Semiconductor Devices

p-*n* Junctions: Part 1

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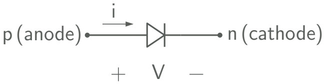
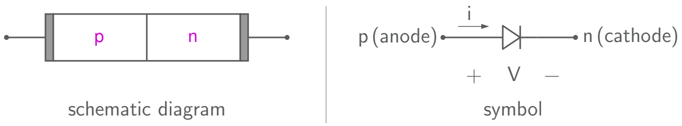
p-n junction diodes

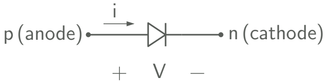
schematic diagram



symbol



* A *p*-*n* junction is useful as a stand-alone device (the diode).



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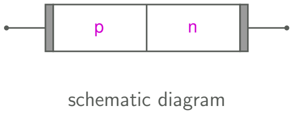
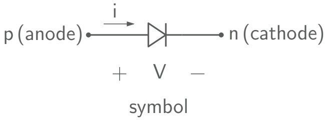
* It is also an integral part of devices such as transistors, IGBTs, thyristors, etc.

p-n junction diodes





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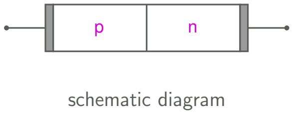
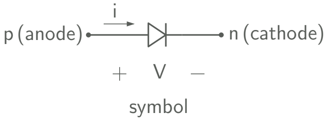
* In integrated circuits, *pn* junctions are used to provide isolation between devices.

p-n junction diodes





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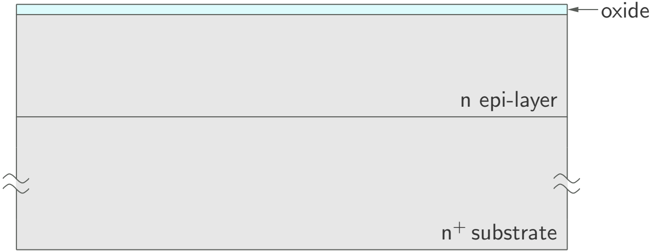
* In integrated circuits, *pn* junctions are used to provide isolation between devices.
* We will focus on semiconductor *p-n* junctions first and look at metal-semiconductor junctions later.

Start with n^+ substrate, with n epitaxial layer grown on top.

Deposit SiO_2.



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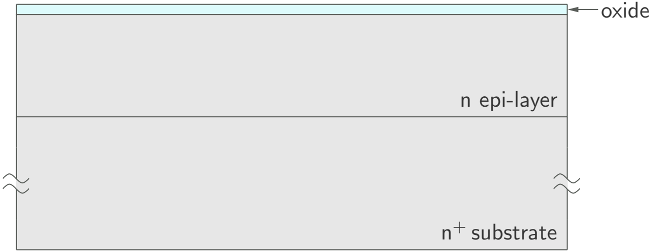
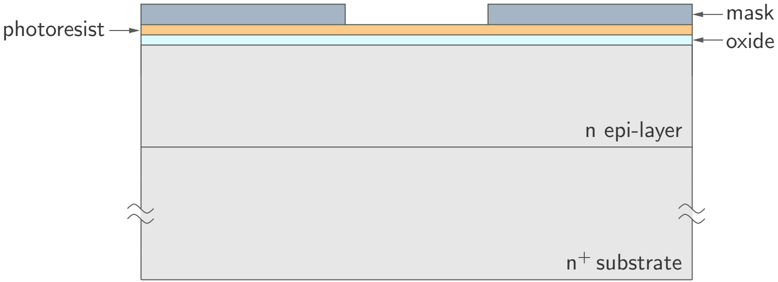


Apply photoresist.

Apply photoresist.

Place mask.



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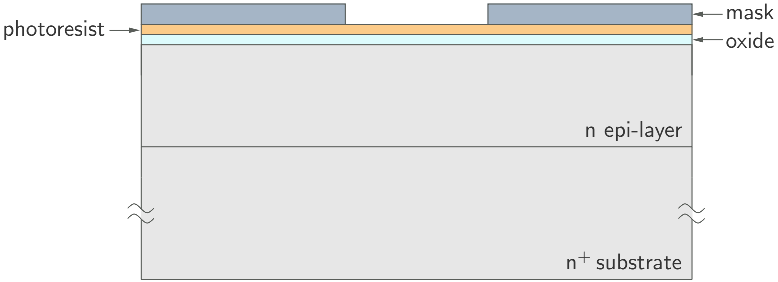
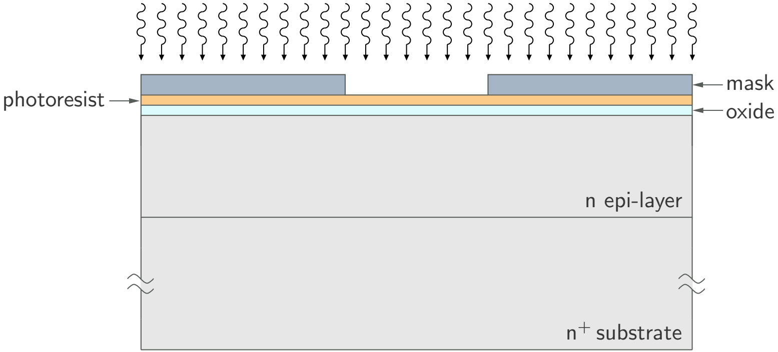


Expose to UV light.



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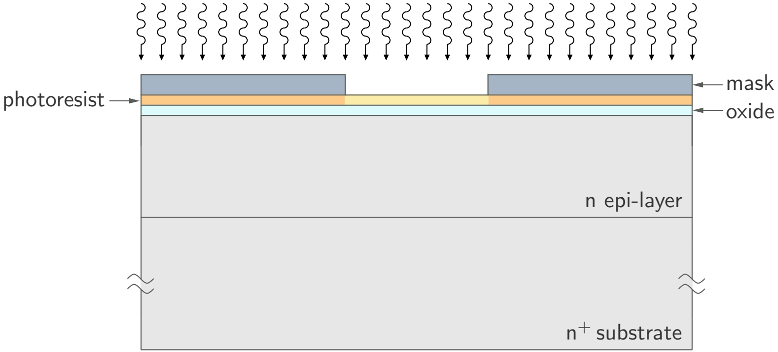

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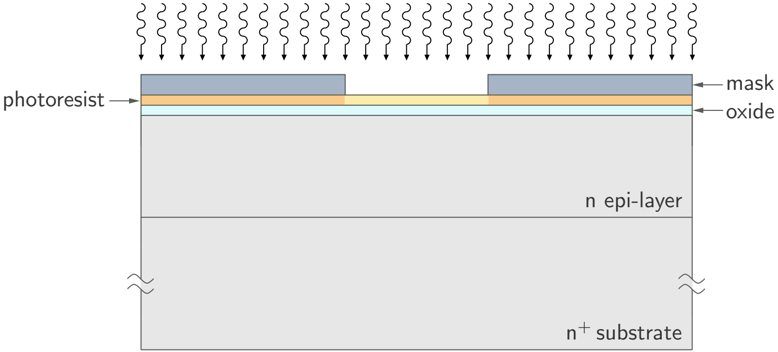

Remove mask.

Remove mask.

p-n junction fabrication

Develop photoresist.

p-*n* junction fabrication

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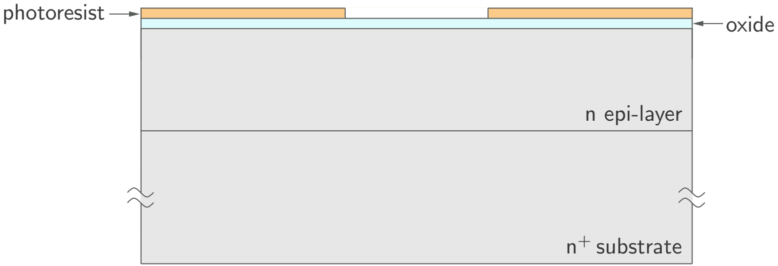
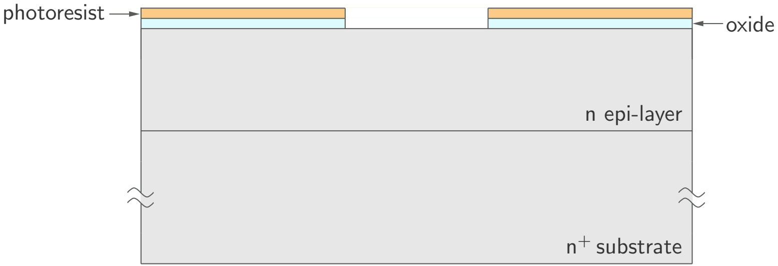


Etch oxide (in HF).



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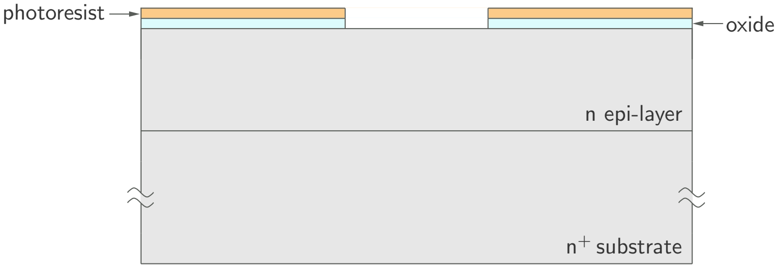

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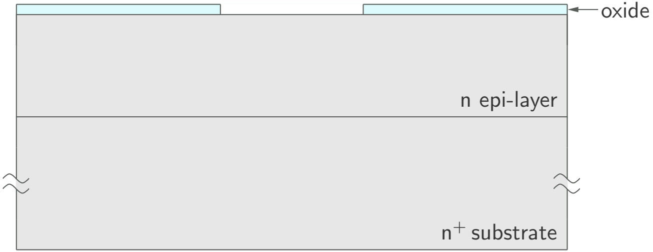

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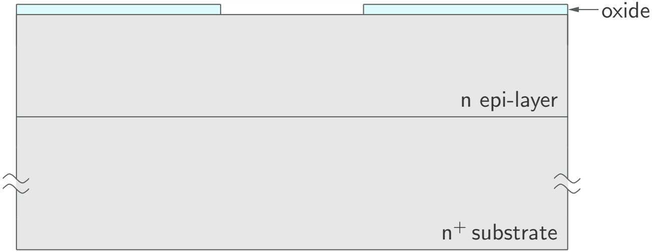
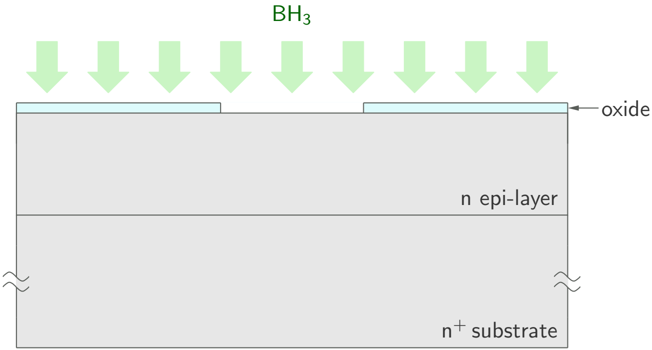


Perform diffusion of Boron.



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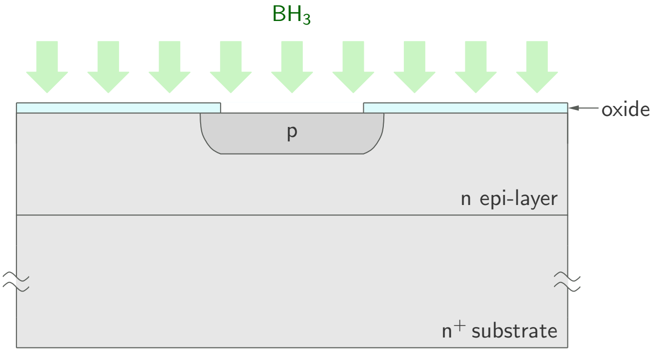

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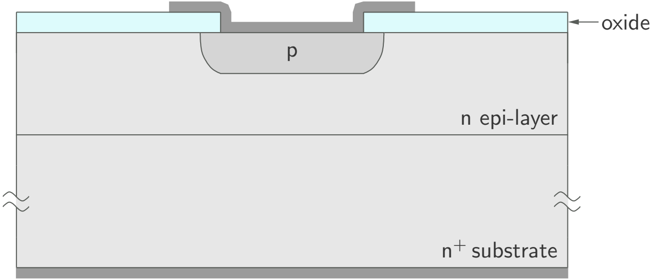
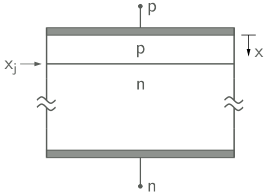
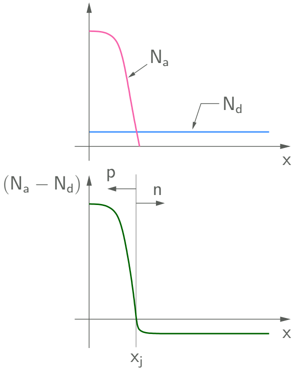


Add metal contacts (a few steps).

Idealised *p*-*n* junction diode structure



Fabricated structure



Doping densities

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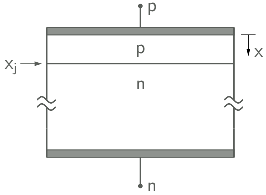

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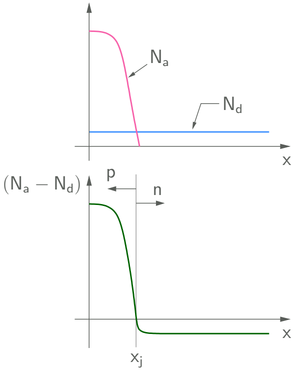
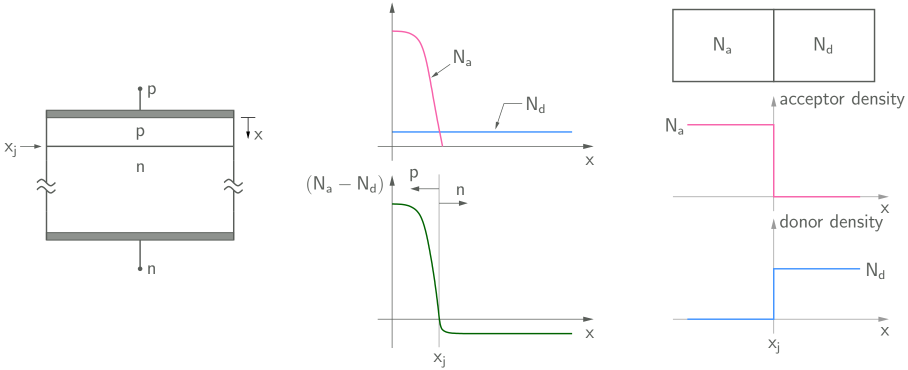


Doping densities

* For our analysis, we will consider a simplified structure with *p*-type doping on one side and *n*-type on the other.

