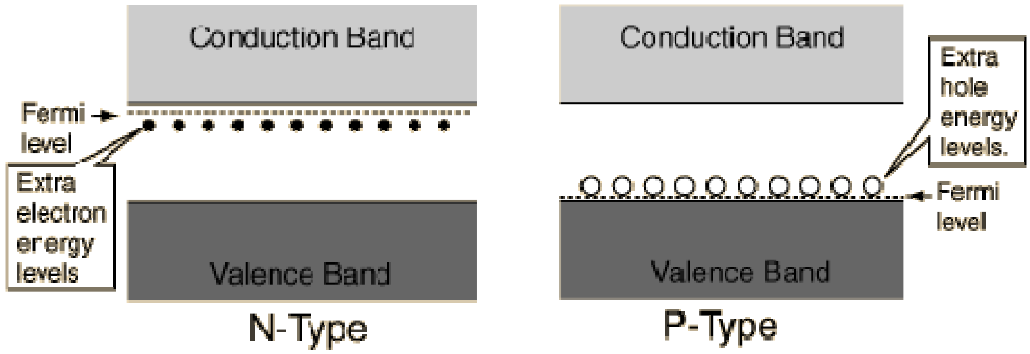
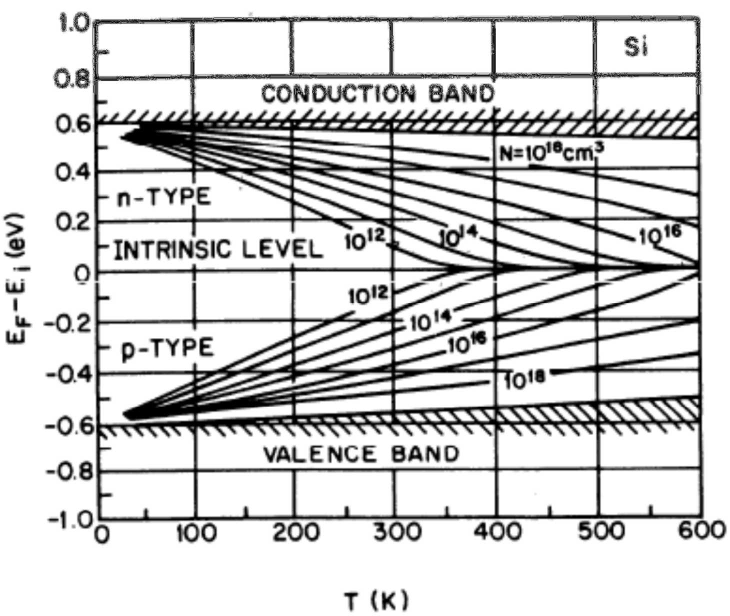
Diagramma a bande per estrinseci:

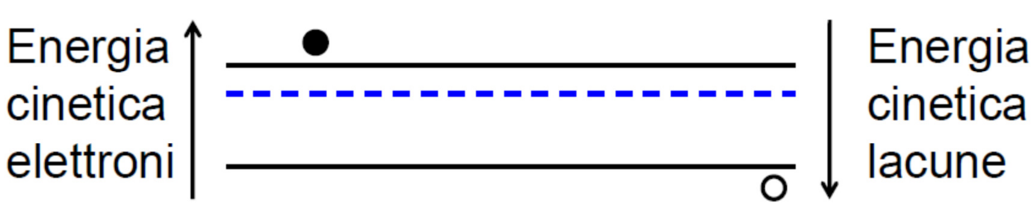


Posizione di E_F evolve con la temperatura e la concentrazione di impurita':



$$E = E_C + \frac{\hbar^2 k^2}{2m_e^*} = E_C + \frac{m_e^* v_e^2}{2}$$

$$E = E_V - \frac{\hbar^2 k^2}{2m_h^*} = E_V - \frac{m_h^* v_h^2}{2}$$



Densita' di corrente di lacune:

$$j = \frac{qN_h}{At_f} = \frac{qN_h v_h}{AL} = qpv_h$$

Includendo anche gli elettroni:

$$j = q\left(pv_h + nv_e\right)$$

Situazione simile a quella dei conduttori, ma:

