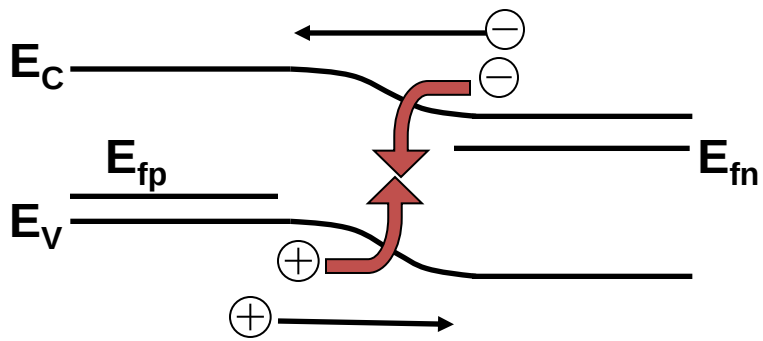
Diode Nonidealities
Transient characteristics

EECS 320

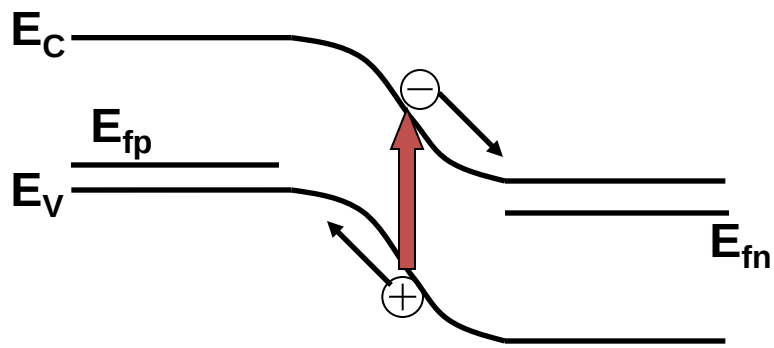
Introduction to Semiconductor Devices

R-G In Depletion Region

In forward bias, injected carriers recombine in depletion region



In reverse bias, carriers generated in depletion region



How does the I-V relation of the diode change if R-G in depletion region is accounted for?

R-G Current

$$I_{R-G} = qA \int_{-x_p}^{x_n} \left. \frac{\partial n}{\partial t} \right|_{R-G} dx$$

Solution not simple, bias-dependent

$$\left. \frac{\partial n}{\partial t} \right|_{R-G} = -\frac{np - n_i^2}{\tau_p (n + n_1) + \tau_n (p + p_1)}$$

$$\boxed{I_{R-G} \approx -\frac{qAn_i}{2\tau_0} W}$$

Significant reverse bias (> few kT/q)

