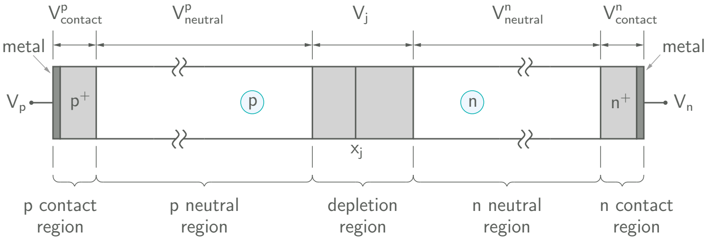
Semiconductor Devices

p-*n* Junctions: Part 3

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

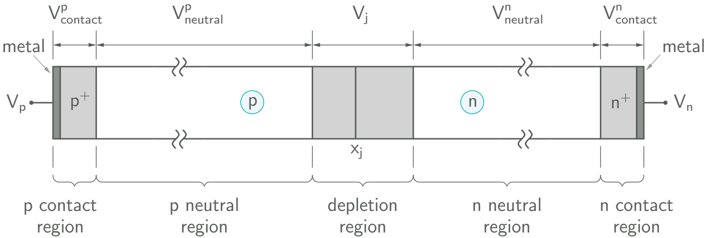
Department of Electrical Engineering
Indian Institute of Technology Bombay

pn junction: derivation of I-V equation



Continuity equation for holes ($x > x_n$): $\dfrac{\partial p(x,t)}{\partial t} = -\dfrac{1}{q}\dfrac{\partial J_p}{\partial x} - (R - G) = 0$ (in DC conditions).

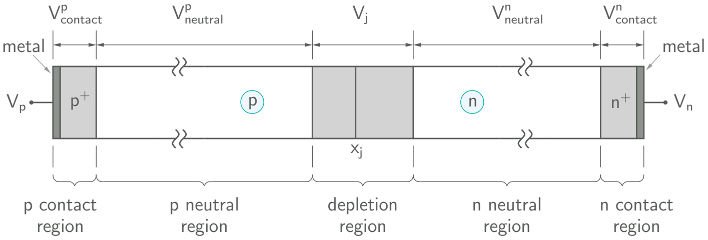
pn junction: derivation of *I*-*V* equation



Continuity equation for holes ($x > x_n$): $\dfrac{\partial p(x,t)}{\partial t} = -\dfrac{1}{q}\dfrac{\partial J_p}{\partial x} - (R - G) = 0$ (in DC conditions).

In the neutral n-region, $\mathcal{E}$ is small. $\rightarrow$ $J_p^{\text{drift}} = qp\mu_p\mathcal{E}$ is small. $\rightarrow$ $J_p \approx J_p^{\text{diff}} = -qD_p\dfrac{dp}{dx}$.

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

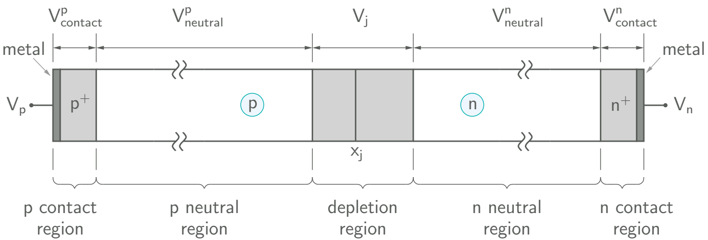


Continuity equation for holes $(x > x_n)$: $\dfrac{\partial p(x,t)}{\partial t} = -\dfrac{1}{q}\dfrac{\partial J_p}{\partial x} - (R - G) = 0$ (in DC conditions).

In the neutral n-region, $\mathcal{E}$ is small. $\rightarrow$ $J_p^{\text{drift}} = qp\mu_p\mathcal{E}$ is small. $\rightarrow$ $J_p \approx J_p^{\text{diff}} = -qD_p\dfrac{dp}{dx}$.

Also, assuming low-level injection, $R - G \approx \dfrac{\Delta p}{\tau_p} = \dfrac{p(x) - p_{n0}}{\tau_p}$.

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

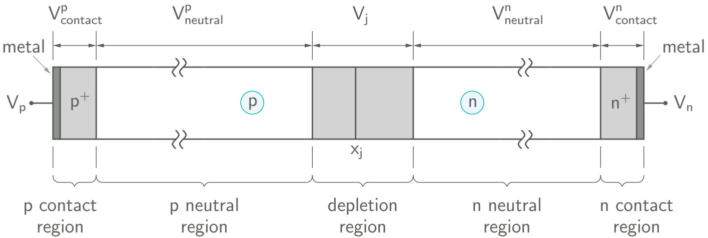


Continuity equation for holes ($x > x_n$): $\dfrac{\partial p(x,t)}{\partial t} = -\dfrac{1}{q}\dfrac{\partial J_p}{\partial x} - (R-G) = 0$ (in DC conditions).

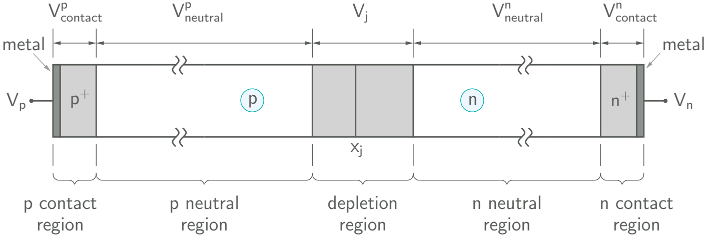
In the neutral n-region, $\mathcal{E}$ is small. $\rightarrow J_p^{\text{drift}} = qp\mu_p\mathcal{E}$ is small. $\rightarrow J_p \approx J_p^{\text{diff}} = -qD_p\dfrac{dp}{dx}$.

Also, assuming low-level injection, $R - G \approx \dfrac{\Delta p}{\tau_p} = \dfrac{p(x)-p_{n0}}{\tau_p}$.

$\rightarrow D_p\dfrac{d^2p}{dx^2} - \dfrac{p-p_{n0}}{\tau_p} = 0$ or $\dfrac{d^2\Delta p}{dx^2} - \dfrac{\Delta p}{L_p^2} = 0$, where $L_p = \sqrt{D_p\tau_p}$ is the hole diffusion length.

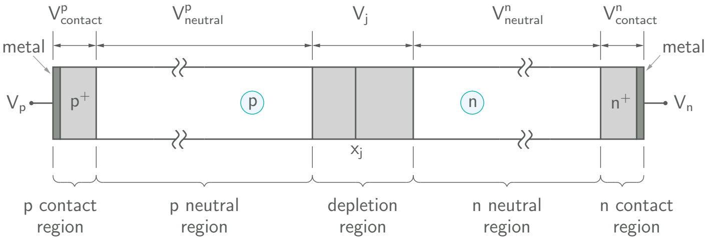


Example: For an abrupt, uniformly doped silicon *pn* junction at $T = 300\,\text{K}$, with $N_a = 10^{16}\,\text{cm}^{-3}$, $N_d = 10^{17}\,\text{cm}^{-3}$, $\mu_p = 500\,\text{cm}^2/\text{V-s}$, calculate the diffusion length L_p for $\tau_p = 1\,\text{ns}$, $10\,\text{ns}$, $100\,\text{ns}$, $1\,\mu\text{s}$, and $10\,\mu\text{s}$, and compare it with the zero-bias value of W, the depletion width.



Example: For an abrupt, uniformly doped silicon *pn* junction at $T = 300\,\text{K}$, with $N_a = 10^{16}\,\text{cm}^{-3}$, $N_d = 10^{17}\,\text{cm}^{-3}$, $\mu_p = 500\,\text{cm}^2/\text{V-s}$, calculate the diffusion length L_p for $\tau_p = 1\,\text{ns}$, $10\,\text{ns}$, $100\,\text{ns}$, $1\,\mu\text{s}$, and $10\,\mu\text{s}$, and compare it with the zero-bias value of W, the depletion width.

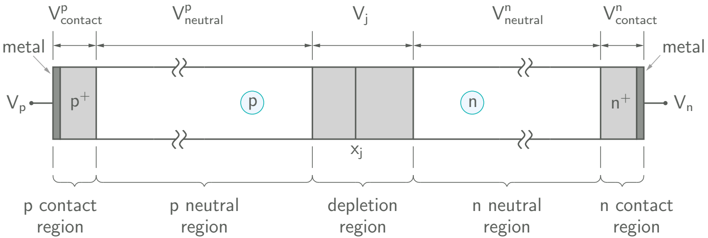
Solution: $V_{\text{bi}} = V_T \log\left(\dfrac{N_a N_d}{n_i^2}\right) = (0.0259\,\text{V}) \log\left(\dfrac{10^{16} \times 10^{17}}{(1.5 \times 10^{10})^2}\right) = 0.75\,\text{V}.$



Example: For an abrupt, uniformly doped silicon *pn* junction at $T = 300\,\text{K}$, with $N_a = 10^{16}\,\text{cm}^{-3}$, $N_d = 10^{17}\,\text{cm}^{-3}$, $\mu_p = 500\,\text{cm}^2/\text{V-s}$, calculate the diffusion length L_p for $\tau_p = 1\,\text{ns}$, $10\,\text{ns}$, $100\,\text{ns}$, $1\,\mu\text{s}$, and $10\,\mu\text{s}$, and compare it with the zero-bias value of W, the depletion width.

Solution: $V_{\text{bi}} = V_T \log\left(\dfrac{N_a N_d}{n_i^2}\right) = (0.0259\,\text{V}) \log\left(\dfrac{10^{16} \times 10^{17}}{(1.5 \times 10^{10})^2}\right) = 0.75\,\text{V}.$

The depletion width is $W = \sqrt{\dfrac{2\epsilon}{q}\,\dfrac{N_a + N_d}{N_a N_d}\,(V_{\text{bi}} - V_a)}$

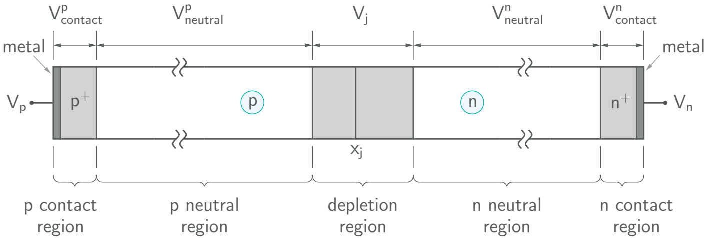


Example: For an abrupt, uniformly doped silicon *pn* junction at $T = 300\,\text{K}$, with $N_a = 10^{16}\,\text{cm}^{-3}$, $N_d = 10^{17}\,\text{cm}^{-3}$, $\mu_p = 500\,\text{cm}^2/\text{V-s}$, calculate the diffusion length L_p for $\tau_p = 1\,\text{ns}$, $10\,\text{ns}$, $100\,\text{ns}$, $1\,\mu\text{s}$, and $10\,\mu\text{s}$, and compare it with the zero-bias value of W, the depletion width.

Solution: $V_{\text{bi}} = V_T \log\left(\dfrac{N_a N_d}{n_i^2}\right) = (0.0259\,\text{V}) \log\left(\dfrac{10^{16} \times 10^{17}}{(1.5 \times 10^{10})^2}\right) = 0.75\,\text{V}.$

The depletion width is $W = \sqrt{\dfrac{2\epsilon}{q}\,\dfrac{N_a + N_d}{N_a N_d}\,(V_{\text{bi}} - V_a)}$

$$= \sqrt{\frac{2 \times 11.8 \times 8.85 \times 10^{-14}}{1.6 \times 10^{-19}}\,\frac{1.1 \times 10^{17}}{10^{16} \times 10^{17}} \times 0.75}\ \ \text{cm} = 0.33\,\mu\text{m}.$$



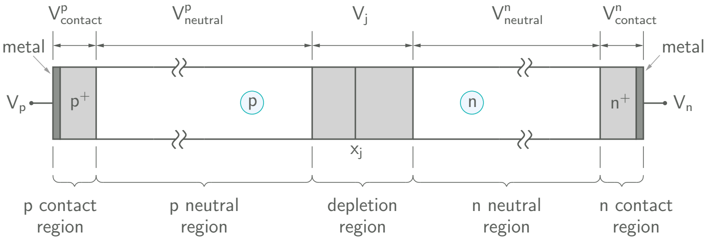
Example: For an abrupt, uniformly doped silicon *pn* junction at $T = 300\,\text{K}$, with $N_a = 10^{16}\,\text{cm}^{-3}$, $N_d = 10^{17}\,\text{cm}^{-3}$, $\mu_p = 500\,\text{cm}^2/\text{V-s}$, calculate the diffusion length L_p for τ_p = 1 ns, 10 ns, 100 ns, 1 µs, and 10 µs, and compare it with the zero-bias value of W, the depletion width.

Solution: $$V_{\text{bi}} = V_T \log\left(\frac{N_a N_d}{n_i^2}\right) = (0.0259\,\text{V}) \log\left(\frac{10^{16} \times 10^{17}}{(1.5 \times 10^{10})^2}\right) = 0.75\,\text{V}.$$

The depletion width is $$W = \sqrt{\frac{2\epsilon}{q}\,\frac{N_a + N_d}{N_a N_d}\,(V_{\text{bi}} - V_a)}$$

$$= \sqrt{\frac{2 \times 11.8 \times 8.85 \times 10^{-14}}{1.6 \times 10^{-19}}\,\frac{1.1 \times 10^{17}}{10^{16} \times 10^{17}} \times 0.75}\ \ \text{cm} = 0.33\,\mu\text{m}.$$

Diffusion coefficient for holes is $D_p = V_T\,\mu_p = 0.0259 \times 500 = 12.9\,\text{cm}^2/\text{s}$.



Example: For an abrupt, uniformly doped silicon *pn* junction at $T = 300\,\text{K}$, with $N_a = 10^{16}\,\text{cm}^{-3}$, $N_d = 10^{17}\,\text{cm}^{-3}$, $\mu_p = 500\,\text{cm}^2/\text{V-s}$, calculate the diffusion length L_p for $\tau_p = 1\,\text{ns}$, $10\,\text{ns}$, $100\,\text{ns}$, $1\,\mu\text{s}$, and $10\,\mu\text{s}$, and compare it with the zero-bias value of W, the depletion width.

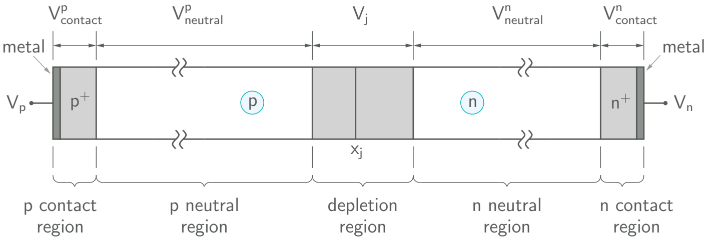
Solution: $V_{\text{bi}} = V_T \log\left(\dfrac{N_a N_d}{n_i^2}\right) = (0.0259\,\text{V}) \log\left(\dfrac{10^{16} \times 10^{17}}{(1.5 \times 10^{10})^2}\right) = 0.75\,\text{V}.$

The depletion width is $W = \sqrt{\dfrac{2\epsilon}{q}\,\dfrac{N_a + N_d}{N_a N_d}\,(V_{\text{bi}} - V_a)}$

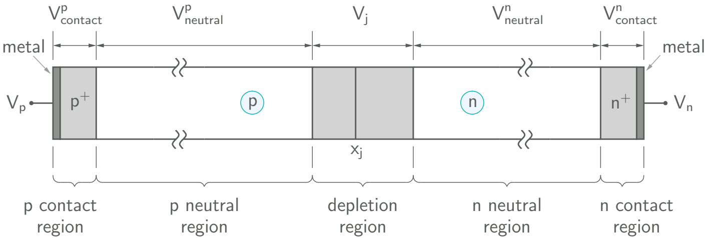
$$= \sqrt{\frac{2 \times 11.8 \times 8.85 \times 10^{-14}}{1.6 \times 10^{-19}}\;\frac{1.1 \times 10^{17}}{10^{16} \times 10^{17}} \times 0.75}\;\;\text{cm} = 0.33\,\mu\text{m}.$$

Diffusion coefficient for holes is $D_p = V_T\,\mu_p = 0.0259 \times 500 = 12.9\,\text{cm}^2/\text{s}.$

For $\tau_p = 1\,\text{ns}$, $L_p = \sqrt{12.9\,\dfrac{\text{cm}^2}{\text{s}} \times (1 \times 10^{-9}\,\text{s})} = 1.14 \times 10^{-4}\,\text{cm} = 1.14\,\mu\text{m}.$

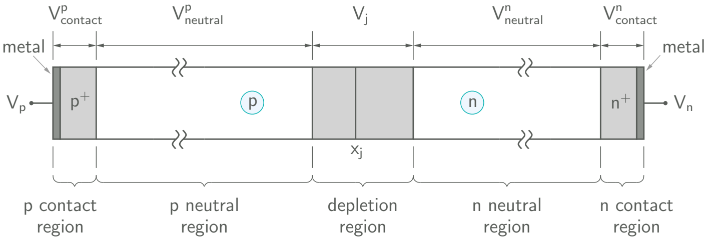


Example: For an abrupt, uniformly doped silicon *pn* junction at $T = 300\,\text{K}$, with $N_a = 10^{16}\,\text{cm}^{-3}$, $N_d = 10^{17}\,\text{cm}^{-3}$, $\mu_p = 500\,\text{cm}^2/\text{V-s}$, calculate the diffusion length L_p for $\tau_p = 1\,\text{ns}$, $10\,\text{ns}$, $100\,\text{ns}$, $1\,\mu\text{s}$, and $10\,\mu\text{s}$, and compare it with the zero-bias value of W, the depletion width.



Example: For an abrupt, uniformly doped silicon *pn* junction at $T = 300\,\text{K}$, with $N_a = 10^{16}\,\text{cm}^{-3}$, $N_d = 10^{17}\,\text{cm}^{-3}$, $\mu_p = 500\,\text{cm}^2/\text{V-s}$, calculate the diffusion length L_p for τ_p = 1 ns, 10 ns, 100 ns, 1 µs, and 10 µs, and compare it with the zero-bias value of W, the depletion width.

