Semiconductor Physics
Part 2

Wei E.I. Sha (沙威)

College of Information Science & Electronic Engineering
Zhejiang University, Hangzhou 310027, P. R. China

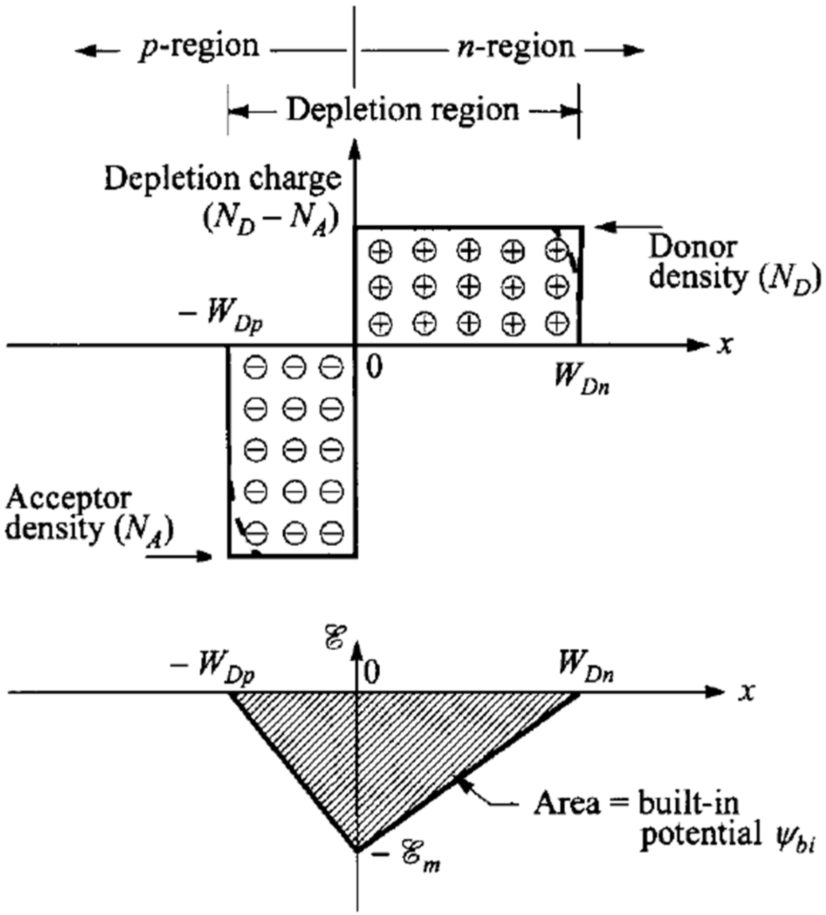
Email: weisha@zju.edu.cn
Website: http://www.isee.zju.edu.cn/weisha

Course Overview

1. P-N homojunction
2. P-N heterojunction

Ref:
Enke Liu, Semiconductor Physics, Chapter 6, Chapter 9;
Shun Lien Chuang, Physics of Photonic Devices, Chapter 2.

Depletion (space charge) region



When electrons (holes) diffuse from the N-type (P-type) region into the P-type (N-type) material, they "leave behind" the ionized donor (acceptor) atoms. These atoms cannot move within the crystal. The region where these charged ions are located constitutes a space-charge region called a depletion region.

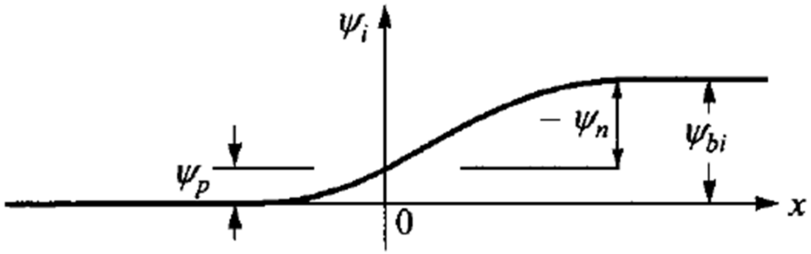
The charge densities in the depletion regions are equal to N_D in the N-type material, and N_A in the P-type material.

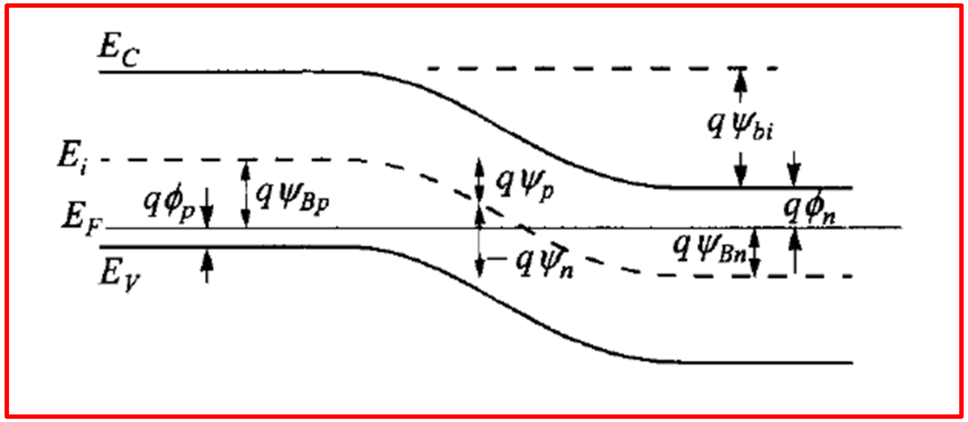
According to the Poisson equation, the E-field is linearly changed. The continuous E field at the PN-junction boundary requires that total negative charge in the depletion region on the N-side, is equal, in absolute value, to the total positive charge on the p-side.

