

SEMICONDUCTOR DEVICES

p-n Junctions: Part 2



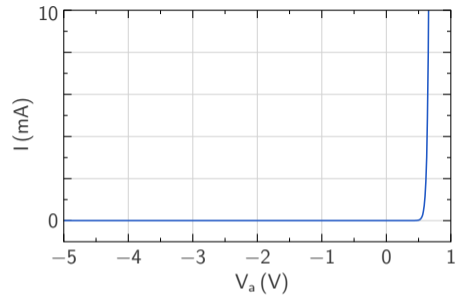
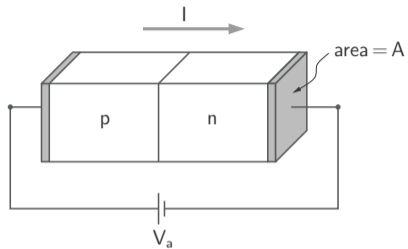
M. B. Patil

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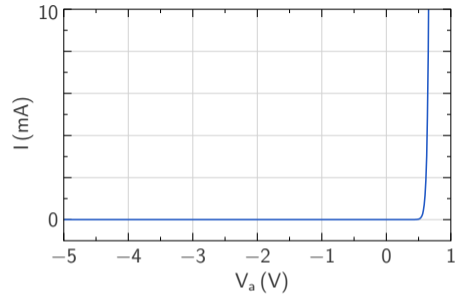
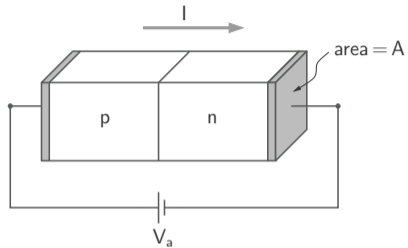
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Department of Electrical Engineering
Indian Institute of Technology Bombay

pn junction under bias

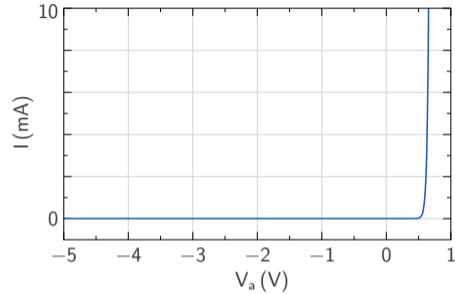
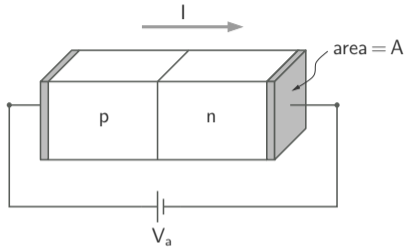


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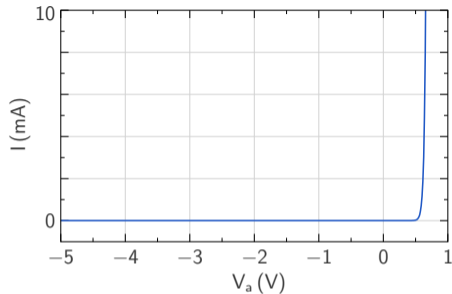
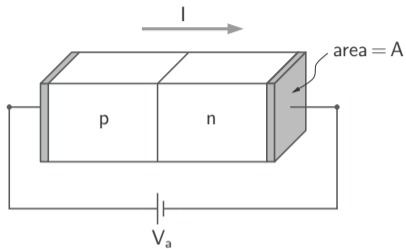
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pn junction under bias



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- * When a reverse bias (i.e., $V_a < 0$, V) is applied, the diode blocks conduction, i.e., the current is negligibly small.

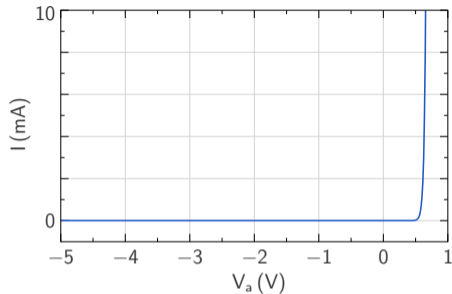
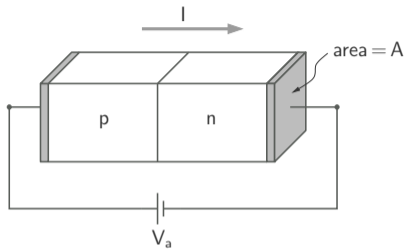
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pn junction under bias



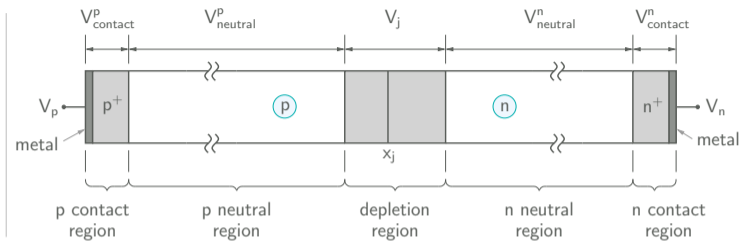
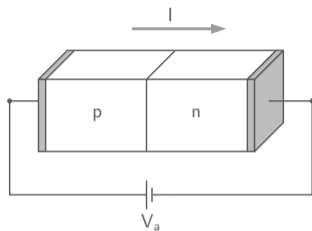
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We want to understand this “rectifying” behaviour.

- * As we increase the forward bias, the current increases rapidly, and at some point, the device will get damaged because of overheating. For silicon diodes used in low-power applications, the forward voltage must be restricted to about 0.8 V.

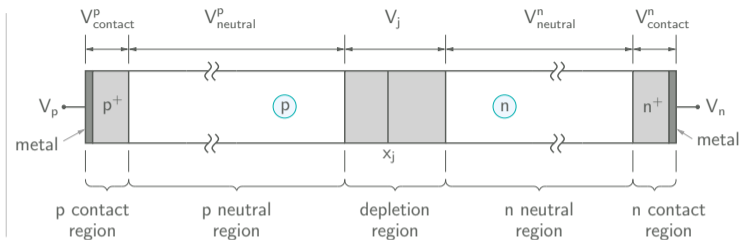
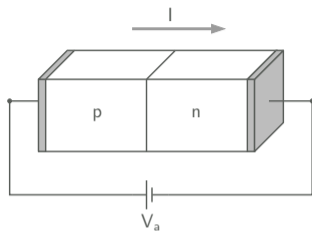
(Note: Although we will show an applied forward/reverse bias with a battery, in practice, a diode is generally not directly connected to a battery.)

Where does the voltage drop?



Consider a *pn* junction in equilibrium ($V_a = 0$ V).

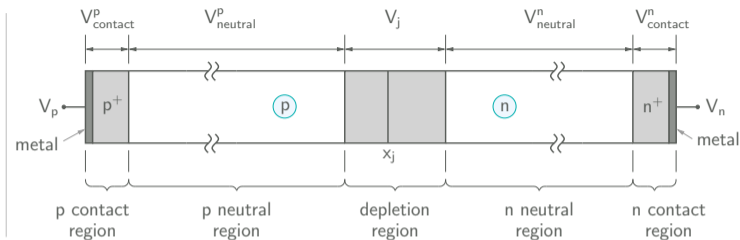
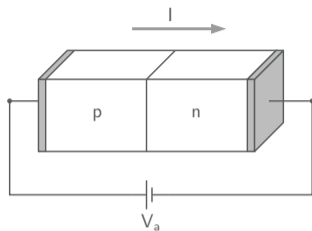
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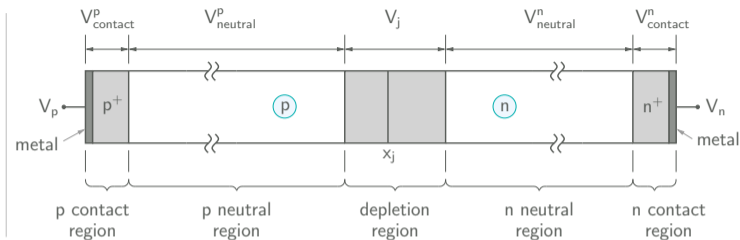
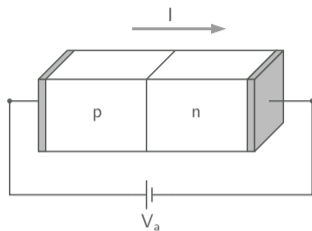
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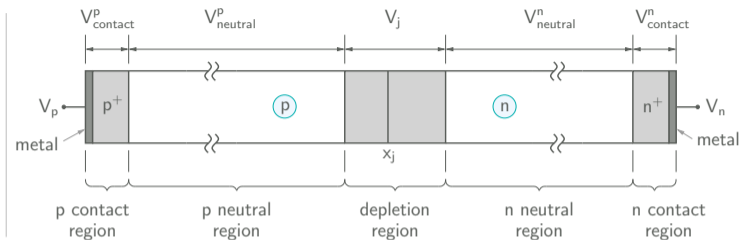
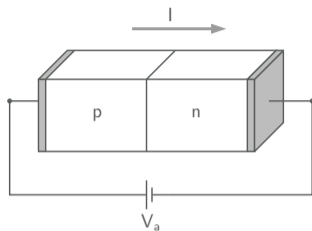
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- * V_{neutral}^p and V_{neutral}^n are the voltage drops across the neutral p and n regions. In equilibrium, they are both zero.

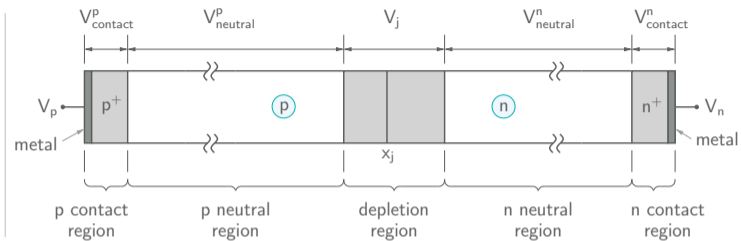
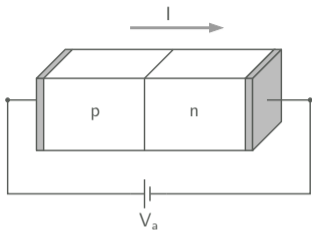
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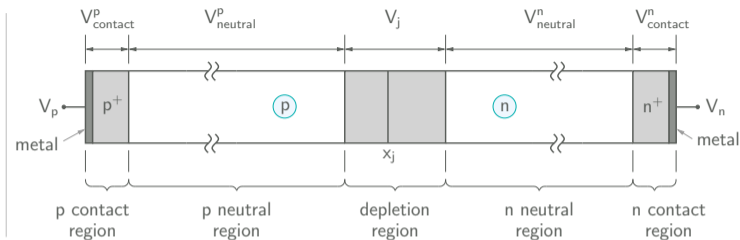
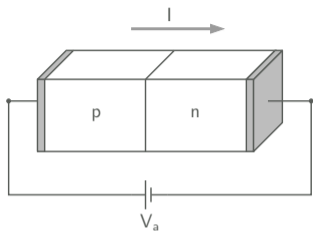
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- * V_{neutral}^p and V_{neutral}^n are the voltage drops across the neutral p and n regions. In equilibrium, they are both zero.
- * Even with current flow, V_{neutral}^p and V_{neutral}^n remain negligibly small since a very small electric field is sufficient to create the required $J_p^{\text{drift}} = q\mu_p p \mathcal{E}$ or $J_n^{\text{drift}} = q\mu_n n \mathcal{E}$ (note that p and n in these equations represent the *majority* carrier densities).

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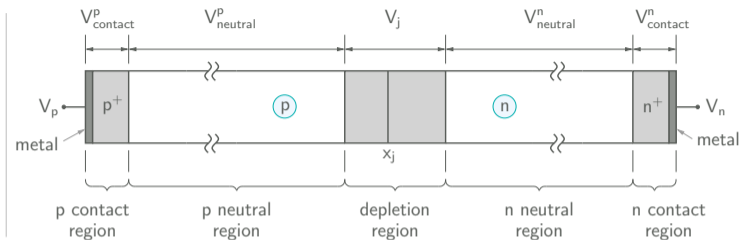
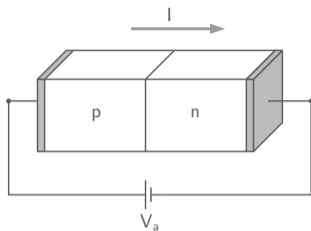


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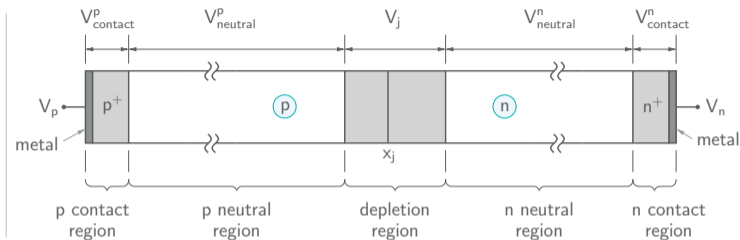
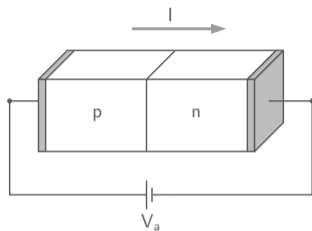
- * V_j is the voltage across the junction and is equal to V_{bi} in equilibrium. We have shown, using Poisson's equation, that $V_j \propto W^2$ where W is the depletion width.

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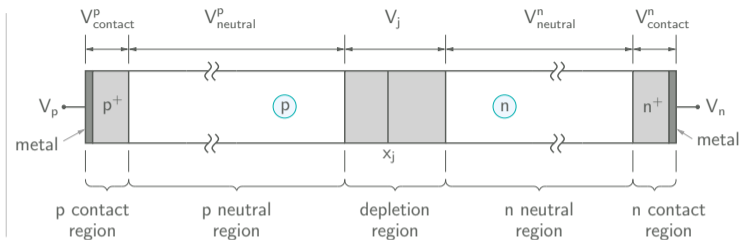
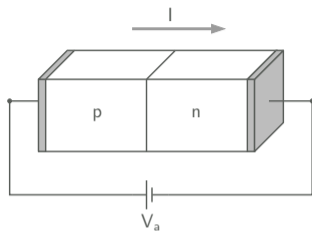
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- * In equilibrium, $V_p = V_n$, and we get
(1): $V_{\text{contact}}^p - V_{bi} + V_{\text{contact}}^n = 0$, taking voltage drop as positive.
(We assume that the signs of V_{contact}^p and V_{contact}^n are taken into account.)

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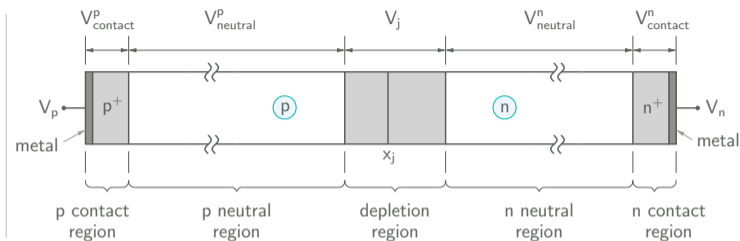
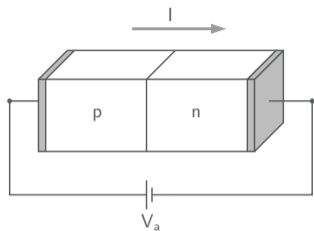
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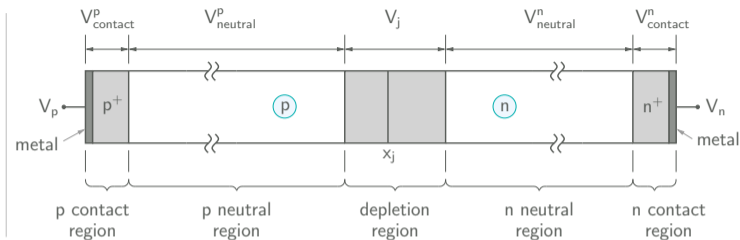
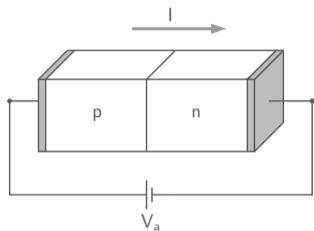
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- * (1) - (2) gives $-V_{bi} + V_j = -V_a$, i.e., $V_j = V_{bi} - V_a$

Example: forward bias



For an abrupt silicon pn junction, the built-in voltage is $V_{bi} = 0.85 \text{ V}$. Let W_0 and W_1 denote the depletion widths for $V_a = 0 \text{ V}$ and $V_a = 0.6 \text{ V}$, respectively. What is W_1/W_0 ?

