Semiconductor Devices

p-n Junctions: Part 3

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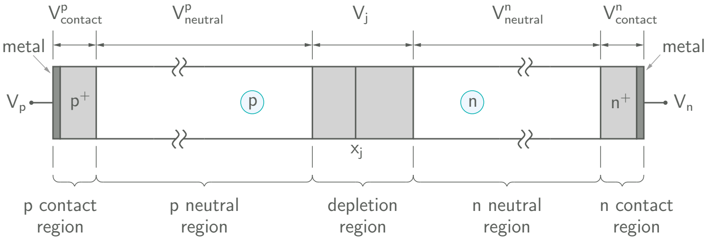
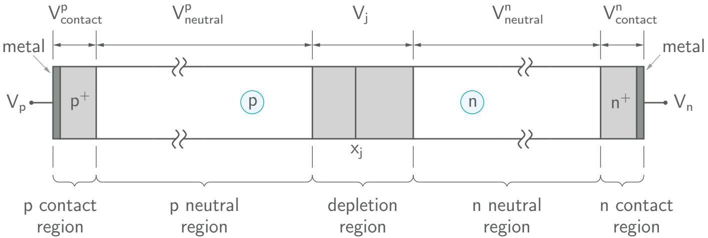


Continuity equation for holes ($x > x_n$): $\dfrac{\partial p(x,t)}{\partial t} = -\dfrac{1}{q}\dfrac{\partial J_p}{\partial x} - (R - G) = 0$ (in DC conditions).

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



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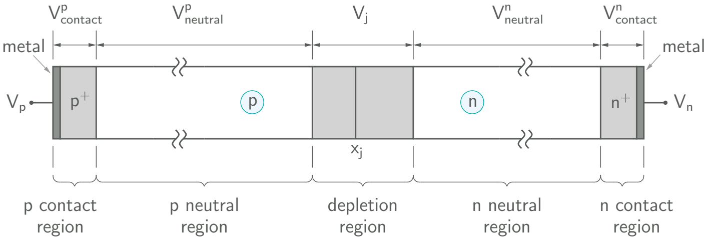

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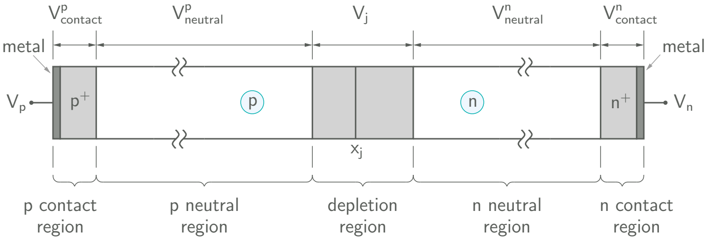

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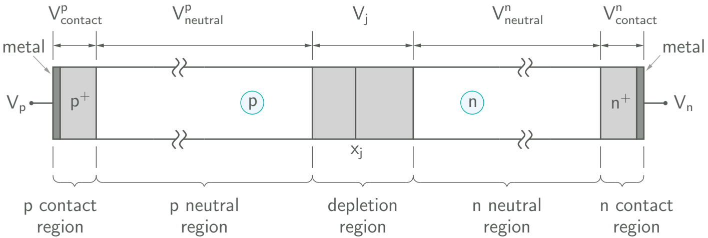
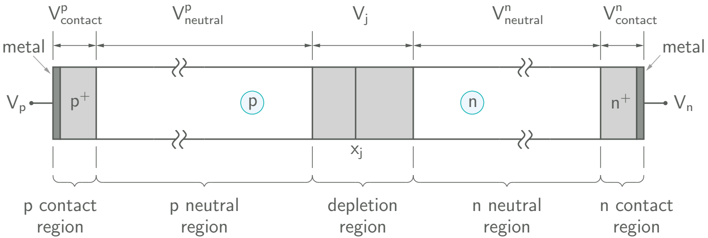
$\rightarrow D_p\dfrac{d^2p}{dx^2} - \dfrac{p - p_{n0}}{\tau_p} = 0$ or $\dfrac{d^2\Delta p}{dx^2} - \dfrac{\Delta p}{L_p^2} = 0$, where $L_p = \sqrt{D_p\tau_p}$ is the hole diffusion length.



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.



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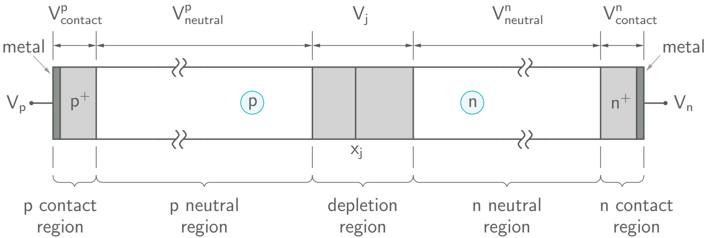
Solution: $V_{\mathrm{bi}} = V_T \log\left(\dfrac{N_a N_d}{n_i^2}\right) = (0.0259\,\mathrm{V}) \log\left(\dfrac{10^{16} \times 10^{17}}{(1.5 \times 10^{10})^2}\right) = 0.75\,\mathrm{V}.$



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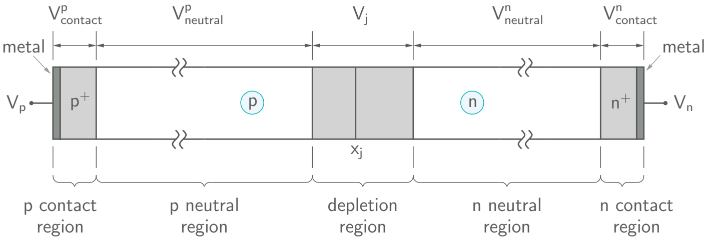

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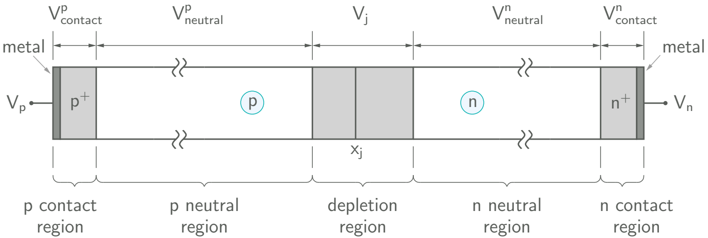

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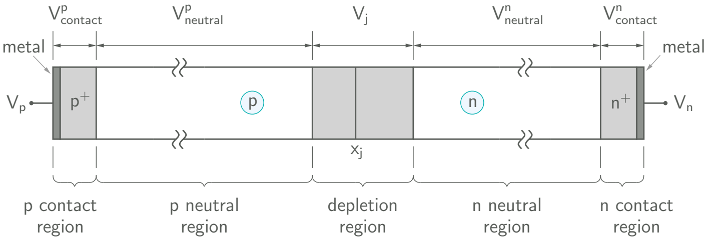

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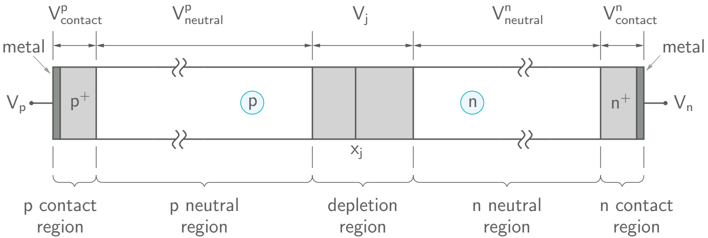
For $\tau_p = 1\,\text{ns}$, $L_p = \sqrt{12.9\,\dfrac{\text{cm}^2}{\text{s}} \times (1 \times 10^{-9}\,\text{s})} = 1.14 \times 10^{-4}\,\text{cm} = 1.14\,\mu\text{m}.$



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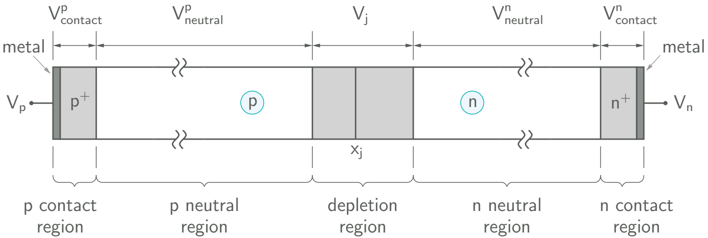

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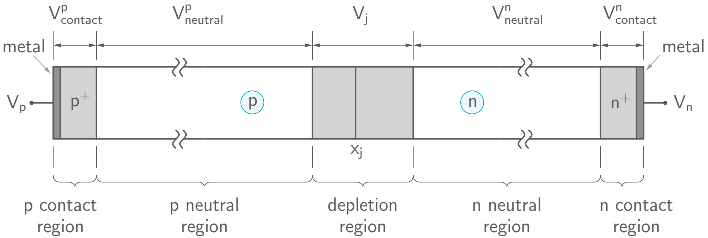

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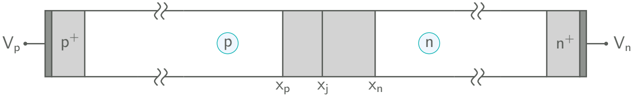
Note that $L_p \gg W|_{0\,\text{V}}$ ($0.33\,\mu$m), a typical situation.



