Estructura de la Materia 2

Clase 14 - Teoría

Docentes

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Web: http://materias.df.uba.ar/edlm2a2020c1

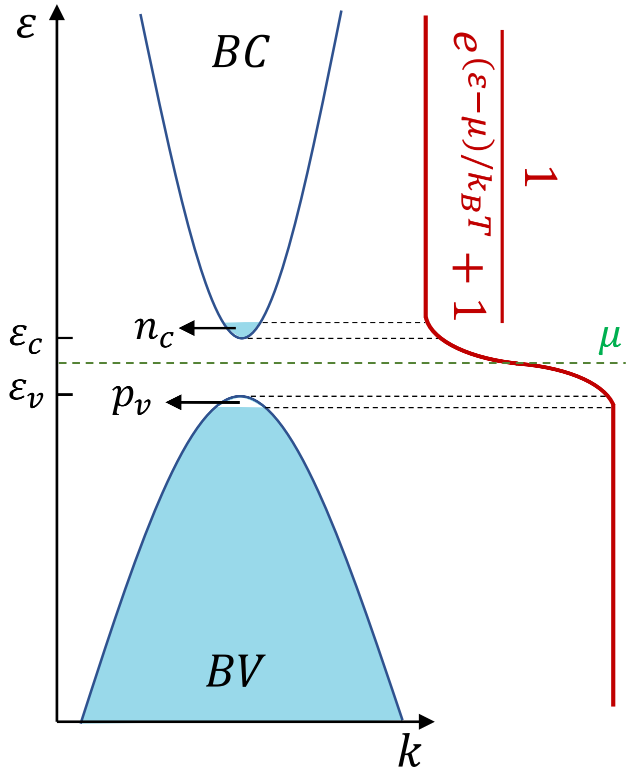
Repaso

Semiconductor en equilibrio térmico y caso intrínseco

$$\begin{cases} n_c(T) = \int_{\varepsilon_c}^{\infty} f(\varepsilon) g_c(\varepsilon) d\varepsilon = \int_{\varepsilon_c}^{\infty} \left[e^{(\varepsilon-\mu)/k_B T} + 1\right]^{-1} g_c(\varepsilon) d\varepsilon \\ p_v(T) = \int_{-\infty}^{\varepsilon_v} \big(1 - f(\varepsilon)\big) g_v(\varepsilon) d\varepsilon = \int_{-\infty}^{\varepsilon_v} \left[e^{(\mu-\varepsilon)/k_B T} + 1\right]^{-1} g_v(\varepsilon) d\varepsilon \end{cases}$$

$$\begin{cases} \varepsilon_c - \mu \gg k_B T \\ \mu - \varepsilon_v \gg k_B T \end{cases}$$

(Condición de no-degeneración)



$$\begin{cases} n_c(T) = N_c(T) e^{-\frac{\varepsilon_c - \mu}{k_B T}} \\ p_v(T) = P_v(T) e^{-\frac{\mu - \varepsilon_v}{k_B T}} \end{cases}$$

$$\begin{cases} N_c(T) = \int_{\varepsilon_c}^{\infty} e^{-\frac{\varepsilon - \varepsilon_c}{k_B T}} g_c(\varepsilon) d\varepsilon = \frac{1}{4}\left(\frac{2 m_c k_B T}{\pi \hbar^2}\right)^{3/2} \\ P_v(T) = \int_{-\infty}^{\varepsilon_v} e^{-\frac{\varepsilon_v - \varepsilon}{k_B T}} g_v(\varepsilon) d\varepsilon = \frac{1}{4}\left(\frac{2 m_v k_B T}{\pi \hbar^2}\right)^{3/2} \end{cases}$$

$$\boxed{n_c p_v = N_c P_v e^{-\frac{\varepsilon_c - \varepsilon_v}{k_B T}} = N_c P_v e^{-\frac{E_g}{k_B T}}}$$

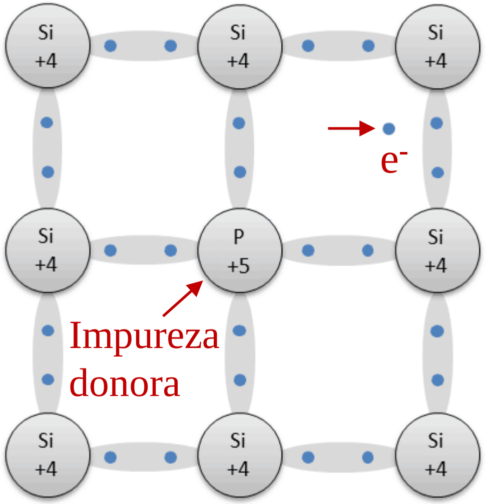
Ley de acción de masas

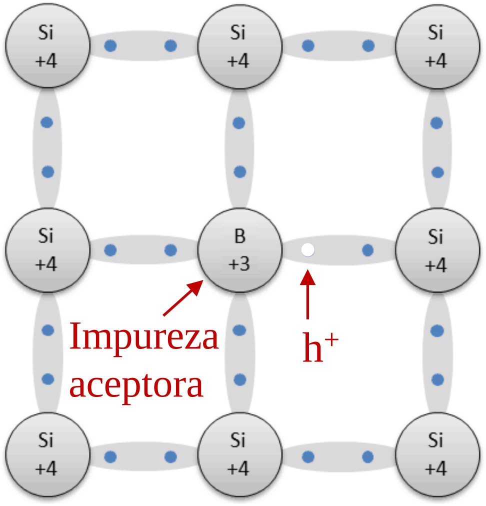
$$\begin{cases} n_i(T) = [N_c P_v]^{1/2} e^{-\frac{E_g}{2 k_B T}} = \frac{1}{4}\left(\frac{2 k_B T}{\pi \hbar^2}\right)^{3/2} (m_c m_v)^{3/4} e^{-\frac{E_g}{2 k_B T}} = n_c^{(i)} = p_v^{(i)} \\ \mu_i = \varepsilon_v + \frac{E_g}{2} + \frac{1}{2} k_B T \ln\left(\frac{P_v}{N_c}\right) = \varepsilon_v + \frac{E_g}{2} + \frac{3}{4} k_B T \ln\left(\frac{m_v}{m_c}\right) \end{cases}$$