Due tipi di portatori

Entrambi i tipi presenti in ogni semiconduttore

Per i semiconduttori intrinseci:

$n = p$

Per i semiconduttori estrinseci:

Maggioritari (*e* per *n*, *h* per *p*)

Minoritari (*h* per *n*, *e* per *p*)

Piu' di un tipo di meccanismo per la corrente:

Drift

Effetto di un campo elettrico

Diffusione

Effetto statistico dovuto a gradienti di concentrazione

Corrente di drift: Caso elettroni

$$\mathbf{J} = \frac{nq^2\tau}{m^*}\mathbf{E} = \underbrace{nq}_{\rho_e}\underbrace{\frac{q\tau}{m^*}\mathbf{E}}_{\mathbf{v}_e},$$ analogo a conduttori (v. prima)

$\rightarrow \mathbf{v}_e = \mu_n \mathbf{E}$, μ_e mobilita' di elettroni

Analogo per lacune

$$\rightarrow \mu = \frac{q\tau}{m^*}$$

$$\rightarrow \mathbf{j} = q\left(p\mu_h + n\mu_e\right)\mathbf{E}$$

Conduttivita', resistivita':

$$\sigma = q\left(p\mu_p + n\mu_n\right)$$

$$\rho = \frac{1}{q\left(p\mu_p + n\mu_n\right)}$$

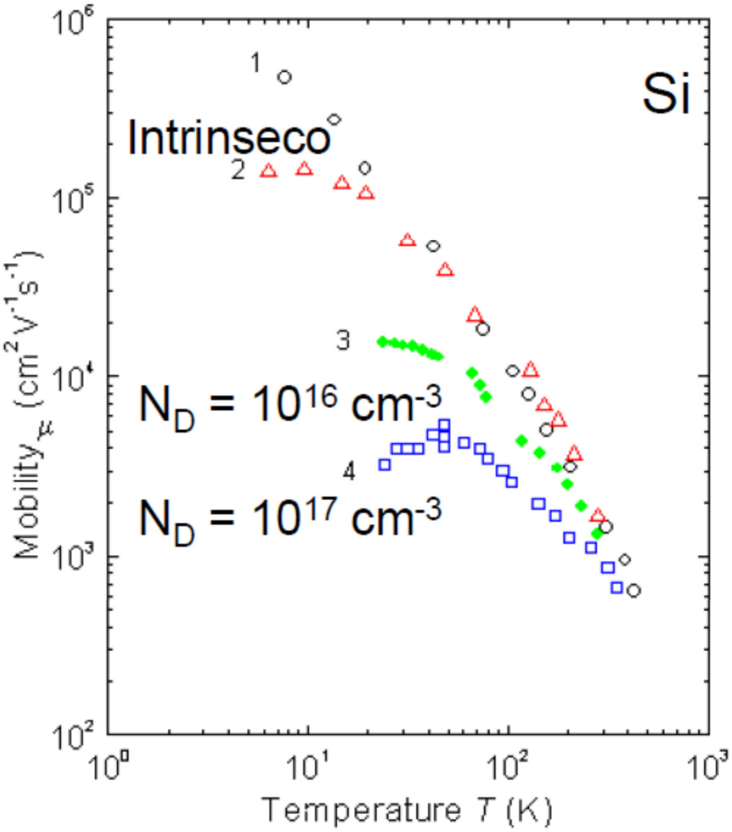
Resistivita' $\propto 1/\mu$: piu' μ **e**' piccolo, piu' grande e' ρ