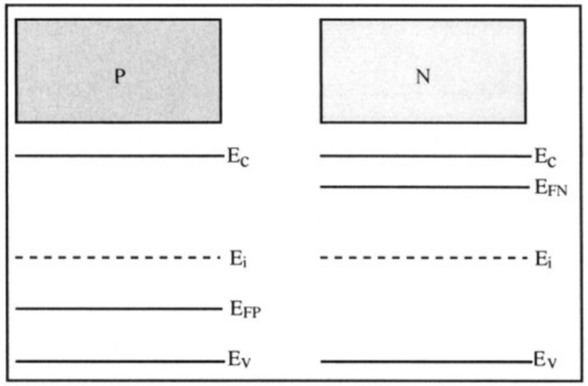
total width of depletion region

$$W = \sqrt{\psi_{bi}\left(\frac{2\varepsilon_r\varepsilon_0}{q}\right)\left(\frac{N_A + N_D}{N_A N_D}\right)}$$

Band diagram







The drift current generated by this potential variation is exactly equal and of opposite sign to the diffusion current caused by the carrier concentration gradients, such that the net current flow (drift + diffusion) is equal to zero. The potential variation actually acts as a barrier which prevents further diffusion of electrons into the P-type region and holes into the N-type region, once equilibrium has been established.

The barrier height compensates the difference of Femi level of p type and n type regions.

$$q\psi_{bi} = E_{Fn} - E_{Fp}$$

Built-in potential

electron densities at the n type and p type regions (before contact)

$$n_{n0} = n_i \exp\left(-\frac{E_i - E_{Fn}}{k_B T}\right) \qquad n_{p0} = n_i \exp\left(-\frac{E_i - E_{Fp}}{k_B T}\right)$$

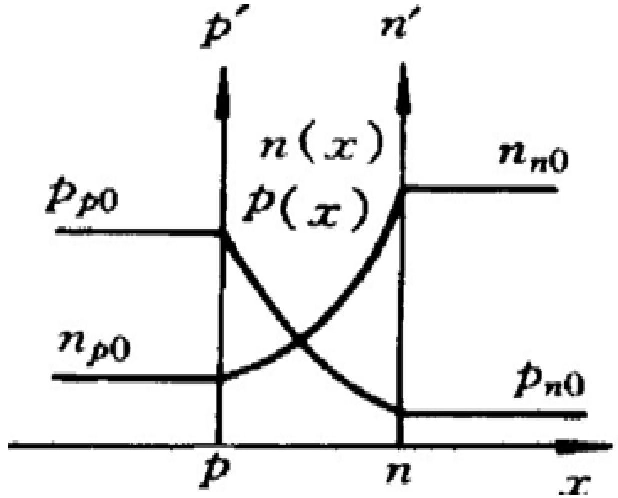
$$n_{n0} \approx N_D, \quad n_{p0} \approx n_i^2 / N_A$$

$$\psi_{bi} = \frac{E_{Fn} - E_{Fp}}{q} = \frac{k_B T}{q} \ln\left(\frac{n_{n0}}{n_{p0}}\right) = \frac{k_B T}{q} \ln\left(\frac{N_D N_A}{n_i^2}\right)$$

Charge density

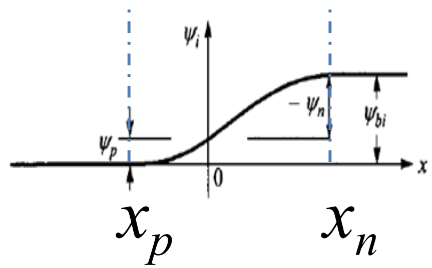
According to Boltzmann statistics, we have

$$n_{p0} = n_{n0} \exp\left(\frac{-q\psi_{bi}}{k_B T}\right), \quad p_{n0} = p_{p0} \exp\left(\frac{-q\psi_{bi}}{k_B T}\right)$$

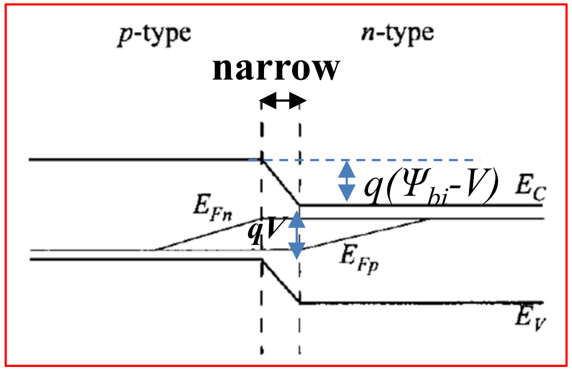


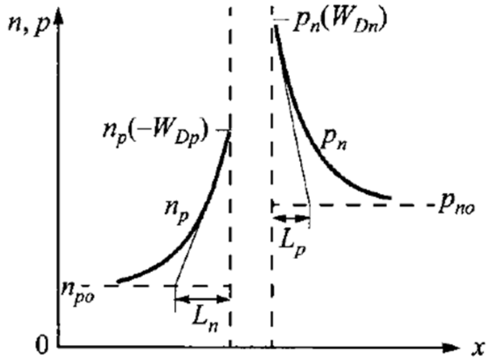
$$n(x) = n_{n0} \exp\left(\frac{q\psi(x) - q\psi_{bi}}{k_B T}\right)$$

