ECE-606: Fall 2016

Ideal Diode Equation

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Pierret, *Semiconductor Device Fundamentals* (SDF)
pp. 235-259

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equilibrium e-band diagram

\[ E = E_{C} \]
\[ E = E_{F} \]
\[ E = E_{V} \]

\[ qV_{bi} \]

\[ I = 0 \]
\[ V_{A} = 0 \]

\[ -x_{n} \]
\[ x_{p} \]
e-band diagram under bias
electrostatics under bias

\[ N_D = 10^{16} \]

\[ N_A = 10^{16} \]

\[ W = \frac{2K_S \varepsilon_0}{q} \left( \frac{N_A + N_D}{N_D N_A} \right)(V_{bi} - V_A) \]^{1/2}

\[ x_n = \frac{N_A}{N_A + N_D} W \]

\[ x_p = \frac{N_D}{N_A + N_D} W \]

\[ V_{bi} = \frac{k_B T}{q} \ln \left( \frac{N_D N_A}{n_i^2} \right) \]

\[ \mathcal{E}(0) = \frac{2(V_{bi} - V_A)}{W} \]

Lundstrom ECE 305 S16
1) Ideal diode equation (qualitative)

2) Law of the Junction

3) Ideal diode equation (long base)

4) Ideal diode equation (short base)
$I = I_0 \left( e^{qV_A/k_BT} - 1 \right)$

"ideal diode equation"

"Shockley diode equation"
1) Why does the current increase exponentially with the applied forward bias?

2) Why is the reverse bias current independent of the reverse bias voltage?
e-band diagram under bias

\[ E_C \quad q(V_{bi} - V_A) \]

\[ F_n \quad F_p \]

\[ E_V \]

\[ -x_n \quad x_p \]
e-band diagram under bias

\[ q(V_{bi} - V_A) \]

Lundstrom ECE 305 S16
\[ P_0 = \frac{e^{-\Delta E/k_B T}}{e^{-qV_{bi}/k_B T}} \]
\[ \Delta E = qV_{bi} \]

\[ n_{0P} = \frac{n_i^2}{N_A} \]

\[ p_0 = \frac{n_{0P}}{n_{0N}} = \frac{n_i^2 / N_A}{N_D} = \frac{n_i^2}{N_A N_D} \]

\[ qV_{bi} = k_B T \ln \left( \frac{N_D N_A}{n_i^2} \right) \]

\[ p_0 = e^{-\Delta E / k_B T} = e^{-qV_{bi} / k_B T} \]
NP junction under bias

\[ P = e^{-\Delta E/k_B T} = e^{-q(V_{bi} - V_A)/k_B T} = P_0 e^{qV_A/k_B T} \]
NP junction under bias

\[ I = qA \left( F_{N \rightarrow P} - F_{P \rightarrow N} \right) \]

\[ F_{N \rightarrow P} = F_{N \rightarrow P}^0 e^{qV_A/k_BT} \]

\[ F_{P \rightarrow N} = F_{P \rightarrow N}^0 \]

\[ P = P_0 e^{qV_A/k_BT} \]

\[ q(V_{bi} - V_A) \]
I = I_0 \left( e^{\frac{qV_A}{k_B T}} - 1 \right)

“ideal diode equation”

“Shockley diode equation”

1) Why does the current increase exponentially with the applied forward bias?

2) Why is the reverse bias current independent of the reverse bias voltage?
Excess carriers under forward bias

\[ n_P \gg n_{0P} \]

\[ q(V_{bi} - V_A) \]

\[ p_{0P} \approx N_A \]

\[ n_{0P} = \frac{n_i^2}{N_A} \]
Every time a minority electron recombines on the p-side, one electron flows in the external current.
excess electrons on the p-side of junction

\[ n_{0N} \approx N_D \quad \text{and} \quad n_P >> n_{0P} \]

\[ q(V_{bi} - V_A) \]

What is \( \Delta n(x) \) on the p-side? Ans. *Solve the MCDE.*
boundary conditions for the MCDE

\[ \Delta n(0) = ? \]

\[ \Delta n(W_P) = 0 \]

\[ q(V_{bi} - V_A) \]

\[ F_n \]

\[ F_p \]

\[ P_{0P} \approx N_A \]

Lundstrom ECE 305 S16
1) Ideal diode equation (qualitative)

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NP junction in equilibrium

\[ \Delta E = qV_{bi} \]

\[ n_{0P} = \frac{n_i^2}{N_A} \]

\[ p_{0P} = N_A \]
NP junction under forward bias

\[ n_p = \frac{n_i^2 e^{q(V_{bi} - V_A)/k_B T}}{N_A} \]

\[
q(V_{bi} - V_A)
\]

\[
F_n
\]

\[
F_p
\]

\[
p_P \approx N_A
\]

\[
n_p(0)p_p(0) = n_i^2 e^{qV_A/k_B T}
\]

“Law of the Junction”
excess carriers

\[ n_p = \frac{n_i^2}{N_A} e^{q(V_A/k_BT)} \]

\[ \Delta n_p(0) = \frac{n_i^2}{N_A} e^{qV_A/k_BT} - n_p(0) \]

\[ \Delta n_p(0) = \frac{n_i^2}{N_A} \left( e^{qV_A/k_BT} - 1 \right) \]

“Law of the Junction”
Assume QFLs are constant across the transition region.

\[ n_p(0) = n_i e^{(F_n - E_i) / k_B T} \]

\[ p_p(0) = n_i e^{(E_i - F_p) / k_B T} \]

\[ n_p(0) p_p(0) = n_i^2 e^{(F_n - F_p) / k_B T} \]

\[ n_p(0) p_p(0) = n_i^2 e^{q(V_A - F_p) / k_B T} \]
1) Ideal diode equation (qualitative)

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