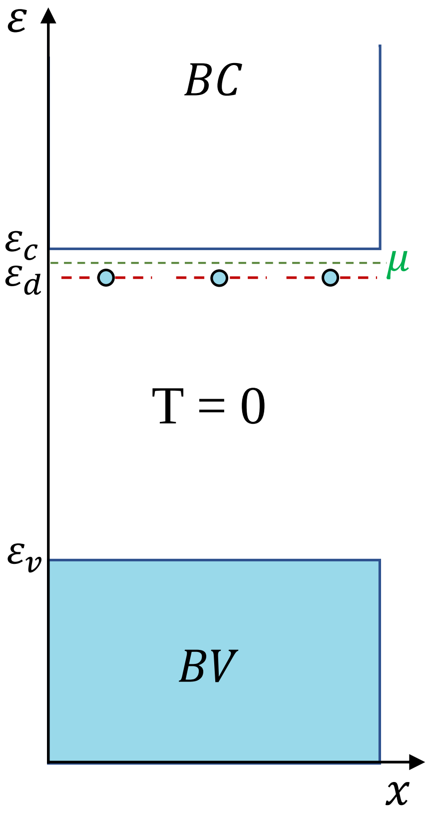
Repaso

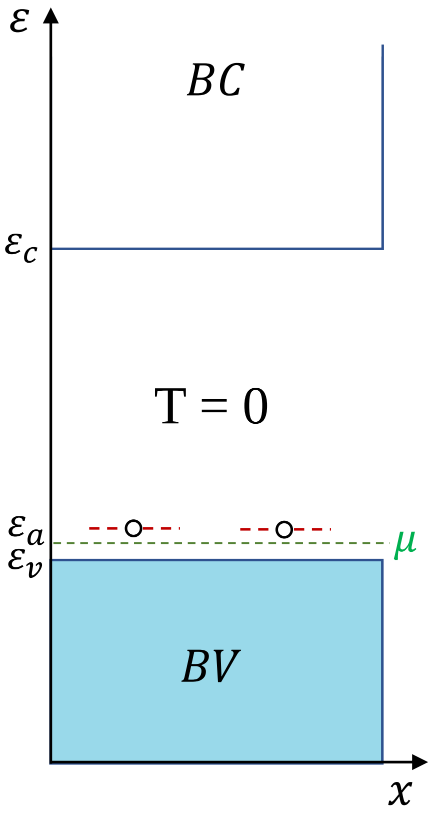
Semiconductor extrínseco

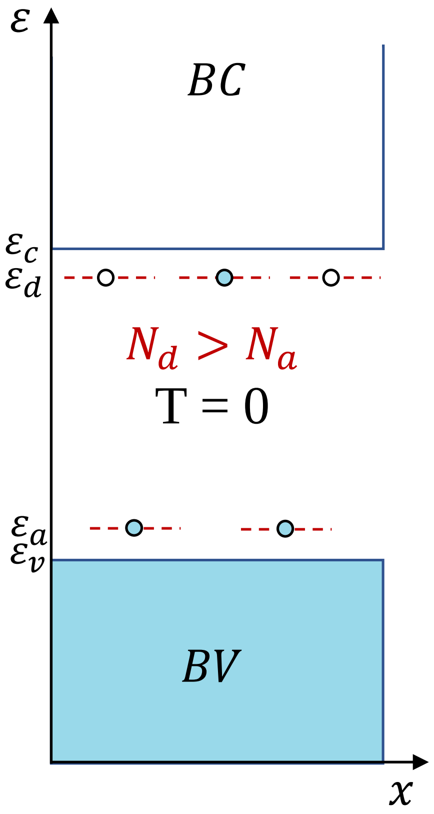
Dopamos al semiconductor con una baja concentración de impurezas donoras o aceptoras.











$$n_d = \frac{N_d}{\frac{1}{2}e^{\beta(\varepsilon_d - \mu)} + 1}$$

$$p_a = \frac{N_a}{\frac{1}{2}e^{\beta(\mu - \varepsilon_a)} + 1}$$

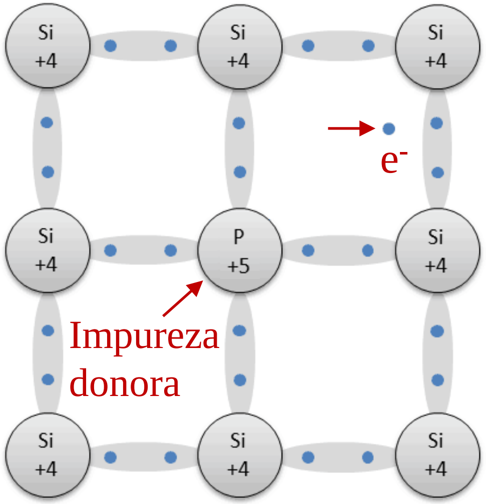
$$n_c + n_d = N_d - N_a + p_v + p_a$$

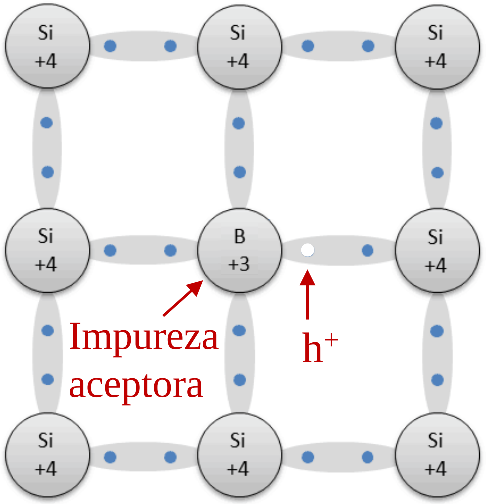
Balance de carga

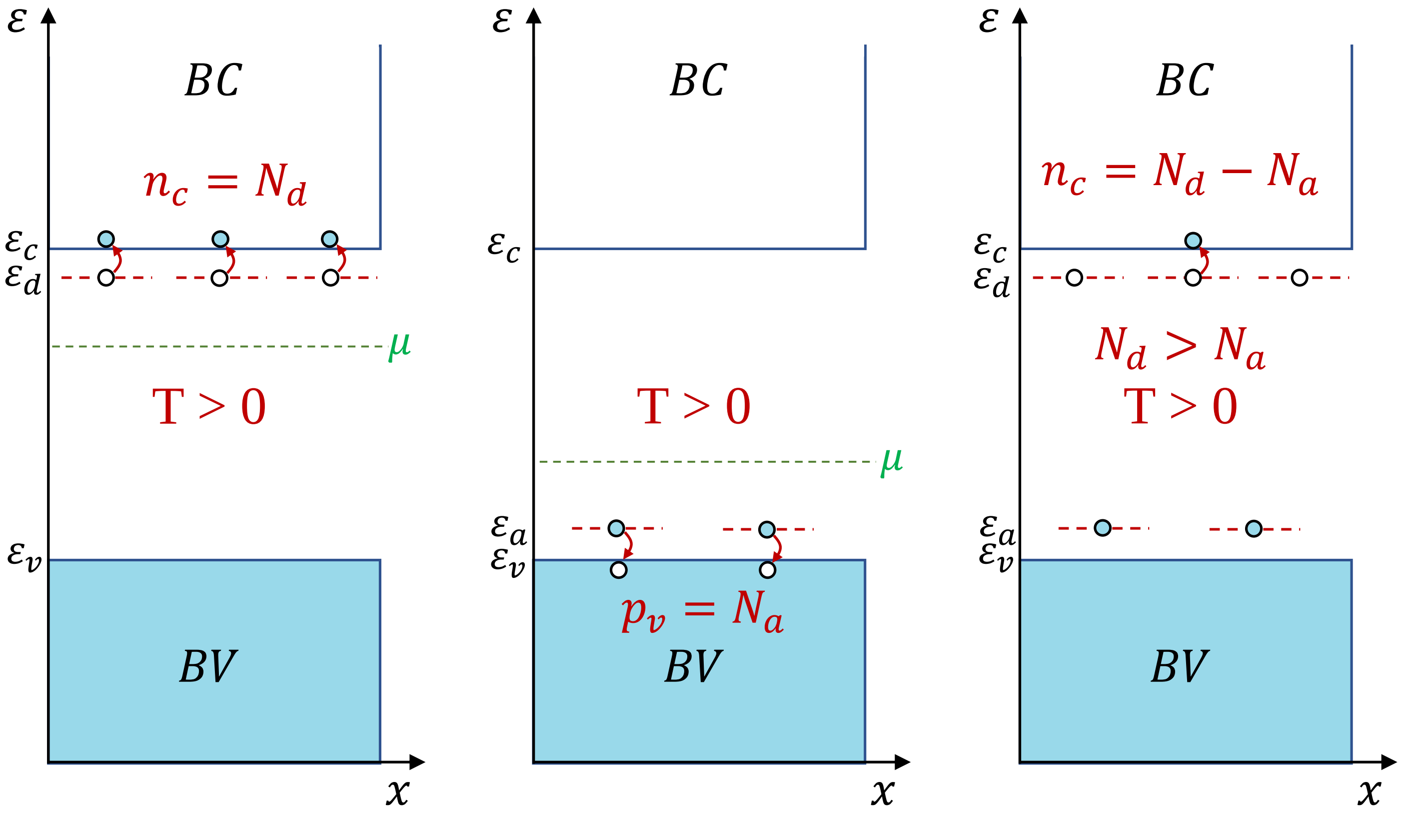
Repaso

Semiconductor extrínseco

Dopamos al semiconductor con una baja concentración de impurezas donoras o aceptoras.







