Lecture 15 - p-n Junction (cont.)

March 9, 2007

Contents:

1. Ideal p-n junction out of equilibrium (cont.)
2. pn junction diode: parasitics, dynamics

Reading assignment:

del Alamo, Ch. 6, §6.2 (6.2.4), §6.3
Key questions

• What happens to the majority carriers in a pn junction under bias?

• What are the main practical issues in synthesizing pn junction diodes?

• How does a pn junction switch? What dominates its dynamic behavior?
1. Ideal p-n junction out of equilibrium (cont.)

□ Minority carrier storage

Quasi-neutrality in QNR’s demands $n' \approx p'$. Consequences:

In n-QNR, quasi-neutrality implies:

$$Q_{hn} \simeq |Q_{en}| \equiv Q_n$$

Also, if $V \uparrow \rightarrow Q_{hn} \uparrow \rightarrow |Q_{en}| \uparrow$ with:

$$\Delta Q_{hn} \simeq |\Delta Q_{en}| \equiv \Delta Q_n$$

$\Delta Q_{hn}$ supplied from p-contact, $\Delta Q_{en}$ supplied from n-contact.
Looks like a capacitor ⇒ **diffusion capacitance**.

Diffusion capacitance (per unit area):

\[ C_d = \frac{dQ_n}{dV} + \frac{dQ_p}{dV} \]

with:

\[ Q_n = q \int_{x_n}^{w_n} p'(x)dx \]
\[ Q_p = q \int_{-w_p}^{-x_p} n'(x)dx \]

• If both sides are "long":

\[ Q_n = qL_h p'(x_n) = \tau_h J_h(x_n) \]
\[ Q_p = qL_e n'(-x_p) = \tau_e J_e(-x_p) \]

and

\[ C_d \approx \frac{q}{kT} \left[ \tau_h J_h(x_n) + \tau_e J_e(-x_p) \right] = \frac{q}{kT} (\tau_h J_{hs} + \tau_e J_{es}) \exp \frac{qV}{kT} \]
• If both sides are short and $S = \infty$:

\[
Q_n = \frac{1}{2} n(x_n)(w_n - x_n) = \tau_{tn}J_h(x_n)
\]

\[
Q_p = \frac{1}{2} p(-x_p)(w_p - x_p) = \tau_{tp}J_e(-x_p)
\]

with $\tau_{tn}$ and $\tau_{tp}$ are the minority carrier transit times through QNR’s:

\[
\tau_{tn} = \frac{(w_n - x_n)^2}{2D_h}
\]

\[
\tau_{tp} = \frac{(w_p - x_p)^2}{2D_e}
\]

Then:

\[
C_d \simeq \frac{q}{kT}[\tau_{tn}J_h(x_n) + \tau_{tp}J_e(-x_p)] = \frac{q}{kT}(\tau_{tn}J_{hs} + \tau_{tp}J_{es}) \exp\left(\frac{qV}{kT}\right)
\]

Similar result to long diode!
• General expression:

\[ C'_d = \frac{q}{kT} \Sigma_{n,p} \text{dominant minority carrier time constant} \times \text{injected minority carrier current density} \]

\( C'_d \) grows exponentially in forward bias, negligible in reverse bias:

\[ C'_d \sim \exp \left( \frac{qV}{kT} \right) \]

[check that \( C'_d \sim \exp \left( \frac{qV}{kT} \right) \) and not \( \sim \exp \left( \frac{qV}{kT} - 1 \right) \)]

• Total diode capacitance:
2. p-n junction diode

- pn junctions present in most semiconductor devices (BJTs and MOSFETs).

- pn junction diodes used in rectifying circuits, detectors in communications applications, bias shifters, input protection devices against electrostatic discharge.

- For integrated p-n diodes, no special process steps available.

Typical cross section of p-n diode implemented in BJT process:
Parasitics

* Series resistance:

- Accounts for ohmic drop in QNR’s (neglected so far).
- Reduces internal diode voltage → $I$ ↓

$$ I = I_s \left[ \exp \left( \frac{q(V - IR_s)}{kT} \right) - 1 \right] $$

- Higher $V_F$ required to deliver desired $I_F$ → more power dissipation, potential process control problems
- $RC$ time constant degraded.
**Minority carrier boundary conditions:**

- At top surface: depending on relative depth of emitter, effective diode area changes
  
  - Top surface = ohmic contact area \((A_c, S = \infty)\)
  
  + Peripheral SiO\(_2\)-covered area \((A_p, S = 0)\)

  
  - If \(W_p \gg L_e\), volume recombination only \(\rightarrow A_{eff} \simeq A_c + A_p\)

  - If \(W_p \ll L_e\), surface recombination only \(\rightarrow A_{eff} \simeq A_c\)

- At bottom surface: high-low junction, characterized by \(S_{hl}\).
* Isolation:

- Parasitic substrate p-n junction \( \rightarrow \) needs to be reverse biased to avoid turning it on.
- Even reverse biased, substrate contributes parasitic capacitance.
- Additional danger: "bipolar effect" between diode and substrate \( \rightarrow \) minority carriers can be extracted by substrate \( \rightarrow \) current diverted away from main body of diode.