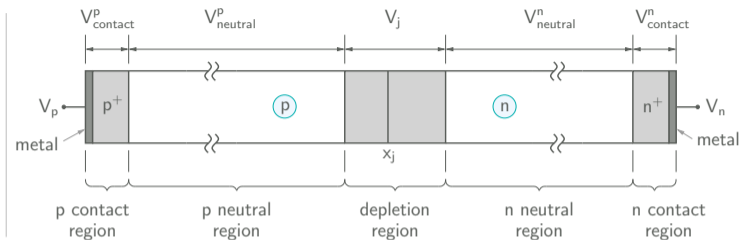
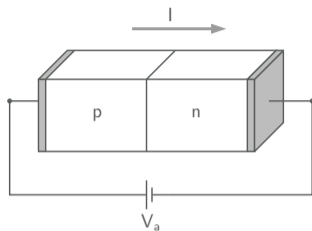
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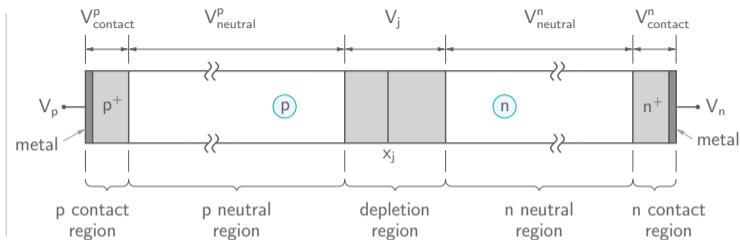
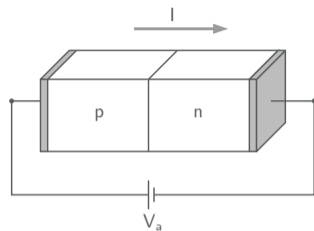


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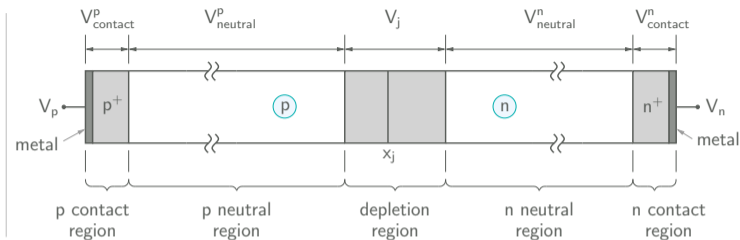
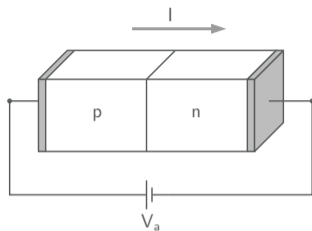
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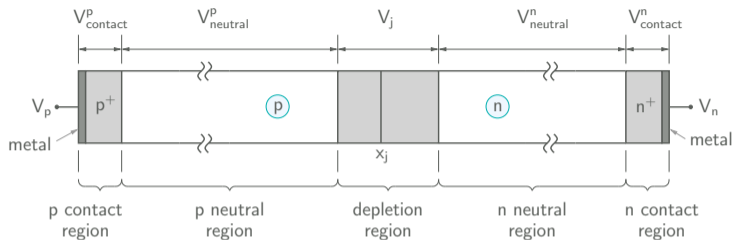
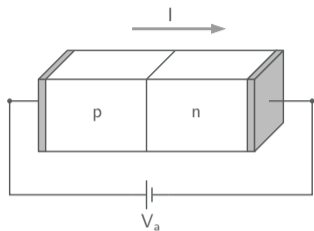
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$$V_{bi} - 0.6 \text{ V} = kW_1^2 \quad (\text{for } V_a = 0.6 \text{ V})$$

$$\rightarrow \frac{0.85 - 0.6}{0.85} = \left(\frac{W_1}{W_0}\right)^2 \rightarrow \frac{W_1}{W_0} = 0.54.$$

Example: forward bias



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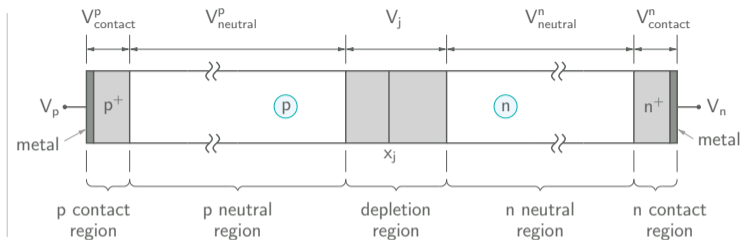
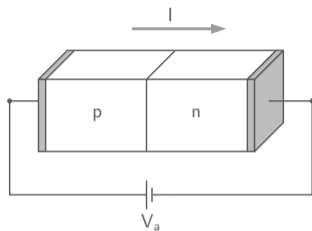
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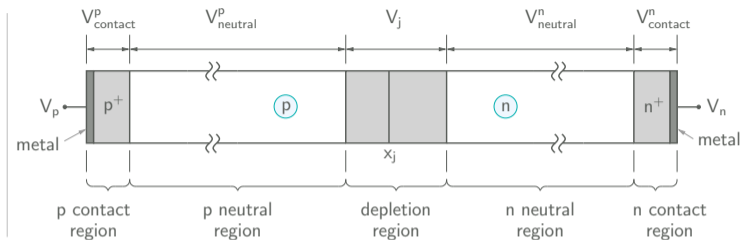
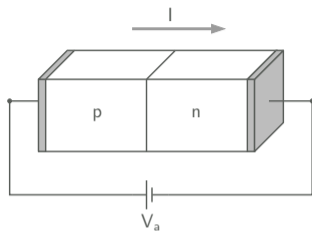
Application of a forward bias of 0.6 V causes the depletion region to shrink by a factor 0.54 .

Example: reverse bias



For an abrupt silicon pn junction, the built-in voltage is $V_{bi} = 0.85$ V. Let W_0 and W_1 denote the depletion widths for $V_a = 0$ V and $V_a = -2$ V (i.e., a reverse bias V_R of 2 V), respectively. What is W_1/W_0 ?

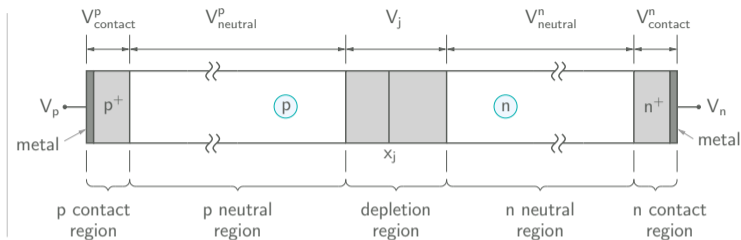
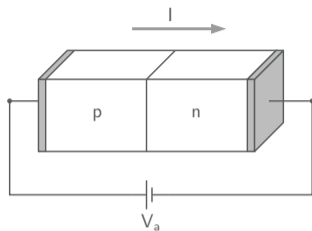
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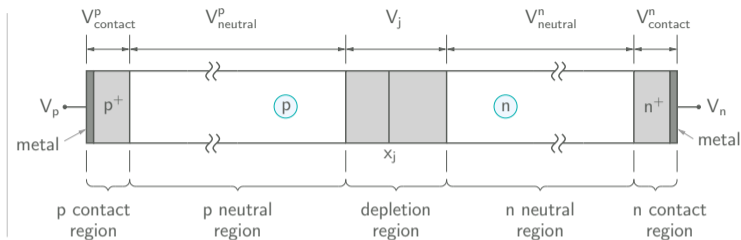
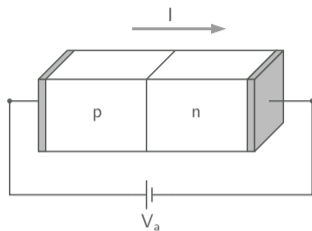


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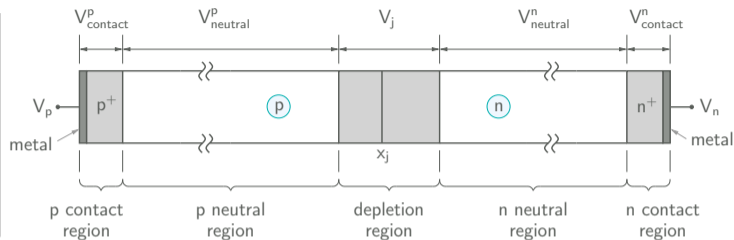
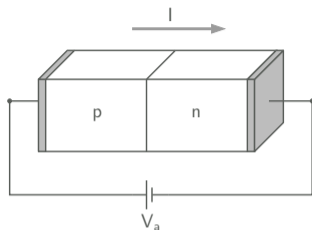
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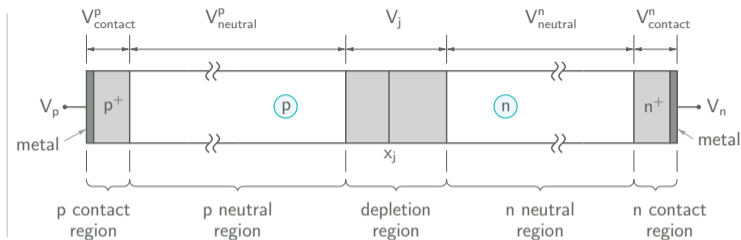
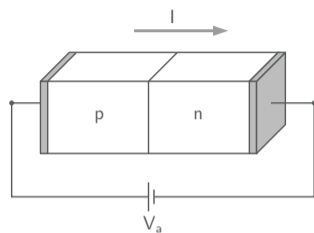
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$$\rightarrow \frac{0.85 + 2}{0.85} = \left(\frac{W_1}{W_0} \right)^2 \rightarrow \frac{W_1}{W_0} = 1.83.$$

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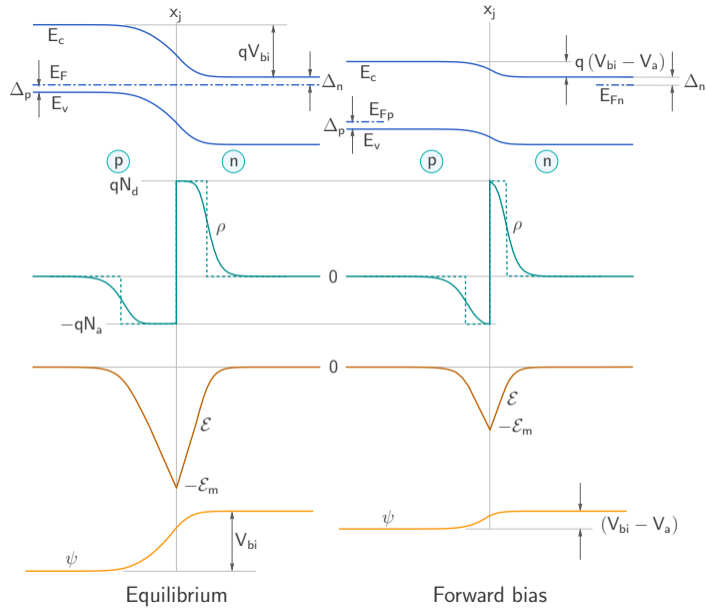
$$V_{bi} = kW_0^2 \quad (\text{for } V_a = 0 \text{ V})$$

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$$\rightarrow \frac{0.85 + 2}{0.85} = \left(\frac{W_1}{W_0} \right)^2 \rightarrow \frac{W_1}{W_0} = 1.83.$$

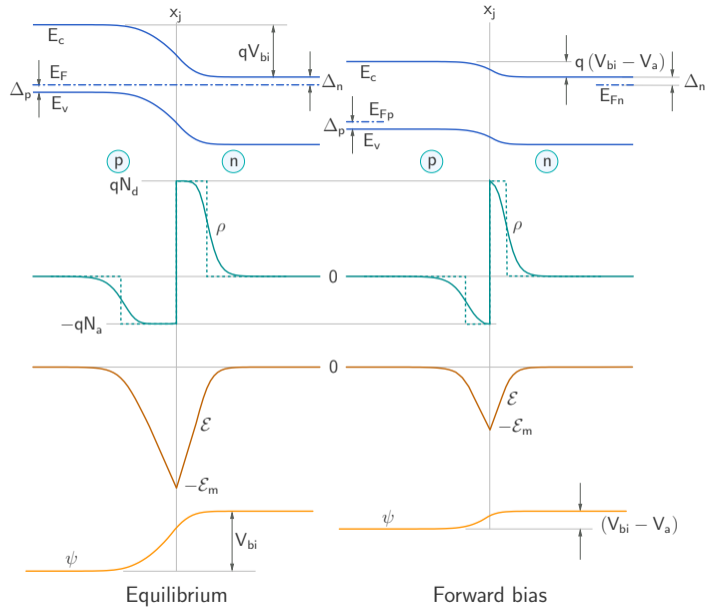
Application of a reverse bias of 2 V causes the depletion region to expand by a factor 1.83 .

Forward bias



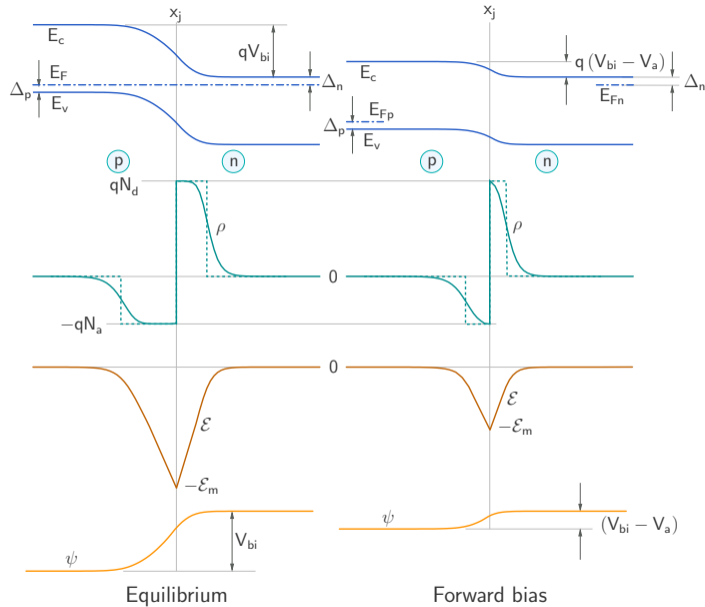
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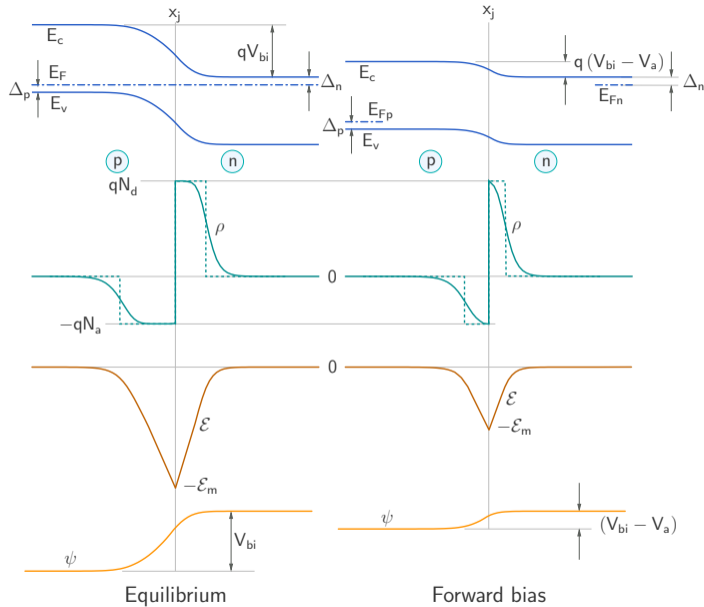


