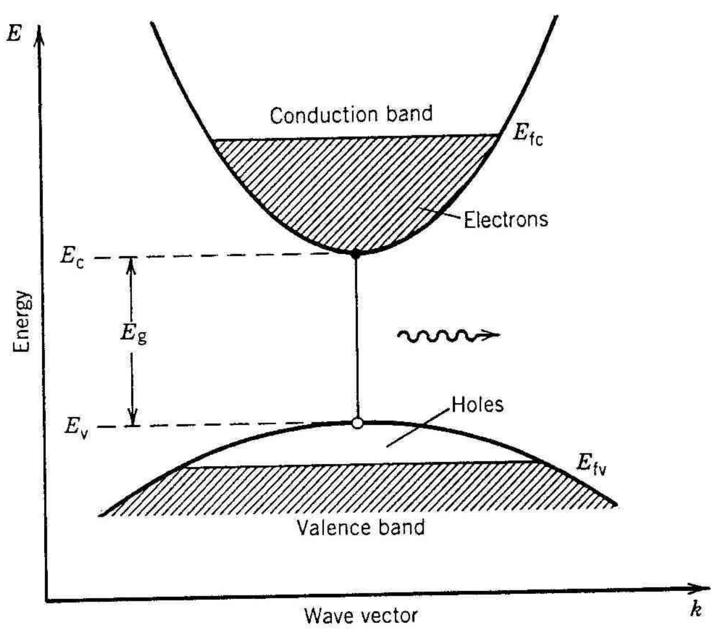
Semiconductor opto-electronic components

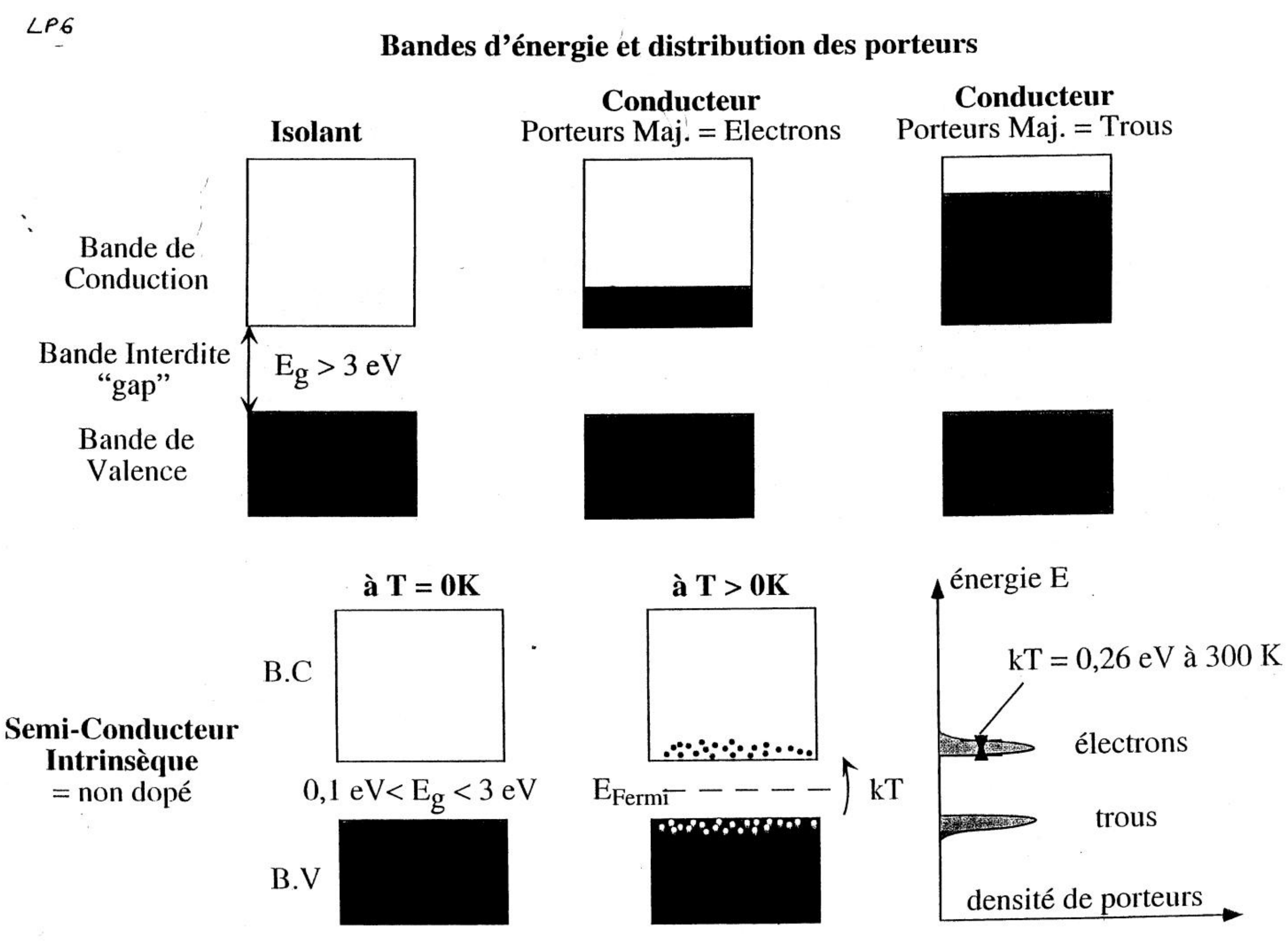
Conduction and valence bands in semiconductors

