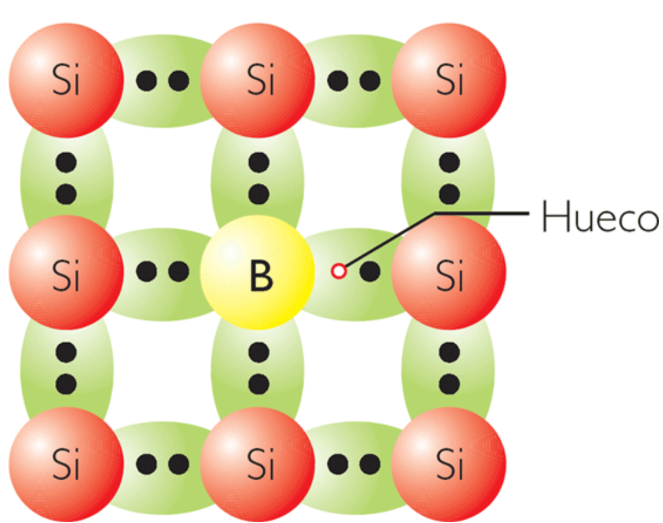
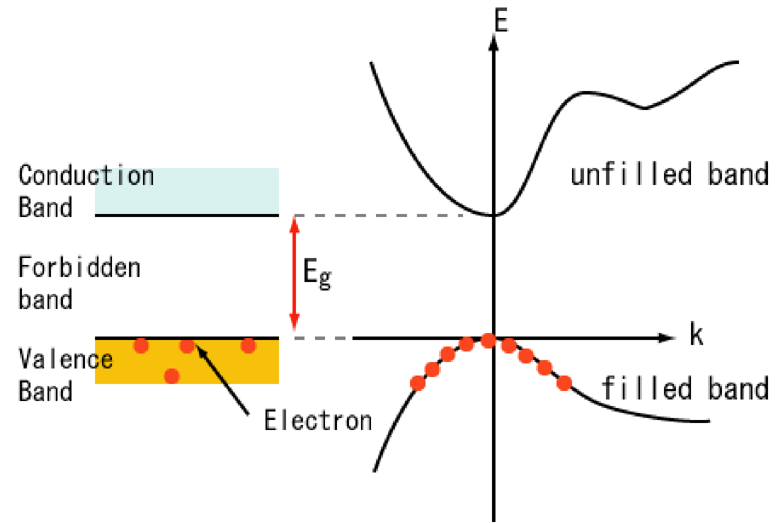
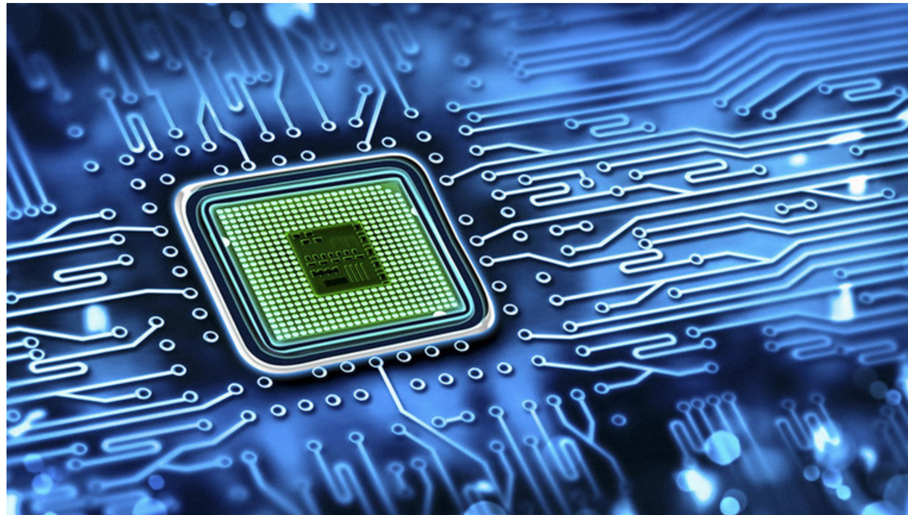
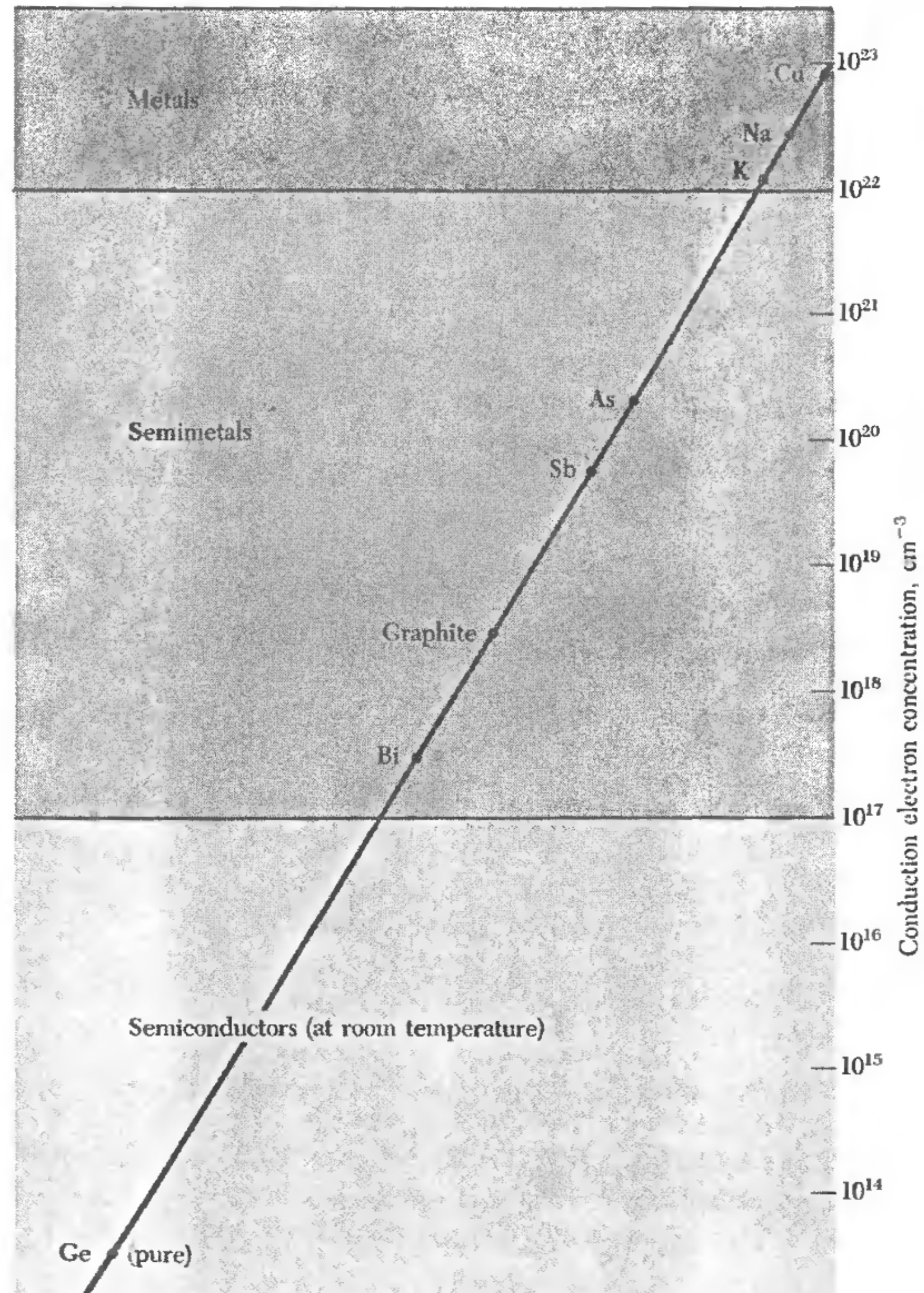


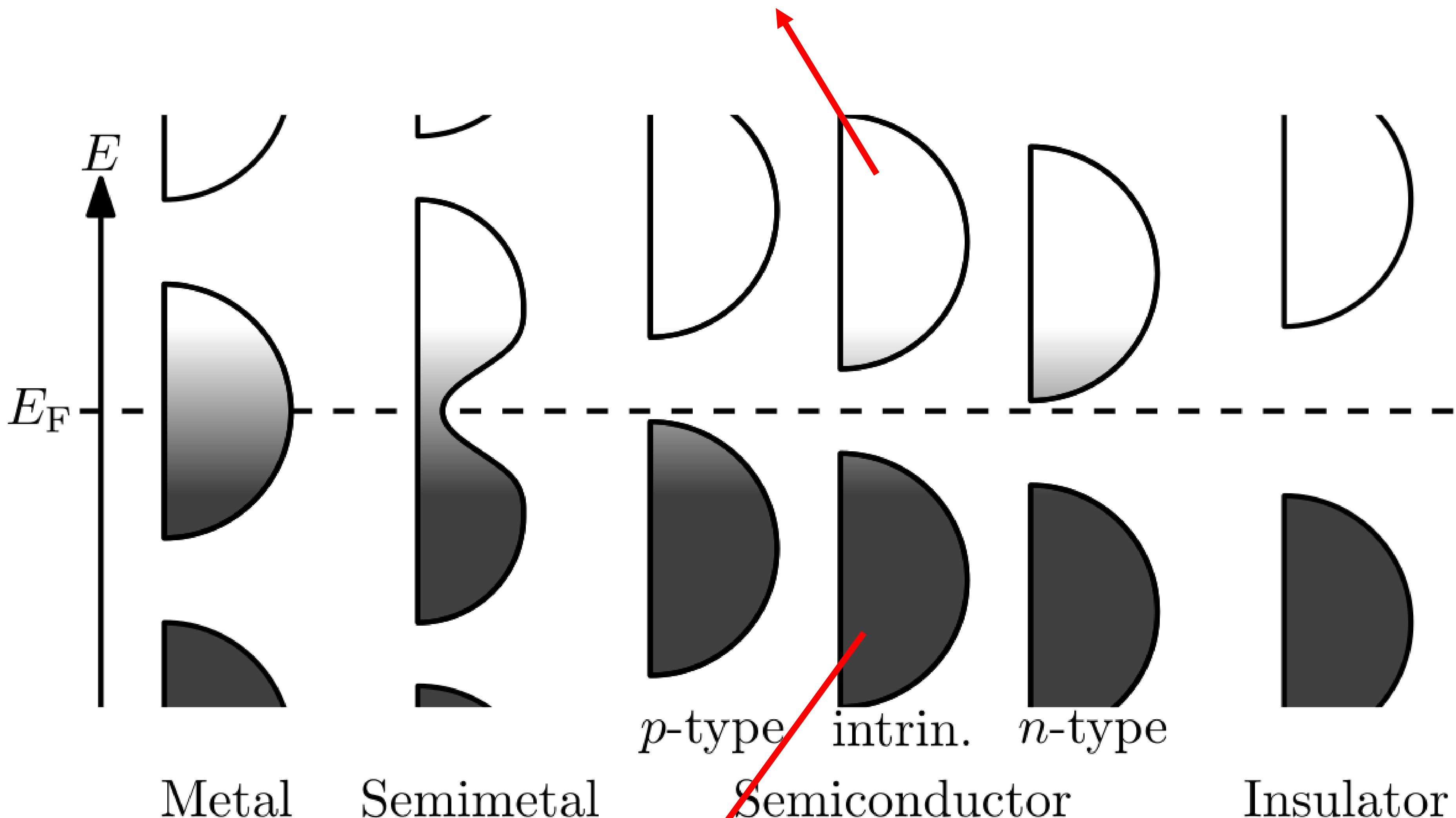


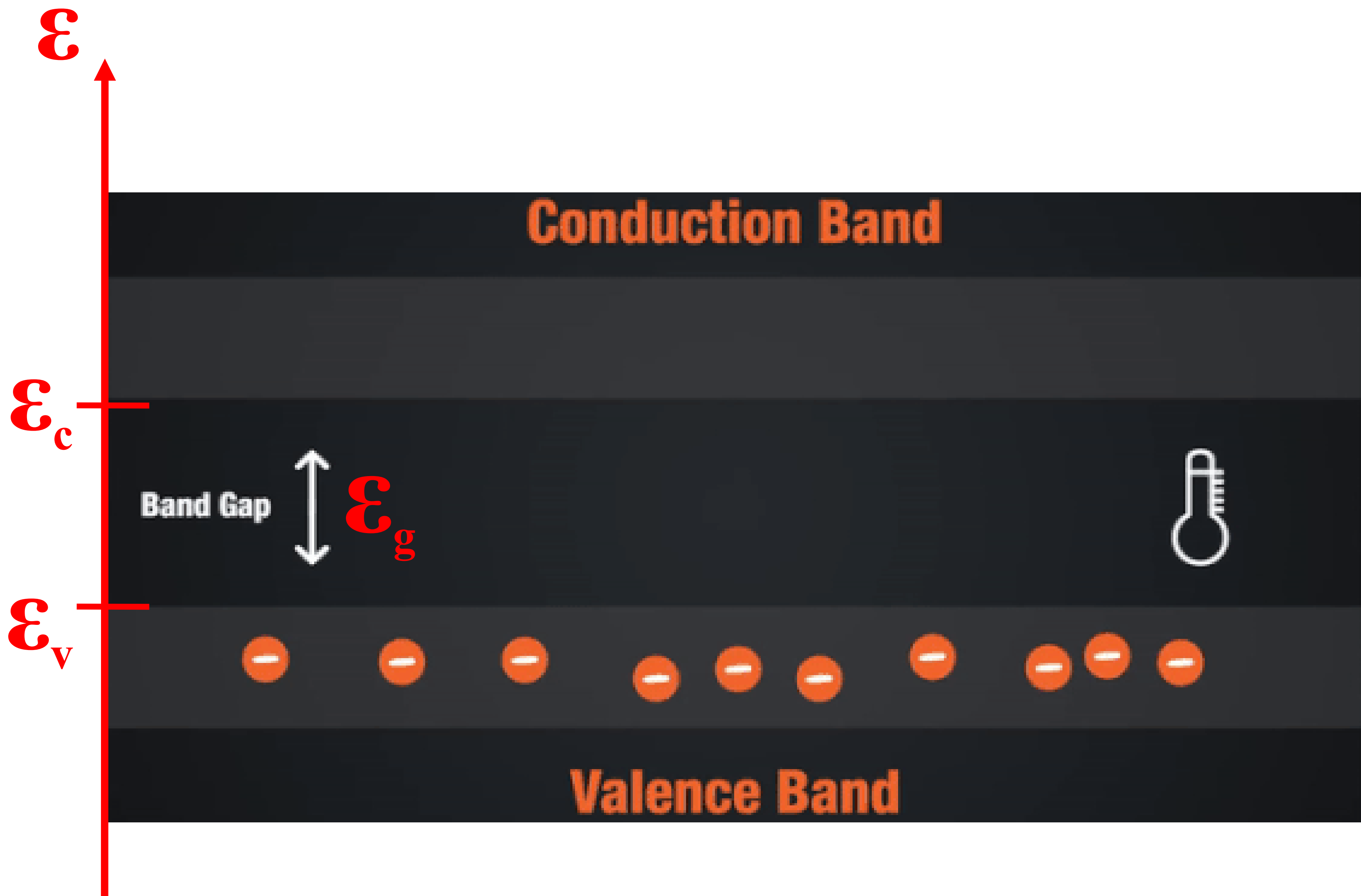
Capítulo 8: Semiconductores



Concentración de portadores que contribuyen a la conducción eléctrica en diferentes materiales




Banda de conducción
E
E_F
p-type
intrin.
n-type
Metal
Semimetal
Semiconductor
Insulator
Banda de valencia