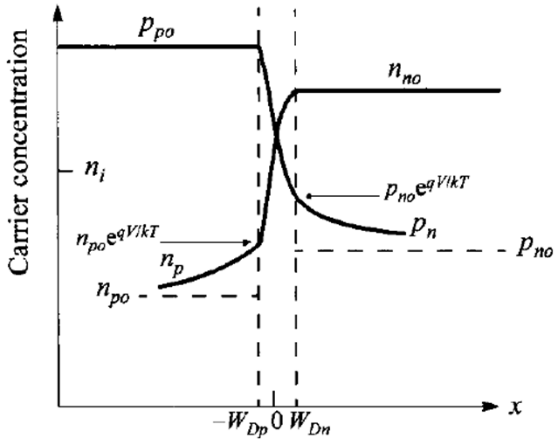
$$p(x) = p_{n0} \exp\left(\frac{q\psi_{bi} - q\psi(x)}{k_B T}\right)$$

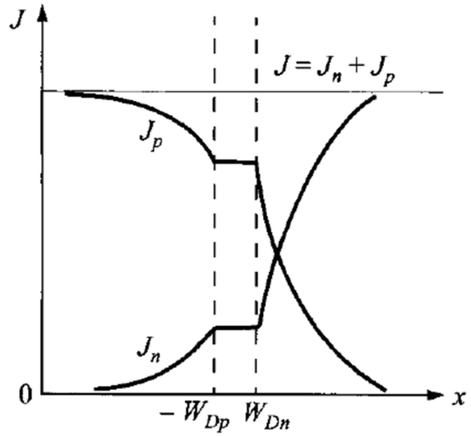


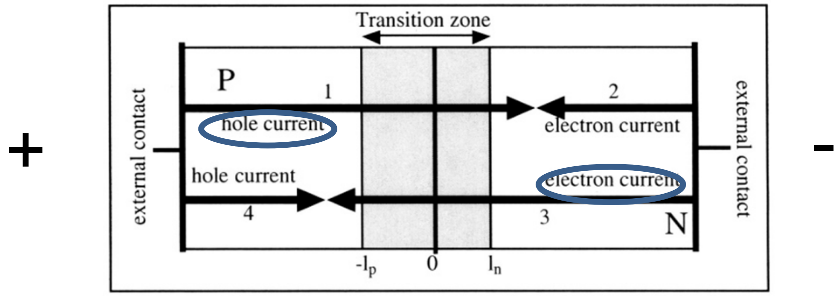
Forward bias $V>0$







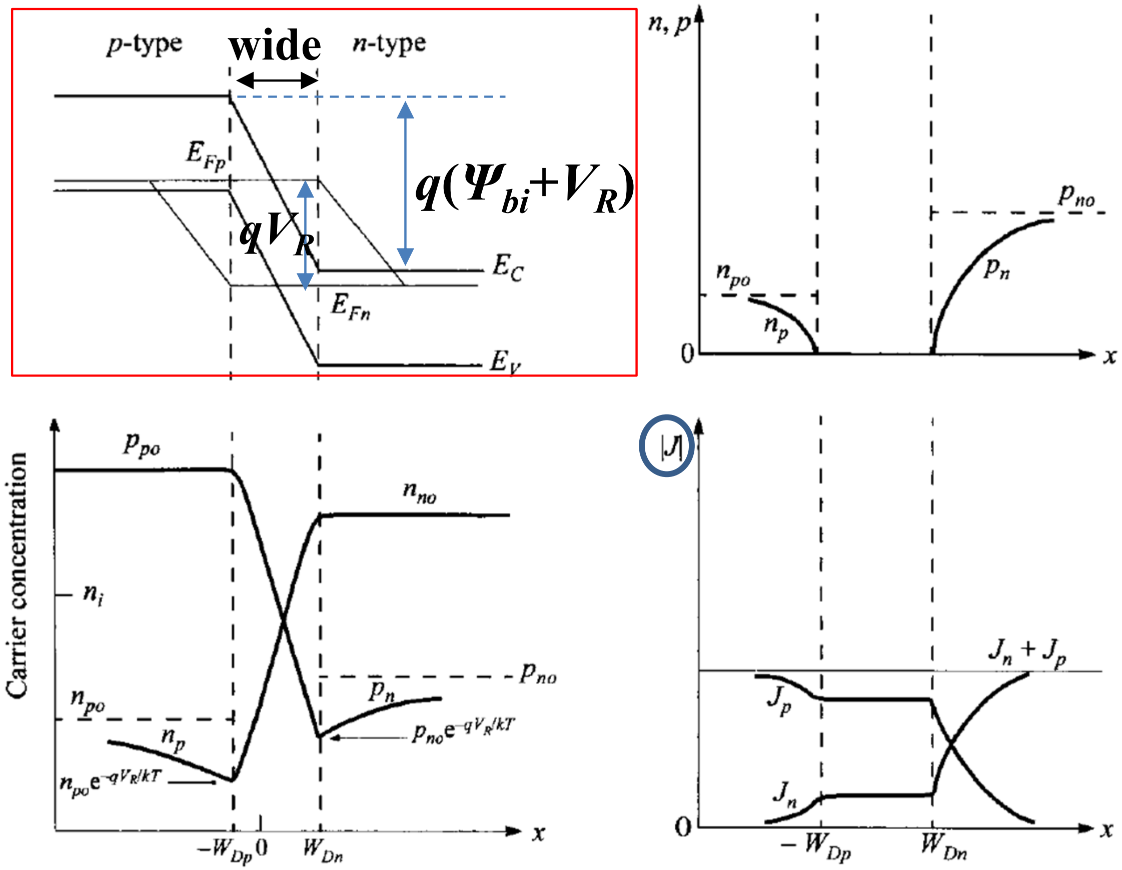




Diffusion acting on the carriers is only partially compensated by the force resulting from the junction potential variation, and therefore, holes can diffuse from the P type region into the N-type semiconductor and electrons can diffuse from the N-type region into the P-type semiconductor.