Idealised *p*-*n* junction diode structure



Fabricated structure   Doping densities   Idealised structure

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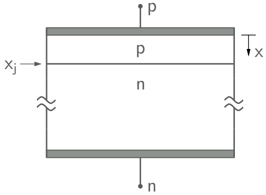
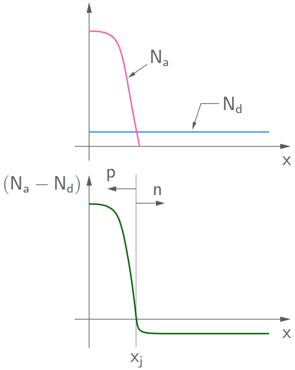
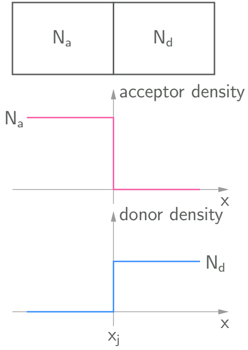
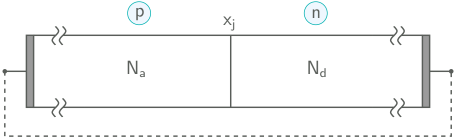






* For our analysis, we will consider a simplified structure with *p*-type doping on one side and *n*-type on the other.
* We will assume the doping densities to change abruptly at the junction → "abrupt" *pn* junction.

pn junction in equilibrium



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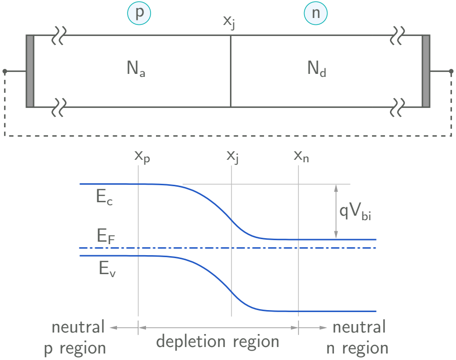

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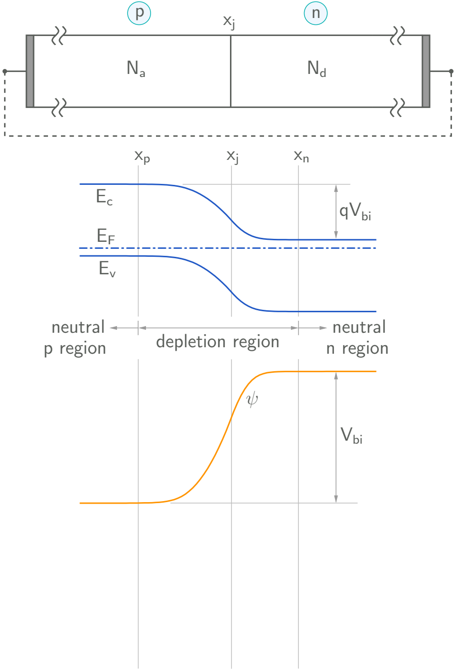

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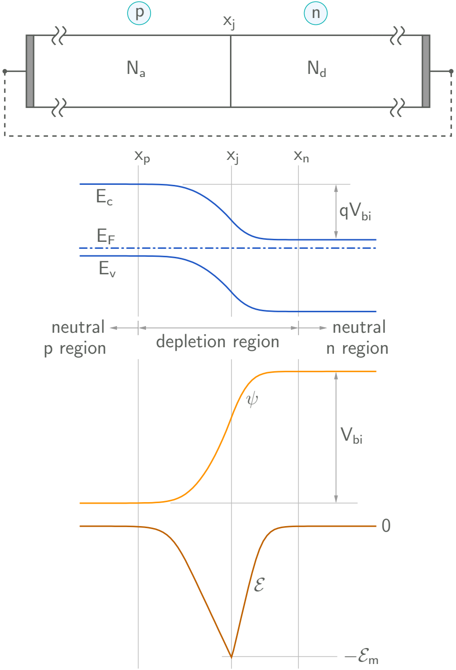
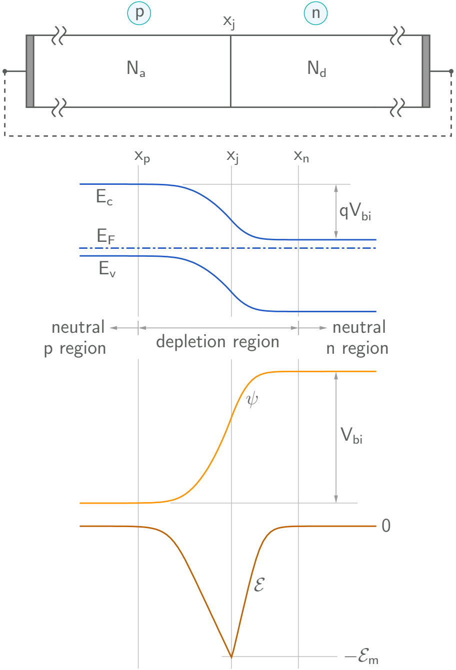


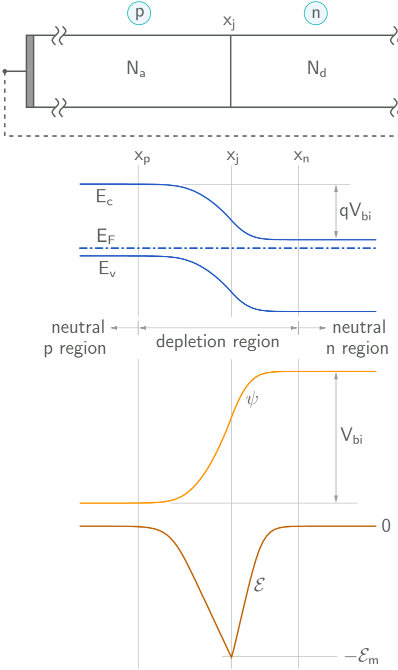
pn junction in equilibrium

∗ There is a "depletion region" in which the potential ψ varies.



pn junction in equilibrium

* There is a "depletion region" in which the potential ψ varies.
* Away from the depletion region, ψ is constant, and the electric field is zero.



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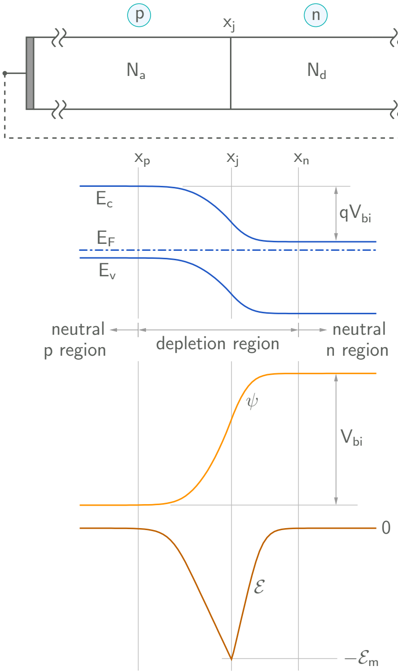

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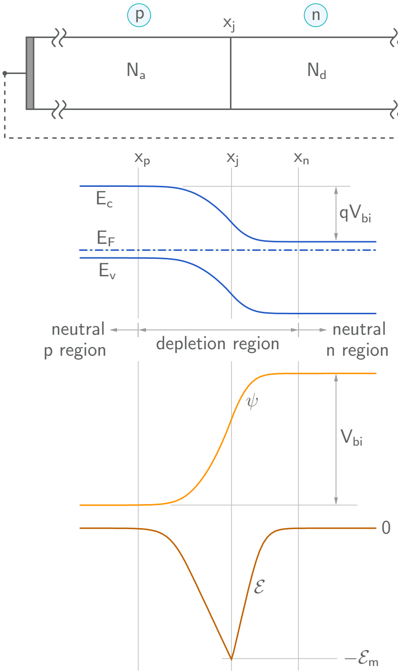
* Note that $\psi = -\dfrac{1}{q}\dfrac{dE_c}{dx}$, and $\mathcal{E} = -\dfrac{d\psi}{dx}$.



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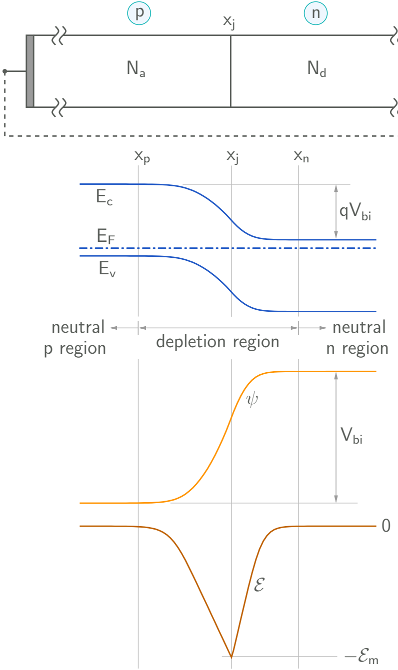
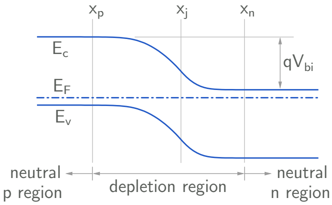
* Let us check if this picture is consistent with Poisson's equation.



pn junction in equilibrium



pn junction in equilibrium

Charge density:

$$p(x) = N_v \, \exp - \left(\frac{E_F - E_v(x)}{kT} \right),$$

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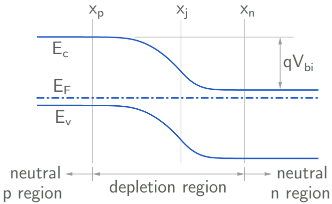

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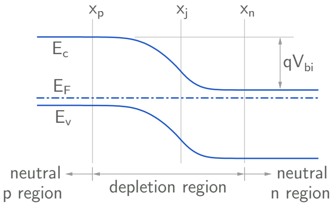

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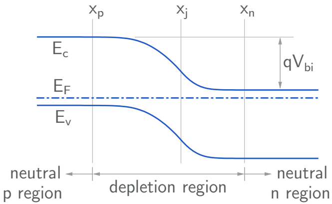
pn junction in equilibrium



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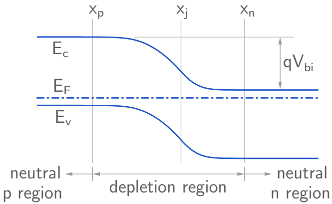

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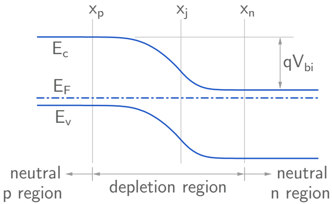

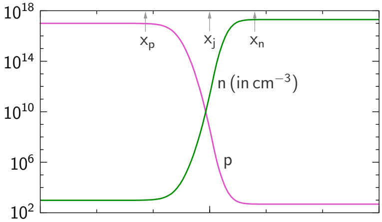

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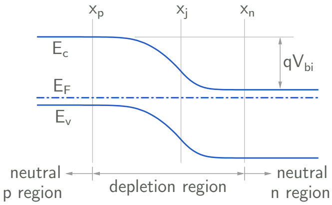

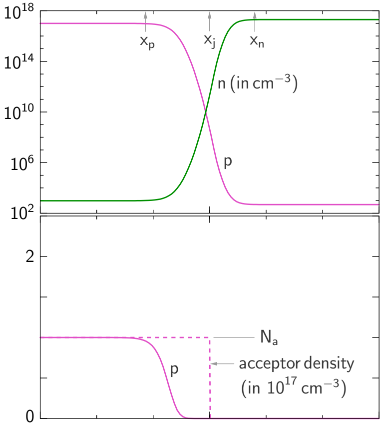

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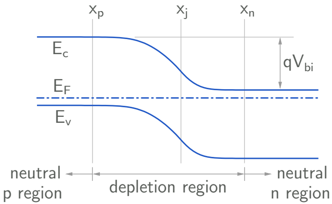

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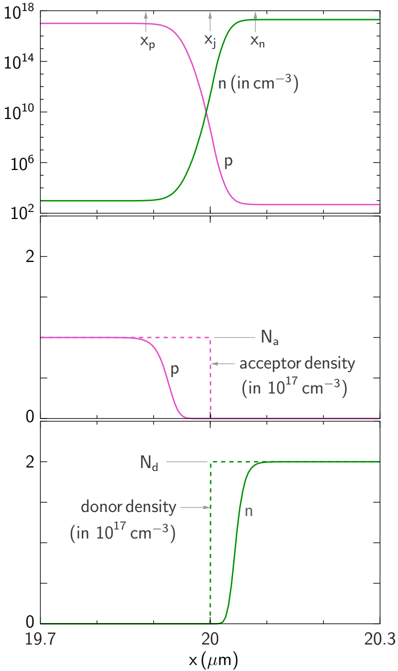

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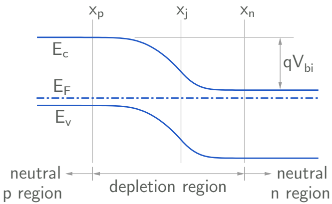

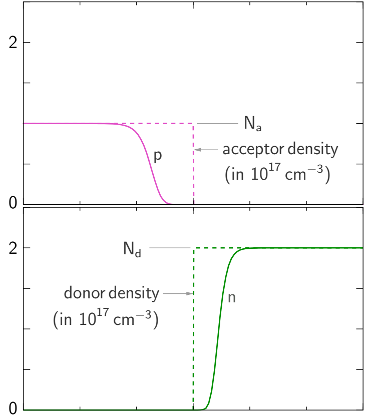

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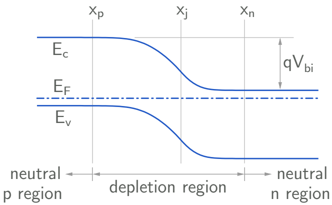
$$\rho(x) = q\left[N_d^+(x) + p(x) - N_a^-(x) - n(x)\right]$$
$$\approx q\left[(N_d(x) - n(x)) - (N_a(x) - p(x))\right].$$

pn junction in equilibrium



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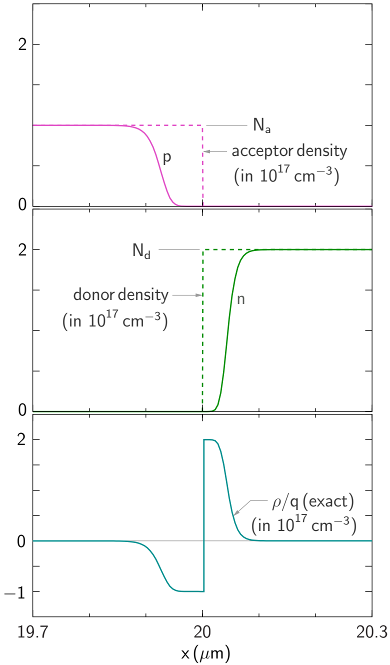

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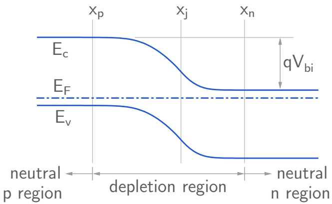

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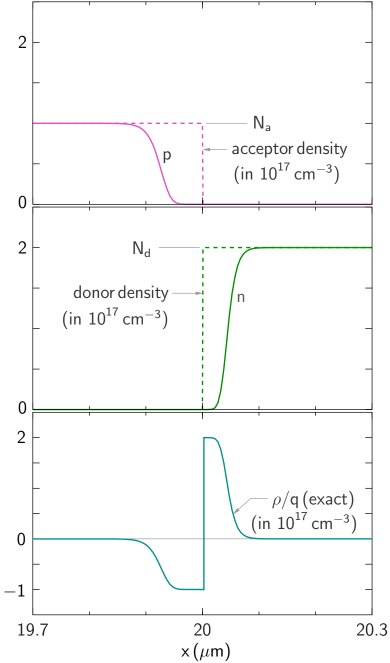

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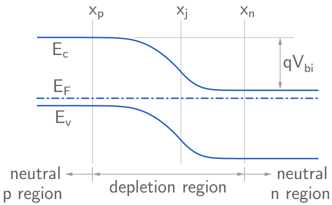

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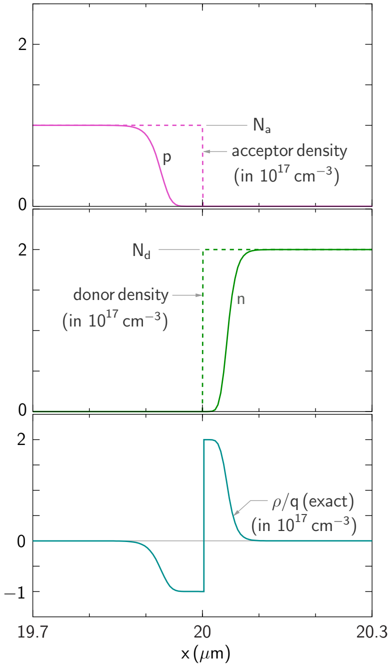

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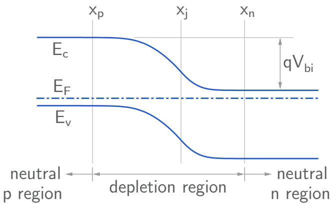

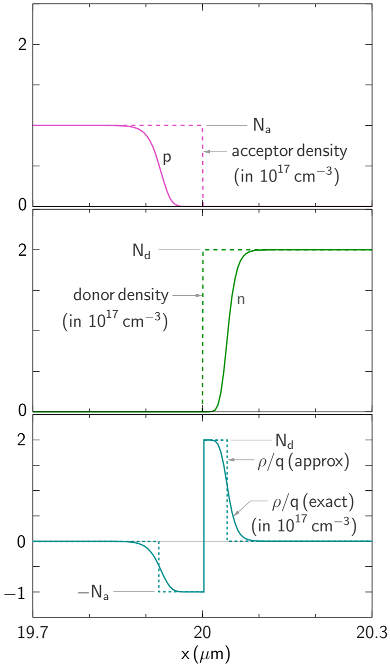

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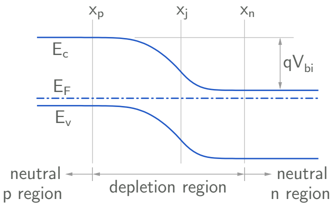

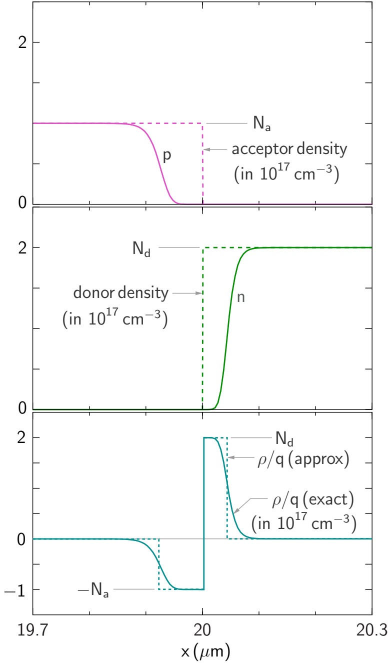

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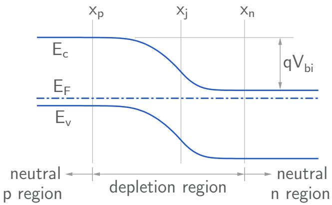
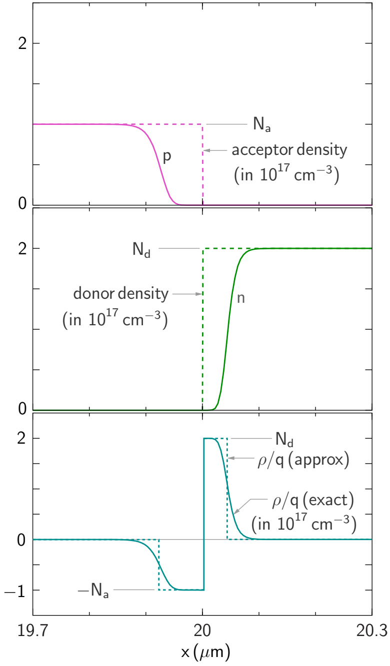
pn junction in equilibrium





