Lecture 07
EE 2303/001-Electronics I
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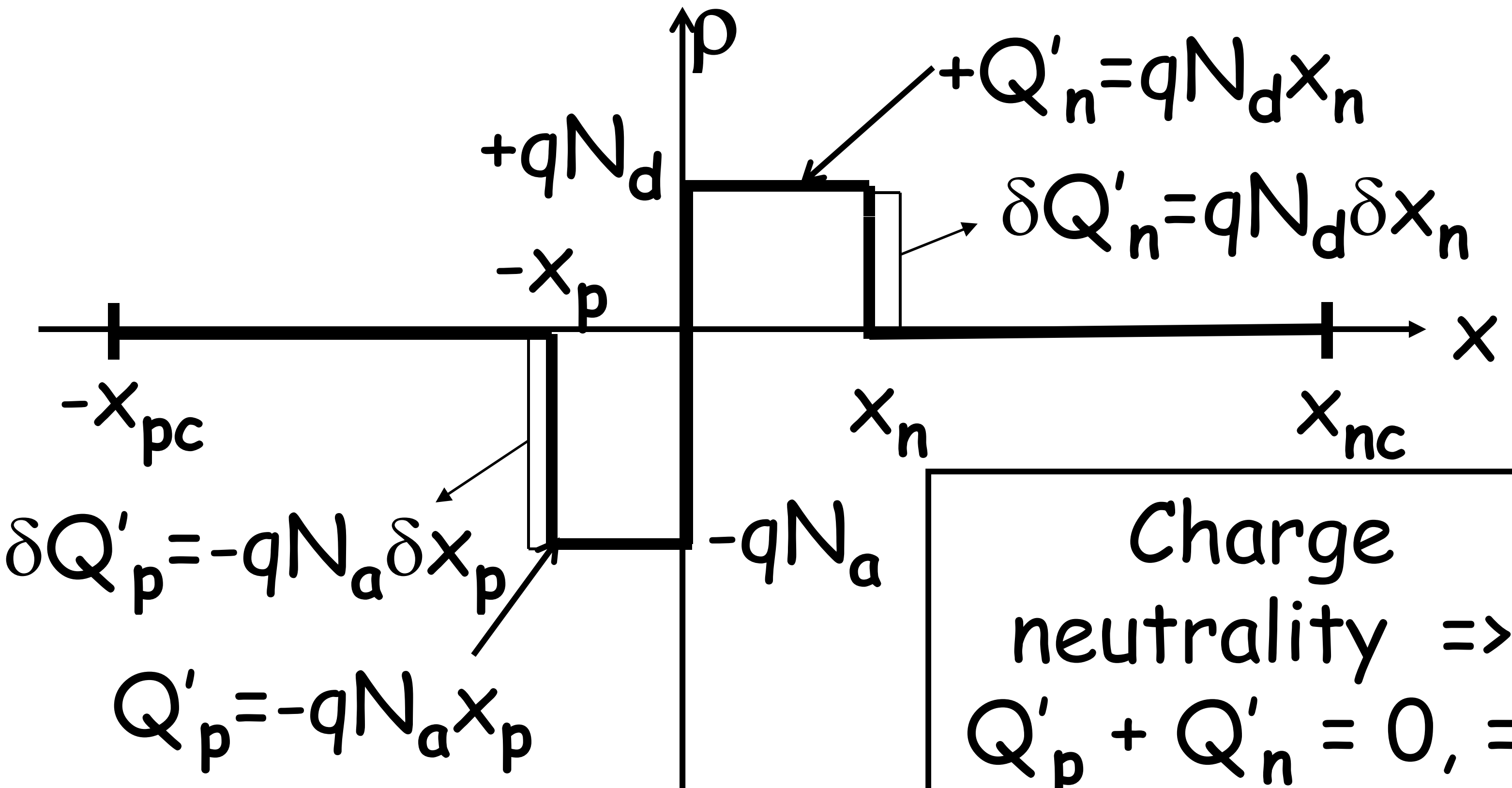
Professor Ronald L. Carter
ronc@uta.edu
http://www.uta.edu/ronc/

Junction C (cont.)

