Also penetration of the depletion region in n-side and p-side can be given by the relation

\[ x_n = \frac{W N_A}{(N_A + N_D)} = \frac{W}{1 + N_D/N_A} = \left\{ \frac{2eV_{bi}'}{q} \left[ \frac{N_D}{N_A(N_A + N_D)} \right] \right\}^{1/2} \]

and

\[ x_p = \frac{W N_D}{(N_A + N_D)} = \frac{W}{1 + N_A/N_D} = \left\{ \frac{2eV_{bi}'}{q} \left[ \frac{N_A}{N_D(N_A + N_D)} \right] \right\}^{1/2} \]
Example

\[ kT = 0.026 \text{ eV} \]
\[ n_i \approx 10^{10} \text{ cm}^{-3} \]
\[ N_A = 10^{16} \text{ cm}^{-3} \]
\[ N_D = 10^{15} \text{ cm}^{-3} \]; p-side is doped more heavily

\[ V_{bi} = \frac{kT}{q} \ln\left(\frac{N_A N_D}{n_i^2}\right) = 0.659 \text{ Volts} \]

\[ W = \sqrt{\frac{2eV_{bi}}{q} \left(\frac{N_A + N_D}{N_A N_D}\right)} = \sqrt{\frac{2 \times 11.8 \times 8.854 \times 10^{-14} \times 0.659}{1.6 \times 10^{-19}}} \times \frac{10^{16} + 10^{15}}{10^{31}} \]

\[ = 0.973 \times 10^{-4} \text{ cm} = 0.973 \mu\text{m} \]

\[ x_n = 0.88455 \mu\text{m} \]

\[ x_p = 0.08845 \mu\text{m} \]
Note that since $p$-side is heavily doped, $\chi_n > \chi_p$.

$\chi_n - \chi_p$ is the junction depleted further into the more lightly doped material.

If $A = 2 \times 10^{-3}$ cm$^2$, then at $Q_+$

$Q_+ = -Q_- = qA \chi_n N_D = 1.6 \times 10^{-19} \times 2 \times 10^{-3} \times 0.88455 \times 10^{-4}$

$= 2.6 \times 10^{-11}$ C

$\varepsilon_0 = \frac{-2N_D \chi_n}{\varepsilon} = \frac{-(1.6 \times 10^{-19})(10^{15})(0.88455 \times 10^{-4})}{(11.8)(8.85 \times 10^{-14})}$
1) Depletion region extends farther into the side with the lighter doping.

For example, if \( N_A << N_D \)

\[ x_p > x_n \]

Deep penetration is necessary in lightly doped side to 'uncover' the same amount of space charge as for a short penetration into heavily doped material.
W varies as $\sqrt{Vbi}$ across the region.

This indicates that if we somehow add some voltage to this, W will increase and vice versa. Adding to voltage means increasing the equilibrium electric field across the depletion region.

This phenomenon is known as biasing.
What happens at the junction when you apply an external voltage bias $V$ across the depletion region $W$?

Consider the situation when the $p-n$ junction is at thermal equilibrium.

![Diagram of a $p-n$ junction with voltage biases and current notation.]

i) No current flows.

ii) The ohmic contacts of metal-semiconductor junctions have contact potentials $V_P$ and $V_N$ that are fixed.

iii) $V_j$ appears across the edges of the $W$. At thermal equilibrium,

$$V_j = V_{bi}$$

iv) There is no bias applied.

$$V_A = 0$$
Writing the loop eqn:

\[ V_f - V_N + V_A - V_P = 0 \]

\[ \Rightarrow V_f = V_N + V_P \quad \text{for} \quad V_A = 0 \]

is a fixed value that depends only on doping values.

Case of forward bias

\[ V_A > 0 \]

\[ \Rightarrow V_f = V_N + V_P - V_A \]

Hence the voltage across the depletion region will reduce by an amount equal to the bias voltage.
Case of Reverse bias

\[ V_j = V_N + V_P + V_A \]

The voltage across the junction will increase linearly by the applied voltage \( V_A \).

Draw the energy band diagram of all these three situations and discuss qualitatively.
Potential well changes linearly, but it impacts concentration exponentially. Hence current rises exponentially.
Reverse bias

\[ V_A < 0 \]

Current is because of minority carriers hence very small
exponential nature