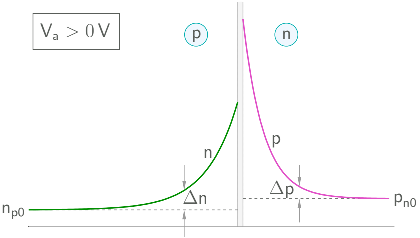
Hole continuity equation ($x > x_n$): $\dfrac{d^2 \Delta p}{dx^2} - \dfrac{\Delta p}{L_p^2} = 0,.$

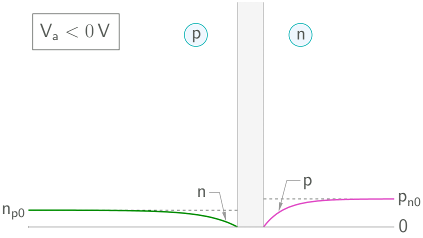
Boundary conditions: $\Delta p(x_n) = p_{n0} \, \exp\left(\dfrac{V_a}{V_T}\right) - p_{n0} = p_{n0} \left[\exp\left(\dfrac{V_a}{V_T}\right) - 1\right]$

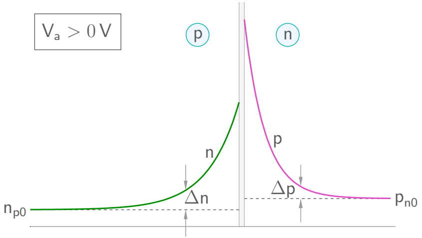
$$\Delta p(x \rightarrow \infty) = p(x \rightarrow \infty) - p_{n0} = 0$$

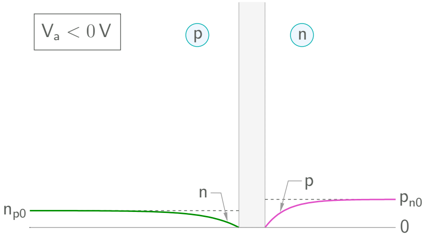
$$\rightarrow \Delta p(x) = p_{n0} \left[\exp\left(\frac{V_a}{V_T}\right) - 1\right] \exp\left(-\frac{x - x_n}{L_p}\right), \quad x > x_n,$$

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









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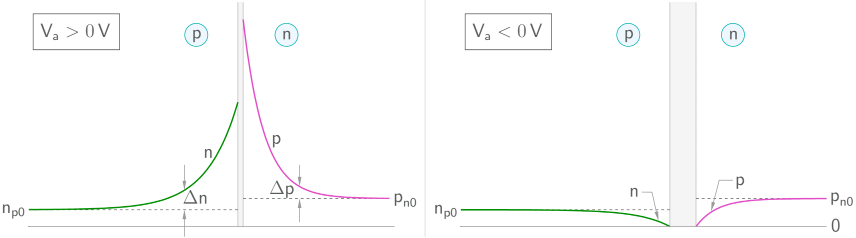

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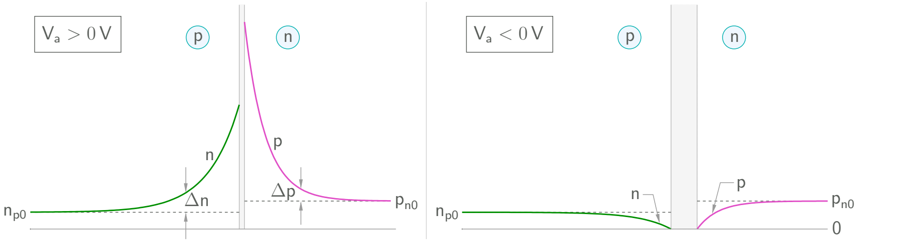
* When $x - x_n = 5L_p$, the exponential factor in $\Delta p(x)$ is $e^{-5} = 0.0067 \rightarrow$ In about five minority carrier diffusion lengths, the disturbance caused by the applied bias vanishes.



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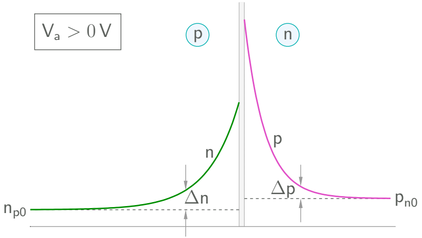

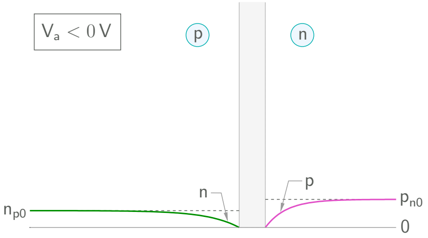

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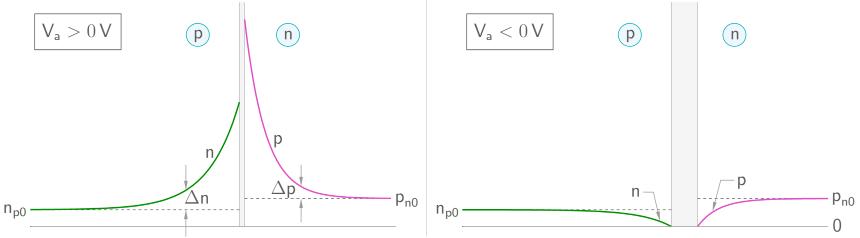
For forward bias, $\Delta p(x_n)$ and $\Delta n(x_p)$ are positive.



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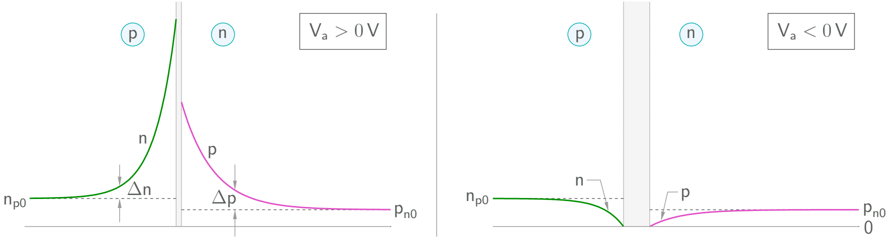
For reverse bias, $\Delta p(x_n)$ and $\Delta n(x_p)$ are negative.



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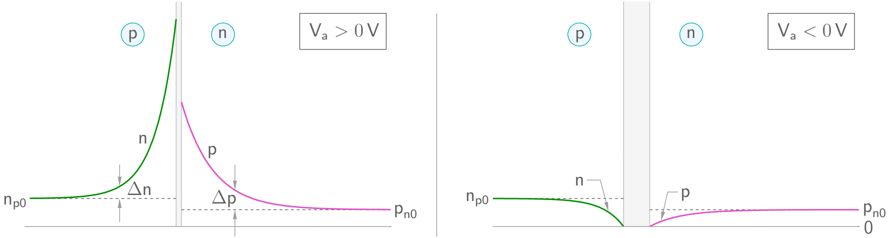
Solution: $p_{p0} \approx N_a = 5 \times 10^{16}\,\text{cm}^{-3} \rightarrow n_{p0} = \dfrac{n_i^2}{p_{p0}} = \dfrac{(1.5 \times 10^{10})^2}{5 \times 10^{16}} = 4.5 \times 10^3\,\text{cm}^{-3}$.



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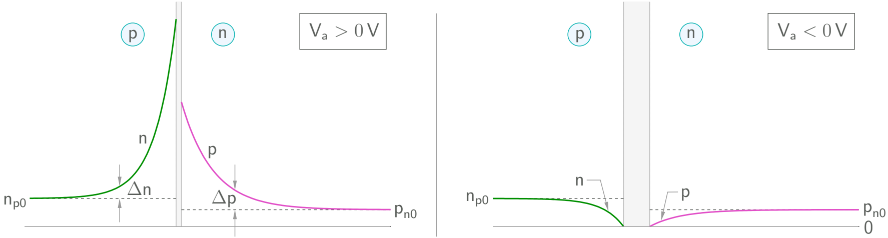

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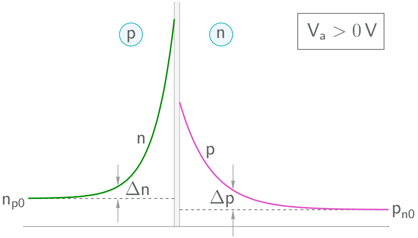
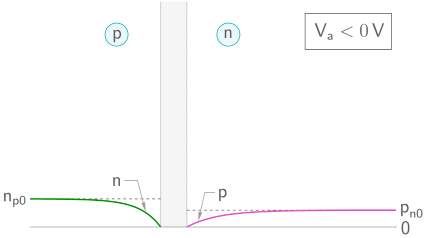
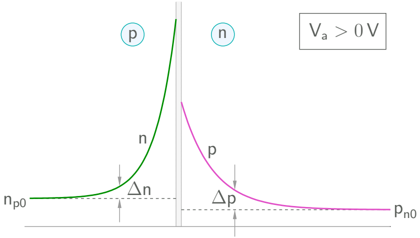
$$n_{n0} \approx N_a = 1 \times 10^{18}\,cm^{-3} \rightarrow p_{n0} = \frac{n_i^2}{n_{n0}} = \frac{(1.5 \times 10^{10})^2}{1 \times 10^{18}} = 2.25 \times 10^2\,cm^{-3}.$$