$$\delta Q_j = \delta Q'_n A$$



Charge neutrality =>
$Q'_p + Q'_n = 0$, =>
$N_a x_p = N_d x_n$

Junction Depletion Capacitance

- The C-V model for a step junction is

$$C_j = C_{j0}\left[1 - \frac{V_a}{V_{bi}}\right]^{-\frac{1}{2}}, V_{bi} = V_t \ln\left(\frac{N_a N_d}{n_i^2}\right)$$

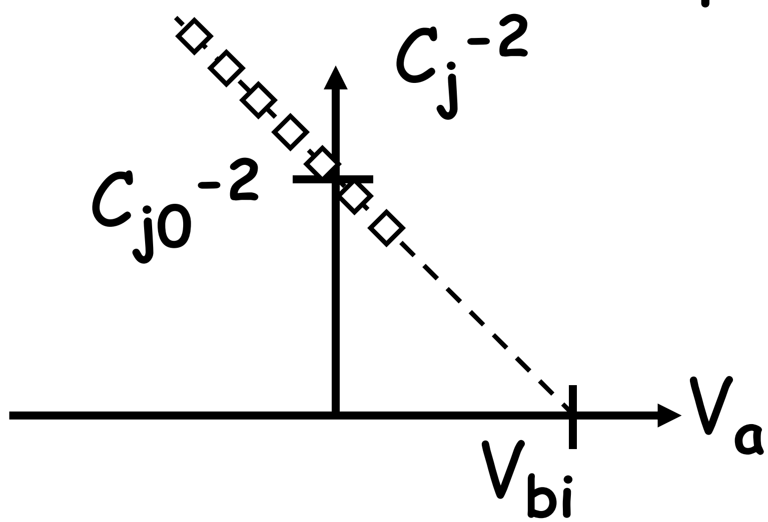
$$C_{j0} = A\sqrt{\frac{\varepsilon q N_{eff}}{2V_{bi}}} = \varepsilon \frac{A}{W_{depl}}, \varepsilon = \varepsilon_r \varepsilon_0$$

$$\varepsilon_{r,Si} = 11.7,\ \ \varepsilon_0 = 8.85 \times 10^{-14}\ \mathrm{Fd/cm}$$