$$n_d = \frac{N_d}{\frac{1}{2} e^{\beta(\varepsilon_d - \mu)} + 1}$$

$$p_a = \frac{N_a}{\frac{1}{2} e^{\beta(\mu - \varepsilon_a)} + 1}$$

$$\begin{cases} \varepsilon_d - \mu \gg k_B T \\ \mu - \varepsilon_a \gg k_B T \end{cases}$$

$$\Delta n = n_c - p_v = N_d - N_a$$

Impurezas totalmente ionizadas

$$n_c + n_d = N_d - N_a + p_v + p_a$$

Balance de carga

Repaso

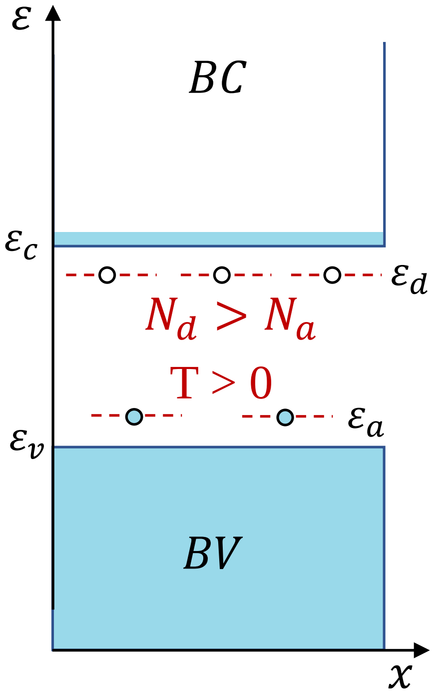
Semiconductor extrínseco

$$\begin{cases} n_c p_v = n_i^2 \\ n_c - p_v = \Delta n \end{cases} \rightarrow \begin{Bmatrix} n_c \\ p_v \end{Bmatrix} = \pm\frac{1}{2}(\Delta n) + \frac{1}{2}\left[(\Delta n)^2 + 4n_i^2\right]^{\frac{1}{2}};\quad \begin{cases} n_c = e^{\beta(\mu-\mu_i)} n_i \\ p_v = e^{-\beta(\mu-\mu_i)} n_i \end{cases} \rightarrow \frac{\Delta n}{n_i} = 2\sinh(\beta(\mu-\mu_i))$$

$\Delta n = N_d - N_a$

$$\begin{cases} \varepsilon_d - \mu \gg k_B T \\ \mu - \varepsilon_a \gg k_B T \end{cases} \rightarrow \begin{Bmatrix} n_c \\ p_v \end{Bmatrix} = \pm\frac{1}{2}(N_d - N_a) + \frac{1}{2}\left[(N_d - N_a)^2 + 4n_i^2\right]^{\frac{1}{2}}$$

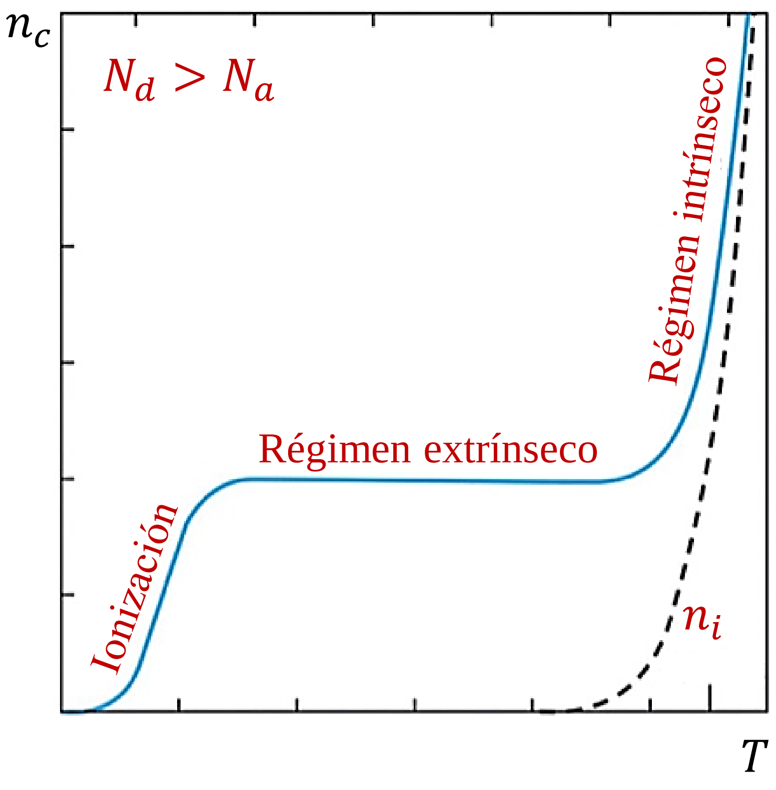
$n_i \gg |N_d - N_a|$ $\rightarrow$ $$\begin{Bmatrix} n_c \\ p_v \end{Bmatrix} \approx \pm\frac{1}{2}(N_d - N_a) + n_i$$



$n_i \ll |N_d - N_a|$ $\rightarrow$

$$\begin{cases} \varepsilon_d - \mu \gg k_B T \\ \mu - \varepsilon_a \gg k_B T \end{cases}$$

$$\begin{cases} N_d > N_a & \begin{cases} n_c \approx N_d - N_a \\ p_v \approx \dfrac{n_i^2}{N_d - N_a} \end{cases} \\ N_a > N_d & \begin{cases} n_c \approx \dfrac{n_i^2}{N_a - N_d} \\ p_v \approx N_a - N_d \end{cases} \end{cases}$$



Repaso

Semiconductor extrínseco

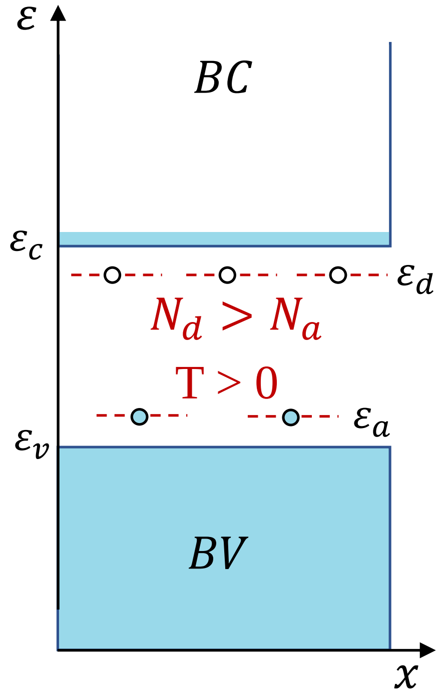
$$\begin{cases} n_c p_v = n_i^2 \\ n_c - p_v = \Delta n \end{cases} \rightarrow \begin{Bmatrix} n_c \\ p_v \end{Bmatrix} = \pm\frac{1}{2}(\Delta n) + \frac{1}{2}\left[(\Delta n)^2 + 4n_i^2\right]^{\frac{1}{2}};\quad \begin{cases} n_c = e^{\beta(\mu-\mu_i)} n_i \\ p_v = e^{-\beta(\mu-\mu_i)} n_i \end{cases} \rightarrow \frac{\Delta n}{n_i} = 2\sinh(\beta(\mu-\mu_i))$$