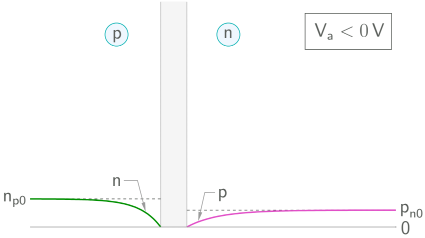
$$\Delta p(x_n) = p_{n0}\left[\exp\left(\frac{V_a}{V_T}\right) - 1\right], \quad \Delta n(x_p) = n_{p0}\left[\exp\left(\frac{V_a}{V_T}\right) - 1\right].$$





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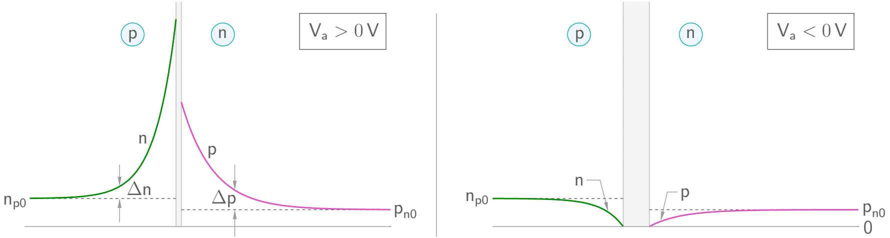
  $\Delta p(x_n)$ and $\Delta n(x_p)$ increase by several orders of magnitude as V_a is increased.



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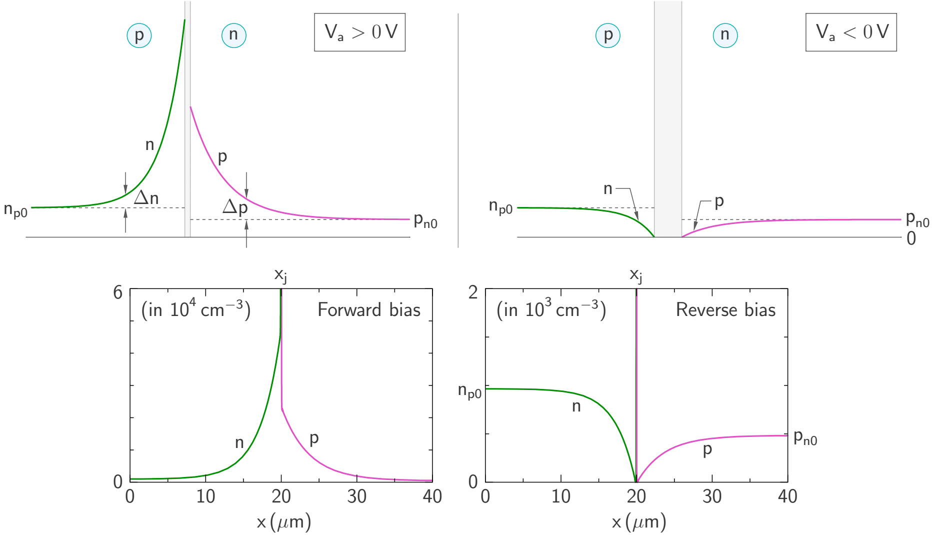
* Forward bias:
  $\Delta p(x_n)$ and $\Delta n(x_p)$ increase by several orders of magnitude as V_a is increased.
* Reverse bias:
  $\Delta p(x_n) \approx -p_{n0}$, $\Delta n(x_p) \approx -n_{p0}$.

pn junction under forward bias: simulation results



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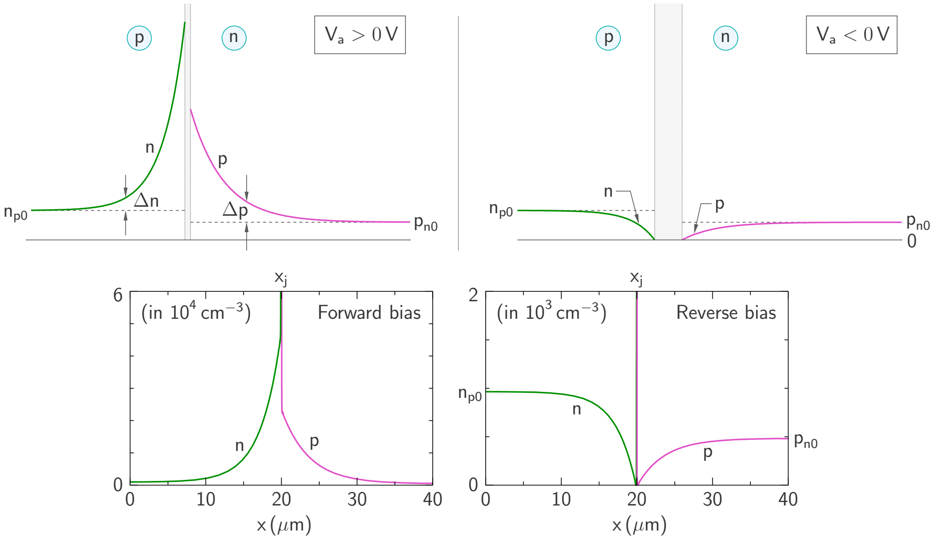
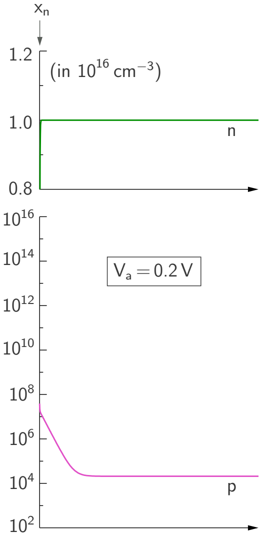


* As we have seen earlier, the minority carrier diffusion lengths (i.e., L_n on the *p*-side, L_p on the *n*-side) are typically much larger than the depletion width.

High-injection regime



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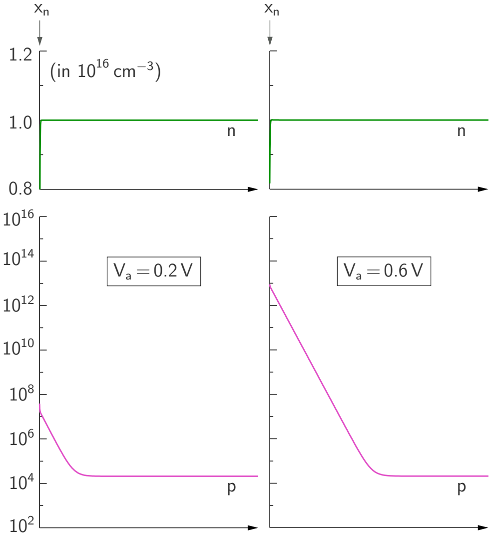

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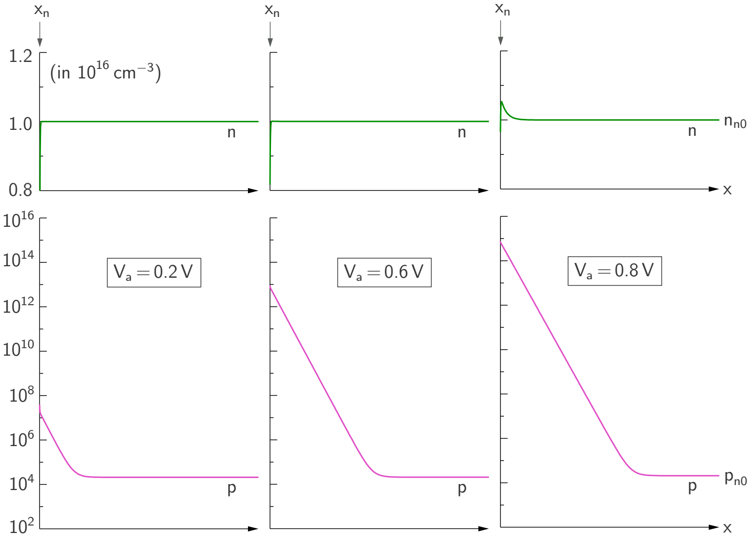