The occupation probabilities of states with energy E_2 and E_1 by electrons in the conduction and valence bands is given by the probability density functions (FERMI-DIRAC DISTRIBUTIONS):

$$f_c(E_2) = \{1 + \exp[(E_2 - E_{fc})/k_B T]\}^{-1},$$
$$f_v(E_1) = \{1 + \exp[(E_1 - E_{fv})/k_B T]\}^{-1}$$
$$E_{fc}, E_{fv} = \text{Conduction and valence Fermi levels}$$



Energy bands and charge distributions: intrinsic SC



PN Junctions

A SC optical source is based on the PN JUNCTION:

- INTRINSIC SC: There is a SINGLE Fermi level, it is situated half-way between the conduction and the valence bands

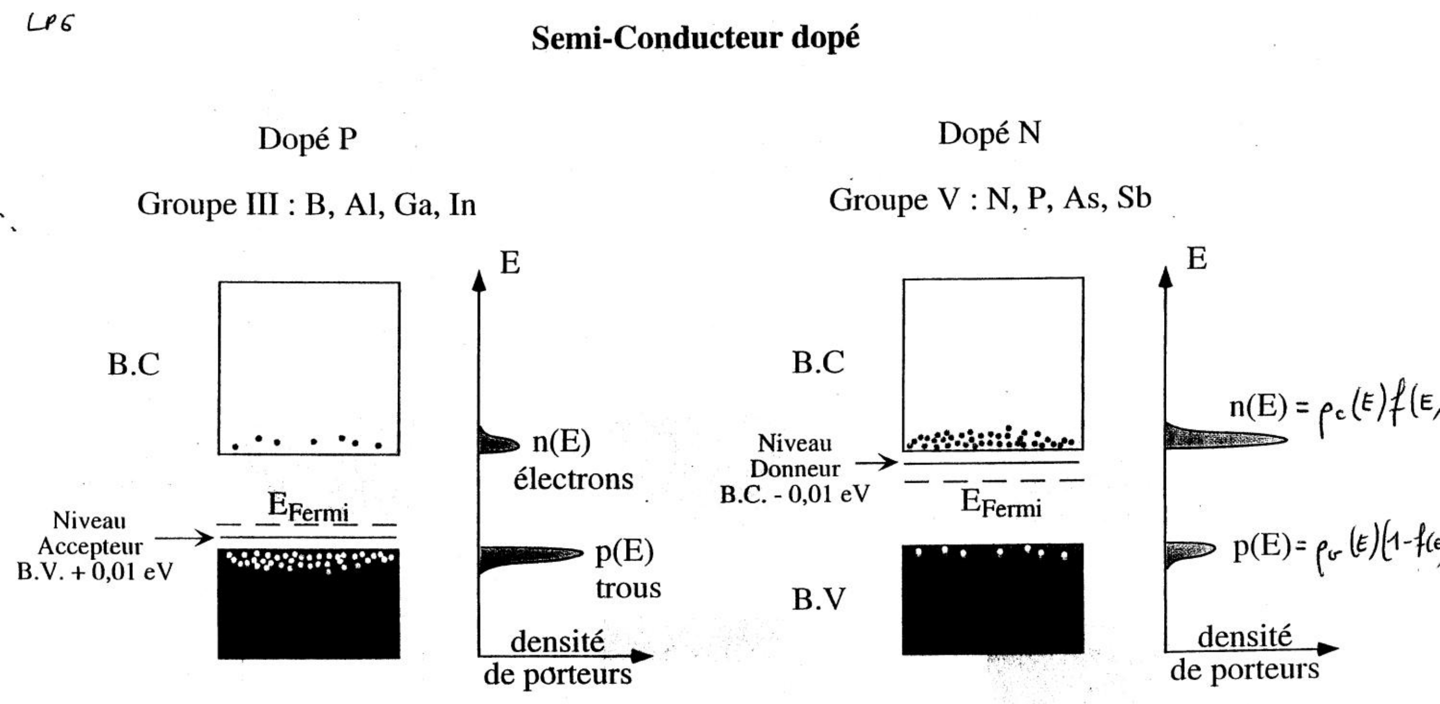
- N type SC: doped with impurities that have an extra valence electron → The Fermi level moves towards the conduction band → For strong doping, the Fermi level is situated INSIDE the conduction band

