Semiconductor Devices

p-*n* Junctions: Part 2

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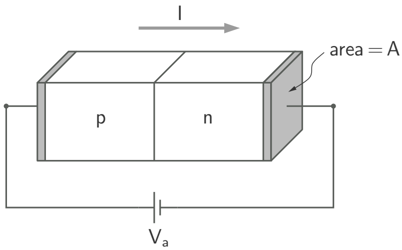
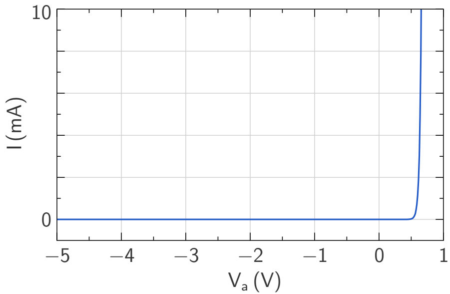
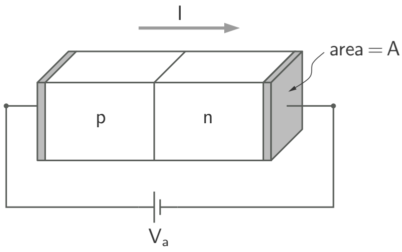
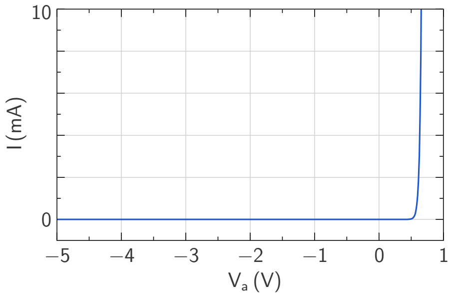

I
area = A
p
n
V a

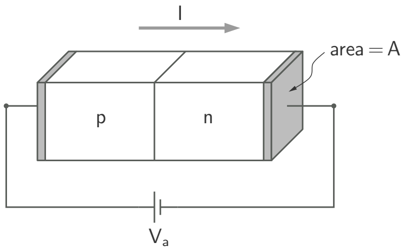

10
0
I (mA)
−5
−4
−3
−2
−1
0
1
V a (V)

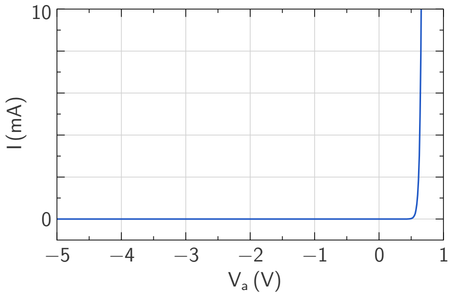




* With $V_a \approx 0.6\,\text{V}$ a substantial current flows. When V_a is increased further, the current increases rapidly.

pn junction under bias





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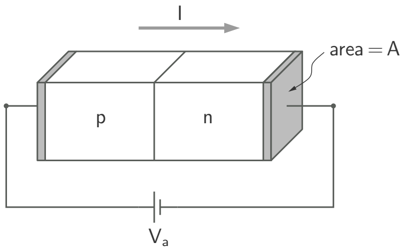
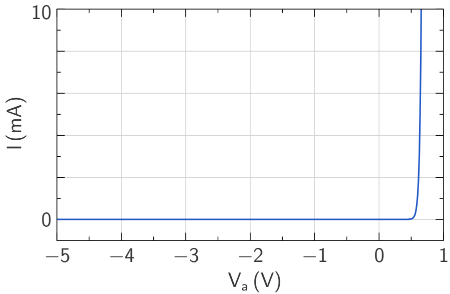
* When a reverse bias (i.e., $V_a < 0$,V) is applied, the diode blocks conduction, i.e., the current is negligibly small.





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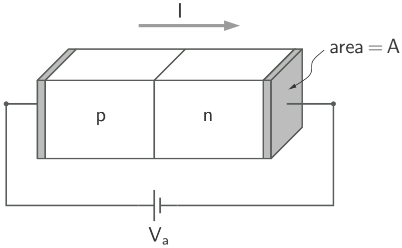
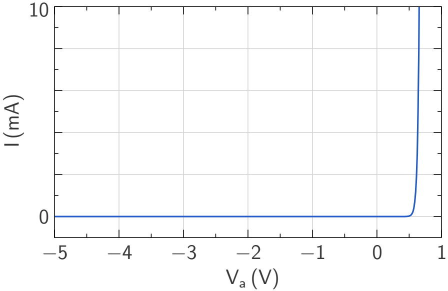
  We want to understand this "rectifying" behaviour.





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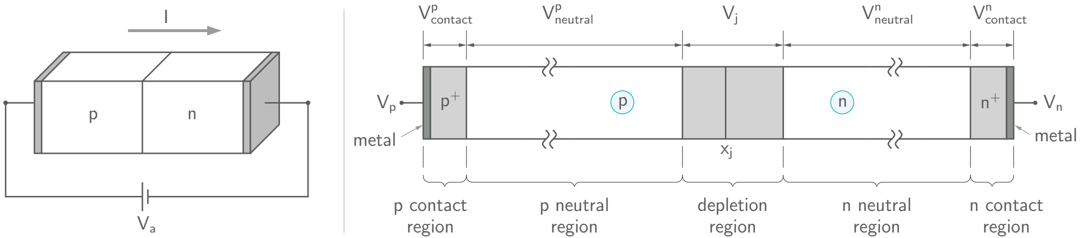
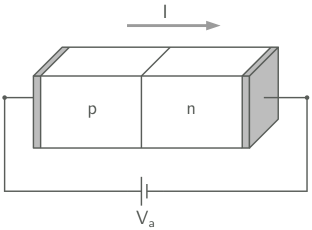
  We want to understand this "rectifying" behaviour.
* As we increase the forward bias, the current increases rapidly, and at some point, the device will get damaged because of overheating. For silicon diodes used in low-power applications, the forward voltge must be restricted to about $0.8\,\text{V}$.

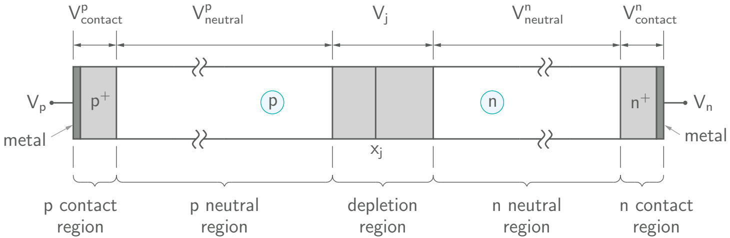
  (Note: Although we will show an applied forward/reverse bias with a battery, in practice, a battery is generally not connected directly across a diode.)



Consider a *pn* junction in equilibrium ($V_a = 0\,\mathrm{V}$).

Where does the voltage drop?





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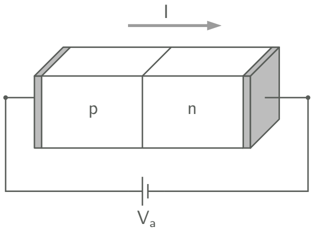

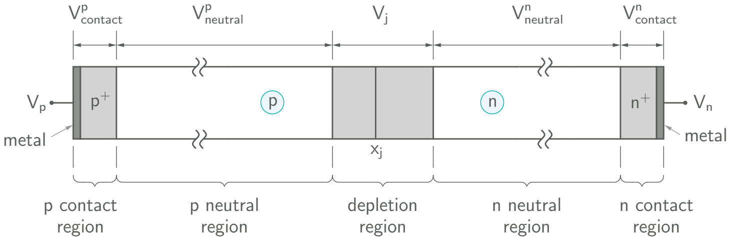

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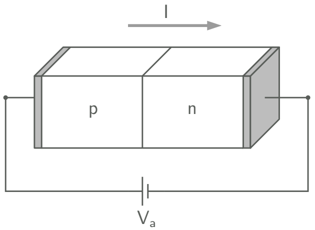

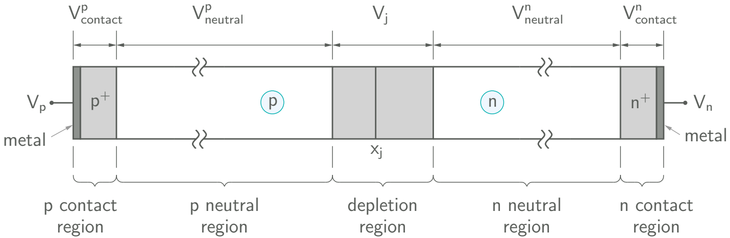

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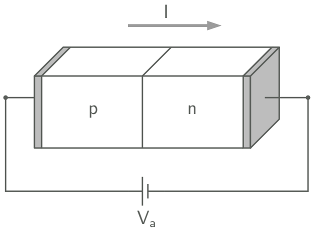

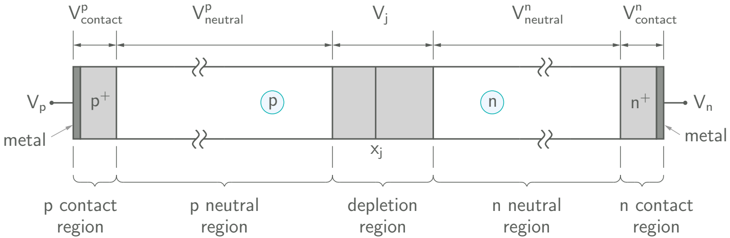

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* V_{contact}^{p} and V_{contact}^{n} are the voltage drops across the contact regions (which generally include heavily doped regions).
* V_{contact}^{p} and V_{contact}^{n} remain constant irrespective of the applied voltage (to be discussed later).
* 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 $J_p^{\text{drift}} = qp\mu_p\mathcal{E}$ or $J_n^{\text{drift}} = qn\mu_n\mathcal{E}$ (note that *p* and *n* in these equations represent the *majority* carrier densities).

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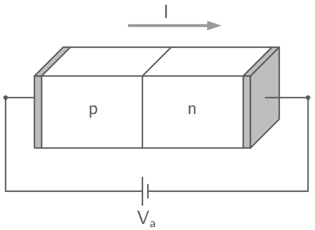

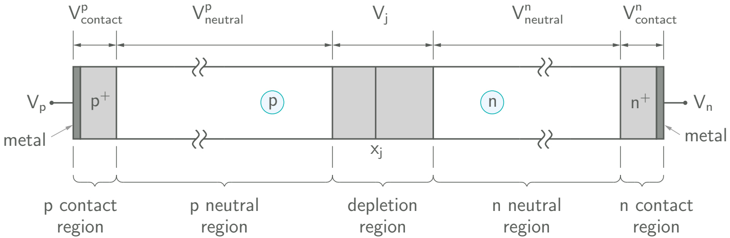

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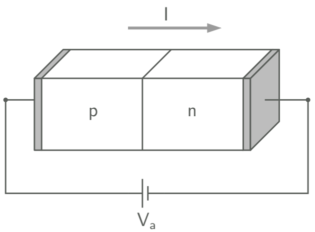

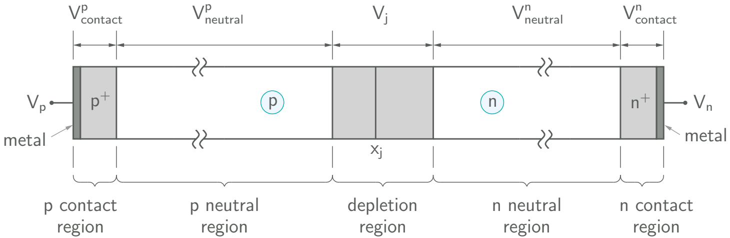

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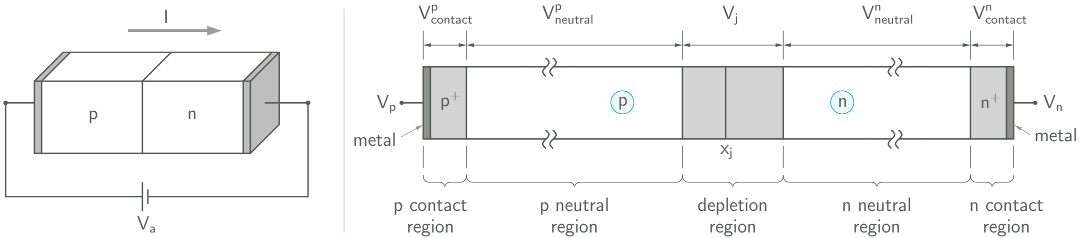

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* In equilibrium, $V_p = V_n$, and we get

  $(1):\ V^p_{\rm contact} - V_{\rm bi} + V^n_{\rm contact} = 0$, taking voltage drop as positive.

  (We assume that the signs of $V^p_{\rm contact}$ and $V^n_{\rm contact}$ are taken into account.)

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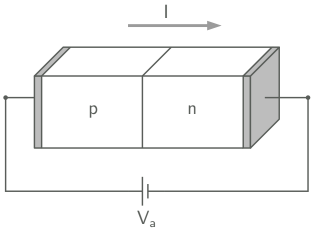

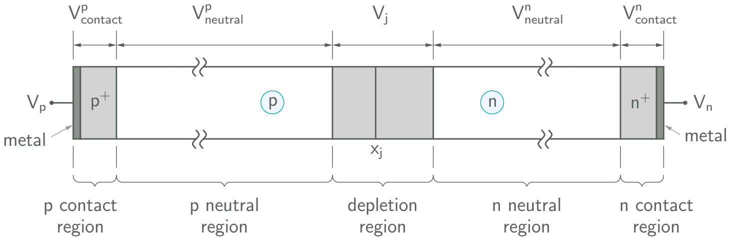

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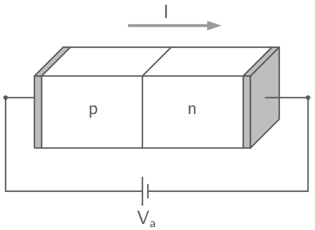

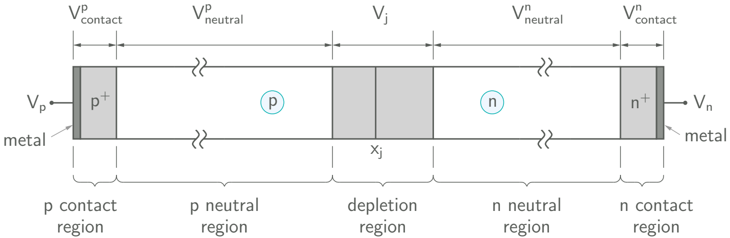

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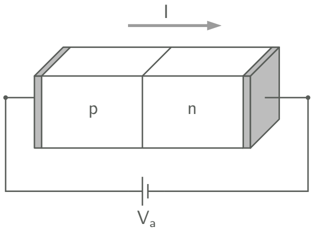
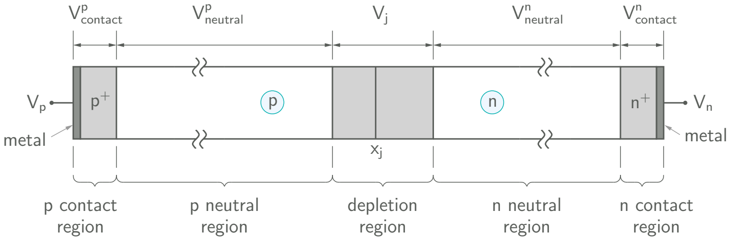
* When a bias is applied, we have
  $(2): \; V^p_{\text{contact}} - V_j + V^n_{\text{contact}} = V_p - V_n = V_a$.
* $(1) - (2)$ gives $-V_{\text{bi}} + V_j = -V_a$, i.e., $\boxed{V_j = V_{\text{bi}} - V_a}$