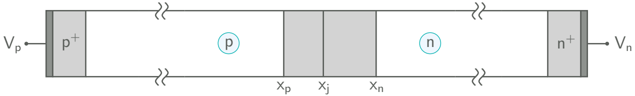
τ_p	L_p (µm)
1 ns	1.14
10 ns	3.6
100 ns	11.4
1 µs	36.0
10 µs	113.8



Example: For an abrupt, uniformly doped silicon *pn* junction at $T = 300\,\mathrm{K}$, with $N_a = 10^{16}\,\mathrm{cm}^{-3}$, $N_d = 10^{17}\,\mathrm{cm}^{-3}$, $\mu_p = 500\,\mathrm{cm}^2/\mathrm{V\text{-}s}$, calculate the diffusion length L_p for $\tau_p = 1\,\mathrm{ns}$, $10\,\mathrm{ns}$, $100\,\mathrm{ns}$, $1\,\mu\mathrm{s}$, and $10\,\mu\mathrm{s}$, and compare it with the zero-bias value of W, the depletion width.

τ_p	L_p (μm)
1 ns	1.14
10 ns	3.6
100 ns	11.4
1 µs	36.0
10 µs	113.8

Note that $L_p \gg W|_{0\,\mathrm{V}}$ ($0.33\,\mu$m), a typical situation.



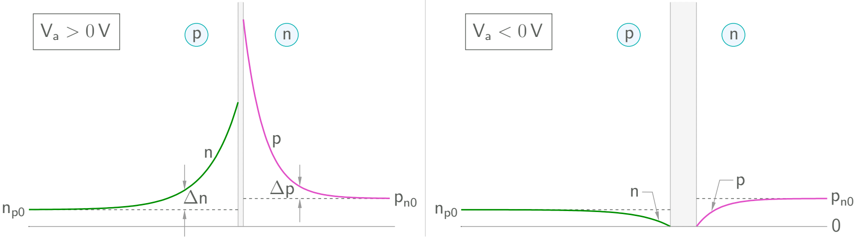
Hole continuity equation ($x > x_n$): $\dfrac{d^2\Delta p}{dx^2} - \dfrac{\Delta p}{L_p^2} = 0,.$

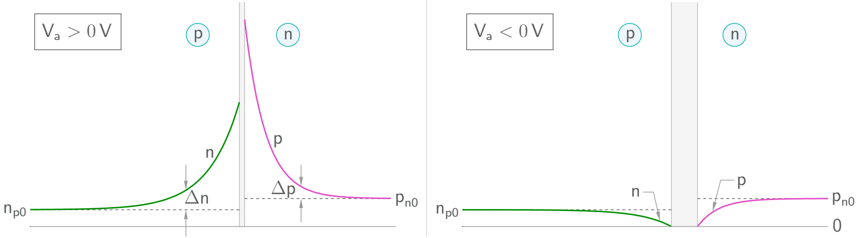
Boundary conditions: $\Delta p(x_n) = p_{n0}\,\exp\left(\dfrac{V_a}{V_T}\right) - p_{n0} = p_{n0}\left[\exp\left(\dfrac{V_a}{V_T}\right) - 1\right]$

$$\Delta p(x \rightarrow \infty) = p(x \rightarrow \infty) - p_{n0} = 0$$

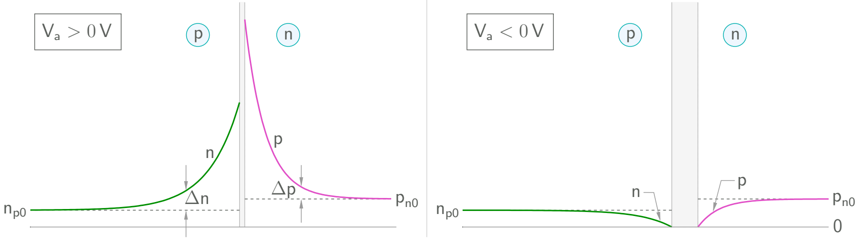
$$\rightarrow \Delta p(x) = p_{n0}\left[\exp\left(\frac{V_a}{V_T}\right) - 1\right]\exp\left(-\frac{x - x_n}{L_p}\right), \quad x > x_n,$$

$$\Delta n(x) = n_{p0}\left[\exp\left(\frac{V_a}{V_T}\right) - 1\right]\exp\left(-\frac{x_p - x}{L_n}\right), \quad x < x_p.$$



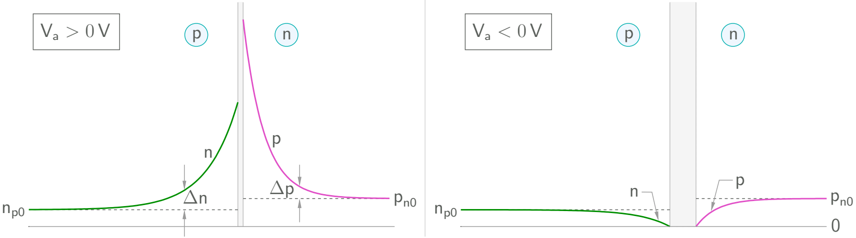


$$\Delta p(x) = p_{n0}\left[\exp\left(\frac{V_a}{V_T}\right) - 1\right]\exp\left(-\frac{x - x_n}{L_p}\right), \quad \Delta n(x) = n_{p0}\left[\exp\left(\frac{V_a}{V_T}\right) - 1\right]\exp\left(-\frac{x_p - x}{L_n}\right).$$



$$\Delta p(x) = p_{n0}\left[\exp\left(\frac{V_a}{V_T}\right) - 1\right]\exp\left(-\frac{x - x_n}{L_p}\right), \quad \Delta n(x) = n_{p0}\left[\exp\left(\frac{V_a}{V_T}\right) - 1\right]\exp\left(-\frac{x_p - x}{L_n}\right).$$

* When $x - x_n = 5L_p$, the exponential factor in $\Delta p(x)$ is $e^{-5} = 0.0067 \rightarrow$ In about five minority carrier diffusion lengths, the disturbance caused by the applied bias vanishes.



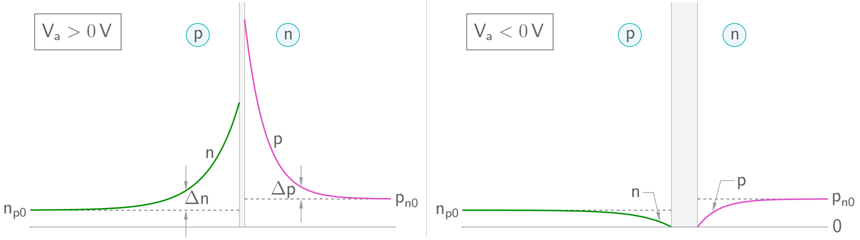
$$\Delta p(x) = p_{n0}\left[\exp\left(\frac{V_a}{V_T}\right) - 1\right]\exp\left(-\frac{x - x_n}{L_p}\right), \quad \Delta n(x) = n_{p0}\left[\exp\left(\frac{V_a}{V_T}\right) - 1\right]\exp\left(-\frac{x_p - x}{L_n}\right).$$

* When $x - x_n = 5L_p$, the exponential factor in $\Delta p(x)$ is $e^{-5} = 0.0067 \rightarrow$ In about five minority carrier diffusion lengths, the disturbance caused by the applied bias vanishes.

* Consider the minority carrier concentrations at the depletion region edges.

$$\Delta p = p_{n0}\left[\exp\left(\frac{V_a}{V_T}\right) - 1\right] \text{ at } x = x_n,$$

$$\Delta n = n_{p0}\left[\exp\left(\frac{V_a}{V_T}\right) - 1\right] \text{ at } x = x_p.$$



$$\Delta p(x) = p_{n0}\left[\exp\left(\frac{V_a}{V_T}\right)-1\right]\exp\left(-\frac{x-x_n}{L_p}\right),\quad \Delta n(x) = n_{p0}\left[\exp\left(\frac{V_a}{V_T}\right)-1\right]\exp\left(-\frac{x_p-x}{L_n}\right).$$

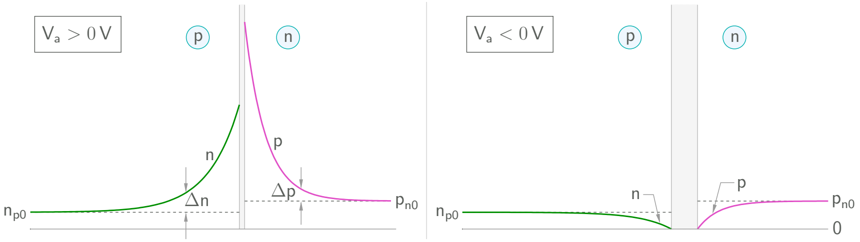
* When $x - x_n = 5L_p$, the exponential factor in $\Delta p(x)$ is $e^{-5} = 0.0067 \rightarrow$ In about five minority carrier diffusion lengths, the disturbance caused by the applied bias vanishes.

* Consider the minority carrier concentrations at the depletion region edges.

$$\Delta p = p_{n0}\left[\exp\left(\frac{V_a}{V_T}\right)-1\right] \text{ at } x = x_n,$$

$$\Delta n = n_{p0}\left[\exp\left(\frac{V_a}{V_T}\right)-1\right] \text{ at } x = x_p.$$

For forward bias, $\Delta p(x_n)$ and $\Delta n(x_p)$ are positive.



$$\Delta p(x) = p_{n0}\left[\exp\left(\frac{V_a}{V_T}\right) - 1\right]\exp\left(-\frac{x-x_n}{L_p}\right), \quad \Delta n(x) = n_{p0}\left[\exp\left(\frac{V_a}{V_T}\right) - 1\right]\exp\left(-\frac{x_p-x}{L_n}\right).$$

* When $x - x_n = 5L_p$, the exponential factor in $\Delta p(x)$ is $e^{-5} = 0.0067 \rightarrow$ In about five minority carrier diffusion lengths, the disturbance caused by the applied bias vanishes.

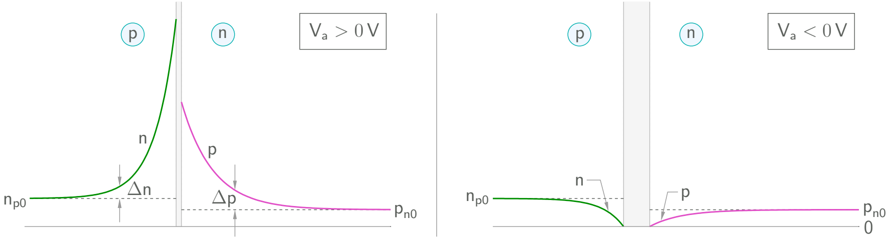
* Consider the minority carrier concentrations at the depletion region edges.

  $\Delta p = p_{n0}\left[\exp\left(\dfrac{V_a}{V_T}\right) - 1\right]$ at $x = x_n$,

  $\Delta n = n_{p0}\left[\exp\left(\dfrac{V_a}{V_T}\right) - 1\right]$ at $x = x_p$.

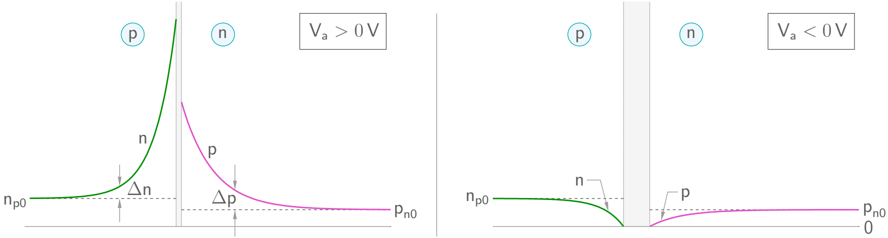
  For forward bias, $\Delta p(x_n)$ and $\Delta n(x_p)$ are positive.

  For reverse bias, $\Delta p(x_n)$ and $\Delta n(x_p)$ are negative.



Consider an abrupt, uniformly doped silicon *pn* junction at $T = 300\,K$, with $N_a = 5 \times 10^{16}\,cm^{-3}$ and $N_d = 10^{18}\,cm^{-3}$. Compute $\Delta n(x_p)$ and $\Delta p(x_n)$ for $V_a = 0.1$, 0.2, 0.3, 0.6, 0.7, -0.1, -0.2, -0.5, -1, and $-2\,V$. ($n_i = 1.5 \times 10^{10}\,cm^{-3}$ for silicon at $T = 300\,K$.)

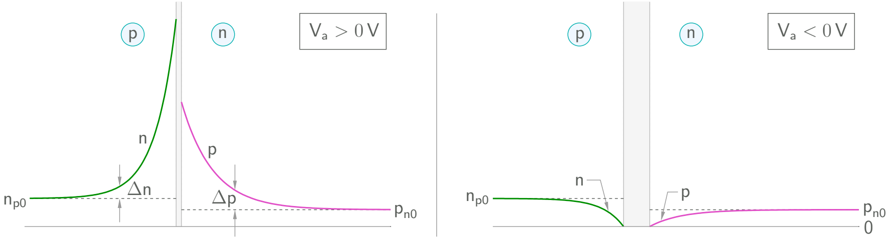
Solution: $p_{p0} \approx N_a = 5 \times 10^{16}\,cm^{-3} \rightarrow n_{p0} = \dfrac{n_i^2}{p_{p0}} = \dfrac{(1.5 \times 10^{10})^2}{5 \times 10^{16}} = 4.5 \times 10^3\,cm^{-3}$.



Consider an abrupt, uniformly doped silicon *pn* junction at $T = 300\,K$, with $N_a = 5 \times 10^{16}\,cm^{-3}$ and $N_d = 10^{18}\,cm^{-3}$. Compute $\Delta n(x_p)$ and $\Delta p(x_n)$ for $V_a = 0.1$, 0.2, 0.3, 0.6, 0.7, -0.1, -0.2, -0.5, -1, and $-2\,V$. ($n_i = 1.5 \times 10^{10}\,cm^{-3}$ for silicon at $T = 300\,K$.)

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

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

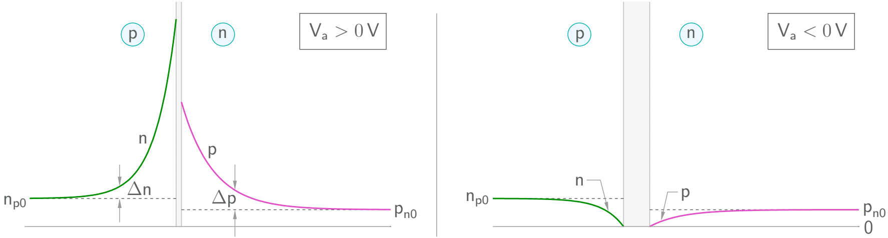


Consider an abrupt, uniformly doped silicon *pn* junction at $T = 300\,\text{K}$, with $N_a = 5 \times 10^{16}\,\text{cm}^{-3}$ and $N_d = 10^{18}\,\text{cm}^{-3}$. Compute $\Delta n(x_p)$ and $\Delta p(x_n)$ for $V_a = 0.1$, 0.2, 0.3, 0.6, 0.7, -0.1, -0.2, -0.5, -1, and $-2\,\text{V}$. ($n_i = 1.5 \times 10^{10}\,\text{cm}^{-3}$ for silicon at $T = 300\,\text{K}$.)

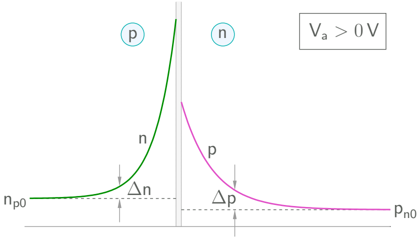
Solution: $p_{p0} \approx N_a = 5 \times 10^{16}\,\text{cm}^{-3} \rightarrow n_{p0} = \dfrac{n_i^2}{p_{p0}} = \dfrac{(1.5 \times 10^{10})^2}{5 \times 10^{16}} = 4.5 \times 10^3\,\text{cm}^{-3}$.

