Lecture #14

OUTLINE

- pn Junctions:
  - transient response
    - turn-off
    - turn-on
- pn diode applications

Reading: Chapters 8 & 9

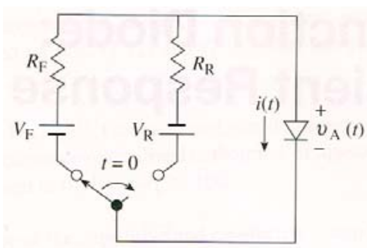
Transient Response of pn Diode

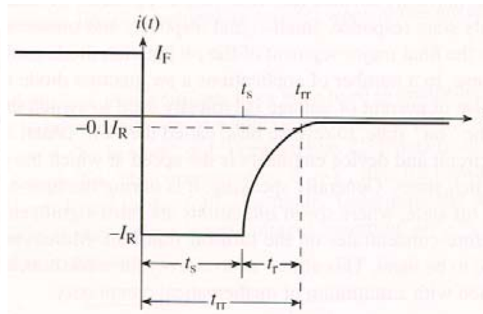
- Suppose a pn-diode is forward biased, then suddenly turned off at time $t = 0$. Because of C_D, the voltage across the pn junction depletion region cannot be changed instantaneously.

(The delay in switching between the ON and OFF states is due to the time required to change the amount of excess minority carriers stored in the quasi-neutral regions.)

Turn-Off Transient

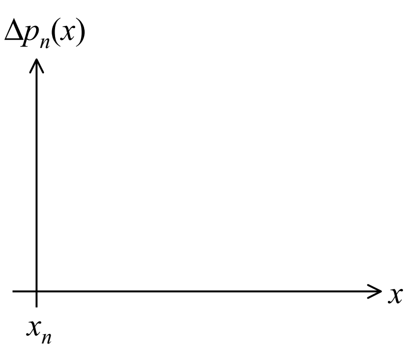
- In order to turn the diode off, the excess minority carriers must be removed by net carrier flow out of the quasi-neutral regions and/or recombination
  - Carrier flow is limited by the switching circuitry

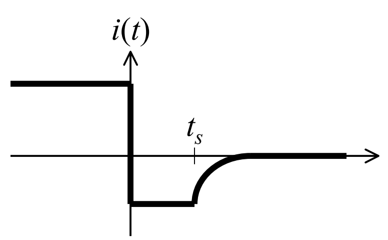


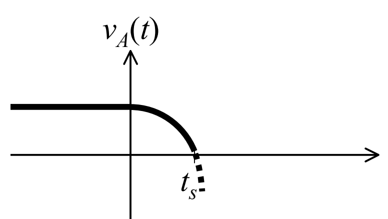


Decay of Stored Charge

Consider a **p⁺n diode** ($Q_p >> Q_n$):



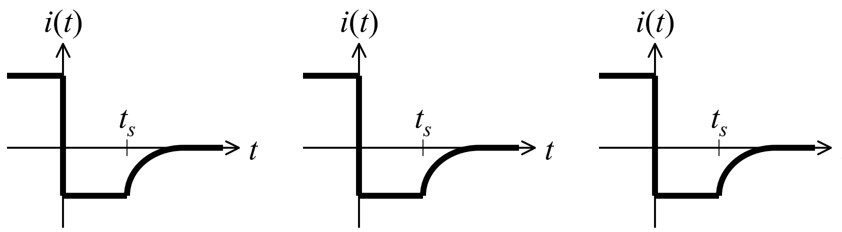




For t > 0: $\left.\frac{dp_n}{dx}\right|_{x=x_n} = -\frac{i}{qAD_p} > 0$

Examples (qualitative)

Increase I_F | Increase I_R | Decrease τ_p



Storage Delay Time t_s

- t_s is the primary "figure of merit" used to characterize the transient response of pn junction diodes

$$\frac{dQ_p}{dt} = i - \frac{Q_p}{\tau_p} = -\left(I_R + \frac{Q_p}{\tau_p}\right) \qquad 0^+ \le t \le t_s$$