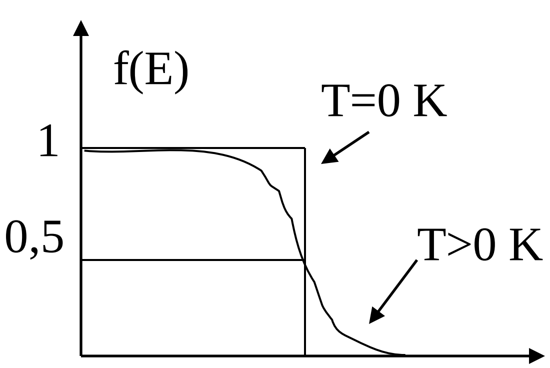
- P type SC: doped with impurities that have a missing valence electron → The Fermi level moves towards the valence band → For strong doping, the Fermi level is situated INSIDE the valence band

→ PN Junction: Contact between a P-type SC and a N-type SC

→ At thermal equilibrium: there is only one Fermi level, which must be continuous through the junction → one obtains a charge diffusion between the two sides of the junction → As a result, positive and negative charges are stored on both sides of the junction → a DC electric field results that, at the equilibrium, stops any further charge diffusion through the junction

Energy bands and charge distributions: doped SC





Fermi distribution

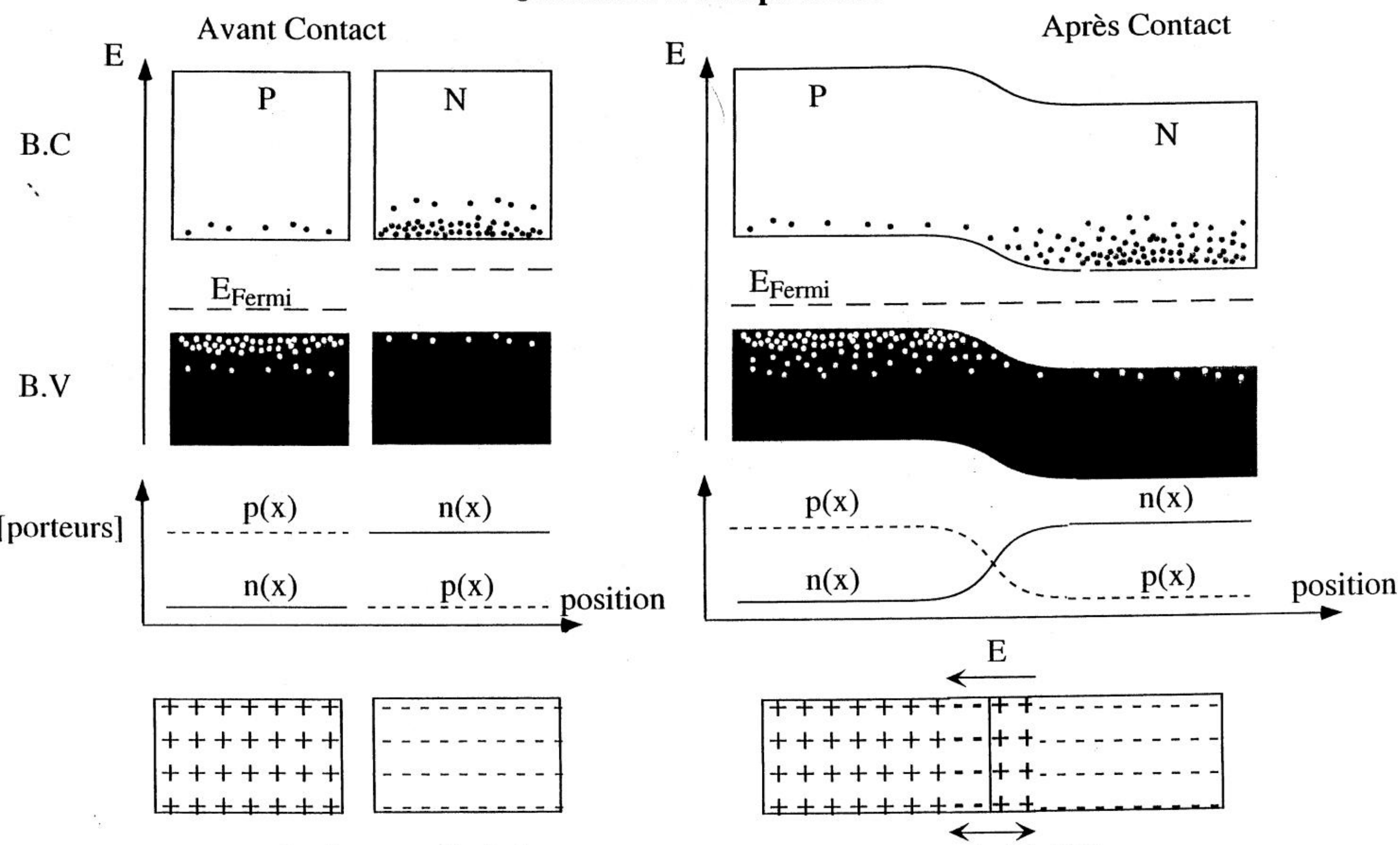
$$f(E) = \frac{1}{1 + \exp\left(\dfrac{E - E_f}{k_B T}\right)}$$

$$f(E_f) = \frac{1}{2}$$

Un-biased PN junction

LP6'