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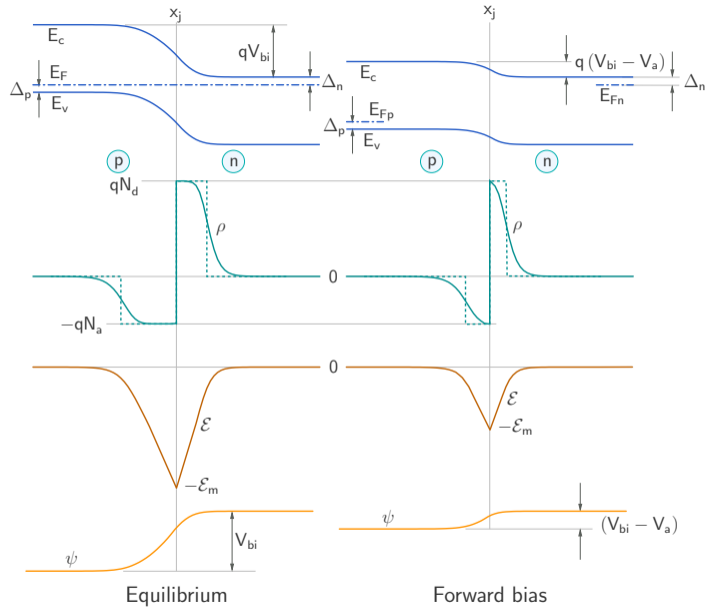
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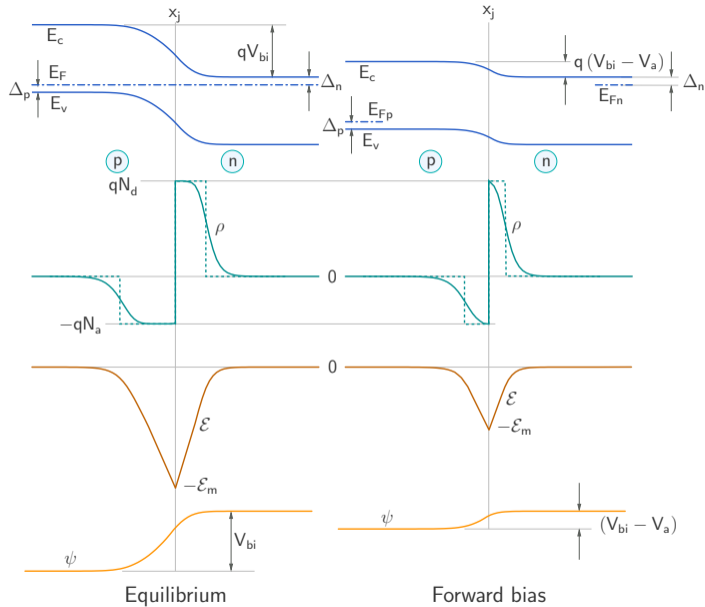


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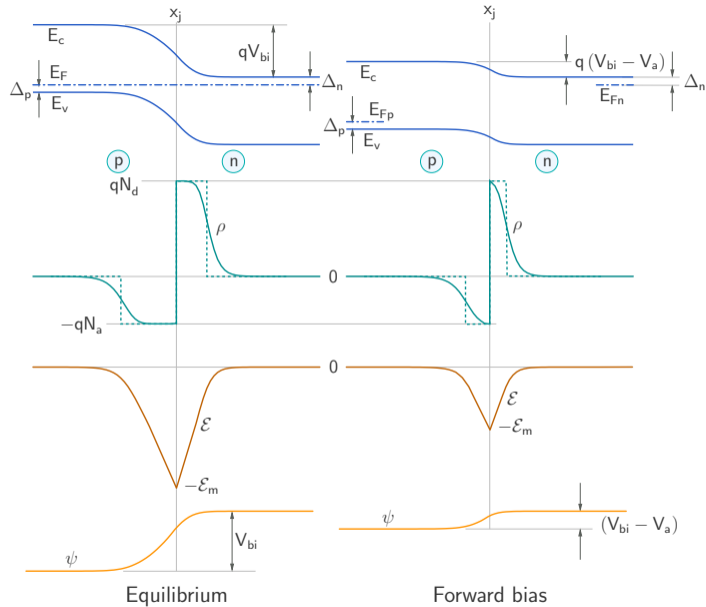
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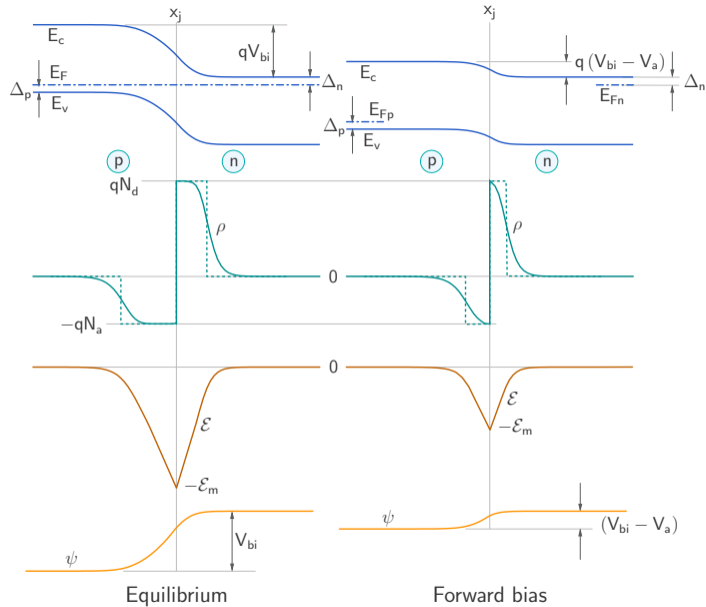
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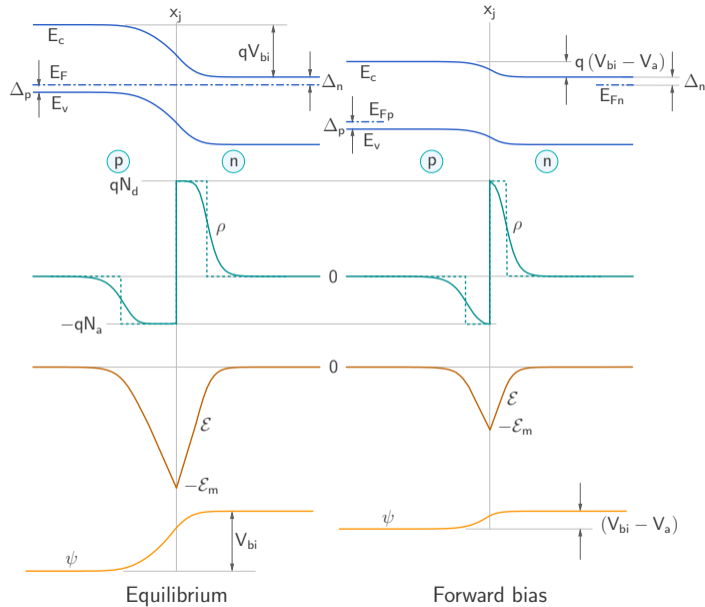
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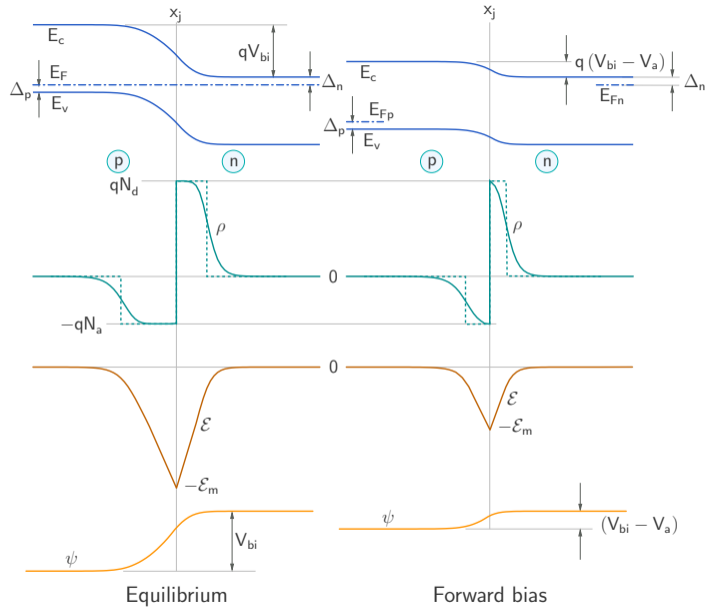
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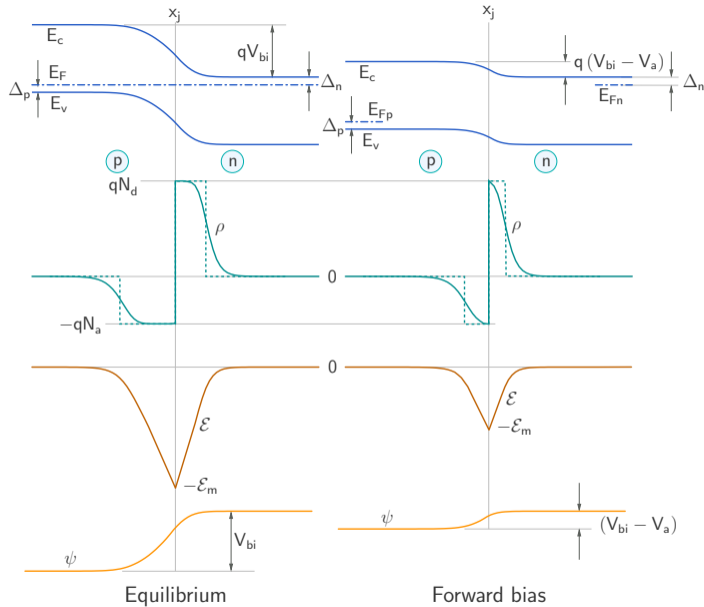
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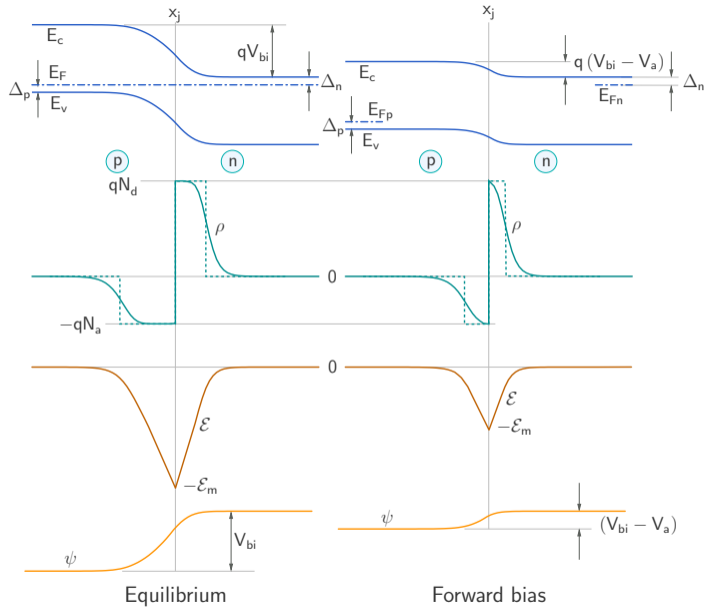
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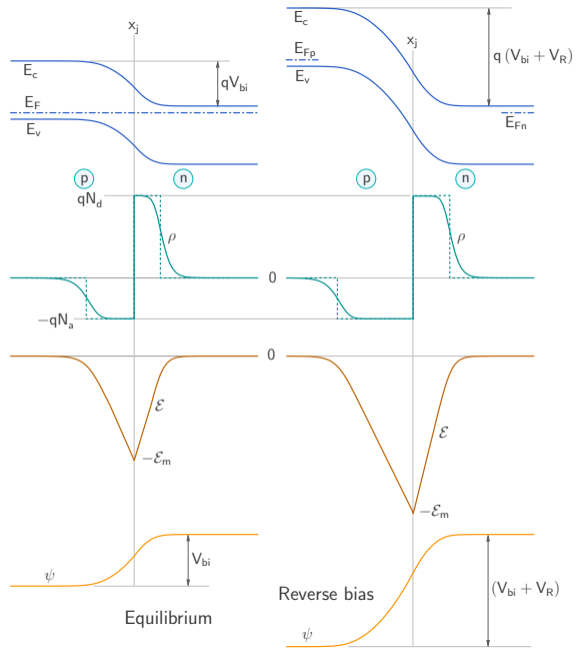
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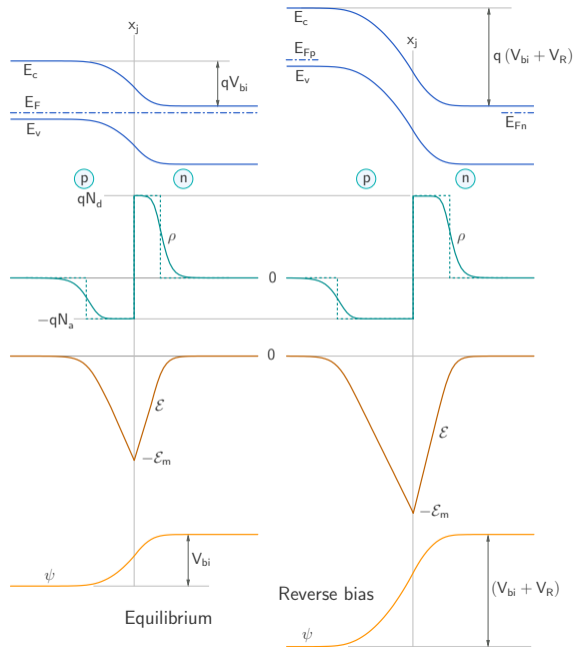


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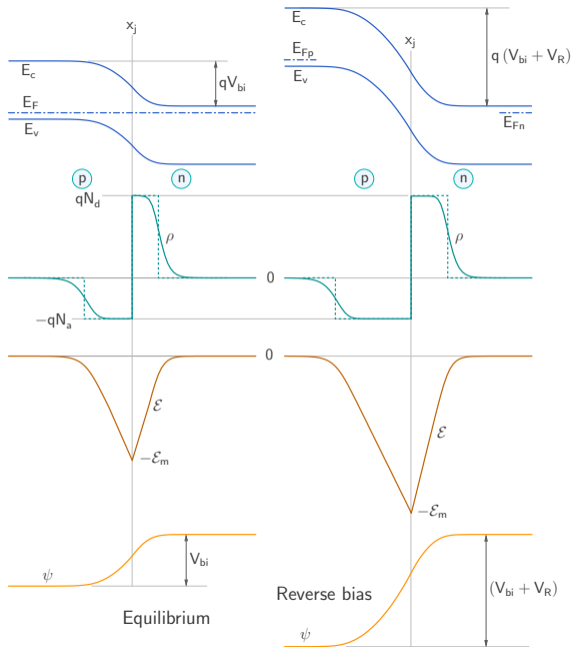
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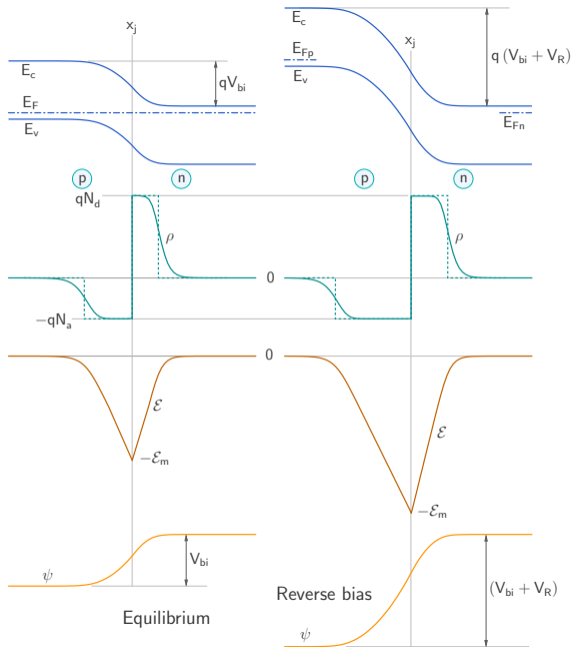