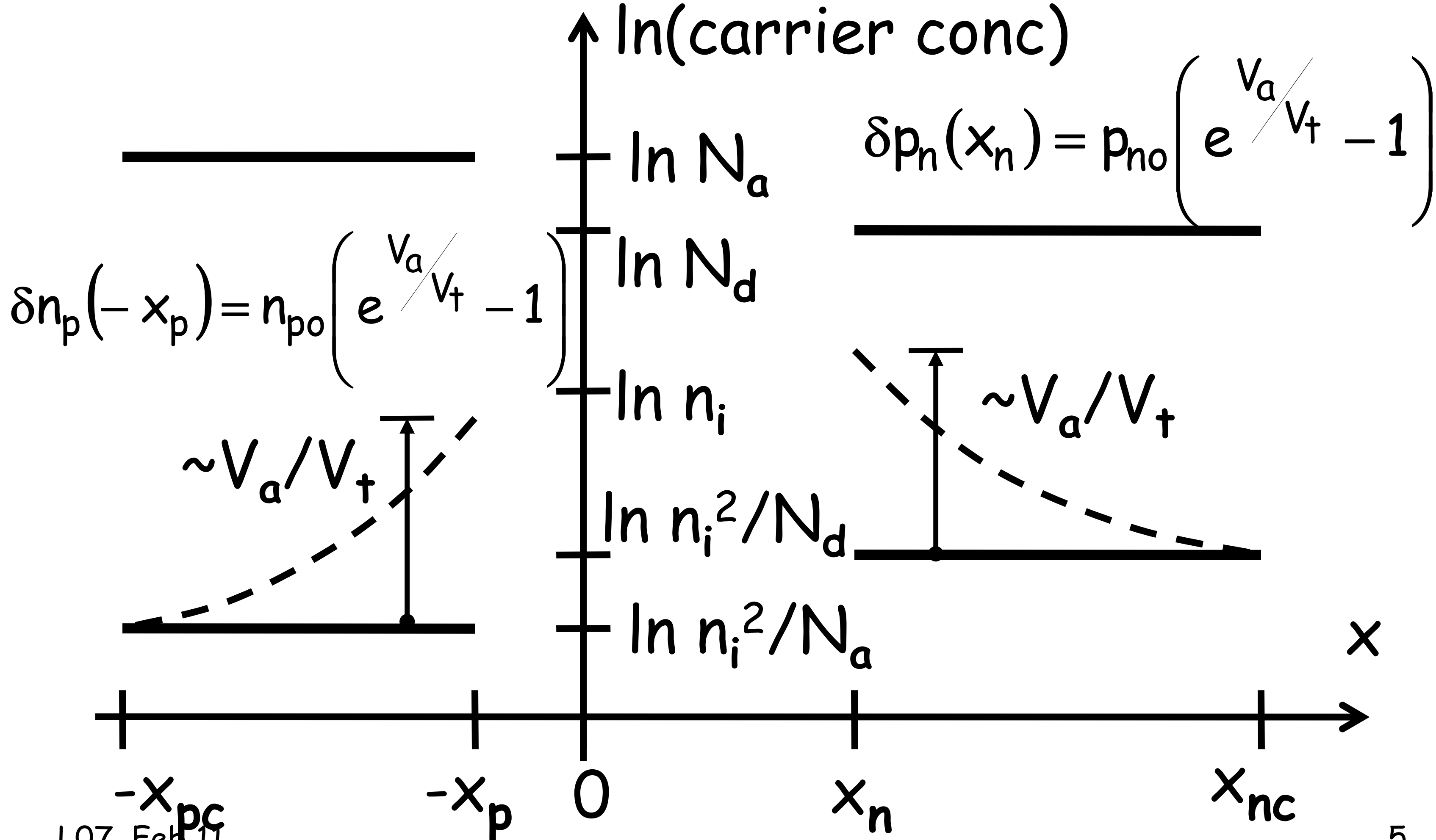
$$q = 1.602 \times 10^{-19}\,\mathrm{Coul.},\ \ V_t = 25.852\,\mathrm{mV}$$

Junction C (cont.)

- If one plots $[C_j]^{-2}$ *vs.* V_a
  Slope = $-[(C_{j0})^2 V_{bi}]^{-1}$
  vertical axis intercept = $[C_{j0}]^{-2}$
  horizontal axis intercept = V_{bi}



Carrier Injection and diff.



Ideal diode equation

- $I = I_s\,[\exp(V_a/nV_t)-1]$, $I_s = I_{sn} + I_{sp}$

Long diode: $W_n >> L_p$, or $W_p >> L_n$

$$I_{sn} = qn_i^2 A \frac{D_n}{N_a L_n}, \text{ and } I_{sp} = qn_i^2 A \frac{D_p}{N_d L_p}$$

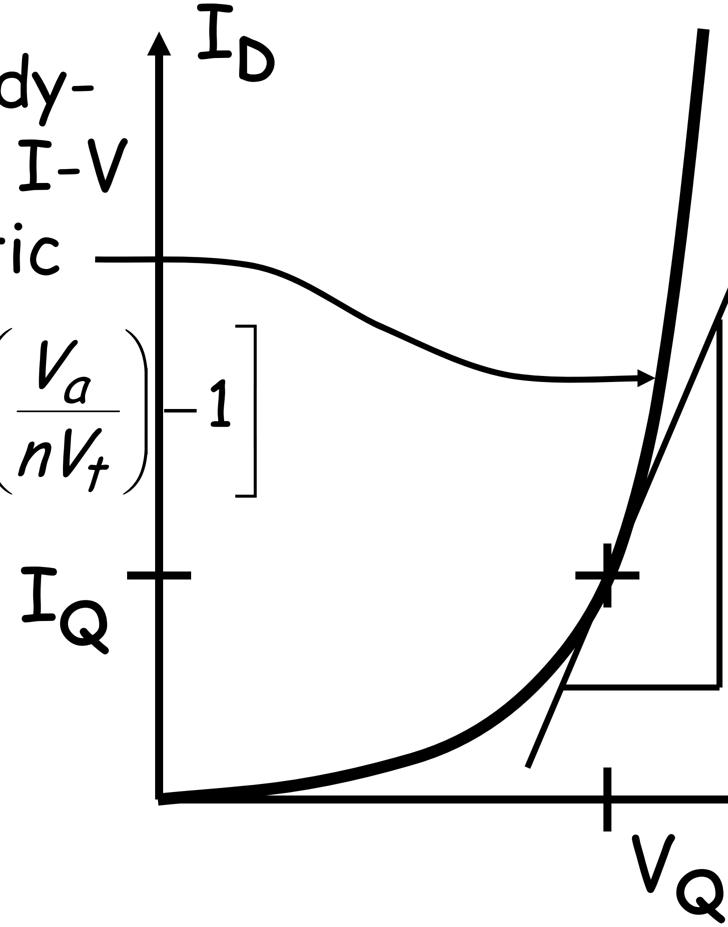
Short diode: $W_n << L_p$, or $W_p << L_n$