$$\boxed{I_{R-G} \approx \frac{qAn_i}{2\tau_0} W e^{qV_A/2kT}}$$

Small forward bias

R-G In Depletion Region, Reverse Bias

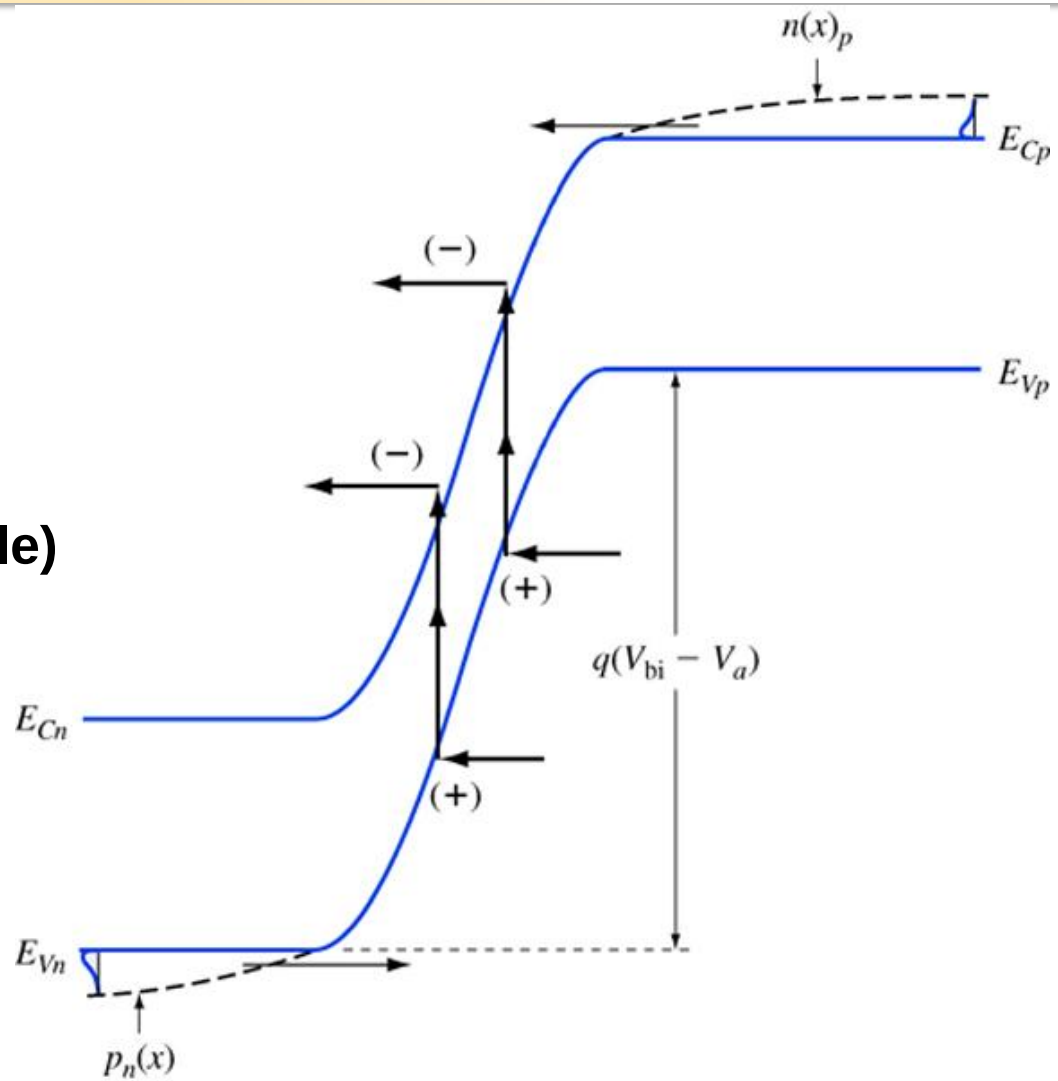
For traps at E_i, $\tau_n=\tau_p$

$$R-G=\frac{np-n_i^2}{\tau_0\left(n+n_i+p+n_i\right)}$$

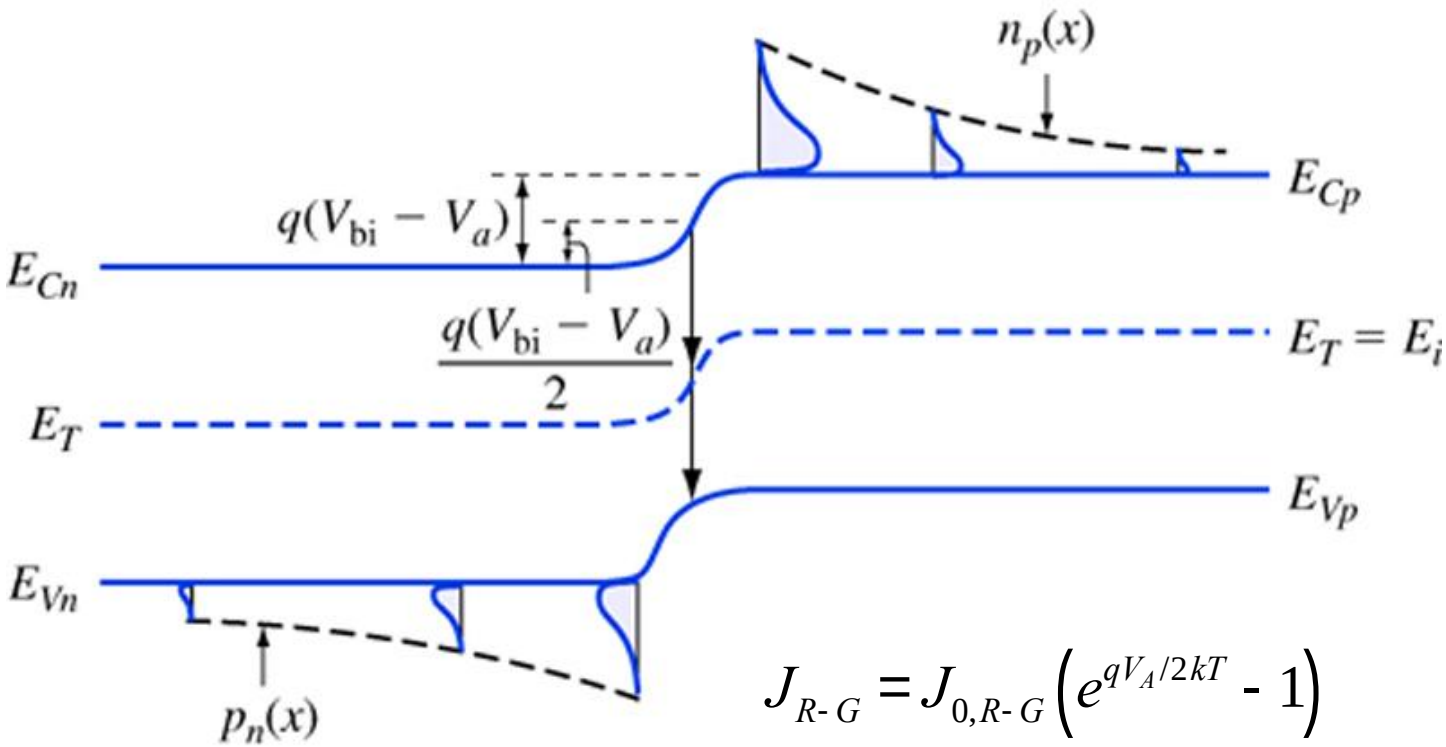
At reverse bias (n, p negligible)

$$R-G=-\frac{n_i}{2\tau_0}$$

$$J_{R\text{-}G}=q(R\text{-}G)w=\text{-}\,q\frac{n_i}{2t_0}w$$



R-G In Depletion Region, Forward Bias



$$J_{R\text{-}G} = J_{0,R\text{-}G}\left(e^{qV_A/2kT} - 1\right)$$

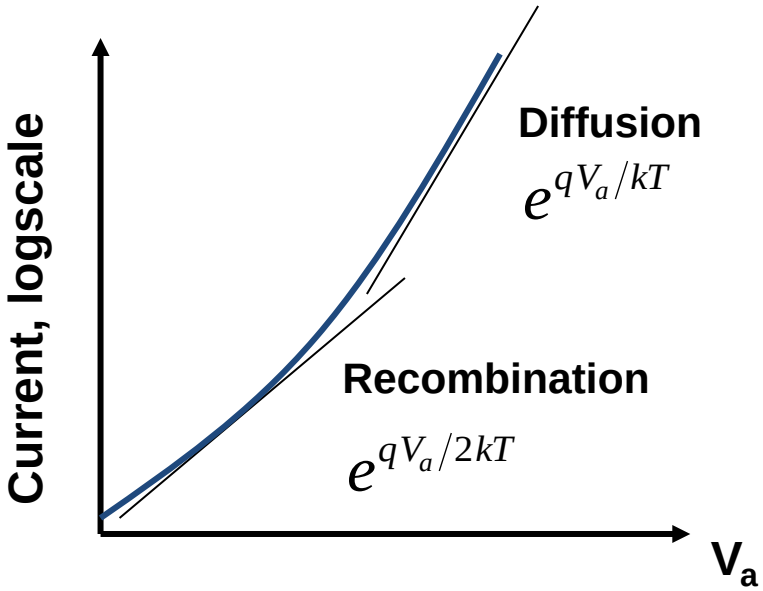
$$R - G = \frac{np}{\tau_0(n+p)} = \frac{n_i^2 e^{qV_A/kT}}{\tau_0(n+p)}$$

$$J_{0,R\text{-}G} \gg \frac{qn_i}{2t_0}W$$ (Small forward bias)

$$(R-G)_{\max} = \frac{n_i e^{qV_A/2kT}}{2\tau_0}$$

$$J_{total} = J_{0,R\text{-}G}\left(e^{qV_A/2kT} - 1\right) + J_0\left(e^{qV_A/kT} - 1\right)$$

Diffusion and R-G Current



- Recombination dominant at low bias
- Diffusion dominates at larger bias
- Recombination often represented by non-ideality factor (n) at given bias

$$J_{total} = J_{diff} + J_{R\text{-}G}$$

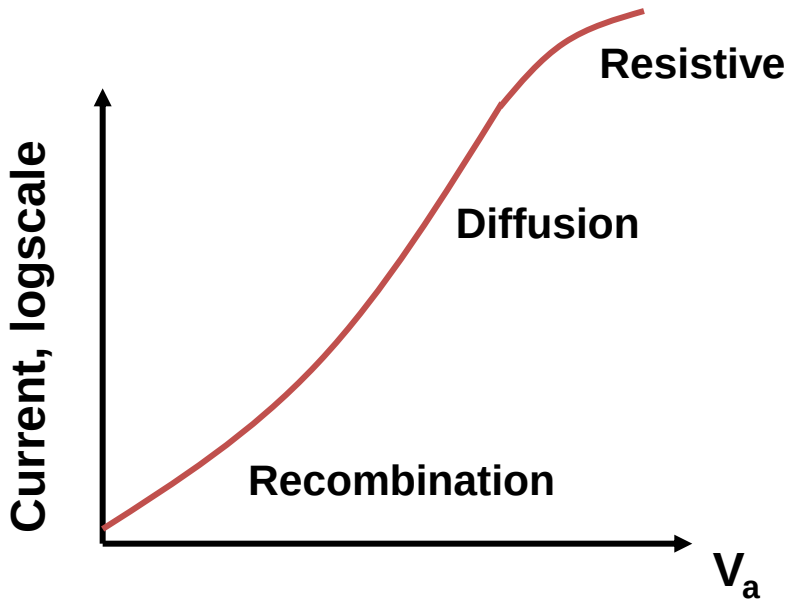
$$J_{total} = J_0^{diff}\left(e^{qV_A/kT} - 1\right) + J_0^{R\text{-}G} e^{qV_A/2kT}$$