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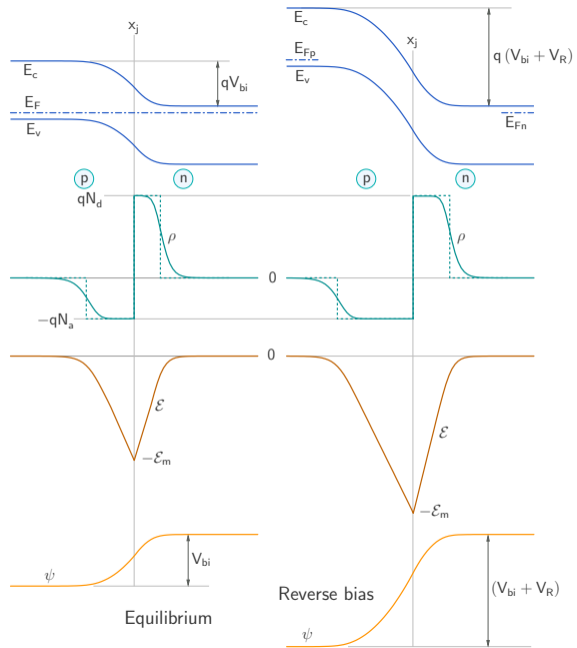
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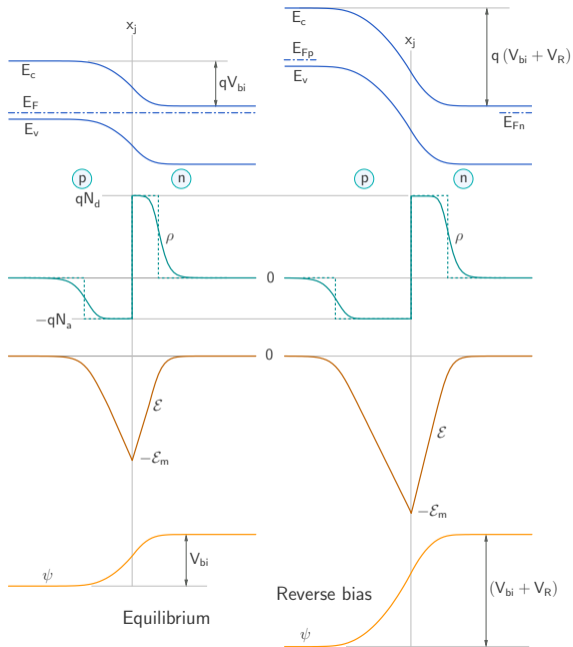


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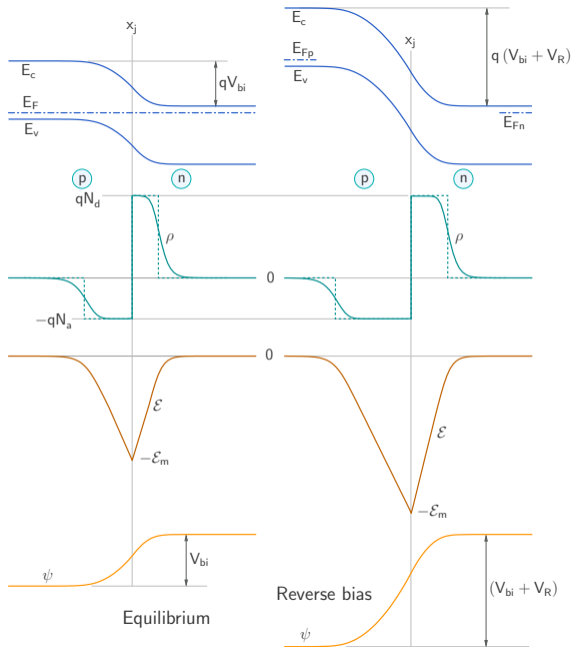
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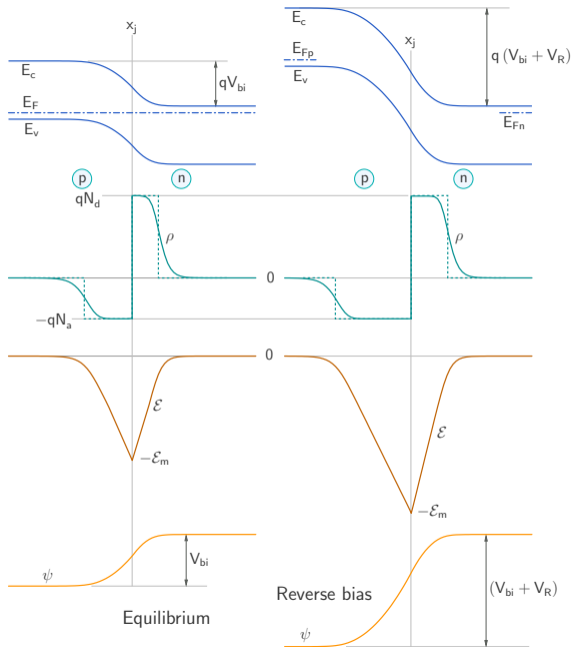
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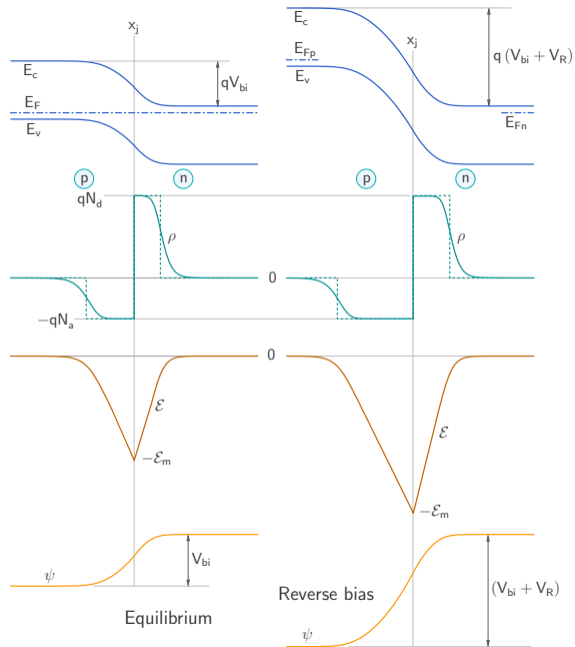
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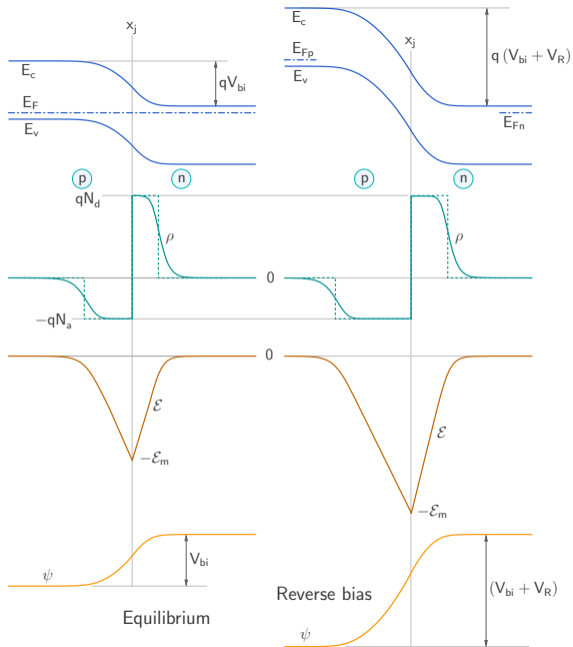
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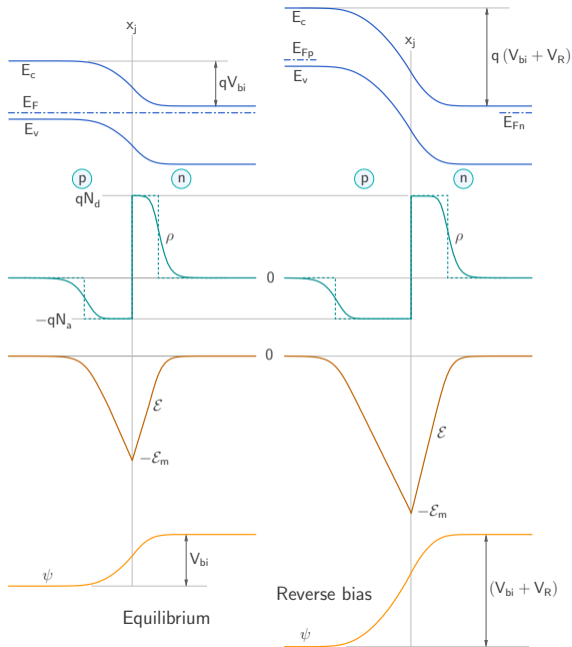
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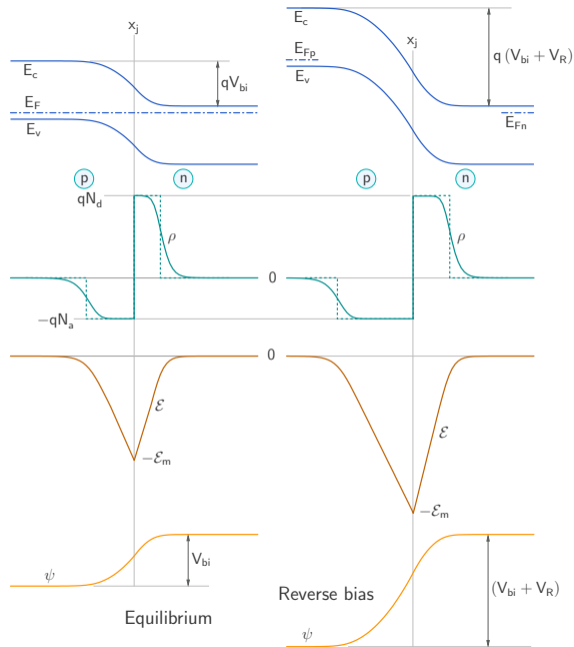
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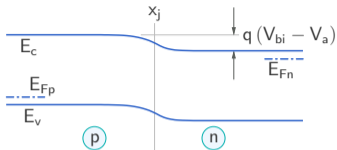
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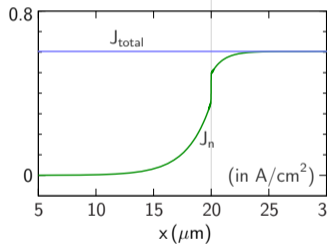
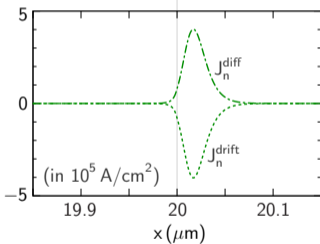
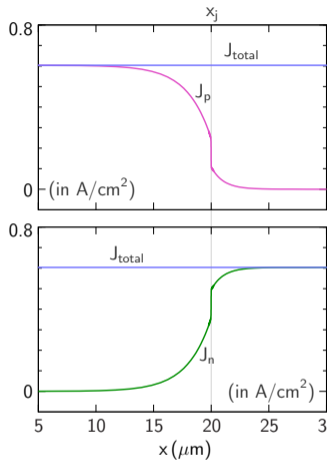
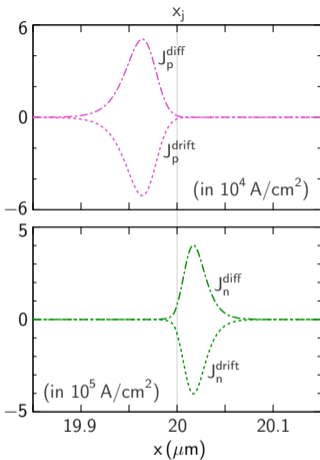
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Current densities in forward bias

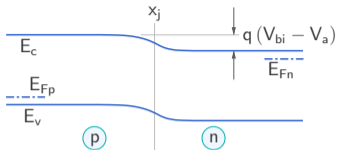


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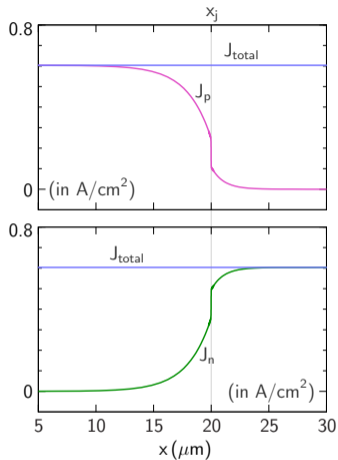
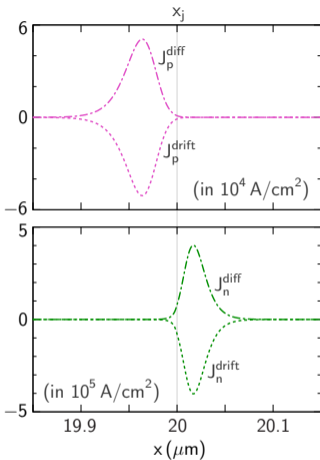


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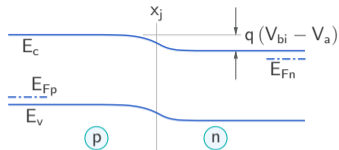
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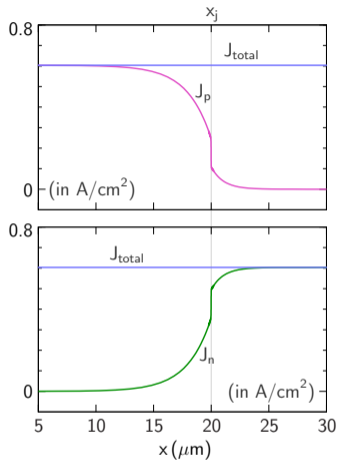
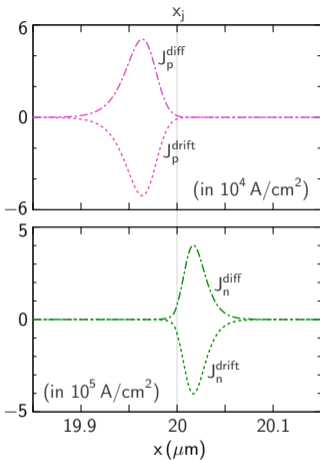
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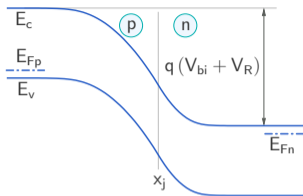
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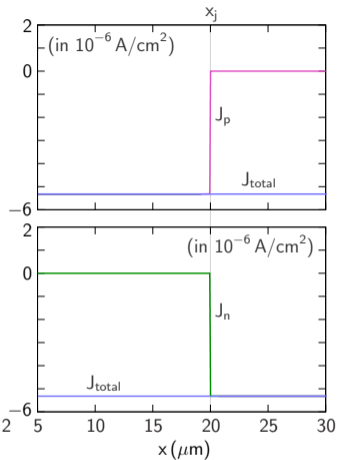
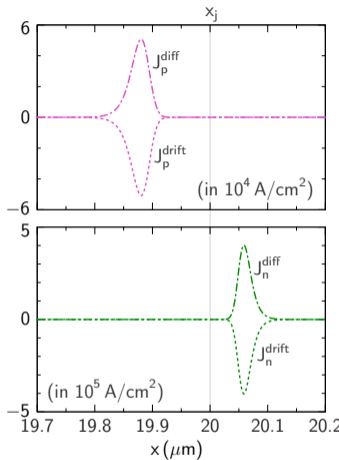
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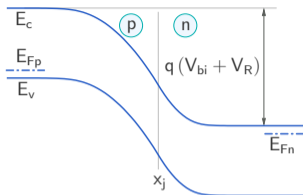