ε
Conduction Band
ε_c
Band Gap
ε_g
ε_v
Valence Band

Concentración de portadores en función de la temperatura

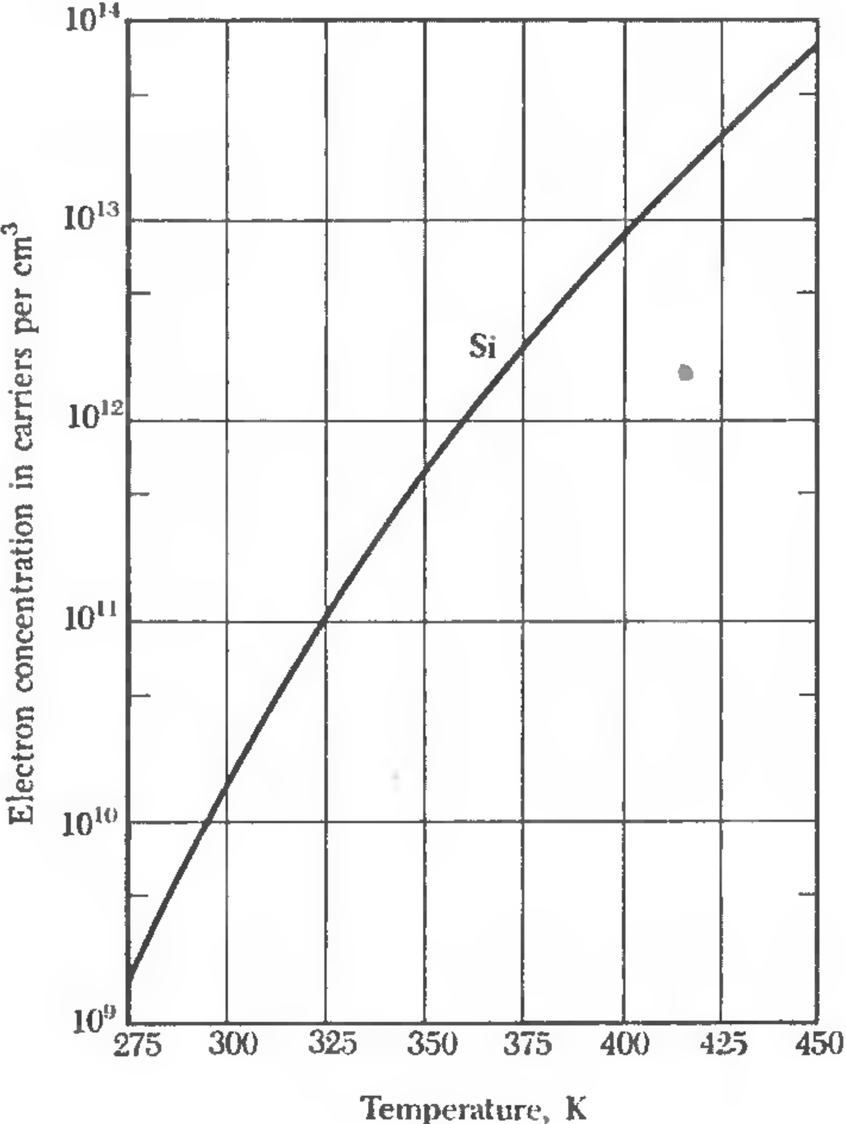
Electron concentration in carriers per cm³

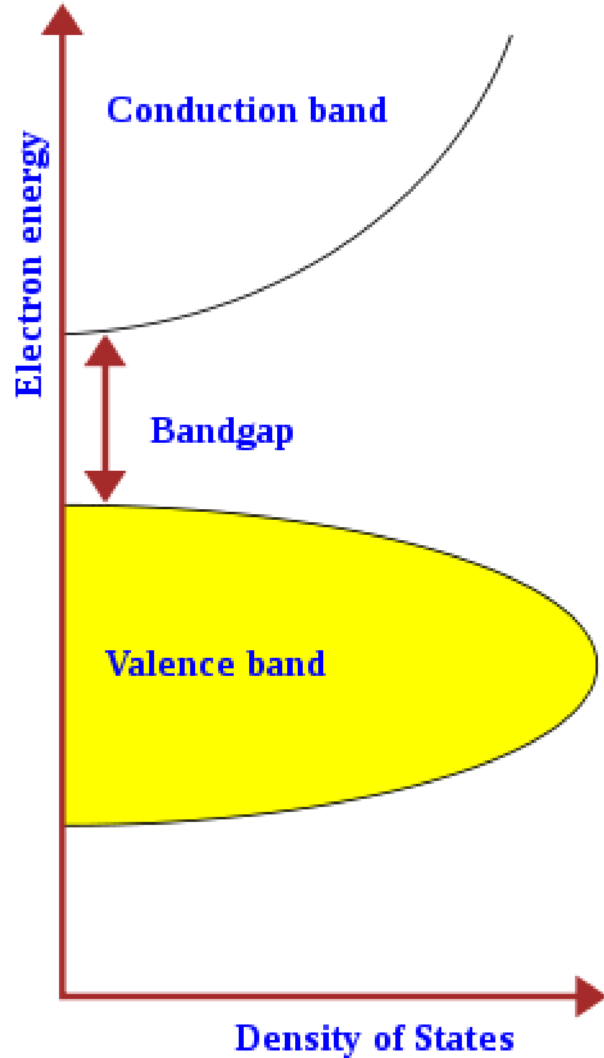
10^{14} 10^{13} 10^{12} 10^{11} 10^{10} 10^{9}

Ge

200 215 230 245 260 275 290 305

Temperature, K

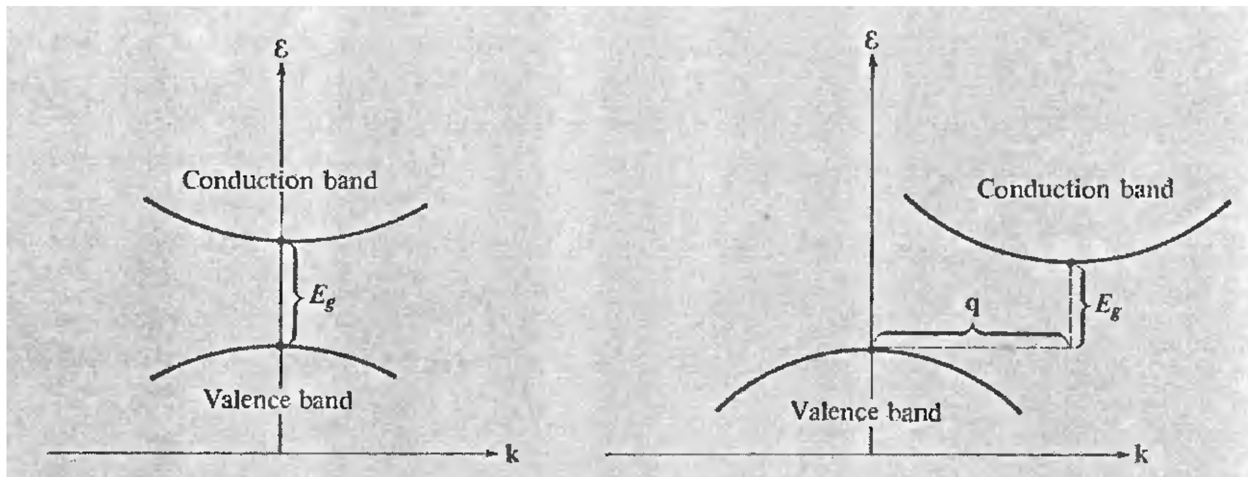




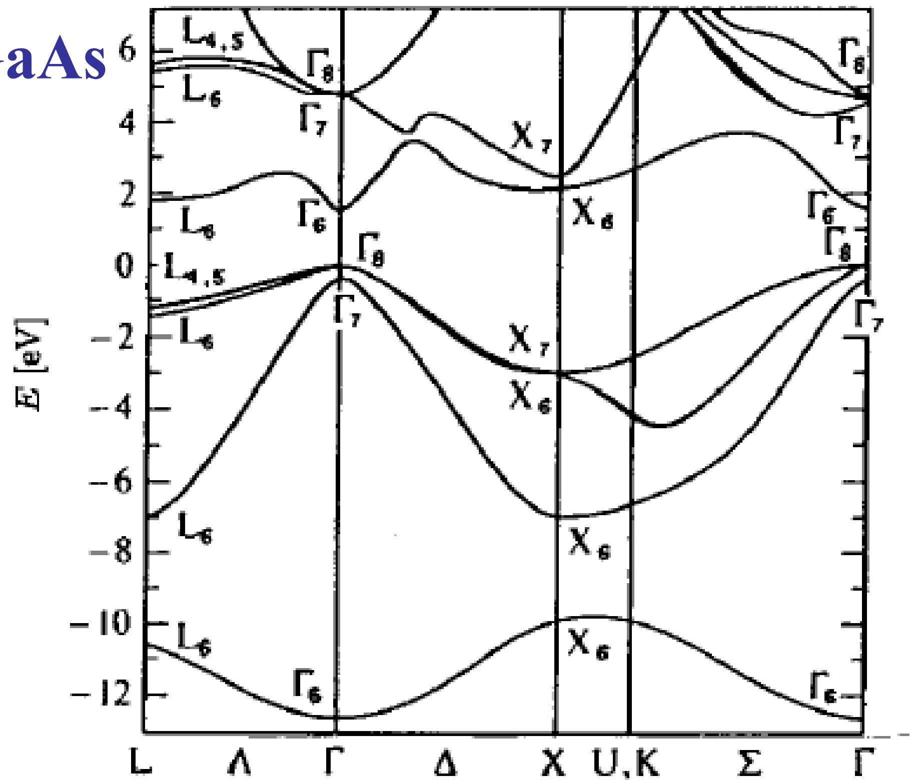
Element	$\varepsilon_g(300\,\mathrm{K})$ (eV)	$\varepsilon_g(T=0)$ (eV)
C	5.48	5.4
Si	1.110	1.170
Ge	0.664	0.744

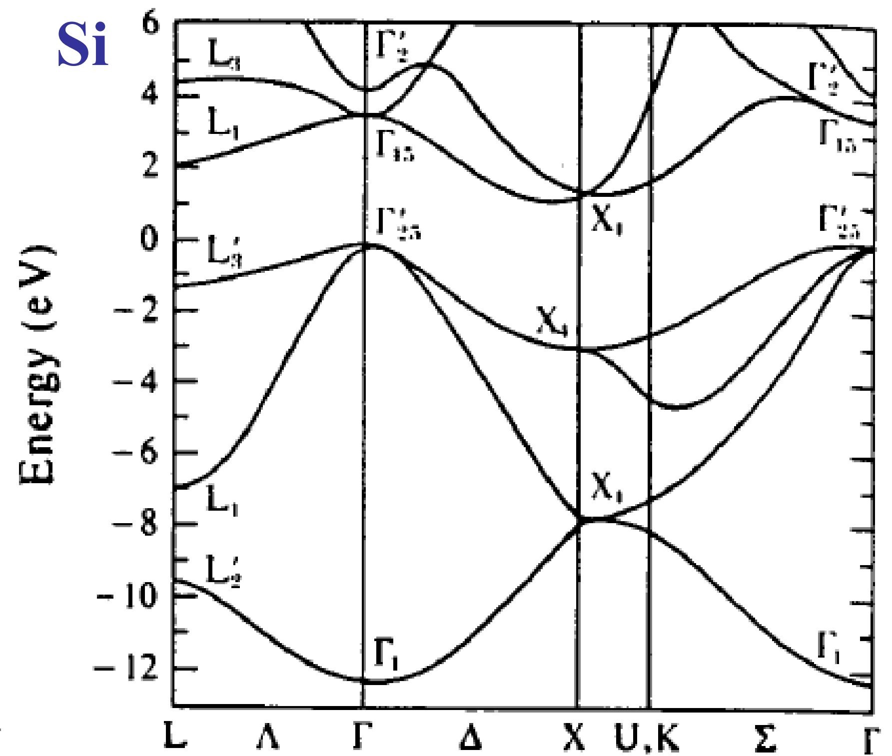
III–V compound	ε_g (eV)	II–VI compound	ε_g (eV)	I–VII compound	ε_g (eV)
AlSb	1.63	ZnO	3.20	AgF	2.8
GaP	2.27	ZnS	3.56	AgCl	3.25
GaAs	1.43	ZnSe	2.67	AgBr	2.68
GaSb	0.71	CdS	2.50	AgI	3.02
InP	1.26	CdSe	1.75	CuCl	3.39
InAs	0.36	CdTe	1.43	CuBr	3.07
InSb	0.18	HgS	2.27	CuI	3.11

Compound	ε_g (eV)	Compound	ε_g (eV)	Compound	ε_g (eV)
LiF	13.7	LiCl	9.4	LiBr	7.6
NaF	11.5	NaCl	8.7	NaBr	7.5
KF	10.8	KCl	8.4	KBr	7.4
RbF	10.3	RbCl	8.2	RbBr	7.4
CsF	9.9	CsCl	8.3	CsBr	7.3



GaAs





Absorción UV-Visible

ϵ

Conduction band edge

ω_g

Valence band edge

k

0

ϵ

Conduction band edge

Ω

ω

Valence band edge

$-k_c$ 0 k_c k

Participan fonones

$$\mathbf{k}(\text{photon}) = \mathbf{k}_c + \mathbf{K} \cong 0$$

$$\hbar\omega = E_g + \hbar\Omega$$

InSb

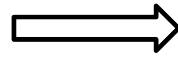
Absorption coefficient in cm^{-1}

10^5, 10^4, 10^3, 10^2, 10, 1

0.1, 0.3, 0.5, 0.7

$\hbar\omega$ in eV →

Modelo Semiclásico



$$\dot{\mathbf{r}} = \mathbf{v}_n(\mathbf{k}) = \frac{1}{\hbar}\frac{\partial \varepsilon_n(\mathbf{k})}{\partial \mathbf{k}},$$

$$\hbar\dot{\mathbf{k}} = -e\left[\mathbf{E}(\mathbf{r}, t) + \frac{1}{c}\mathbf{v}_n(\mathbf{k}) \times \mathbf{H}(\mathbf{r}, t)\right].$$

$$\dot{v}_{\boldsymbol{k}} = \frac{\partial}{\partial k}\left(\frac{1}{\hbar}\frac{\partial \varepsilon_{\boldsymbol{k}}}{\partial k}\right)\frac{\mathrm{d}k}{\mathrm{d}t} = \frac{1}{\hbar^2}\frac{\partial^2 \varepsilon_{\boldsymbol{k}}}{\partial k^2}\hbar\dot{k}\,.$$

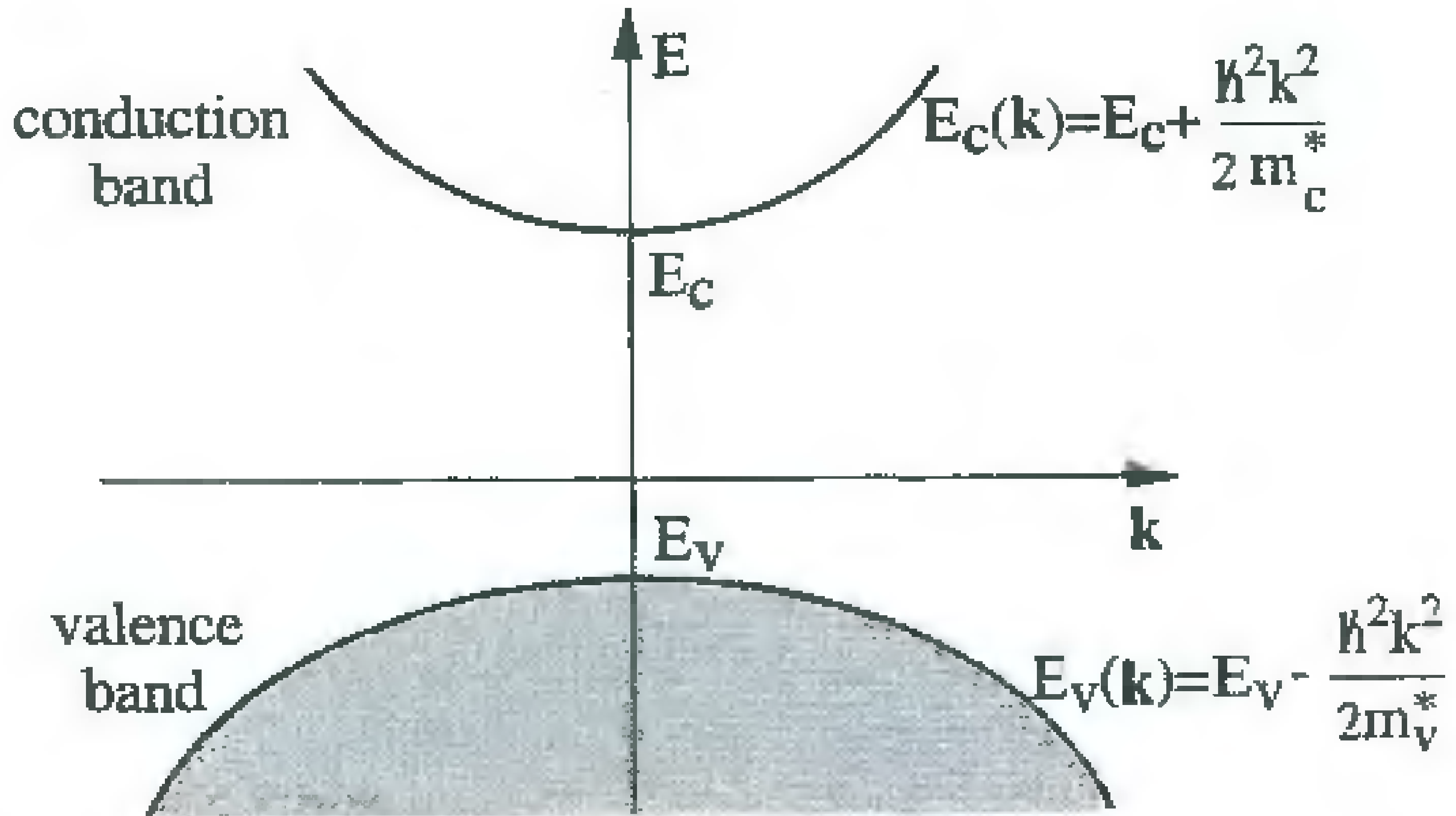
$$\frac{1}{m^*} = \frac{1}{\hbar^2}\frac{\partial^2 \varepsilon_{\boldsymbol{k}}}{\partial k^2},$$

$$\left(\frac{1}{m^*}\right)_{\alpha\beta} = \frac{1}{\hbar^2}\frac{\partial^2 E}{\partial k_\alpha \partial k_\beta}$$

Tensor masa efectiva

$$E(k) = E_o(k) + \sum_{\alpha\beta}\frac{\hbar^2}{2}\left(\frac{1}{m^*}\right)_{\alpha\beta} k_\alpha\, k_\beta$$

Muy útil en semiconductores !!!!