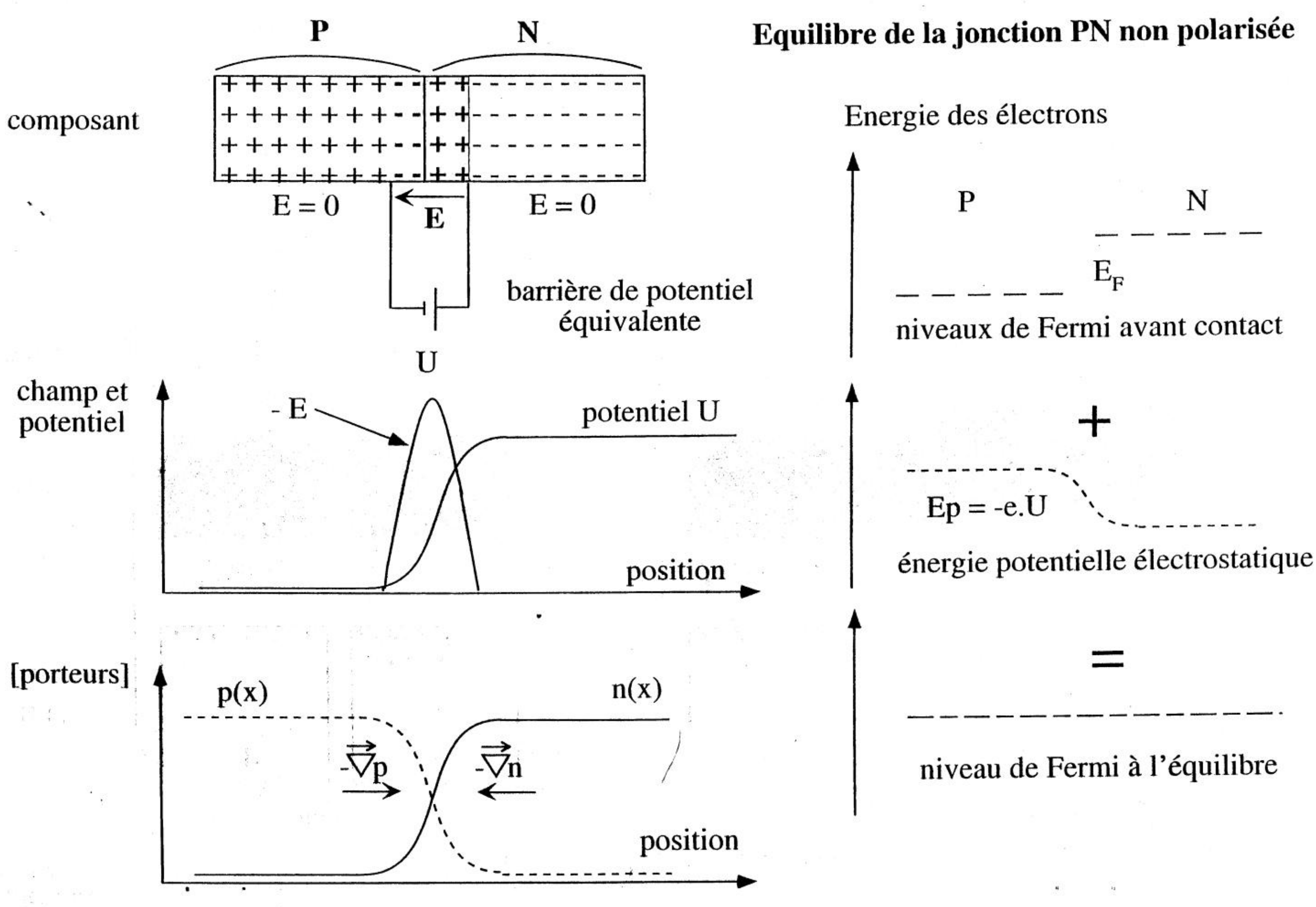
Jonction PN non polarisée



porteurs de charge majoritaires
équilibrés par le réseau ->
pas de charge électrostatique -> champ E = 0

zone de déplétion
porteurs en excès ->
charges électrostatiques -> champ E ≠ 0

Equilibrium of un-biased PN junction



Biasing of PN junctions

A PN junction may be biased by applying an external voltage

