

Transizioni Intersande $B^V \rightleftharpoons BC$

Transizioni Intersande

Prob. Transizione

ψ_i, ψ_f

$$W = \frac{2\pi}{\hbar} \left| \langle \psi_f | H_R | \psi_i \rangle \right|^2 \delta(\epsilon_f - \epsilon_i + \hbar\omega)$$

$$H_R = e \vec{E} \cdot \vec{\sigma} : \text{App. Dipolo}$$

Prob. Assorbimento

$$R = \frac{2\pi}{\hbar} \int \int_{k_c k_v} \left| \langle c | H_{em} | v \rangle \right|^2 \delta(E_c(k_c) - E_v(k_v) + \hbar\omega) dk_c dk_v$$

se $\langle \langle c | H_R | v \rangle \rangle^2$ non dipende da k

$$R(\omega) = \frac{2\pi}{\hbar} \left(\frac{e}{m\omega} \right)^2 \left| \frac{E(\omega)}{2} \right|^2 |H_{R0}|^2.$$

$$\int_{k_c, k_V} \delta(E_c(k_c) - E_V(k_V) - \omega) dk_c dk_V$$

$$k_c = k_{ph} + k_V$$

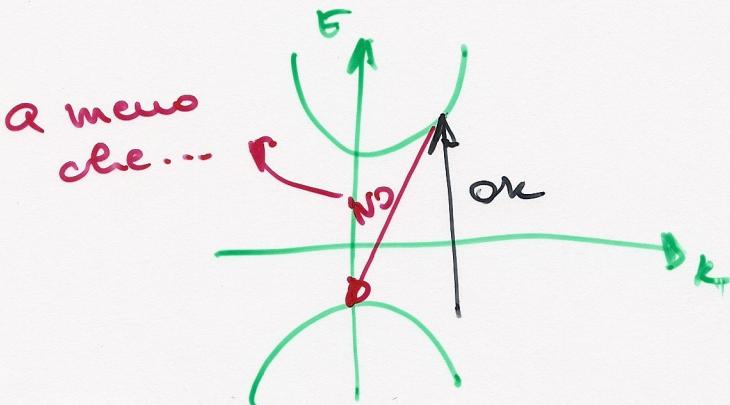
Transizioni che conservano k e E

$$k_{ph} = \frac{2\pi}{\lambda} \approx 8 \cdot 10^4 \text{ cm}^{-1}$$

$$k_{c, k_V} \approx \frac{\pi}{d} \approx 10^7 \text{ cm}^{-1}$$

$$k_{ph} \ll k_{c, k_V}$$

Transizioni verbicelli



Assorbimento: oh

R-combinazione bad:

Semiconduttori a Gap
diretta

Semiconduttori a Gap indiretta:

Transizioni avviate da forze

Riassunto e Ricombinazione

Regime coerente ($\leq 200 \text{ fs}$)

- Scattering k
- Scattering cione - canica
- ① • Intervalley scattering $\Gamma \rightarrow L, T$
- photo scattering lecone - formare ottico

Regime non coerente ($\leq 2 \text{ ps}$)

- ② • scattering $e-h$
- scattering e - formare ottico
- intervalley $L, T \rightarrow \Gamma$
- cotene
- scattering intervallobande

Regime di caniche calde ($1-100 \text{ ps}$)

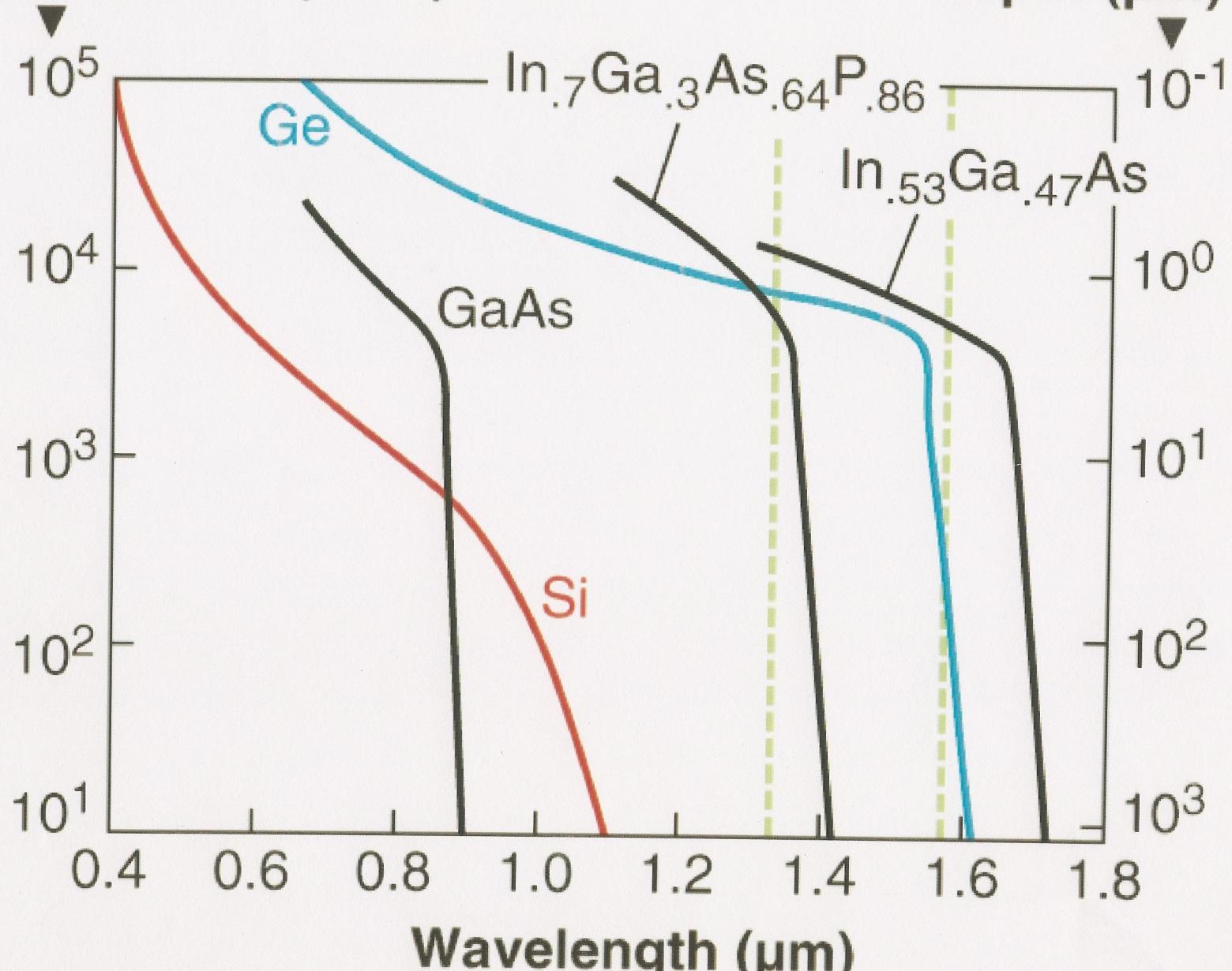
- interazione con formi

Regime Isodens ($> 100 \text{ ps}$)