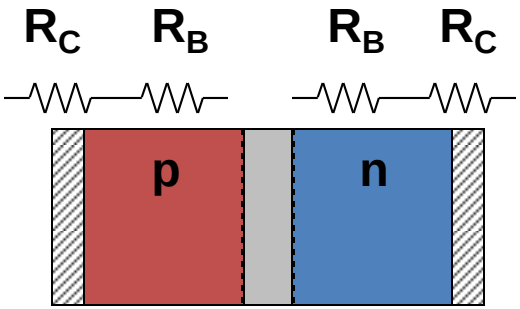
$$J_{total} = J_0\left(e^{qV_A/nkT} - 1\right)$$

High Current Levels

At high forward bias, I-V becomes resistive

- Resistive drop across bulk semiconductor regions
- Contact resistance
- High-level injection: minority carrier density approaches majority carrier density





Bandgap Dependence Of I-V

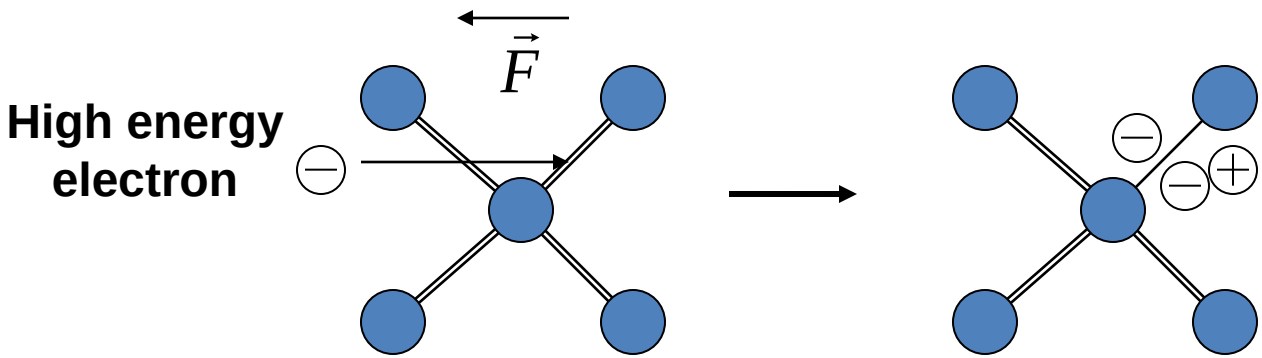
How does bandgap affect I-V characteristics?

Reverse Bias? Forward Bias?

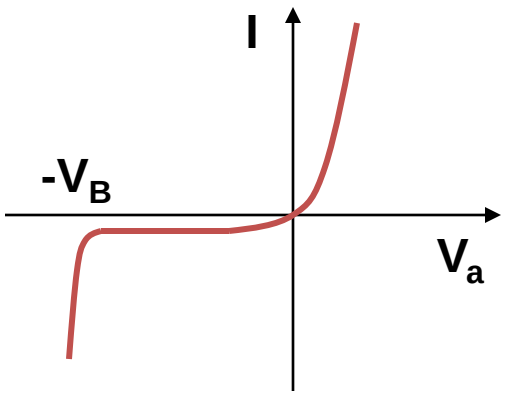
Does bandgap change the effect of SCG?

Avalanche Breakdown

At high fields (reverse bias), high energy scattering can break electron bond in lattice



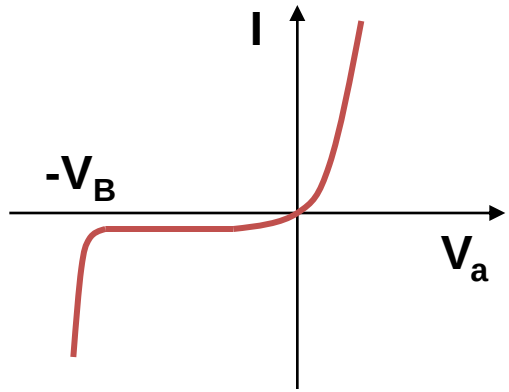
- "Impact Ionization"
- Created carriers can further contribute to process
- Multiplicative or "Avalanche" process



$$V_B \approx 60\left(E_G/1.1\right)^{3/2}\left(10^{16}/N_B\right)^{3/4} \quad [V]$$

