Course 13

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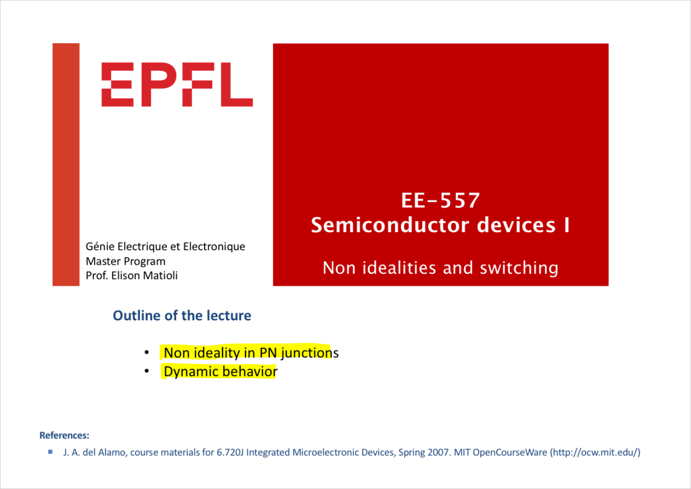
EE557 - Cours 13 -...



EE-557
Semiconductor devices I

Non idealities and switching

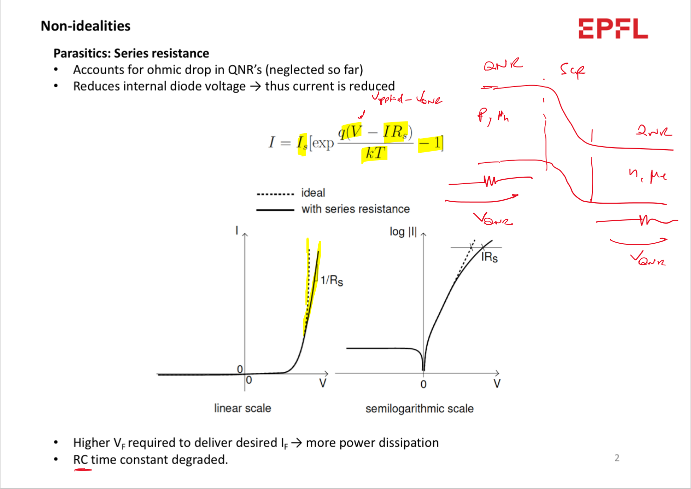
Génie Electrique et Electronique
Master Program
Prof. Elison Matioli

Outline of the lecture

- Non ideality in PN junctions
- Dynamic behavior

References:

- J. A. del Alamo, course materials for 6.720J Integrated Microelectronic Devices, Spring 2007. MIT OpenCourseWare (http://ocw.mit.edu/)



Non-idealities

Parasitics: Series resistance

- Accounts for ohmic drop in QNR's (neglected so far)
- Reduces internal diode voltage → thus current is reduced

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

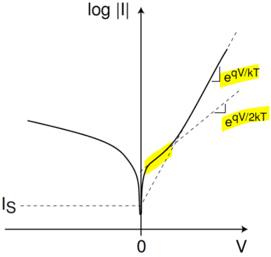
$V_{applied} - V_{QNR}$
QNR
SCR
p, μ_h
QNR
n, μ_e
V_{QNR}
V_{QNR}
ideal
with series resistance
I
0
0
V
$1/R_S$
linear scale
log |I|
IR_S
0
V
semilogarithmic scale

- Higher V_F required to deliver desired I_F → more power dissipation
- RC time constant degraded.

Non-idealities

Space-charge generation and recombination

In real devices, non-ideal I-V characteristics often seen:



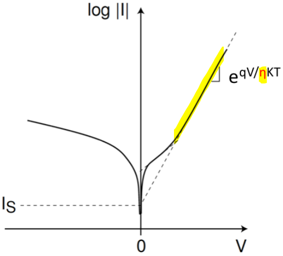
Anomalies often due to:

- Recombination through traps in SCR (in forward bias)
- Generation through traps in SCR (in reverse bias)

Non-idealities

Ideality factor η

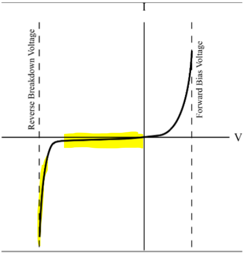
$\eta = 1$ ideal device

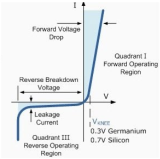


η represents the deviation from the ideal case ($\eta = 1$)

