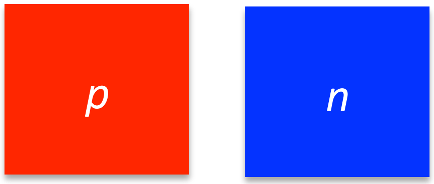
Overview

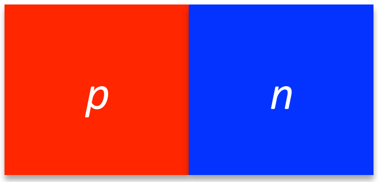
- Junctions between *n* and *p*-type doped semiconductors are called **p-n junctions**
- These junctions are at the heart of most semiconductor devices
- If the transition between n- and p-areas are abrupt we speak of an **abrupt p-n junction**
- Electrons and holes of both sides can combine via drift and diffusion, resulting in a **depletion or space charge zone**
- The redistribution of charge results in a **built-in potential** V_{bi}
- **Band structure, doping levels and profiles, ionization energies as well as generation and recombination rates** determine the performance of the junction and hence that of the devices
- Junctions between different semiconductors (band structure, doping levels, work functions and electron affinities) are called **heterojunctions**

Equilibrium case (no external fields)

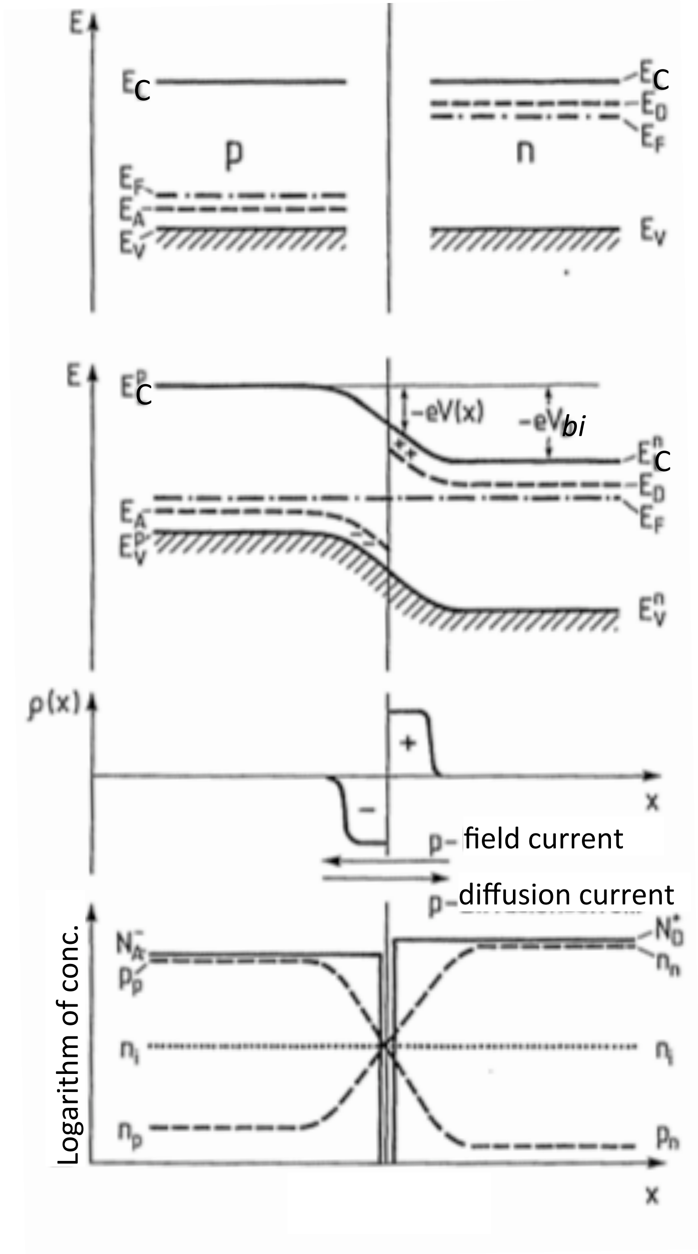
- *p* and *n* semiconductors separated



- *p* and *n* semiconductors in contact

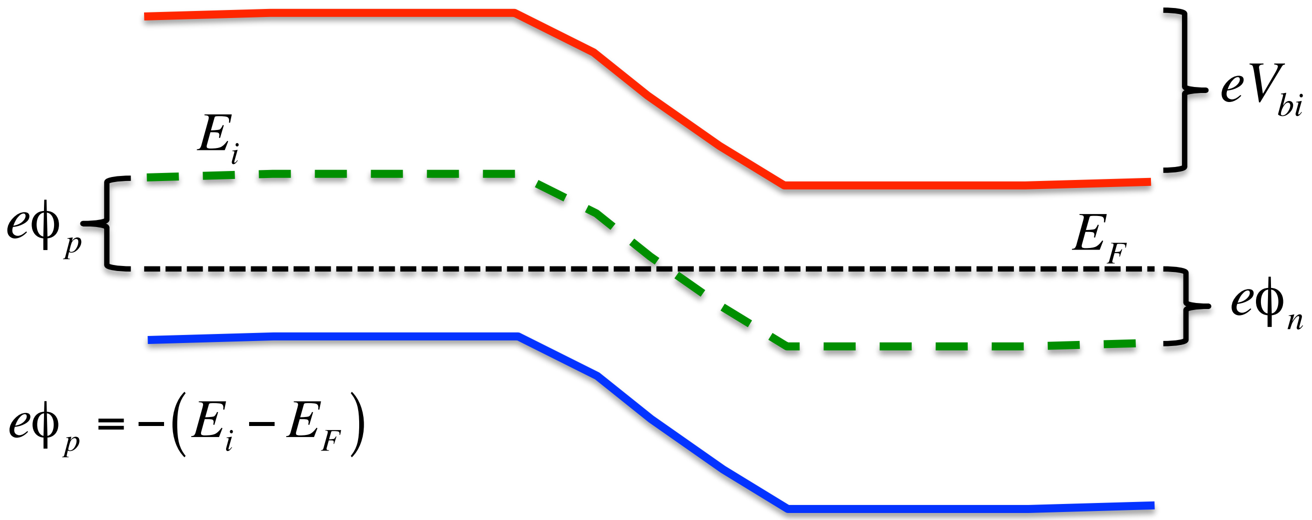


- Chemical potentials (~E_F) equilibrate at interface
- Charge carrier drift and diffusion fluxes equilibrate
- A built-in potential V_{bi} forms due to charge separation
- Charge carrier densities become spatially dependent