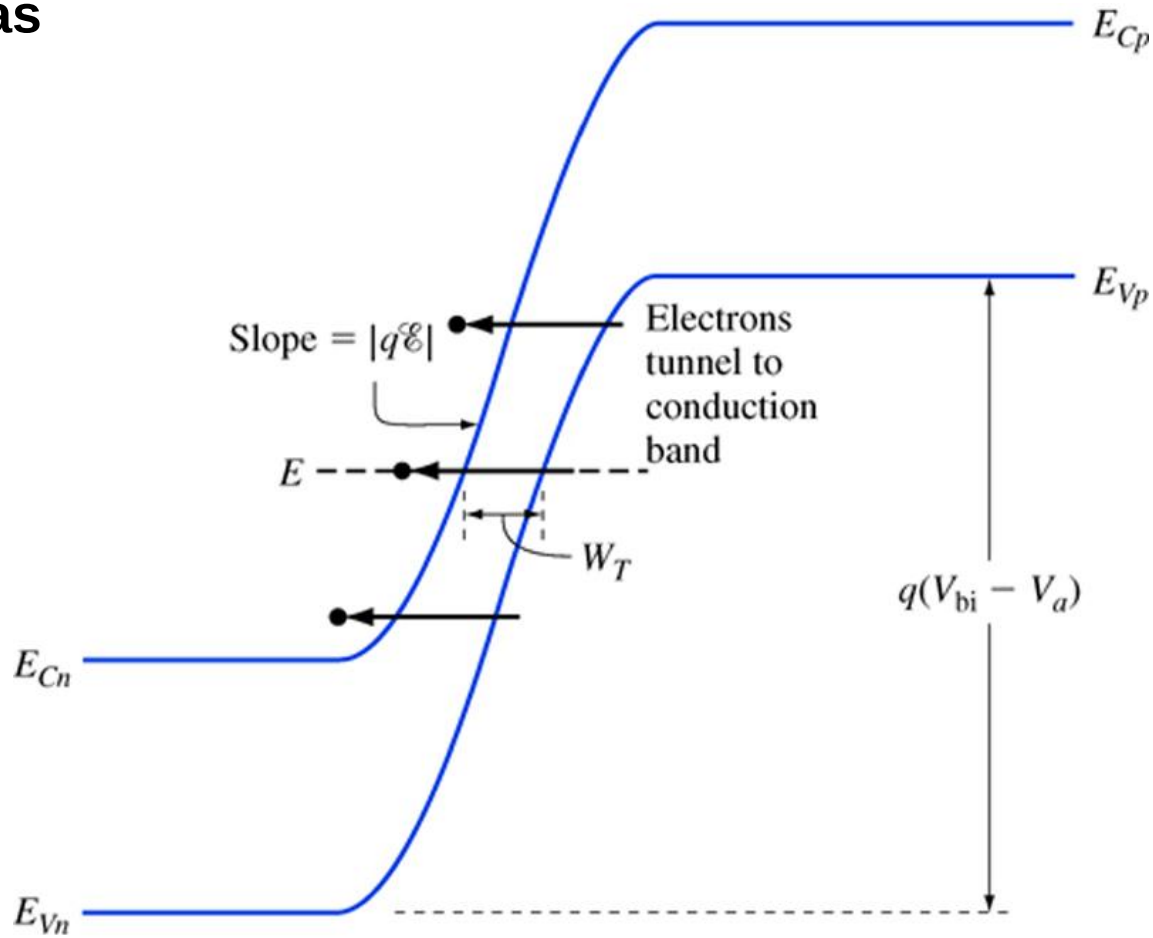
Reverse Bias Tunneling

Breakdown in reverse bias



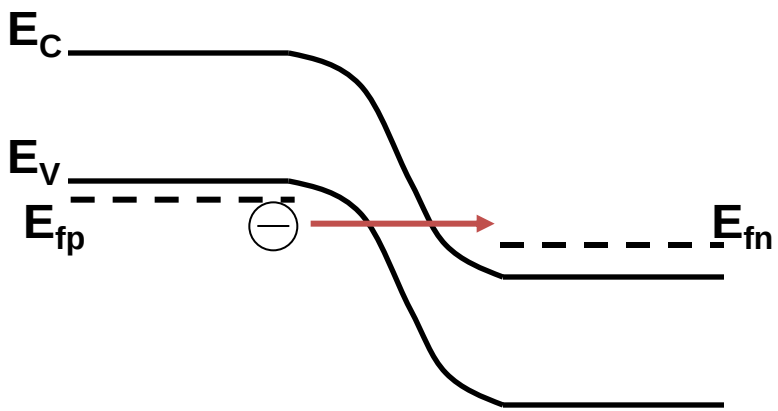
Tunneling probability

$$T = e^{-\pi W_T} \frac{\sqrt{m^* E_g}}{2^{3/2}\hbar}$$



Tunneling – Zener Breakdown

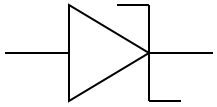
Narrow depletion region widths in reverse bias can enable quantum mechanical tunneling

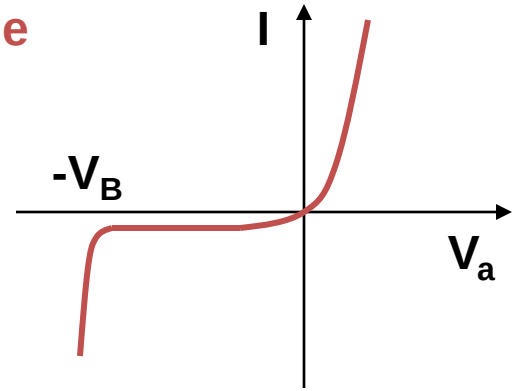


Tunneling Probability

$$T \approx \exp\left(-\frac{4\sqrt{2m^*}}{3q\hbar F}E_G^{3/2}\right)$$

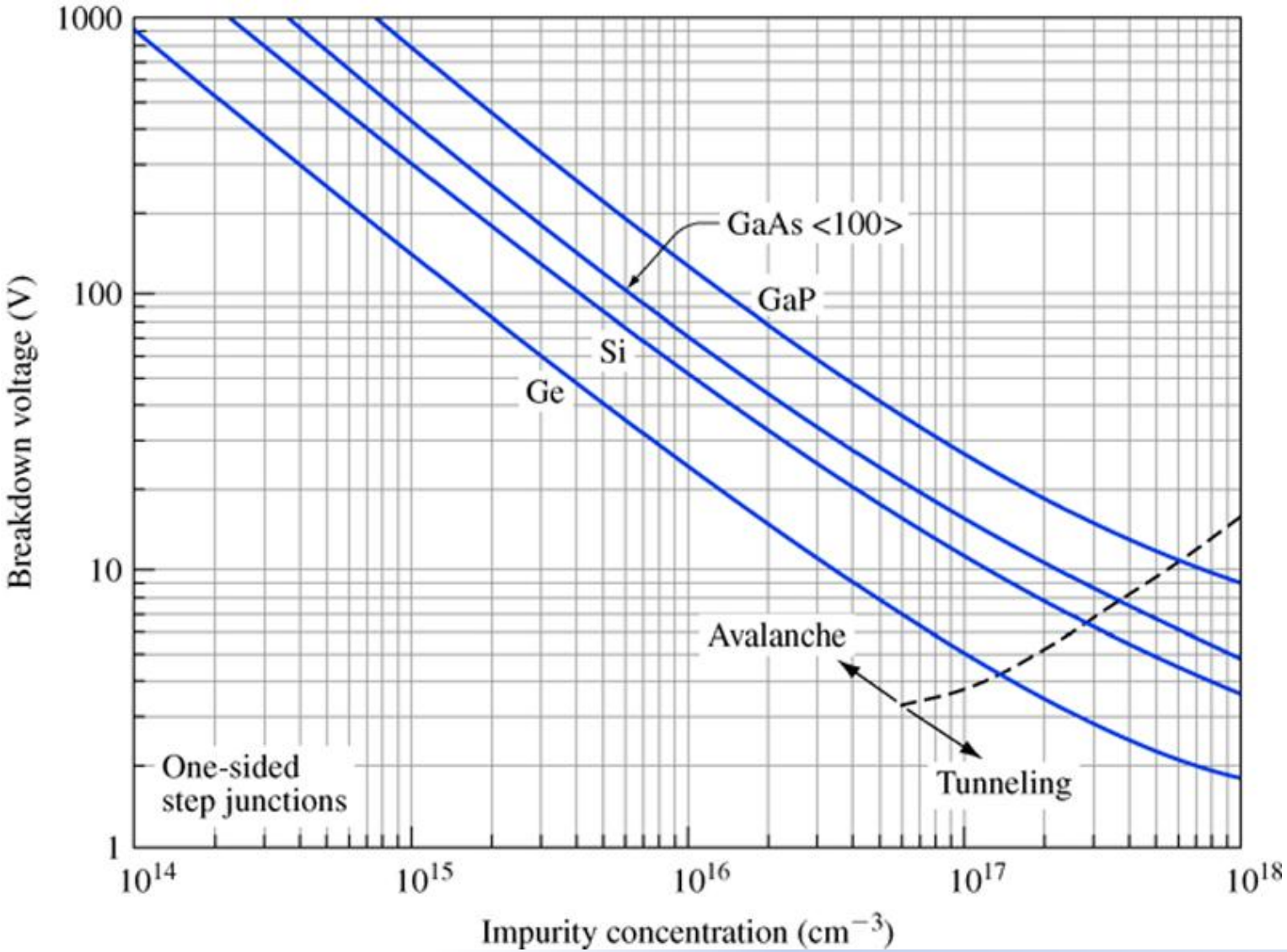
Useful Device: Zener Diode





- Voltage regulator
- Convert sinusoidal to square-wave

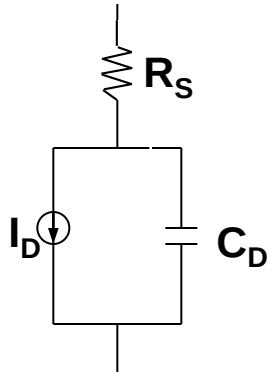
Reverse Bias Breakdown



Transient Response

Large Signal

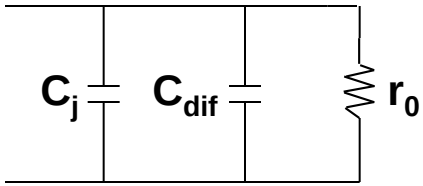
- Switching applications
- Fwd ↔ Rev bias
- Charge storage and extraction