→ Con diversi contributi, domina il piu' piccolo

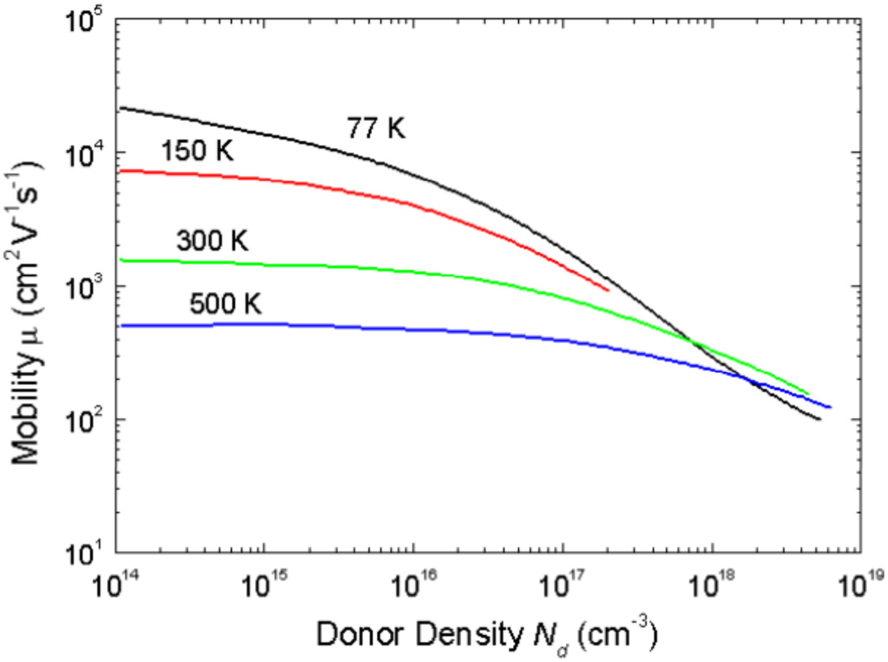
→ Mobilita' si combinano come resistenze in parallelo

$$\rightarrow \frac{1}{\mu_n} = \frac{1}{\mu_{n1}} + \frac{1}{\mu_{n2}} + .., \quad \frac{1}{\mu_p} = \frac{1}{\mu_{p1}} + \frac{1}{\mu_{p2}} + ..$$

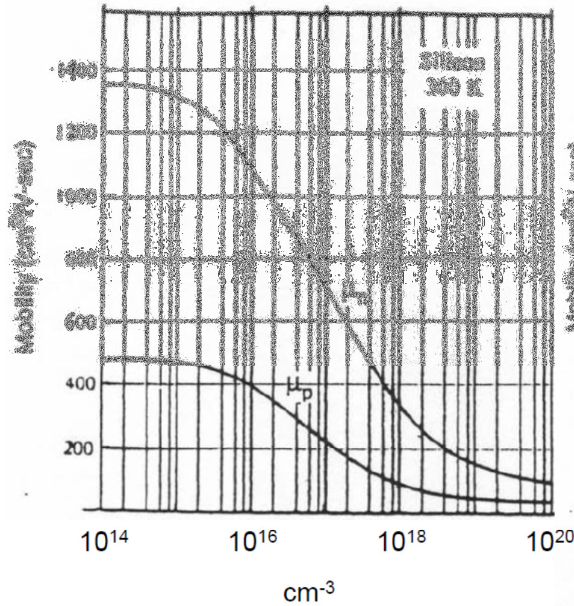
	μ_n [$cm^2V^{-1}s^{-1}$]	μ_p [$cm^2V^{-1}s^{-1}$]
Si	1360	460
GaAs	8000	320



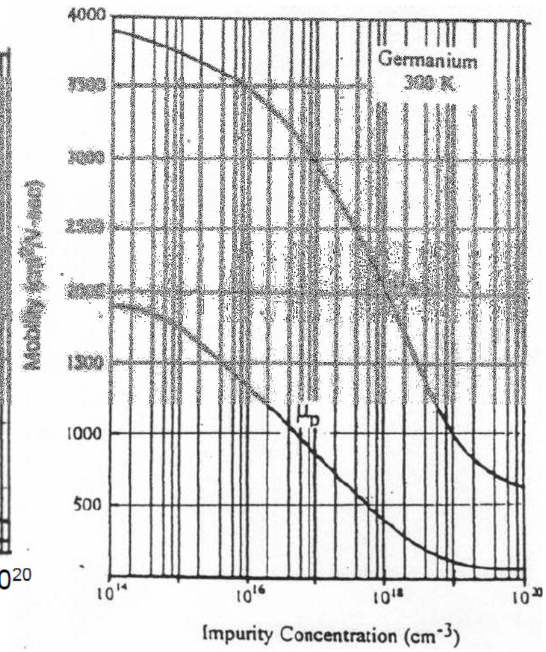
Si
Intrinseco
$N_D = 10^{16}$ cm^{-3}
$N_D = 10^{17}$ cm^{-3}
1
2
3
4
Mobility μ (cm^{2}V^{-1}s^{-1})
Temperature T (K)