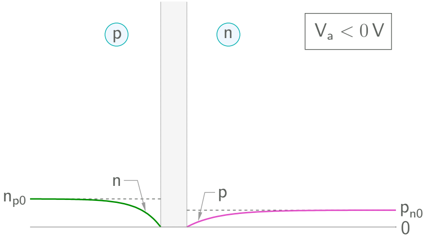
$$n_{n0} \approx N_d = 1 \times 10^{18}\,\text{cm}^{-3} \rightarrow p_{n0} = \frac{n_i^2}{n_{n0}} = \frac{(1.5 \times 10^{10})^2}{1 \times 10^{18}} = 2.25 \times 10^2\,\text{cm}^{-3}.$$

$$\Delta p(x_n) = p_{n0}\left[\exp\left(\frac{V_a}{V_T}\right) - 1\right], \quad \Delta n(x_p) = n_{p0}\left[\exp\left(\frac{V_a}{V_T}\right) - 1\right].$$



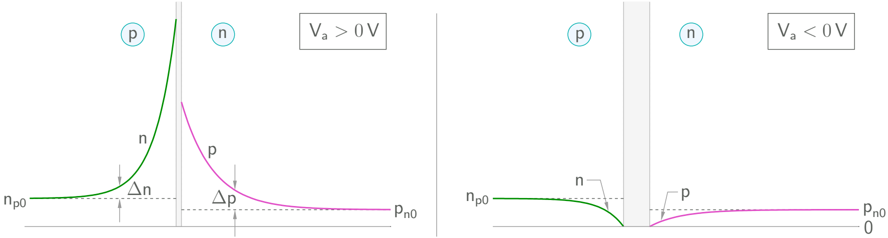
V_a (V)	$\Delta n(x_p)$ (cm^{-3})	$\Delta p(x_n)$ (cm^{-3})	V_a (V)	$\Delta n(x_p)$ (cm^{-3})	$\Delta p(x_n)$ (cm^{-3})
0	0	0	0	0	0
0.1	2.09×10^5	1.05×10^4	-0.1	-4.41×10^3	-2.20×10^2
0.2	1.02×10^7	5.08×10^5	-0.2	-4.50×10^3	-2.25×10^2
0.3	4.83×10^8	2.41×10^7	-0.5	-4.50×10^3	-2.25×10^2
0.6	5.18×10^{13}	2.59×10^{12}	-1	-4.50×10^3	-2.25×10^2
0.7	2.46×10^{15}	1.23×10^{14}	-2	-4.50×10^3	-2.25×10^2





V_a (V)	$\Delta n(x_p)$ (cm^{-3})	$\Delta p(x_n)$ (cm^{-3})	V_a (V)	$\Delta n(x_p)$ (cm^{-3})	$\Delta p(x_n)$ (cm^{-3})
0	0	0	0	0	0
0.1	2.09×10^5	1.05×10^4	-0.1	-4.41×10^3	-2.20×10^2
0.2	1.02×10^7	5.08×10^5	-0.2	-4.50×10^3	-2.25×10^2
0.3	4.83×10^8	2.41×10^7	-0.5	-4.50×10^3	-2.25×10^2
0.6	5.18×10^{13}	2.59×10^{12}	-1	-4.50×10^3	-2.25×10^2
0.7	2.46×10^{15}	1.23×10^{14}	-2	-4.50×10^3	-2.25×10^2

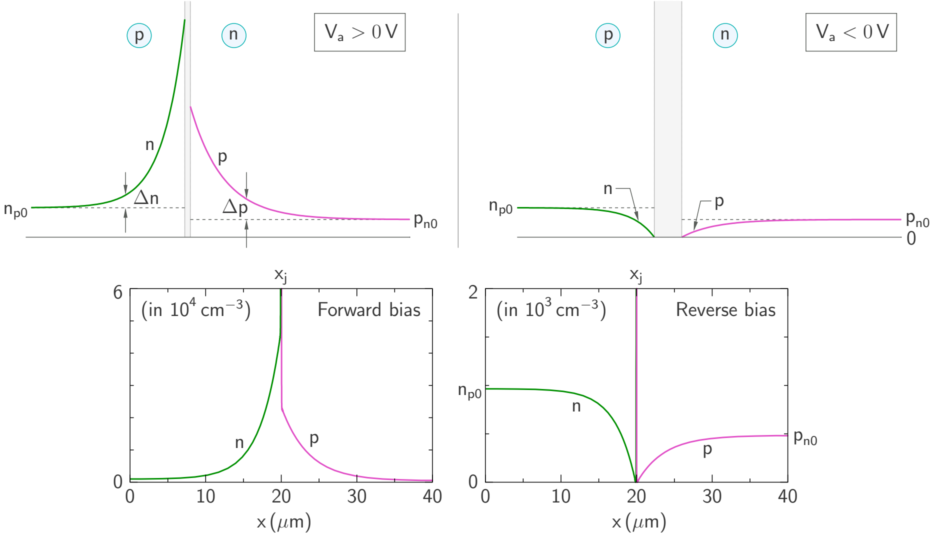
* Forward bias:
  $\Delta p(x_n)$ and $\Delta n(x_p)$ increase by several orders of magnitude as V_a is increased.



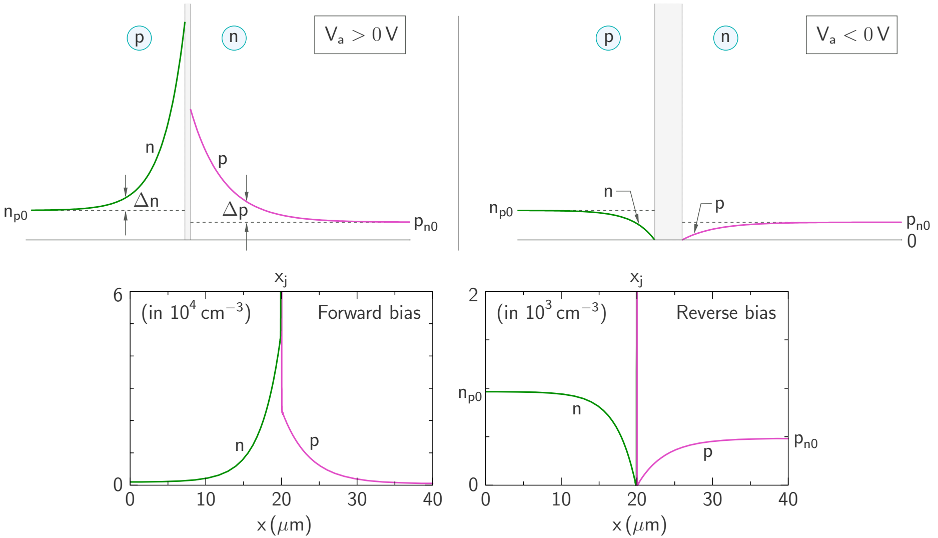
V_a (V)	$\Delta n(x_p)$ (cm^{-3})	$\Delta p(x_n)$ (cm^{-3})	V_a (V)	$\Delta n(x_p)$ (cm^{-3})	$\Delta p(x_n)$ (cm^{-3})
0	0	0	0	0	0
0.1	2.09×10^{5}	1.05×10^{4}	-0.1	-4.41×10^{3}	-2.20×10^{2}
0.2	1.02×10^{7}	5.08×10^{5}	-0.2	-4.50×10^{3}	-2.25×10^{2}
0.3	4.83×10^{8}	2.41×10^{7}	-0.5	-4.50×10^{3}	-2.25×10^{2}
0.6	5.18×10^{13}	2.59×10^{12}	-1	-4.50×10^{3}	-2.25×10^{2}
0.7	2.46×10^{15}	1.23×10^{14}	-2	-4.50×10^{3}	-2.25×10^{2}

* Forward bias:
  $\Delta p(x_n)$ and $\Delta n(x_p)$ increase by several orders of magnitude as V_a is increased.
* Reverse bias:
  $\Delta p(x_n) \approx -p_{n0}$, $\Delta n(x_p) \approx -n_{p0}$.

pn junction under forward bias: simulation results

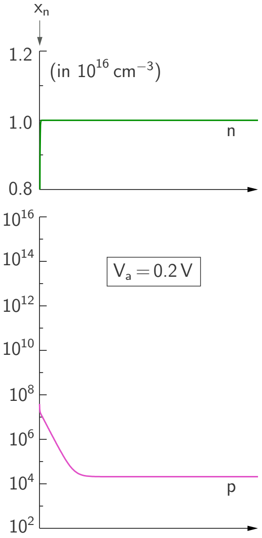


pn junction under forward bias: simulation results

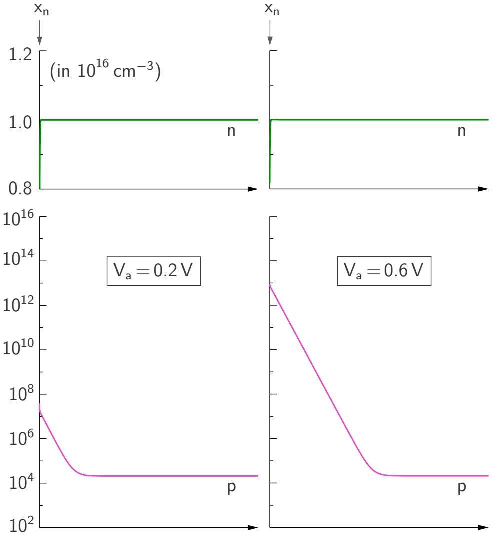


* As we have seen earlier, the minority carrier diffusion lengths (i.e., L_n on the *p*-side, L_p on the *n*-side) are typically much larger than the depletion width.

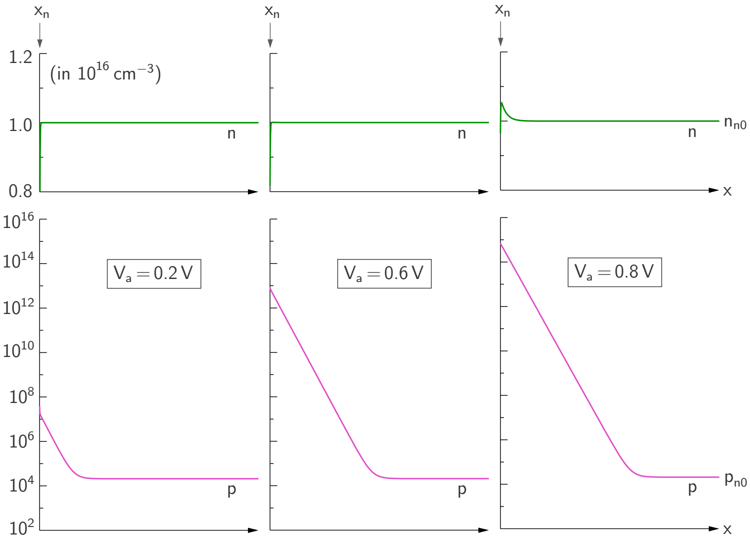
High-injection regime



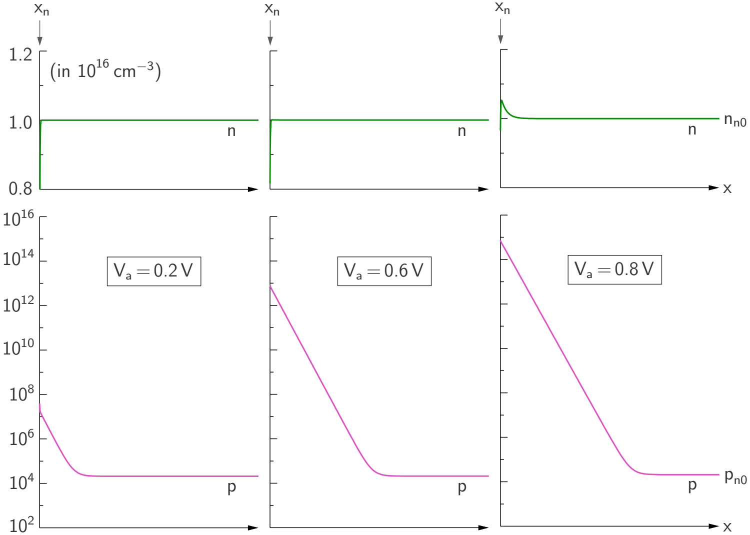
High-injection regime



High-injection regime

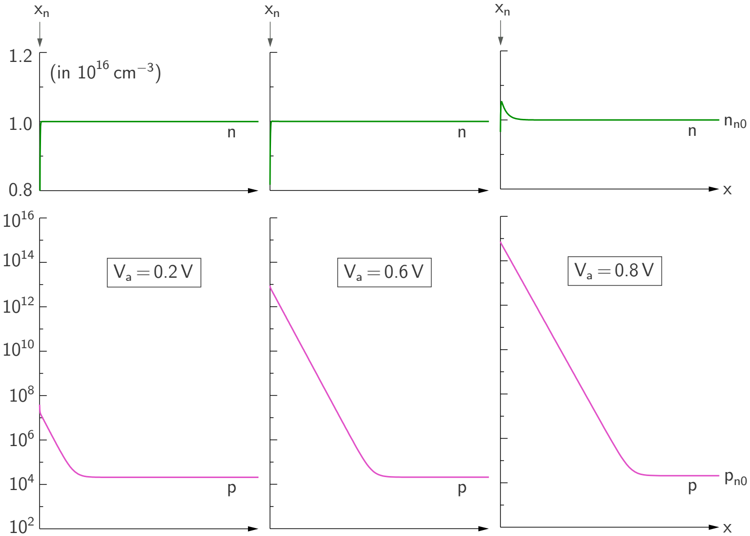


High-injection regime



* As the forward bias is increased, the minority carrier concentration increases rapidly, and at some point becomes comparable to the majority carrier concentration. This regime is called the "high-injection" regime.

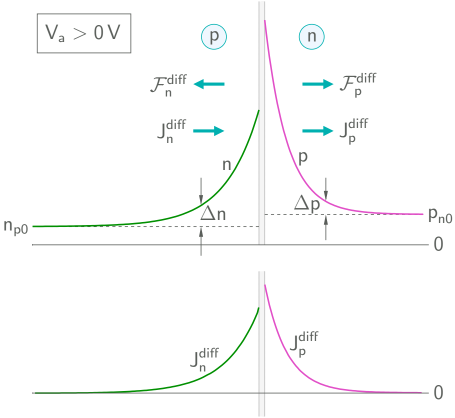
High-injection regime



* As the forward bias is increased, the minority carrier concentration increases rapidly, and at some point becomes comparable to the majority carrier concentration. This regime is called the "high-injection" regime.
* In the high-injection regime, the majority carrier concentration also increases appreciably (e.g., $\Delta n \approx \Delta p$ on the n side), and the overall charge neutrality is maintained in the neutral regions.

$$\Delta p(x) = p_{n0} \left[\exp\left(\frac{V_a}{V_T}\right) - 1 \right] \exp\left(-\frac{x - x_n}{L_p}\right), \quad x > x_n.$$

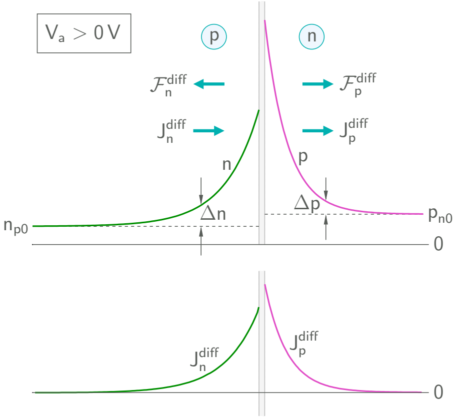
$$\Delta n(x) = n_{p0} \left[\exp\left(\frac{V_a}{V_T}\right) - 1 \right] \exp\left(-\frac{x_p - x}{L_n}\right), \quad x < x_p.$$



$$\Delta p(x) = p_{n0} \left[\exp\left(\frac{V_a}{V_T}\right) - 1\right] \exp\left(-\frac{x - x_n}{L_p}\right), \quad x > x_n.$$

$$\Delta n(x) = n_{p0} \left[\exp\left(\frac{V_a}{V_T}\right) - 1\right] \exp\left(-\frac{x_p - x}{L_n}\right), \quad x < x_p.$$

Note that, although $\mathcal{F}_n^{\text{diff}}$ (for $x < x_p$) and $\mathcal{F}_p^{\text{diff}}$ (for $x > x_n$) are in opposite directions, J_n^{diff} (for $x < x_p$) and J_p^{diff} (for $x > x_n$) are in the same direction.



$$\Delta p(x) = p_{n0}\left[\exp\left(\frac{V_a}{V_T}\right) - 1\right]\exp\left(-\frac{x-x_n}{L_p}\right), \quad x > x_n.$$

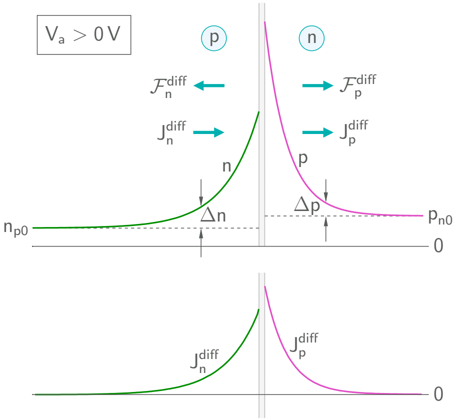
$$\Delta n(x) = n_{p0}\left[\exp\left(\frac{V_a}{V_T}\right) - 1\right]\exp\left(-\frac{x_p-x}{L_n}\right), \quad x < x_p.$$

Note that, although $\mathcal{F}_n^{\text{diff}}$ (for $x < x_p$) and $\mathcal{F}_p^{\text{diff}}$ (for $x > x_n$) are in opposite directions, J_n^{diff} (for $x < x_p$) and J_p^{diff} (for $x > x_n$) are in the same direction.

In particular, we are interested in $J_n^{\text{diff}}(x_p)$ and $J_p^{\text{diff}}(x_n)$.

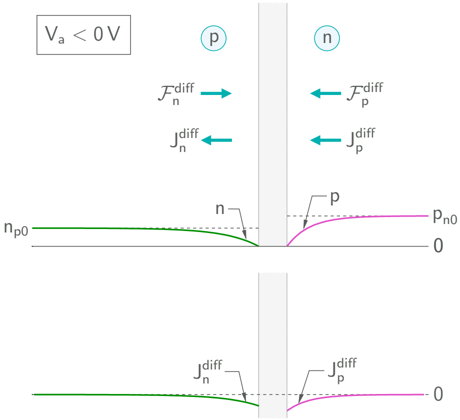
$$J_n^{\text{diff}}(x_p) = \frac{qD_n n_{p0}}{L_n}\left(e^{V_a/V_T} - 1\right),$$

$$J_p^{\text{diff}}(x_n) = \frac{qD_p p_{n0}}{L_p}\left(e^{V_a/V_T} - 1\right).$$



$$\Delta p(x) = p_{n0} \left[\exp\left(\frac{V_a}{V_T}\right) - 1 \right] \exp\left(-\frac{x - x_n}{L_p}\right), \quad x > x_n.$$

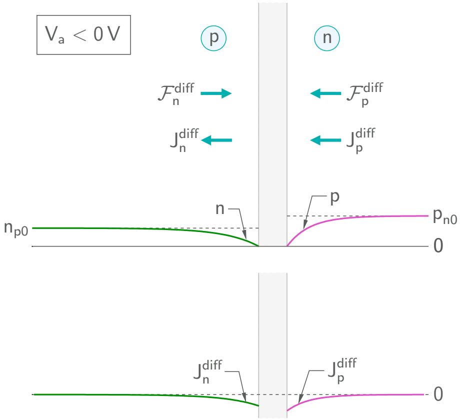
$$\Delta n(x) = n_{p0} \left[\exp\left(\frac{V_a}{V_T}\right) - 1 \right] \exp\left(-\frac{x_p - x}{L_n}\right), \quad x < x_p.$$



$$\Delta p(x) = p_{n0}\left[\exp\left(\frac{V_a}{V_T}\right) - 1\right]\exp\left(-\frac{x - x_n}{L_p}\right), \quad x > x_n.$$

$$\Delta n(x) = n_{p0}\left[\exp\left(\frac{V_a}{V_T}\right) - 1\right]\exp\left(-\frac{x_p - x}{L_n}\right), \quad x < x_p.$$

Note that, although $\mathcal{F}_n^{\rm diff}$ (for $x < x_p$) and $\mathcal{F}_p^{\rm diff}$ (for $x > x_n$) are in opposite directions, $J_n^{\rm diff}$ (for $x < x_p$) and $J_p^{\rm diff}$ (for $x > x_n$) are in the same direction.



$$\Delta p(x) = p_{n0}\left[\exp\left(\frac{V_a}{V_T}\right) - 1\right]\exp\left(-\frac{x - x_n}{L_p}\right), \quad x > x_n.$$

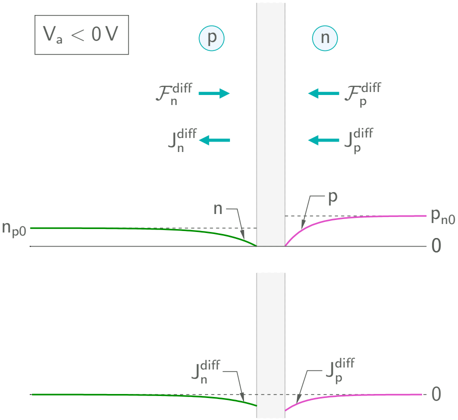
$$\Delta n(x) = n_{p0}\left[\exp\left(\frac{V_a}{V_T}\right) - 1\right]\exp\left(-\frac{x_p - x}{L_n}\right), \quad x < x_p.$$

Note that, although $\mathcal{F}_n^{\text{diff}}$ (for $x < x_p$) and $\mathcal{F}_p^{\text{diff}}$ (for $x > x_n$) are in opposite directions, J_n^{diff} (for $x < x_p$) and J_p^{diff} (for $x > x_n$) are in the same direction.