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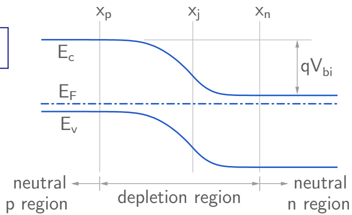
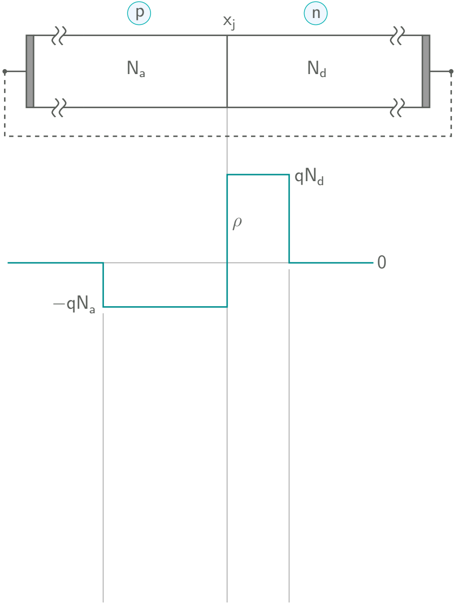
* Since the depletion region has non-zero charge density, it is also called "space charge region."

pn junction in equilibrium





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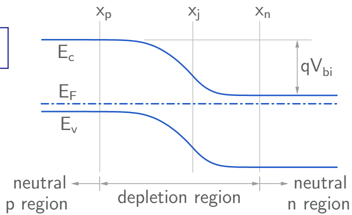

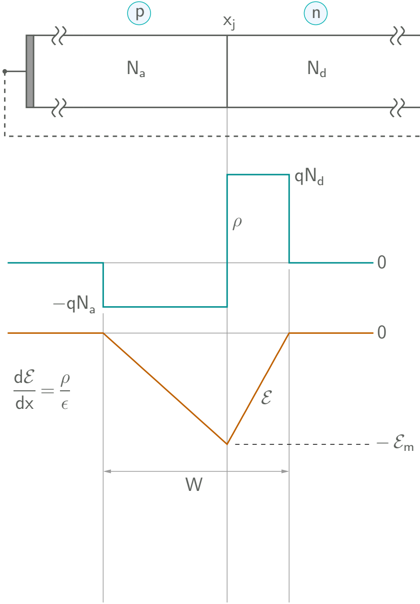

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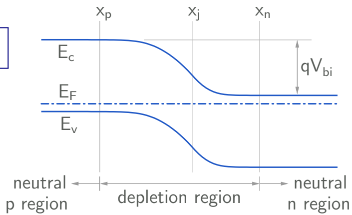

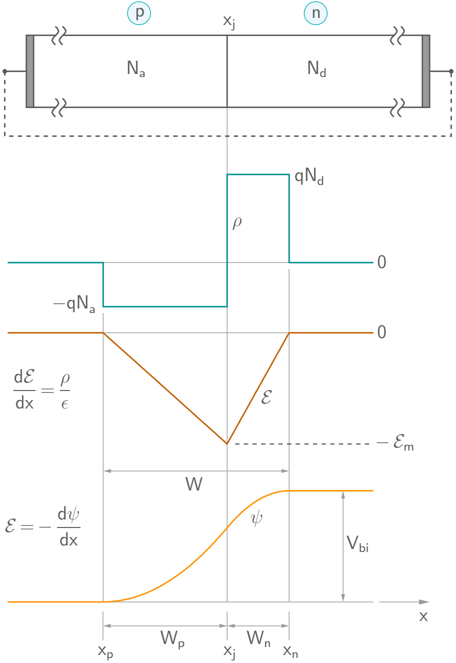

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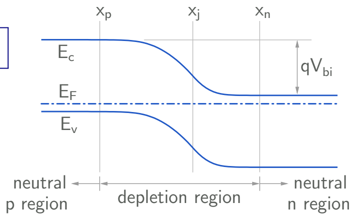
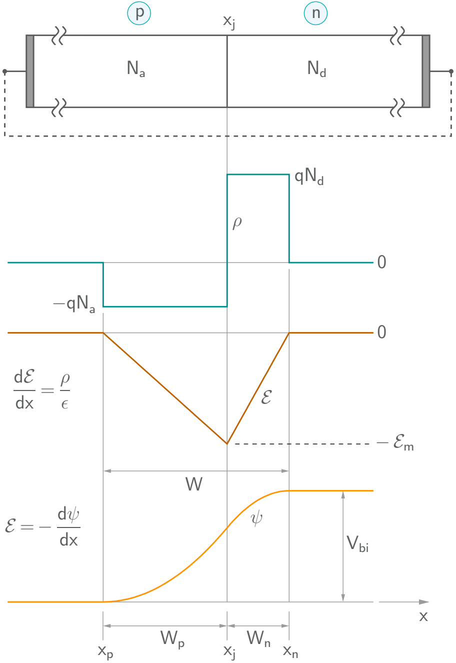
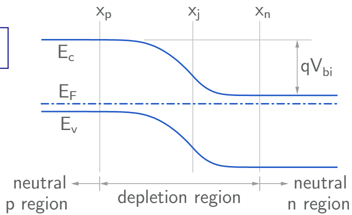
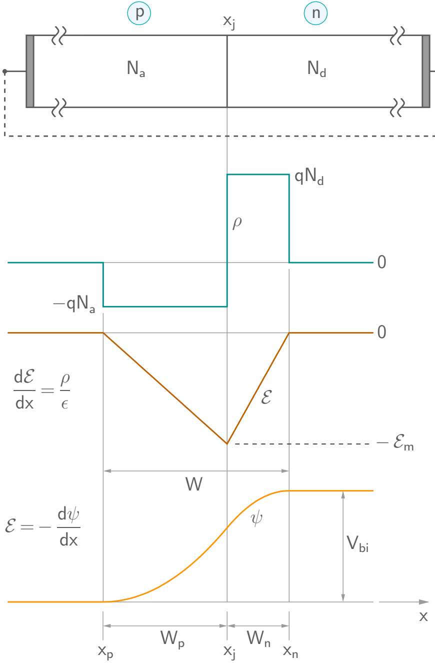




* Built-in voltage V_{bi}:

pn junction in equilibrium



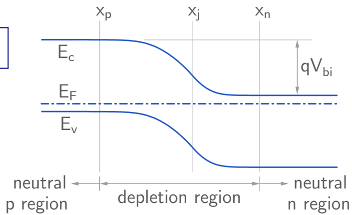


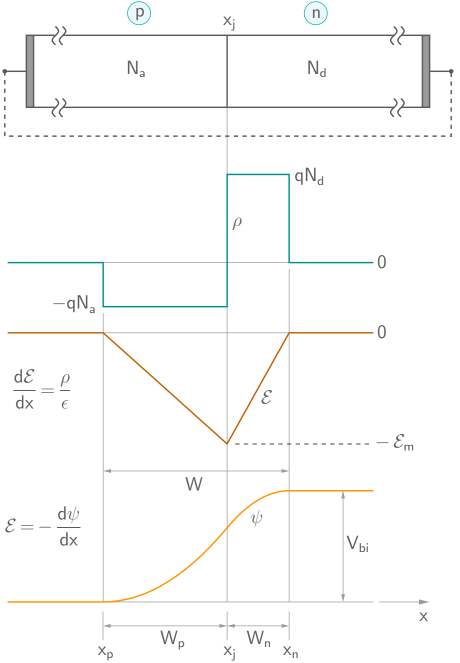
* Built-in voltage V_{bi}:

$$p(x) = N_v \, \exp\left[-\frac{E_F - E_v(x)}{kT}\right], \;\; n(x) = N_c \, \exp\left[-\frac{E_c(x) - E_F}{kT}\right].$$

$$\rightarrow \frac{p(x_n)}{p(x_p)} = \exp\left[-\frac{E_v(x_p) - E_v(x_n)}{kT}\right].$$

pn junction in equilibrium





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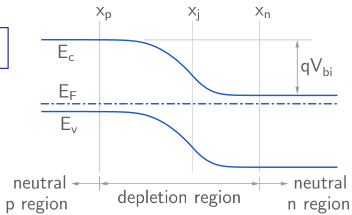
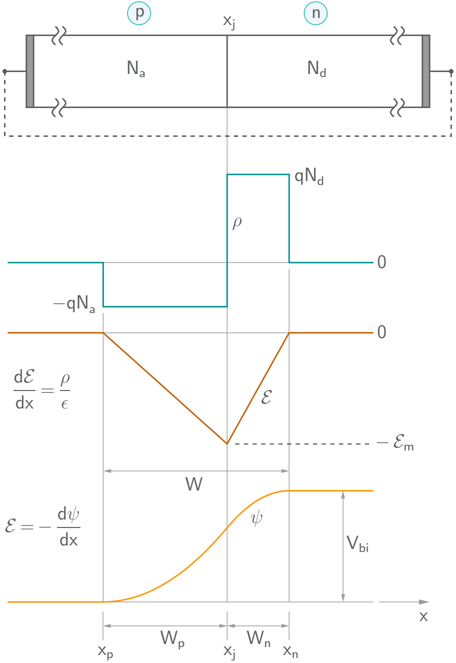
$$\rightarrow \frac{p(x_n)}{p(x_p)} = \exp\left[-\frac{E_v(x_p) - E_v(x_n)}{kT}\right].$$

$$\rightarrow \frac{p(x_n)n(x_n)}{p(x_p)n(x_n)} = \frac{n_i^2}{N_a N_d} = \exp\left(-\frac{qV_{\rm bi}}{kT}\right).$$

pn junction in equilibrium





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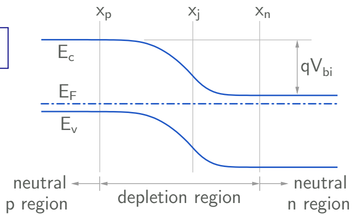
The built-in voltage V_{bi} is therefore given by

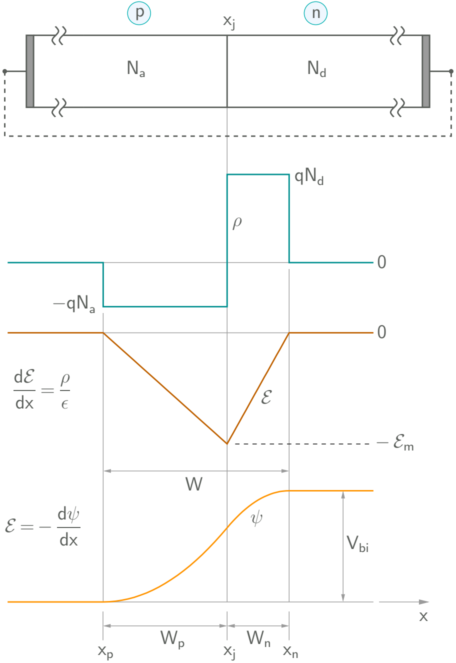
$$\boxed{V_{\text{bi}} = \frac{kT}{q} \log\left(\frac{N_a N_d}{n_i^2}\right)}$$

pn junction in equilibrium

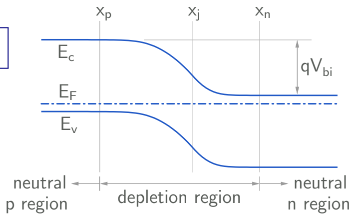


Example:

For a silicon *pn* junction with $N_a = 5 \times 10^{17}\,\text{cm}^{-3}$, $N_d = 10^{17}\,\text{cm}^{-3}$, compute V_{bi} at $T = 300\,\text{K}$. ($n_i = 1.5 \times 10^{10}\,\text{cm}^{-3}$ at 300 K.)



pn junction in equilibrium



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Solution:

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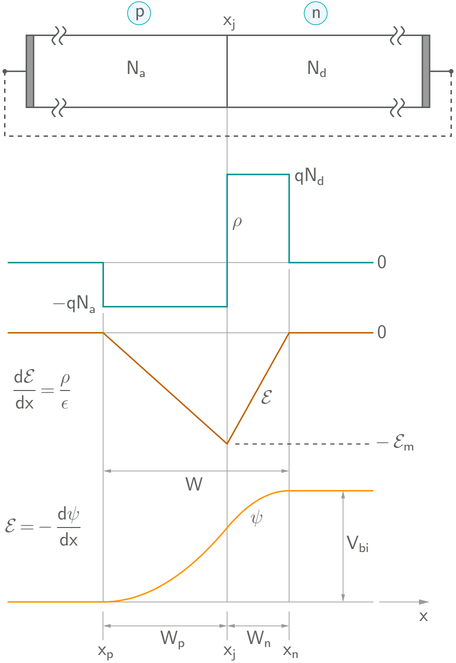
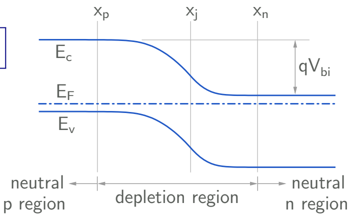
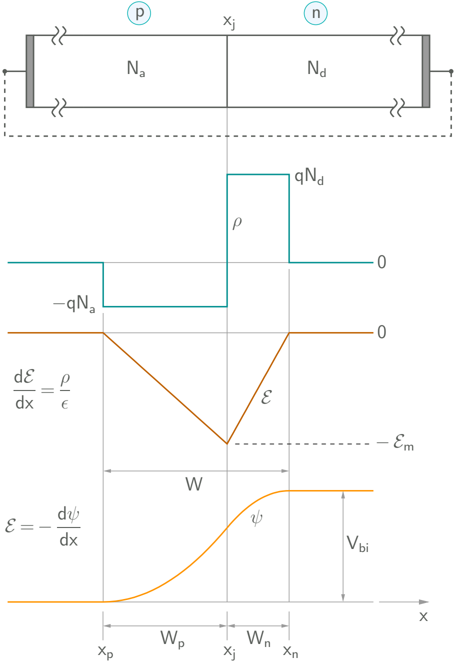


pn junction in equilibrium





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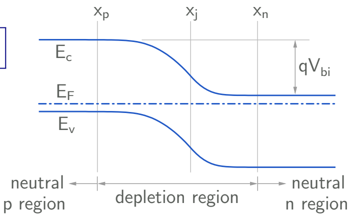
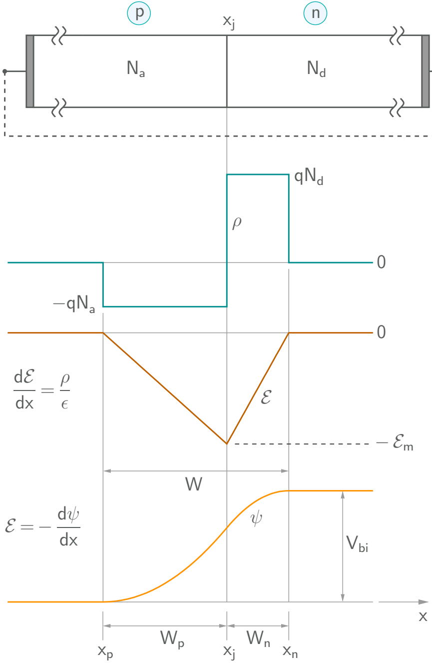
Solution:

$$V_{\text{bi}} = \frac{kT}{q}\log\frac{N_a N_d}{n_i^2}$$

$$= (0.0259\,\text{V})\log\frac{(5 \times 10^{17})(10^{17})}{(1.5 \times 10^{10})^2}$$

pn junction in equilibrium





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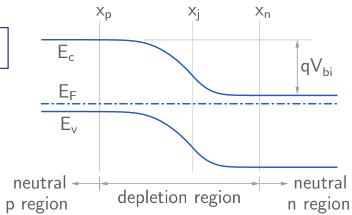
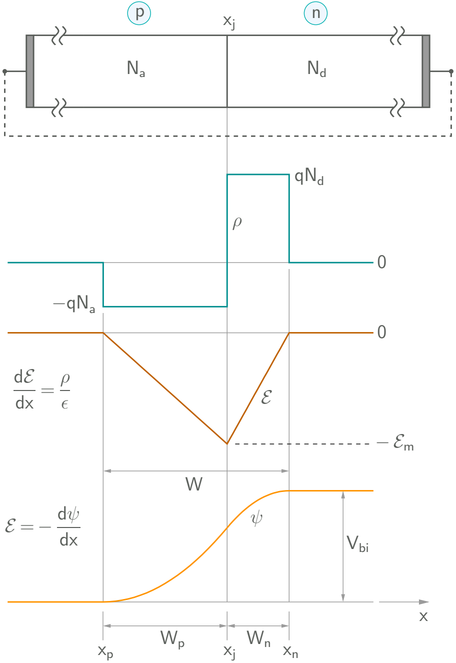
$$= 0.86\,\text{V}$$

pn junction in equilibrium



Electric field $\mathcal{E}(x)$:



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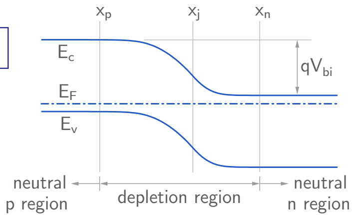

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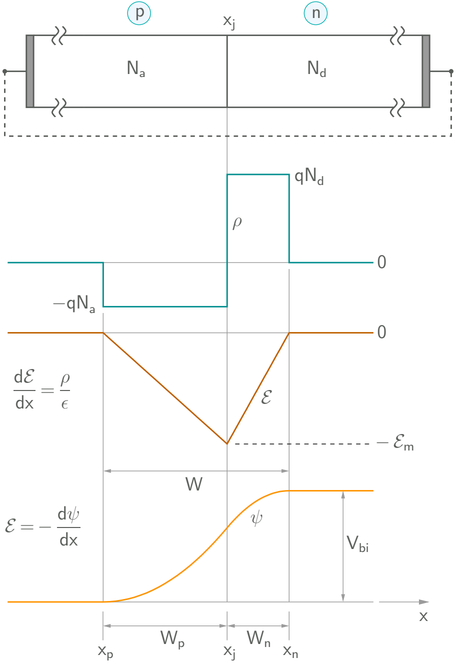

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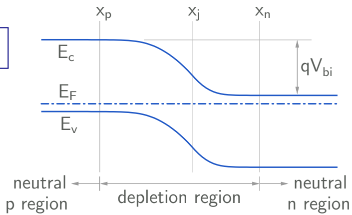

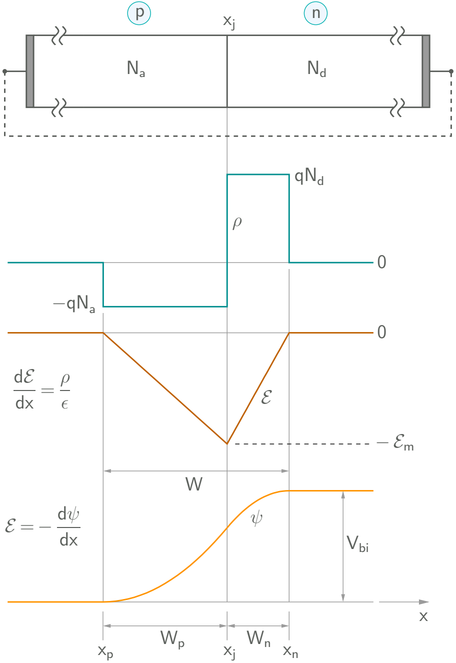

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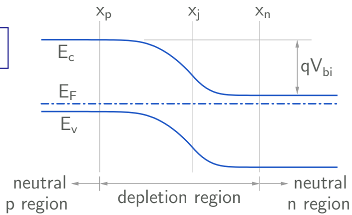
pn junction in equilibrium



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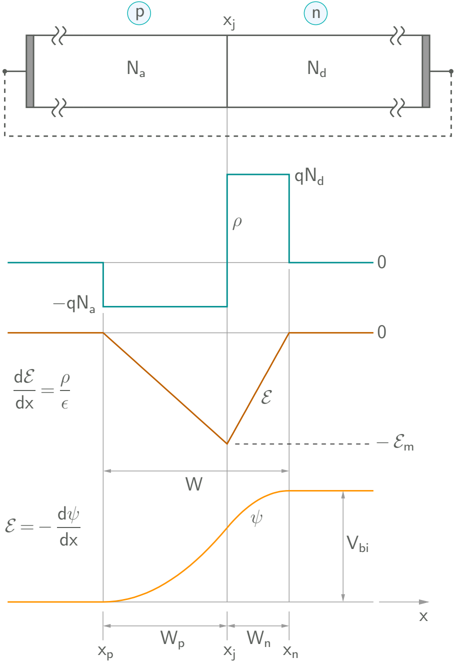
  Since $\mathcal{E}(x_p) = \mathcal{E}(x_n) = 0$, we must have $\displaystyle\int_{x_p}^{x_n} \frac{\rho}{\epsilon}\, dx = 0$,

  which means the area under the ρ versus x curve must be zero.



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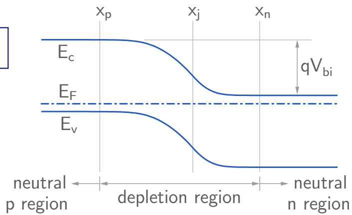

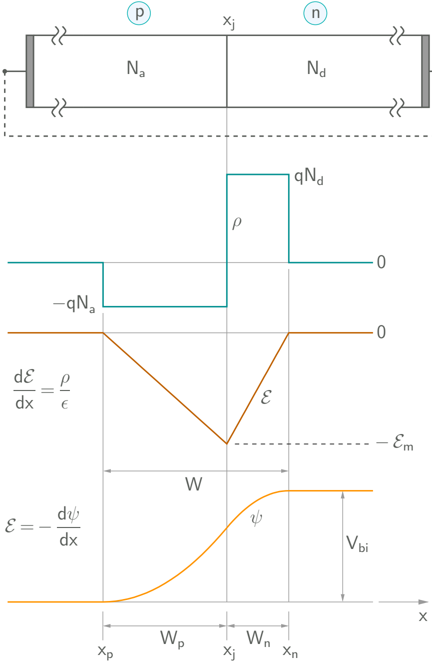

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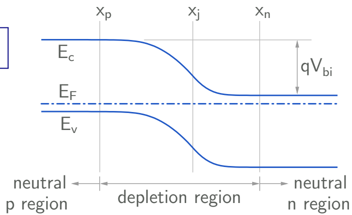
  which means the area under the ρ versus x curve must be zero.

  i.e., $N_a W_p = N_d W_n \rightarrow \dfrac{W_p}{W_n} = \dfrac{N_d}{N_a}$.

  $\rightarrow$ The depletion width is larger on the lightly doped side.

pn junction in equilibrium



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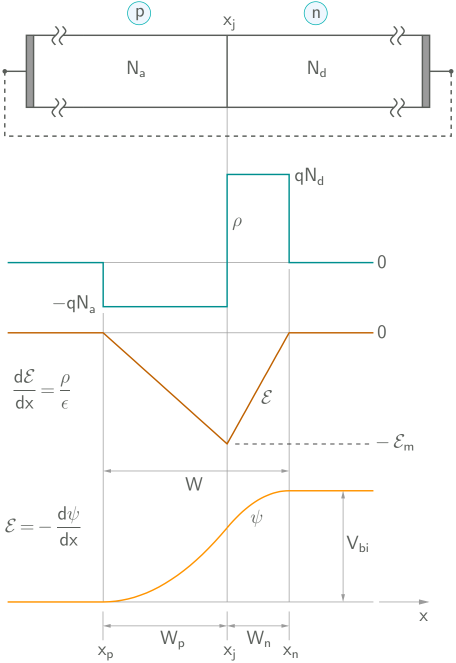

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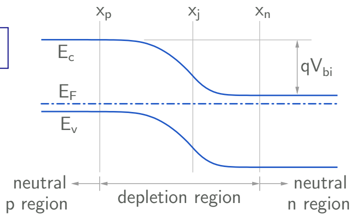
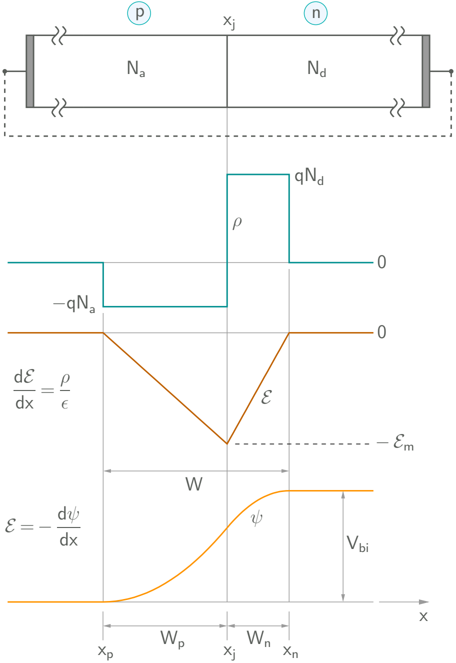
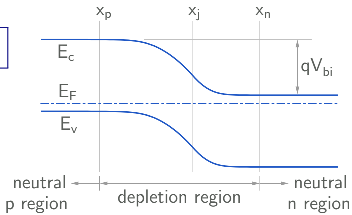




Electric field $\mathcal{E}(x)$:

- Since ρ is piecewise constant, $\mathcal{E}$ must be piecewise linear.

pn junction in equilibrium

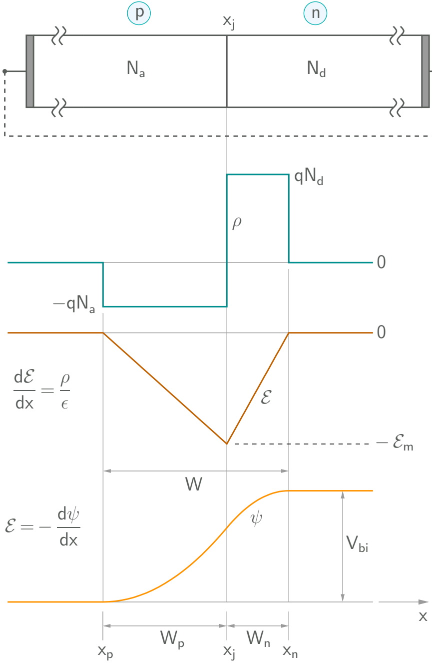


Electric field $\mathcal{E}(x)$:

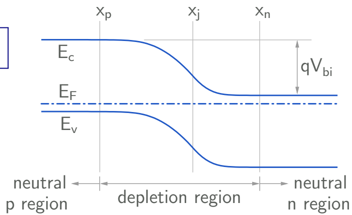
* Since ρ is piecewise constant, $\mathcal{E}$ must be piecewise linear.
* The maximum value (magnitude) of $\mathcal{E}$ occurs at $x = x_j$.

$$\int_{x_p}^{x_j} d\mathcal{E} = \frac{1}{\epsilon}\int_{x_p}^{x_j} \rho dx \rightarrow -\mathcal{E}_m - 0 = \frac{1}{\epsilon}(-qN_a W_p)$$

$$\rightarrow \mathcal{E}_m = \frac{qN_a W_p}{\epsilon} = \frac{qN_d W_n}{\epsilon} \quad \because N_a W_p = N_d W_n.$$



pn junction in equilibrium



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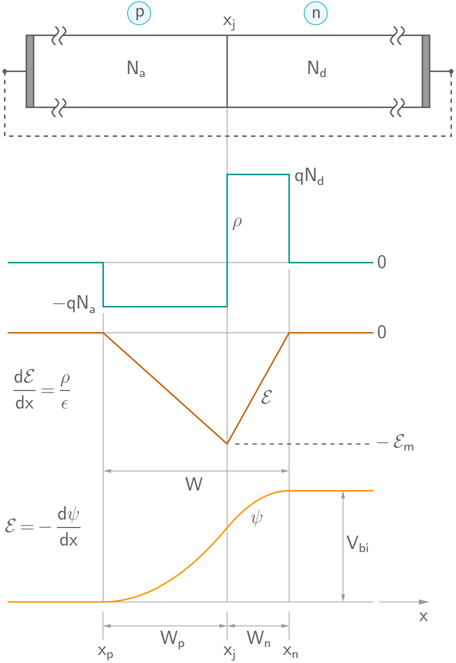

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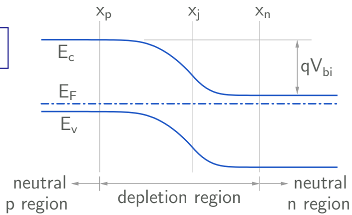

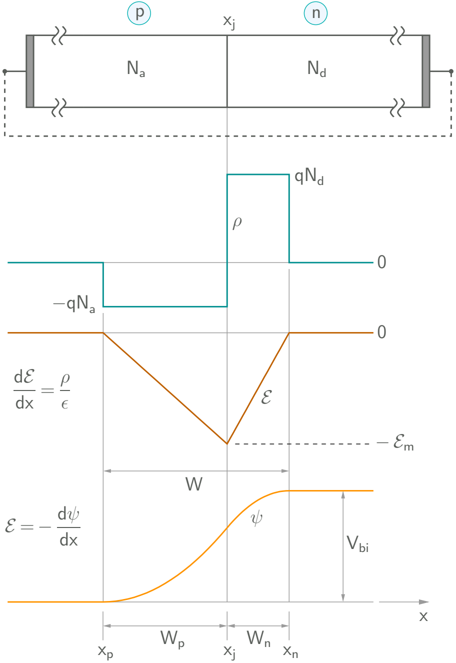

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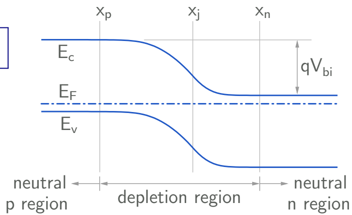

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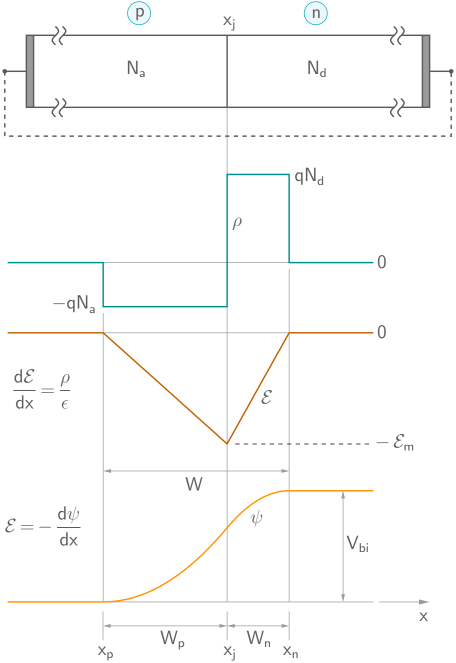

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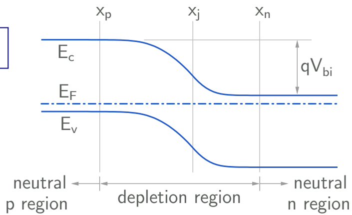

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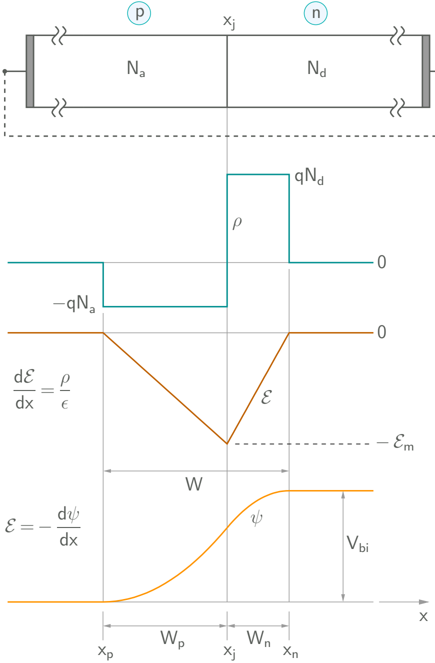

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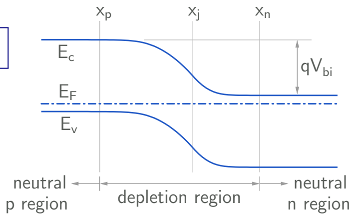

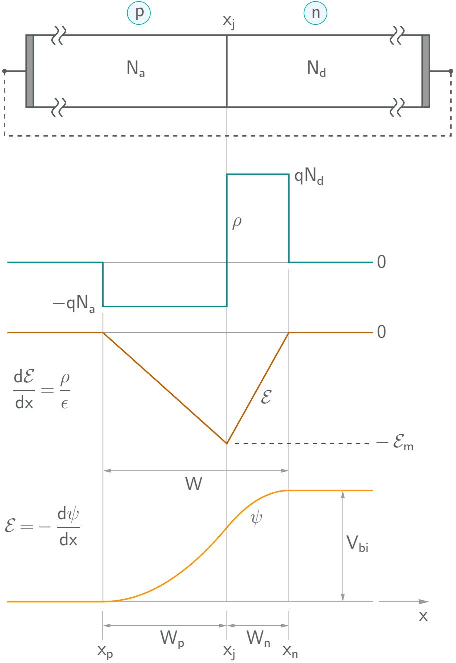

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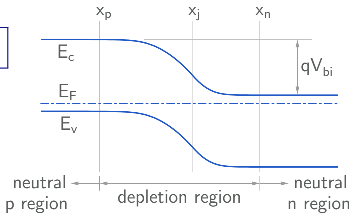
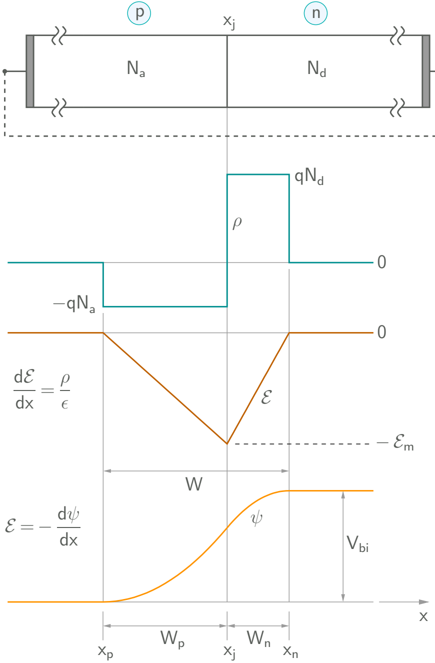
pn junction in equilibrium