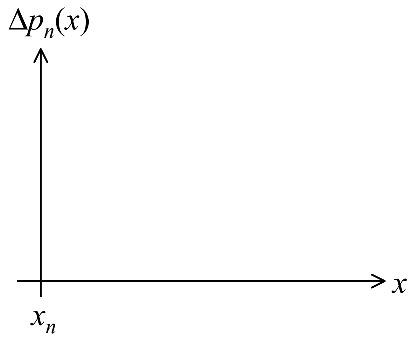
- By separation of variables and integration from $t = 0^+$ to $t = t_s$, noting that $I_F = Q_p(t=0)/\tau_p$

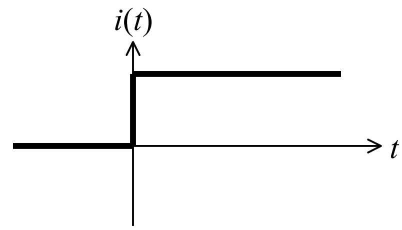
  and making the approximation $Q_p(t = t_s) = 0$

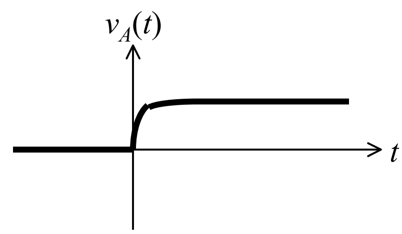
  We conclude that $t_s \cong \tau_p \ln\left(1 + \frac{I_F}{I_R}\right)$

Turn-On Transient

Again, consider a **p⁺n diode** ($Q_p >> Q_n$):







For t > 0: $\left.\dfrac{dp_n}{dx}\right|_{x=x_n} = -\dfrac{i}{qAD_p} < 0$

$$\frac{dQ_p}{dt} = i - \frac{Q_p}{\tau_p} = I_F - \frac{Q_p}{\tau_p} \quad \text{for } t \geq 0^+$$

- By separation of variables and integration, we have

$$Q_p(t) = I_F \tau_p \left(1 - e^{-t/\tau_p}\right)$$

- If we assume that the build-up of stored charge occurs quasi-statically so that

$$Q_p(t) = I_{diffusion} \tau_p = I_0 \left(e^{qv_A/kT} - 1\right)\tau_p$$

then $v_A(t) = \dfrac{kT}{q} \ln\left[1 + \dfrac{I_F}{I_0}\left(1 - e^{-t/\tau_p}\right)\right]$

- If τ_p is large, then the time required to turn on the diode is approximately $\Delta Q/I_F$

$$\text{where} \quad \Delta Q = \Delta Q_p + \Delta Q_j$$

Summary of Important Concepts

- Under **forward** bias, minority carriers are **injected** into the quasi-neutral regions of the diode
- Current flowing across junction is comprised of hole and electron components
- In order for one of these components to be dominant, the junction must be asymmetrically doped

Summary of Important Concepts (cont.)

- The ideal diode equation stipulates the relationship between $J_N(-x_p)$ and $J_P(x_n)$

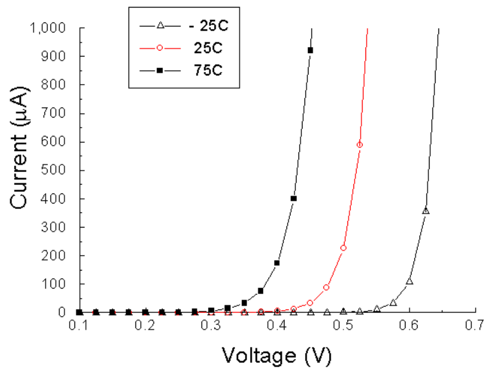
➢ If holes are forced to flow across a forward-biased junction, then electrons must also be injected across the junction

Summary of Important Concepts (cont.)

