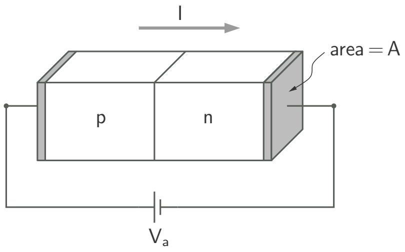
Semiconductor Devices

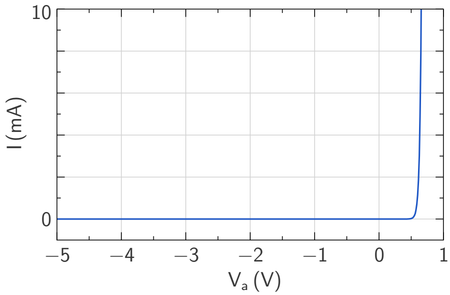
p-*n* Junctions: Part 2

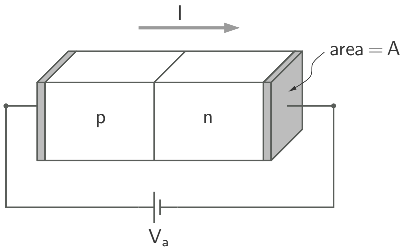
M. B. Patil
mbpatil@ee.iitb.ac.in
www.ee.iitb.ac.in/~sequel

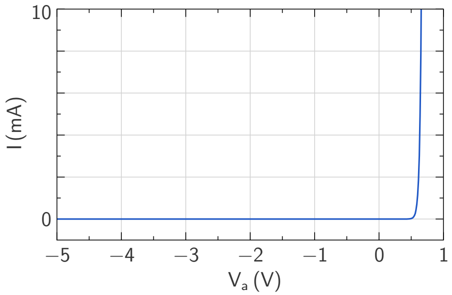
Department of Electrical Engineering
Indian Institute of Technology Bombay

pn junction under bias



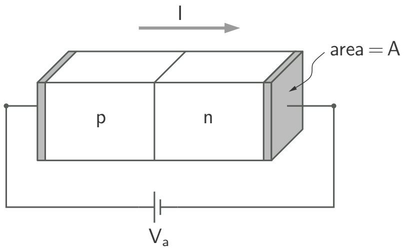


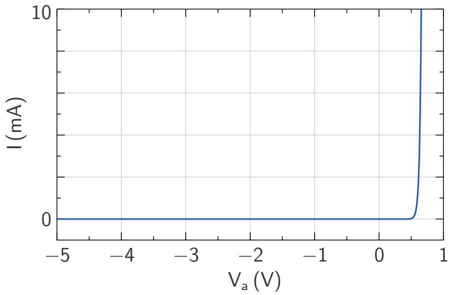




* With $V_a \approx 0.6\,\text{V}$ a substantial current flows. When V_a is increased further, the current increases rapidly.

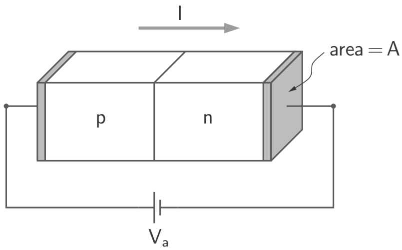
pn junction under bias

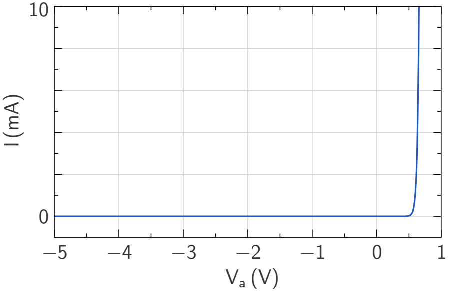




* With $V_a \approx 0.6\,\text{V}$ a substantial current flows. When V_a is increased further, the current increases rapidly.
* When a reverse bias (i.e., $V_a < 0$,V) is applied, the diode blocks conduction, i.e., the current is negligibly small.

pn junction under bias

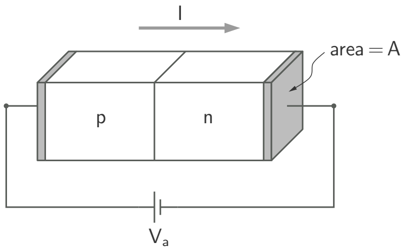


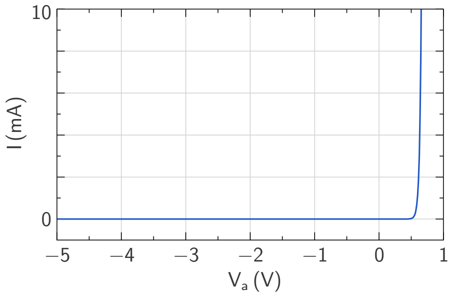


* With $V_a \approx 0.6$ V a substantial current flows. When V_a is increased further, the current increases rapidly.
* When a reverse bias (i.e., $V_a < 0$,V) is applied, the diode blocks conduction, i.e., the current is negligibly small.

  We want to understand this "rectifying" behaviour.

pn junction under bias



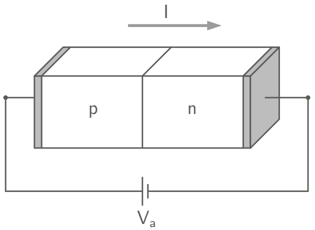


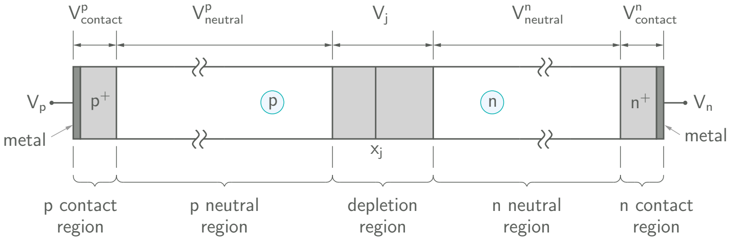
* With $V_a \approx 0.6\,\text{V}$ a substantial current flows. When V_a is increased further, the current increases rapidly.
* When a reverse bias (i.e., $V_a < 0$,V) is applied, the diode blocks conduction, i.e., the current is negligibly small.

  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.)

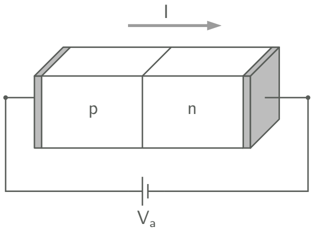
Where does the voltage drop?

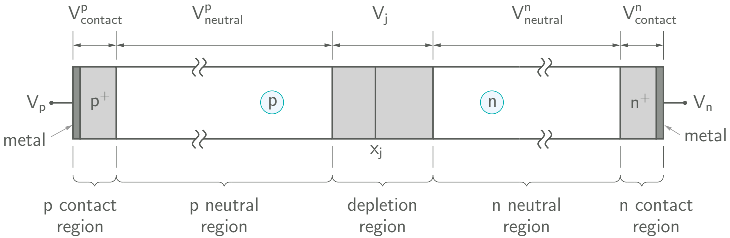




Consider a *pn* junction in equilibrium ($V_a = 0\,V$).

Where does the voltage drop?

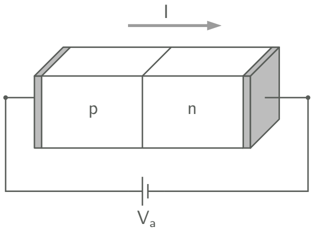


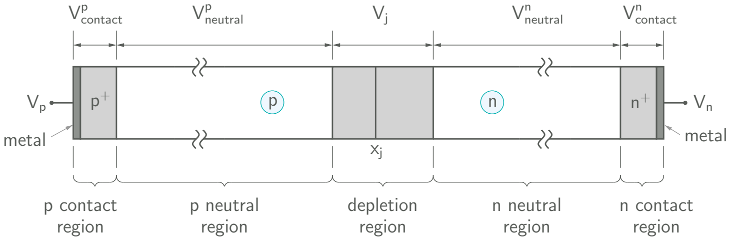


Consider a *pn* junction in equilibrium ($V_a = 0\,\text{V}$).

* V^p_{contact} and V^n_{contact} are the voltage drops across the contact regions (which generally include heavily doped regions).

Where does the voltage drop?

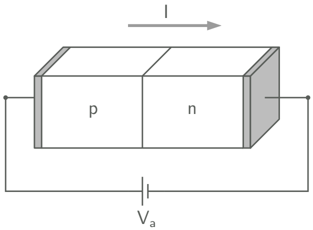


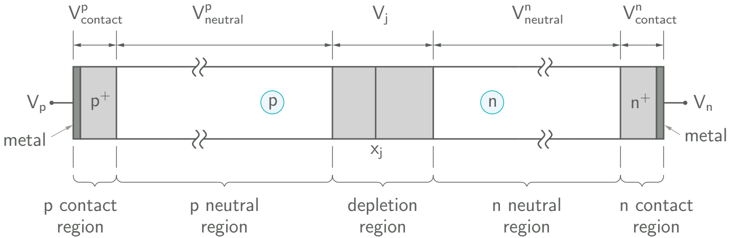


Consider a *pn* junction in equilibrium ($V_a = 0\,\text{V}$).

* V^p_{contact} and V^n_{contact} are the voltage drops across the contact regions (which generally include heavily doped regions).
* V^p_{contact} and V^n_{contact} remain constant irrespective of the applied voltage (to be discussed later).

Where does the voltage drop?

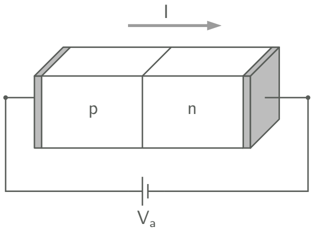


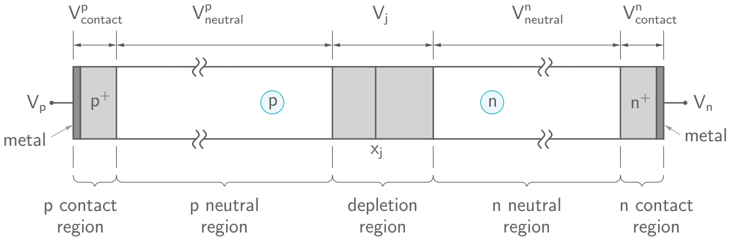


Consider a *pn* junction in equilibrium ($V_a = 0\,\mathrm{V}$).

* V^p_{contact} and V^n_{contact} are the voltage drops across the contact regions (which generally include heavily doped regions).
* V^p_{contact} and V^n_{contact} remain constant irrespective of the applied voltage (to be discussed later).
* V^p_{neutral} and V^n_{neutral} are the voltage drops across the neutral *p* and *n* regions. In equilibrium, they are both zero.

Where does the voltage drop?

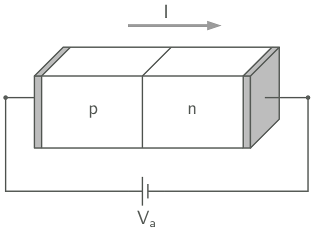


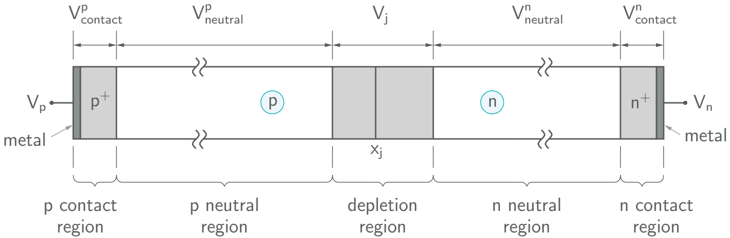


Consider a *pn* junction in equilibrium ($V_a = 0\,\text{V}$).

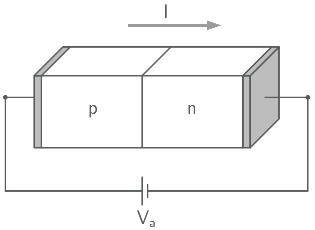
* V^p_{contact} and V^n_{contact} are the voltage drops across the contact regions (which generally include heavily doped regions).
* V^p_{contact} and V^n_{contact} remain constant irrespective of the applied voltage (to be discussed later).
* V^p_{neutral} and V^n_{neutral} are the voltage drops across the neutral *p* and *n* regions. In equilibrium, they are both zero.
* Even with current flow, V^p_{neutral} and V^n_{neutral} 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).

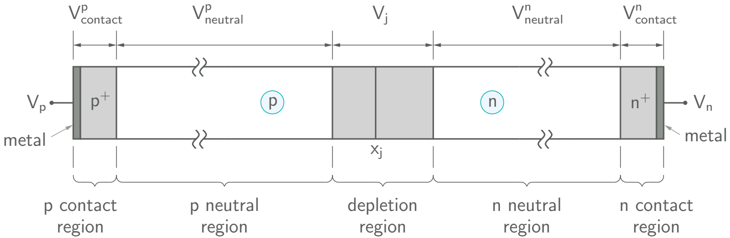
Where does the voltage drop?





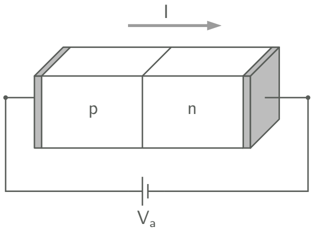
Where does the voltage drop?

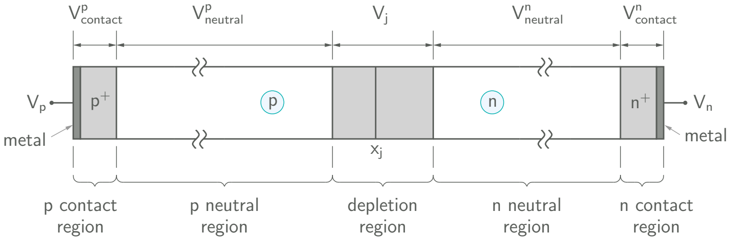




* V_j is the voltage across the junction and is equal to V_{bi} in equilibrium. We have shown, using Poisson's equation, that $V_j \propto W^2$ where W is the depletion width.

Where does the voltage drop?



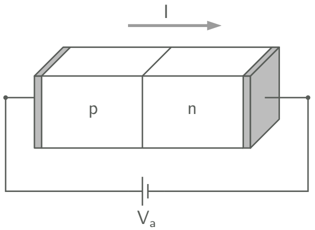


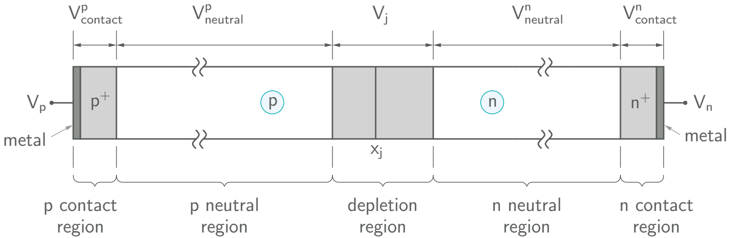
* V_j is the voltage across the junction and is equal to $V_{\rm bi}$ in equilibrium. We have shown, using Poisson's equation, that $V_j \propto W^2$ where W is the depletion width.
* In equilibrium, $V_p = V_n$, and we get

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

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

Where does the voltage drop?





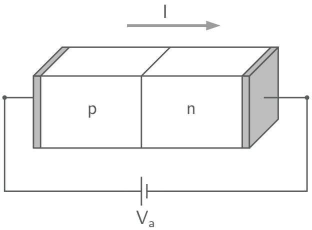
- V_j is the voltage across the junction and is equal to V_{bi} in equilibrium. We have shown, using Poisson's equation, that $V_j \propto W^2$ where W is the depletion width.
- In equilibrium, $V_p = V_n$, and we get

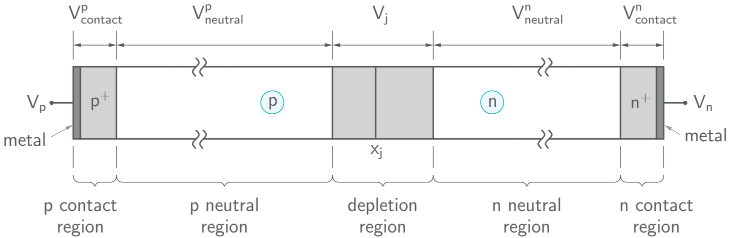
  $(1): \; V^p_{\text{contact}} - V_{\text{bi}} + V^n_{\text{contact}} = 0$, taking voltage drop as positive.

  (We assume that the signs of V^p_{contact} and V^n_{contact} are taken into account.)
- When a bias is applied, we have

  $(2): \; V^p_{\text{contact}} - V_j + V^n_{\text{contact}} = V_p - V_n = V_a$.

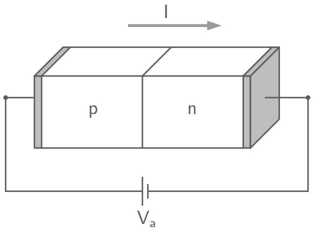
Where does the voltage drop?

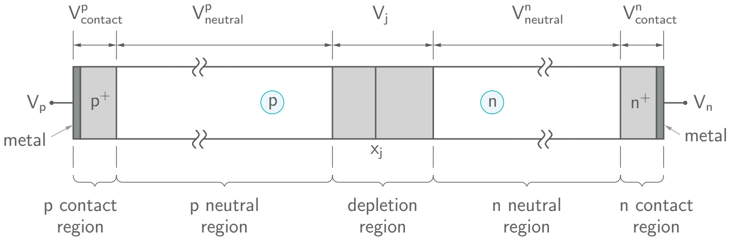




* V_j is the voltage across the junction and is equal to $V_{\rm bi}$ in equilibrium. We have shown, using Poisson's equation, that $V_j \propto W^2$ where W is the depletion width.
* In equilibrium, $V_p = V_n$, and we get
  (1) : $V^p_{\rm contact} - V_{\rm bi} + V^n_{\rm contact} = 0$, taking voltage drop as positive.
  (We assume that the signs of $V^p_{\rm contact}$ and $V^n_{\rm contact}$ are taken into account.)
* When a bias is applied, we have
  (2) : $V^p_{\rm contact} - V_j + V^n_{\rm contact} = V_p - V_n = V_a$.
* (1) − (2) gives $-V_{\rm bi} + V_j = -V_a$, i.e., $\boxed{V_j = V_{\rm bi} - V_a}$

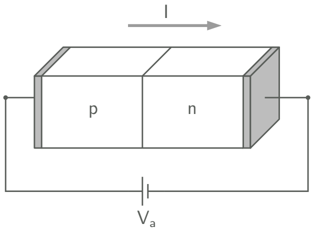
Example: forward bias

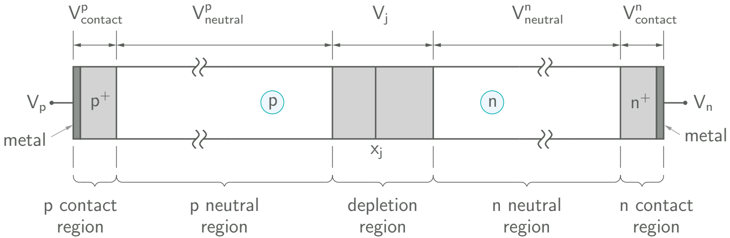




For an abrupt silicon *pn* junction, the built-in voltage is $V_{bi} = 0.85\,\text{V}$. Let W_0 and W_1 denote the depletion widths for $V_a = 0\,\text{V}$ and $V_a = 0.6\,\text{V}$, respectively. What is W_1/W_0?

