

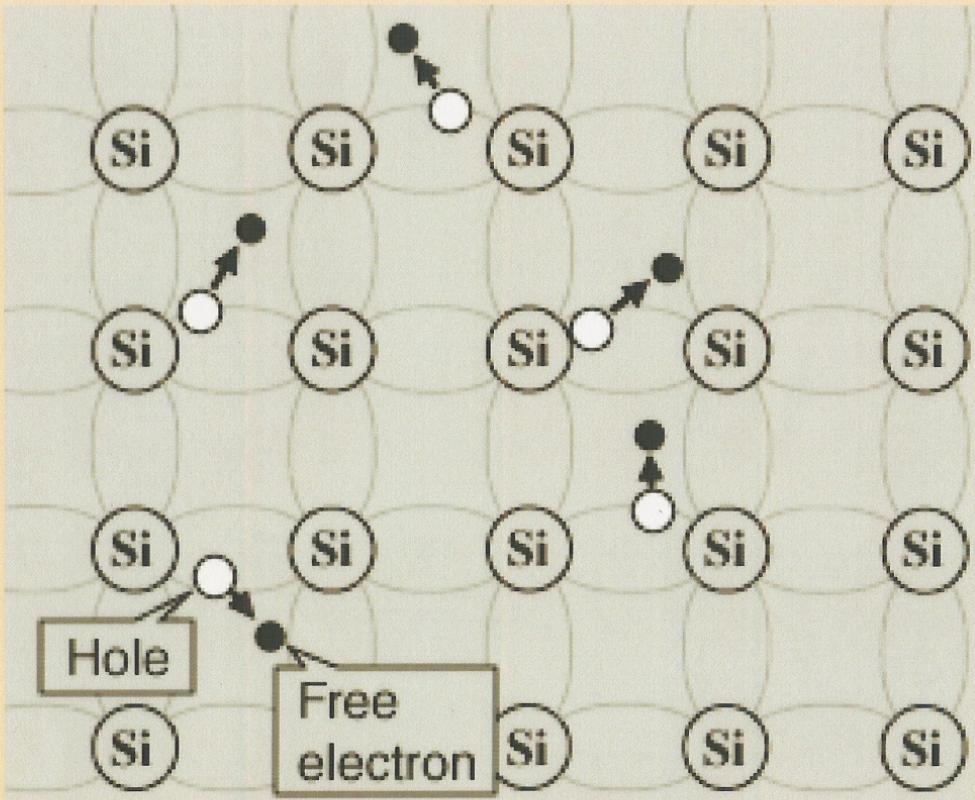
Trasporto

- Carica (conduzione elettrica)
- Massa (diffusione)
- Energia (conduzione termica)

Sistema fuori equilibrio Rilassamento {

Interbanda (10^{-3} - 10^{-9} s)
Intrabanda (10^{-13} s)

Hp: popolazioni bande costanti
(n e p non ricombinano



Electrons and holes

Modello di Drude

Hyp: elettroni, m_e^* , $\propto \tilde{\epsilon}$ scattering costante indipendente da $\tilde{\epsilon}$

$$\underline{F}_e = -\frac{d\underline{p}_e}{dt} = -e\underline{E}$$

$$\rightarrow \frac{1}{m_e^*} \frac{d\tilde{u}}{dt} = e \tilde{\epsilon}$$

$$\rightarrow \Delta t \sim 10^{-12} \text{ s}$$

$$\langle v^2 \rangle = \frac{3kT}{m} \rightarrow v \sim 10^5 \text{ m/s}$$

libero cammino medio

$$\chi = v \bar{t} = 10^5 * 10^{-13} \text{ m} = 10^{-8} \text{ m}$$

No trasporto bellico

Modello di Drude

Hyp: All' equilibrio $\langle v \rangle = 0$

$$\underline{F} = m \frac{d\underline{v}}{dt}$$

collissioni istantanee, casuali

$$F_e = -e \underline{E} = m e^* \frac{d\underline{v}}{dt}$$

$$\langle v \rangle = \langle v_0 \rangle + a \tilde{v}$$

~~#~~
~~o~~

 $\left\{ \begin{array}{l} m e^* \frac{d\underline{v}}{dt} + m e^* \frac{v}{\tau} = -e \underline{E} \\ \text{cond. stat.} \end{array} \right.$

 $v = -\frac{e \tau}{m e^*} \underline{E}$

$$\langle v \rangle = -\frac{e \tilde{v}}{m e^*} \underline{E} = -\frac{me^*}{m e^*} \underline{E}$$

indreitato = $\frac{e \tilde{v}}{m e^*}$

$$J_e = -n e \langle v \rangle = n e \cancel{v} e^* E = Q_e E$$

$$\delta_e = \frac{n e^* \tilde{v}}{m e^*}$$

Analogamente per le locune:

$$J_n = \sigma_n E$$

$$\sigma_n = \rho e \mu_n$$

$$\sigma_{\text{tot}} = \sigma_e + \sigma_h$$

le correnti di Drift si sommano

limitazioni modello Drude

- ① τ non dipende da Energie
- ② Il modello vale solo per campi piccoli: vuole reale di dispersione lente.

Prob. scattering -

$p(t)$: num into $[0, t]$

$R dt$: prob. into dt

$\Rightarrow p(t) R dt$: Prob. the average in
into step dt

$$p(t+dt) = p(t) \underbrace{[1 - R dt]}_{\substack{\text{No new} \\ \text{events}}} \quad \underbrace{\downarrow}_{\substack{\text{No new} \\ \text{in } dt}}$$

\Rightarrow

$$p(t+dt) - p(t) = -R p(t) dt$$

$$\Rightarrow \frac{1}{p(t)} \frac{dp}{dt} = -R dt$$

$$\Rightarrow \frac{dp}{p(t)} = -R dt$$

$$-Rt$$

$$\Rightarrow p(t) = e$$

tempo fa due ubi:

$$\langle t \rangle = \int_0^\infty t e^{-Rt} R dt = \frac{1}{R} = \bar{t}$$

$$\langle t^2 \rangle = \int_0^\infty t^2 e^{-Rt} R dt = 2 \langle t \rangle^2$$

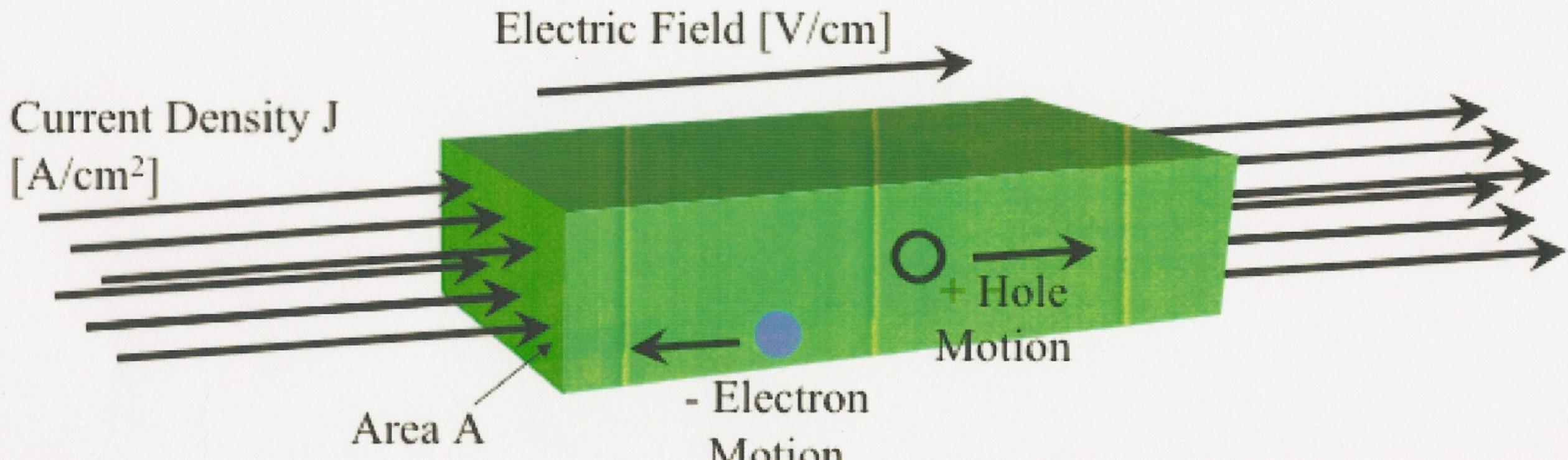
$$\langle v \rangle = a \langle t \rangle = -\frac{eE}{m} \bar{t} = -\mu e E$$

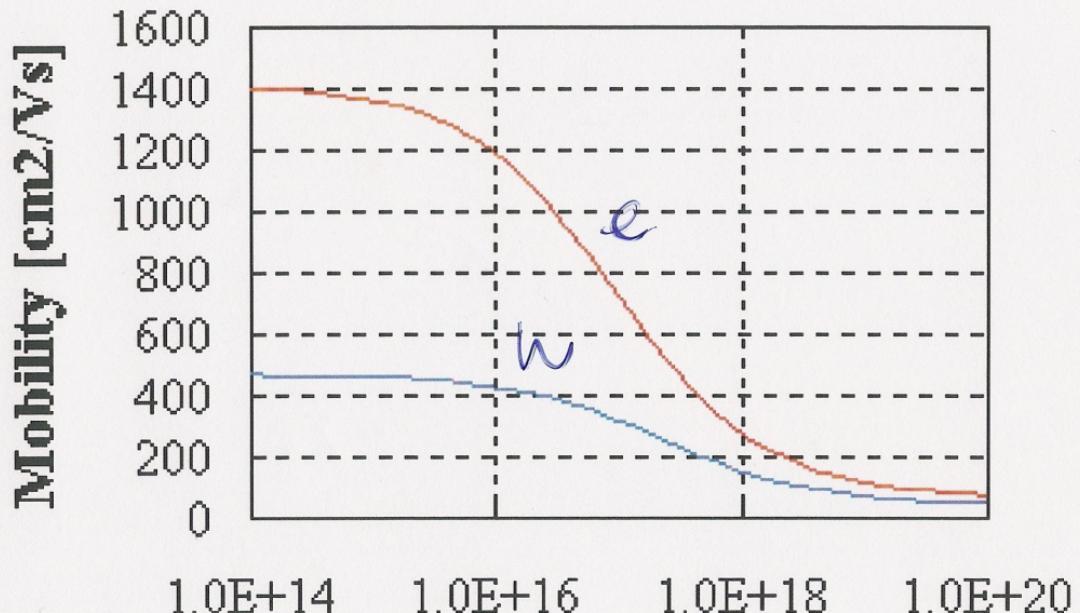
$$\Delta S = \frac{1}{2} a \langle t^2 \rangle = a \langle t \rangle^2 = \langle v \rangle^2 \bar{t}^2$$

fra due collisioni tutti ve
come se le particelle si
muovono a velocità costante

$$\langle v \rangle$$

Drift

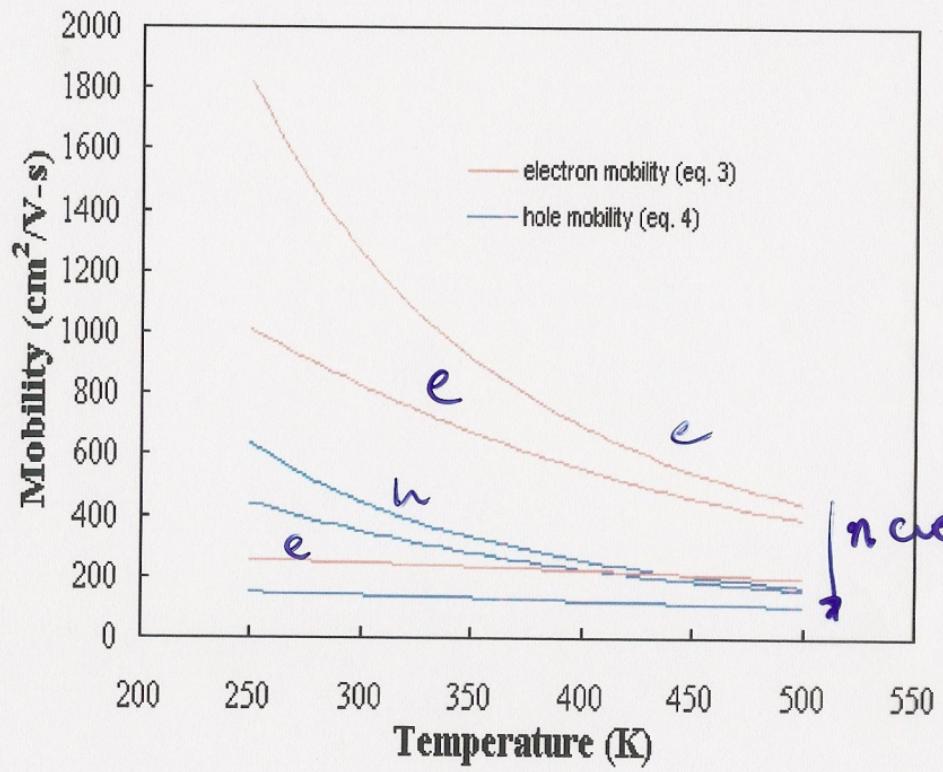




Doping concentration [cm⁻³]

resistiv.xls - mobility.gif

Fig.2.8.3 Electron and hole mobility versus doping density for silicon



mobilitt.xls

Fig.2.8.4 Electron and hole mobility versus temperature. The doping density equals 10^{16} (top curve), 10^{17} and 10^{18} (bottom curve) cm^{-3}