- Hard to make integrated pn diodes in CMOS process (unless they hang directly from the power rail that is connected to the substrate).
- Easier in bipolar since \( n^+ \) buried layer and collector plug can prevent minority carrier injection.
\[ \text{\textbf{Dynamics}} \]

Fundamental difference between p-n and Schottky diodes: minority carrier storage slows down p-n diode.

Consider simple voltage switching:

\[ I \quad V \quad V_f \quad V_r \]

As in Schottky diode, delays associated with \( R_s C_j \).

Additionally, delays associated with minority carrier storage.
Switch-off transient

Evolution of excess minority carrier concentration (long diode):

At \( t = 0^- \), \( V_f \rightarrow I_f \); minority carrier stored charge:

\[
Q = \tau_t I_f
\]

with \( \tau_t \), dominant minority carrier time constant.

At \( t = 0^+ \), external \( V \) abruptly changes from \( V_f \) to \( V_r \); internal \( V \) cannot change abruptly → need to get rid of minority carriers!
\[ I(0^-) = I_f(V_f) \quad I(0^+) = -\frac{1}{R_s}(V_f - I_f R_s + V_r) \approx \frac{-V_r}{R_s} \]

Two phases to discharge:

**Phase I** - From \( V_j = V_f - I_f R_s \) to \( V_j \approx 0 \).

Since \( Q \sim \exp \frac{qV_f}{kT} \), as \( Q \) discharges, \( V_f \) cannot change much.

Discharge proceeds nearly at constant current \( I_r(pk) \approx -\frac{V_r}{R_s} \).

Time to discharge (reverse recovery time):

\[ t_{rr} \approx \frac{Q}{|I_r(pk)|} \approx \tau I_f(V_f) R_s V_r \]

**Phase II** - From \( V_j \approx 0 \) to \( V_j = -V_r \).

Charge depletion capacitance \( \rightarrow R_s C_j \) time constant (as in Schottky diode).
Switch-on transient

\[ I(0^-) = -I_s \quad \text{and} \quad I(0^+) = \frac{V_f + V_r}{R_s} \]

Evolution of excess minority carrier concentration (long diode):

- First, \( R_s C_{j} \)-type charge up of junction capacitance.
- Then, minority carrier charge injection → takes \( \tau_t \).
Example of SPICE simulations:

\[ IS = 6e^{-17}, \quad N = 1, \quad EG = 1.12, \quad RS = 8, \quad CJO = 1.2e^{-13}, \quad VJ = 0.6, \quad M = 0.41, \quad XTI = 3.814, \quad \text{and} \quad TT = 4e^{-9} \]

\[ V_f = +0.89 \text{ V}, \quad V_r = -5 \text{ V} \]

<table>
<thead>
<tr>
<th>parameter</th>
<th>SPICE</th>
<th>hand calculation</th>
</tr>
</thead>
<tbody>
<tr>
<td>( t_{rr} )</td>
<td>41 ps</td>
<td>46 ps</td>
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<tr>
<td>( \tau_{on} )</td>
<td>2.6 ns</td>
<td>4 ns</td>
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<td>( I_{rr} )</td>
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<td>736 mA</td>
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<tr>
<td>( I_f(pk) )</td>
<td>?</td>
<td>736 mA</td>
</tr>
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</table>
Key conclusions

- **Diffusion capacitance** arises from minority carrier storage in QNR’s and quasi-neutrality:

\[ C_d = \frac{q}{kT} \sum_{n,p} \text{time constant} \times \text{current density} \]

- **\( C_d \propto J \propto \exp \left( \frac{qV}{kT} \right) \)** ⇒ **\( C_d \)** dominates in forward bias, **\( C_j \)** dominates in reverse bias.

- Difficult to implemented integrated diodes in CMOS process: parasitic bipolar transistor.

- Dynamics of p-n diode dominated by minority carrier storage.

- **Reverse recovery time** is time required to eliminate minority carrier stored charge in switch-off transient.
Self study

- Diffusion capacitance in short diode.
- Equivalent circuit models for pn diode