$$I_{sn} = qn_i^2 A \frac{D_n}{N_a W_p}, \text{ and } I_{sp} = qn_i^2 A \frac{D_p}{N_d W_n}$$

Diffnt'l, one-sided diode conductance

Static (steady-state) diode I-V characteristic

$$I_D = I_s\left[\exp\left(\frac{V_a}{nV_t}\right)-1\right]$$



$$g_D \equiv \left[\frac{dI_D}{dV_a}\right]_{V_Q}$$

Diffnt'l, one-sided diode cond. (cont.)

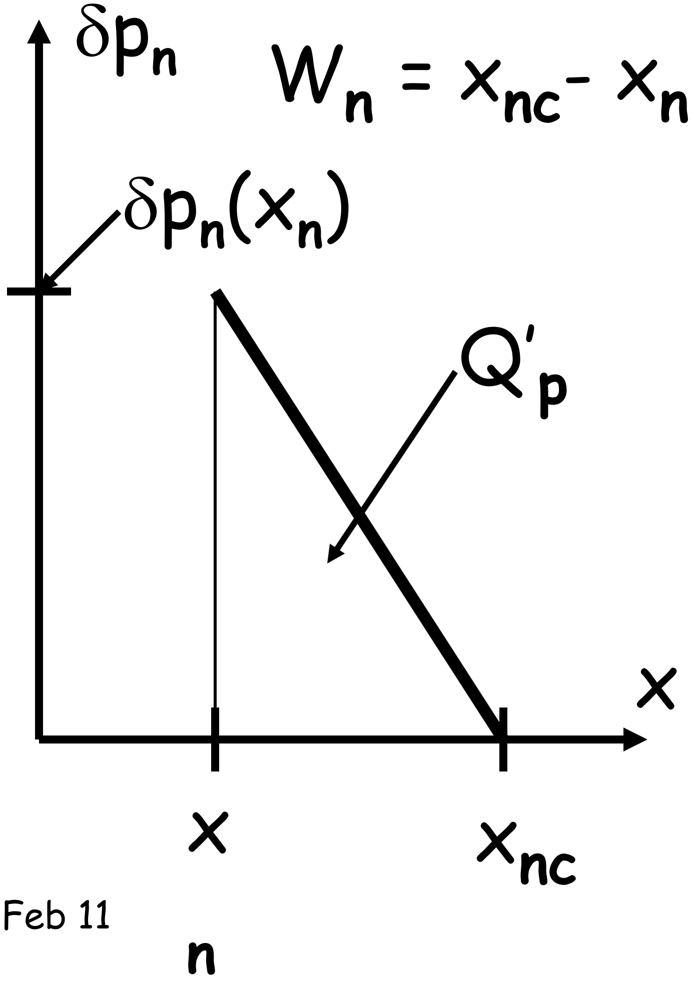
$$I_D = JA = J_s A\left[\exp(V_a / nV_t) - 1\right] = I_s\left[\exp(V_a / nV_t) - 1\right]$$

$$g_d(V_Q) = \left[\frac{dI_D}{dV_a}\right]_{V_Q} = \frac{I_s \exp(V_Q / nV_t)}{V_t}.$$ If $V_a > V_t$,

then $g_d(V_Q) = \dfrac{I_{DQ}}{nV_t}$, where $I_{DQ} = I_D(V_Q)$.