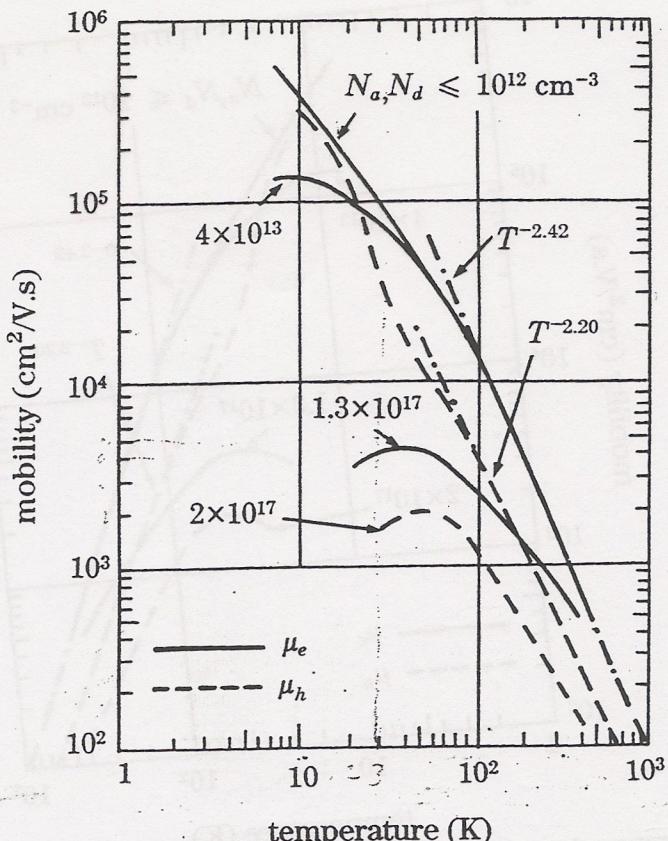


Fig. 5.4. Temperature dependence of the electron and hole mobilities μ_e, μ_h for silicon samples with different doping levels. The electron mobility is shown as continuous curves and the hole mobility as dashed. The dash-dot curves are the best fits to the experimental results.

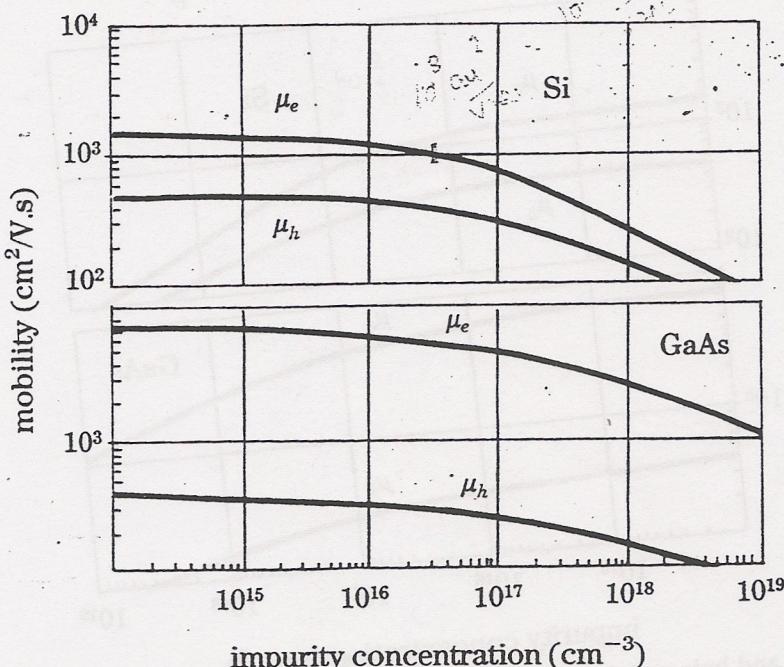


Fig. 5.5. Electron and hole mobility in silicon and gallium arsenide at room temperature, as a function of the impurity concentration.