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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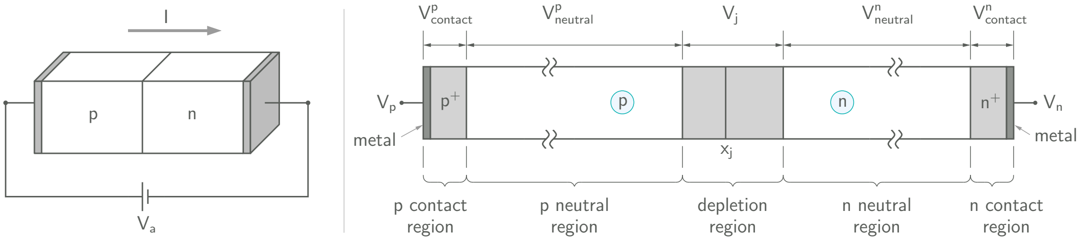

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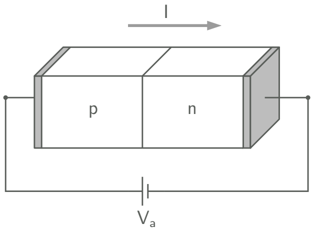

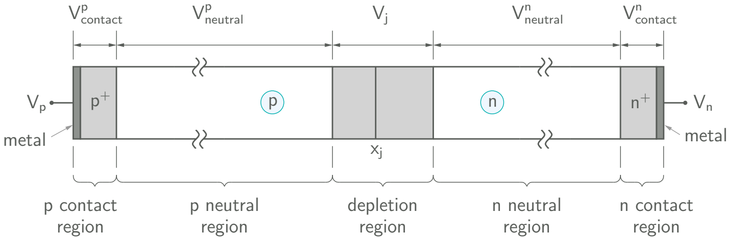

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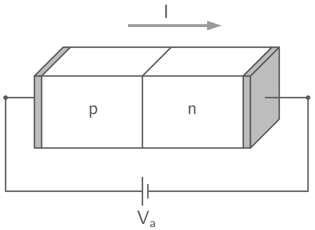

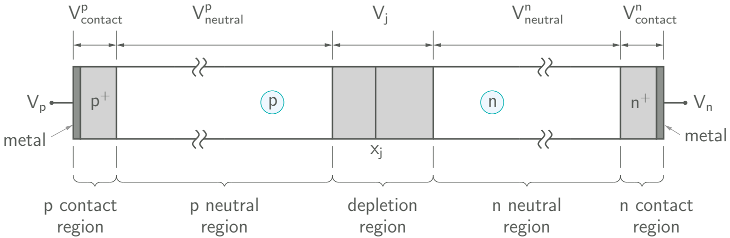

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$$V_{\rm bi} = kW_0^2 \quad (\text{for } V_a = 0\,{\rm V})$$

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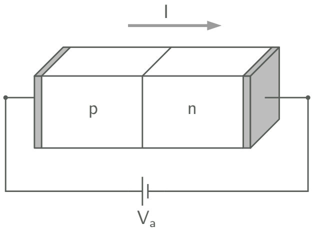

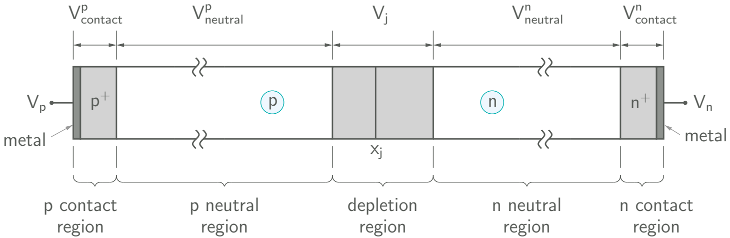

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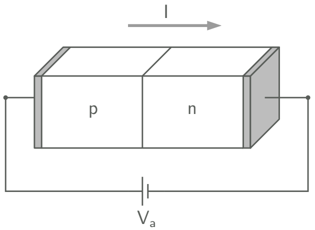
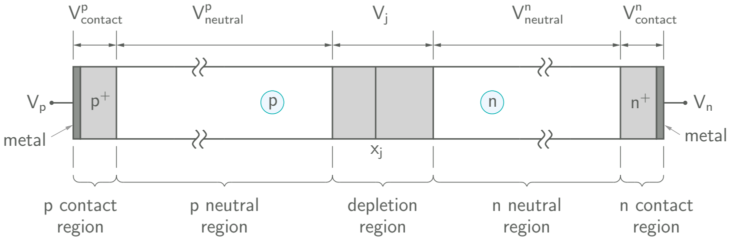
$$V_{bi} - 0.6\,\text{V} = kW_1^2 \quad (\text{for } V_a = 0.6\,\text{V})$$

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





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$$\begin{aligned} V_{\text{bi}} &= kW_0^2 \qquad (\text{for } V_a = 0\,\text{V}) \\ V_{\text{bi}} - 0.6\,\text{V} &= kW_1^2 \qquad (\text{for } V_a = 0.6\,\text{V}) \end{aligned}$$

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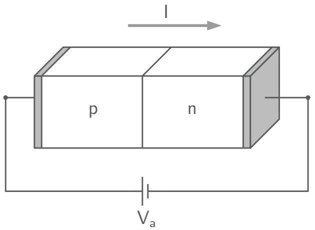
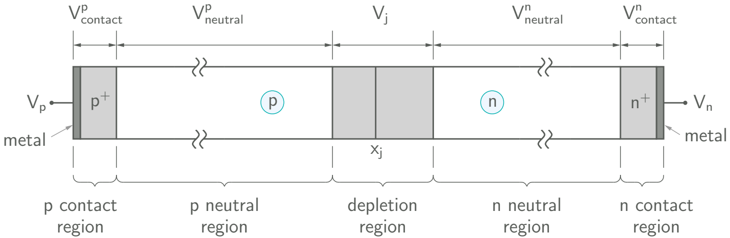
Application of a forward bias of 0.6 V causes the depletion regoin to shrink by a factor 0.54.

Example: reverse bias





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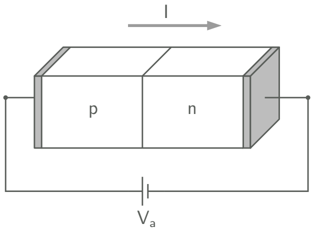

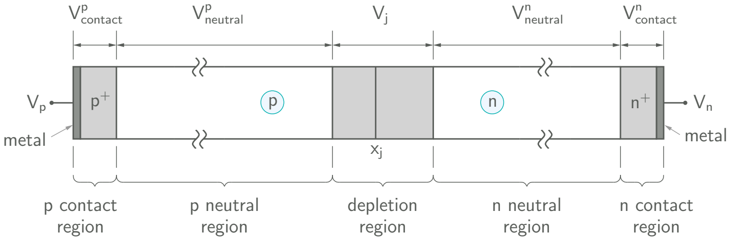

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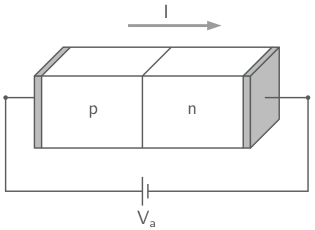

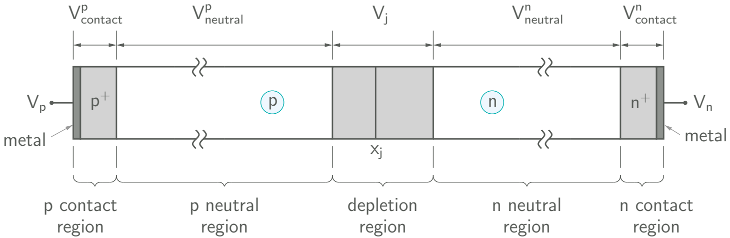

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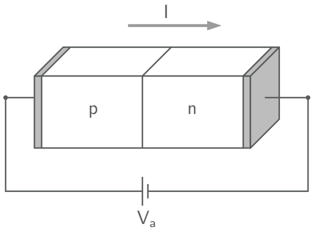

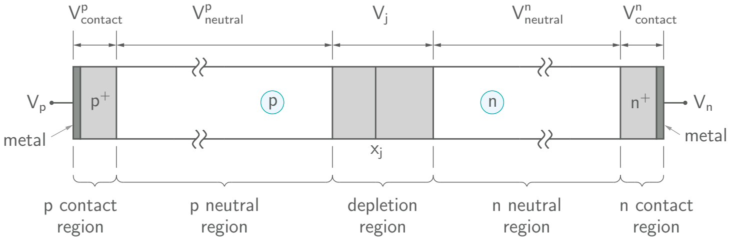

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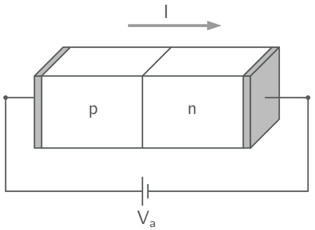
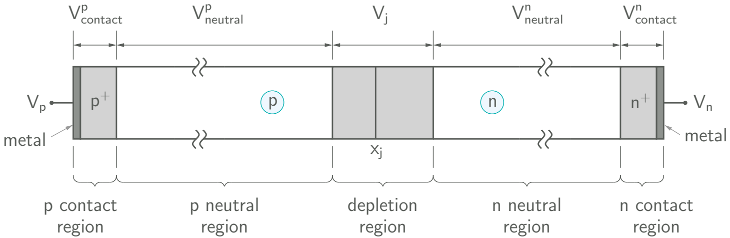
Example: reverse bias





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

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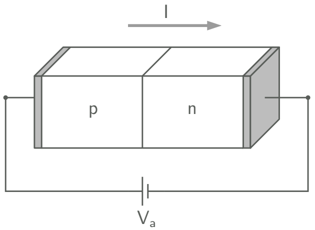

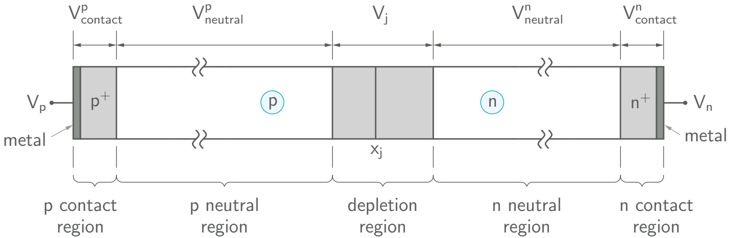

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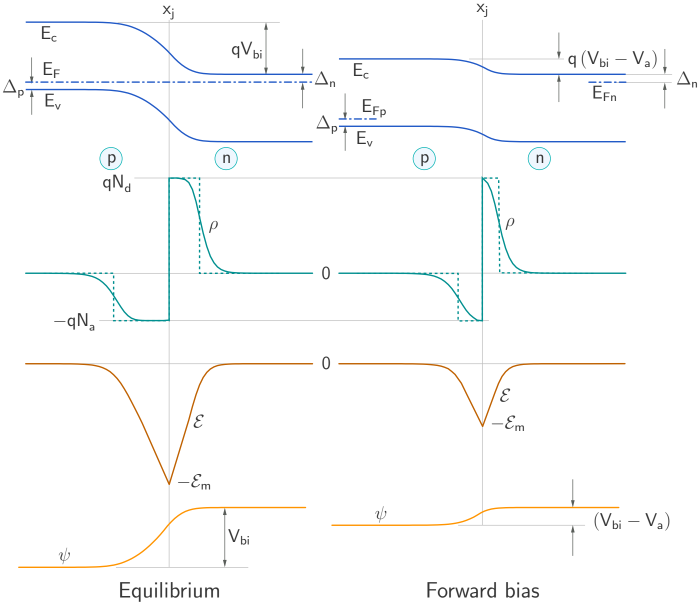
Application of a reverse bias of 2 V causes the depletion regoin to expand by a factor 1.83.

Forward bias



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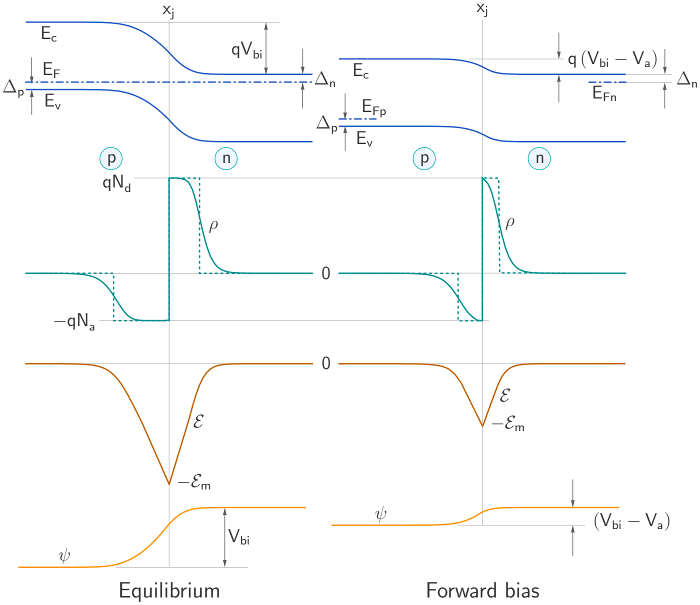

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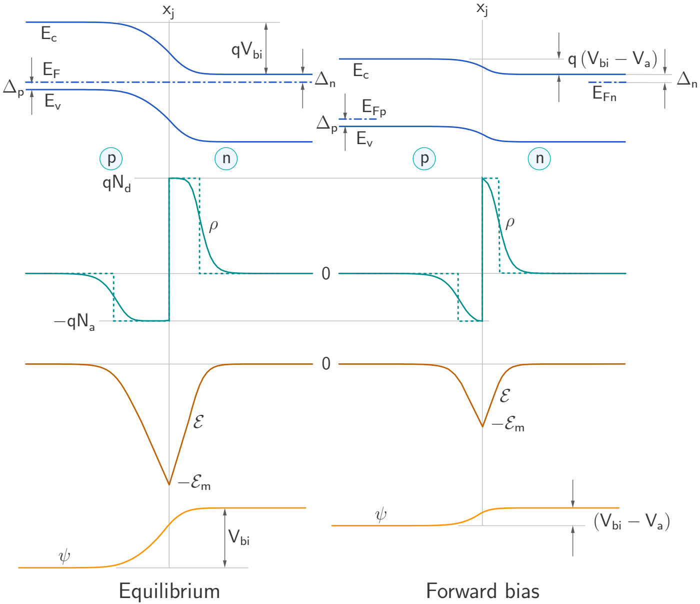

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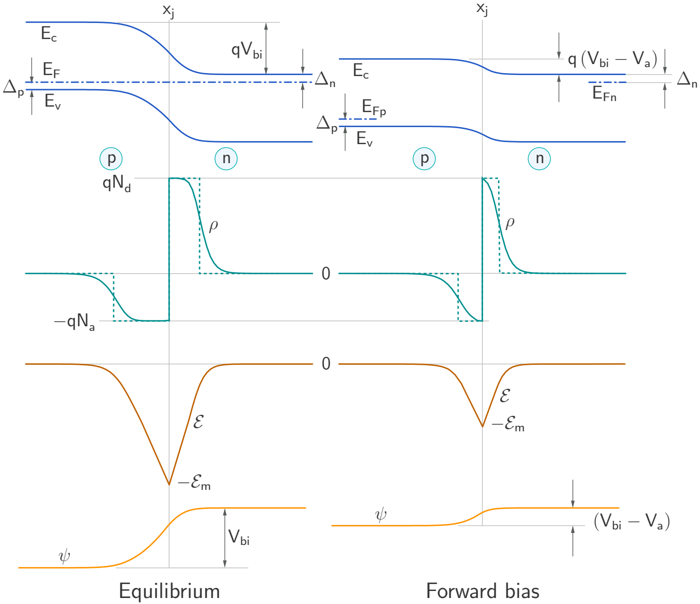