The diode resistance, $r_d(V_Q) = \dfrac{1}{g_d} = \dfrac{nV_t}{I_{DQ}}$

Charge distr in a (1-sided) short diode

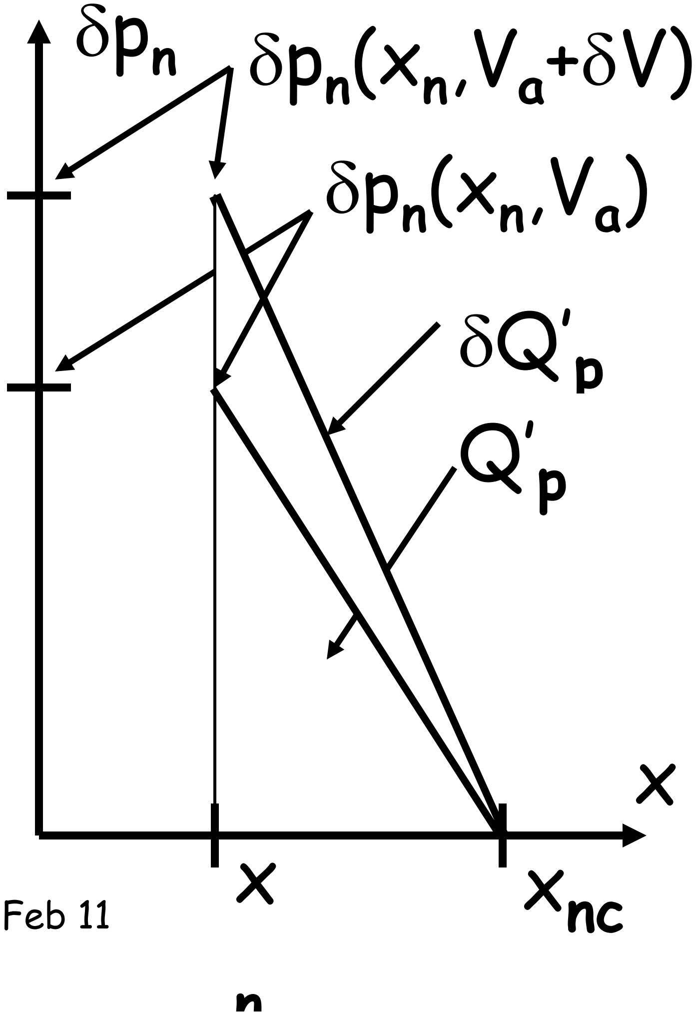


- Assume $N_d \ll N_a$
- The sinh (see L12) excess minority carrier distribution becomes linear for $W_n \ll L_p$

$\delta p_n(x_n) = p_{n0} \text{expd}(V_a/V_t)$

- Total chg = Q'_p = $Q'_p = q\delta p_n(x_n)W_n/2$

Charge distr in a 1-sided short diode



- Assume Quasi-static charge distributions
- $Q'_p = Q'_p = q\delta p_n(x_n)W_n/2$
- $d\delta p_n(x_n) = (W/2)^* \{\delta p_n(x_n,V_a+\delta V) - \delta p_n(x_n,V_a)\}$

Cap. of a (1-sided) short diode (cont.)

$$Q_p = Q'_p A, \quad A = \text{diode area. Define } C_d \equiv \frac{dQ_p}{dV_a} =$$

$$\frac{d}{dV_a}\left(\frac{qA\delta p_n(x_n)W_n}{2}\right) = \frac{d}{dV_a}\left(\frac{qAp_{n0}W_n}{2}\exp d\left(V_a / V_t\right)\right)$$

$$\text{When } V_a > V_t,\ C_d(V_Q) = \frac{I_{DQ}}{V_t}\frac{W_n^2}{2D_p} \equiv \frac{I_{DQ}}{V_t}\tau_{transit}\ .$$

$$\text{So, } r_d(V_Q)C_d(V_Q) = \tau_{transit} \equiv \int_{x_n}^{x_{nc}} q\frac{\delta p_n}{J_p}dx = \frac{W_n^2}{2D_p}$$