SPICE useful for transient analysis

Small Signal

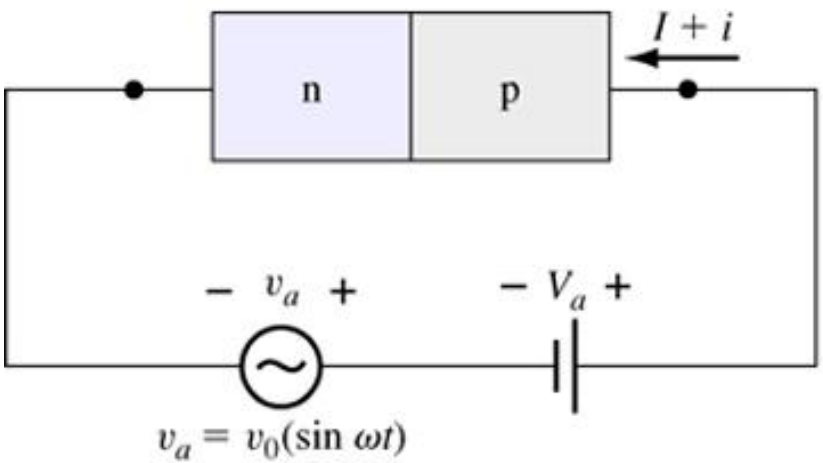
- Small AC bias
- Equivalent circuit
- Frequency response