The holes injected into the N-type region are excess minority carriers. These carriers diffuse into the N-type quasi-neutral region with diffusion length L_p before recombining with the majority electrons. Since each recombination event consumes an electron, a resulting electron current appears in the N-type region where electrons are continuously supplied by the external contact ($J_1=J_2$ at contact).

Reverse bias V_R



$$|V|=V_R$$

Diffusion of holes in the N-type region and diffusion of electrons in the P-type region are reduced and net current, resulting from the drift of holes from the N-type region into the P-type region and the drift of electrons from the P-type region into the N-type region, is observed. The magnitude of this current, however, is extremely small since it involves only *minority* carriers in the vicinity of the edges of the transition region (W_{Dp} and W_{Dn}).

When *minority* carriers are extracted by the reverse bias and other minority carriers in quasi-neutral regions will diffuse towards the edges. Under revise bias, current direction is reversed compared to forward bias.

1. P-N homojunction (7) — Ideal Diode Equation

1. Low-level (weak) injection
2. Current flow in the quasi-neutral regions is due to a diffusion mechanism
3. The length of the quasi-neutral regions is much larger than the diffusion length of the minority carriers.
4. No generation/recombination occurs in the transition zone.
5. The Boltzmann statistics are valid in the quasi-neutral regions as well as in the transition region.

Boltzmann statistics

$$J = J_s\left[\exp\left(\frac{qV}{k_B T}\right) - 1\right]$$

J_s: reverse saturation current

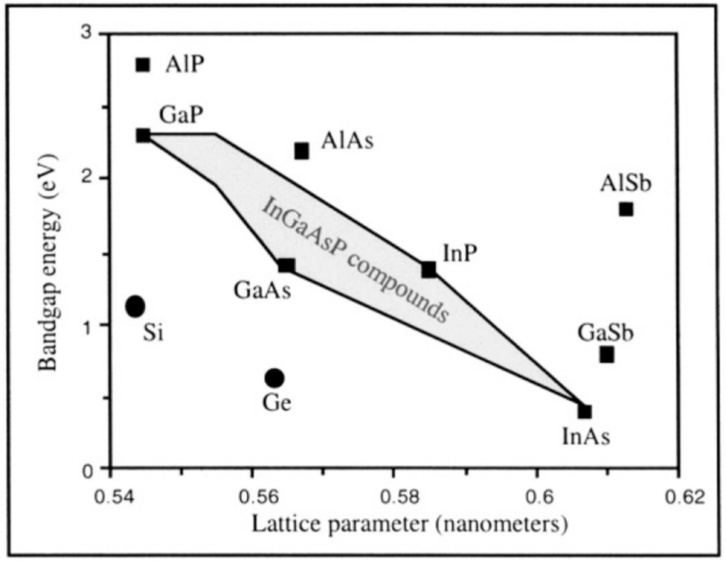
Saturated "diffusion current" for minority carriers

$$J_s = (q n_{p0})\left(\frac{D_n}{L_n}\right) + (q p_{n0})\left(\frac{D_p}{L_p}\right) = q\frac{D_n n_i^2}{L_n N_A} + q\frac{D_p n_i^2}{L_p N_D}$$

1. P-N heterojunction (1)

Basic concepts

Beside elements from the fourth column of the periodic table and compounds thereof (Si, Ge, C, SiC and SiGe), a whole range of semiconductors can be synthesized using elements from columns III and V, such as GaAs, InP, $Ga_xAl_{1-x}As$, etc. Arbitrary values of the bandgap energy can be obtained using ternary or quaternary compounds, such as $Ga_xAl_{1-x}As$ and $Ga_xIn_{1-x}As_yP_{1-y}$.



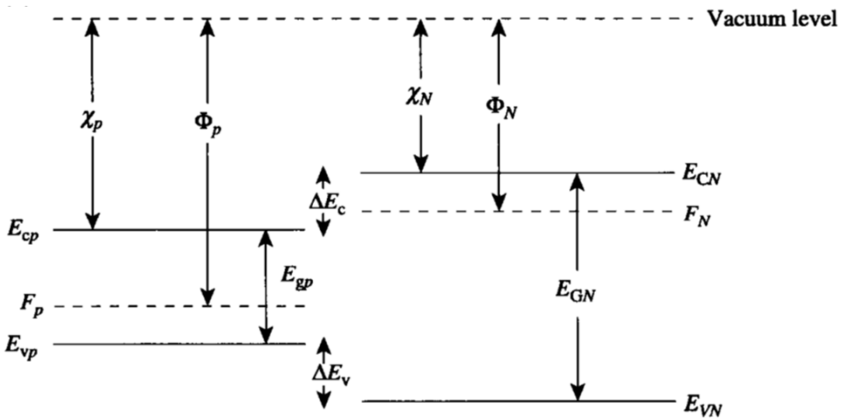
A P-N junction that encompasses two different semiconductors is called a <u>heterojunction</u>. The most distinctive feature of such junctions is that the P and the N region have <u>different energy band gaps</u>. A junction containing only one semiconductor, such as a classical silicon PN junction, is called a <u>homojunction</u>.

$$\mathbf{E}_n = -\nabla \psi_n \quad \psi_n = \varphi + \chi / q + (k_B T / q)\ln(N_c)$$

$$\mathbf{E}_p = -\nabla \psi_p \quad \psi_p = \varphi + \chi / q + E_g / q - (k_B T / q)\ln(N_v)$$