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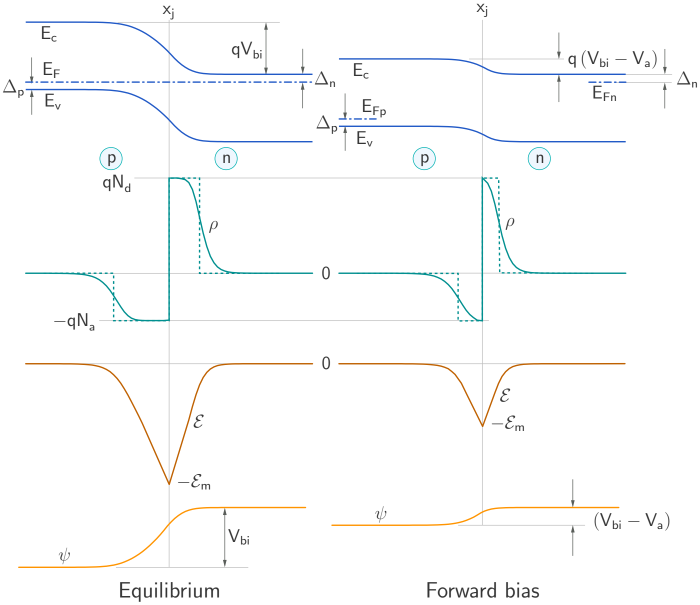

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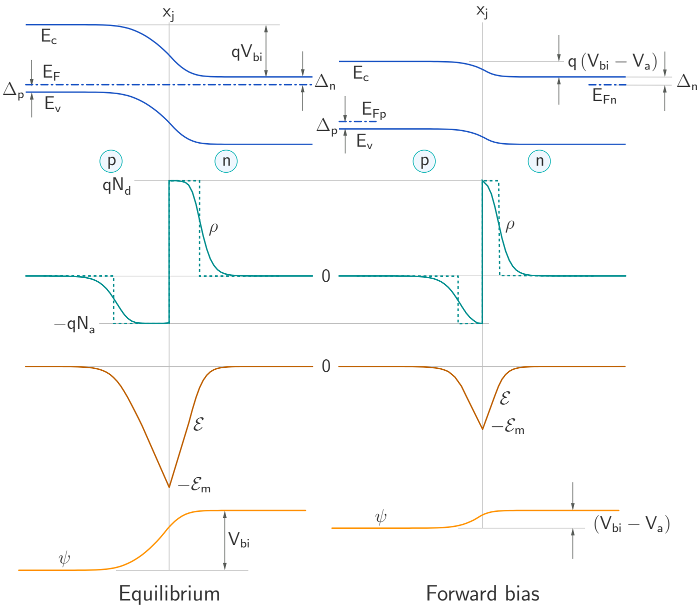

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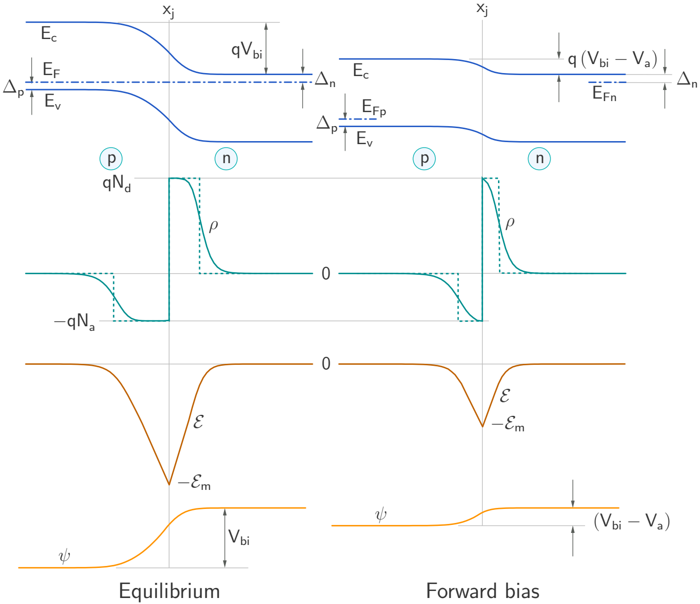

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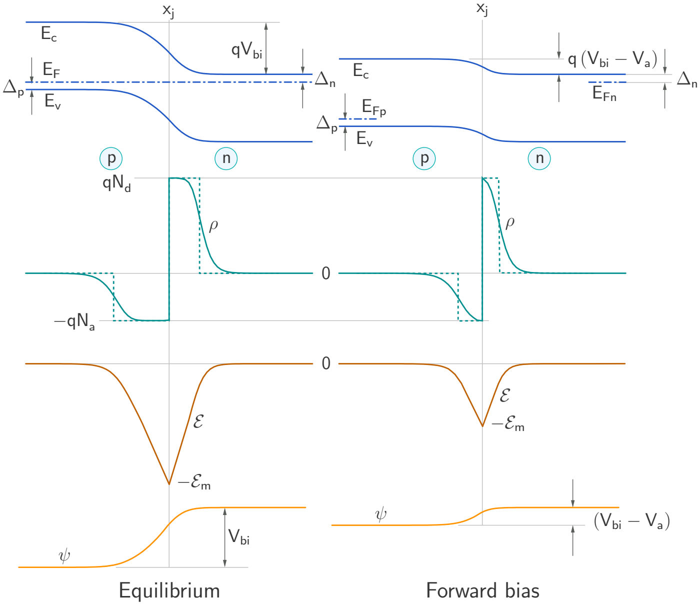

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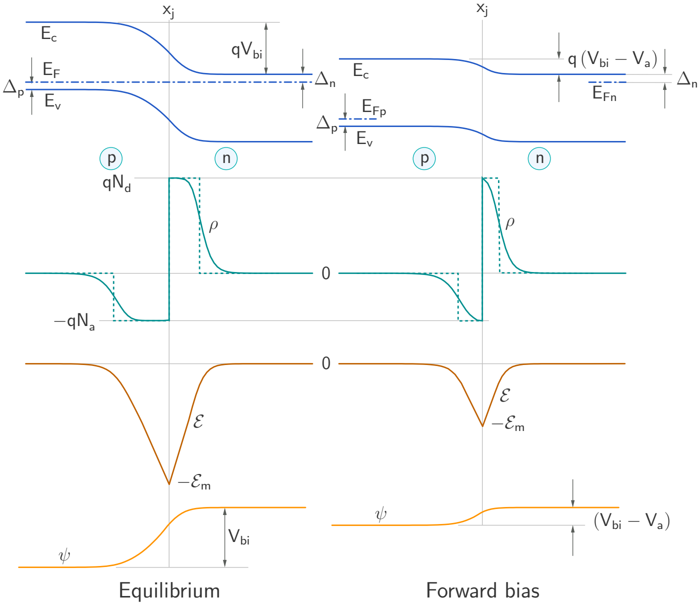

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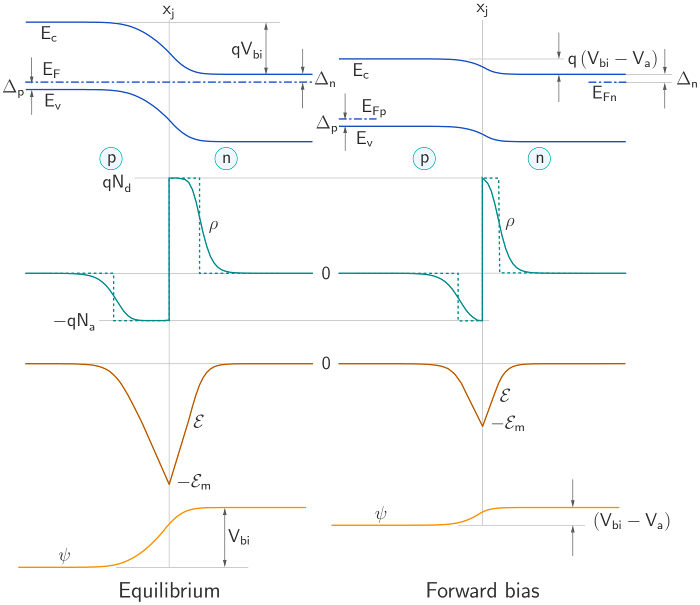

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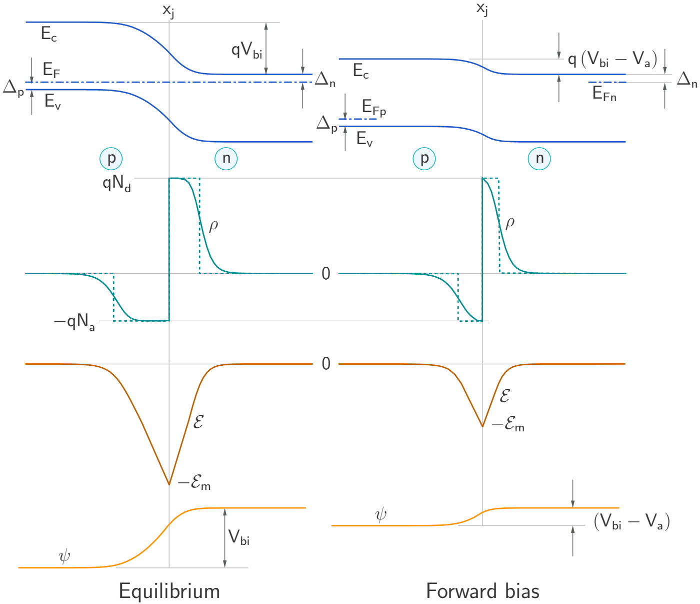

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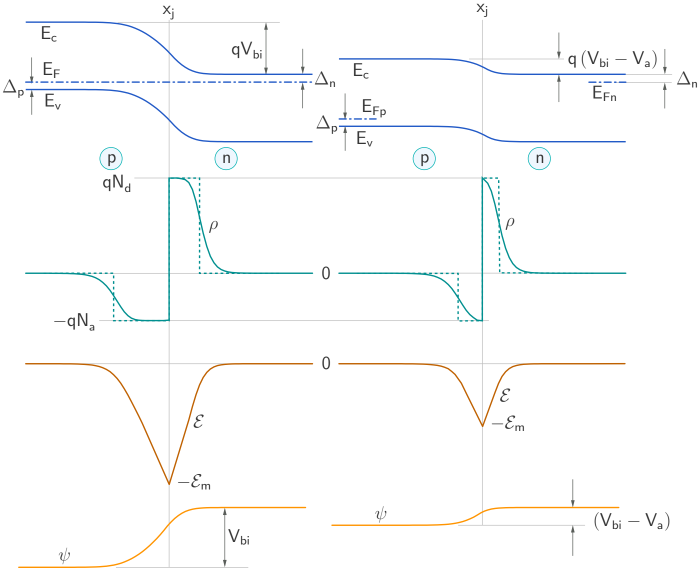

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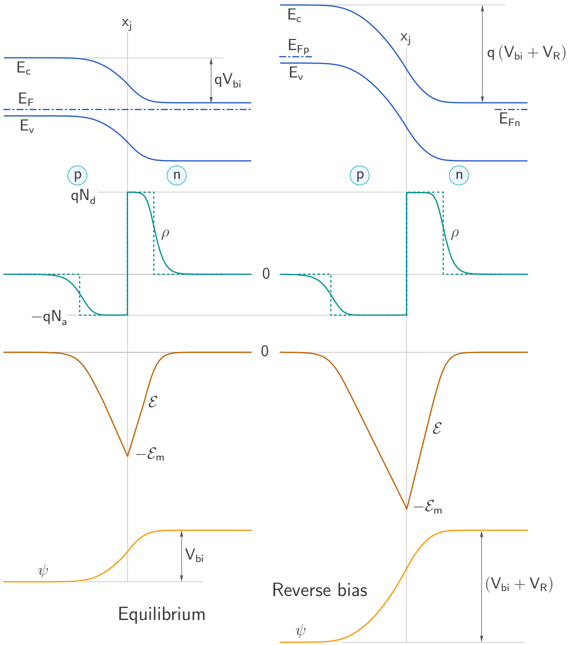

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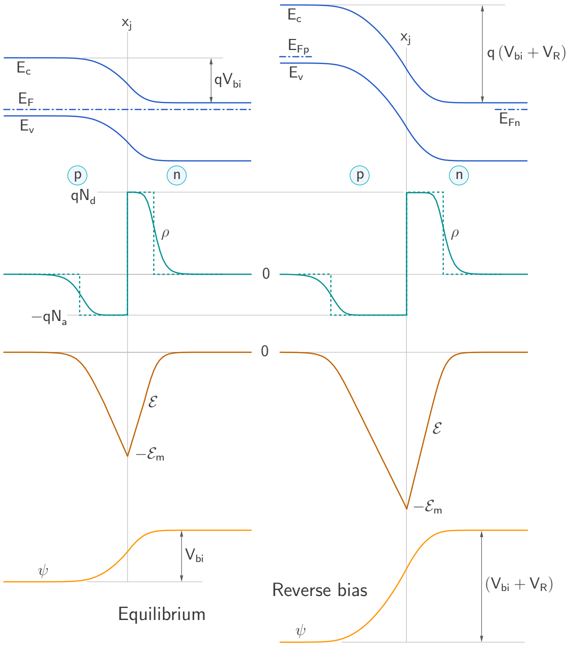

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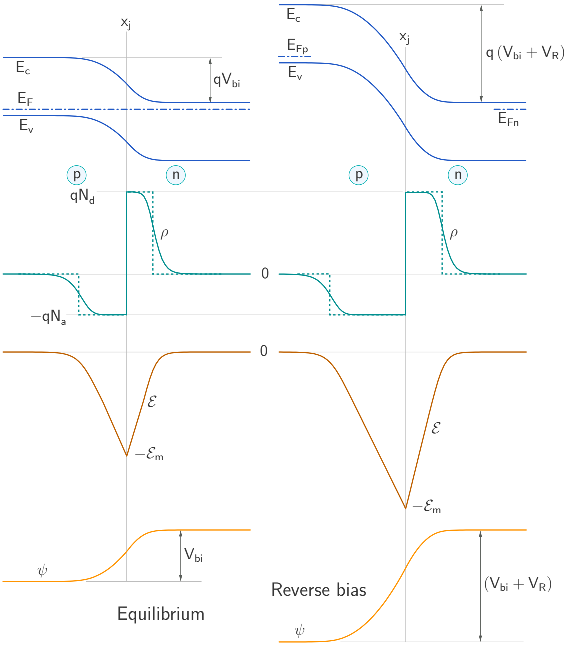

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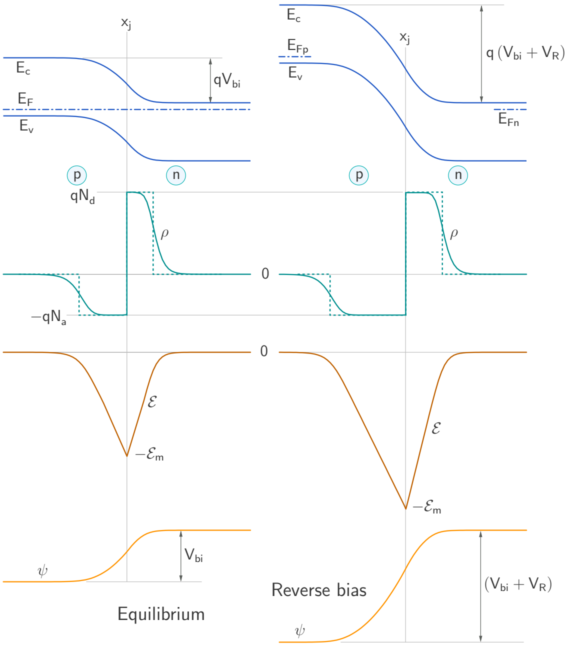