- In the case of direct biasing, the DC field in the junction is reduced

→ As a consequence, one observes a diffusion of electrons and holes through the junction

→ This leads to an electrical current I that increases with the external voltage U_g according to

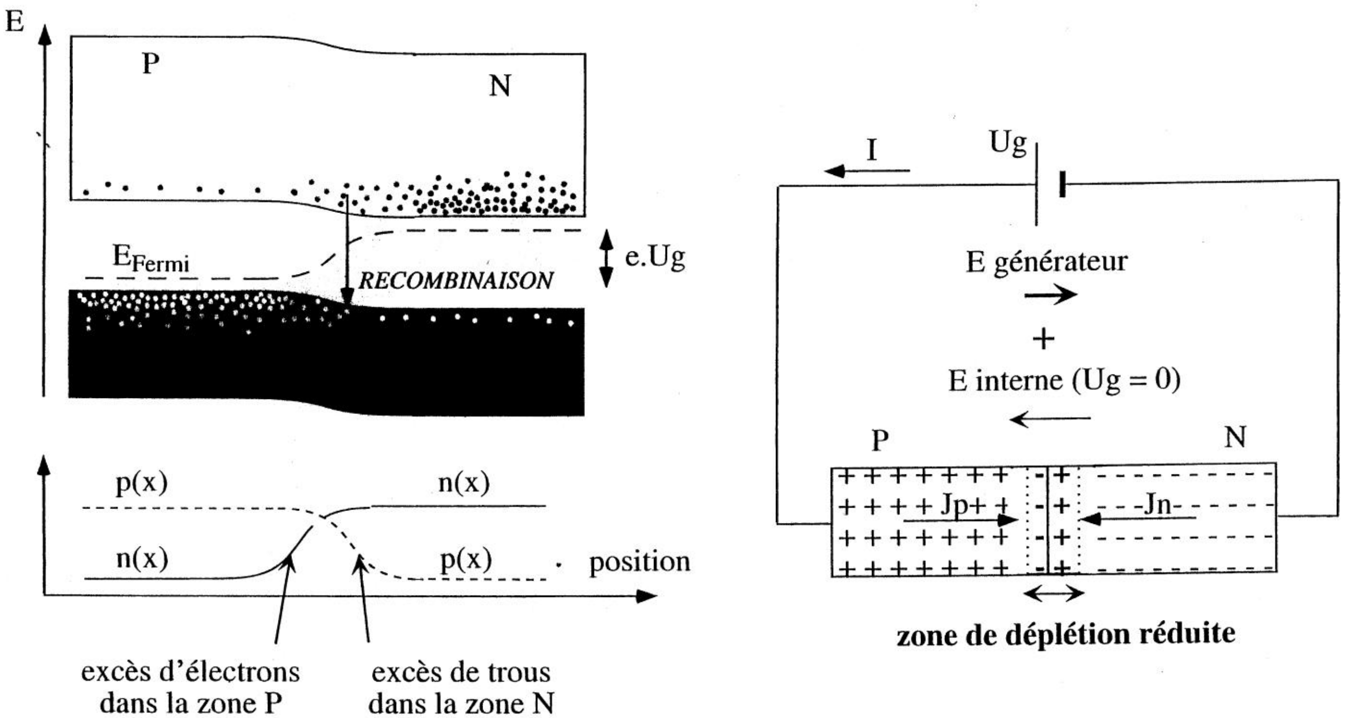
$$I = I_s \left[\exp\left(qU_g / k_B T \right) - 1 \right]$$