$\Delta n = N_d - N_a$

$$\begin{cases} \varepsilon_d - \mu \gg k_B T \\ \mu - \varepsilon_a \gg k_B T \end{cases} \rightarrow \begin{Bmatrix} n_c \\ p_v \end{Bmatrix} = \pm\frac{1}{2}(N_d - N_a) + \frac{1}{2}\left[(N_d - N_a)^2 + 4n_i^2\right]^{\frac{1}{2}}$$

$n_i \gg |N_d - N_a|$

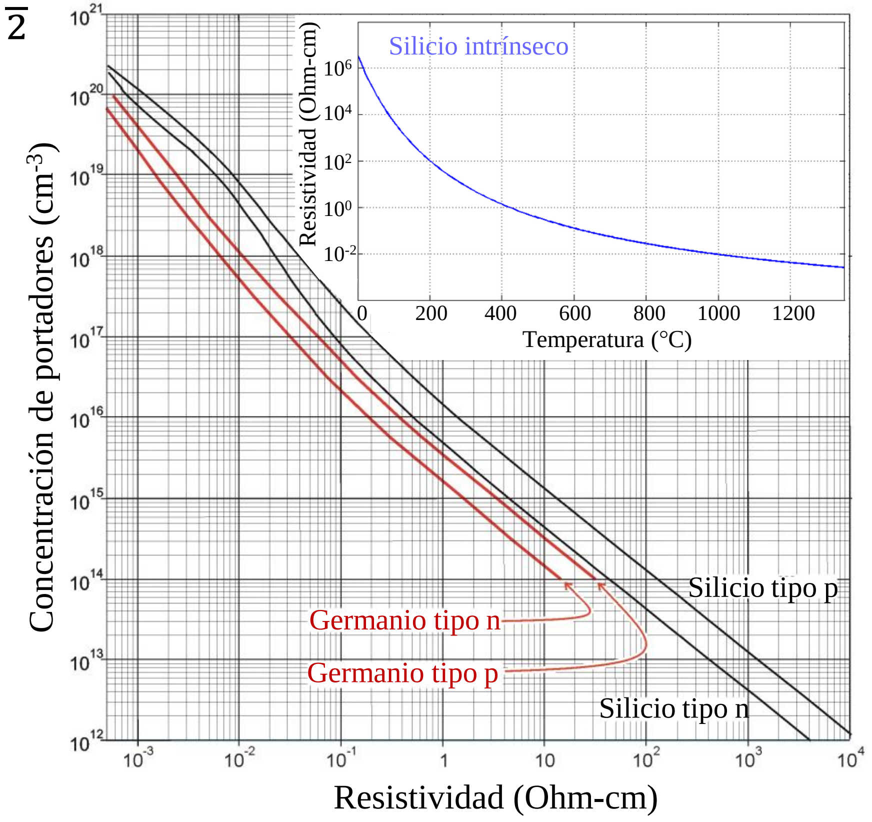
$$\begin{Bmatrix} n_c \\ p_v \end{Bmatrix} \approx \pm\frac{1}{2}(N_d - N_a) + n_i$$



$n_i \ll |N_d - N_a|$

$$\begin{cases} \varepsilon_d - \mu \gg k_B T \\ \mu - \varepsilon_a \gg k_B T \end{cases}$$

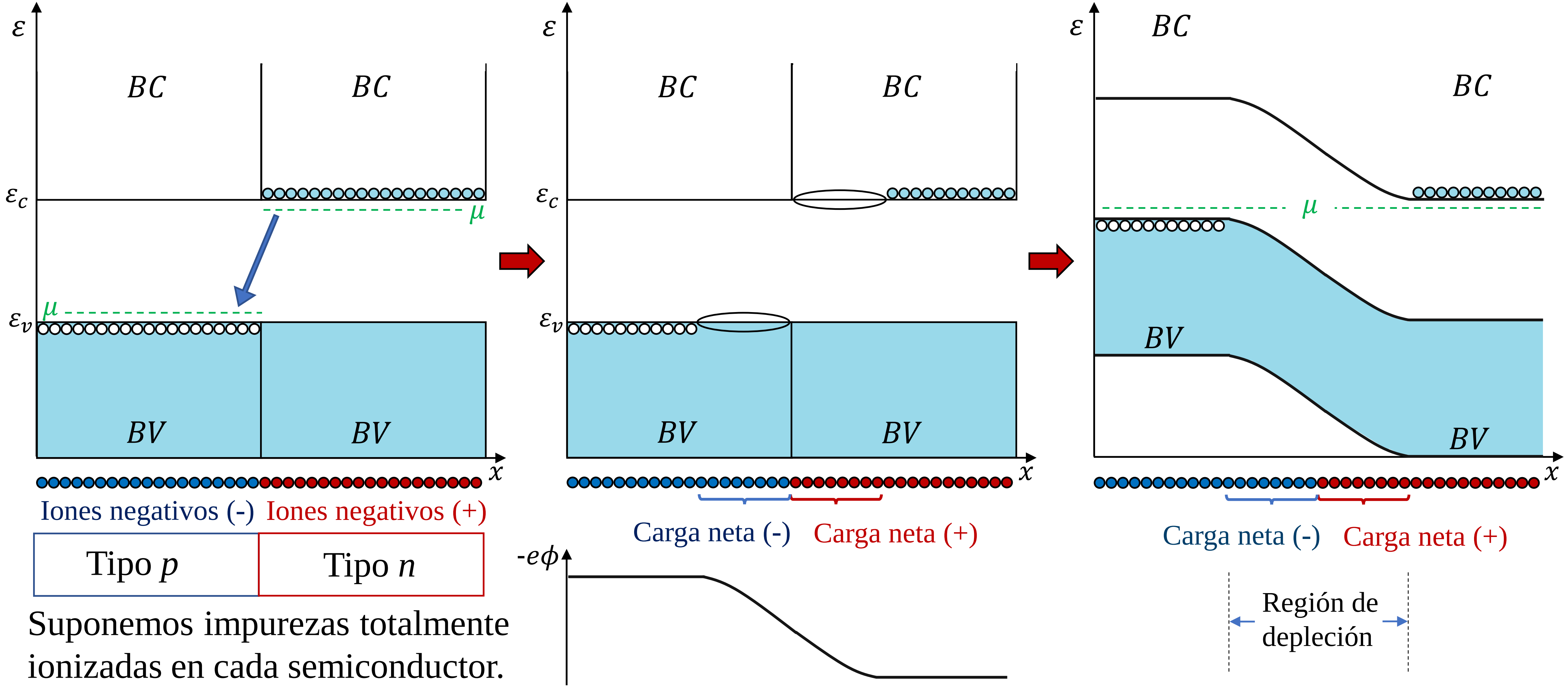
$$\begin{cases} N_d > N_a & \begin{cases} n_c \approx N_d - N_a \\ p_v \approx \dfrac{n_i^2}{N_d - N_a} \end{cases} \\ N_a > N_d & \begin{cases} n_c \approx \dfrac{n_i^2}{N_a - N_d} \\ p_v \approx N_a - N_d \end{cases} \end{cases}$$