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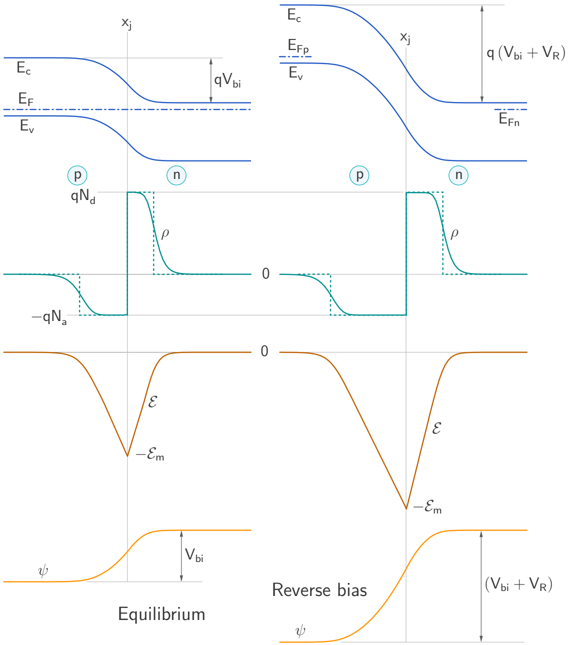

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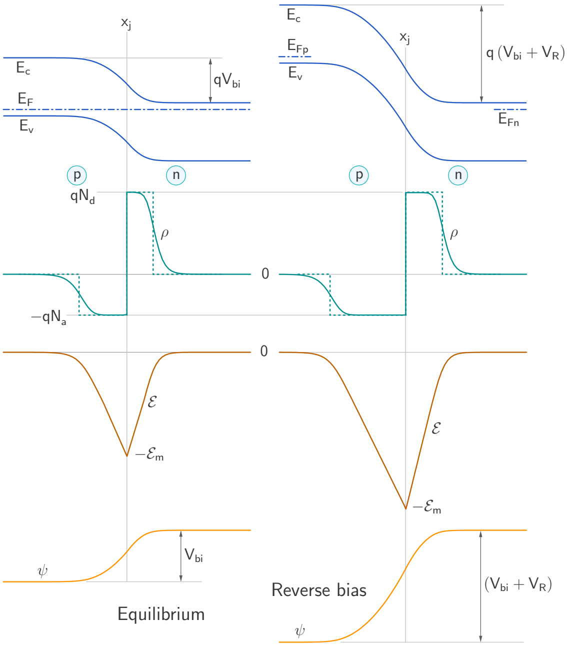

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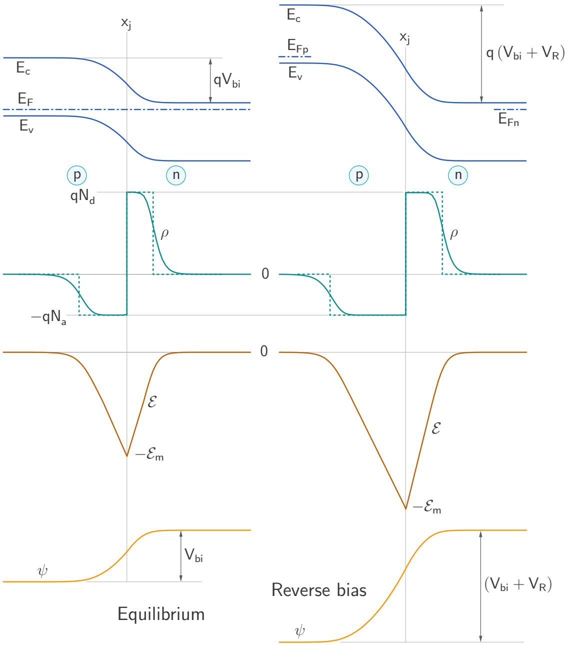

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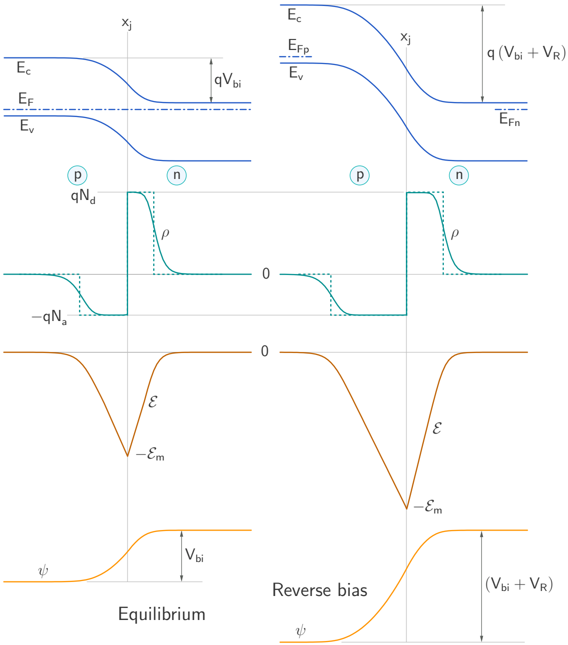

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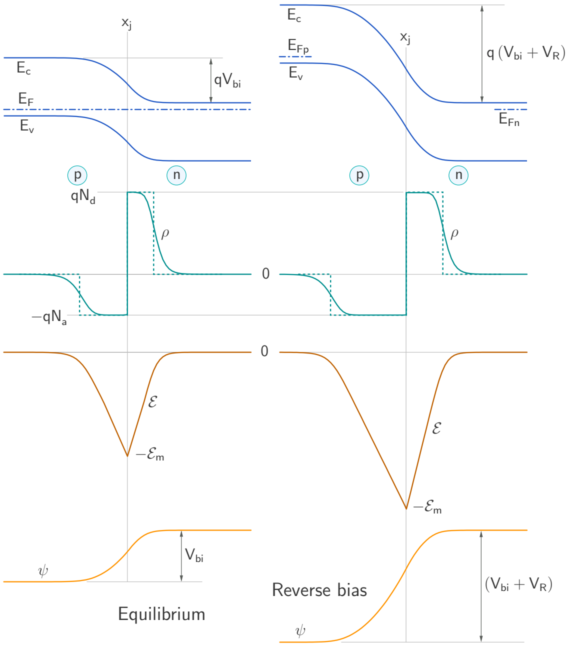

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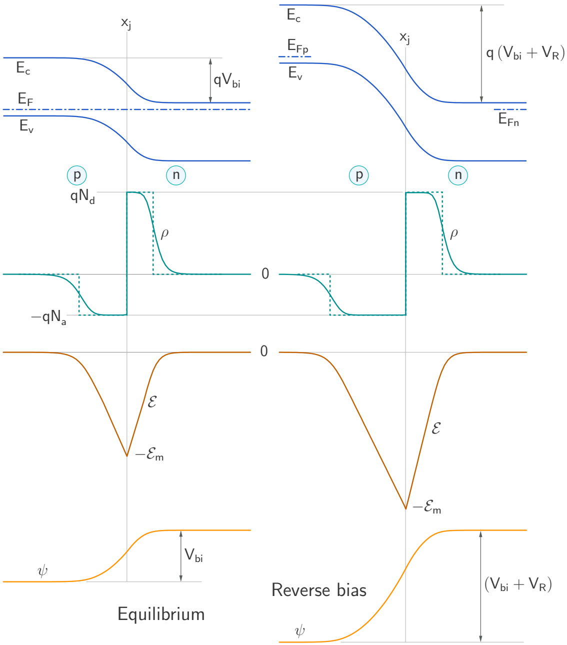

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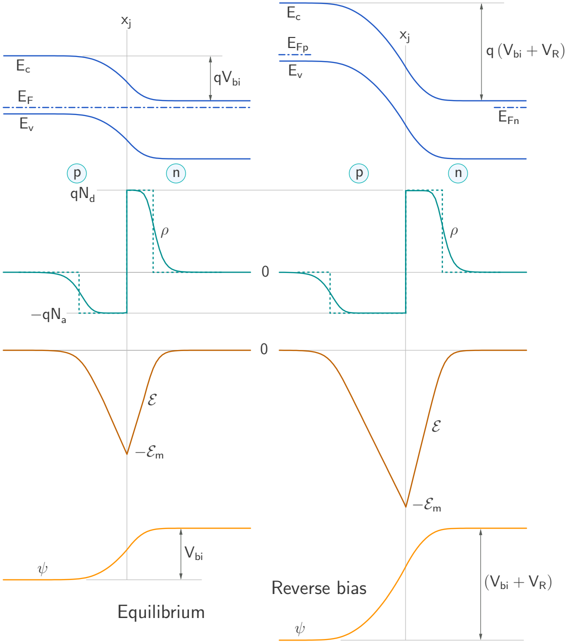

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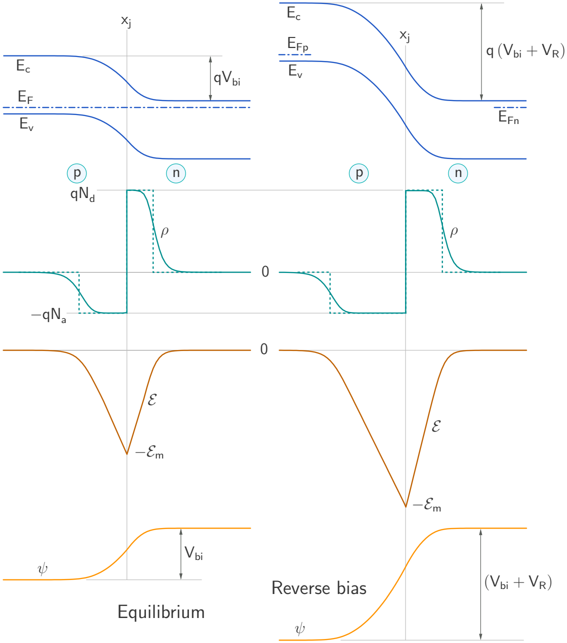
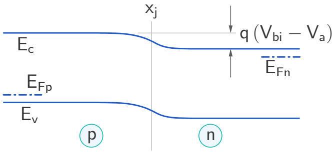


M. B. Patil, IIT Bombay

Current densities in forward bias



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$\mu_n = 1400\ \text{cm}^2/\text{V-s}$	$T = 300\ \text{K}$
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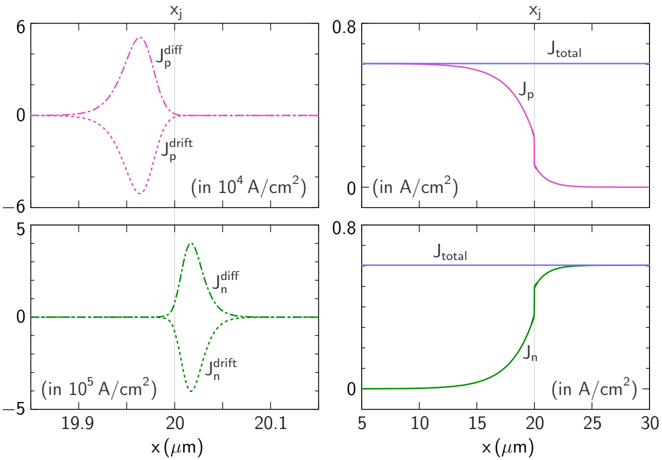
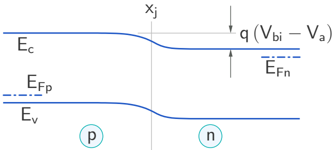


Near the junction,

Current densities in forward bias



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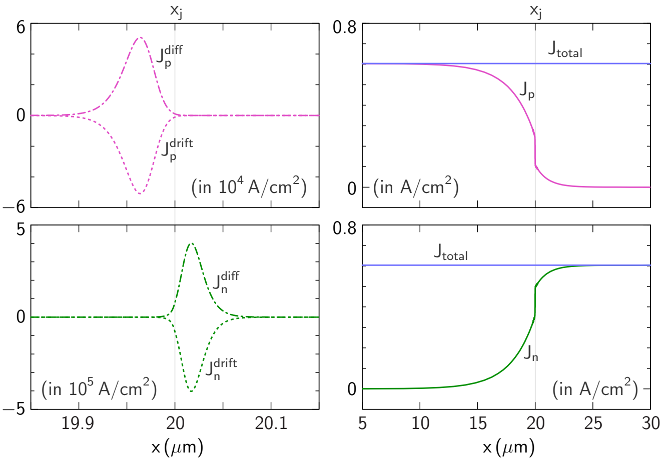

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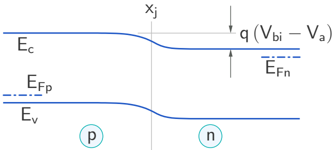

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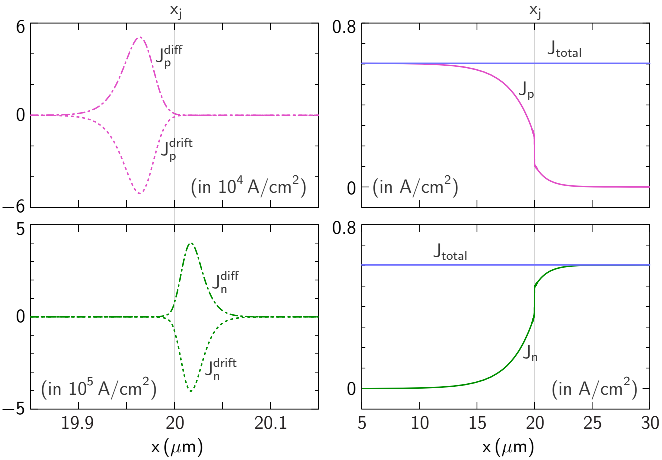

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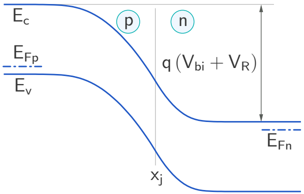
* The net current densities J_n and J_p are much smaller than the drift and diffusion components.