Where I_s is a saturation current that depends upon the diffusion properties of the carriers

→ In a junction with direct bias, one obtains extra electrons and charges inside the junction → their recombination through either spontaneous or stimulated emission leads to photons

DIRECT BIASING of PN junction

Jonction PN polarisée DIRECTE

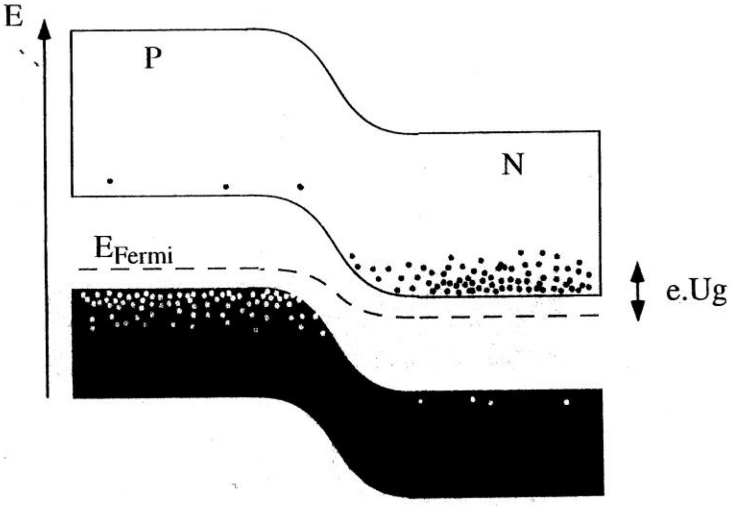


RECOMBINAISON e + t dans la zone de déplétion = Jonction HORS ÉQUILIBRE ($E_{Fermi} \neq$ cste)
-> Circulation d'un courant électrique I

INVERSE BIASING of PN junction

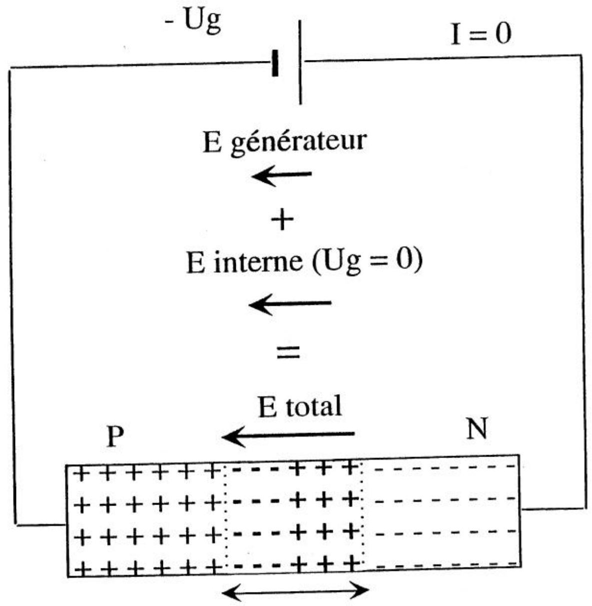
LP6

Jonction PN polarisée INVERSE



barrière de potentiel -> n . p faible dans la ZD
-> pas de recombinaison -> I = 0 : diode bloquée

jamais de courant...? à suivre : Photodiodes !