Equilibrium case (no external fields)

- The built-in potential V_{bi}



$$e\phi_p = -(E_i - E_F)$$

- Charge neutrality

$$N_D - N_A + p - n = 0 \quad \Bigg| \quad p = p_0 \exp\left(\frac{E_i - E_F}{k_B T}\right) \quad \Bigg| \quad p_0 \approx n_i \Rightarrow k_B T \ln\left(\frac{p}{n_i}\right) = E_i - E_F$$

- Full ionisation

$$p = N_A \Rightarrow e\phi_p = -k_B T \ln\left(\frac{N_A}{n_i}\right) \,\&\, e\phi_n = -k_B T \ln\left(\frac{N_D}{n_i}\right)$$

- Built-in potential

$$\boxed{V_{bi} = \phi_n - \phi_p = \frac{k_B T}{e} \ln\left(\frac{N_A N_D}{n_i^2}\right)}$$

Equilibrium case (no external fields)

- Charge carrier densities

$$n = n_0 e^{-\frac{E_C-\mu-eV(x)}{k_BT}} \qquad p = p_0 e^{-\frac{\mu-E_V+eV(x)}{k_BT}}$$

$$\Rightarrow \qquad \Rightarrow$$

$$\frac{\partial n}{\partial x} = n\frac{e}{k_BT}\frac{\partial V(x)}{\partial x} \qquad \frac{\partial p}{\partial x} = -p\frac{e}{k_BT}\frac{\partial V(x)}{\partial x}$$

- Diffusion current

$$j^{diff} = j_n^{diff} + j_p^{diff}$$

$$= e\left(D_n\frac{\partial n}{\partial x} - D_p\frac{\partial p}{\partial x}\right) = e^2\left(n\frac{D_n}{k_BT} + p\frac{D_p}{k_BT}\right)\frac{\partial V(x)}{\partial x}$$

- Drift current

$$j^{field} = j_n^{field} + j_p^{field}$$

$$= e\left(n\mu_n + p\mu_p\right)E_x = -e\left(n\mu_n + p\mu_p\right)\frac{\partial V(x)}{\partial x}$$

Equilibrium case (no external fields)

- Equilibrium:

$$j_n^{diff} = j_n^{field}$$
$$j_p^{diff} = j_p^{field}$$

- Diffusivities:

$$\boxed{\Rightarrow D_n = \frac{k_B T}{e}\mu_n, D_p = \frac{k_B T}{e}\mu_p}$$

Einstein-relation

- Mobilities:

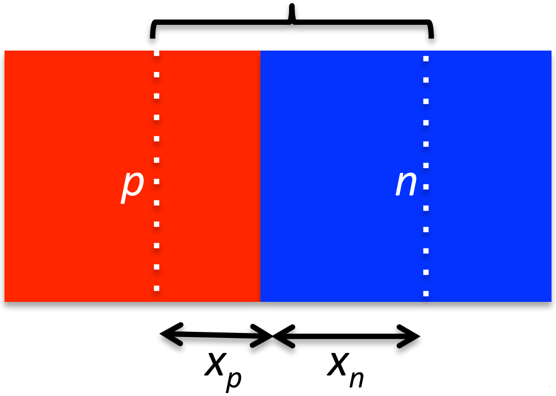
$$\mu_n = e\frac{\tau_n}{m_e^*}, \mu_p = e\frac{\tau_p}{m_h^*}$$

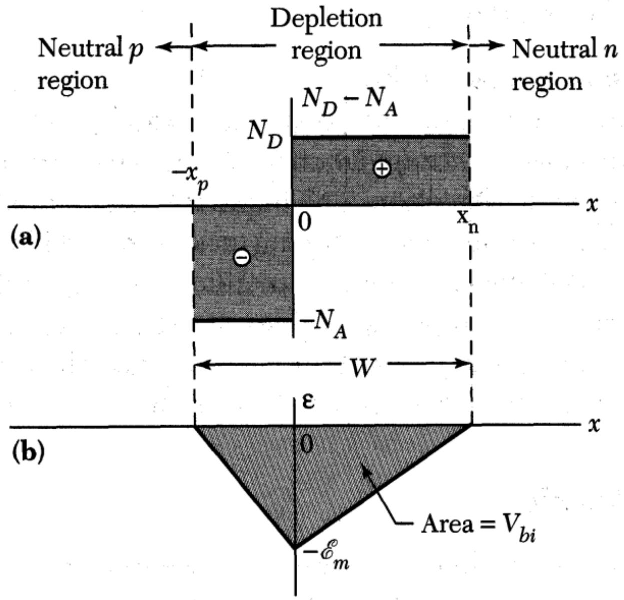
τ_n, τ_p: lifetimes of electrons and holes, respectively
m_e*,m_h*: effective masses of electrons in the CB and holes in the VB, respectively

Equilibrium case (no external fields)

Abrupt junction

W: depletion zone





- Charge neutrality: $N_A x_p = N_D x_n$

- n-side: $$\frac{d^2V}{dx^2} = -\frac{eN_D}{\varepsilon_s} \qquad 0 < x \le x_n$$

$$\Rightarrow E_x = -\frac{dV}{dx} = -E_{\max} + \frac{eN_D}{\varepsilon_s}(x - x_n)$$

- p-side: $$\frac{d^2V}{dx^2} = \frac{eN_A}{\varepsilon_s} \qquad -x_p \le x < 0$$

$$\Rightarrow E_x = -\frac{dV}{dx} = -\frac{eN_A}{\varepsilon_s}(x + x_p)$$

- Maximum field at x = 0: $$E_{\max} = \frac{eN_D x_p}{\varepsilon_s} = \frac{eN_A x_n}{\varepsilon_s}$$

- Built-in potential and depletion layer width W:

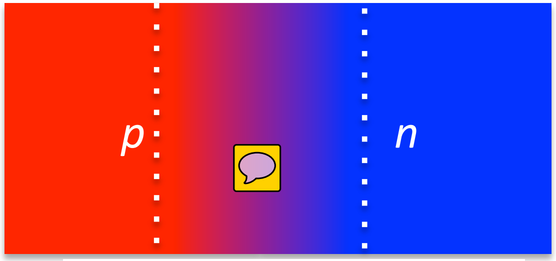
$$V_{bi} = -\int_{-x_p}^{x_n} E_x\, dx$$