Agujeros (Holes)

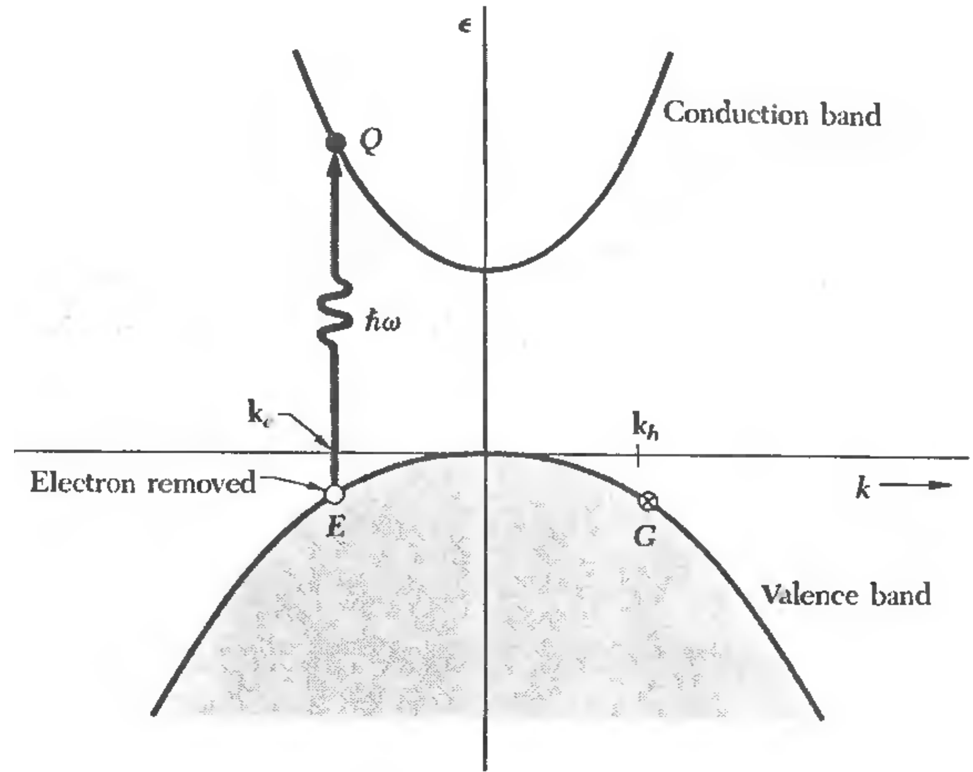
Los orbitales vacios en una banda son denominados “holes”.
Un hole actúa bajo un campo E o B como si tuviera carga +e.

1) $\mathbf{k}_h = -\mathbf{k}_e$

En una banda llena

$\Sigma \mathbf{k} = 0.$

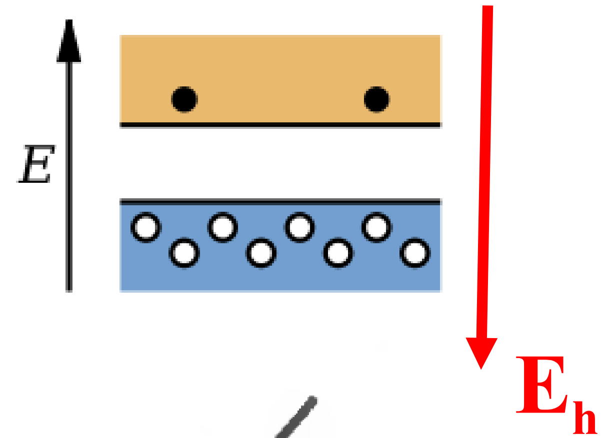
debido a la simetría de inversión $\mathbf{r} \rightarrow -\mathbf{r}$



Si falta un e^- con $k=k_e$

$$k_h = \sum_{k \neq k_e} k = \sum_{k \neq k_e} k + k_e - k_e = \Sigma\, k - k_e = -k_e$$

2) $$\epsilon_h(\mathbf{k}_h) = -\epsilon_e(\mathbf{k}_e)$$



ϵ

Hole band constructed with $\mathbf{k}_h = -\mathbf{k}_e$ and $\epsilon_h(\mathbf{k}_h) = -\epsilon_e(\mathbf{k}_e)$, to simulate dynamics of a hole.

$\mathbf{k}_h$

k

$\mathbf{k}_e$

Valence band with one electron missing

3) $$\mathbf{v}_h = \mathbf{v}_e$$

La velocidad del hole es igual a la velocidad del electrón faltante.
Se ve claramente en la Figura anterior que $\nabla\epsilon_h(k_h) = \nabla\epsilon_e(k_e)$

4) $$m_h = -m_e$$

5) $$\hbar\frac{d\mathbf{k}_h}{dt} = e(\mathbf{E} + \frac{1}{c}\mathbf{v}_h \times \mathbf{B})$$

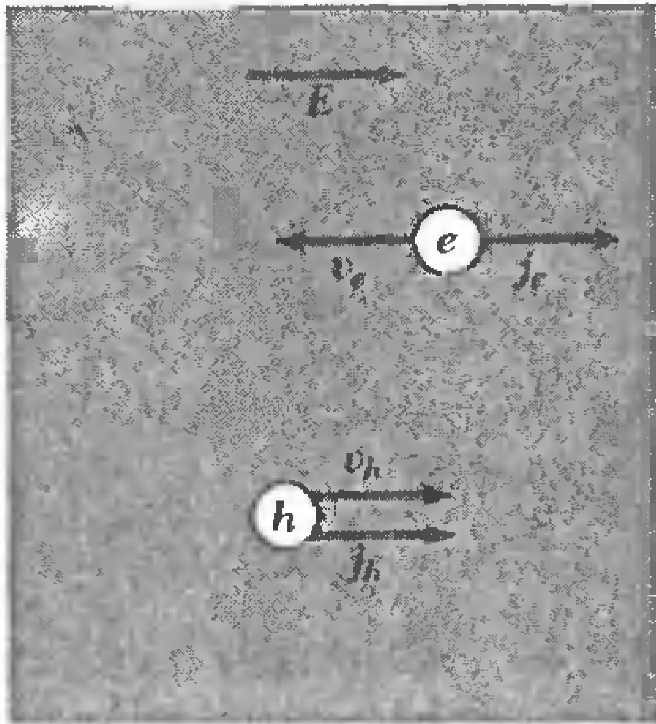
$$\hbar\frac{d\mathbf{k}_e}{dt} = -e(\mathbf{E} + \frac{1}{c}\mathbf{v}_e \times \mathbf{B})$$

Remplazando: $\mathbf{k}_e \longrightarrow -\mathbf{k}_h$

$\mathbf{v}_e \longrightarrow \mathbf{v}_h$

6) $$\mathbf{j} = (-e)\int_{\text{occupied}} \frac{d\mathbf{k}}{4\pi^3}\mathbf{v}(\mathbf{k}), = (+e)\int_{\text{unoccupied}} \frac{d\mathbf{k}}{4\pi^3}\mathbf{v}(\mathbf{k}).$$

$$0 = \int_{\text{zone}} \frac{d\mathbf{k}}{4\pi^3}\mathbf{v}(\mathbf{k}) = \int_{\text{occupied}} \frac{d\mathbf{k}}{4\pi^3}\mathbf{v}(\mathbf{k}) + \int_{\text{unoccupied}} \frac{d\mathbf{k}}{4\pi^3}\mathbf{v}(\mathbf{k}),$$



Si en un SC hay electrones en la banda de conducción y holes en la banda de valencia:

Los dos tipos de portadores contribuyen a la corriente.

conductividad → electrons + holes

$$\sigma = (ne\mu_e + pe\mu_h)$$

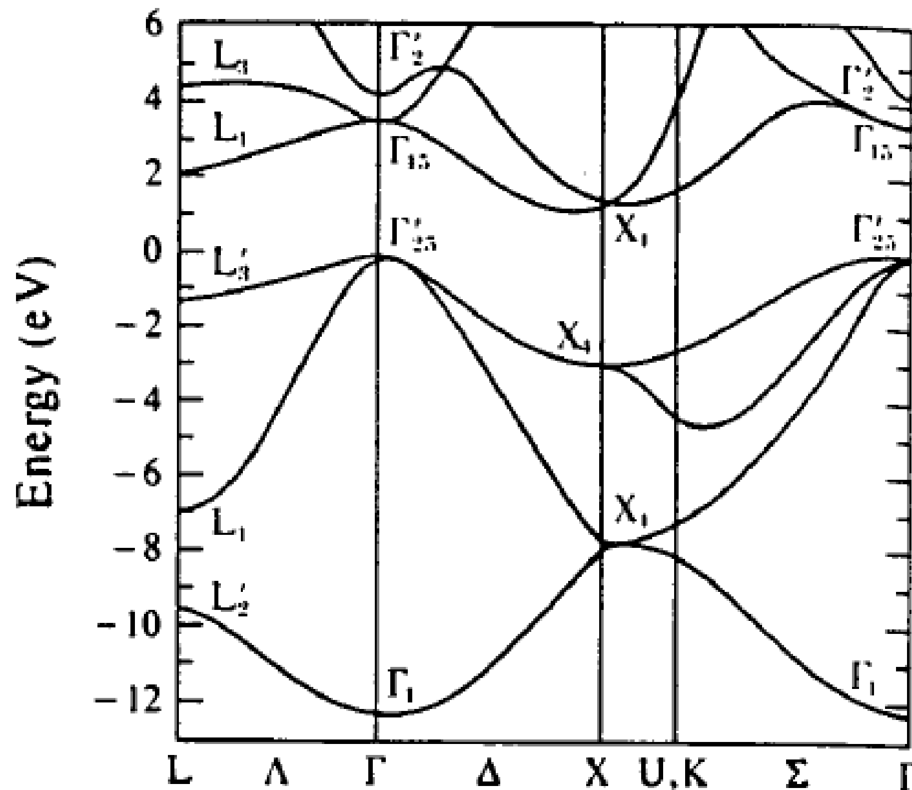
$$\mu_e = e\tau_e/m_e \; ; \qquad \mu_h = e\tau_h/m_h$$

Table 3 Carrier mobilities at room temperature, in $cm^2/V\text{-}s$

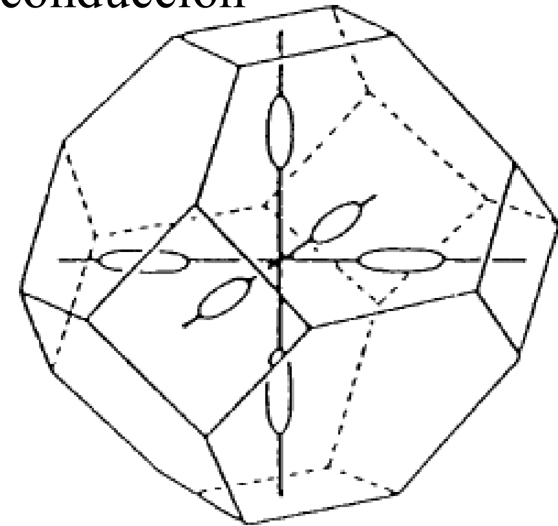
Crystal	Electrons	Holes	Crystal	Electrons	Holes
Diamond	1800	1200	GaAs	8000	300
Si	1350	480	GaSb	5000	1000
Ge	3600	1800	PbS	550	600
InSb	800	450	PbSe	1020	930
InAs	30000	450	PbTe	2500	1000
InP	4500	100	AgCl	50	—
AlAs	280	—	KBr (100 K)	100	—
AlSb	900	400	SiC	100	10–20