Current densities in reverse bias



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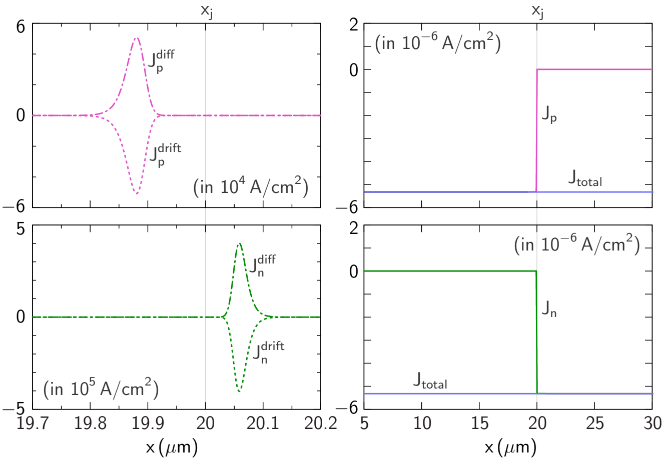

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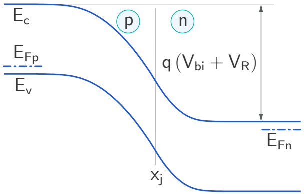

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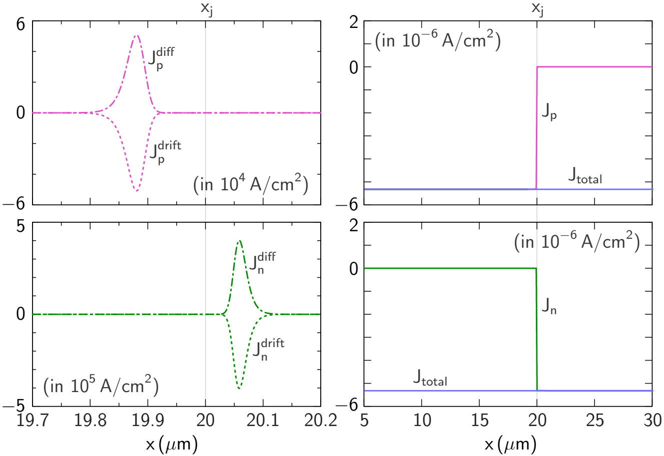

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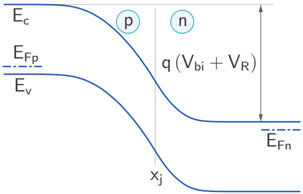

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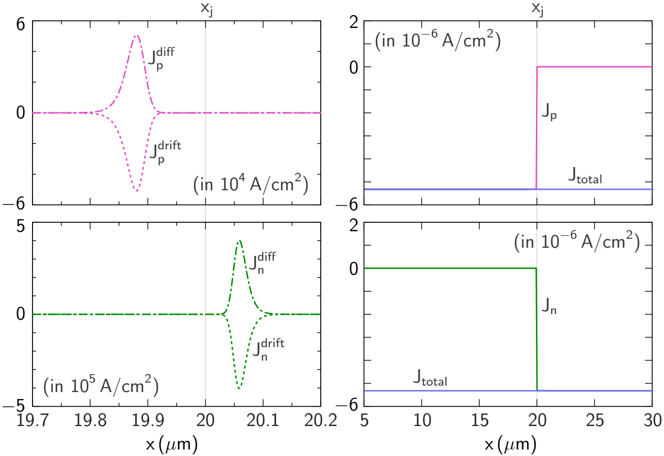
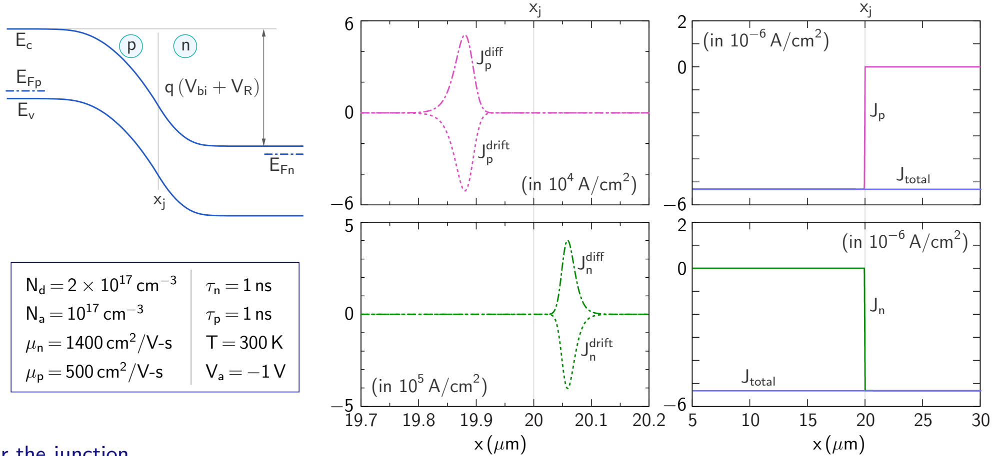
$N_a = 10^{17}\,\text{cm}^{-3}$	$\tau_p = 1\,\text{ns}$
$\mu_n = 1400\,\text{cm}^2/\text{V-s}$	$T = 300\,\text{K}$
$\mu_p = 500\,\text{cm}^2/\text{V-s}$	$V_a = -1\,\text{V}$



Near the junction,

* Although the equilibrium condition is disturbed, we still have $J_p^{\text{diff}} \approx -J_p^{\text{drift}}$, and $J_n^{\text{diff}} \approx -J_n^{\text{drift}}$.
* The net current densities J_n and J_p are much smaller than the drift and diffusion components.

Current densities in reverse bias



$N_d = 2\times10^{17}\,\text{cm}^{-3}$	$\tau_n = 1\,\text{ns}$
$N_a = 10^{17}\,\text{cm}^{-3}$	$\tau_p = 1\,\text{ns}$
$\mu_n = 1400\,\text{cm}^2/\text{V-s}$	$T = 300\,\text{K}$
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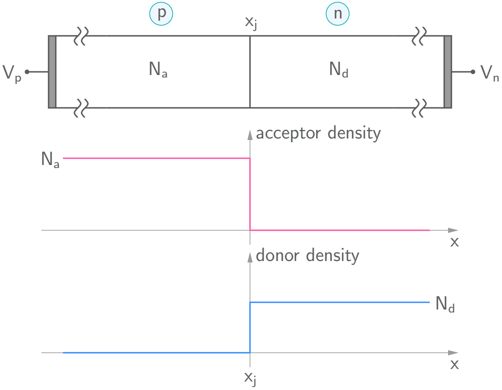
Near the junction,

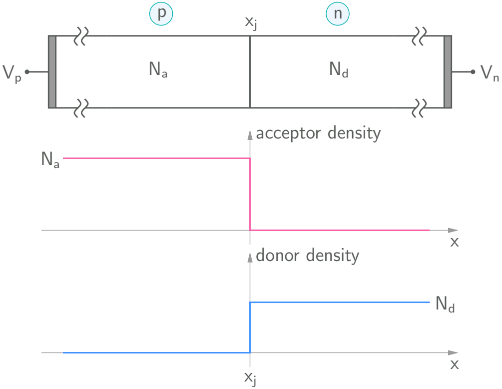
* Although the equilibrium condition is disturbed, we still have $J_p^{diff} \approx -J_p^{drift}$, and $J_n^{diff} \approx -J_n^{drift}$.
* The net current densities J_n and J_p are much smaller than the drift and diffusion components.
* Note that J_{total} in reverse bias is negligibly small compared to the forward bias case ($0.7\,\text{A/cm}^2$ for $V_a = 0.6\,\text{V}$). For all practical purposes, we can say that the current is zero for reverse bias.

Definitions:



Definitions:

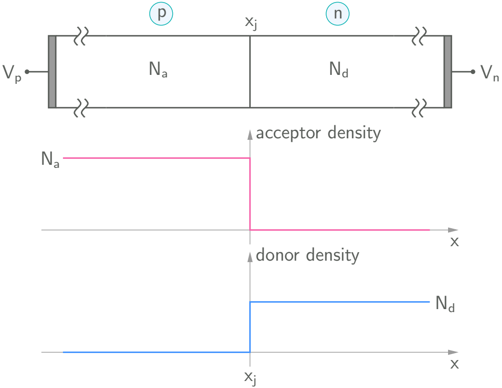
p_{p0}: equilibrium hole density in the neutral p-region



Definitions:

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

p_{n0}: equilibrium hole density in the neutral *n*-region



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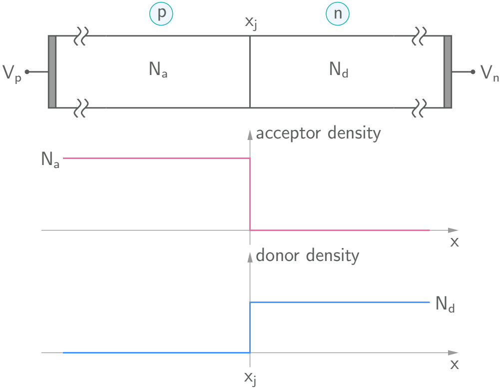

pn junction: derivation of *I*-*V* equation

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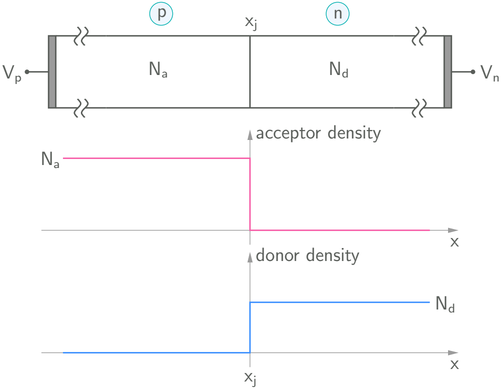

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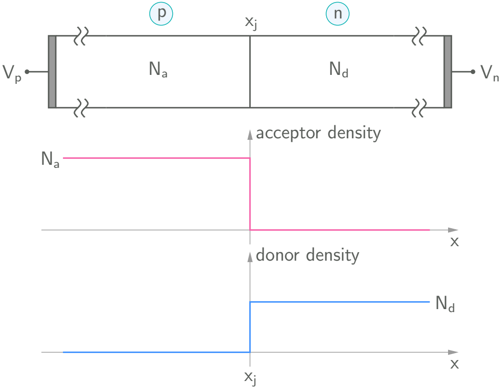

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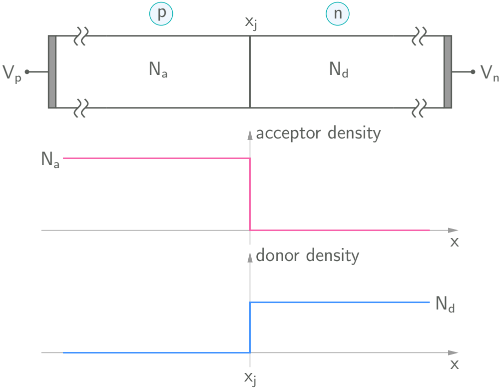

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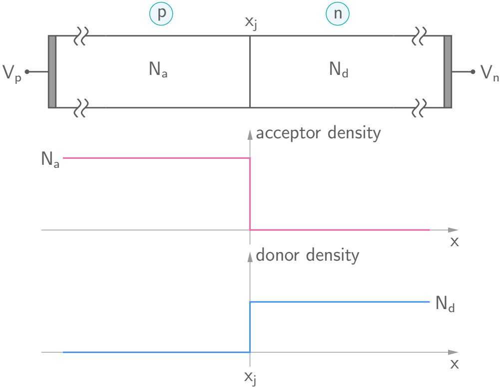
Example: $N_a = 5 \times 10^{16}\,\text{cm}^{-3}$, $N_d = 10^{18}\,\text{cm}^{-3}$ $(T = 300\,\text{K})$.



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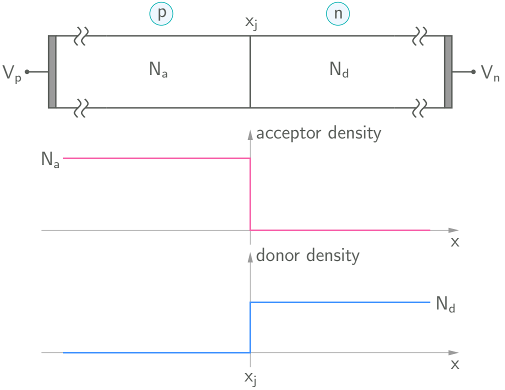
$\rightarrow p_{p0} \approx N_a = 5 \times 10^{16}\,\text{cm}^{-3}$,



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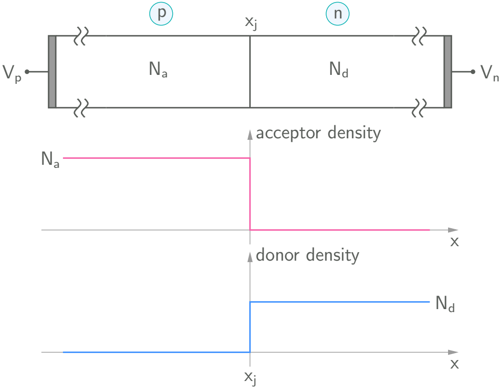

pn junction: derivation of *I*-*V* equation

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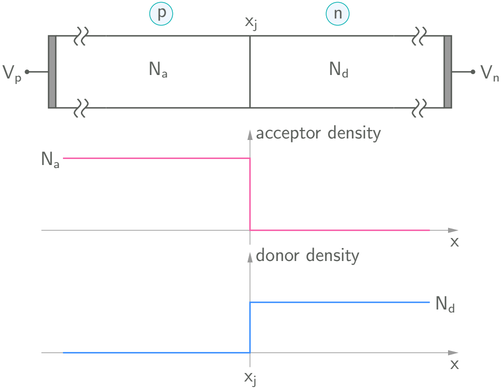
$$n_{p0} = \frac{n_i^2}{p_{p0}} = \frac{(1.5 \times 10^{10})^2}{5 \times 10^{16}} = 4.5 \times 10^3\,\text{cm}^{-3},$$



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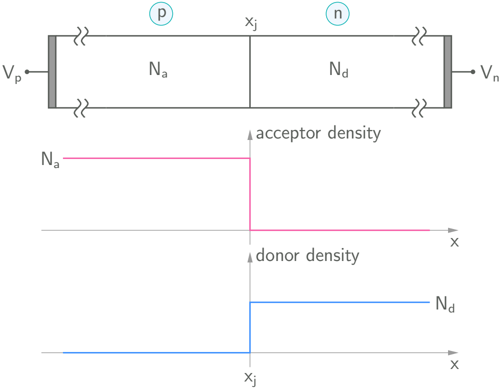
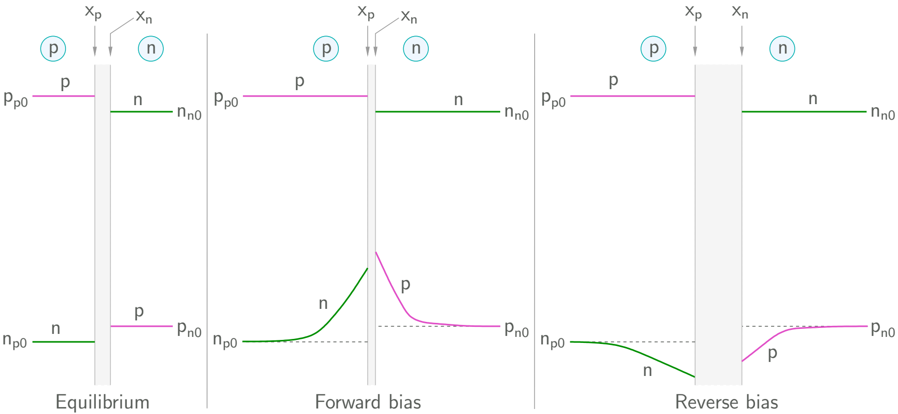
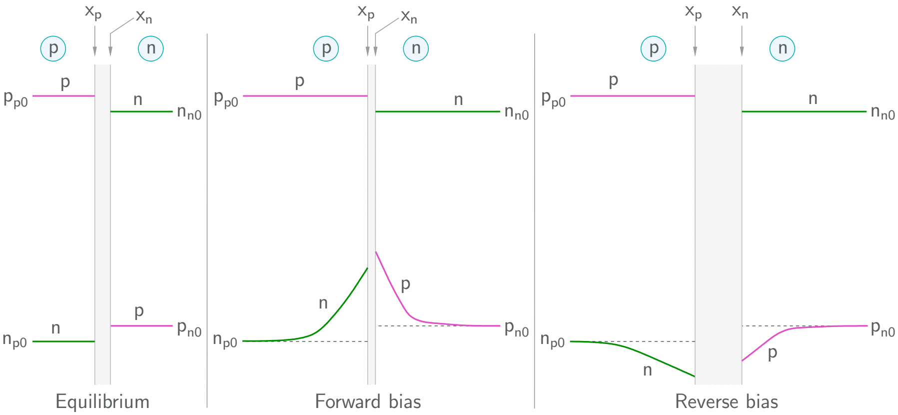
$$p_{n0} = \frac{n_i^2}{n_{n0}} = \frac{(1.5 \times 10^{10})^2}{10^{18}} = 2.25 \times 10^2\,\text{cm}^{-3}.$$



pn junction: derivation of *I*-*V* equation

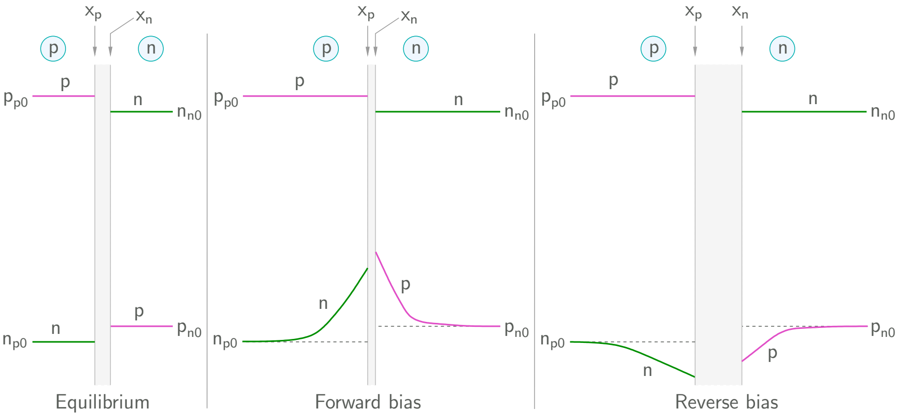


pn junction: derivation of *I*-*V* equation



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

pn junction: derivation of *I*-*V* equation



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  $p = p_{p0}$, $n = n_{p0}$ in the neutral p-region.