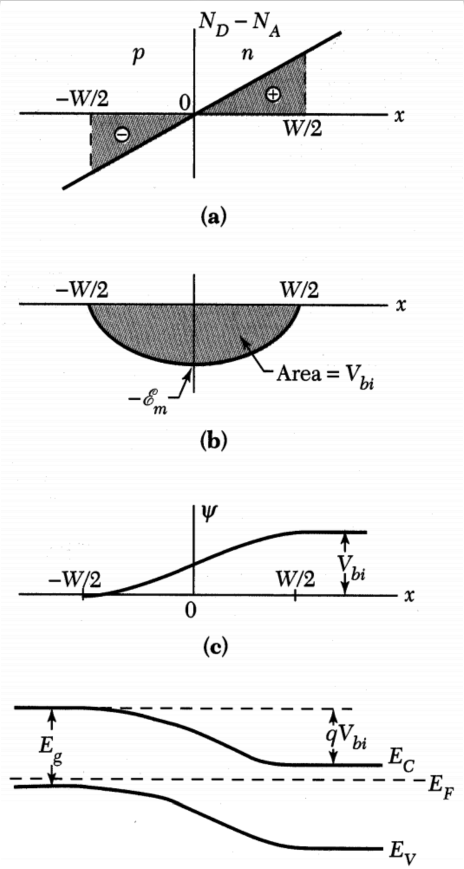
$$\Rightarrow V_{bi} = \frac{1}{2} E_{\max} W$$

$$W = \sqrt{\frac{2\varepsilon_s}{e}\left(\frac{N_A + N_D}{N_A N_D}\right) V_{bi}}$$

Equilibrium case (no external fields)

Linearly graded junction





$$\frac{d^2V}{dx^2} = \frac{-\rho_s}{\varepsilon_s} = \frac{-eax}{\varepsilon_s} \qquad -\frac{W}{2} \le x < +\frac{W}{2}$$

$$\Rightarrow E_x = -\int_{-W/2}^{+W/2} \frac{d^2V}{dx^2} dx$$

$$\Rightarrow E_x = -\frac{ea}{\varepsilon_s}\left(\frac{(W/2)^2 - x^2}{2}\right)$$

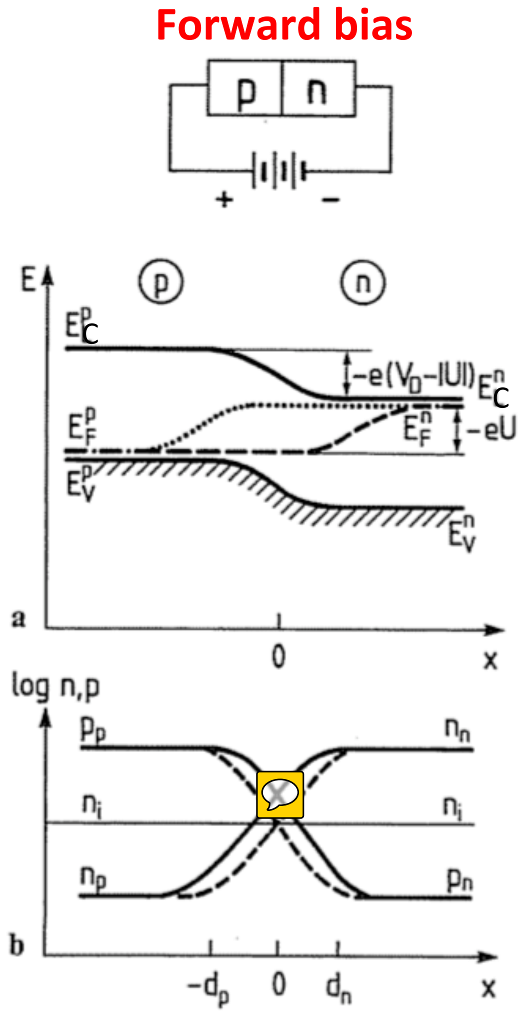
- Maximum field at x = 0:

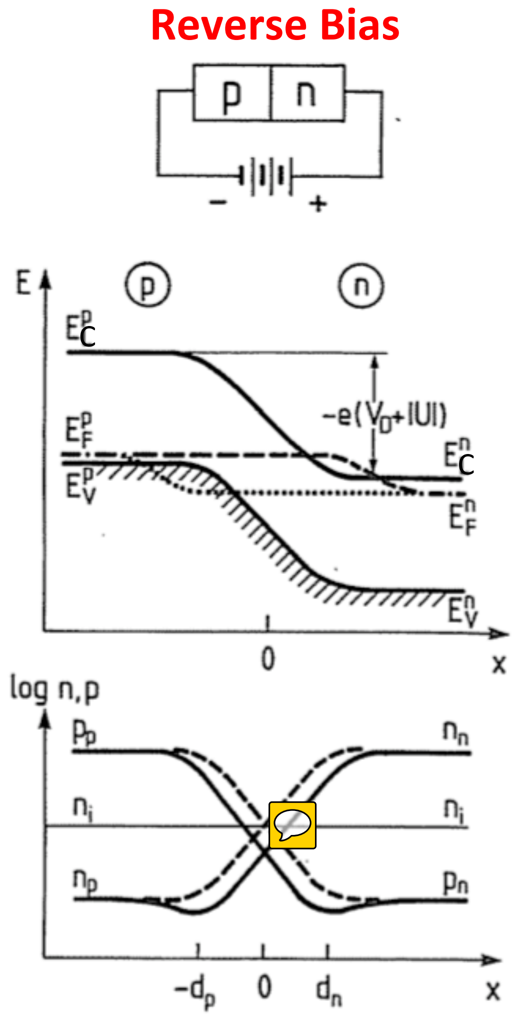
$$E_{\max} = \frac{eaW^2}{8\varepsilon_s}$$

- Built-in potential and depletion zone width:

$$V_{bi} = \frac{k_B T}{e}\ln\left(\frac{aW}{2n_i}\right) \qquad W = \sqrt[3]{\frac{12\varepsilon_s V_{bi}}{ea}}$$

Effect of an external electric field in p-n-junctions





Effect of an external electric field in p-n-junctions

- Charge carrier concentrations not in equilibrium:

$$n \rightarrow n_p$$
$$p \rightarrow p_n$$

Minority charge carriers

- Calculation of j_n, j_p, n_p and p_n for the stationary state:

$$j_n = e n_p \mu_n \frac{\partial V}{\partial x} + e D_n \frac{\partial n_p}{\partial x}$$

$$j_p = e p_n \mu_p \frac{\partial V}{\partial x} - e D_n \frac{\partial p_n}{\partial x}$$