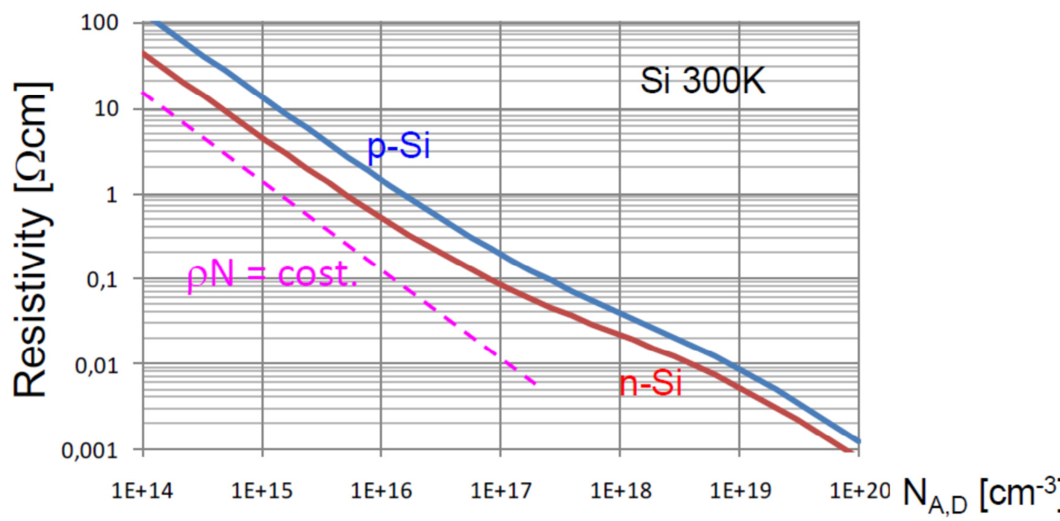
77 K
150 K
300 K
500 K
Mobility μ (cm^{2}V^{-1}s^{-1})
Donor Density N_d (cm^{-3})



Silicon
300 K
Mobility (cm²/V-sec)
400
200
600
μp
10^14
10^16
10^18
10^20
cm^-3



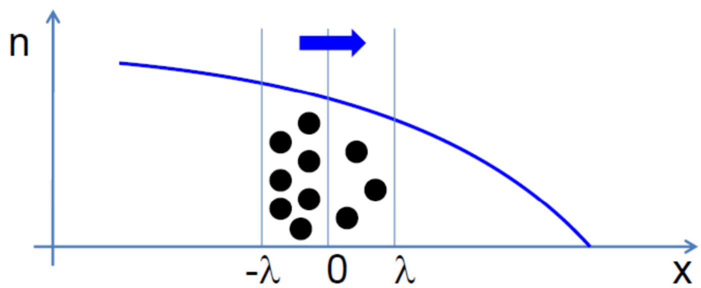
Germanium
300 K
4000
1000
500
μp
Impurity Concentration (cm^-3)



Si 300K
p-Si
n-Si
ρN = cost.
Resistivity [Ωcm]
100
10
1
0,1
0,01
0,001
1E+14
1E+15
1E+16
1E+17
1E+18
1E+19
1E+20
N_A,D [cm^-3]