- Under **reverse** bias, minority carriers are **collected** into the quasi-neutral regions of the diode
- Minority carriers within a diffusion length of the depletion region will diffuse into the depletion region and then be swept across the junction by the electric field.

$\rightarrow$ Current flowing in a reverse-biased diode depends on the rate at which minority carriers are supplied in the quasi-neutral regions

The pn Junction as a Temperature Sensor



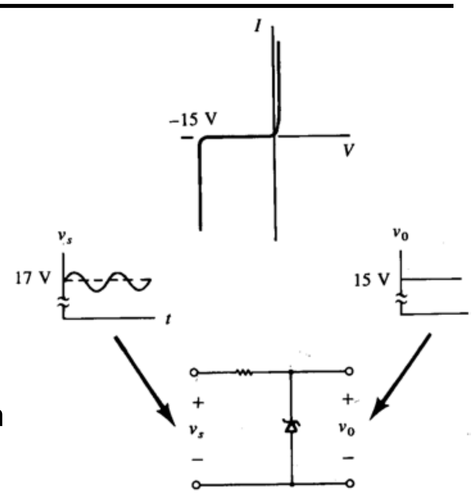
$$I = I_0 (e^{qV/kT} - 1)$$

$$I_0 = Aqn_i^2 \left(\frac{D_p}{L_p N_d} + \frac{D_n}{L_n N_a} \right)$$

What causes the I-V curves to shift to lower V at higher T ?

Zener Diodes

- Diode specifically designed to nondestructively break down at predetermined voltage
- Commonly referred to as Zener diodes (though avalanche is often the more common mechanism)



Varactor Diodes

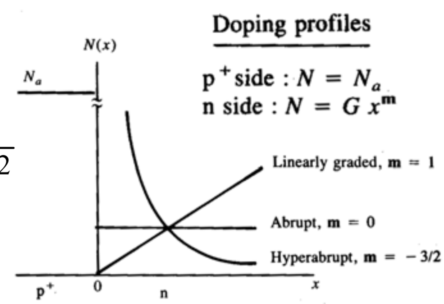
- Voltage-controlled capacitor
  - Used in oscillators and detectors
    (*e.g.* FM demodulation circuits in your radios)
  - Response changes by tailoring doping profile:

$$C_j \propto V_r^{-n}$$

for

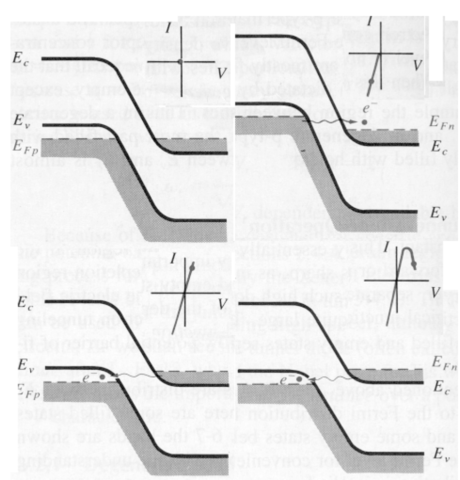
$$V_r >> V_{bi}$$

$$n = \frac{1}{m+2}$$

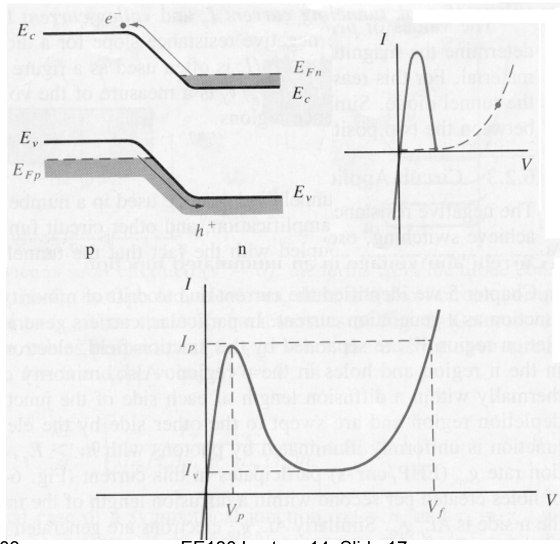


Tunnel Diodes

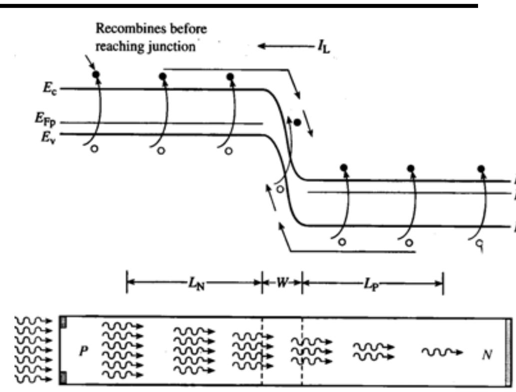
- Degenerately doped such that $E_{Fp} < E_v$ and $E_{Fn} > E_c$
- Can achieve negative differential resistance
  - useful in high-speed circuits and perhaps static memories



Tunnel Diodes (cont.)



Optoelectronic Diodes



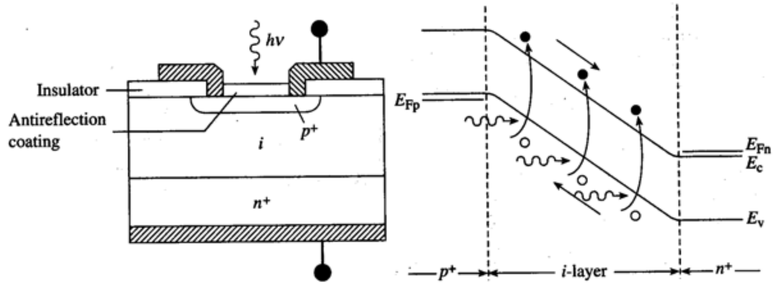
$$I = I_0(e^{qV_A/kT} - 1) - I_{op}$$

$$I_{op} = qAg_{op}(L_P + W + L_N) \sim qAg_{op}(L_P + L_N)$$

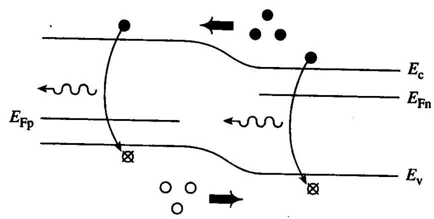
$$V_{oc} = V_A\Big|_{I=0} = \frac{kT}{q}\ln\left[\frac{L_p + L_n}{\left(\frac{L_p}{\tau_p}\right)p_n + \left(\frac{L_n}{\tau_n}\right)n_p} g_{op} + 1\right]$$

p-i-n Photodiodes

- $W \cong W_{\text{i-region}}$, so most carriers are generated in the depletion region
  → faster response time (~10 GHz operation)
- Operate near avalanche to amplify signal

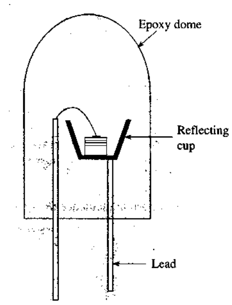


Light Emitting Diodes (LEDs)



Semiconductor	*Color*	*Peak λ(μm)*
$GaAs_{0.6}P_{0.4}$	Red	0.650
$GaAs_{0.35}P_{0.65}$:N	Orange-Red	0.630
$GaAs_{0.14}P_{0.86}$:N	Yellow	0.585
GaP:N	Green	0.565
GaP:Zn-O	Red	0.700
AlGaAs	Red	0.650
AlInGaP	Orange	0.620
AlInGaP	Yellow	0.585
AlInGaP	Green	0.570
SiC	Blue	0.470
GaN	Blue	0.450

•LEDs are typically made of compound semiconductors (direct bandgap)



Organic LEDs

- Some organic materials exhibit semiconducting properties
  - OLEDs are attractive for low-cost, high-quality flat-panel displays