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  If x_j is taken as 0, i.e., $x \leftarrow (x-x_j)$, we get

  $$\psi(x) = \frac{qN_a}{2\epsilon}(x+W_p)^2.$$

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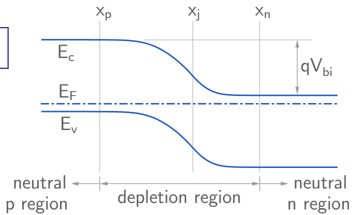
pn junction in equilibrium



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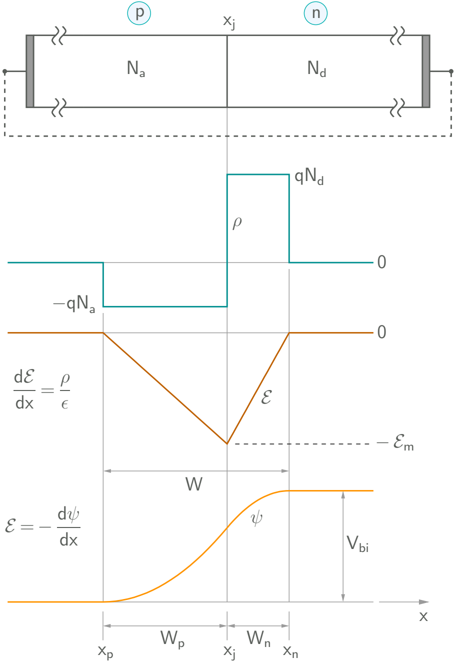

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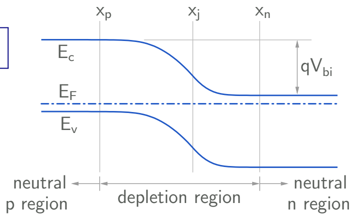

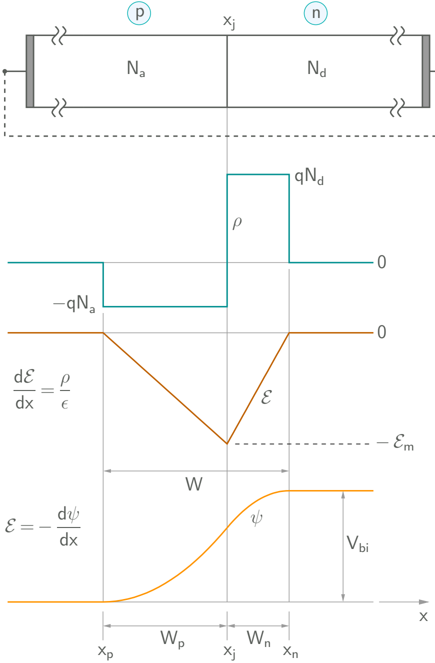

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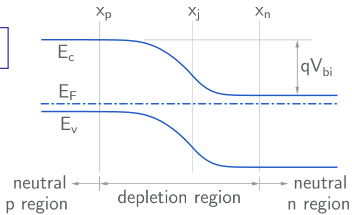

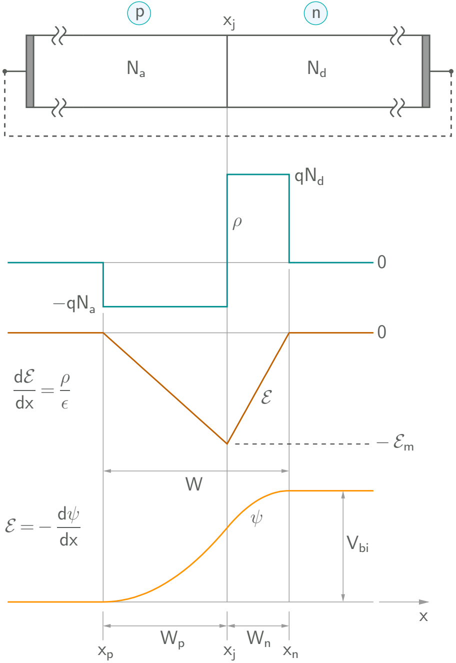

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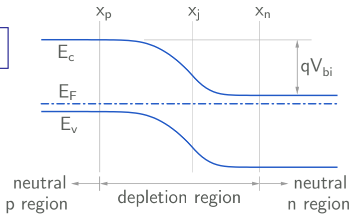
pn junction in equilibrium



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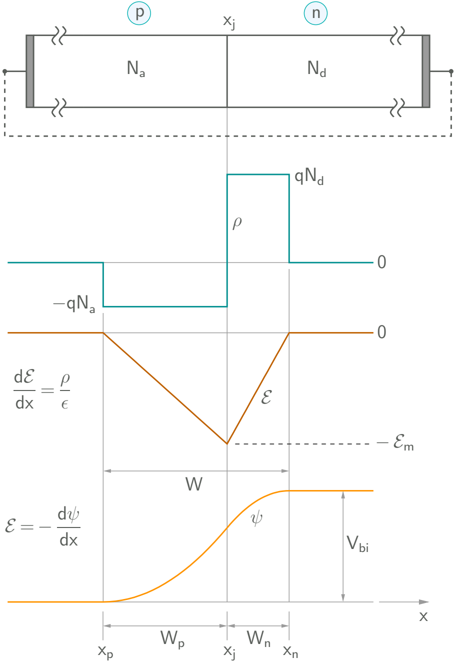

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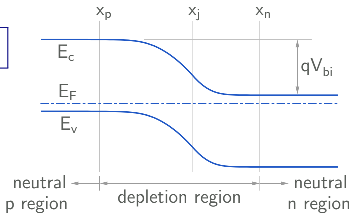

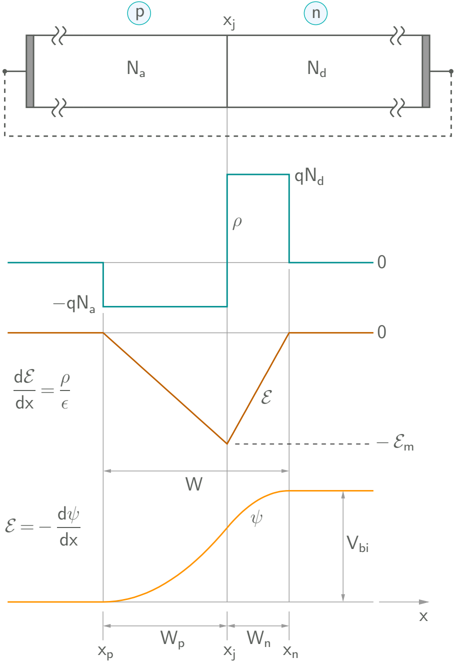

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We can find k_4 using continuity of ψ at $x = 0$.

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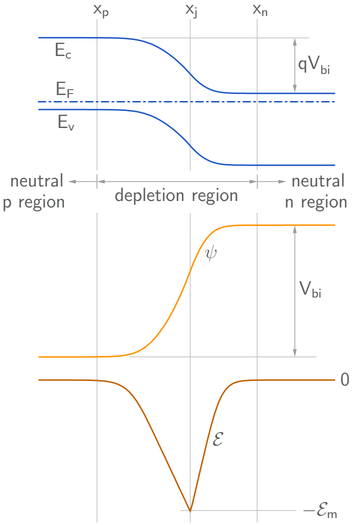
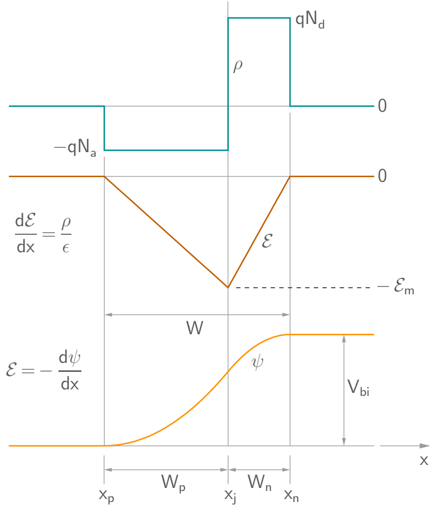
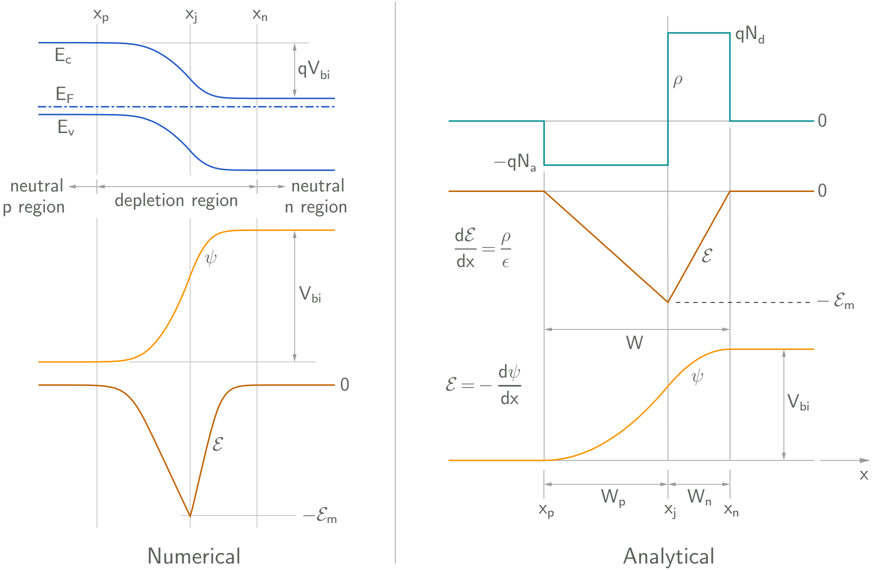


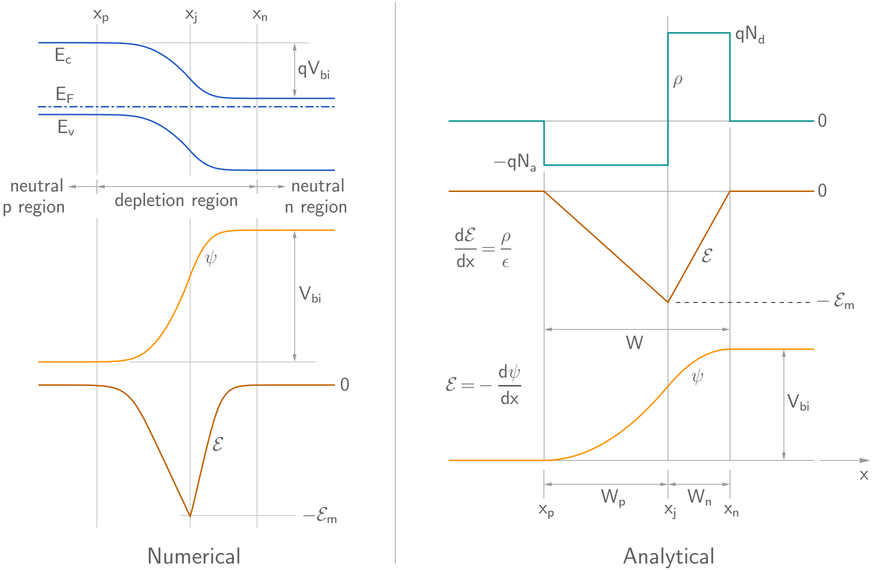
Numerical



Analytical

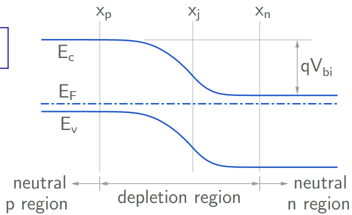


* *pn* junction in equilibrium: The band diagram is consistent with Poisson's equation.



* *pn* junction in equilibrium: Depletion approximation agrees well with numerical results.

pn junction in equilibrium



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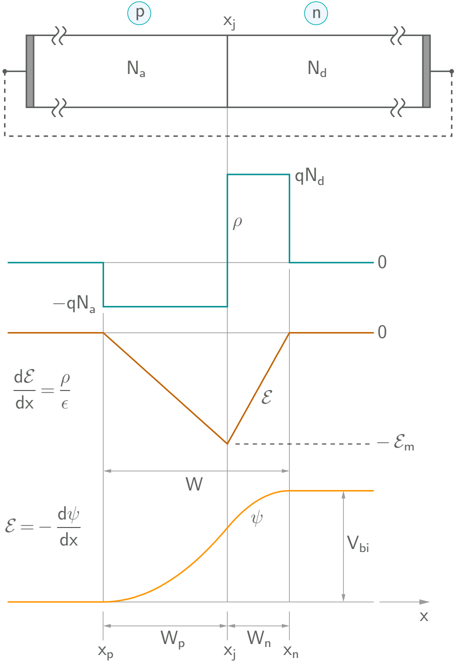

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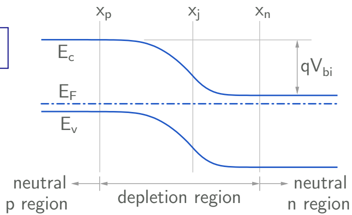

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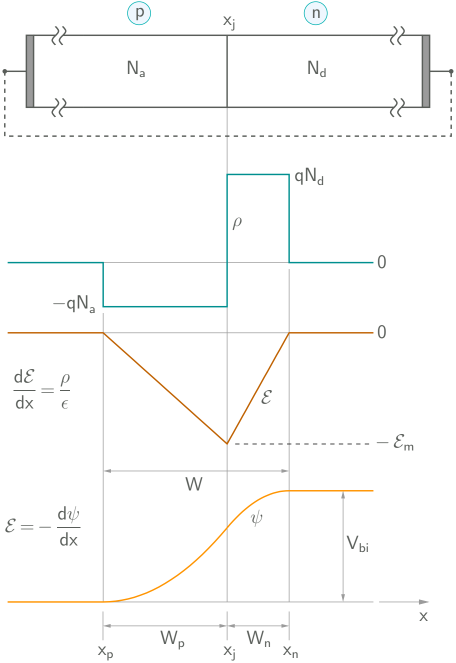

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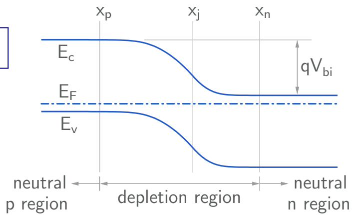

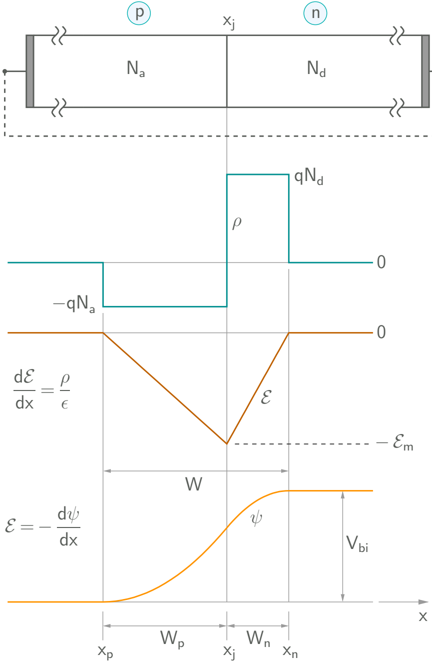

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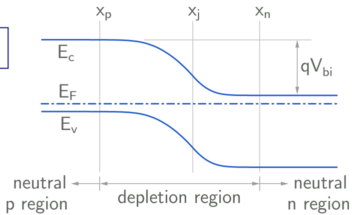

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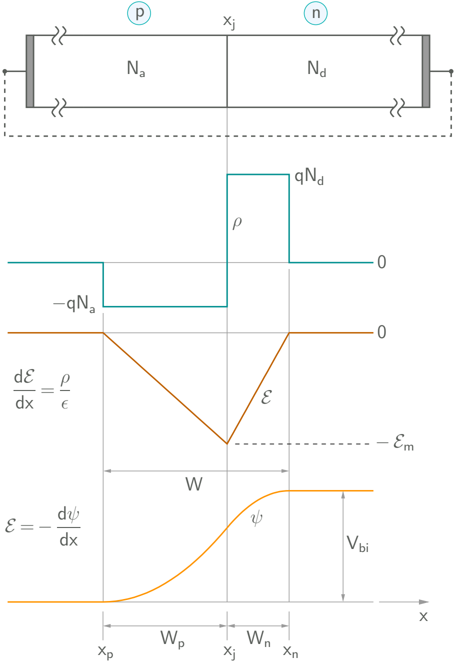

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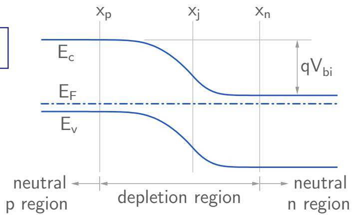

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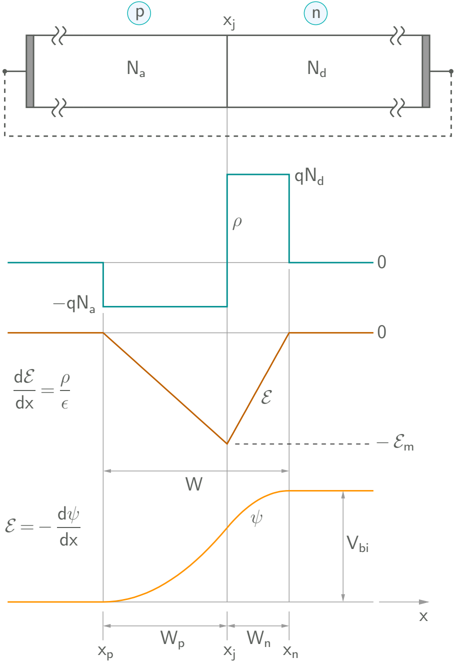
$$\rightarrow V_{bi} = \frac{1}{2}\,\frac{q}{\epsilon}\,\frac{N_aN_d}{N_a+N_d}\,W^2, \quad \text{i.e., } W = \sqrt{\frac{2\epsilon}{q}\left(\frac{N_a+N_d}{N_aN_d}\right)V_{bi}}.$$



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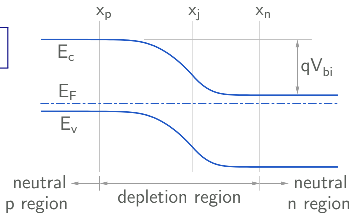
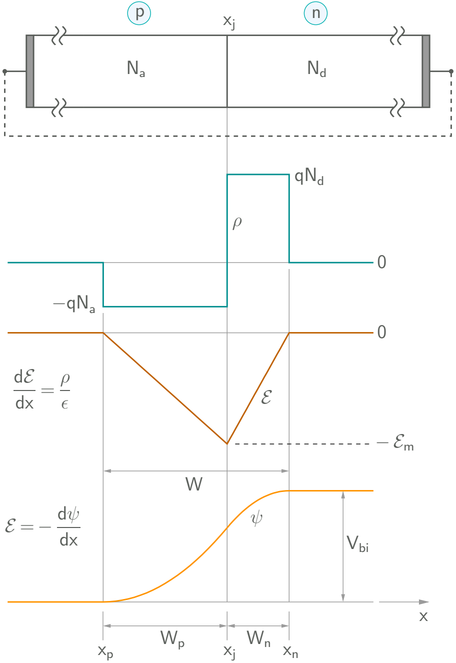


For an abrupt, uniformly doped silicon *pn* junction, $N_a = 5 \times 10^{17}\,\text{cm}^{-3}$. Compute $V_{\rm bi}$, W, W_n, W_p, and $\mathcal{E}_m$ for $N_d = 10^{16}$, 10^{17}, 5×10^{17}, 10^{18}, and $5 \times 10^{18}\,\text{cm}^{-3}$ ($T = 300\,\text{K}$).