Juntura semiconductora *p-n*

Juntura semiconductora *p-n*

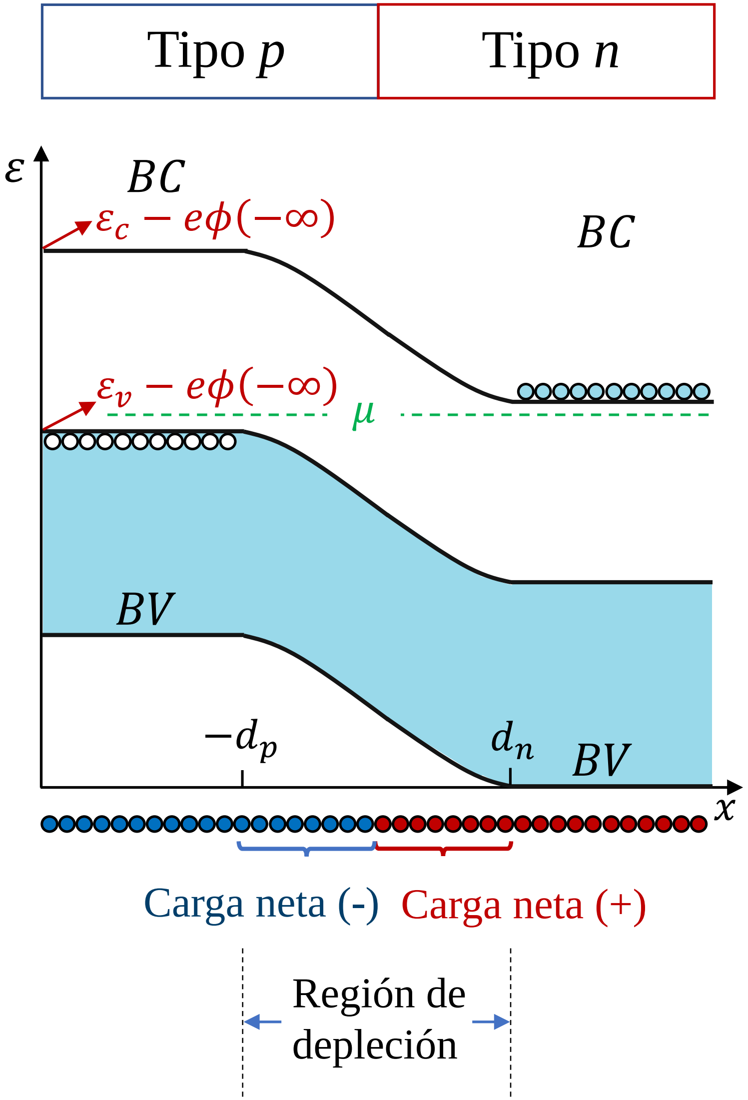
Construimos una juntura *p-n* poniendo semiconductores tipo *p* y *n* en contacto directo.



Suponemos impurezas totalmente ionizadas en cada semiconductor.

Juntura semiconductora *p-n*

Juntura semiconductora *p-n*: Región de depleción



$$\begin{cases} n_c(x) = N_c(T)e^{-\frac{[\varepsilon_c - e\phi(x) - \mu]}{k_B T}} \\ p_v(x) = P_v(T)e^{-\frac{[\mu - \varepsilon_v + e\phi(x)]}{k_B T}} \end{cases} \qquad \begin{cases} n_c(\infty) = N_c(T)e^{-\frac{[\varepsilon_c - e\phi(\infty) - \mu]}{k_B T}} \\ p_v(-\infty) = P_v(T)e^{-\frac{[\mu - \varepsilon_v + e\phi(-\infty)]}{k_B T}} \end{cases}$$

$$\rightarrow \mu = k_B T \ln \frac{N_d}{N_c} + \varepsilon_c - e\phi(\infty) = k_B T \ln \frac{P_v}{N_a} + \varepsilon_v - e\phi(-\infty)$$

$$\rightarrow e[\phi(\infty) - \phi(-\infty)] = \boxed{e\Delta\phi = E_g + k_B T \ln \left[\frac{N_d N_a}{N_c P_v}\right]}$$

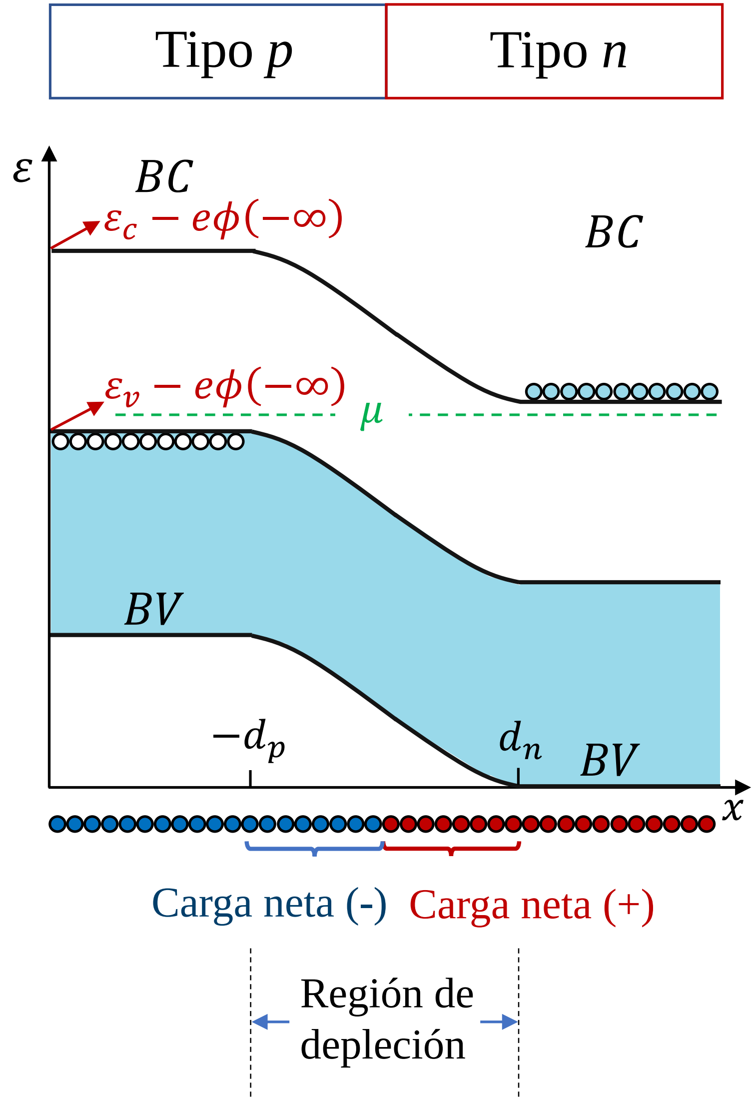
Nos sirve como condición de contorno para determinar $\phi(x)$ de la ecuación de Poisson: $\nabla^2\phi = \frac{d^2\phi}{dx^2} = -\frac{4\pi\rho(x)}{\epsilon}$

Dentro de la región de depleción: $\rho(x) = e[N_d(x) - N_a(x)]$

Fuera de la región de depleción: $\rho(x) = 0$

Juntura semiconductora *p-n*

<u>Juntura semiconductora *p-n*</u>: Región de depleción



$$\phi''(x) = \begin{cases} 0, & x > d_n \\ -\dfrac{4\pi e N_d}{\epsilon}, & d_n > x > 0 \\ \dfrac{4\pi e N_a}{\epsilon}, & 0 > x > -d_p \\ 0, & -d_p > x \end{cases} \rightarrow \phi(x) = \begin{cases} \phi(\infty) \\ \phi(\infty) - \dfrac{2\pi e N_d}{\epsilon}(x - d_n)^2 \\ \phi(-\infty) + \dfrac{2\pi e N_a}{\epsilon}(x + d_p)^2 \\ \phi(-\infty) \end{cases}$$