In particular, we are interested in $J_n^{\text{diff}}(x_p)$ and $J_p^{\text{diff}}(x_n)$.

$$J_n^{\text{diff}}(x_p) = \frac{qD_n n_{p0}}{L_n}\left(e^{V_a/V_T} - 1\right) \approx -\frac{qD_n n_{p0}}{L_n},$$

$$J_p^{\text{diff}}(x_n) = \frac{qD_p p_{n0}}{L_p}\left(e^{V_a/V_T} - 1\right) \approx -\frac{qD_p p_{n0}}{L_p}.$$



$$\Delta p(x) = p_{n0}\left[\exp\left(\frac{V_a}{V_T}\right)-1\right]\exp\left(-\frac{x-x_n}{L_p}\right),\quad x > x_n.$$

$$\Delta n(x) = n_{p0}\left[\exp\left(\frac{V_a}{V_T}\right)-1\right]\exp\left(-\frac{x_p-x}{L_n}\right),\quad x < x_p.$$

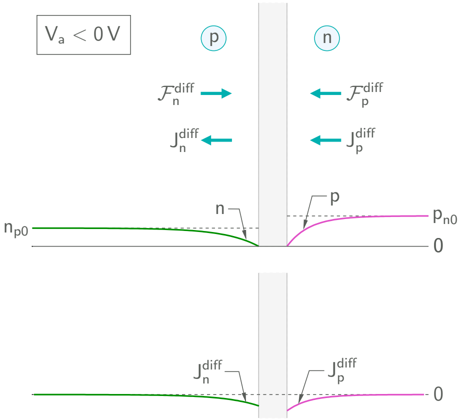
Note that, although $\mathcal{F}_n^{\text{diff}}$ (for $x < x_p$) and $\mathcal{F}_p^{\text{diff}}$ (for $x > x_n$) are in opposite directions, J_n^{diff} (for $x < x_p$) and J_p^{diff} (for $x > x_n$) are in the same direction.

In particular, we are interested in $J_n^{\text{diff}}(x_p)$ and $J_p^{\text{diff}}(x_n)$.

$$J_n^{\text{diff}}(x_p) = \frac{qD_n n_{p0}}{L_n}\left(e^{V_a/V_T}-1\right) \approx -\frac{qD_n n_{p0}}{L_n},$$

$$J_p^{\text{diff}}(x_n) = \frac{qD_p p_{n0}}{L_p}\left(e^{V_a/V_T}-1\right) \approx -\frac{qD_p p_{n0}}{L_p}.$$

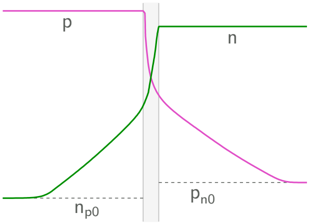
The currents are much smaller under reverse bias.



pn junction: What is happening inside the depletion region?

Consider x in the depletion region, i.e., $x_p < x < x_n$.

$$J_p^{\text{diff}} \approx -J_p^{\text{drift}} \rightarrow \int d\psi = -V_T \int \frac{1}{p}\, dp \rightarrow \frac{p(x)}{p(x_p)} = \exp \frac{\psi(x_p) - \psi(x)}{V_T}.$$

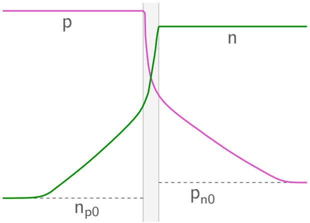


pn junction: What is happening inside the depletion region?

Consider x in the depletion region, i.e., $x_p < x < x_n$.

$$J_p^{\text{diff}} \approx -J_p^{\text{drift}} \rightarrow \int d\psi = -V_T \int \frac{1}{p}\, dp \rightarrow \frac{p(x)}{p(x_p)} = \exp \frac{\psi(x_p) - \psi(x)}{V_T}.$$

$$J_n^{\text{diff}} \approx -J_n^{\text{drift}} \rightarrow \int d\psi = +V_T \int \frac{1}{n}\, dn \rightarrow \frac{n(x)}{n(x_p)} = \exp \frac{\psi(x) - \psi(x_p)}{V_T}.$$



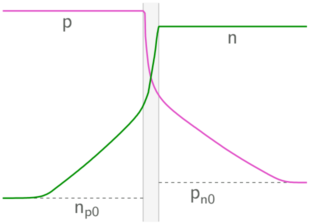
pn junction: What is happening inside the depletion region?

Consider x in the depletion region, i.e., $x_p < x < x_n$.

$$J_p^{\text{diff}} \approx -J_p^{\text{drift}} \rightarrow \int d\psi = -V_T \int \frac{1}{p}\, dp \rightarrow \frac{p(x)}{p(x_p)} = \exp \frac{\psi(x_p) - \psi(x)}{V_T}.$$

$$J_n^{\text{diff}} \approx -J_n^{\text{drift}} \rightarrow \int d\psi = +V_T \int \frac{1}{n}\, dn \rightarrow \frac{n(x)}{n(x_p)} = \exp \frac{\psi(x) - \psi(x_p)}{V_T}.$$

$$\rightarrow p(x)n(x) = p(x_p)n(x_p) = p_{p0}\, n_{p0}\, e^{V_a/V_T} = n_i^2\, e^{V_a/V_T}$$



pn junction: What is happening inside the depletion region?

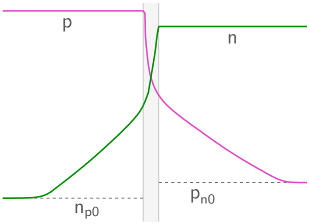
Consider x in the depletion region, i.e., $x_p < x < x_n$.

$$J_p^{\text{diff}} \approx -J_p^{\text{drift}} \rightarrow \int d\psi = -V_T \int \frac{1}{p}\, dp \rightarrow \frac{p(x)}{p(x_p)} = \exp \frac{\psi(x_p) - \psi(x)}{V_T}.$$

$$J_n^{\text{diff}} \approx -J_n^{\text{drift}} \rightarrow \int d\psi = +V_T \int \frac{1}{n}\, dn \rightarrow \frac{n(x)}{n(x_p)} = \exp \frac{\psi(x) - \psi(x_p)}{V_T}.$$

$$\rightarrow p(x)n(x) = p(x_p)n(x_p) = p_{p0}\, n_{p0}\, e^{V_a/V_T} = n_i^2\, e^{V_a/V_T}$$

If $V_a > 0\,\mathrm{V}$, $pn > n_i^2$ in the depletion region; else, $pn < n_i^2$.



pn junction: What is happening inside the depletion region?

Consider x in the depletion region, i.e., $x_p < x < x_n$.

$$J_p^{\text{diff}} \approx -J_p^{\text{drift}} \rightarrow \int d\psi = -V_T \int \frac{1}{p}\, dp \rightarrow \frac{p(x)}{p(x_p)} = \exp \frac{\psi(x_p) - \psi(x)}{V_T}.$$

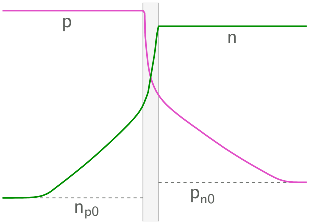
$$J_n^{\text{diff}} \approx -J_n^{\text{drift}} \rightarrow \int d\psi = +V_T \int \frac{1}{n}\, dn \rightarrow \frac{n(x)}{n(x_p)} = \exp \frac{\psi(x) - \psi(x_p)}{V_T}.$$

$$\rightarrow p(x)n(x) = p(x_p)n(x_p) = p_{p0}\, n_{p0}\, e^{V_a/V_T} = n_i^2\, e^{V_a/V_T}$$

If $V_a > 0\,\text{V}$, $pn > n_i^2$ in the depletion region; else, $pn < n_i^2$.

$$R - G = \frac{pn - n_i^2}{\tau_n(n + n_1) + \tau_p(p + p_1)}$$

$\rightarrow$ we have a net recombination inside the depletion region if $V_a > 0\,\text{V}$, and a net generation if $V_a < 0\,\text{V}$.



pn junction: What is happening inside the depletion region?

Consider x in the depletion region, i.e., $x_p < x < x_n$.

$$J_p^{\text{diff}} \approx -J_p^{\text{drift}} \rightarrow \int d\psi = -V_T \int \frac{1}{p}\,dp \rightarrow \frac{p(x)}{p(x_p)} = \exp\frac{\psi(x_p)-\psi(x)}{V_T}.$$

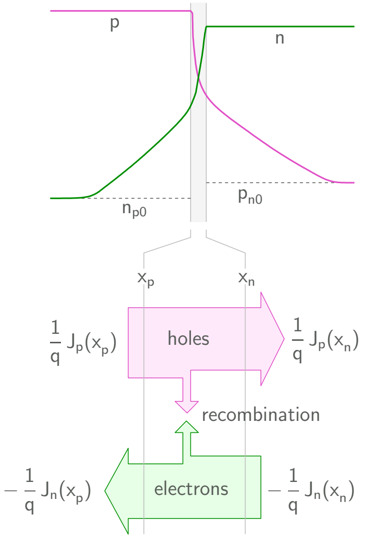
$$J_n^{\text{diff}} \approx -J_n^{\text{drift}} \rightarrow \int d\psi = +V_T \int \frac{1}{n}\,dn \rightarrow \frac{n(x)}{n(x_p)} = \exp\frac{\psi(x)-\psi(x_p)}{V_T}.$$

$$\rightarrow p(x)n(x) = p(x_p)n(x_p) = p_{p0}\,n_{p0}\,e^{V_a/V_T} = n_i^2\,e^{V_a/V_T}$$

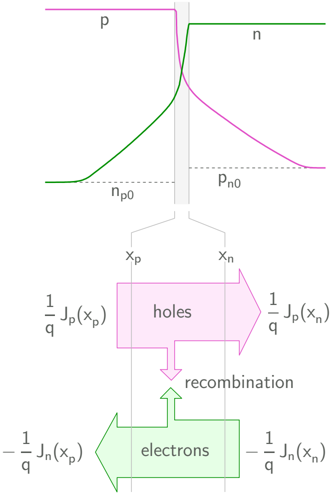
If $V_a > 0\,\text{V}$, $pn > n_i^2$ in the depletion region; else, $pn < n_i^2$.

$$R - G = \frac{pn - n_i^2}{\tau_n(n+n_1)+\tau_p(p+p_1)}$$

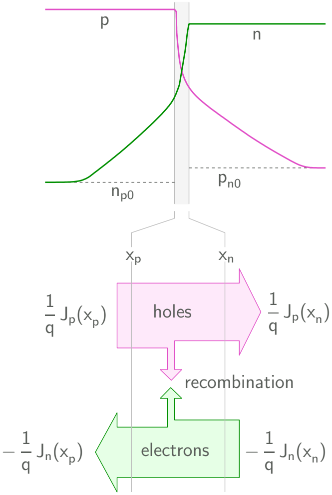
$\rightarrow$ we have a net recombination inside the depletion region if $V_a > 0\,\text{V}$, and a net generation if $V_a < 0\,\text{V}$.



pn junction: What is happening inside the depletion region?

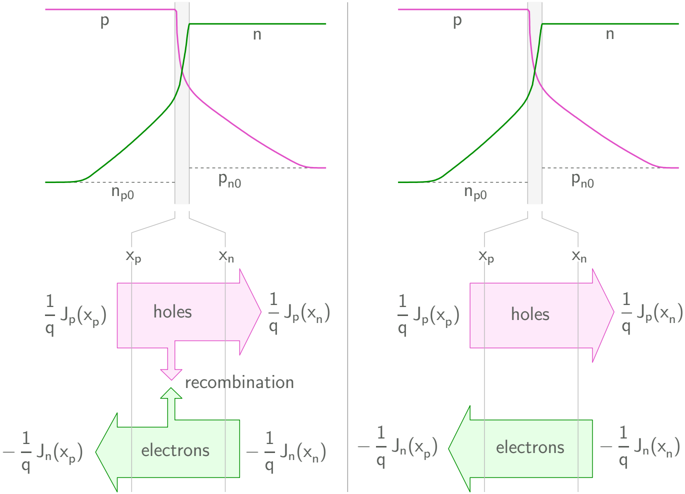


pn junction: What is happening inside the depletion region?



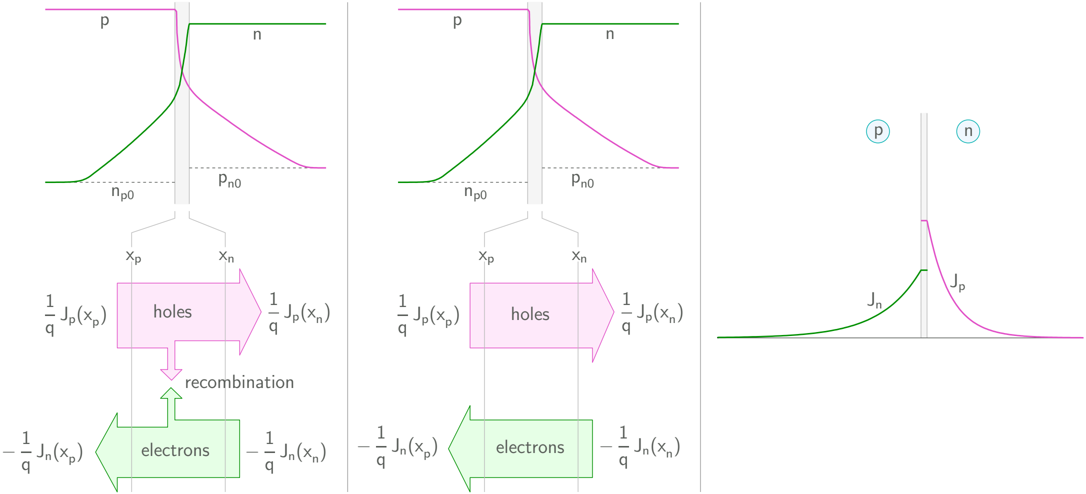
* To obtain a first-order *I*-*V* model, we ignore G-R in the depletion region.

pn junction: What is happening inside the depletion region?



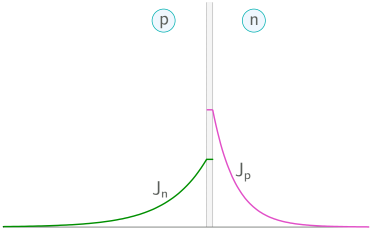
* To obtain a first-order *I*-*V* model, we ignore G-R in the depletion region.

pn junction: What is happening inside the depletion region?

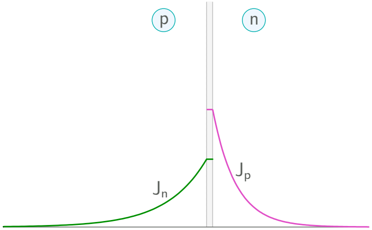


* To obtain a first-order *I-V* model, we ignore G-R in the depletion region.

pn junction: total current density

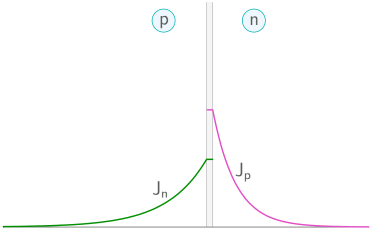


pn junction: total current density



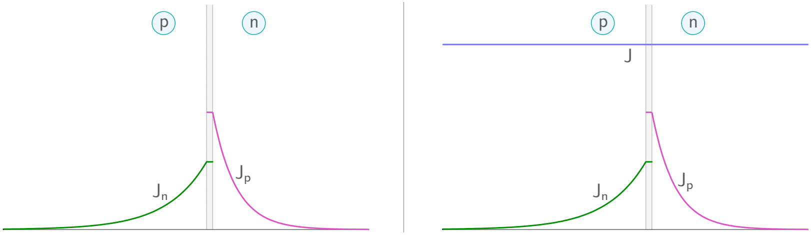
∗ The total current density is the same throughout the device.

pn junction: total current density



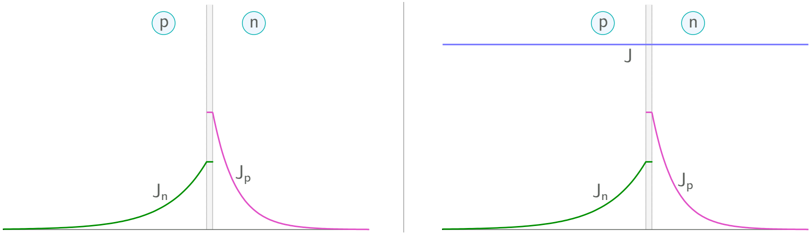
* The total current density is the same throughout the device.
* If there is no G-R in the depletion region, we have $J = J_n(x_p) + J_p(x_n)$.

pn junction: total current density



* The total current density is the same throughout the device.
* If there is no G-R in the depletion region, we have $J = J_n(x_p) + J_p(x_n)$.