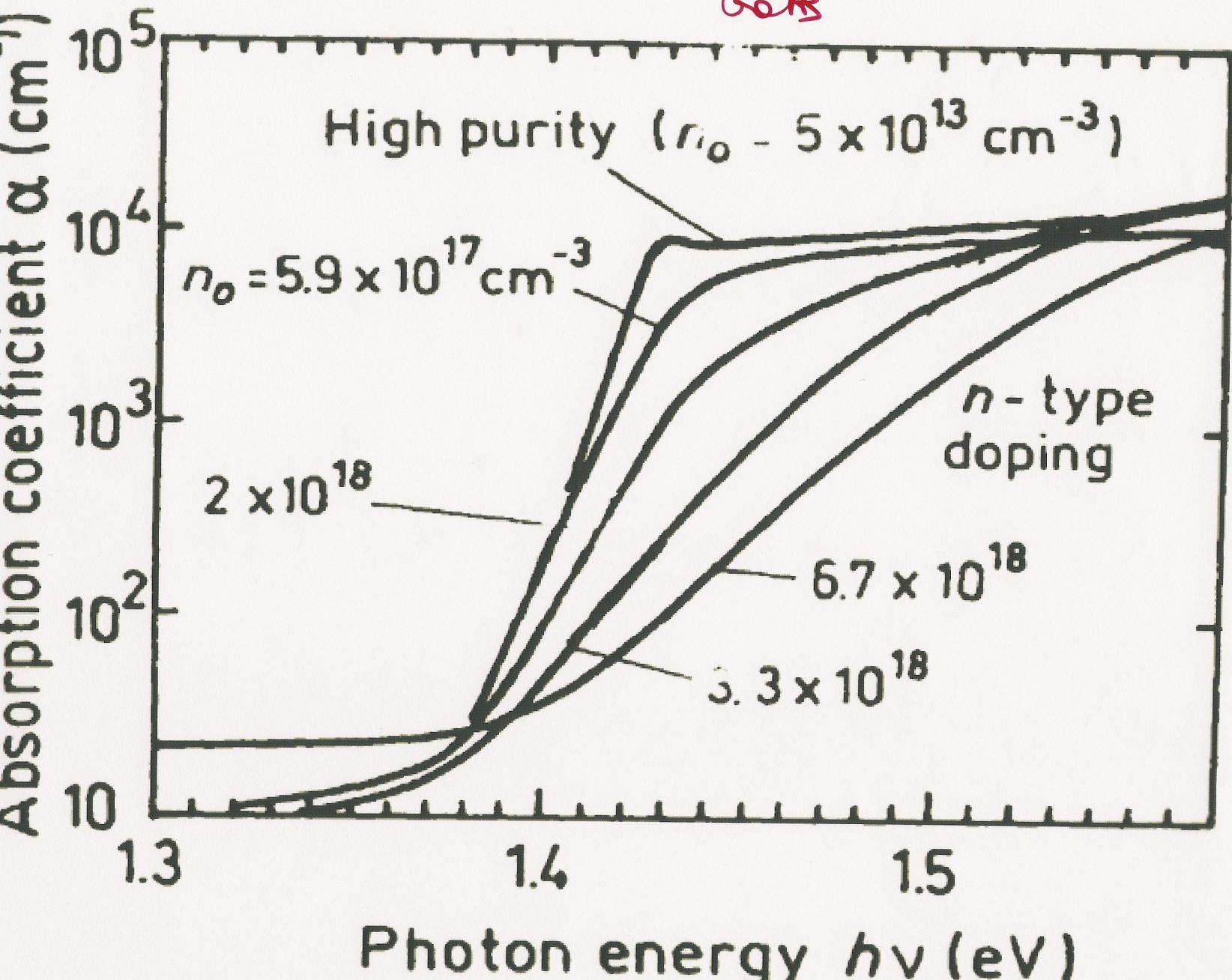
- Ricombinazione
rad e non rad.

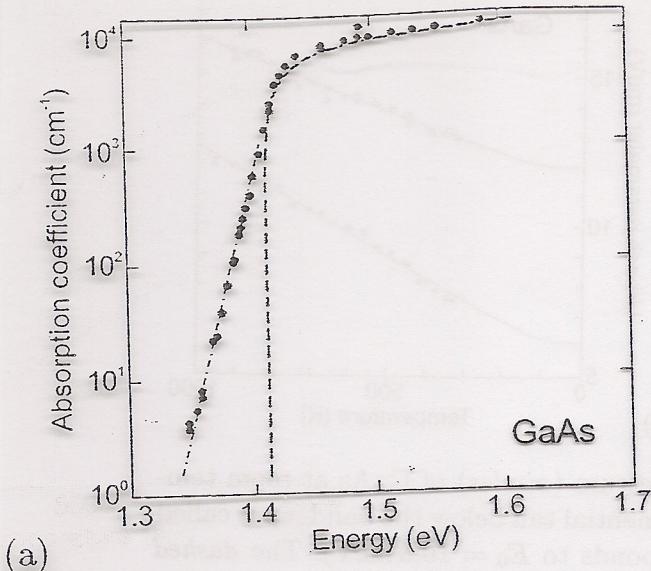
Absorption
coefficient (cm^{-1})

Penetration
depth (μm)

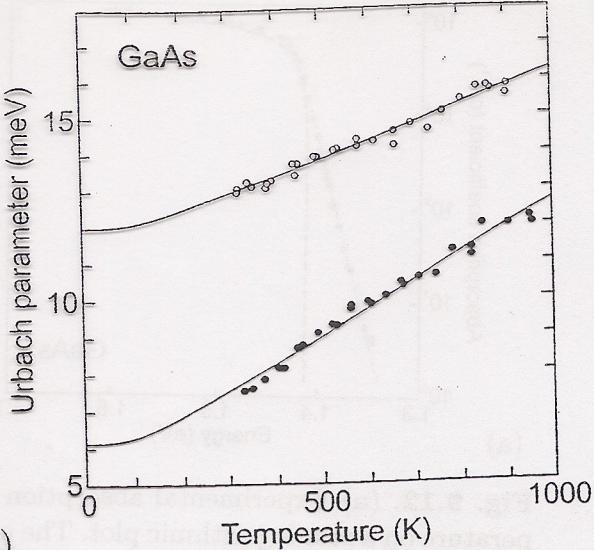


Wavelength (μm)