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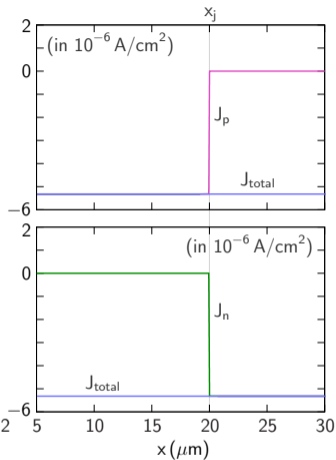
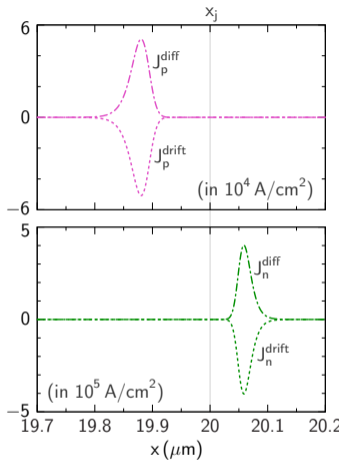
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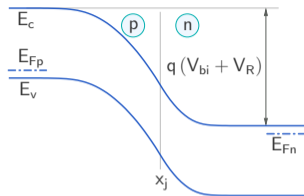
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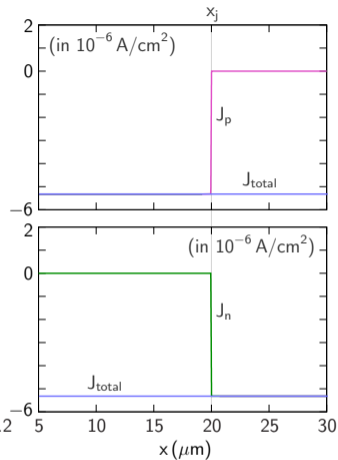
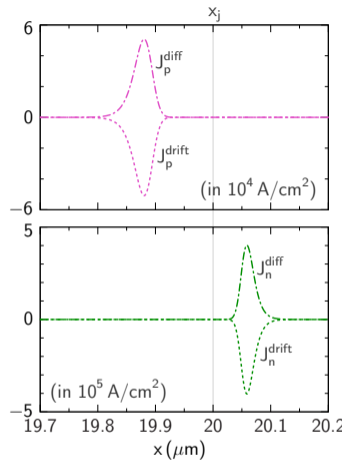
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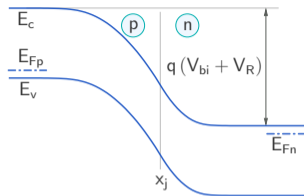
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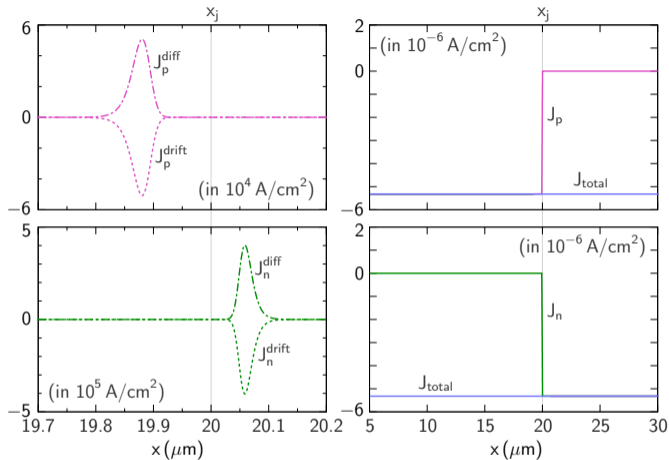
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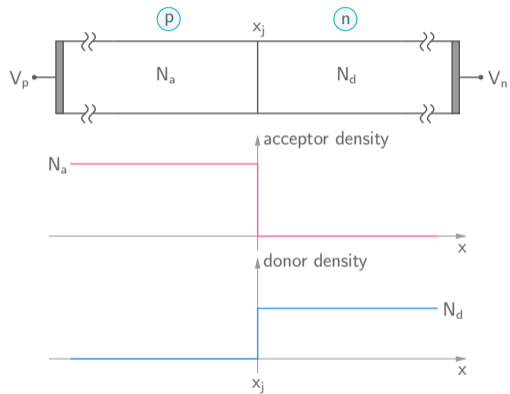
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- * Note that J_{total} in reverse bias is negligibly small compared to the forward bias case (0.7 A/cm^2 for $V_a = 0.6 \text{ V}$). For all practical purposes, we can say that the current is zero for reverse bias.

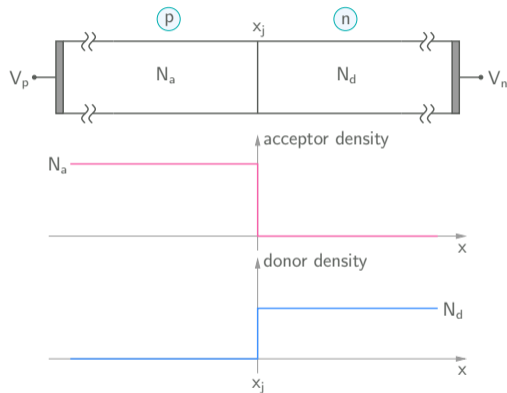
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pn junction: derivation of I - V equation

Definitions:

p_{p0} : equilibrium hole density in the neutral p -region

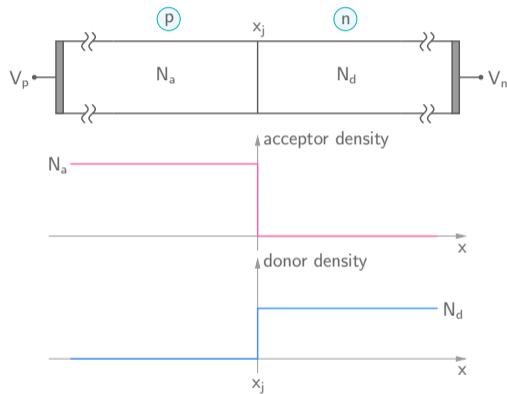


pn junction: derivation of I - V equation

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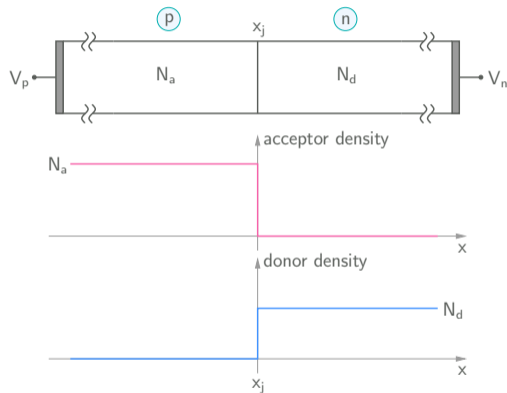
pn junction: derivation of I - V equation

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pn junction: derivation of I - V equation

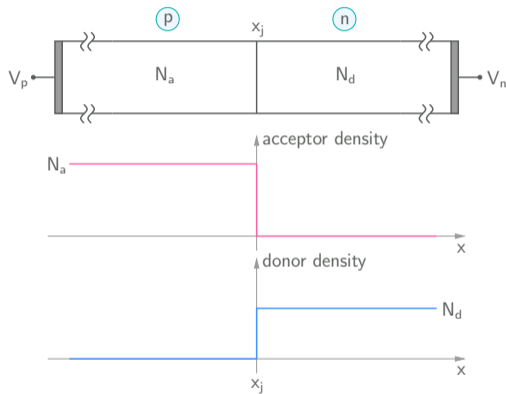
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pn junction: derivation of I - V equation

Definitions:

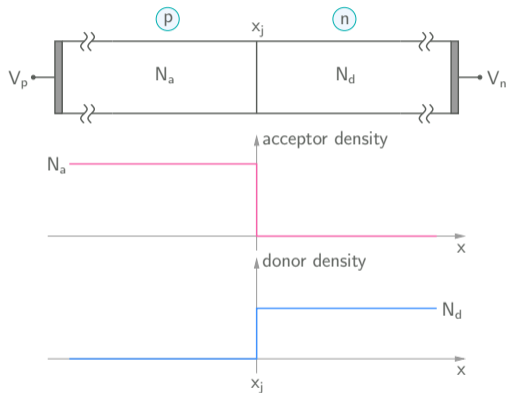
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pn junction: derivation of I - V equation

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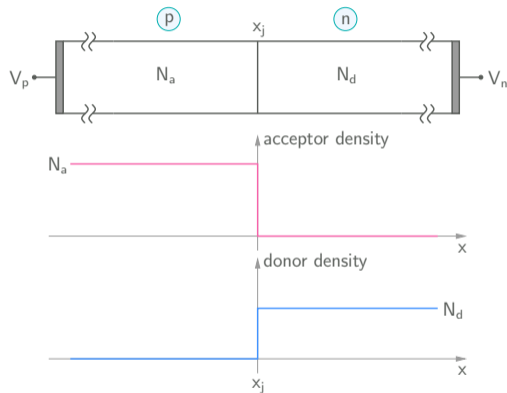
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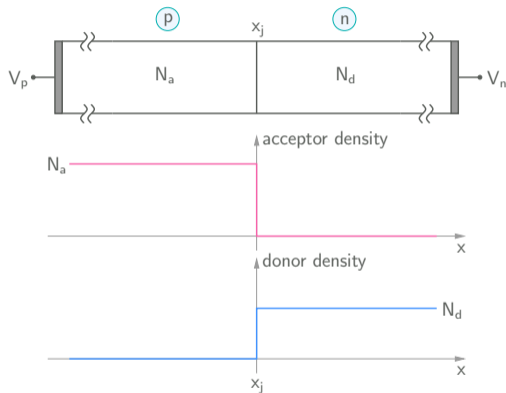
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Example: $N_a = 5 \times 10^{16} \text{ cm}^{-3}$, $N_d = 10^{18} \text{ cm}^{-3}$ ($T = 300 \text{ K}$).



pn junction: derivation of I - V equation

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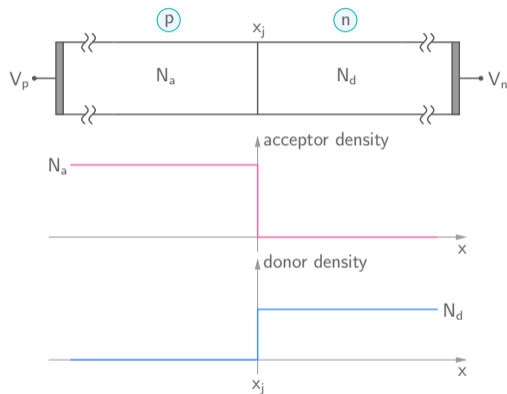
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pn junction: derivation of I - V equation

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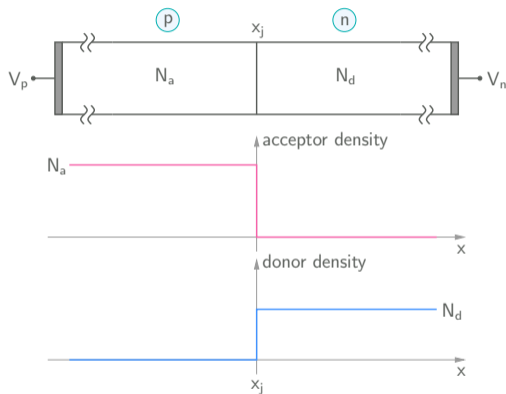
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pn junction: derivation of I - V equation

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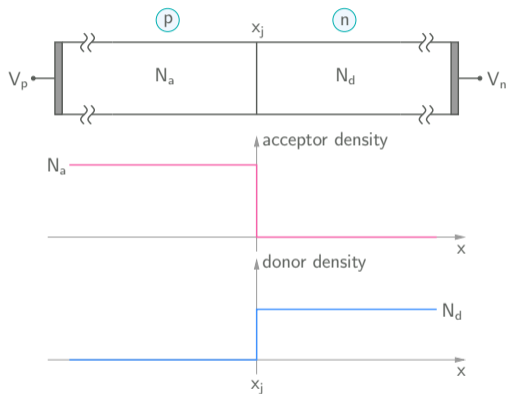
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$$n_{n0} \approx N_d = 10^{18} \text{ cm}^{-3},$$

$$n_{p0} = \frac{n_i^2}{p_{p0}} = \frac{(1.5 \times 10^{10})^2}{5 \times 10^{16}} = 4.5 \times 10^3 \text{ cm}^{-3},$$



pn junction: derivation of I - V equation

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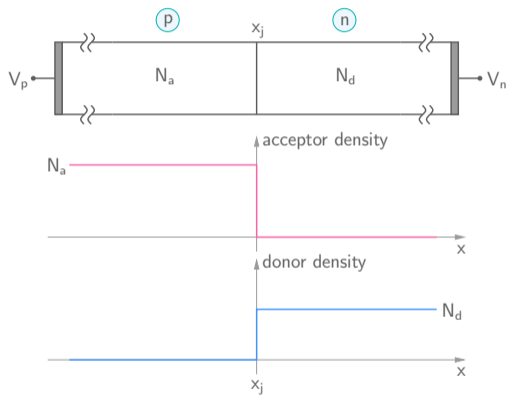
Example: $N_a = 5 \times 10^{16} \text{ cm}^{-3}$, $N_d = 10^{18} \text{ cm}^{-3}$ ($T = 300 \text{ K}$).

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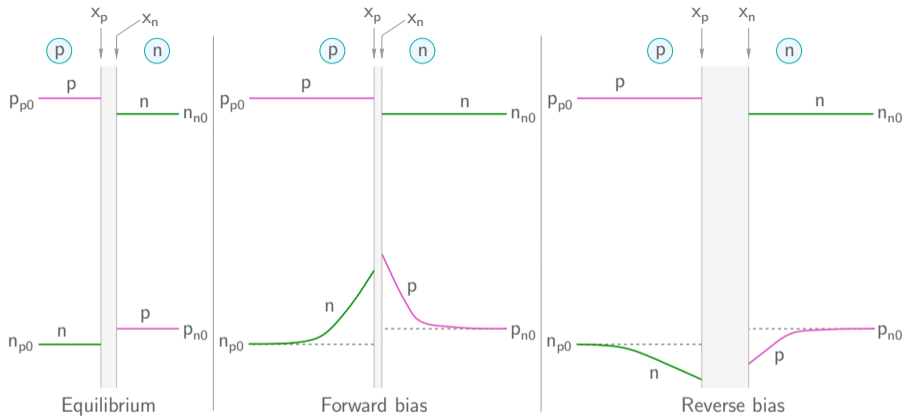
$$n_{n0} \approx N_d = 10^{18} \text{ cm}^{-3},$$

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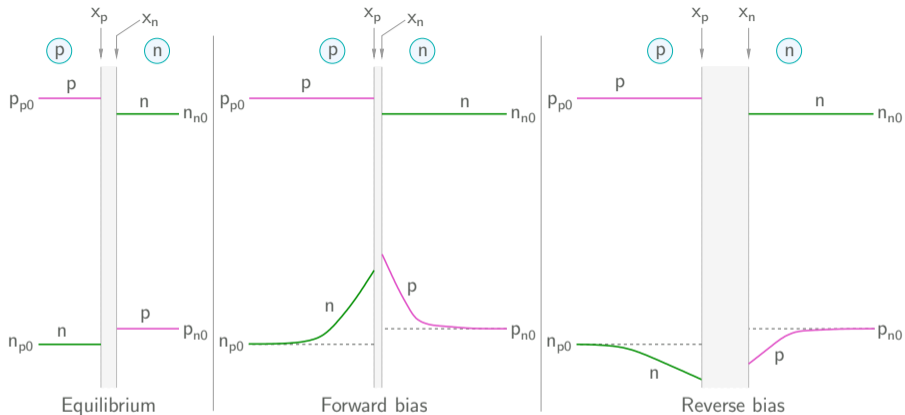
$$p_{n0} = \frac{n_i^2}{n_{n0}} = \frac{(1.5 \times 10^{10})^2}{10^{18}} = 2.25 \times 10^2 \text{ cm}^{-3}.$$



pn junction: derivation of I - V equation

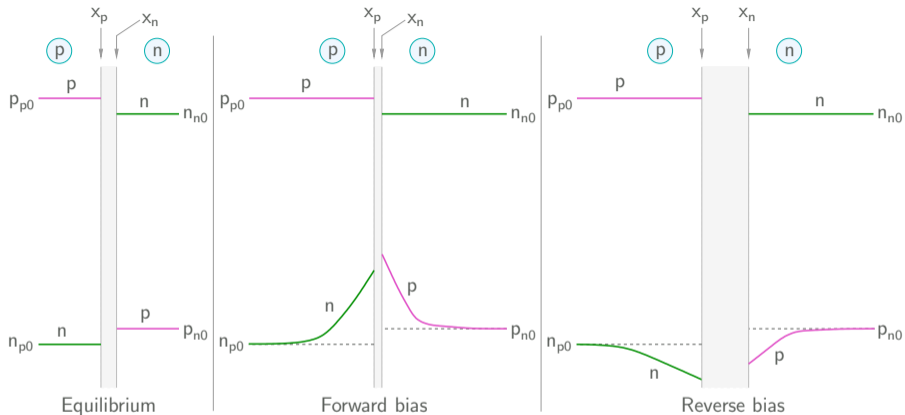


pn junction: derivation of I - V equation



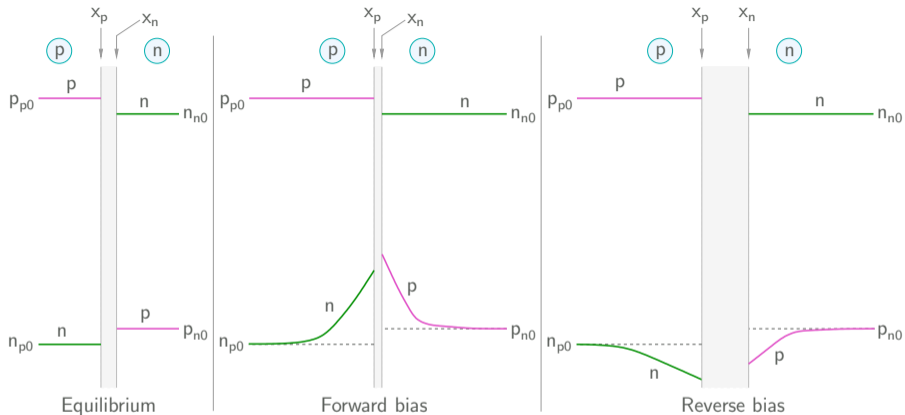
* Since $V_j = V_{bi} - V_a$ and $W \propto \sqrt{V_j}$, the depletion region is narrower under forward bias, wider under reverse bias.