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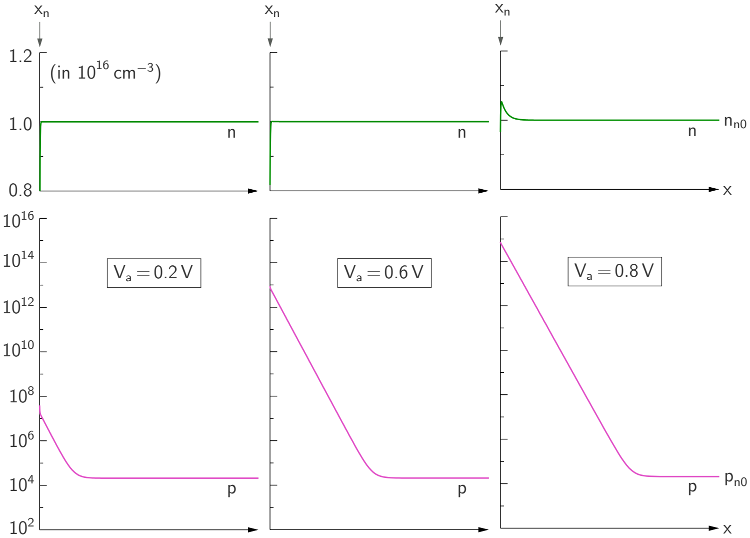
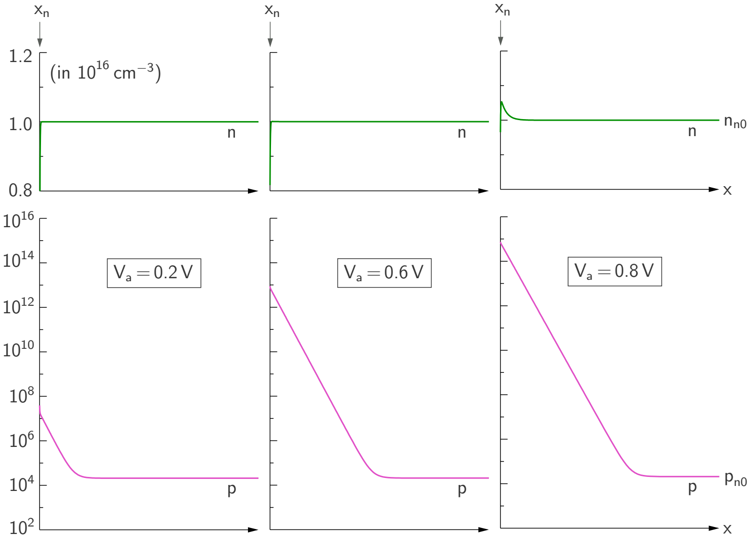


* As the forward bias is increased, the minority carrier concentration increases rapidly, and at some point becomes comparable to the majority carrier concentration. This regime is called the "high-injection" regime.

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.

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

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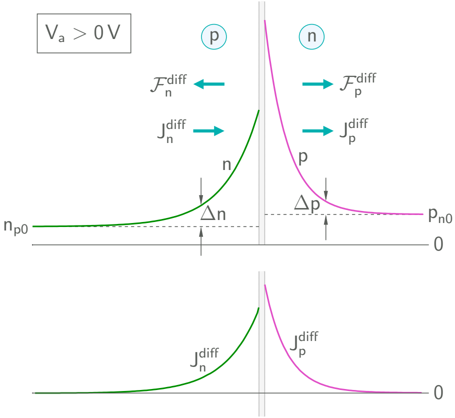

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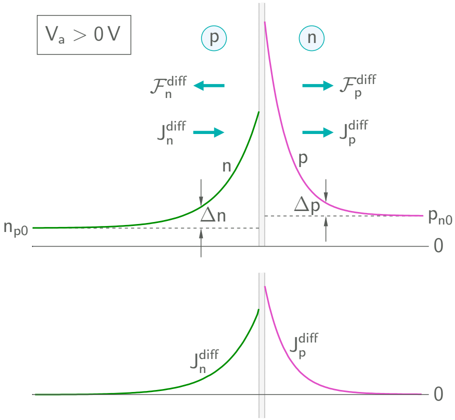

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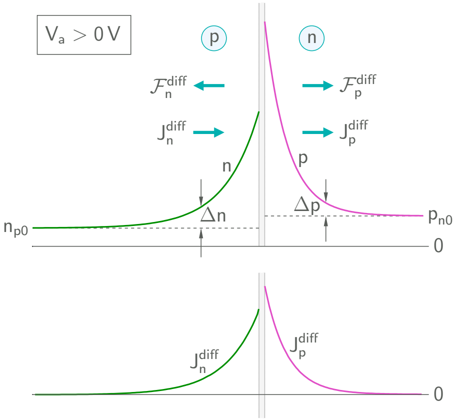

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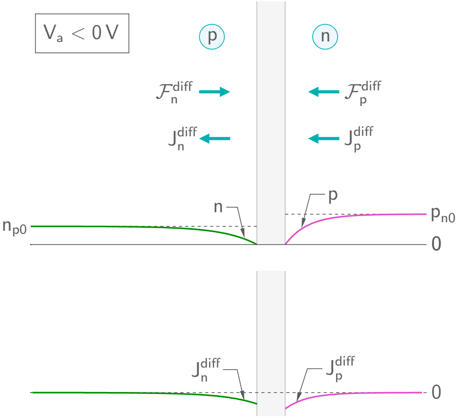

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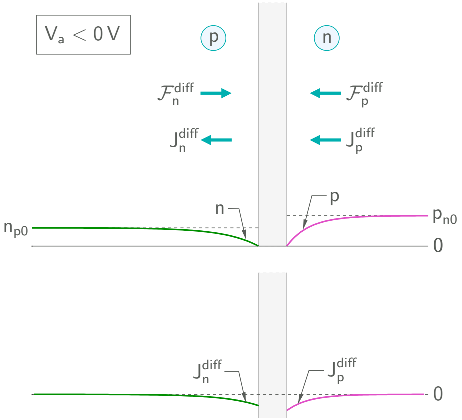

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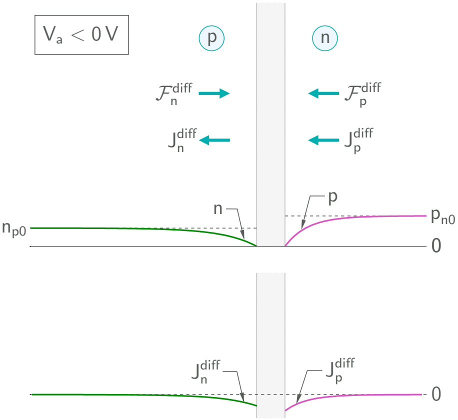

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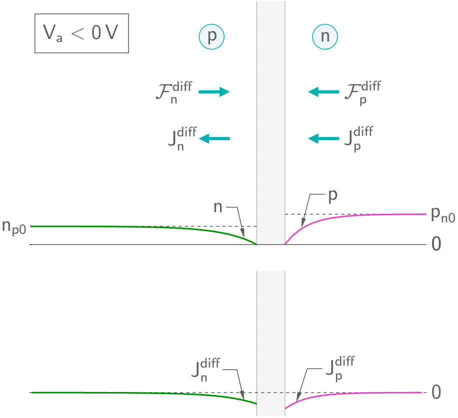
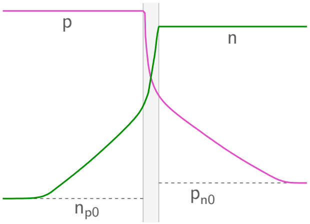
The currents are much smaller under reverse bias.



pn junction: What is happening inside the depletion region?

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

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



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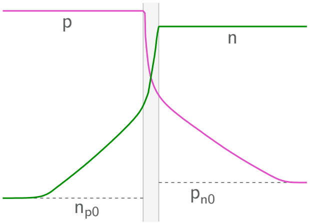

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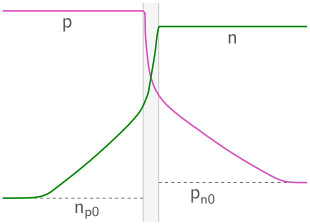

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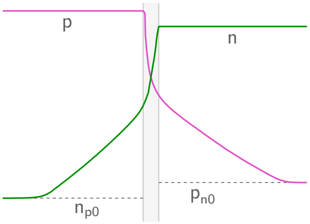

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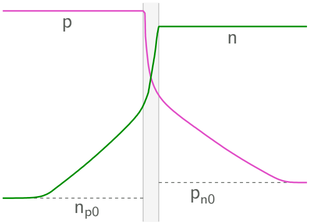
$$R - G = \frac{pn - n_i^2}{\tau_n(n + n_1) + \tau_p(p + p_1)}$$

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



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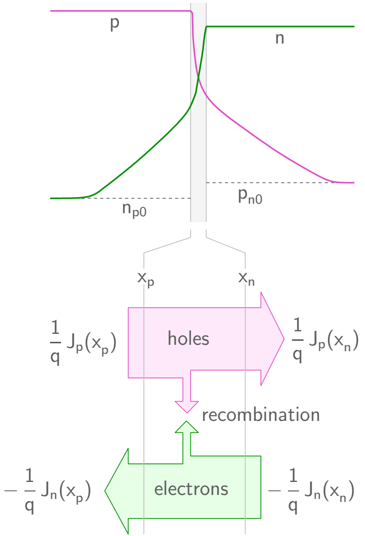