Corrente di diffusione: Effetto statistico

Concentrazione non uniforme: Flusso netto



$$\phi = nv$$

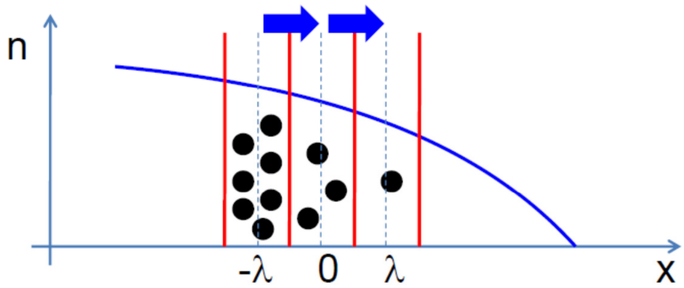
$$\phi = \phi_{\rightarrow} - \phi_{\leftarrow} = -\frac{1}{2} v_t \left[n\left(+\frac{\lambda}{2}\right) - n\left(-\frac{\lambda}{2}\right) \right]$$

$$\rightarrow \phi \approx -\frac{1}{2} v_t \left[n(0) + \left.\frac{dn}{dx}\right|_0 \frac{\lambda}{2} - \left(n(0) + \left.\frac{dn}{dx}\right|_0 \left(-\frac{\lambda}{2}\right) \right) \right]$$

$$\rightarrow \phi \approx -\frac{1}{2} v_t \lambda \frac{dn}{dx} = -D_n \frac{dn}{dx}$$

$$\left.\begin{aligned} D_n &= \frac{1}{2} v_t \lambda \\ \lambda &= v_t \tau \\ kT &= \frac{1}{2} m^* v_t^2 \end{aligned}\right\} \rightarrow D_n = \frac{1}{2} v_t^2 \tau = \frac{kT}{m^*} \tau = \frac{kT}{q} \frac{q\tau}{m^*} = \frac{kT}{q} \mu_n$$

Concentrazione non uniforme: Variazione nel tempo



Differenza di flusso $(+\text{vo da sinistra a destra})$:

Entrante $\left(-\frac{\lambda}{2}\right)-$ Uscente $\left(+\frac{\lambda}{2}\right)$ = In/De-cremento contenuto scatola lunga λ

$$\phi\left(-\frac{\lambda}{2}\right)-\phi\left(+\frac{\lambda}{2}\right)=\frac{dn}{dt}\lambda \quad \text{eq. di continuita'}$$

$$\phi \approx -\frac{1}{2}v_t\lambda\frac{dn}{dx}=-D_n\frac{dn}{dx} \quad (\text{v. prima})$$

Sviluppo in serie di Taylor per $\frac{dn}{dx}$:

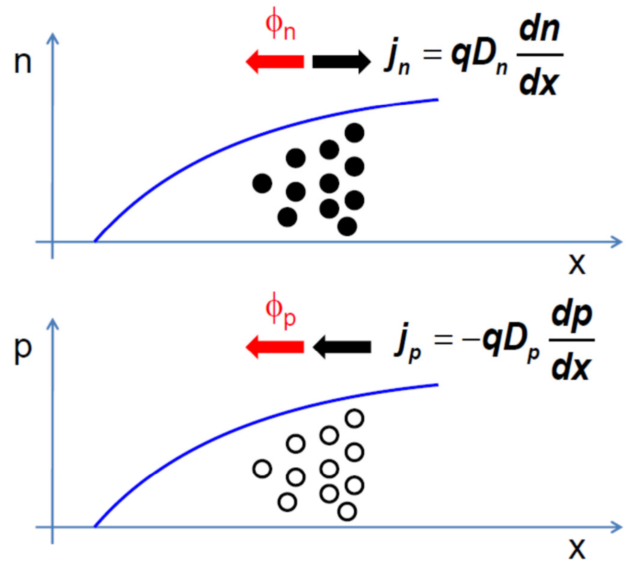
$$\rightarrow\left(-D_n\left.\frac{dn}{dx}\right|_{-\frac{\lambda}{2}}\right)-\left(-D_n\left.\frac{dn}{dx}\right|_{+\frac{\lambda}{2}}\right)=D_n\left[\underbrace{\left.\frac{dn}{dx}\right|_0+\left.\frac{d^2n}{dx^2}\right|_0\frac{\lambda}{2}}_{\sim\left.\frac{dn}{dx}\right|_{+\frac{\lambda}{2}}}-\left(\underbrace{\left.\frac{dn}{dx}\right|_0+\left.\frac{d^2n}{dx^2}\right|_0\left(-\frac{\lambda}{2}\right)}_{\sim\left.\frac{dn}{dx}\right|_{-\frac{\lambda}{2}}}\right)\right]$$