(a)



(b)

Fig. 9.12. (a) Experimental absorption spectrum (*circles*) of GaAs at room temperature on a semilogarithmic plot. The exponential tail below the bandgap is called the Urbach tail (the *dash-dotted* line corresponds to $E_0 = 10.3$ meV). The *dashed* line is the theoretical dependence from (9.23). Adapted from [287]. (b) Temperature dependence of Urbach parameter E_0 for two GaAs samples. Experimental data for undoped (*solid circles*) and Si-doped ($n = 2 \times 10^{18} \text{ cm}^{-3}$, *empty circles*) GaAs and theoretical fits (*solid lines*) with one-phonon model. Adapted from [285]

Urbach tail

$$\frac{E - E_g}{E_0}$$

$$d(\epsilon) \propto \epsilon^{\alpha}$$

E_0 = Urbach parameter

Disorder - Defects

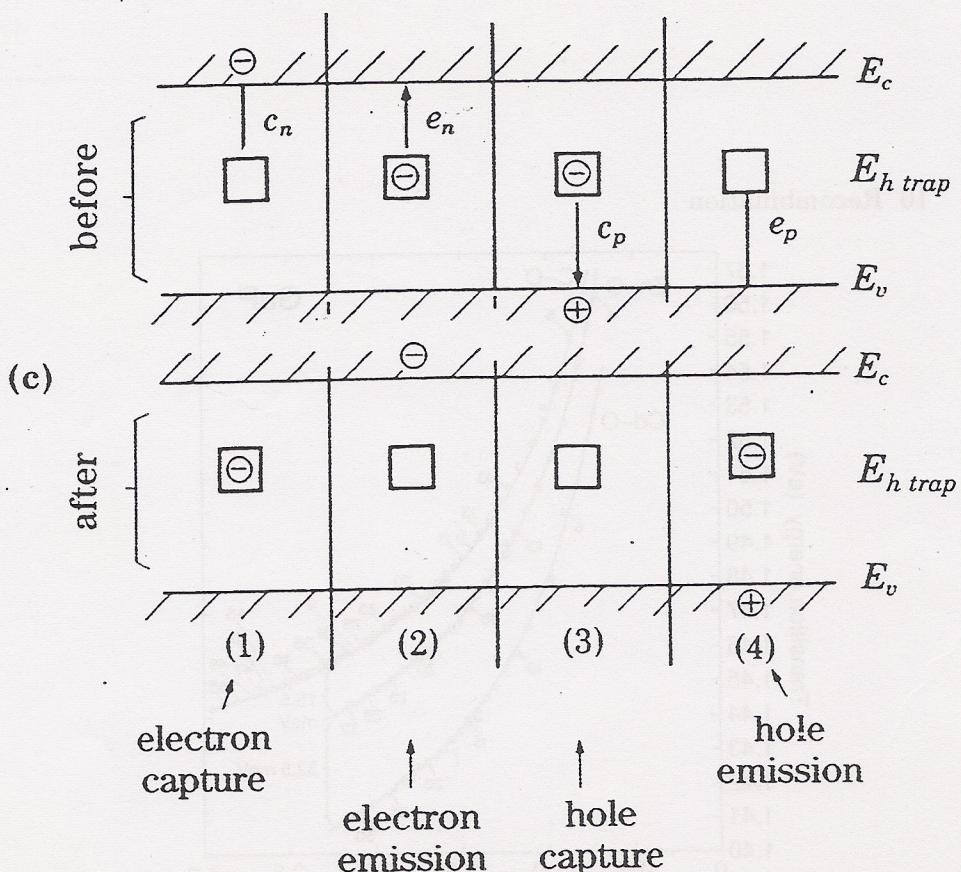
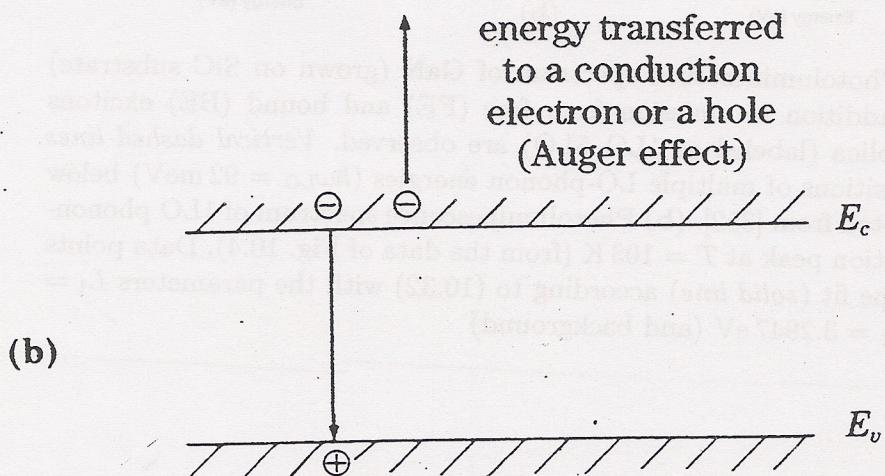
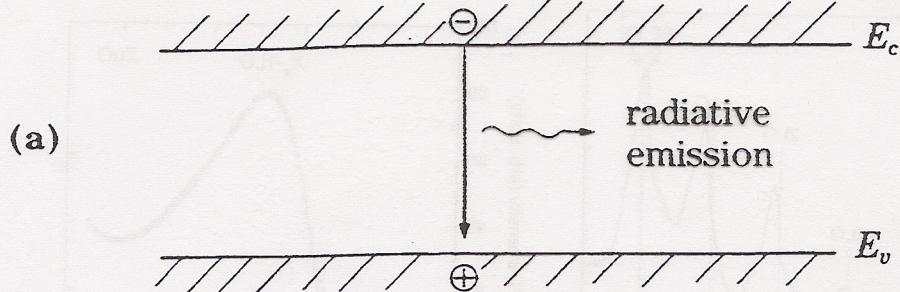
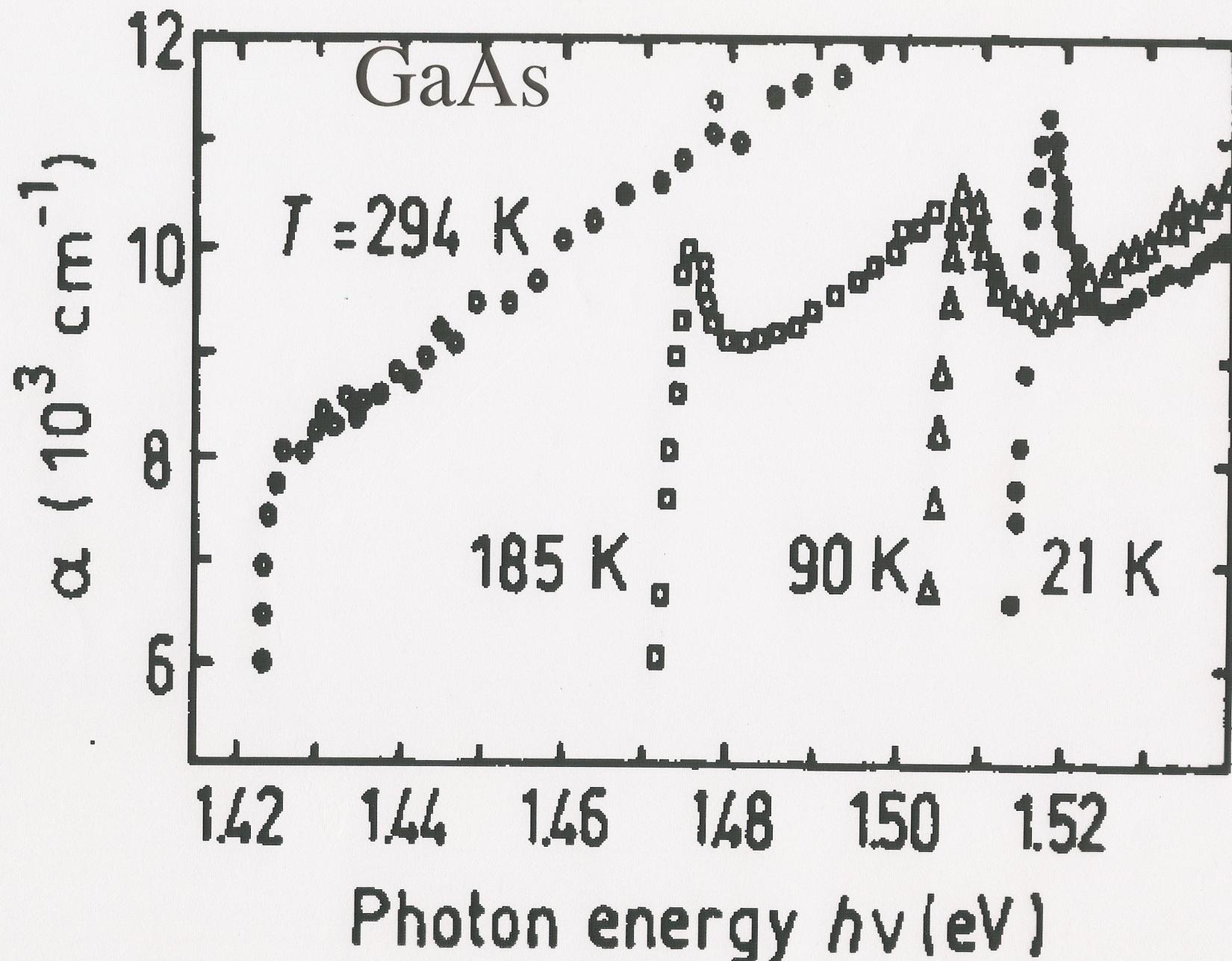