Algunos ejemplos del tensor masa efectiva de e^- y h^+ en semiconductores

Si



Superficie de energía cte (baja) para la banda de conducción



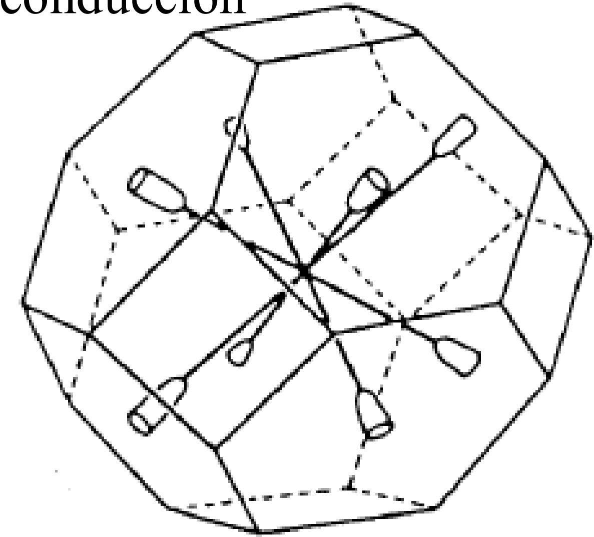
$$k_c = (2\pi/a)(0, 0, \pm 0.85)$$

$$\varepsilon_{\boldsymbol{k}} = \hbar^2 \left[\frac{k_x^2 + k_y^2}{2m_{n\perp}^*} + \frac{(k_z - k_{cz})^2}{2m_{n\parallel}^*} \right]$$

$$m_{n\parallel}^* = 0.916\, m_e, \qquad m_{n\perp}^* = 0.191\, m_e$$

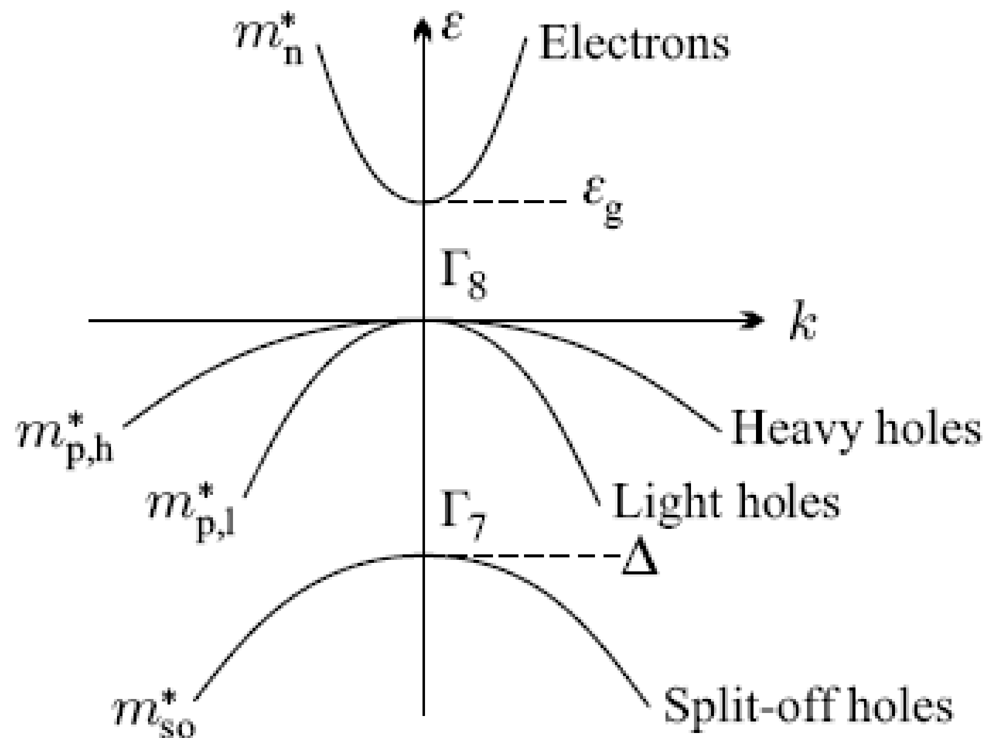
Ge

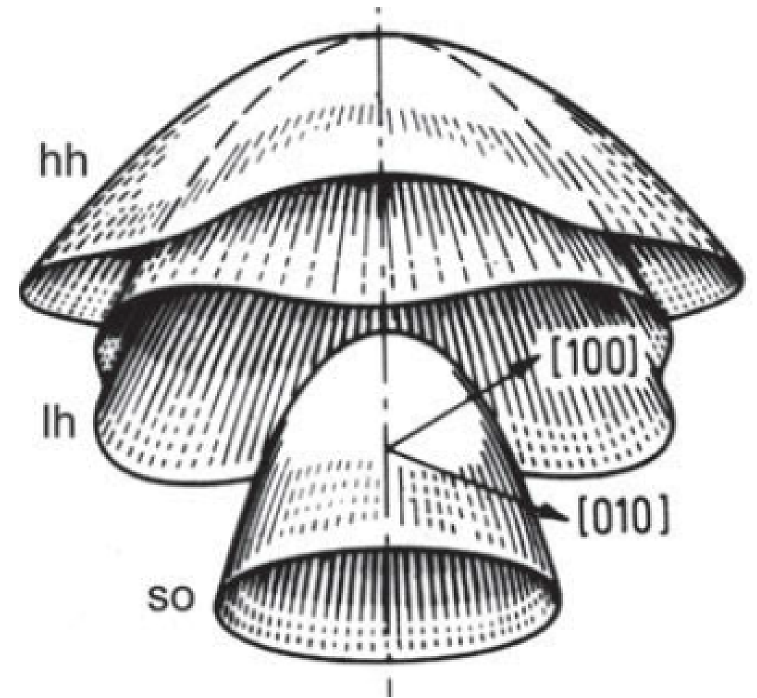
Superficie de energía cte (baja) para la banda de conducción



$$k_c = L = (2\pi/a)(\tfrac{1}{2}, \tfrac{1}{2}, \tfrac{1}{2})$$

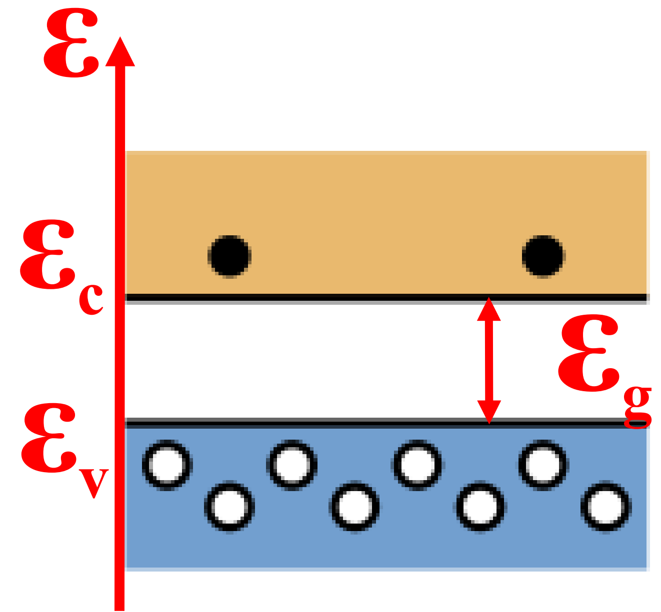
$$m^*_{n\|} = 1.588\, m_e \qquad \text{and} \qquad m^*_{n\perp} = 0.082\, m_e\,.$$

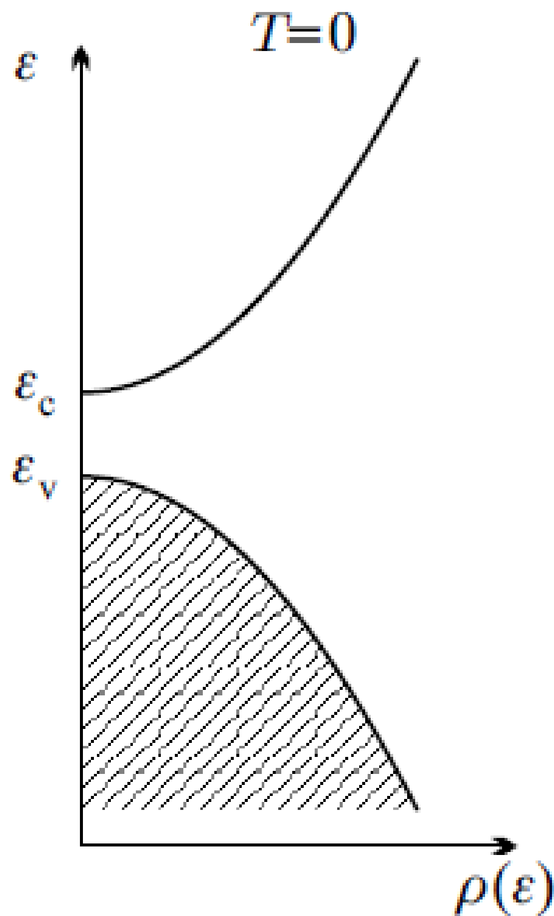




Crystal	m_n^*/m_e	$m_{p,h}^*/m_e$	$m_{p,l}^*/m_e$	m_{so}^*/m_e
GaAs	0.066	0.47	0.07	0.15
GaSb	0.042	0.35	0.05	0.12
InP	0.077	0.56	0.12	0.12
InAs	0.024	0.43	0.026	0.14
InSb	0.014	0.39	0.016	0.43

Concentración de portadores en equilibrio térmico





Asumiremos que las bandas están caracterizadas por masas efectivas escalares

$$\rho_c(\varepsilon) = \frac{1}{2\pi^2}\left(\frac{2m_n^*}{\hbar^2}\right)^{3/2}\sqrt{\varepsilon - \varepsilon_c}\,,$$

$$\rho_v(\varepsilon) = \frac{1}{2\pi^2}\left(\frac{2m_p^*}{\hbar^2}\right)^{3/2}\sqrt{\varepsilon_v - \varepsilon}$$

Densidad de electrones en la banda de conducción:

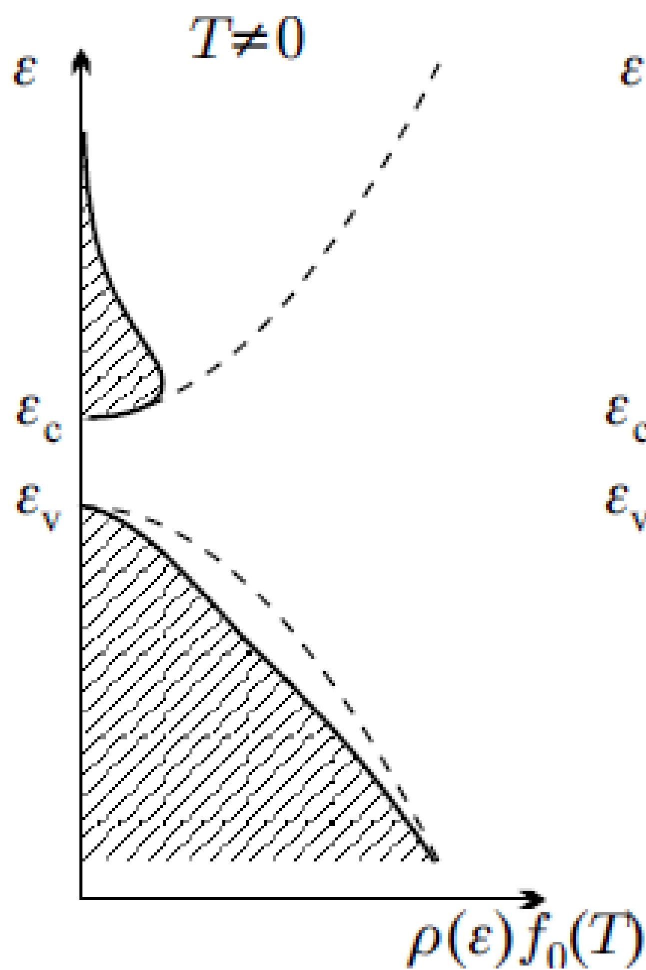
$$n(T) = \int_{\varepsilon_c}^{\infty} \rho_c(\varepsilon) \frac{1}{e^{(\varepsilon-\mu)/k_B T} + 1} \, d\varepsilon$$

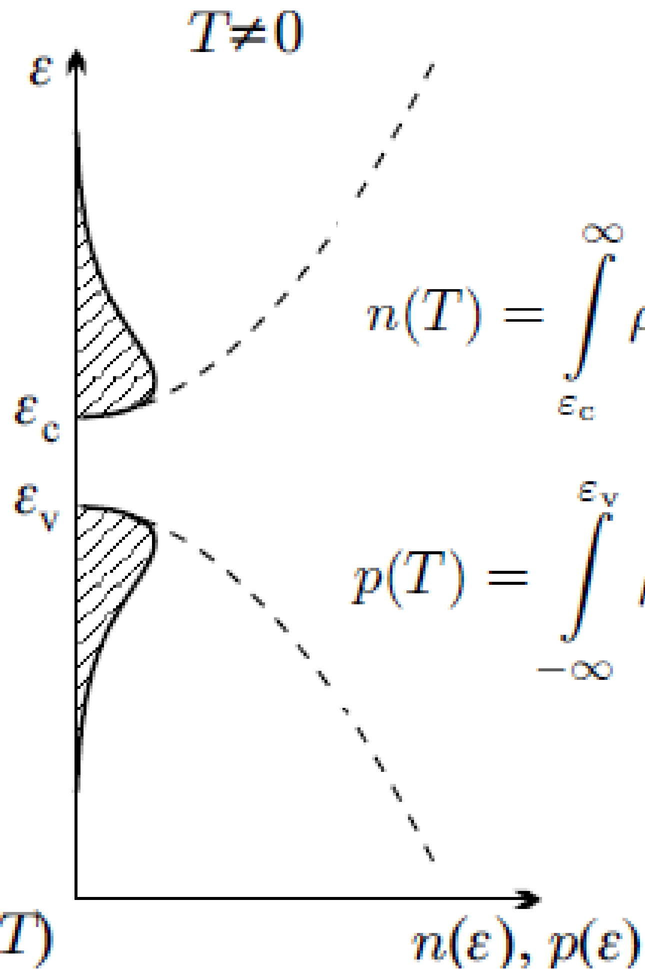
Densidad de electrones en la banda de valencia:

$$n_v(T) = \int_{-\infty}^{\varepsilon_v} \rho_v(\varepsilon) \frac{1}{e^{(\varepsilon-\mu)/k_B T} + 1} \, d\varepsilon \, .$$

Es mas práctico trabajar con agujeros. La densidad de holes en la banda de valencia es :

$$p(T) = \int_{-\infty}^{\varepsilon_v} \rho_v(\varepsilon) \left[1 - \frac{1}{e^{(\varepsilon-\mu)/k_B T} + 1}\right] d\varepsilon = \int_{-\infty}^{\varepsilon_v} \rho_v(\varepsilon) \frac{1}{e^{(\mu-\varepsilon)/k_B T} + 1} \, d\varepsilon$$

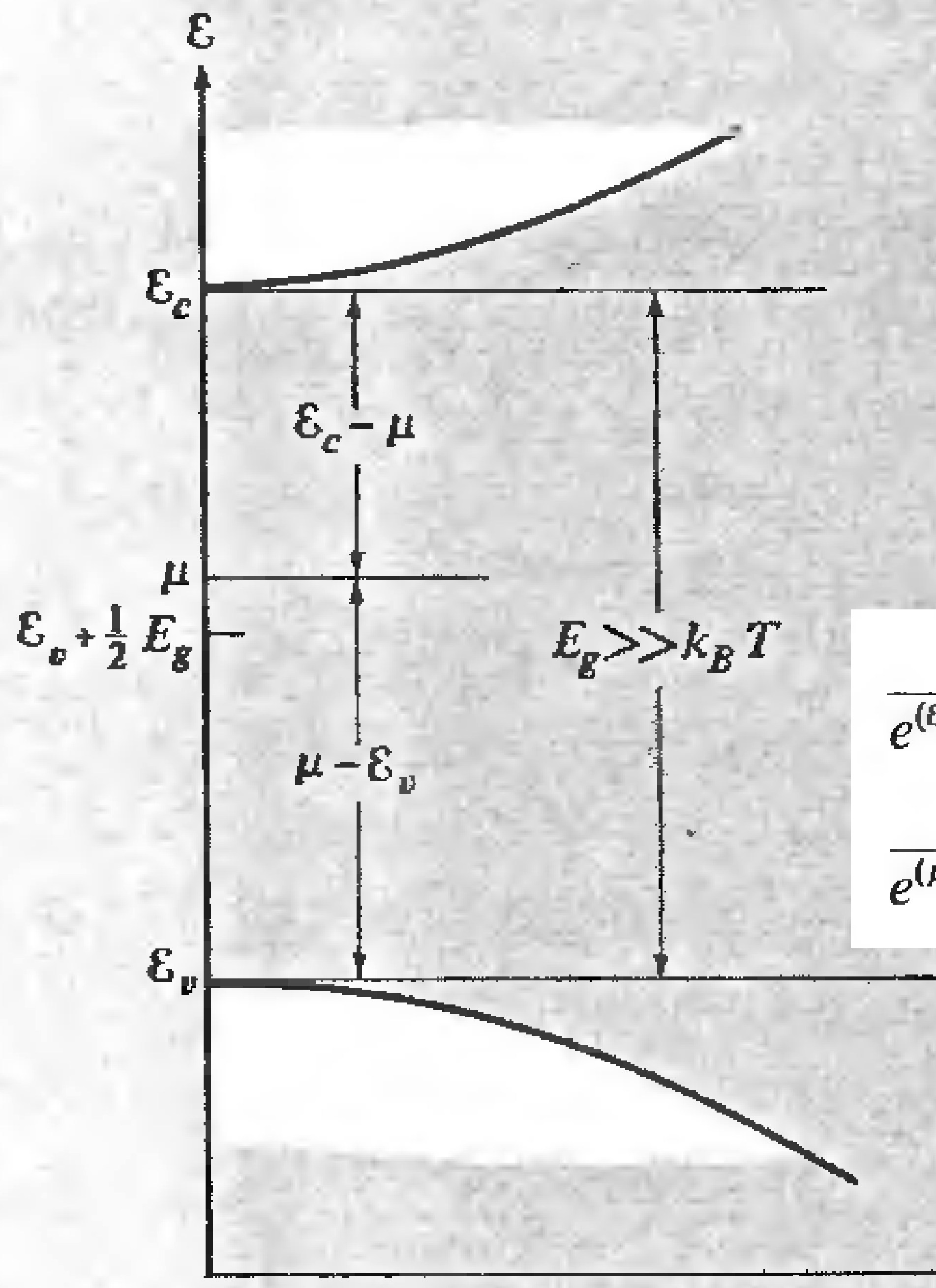




$$n(T) = \int_{\varepsilon_c}^{\infty} \rho_c(\varepsilon) \frac{1}{e^{(\varepsilon-\mu)/k_B T} + 1} \, d\varepsilon$$

$$p(T) = \int_{-\infty}^{\varepsilon_v} \rho_v(\varepsilon) \frac{1}{e^{(\mu-\varepsilon)/k_B T} + 1} \, d\varepsilon$$