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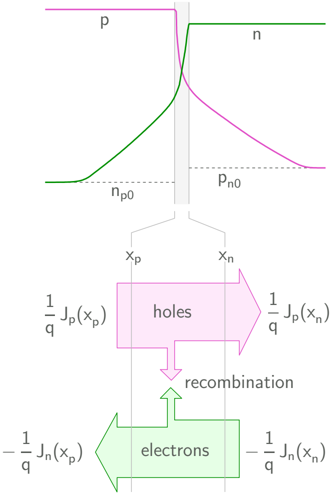

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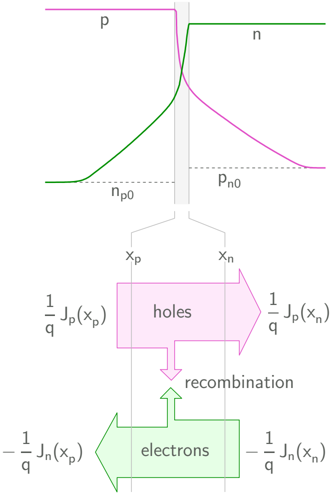

∗ To obtain a first-order *I*-*V* model, we ignore G-R in the depletion region.

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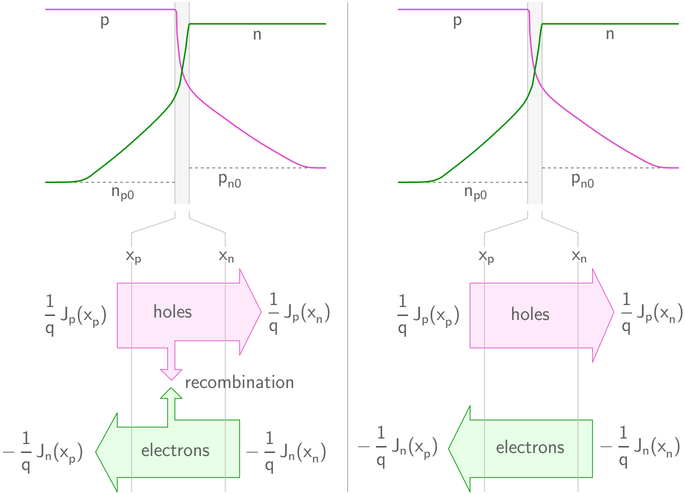

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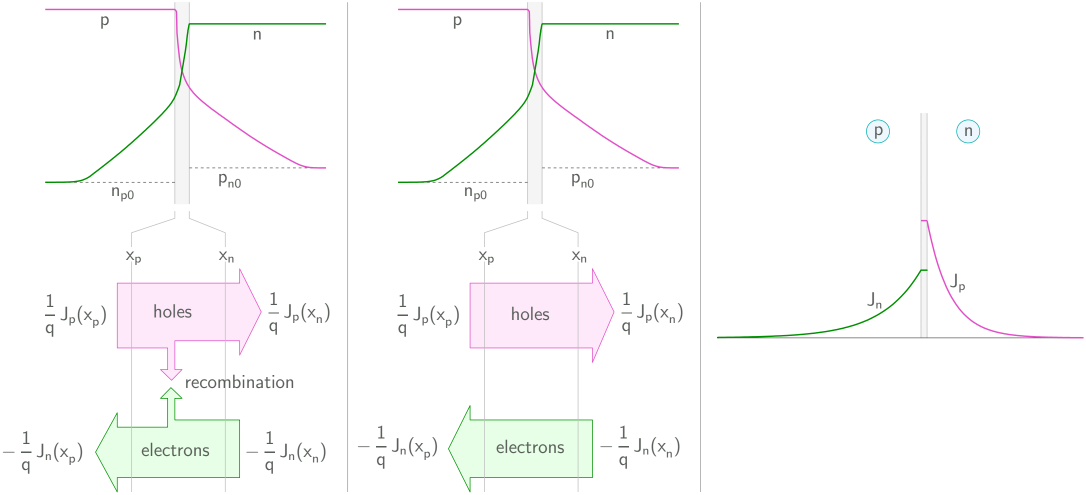
pn junction: What is happening inside the depletion region?



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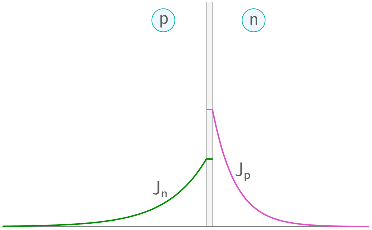
pn junction: total current density



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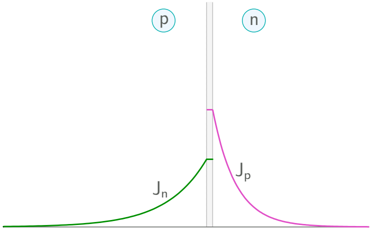
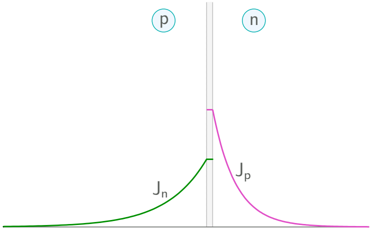


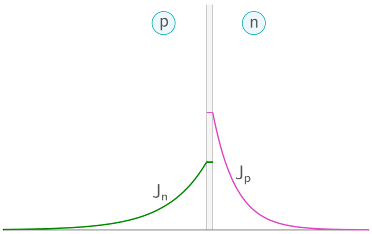
* The total current density is the same throughout the device.

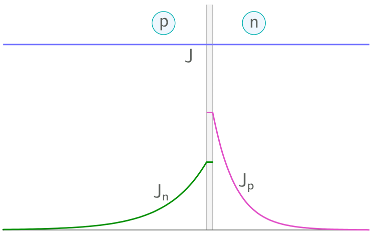
pn junction: total current density



* 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





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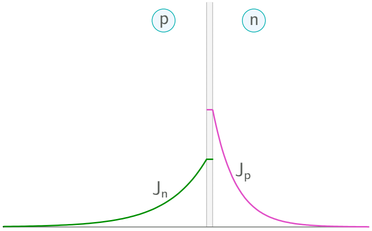

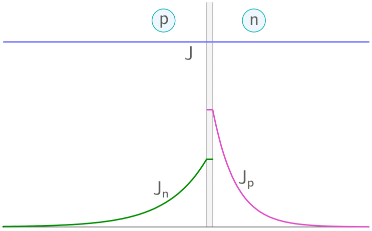

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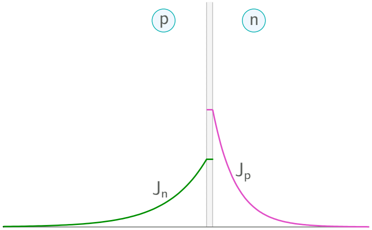
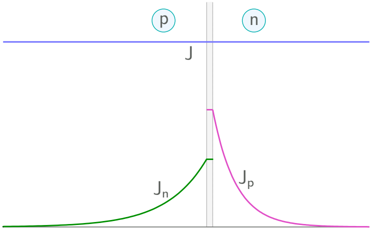
$$J = J_p(x_n) + J_n(x_p) = \left[\frac{qD_p p_{n0}}{L_p} + \frac{qD_n n_{p0}}{L_n}\right] \left(e^{V_a/V_T} - 1\right).$$

pn junction: total current density





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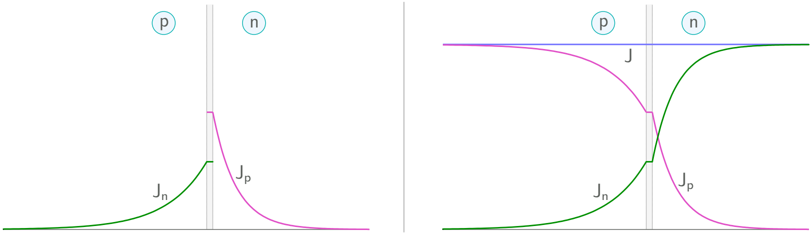
- We can now obtain J_n $(x > x_n)$ and J_p $(x < x_p)$ using $J_n(x) + J_p(x) = J$.

pn junction: total current density



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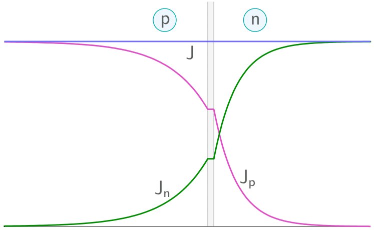
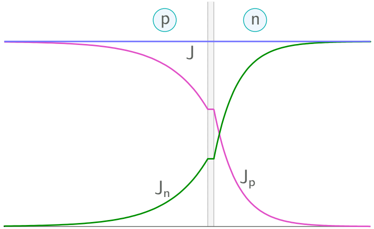


Consider the situation sufficiently far from the depletion region (i.e., about $5L_n$ on the *p*-side and $5L_p$ on the *n*-side).