Example: forward bias

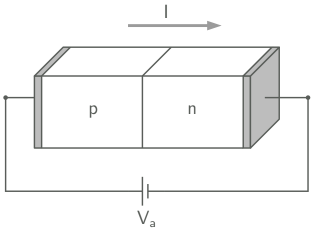


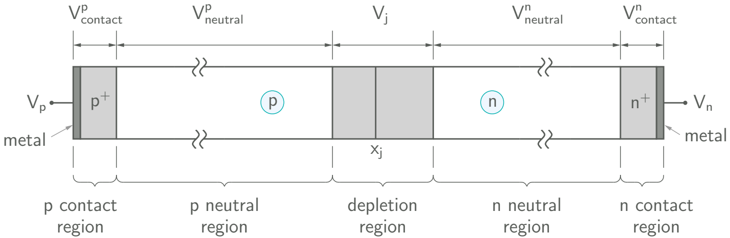


For an abrupt silicon *pn* junction, the built-in voltage is $V_{\rm bi} = 0.85\,\rm V$. Let W_0 and W_1 denote the depletion widths for $V_a = 0\,\rm V$ and $V_a = 0.6\,\rm V$, respectively. What is W_1/W_0?

Solution: $V_j \propto W^2 \rightarrow V_j = kW^2$.

Example: forward bias



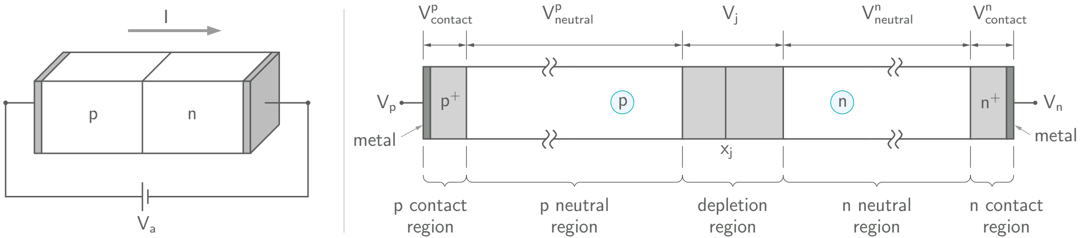


For an abrupt silicon *pn* junction, the built-in voltage is $V_{bi} = 0.85\,V$. Let W_0 and W_1 denote the depletion widths for $V_a = 0\,V$ and $V_a = 0.6\,V$, respectively. What is W_1/W_0?

Solution: $V_j \propto W^2 \rightarrow V_j = kW^2$.

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

Example: forward bias

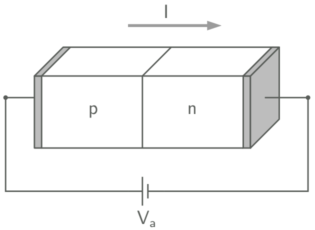


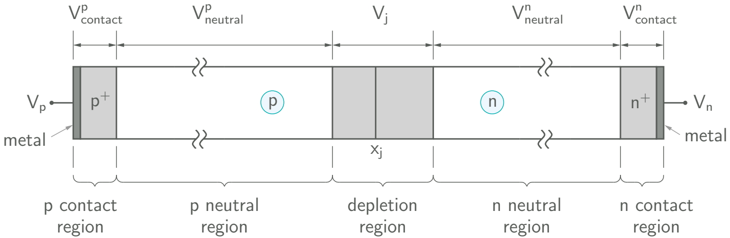
For an abrupt silicon *pn* junction, the built-in voltage is $V_{bi} = 0.85\,\text{V}$. Let W_0 and W_1 denote the depletion widths for $V_a = 0\,\text{V}$ and $V_a = 0.6\,\text{V}$, respectively. What is W_1/W_0?

Solution: $V_j \propto W^2 \rightarrow V_j = kW^2$.

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

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





For an abrupt silicon *pn* junction, the built-in voltage is $V_{\text{bi}} = 0.85\,\text{V}$. 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?

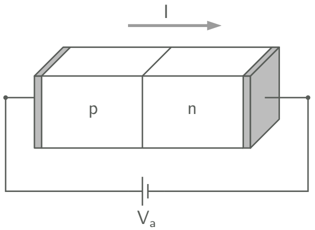
Solution: $V_j \propto W^2 \rightarrow V_j = kW^2$.

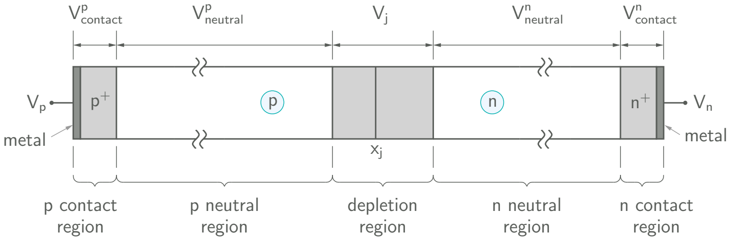
$$V_{\text{bi}} = kW_0^2 \quad (\text{for } V_a = 0\,\text{V})$$

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

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

Example: forward bias





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?

Solution: $V_j \propto W^2 \rightarrow V_j = kW^2$.

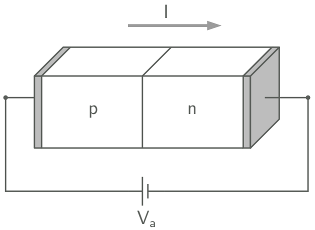
$$V_{bi} = kW_0^2 \qquad (\text{for } V_a = 0\,\text{V})$$

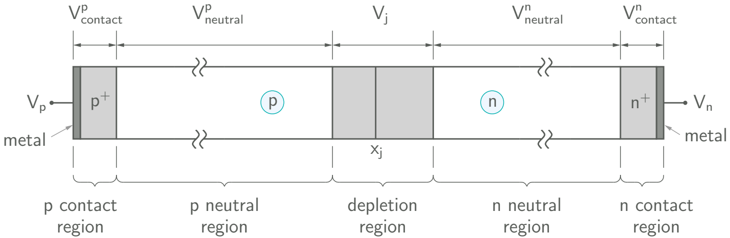
$$V_{bi} - 0.6\,\text{V} = kW_1^2 \qquad (\text{for } V_a = 0.6\,\text{V})$$

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

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

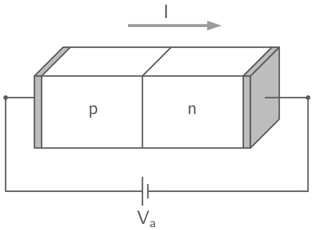
Example: reverse bias

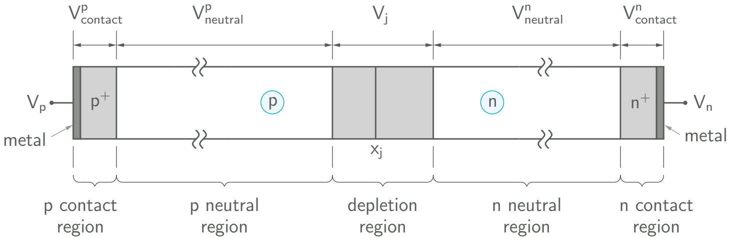




For an abrupt silicon *pn* junction, the built-in voltage is $V_{bi} = 0.85\,\text{V}$. Let W_0 and W_1 denote the depletion widths for $V_a = 0\,\text{V}$ and $V_a = -2\,\text{V}$ (i.e., a reverse bias V_R of $2\,\text{V}$), respectively. What is W_1/W_0?

Example: reverse bias

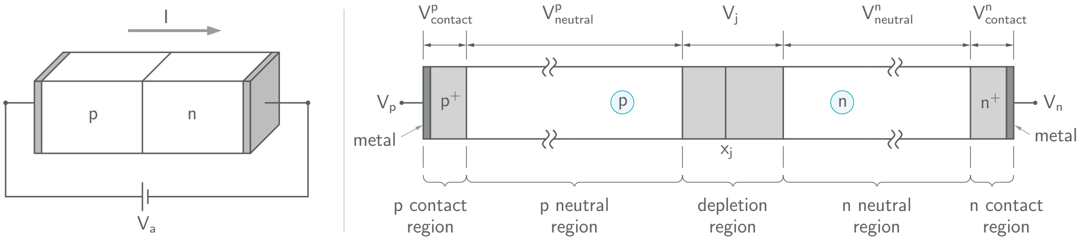




For an abrupt silicon *pn* junction, the built-in voltage is $V_{\rm bi} = 0.85\,\text{V}$. Let W_0 and W_1 denote the depletion widths for $V_a = 0\,\text{V}$ and $V_a = -2\,\text{V}$ (i.e., a reverse bias V_R of $2\,\text{V}$), respectively. What is W_1/W_0?

Solution: $V_j \propto W^2 \rightarrow V_j = kW^2$.

Example: reverse bias

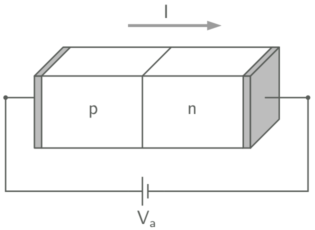


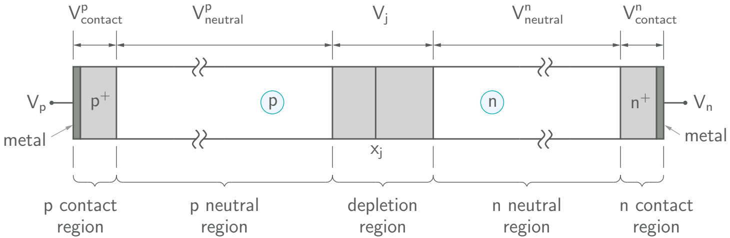
For an abrupt silicon *pn* junction, the built-in voltage is $V_{\rm bi} = 0.85\,$V. Let W_0 and W_1 denote the depletion widths for $V_a = 0\,$V and $V_a = -2\,$V (i.e., a reverse bias V_R of 2 V), respectively. What is W_1/W_0?

Solution: $V_j \propto W^2 \rightarrow V_j = kW^2$.

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

Example: reverse bias





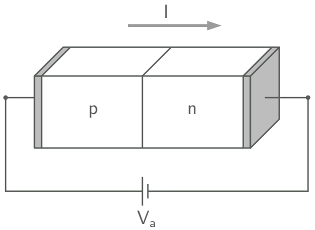
For an abrupt silicon *pn* junction, the built-in voltage is $V_{\rm bi} = 0.85\,{\rm V}$. Let W_0 and W_1 denote the depletion widths for $V_a = 0\,{\rm V}$ and $V_a = -2\,{\rm V}$ (i.e., a reverse bias V_R of 2 V), respectively. What is W_1/W_0?

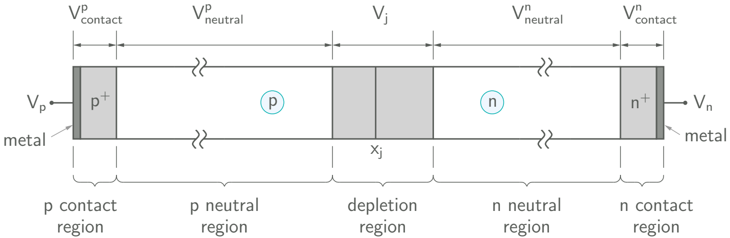
Solution: $V_j \propto W^2 \rightarrow V_j = kW^2$.

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

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

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?

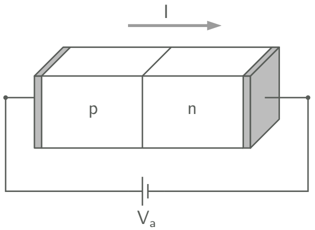
Solution: $V_j \propto W^2 \rightarrow V_j = kW^2$.

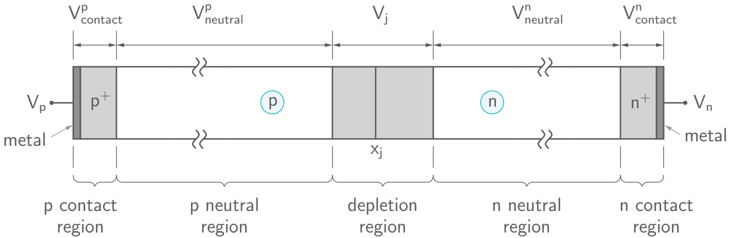
$$V_{bi} = kW_0^2 \quad (\text{for } V_a = 0\,V)$$

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

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

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?

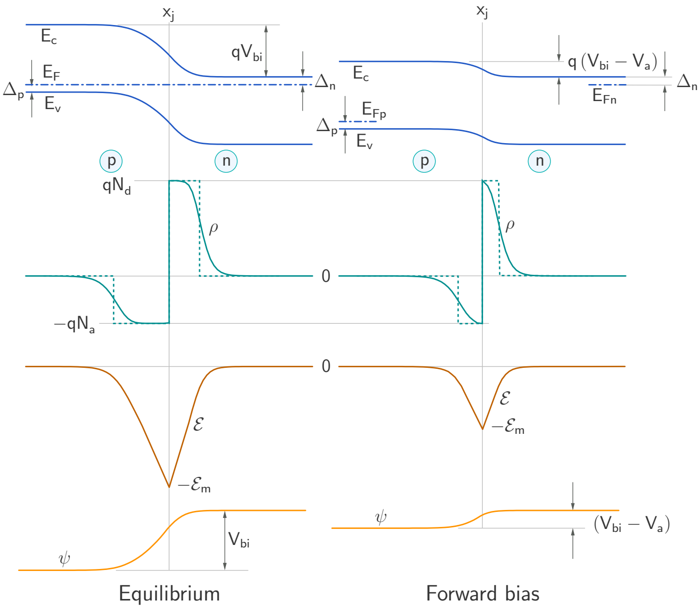
Solution: $V_j \propto W^2 \rightarrow V_j = kW^2$.

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

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

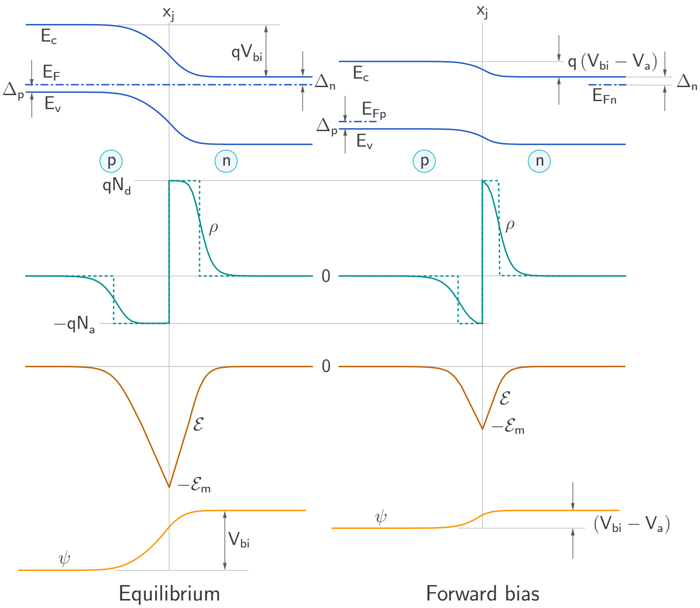
Application of a reverse bias of $2\,\mathrm{V}$ causes the depletion regoin to expand by a factor 1.83.

Forward bias



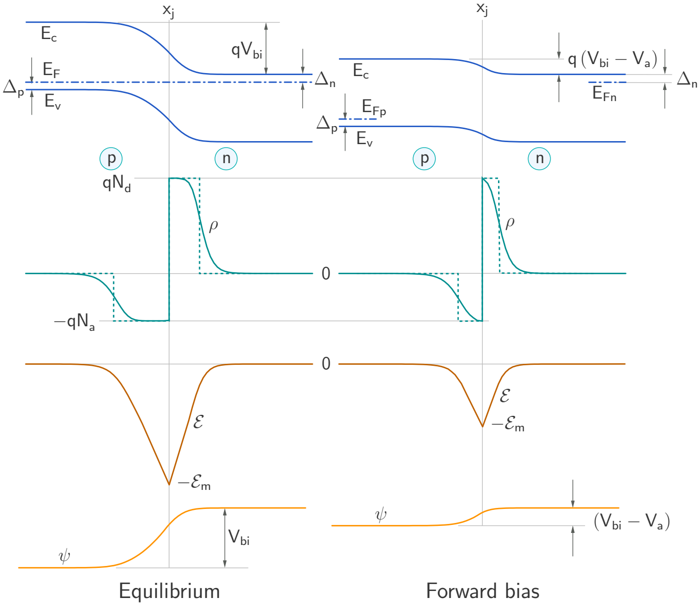
Forward bias

* The electrostatic conditions (viz., $\rho(x)$, $\mathcal{E}(x)$, $\psi(x)$) under forward bias are similar to the equilibrium situation except for a reduced junction voltage $(V_{bi} - V_a)$.



Forward bias

* The electrostatic conditions (viz., $\rho(x)$, $\mathcal{E}(x)$, $\psi(x)$) under forward bias are similar to the equilibrium situation except for a reduced junction voltage $(V_{\rm bi} - V_a)$.
* The depletion width, the maximum electric field, and the junction voltage drop decrease with forward bias.