Meccanismi di collisione

➤ Interazione con il reticolo- fononi

$$\tau = \frac{a}{\sqrt{E}} \frac{1}{T}$$

$$\mu = \mu_0 \left(\frac{T^0}{T} \right)^{\frac{3}{2}}$$

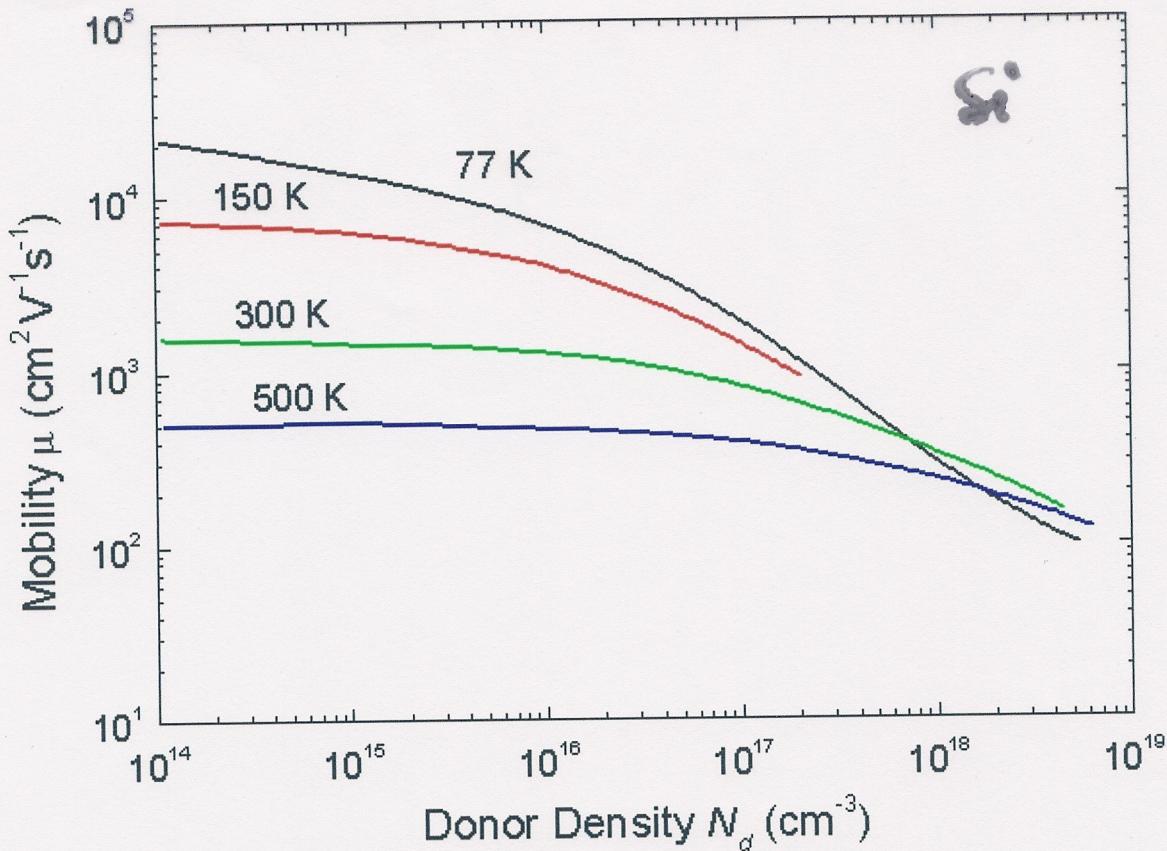
➤ Collisioni con impurezze ionizzate

$$\tau = a T^{\frac{3}{2}}$$

$$\mu = \mu_0 T^{\frac{3}{2}}$$

$$\tau \sim a \bar{E}^{3/2}$$

→ Recresce di τ
il potere
u sente "meno"
campo concentrico
impurezze ionizzate



Per ridurre scattering de impurità
vedi Nanostructure a modulazione
disegno

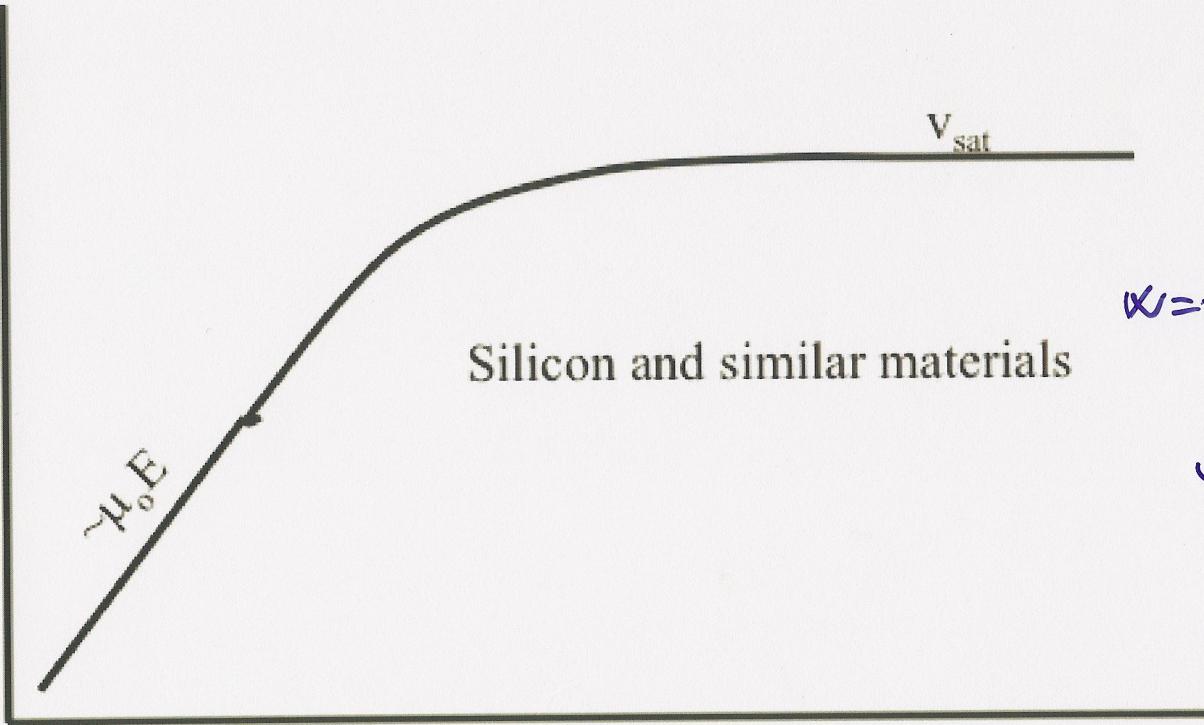
More generally, for Silicon and Similar Materials the drift velocity can be empirically given as:

$$v_d = \frac{\mu_o E}{\left[1 + \left(\frac{\mu_o E}{v_{sat}}\right)^\beta\right]^{1/\beta}} \cong \begin{cases} \mu_o E & \text{when } E \rightarrow 0 \\ v_{sat} & \text{when } E \rightarrow \infty \end{cases}$$

where v_{sat} is the saturation velocity

Drift

Drift Velocity [cm/Sec]



Mechanisms

$$v_{sat} \propto \sqrt{\frac{t_n w_{L0}}{m_e^*}}$$



$$\omega = e \delta E = \frac{t_n w_{L0}}{\tau}$$

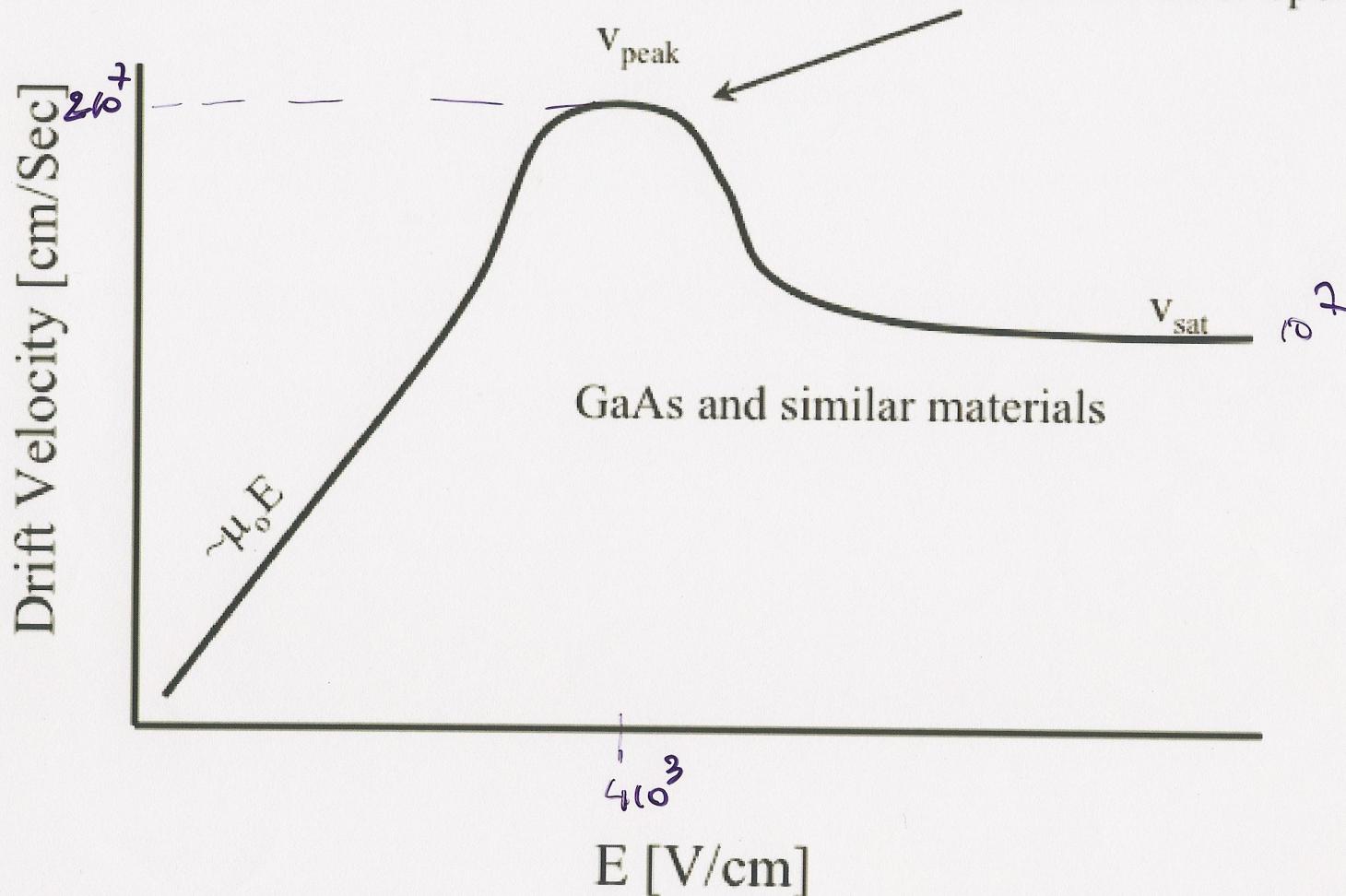
$$\sigma = -\frac{e \delta \tau}{m}$$

$$\Rightarrow \frac{\sigma^2 m^*}{\tau} = \frac{t_n w_{L0}}{\tau}$$

E [V/cm]