μ?



$$\mathcal{E}_c - \mu \gg k_B T,$$
$$\mu - \mathcal{E}_v \gg k_B T.$$

$$\frac{1}{e^{(\mathcal{E}-\mu)/k_B T}+1} \approx e^{-(\mathcal{E}-\mu)/k_B T}, \qquad \mathcal{E} > \mathcal{E}_c;$$
$$\frac{1}{e^{(\mu-\mathcal{E})/k_B T}+1} \approx e^{-(\mu-\mathcal{E})/k_B T}, \qquad \mathcal{E} < \mathcal{E}_v.$$

$$n(T) = \int_{\varepsilon_c}^{\infty} \rho_c(\varepsilon) e^{-(\varepsilon-\mu)/k_B T} \, d\varepsilon \, .$$

Sumando y restando ε_c en el exponente:

$$n(T) = N_c(T) e^{-(\varepsilon_c-\mu)/k_B T}$$

donde:

$$N_c(T) = \int_{\varepsilon_c}^{\infty} \rho_c(\varepsilon) e^{-(\varepsilon-\varepsilon_c)/k_B T} \, d\varepsilon$$

Usando la densidad de estados anterior, la integral da:

$$N_c(T) = 2 \left(\frac{m_n^* k_B T}{2\pi\hbar^2} \right)^{3/2}$$

De manera análoga para de densidad de holes

$$p(T) = \int_{-\infty}^{\varepsilon_\mathrm{v}} \rho_\mathrm{v}(\varepsilon)\frac{1}{\mathrm{e}^{(\mu-\varepsilon)/k_\mathrm{B}T}+1}\,\mathrm{d}\varepsilon$$

Sumando y restando ε_v en el exponente:

$$p(T) = P_\mathrm{v}(T)\mathrm{e}^{-(\mu-\varepsilon_\mathrm{v})/k_\mathrm{B}T}$$

donde:

$$P_\mathrm{v}(T) = \int_{-\infty}^{\varepsilon_\mathrm{v}} \rho_\mathrm{v}(\varepsilon)\mathrm{e}^{-(\varepsilon_\mathrm{v}-\varepsilon)/k_\mathrm{B}T}\,\mathrm{d}\varepsilon$$

$$P_\mathrm{v}(T) = 2\left(\frac{m_\mathrm{p}^* k_\mathrm{B}T}{2\pi\hbar^2}\right)^{3/2}$$

Por lo tanto:

$$n(T) = N_c(T)e^{-(\varepsilon_c - \mu)/k_B T}$$

$$p(T) = P_v(T)e^{-(\mu - \varepsilon_v)/k_B T}$$

$$n(T)\,p(T) = N_c(T)\,P_v(T)\,e^{-(\varepsilon_c - \varepsilon_v)/k_B T}$$

Ley de acción de masas

Para un semiconductor a una dada temperatura, el producto de la concentración de electrones en la banda de conducción por la concentración de holes en la banda de valencia es constante.

Para obtener este resultado no hemos supuesto nada respecto al origen de los portadores: pueden ser intrínsecos o extrínsecos (impurezas).

Semiconductor intrínseco $\Longrightarrow$ $n(T) = p(T)$

Se la denomina concentración de portadores intrínsecos $n_{\mathrm{i}}(T)$

$$n(T)\,p(T) = N_{\mathrm{c}}(T)\,P_{\mathrm{v}}(T)\,\mathrm{e}^{-(\varepsilon_{\mathrm{c}}-\varepsilon_{\mathrm{v}})/k_{\mathrm{B}}T}$$

$$n_{\mathrm{i}}(T) = \sqrt{N_{\mathrm{c}}(T)P_{\mathrm{v}}(T)}\mathrm{e}^{-(\varepsilon_{\mathrm{c}}-\varepsilon_{\mathrm{v}})/2k_{\mathrm{B}}T}$$

$$= \sqrt{N_{\mathrm{c}}(T)P_{\mathrm{v}}(T)}\mathrm{e}^{-\varepsilon_{\mathrm{g}}/2k_{\mathrm{B}}T}$$

$$n_{\mathrm{i}}(T) = 2\left(\frac{k_{\mathrm{B}}T}{2\pi\hbar^2}\right)^{3/2}(m_{\mathrm{n}}^{*}m_{\mathrm{p}}^{*})^{3/4}\mathrm{e}^{-\varepsilon_{\mathrm{g}}/2k_{\mathrm{B}}T}$$

Para obtener valores numéricos es conveniente escribirla así:

$$n_{\mathrm{i}}(T) = 2.5 \left(\frac{m_{\mathrm{n}}^{*}}{m_{\mathrm{e}}}\right)^{3/4} \left(\frac{m_{\mathrm{p}}^{*}}{m_{\mathrm{e}}}\right)^{3/4} \left(\frac{T}{300\,\mathrm{K}}\right)^{3/2} \mathrm{e}^{-\varepsilon_{\mathrm{g}}/2k_{\mathrm{B}}T} \times 10^{19}/\mathrm{cm}^{3}$$

	E_{g} (eV)	n_{i} (cm^{-3})
InSb	0.18	1.6×10^{16}
InAs	0.36	8.6×10^{14}
Ge	0.67	2.4×10^{13}
Si	1.124	1.0×10^{10}
GaAs	1.43	1.8×10^{6}
GaP	2.26	2.7×10^{0}
GaN	3.3	$\ll 1$

conductividad electrons + holes

$$\sigma = (ne\mu_e + pe\mu_h)$$

$$\mu_e = e\tau_e/m_e \quad ; \qquad \mu_h = e\tau_h/m_h$$

Table 3 Carrier mobilities at room temperature, in $cm^2/V\text{-}s$

Crystal	Electrons	Holes	Crystal	Electrons	Holes
Diamond	1800	1200	GaAs	8000	300
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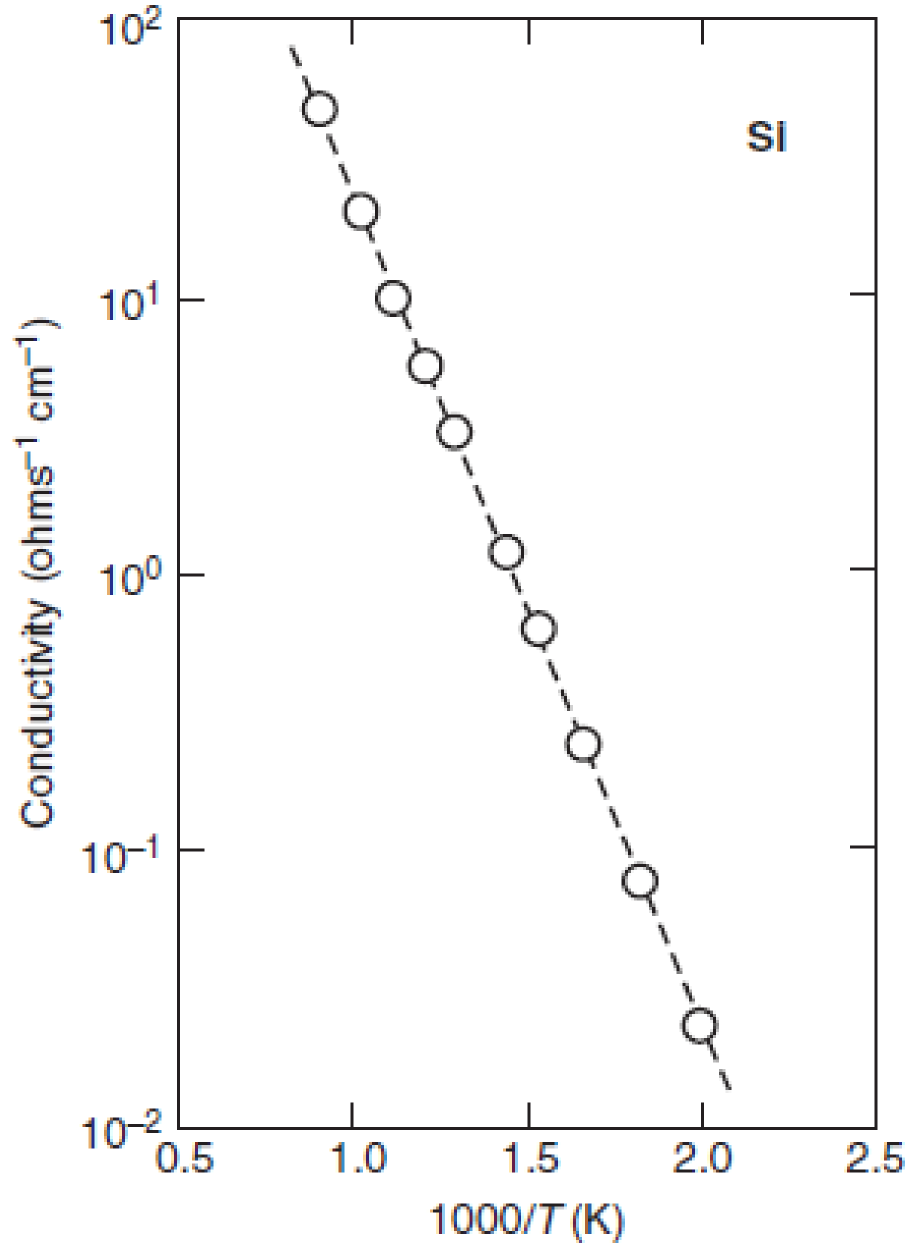
AlAs	280	—	KBr (100 K)	100	—
AlSb	900	400	SiC	100	10–20



Intrinsic conductivity of Si plotted against inverse temperature (adapted from Moran and

μ?

$$N_c(T)e^{-(\varepsilon_c-\mu)/k_BT} = P_v(T)e^{-(\mu-\varepsilon_v)/k_BT}$$

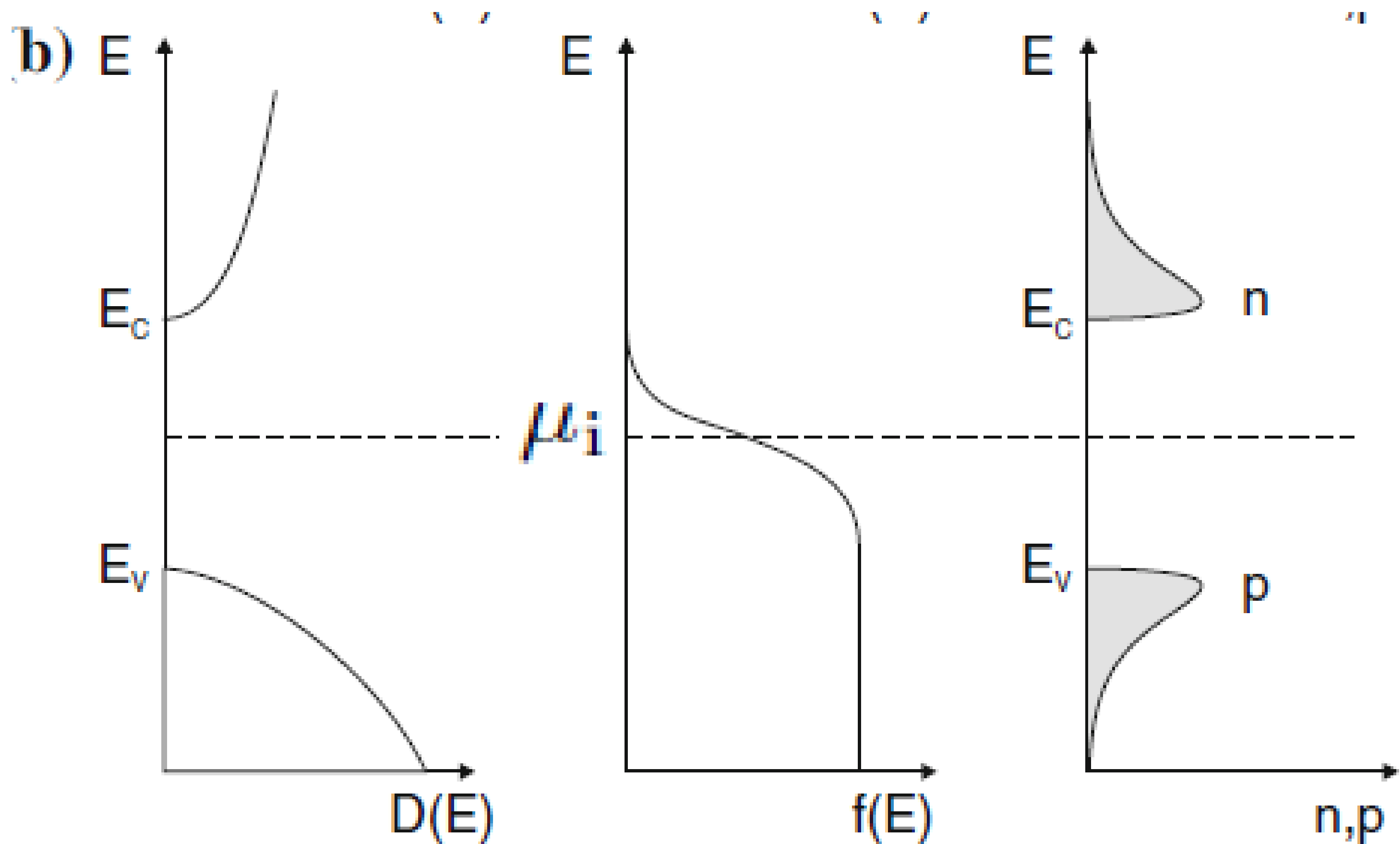
$$\frac{P_v(T)}{N_c(T)} = \exp\left[\frac{2\mu-(\varepsilon_c+\varepsilon_v)}{k_BT}\right]$$

$$\mu = \frac{1}{2}(\varepsilon_c+\varepsilon_v)+\frac{1}{2}k_BT\ln\frac{P_v(T)}{N_c(T)}$$