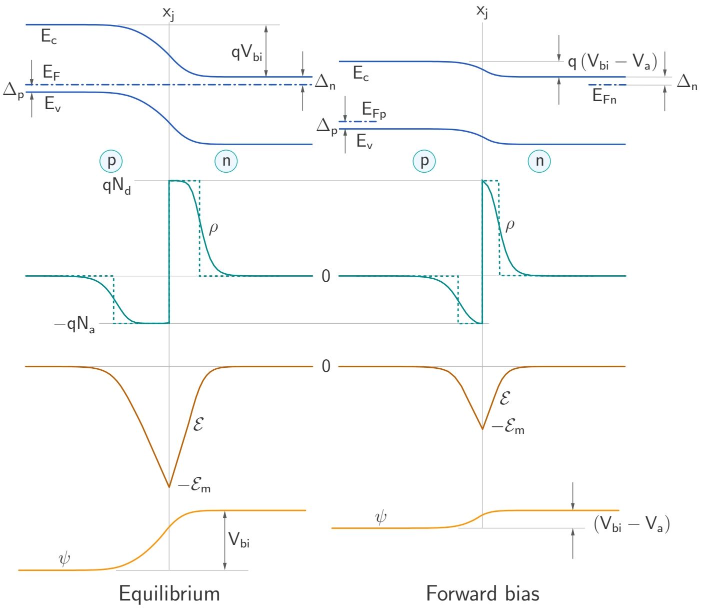


Forward bias

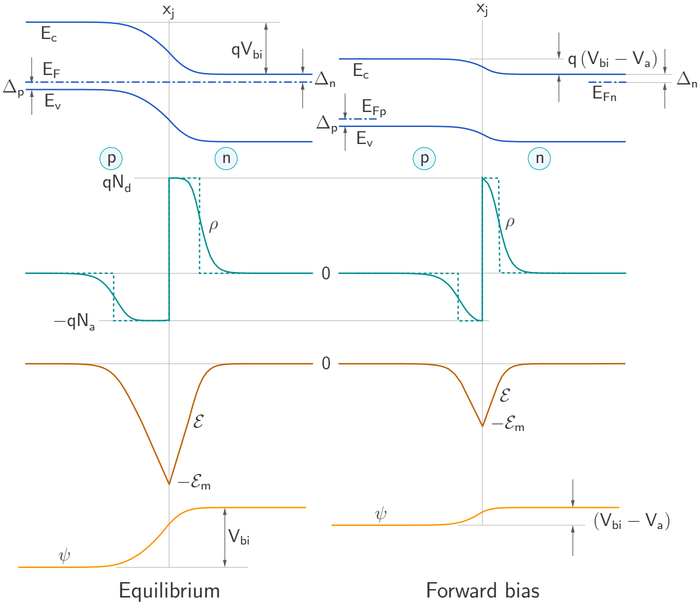
* The electrostatic conditions (viz., $\rho(x)$, $\mathcal{E}(x)$, $\psi(x)$) under forward bias are similar to the equilibrium situation except for a reduced junction voltage $(V_{\text{bi}} - V_a)$.
* The depletion width, the maximum electric field, and the junction voltage drop decrease with forward bias.
* Solving Poisson's equation using the depletion approximation, we get

$$W = \sqrt{\frac{2\epsilon}{q}\left(\frac{N_a + N_d}{N_a N_d}\right)(V_{\text{bi}} - V_a)},$$

$$W_n = \frac{N_a}{N_a + N_d}\, W, \quad W_p = \frac{N_d}{N_a + N_d}\, W.$$

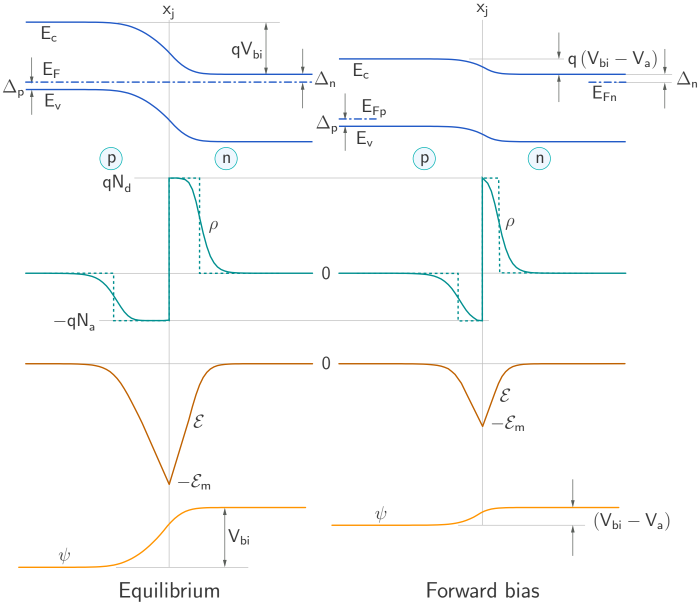


Forward bias



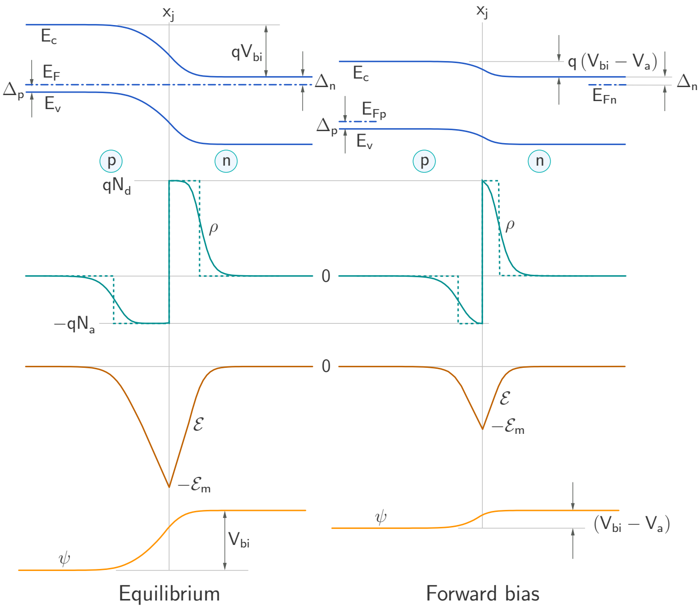
Forward bias

* Although the equilibrium condition is disturbed with an applied bias, the situation sufficiently far from the depletion region is hardly different.



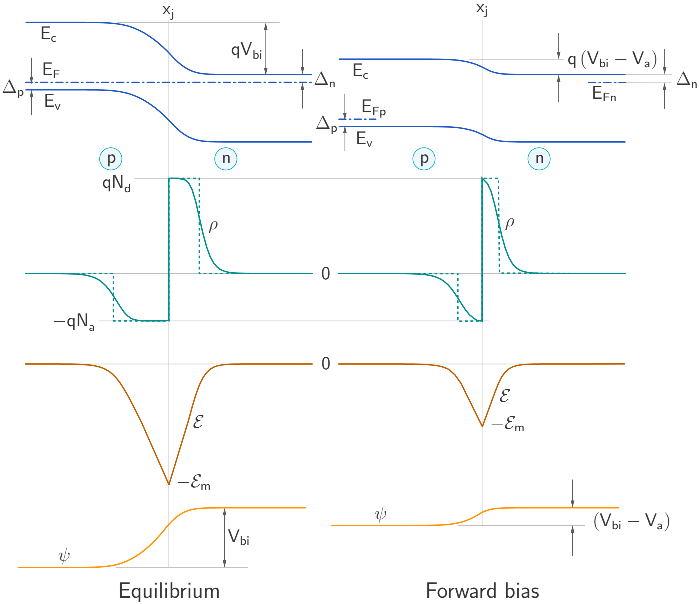
Forward bias

* Although the equilibrium condition is disturbed with an applied bias, the situation sufficiently far from the depletion region is hardly different.
* We can extend the Fermi level concept to describe carrier concentrations sufficiently far from the depletion region.



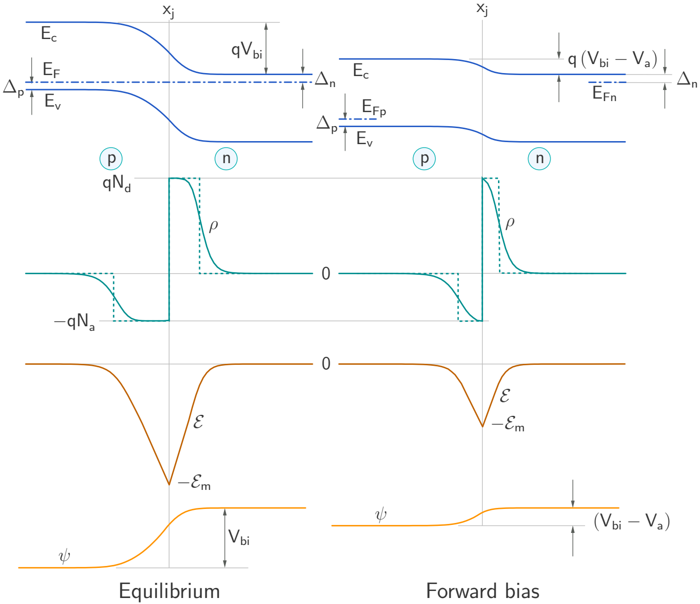
Forward bias

* Although the equilibrium condition is disturbed with an applied bias, the situation sufficiently far from the depletion region is hardly different.
* We can extend the Fermi level concept to describe carrier concentrations sufficiently far from the depletion region.
* $p = N_v e^{-(E_{Fp}-E_v)/kT}$ on the p-side,
  $n = N_c e^{-(E_c-E_{Fn})/kT}$ on the n-side.



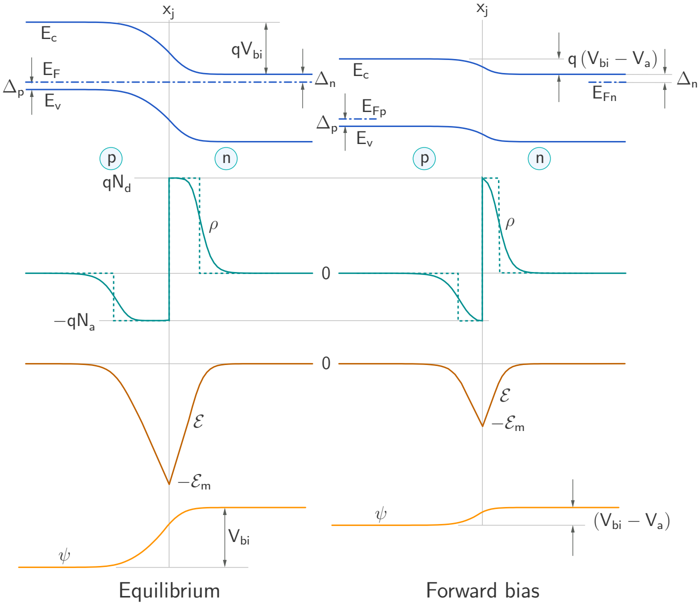
Forward bias

* Although the equilibrium condition is disturbed with an applied bias, the situation sufficiently far from the depletion region is hardly different.
* We can extend the Fermi level concept to describe carrier concentrations sufficiently far from the depletion region.
* $p = N_v e^{-(E_{Fp}-E_v)/kT}$ on the p-side,
  $n = N_c e^{-(E_c-E_{Fn})/kT}$ on the n-side.
* The Fermi levels are called "quasi Fermi levels" since the situation is *almost* like equilibrium.



Forward bias

* Although the equilibrium condition is disturbed with an applied bias, the situation sufficiently far from the depletion region is hardly different.
* We can extend the Fermi level concept to describe carrier concentrations sufficiently far from the depletion region.
* $p = N_v e^{-(E_{Fp}-E_v)/kT}$ on the *p*-side,
  $n = N_c e^{-(E_c-E_{Fn})/kT}$ on the *n*-side.
* The Fermi levels are called "quasi Fermi levels" since the situation is *almost* like equilibrium.
* From the band diagram, we see that
  $E_g = \Delta_p + \Delta_n + qV_{\text{bi}}$,



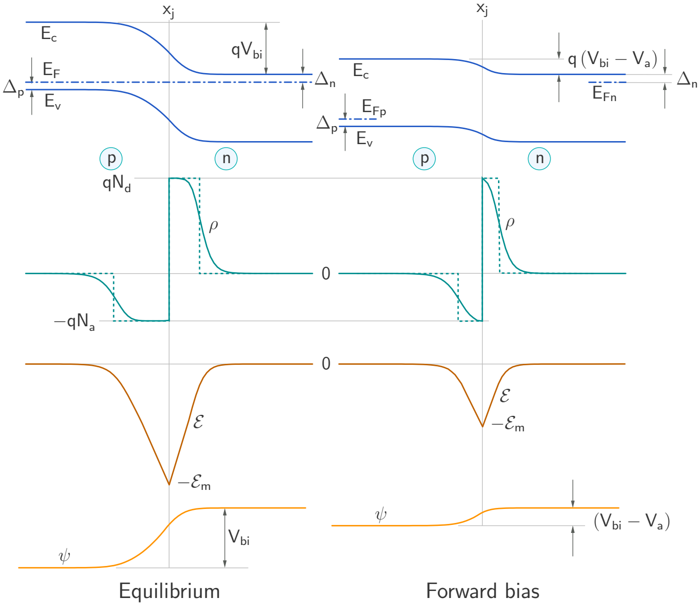
Forward bias

* Although the equilibrium condition is disturbed with an applied bias, the situation sufficiently far from the depletion region is hardly different.
* We can extend the Fermi level concept to describe carrier concentrations sufficiently far from the depletion region.
* $p = N_v e^{-(E_{Fp}-E_v)/kT}$ on the p-side,

  $n = N_c e^{-(E_c-E_{Fn})/kT}$ on the n-side.
* The Fermi levels are called "quasi Fermi levels" since the situation is *almost* like equilibrium.
* From the band diagram, we see that

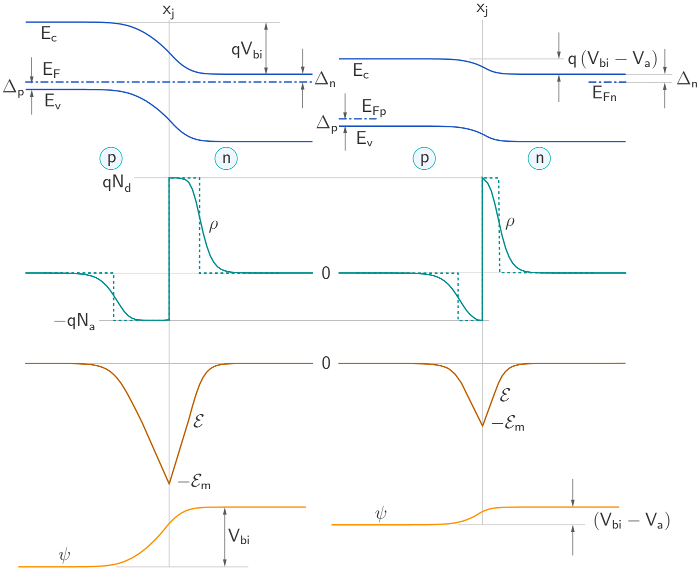
  $E_g = \Delta_p + \Delta_n + qV_{\text{bi}}$,

  $E_g = \Delta_p + (E_{Fn} - E_{Fp}) + \Delta_n + q(V_{\text{bi}} - V_a)$



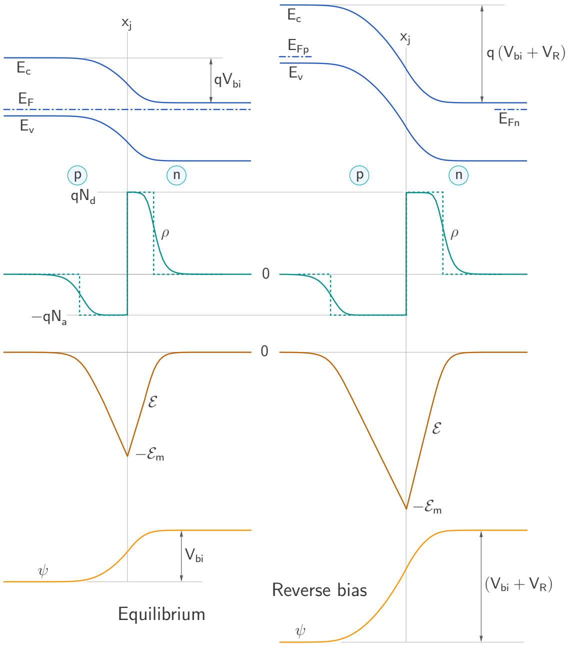
Forward bias

* Although the equilibrium condition is disturbed with an applied bias, the situation sufficiently far from the depletion region is hardly different.
* We can extend the Fermi level concept to describe carrier concentrations sufficiently far from the depletion region.
* $p = N_v e^{-(E_{Fp}-E_v)/kT}$ on the p-side,
  $n = N_c e^{-(E_c-E_{Fn})/kT}$ on the n-side.
* The Fermi levels are called "quasi Fermi levels" since the situation is *almost* like equilibrium.
* From the band diagram, we see that
  $E_g = \Delta_p + \Delta_n + qV_{\text{bi}}$,
  $E_g = \Delta_p + (E_{Fn} - E_{Fp}) + \Delta_n + q(V_{\text{bi}} - V_a)$
  $\rightarrow E_{Fn} - E_{Fp} = qV_a$.



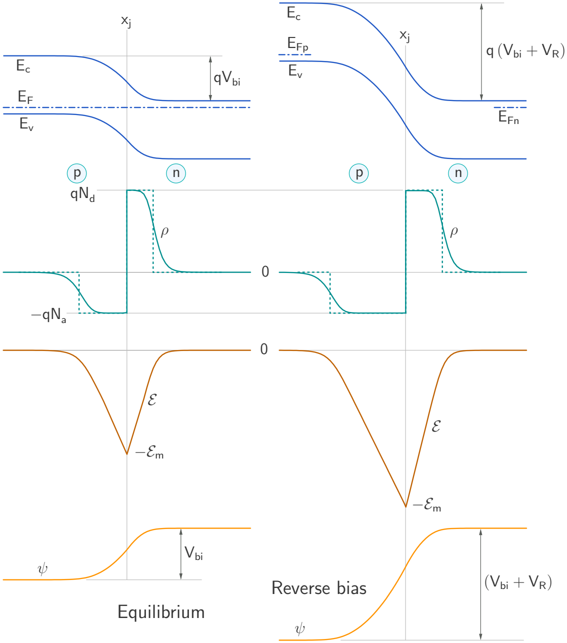
Equilibrium Forward bias

Reverse bias



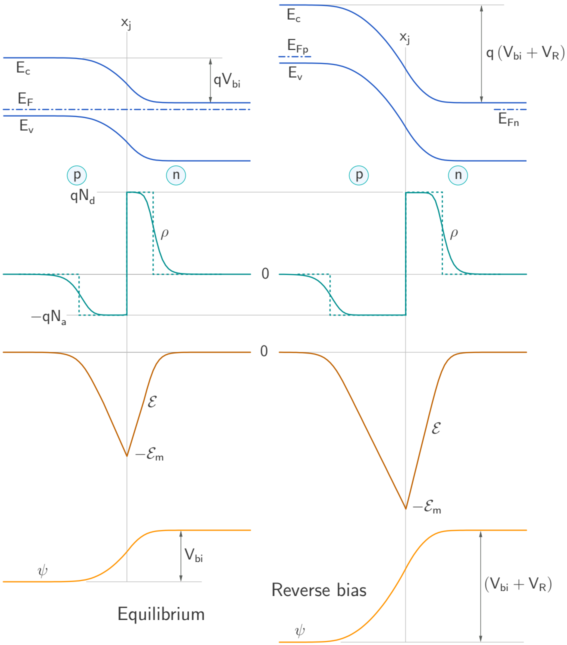
Reverse bias

* The electrostatic conditions (viz., $\rho(x)$, $\mathcal{E}(x)$, $\psi(x)$) under reverse bias are similar to the equilibrium situation except for an increased junction voltage ($V_{bi} + V_R$).