Continuidad de ϕ en $x = 0$ → $\Delta\phi = \dfrac{2\pi e}{\epsilon}(N_d {d_n}^2 + N_a {d_p}^2)$

Continuidad de ϕ' en $x = 0$ → $N_d d_n = N_a d_p$

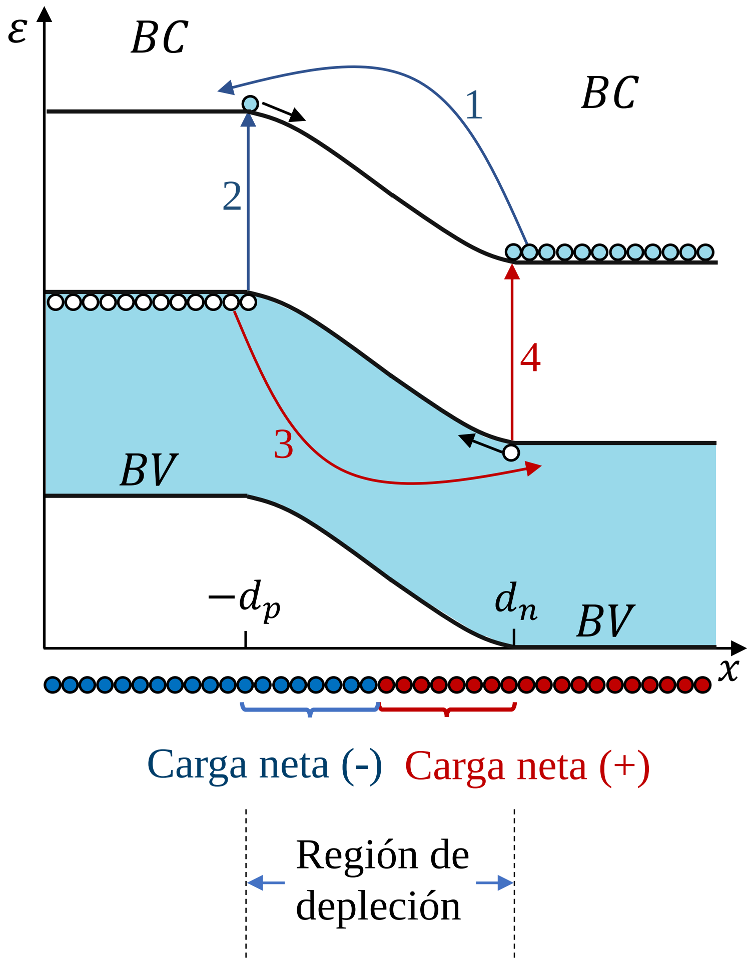
$$\rightarrow d_{n,p} = \left[\frac{(N_a/N_d)^{\pm 1}}{N_d + N_a}\frac{\epsilon\Delta\phi}{2\pi e}\right]^{1/2}$$

Para valores típicos $e\epsilon\Delta\phi \sim 1eV$, y concentraciones de impurezas en el rango de 10^{14} - 10^{18} cm^{-3}, encontramos $d_{n,p} \sim 10^4$-10^2 Å.

Juntura semiconductora *p-n*

<u>Juntura semiconductora *p-n*</u>: ¿Qué pasa si aplicamos un potencial externo?

Tipo p	Tipo n



$$V \neq 0 \rightarrow \Delta\phi = (\Delta\phi)_0 - V \rightarrow d_{n,p}(V) = d_{n,p}(0)\left[1 - \frac{V}{(\Delta\phi)_0}\right]^{1/2}$$

Definimos: $j_e = -eJ_e$; $j_h = eJ_h$ ($J_{e,h}$: Densidades de corriente numéricas)

$$(1)\ J_e^{rec} \propto e^{-\frac{e\Delta\phi}{k_BT}} \quad (2)\ J_e^{gen} \propto e^{-\frac{E_g}{k_BT}} \quad (3)\ J_h^{rec} \propto e^{-\frac{e\Delta\phi}{k_BT}} \quad (4)\ J_h^{gen} \propto e^{-\frac{E_g}{k_BT}}$$

Insensibles a V

Si $V = 0$, corrientes netas de electrones y huecos deben anularse.

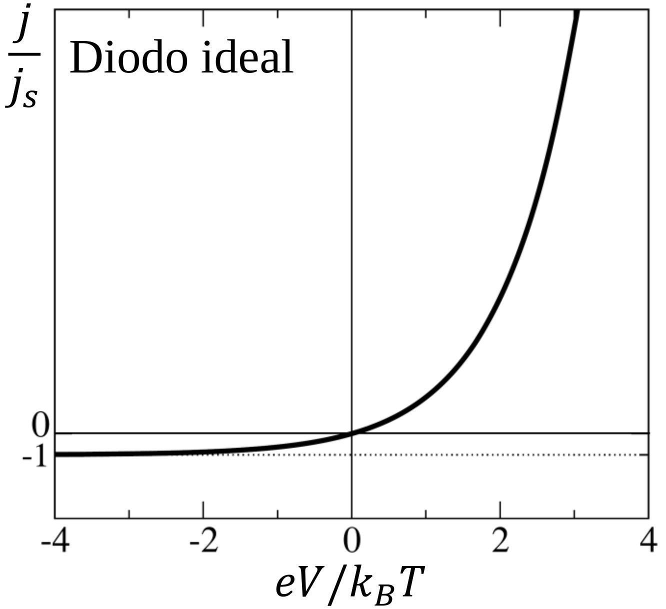
$$\rightarrow J_{e,h}^{rec}(V=0) = J_{e,h}^{gen}$$

$$\rightarrow J_{e,h}^{rec} = J_{e,h}^{rec}(0)e^{\frac{eV}{k_BT}} = J_{e,h}^{gen}e^{\frac{eV}{k_BT}}$$

$$j = e\left(J_e^{rec} - J_e^{gen} + J_h^{rec} - J_h^{gen}\right)$$

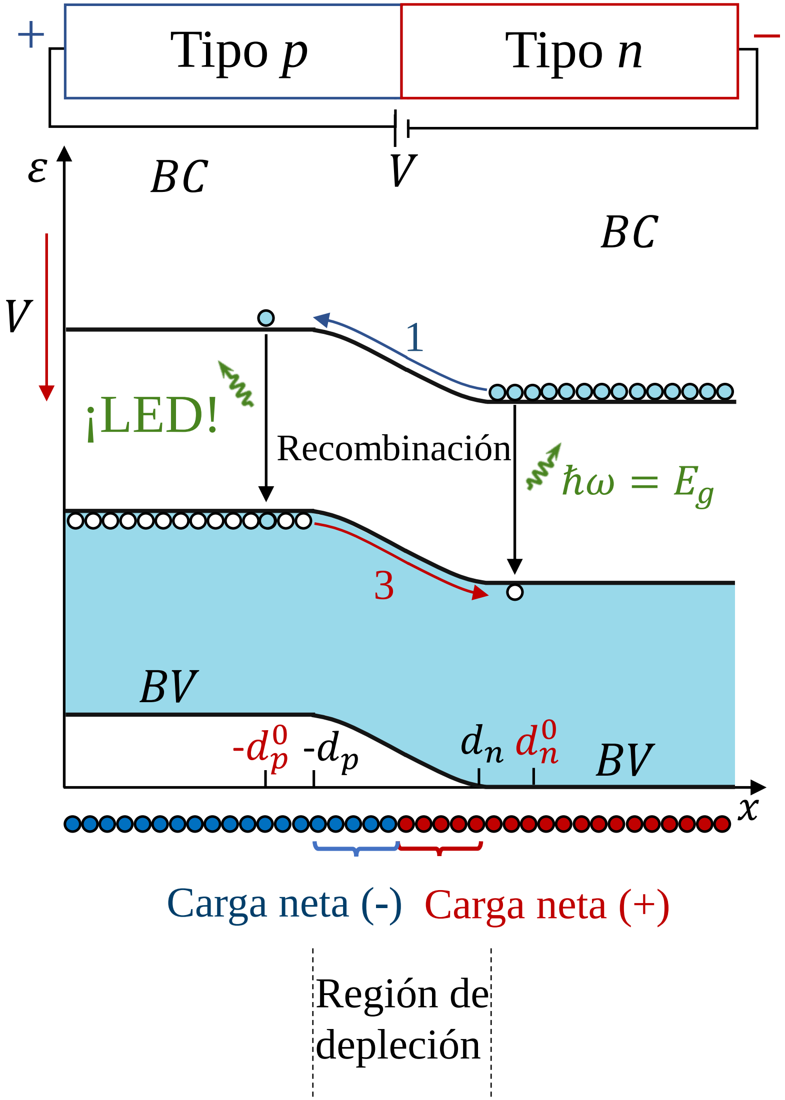
$$= \boxed{e\left(J_e^{gen} + J_h^{gen}\right)\left(e^{eV/k_BT} - 1\right)}$$