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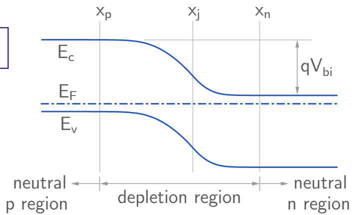

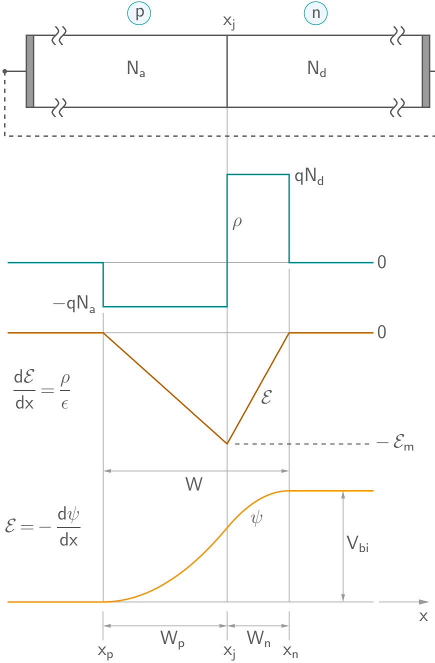

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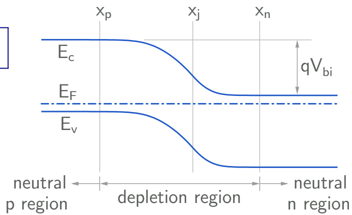
Solution:

$$V_{\text{bi}} = V_T \log \frac{N_a N_d}{n_i^2}$$

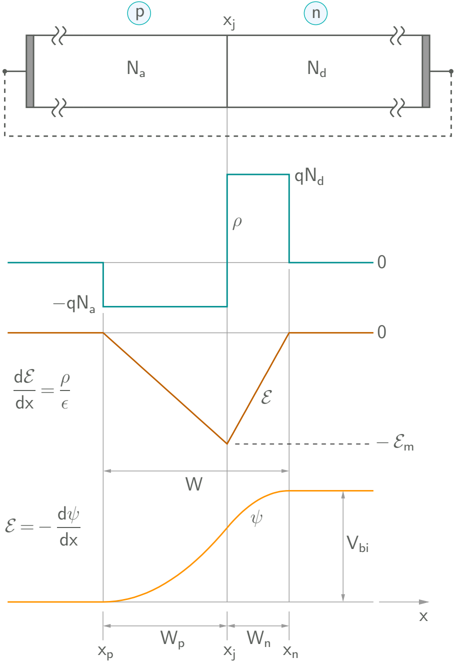
$$= 0.0259\,\text{V} \times \log \frac{(5 \times 10^{17})(1 \times 10^{16})}{(1.5 \times 10^{10})^2}$$

$$= 0.8\,\text{V}.$$

pn junction in equilibrium



$$W = \sqrt{\frac{2\epsilon_r\epsilon_0}{q}\left(\frac{N_a+N_d}{N_aN_d}\right)V_{bi}}$$



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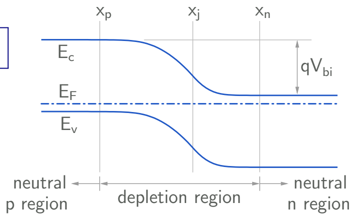

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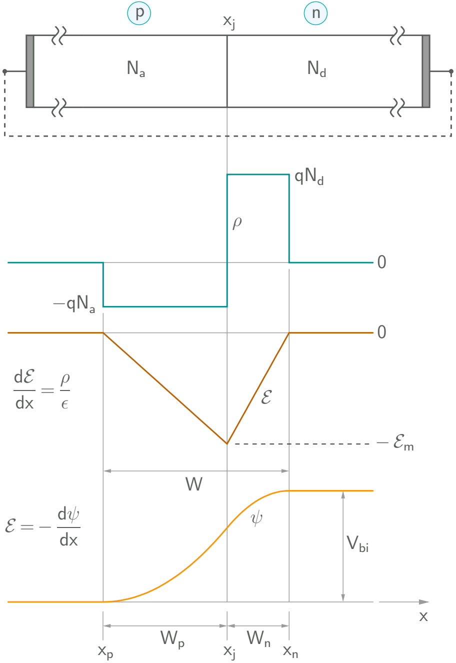

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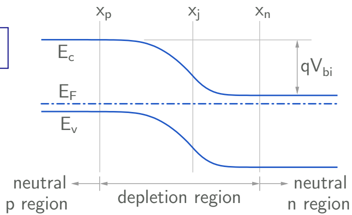

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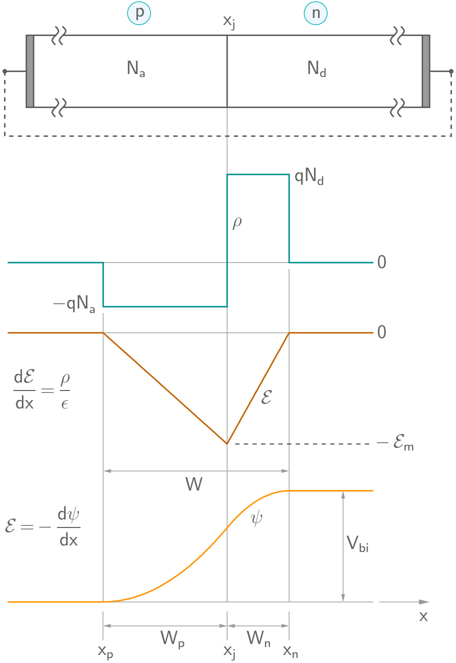
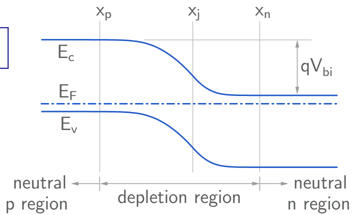
$$= 3.24\times 10^{-5}\,\text{cm}$$



pn junction in equilibrium

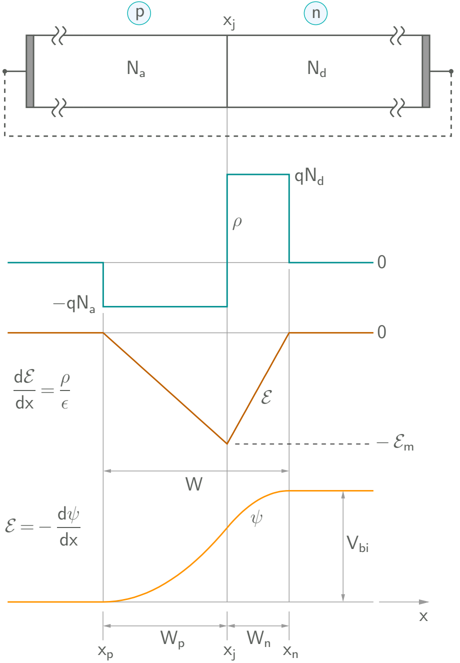


$$W = \sqrt{\frac{2\epsilon_r\epsilon_0}{q}\left(\frac{N_a+N_d}{N_aN_d}\right)V_{\text{bi}}}$$

$$= \sqrt{\frac{2\times 11.7\times 8.85\times 10^{-14}}{1.6\times 10^{-19}}\left(\frac{5\times 10^{17}+1\times 10^{16}}{(5\times 10^{17})(1\times 10^{16})}\right)(0.8)}$$

$$= 3.24\times 10^{-5}\ \text{cm}$$

$$= 0.324\ \mu\text{m}.$$



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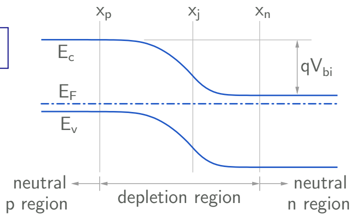
pn junction in equilibrium



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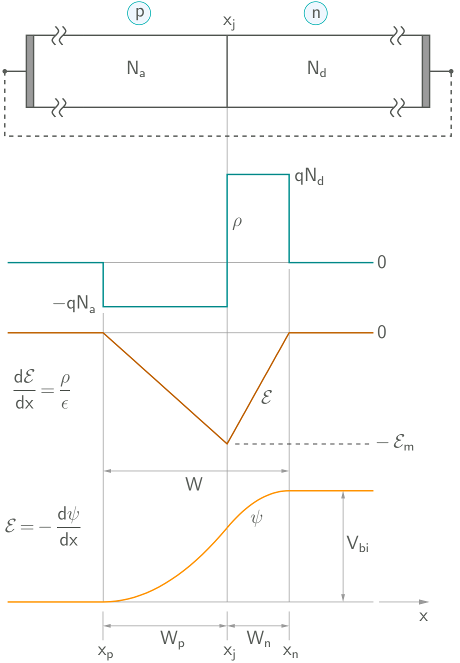
$$\text{Units:}\ \sqrt{\frac{\text{F/cm}}{\text{Coul}}\times\frac{\text{cm}^{-3}}{\text{cm}^{-6}}\times \text{V}} = \text{cm}$$



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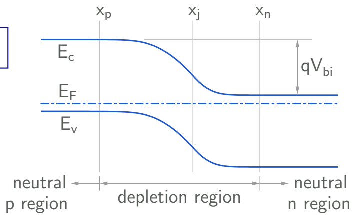
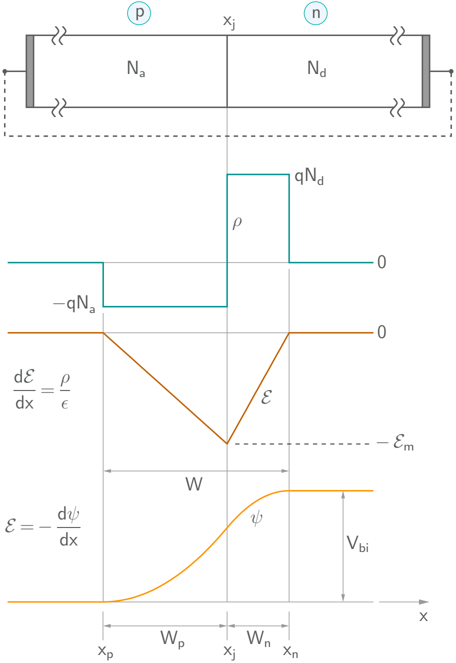


$$W_n = \frac{N_a}{N_a + N_d}\, W = 0.318\,\mu\text{m}, \quad W_p = \frac{N_d}{N_a + N_d}\, W = 0.006\,\mu\text{m}.$$



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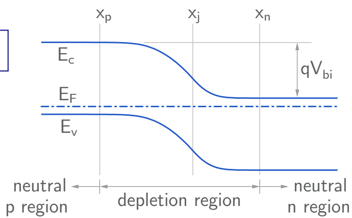

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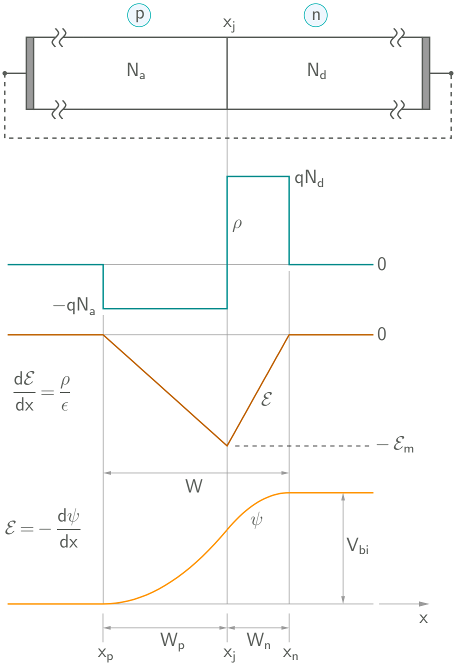

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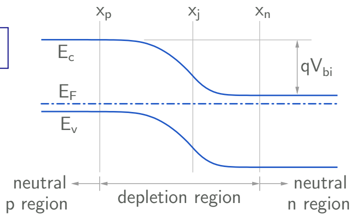

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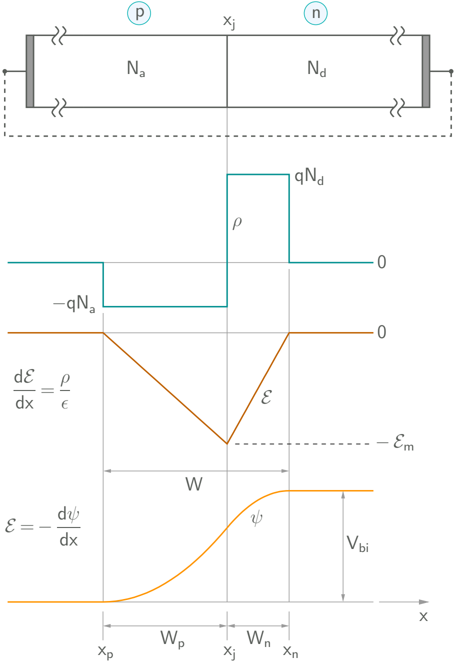
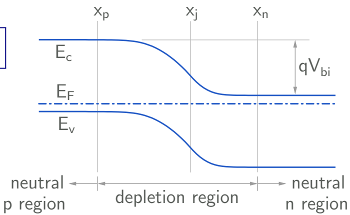


pn junction in equilibrium



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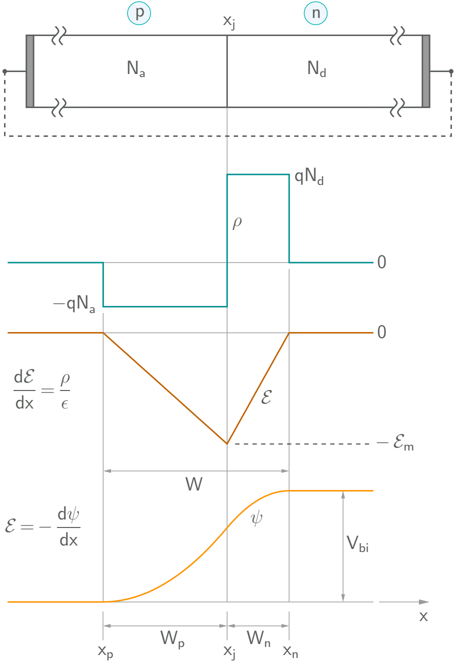

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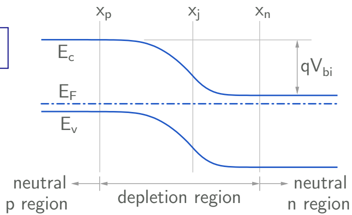

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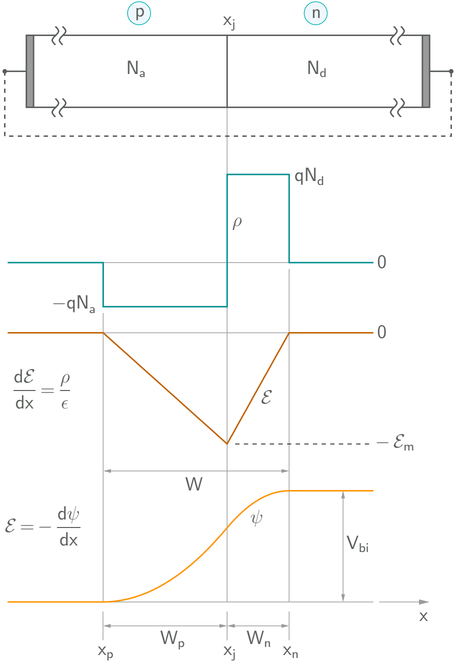
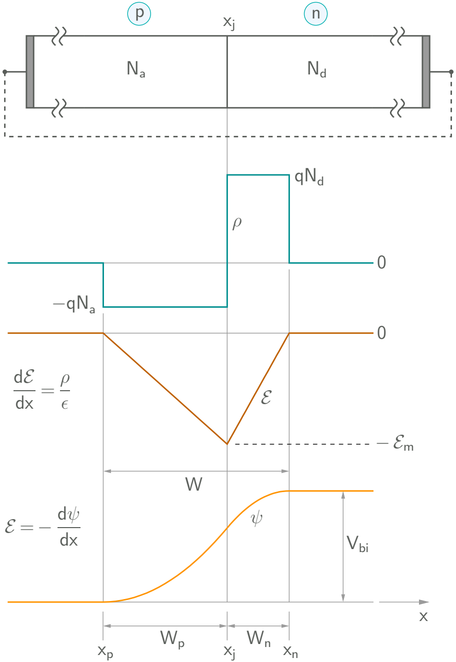
$$= 49\,\text{kV/cm}.$$



Effect of N_d, with $N_a = 5 \times 10^{17}\ \text{cm}^{-3}$ held fixed.
(V_{bi} in Volts, W, W_n, W_p in μm, $\mathcal{E}_m$ in kV/cm.)