pn junction: derivation of I - V equation



- * Since $V_j = V_{bi} - V_a$ and $W \propto \sqrt{V_j}$, the depletion region is narrower under forward bias, wider under reverse bias.
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pn junction: derivation of I - V equation



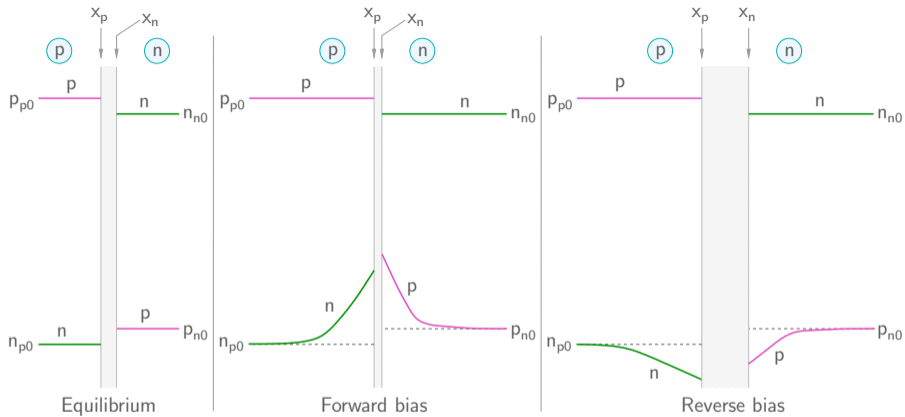
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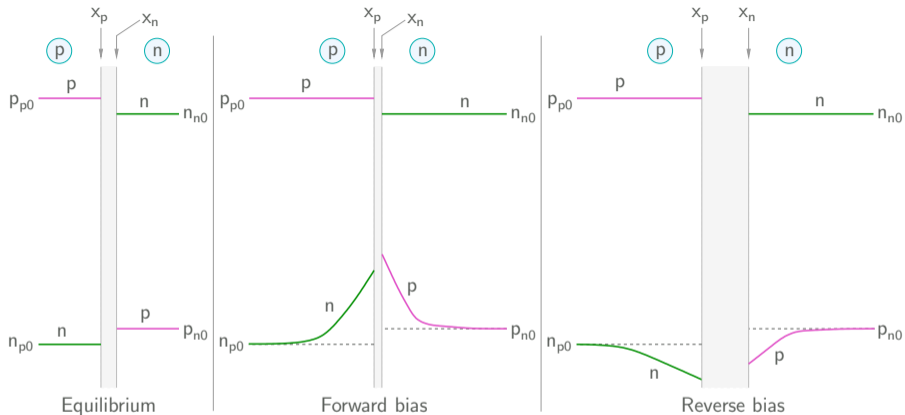
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pn junction: derivation of I - V equation



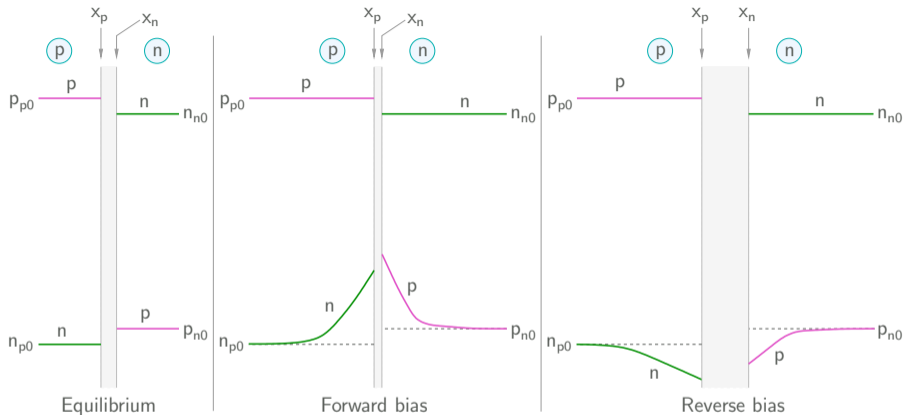
$$J_p^{\text{diff}} \approx -J_p^{\text{drift}}$$

pn junction: derivation of I-V equation



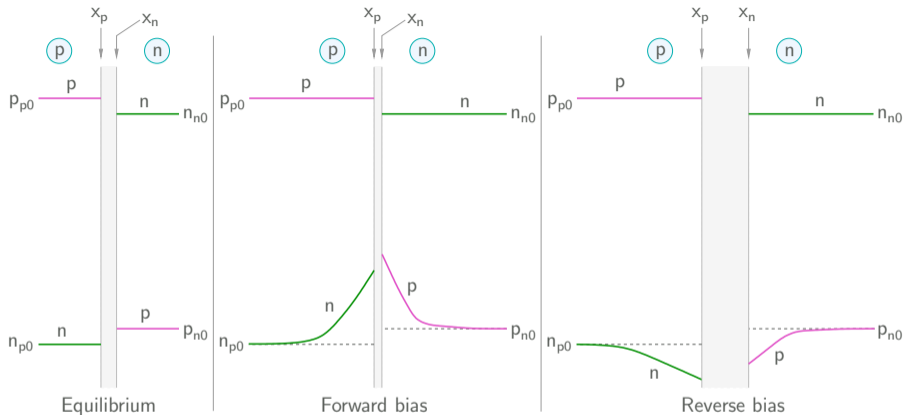
$$J_p^{\text{diff}} \approx -J_p^{\text{drift}} \rightarrow q \mu_p p \mathcal{E} = q D_p \frac{dp}{dx},$$

pn junction: derivation of I-V equation



$$J_p^{\text{diff}} \approx -J_p^{\text{drift}} \rightarrow q \mu_p p \mathcal{E} = q D_p \frac{dp}{dx}, \text{ i.e., } \mathcal{E} = -\frac{d\psi}{dx} = \frac{D_p}{\mu_p} \frac{1}{p} \frac{dp}{dx}.$$

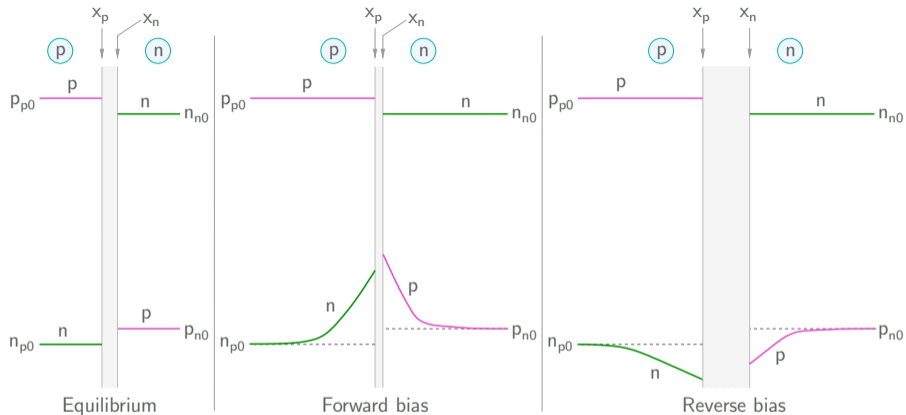
pn junction: derivation of I-V equation



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$$\frac{D}{\mu} = \frac{kT}{q} \rightarrow \int d\psi = -V_T \int \frac{1}{p} dp$$

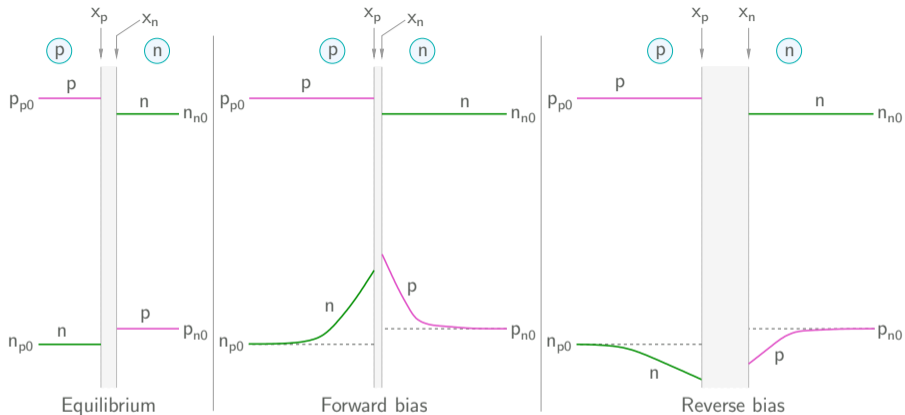
pn junction: derivation of I-V equation



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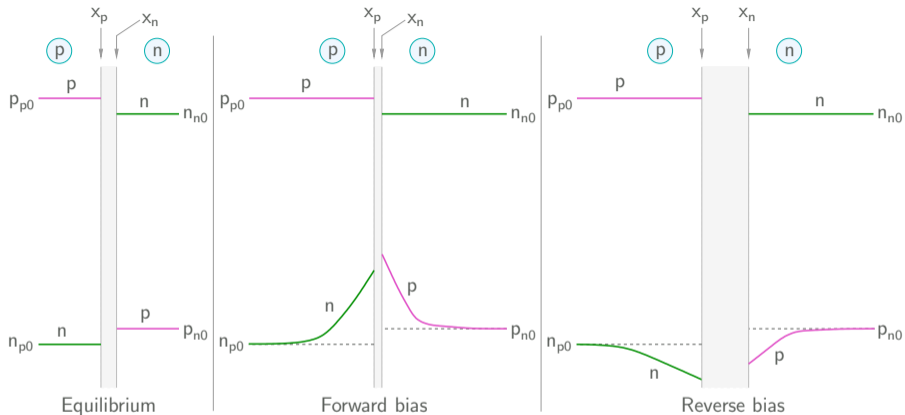
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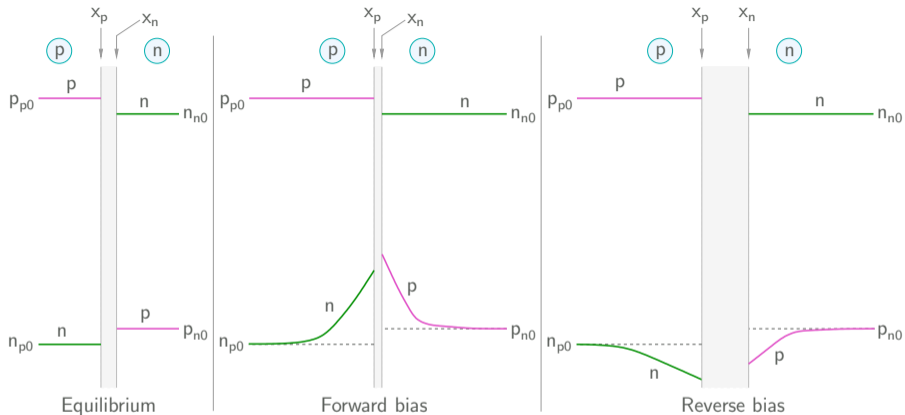
$$\frac{D}{\mu} = \frac{kT}{q} \rightarrow \int d\psi = -V_T \int \frac{1}{p} dp \rightarrow \psi \Big|_{x_1}^{x_2} = -V_T \log \frac{p(x_2)}{p(x_1)} \rightarrow \frac{p(x_n)}{p(x_p)} = \exp \left(\frac{\psi(x_p) - \psi(x_n)}{V_T} \right).$$

pn junction: derivation of I - V equation



$$J_p^{\text{diff}} \approx -J_p^{\text{drift}} \rightarrow \frac{p(x_n)}{p(x_p)} = \exp\left(\frac{\psi(x_p) - \psi(x_n)}{V_T}\right).$$

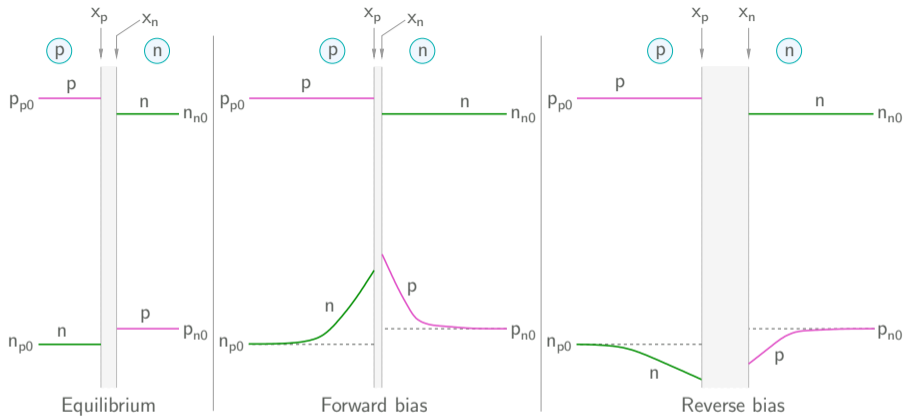
pn junction: derivation of I - V equation



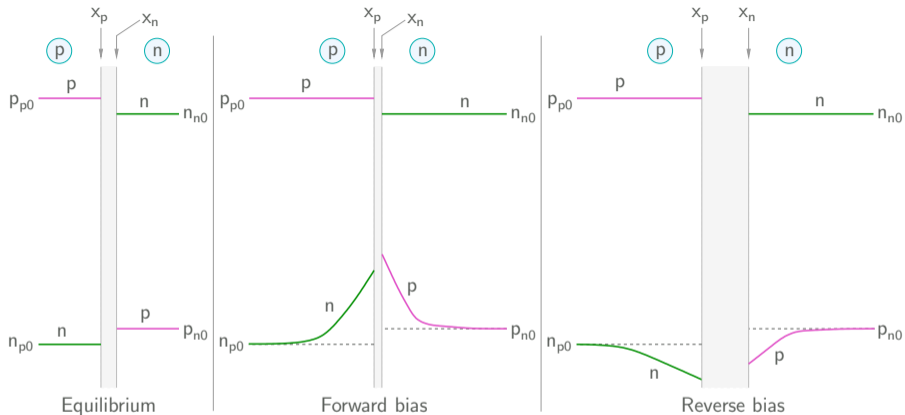
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pn junction: derivation of I - V equation