Reverse bias

* The electrostatic conditions (viz., $\rho(x)$, $\mathcal{E}(x)$, $\psi(x)$) under reverse bias are similar to the equilibrium situation except for an increased junction voltage ($V_{\rm bi} + V_R$).
* The depletion width, the maximum electric field, and the junction voltage drop increase with reverse bias.

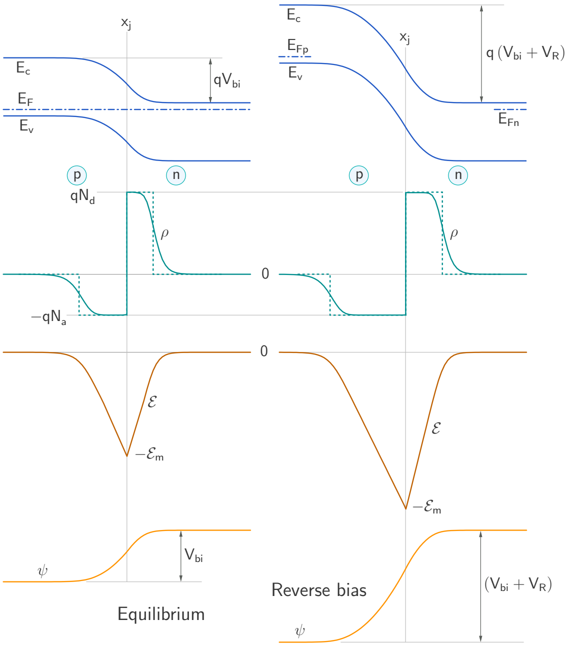


Reverse bias

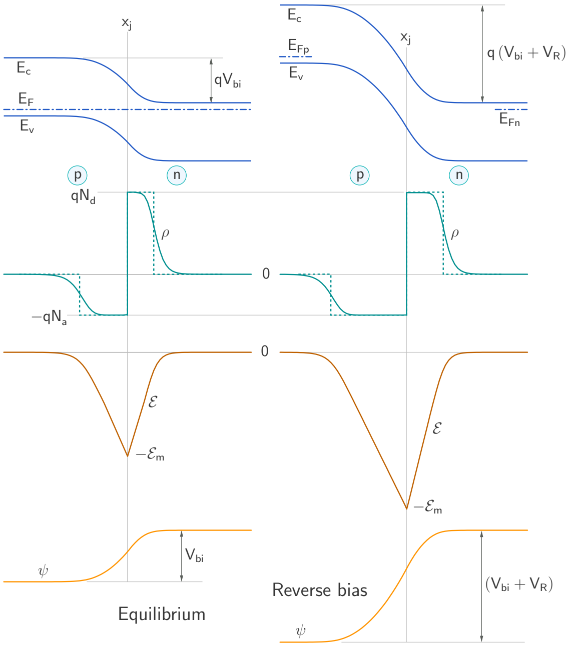
* The electrostatic conditions (viz., $\rho(x)$, $\mathcal{E}(x)$, $\psi(x)$) under reverse bias are similar to the equilibrium situation except for an increased junction voltage ($V_{\rm bi} + V_R$).
* The depletion width, the maximum electric field, and the junction voltage drop increase with reverse bias.
* Solving Poisson's equation using the depletion approximation, we get

$$W = \sqrt{\frac{2\epsilon}{q}\left(\frac{N_a + N_d}{N_a N_d}\right)(V_{\rm bi} + V_R)},$$

$$W_n = \frac{N_a}{N_a + N_d}\,W, \quad W_p = \frac{N_d}{N_a + N_d}\,W.$$

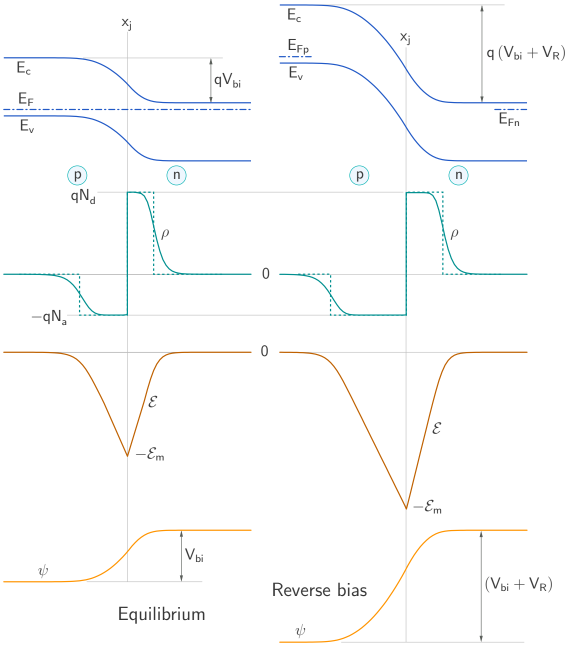


Reverse bias



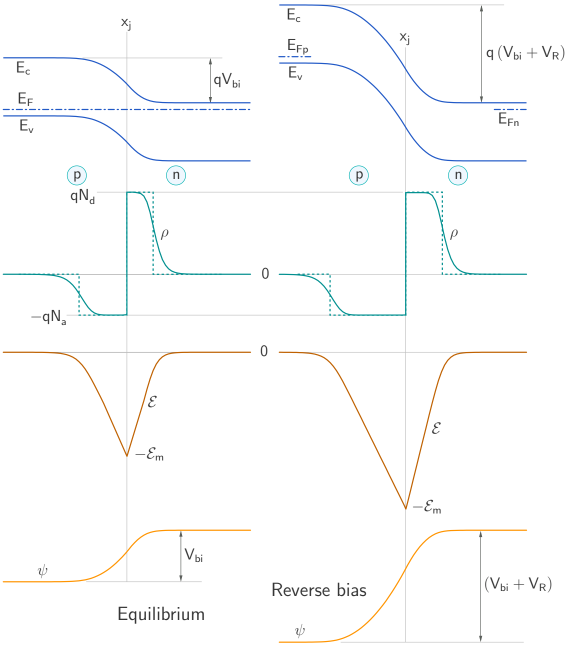
Reverse bias

* Although the equilibrium condition is disturbed with an applied bias, the situation sufficiently far from the depletion region is hardly different.



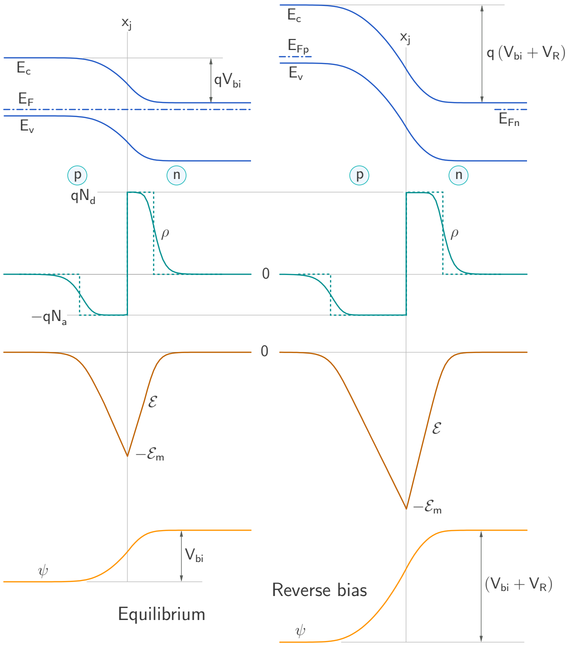
Reverse bias

* Although the equilibrium condition is disturbed with an applied bias, the situation sufficiently far from the depletion region is hardly different.
* We can extend the Fermi level concept to describe carrier concentrations sufficiently far from the depletion region.



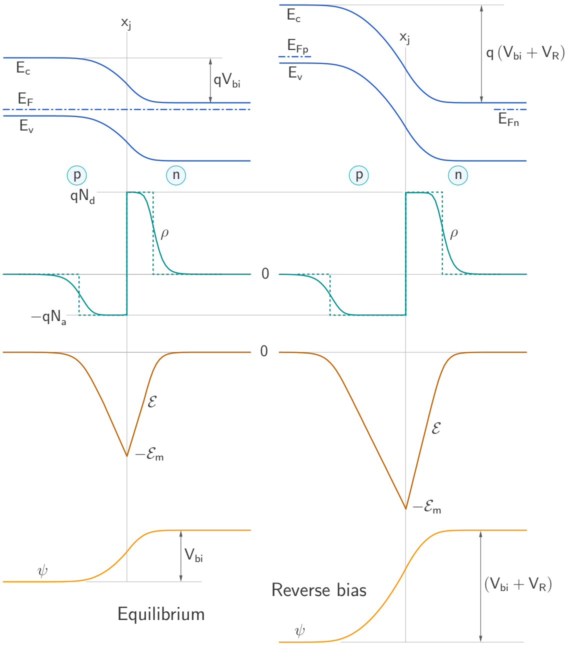
Reverse bias

* Although the equilibrium condition is disturbed with an applied bias, the situation sufficiently far from the depletion region is hardly different.
* We can extend the Fermi level concept to describe carrier concentrations sufficiently far from the depletion region.
* $p = N_v e^{-(E_{Fp}-E_v)/kT}$ on the p-side,
  $n = N_c e^{-(E_c-E_{Fn})/kT}$ on the n-side.



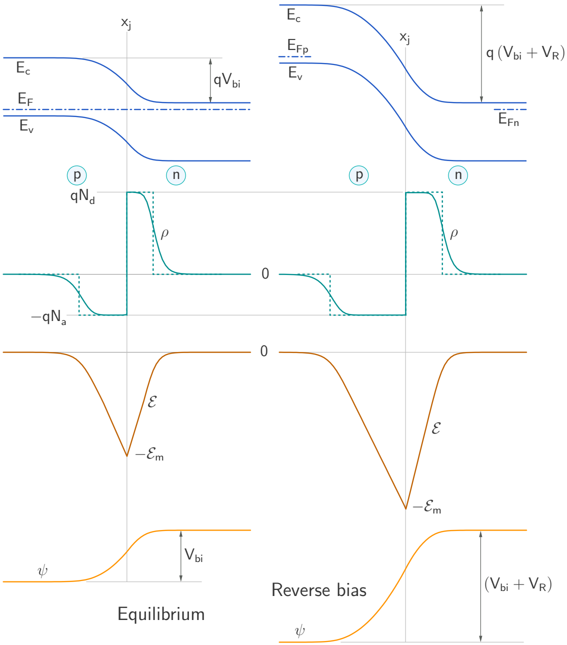
Reverse bias

* Although the equilibrium condition is disturbed with an applied bias, the situation sufficiently far from the depletion region is hardly different.
* We can extend the Fermi level concept to describe carrier concentrations sufficiently far from the depletion region.
* $p = N_v e^{-(E_{Fp}-E_v)/kT}$ on the p-side,
  $n = N_c e^{-(E_c-E_{Fn})/kT}$ on the n-side.
* The Fermi levels are called "quasi Fermi levels" since the situation is *almost* like equilibrium.



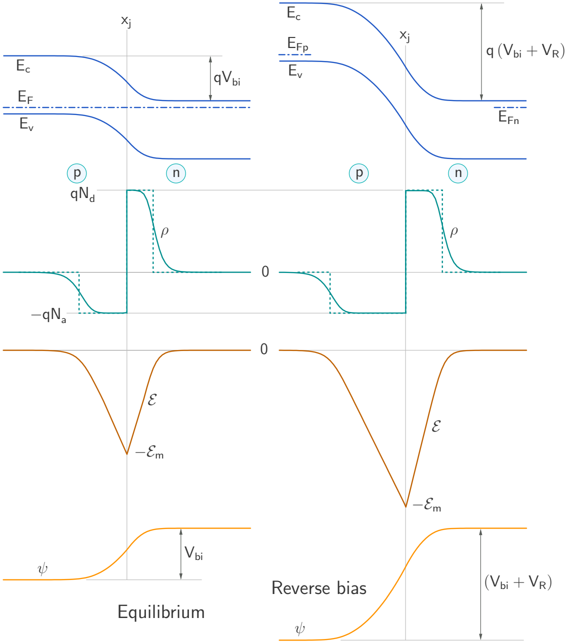
Reverse bias

* Although the equilibrium condition is disturbed with an applied bias, the situation sufficiently far from the depletion region is hardly different.
* We can extend the Fermi level concept to describe carrier concentrations sufficiently far from the depletion region.
* $p = N_v e^{-(E_{Fp}-E_v)/kT}$ on the p-side,
  $n = N_c e^{-(E_c-E_{Fn})/kT}$ on the n-side.
* The Fermi levels are called "quasi Fermi levels" since the situation is *almost* like equilibrium.
* From the band diagram, we see that
  $E_g = \Delta_p + \Delta_n + qV_{bi}$,



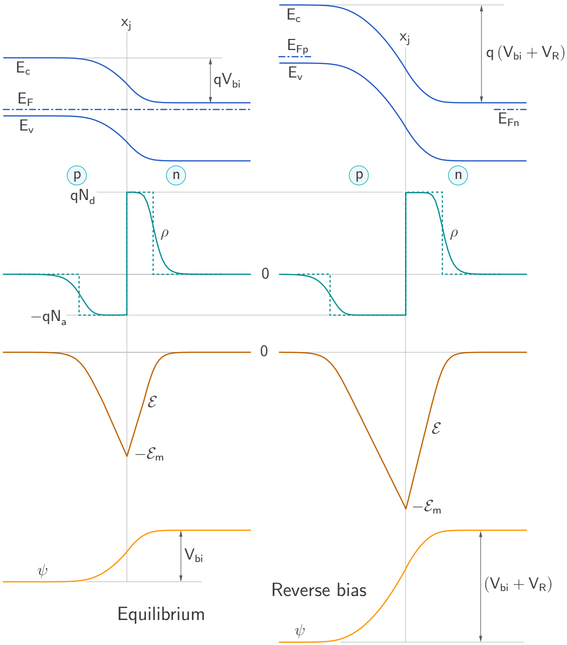
Reverse bias

* Although the equilibrium condition is disturbed with an applied bias, the situation sufficiently far from the depletion region is hardly different.
* We can extend the Fermi level concept to describe carrier concentrations sufficiently far from the depletion region.
* $p = N_v e^{-(E_{Fp}-E_v)/kT}$ on the p-side,
  $n = N_c e^{-(E_c-E_{Fn})/kT}$ on the n-side.
* The Fermi levels are called "quasi Fermi levels" since the situation is *almost* like equilibrium.
* From the band diagram, we see that
  $E_g = \Delta_p + \Delta_n + qV_{\text{bi}}$,
  $E_g = \Delta_p - (E_{Fp} - E_{Fn}) + \Delta_n + q(V_{\text{bi}} + V_R)$

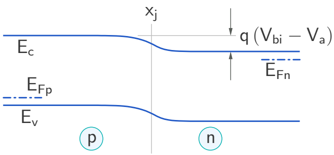


Reverse bias

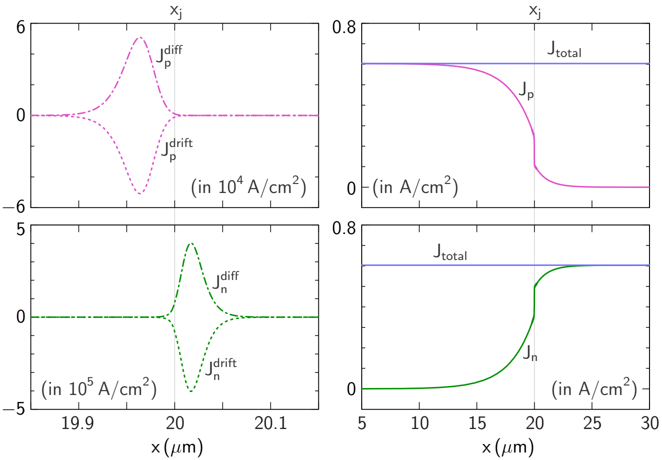
* Although the equilibrium condition is disturbed with an applied bias, the situation sufficiently far from the depletion region is hardly different.
* We can extend the Fermi level concept to describe carrier concentrations sufficiently far from the depletion region.
* $p = N_v e^{-(E_{Fp} - E_v)/kT}$ on the p-side,
  $n = N_c e^{-(E_c - E_{Fn})/kT}$ on the n-side.
* The Fermi levels are called "quasi Fermi levels" since the situation is *almost* like equilibrium.
* From the band diagram, we see that
  $E_g = \Delta_p + \Delta_n + qV_{\text{bi}}$,
  $E_g = \Delta_p - (E_{Fp} - E_{Fn}) + \Delta_n + q(V_{\text{bi}} + V_R)$
  $\rightarrow E_{Fp} - E_{Fn} = qV_R$.



