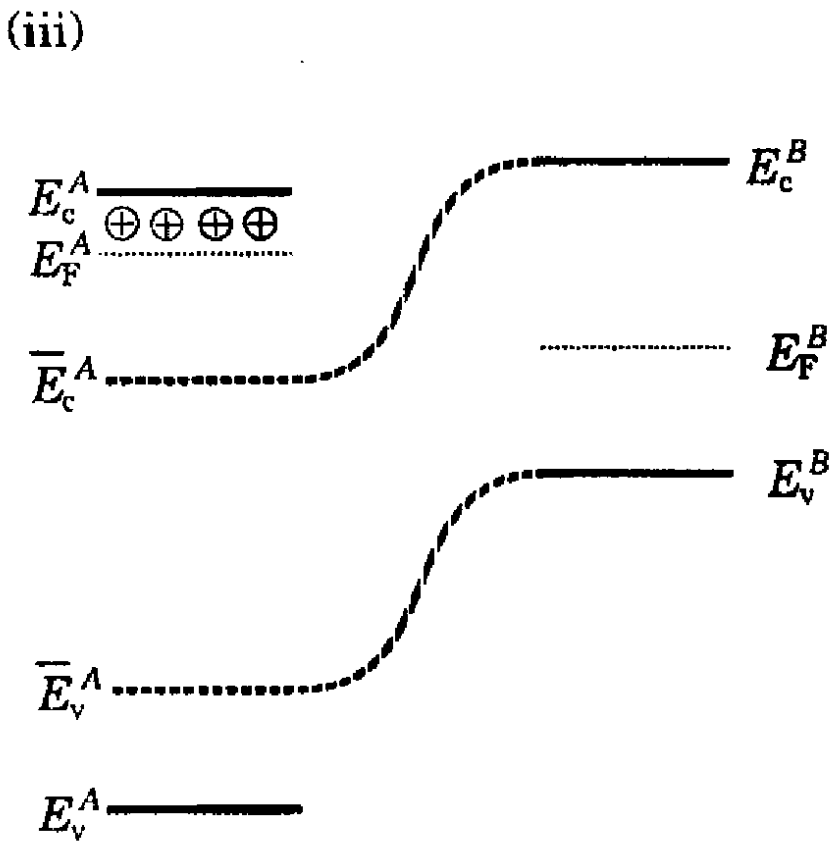


Assume that there is a positive voltage

$$E_F^A - E_F^B = ev$$

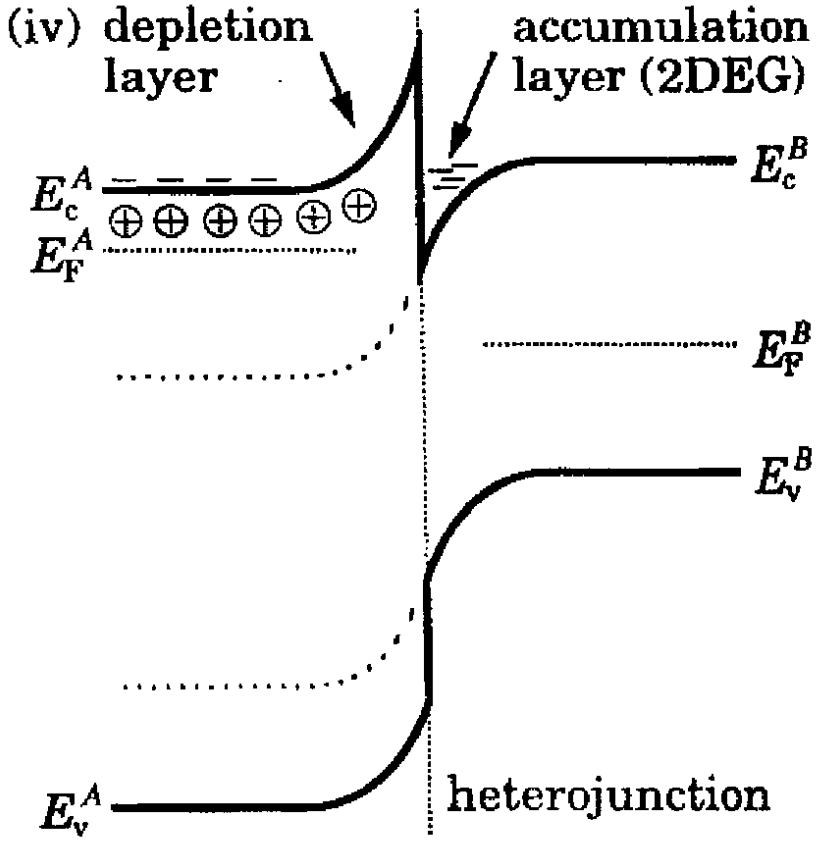
Align the Fermi levels (or the difference between them is set to applied volatge ev)