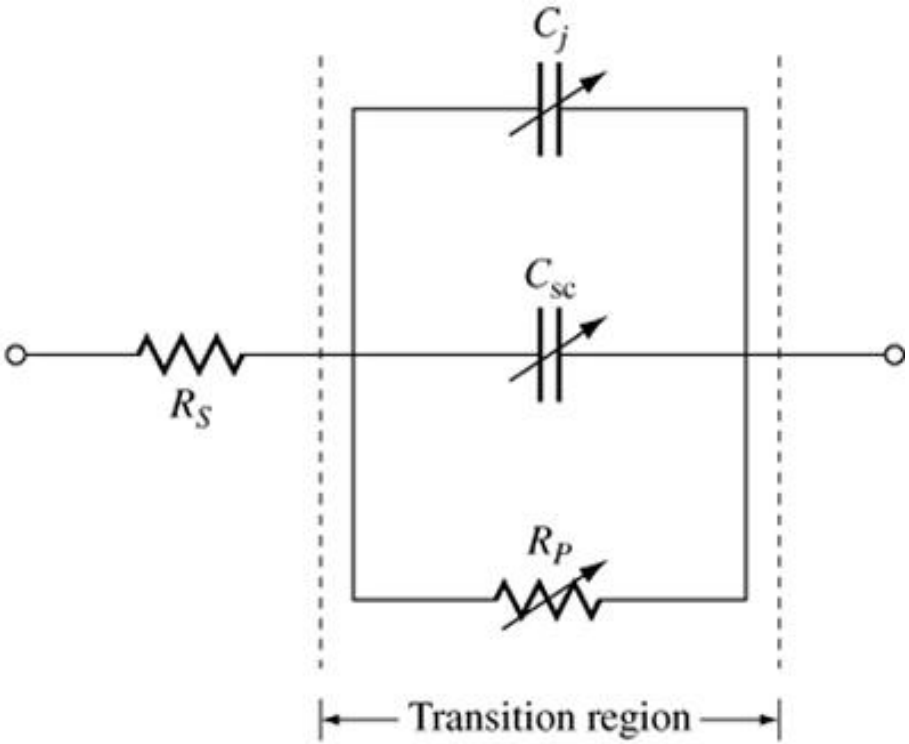


Equivalent circuit useful for small-signal analysis

Small Signal AC Response

Determine equivalent RC circuit to represent diode





R_S= series resistance of contacts and quasi-neutral bulk regions

Determine remaining R_P, C_j, and C_{sc}

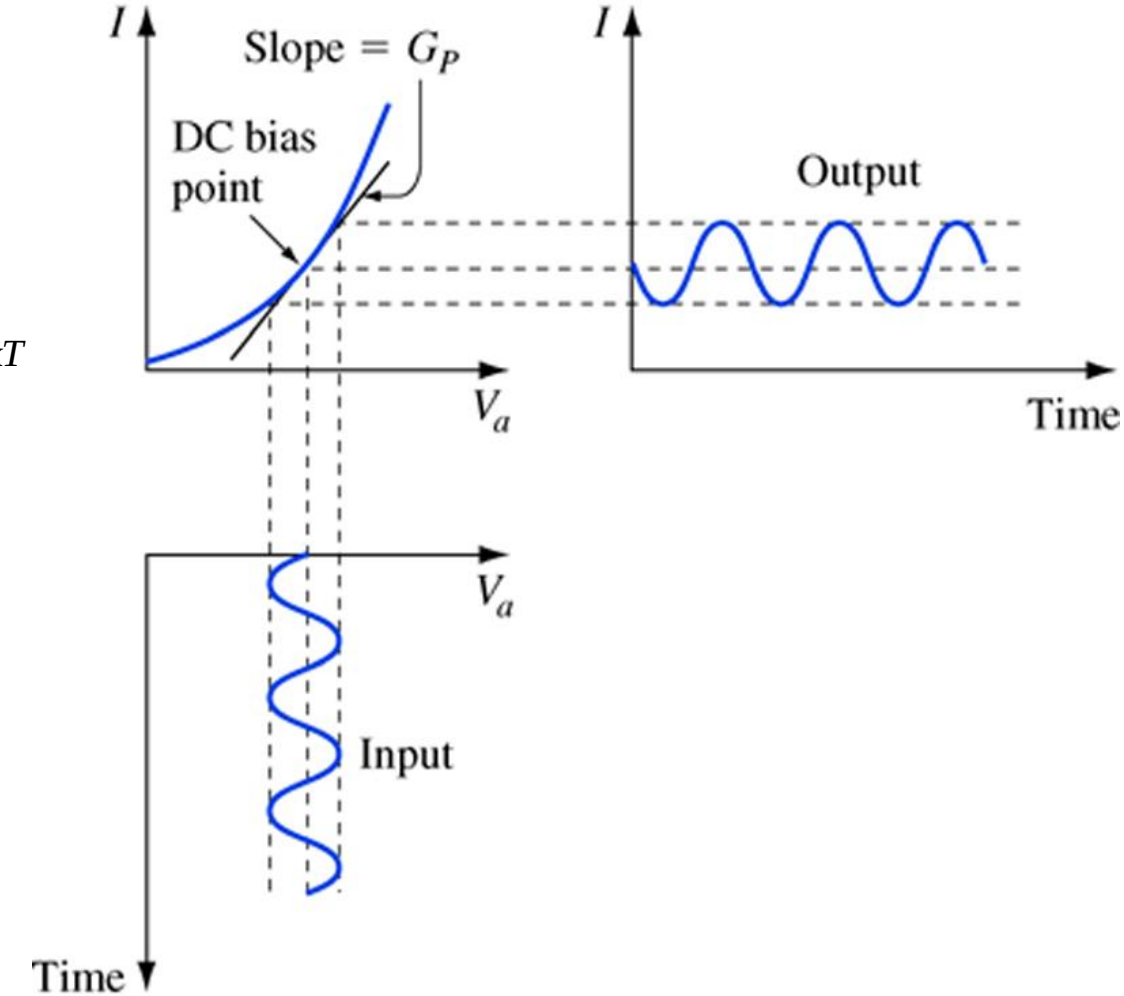
Junction Resistance

$$R_P = \frac{1}{G_P} = \left(\frac{dI}{dV_A}\right)^{-1}$$

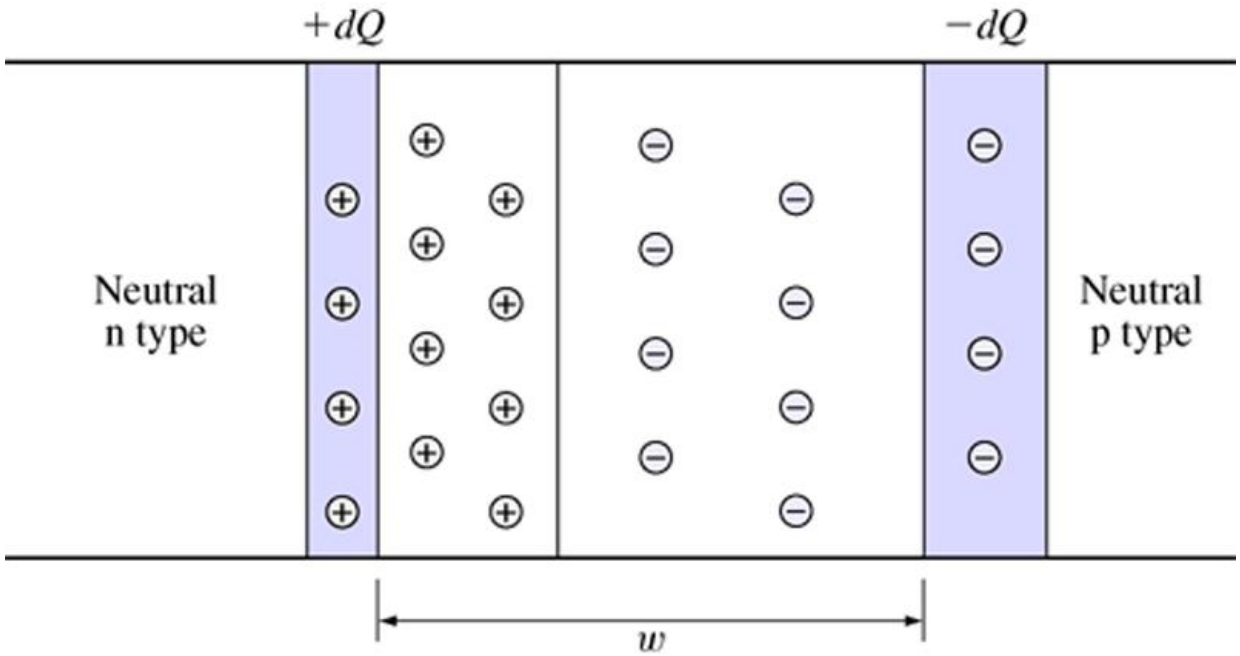
$$I = I_0\left(e^{qV_A/kT} - 1\right) \approx I_0 e^{qV_A/kT}$$

$$\frac{dI}{dV_A} = \frac{q}{kT} I_0 e^{qV_A/kT} = \frac{qI}{kT}$$

$$\boxed{R_P = \frac{kT}{qI}}$$



Junction Capacitance



$$C_{diff} = \left|\frac{dQ}{dV}\right| \qquad |Q| = qN_aW_pA = qN_dW_nA$$

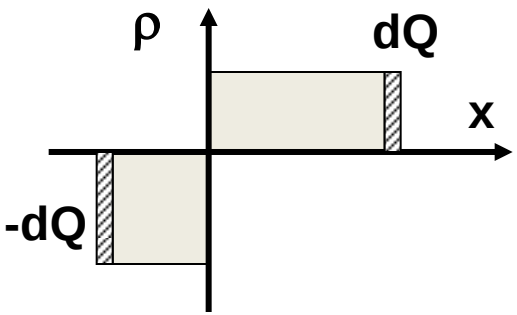
Change in depletion region fixed charge

$$\boxed{C_j = A\sqrt{\frac{q\varepsilon N_a N_d}{2(V_{bi}-V_a)(N_d+N_a)}} = \frac{\varepsilon A}{W}} \qquad C_j = C_{j0}\sqrt{\frac{V_{bi}}{(V_{bi}-V_a)}}$$

Junction Capacitance

Differential Capacitance

$$C_{diff} = \left| \frac{dQ}{dV} \right|$$

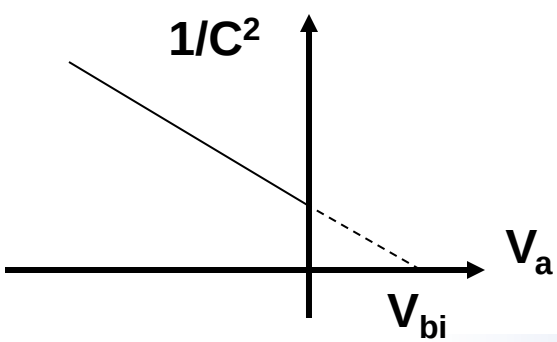


Capacitance associated with depletion region

$$|Q| = qN_a W_p A = qN_d W_n A$$

$$\boxed{C_j = A\sqrt{\frac{q\varepsilon N_a N_d}{2(V_{bi} - V_a)(N_d + N_a)}} = \frac{\varepsilon A}{W}}$$

$$C_j = C_{j0}\sqrt{\frac{V_{bi}}{(V_{bi} - V_a)}}$$



Depletion capacitance is proportional to applied voltage, Used as a voltage-dependent capacitor (varactor)

Capacitance In P-N Diode

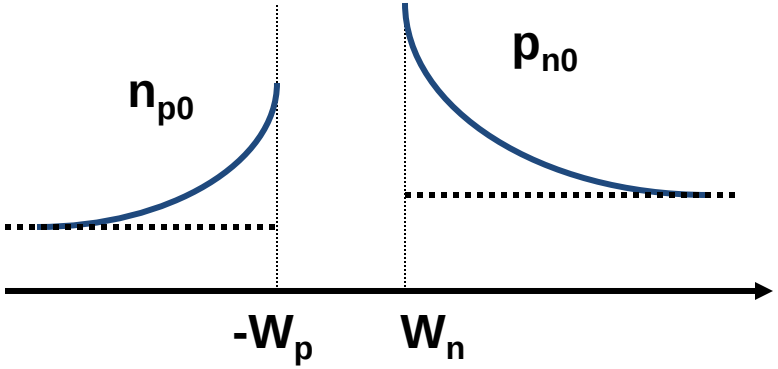
Sketch *mobile* charge density for p-n diode in forward and reverse bias

Is there another source of capacitance?