Fig. 6.8. The various recombination processes: (a) direct radiative recombination; (b) direct Auger recombination; (c) recombination via trapping on a deep center. In the latter case the figure shows the state of the system before and after each of the stages (1), (2), (3), (4). (After S.M. Sze, Physics of Semiconductor Devices.)



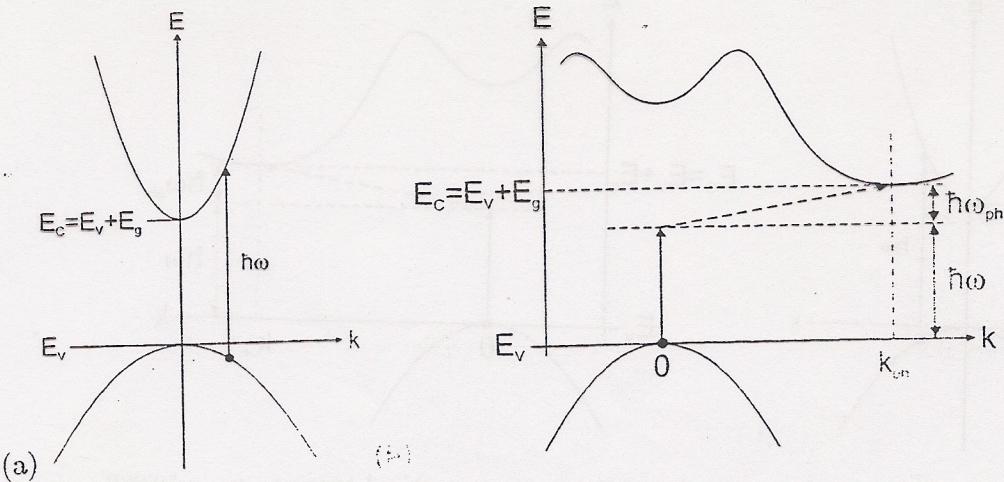
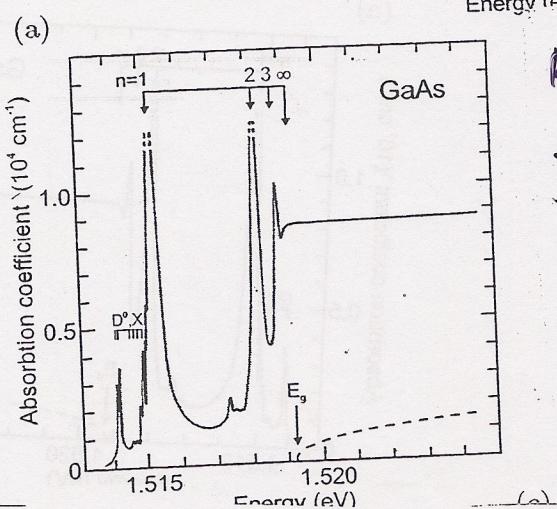
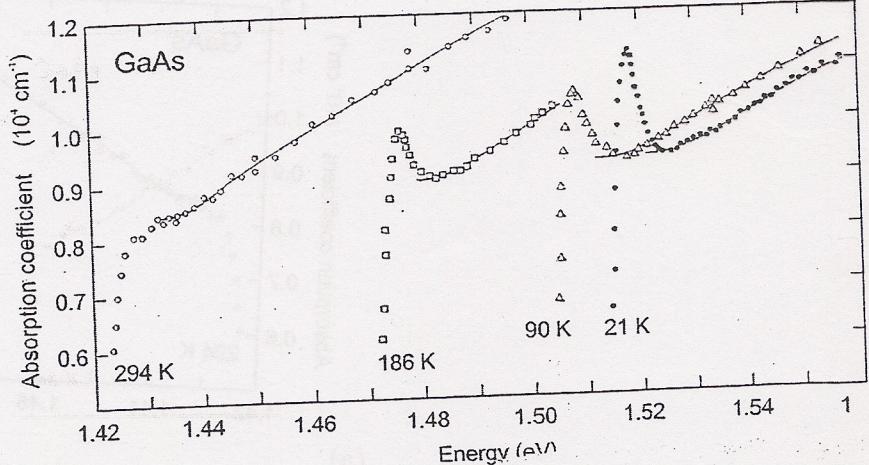