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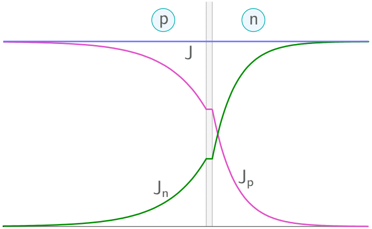
* The current density is due to majority carriers (drift component).



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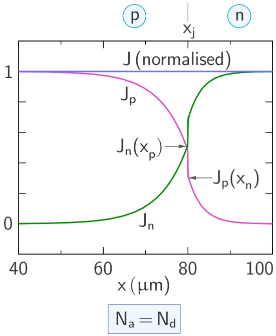
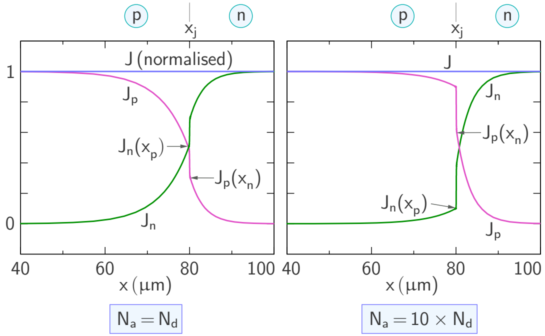
* The current density is due to majority carriers (drift component).
* Since the majority carrier concentration is large, a very small electric field suffices to produce the required current density ($J_n^{\text{drift}} = qn\mu_n\mathcal{E}$, $J_p^{\text{drift}} = qp\mu_p\mathcal{E}$).



Doping densities:

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

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



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

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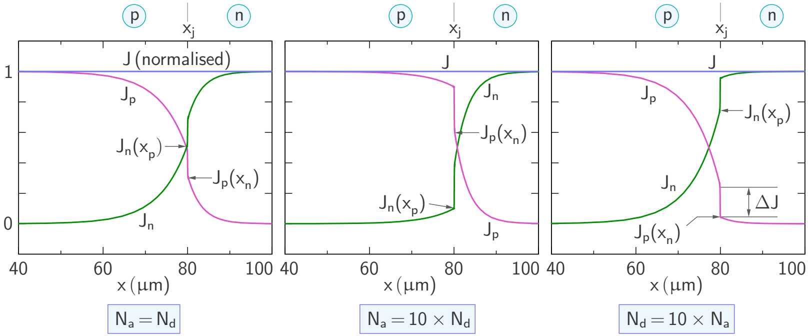
pn junction under forward bias: numerical results



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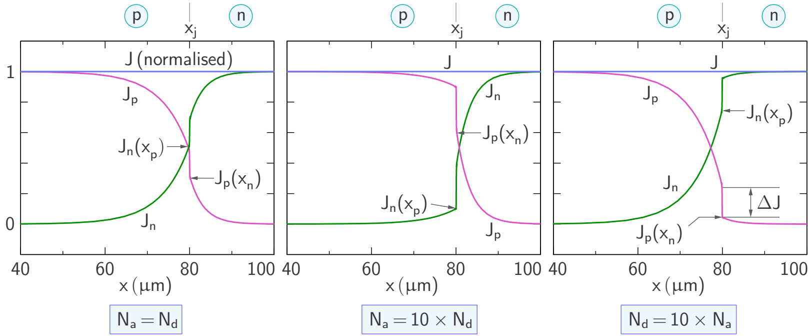

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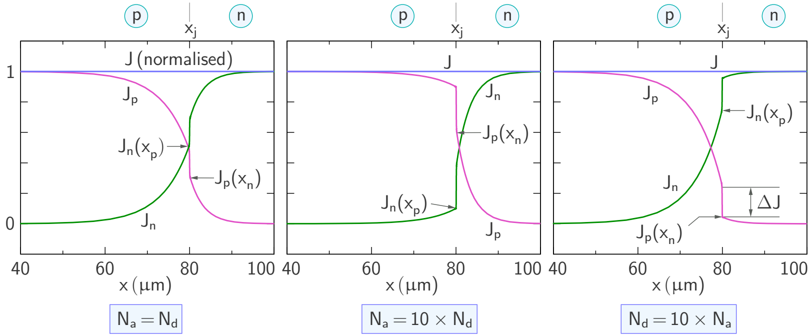
$$J_p(x_n) = \frac{qD_p p_{n0}}{L_p}\left(e^{V_a/V_T} - 1\right),\quad J_n(x_p) = \frac{qD_n n_{p0}}{L_n}\left(e^{V_a/V_T} - 1\right),\quad p_{n0} = \frac{n_i^2}{n_{n0}} \approx \frac{n_i^2}{N_d},\quad n_{p0} = \frac{n_i^2}{p_{p0}} \approx \frac{n_i^2}{N_a}.$$

* 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



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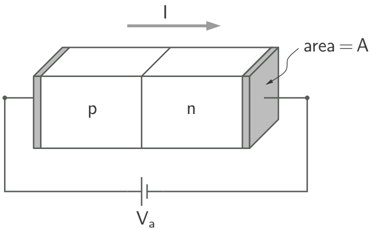
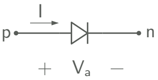
* Because of recombination, there is a change in J_p and J_n across the depletion region (which has been ignored in our analysis). This change is seen as vertical lines in the figure since the depletion width is much smaller than the diffusion lengths.

M. B. Patil, IIT Bombay





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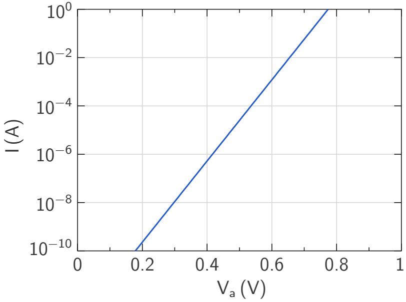
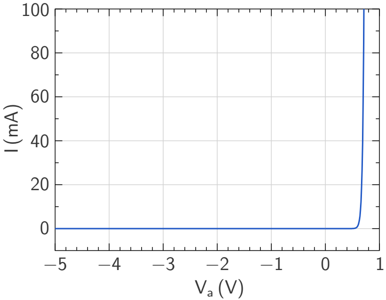
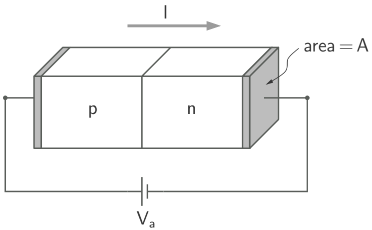
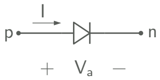
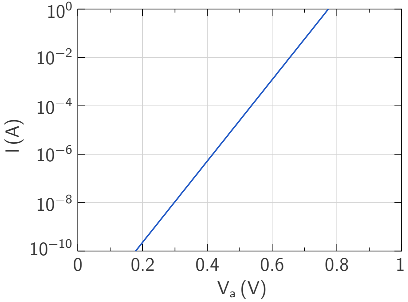


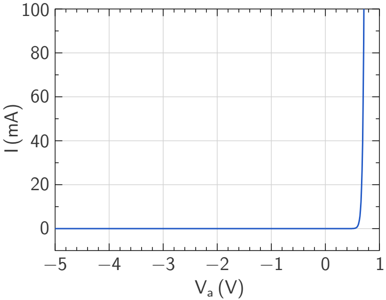


Diode I-V equation









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

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

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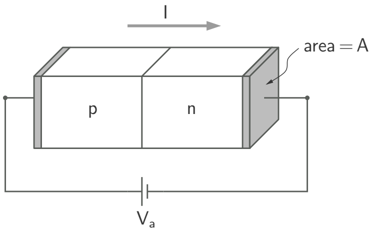

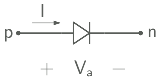

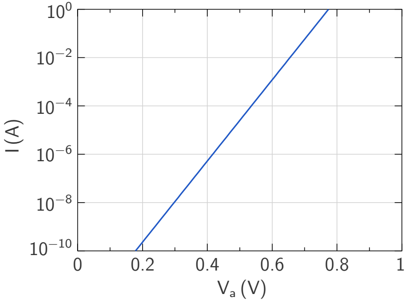

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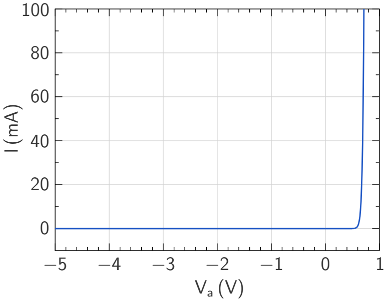
* This equation is known as the "Shockley diode equation."