Diffusion Capacitance

Excess minority carrier density near depletion region edge is stored charge : capacitance

$$C_{diff} = \left| \frac{dQ}{dV} \right|$$



$$Q_p = qA\int_{x_n}^{\infty} \left[p_n(x) - p_{n0} \right] dx$$

$$Q_p = qAp_{n0}L_p\left(e^{qV_a/kT} - 1\right)$$

$$Q_p = J_{p_n}(x_n)A\tau_p = I_d\tau_p$$

$$\boxed{C = \frac{q}{kT}\tau_p I_S e^{qV_a/kT}}$$

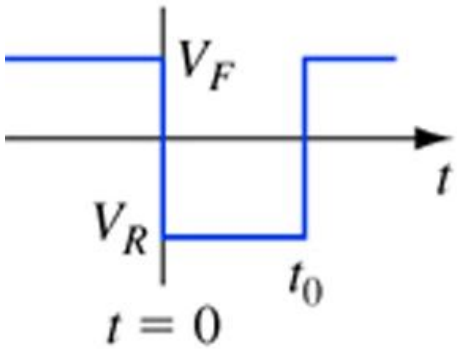
For short diode

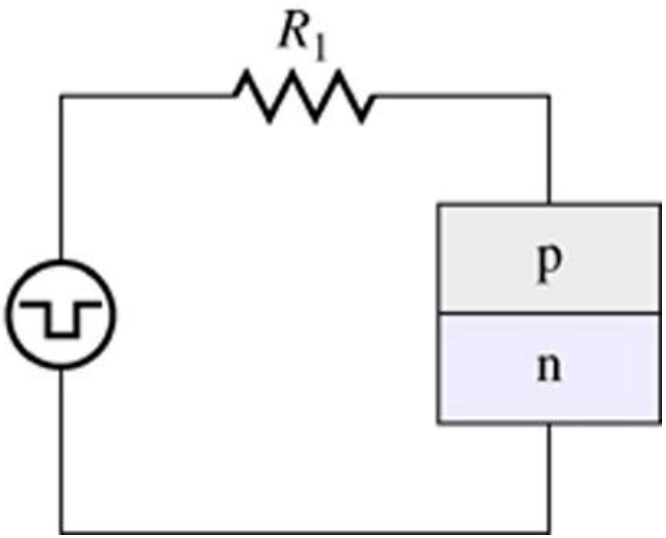
$$\boxed{C = \frac{q}{kT}\tau_D I_p}$$

τ_D = transit time

Transient Response

Determine the speed at which a diode will switch between forward and reverse bias

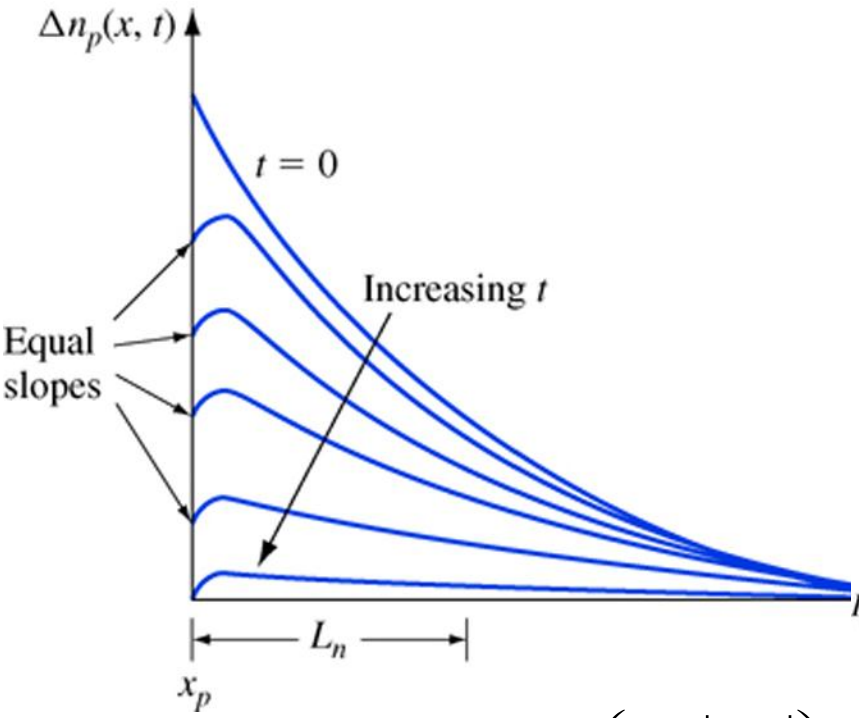




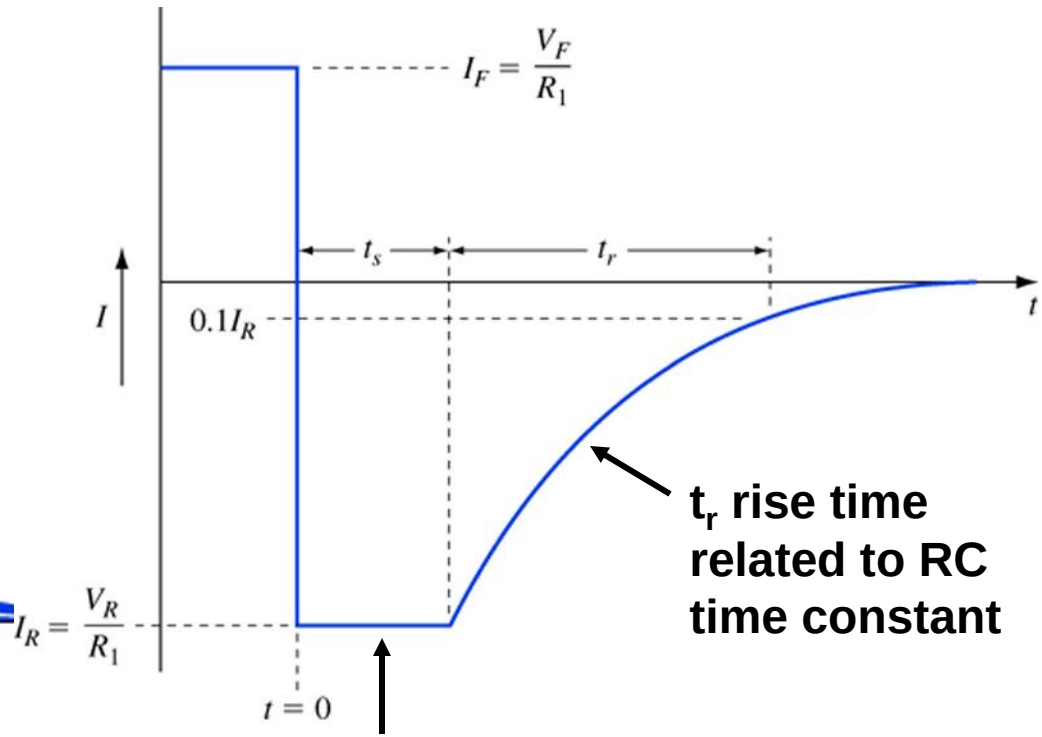
Turn-Off Transient

In forward bias, large minority carrier storage

Minority carrier profile



Current transient



t_r rise time related to RC time constant

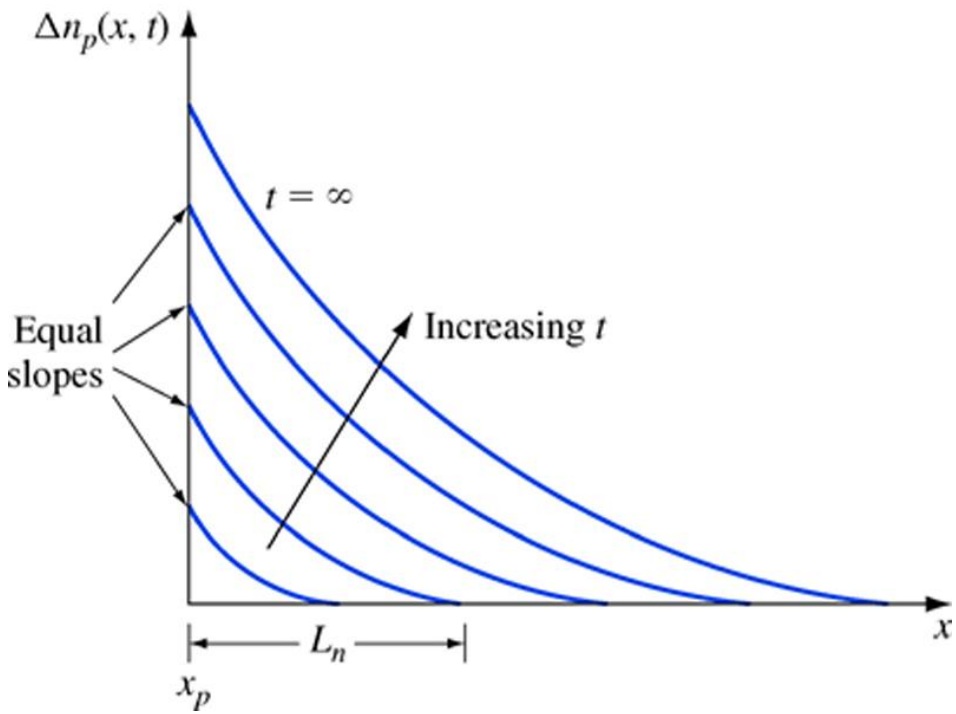
t_s storage time to remove stored minority carriers