N_d (cm^{-3})	V_{bi}	W	W_n	W_p	$\mathcal{E}_m$
1.0×10^{16}	0.80	0.324	0.318	0.006	49
1.0×10^{17}	0.86	0.115	0.096	0.019	148
5.0×10^{17}	0.90	0.068	0.034	0.034	263
1.0×10^{18}	0.92	0.060	0.020	0.040	307
5.0×10^{18}	0.96	0.052	0.004	0.047	366



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$$* \quad V_{\text{bi}} = V_T \log \frac{N_a N_d}{n_i^2}, \quad W = \sqrt{\frac{2\epsilon}{q}\left(\frac{N_a + N_d}{N_a N_d}\right) V_{\text{bi}}},$$

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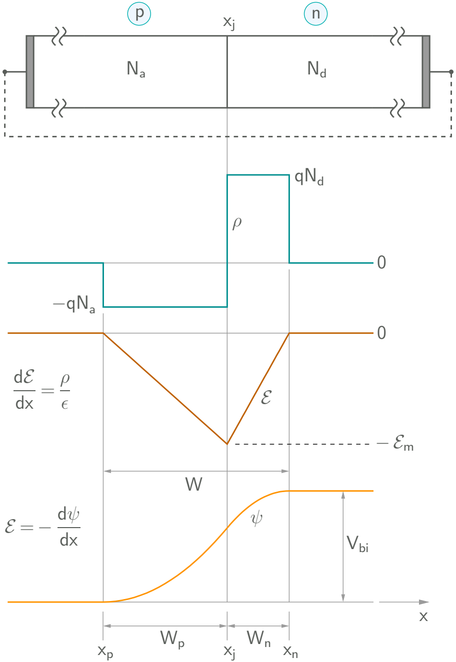

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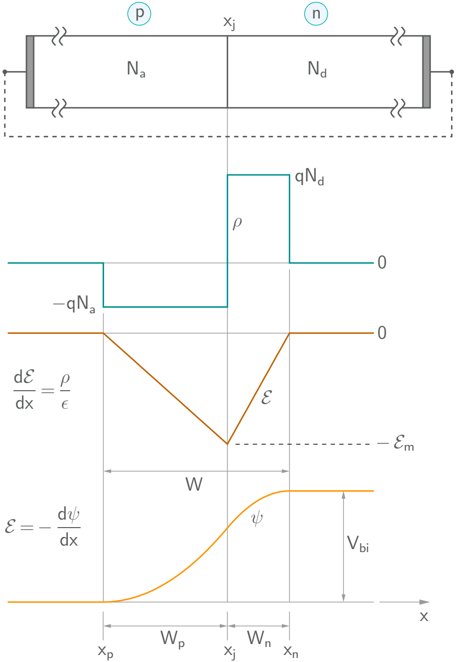
$N_d \ll N_a$ ($p^+ n$ junction):

$W_n \approx W$, and W is determined mainly by N_d.



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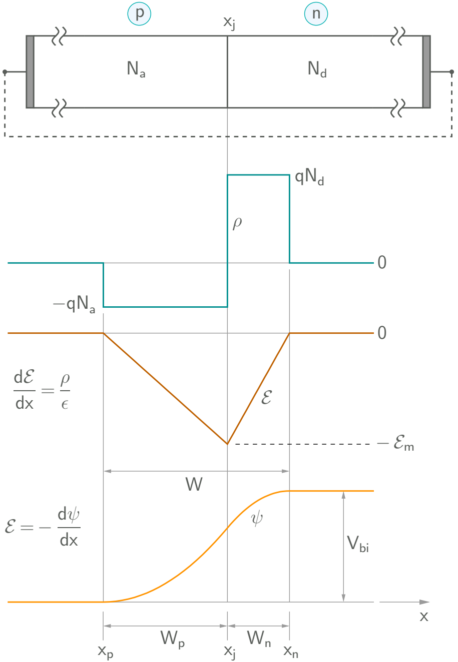

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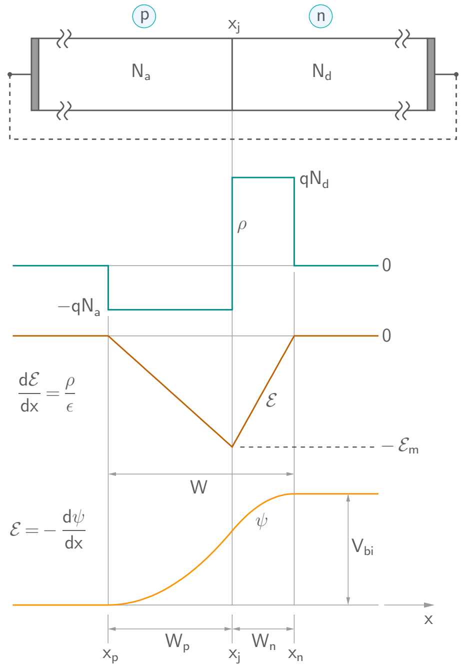

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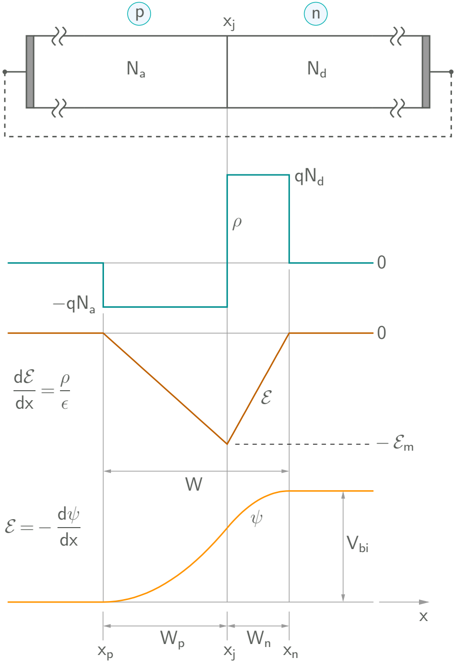
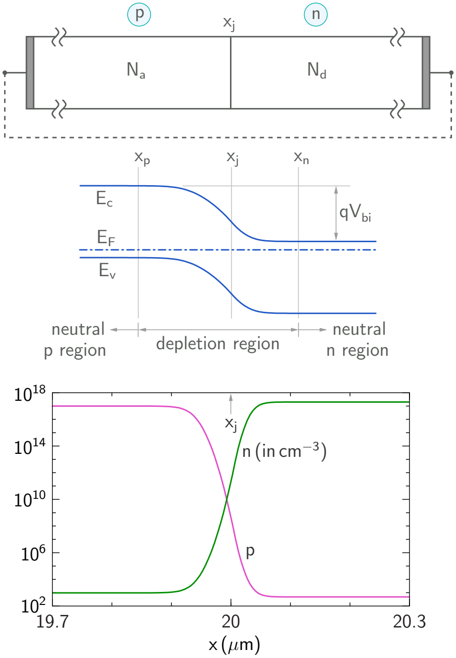
* For high doping densities such as $10^{18}\,\text{cm}^{-3}$, degenerate statistics should be used for higher accuracy, i.e.,

$$n = N_c \frac{2}{\sqrt{\pi}} \mathcal{F}_{1/2}(\eta_c), \text{ with } \eta_c = \frac{E_F - E_c}{kT}, \text{ and}$$

$$p = N_v \frac{2}{\sqrt{\pi}} \mathcal{F}_{1/2}(\eta_v), \text{ with } \eta_v = \frac{E_v - E_F}{kT}.$$

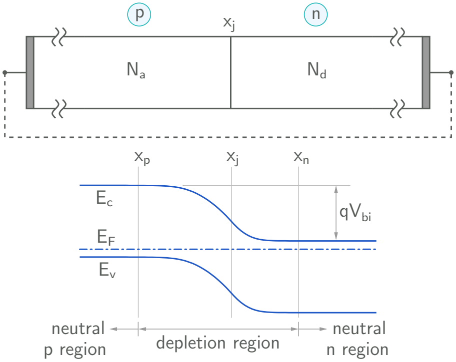


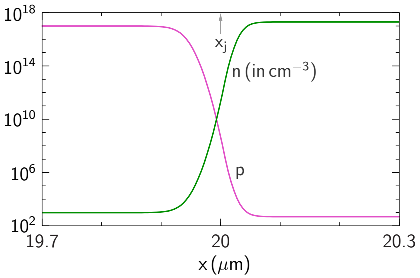
pn junction in equilibrium: current densities



pn junction in equilibrium: current densities

* The diffusion currents can be expected to be substantial since there is a large change in n or p between the p-side and the n-side.





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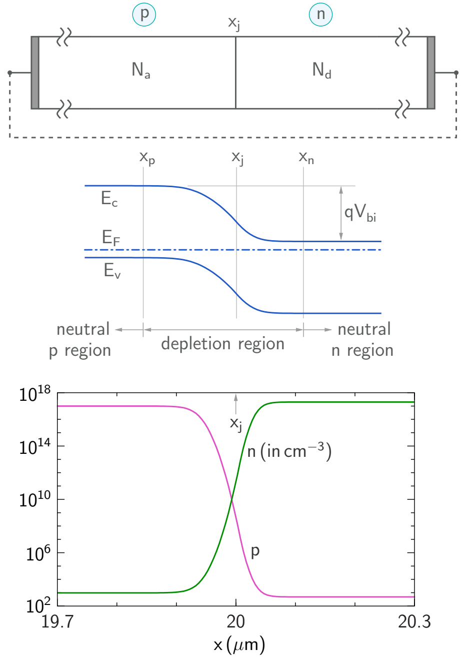

* The diffusion currents can be expected to be substantial since there is a large change in n or p between the p-side and the n-side.
* In equilibrium, the drift and diffusion currents are equal and opposite for eletrons as well as holes, i.e., $J_n^{\text{diff}} = -J_n^{\text{drift}}$, $J_p^{\text{diff}} = -J_p^{\text{drift}}$.

pn junction in equilibrium: current densities

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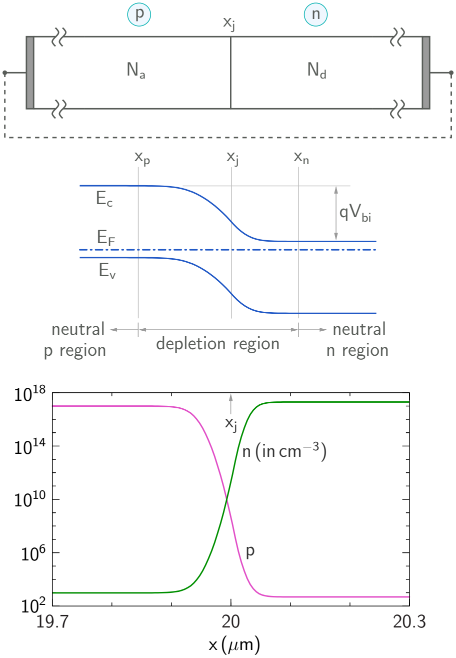
* Qualitatively, we can see that the diffusion and drift currents will be in opposite directions:



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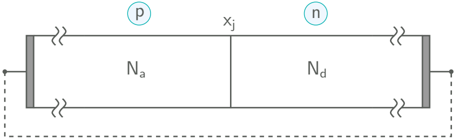

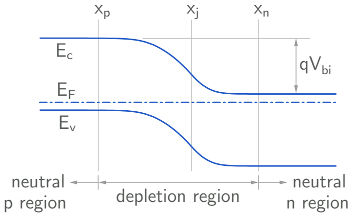

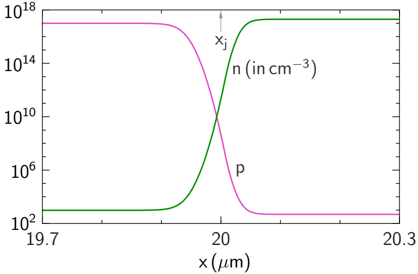

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  Electrons:

  $\mathcal{F}_n^{\text{diff}} : \longleftarrow\,, \ \mathcal{E} : \longleftarrow\,, \ \mathcal{F}_n^{\text{drift}} : \longrightarrow\,.$

pn junction in equilibrium: current densities

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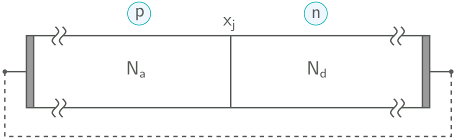
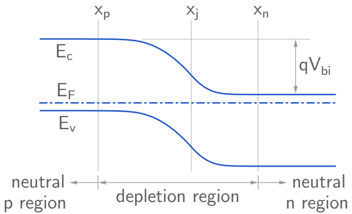
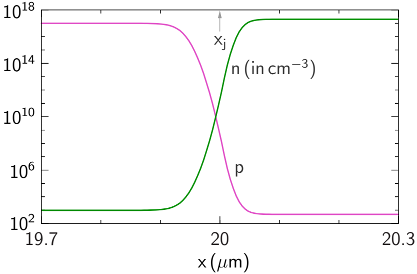
  Holes:

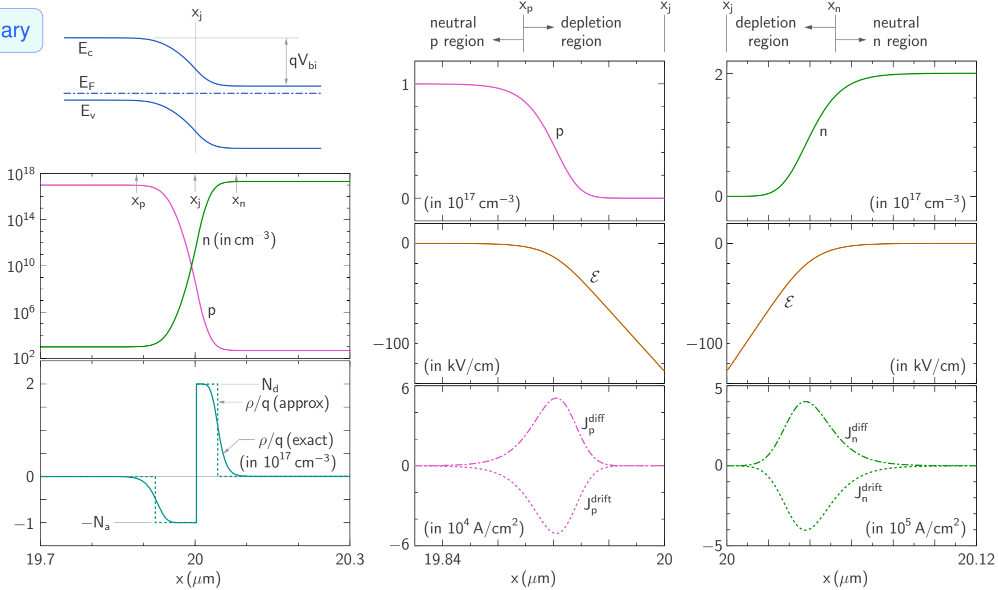
  $\mathcal{F}_p^{\text{diff}} : \longrightarrow, \; \mathcal{E} : \longleftarrow, \; \mathcal{F}_p^{\text{drift}} : \longleftarrow$.