Drift

Designing devices to work here results in faster operation



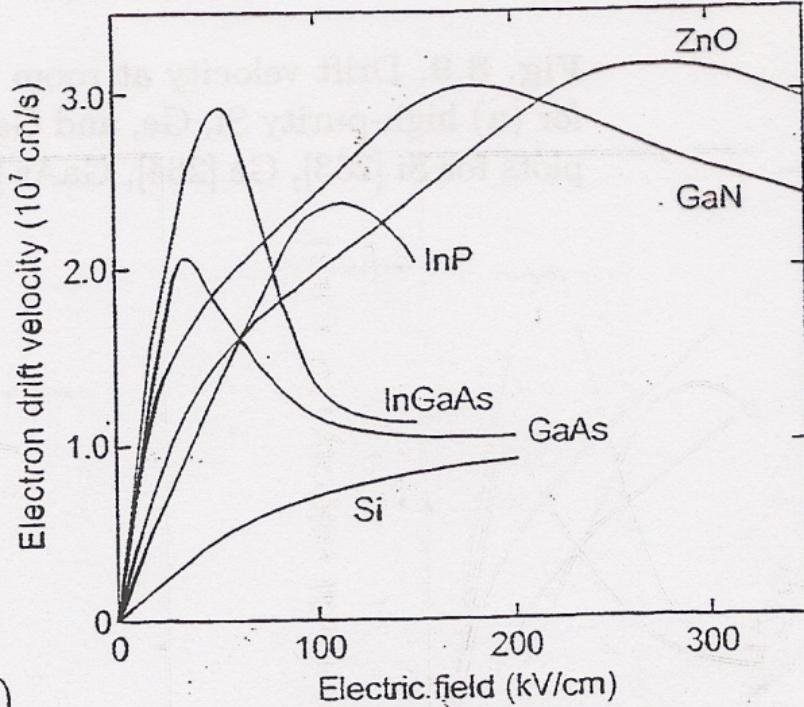
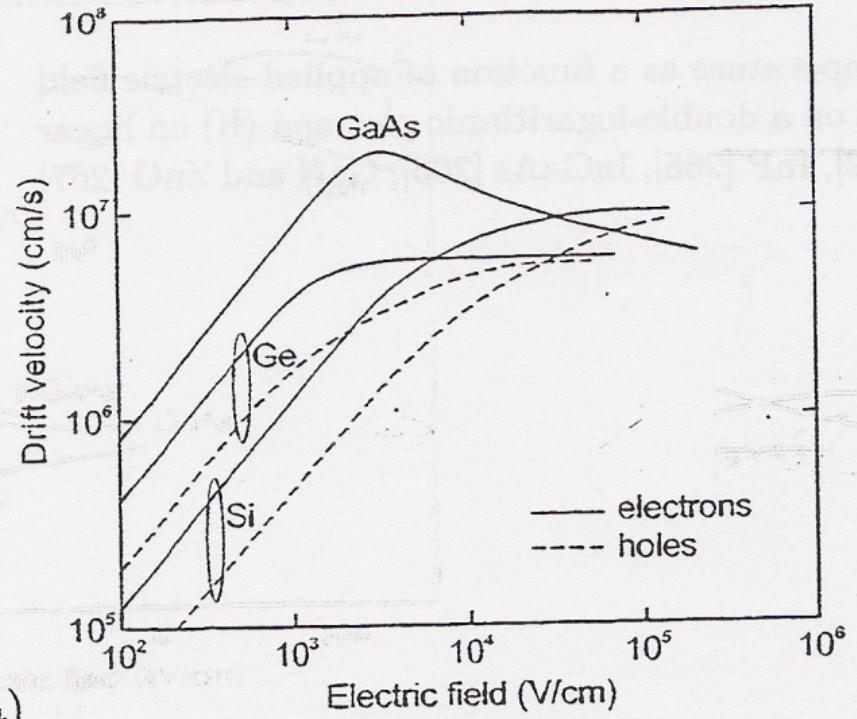


Fig. 8.9. Drift velocity at room temperature as a function of applied electric field for (a) high-purity Si, Ge, and GaAs on a double-logarithmic plot and (b) on linear plots for Si [263], Ge [264], GaAs [222], InP [265], InGaAs [266], GaN and ZnO [267]

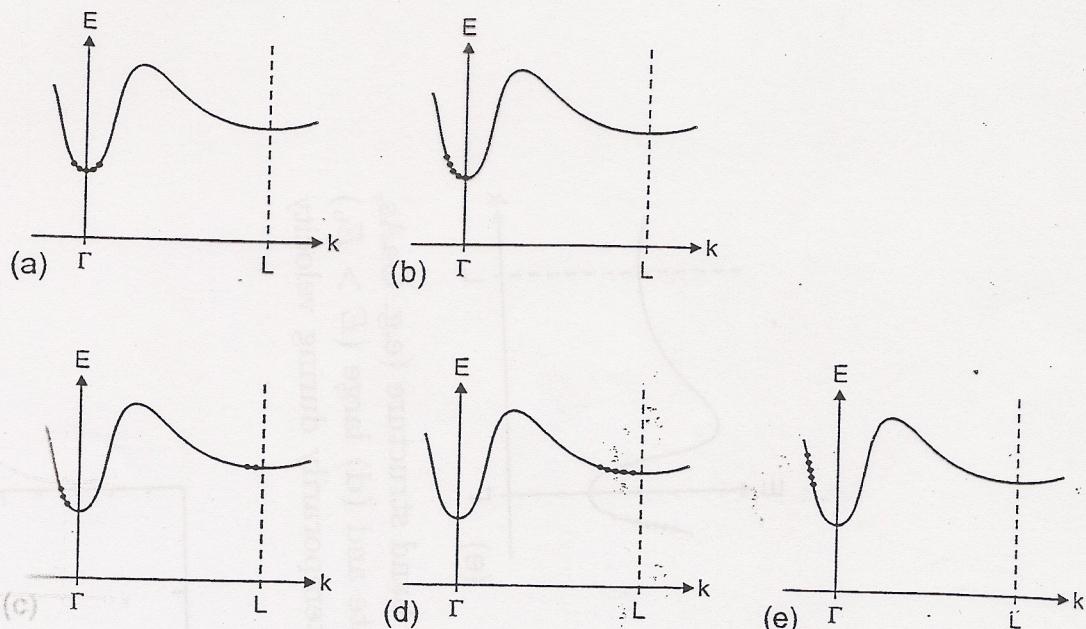


Fig. 8.10. Charge-carrier distribution in a multivalley band structure (e.g. GaAs, InP) for (a) zero, (b) small ($E < E_a$), (c) intermediate and (d) large ($E > E_b$) field strength. The situation shown in (e) is reached temporarily during velocity overshoot (see also Fig. 8.12)