$$\rightarrow D_n\left.\frac{d^2n}{dx^2}\right|_0\lambda=\frac{dn}{dt}\lambda$$

$$\rightarrow D_n\frac{d^2n}{dx^2}=\frac{dn}{dt}$$

Equazione della diffusione $\equiv$ Equazione del calore

Concentrazione non uniforme: Corrente di diffusione

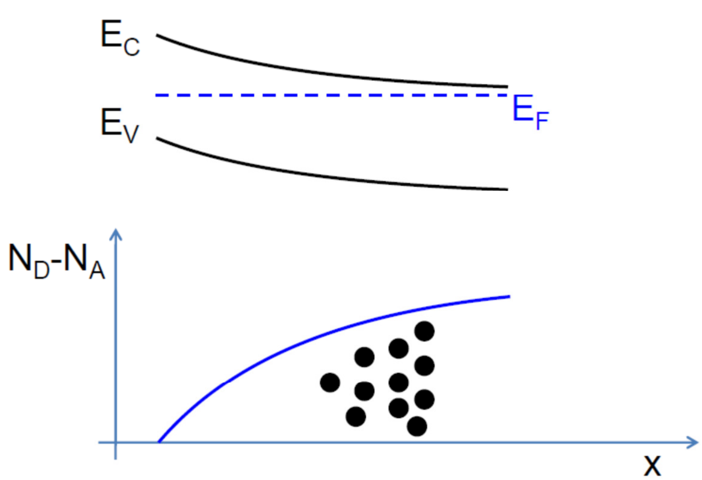


Concentrazione non uniforme:

$$n(x) = N_D(x) = N_C e^{-\frac{E_C - E_F}{kT}} \rightarrow E_C(x) = E_F + kT \ln \frac{N_C}{N_D(x)}$$

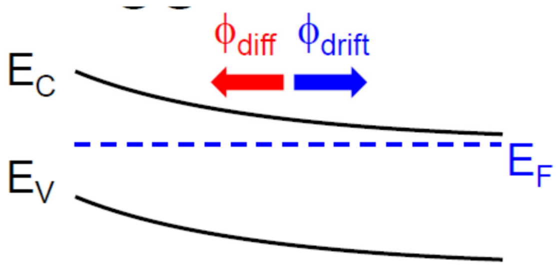
Livello di Fermi costante $(\leftarrow$ Sistema in equilibrio$)$

$\rightarrow E_C = E_C(x)$ Band bending



Concentrazioni non uniformi: Corrente totale

Drift + Diffusione



$$j_n = qn\mu_n E + qD_n \frac{dn}{dx} = 0$$

$$E = -\frac{dV}{dx} = \frac{1}{q}\frac{dE_c}{dx}$$

$$\rightarrow j_n = n\mu_n \frac{dE_c}{dx} + qD_n \frac{dn}{dx} = 0$$

Ritroviamo la relazione di Einstein:

$$n = N_C e^{-\frac{E_C - E_F}{kT}} \rightarrow E_C = -kT \ln \frac{n}{N_C} + E_F$$

$$\rightarrow \frac{dE_c}{dx} = -kT \frac{d(\ln n)}{dx}$$

$$\rightarrow j_n = -n\mu_n kT \frac{d(\ln n)}{dx} + qD_n \frac{dn}{dx} = 0$$

$$\rightarrow j_n = -\mu_n kT \frac{dn}{dx} + qD_n \frac{dn}{dx} = 0$$

$$\rightarrow D_n = -\frac{\mu_n kT}{q}$$

Correnti in un semiconduttore:

Elettroni

$$j_n = qn\mu_n E + qD_n \frac{dn}{dx}$$

Lacune

$$j_p = qp\mu_p E - qD_p \frac{dp}{dx}$$

Totale:

$$j = j_n + j_p = qn\mu_n E + qD_n \frac{dn}{dx} + qp\mu_p E - qD_p \frac{dp}{dx}$$

In 3D:

$$\mathbf{j} = qn\mu_n \mathbf{E} + qD_n \nabla n + qp\mu_p \mathbf{E} - qD_p \nabla p$$