Field- and Diffusion currents

- Electron-hole recombination

$$\frac{\partial j_n}{\partial x} = -\frac{\partial j_p}{\partial x} = eR$$

$$R = \frac{n_p - n_{p0}}{\tau_n} = \frac{p_n - p_{n0}}{\tau_p}$$

Excess charge carrier current density, τ_n, τ_p: lifetime of electrons and holes, n_{p0}, p_{n0} : equilibrium electron and hole concentrations on the p- and n-side, respectively

Effect of an external electric field in p-n-junctions

- Poisson-Equation for abrupt junction: $$\frac{\partial^2 V(x)}{\partial x^2} = -\frac{e}{\varepsilon_s}\left(p + N_D^+ - n - N_A^-\right)$$
- No general analytical solution for Poisson-Equation
- Approximation $x_{n,p}$ << diffusion lengths L_n, L_p:

$$\boxed{j_s = e\sum_i D_i \frac{dc_i}{dx} \approx e\left(D_p \frac{p_{n0}}{L_p} + D_n \frac{n_{p0}}{L_n}\right)}$$

Conduction

$$\boxed{j = j_s\left(e^{\frac{eV}{k_B T}} - 1\right)}$$

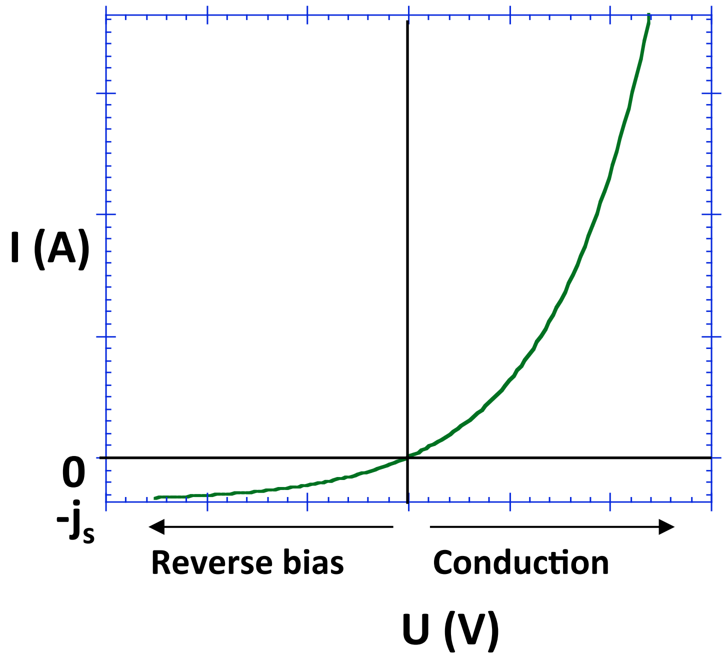
Reverse bias

$$\boxed{j = -j_s}$$

With saturation current density

$$\boxed{j_s = e\left(\frac{D_p p_{n0}}{L_p} + \frac{D_n n_{p0}}{L_n}\right)}$$

n_C, p_V: minority charge carrier densities



Effect of an external electric field in p-n-junctions

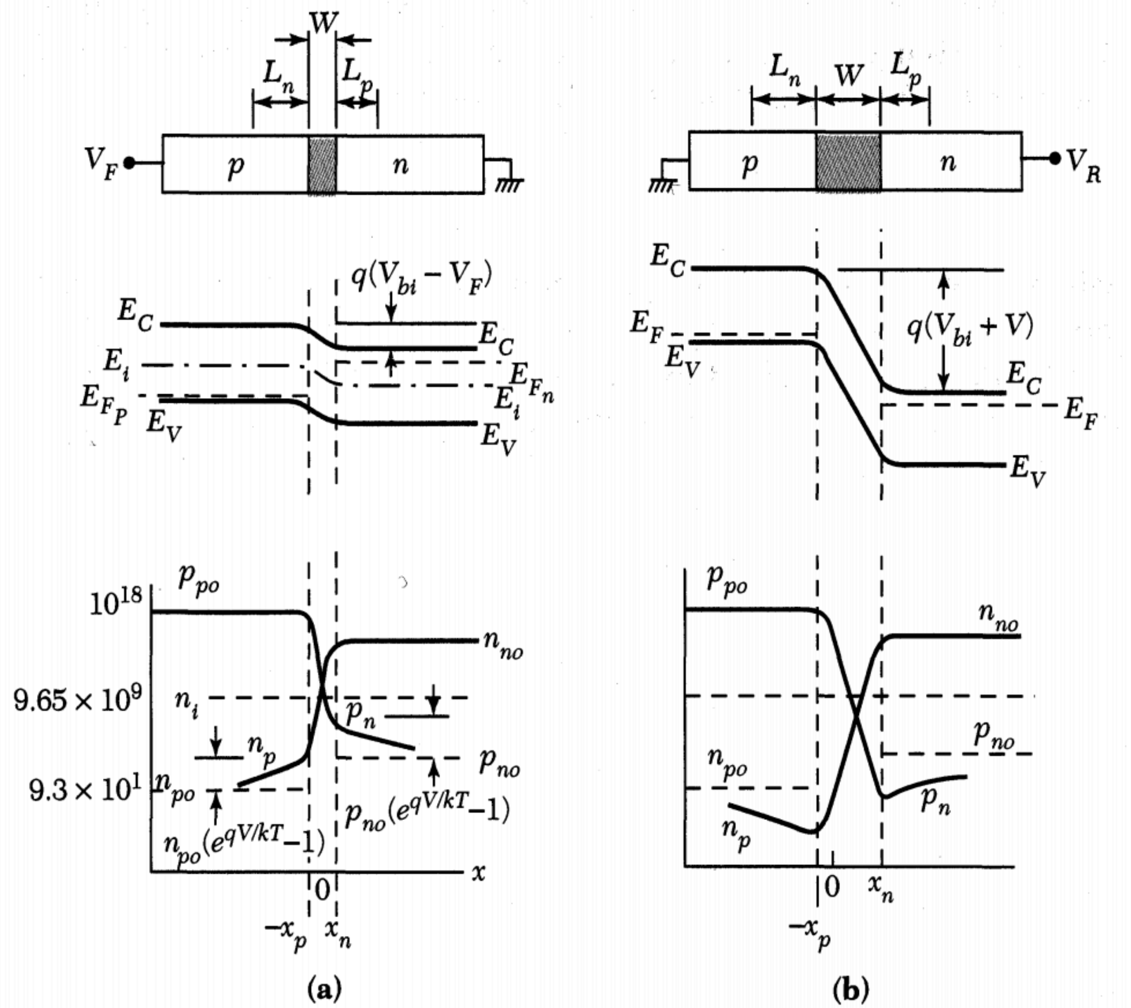


Fig. 16 Depletion region, energy band diagram and carrier distribution. (*a*) Forward bias. (*b*) Reverse bias.