Zone de Déplétion (ZD) ELARGIE

Characteristics of a SC laser

Characteristics of SC lasers: described by the « rate equations » for photons and electrons

<u>Continuous wave (CW) properties</u>

For a monomode laser, one obtains the equations for the time evolution of the number of photons P and electrons N

$$\frac{dP}{dt} = GP + R_{sp} - \frac{P}{\tau_p},$$

$$\frac{dN}{dt} = \frac{I}{q} - GP - \frac{N}{\tau_c},$$

$$\text{where}: \mathrm{G} = \Gamma \nu_{\mathrm{g}} g_m = G_N (N - N_0) = \Gamma \nu_{\mathrm{g}} \sigma_g (N - N_0) / V$$

G: rate of stimulated emission; R_{sp}: spontaneous emission rate; one has $R_{sp}= n_{sp}G$, with n : n_{sp} = spontaneous emission factor ~2; v_g= group velocity, $N_0=N_TV$; τ_p: lifetime of photons in the cavity:

$$\tau_p^{-1} = v_g \alpha_{cav} = v_g (\alpha_{mir} + \alpha_{\text{int}})$$

Term proportional to GP: stimulated emission-induced recombination of electrons and holes

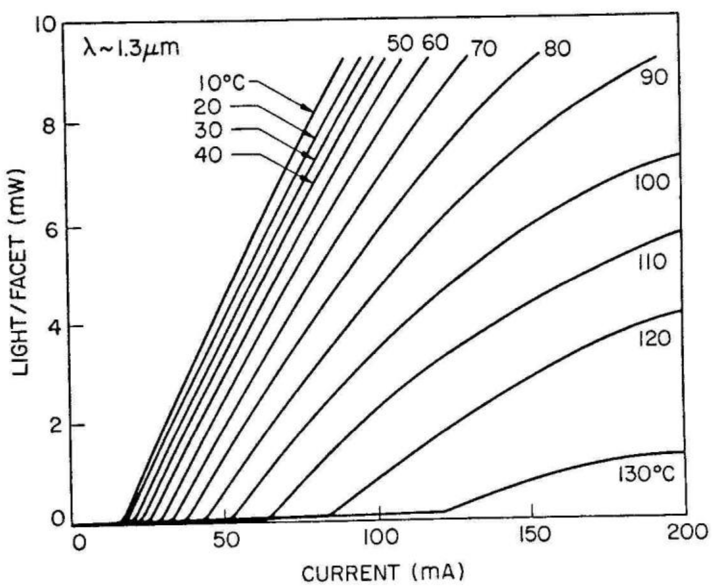
Term proportional to $1/\tau_c$: loss of electrons due to spontaneous emission and non radiative recombination

Characteristics of a SC laser

P-I curve of a SC laser

Consider a InGaAsP laser at 1,3 μm operating at temperatures between 10° and 130°.

At room temperature, threshold is obtained for ~20 mA, → 10 mW of optical power for 100 mA of electrical current



The threshold is a function of temperature:

$$I_{th} = I_0 \exp(T / T_0)$$

T_0: Characteristic temperature, ~50-70 K for InGaAsP, ~120 K for GaAs; this means it is necessary to control the T of a SC laser!

Characteristics of a SC laser

<u>CW operation of a SC laser</u>

In CW (« continuous wave ») mode:

I=cnst, d/dt=0; supposing also $R_{sp}=0 \rightarrow$

- if $G\tau_p<1 \rightarrow P=0$, $N=\tau_c I/q$
- If $G\tau_p=1$ (laser threshold)$\rightarrow$ the number of charges is fixed at $N=N_{th}=N_0+(G_N\tau_p)^{-1}$; $I_{th}=qN_{th}/\tau_c$;
- If $I>I_{th} \rightarrow P=(\tau_p/q)(I-I_{th})$ (photon number)

Power emitted from one of the two faces of laser:

$$P_e = \frac{1}{2}\left(v_g \alpha_{mir}\right)\hbar\omega P = \frac{\hbar\omega}{2q}\frac{\eta_{\text{int}}\alpha_{mir}}{\alpha_{mir}+\alpha_{\text{int}}}(I-I_{th})$$

Here η_{int}= « internal quantum efficiency »= fraction of electrons converted into photons by means of stimulated emission (~100%)