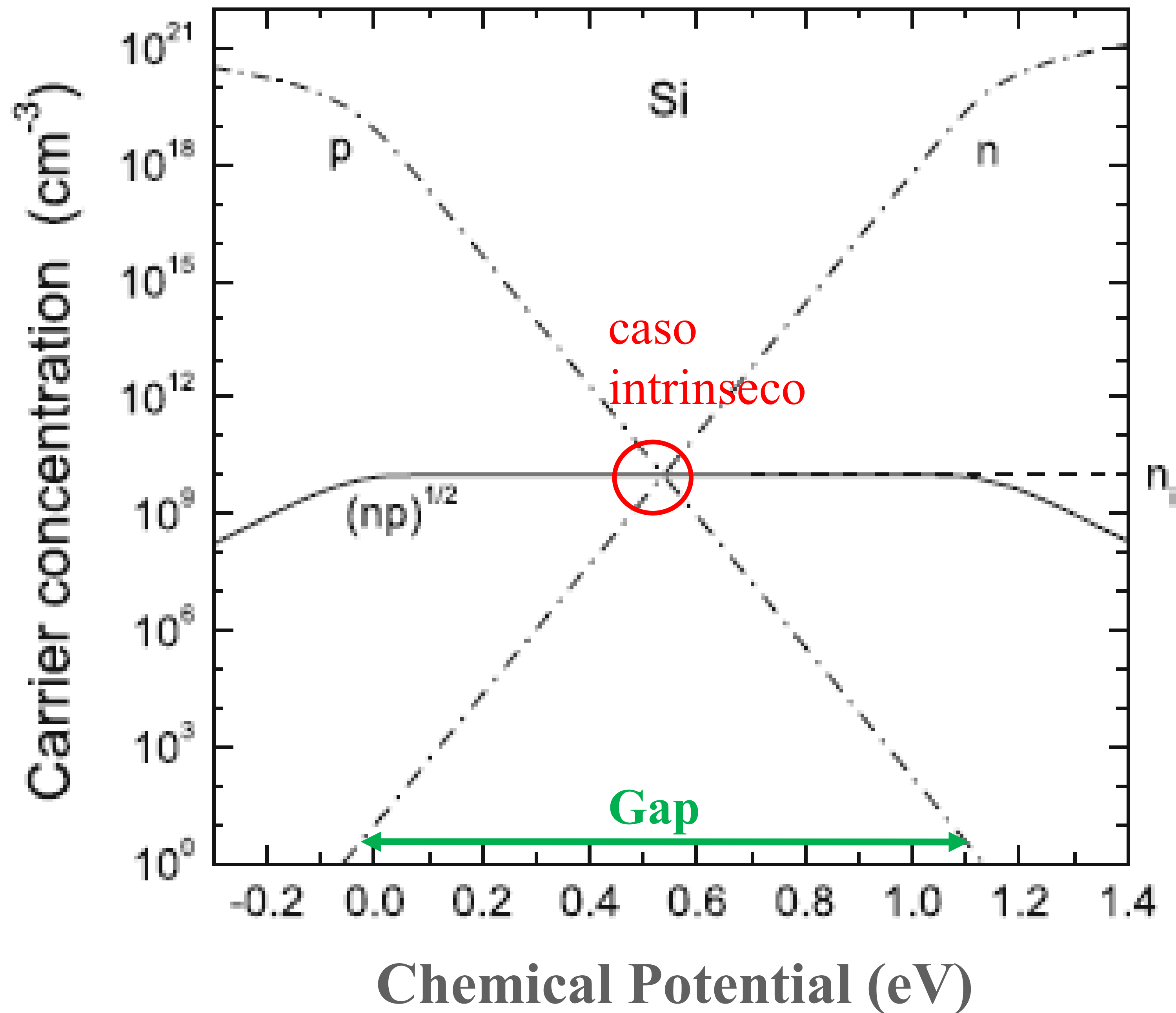
$$\boxed{\mu = \frac{1}{2}(\varepsilon_c+\varepsilon_v)+\frac{3}{4}k_BT\ln\frac{m_p^*}{m_n^*}}$$

T = 0 ⟹ $\mu = \frac{1}{2}(\varepsilon_c+\varepsilon_v)$

E_F en el medio del gap



$$n_{\mathrm{i}} = N_{\mathrm{c}}(T)\mathrm{e}^{-(\varepsilon_{\mathrm{c}}-\mu_{\mathrm{i}})/k_{\mathrm{B}}T} = P_{\mathrm{v}}(T)\mathrm{e}^{-(\mu_{\mathrm{i}}-\varepsilon_{\mathrm{v}})/k_{\mathrm{B}}T}$$

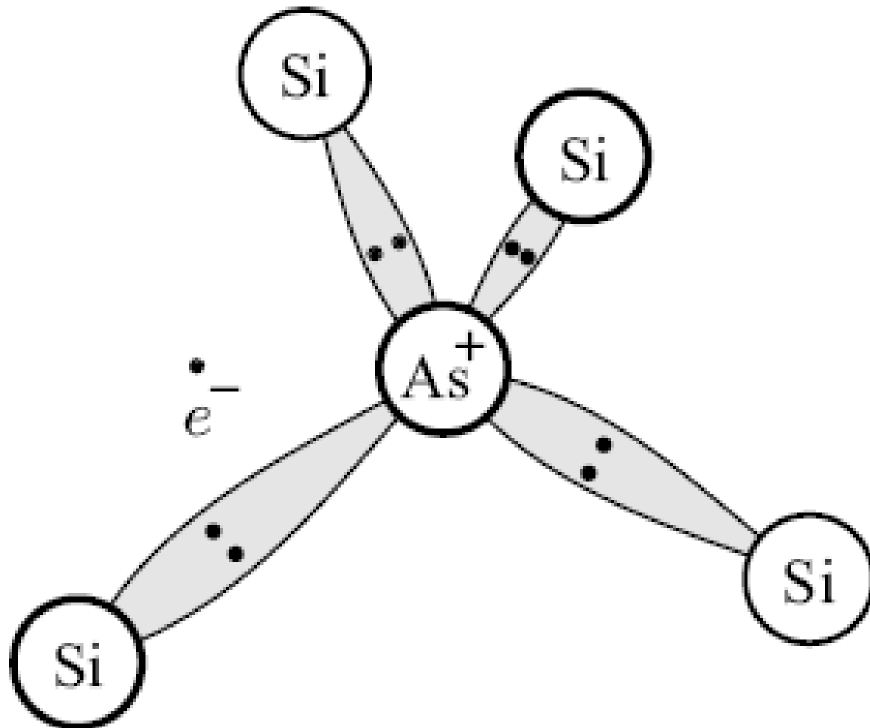


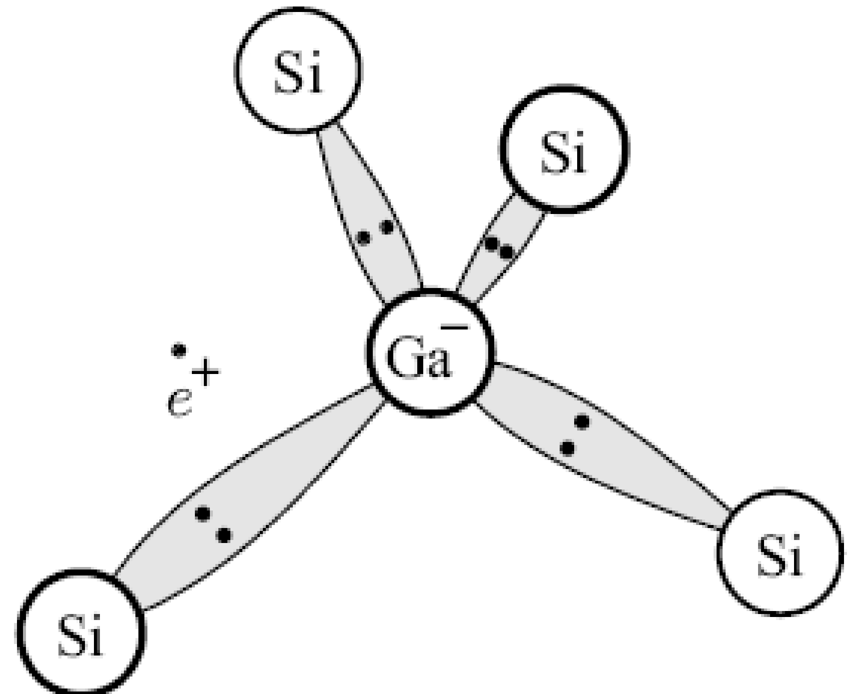
Si
p
n
caso
intrinseco
(np)^1/2
n_i
Gap
Carrier concentration (cm^-3)
Chemical Potential (eV)
10^21
10^18
10^15
10^12
10^9
10^6
10^3
10^0
-0.2
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4

Portadores extrínsecos: impurezas

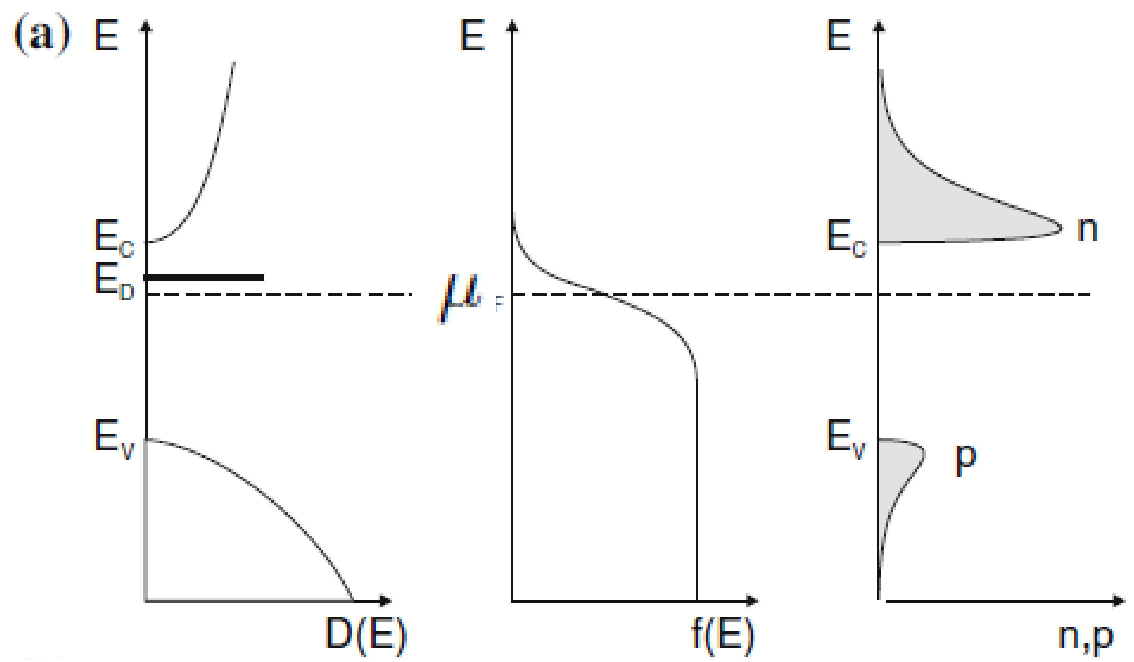
Donoras
valencia 5
(P,As,Sb)

Aceptoras
valencia 3
(B,Al,Ga)

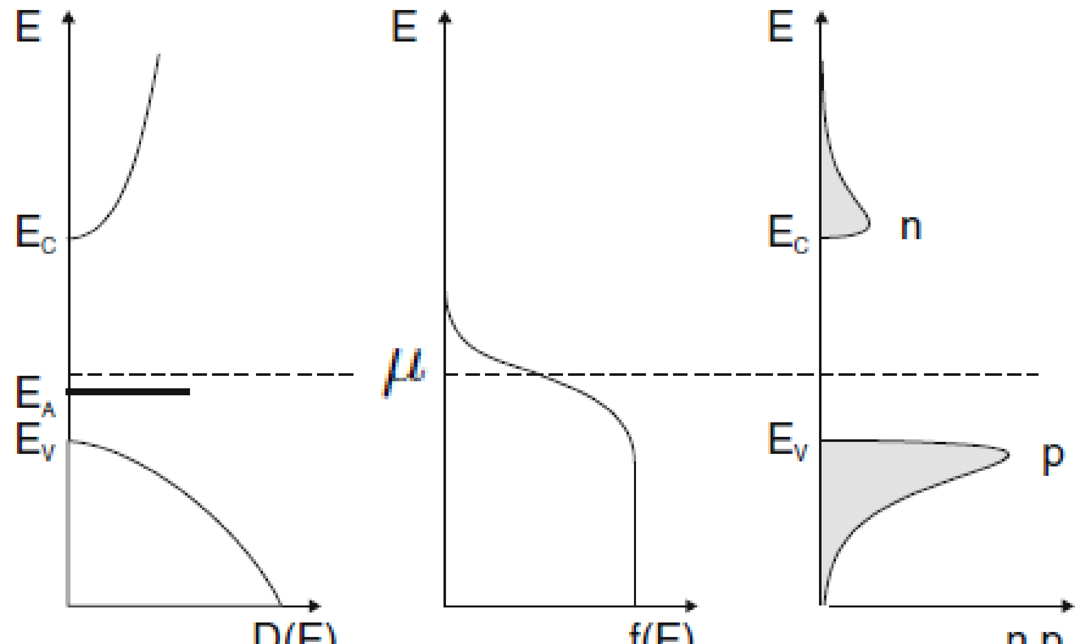




Donoras



Aceptoras



Modelizaremos esta situación como si fuera un átomo de hidrogeno: un electrón en un potencial colombiano pero apantallado por el material dieléctrico

$$\tilde{e} \longrightarrow \frac{\tilde{e}}{\sqrt{\epsilon_{\rm r}}}$$

$$m_{\rm e} \longrightarrow m^*$$

$$\longrightarrow \left\{ -\frac{\hbar^2}{2m^*}\nabla^2 - \frac{\tilde{e}^2}{\epsilon_{\rm r} r} \right\} \psi(r) = \varepsilon \psi(r)$$

Radio de la orbita

$$r_0 = \frac{\hbar^2}{m^*(\tilde{e}^2/\epsilon_{\rm r})} = \frac{m_{\rm e}}{m^*}\epsilon_{\rm r}\, a_0$$

a_0 **radio de Bohr del átomo de H (0.5291 A)**

Estimaciones

$$r_0^{\rm Si} \approx 30\,\text{Å} \qquad r_0^{\rm Ge} \approx 80\,\text{Å}$$

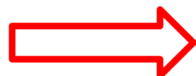
Energía de ionización del átomo de H

$$\varepsilon_0 = m_e \tilde{e}^4 / 2\hbar^2 = 13.6\,\mathrm{eV}$$

Para la impureza

$$\varepsilon_b = \frac{m^* (\tilde{e}^2/\epsilon_r)^2}{2\hbar^2} = \frac{m^*}{m_e} \frac{1}{\epsilon_r^2} \frac{m_e \tilde{e}^4}{2\hbar^2}$$

$$\boxed{\varepsilon_b = \frac{m^*}{m_e} \frac{1}{\epsilon_r^2} \times 13.6\,\mathrm{eV}}$$

Estimaciones 

20 meV for silicon

5.5 meV for germanium

Table 2 Effective masses of electrons and holes in direct gap semiconductors

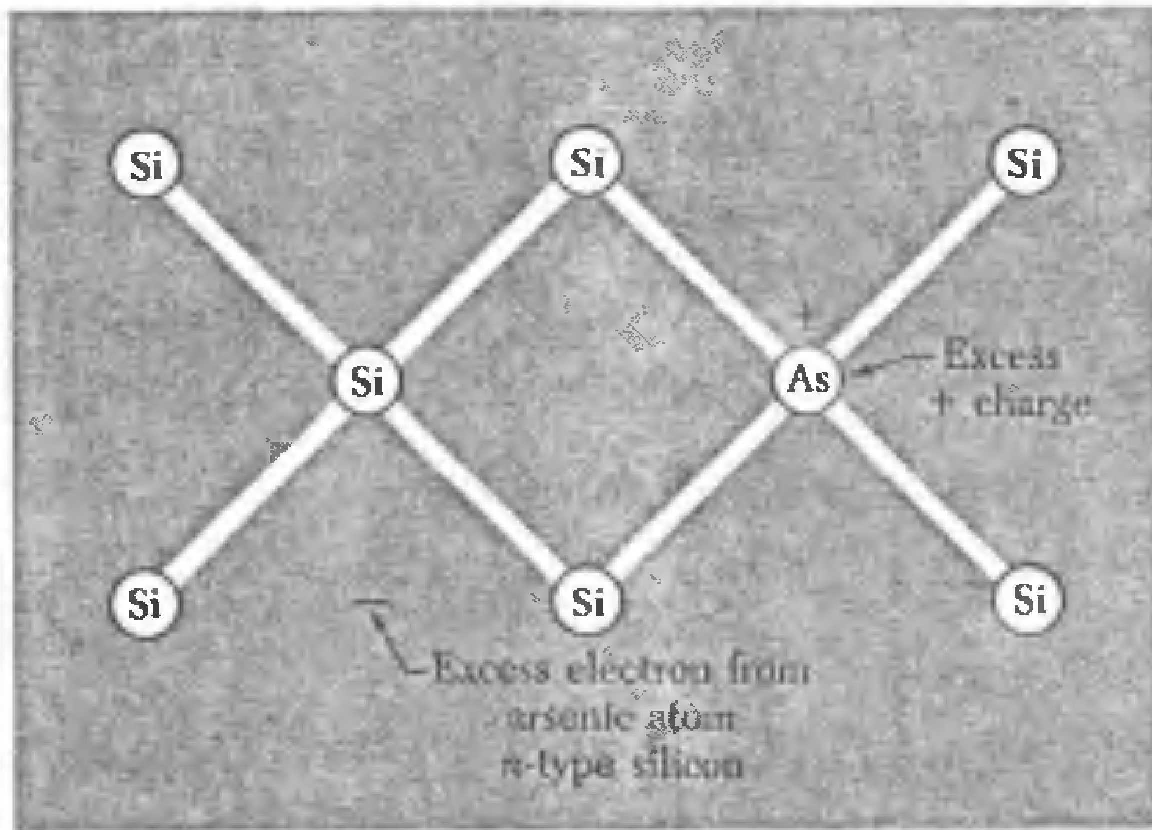
Crystal	Electron m_e/m	Heavy hole m_{hh}/m	Light hole m_{lh}/m	Split-off hole m_{soh}/m	Spin-orbit Δ, eV
InSb	0.015	0.39	0.021	(0.11)	0.82
InAs	0.026	0.41	0.025	0.08	0.43
InP	0.073	0.4	(0.078)	(0.15)	0.11
GaSb	0.047	0.3	0.06	(0.14)	0.80
GaAs	0.066	0.5	0.082	0.17	0.34
Cu_2O	0.99	—	0.58	0.69	0.13