Effect of an external electric field in p-n-junctions

Built-in potential

$$V_{bi} = \frac{k_B T}{e} \ln\left(\frac{p_{p0} n_{n0}}{n_i^2}\right) = \frac{k_B T}{e} \ln\left(\frac{n_{n0}}{n_{p0}}\right)$$

Mass action law: $p_{p0} n_{p0} = n_i^2$

$$\Rightarrow n_{n0} = n_{p0} \exp\left(\frac{eV_{bi}}{k_B T}\right)$$

Bias Voltage *V*: $n_n = n_p \exp\left(\frac{e(V_{bi} - V)}{k_B T}\right)$

Low injection: $n_n \approx n_{n0}$

$$\Rightarrow n_p - n_{p0} = n_{p0}\left[\exp\left(\frac{eV}{k_B T}\right) - 1\right]$$

$$p_n - p_{n0} = p_{n0}\left[\exp\left(\frac{eV}{k_B T}\right) - 1\right]$$

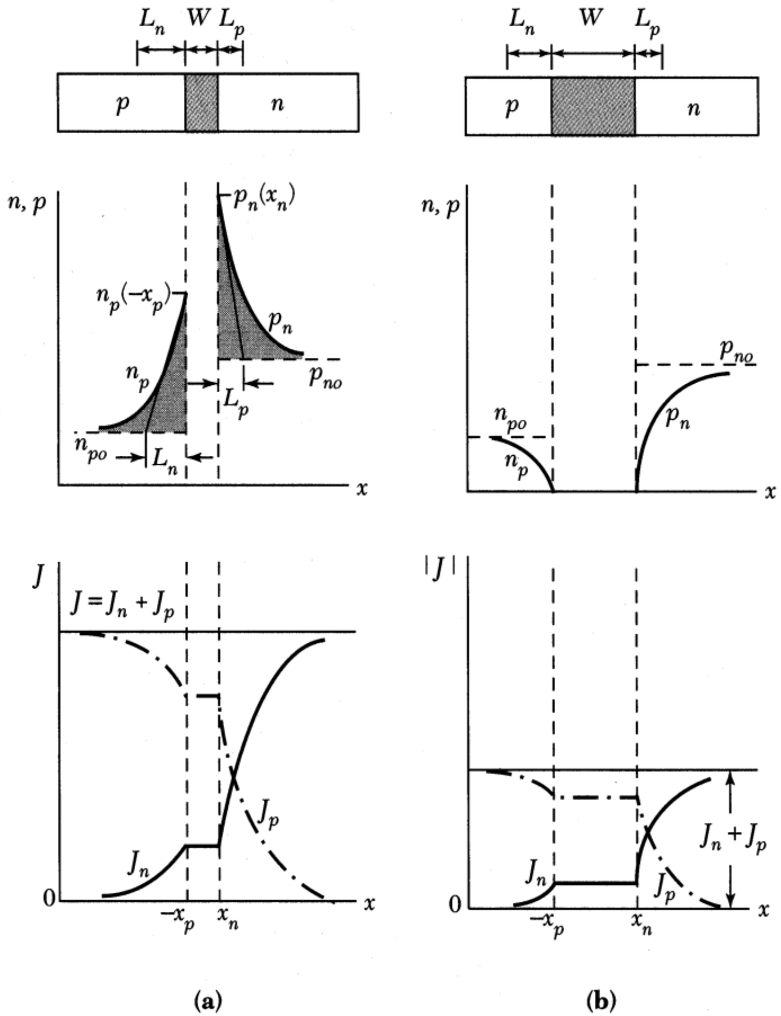
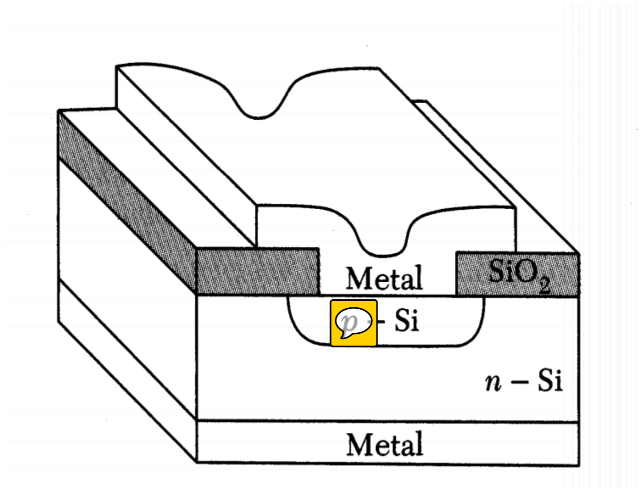


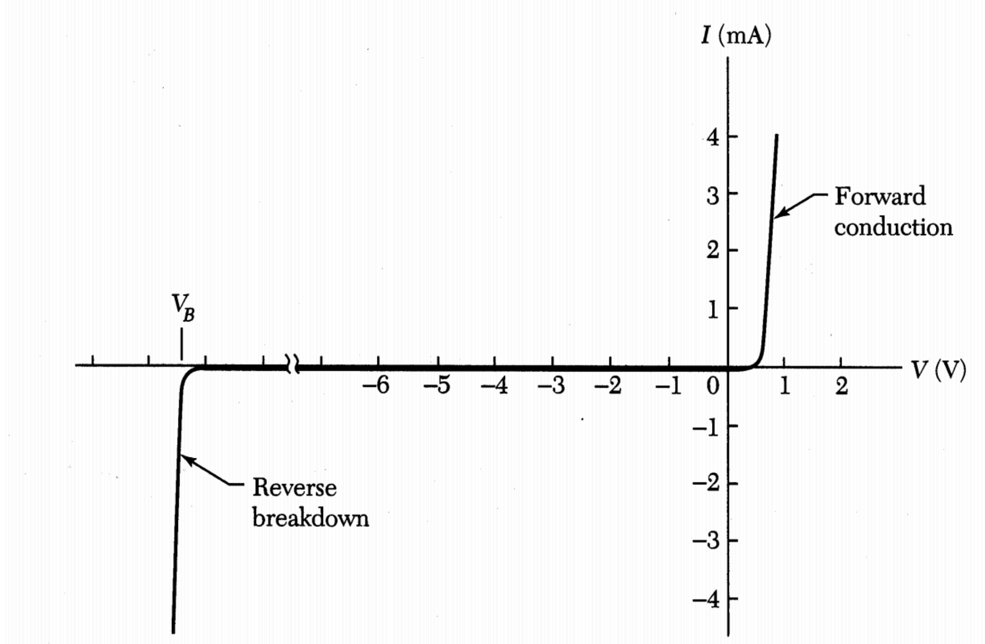
Fig. 17 Injected minority carrier distribution and electron and hole currents. (*a*) Forward bias. (*b*) Reverse bias. The figure illustrates idealized currents. For practical devices, the currents are not constant across the space charge layer.