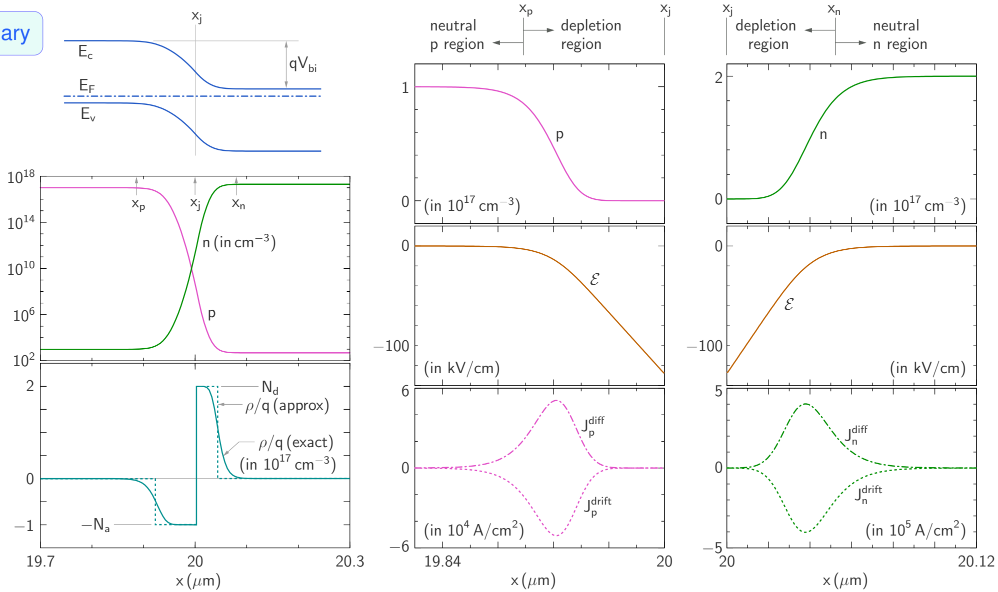


Summary



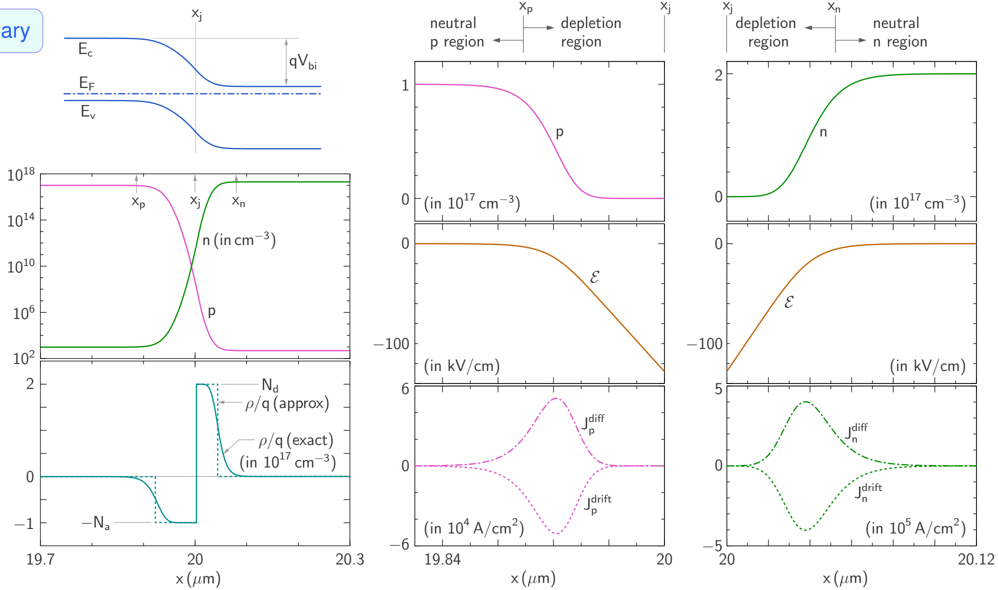
x_j
E_c
qV_{bi}
E_F
E_v
10^{18}
10^{14}
10^{10}
10^{6}
10^{2}
x_p
x_j
x_n
n (in cm^{-3})
p
2
0
−1
N_d
ρ/q (approx)
ρ/q (exact)
(in 10^{17} cm^{-3})
$-N_a$
19.7
20
20.3
x (μm)
x_p
x_j
neutral
p region
depletion
region
1
0
p
(in 10^{17} cm^{-3})
0
−100
$\mathcal{E}$
(in kV/cm)
6
0
−6
J_p^{diff}
J_p^{drift}
(in 10^4 A/cm^2)
19.84
20
x (μm)
x_j
x_n
depletion
region
neutral
n region
2
0
n
(in 10^{17} cm^{-3})
0
−100
$\mathcal{E}$
(in kV/cm)
5
0
−5
J_n^{diff}
J_n^{drift}
(in 10^5 A/cm^2)
20
20.12
x (μm)

Summary



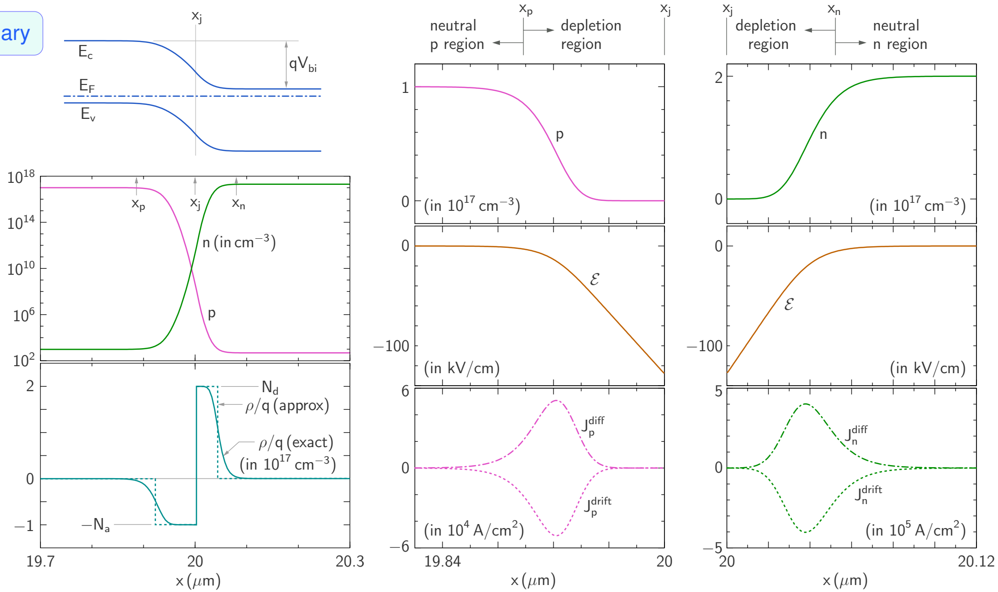
* There are three regions: *p* neutral region, *n* neutral region, and depletion region.

Summary



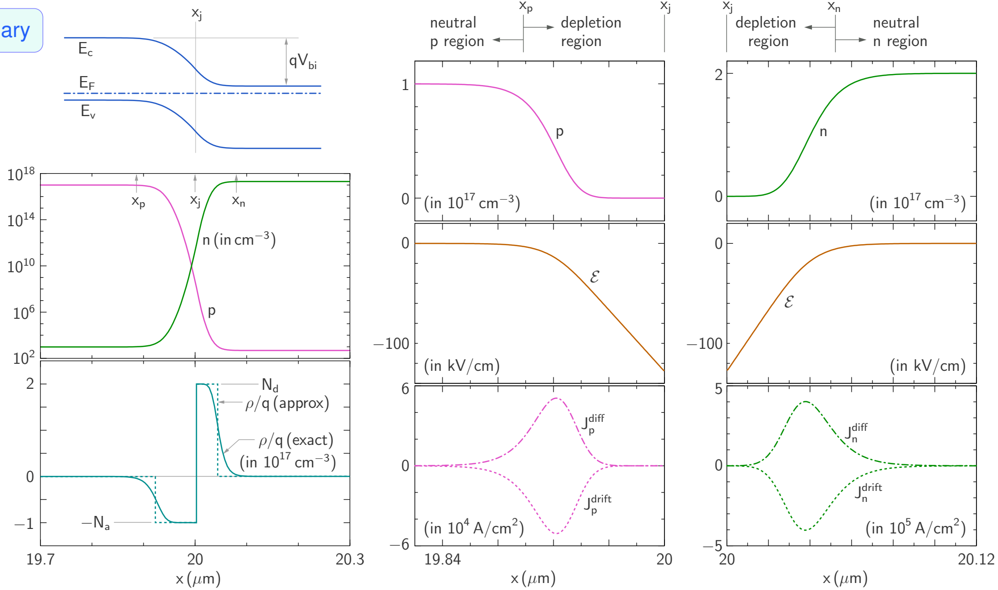
x_j
E_c
qV_{bi}
E_F
E_v
10^{18}
10^{14}
10^{10}
10^{6}
10^{2}
x_p
x_j
x_n
n (in cm^{-3})
p
2
0
−1
N_d
ρ/q (approx)
ρ/q (exact)
(in 10^{17} cm^{-3})
$-N_a$
19.7
20
20.3
x (μm)
neutral p region
x_p
depletion region
x_j
1
0
p
(in 10^{17} cm^{-3})
0
$\mathcal{E}$
−100
(in kV/cm)
6
0
−6
J_p^{diff}
J_p^{drift}
(in 10^4 A/cm^2)
19.84
20
x (μm)
x_j
depletion region
x_n
neutral n region
2
0
n
(in 10^{17} cm^{-3})
0
$\mathcal{E}$
−100
(in kV/cm)
5
0
−5
J_n^{diff}
J_n^{drift}
(in 10^5 A/cm^2)
20
20.12
x (μm)

Summary



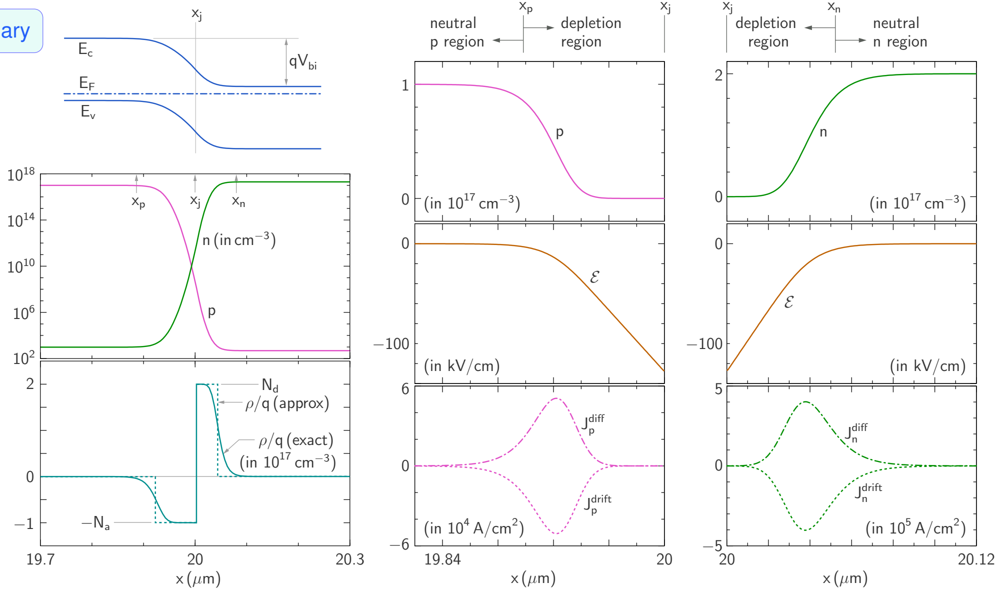
* The electric field is zero in the neutral regions and maximum (in magnitude) at the junction.

Summary



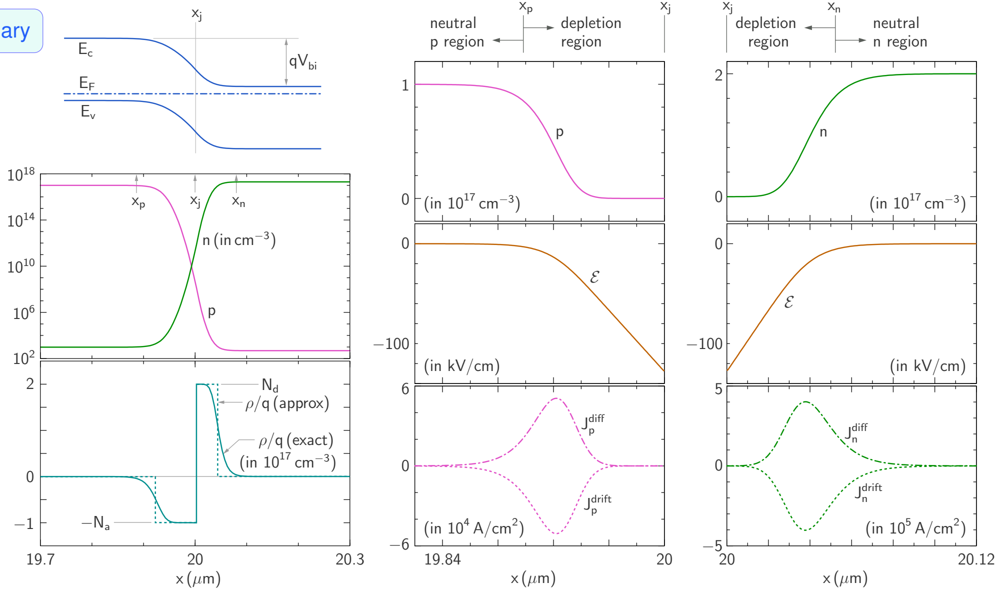
x_j
E_c
E_F
E_v
qV_{bi}
10^{18}
10^{14}
10^{10}
10^{6}
10^{2}
x_p
x_j
x_n
n (in cm^{-3})
p
2
0
−1
N_d
ρ/q (approx)
ρ/q (exact)
(in 10^{17} cm^{-3})
$-N_a$
19.7
20
20.3
x (μm)
neutral
p region
depletion
region
x_p
x_j
1
0
p
(in 10^{17} cm^{-3})
0
−100
$\mathcal{E}$
(in kV/cm)
6
0
−6
J_p^{diff}
J_p^{drift}
(in 10^4 A/cm^2)
19.84
20
x (μm)
x_j
x_n
depletion
region
neutral
n region
2
0
n
(in 10^{17} cm^{-3})
0
−100
$\mathcal{E}$
(in kV/cm)
5
0
−5
J_n^{diff}
J_n^{drift}
(in 10^5 A/cm^2)
20
20.12
x (μm)

Summary



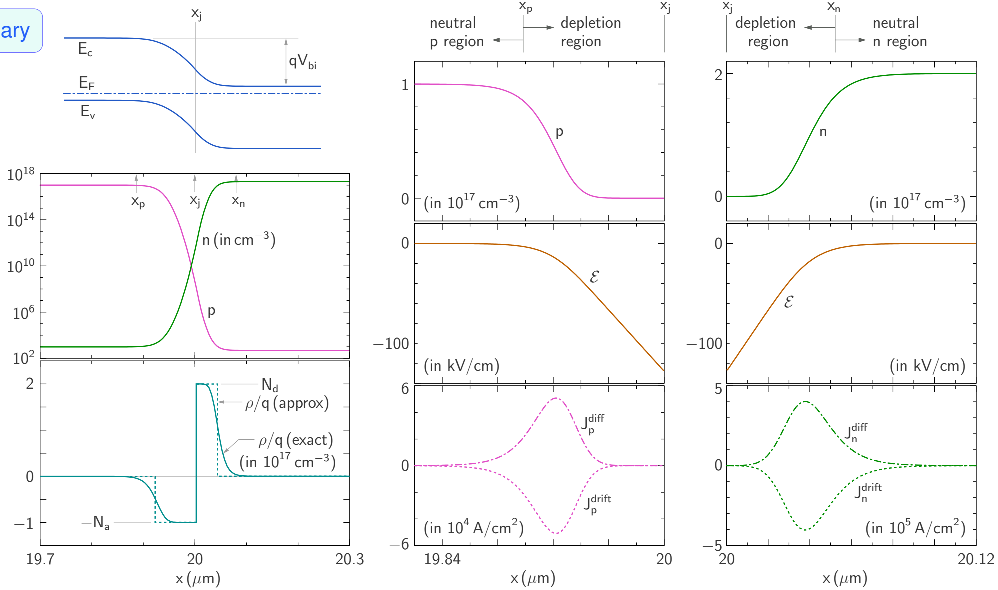
* There is a potential difference – the built-in voltage V_{bi} – between the neutral p and neutral n sides.

Summary



x_j
E_c
E_F
E_v
qV_{bi}
10^{18}
10^{14}
10^{10}
10^{6}
10^{2}
x_p
x_j
x_n
n (in cm^{-3})
p
N_d
ρ/q (approx)
ρ/q (exact)
(in 10^{17} cm^{-3})
$-N_a$
2
0
−1
19.7
20
20.3
x (μm)
neutral p region
depletion region
x_p
x_j
1
0
p
(in 10^{17} cm^{-3})
0
−100
$\mathcal{E}$
(in kV/cm)
6
0
−6
J_p^{diff}
J_p^{drift}
(in 10^4 A/cm^2)
19.84
20
x (μm)
x_j
x_n
depletion region
neutral n region
2
0
n
(in 10^{17} cm^{-3})
0
−100
$\mathcal{E}$
(in kV/cm)
5
0
−5
J_n^{diff}
J_n^{drift}
(in 10^5 A/cm^2)
20
20.12
x (μm)

Summary



* J_n and J_p are individually zero because the drift and diffusion components cancel out.