$$t_s \approx \tau_n \ln\left(1 + \left|\frac{I_F}{I_R}\right|\right)$$

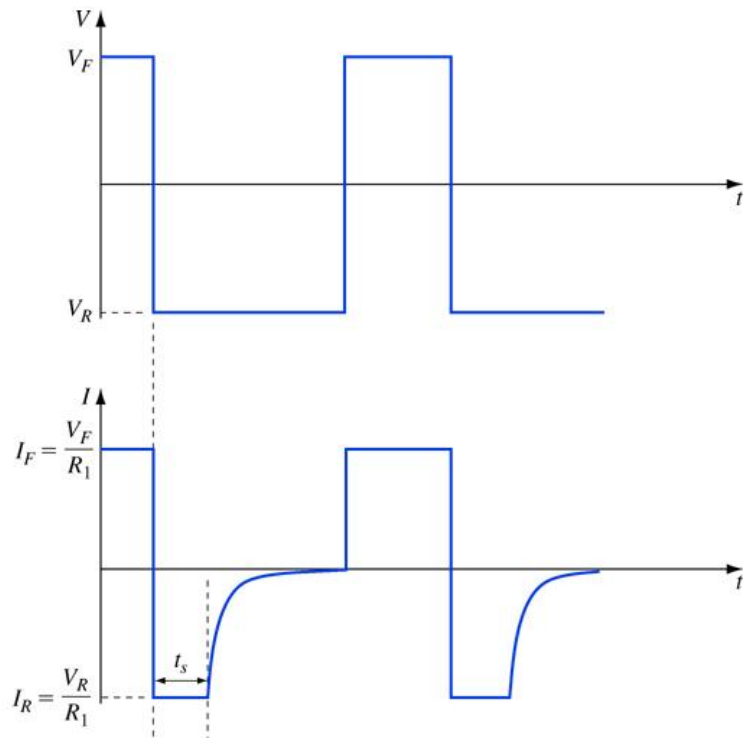
Turn-On Transient

To reach forward bias, need to discharge junction capacitance and inject minority carriers

Minority carrier profile



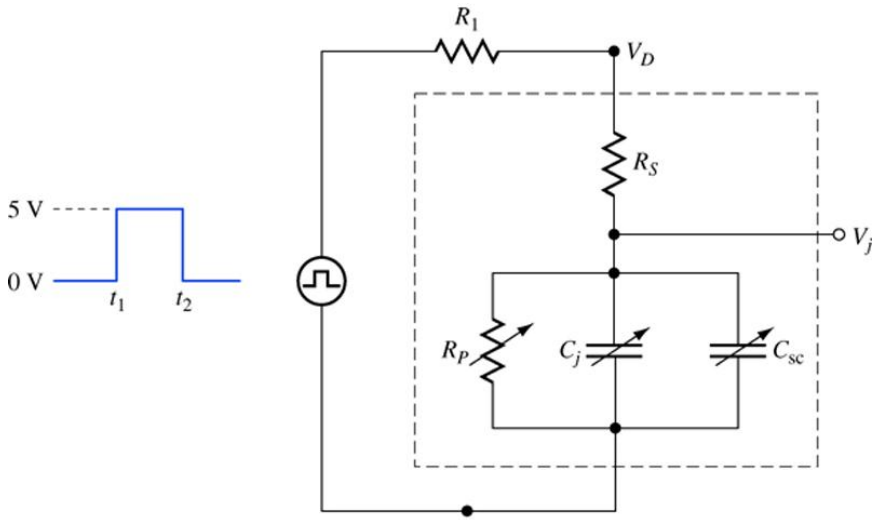
Current transient



Charge to discharge junction capacitance small, carrier injection fast: turn-on transient much faster than turn-off

Circuit Model For Switching

Equivalent circuit for simulation (SPICE, etc)



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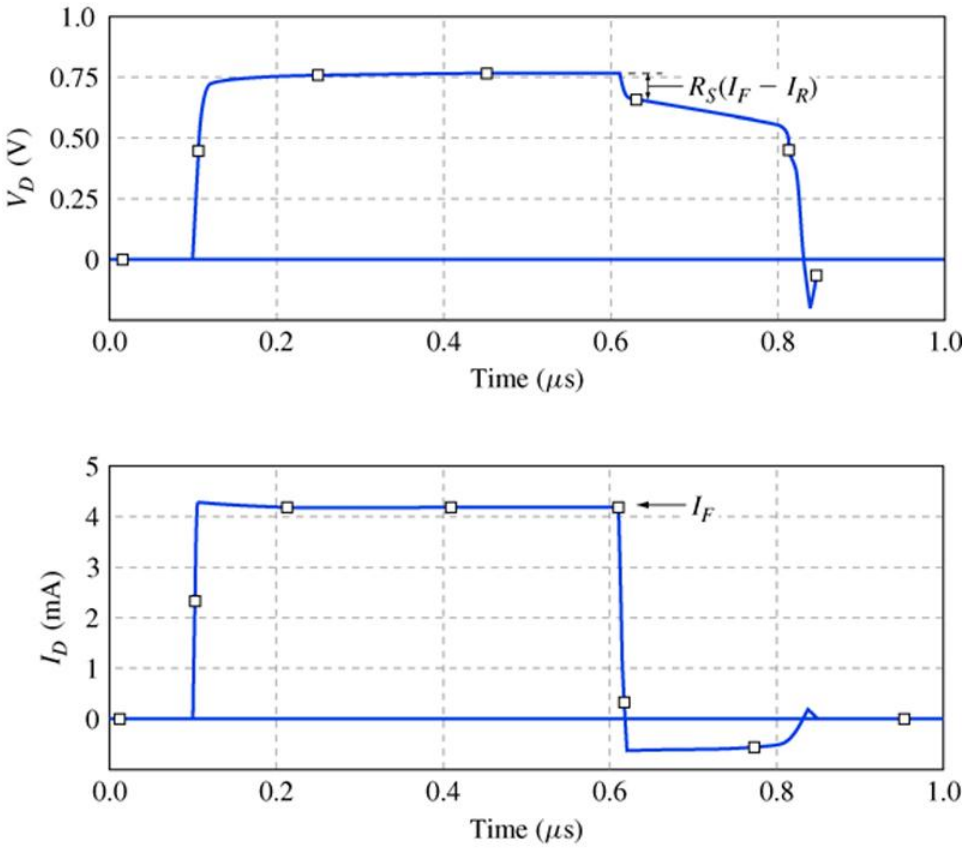

(b)