Effect of an external electric field in p-n-junctions

- Structure of a p-n junction



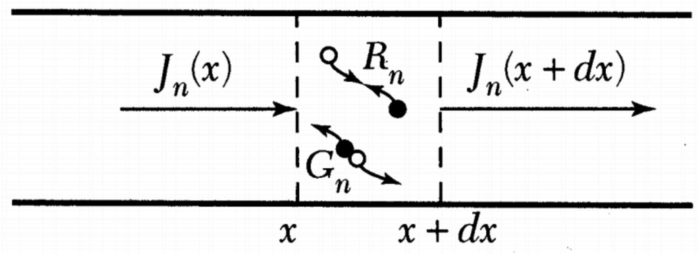
- Current/Voltage characteristic



p-n junction disrupted at a critical voltage V_B when reversed biased

Role of recombination centers

- Recombination centers in the band gap will constantly produce holes and electrons under bias conditions:



Net recombination rate:

$$U = \frac{v_{th}\sigma_n\sigma_p N_t\left(p_n n_n - n_i^2\right)}{\sigma_p\left(p_n + n_i \exp\left(\frac{E_i - E_t}{k_B T}\right)\right) + \sigma_n\left(n_n + n_i \exp\left(\frac{E_t - E_i}{k_B T}\right)\right)}$$

Assume $p_n < n_i$, $n_n < n_i$,
$\sigma_n = \sigma_p = \sigma_0$:

$$G = -U = \frac{v_{th}\sigma_o N_t n_i}{2\cosh\left(\frac{E_t - E_i}{k_B T}\right)} = \frac{n_i}{\tau_g}$$

Generation life time τ_g has pronounced maximum at $E_t = E_i$: only centers in the middle of the band gap contribute significantly to charge carrier generation

Role of recombination centers

- Current due to generation under reverse bias conditions:

$$J_G = e\int_0^W G\,dx \approx eGW = \frac{en_i W}{\tau_g}$$

Assume p^+-n junction ($N_A >> N_D$) and $V_R > 3k_BT/e$, the total current under reverse bias is then:

$$J_R = J_{diff} + J_G = e\sqrt{\frac{D_p}{\tau_p}}\frac{n_i^2}{N_D} + \frac{en_i W}{\tau_g} \quad \text{using} \quad L_p = \sqrt{D_p \tau_p}$$

Semiconductors with large n_i (e.g. Ge) are dominated by diffusion current and follow ideal diode characteristics, whereas materials with low n_i (e.g. Si, GaAs) will have a significant contribution of generation centers in the band gap.

Role of recombination centers

- For the forward biased current we find:

$$J_F = e\sqrt{\frac{D_p}{\tau_p}}\frac{n_i^2}{N_D}\exp\left(\frac{eV}{k_BT}\right) + \frac{en_iW}{2\tau_r}\exp\left(\frac{eV}{2k_BT}\right)$$

With the effective recombination lifetime $\tau_r = 1/(\sigma_0 v_{th} N_t)$

Similar relationship between n_i and contribution of recombination centers found as for the reverse bias case

Introducing an *ideality factor* η experiments can be empirically represented by:

$$J_F = \exp\left(\frac{eV}{\eta k_BT}\right)$$

η = 1: diffusion current dominates
η = 2: recombination current dominates

Role of recombination centers

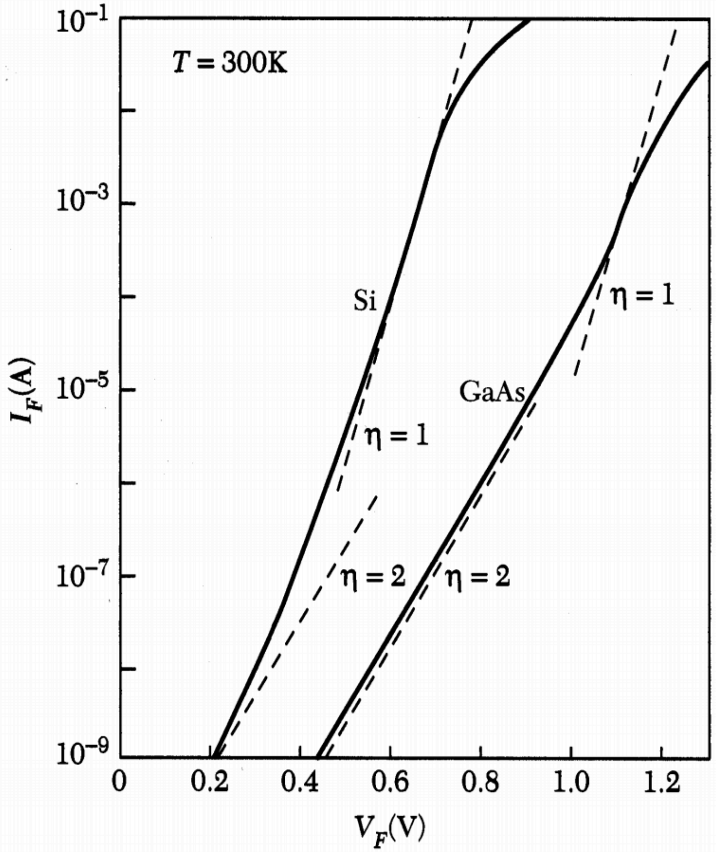


Fig. 19 Comparison of the forward current-voltage characteristics of Si and GaAs diodes[2] at 300 K. Dashed lines indicate slopes of different ideality factors η.