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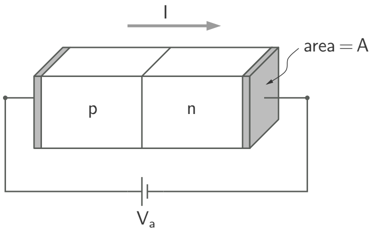

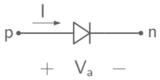

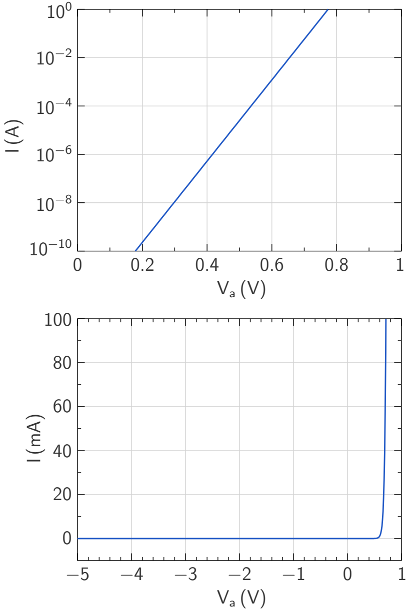

$$J = \left[\frac{qD_p p_{n0}}{L_p} + \frac{qD_n n_{p0}}{L_n}\right] \left(e^{V_a/V_T} - 1\right).$$

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* 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."

Diode I-V equation

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

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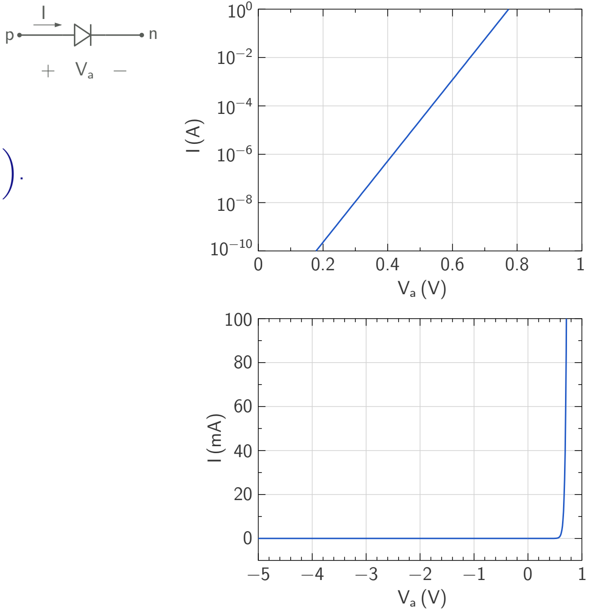

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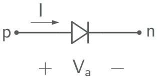

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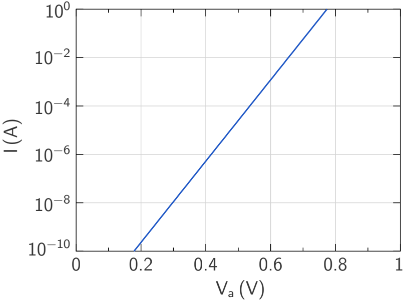
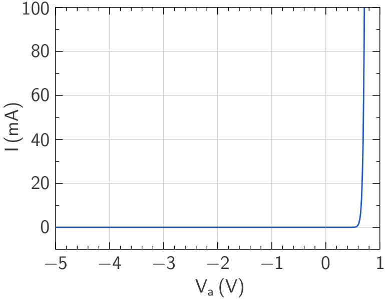
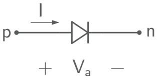
* In a real diode, other factors often dominate in reverse bias, including generation in the depletion region and surface leakage. Also, as we will see, a real diode cannot withstand indefinitely large reverse voltages and will "break down" at some point.







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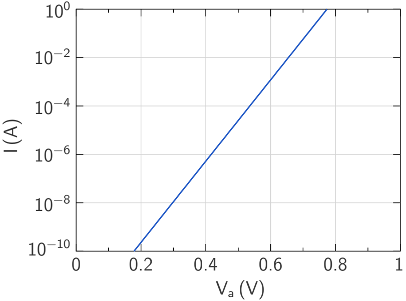
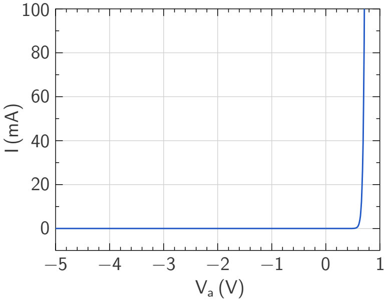
* In a real diode, other factors often dominate in reverse bias, including generation in the depletion region and surface leakage. Also, as we will see, a real diode cannot withstand indefinitely large reverse voltages and will "break down" at some point.
* Recombination in the depletion region under forward bias can be incorporated in the Shockley equation with an "ideality factor" η $(1 < \eta < 2)$:

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





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 $T = 300\,\text{K}$:

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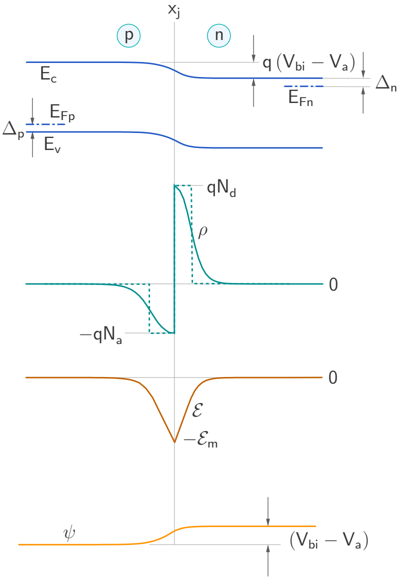
(3) $J_n(x_p)$ and $J_p(x_n)$,

(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.

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



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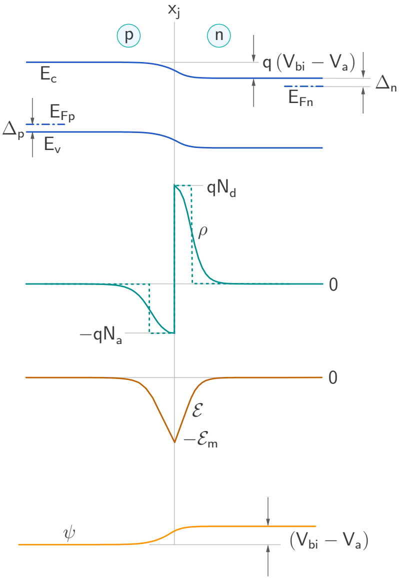

Example (continued)

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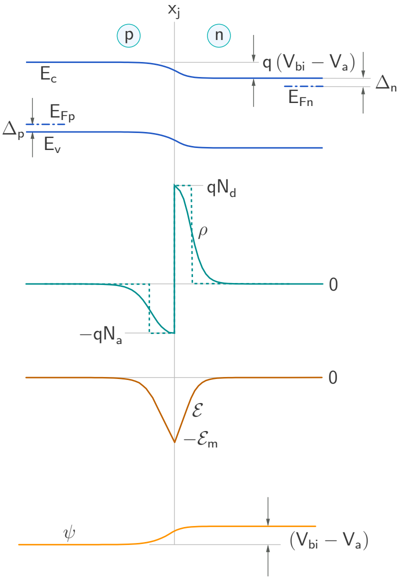

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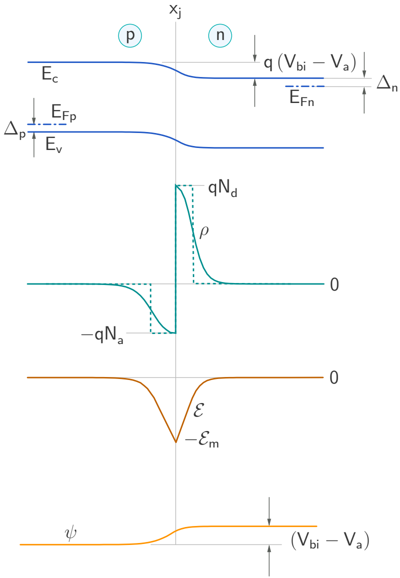
$$(V_{\text{bi}}-V_a) = \frac{1}{2}\,\mathcal{E}_m W$$



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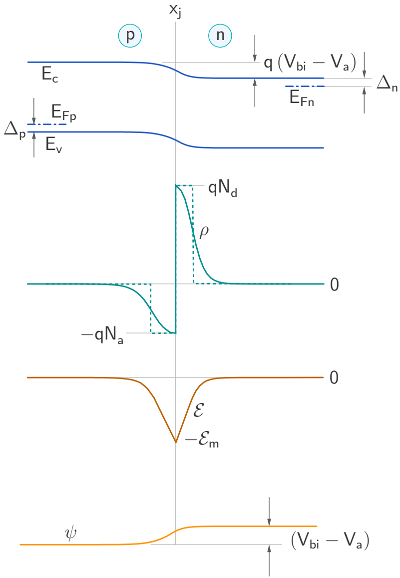
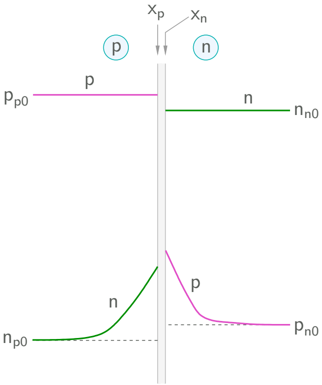
$$(V_{\rm bi}-V_a) = \frac{1}{2}\,\mathcal{E}_m W$$

