# SEMICONDUTTORE INTRINSECO

## EFFETTO DELLA TEMPERATURA

CONCENTRAZIONE PORTATORI

$n_i = p_i$

$E_g$

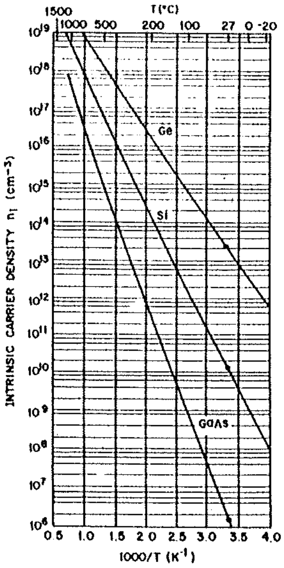


Fig. 11 Intrinsic carrier densities of Ge, Si, and GaAs as a function of reciprocal temperature. (After Thurmond, Ref. 20.)

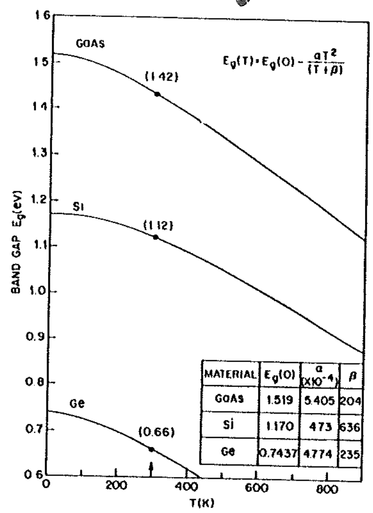


Fig. 8 Energy bandgaps of Ge, Si, and GaAs as a function of temperature. (After Thurmond, Ref. 20.)

$T_i$ = TEMPERATURA INTRINSECA

per $T = T_i$

n (dovuto ad impurezze) = $n_i$ (intrinseco)

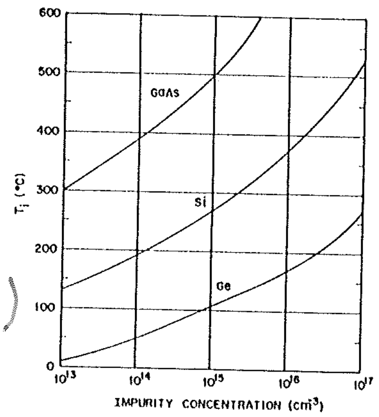


Fig. 12 Intrinsic temperature as a function of background concentration.

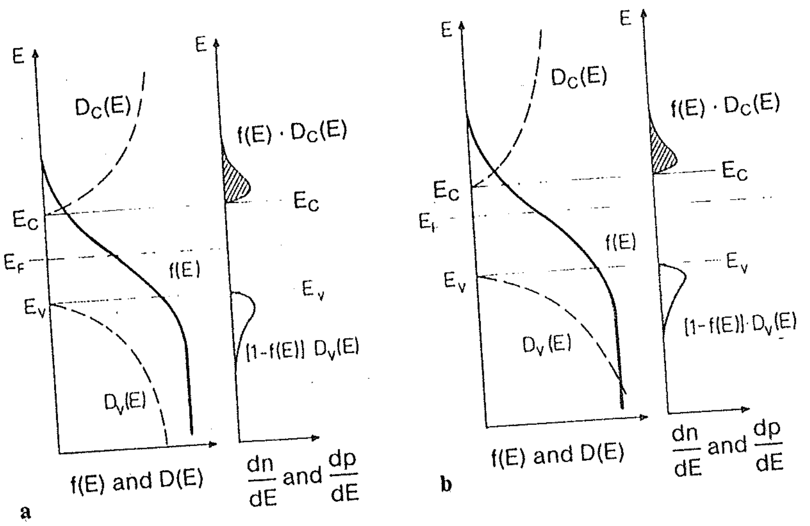


**Fig. 12.5.** a Fermi function $f(E)$, density of states $D(E)$ and electron ($n$) and hole ($p$) concentrations in the conduction and valence bands for the case of equal densities of states in the conduction and valence bands (schematic); **b** The same figure for the case of differing densities of states in the conduction and valence bands. The number of holes must again be equal to the number of electrons, and thus the Fermi level no longer lies in the middle of the gap between conduction and valence bands; its position then becomes temperature dependent