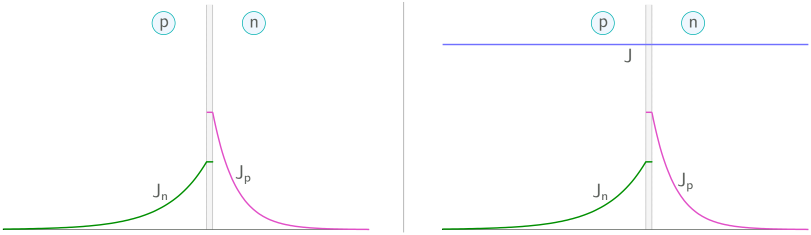
pn junction: total current density



* The total current density is the same throughout the device.
* If there is no G-R in the depletion region, we have $J = J_n(x_p) + J_p(x_n)$.
* Using our earlier results for $J_p(x_n)$ and $J_n(x_p)$, we get

$$J = J_p(x_n) + J_n(x_p) = \left[\frac{qD_p p_{n0}}{L_p} + \frac{qD_n n_{p0}}{L_n} \right] \left(e^{V_a/V_T} - 1 \right).$$

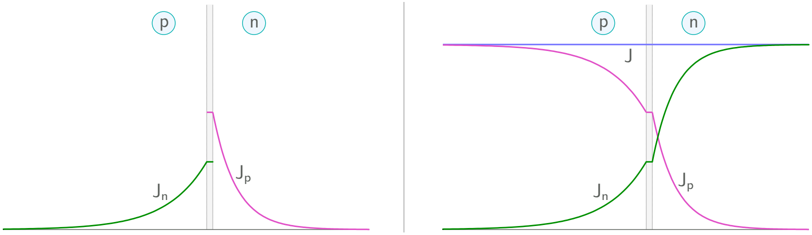
pn junction: total current density



* The total current density is the same throughout the device.
* If there is no G-R in the depletion region, we have $J = J_n(x_p) + J_p(x_n)$.
* Using our earlier results for $J_p(x_n)$ and $J_n(x_p)$, we get

$$J = J_p(x_n) + J_n(x_p) = \left[\frac{qD_p p_{n0}}{L_p} + \frac{qD_n n_{p0}}{L_n}\right] \left(e^{V_a/V_T} - 1\right).$$

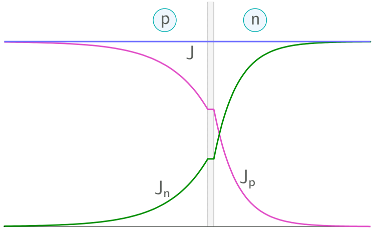
* We can now obtain J_n $(x > x_n)$ and J_p $(x < x_p)$ using $J_n(x) + J_p(x) = J$.



* The total current density is the same throughout the device.
* If there is no G-R in the depletion region, we have $J = J_n(x_p) + J_p(x_n)$.
* Using our earlier results for $J_p(x_n)$ and $J_n(x_p)$, we get

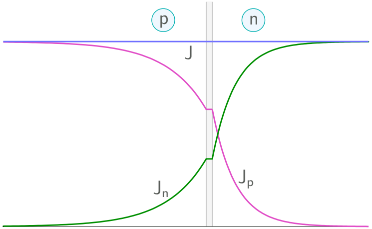
$$J = J_p(x_n) + J_n(x_p) = \left[\frac{qD_p p_{n0}}{L_p} + \frac{qD_n n_{p0}}{L_n}\right]\left(e^{V_a/V_T} - 1\right).$$

* We can now obtain J_n $(x > x_n)$ and J_p $(x < x_p)$ using $J_n(x) + J_p(x) = J$.



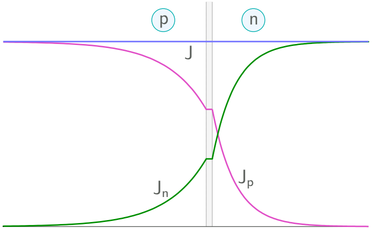
Consider the situation sufficiently far from the depletion region (i.e., about $5L_n$ on the *p*-side and $5L_p$ on the *n*-side).

pn junction: total current density



Consider the situation sufficiently far from the depletion region (i.e., about $5L_n$ on the *p*-side and $5L_p$ on the *n*-side).

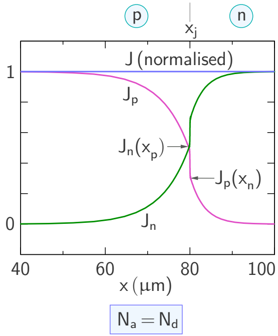
- ∗ The current density is due to majority carriers (drift component).



Consider the situation sufficiently far from the depletion region (i.e., about $5L_n$ on the p-side and $5L_p$ on the n-side).

* The current density is due to majority carriers (drift component).
* Since the majority carrier concentration is large, a very small electric field suffices to produce the required current density ($J_n^{\text{drift}} = qn\mu_n\mathcal{E}$, $J_p^{\text{drift}} = qp\mu_p\mathcal{E}$).

pn junction under forward bias: numerical results

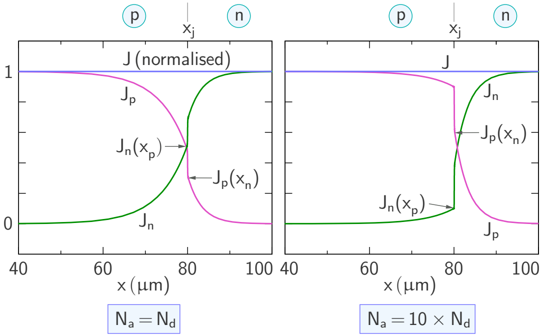


Doping densities:

(1) $N_a = N_d = 10^{16}\,\text{cm}^{-3}$

(Parameters: $V_a = 0.5\,\text{V}$, $\mu_n = 1400\,\text{cm}^2/\text{V-s}$, $\mu_p = 500\,\text{cm}^2/\text{V-s}$, $\tau_n = 10\,\text{ns}$, $\tau_p = 10\,\text{ns}$, $T = 300\,\text{K}$)

pn junction under forward bias: numerical results



Doping densities:

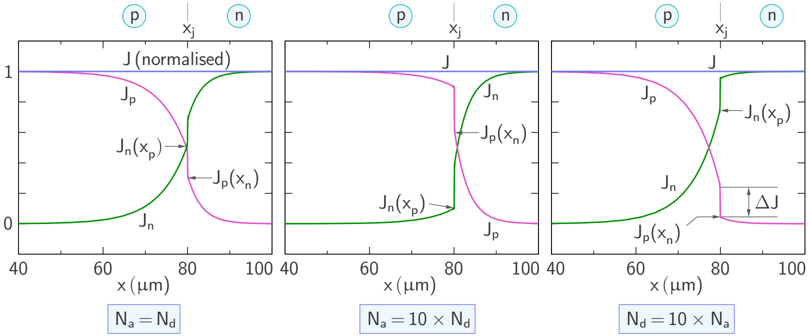
(1) $N_a = N_d = 10^{16}\ \mathrm{cm}^{-3}$

(2) $N_a = 10^{17}\ \mathrm{cm}^{-3}$

$N_d = 10^{16}\ \mathrm{cm}^{-3}$

(Parameters: $V_a = 0.5\,\mathrm{V}$, $\mu_n = 1400\,\mathrm{cm}^2/\mathrm{V\text{-}s}$, $\mu_p = 500\,\mathrm{cm}^2/\mathrm{V\text{-}s}$, $\tau_n = 10\,\mathrm{ns}$, $\tau_p = 10\,\mathrm{ns}$, $T = 300\,\mathrm{K}$)

pn junction under forward bias: numerical results



Doping densities:

(1) $N_a = N_d = 10^{16}\ \text{cm}^{-3}$

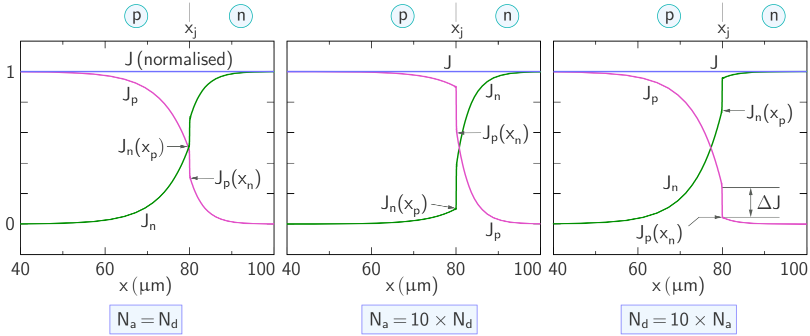
(2) $N_a = 10^{17}\ \text{cm}^{-3}$

$N_d = 10^{16}\ \text{cm}^{-3}$

(3) $N_a = 10^{16}\ \text{cm}^{-3}$

$N_d = 10^{17}\ \text{cm}^{-3}$

(Parameters: $V_a = 0.5\,\text{V}$, $\mu_n = 1400\,\text{cm}^2/\text{V-s}$, $\mu_p = 500\,\text{cm}^2/\text{V-s}$, $\tau_n = 10\,\text{ns}$, $\tau_p = 10\,\text{ns}$, $T = 300\,\text{K}$)



Doping densities:

(1) $N_a = N_d = 10^{16}\ \text{cm}^{-3}$

(2) $N_a = 10^{17}\ \text{cm}^{-3}$

$N_d = 10^{16}\ \text{cm}^{-3}$

(3) $N_a = 10^{16}\ \text{cm}^{-3}$

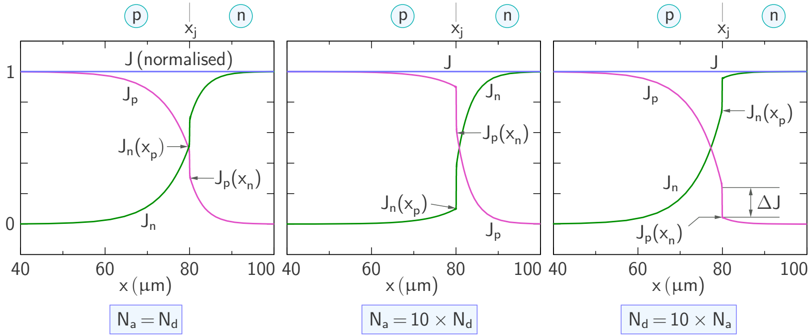
$N_d = 10^{17}\ \text{cm}^{-3}$

(Parameters: $V_a = 0.5\,\text{V}$, $\mu_n = 1400\,\text{cm}^2/\text{V-s}$, $\mu_p = 500\,\text{cm}^2/\text{V-s}$, $\tau_n = 10\,\text{ns}$, $\tau_p = 10\,\text{ns}$, $T = 300\,\text{K}$)

$$J_p(x_n) = \frac{qD_p p_{n0}}{L_p}\left(e^{V_a/V_T} - 1\right),\quad J_n(x_p) = \frac{qD_n n_{p0}}{L_n}\left(e^{V_a/V_T} - 1\right),\quad p_{n0} = \frac{n_i^2}{n_{n0}} \approx \frac{n_i^2}{N_d},\quad n_{p0} = \frac{n_i^2}{p_{p0}} \approx \frac{n_i^2}{N_a}.$$

$*$ The ratio $\dfrac{J_p(x_n)}{J_n(x_p)}$ is $\dfrac{D_p}{D_n}\,\dfrac{L_n}{L_p}\,\dfrac{p_{n0}}{n_{p0}} = \dfrac{D_p}{D_n}\,\dfrac{\sqrt{D_n\tau_n}}{\sqrt{D_p\tau_p}}\,\dfrac{N_a}{N_d} = \sqrt{\dfrac{\mu_p}{\mu_n}\,\dfrac{\tau_n}{\tau_p}\,\dfrac{N_a}{N_d}}.$

pn junction under forward bias: numerical results



Doping densities:

(1) $N_a = N_d = 10^{16}\ \text{cm}^{-3}$

(2) $N_a = 10^{17}\ \text{cm}^{-3}$

$N_d = 10^{16}\ \text{cm}^{-3}$

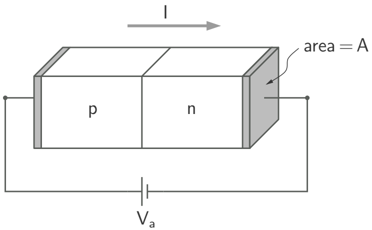
(3) $N_a = 10^{16}\ \text{cm}^{-3}$

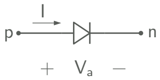
$N_d = 10^{17}\ \text{cm}^{-3}$

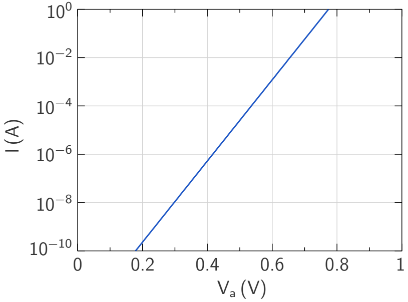
(Parameters: $V_a = 0.5\,\text{V}$, $\mu_n = 1400\,\text{cm}^2/\text{V-s}$, $\mu_p = 500\,\text{cm}^2/\text{V-s}$, $\tau_n = 10\,\text{ns}$, $\tau_p = 10\,\text{ns}$, $T = 300\,\text{K}$)

$$J_p(x_n) = \frac{qD_p p_{n0}}{L_p}\left(e^{V_a/V_T} - 1\right), \quad J_n(x_p) = \frac{qD_n n_{p0}}{L_n}\left(e^{V_a/V_T} - 1\right), \quad p_{n0} = \frac{n_i^2}{n_{n0}} \approx \frac{n_i^2}{N_d}, \quad n_{p0} = \frac{n_i^2}{p_{p0}} \approx \frac{n_i^2}{N_a}.$$

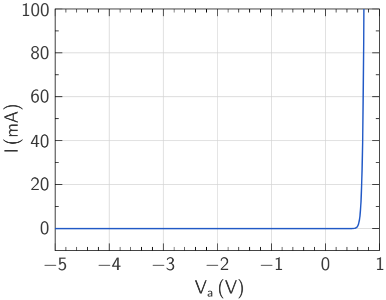
* The ratio $\dfrac{J_p(x_n)}{J_n(x_p)}$ is $\dfrac{D_p}{D_n}\dfrac{L_n}{L_p}\dfrac{p_{n0}}{n_{p0}} = \dfrac{D_p}{D_n}\dfrac{\sqrt{D_n\tau_n}}{\sqrt{D_p\tau_p}}\dfrac{N_a}{N_d} = \sqrt{\dfrac{\mu_p}{\mu_n}\dfrac{\tau_n}{\tau_p}}\dfrac{N_a}{N_d}$.
* Because of recombination, there is a change in J_p and J_n across the depletion region (which has been ignored in our analysis). This change is seen as vertical lines in the figure since the depletion width is much smaller than the diffusion lengths.



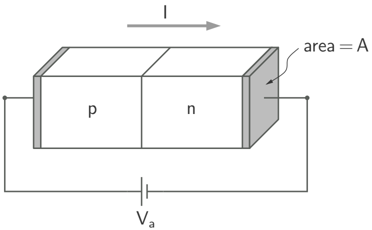


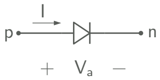


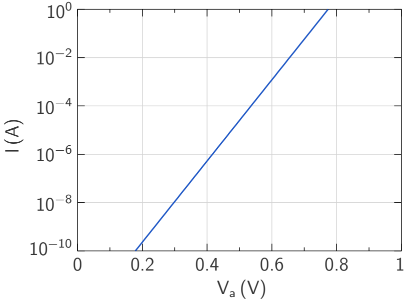
$$J = \left[\frac{qD_p p_{n0}}{L_p} + \frac{qD_n n_{p0}}{L_n} \right] \left(e^{V_a/V_T} - 1 \right).$$



Diode I-V equation

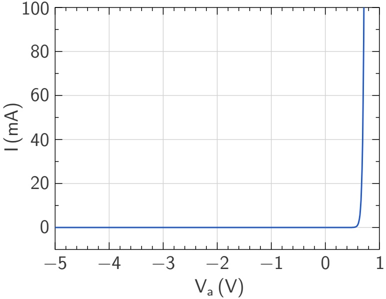




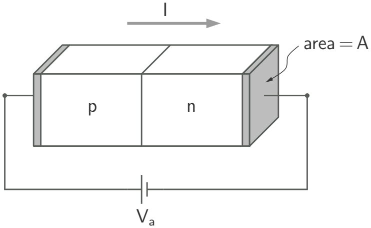


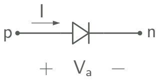
$$J = \left[\frac{qD_p p_{n0}}{L_p} + \frac{qD_n n_{p0}}{L_n} \right] \left(e^{V_a/V_T} - 1 \right).$$

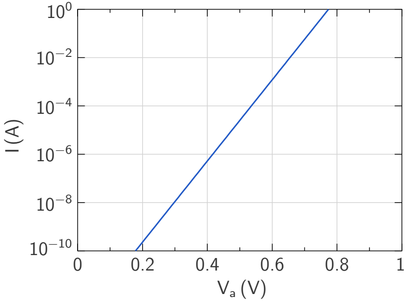
$$\rightarrow I = A \times J = I_s \left(e^{V_a/V_T} - 1 \right), \text{ with } I_s = A \left(\frac{qD_p p_{n0}}{L_p} + \frac{qD_n n_{p0}}{L_n} \right).$$



Diode I-V equation



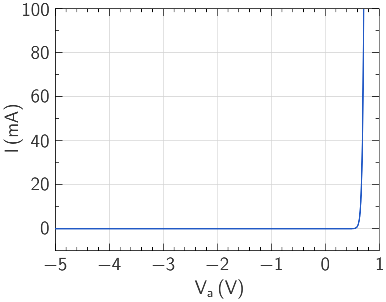




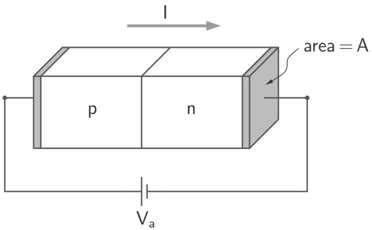
$$J = \left[\frac{qD_p p_{n0}}{L_p} + \frac{qD_n n_{p0}}{L_n} \right] \left(e^{V_a/V_T} - 1 \right).$$

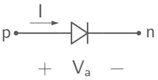
$$\rightarrow I = A \times J = I_s \left(e^{V_a/V_T} - 1 \right), \text{ with } I_s = A \left(\frac{qD_p p_{n0}}{L_p} + \frac{qD_n n_{p0}}{L_n} \right).$$

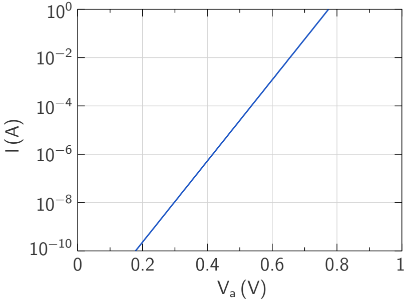
* This equation is known as the "Shockley diode equation."