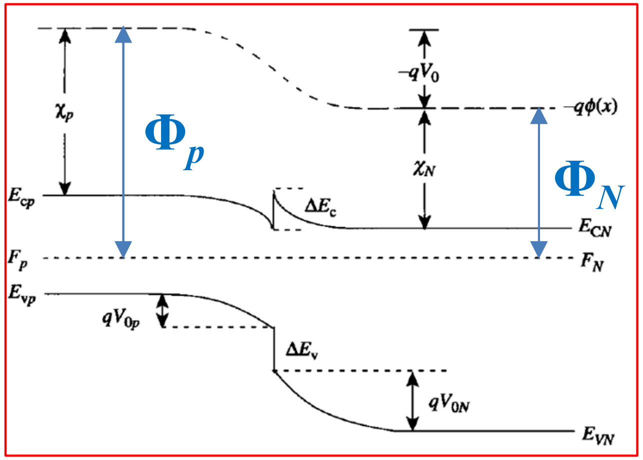
Band-diagram

Why can carriers be blocked by heterojunction?



$$\Delta E_c = \chi_p - \chi_n$$

$$\Delta E_c + \Delta E_v = E_{GN} - E_{gp}$$



1. Under equilibrium conditions, the Fermi level in the two semiconductors is equal and constant. Far from the junction, the semiconductor will be neutral and their energy band diagram will be the same as when the two semiconductors are taken separately; 2. The work functions Φ remain unchanged in the neutral zones. This enables us to draw the vacuum levels, far from the junction; 3. The vacuum levels of the two semiconductors are connected by a smooth, continuous curve. The vacuum level bends only within the transition region with the potential drop $V_0=(F_N-F_p)/q$; 4. Electrons (holes) will diffuse from the N-type (P-type) semiconductor into the P-type (N-type) one. The resulting charge distribution gives rise to a depletion region, an internal junction potential is parallel to that of the vacuum level; 5. Finally, the valence and conduction levels are connected using vertical line segments, at the metallurgical junction.

Charge, electrostatic field, and potential distribution

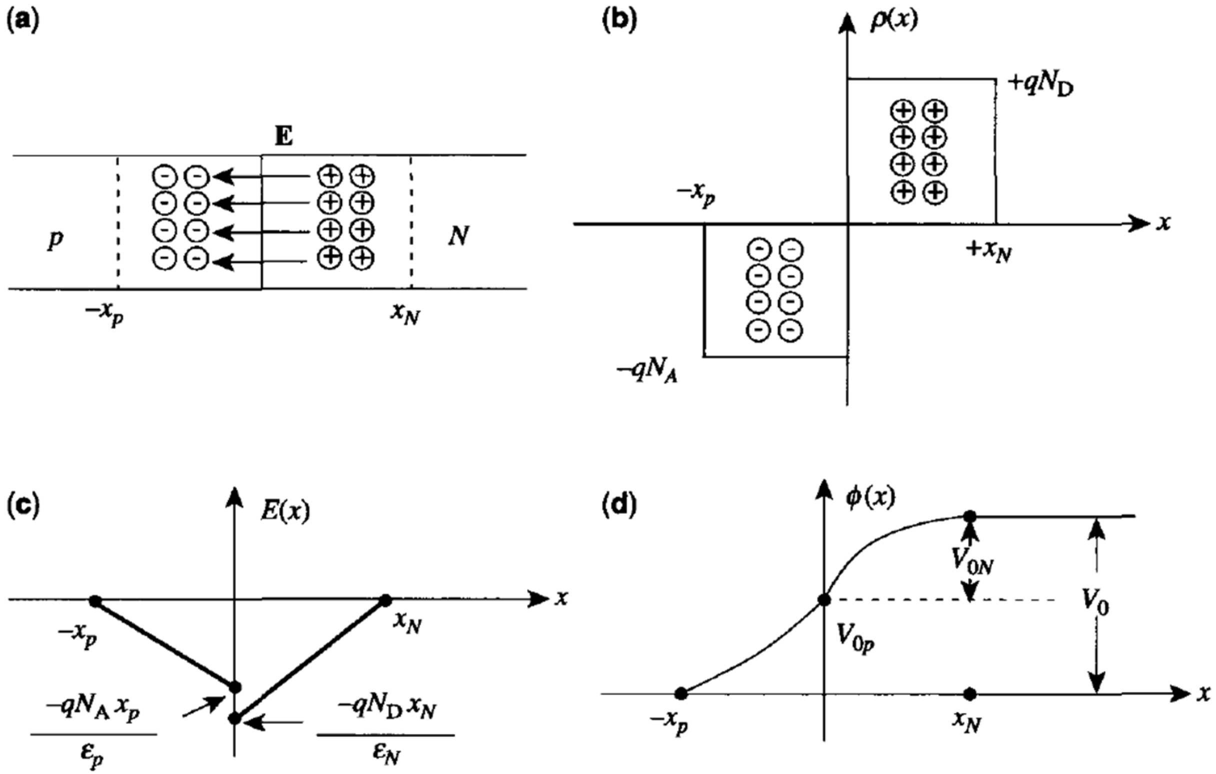
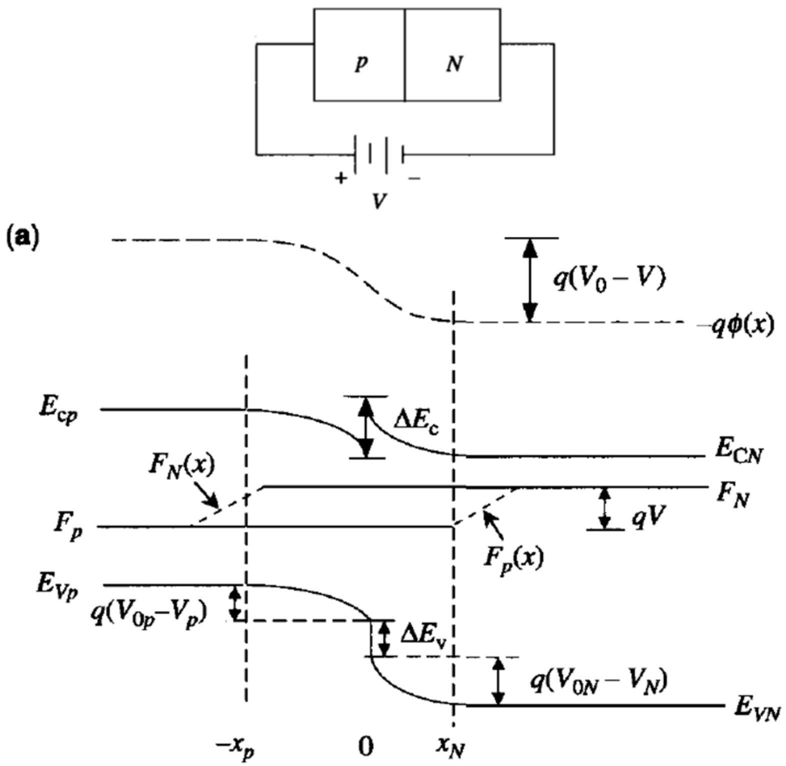