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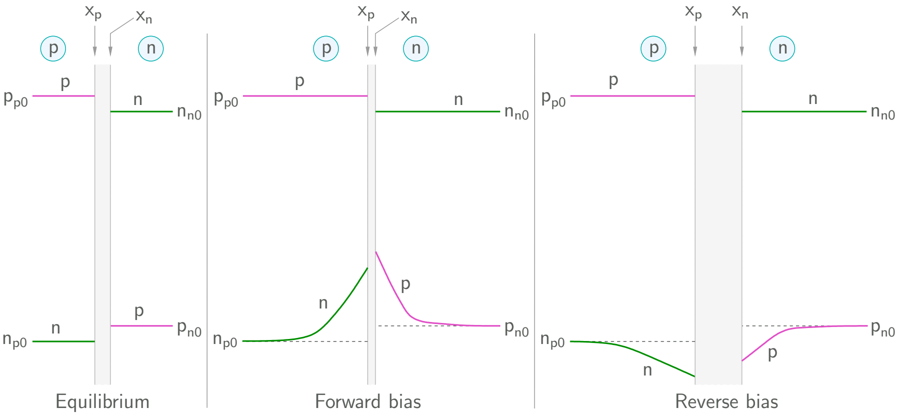

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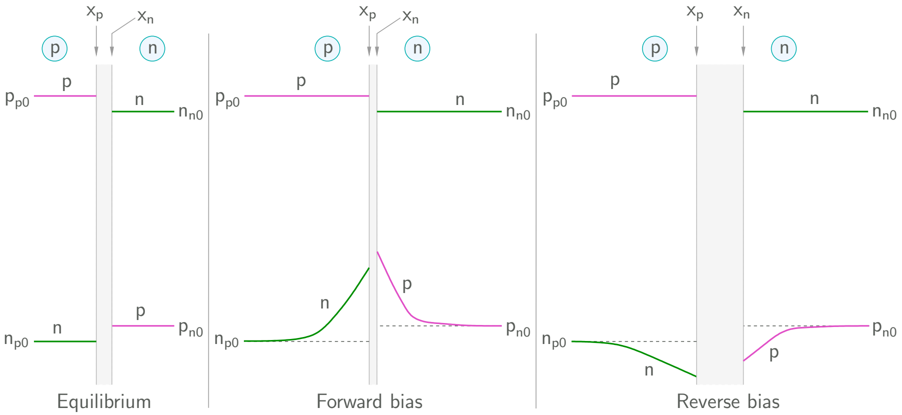
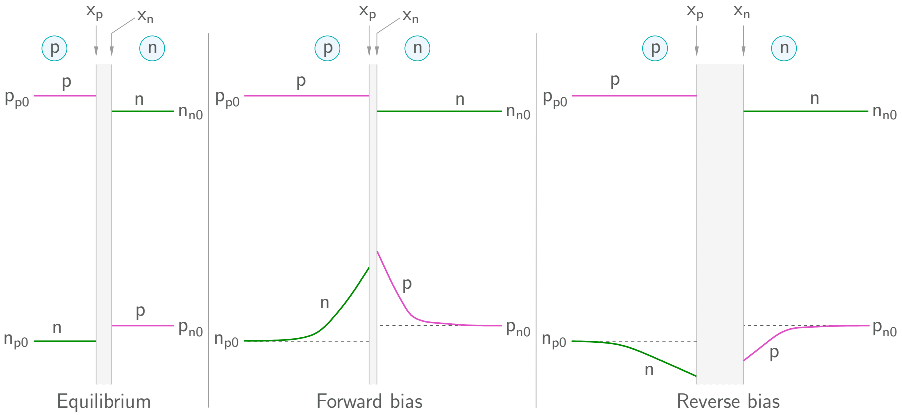
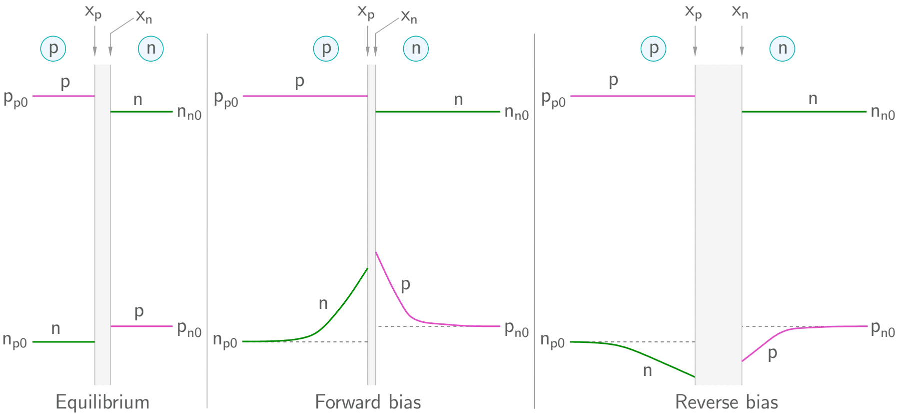


$J_p^{\text{diff}} \approx -J_p^{\text{drift}}$

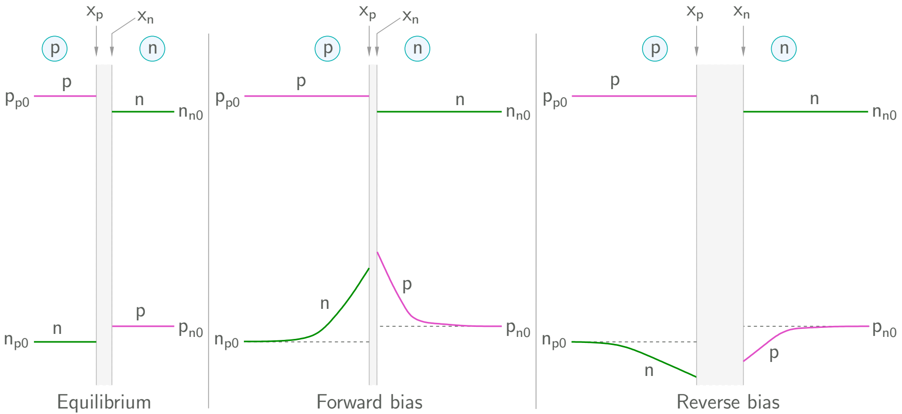


$$J_p^{\text{diff}} \approx -J_p^{\text{drift}} \;\rightarrow q\,\mu_p\,p\,\mathcal{E} = qD_p\,\frac{dp}{dx},$$

pn junction: derivation of *I*-*V* equation



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



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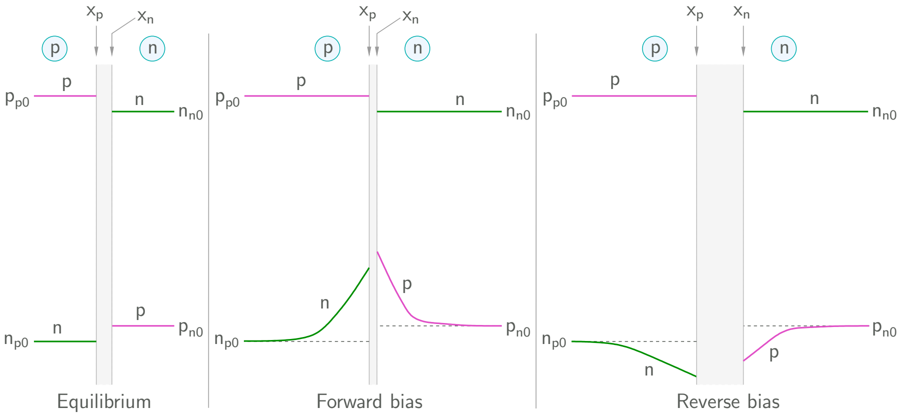
$$\frac{D}{\mu} = \frac{kT}{q} \rightarrow \int d\psi = -V_T \int \frac{1}{p}\,dp$$

pn junction: derivation of *I*-*V* equation



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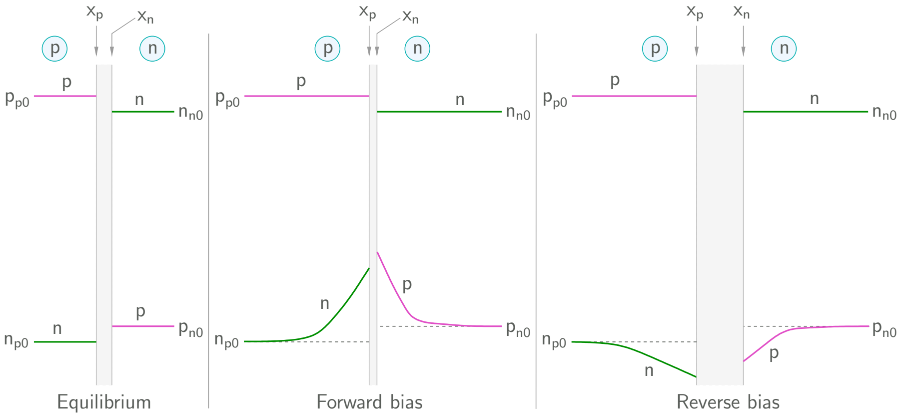
$$\frac{D}{\mu} = \frac{kT}{q} \rightarrow \int d\psi = -V_T \int \frac{1}{p}\,dp \rightarrow \psi\Big|_{x_1}^{x_2} = -V_T \log\frac{p(x_2)}{p(x_1)}$$

pn junction: derivation of *I-V* equation



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

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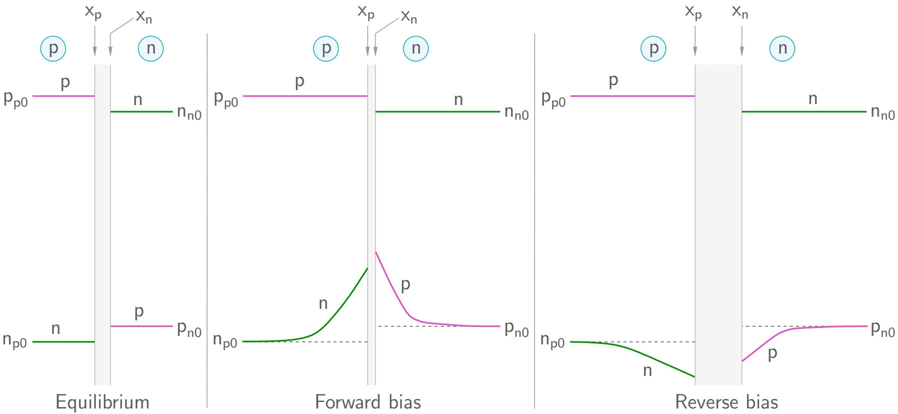
pn junction: derivation of *I*-*V* equation



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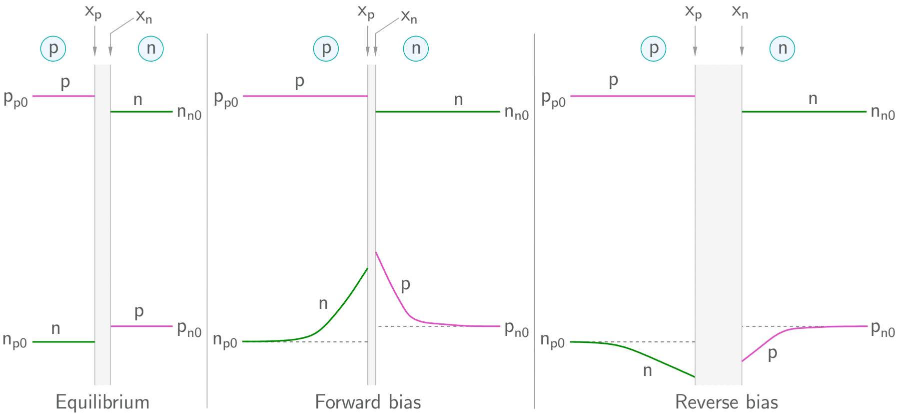
M. B. Patil, IIT Bombay

pn junction: derivation of I-V equation



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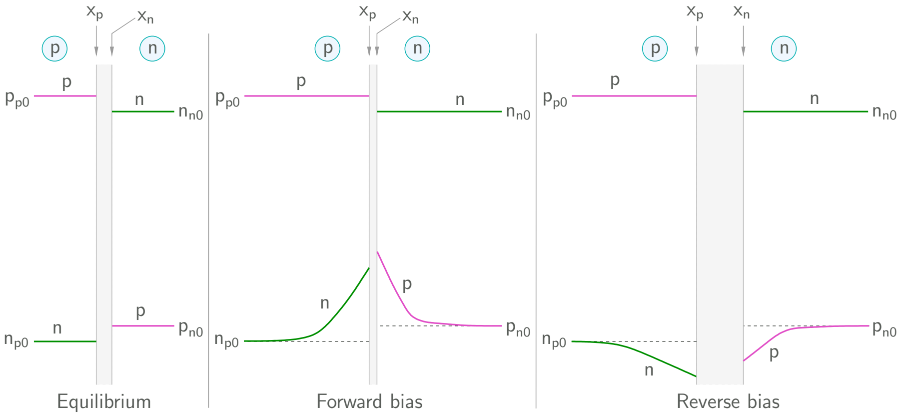
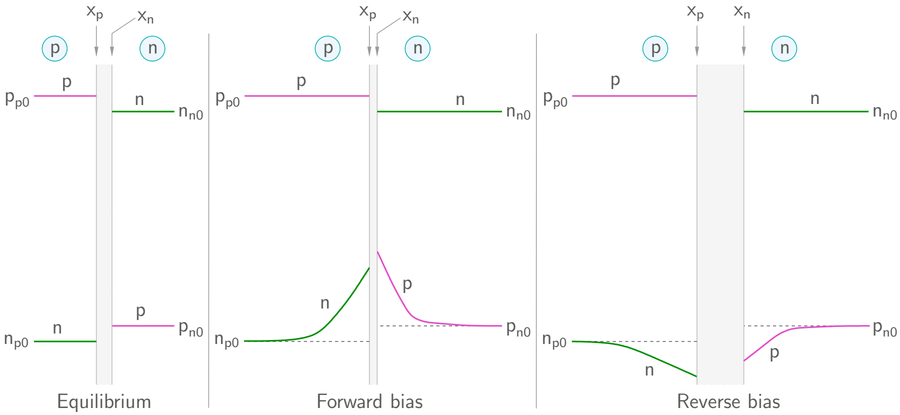
pn junction: derivation of *I*-*V* equation