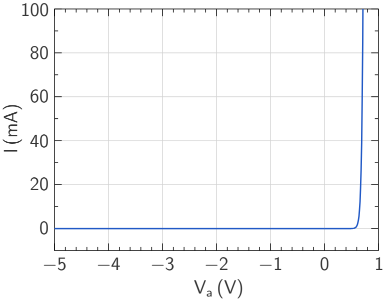


Diode I-V equation





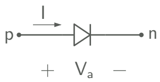




$$J = \left[\frac{qD_p p_{n0}}{L_p} + \frac{qD_n n_{p0}}{L_n}\right]\left(e^{V_a/V_T} - 1\right).$$

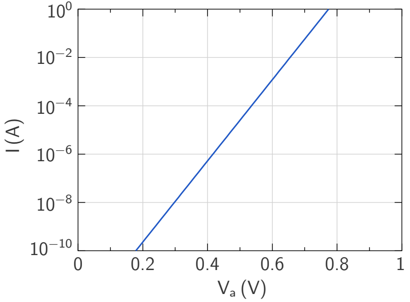
$$\rightarrow I = A \times J = I_s\left(e^{V_a/V_T} - 1\right), \text{ with } I_s = A\left(\frac{qD_p p_{n0}}{L_p} + \frac{qD_n n_{p0}}{L_n}\right).$$

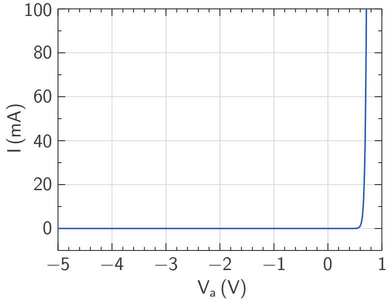
* This equation is known as the "Shockley diode equation."
* Under reverse bias, with V_R equal to a few V_T or larger, $e^{V_a/V_T} = e^{-V_R/V_T} \approx 0$, and $I \approx -I_s$, i.e., the diode current "saturates" (at $-I_s$). I_s is therefore called the "reverse saturation current."



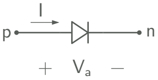
$$J = \left[\frac{qD_p p_{n0}}{L_p} + \frac{qD_n n_{p0}}{L_n} \right] \left(e^{V_a/V_T} - 1 \right).$$

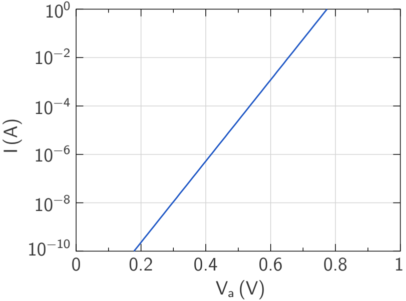
$$\rightarrow I = I_s \left(e^{V_a/V_T} - 1 \right), \text{ with } I_s = A \left(\frac{qD_p p_{n0}}{L_p} + \frac{qD_n n_{p0}}{L_n} \right).$$





Diode I-V equation

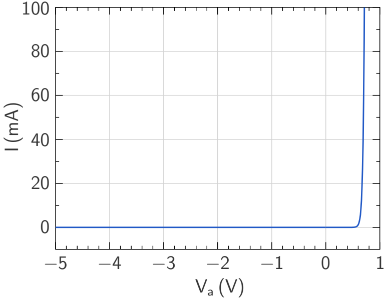




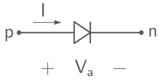
$$J = \left[\frac{qD_p p_{n0}}{L_p} + \frac{qD_n n_{p0}}{L_n} \right] \left(e^{V_a/V_T} - 1 \right).$$

$$\rightarrow I = I_s \left(e^{V_a/V_T} - 1 \right), \text{ with } I_s = A \left(\frac{qD_p p_{n0}}{L_p} + \frac{qD_n n_{p0}}{L_n} \right).$$

* In a real diode, other factors often dominate in reverse bias, including generation in the depletion region and surface leakage. Also, as we will see, a real diode cannot withstand indefinitely large reverse voltages and will "break down" at some point.



Diode I-V equation



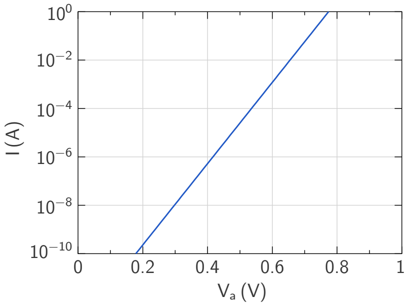
$$J = \left[\frac{qD_p p_{n0}}{L_p} + \frac{qD_n n_{p0}}{L_n} \right] \left(e^{V_a/V_T} - 1 \right).$$

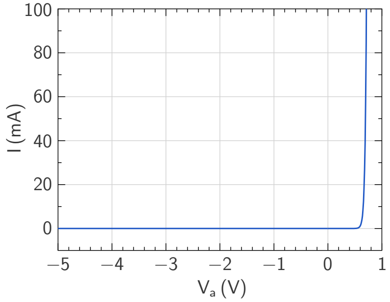
$$\rightarrow I = I_s \left(e^{V_a/V_T} - 1 \right), \text{ with } I_s = A \left(\frac{qD_p p_{n0}}{L_p} + \frac{qD_n n_{p0}}{L_n} \right).$$

* In a real diode, other factors often dominate in reverse bias, including generation in the depletion region and surface leakage. Also, as we will see, a real diode cannot withstand indefinitely large reverse voltages and will "break down" at some point.

* Recombination in the depletion region under forward bias can be incorporated in the Shockley equation with an "ideality factor" η $(1 < \eta < 2)$:

$$\begin{aligned} I &= I_{s1} \exp\left(\frac{V_a}{\eta_1 V_T}\right) + I_{s2} \exp\left(\frac{V_a}{\eta_2 V_T}\right) \\ &\approx I_s^{\text{eff}} \exp\left(\frac{V_a}{\eta V_T}\right) \end{aligned}$$





Example

For an abrupt, uniformly doped silicon *pn* junction diode, $N_a = 10^{17}\,\text{cm}^{-3}$, $N_d = 2 \times 10^{16}\,\text{cm}^{-3}$, $\mu_n = 1500\,\text{cm}^2/\text{V-s}$, $\mu_p = 500\,\text{cm}^2/\text{V-s}$, $\tau_n = 2\,\mu\text{s}$, $\tau_p = 5\,\mu\text{s}$, $A = 10^{-3}\,\text{cm}^2$. Compute the following for a forward bias of 0.65 V at $T = 300\,\text{K}$:

For an abrupt, uniformly doped silicon *pn* junction diode, $N_a = 10^{17}\,\text{cm}^{-3}$, $N_d = 2 \times 10^{16}\,\text{cm}^{-3}$, $\mu_n = 1500\,\text{cm}^2/\text{V-s}$, $\mu_p = 500\,\text{cm}^2/\text{V-s}$, $\tau_n = 2\,\mu\text{s}$, $\tau_p = 5\,\mu\text{s}$, $A = 10^{-3}\,\text{cm}^2$. Compute the following for a forward bias of 0.65 V at $T = 300\,\text{K}$:

(1) depletion width W and the maximum electric field $\mathcal{E}_m$,

For an abrupt, uniformly doped silicon *pn* junction diode, $N_a = 10^{17}\,\text{cm}^{-3}$, $N_d = 2 \times 10^{16}\,\text{cm}^{-3}$, $\mu_n = 1500\,\text{cm}^2/\text{V-s}$, $\mu_p = 500\,\text{cm}^2/\text{V-s}$, $\tau_n = 2\,\mu\text{s}$, $\tau_p = 5\,\mu\text{s}$, $A = 10^{-3}\,\text{cm}^2$. Compute the following for a forward bias of 0.65 V at $T = 300\,\text{K}$:

(1) depletion width W and the maximum electric field $\mathcal{E}_m$,

(2) $n(x_p)$ and $p(x_n)$,

For an abrupt, uniformly doped silicon *pn* junction diode, $N_a = 10^{17}\,\text{cm}^{-3}$, $N_d = 2 \times 10^{16}\,\text{cm}^{-3}$, $\mu_n = 1500\,\text{cm}^2/\text{V-s}$, $\mu_p = 500\,\text{cm}^2/\text{V-s}$, $\tau_n = 2\,\mu\text{s}$, $\tau_p = 5\,\mu\text{s}$, $A = 10^{-3}\,\text{cm}^2$. Compute the following for a forward bias of 0.65 V at $T = 300\,\text{K}$:

(1) depletion width W and the maximum electric field $\mathcal{E}_m$,

(2) $n(x_p)$ and $p(x_n)$,

(3) $J_n(x_p)$ and $J_p(x_n)$,

For an abrupt, uniformly doped silicon *pn* junction diode, $N_a = 10^{17}\,\text{cm}^{-3}$, $N_d = 2\times 10^{16}\,\text{cm}^{-3}$, $\mu_n = 1500\,\text{cm}^2/\text{V-s}$, $\mu_p = 500\,\text{cm}^2/\text{V-s}$, $\tau_n = 2\,\mu\text{s}$, $\tau_p = 5\,\mu\text{s}$, $A = 10^{-3}\,\text{cm}^2$. Compute the following for a forward bias of 0.65 V at $T = 300\,\text{K}$:

(1) depletion width W and the maximum electric field $\mathcal{E}_m$,

(2) $n(x_p)$ and $p(x_n)$,

(3) $J_n(x_p)$ and $J_p(x_n)$,

(4) the diode current I,

For an abrupt, uniformly doped silicon *pn* junction diode, $N_a = 10^{17}\,\text{cm}^{-3}$, $N_d = 2\times10^{16}\,\text{cm}^{-3}$, $\mu_n = 1500\,\text{cm}^2/\text{V-s}$, $\mu_p = 500\,\text{cm}^2/\text{V-s}$, $\tau_n = 2\,\mu\text{s}$, $\tau_p = 5\,\mu\text{s}$, $A = 10^{-3}\,\text{cm}^2$. Compute the following for a forward bias of 0.65 V at $T = 300\,\text{K}$:

(1) depletion width W and the maximum electric field $\mathcal{E}_m$,

(2) $n(x_p)$ and $p(x_n)$,

(3) $J_n(x_p)$ and $J_p(x_n)$,

(4) the diode current I,

(5) electric fields in the neutral p and n regions, more than five diffusion lengths away from the depletion region,

Example

For an abrupt, uniformly doped silicon *pn* junction diode, $N_a = 10^{17}\,\text{cm}^{-3}$, $N_d = 2\times10^{16}\,\text{cm}^{-3}$, $\mu_n = 1500\,\text{cm}^2/\text{V-s}$, $\mu_p = 500\,\text{cm}^2/\text{V-s}$, $\tau_n = 2\,\mu\text{s}$, $\tau_p = 5\,\mu\text{s}$, $A = 10^{-3}\,\text{cm}^2$. Compute the following for a forward bias of $0.65\,\text{V}$ at $T = 300\,\text{K}$:

(1) depletion width W and the maximum electric field $\mathcal{E}_m$,

(2) $n(x_p)$ and $p(x_n)$,

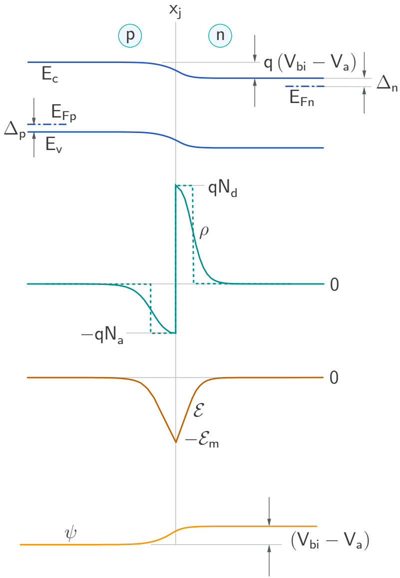
(3) $J_n(x_p)$ and $J_p(x_n)$,

(4) the diode current I,

(5) electric fields in the neutral p and n regions, more than five diffusion lengths away from the depletion region,

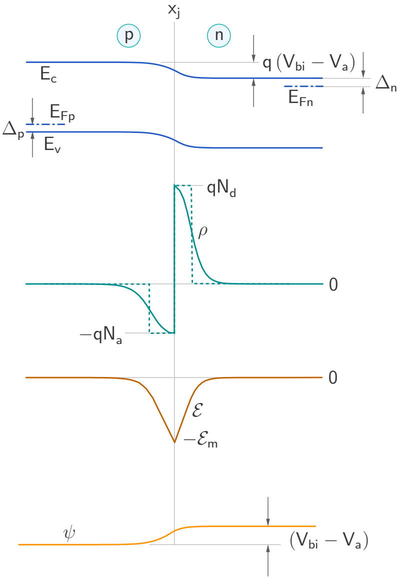
(6) the reverse saturation current I_s.

$$V_{\rm bi} = V_T \, \log\left(\frac{N_a N_d}{n_i^2}\right) = (0.0259\,\text{V})\,\log\frac{(10^{17})(2\times10^{16})}{(1.5\times10^{10})^2} = 0.77\,\text{V}\,.$$



$$V_{bi} = V_T \log \left(\frac{N_a N_d}{n_i^2} \right) = (0.0259\,\mathrm{V}) \log \frac{(10^{17})(2 \times 10^{16})}{(1.5 \times 10^{10})^2} = 0.77\,\mathrm{V}\,.$$

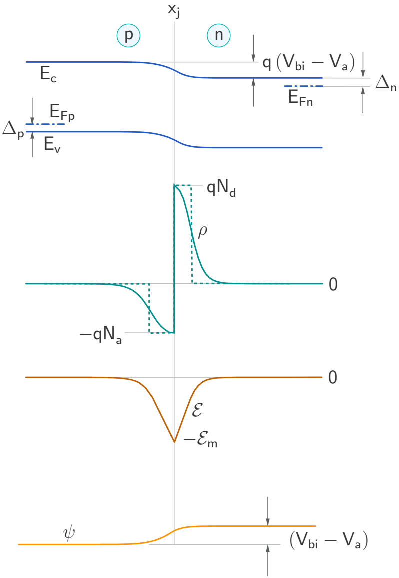
$$W = \sqrt{\frac{2\epsilon}{q} \frac{N_a + N_d}{N_a N_d} (V_{bi} - V_a)}$$



$$V_{\rm bi} = V_T \log\left(\frac{N_a N_d}{n_i^2}\right) = (0.0259\,\text{V}) \log \frac{(10^{17})(2\times 10^{16})}{(1.5\times 10^{10})^2} = 0.77\,\text{V}\,.$$

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

$$= \sqrt{\frac{2\times 11.8\times 8.85\times 10^{-14}}{1.6\times 10^{-19}}\,\frac{1.2\times 10^{17}}{2\times 10^{33}}\times 0.12}\ \ \text{cm} = 0.097\,\mu\text{m}.$$

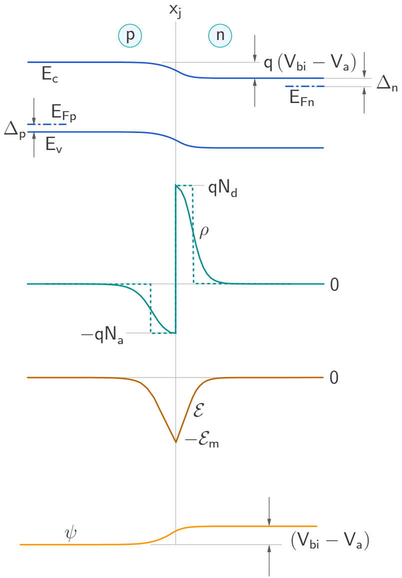


$$V_{\text{bi}} = V_T \log\left(\frac{N_a N_d}{n_i^2}\right) = (0.0259\,\text{V})\log\frac{(10^{17})(2\times10^{16})}{(1.5\times10^{10})^2} = 0.77\,\text{V}\,.$$