The construction of energy band diagrams



Join $\bar{E}_c^A$ with E_c^B and $\bar{E}_v^A$ with E_v^B with parallel curves (usually the point of inflexion is at the junction)

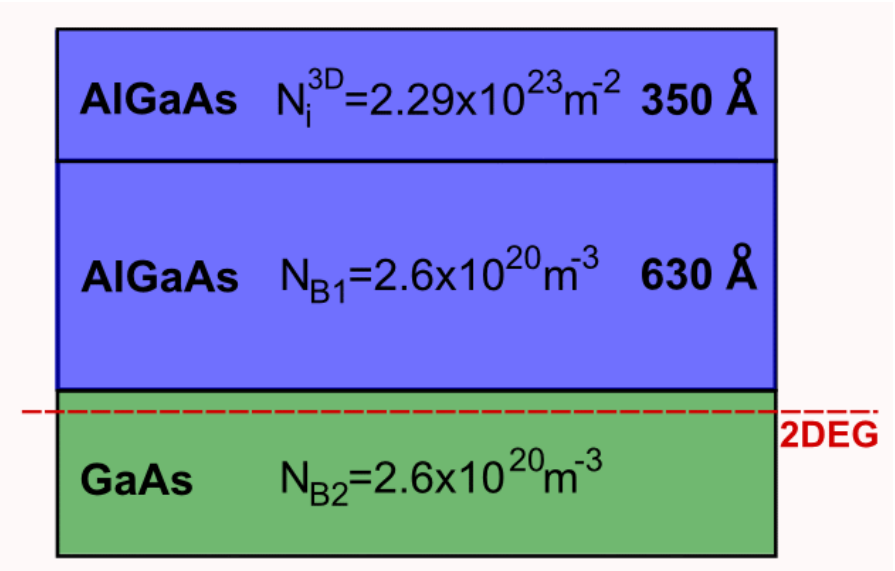
The construction of energy band diagrams

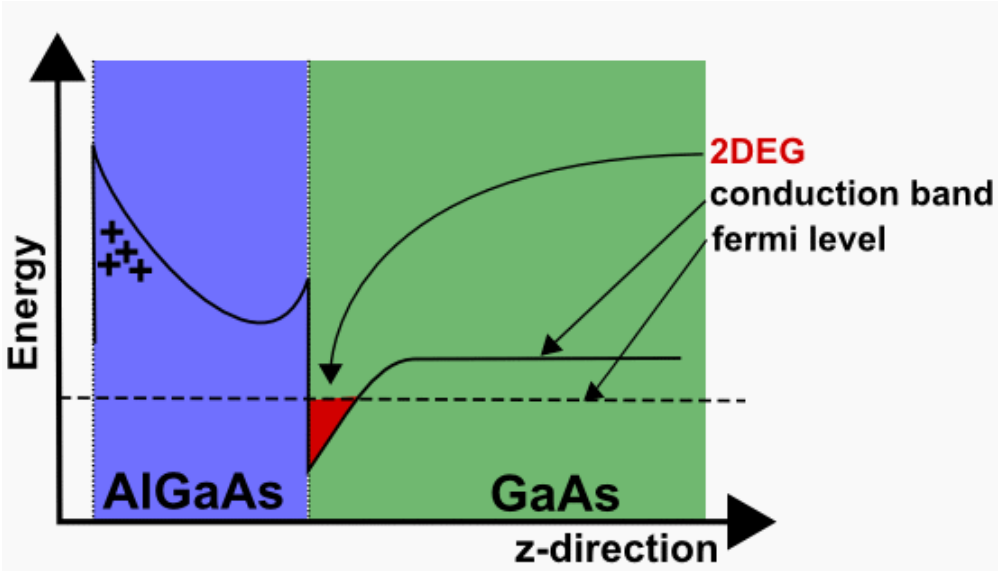


Restore $\bar{E}_c^A$ on side E_c^A and $\bar{E}_v^A$ on side E_v^A, including discontinuities at the junction.