Table 4 Static relative dielectric constant of semiconductors

Crystal	ϵ	Crystal	ϵ
Diamond	5.5	GaSb	15.69
Si	11.7	GaAs	13.13
Ge	15.8	AlAs	10.1
InSb	17.88	AlSb	10.3
InAs	14.55	SiC	10.2
InP	12.37	Cu_2O	7.1

Table 5 Donor ionization energies E_d of pentavalent impurities in germanium and silicon, in meV

	P	As	Sb
Si	45.	49.	39.
Ge	12.0	12.7	9.6



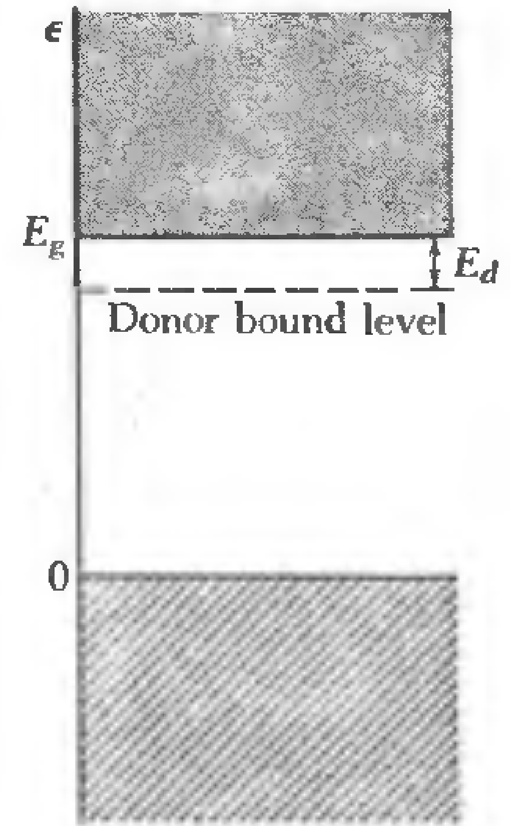
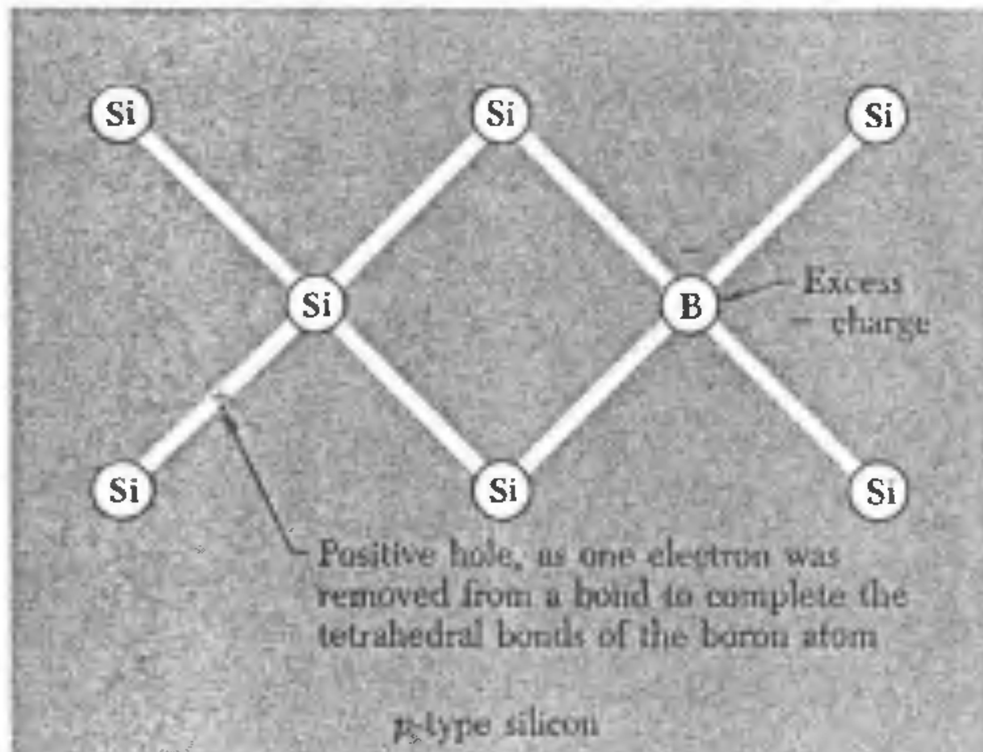
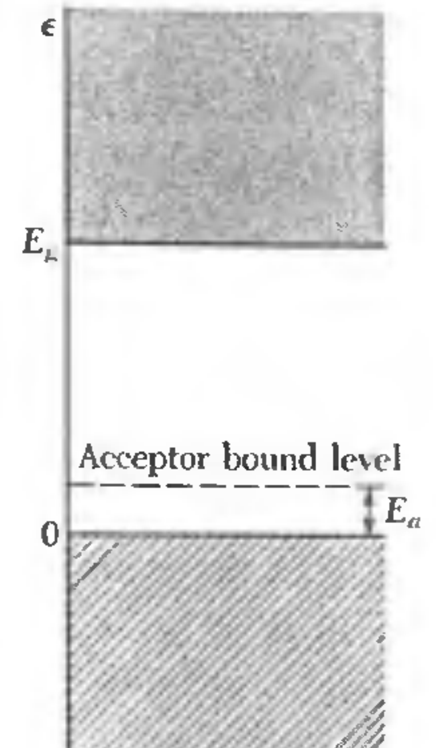


Table 6 Acceptor ionization energies E_a of trivalent impurities in germanium and silicon, in meV

	B	Al	Ga	In
Si	45.	57.	65.	157.
Ge	10.4	10.2	10.8	11.2





Para participar en la conducción se tiene que excitar a la BC

El electrón esta ligado a la impureza

ε

ε_c

ε_d

ε_v

(a)

$\rho(\varepsilon)$

ε

ε_c

ε_a

ε_v

(b)

$\rho(\varepsilon)$

Densidad de portadores en semiconductores dopados

Densidad de impurezas donaras N_D → N_D^0 **neutras**, N_D^+ **ionizadas**

Densidad de impurezas aceptoras N_A → N_A^0 **neutras**, N_A^- **ionizadas**

$$N_D = N_D^0 + N_D^+$$

$$N_A = N_A^0 + N_A^-$$

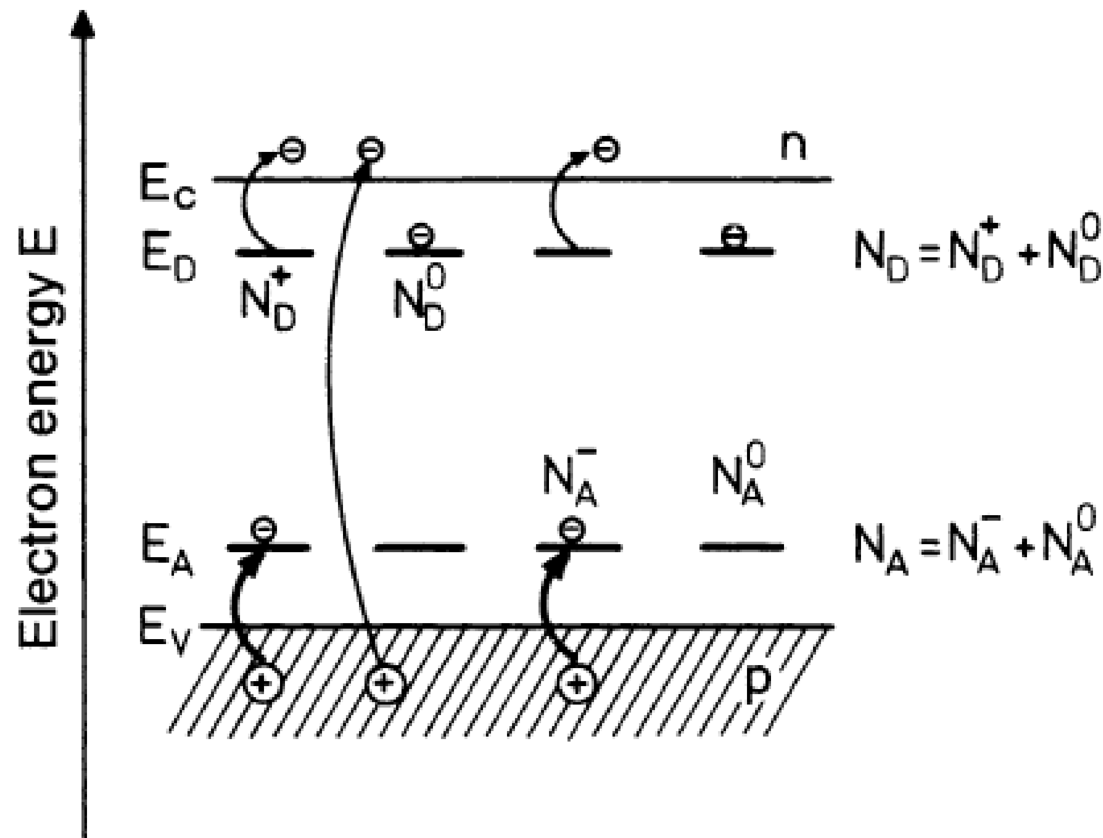
Condición de neutralidad:

$$n + N_A^- = p + N_D^+$$

La concentración de impurezas neutras a una dada temperatura esta por

$$N_D^0 = N_D[1 + \exp(E_D - \mu)/k T]^{-1}$$

$$N_A^0 = N_A[1 + \exp(\mu - E_A)/k T]^{-1}$$



Consideremos un semiconductor de tipo n “puro” ($N_A = 0$)

$$n = N_{\mathrm{eff}}^{\mathrm{C}} e^{-(E_{\mathrm{C}} - \mu)/k T}, \quad N_{\mathrm{eff}}^{\mathrm{C}} = 2\left(\frac{m_{\mathrm{n}}^{*} k_{\mathrm{B}} T}{2\pi\hbar^2}\right)^{3/2}$$

$$N_{\mathrm{D}} = N_{\mathrm{D}}^{0} + N_{\mathrm{D}}^{+},$$

$$N_{\mathrm{D}}^{0} = N_{\mathrm{D}}[1 + \exp(E_{\mathrm{D}} - \mu)/k T]^{-1}$$

μ ?

Asumiremos que la principal contribución proviene de las impurezas ionizadas $N_{\mathrm{D}}^{+} \gg n_{\mathrm{i}}$ $(np = n_{\mathrm{i}}^{2})$

$$n \approx N_{\mathrm{D}}^{+} = N_{\mathrm{D}} - N_{\mathrm{D}}^{0}$$

$$n \approx N_{\mathrm{D}}\left(1 - \frac{1}{1 + \exp[(E_{\mathrm{D}} - \mu)/k T]}\right)$$

$$n = N_{\mathrm{eff}}^{\mathrm{C}} \exp\left(-\frac{E_{\mathrm{C}} - \mu}{k T}\right) \longrightarrow (n/N_{\mathrm{eff}}^{\mathrm{C}})\mathrm{e}^{E_{\mathrm{C}}/k T} = \mathrm{e}^{\mu/k T}$$

$$n \approx \frac{N_{\mathrm{D}}}{1 + \mathrm{e}^{E_{\mathrm{d}}/k T} n/N_{\mathrm{eff}}^{\mathrm{C}}}$$

donde $E_{\mathrm{d}} = E_{\mathrm{C}} - E_{\mathrm{D}}$

$$n + \frac{n^2}{N_{\mathrm{eff}}^{\mathrm{C}}}\mathrm{e}^{E_{\mathrm{d}}/k T} \approx N_{\mathrm{D}}$$

La solución con sentido físico es:

$$n \approx 2N_{\mathrm{D}}\left(1 + \sqrt{1 + 4\frac{N_{\mathrm{D}}}{N_{\mathrm{eff}}^{\mathrm{C}}}\mathrm{e}^{E_{\mathrm{d}}/k T}}\right)^{-1}$$

- Si la temperatura es tan baja que

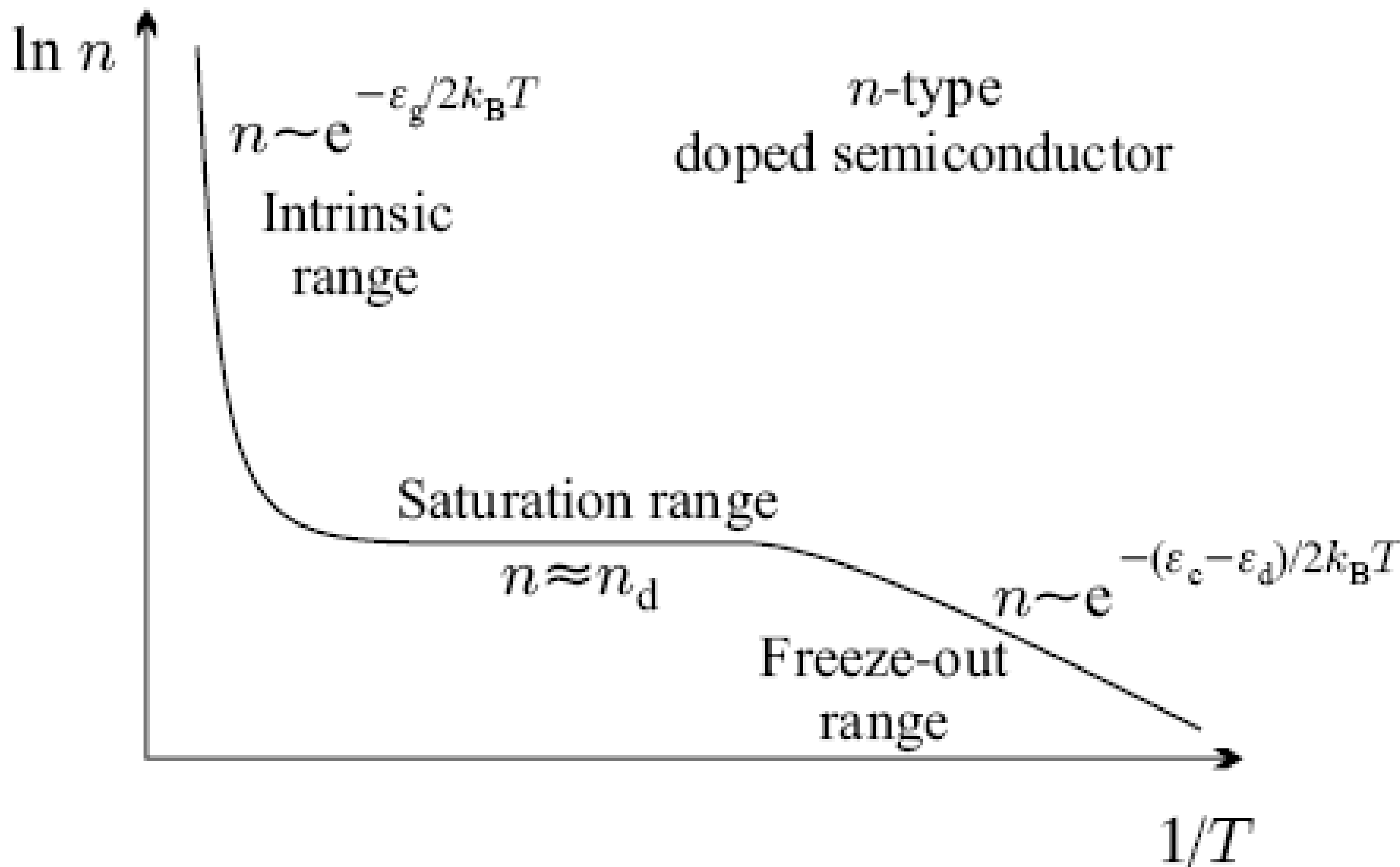
$$4(N_\mathrm{D}/N^\mathrm{L}_\mathrm{eff})\mathrm{e}^{E_\mathrm{d}/kT} \gg 1 \quad \Longrightarrow \quad \boxed{n \approx \sqrt{N_\mathrm{D} N^\mathrm{C}_\mathrm{eff}}\,\mathrm{e}^{-E_\mathrm{d}/2kT}}$$