Non-idealities

Breakdown voltage

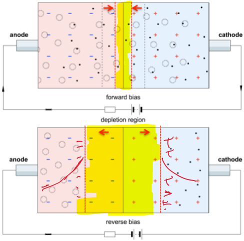


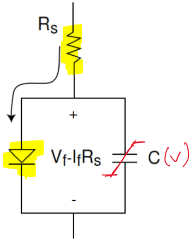


This happens when the electric field reaches the critical electric field E_{CR}

Equivalent model of pn junctions

Charges at the junction: effective variable capacitor

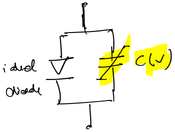




C(V) ① **Depletion (junction) capacitance (C_j)**: related to the depletion at the junction
② **Diffusion capacitance (C_d)**: related to the injection of minority carriers from QNRs

Total Capacitance: Depletion (junction) capacitance (C_j) + diffusion capacitance (C_d)

$$C = C_j + C_d$$



$$I = I_S \left(\exp\left(\frac{qV}{kT}\right) - 1\right) + \frac{dQ}{dt}$$

$$\underbrace{\frac{dQ}{dt}}_{I} = \underbrace{\frac{dQ}{dV}}_{C} \cdot \frac{dV}{dt} = C \cdot \frac{dV}{dt}$$

$$C = \underbrace{C_j}_{\text{depletion}} + \underbrace{C_d}_{\text{diffusion}}$$

1) Junction capacitance

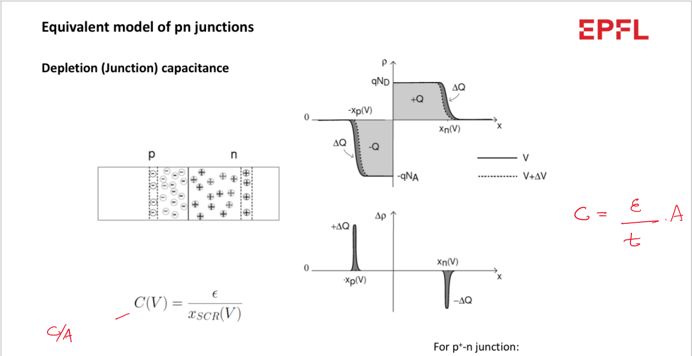
$$Q_j(V) = -\underbrace{q \cdot N_A \cdot x_p} \cdot \overset{\text{area}}{A} = -A \cdot \sqrt{\frac{2q \cdot \varepsilon \cdot N_D N_A \cdot (\phi_{bi} - V)}{N_D + N_A}}$$

$$= Q_j(V=0) \cdot \sqrt{1 - \frac{V}{\phi_{bi}}}$$

$$C_j(V) = \frac{dQ_j(V)}{dV} = A \sqrt{\frac{q \varepsilon \cdot N_D N_A}{2(N_D + N_A)(\phi_{bi} - V)}} = \frac{C_j(V=0)}{\sqrt{1 - V/\phi_{bi}}}$$

for p^+-n junction:

$$C_j(V) = A \sqrt{\frac{q \cdot N_D \cdot \varepsilon}{2(\phi_{bi} - V)}} \Rightarrow \frac{1}{C_j^2} = \frac{2(\phi_{bi} - V)}{\varepsilon \cdot q N_D \cdot A^2}$$



Equivalent model of pn junctions

EPFL

Depletion (Junction) capacitance

$$C(V) = \frac{\epsilon}{x_{SCR}(V)}$$

C/A

For p⁺-n junction:

$$C = \frac{\varepsilon}{t} \cdot A$$

$$C(V) = \sqrt{\frac{\epsilon q N_A N_D}{2(N_D + N_A)(\phi_{bi} - V)}} = \frac{C(V=0)}{\sqrt{1 - \frac{V}{\phi_{bi}}}}$$

$$C(V) = \sqrt{\frac{\epsilon q N_D}{2(\phi_{bi} - V)}}$$

*** Here *C*(V) is the capacitance per unit area, thus we must multiply by A to get the total capacitance (see class notes)

Equivalent model of pn junctions

Depletion (Junction) capacitance

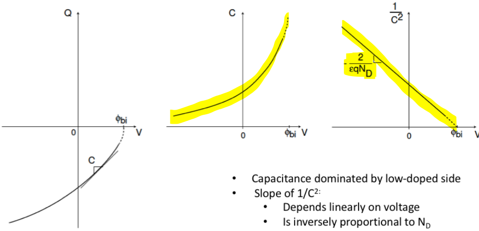
$$C(V) = \sqrt{\frac{\epsilon q N_A N_D}{2(N_D + N_A)(\phi_{bi} - V)}} = \frac{C(V=0)}{\sqrt{1 - \frac{V}{\phi_{bi}}}}$$

For p$^+$-n junction:

$$C(V) = \sqrt{\frac{\epsilon q N_D}{2(\phi_{bi} - V)}}$$

Capacitance dominated by low-doped side

Technique to extract ϕ_{bi} and N_{low}:



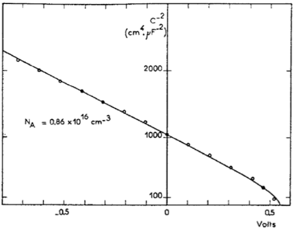
$$\frac{1}{C^2} = \frac{2(\phi_{bi} - V)}{\epsilon q N_D}$$

- Capacitance dominated by low-doped side
- Slope of 1/C^2:
  - Depends linearly on voltage
  - Is inversely proportional to N_D

*** Here *C*(V) is the capacitance per unit area, thus we must multiply by A to get the total capacitance (see class notes)

Equivalent model of pn junctions

Experimental verification:



Fortini, A., A. Hairie, and M. Gomina. "Analysis and Capacitive Measurement of the Built-in-field Parameter in Highly Doped Emitters."*IEEE Transactions on Electron Devices* 29, no. 10 (1982): 1604-1610.

Equivalent model of pn junctions

Exercise:

Consider a p-n junction with $N_A=5\times10^{18}$ cm^{-3} and $N_D = 10^{17}$ cm^{-3}. The diode has an area of 10 um^2. Estimate the junction capacitance associated with this diode at room temperature and under an applied bias of 0.6 V.

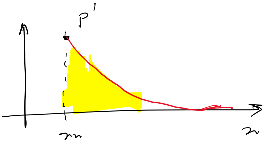
from past exercise: $x_{scr} = 0.11\,\mu m$

$$C_j(V=0) = A \cdot \frac{\varepsilon}{x_{scr}} = 10\times10^{-8}\,cm^2 \cdot \frac{11.7\times 8.85\times10^{-14}\,F/cm}{0.11\times10^{-4}\,cm} = 1\,fF$$

[F]

$$C_j(V) = \frac{C_j(V=0)}{\sqrt{1-\frac{V}{\phi_{bi}}}} \underset{V=0.6}{=} \frac{C_j(V=0)}{\sqrt{1-\frac{0.6}{0.94}}} = 1.66\,fF$$

Diffusion capacitance:



$$p'(x) = p'(x_n)\cdot \exp\left(-\frac{x-x_n}{L_h}\right)$$

$$Q_h = \int_{x_n}^{\infty} p'(x)\cdot q\cdot A\cdot dx$$

$$\boxed{Q_h = q\cdot A\cdot p'(x_n)\cdot L_h}$$

$$Q_p = q\cdot A\cdot L_e\cdot n'(-x_p) = A\cdot\frac{L_e^2}{D_e}\cdot J_e(-x_p)$$

$$Q_n = q\cdot A\cdot L_h\cdot p'(x_n) = A\cdot\frac{L_h^2}{D_h}\cdot J_h(x_n)$$

Also:

$$Q_p = I_e\cdot\tau_p$$

$$Q_n = I_h\cdot\tau_n$$

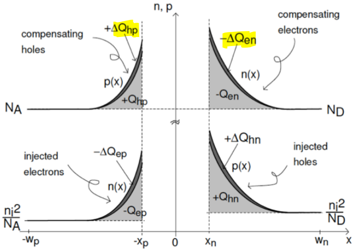
$$L_e = \sqrt{D_e\cdot\tau}$$

$$\tau = \frac{L_e^2}{D_e}$$

Equivalent model of pn junctions

Diffusion capacitance: due to minority carrier storage

Quasi-neutrality in QNR's demands n' ~ p' :



majority

minority

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:

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

ΔQ_{hn} supplied from p-contact, ΔQ_{en} supplied from n-contact

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Equivalent model of pn junctions

Minority carrier storage

Diffusion capacitance (per unit area):

$$C_d = \frac{dQ_n}{dV} + \frac{dQ_p}{dV}$$

$$\begin{aligned} Q_n &= qL_h p'(x_n) = \tau_h J_h(x_n) \\ Q_p &= qL_e n'(-x_p) = \tau_e J_e(-x_p) \end{aligned}$$

dominant minority carrier **time constant** × injected minority carrier **current density**

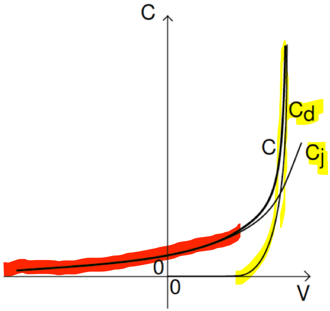
$$C_d \simeq \frac{q}{kT}[\tau_h J_h(x_n) + \tau_e J_e(-x_p)] = \frac{q}{kT}(\tau_h J_{hs} + \tau_e J_{es}) \exp \frac{qV}{kT}$$

$$\boxed{C_d = q/KT\ Q_s \exp(qV/KT)}$$

C_d grows exponentially in forward bias, negligible in reverse bias: $C_d \sim \exp \frac{qV}{kT}$