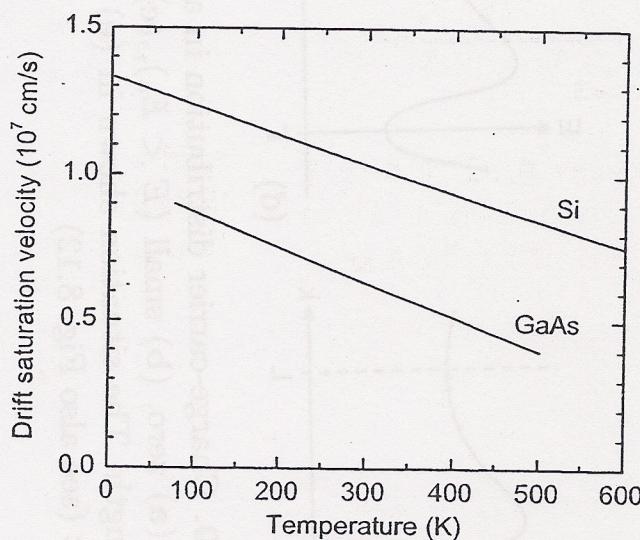


Fig. 8.11. Temperature dependence of the saturation velocity for Si (following $v_s = 0.8 \exp(T/600\text{ K})^{-1}$ with $v_{s0} = 2.4 \times 10^7 \text{ cm/s}$ from [263]) and GaAs [222,

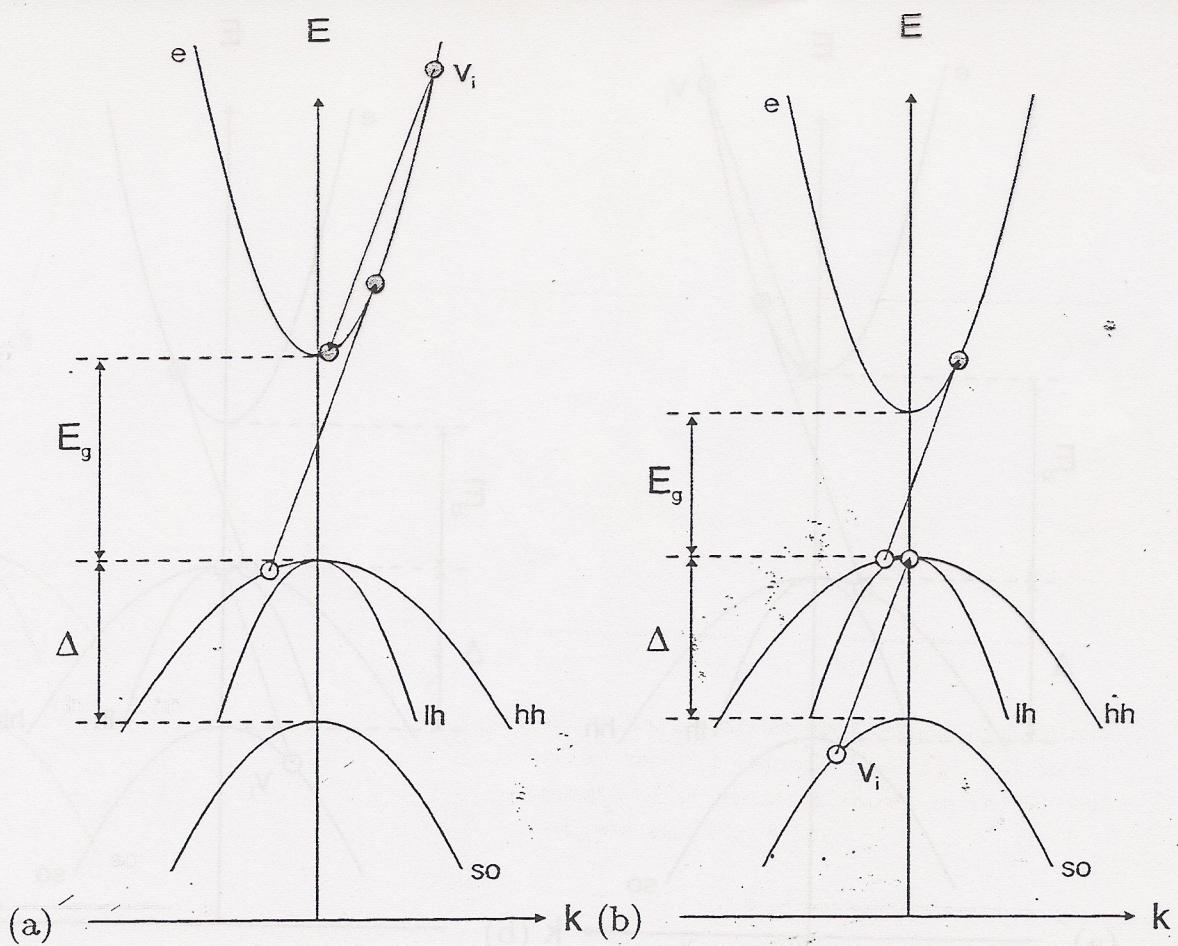
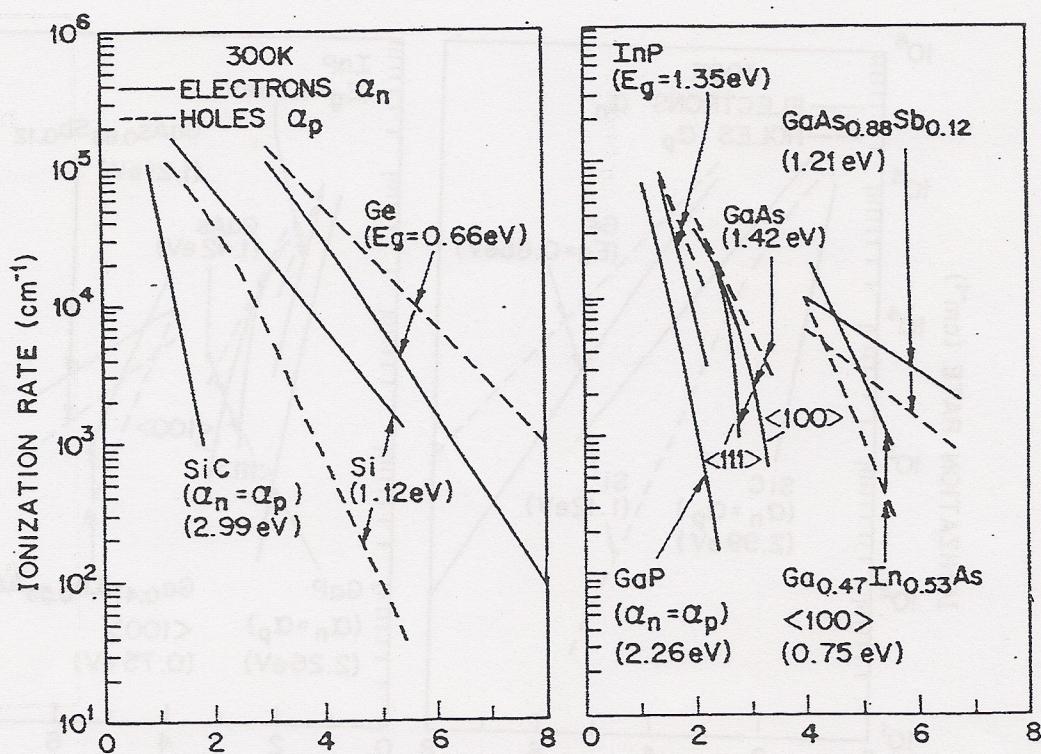