$j_s \propto e^{-E_g/k_BT}$ (Corriente de saturación)



Juntura semiconductora *p-n*

Juntura semiconductora *p-n*: Polarización directa



$V \neq 0 \rightarrow \Delta\phi = (\Delta\phi)_0 - V \rightarrow d_{n,p}(V) = d_{n,p}(0)\left[1 - \frac{V}{(\Delta\phi)_0}\right]^{1/2}$

Definimos: $j_e = -eJ_e$; $j_h = eJ_h$ ($J_{e,h}$: Densidades de corriente numéricas)

(1) $J_e^{rec} \propto e^{-\frac{e\Delta\phi}{k_BT}}$ (2) $J_e^{gen} \propto e^{-\frac{E_g}{k_BT}}$ (3) $J_h^{rec} \propto e^{-\frac{e\Delta\phi}{k_BT}}$ (4) $J_h^{gen} \propto e^{-\frac{E_g}{k_BT}}$

Insensibles a V

Si $V = 0$, corrientes netas de electrones y huecos deben anularse.

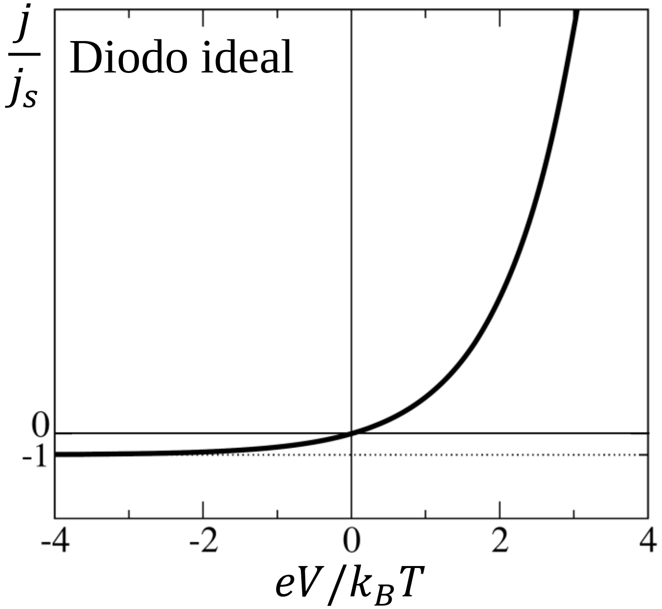
$\rightarrow J_{e,h}^{rec}(V=0) = J_{e,h}^{gen}$

$\rightarrow J_{e,h}^{rec} = J_{e,h}^{rec}(0)e^{\frac{eV}{k_BT}} = J_{e,h}^{gen}e^{\frac{eV}{k_BT}}$

$j = e\left(J_e^{rec} - J_e^{gen} + J_h^{rec} - J_h^{gen}\right)$

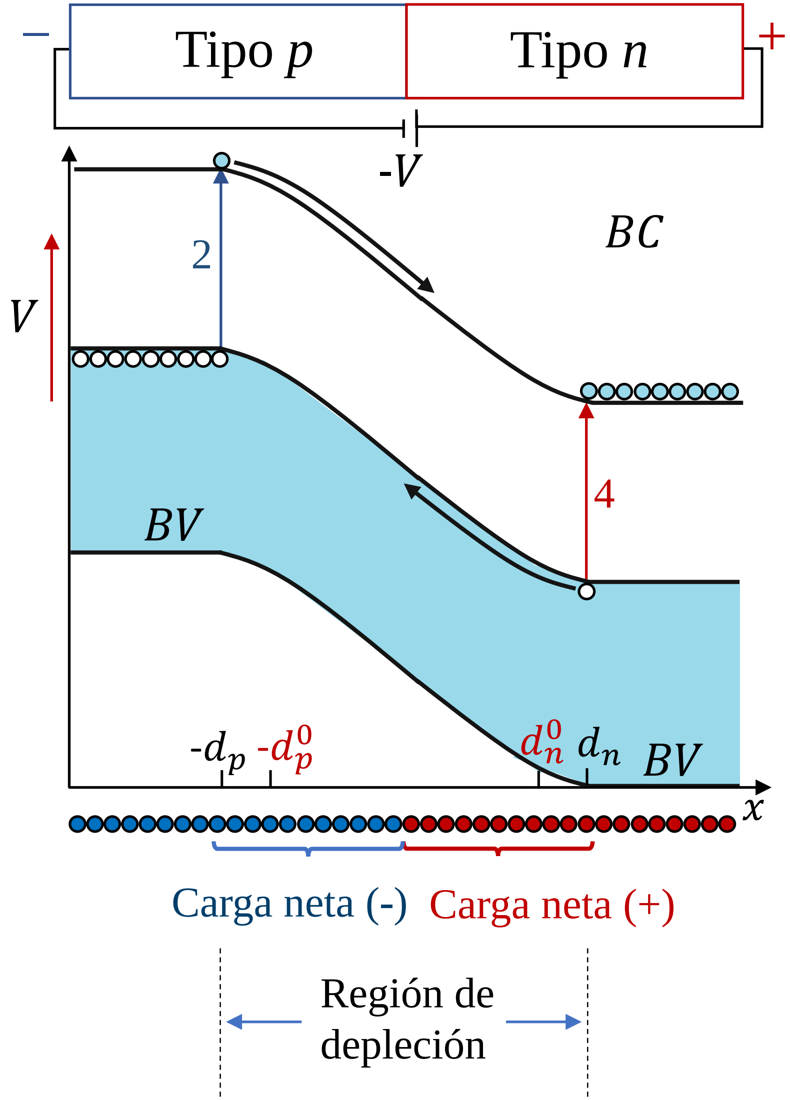
$= \boxed{e\left(J_e^{gen} + J_h^{gen}\right)\left(e^{eV/k_BT} - 1\right)}$

$j_s \propto e^{-E_g/k_BT}$ (Corriente de saturación)



Juntura semiconductora *p-n*

Juntura semiconductora *p-n*: Polarización inversa



$V \neq 0 \rightarrow \Delta\phi = (\Delta\phi)_0 - V \rightarrow d_{n,p}(V) = d_{n,p}(0)\left[1 - \frac{V}{(\Delta\phi)_0}\right]^{1/2}$

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Insensibles a V

Si $V = 0$, corrientes netas de electrones y huecos deben anularse.