$D_c = D_v$ $\qquad$ $D_c \neq D_v$

D = densità degli stati

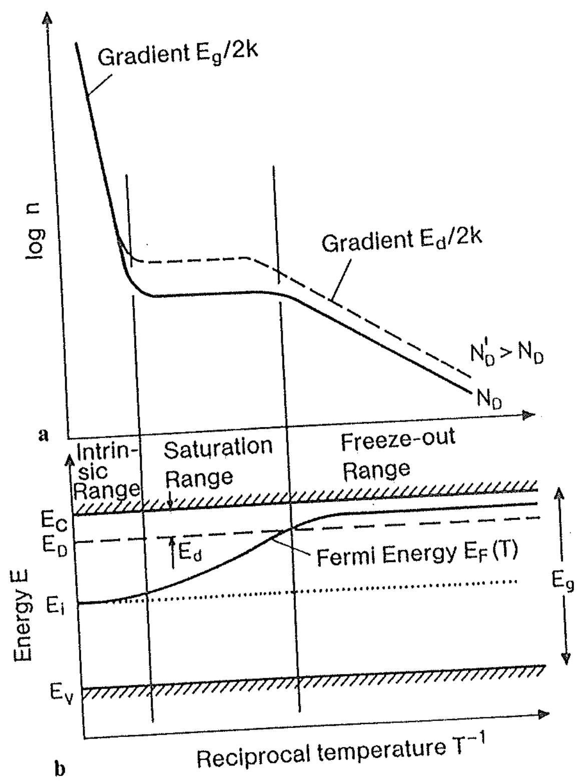


**Fig. 12.10a.** Qualitative temperature dependence of the concentration $n$ of electrons in the conduction band of an $n$-type semiconductor for two different donor concentrations $N'_D > N_D$. The width of the forbidden band is $E_g$ and $E_d$ is the ionization energy of the donors; **b** Qualitative temperature dependence of the Fermi energy $E_F(T)$ in the same semiconductor. $E_C$ and $E_V$ are the lower edge of the conduction band and the upper edge of the valence band, respectively, $E_D$ is the position of the donor levels and $E_i$ is the Fermi level of an intrinsic semiconductor

## n - type

1) Bassa temperatura

$$n \simeq N_d^+ + p$$

$$\ln n = \frac{1}{2}\ln\frac{N_c N_d}{2} + \underbrace{\frac{E_d - E_c}{2k}}_{<0}\cdot\frac{1}{T}$$

2) Intermedia

$$n \sim N_d \qquad \boxed{\text{saturazione}}$$

3) Alta temperatura

$$n_i \gg N_d \qquad n \sim n_i$$

$$\ln n = \frac{1}{2}\ln N_c N_v - \frac{E_g}{2k}\,\frac{1}{T}$$

Intrinseco

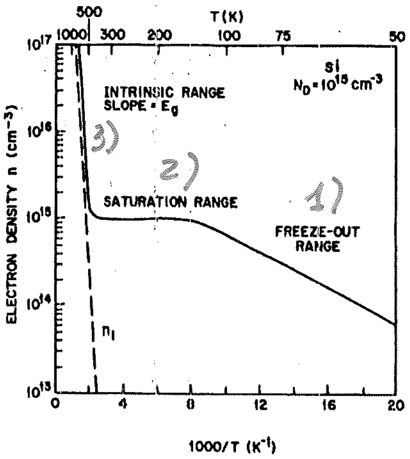


**Fig. 16** Electron density as a function of temperature for a Si sample with donor impurity concentration of $10^{15}$ cm$^{-3}$. (After Smith, Ref. 5.)

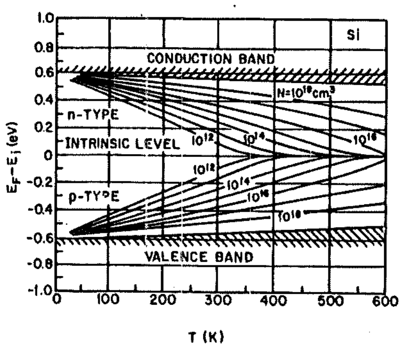


**Fig. 17** Fermi level for Si as a function of temperature and impurity concentration. The dependence of the bandgap on temperature is also incorporated in the figure. (After Grove, Ref. 32.)

$$n = N_d^+ + p$$

$$N_c\, e^{(E_F - E_c)/kT} = N_d \frac{1}{1 + 2e^{(E_F - E_d)/kT}} + N_v\, e^{(E_v - E_F)/kT}$$

Conoscendo $N_c, N_v, N_d, E_c, E_d, E_v$ e $T$

$$\Downarrow$$

$$E_F$$

1) INTRINSECO

$$n = p = n_i = \sqrt{N_c N_v}\, e^{-E_g/kT}$$

$$n = N_c\, e^{(E_F - E_c)/kT}$$

$$p = N_v\, e^{(E_v - E_F)/kT}$$

$$E_F = \frac{E_v + E_c}{2} + \frac{kT}{2} \ln \frac{N_v}{N_c}$$

$$\simeq \frac{E_v + E_c}{2}$$

1)

2)

3)