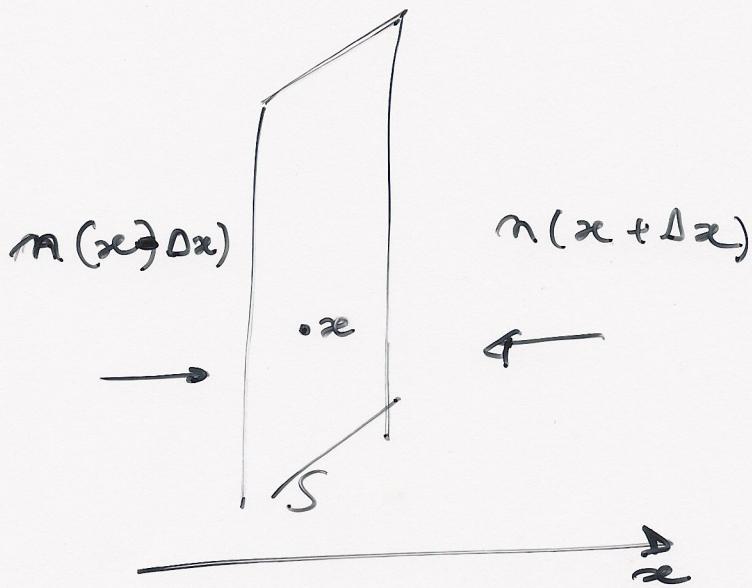
Fig. 8.13. Electron and hole transitions for impact ionization close to the threshold energy. Ionization is triggered by (a) an electron and (b) a split-off hole of velocity v



Diffusione

Gradiente di concentrazione
(Giunture, illuminazione
non uniforme, etc)

$$u \propto \phi$$



Per convenzione
se flusso > 0
verso destra

$$\dot{F} = n(x - \Delta x) \frac{1}{6} v_x - \frac{1}{6} v_x n(x + \Delta x)$$

$$= -\frac{1}{3} \Delta x \frac{\partial n(x)}{\partial x} v$$

$$\Delta x = \sqrt{v t}$$

$$\dot{F} = -\frac{1}{3} v^2 \sqrt{\frac{\partial n}{\partial x}}$$

$$\langle v^2 \rangle = \frac{3 k T}{m^*}$$

$$\dot{F} = -\frac{k T}{m^*} \tau \frac{\partial n}{\partial x}$$

$$\vec{J} = -D \frac{\partial n}{\partial x}$$

: I legge di Fick



$$J_{\text{diff}} = -D \frac{\partial n}{\partial x}$$

$$\vec{J}_{\text{diff}} = -D \vec{\nabla} n$$

$$D = \frac{kT}{m_e^*} \tilde{v} : \text{Coeff. di diffusione}$$

$$J_e = \frac{kT}{m_e^*} \tilde{v} \frac{e}{e} = \frac{kT}{e} \mu_e \quad] \quad \text{rel. di Giuskin}$$

$$J_n = \frac{kT}{e} \mu_n$$

Conservazione numero partecelle

$$\frac{\partial n}{\partial t} + \nabla \cdot \vec{J}_{\text{diff}} = 0$$

$$\Rightarrow \frac{\partial n}{\partial t} = -D \nabla^2 n$$

Concrete hole

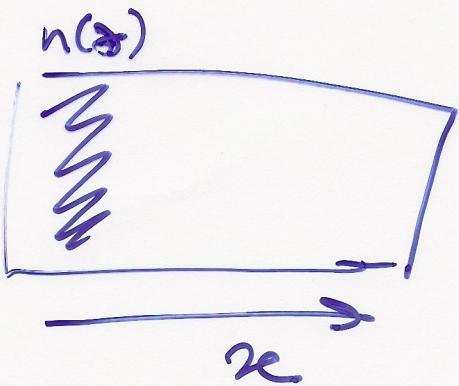
$$T_{\text{for}} = T_{\text{diff}} + T_{\text{diff}}$$

$$J_e = n e \mu_e E + e D e \nabla m$$

$$J_h = p e \mu_h E - e D h \nabla p$$

↓ ↓

Hemo segno segno opposto



Fun gradiente di concentrazione
(per semplicità 1D)

$$J_x = -D \frac{\partial n}{\partial x}$$

legge di Fick

spu. continuità

$$\vec{D} \cdot \vec{J} + \frac{\partial u(x)}{\partial t} = 0$$

$$\Rightarrow \boxed{\frac{\partial u(x)}{\partial t} = D \frac{\partial^2 u}{\partial x^2}}$$

: eqn. Diffusione

$$T_x = \mu n_c E + e D_c \nabla n_c$$

In condizioni di equilibrio

$$\nabla u \rightarrow \frac{\partial n_c}{\partial x}$$

$$\mu_u = - \frac{D_e}{n_c} \frac{\partial n_c}{E \partial x} = \frac{D_e}{n_c} \frac{\partial n_c}{\partial r}$$

In condiz. di equilibrio

$$\mu_u = D_e \frac{e}{n_c} \frac{\partial n_c}{\partial E_F} - \left(\frac{E - E_F}{kT} \right)$$