Current densities in forward bias

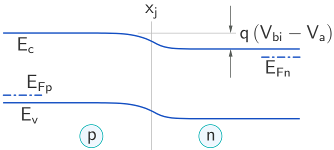


$N_d = 2 \times 10^{17}\ \mathrm{cm}^{-3}$	$\tau_n = 1\ \mathrm{ns}$
$N_a = 10^{17}\ \mathrm{cm}^{-3}$	$\tau_p = 1\ \mathrm{ns}$
$\mu_n = 1400\ \mathrm{cm}^2/\mathrm{V\text{-}s}$	$T = 300\ \mathrm{K}$
$\mu_p = 500\ \mathrm{cm}^2/\mathrm{V\text{-}s}$	$V_a = 0.6\ \mathrm{V}$

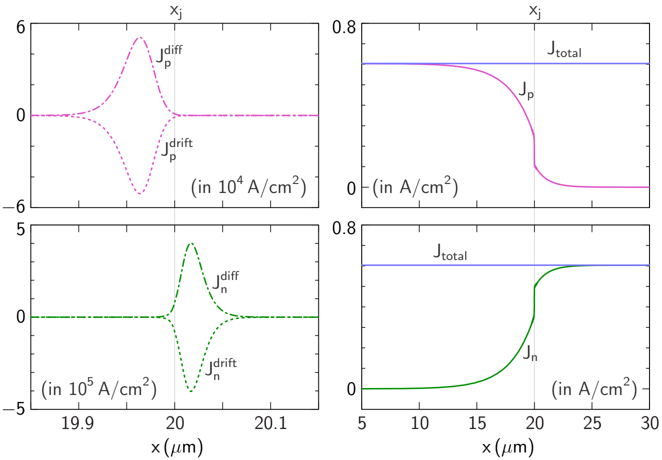


Near the junction,

Current densities in forward bias



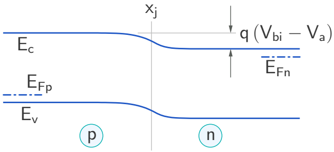
$N_d = 2 \times 10^{17}\ \text{cm}^{-3}$	$\tau_n = 1\ \text{ns}$
$N_a = 10^{17}\ \text{cm}^{-3}$	$\tau_p = 1\ \text{ns}$
$\mu_n = 1400\ \text{cm}^2/\text{V-s}$	$T = 300\ \text{K}$
$\mu_p = 500\ \text{cm}^2/\text{V-s}$	$V_a = 0.6\ \text{V}$



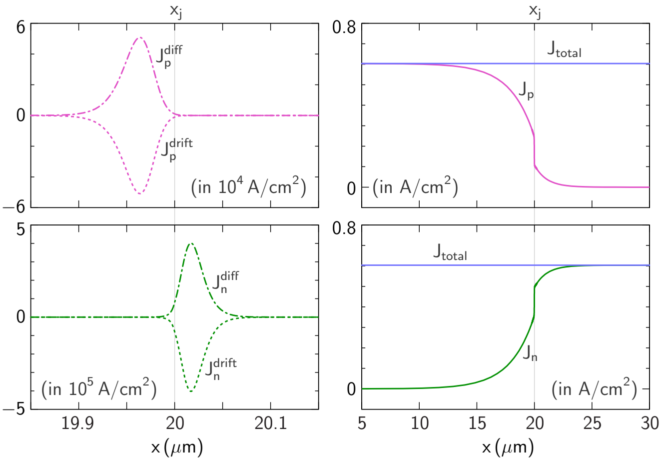
Near the junction,

- Although the equilibrium condition is disturbed, we still have $J_p^{\text{diff}} \approx -J_p^{\text{drift}}$, and $J_n^{\text{diff}} \approx -J_n^{\text{drift}}$.

Current densities in forward bias



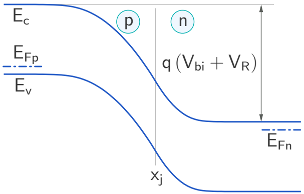
$N_d = 2 \times 10^{17}\ \mathrm{cm}^{-3}$	$\tau_n = 1\ \mathrm{ns}$
$N_a = 10^{17}\ \mathrm{cm}^{-3}$	$\tau_p = 1\ \mathrm{ns}$
$\mu_n = 1400\ \mathrm{cm}^2/\mathrm{V\text{-}s}$	$T = 300\ \mathrm{K}$
$\mu_p = 500\ \mathrm{cm}^2/\mathrm{V\text{-}s}$	$V_a = 0.6\ \mathrm{V}$



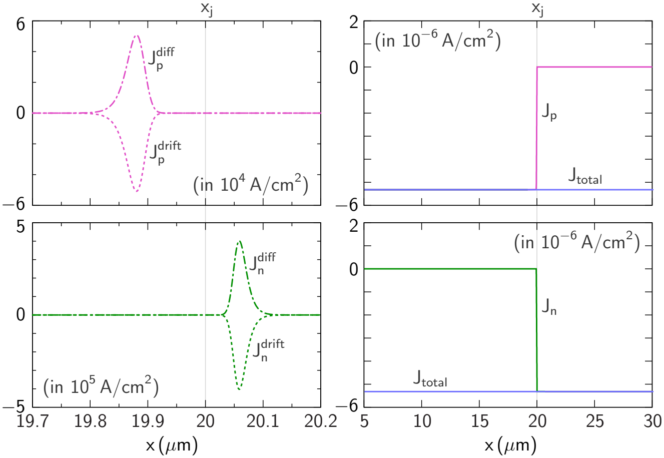
Near the junction,

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

Current densities in reverse bias

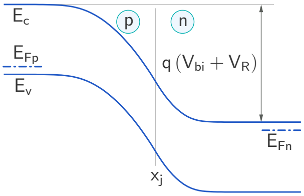


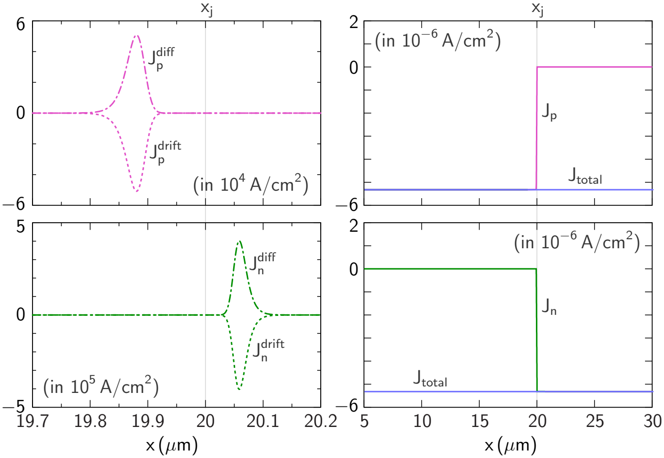
$N_d = 2 \times 10^{17}\ \mathrm{cm}^{-3}$	$\tau_n = 1\ \mathrm{ns}$
$N_a = 10^{17}\ \mathrm{cm}^{-3}$	$\tau_p = 1\ \mathrm{ns}$
$\mu_n = 1400\ \mathrm{cm}^2/\mathrm{V\text{-}s}$	$T = 300\ \mathrm{K}$
$\mu_p = 500\ \mathrm{cm}^2/\mathrm{V\text{-}s}$	$V_a = -1\ \mathrm{V}$



Near the junction,

Current densities in reverse bias

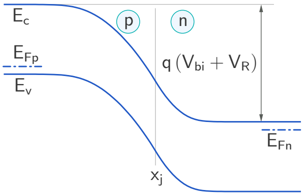




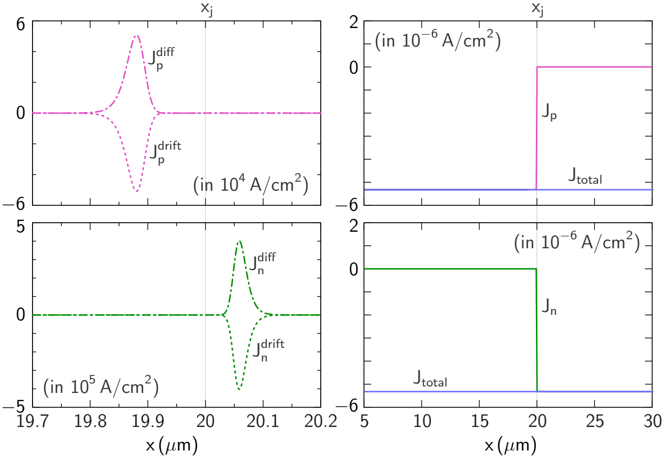
$N_d = 2 \times 10^{17}\ \text{cm}^{-3}$	$\tau_n = 1$ ns
$N_a = 10^{17}\ \text{cm}^{-3}$	$\tau_p = 1$ ns
$\mu_n = 1400\ \text{cm}^2/\text{V-s}$	$T = 300$ K
$\mu_p = 500\ \text{cm}^2/\text{V-s}$	$V_a = -1$ V

Near the junction,

* Although the equilibrium condition is disturbed, we still have $J_p^{diff} \approx -J_p^{drift}$, and $J_n^{diff} \approx -J_n^{drift}$.



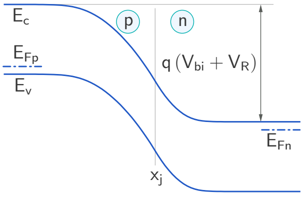
$N_d = 2 \times 10^{17}\ \mathrm{cm}^{-3}$	$\tau_n = 1\ \mathrm{ns}$
$N_a = 10^{17}\ \mathrm{cm}^{-3}$	$\tau_p = 1\ \mathrm{ns}$
$\mu_n = 1400\ \mathrm{cm}^2/\mathrm{V\text{-}s}$	$T = 300\ \mathrm{K}$
$\mu_p = 500\ \mathrm{cm}^2/\mathrm{V\text{-}s}$	$V_a = -1\ \mathrm{V}$



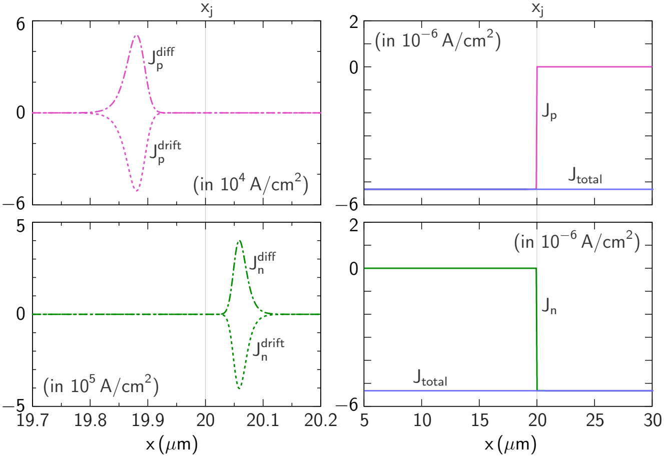
Near the junction,

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

Current densities in reverse bias



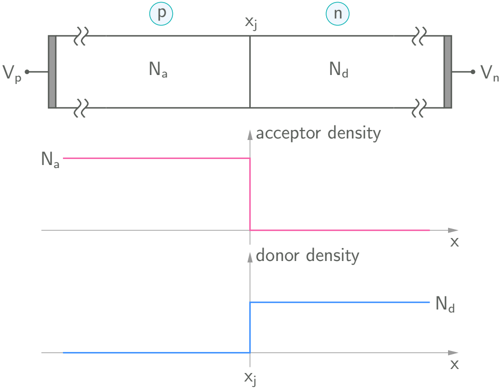
$N_d = 2 \times 10^{17}\ \text{cm}^{-3}$	$\tau_n = 1\ \text{ns}$
$N_a = 10^{17}\ \text{cm}^{-3}$	$\tau_p = 1\ \text{ns}$
$\mu_n = 1400\ \text{cm}^2/\text{V-s}$	$T = 300\ \text{K}$
$\mu_p = 500\ \text{cm}^2/\text{V-s}$	$V_a = -1\ \text{V}$



Near the junction,

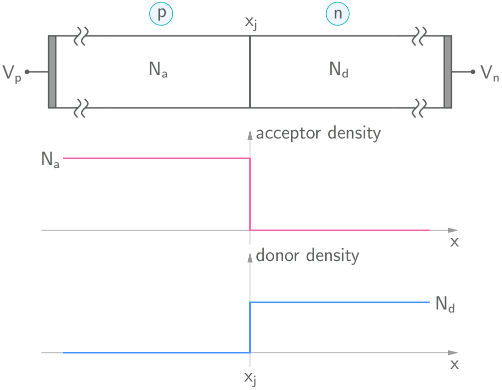
* Although the equilibrium condition is disturbed, we still have $J_p^{diff} \approx -J_p^{drift}$, and $J_n^{diff} \approx -J_n^{drift}$.
* The net current densities J_n and J_p are much smaller than the drift and diffusion components.
* Note that J_{total} in reverse bias is negligibly small compared to the forward bias case (0.7 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:

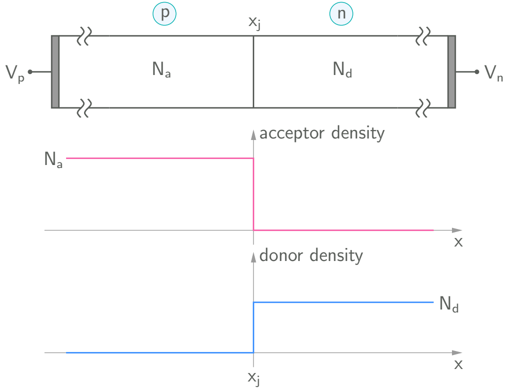
p_{p0}: equilibrium hole density in the neutral p-region



Definitions:

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

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

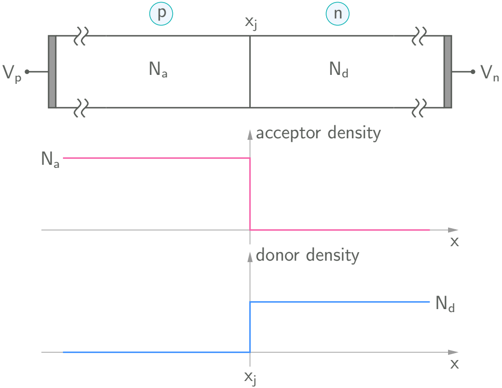


Definitions:

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

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

n_{p0}: equilibrium electron density in the neutral *p*-region



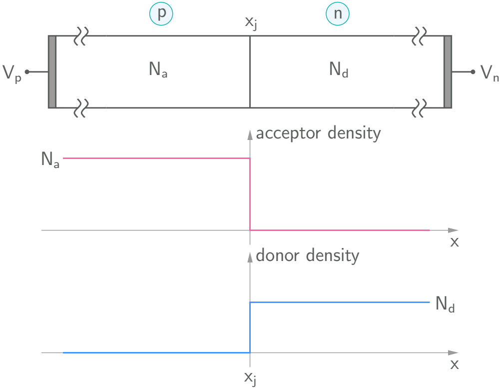
Definitions:

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

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

n_{p0}: equilibrium electron density in the neutral *p*-region

n_{n0}: equilibrium electron density in the neutral *n*-region



Definitions:

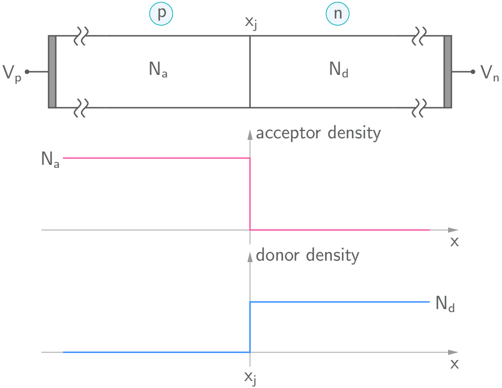
p_{p0}: equilibrium hole density in the neutral *p*-region

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

n_{p0}: equilibrium electron density in the neutral *p*-region

n_{n0}: equilibrium electron density in the neutral *n*-region

p_{p0} and n_{n0} are majority carrier densities.



Definitions:

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

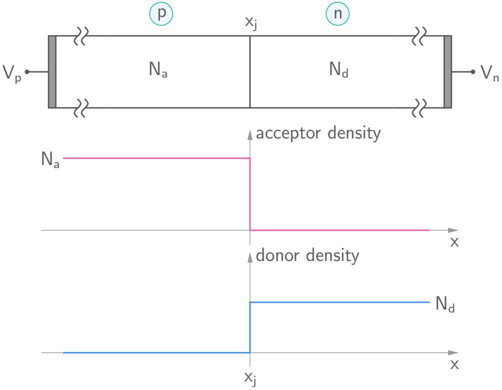
p_{n0}: equilibrium hole density in the neutral *n*-region

n_{p0}: equilibrium electron density in the neutral *p*-region

n_{n0}: equilibrium electron density in the neutral *n*-region

p_{p0} and n_{n0} are majority carrier densities.

p_{n0} and n_{p0} are minority carrier densities.



Definitions:

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

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

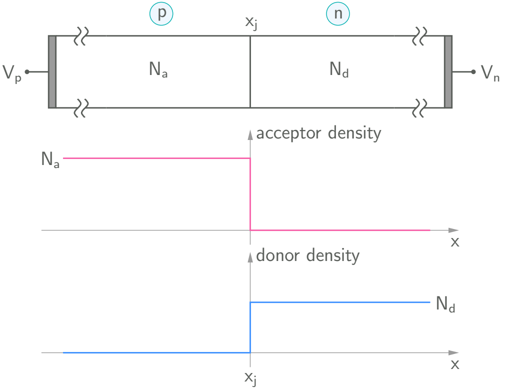
n_{p0}: equilibrium electron density in the neutral *p*-region

n_{n0}: equilibrium electron density in the neutral *n*-region

p_{p0} and n_{n0} are majority carrier densities.

p_{n0} and n_{p0} are minority carrier densities.

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



Definitions:

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

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

n_{p0}: equilibrium electron density in the neutral *p*-region

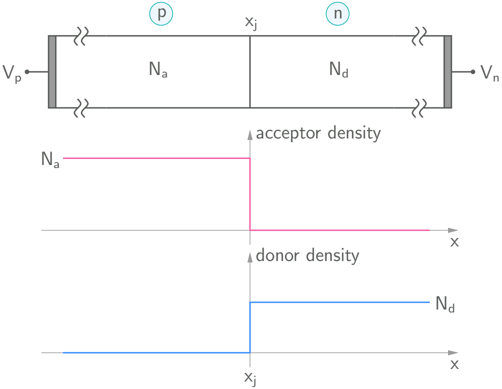
n_{n0}: equilibrium electron density in the neutral *n*-region

p_{p0} and n_{n0} are majority carrier densities.

p_{n0} and n_{p0} are minority carrier densities.

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

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



Definitions:

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

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

n_{p0}: equilibrium electron density in the neutral *p*-region

n_{n0}: equilibrium electron density in the neutral *n*-region

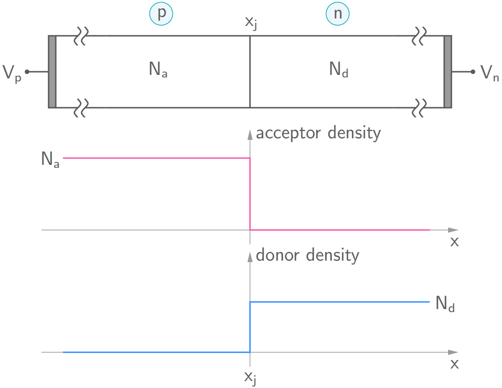
p_{p0} and n_{n0} are majority carrier densities.

p_{n0} and n_{p0} are minority carrier densities.

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

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

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



Definitions:

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

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

n_{p0}: equilibrium electron density in the neutral *p*-region

n_{n0}: equilibrium electron density in the neutral *n*-region

p_{p0} and n_{n0} are majority carrier densities.