Fig. 9.6. (a) Direct optical transition and (b) indirect optical transitions between valence and conduction bands. The photon energy is $\hbar\omega$. The indirect transition involves a phonon with energy $\hbar\omega_{ph}$ and wavevector k_{ph} .

Abschimante
2 adō $\sqrt{E-E_g}$
at band edge
 $20 \sim 10^4 \text{ cm}^{-1}$
Ter



*Risouante
electroiche*

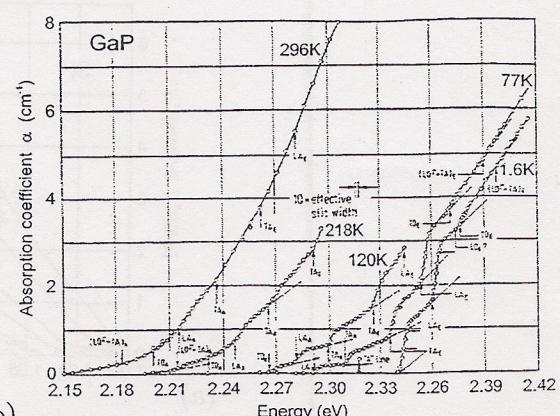
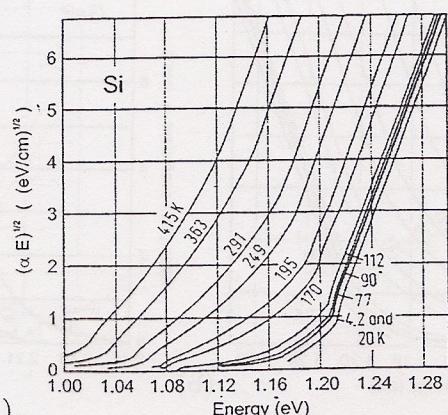


Fig. 9.9. Absorption edge of (a) Si and (b) GaP at various temperatures. Part (a) adapted from [93], based on [281], part (b) adapted from [93] based on [282]

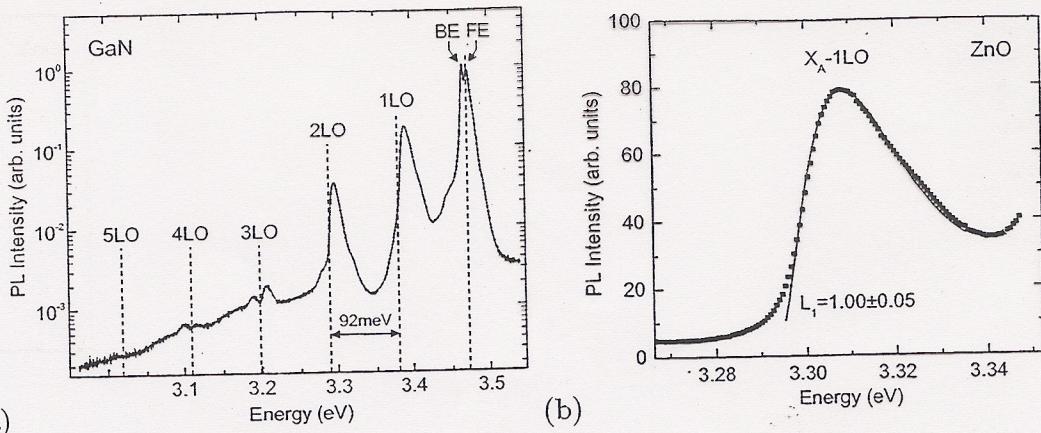


Fig. 10.11. (a) Photoluminescence spectrum of GaN (grown on SiC substrate) at $T = 50\text{ K}$. In addition to emission from free (FE) and bound (BE) excitons several phonon replica (labeled as 1LO–5LO) are observed. Vertical dashed lines indicate energy positions of multiple LO-phonon energies ($\hbar\omega_{\text{LO}} = 92\text{ meV}$) below the FE peak. Adapted from [352]. (b) Photoluminescence spectrum of 1LO phonon-assisted recombination peak at $T = 103\text{ K}$ (from the data of Fig. 10.4). Data points (dots) and lineshape fit (solid line) according to (10.32) with the parameters $L_1 = 1.00 \pm 0.05$ and $E_1 = 3.2947\text{ eV}$ (and background)

Phonon Replica $E_{\text{Rep}} = E_x - n \pm \omega_{\text{LO}}$ (sem. Polar)
 $I_{\text{Rep}} \propto e^{-\omega_{\text{LO}} S^2 / n!}$
D-A recombination

$$\omega = \epsilon_g - \epsilon_d - \epsilon_A - \frac{1}{2\pi n \epsilon_0} \frac{e^2}{\epsilon_2 \epsilon_B^2} \alpha_B$$