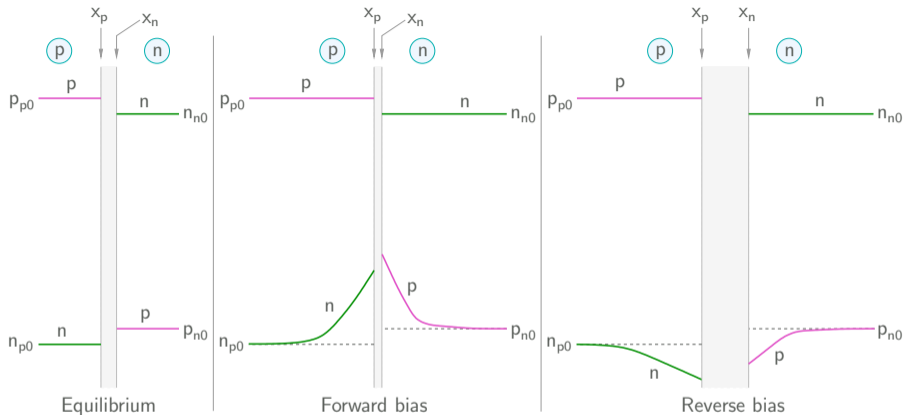


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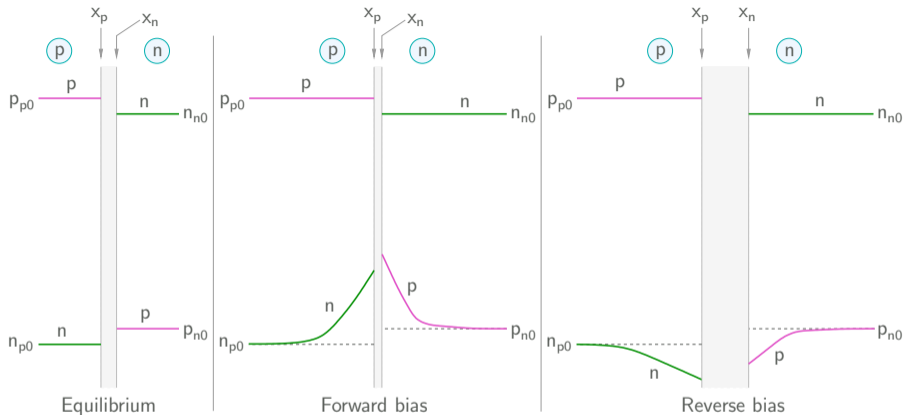
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pn junction: derivation of I - V equation

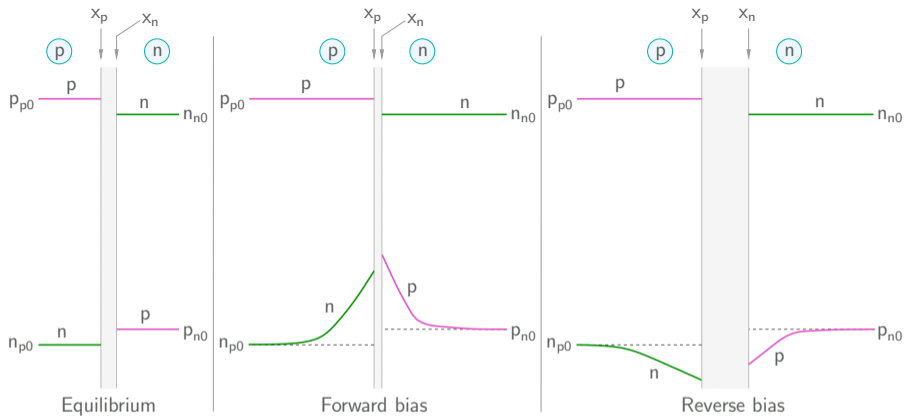


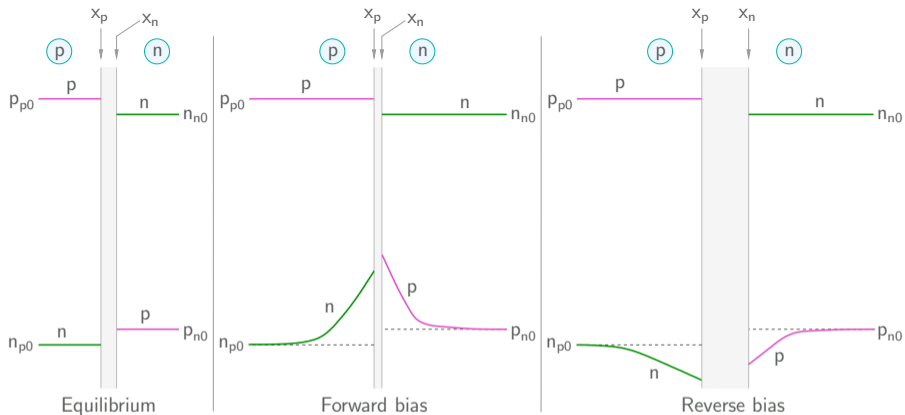
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pn junction: derivation of I - V equation

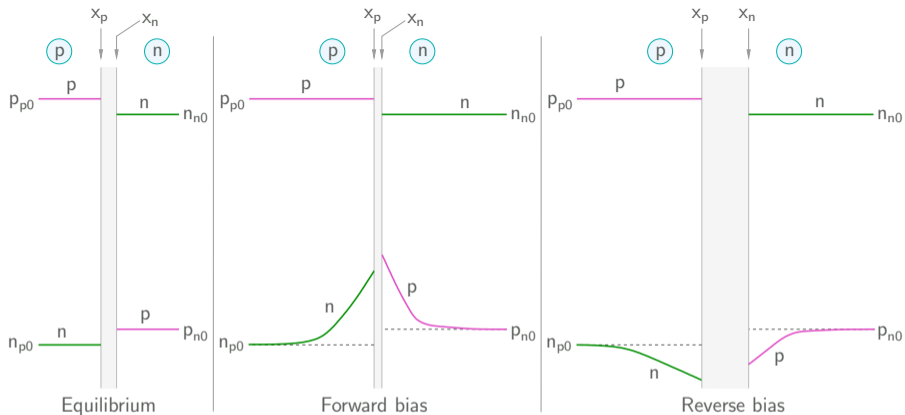


- * When a bias is applied, the minority carrier concentrations in the neutral regions can change substantially.
- * There is a corresponding change in the majority carrier concentrations as well, and it serves to keep these regions charge-neutral.
- * Low-level injection: $\Delta n \approx \Delta p \ll p_{p0}$ in the neutral p -region $\rightarrow p(x) \approx p_{p0}$ for $x \leq x_p$
 $\Delta p \approx \Delta n \ll n_{n0}$ in the neutral n -region $\rightarrow n(x) \approx n_{n0}$ for $x \geq x_n$



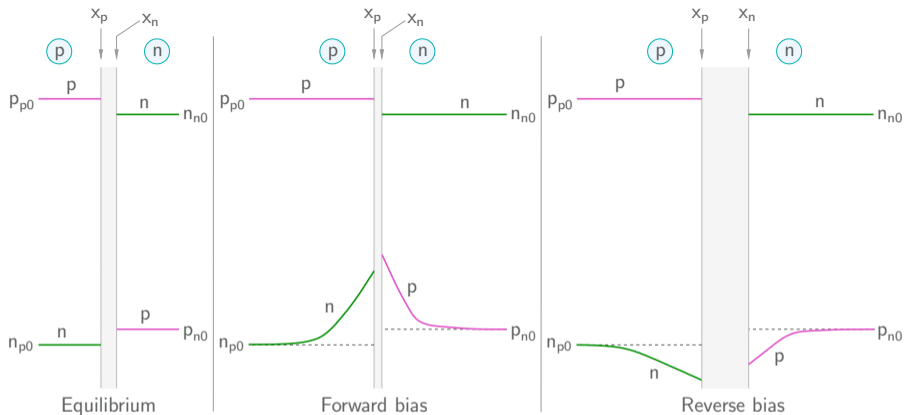


* $\frac{p(x_n)}{p(x_p)} = \exp\left(\frac{\psi(x_p) - \psi(x_n)}{V_T}\right)$, $\frac{n(x_n)}{n(x_p)} = \exp\left(\frac{\psi(x_n) - \psi(x_p)}{V_T}\right)$. Also, $\psi(x_n) - \psi(x_p) = V_j$.



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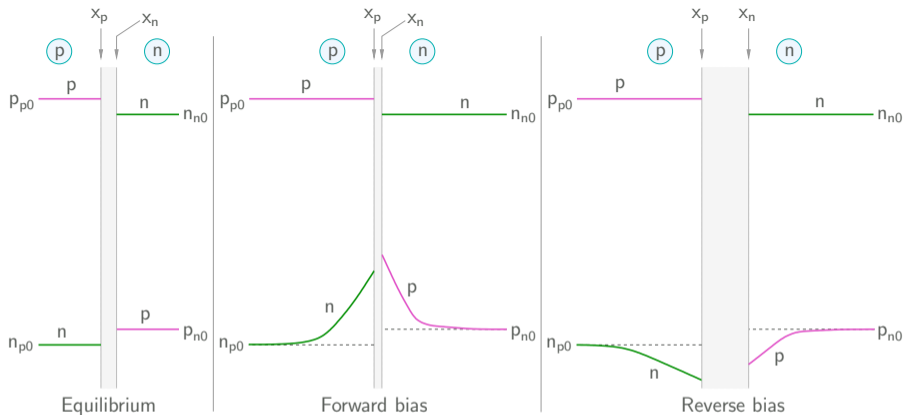
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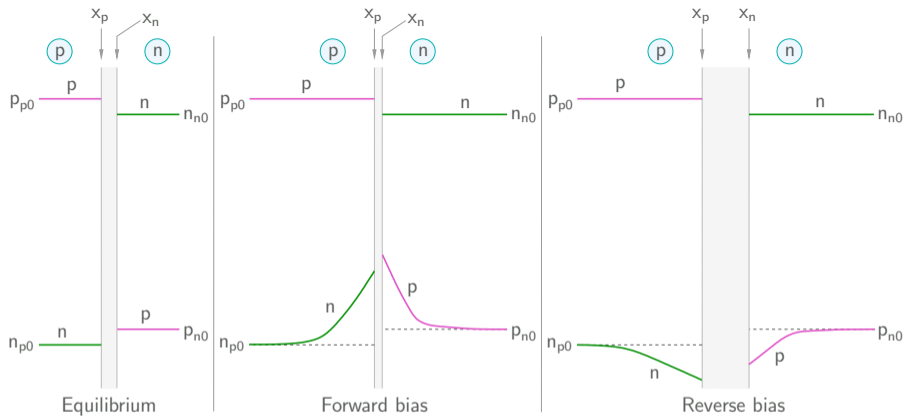


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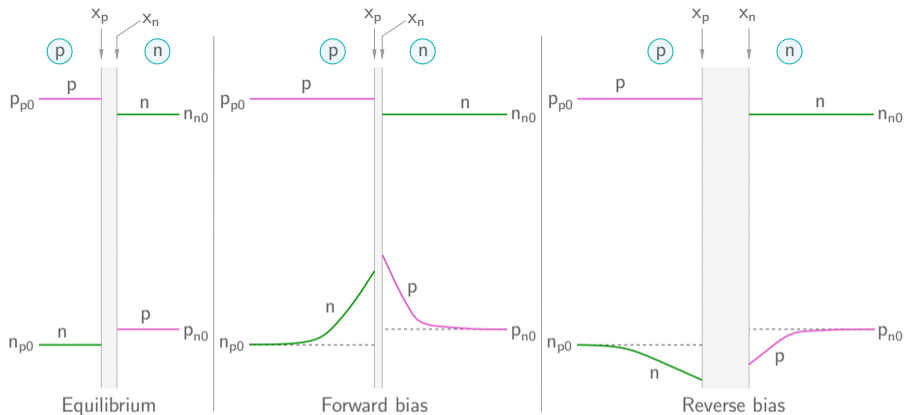
$$\frac{n_{n0}}{n(x_p)} = e^{V_j/V_T} \rightarrow n(x_p) = n_{n0} e^{-V_j/V_T}.$$



$$p(x_n) = p_{p0} e^{-V_j/V_T}$$

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$$V_j = V_{bi} - V_a$$

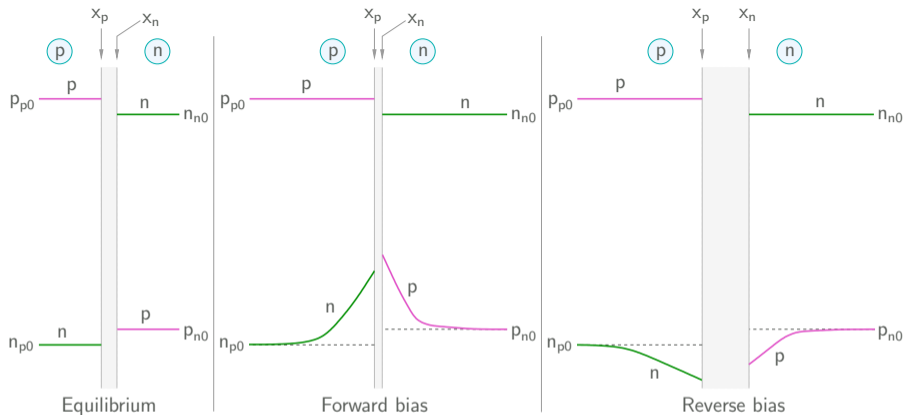


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$$V_j = V_{bi} - V_a$$

$$\text{Equilibrium: } p(x_n) = p_{n0} = p_{p0} \exp\left(\frac{-V_{bi}}{V_T}\right), \quad n(x_p) = n_{p0} = n_{n0} \exp\left(\frac{-V_{bi}}{V_T}\right).$$



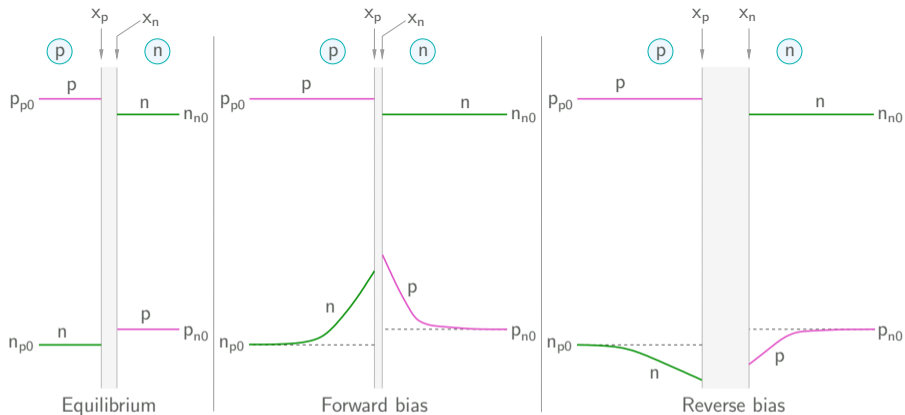
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$$\text{With bias: } p(x_n) = p_{p0} \exp\left(\frac{-V_{bi} + V_a}{V_T}\right), \quad n(x_p) = n_{n0} \exp\left(\frac{-V_{bi} + V_a}{V_T}\right).$$



$$p(x_n) = p_{p0} e^{-V_j/V_T}$$

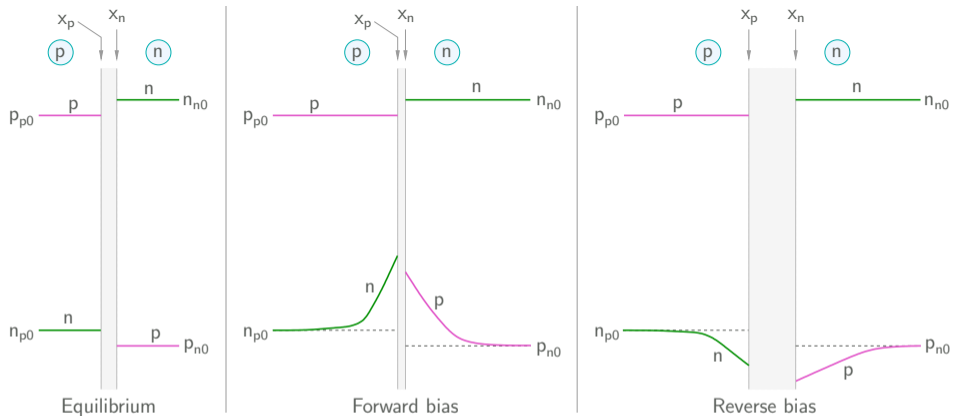
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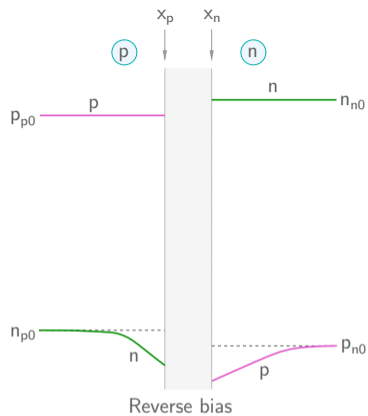
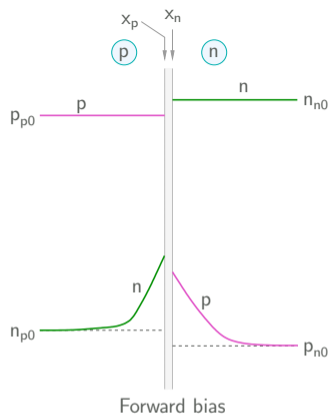
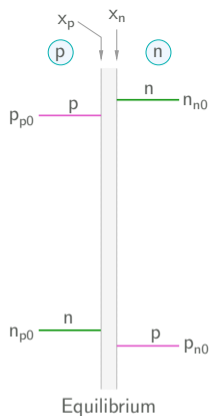
With bias: $p(x_n) = p_{p0} \exp\left(\frac{-V_{bi} + V_a}{V_T}\right)$, $n(x_p) = n_{n0} \exp\left(\frac{-V_{bi} + V_a}{V_T}\right)$.

$$p(x_n) = p_{n0} \exp\left(\frac{V_a}{V_T}\right), \quad n(x_p) = n_{p0} \exp\left(\frac{V_a}{V_T}\right).$$

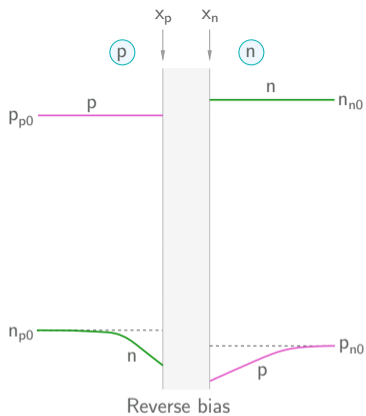
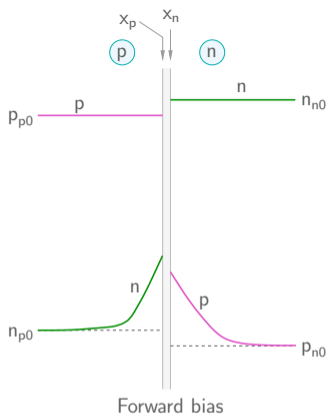
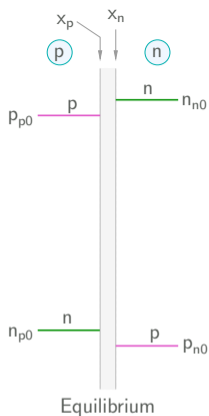


Example: Consider an abrupt, uniformly doped silicon pn junction at $T = 300$ K, with $N_a = 5 \times 10^{16} \text{ cm}^{-3}$ and $N_d = 10^{18} \text{ cm}^{-3}$. Compute the depletion width and the minority carrier densities at the depletion region edges (x_p and x_n) for an applied bias of $+0.3$ V, $+0.6$ V, -1 V, -5 V.