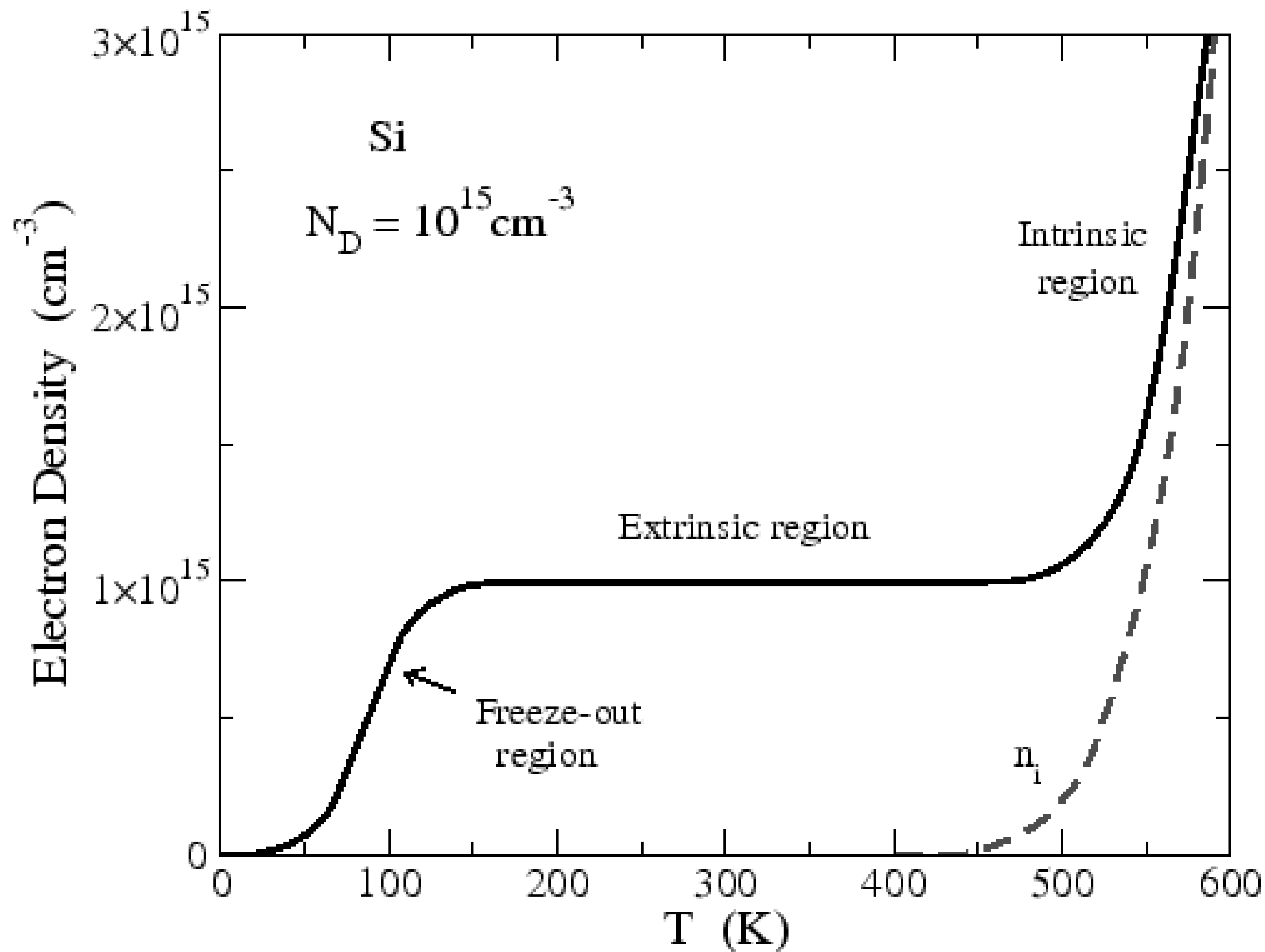
- Si la temperatura es tal que

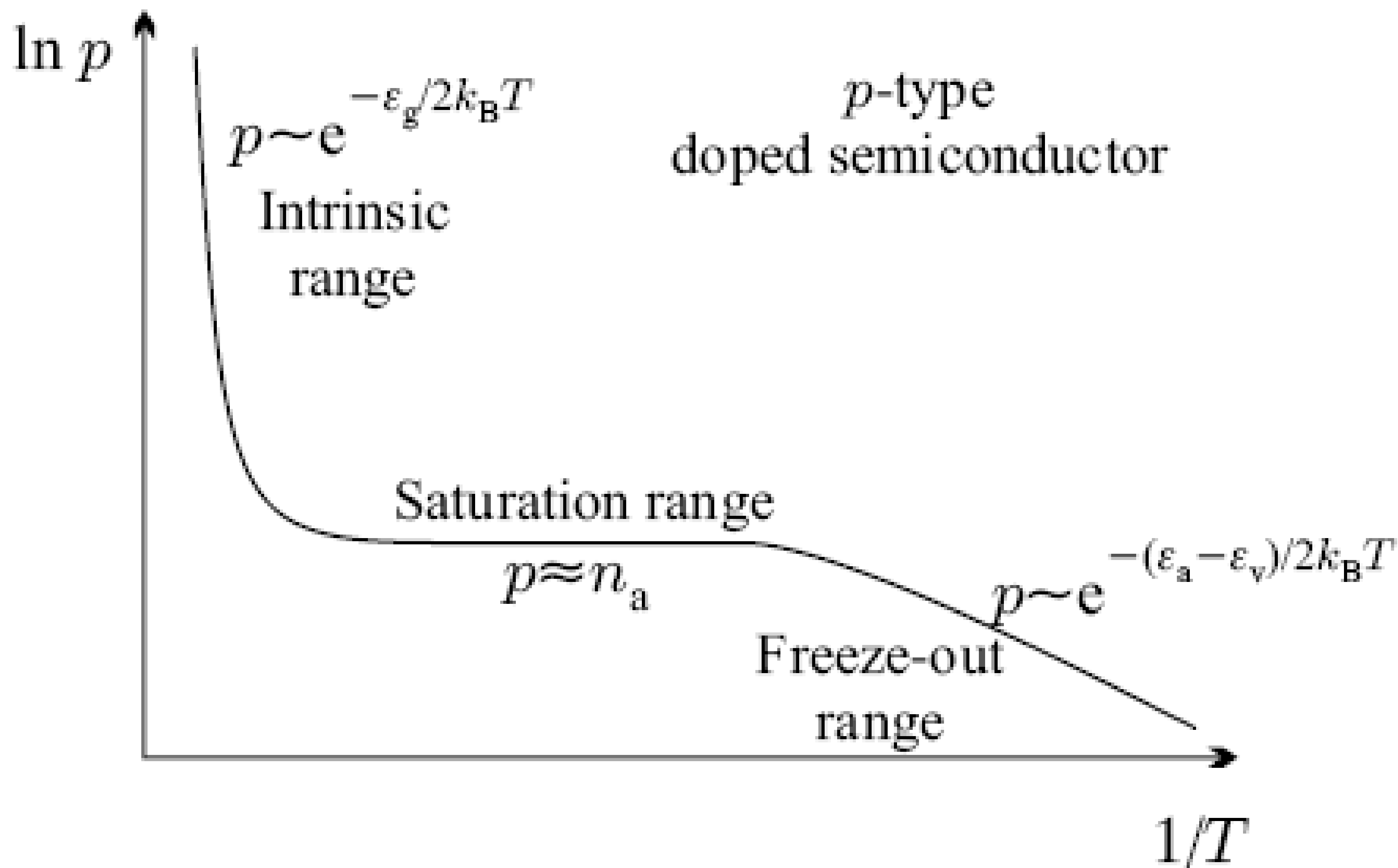
$$4(N_\mathrm{D}/N^\mathrm{C}_\mathrm{eff})\mathrm{e}^{E_\mathrm{d}/kT} \ll 1 \quad \Longrightarrow \quad \boxed{n \approx N_\mathrm{D} = \mathrm{const}}$$

- Si la temperatura es muy alta

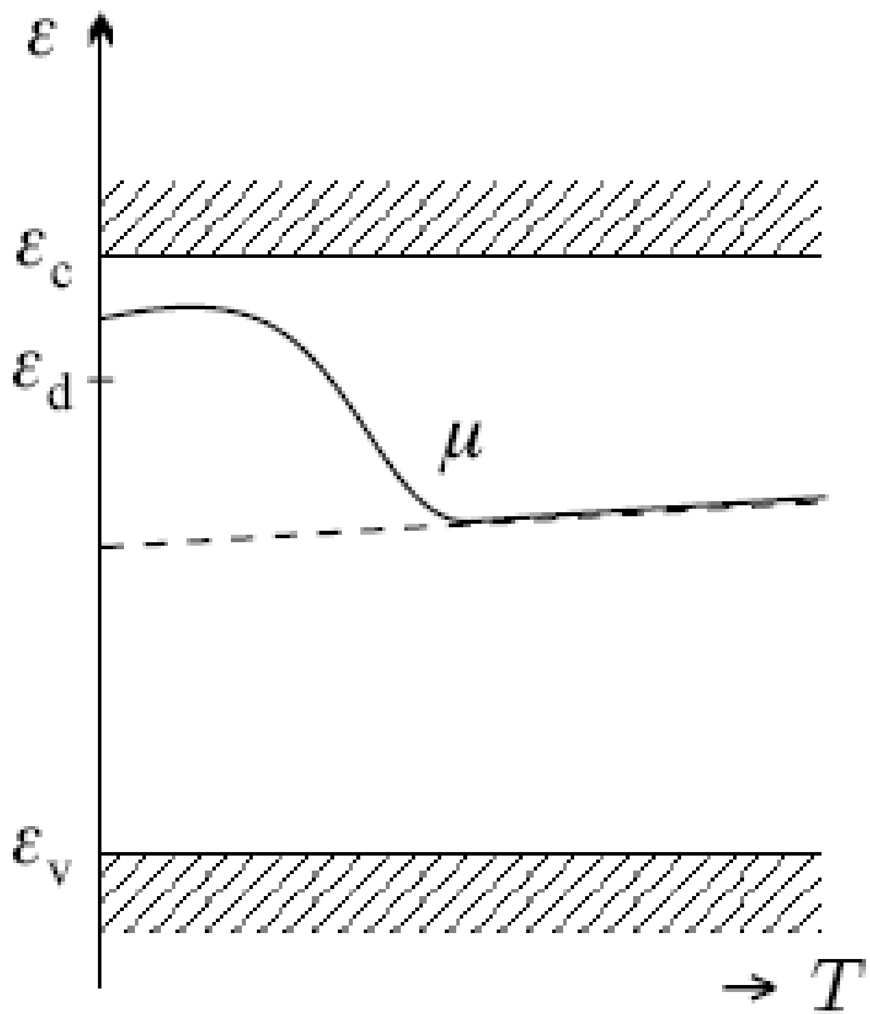
$$n = \cancel{N^+_\mathrm{D}} + p \quad \Longrightarrow \quad \boxed{n_\mathrm{i} = p_\mathrm{i} = \sqrt{N^\mathrm{C}_\mathrm{eff} N^\mathrm{V}_\mathrm{eff}}\,\mathrm{e}^{-E_\mathrm{g}/2kT}}$$


$\ln n$
$n \sim e^{-\varepsilon_g/2k_B T}$
Intrinsic
range
n-type
doped semiconductor
Saturation range
$n \approx n_d$
$n \sim e^{-(\varepsilon_c - \varepsilon_d)/2k_B T}$
Freeze-out
range
$1/T$

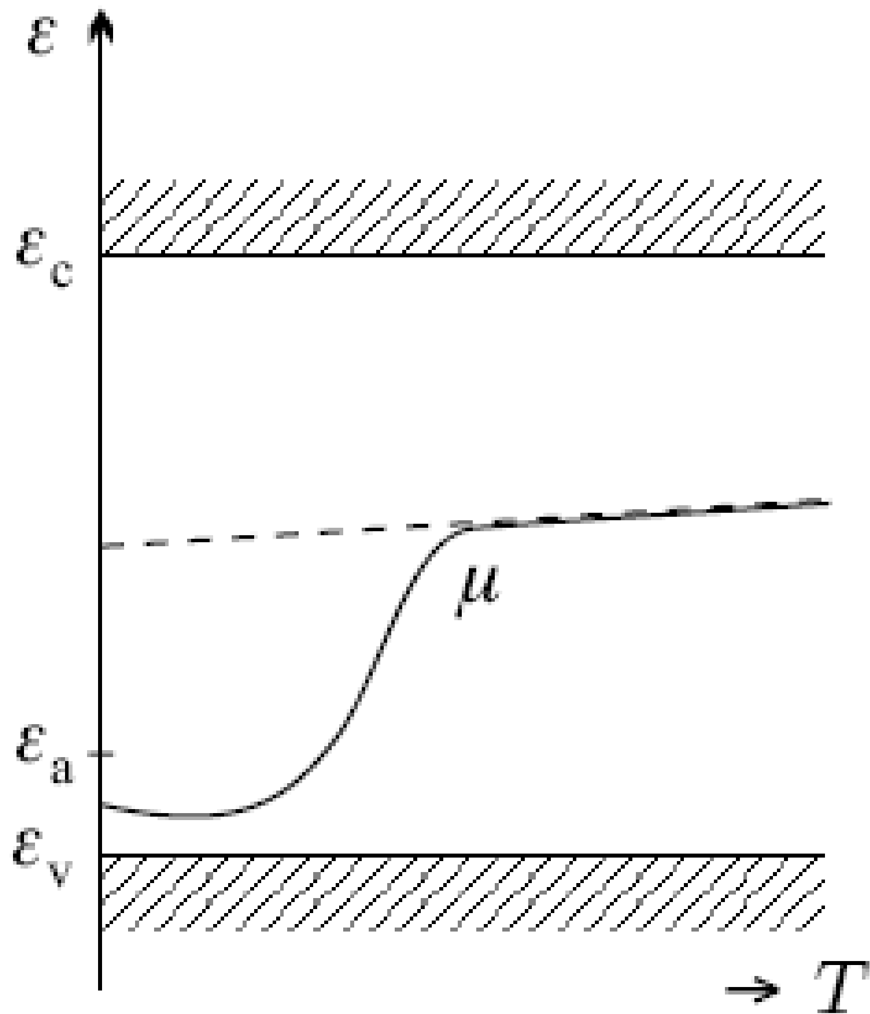

Si
$N_D = 10^{15} cm^{-3}$
Intrinsic region
Extrinsic region
Freeze-out region
n_i
Electron Density (cm^{-3})
3×10^{15}
2×10^{15}
1×10^{15}
0
0
100
200
300
400
500
600
T (K)



$\ln p$
$p\sim e^{-\varepsilon_g/2k_B T}$
Intrinsic
range
p-type
doped semiconductor
Saturation range
$p\approx n_a$
$p\sim e^{-(\varepsilon_a-\varepsilon_v)/2k_B T}$
Freeze-out
range
$1/T$



ε
ε_c
ε_d
μ
ε_v
$\rightarrow T$



ε
ε_c
μ
ε_a
ε_v
$\rightarrow T$