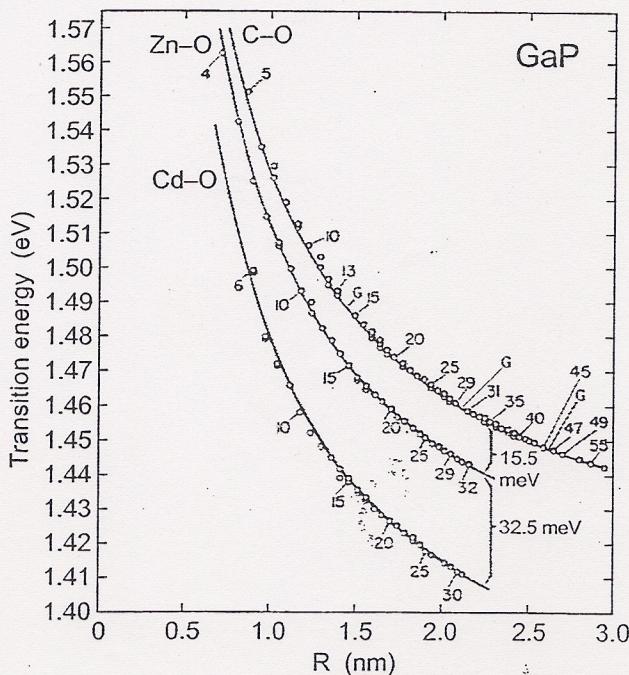
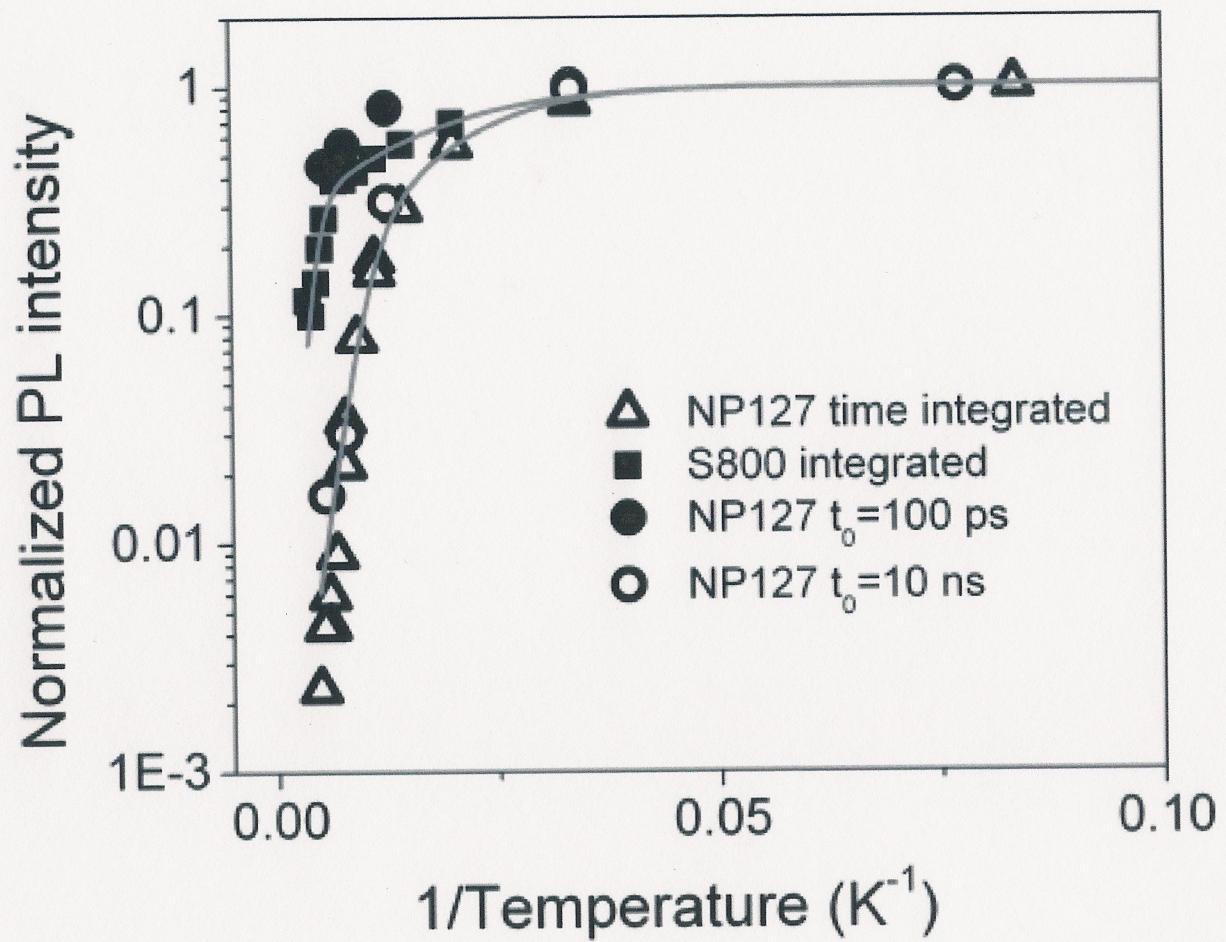


Fig. 10.14. Transition energies in GaP ($T = 1.6\text{ K}$) of the donor–acceptor recombination involving the deep oxygen donor and C, Zn, and Cd acceptors, respectively. The lines follow (10.37) for $E_g^{\text{GaP}} = 2.339\text{ eV}$, $\epsilon_r = 11.1$ and $(E_D^b)_O = 893\text{ meV}$, $(E_A^b)_C = 48.5\text{ meV}$, $(E_A^b)_{\text{Zn}} = 64\text{ meV}$, and $(E_A^b)_{\text{Cd}} = 96.5\text{ meV}$. Predicted missing modes for GaP:C,O are labeled with 'G'. Adapted from [359]

Rik. non radiative
Afh. op temperature



Introduzione e Ricombinazione

$$n = n_0 + \Delta n$$

$$p = p_0 + \Delta p$$

n_0, p_0 : conc. equilibrio

$$\frac{du}{dt} = G_0(T) - \frac{u}{\tau_n}$$

$G_0(T)$: Rate creazione
termica

In equilibrio

$$G_0(T) = \frac{n_0}{\tau_{n_0}}$$

$$\frac{du}{dt} = \frac{n_0}{\tau_{n_0}} - \frac{u}{\tau_n}$$

$\tau_n = \tau_n(u)$: in genere

Caso Degrado: ad es. $n_0 \gg p_0$

$$\approx \frac{dp}{dt} = \frac{p_0}{\tau_{p_0}} - \frac{p}{\tau_p}$$

in questo caso $\tau_p = \tau_{p_0}$
 $-t \tau_p$

$$\Rightarrow \frac{d\Delta p}{dt} = - \frac{p}{\tau_p}$$

$$\Rightarrow p = p_0 e$$

τ_p = vite media
folatori
minoritari

Ricombinazione diretta e-h

$$\frac{dn}{dt} = -Anp + f$$

In gen. teniamo

$$G_0(T) = An_0 p_0 = A u_i^2$$

$$G = G_0(T) + f$$

f = rate dovuto
a generazione
esterna $\neq T$

$$\Rightarrow \frac{dn}{dt} = -Anp + G_0(T) + f$$

$$\frac{d\Delta n}{dt} = \frac{d\Delta p}{dt} = \frac{d(n-n_0)}{dt} = \frac{d(p-p_0)}{dt}$$

$$= -A(u_0 + \Delta u)(p_0 + \Delta p) + G_0 + f$$

$$\frac{d\Delta n}{dt} = \frac{d\Delta p}{dt} = -A p_0 \Delta n - A(n_0 + \Delta n) \Delta p + f$$