Triangular well

WKB approximation (Wentzel – Krammers – Brillouin) – for slowly changing potential



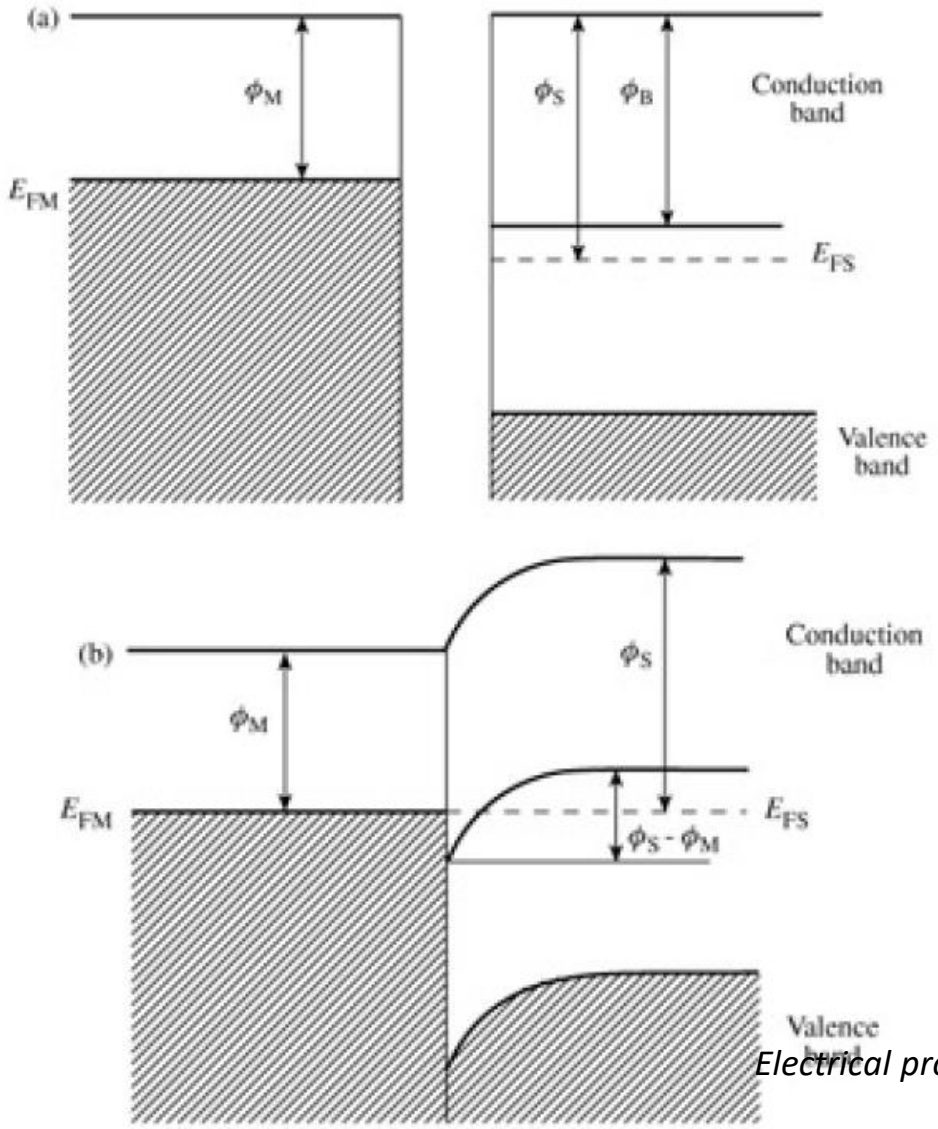


http://www.phys.unsw.edu.au/QED/research/2D_scattering.htm

$$E_n = \left[\frac{3}{2}\pi\left(n-\frac{1}{4}\right)\right]^{2/3}\left[\frac{(eF\hbar)^2}{2m}\right]^{1/3}$$