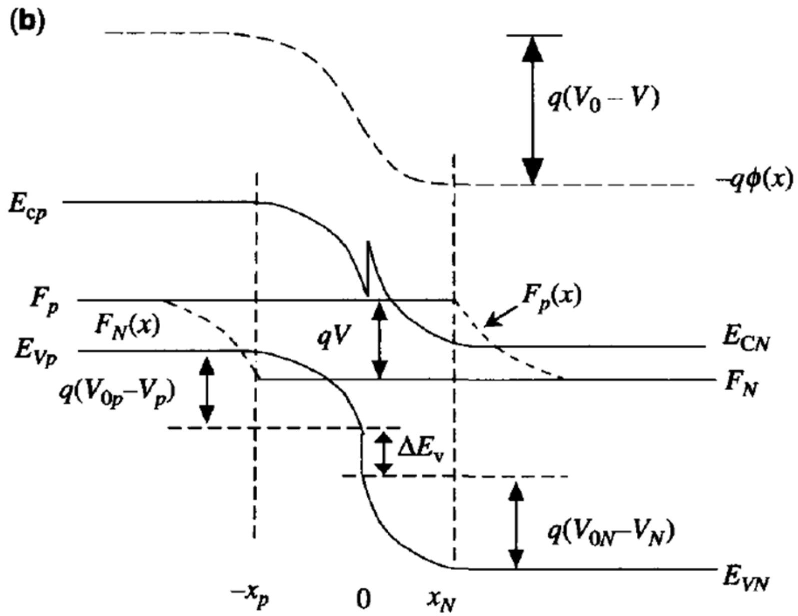
Figure 2.11 Illustrations of (a) a *p-N* junction geometry, (b) the charge distribution, (c) the electric field, and (d) the electrostatic potential based on the depletion approximation.