$n_0 \gg p_0 \quad \Delta p \ll n_0 \quad \Delta u \ll n_0$

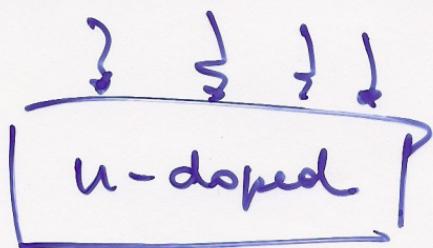
Dunque n

$$\Rightarrow \frac{d\Delta n}{dt} = \frac{d\Delta p}{dt} = -A n_0 \Delta p + f \quad \delta p = \frac{1}{A n_0}$$

$$\text{Se } f = 0 \quad \frac{d\Delta p}{dt} = -\frac{\Delta p}{\delta p} = \frac{d\Delta n}{dt}$$

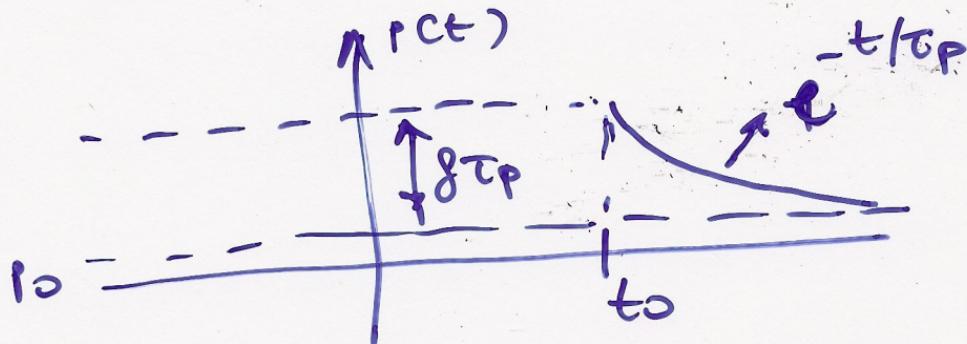
e, h misurare
con σ
misurando

Rise time mesură plată în moment



$$\rho = \rho_0 + g \tau_p \quad : \text{Cond. statioanare}$$

Pentru $t = t_0$: Ece. OFF



Ge - Germanium

Recombination Parameters

Pure n-type material

300 K

The longest lifetime of holes

$$\tau_p \geq 10^{-3} \text{ s}$$

Diffusion length

$$L_p \geq 0.2 \text{ cm}$$

77 K

The longest lifetime of holes

$$\tau_p \geq 10^{-4} \text{ s}$$

Diffusion length

$$L_p \geq 0.15 \text{ cm}$$

Pure p-type material

300 K

The longest lifetime of electrons

$$\tau_n \geq 10^{-3} \text{ s}$$

Diffusion length

$$L_n \geq 0.3 \text{ cm}$$

77 K

The longest lifetime of electrons

$$\tau_n \geq 10^{-4} \text{ s}$$

Diffusion length

$$L_n \geq 0.15 \text{ cm}$$

Surface recombination

$$10 \div 10^6 \text{ cm/s.}$$

Radiative recombination coefficient at 300 K $6.41 \cdot 10^{-14} \text{ cm}^3 \text{ s}^{-1}$

Auger coefficient at 300 K

$$\sim 10^{-30} \text{ cm}^6 \text{ s}^{-1}$$

GaAs - Gallium Arsenide

Recombination Parameter

Pure n-type material ($n_o \sim 10^{14} \text{ cm}^{-3}$)

The longest lifetime of holes $\tau_p \sim 3 \cdot 10^{-6} \text{ s}$

Diffusion length $L_p = (D_p \cdot \tau_p)^{1/2} \sim 30\text{-}50 \mu\text{m}$.

Pure p-type material

(a) Low injection level

The longest lifetime of electrons $\tau_n \sim 5 \cdot 10^{-9} \text{ s}$

Diffusion length $L_n = (D_n \cdot \tau_n)^{1/2} \sim 10 \mu\text{m}$

(b) High injection level (filled traps)

The longest lifetime of electrons $\tau \sim 2.5 \cdot 10^{-7} \text{ s}$

Diffusion length $L_n \sim 70 \mu\text{m}$

Radiative recombination coefficient (Varshni[1967])

90 K $1.8 \cdot 10^{-8} \text{ cm}^3/\text{s}$

185 K $1.9 \cdot 10^{-9} \text{ cm}^3/\text{s}$

300 K $7.2 \cdot 10^{-10} \text{ cm}^3/\text{s}$

$$J_e = ne\mu_e E + e D_e \nabla n$$

$$J_h = p e \mu_h E - e D_h \nabla p$$

$$J = J_e + J_h$$

equ. di continuità con termini di ricompenze
per i potatori minoritari

$$\frac{\partial n_p}{\partial t} = g_n - \frac{n_p - n_p^0}{\tau_n} + \frac{D \cdot J_e}{e} \quad : \text{elettroni in materiale p}$$

$$\frac{\partial n_p}{\partial t} = g_p - \frac{p_m - p_p^0}{\tau_p} - \frac{D \cdot J_h}{e} \quad : \text{le donne in materiale n}$$

Condizioni neutralità:

$$n_m - n_m^0 = p_n - p_n^0 : \text{materiale n}$$

$$n_p - n_p^0 = p_p - p_p^0 : \text{materiale p}$$

Neutralità di carica



Doping omogeneo

$$\text{Creazione } \Delta n \text{ e } \Delta p \implies n = n_0 + \Delta n$$
$$p = p_0 + \Delta p$$