At higher forward bias diffusion current dominates

Break-through voltage

• The critical voltage for the break through of a p-n junction under reverse bias operation caused by tunelling ($V > 4E_g/e$) or avalanche multiplication ($V > 6E_g/e$)

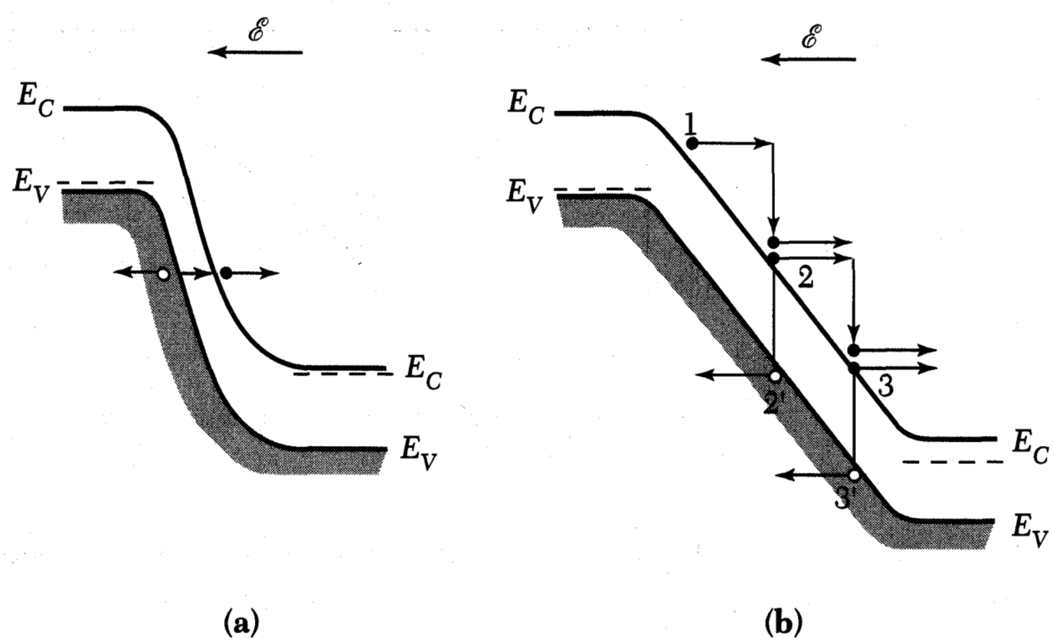


Fig. 24 Energy band diagrams under junction-breakdown conditions. (*a*) Tunneling effect. (*b*) Avalanche multiplication.

• Requires fields > 10^6 V/m
• Needs sufficient doping levels (> 5 10^{17}cm^{-3})

Break-through voltage

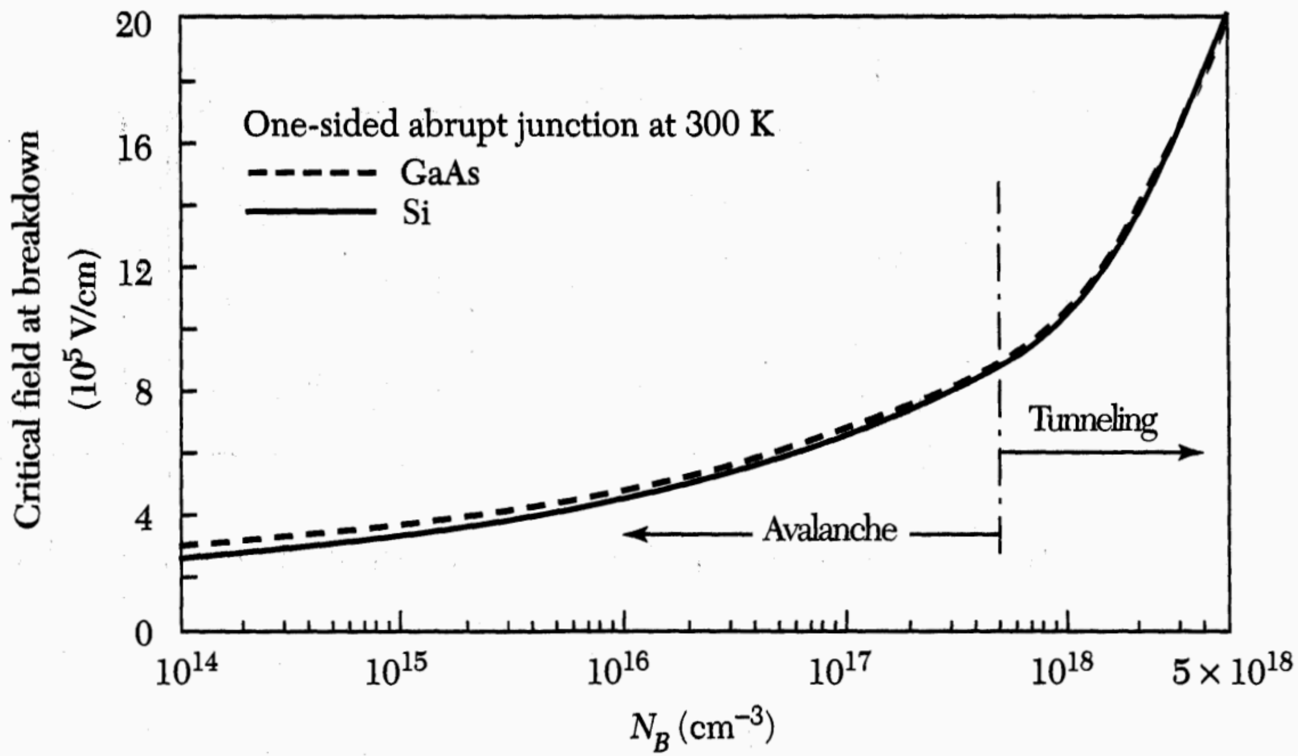
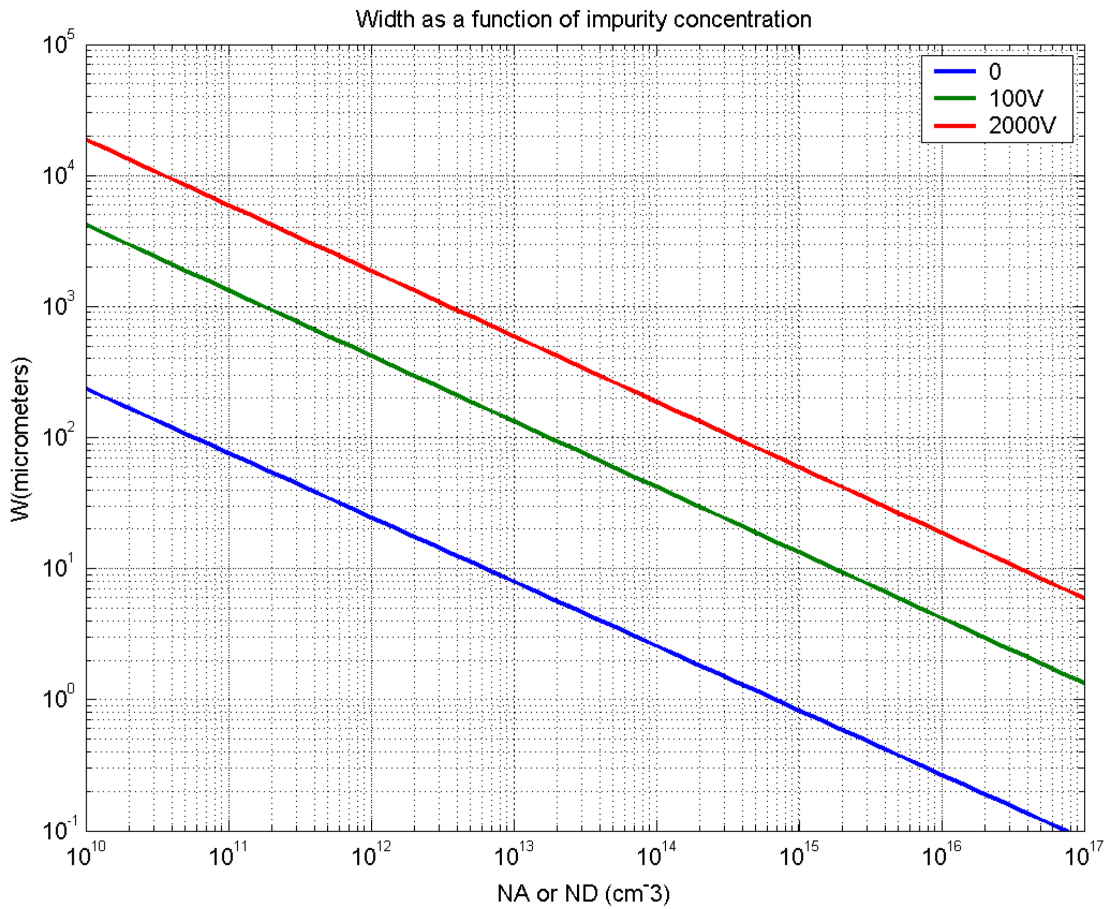