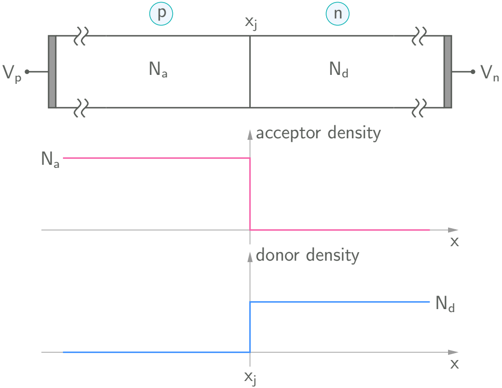
p_{n0} and n_{p0} are minority carrier densities.

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

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

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

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



Definitions:

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

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

n_{p0}: equilibrium electron density in the neutral p-region

n_{n0}: equilibrium electron density in the neutral n-region

p_{p0} and n_{n0} are majority carrier densities.

p_{n0} and n_{p0} are minority carrier densities.

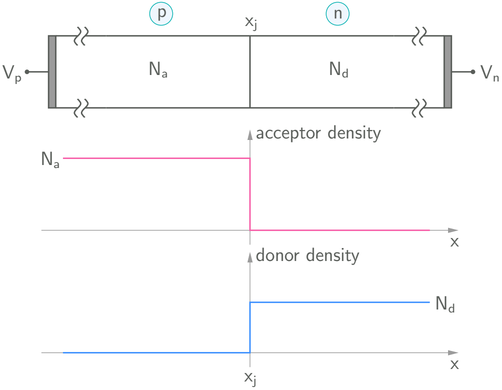
Example: $N_a = 5 \times 10^{16}\,\text{cm}^{-3}$, $N_d = 10^{18}\,\text{cm}^{-3}$ $(T = 300\,\text{K})$.

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

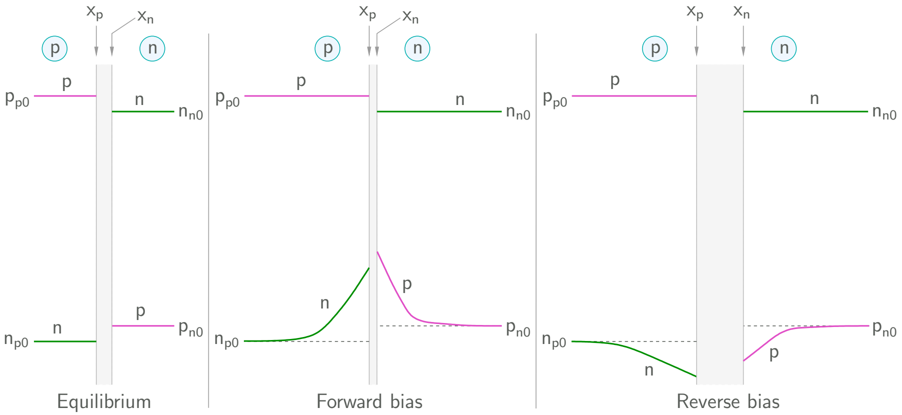
$n_{n0} \approx N_d = 10^{18}\,\text{cm}^{-3}$,

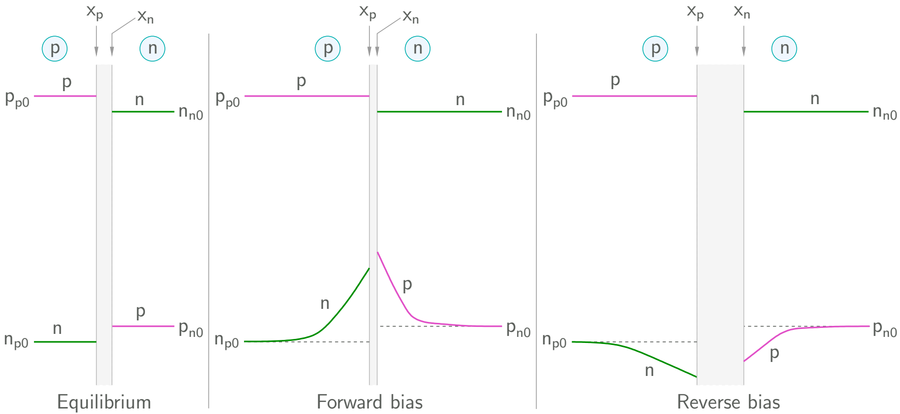
$$n_{p0} = \frac{n_i^2}{p_{p0}} = \frac{(1.5 \times 10^{10})^2}{5 \times 10^{16}} = 4.5 \times 10^3\,\text{cm}^{-3},$$

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

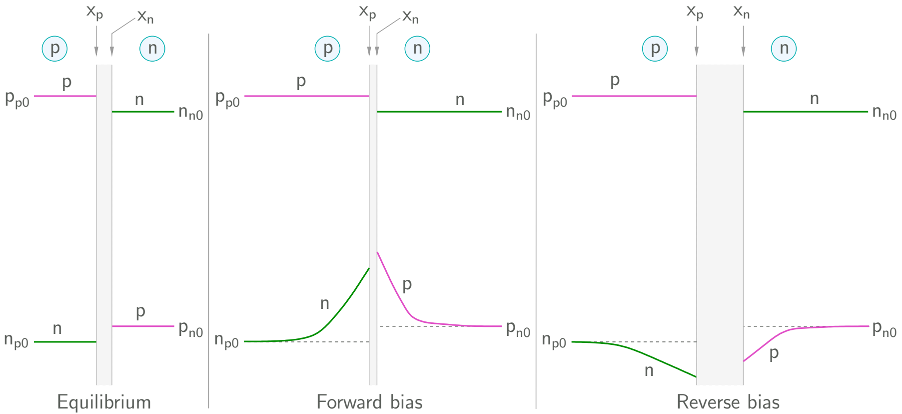


pn junction: derivation of *I*-*V* equation

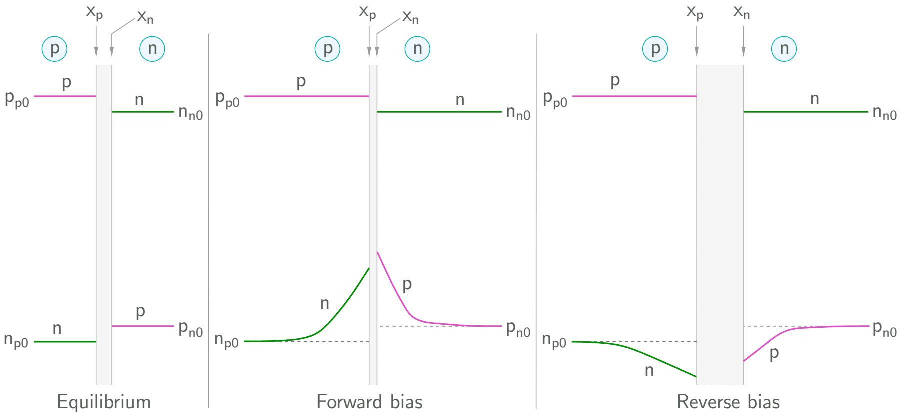




* Since $V_j = V_{\rm bi} - V_a$ and $W \propto \sqrt{V_j}$, the depletion is region is narrower under forward bias, wider under reverse bias.



* Since $V_j = V_{\rm bi} - V_a$ and $W \propto \sqrt{V_j}$, the depletion is region is narrower under forward bias, wider under reverse bias.
* Equilibrium concentrations (note: log scale for n and p):
  $p = p_{p0}$, $n = n_{p0}$ in the neutral p-region.

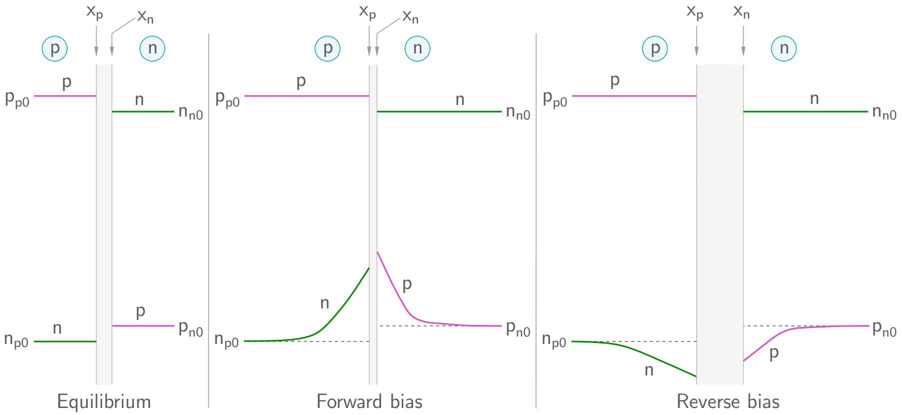


- Since $V_j = V_{\text{bi}} - V_a$ and $W \propto \sqrt{V_j}$, the depletion is region is narrower under forward bias, wider under reverse bias.
- Equilibrium concentrations (note: log scale for n and p):

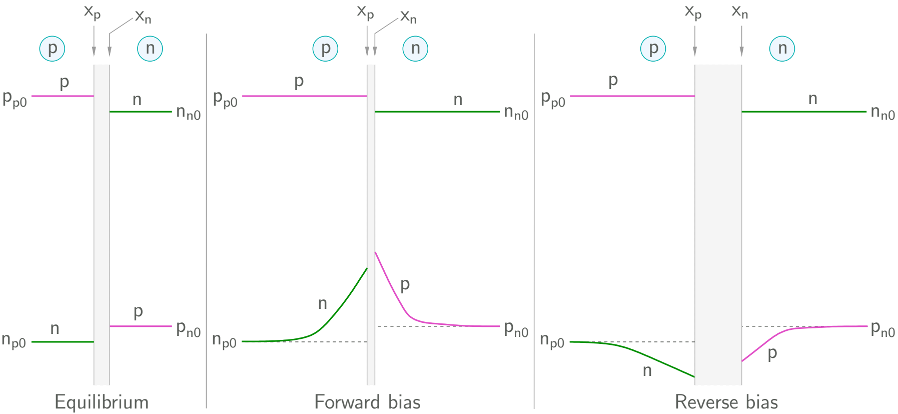
  $p = p_{p0}$, $n = n_{p0}$ in the neutral p-region.

  $n = n_{n0}$, $p = p_{n0}$ in the neutral p-region.

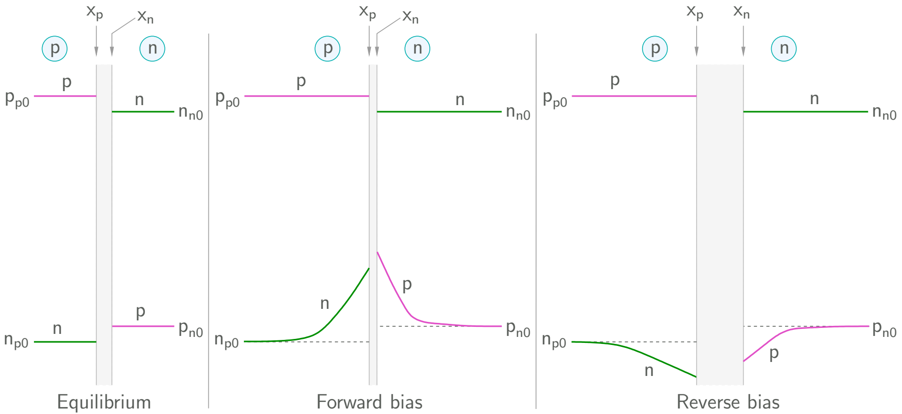
pn junction: derivation of *I*-*V* equation



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

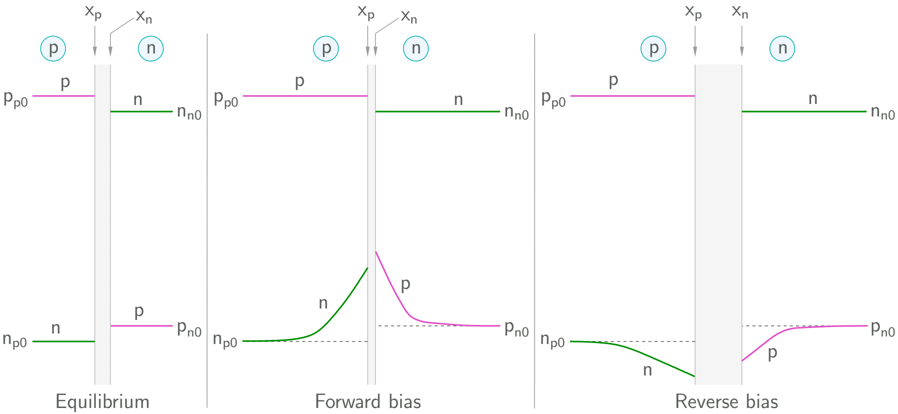


$$J_p^{\rm diff} \approx -J_p^{\rm drift} \;\rightarrow q\,\mu_p\,p\,\mathcal{E} = qD_p\,\frac{dp}{dx},$$



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

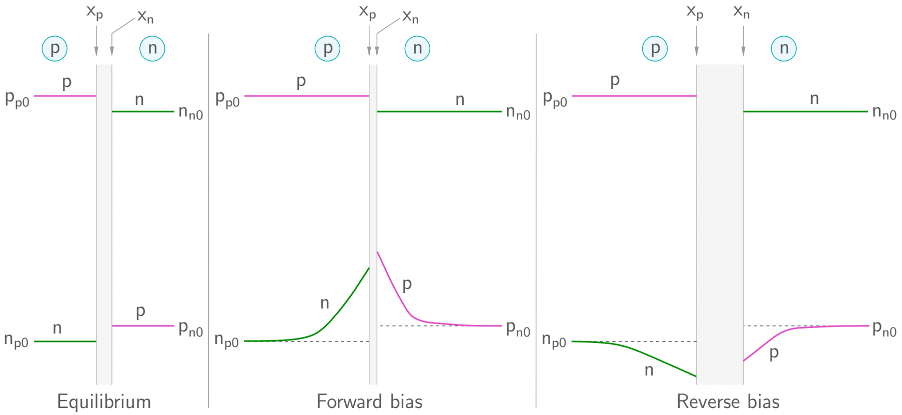
pn junction: derivation of *I*-*V* equation



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

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

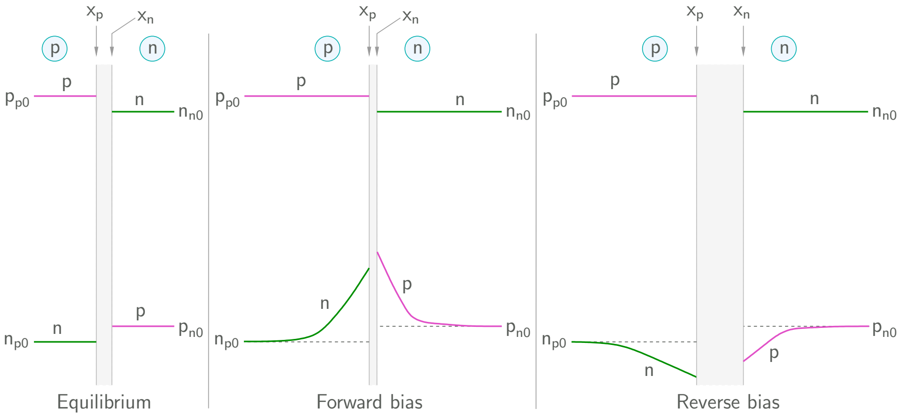
pn junction: derivation of *I*-*V* equation



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

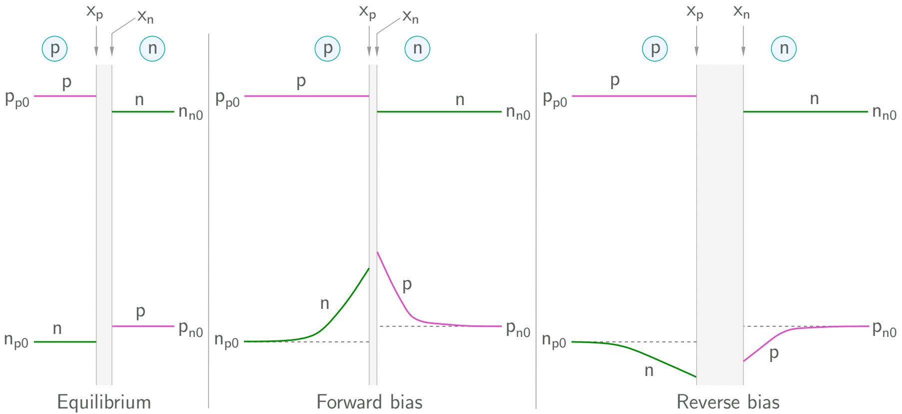
$$\frac{D}{\mu} = \frac{kT}{q} \rightarrow \int d\psi = -V_T \int \frac{1}{p}\,dp \rightarrow \psi\Big|_{x_1}^{x_2} = -V_T \log\frac{p(x_2)}{p(x_1)}$$

M. B. Patil, IIT Bombay

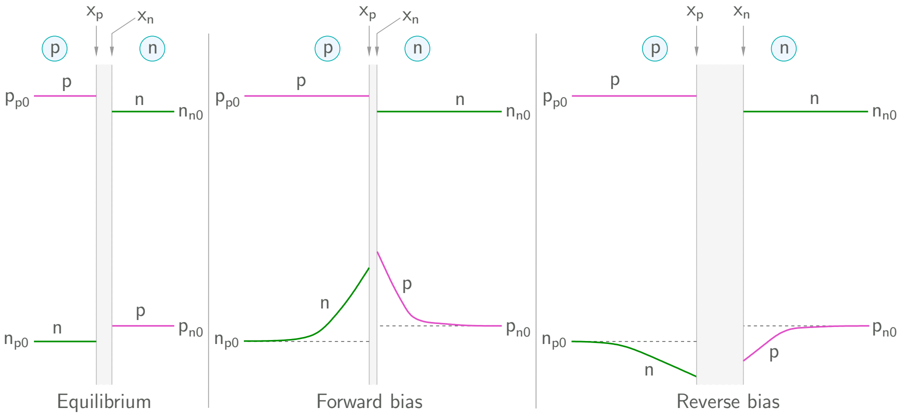


$$J_p^{\text{diff}} \approx -J_p^{\text{drift}} \;\rightarrow q\,\mu_p\,p\,\mathcal{E} = qD_p\,\frac{dp}{dx}, \text{ i.e., } \;\mathcal{E} = -\frac{d\psi}{dx} = \frac{D_p}{\mu_p}\,\frac{1}{p}\,\frac{dp}{dx}.$$