Se nucle si mostra: $\Delta n = \Delta p$ (compensato)

$$\text{Se } \Delta n \neq \Delta p \implies p = e(\Delta p - \Delta n)$$

$$D.E = \frac{p}{\epsilon_0 \epsilon_r} = e \frac{(\Delta p - \Delta n)}{\epsilon_0 \epsilon_r}$$

$$\Delta p - \Delta n \sim 10^{-2} \quad p \sim 10^{18} / m^3 \quad \epsilon_r \sim 10$$

$$D.E \sim 10^7 V/m$$

Se considero un parallelepipedo di spessore 1 cm

$$\rightarrow E \sim 10^5 V/m \quad \text{: No quindi}$$

$\Delta p = \Delta n$: quasi neutralità di carica

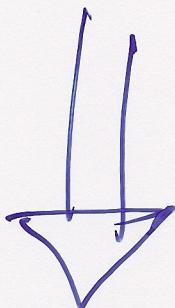
$$D.J = \sigma D.E = - \frac{d\rho}{dt}$$

$$\rightarrow \frac{d(\Delta n - \Delta p)}{dt} = -\frac{\sigma}{\epsilon_0 \epsilon_2} (\Delta n - \Delta p) \quad - t/\tau_0$$

$$\rightarrow (\Delta n - \Delta p) = (\Delta n - \Delta p)_0 e$$

$\tau_0 = \frac{\epsilon_0 \epsilon_2}{\sigma}$: Tempo di rilasciamento
dei treletti ω

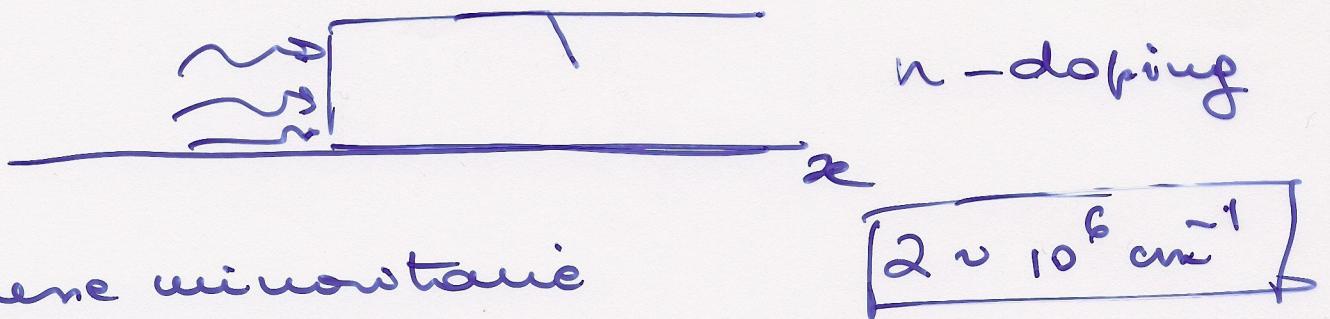
$$\sigma \sim 100 \text{ a.u.} \rightarrow \tau_0 \sim 1 \text{ ps}$$



Quasi-neutralità di coulomb

Anche in presenza di eccitazioni esterne

Trilicue portatori minoritari



$$\frac{\partial \phi_n}{\partial t} = g_p - \frac{p_n - p_n^0}{\tau_p} + D_n \frac{\partial^2 \phi_n}{\partial x^2}$$

g_p
 $\Rightarrow 0$ n.c.e
volume

Condizioni stazionarie

$$\rightarrow \frac{p_n - p_n^0}{\tau_p} = D_n \frac{\partial^2 \phi_n}{\partial x^2}$$

Condizioni al contorno: $\phi_n(0) = p_n^0 + \Delta p_n(0)$

$$-x/L_n \quad \phi_n(\infty) = p_n^{\infty}$$

$$\phi_n(x) = p_n^0 + \Delta p_n(0) e^{-x/L_n}$$

$$L_n = \sqrt{D_n \tau_p} : \text{lunghezza diffusione}$$

$$D_n \sim 10^{-4} \frac{m^2}{s} \quad \tau_p \sim 10^{-6} s \Rightarrow L_n \sim 10^{-8} m$$

$$J_h(x) = -D_h e \frac{\partial \Delta p}{\partial x} = \frac{D_h e}{L_h} \Delta p_h(0) e^{-x/L_h}$$

$$J_h(0) = \frac{D_h}{L_h} e \Delta p_h(0)$$

$$\frac{D_h}{L_h} = \text{Velocità di Diffusione} \\ \sim 50 \frac{\text{m}}{\text{s}}$$

$$J_{tot} = J_e - e J_h = n_e \mu_e \mathcal{E} + p_e \mu_n \mathcal{E} + e D_e \nabla p - e D_h \nabla p$$

$$\text{Condiz. Stazionaria} \quad \nabla \cdot \vec{j} = 0$$

$$\text{Se appi esterni siano } J=0$$

$$\Rightarrow (n_e \mu_e + p_e \mu_n) \mathcal{E} = e (D_h \nabla p - D_e \nabla p)$$

Se vale la neutralità di carica $D_h \approx D_e$

$$\mathcal{E} \approx \frac{D_h}{n \mu_e} \left(1 - \frac{D_e}{D_h}\right) \nabla p$$

Sotto equ. di Poisson

$$\rho = \epsilon_0 \epsilon_r D_e \mathcal{E} = \frac{\epsilon_0 \epsilon_r}{n \mu_e} D_h \left(1 - \frac{D_e}{D_h}\right) \frac{\Delta p(0)}{L_h^2} e^{-x/L_h}$$

Per $x \approx 0$

$$\text{ne } l_n^2 = D_n \tau_p$$

$$\rho(0) = \frac{\epsilon_0 \epsilon_r}{n \mu e} \left(1 - \frac{\sigma_e}{D_n}\right) \frac{\Delta \rho(0)}{\tau_p} = (\Delta \rho - \Delta n)(0) e^{-t/\tau_p}$$

se $(\Delta \rho - \Delta n)(t) = (\Delta \rho - \Delta n)(0) e^{-t/\tau_p}$

$$\tau_p = \frac{\epsilon_0 \epsilon_r}{6}$$

$$\rho(0) = \frac{\epsilon_0 \epsilon_r}{n \mu e} \frac{6}{6} \left(1 - \frac{\sigma_e}{D_n}\right) \frac{\Delta \rho(0)}{\tau_p}$$

$$\rho(0) \propto \Delta \rho(0) \left(\frac{\epsilon_0}{\tau_p} \left(1 - \frac{\sigma_e}{D_n}\right) \right) \stackrel{e^{-t}}{\approx}$$

$\downarrow 10^{-6}$

VALIDITÀ QUASI
neutralità Caico