Earlier using depletion approximation, we obtained

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

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

\[
W = \left[ \frac{2eV_{bi}}{q} \frac{N_A+N_D}{N_A N_D} \right]^{\frac{1}{2}}
\]
On biasing, these will change just by replacing $V_{bi}$ by $V_{bi} - V_A$ with proper sign of $V_A$, i.e.,

- $V_A > 0 \rightarrow$ Forward bias
- $V_A < 0 \rightarrow$ Reverse bias

Hence, the $n$-depletion Region, $0 \leq x_0 \leq x_n$,

$$x_n = \left[ \frac{2e}{q} (V_{bi} - V_A) \frac{N_A}{N_D (N_A+N_D)} \right]^{1/2}$$

$$V(x) = (V_{bi} - V_A) - \frac{q N_D}{2e} (x_0 - x)^2$$

$$\Phi(x) = -\frac{q N_D}{e} (x_n - x)$$
The \( p \)-depletion region, \(-x_p \leq x \leq 0\)

\[ x_p = \left[ \frac{2e}{q} \left( V_{bi} - V_A \right) \frac{N_D}{N_A (N_A + N_D)} \right]^{1/2} \]

\[ V(x) = \frac{q N_A}{2e} \left( x_p + x \right)^2 \]

\[ \varepsilon(x) = -\frac{q N_A}{\varepsilon} \left( x_p + x \right) \]

and therefore,

\[ W = \left[ \frac{2e}{q} \left( V_{bi} - V_A \right) \frac{(N_A + N_D)}{N_A N_D} \right]^{1/2} \]
Please note that for these equations to be valid, 

\[ V_A < V_{bi} \]  for Forward Bias case.

If not, Kirchhoff's Voltage Law is violated.

This is not a requirement in case of Reverse bias because \( V_A \) is a negative number and is therefore always less than \( V_{bi} \).
Charge density

Forward bias

Electric field

at thermal equilibrium

$V_A > 0$

$V_A = 0$

$V_{bi} - V_A$

$-Z_P$

$Z_N$

$V(x)$

$V_{bi}$
Reverse Bias

$V_A < 0$

$E(x)$

$N_A$

$p$

$q_n N_D$

$-x_p$

$x_n$

$-2 N_A$

$V_{bi} - V_A$

$V_{bi}$

$V_A$

$-x_p$

$x_n$
In case of reverse bias

\( V \) increases.

This increases depletion width.

This produces larger fixed charge.

This, in turn, results in a larger electric field.

This all considered, fixed charge density in the depletion region.

But it seldom happens.
Change density does not remain uniform throughout the depletion region.

Let's assume it varies linearly with $x$.

Linearly Graded Functions

\[ NA - ND \]
We are adding/injecting p-impurity in n-substrate. Let’s assume this straight line has a slope of $-a$.

\[ N_A(x) - N_A = -ax \]