1. P-N heterojunction (4)

Biased P-N heterojunction — Band diagram



forward bias

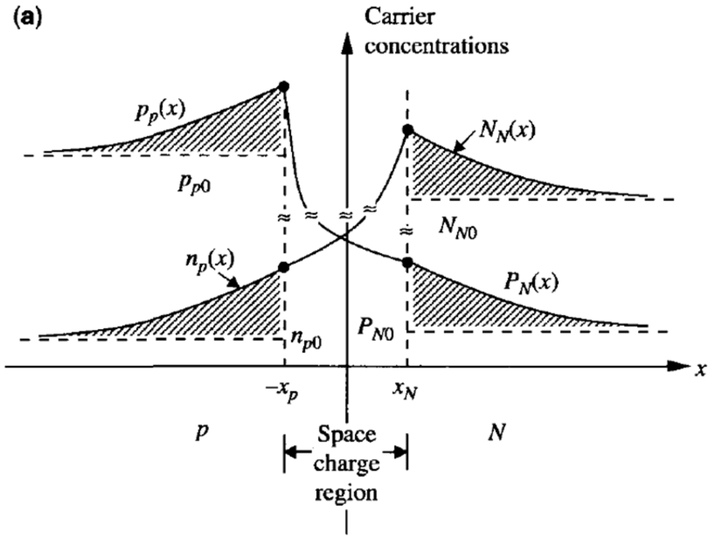


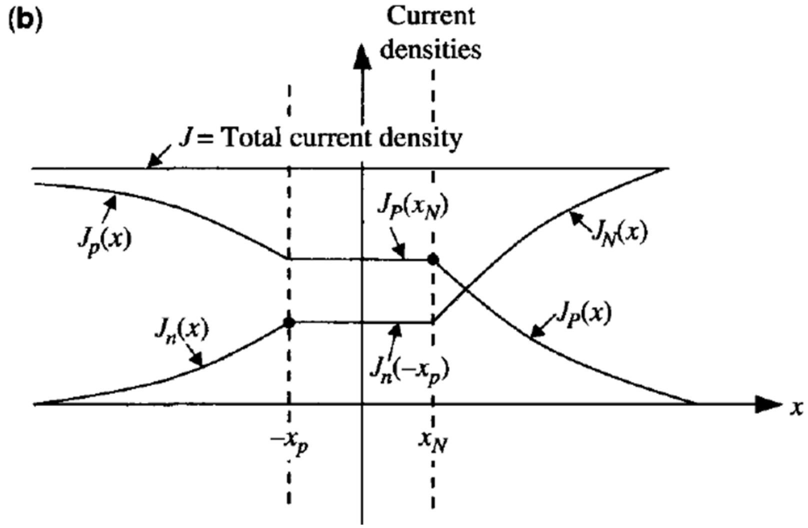
reverse bias

$$F_N - F_p = qV$$

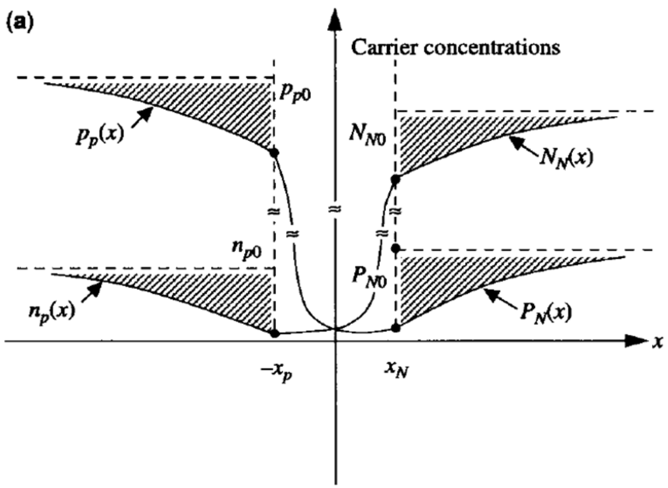
Biased P-N heterojunction — Carrier Densities and Currents

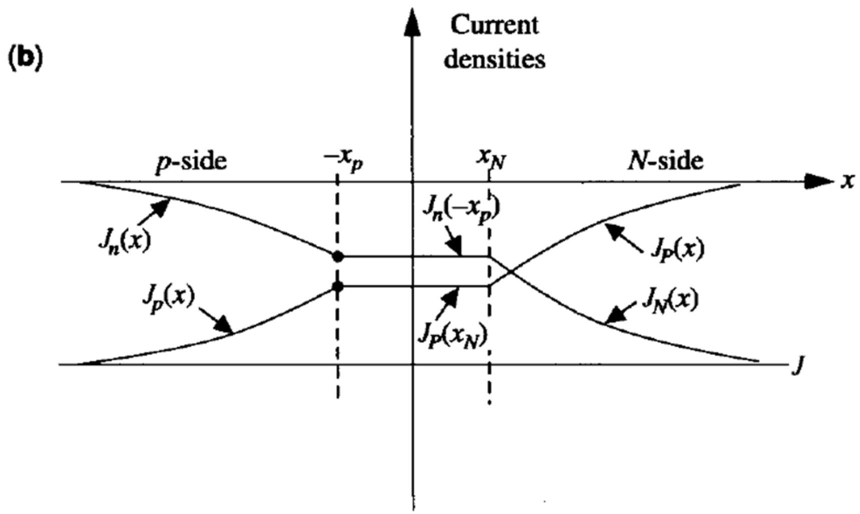
forward





reverse





1. P-N heterojunction (6)

Ideal diode equation for heterojunction (diffusion type)

$$J = J_s \left[\exp\left(\frac{qV}{k_B T} \right) - 1 \right]$$

Saturated "diffusion current" for minority carriers

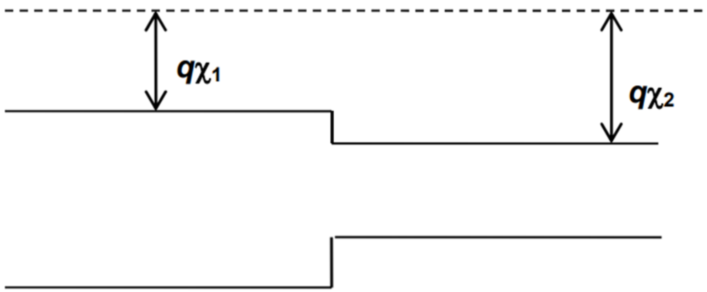
$$J_s = \left(q n_{p0} \right) \left(\frac{D_n}{L_n} \right) + \left(q P_{N0} \right) \left(\frac{D_p}{L_p} \right)$$

$$\frac{J_n}{J_p} = \frac{D_n L_p n_{p0}}{D_p L_n P_{N0}} = \frac{D_n L_p N_D n_{iP}^2}{D_p L_n N_A n_{iN}^2} = \frac{D_n L_p N_D N_{CP} N_{VP} \exp(-E_{gP} / k_B T)}{D_p L_n N_A N_{CN} N_{VN} \exp(-E_{GN} / k_B T)}$$

$$\frac{J_n}{J_p} \sim \exp\left(\frac{E_{GN} - E_{gP}}{k_B T} \right)$$

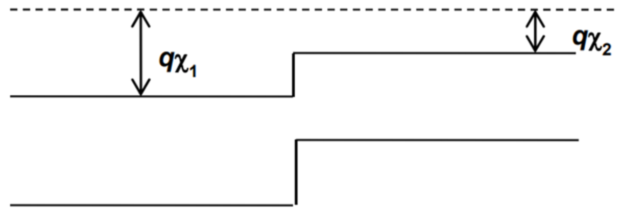
The **injection ratio** depends exponentially on the bandgap difference. This is critical in designing a bipolar transistor and laser.