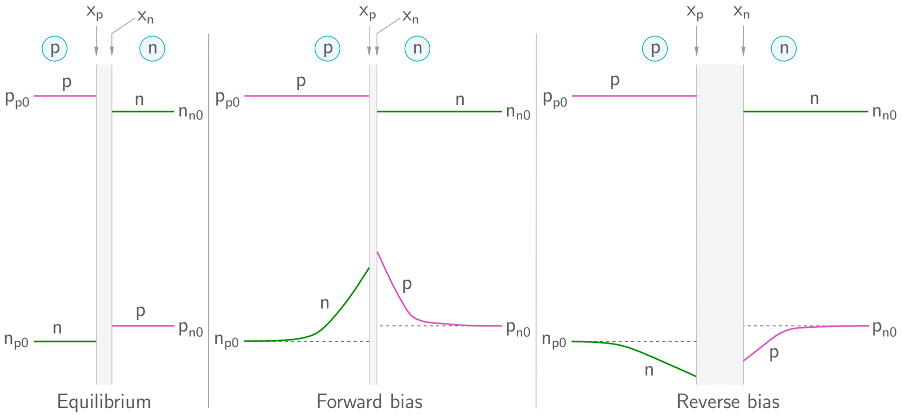


pn junction: derivation of *I-V* equation



* When a bias is applied, the minority carrier concentrations in the neutral regions can change substantially.

pn junction: derivation of *I*-*V* equation



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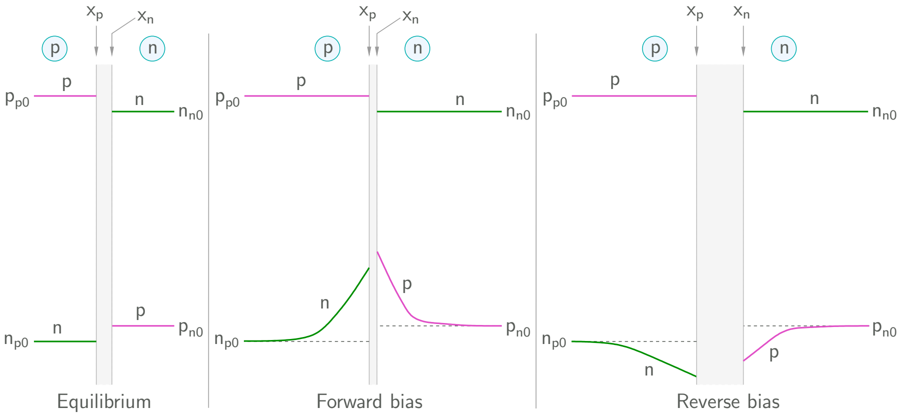
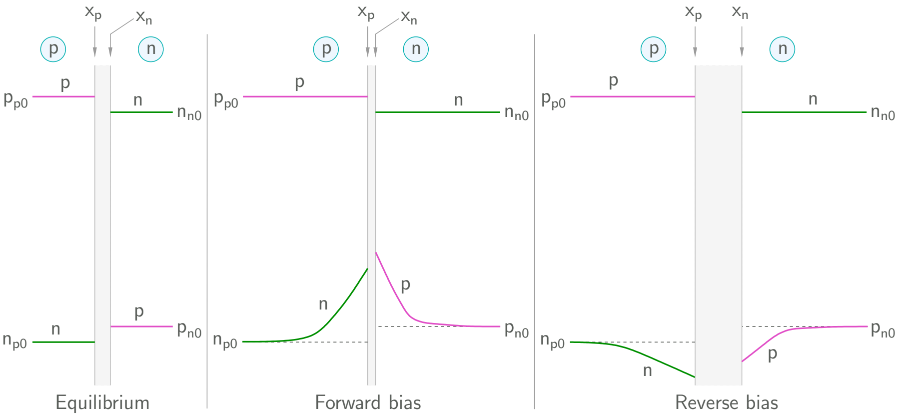
* There is a corresponding change in the majority carrier concentrations as well, and it serves to keep these regions charge-neutral.

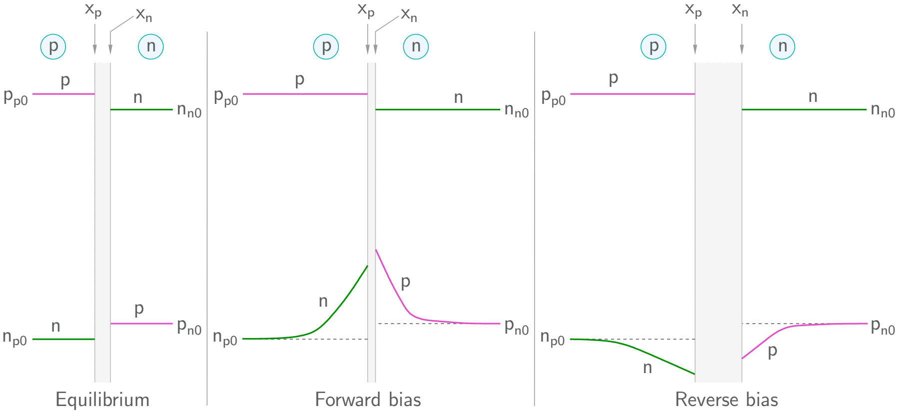


* When a bias is applied, the minority carrier concentrations in the neutral regions can change substantially.
* There is a corresponding change in the majority carrier concentrations as well, and it serves to keep these regions charge-neutral.
* Low-level injection: $\Delta n \approx \Delta p \ll p_{p0}$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

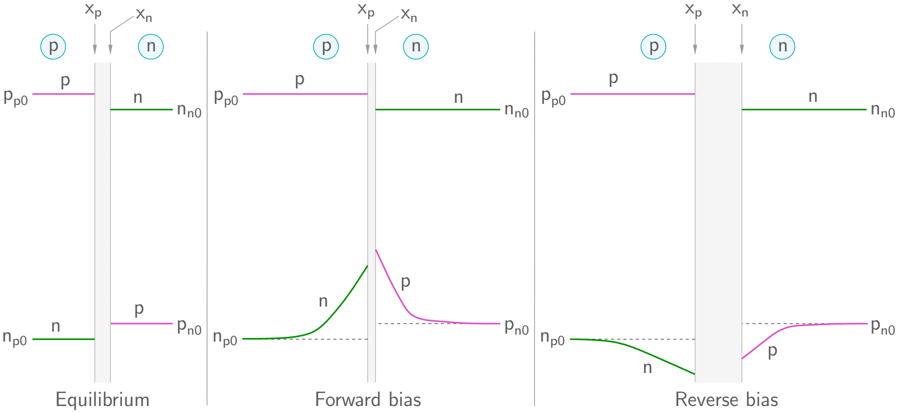
  $\Delta p \approx \Delta n \ll n_{n0}$ in the neutral *n*-region $\rightarrow n(x) \approx n_{n0}$ for $x \geq x_n$



x_p
x_n
p
n
p_{p0}
p
n
n_{n0}
p
n
n_{p0}
p_{n0}
Equilibrium
Forward bias
Reverse bias



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



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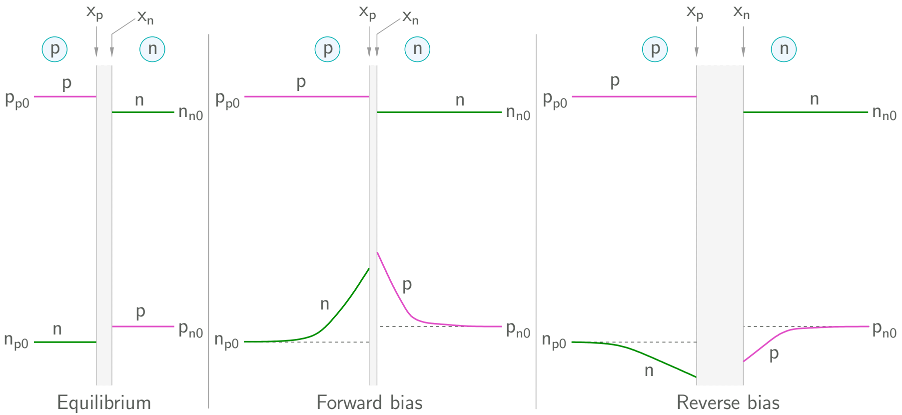

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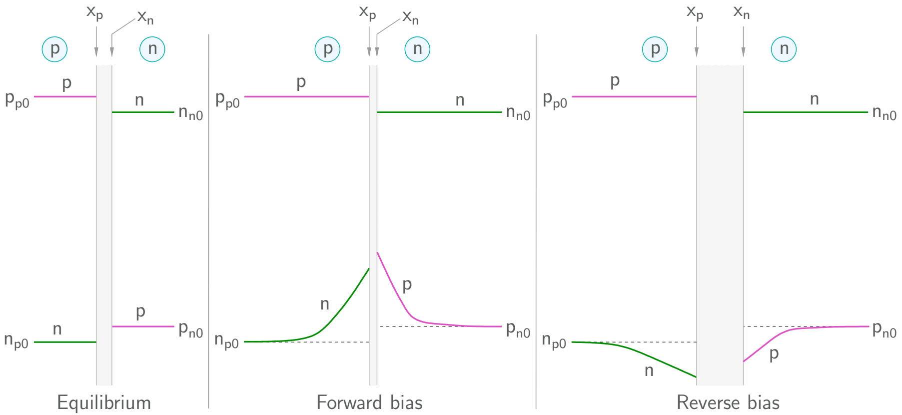
  $\rightarrow \dfrac{p(x_n)}{p_{p0}} = e^{-V_j/V_T} \rightarrow p(x_n) = p_{p0}\, e^{-V_j/V_T}$



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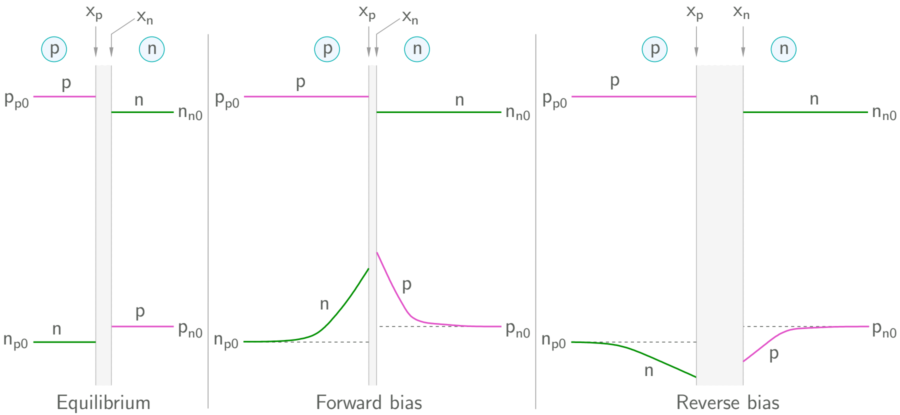
$\rightarrow \dfrac{p(x_n)}{p_{p0}} = e^{-V_j/V_T} \rightarrow p(x_n) = p_{p0}\, e^{-V_j/V_T}$

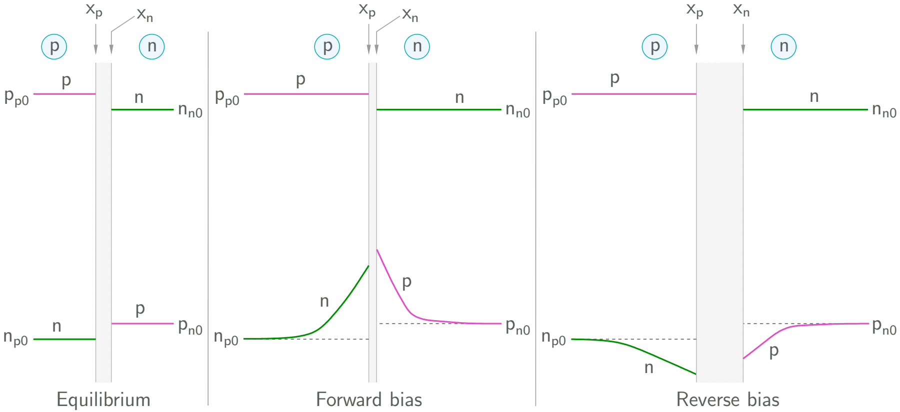
$\dfrac{n_{n0}}{n(x_p)} = e^{V_j/V_T} \quad \rightarrow n(x_p) = n_{n0}\, e^{-V_j/V_T}$.



