Lecture 17

• Last time:
  ✓ – Complete small-signal model: add capacitors
  ✓ – P-channel MOSFET

• Today:
  – pn junctions under forward bias ($V_D$)

(Chapter 6)
Junction Diode with $V_D \approx 0.7$ V

Barrier is reduced by forward bias (what about "ohmic contacts"?)
Current density $J_p$ is positive for holes

$\frac{dp}{dx} < 0$

Downhill.

$J_p \text{diff} > 0$

$-q \frac{dp}{dx}$

$\frac{q}{\mu_p} = \frac{kT}{q} = V_{th}$

$10 \text{ cm}^2/\text{s}$.
What Happens Inside the Junction?

Electric field in the depletion region is reduced → imbalance and net transport of holes from p side into n side and electrons in the other direction.

Physical process is called diffusion and results in a diffusion current density

\[ J_{p}^{\text{diff}} = -qD_{p} \frac{dp}{dx} \]

\[ J_{n}^{\text{diff}} = qD_{n} \frac{dn}{dx} \]

Note "downhill" = \(-\frac{dn}{dx}\)

\[ \frac{\Delta p}{\Delta x} \frac{cm^{-3}}{cm} = \frac{cm^{-2}}{cm} \]

\[ q(=) C \]
Minority Carriers at Junction Edges

Minority carrier concentration at boundaries of depletion region increase as barrier lowers ... the function is

\[ \frac{p_n(x = x_n)}{p_p(x = -x_p)} = \frac{\text{(minority) hole conc. on n-side of barrier}}{\text{(majority) hole conc. on p-side of barrier}} \]

\[ = e^{-\frac{(\text{Barrier Energy})}{kT}} \]

(Boltzmann’s Law)
The Thermal Voltage

- Define \( V_{th} = \frac{q}{kT} \) as the thermal voltage.

Value: \( q = 1.6 \times 10^{-19} \text{ C}, \ k = 1.38 \times 10^{-23} \text{ J/K}, \ T = 300 \text{ K} \).

\( V_{th} = 26 \text{ mV at room temperature} \ldots 25 \text{ mV}. \)

\( P_n(x=x_w) = N_a \cdot e^{\frac{qV}{kT}} \ldots \text{EE 105}. \)

\( \text{EE 140, 240, \ldots T = variable}. \)
Thermal Equilibrium Case

- Define $p_{no}$ as thermal equilibrium hole concentration on the n-side of the junction ...

$$p_{no} = \frac{n_i^2}{N_D} = N_Ae^{(\phi_B - \frac{V_{th}}{V_{th}})}$$

Solve for the built-in barrier:

$$n_i^2 = N_A N_D e^{-\phi_B N_D}$$

Alternative form of junction law:

$$P_n(x=x_n) = p_{no} e^{V_B/V_D n_i}$$
“Law of the Junction”

Minority carrier concentrations at the edges of the depletion region are given by:

\[
\begin{align*}
    p_n(x = x_n) &= N_A e^{-q(\phi_B - V_D)/kT} \\
    p_p(x = x_p) &= N_D e^{-q(\phi_B - V_D)/kT}
\end{align*}
\]

\[\text{Note 1: } N_A \text{ and } N_D \text{ are the majority carrier concentrations on the other side of the junction}\]

\[\text{Note 2: we can reduce these equations further by substituting } V_D = 0 \text{ V (thermal equilibrium)}\]

\[\text{Note 3: assumption that } p_n << N_D \text{ and } n_p << N_A \]


\[\text{HIGH-LEVEL INJECTION}\]
\[ p_n (x = x_n) = N_a e^{-\left(\frac{\phi_x}{V_{th}} + N_a V_x\right)} \]

\[ = N_a e^{-\frac{\phi_x}{V_{th}}} e^{+V_x N_a} \]

\[ p_n (x_n) = p_{no} e^{\frac{V_x}{V_{th}}} \]

\[ n_p (x = x_p) = n_{po} e^{\frac{V_x}{V_{th}}} \]
Boundary Conditions

Depletion region edges:
Ohmic contacts:

SET THE MINORITY CARRIER CONC... TO THERMAL EQUILIBRIUM.