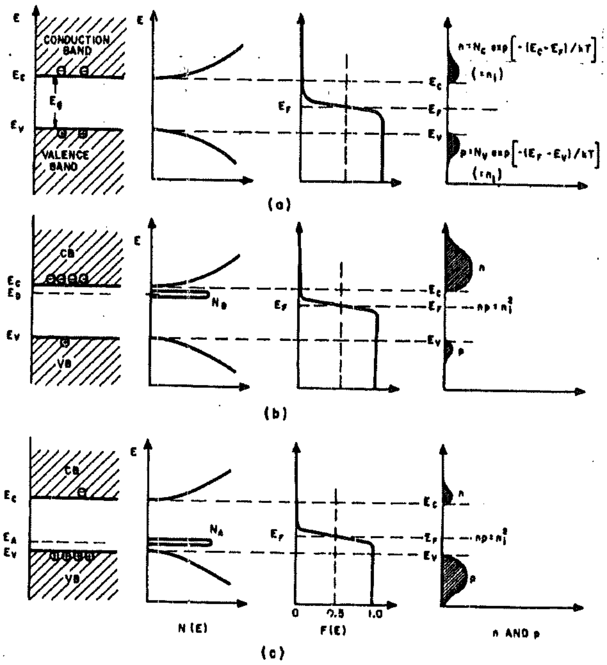


Fig. 14 Schematic band diagram, density of states, Fermi–Dirac distribution, and the carrier concentrations for (a) intrinsic, (b) $n$-type, and (c) $p$-type semiconductors at thermal equilibrium. Note that $pn = n_i^2$ for all three cases.

2) n-type

$$n = \frac{N_d}{2} + \left(\frac{N_d^2}{4} + n_i^2\right)^{1/2}$$

$$p = -\frac{N_d}{2} + \left(\frac{N_d^2}{4} + n_i^2\right)^{1/2}$$

3) p-type

$$p = \frac{N_a}{2} + \left(\frac{N_a^2}{4} + n_i^2\right)^{1/2}$$

$$n = -\frac{N_a}{2} + \left(\frac{N_e^2}{4} + n_i^2\right)^{1/2}$$

# CASO GENERALE

$$n = N_d^+ + p$$

$$n = N_c\, e^{(E_F - E_c)/kT}$$

$$N_d^+ = N_d - N_d^0 = N_d \frac{\frac{1}{2} e^{(E_d - E_F)/kT}}{1 + \frac{1}{2} e^{(E_d - E_F)/kT}} = N_d \frac{1}{1 + 2 e^{(E_F - E_d)/kT}}$$

$$p = N_v\, e^{(E_v - E_F)/kT}$$

$$\Rightarrow \quad N_c\, e^{(E_F - E_c)/kT} = N_d \frac{1}{1 + 2 e^{(E_F - E_d)/kT}} + N_v\, e^{(E_v - E_F)/kT}$$

Si risolve graficamente per ottenere $E_F$ conoscendo $N_c$, $N_v$, $N_d$, $E_c$, $E_d$, $E_v$, $T$

$\Downarrow$

n-type
Si 300K $N_D = 10^{16}\ cm^{-3}$

$\downarrow$

$N_c = 2.9 \cdot 10^{19}\ cm^{-3}$
$N_v = 1 \cdot 10^{19}\ cm^{-3}$
$n_i = 1.5 \cdot 10^{10}\ cm^{-3}$

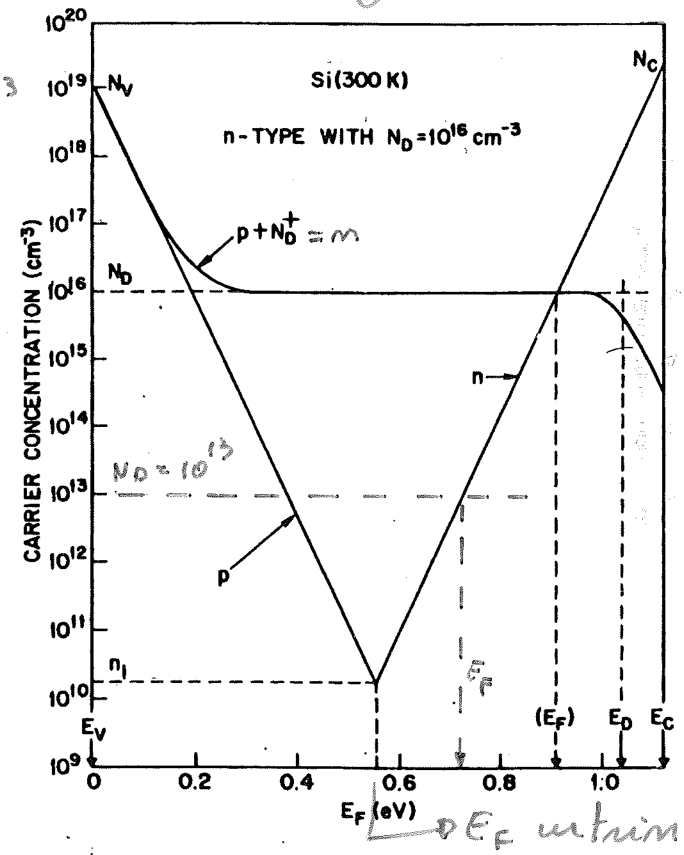


**Fig. 15** Graphical method to determine the Fermi energy level $E_F$. (After Shockley, Ref. 31.)

$E_F < E_d$

$\downarrow$

tutti i donori sono ionizzati