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

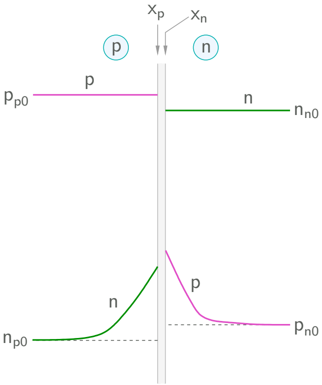




x_p
x_n
p
n
p
p_{p0}
n
n_{n0}
p
n
n_{p0}
p_{n0}

The equilibrium minority carrier densities are

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



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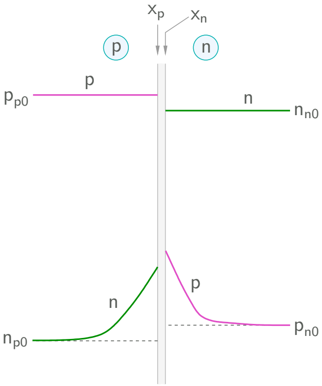

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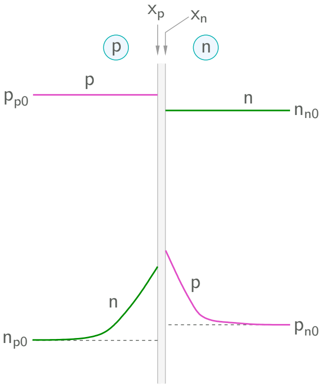
The minority carrier densities at x_p and x_n are

$$n(x_p) = n_{p0} \left(e^{V_a/V_T} - 1\right) = 2.25 \times 10^3 \times e^{0.65/0.0259} = 1.8 \times 10^{14} \,\text{cm}^{-3},$$



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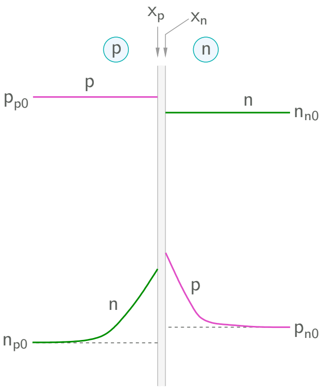


The diffusion coefficients are

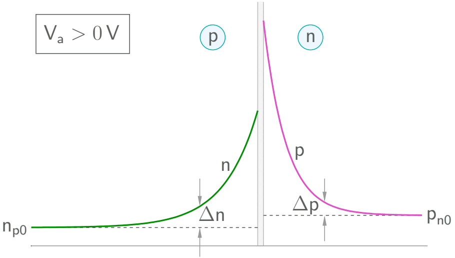
$$D_p = V_T \mu_p = 0.0259 \times 500 = 12.9\,\text{cm}^2/\text{s},$$

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

The minority carrier diffusion lengths in the neutral regions are

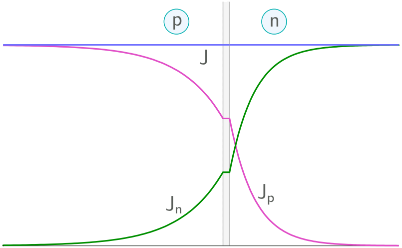
$$L_p = \sqrt{D_p \tau_p} = \sqrt{12.9 \times 5 \times 10^{-6}}\,\text{cm} = 80.3\,\mu\text{m},$$

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



The minority carrier current densities at x_n and x_p are

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

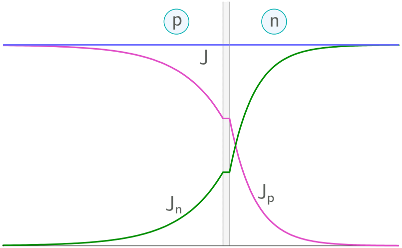


Example (continued)

The minority carrier current densities at x_n and x_p are

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

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



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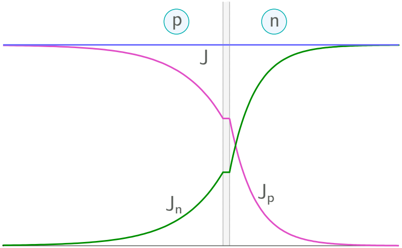
$$= 0.235\,\mathrm{A/cm^2}.$$



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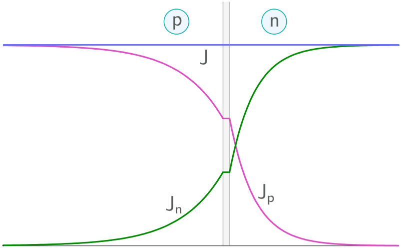
$$J_n(x_p) = \frac{qD_n n_{p0}}{L_n}\left(e^{V_a/V_T} - 1\right)$$

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

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



Example (continued)

The minority carrier current densities at x_n and x_p are

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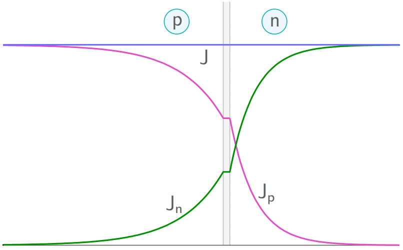
$$= 0.13\,\mathrm{A/cm^2}.$$

The diode current I is

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



Example (continued)

The minority carrier current densities at x_n and x_p are

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

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

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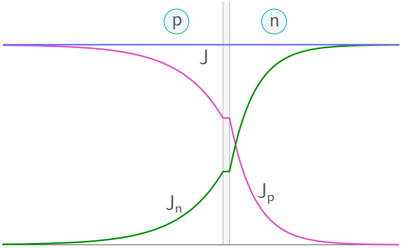

The diode current I is

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

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

Example (continued)

The minority carrier current densities at x_n and x_p are

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

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

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

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

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

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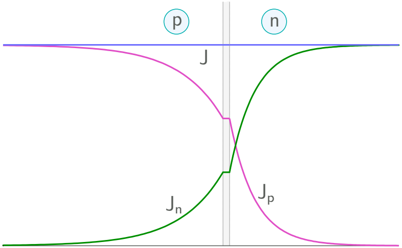
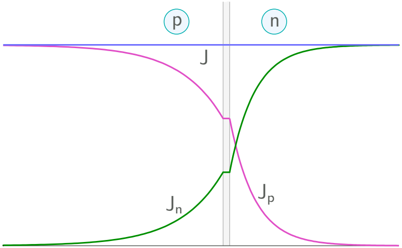
$$= 0.365\,\mathrm{mA}.$$



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)

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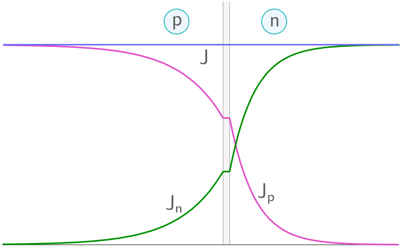
$$= 0.076\,\text{V/cm}.$$



Example (continued)

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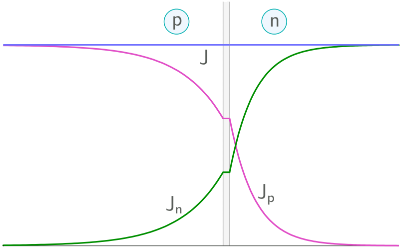
$$= 0.076\,\text{V/cm}.$$

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

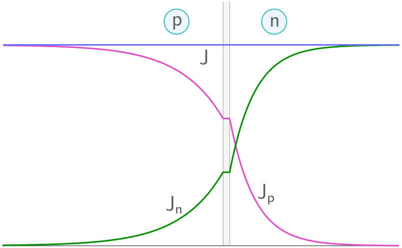
$$\mathcal{E}^n_{\text{neutral}} = \frac{J}{q\mu_n n_{n0}} = \frac{0.365 \left[\dfrac{\text{A}}{\text{cm}^2}\right]}{1.6 \times 10^{-19}\,[\text{C}] \times 1500 \left[\dfrac{\text{cm}^2}{\text{V-s}}\right] \times 2 \times 10^{16} \left[\dfrac{1}{\text{cm}^3}\right]}$$

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

Similarly,

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

$$= 0.045\,\text{V/cm}.$$



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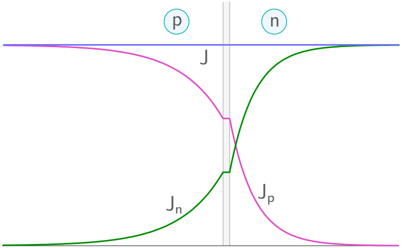
Note that these values are much smaller than $\mathcal{E}_m$ in the depletion region (25 kV/cm).



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)

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

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.