The construction of energy band diagrams

The metal-semiconductor junction ($\phi_M > \phi_S$)



n-type

Theoretically there should be no Shotky barrier

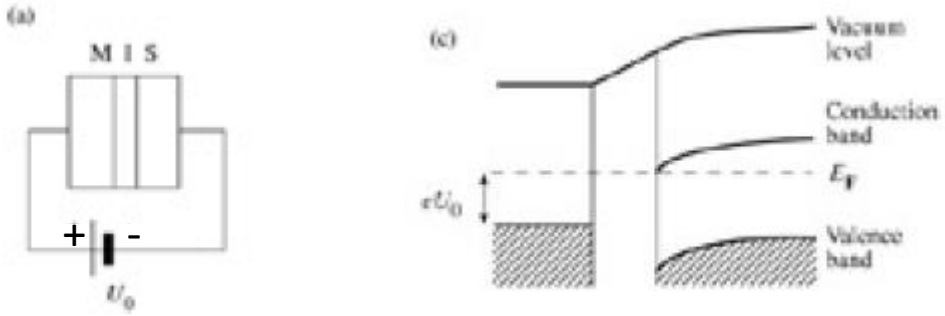
Electrical properties of materials Solymar, Walsh

The construction of energy band diagrams

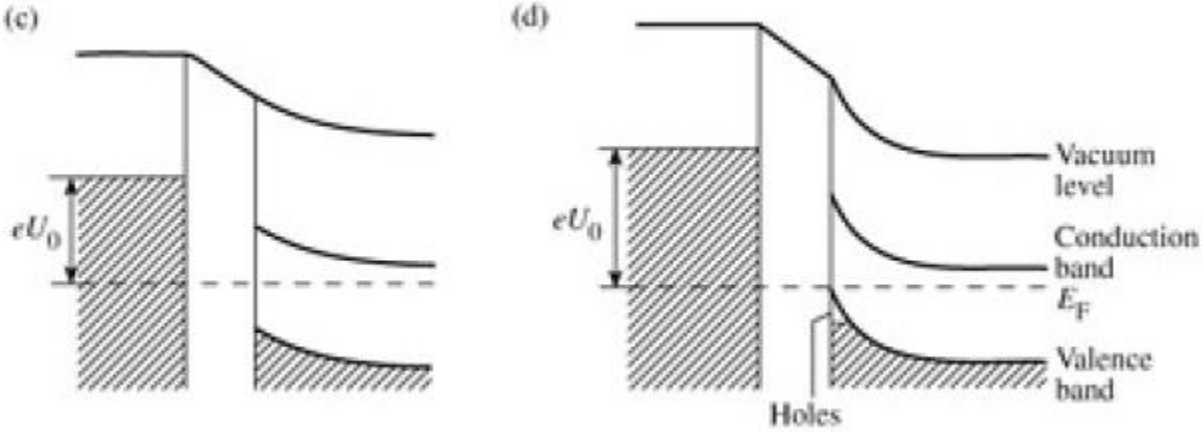
The metal-semiconductor junction ($\phi_M > \phi_S$)