$$\Rightarrow n_c = N_c \quad \text{e}$$

$$\Rightarrow \mu_u = \frac{D_e e}{n_c} \frac{1}{kT} n_c$$

$$\Rightarrow \boxed{\frac{D_e}{\mu_u} = \frac{kT}{e}} : \text{rel. Einstein}$$

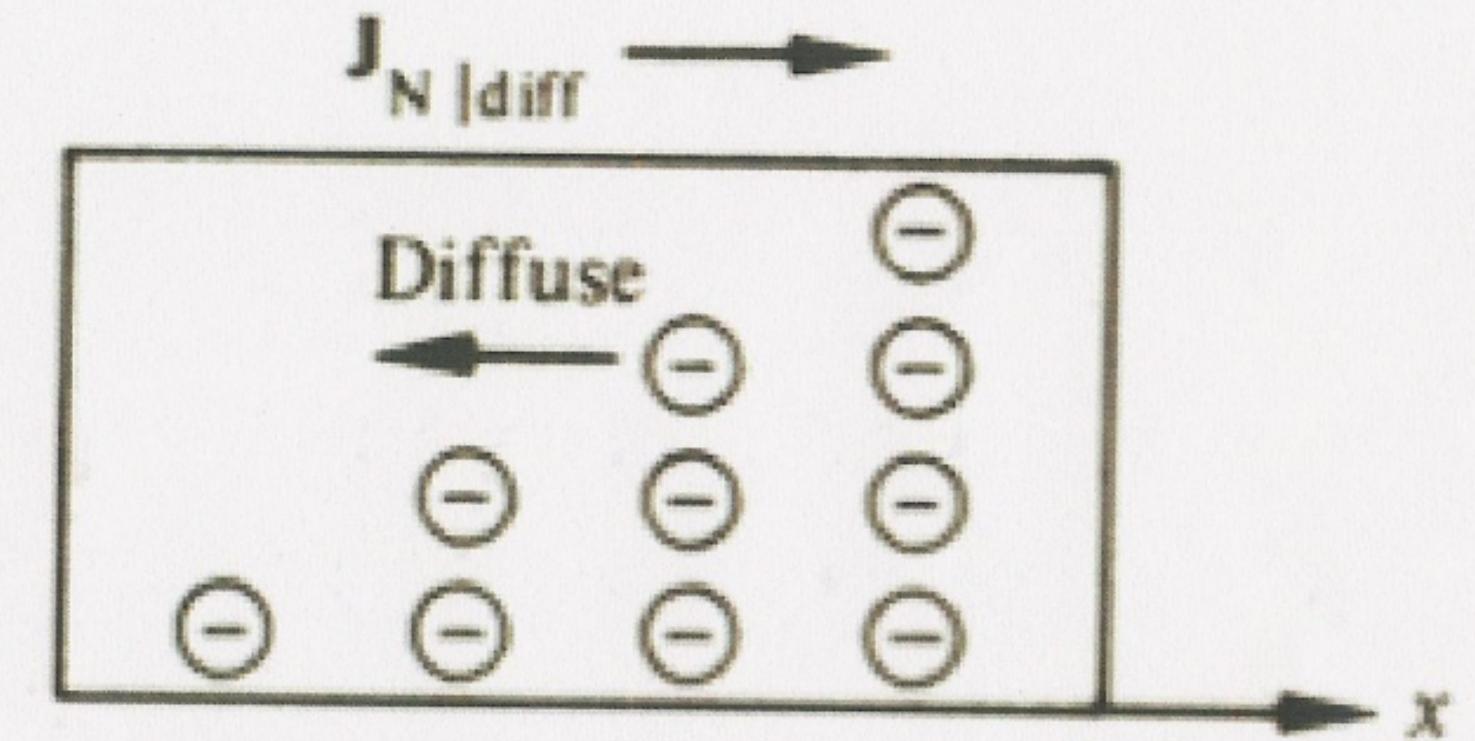
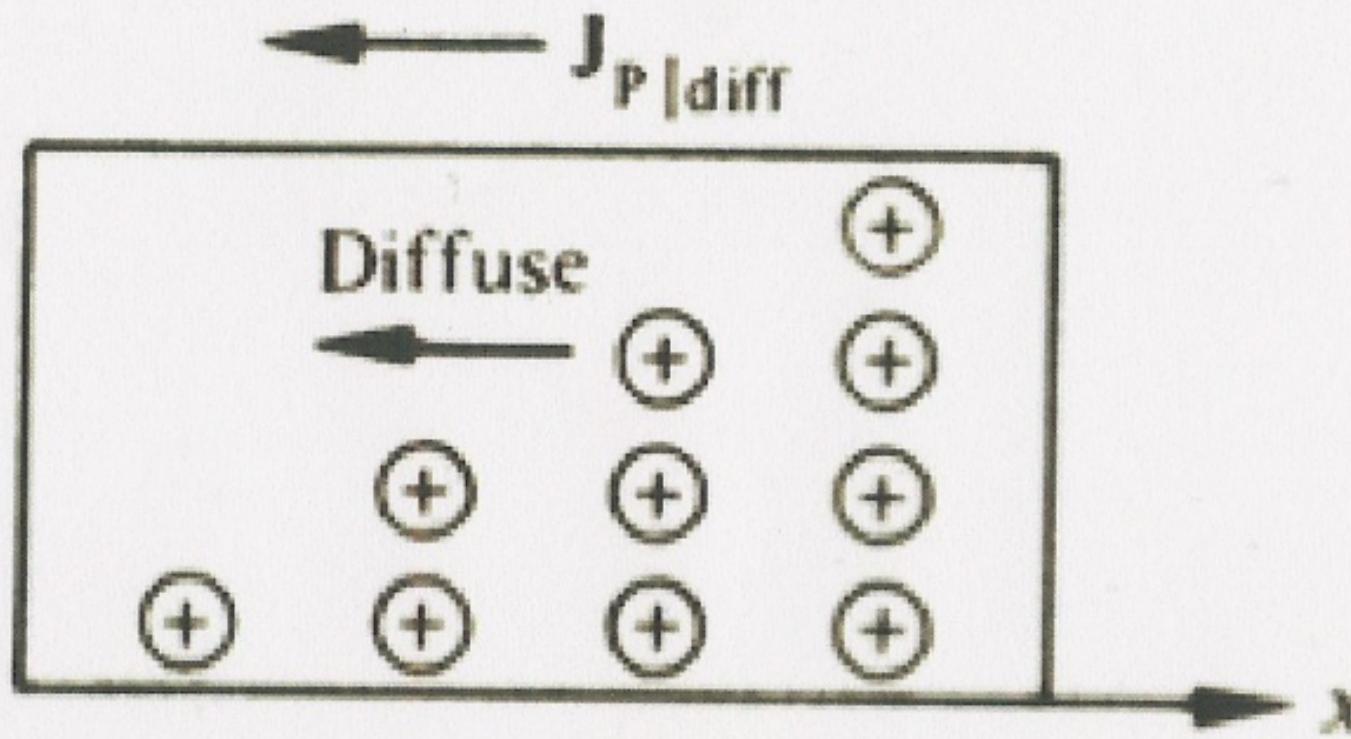


Figure 3.12 Visualization of electron and hole diffusion on a macroscopic scale

Coleodo 5

Ad es. GeTe 300 K

$$\mu_e = 8500 \text{ cm}^2/\text{V sec}$$

$$\mu_h = 400 \text{ cm}^2/\text{V sec}$$

$$\epsilon_0 = 1.42$$

$$n = N_c e^{\frac{E_F - E_C}{kT}}$$

$$N_{c,v} = 2 \left(\frac{2\pi m_{e,h}^* kT}{e^2} \right)^{3/2}$$

$$p = N_v e^{\frac{E_V - E_F}{kT}}$$

$$N_c \approx 4 \cdot 10^{23} / \text{m}^3$$

$$N_v \approx 3 \cdot 10^{24} / \text{m}^3$$

$$mp = m_i^2 \Rightarrow n = \sqrt{N_c N_v e^{-\frac{\epsilon_0}{kT}}} = \frac{3 \cdot 10^{12}}{\text{m}^3}$$

$$G = e(n \mu_e + p \mu_h) = 4 \cdot 10^{-7} \Omega^{-1} \text{ m}^{-1}$$

$$\rho = \frac{1}{G} \approx 2.5 \cdot 10^6 \Omega \text{ m}$$

In reale : $\sim 10^{20}$ donori/ m^3 : Bouinotti a 300 K

$$\Rightarrow n = N_d \quad p \ll n$$

$$\rho = \frac{1}{e N_d \mu_e} \approx 7 \cdot 10^{-2} \Omega \text{ m}$$



Sub. conduttori

Compensation

$$\mu_n/\mu_e \approx \frac{1}{20}$$

Per Ge AG

$$\sigma = e(\mu_e n + \mu_h p) \approx e \mu_n (20n + p)$$

$$\sigma = \underbrace{e \mu_n}_{\delta_0} \left(20 \frac{n_i^2}{p} + p \right)$$

case minuscus : $\sigma_{\text{min}} = \delta_0 21 n_i$

$$\frac{d\sigma}{dp} = -\delta_0 \left(20 \frac{n_i^2}{p^2} + 1 \right) = 0$$

$$\Rightarrow p = \sqrt{20} n_i$$

$$\sigma_{\text{min}} = \delta_0 2 \sqrt{20} n_i \approx 9 \delta_0 n_i$$

Per controllone 6 Ne e Nd : dominante

$$n = N_d - N_a = N_c \exp \left\{ \frac{\bar{\epsilon}_F - \epsilon_c}{kT} \right\}$$

$$\bar{\epsilon}_F = \epsilon_c + kT \ln \left(\frac{N_c}{N_d - N_a} \right)$$