Fig. 26 Critical field at breakdown versus background doping for Si and GaAs one-sided abrupt junctions.[5]

N_B: background doping of the lightly doped side of the junction, α: ionisation rate

- Condition for breakdown: $\frac{I_n(W)-I_n(0)}{I} = \int_0^W \alpha \, dx = 1$ I_n: electron current

Break-through voltage



- Depletion zone width as a function of dopant concentration

Heterojunctions

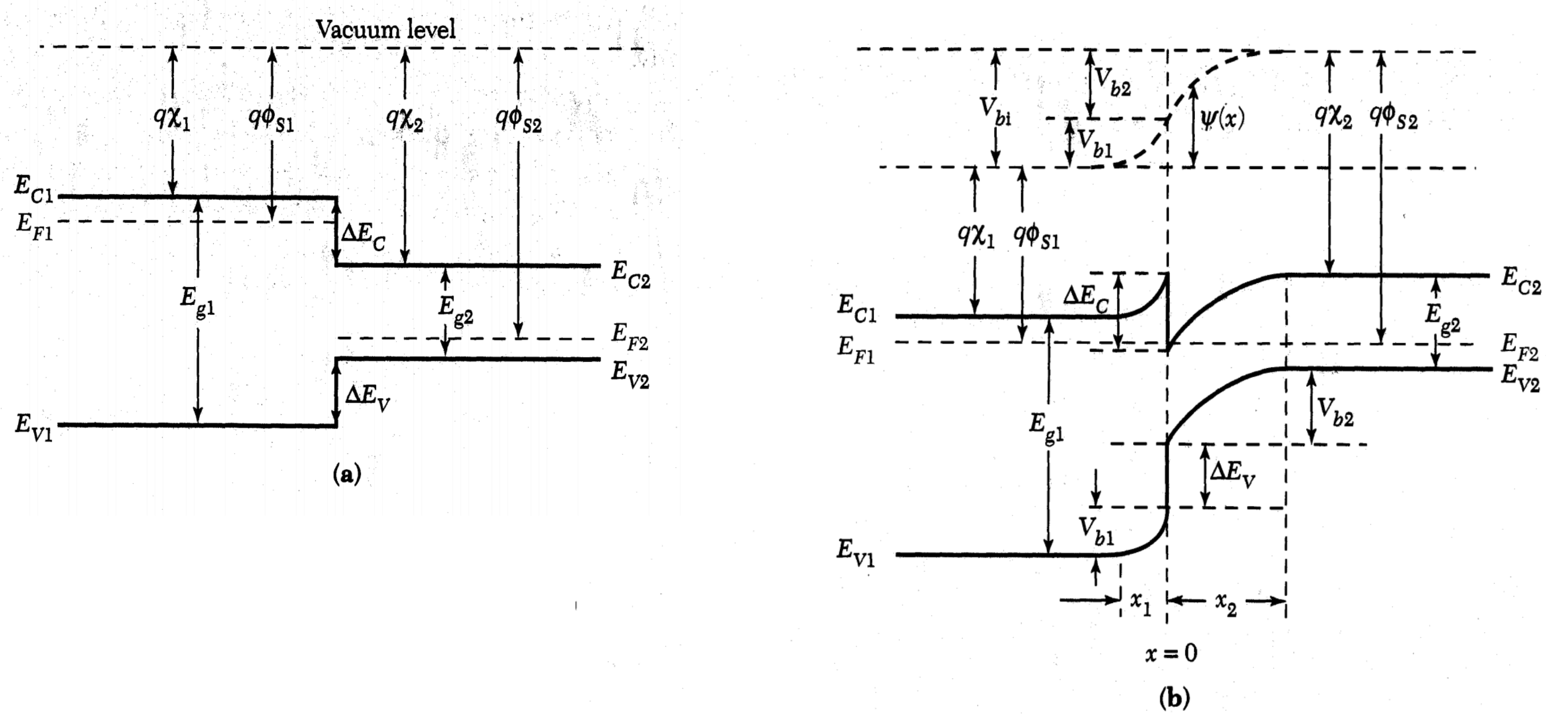


Fig. 32 (*a*) Energy band diagram of two isolated semiconductors. (*b*) Energy band diagram of an ideal *n–p* heterojunction at thermal equilibrium.

Heterojunctions important for devices using confinement effects such as laser diodes