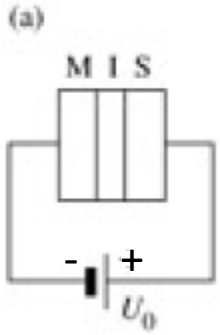
n-type

isolator



forward bias
napięcie przewodzenia



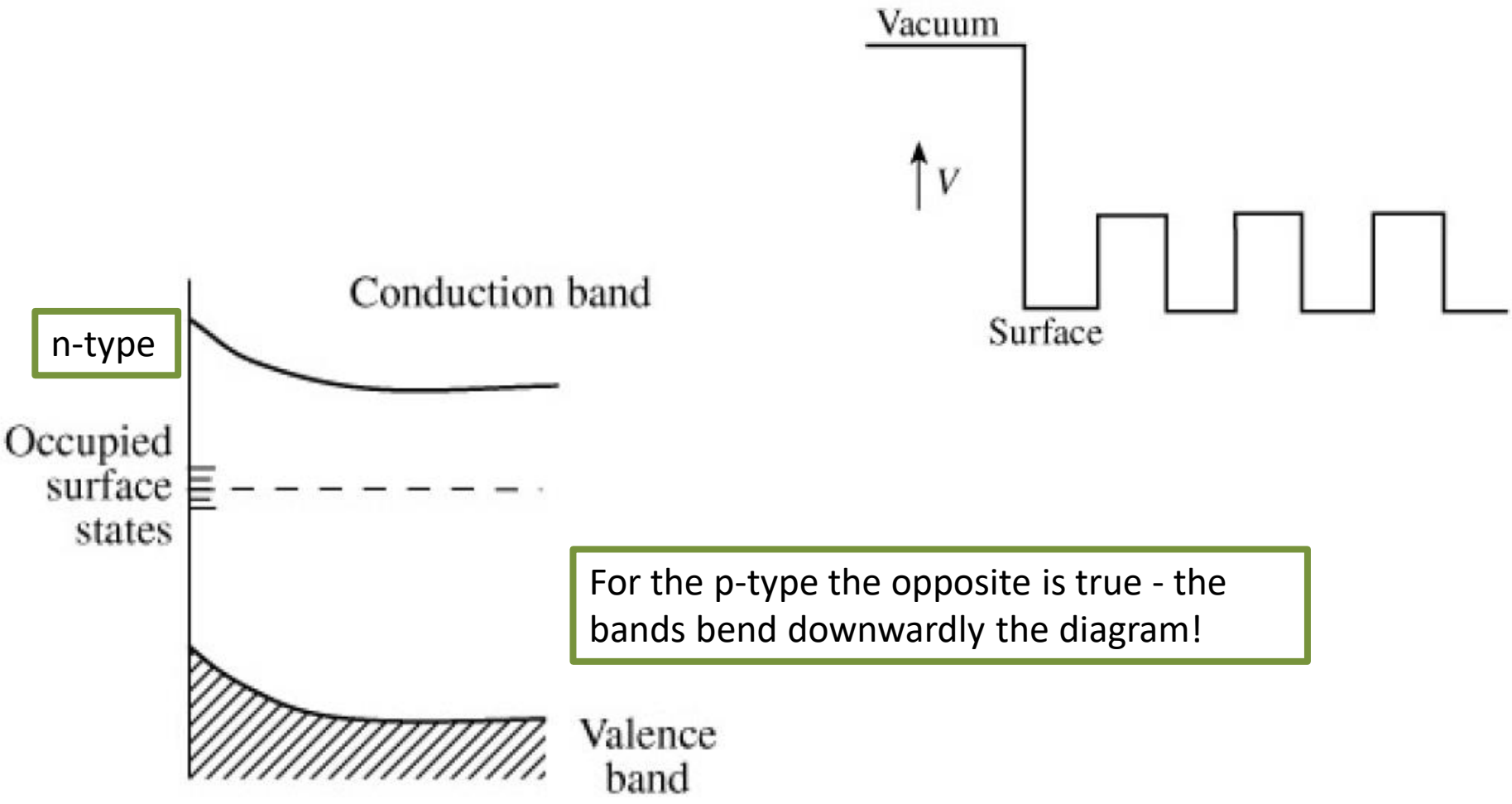


reverse bias
napięcie zaporowe

Electrical properties of materials Solymar, Walsh

The construction of energy band diagrams

The surface of the semiconductor is usually charged



For the p-type the opposite is true - the bands bend downwardly the diagram!

Electrical properties of materials Solymar, Walsh

WKB approximation

$$V(x) = V_b\left[1 - \left(\frac{x}{d}\right)^2\right]$$

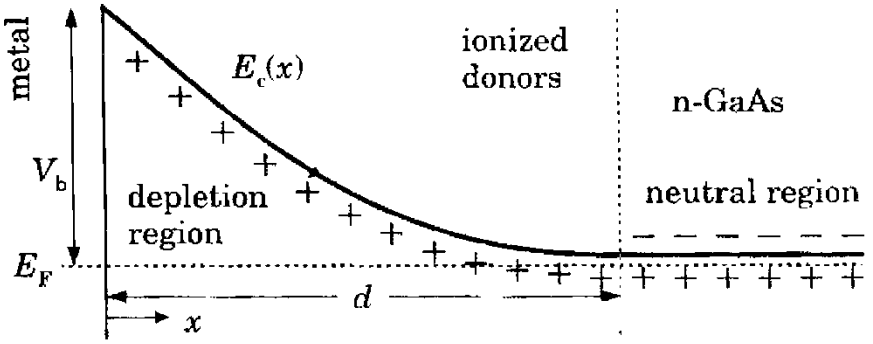


FIGURE 7.7. Schottky barrier in the conduction band $E_c(x)$ between a metal and n-GaAs. The potential is parabolic with height V_b and thickness d.

$$k_n(x) = \frac{1}{\hbar}\sqrt{2mV(x)} = \frac{1}{\hbar}\sqrt{2mV_b\left[1 - \left(\frac{x}{d}\right)^2\right]}$$

We will return discussing the transport