Types of heterojunction



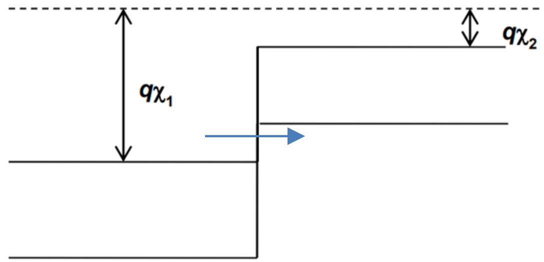
Straddling gap

2D electron gas
quantum well
LED/laser



Staggered gap

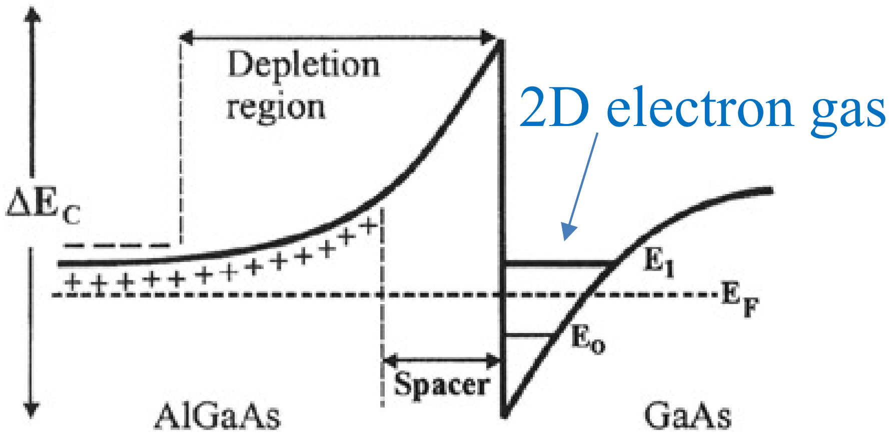
solar cells
photodetectors

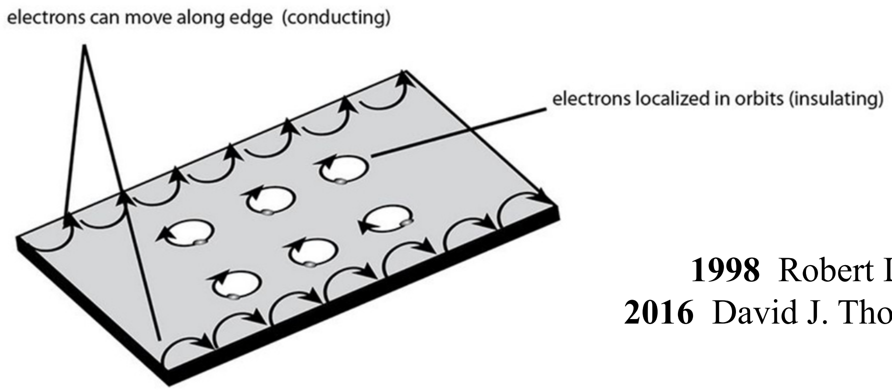


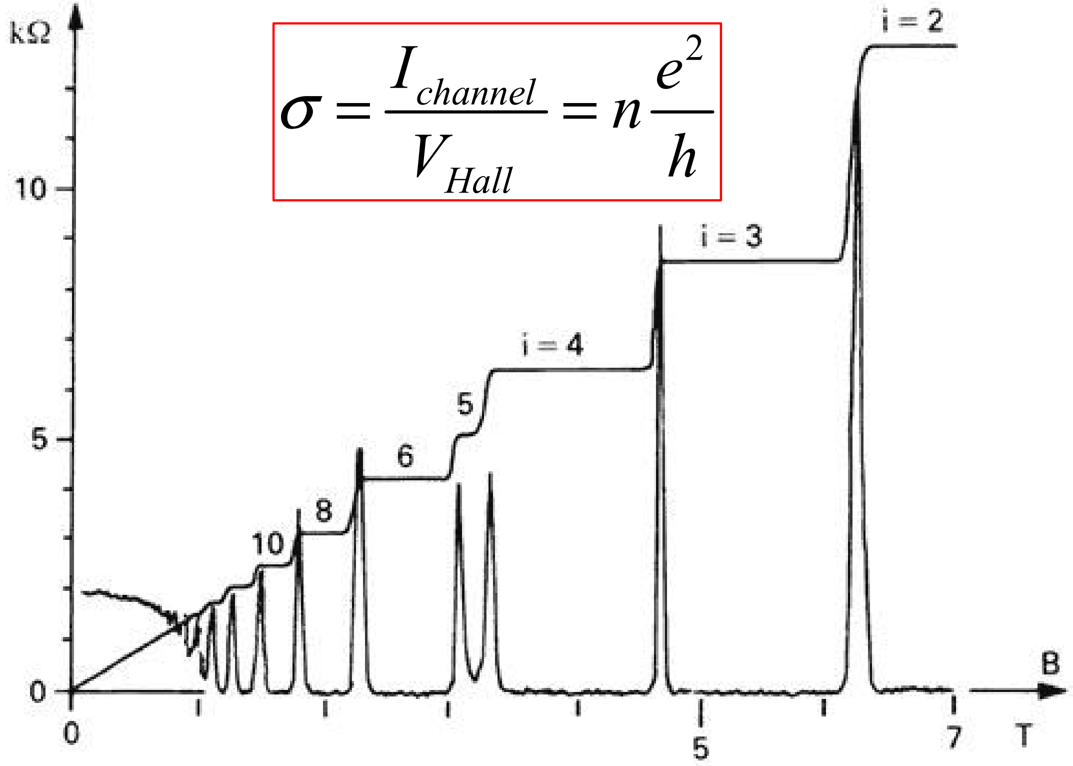
Broken gap

tunneling junction

Quantum hall effect (optional)







$$\sigma = \frac{I_{channel}}{V_{Hall}} = n\frac{e^2}{h}$$

1985 Von Klitzing **quantum hall effect**

1998 Robert Laughlin, Horst Störmer, and Daniel Tsui **fractional quantum hall effect**

2016 David J. Thouless, F. Duncan M. Haldane, and J. Michael Kosterlitz **topological insulator**

The quantum Hall effect is a quantum-mechanical version of the Hall effect, observed in two-dimensional electron systems subjected to low temperatures and strong magnetic fields, in which the Hall conductance σ undergoes quantum Hall transitions to take on the quantized values.