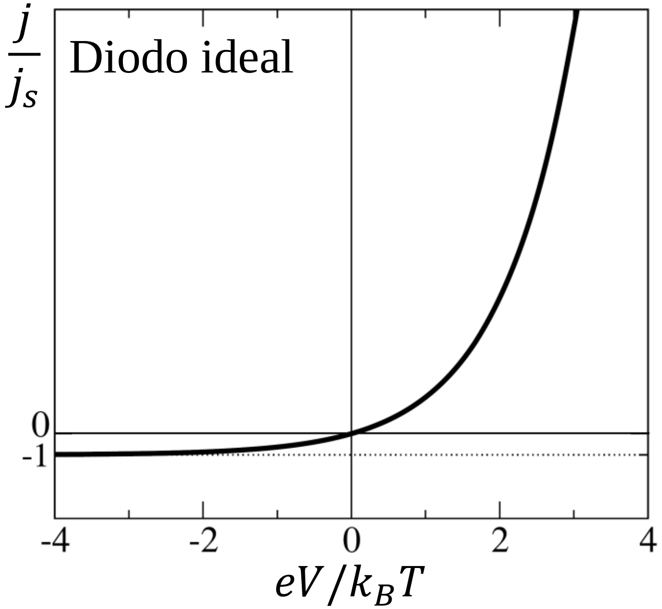
$\rightarrow J_{e,h}^{rec}(V=0) = J_{e,h}^{gen}$

$\rightarrow J_{e,h}^{rec} = J_{e,h}^{rec}(0)e^{\frac{eV}{k_BT}} = J_{e,h}^{gen}e^{\frac{eV}{k_BT}}$

$$j = e\left(J_e^{rec} - J_e^{gen} + J_h^{rec} - J_h^{gen}\right)$$

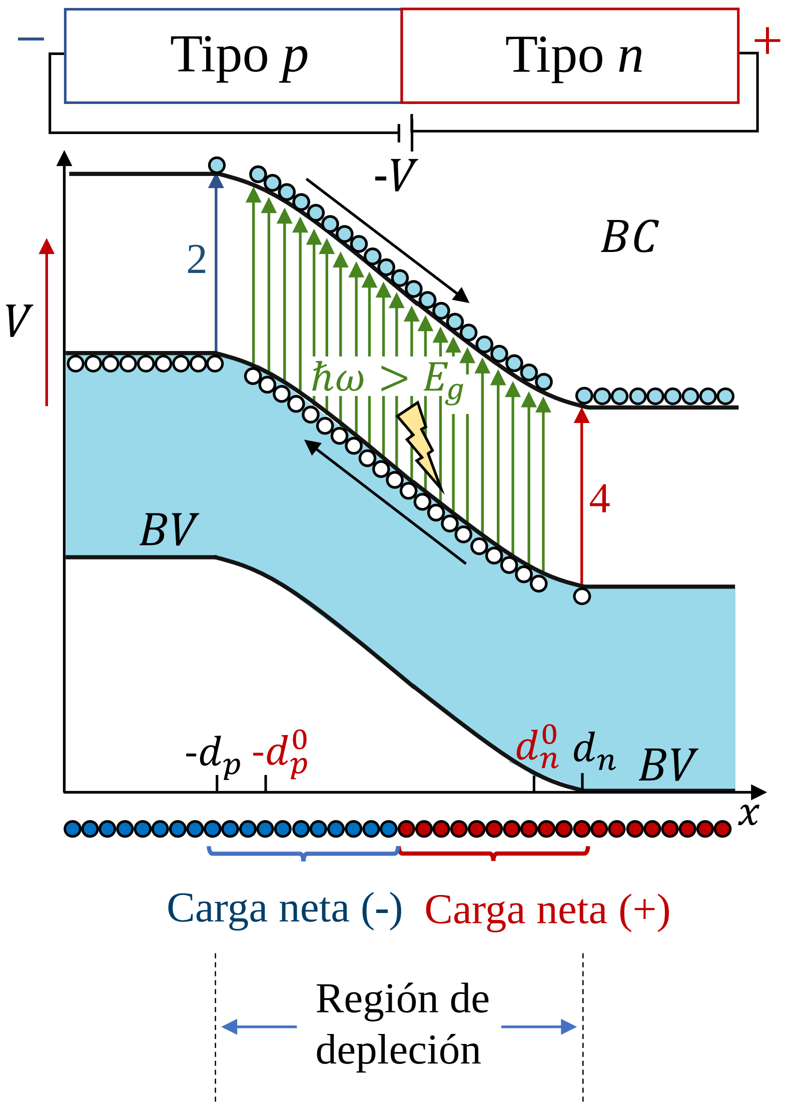
$$= \boxed{e\left(J_e^{gen} + J_h^{gen}\right)\left(e^{eV/k_BT} - 1\right)}$$

$j_s \propto e^{-E_g/k_BT}$ (Corriente de saturación)



Juntura semiconductora *p-n*

Juntura semiconductora *p-n*: Polarización inversa



$V \neq 0 \rightarrow \Delta\phi = (\Delta\phi)_0 - V \rightarrow d_{n,p}(V) = d_{n,p}(0)\left[1 - \frac{V}{(\Delta\phi)_0}\right]^{1/2}$

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Insensibles a *V*

Si $V = 0$, corrientes netas de electrones y huecos deben anularse.

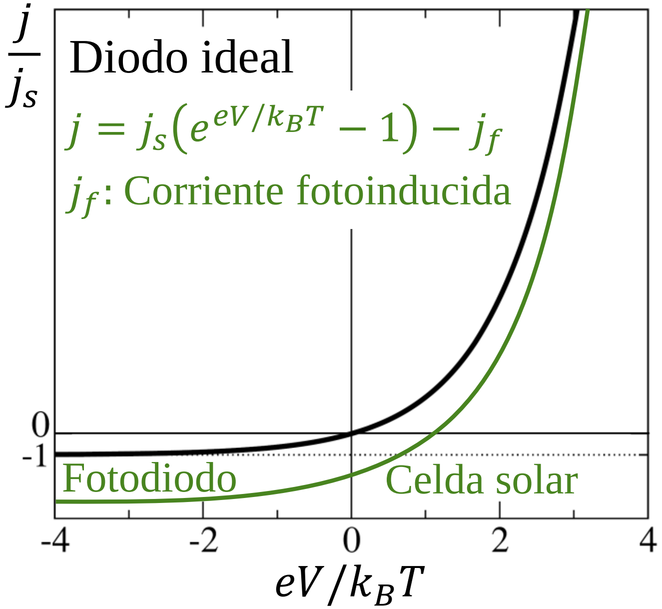
$\rightarrow J_{e,h}^{rec}(V = 0) = J_{e,h}^{gen}$

$\rightarrow J_{e,h}^{rec} = J_{e,h}^{rec}(0)e^{\frac{eV}{k_B T}} = J_{e,h}^{gen}e^{\frac{eV}{k_B T}}$

$$j = e\left(J_e^{rec} - J_e^{gen} + J_h^{rec} - J_h^{gen}\right)$$

$$= e\left(J_e^{gen} + J_h^{gen}\right)\left(e^{eV/k_B T} - 1\right)$$

$j_s \propto e^{-E_g/k_B T}$ (Corriente de saturación)



Resumen

- Región de depleción en la juntura *p*-*n*
- Respuesta ante un voltaje aplicado
- Caso de polarización directa
- Caso de polarización inversa
- Aplicaciones de junturas *p*-*n*