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

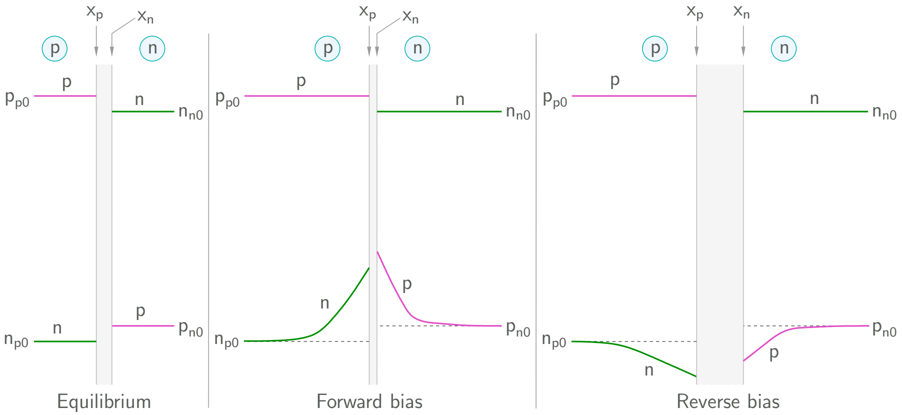


$$J_p^{\text{diff}} \approx -J_p^{\text{drift}} \rightarrow \frac{p(x_n)}{p(x_p)} = \exp\left(\frac{\psi(x_p) - \psi(x_n)}{V_T}\right).$$



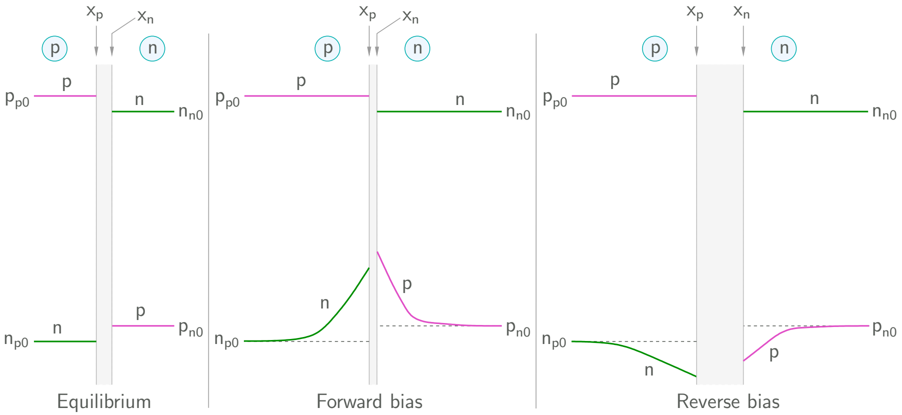
$$J_p^{\text{diff}} \approx -J_p^{\text{drift}} \rightarrow \frac{p(x_n)}{p(x_p)} = \exp\left(\frac{\psi(x_p)-\psi(x_n)}{V_T}\right).$$

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



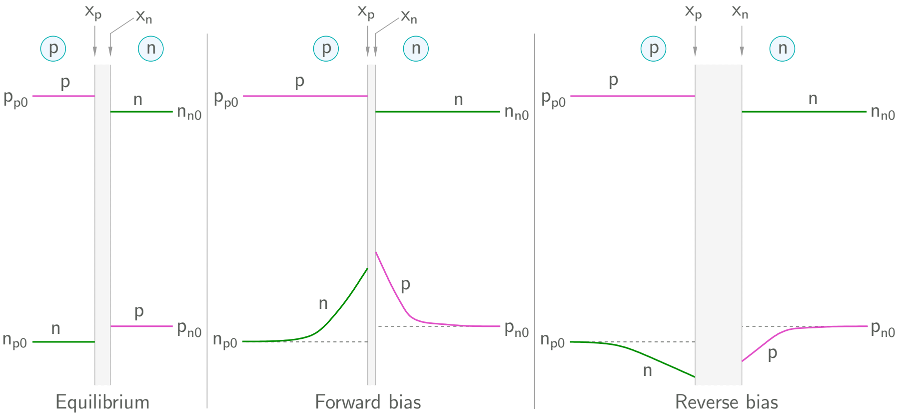
x_p
x_n
p
n
p_{p0}
n_{n0}
n_{p0}
p_{n0}
p
n
Equilibrium
Forward bias
Reverse bias

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



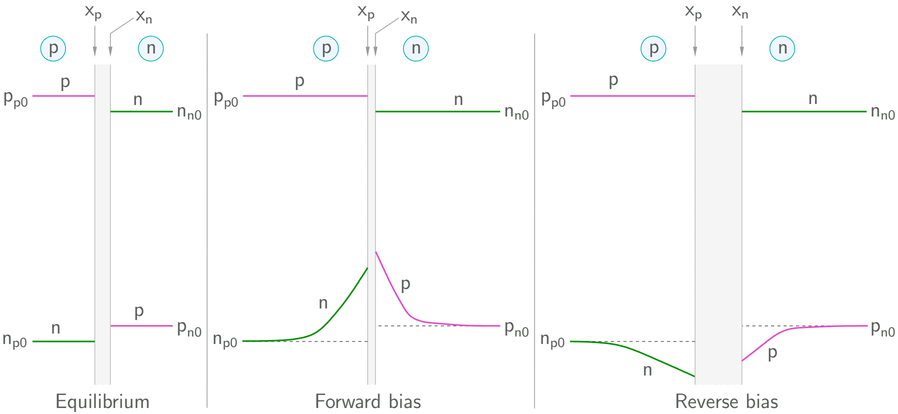
* When a bias is applied, the minority carrier concentrations in the neutral regions can change substantially.

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



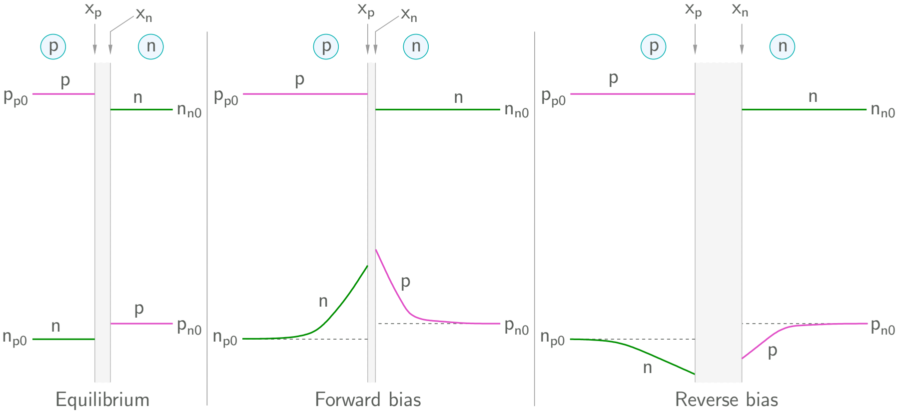
* When a bias is applied, the minority carrier concentrations in the neutral regions can change substantially.
* There is a corresponding change in the majority carrier concentrations as well, and it serves to keep these regions charge-neutral.

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

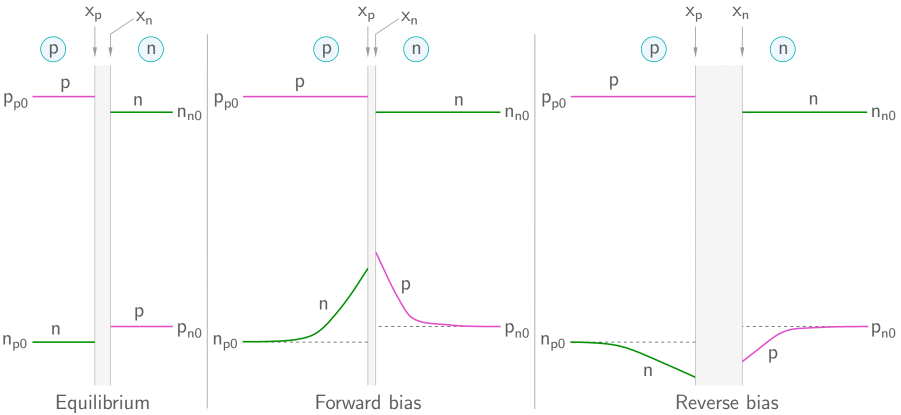


* When a bias is applied, the minority carrier concentrations in the neutral regions can change substantially.
* There is a corresponding change in the majority carrier concentrations as well, and it serves to keep these regions charge-neutral.
* Low-level injection: $\Delta n \approx \Delta p \ll p_{p0}$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

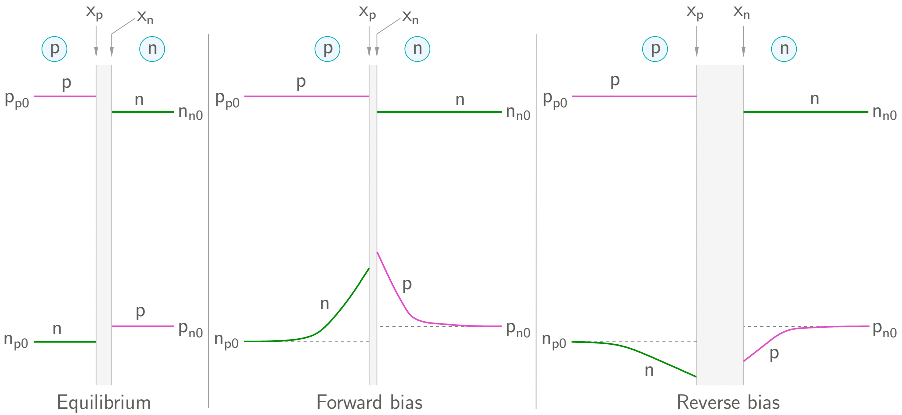
  $\Delta p \approx \Delta n \ll n_{n0}$ in the neutral n-region $\rightarrow n(x) \approx n_{n0}$ for $x \geq x_n$



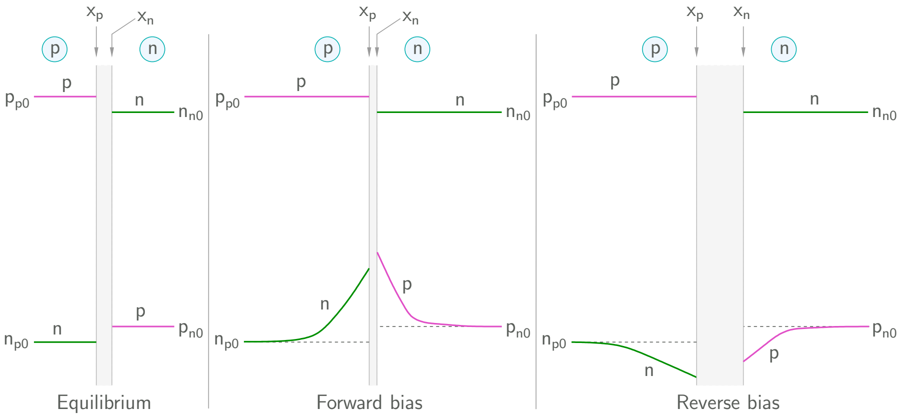
x_p
x_n
p
n
p
p_{p0}
n
n_{n0}
p
p_{n0}
n
n_{p0}
Equilibrium
x_p
x_n
p
n
p
p_{p0}
n
n_{n0}
n
p
n_{p0}
p_{n0}
Forward bias
x_p
x_n
p
n
p
p_{p0}
n
n_{n0}
n_{p0}
p_{n0}
p
n
Reverse bias



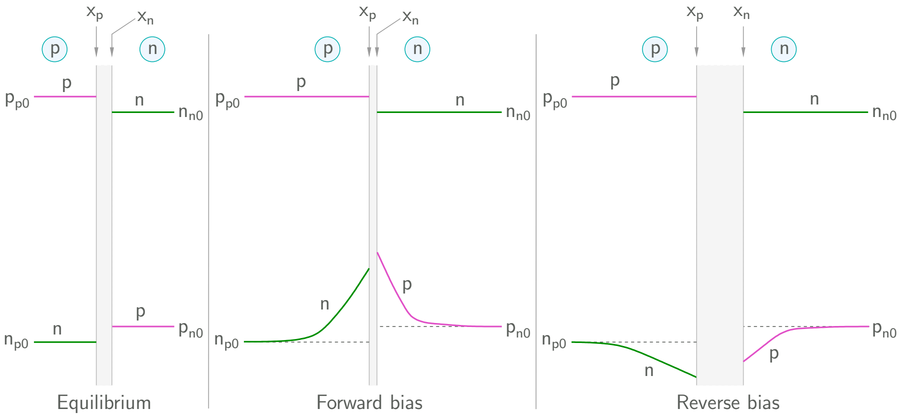
* $\dfrac{p(x_n)}{p(x_p)} = \exp\left(\dfrac{\psi(x_p)-\psi(x_n)}{V_T}\right)$, $\quad \dfrac{n(x_n)}{n(x_p)} = \exp\left(\dfrac{\psi(x_n)-\psi(x_p)}{V_T}\right)$. Also, $\psi(x_n)-\psi(x_p) = V_j$.



* $\dfrac{p(x_n)}{p(x_p)} = \exp\left(\dfrac{\psi(x_p)-\psi(x_n)}{V_T}\right)$, $\dfrac{n(x_n)}{n(x_p)} = \exp\left(\dfrac{\psi(x_n)-\psi(x_p)}{V_T}\right)$. Also, $\psi(x_n)-\psi(x_p)=V_j$.
* Low-level injection: $p(x) \approx p_{p0}$ for $x \leq x_p$, and $n(x) \approx n_{n0}$ for $x \geq x_n$.



* $\dfrac{p(x_n)}{p(x_p)} = \exp\left(\dfrac{\psi(x_p)-\psi(x_n)}{V_T}\right)$, $\dfrac{n(x_n)}{n(x_p)} = \exp\left(\dfrac{\psi(x_n)-\psi(x_p)}{V_T}\right)$. Also, $\psi(x_n)-\psi(x_p) = V_j$.
* Low-level injection: $p(x) \approx p_{p0}$ for $x \leq x_p$, and $n(x) \approx n_{n0}$ for $x \geq x_n$.
  $\rightarrow \dfrac{p(x_n)}{p_{p0}} = e^{-V_j/V_T} \rightarrow p(x_n) = p_{p0}\,e^{-V_j/V_T}$

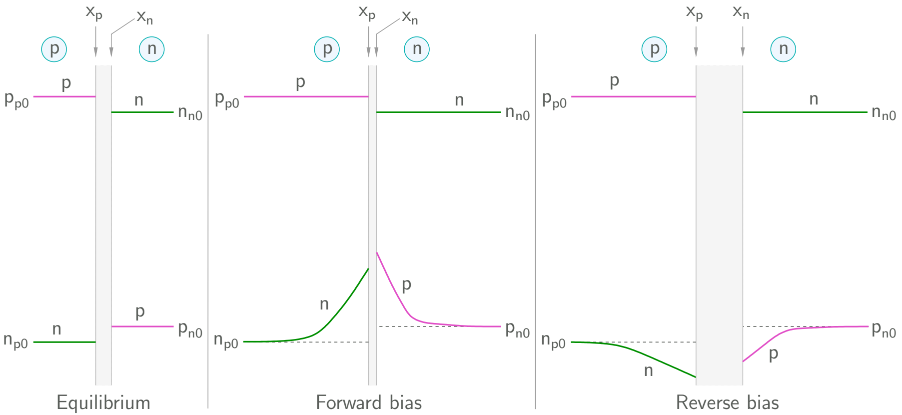


* $\dfrac{p(x_n)}{p(x_p)} = \exp\left(\dfrac{\psi(x_p) - \psi(x_n)}{V_T}\right)$, $\dfrac{n(x_n)}{n(x_p)} = \exp\left(\dfrac{\psi(x_n) - \psi(x_p)}{V_T}\right)$. Also, $\psi(x_n) - \psi(x_p) = V_j$.

* Low-level injection: $p(x) \approx p_{p0}$ for $x \leq x_p$, and $n(x) \approx n_{n0}$ for $x \geq x_n$.