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

$$= \sqrt{\frac{2\times11.8\times8.85\times10^{-14}}{1.6\times10^{-19}}\,\frac{1.2\times10^{17}}{2\times10^{33}}\times0.12}\;\;\text{cm} = 0.097\,\mu\text{m}.$$

$$(V_{\text{bi}}-V_a) = \frac{1}{2}\,\mathcal{E}_m W$$



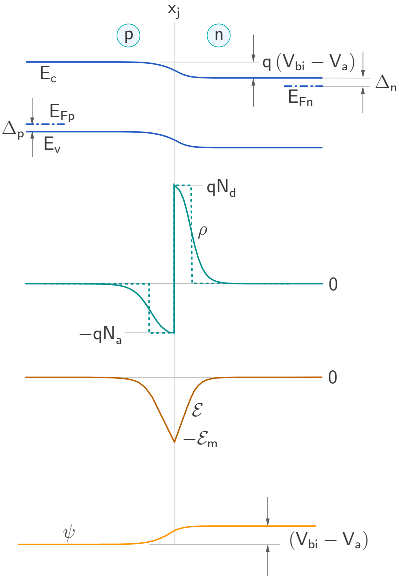
$$V_{bi} = V_T \log\left(\frac{N_a N_d}{n_i^2}\right) = (0.0259\,\text{V}) \log \frac{(10^{17})(2\times 10^{16})}{(1.5\times 10^{10})^2} = 0.77\,\text{V}\,.$$

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

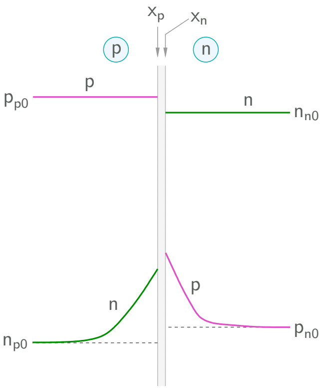
$$= \sqrt{\frac{2\times 11.8\times 8.85\times 10^{-14}}{1.6\times 10^{-19}}\,\frac{1.2\times 10^{17}}{2\times 10^{33}}\times 0.12}\ \ \text{cm} = 0.097\,\mu\text{m}.$$

$$(V_{bi}-V_a) = \frac{1}{2}\,\mathcal{E}_m W$$

$$\rightarrow \mathcal{E}_m = \frac{2\,(V_{bi}-V_a)}{W} = \frac{2\times 0.12\,\text{V}}{0.097\times 10^{-4}\ \text{cm}} = 25\,\text{kV/cm}.$$

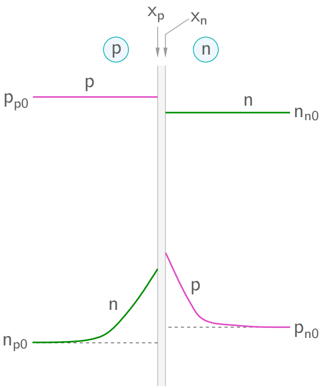


Example (continued)



The equilibrium minority carrier densities are

$$p_{n0} = \frac{n_i^2}{n_{n0}} \approx \frac{n_i^2}{N_d} = \frac{(1.5 \times 10^{10})^2}{2 \times 10^{16}} = 1.125 \times 10^4 \, \mathrm{cm}^{-3},$$

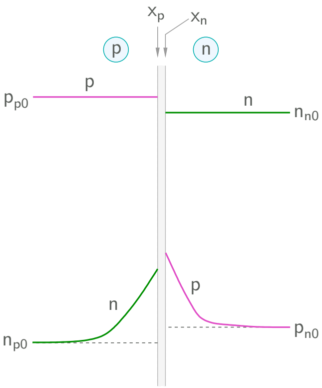


Example (continued)

The equilibrium minority carrier densities are

$$p_{n0} = \frac{n_i^2}{n_{n0}} \approx \frac{n_i^2}{N_d} = \frac{(1.5 \times 10^{10})^2}{2 \times 10^{16}} = 1.125 \times 10^4 \,\text{cm}^{-3},$$

$$n_{p0} = \frac{n_i^2}{p_{p0}} \approx \frac{n_i^2}{N_a} = \frac{(1.5 \times 10^{10})^2}{1 \times 10^{17}} = 2.25 \times 10^3 \,\text{cm}^{-3}.$$



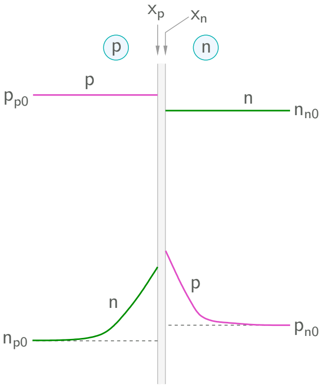
The equilibrium minority carrier densities are

$$p_{n0} = \frac{n_i^2}{n_{n0}} \approx \frac{n_i^2}{N_d} = \frac{(1.5 \times 10^{10})^2}{2 \times 10^{16}} = 1.125 \times 10^4 \,\mathrm{cm}^{-3},$$

$$n_{p0} = \frac{n_i^2}{p_{p0}} \approx \frac{n_i^2}{N_a} = \frac{(1.5 \times 10^{10})^2}{1 \times 10^{17}} = 2.25 \times 10^3 \,\mathrm{cm}^{-3}.$$

The minority carrier densities at x_p and x_n are

$$n(x_p) = n_{p0}\, e^{V_a/V_T} = 2.25 \times 10^3 \times e^{0.65/0.0259} = 1.8 \times 10^{14} \,\mathrm{cm}^{-3},$$



Example (continued)

The equilibrium minority carrier densities are

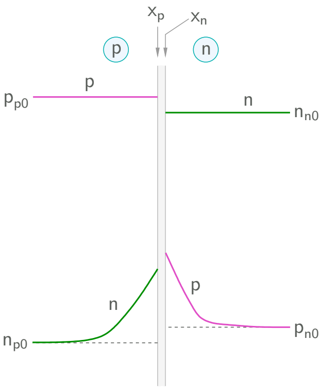
$$p_{n0} = \frac{n_i^2}{n_{n0}} \approx \frac{n_i^2}{N_d} = \frac{(1.5 \times 10^{10})^2}{2 \times 10^{16}} = 1.125 \times 10^4 \,\text{cm}^{-3},$$

$$n_{p0} = \frac{n_i^2}{p_{p0}} \approx \frac{n_i^2}{N_a} = \frac{(1.5 \times 10^{10})^2}{1 \times 10^{17}} = 2.25 \times 10^3 \,\text{cm}^{-3}.$$

The minority carrier densities at x_p and x_n are

$$n(x_p) = n_{p0}\, e^{V_a/V_T} = 2.25 \times 10^3 \times e^{0.65/0.0259} = 1.8 \times 10^{14} \,\text{cm}^{-3},$$

$$p(x_n) = p_{n0}\, e^{V_a/V_T} = 1.125 \times 10^4 \times e^{0.65/0.0259} = 8.9 \times 10^{14} \,\text{cm}^{-3}.$$



Example (continued)

The diffusion coefficients are

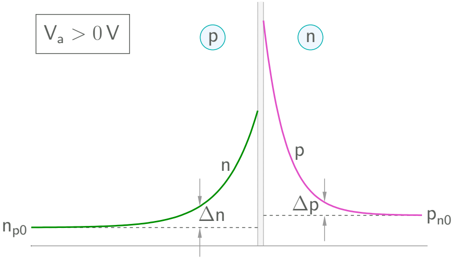
$D_p = V_T \mu_p = 0.0259 \times 500 = 12.9\,\text{cm}^2/\text{s}$,

$D_n = V_T \mu_n = 0.0259 \times 1500 = 38.7\,\text{cm}^2/\text{s}$.

The minority carrier diffusion lengths in the neutral regions are

$L_p = \sqrt{D_p \tau_p} = \sqrt{12.9 \times 5 \times 10^{-6}}\,\text{cm} = 80.3\,\mu\text{m}$,

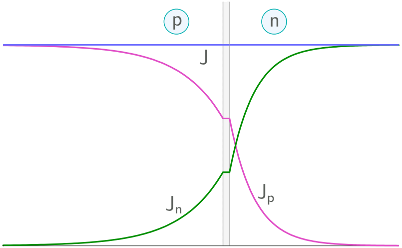
$L_n = \sqrt{D_n \tau_n} = \sqrt{38.7 \times 2 \times 10^{-6}}\,\text{cm} = 88\,\mu\text{m}$.



Example (continued)

The minority carrier current densities at x_n and x_p are

$$J_p(x_n) = \frac{qD_p p_{n0}}{L_p} \left(e^{V_a/V_T} - 1 \right)$$

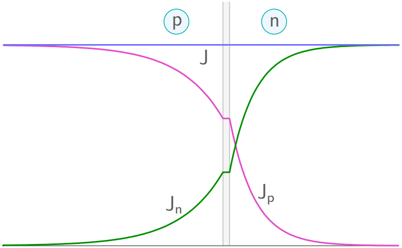


Example (continued)

The minority carrier current densities at x_n and x_p are

$$J_p(x_n) = \frac{qD_p p_{n0}}{L_p}\left(e^{V_a/V_T} - 1\right)$$

$$= \frac{1.6 \times 10^{-19} \times 12.9 \times 1.125 \times 10^4}{80.3 \times 10^{-4}} \times 8.12 \times 10^{10}$$



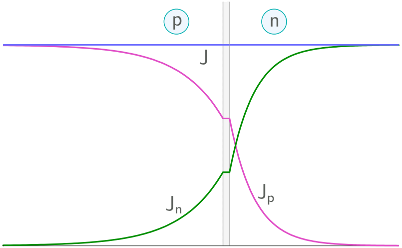
Example (continued)

The minority carrier current densities at x_n and x_p are

$$J_p(x_n) = \frac{qD_p p_{n0}}{L_p}\left(e^{V_a/V_T} - 1\right)$$

$$= \frac{1.6 \times 10^{-19} \times 12.9 \times 1.125 \times 10^4}{80.3 \times 10^{-4}} \times 8.12 \times 10^{10}$$

$$= 0.235\,\mathrm{A/cm^2}.$$



Example (continued)

The minority carrier current densities at x_n and x_p are

$$J_p(x_n) = \frac{qD_p p_{n0}}{L_p}\left(e^{V_a/V_T}-1\right)$$

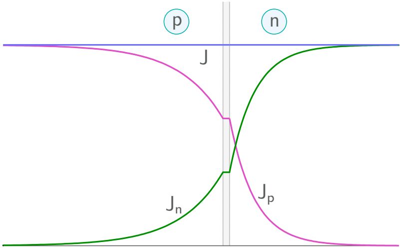
$$= \frac{1.6\times10^{-19}\times12.9\times1.125\times10^4}{80.3\times10^{-4}}\times8.12\times10^{10}$$

$$= 0.235\,\mathrm{A/cm^2}.$$

$$J_n(x_p) = \frac{qD_n n_{p0}}{L_n}\left(e^{V_a/V_T}-1\right)$$

$$= \frac{1.6\times10^{-19}\times38.7\times2.25\times10^3}{88\times10^{-4}}\times8.12\times10^{10}$$

$$= 0.13\,\mathrm{A/cm^2}.$$



Example (continued)

The minority carrier current densities at x_n and x_p are

$$J_p(x_n) = \frac{qD_p p_{n0}}{L_p}\left(e^{V_a/V_T} - 1\right)$$

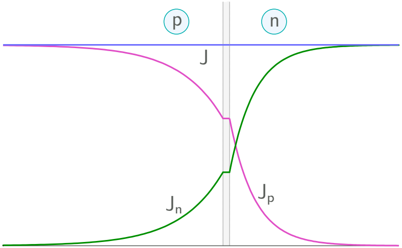
$$= \frac{1.6 \times 10^{-19} \times 12.9 \times 1.125 \times 10^4}{80.3 \times 10^{-4}} \times 8.12 \times 10^{10}$$

$$= 0.235\,\mathrm{A/cm^2}.$$

$$J_n(x_p) = \frac{qD_n n_{p0}}{L_n}\left(e^{V_a/V_T} - 1\right)$$

$$= \frac{1.6 \times 10^{-19} \times 38.7 \times 2.25 \times 10^3}{88 \times 10^{-4}} \times 8.12 \times 10^{10}$$

$$= 0.13\,\mathrm{A/cm^2}.$$



The diode current I is

$$I = A\left(J_p(x_n) + J_n(x_p)\right)$$

Example (continued)

The minority carrier current densities at x_n and x_p are

$$J_p(x_n) = \frac{qD_p p_{n0}}{L_p}\left(e^{V_a/V_T} - 1\right)$$

$$= \frac{1.6 \times 10^{-19} \times 12.9 \times 1.125 \times 10^4}{80.3 \times 10^{-4}} \times 8.12 \times 10^{10}$$

$$= 0.235\,\mathrm{A/cm^2}.$$

$$J_n(x_p) = \frac{qD_n n_{p0}}{L_n}\left(e^{V_a/V_T} - 1\right)$$

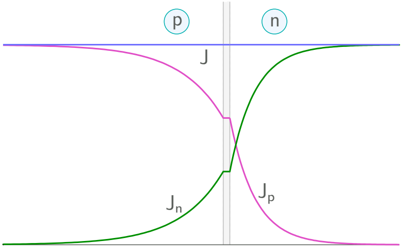
$$= \frac{1.6 \times 10^{-19} \times 38.7 \times 2.25 \times 10^3}{88 \times 10^{-4}} \times 8.12 \times 10^{10}$$

$$= 0.13\,\mathrm{A/cm^2}.$$

The diode current I is

$$I = A\left(J_p(x_n) + J_n(x_p)\right)$$

$$= 10^{-3}\,\mathrm{cm^2} \times (0.235 + 0.13)\,\mathrm{A/cm^2}$$

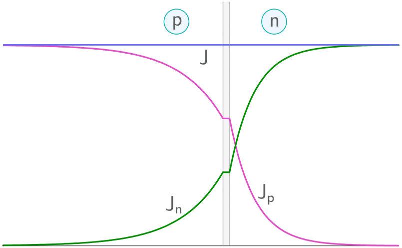


Example (continued)

The minority carrier current densities at x_n and x_p are

$$J_p(x_n) = \frac{qD_p p_{n0}}{L_p}\left(e^{V_a/V_T} - 1\right)$$
$$= \frac{1.6 \times 10^{-19} \times 12.9 \times 1.125 \times 10^4}{80.3 \times 10^{-4}} \times 8.12 \times 10^{10}$$
$$= 0.235\,\mathrm{A/cm^2}.$$

$$J_n(x_p) = \frac{qD_n n_{p0}}{L_n}\left(e^{V_a/V_T} - 1\right)$$
$$= \frac{1.6 \times 10^{-19} \times 38.7 \times 2.25 \times 10^3}{88 \times 10^{-4}} \times 8.12 \times 10^{10}$$
$$= 0.13\,\mathrm{A/cm^2}.$$



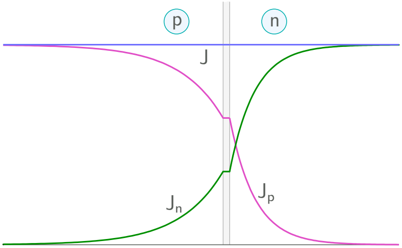
The diode current I is

$$I = A\,(J_p(x_n) + J_n(x_p))$$
$$= 10^{-3}\,\mathrm{cm^2} \times (0.235 + 0.13)\,\mathrm{A/cm^2}$$
$$= 0.365\,\mathrm{mA}.$$

Example (continued)

In the neutral n region more than $5L_p$ away from the depletion region, $J \approx J_n = q\mu_n \mathcal{E}^n_{\text{neutral}} n_{n0}$, leading to

$$\mathcal{E}^n_{\text{neutral}} = \frac{J}{q\mu_n n_{n0}} = \frac{0.365 \left[\dfrac{\text{A}}{\text{cm}^2}\right]}{1.6 \times 10^{-19}\,[\text{C}] \times 1500 \left[\dfrac{\text{cm}^2}{\text{V-s}}\right] \times 2 \times 10^{16} \left[\dfrac{1}{\text{cm}^3}\right]}$$

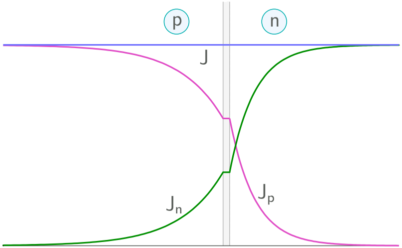


Example (continued)

In the neutral n region more than $5L_p$ away from the depletion region, $J \approx J_n = q\mu_n \mathcal{E}^n_{\text{neutral}} n_{n0}$, leading to

$$\mathcal{E}^n_{\text{neutral}} = \frac{J}{q\mu_n n_{n0}} = \frac{0.365 \left[\dfrac{\text{A}}{\text{cm}^2}\right]}{1.6 \times 10^{-19}\,[\text{C}] \times 1500 \left[\dfrac{\text{cm}^2}{\text{V-s}}\right] \times 2 \times 10^{16} \left[\dfrac{1}{\text{cm}^3}\right]}$$

$$= 0.076\,\text{V/cm}.$$



Example (continued)

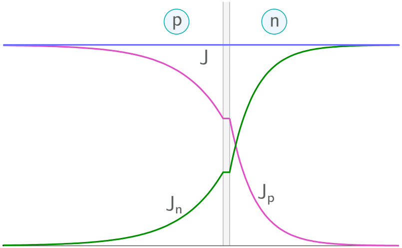
In the neutral n region more than $5L_p$ away from the depletion region, $J \approx J_n = q\mu_n \mathcal{E}^n_{\text{neutral}} n_{n0}$, leading to

$$\mathcal{E}^n_{\text{neutral}} = \frac{J}{q\mu_n n_{n0}} = \frac{0.365 \left[\dfrac{\text{A}}{\text{cm}^2}\right]}{1.6 \times 10^{-19}\,[\text{C}] \times 1500 \left[\dfrac{\text{cm}^2}{\text{V-s}}\right] \times 2 \times 10^{16} \left[\dfrac{1}{\text{cm}^3}\right]}$$

$$= 0.076\,\text{V/cm}.$$

Similarly,

$$\mathcal{E}^p_{\text{neutral}} = \frac{J}{q\mu_p p_{p0}} = \frac{0.365 \left[\dfrac{\text{A}}{\text{cm}^2}\right]}{1.6 \times 10^{-19}\,[\text{C}] \times 500 \left[\dfrac{\text{cm}^2}{\text{V-s}}\right] \times 1 \times 10^{17} \left[\dfrac{1}{\text{cm}^3}\right]}$$