Equivalent model of pn junctions

Total diode capacitance:



Junction capacitance:

Dominant at negative V

$$C(V) = \sqrt{\frac{\epsilon q N_D}{2(\phi_{bi} - V)}}$$

Diffusion capacitance:

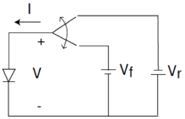
Dominant at positive bias

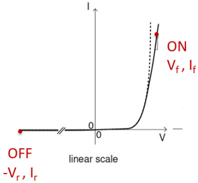
$$C_d \sim \exp\frac{qV}{kT}$$

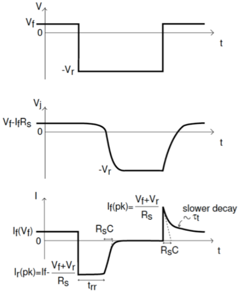
Dynamics: Switching behavior of pn diodes

Fundamental weakness of p-n diodes: **minority carrier storage slows down p-n diode**

Consider simple voltage switching:





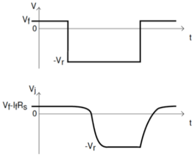


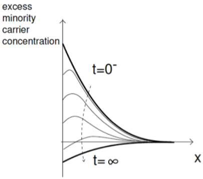
Delays are associated with R_sC_j and with minority carrier storage.

Dynamics: Switching behavior of pn diodes

Switch-off transient

Evolution of excess minority carrier concentration:





switch-off

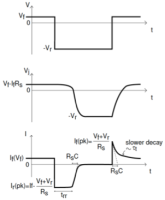
At t =0⁻, $V_f \rightarrow I_f$; minority carrier stored charge: $Q = \tau_t I_f$

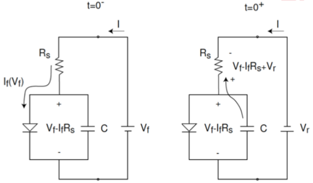
with τ_t: dominant minority carrier time constant.

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!

Dynamics: Switching behavior of pn diodes

Switch-off transient





$$I(0^-) = I_f(V_f) \qquad I(0^+) = -\frac{1}{R_s}(V_f - I_f R_s + V_r) \simeq -\frac{V_r}{R_s}$$

Two phases to discharge:

Phase I - From $V_j = V_f - I_f R_s$ to $V_j \approx 0$.
Since $Q \sim \exp(qV_j/KT)$, as Q discharges, V_f cannot change much.
Discharge proceeds nearly at constant current $I_r(pk) \sim -V_r/R_s$: limited by R_s
Time to discharge (**reverse recovery time**):

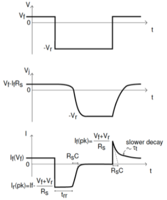
$$t_{rr} \simeq \frac{Q}{|I_r(pk)|} \simeq \tau_t \frac{I_f(V_f)R_s}{V_r}$$

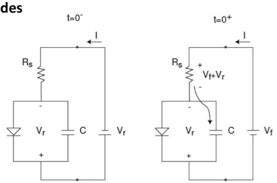
$V_f << |V_r|$: $t_{rr} << \tau$ removing carriers is much faster than letting them recombine!

Phase II - From $V_j \sim 0$ to $V_j = -V_r$.
Discharge of the depletion capacitance → R_sC_j time constant is what limits this process

Dynamics: Switching behavior of pn diodes

Switch-on transient





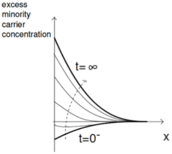
produces a peak of current

$$I(0^-) = -I_s$$

$$I(0^+) = \frac{V_f + V_r}{R_s}$$

Evolution of excess minority carrier concentration:

- First, R_sC_j-type charge up of junction capacitance: V_j increases
- Then, minority carrier charge injection → takes τ_t (τ is the dominant minority carrier time constant)
- After a few τ_t the system reaches equilibrium



switch-on

Equivalent model of pn junctions

Exercise:

Consider a p-n junction with N_A=5x10^{18} cm^{-3} and N_D = 1x10^{17} cm^{-3}. The diode has an area of 10 um^2 and the p and n regions are long (>> L) Estimate the diffusion capacitance associated with this diode at room temperature and under an applied bias of 0.6 V.

Key conclusions

Junction or depletion capacitance:
Depletion capacitance due to SCR width modulation:

$$C(V) = \frac{\epsilon}{x_{SCR}(V)}$$

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

$$C_d = \frac{q}{kT}\Sigma_{n,p}$$

(dominant minority carrier time constant × minority carrier current density)

$$C_d \propto J \propto \exp\frac{qV}{kT} \Rightarrow C_d$$

C_d dominates in forward bias, C_j dominates in reverse bias.

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.