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

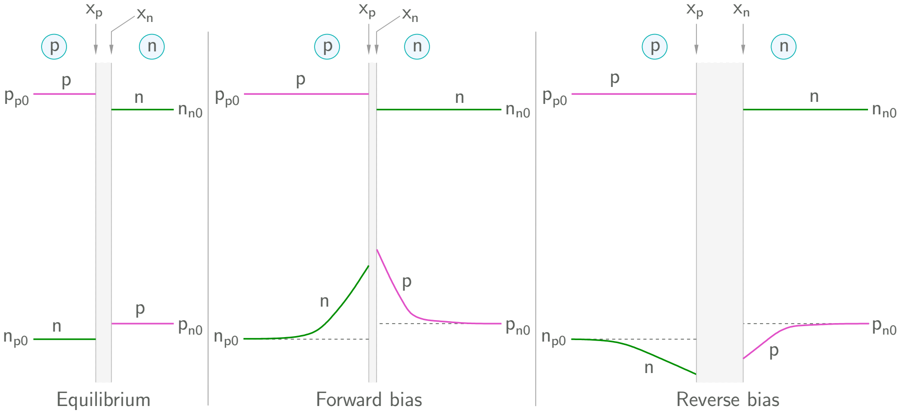
$$\frac{n_{n0}}{n(x_p)} = e^{V_j/V_T} \rightarrow n(x_p) = n_{n0}\, e^{-V_j/V_T}.$$



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

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

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

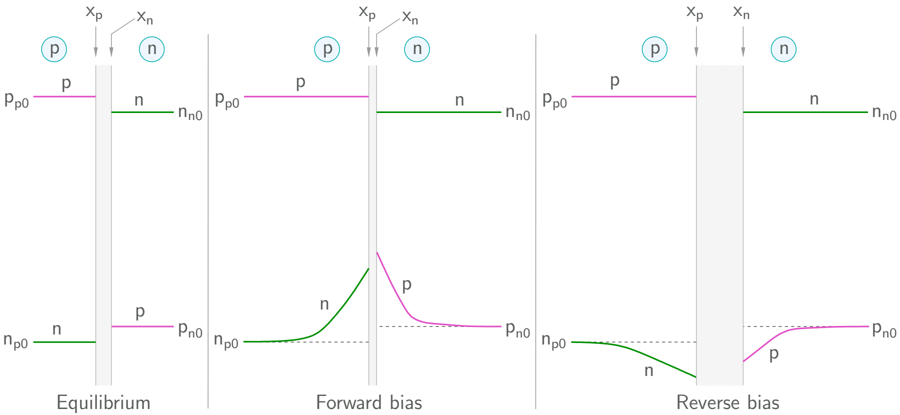


$$p(x_n) = p_{p0}\, e^{-V_j/V_T}$$

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

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

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



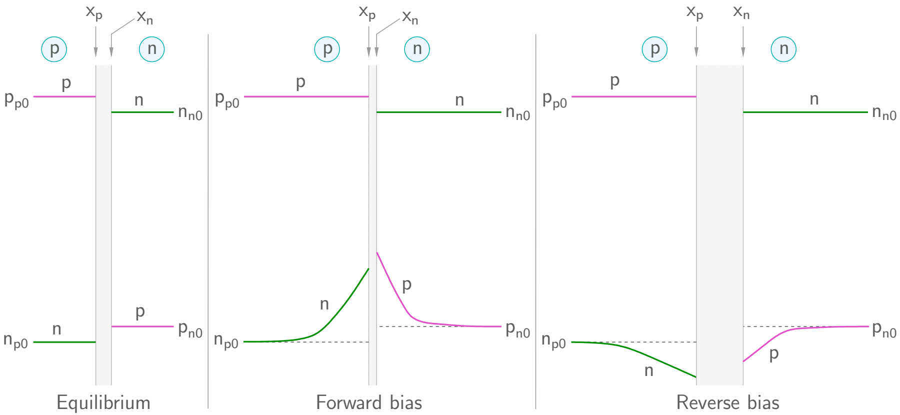
$$p(x_n) = p_{p0}\, e^{-V_j/V_T}$$

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

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

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



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

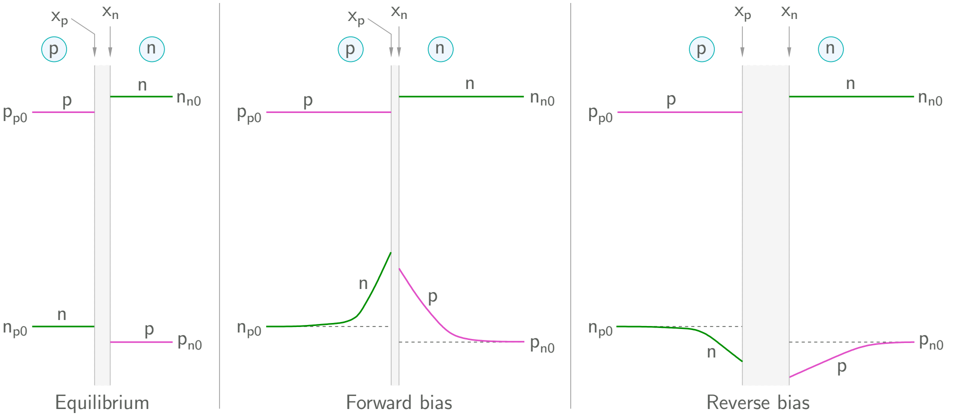
$$n(x_p) = n_{n0}\, e^{-V_j/V_T}$$

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

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

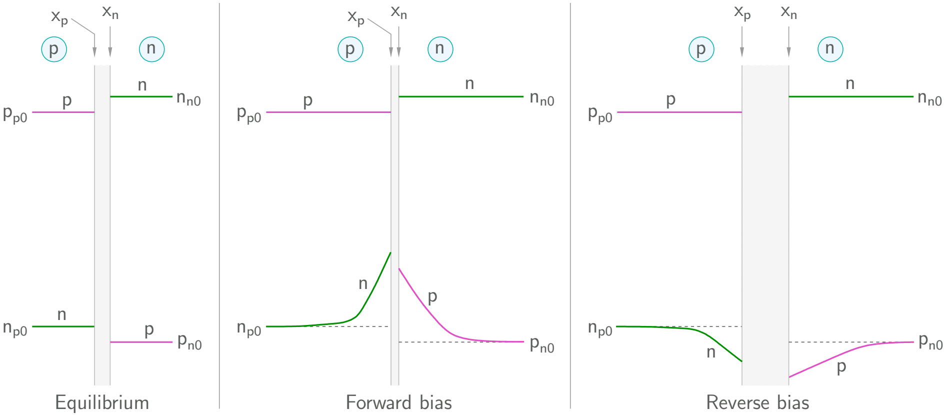
With bias: $p(x_n) = p_{p0}\ \exp\left(\dfrac{-V_{\rm bi}+V_a}{V_T}\right)$, $\quad n(x_p) = n_{n0}\ \exp\left(\dfrac{-V_{\rm bi}+V_a}{V_T}\right)$.

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

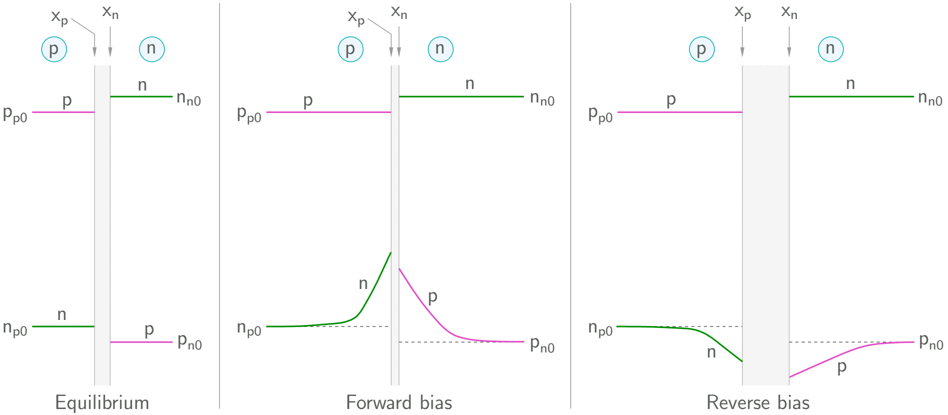


Example: Consider an abrupt, uniformly doped silicon *pn* junction at $T = 300\,\text{K}$, with $N_a = 5 \times 10^{16}\,\text{cm}^{-3}$ and $N_d = 10^{18}\,\text{cm}^{-3}$. Compute the depletion width and the minority carrier densities at the depletion region edges (x_p and x_n) for an applied bias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

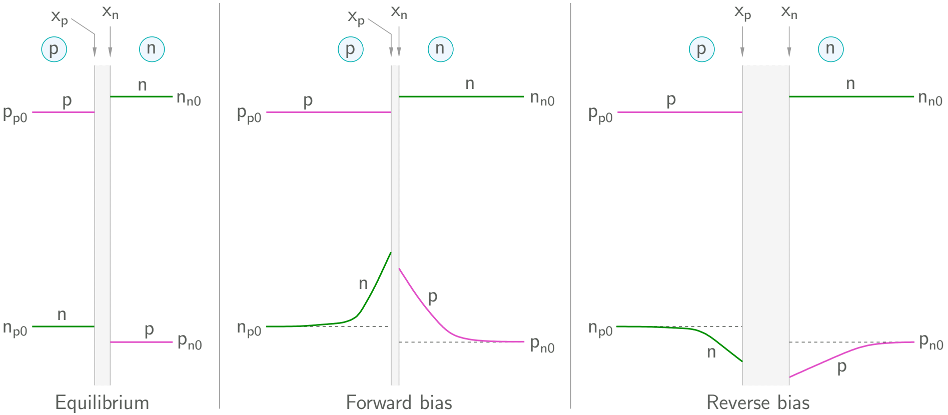


Solution: $p_{p0} \approx N_a = 5 \times 10^{16}\,\text{cm}^{-3} \rightarrow n_{p0} = \dfrac{n_i^2}{p_{p0}} = \dfrac{(1.5 \times 10^{10})^2}{5 \times 10^{16}} = 4.5 \times 10^3\,\text{cm}^{-3}$.



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

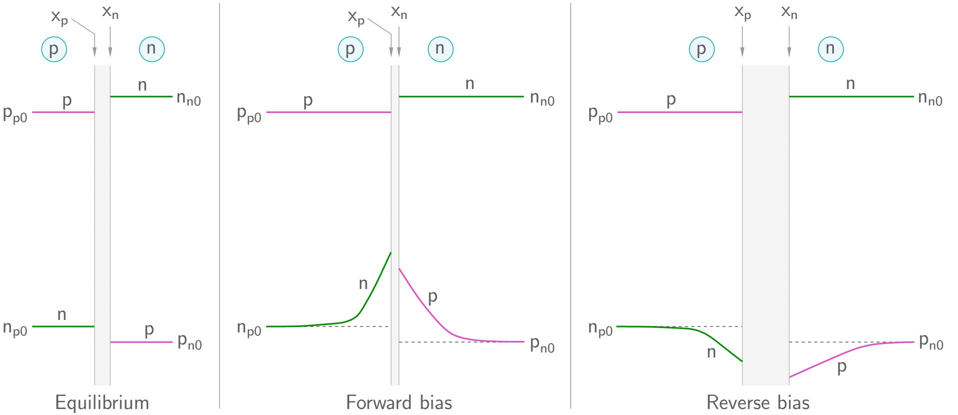
$n_{n0} \approx N_d = 1 \times 10^{18}\,\text{cm}^{-3} \rightarrow p_{n0} = \dfrac{n_i^2}{n_{n0}} = \dfrac{(1.5 \times 10^{10})^2}{1 \times 10^{18}} = 2.25 \times 10^2\,\text{cm}^{-3}.$



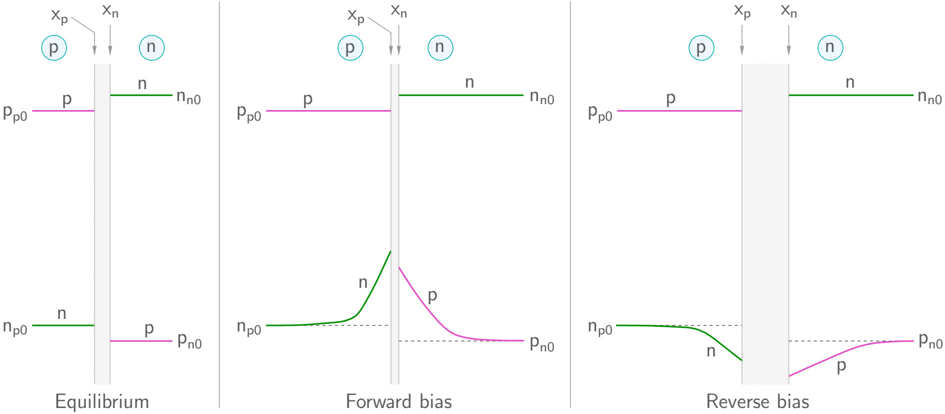
Solution: $p_{p0} \approx N_a = 5 \times 10^{16}\,\text{cm}^{-3} \rightarrow n_{p0} = \dfrac{n_i^2}{p_{p0}} = \dfrac{(1.5 \times 10^{10})^2}{5 \times 10^{16}} = 4.5 \times 10^3\,\text{cm}^{-3}.$

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

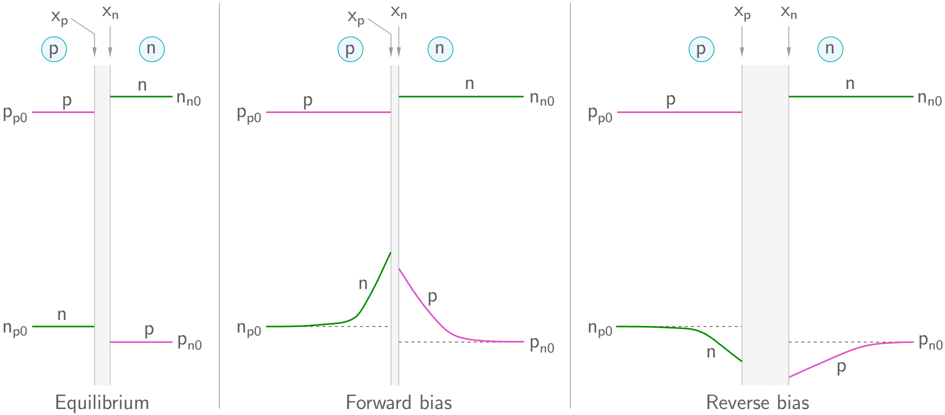
$$V_{\text{bi}} = V_T \,\log\left(\frac{N_a N_d}{n_i^2}\right) = (0.0259\,\text{V})\,\log\left(\frac{5 \times 10^{16} \times 10^{18}}{(1.5 \times 10^{10})^2}\right) = 0.86\,\text{V}.$$



xp
xn
p
n
ppp0
npp0
nnn0
pnn0
Equilibrium
Forward bias
Reverse bias

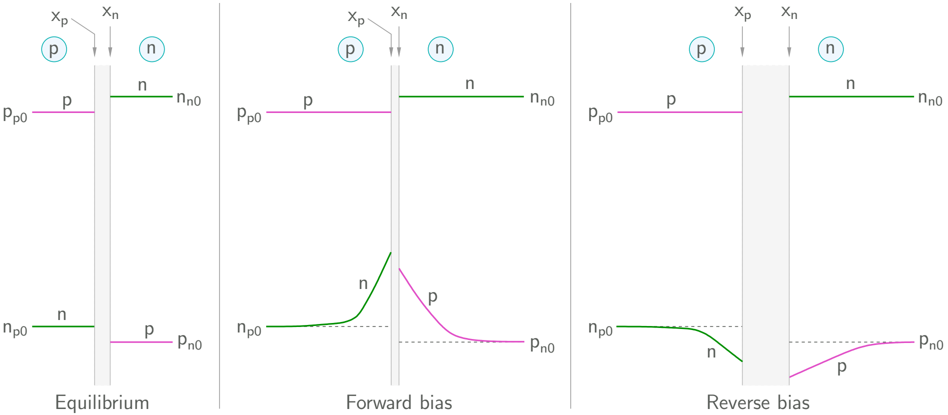


$$V_a = 0.3\,\text{V}: \quad W = \sqrt{\frac{2\epsilon}{q}\,\frac{N_a + N_d}{N_a N_d}\,(V_{\text{bi}} - V_a)} = 0.12\,\mu\text{m}.$$



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

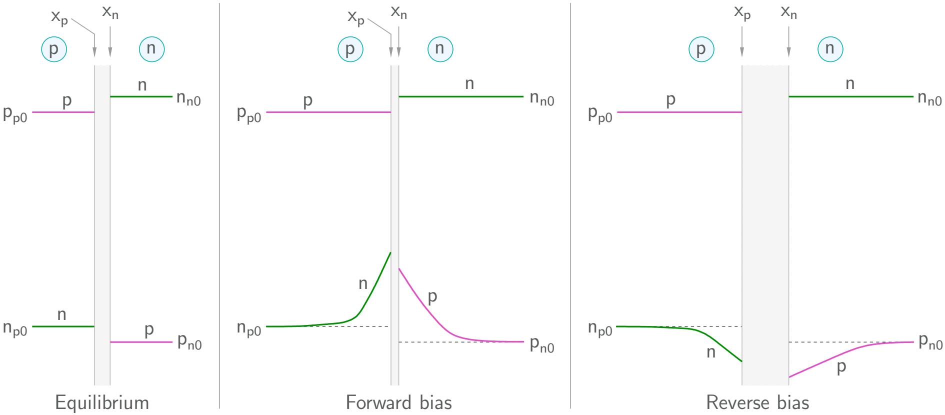
$$n(x_p) = n_{p0}\,\exp\left(\frac{V_a}{V_T}\right) = 4.5 \times 10^3 \times \exp\left(\frac{0.3}{0.0259}\right) = 4.83 \times 10^8\,\text{cm}^{-3}.$$



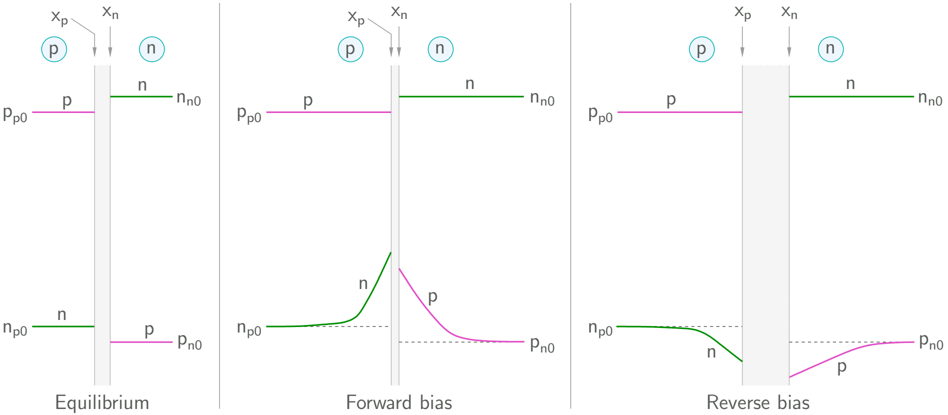
$$V_a = 0.3\,\text{V}: \quad W = \sqrt{\frac{2\epsilon}{q}\,\frac{N_a + N_d}{N_a N_d}\,(V_{\text{bi}} - V_a)} = 0.12\,\mu\text{m}.$$

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

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

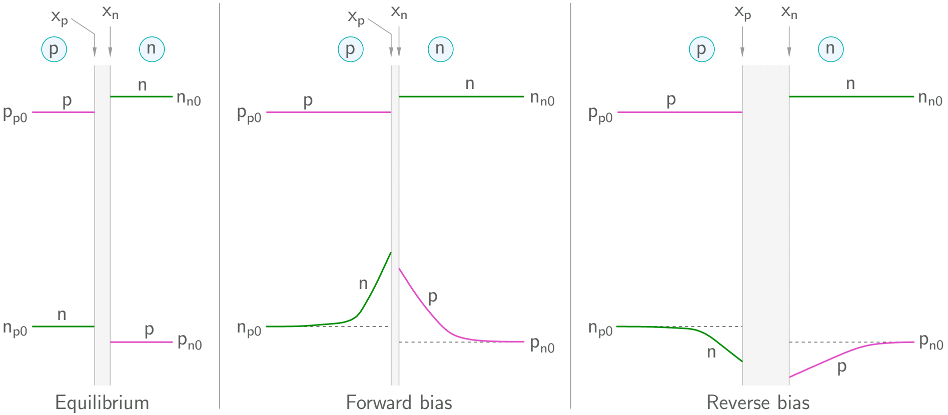


V_a (V)	W (µm)	$\mathcal{E}_m$ (kV/cm)	$n(x_p)$ (cm^{-3})	$p(x_n)$ (cm^{-3})
0.6	0.08	61.3	5.18×10^{13}	2.59×10^{12}
0.3	0.12	90.4	4.83×10^{8}	2.41×10^{7}
0.0	0.15	112.2	4.50×10^{3}	2.25×10^{2}
−1.0	0.22	165.3	$7.68 \times 10^{-14} \approx 0$	$3.84 \times 10^{-15} \approx 0$
−5.0	0.40	293.6	≈ 0	≈ 0



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

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



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

* 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.