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

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

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

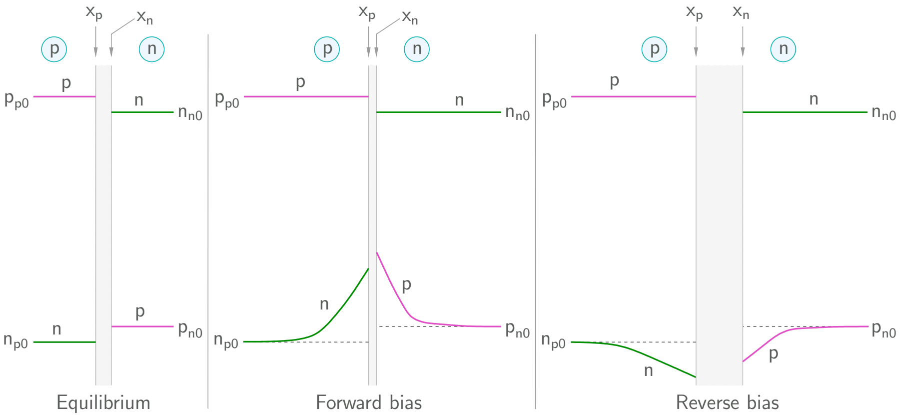


$$p(x_n) = p_{p0}\, e^{-V_j/V_T}$$

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

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

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



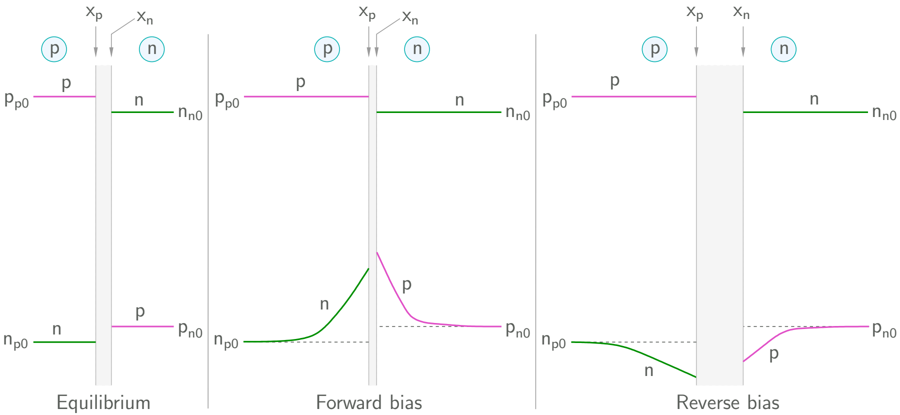
$$p(x_n) = p_{p0}\, e^{-V_j/V_T}$$

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

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

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

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



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

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

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

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

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

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

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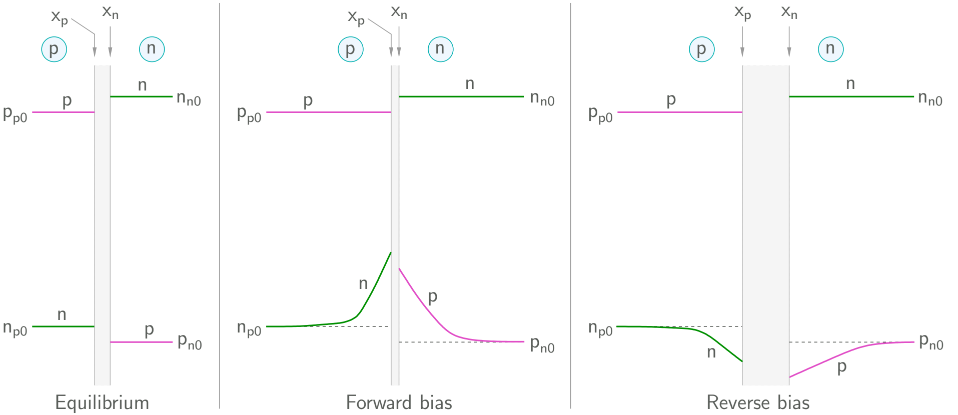
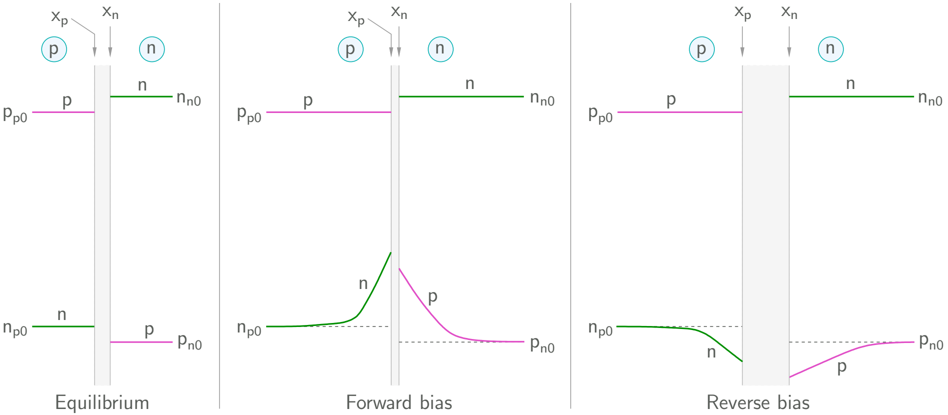
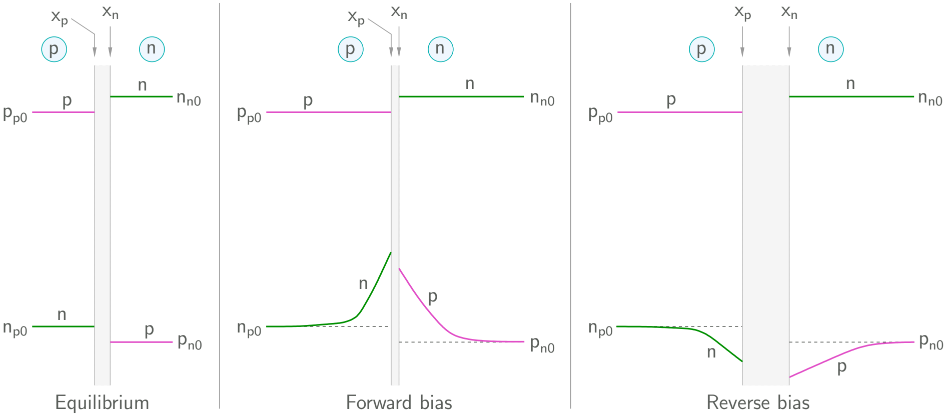


Example: Consider an abrupt, uniformly doped silicon *pn* junction at $T = 300\,\text{K}$, with $N_a = 5 \times 10^{16}\,\text{cm}^{-3}$ and $N_d = 10^{18}\,\text{cm}^{-3}$. Compute the depletion width and the minority carrier densities at the depletion region edges (x_p and x_n) for an applied bias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

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



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



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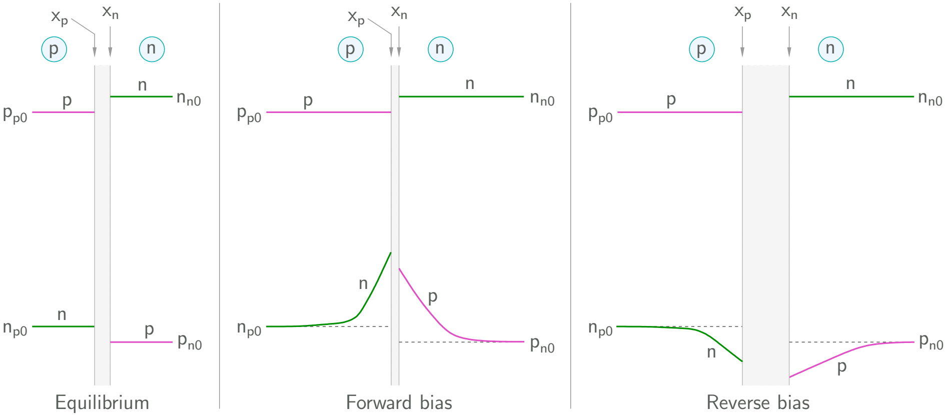
$$n_{n0} \approx N_a = 1 \times 10^{18}\,\text{cm}^{-3} \rightarrow p_{n0} = \frac{n_i^2}{n_{n0}} = \frac{(1.5 \times 10^{10})^2}{1 \times 10^{18}} = 2.25 \times 10^2\,\text{cm}^{-3}.$$



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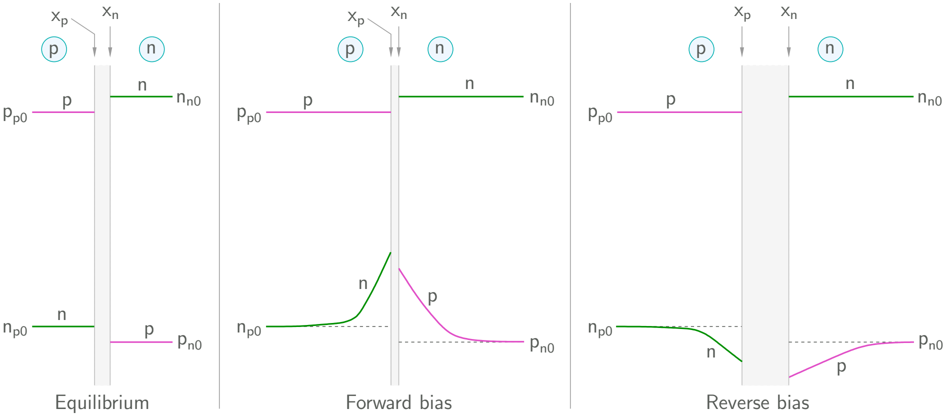
$$V_{\text{bi}} = V_T \log\left(\frac{N_a N_d}{n_i^2}\right) = (0.0259\,\text{V}) \log\left(\frac{5 \times 10^{16} \times 10^{18}}{(1.5 \times 10^{10})^2}\right) = 0.86\,\text{V}.$$



x_p
x_n
p
n
p
n
p_{p0}
n_{n0}
n
p
n_{p0}
p_{n0}
Equilibrium
x_p
x_n
p
n
p
n
p_{p0}
n_{n0}
n
p
n_{p0}
p_{n0}
Forward bias
x_p
x_n
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n
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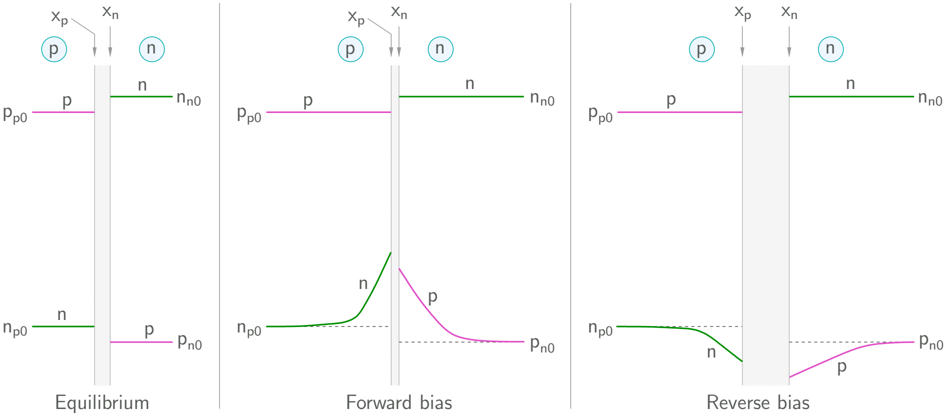
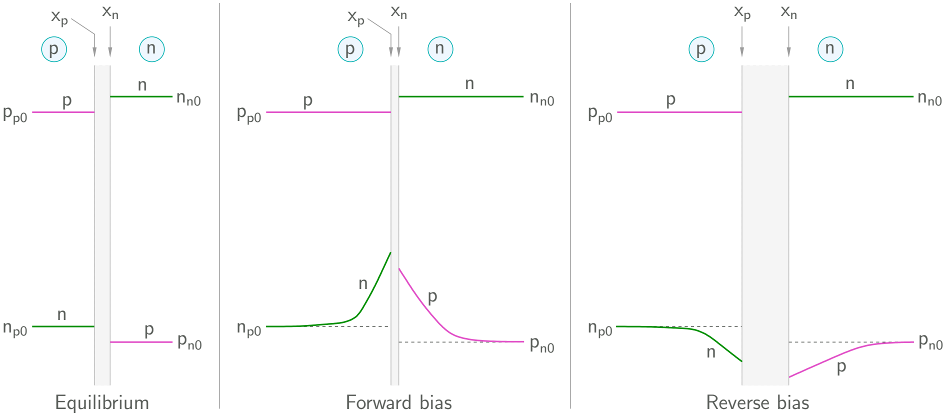
n
p_{p0}
n_{n0}
n
p
n_{p0}
p_{n0}
Reverse bias



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



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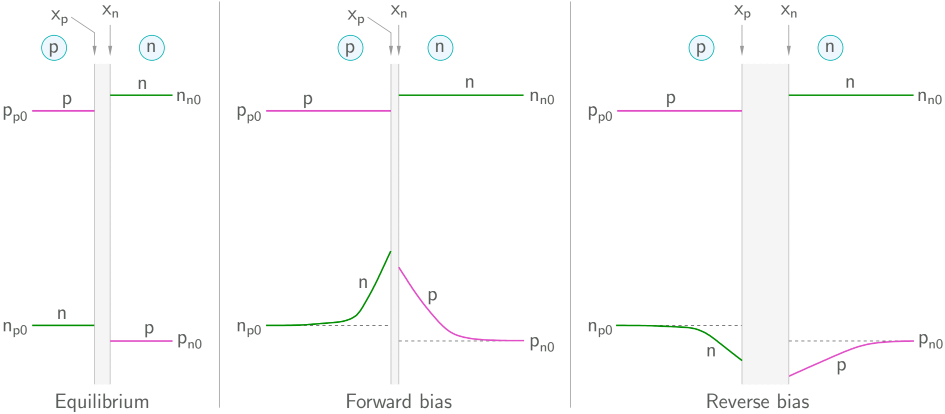
$$n(x_p) = n_{p0}\,\exp\left(\frac{V_a}{V_T}\right) = 4.5 \times 10^3 \times \exp\left(\frac{0.3}{0.0259}\right) = 4.83 \times 10^8\,\text{cm}^{-3}.$$



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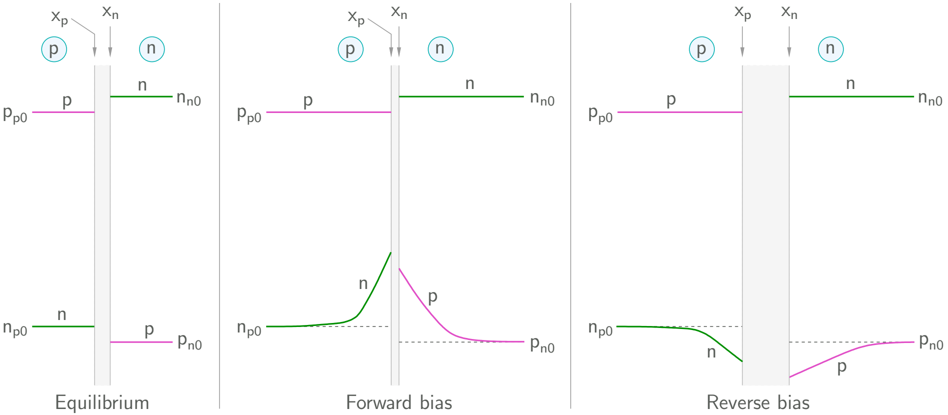
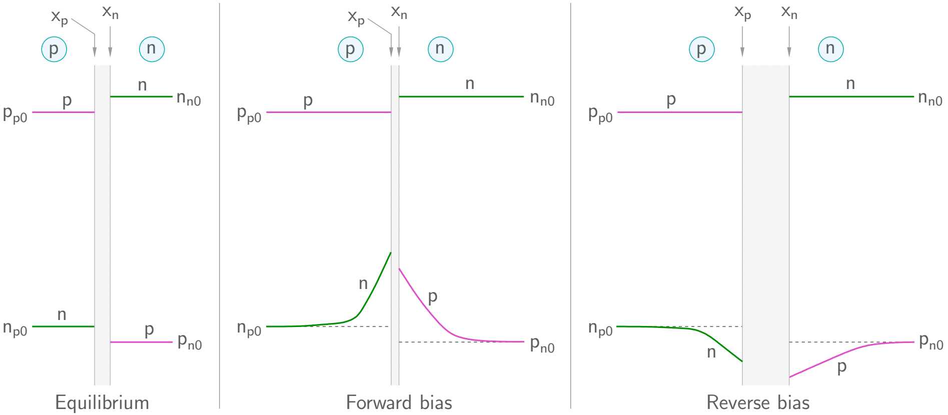
$$p(x_n) = p_{n0}\,\exp\left(\frac{V_a}{V_T}\right) = 2.25 \times 10^2 \times \exp\left(\frac{0.3}{0.0259}\right) = 2.41 \times 10^7\,\text{cm}^{-3}.$$



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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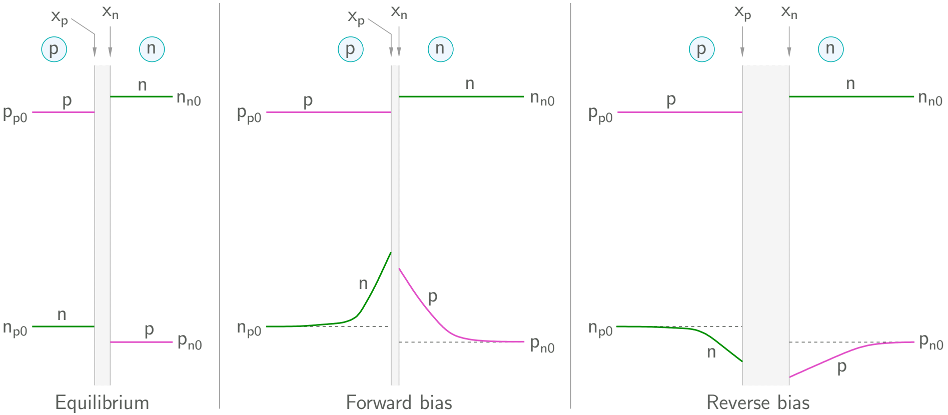

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-5.0	0.40	293.6	≈ 0	≈ 0

* 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.

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