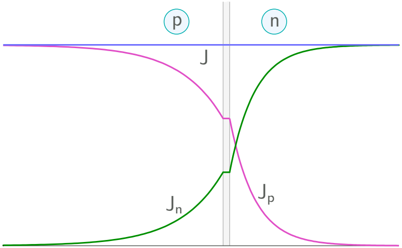
Example (continued)

In the neutral n region more than $5L_p$ away from the depletion region,
$J \approx J_n = q\mu_n \mathcal{E}^n_{\text{neutral}} n_{n0}$, leading to

$$\mathcal{E}^n_{\text{neutral}} = \frac{J}{q\mu_n n_{n0}} = \frac{0.365 \left[\dfrac{\text{A}}{\text{cm}^2}\right]}{1.6 \times 10^{-19}\,[\text{C}] \times 1500 \left[\dfrac{\text{cm}^2}{\text{V-s}}\right] \times 2 \times 10^{16} \left[\dfrac{1}{\text{cm}^3}\right]}$$
$$= 0.076\,\text{V/cm}.$$

Similarly,

$$\mathcal{E}^p_{\text{neutral}} = \frac{J}{q\mu_p p_{p0}} = \frac{0.365 \left[\dfrac{\text{A}}{\text{cm}^2}\right]}{1.6 \times 10^{-19}\,[\text{C}] \times 500 \left[\dfrac{\text{cm}^2}{\text{V-s}}\right] \times 1 \times 10^{17} \left[\dfrac{1}{\text{cm}^3}\right]}$$
$$= 0.045\,\text{V/cm}.$$



Example (continued)

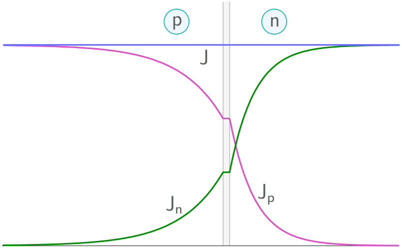
In the neutral n region more than $5L_p$ away from the depletion region, $J \approx J_n = q\mu_n \mathcal{E}^n_{\text{neutral}} n_{n0}$, leading to

$$\mathcal{E}^n_{\text{neutral}} = \frac{J}{q\mu_n n_{n0}} = \frac{0.365\left[\dfrac{\text{A}}{\text{cm}^2}\right]}{1.6\times10^{-19}\,[\text{C}]\times 1500\left[\dfrac{\text{cm}^2}{\text{V-s}}\right]\times 2\times 10^{16}\left[\dfrac{1}{\text{cm}^3}\right]}$$
$$= 0.076\,\text{V/cm}.$$

Similarly,

$$\mathcal{E}^p_{\text{neutral}} = \frac{J}{q\mu_p p_{p0}} = \frac{0.365\left[\dfrac{\text{A}}{\text{cm}^2}\right]}{1.6\times10^{-19}\,[\text{C}]\times 500\left[\dfrac{\text{cm}^2}{\text{V-s}}\right]\times 1\times 10^{17}\left[\dfrac{1}{\text{cm}^3}\right]}$$
$$= 0.045\,\text{V/cm}.$$

Note that these values are much smaller than $\mathcal{E}_m$ in the depletion region (25 kV/cm).



Example (continued)

The reverse saturation current I_s is given by

$$I_s = A \times \left(\frac{qD_p p_{n0}}{L_p} + \frac{qD_n n_{p0}}{L_n} \right)$$

Example (continued)

The reverse saturation current I_s is given by

$$I_s = A \times \left(\frac{qD_p p_{n0}}{L_p} + \frac{qD_n n_{p0}}{L_n} \right)$$

$$= 10^{-3} \left(\frac{1.6 \times 10^{-19} \times 12.9 \times 1.125 \times 10^4}{80.3 \times 10^{-4}} + \frac{1.6 \times 10^{-19} \times 38.7 \times 2.25 \times 10^3}{88 \times 10^{-4}} \right)$$

The reverse saturation current I_s is given by

$$
\begin{aligned}
I_s &= A \times \left(\frac{qD_p p_{n0}}{L_p} + \frac{qD_n n_{p0}}{L_n} \right) \\
&= 10^{-3} \left(\frac{1.6 \times 10^{-19} \times 12.9 \times 1.125 \times 10^4}{80.3 \times 10^{-4}} + \frac{1.6 \times 10^{-19} \times 38.7 \times 2.25 \times 10^3}{88 \times 10^{-4}} \right) \\
&= 4.5 \times 10^{-15}\,\text{A (i.e., } 4.5\,\text{fA).}
\end{aligned}
$$

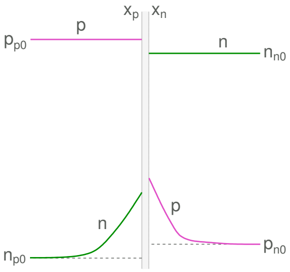
Example (continued)

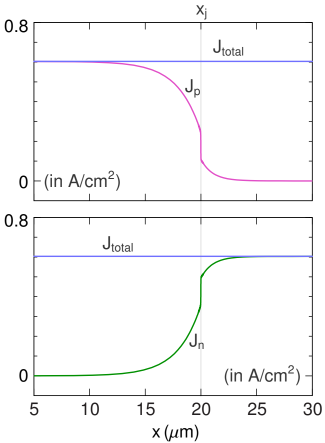
The reverse saturation current I_s is given by

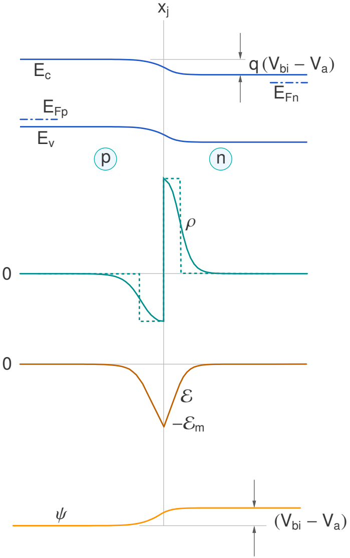
$$
\begin{aligned}
I_s &= A \times \left(\frac{qD_p p_{n0}}{L_p} + \frac{qD_n n_{p0}}{L_n} \right) \\
&= 10^{-3} \left(\frac{1.6 \times 10^{-19} \times 12.9 \times 1.125 \times 10^4}{80.3 \times 10^{-4}} + \frac{1.6 \times 10^{-19} \times 38.7 \times 2.25 \times 10^3}{88 \times 10^{-4}} \right) \\
&= 4.5 \times 10^{-15}\,\text{A (i.e., 4.5 fA).}
\end{aligned}
$$

Note how small I_s is. The only reason we can get significant currents ($\sim$ mA) in forward bias is the *huge* exponential factor (e^{V_a/V_T}) in the Shockley equation.

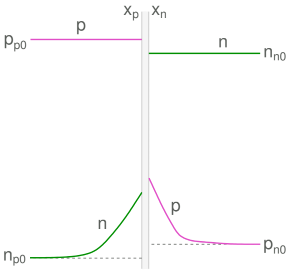
Forward bias: summary



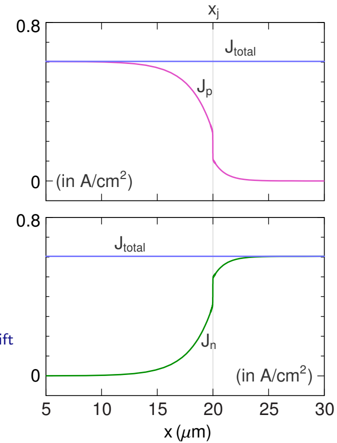


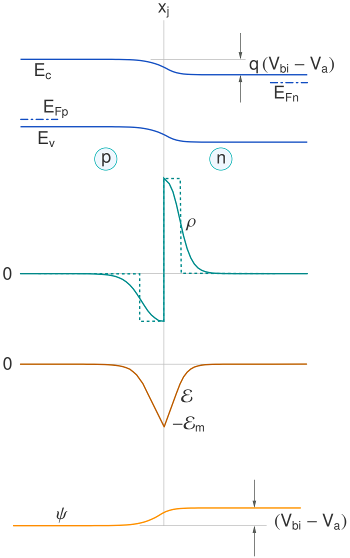


Forward bias: summary



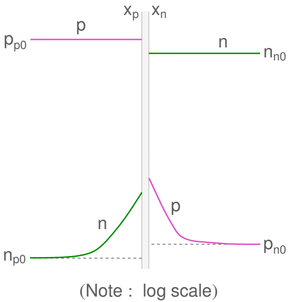
(Note : log scale)

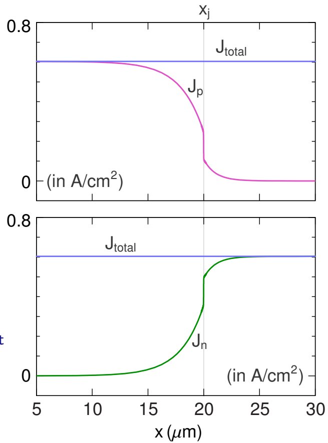


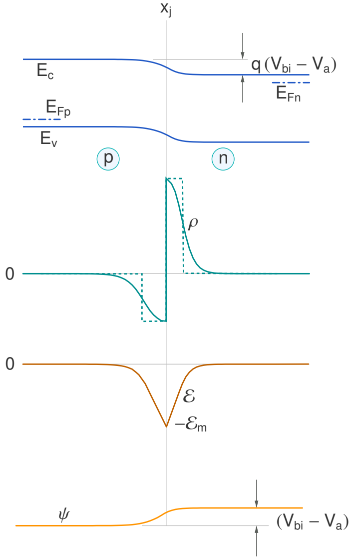


* On the p side, $5\,L_n$ away from x_p, $J \approx J_p^{\text{drift}}$ resulting from a small (positive) electric field.

Forward bias: summary

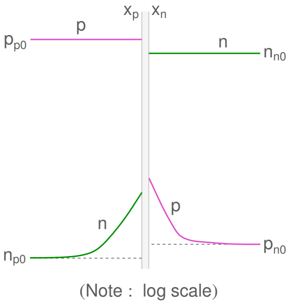


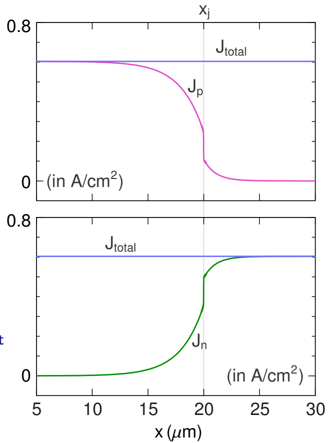


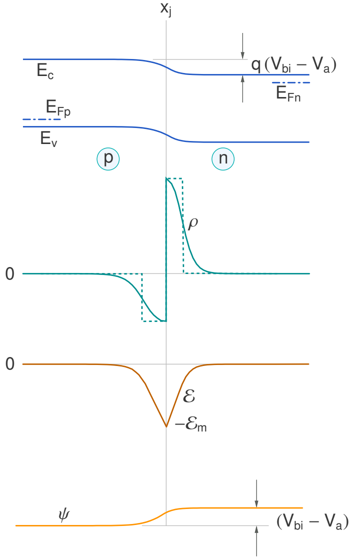


* On the p side, $5\,L_n$ away from x_p, $J \approx J_p^{\mathrm{drift}}$ resulting from a small (positive) electric field.
* Holes continuously injected from the p side recombine with electrons on the n side.

Forward bias: summary

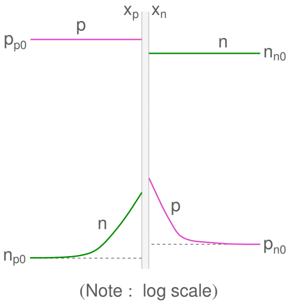


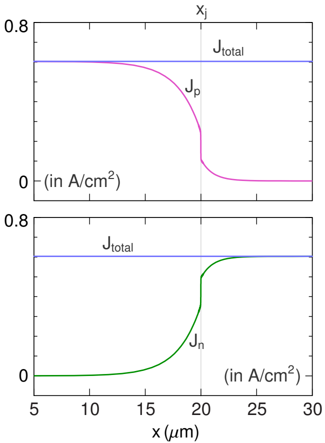


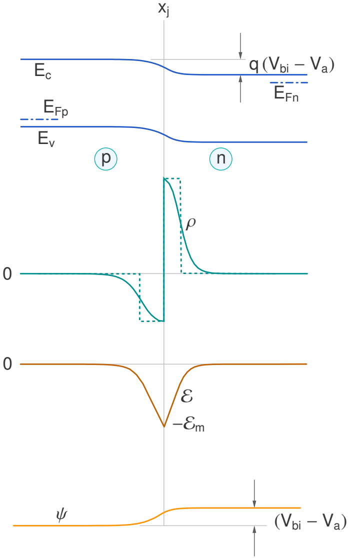


* On the p side, $5\,L_n$ away from x_p, $J \approx J_p^{\text{drift}}$ resulting from a small (positive) electric field.
* Holes continuously injected from the p side recombine with electrons on the n side.
* $5\,L_p$ away from x_n, there are no excess holes, and $p \approx p_{n0}$.

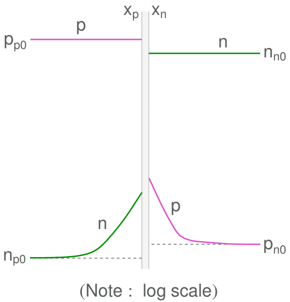
Forward bias: summary

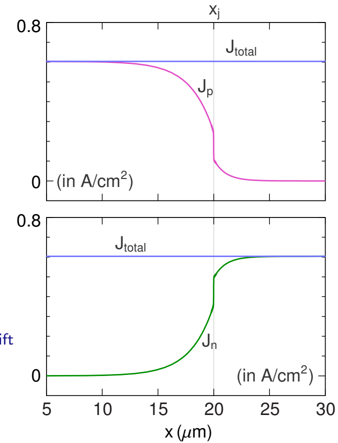


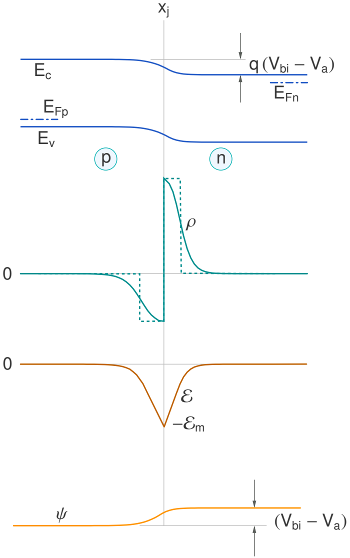




Forward bias: summary

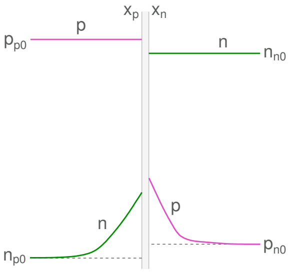




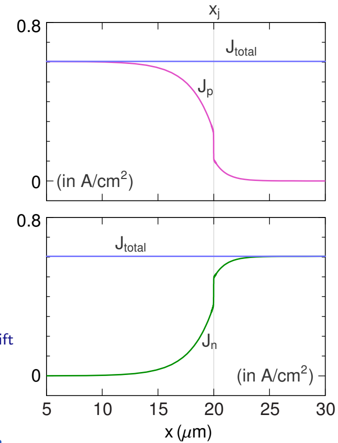


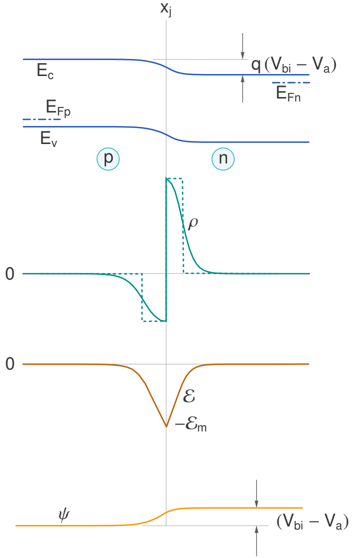
* On the n side, $5\,L_p$ away from x_n, $J \approx J_n^{\mathrm{drift}}$ resulting from a small (positive) electric field.

Forward bias: summary



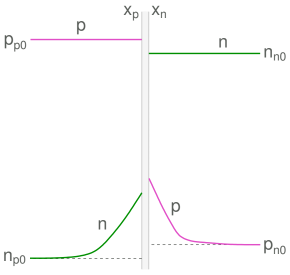
(Note : log scale)



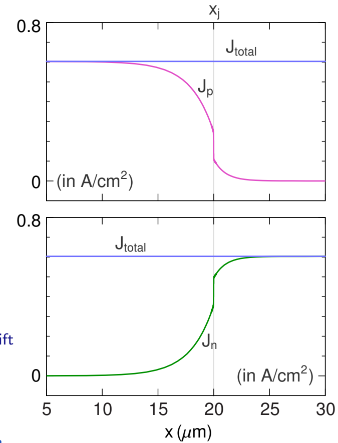


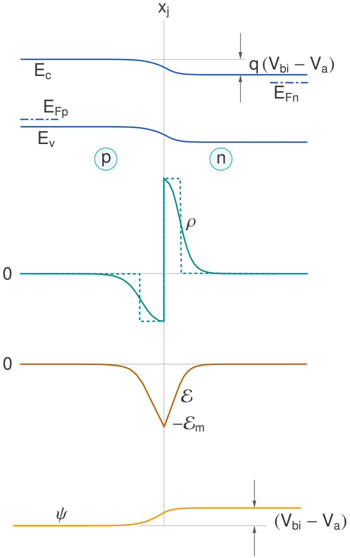
* On the n side, $5\,L_p$ away from x_n, $J \approx J_n^{\text{drift}}$ resulting from a small (positive) electric field.
* Electrons continuously injected from the n side recombine with holes on the p side.

Forward bias: summary



(Note : log scale)





* On the n side, $5\,L_p$ away from x_n, $J \approx J_n^{\text{drift}}$ resulting from a small (positive) electric field.
* Electrons continuously injected from the n side recombine with holes on the p side.
* $5\,L_n$ away from x_p, there are no excess electrons, and $n \approx n_{p0}$.