($n_i = 1.5 \times 10^{10} \text{ cm}^{-3}$ for silicon at $T = 300$ K.)

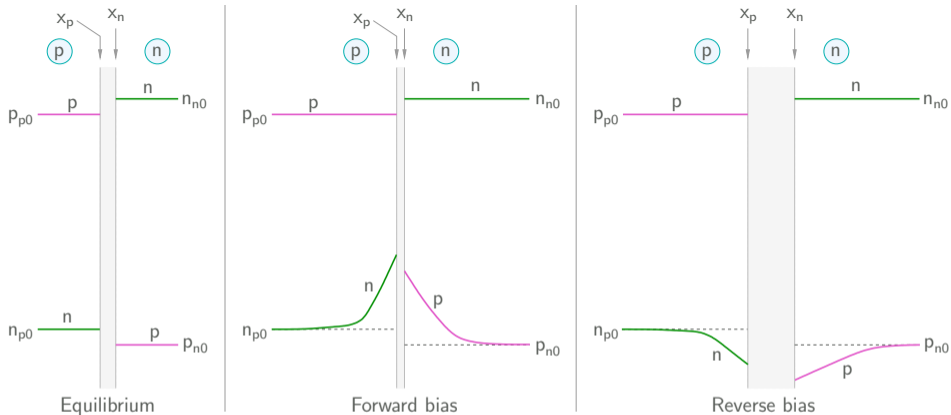


Solution: $p_{p0} \approx N_a = 5 \times 10^{16} \text{ cm}^{-3} \rightarrow n_{p0} = \frac{n_i^2}{p_{p0}} = \frac{(1.5 \times 10^{10})^2}{5 \times 10^{16}} = 4.5 \times 10^3 \text{ cm}^{-3}$.



Solution: $p_{p0} \approx N_a = 5 \times 10^{16} \text{ cm}^{-3} \rightarrow n_{p0} = \frac{n_i^2}{p_{p0}} = \frac{(1.5 \times 10^{10})^2}{5 \times 10^{16}} = 4.5 \times 10^3 \text{ cm}^{-3}.$

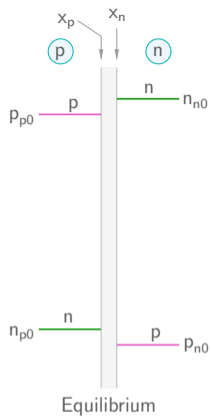
$n_{n0} \approx N_d = 1 \times 10^{18} \text{ cm}^{-3} \rightarrow p_{n0} = \frac{n_i^2}{n_{n0}} = \frac{(1.5 \times 10^{10})^2}{1 \times 10^{18}} = 2.25 \times 10^2 \text{ cm}^{-3}.$



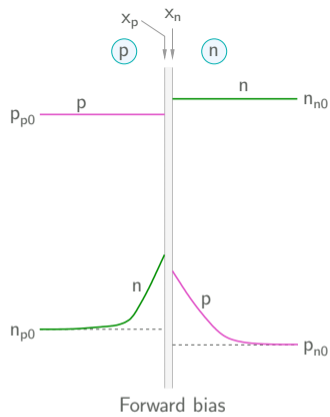
Solution: $p_{p0} \approx N_a = 5 \times 10^{16} \text{ cm}^{-3} \rightarrow n_{p0} = \frac{n_i^2}{p_{p0}} = \frac{(1.5 \times 10^{10})^2}{5 \times 10^{16}} = 4.5 \times 10^3 \text{ cm}^{-3}$.

$$n_{n0} \approx N_d = 1 \times 10^{18} \text{ cm}^{-3} \rightarrow p_{n0} = \frac{n_i^2}{n_{n0}} = \frac{(1.5 \times 10^{10})^2}{1 \times 10^{18}} = 2.25 \times 10^2 \text{ cm}^{-3}$$

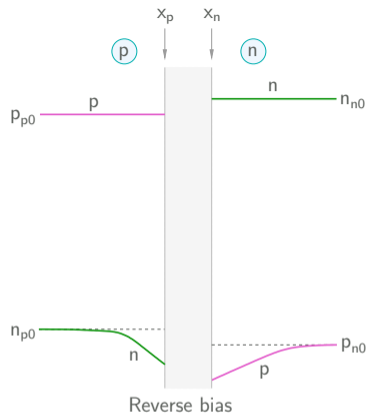
$$V_{bi} = V_T \log \left(\frac{N_a N_d}{n_i^2} \right) = (0.0259 \text{ V}) \log \left(\frac{5 \times 10^{16} \times 10^{18}}{(1.5 \times 10^{10})^2} \right) = 0.86 \text{ V}$$



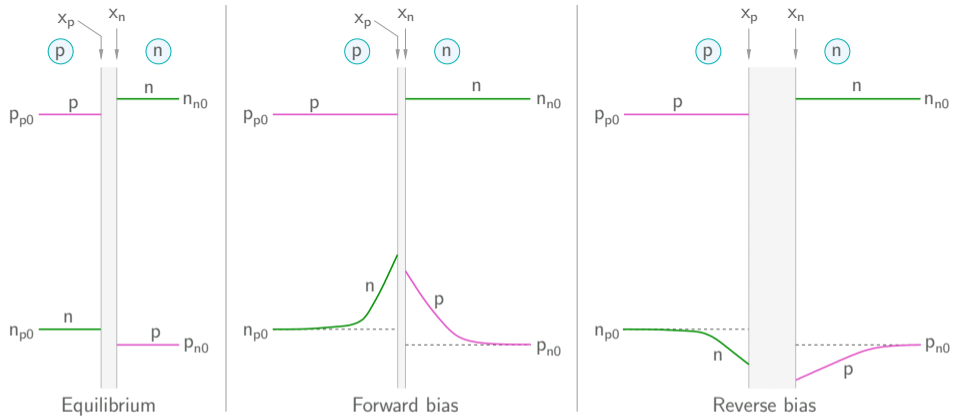
Equilibrium



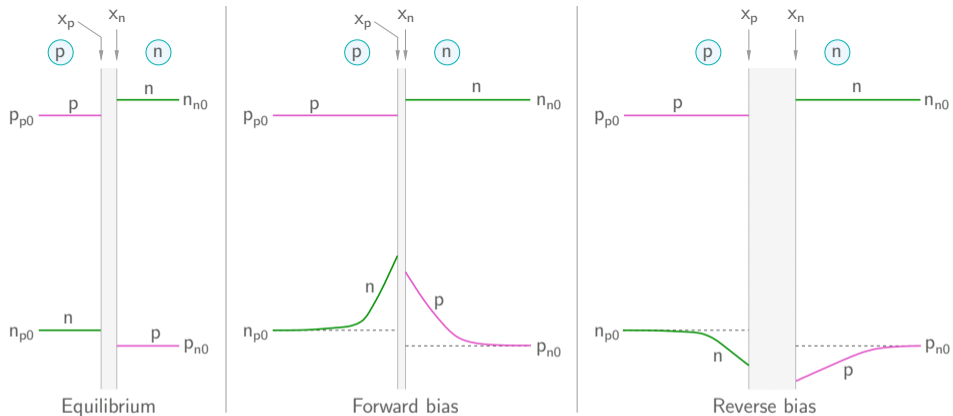
Forward bias



Reverse bias

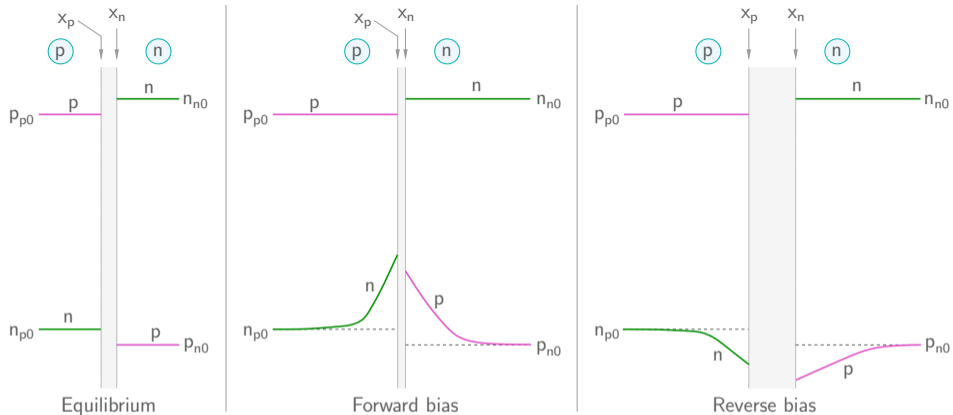


$$V_a = 0.3 \text{ V}: W = \sqrt{\frac{2\epsilon}{q} \frac{N_a + N_d}{N_a N_d} (V_{bi} - V_a)} = 0.12 \mu\text{m}.$$



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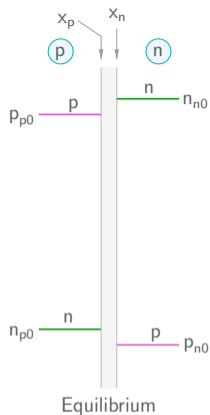
$$n(x_p) = n_{p0} \exp\left(\frac{V_a}{V_T}\right) = 4.5 \times 10^3 \times \exp\left(\frac{0.3}{0.0259}\right) = 4.83 \times 10^8 \text{ cm}^{-3}.$$



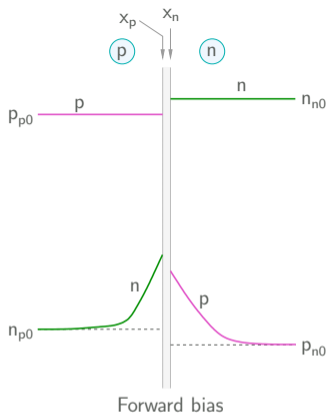
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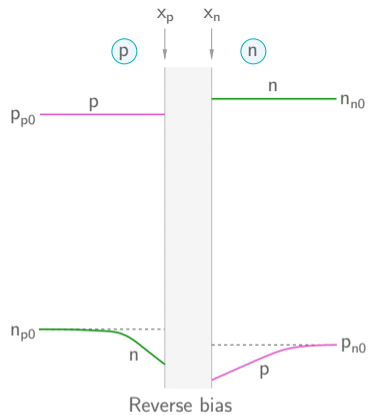
$$p(x_n) = p_{n0} \exp\left(\frac{V_a}{V_T}\right) = 2.25 \times 10^2 \times \exp\left(\frac{0.3}{0.0259}\right) = 2.41 \times 10^7 \text{ cm}^{-3}.$$



Equilibrium

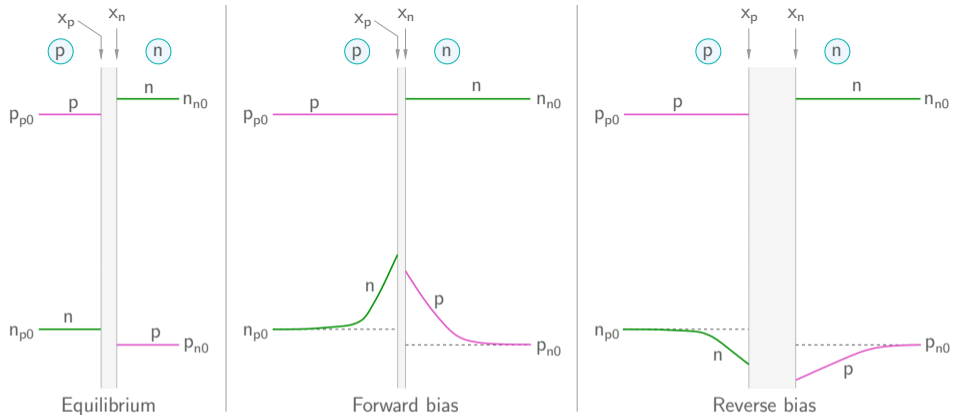


Forward bias



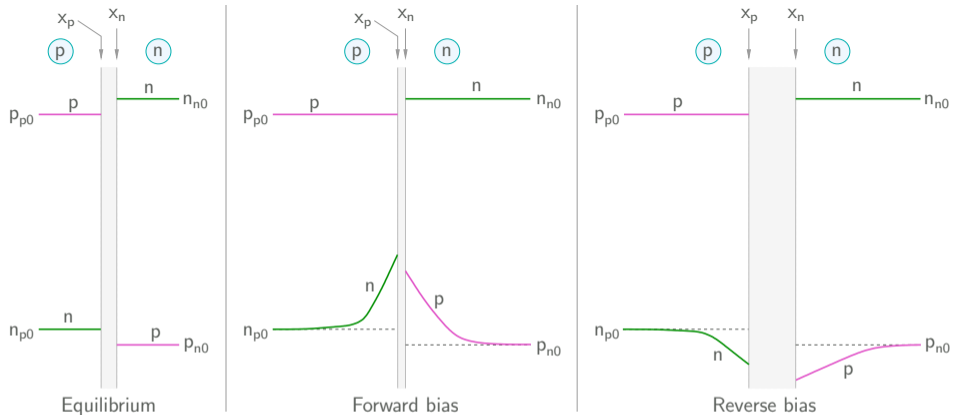
Reverse bias

V_a (V)	W (μm)	\mathcal{E}_m (kV/cm)	$n(x_p)$ (cm^{-3})	$p(x_n)$ (cm^{-3})
0.6	0.08	61.3	5.18×10^{13}	2.59×10^{12}
0.3	0.12	90.4	4.83×10^8	2.41×10^7
0.0	0.15	112.2	4.50×10^3	2.25×10^2
-1.0	0.22	165.3	$7.68 \times 10^{-14} \approx 0$	$3.84 \times 10^{-15} \approx 0$
-5.0	0.40	293.6	≈ 0	≈ 0



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* With forward bias, the minority carrier concentrations can increase by several orders of magnitude.



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-5.0	0.40	293.6	≈ 0	≈ 0

- * With forward bias, the minority carrier concentrations can increase by several orders of magnitude.
- * With reverse bias, the minority carrier concentrations become very small and can be replaced with zero for all practical purposes.