Reverse bias junction breakdown

- Avalanche breakdown
  - Electric field accelerates electrons to sufficient energy to initiate multiplication of impact ionization of valence bonding electrons
  - field dependence shown on next slide
- Heavily doped narrow junction will allow tunneling - see Neamen*, p. 274
  - Zener breakdown

E_{crit} for reverse breakdown (M&K**)

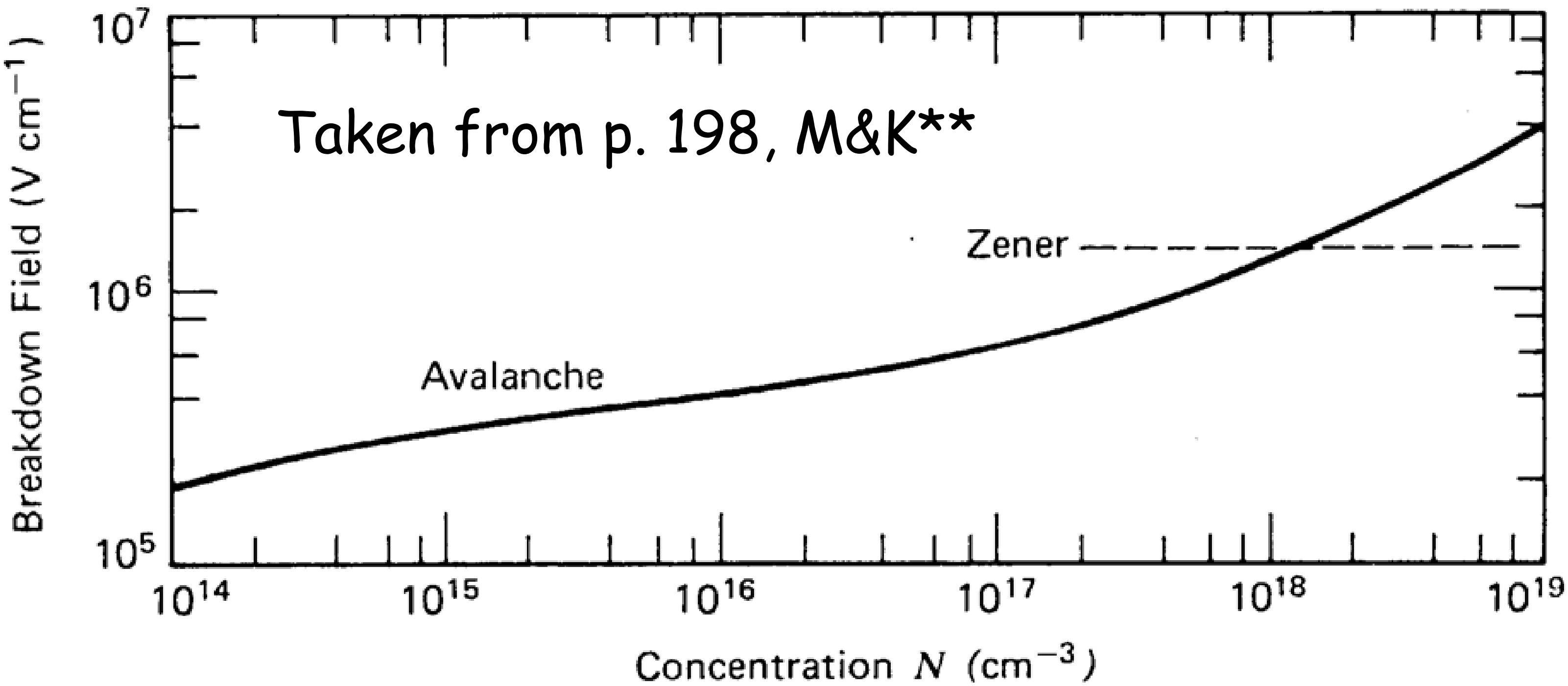


Figure 4.12 The critical electric fields for avalanche and Zener breakdown in silicon as functions of dopant concentration.[1,2,3]

Reverse bias junction breakdown

- Assume $-V_a \equiv V_R >> V_{bi}$, so $V_{bi}-V_a \dashrightarrow V_R$
- Since $E_{max} = 2(V_{bi}-V_a)/W$,

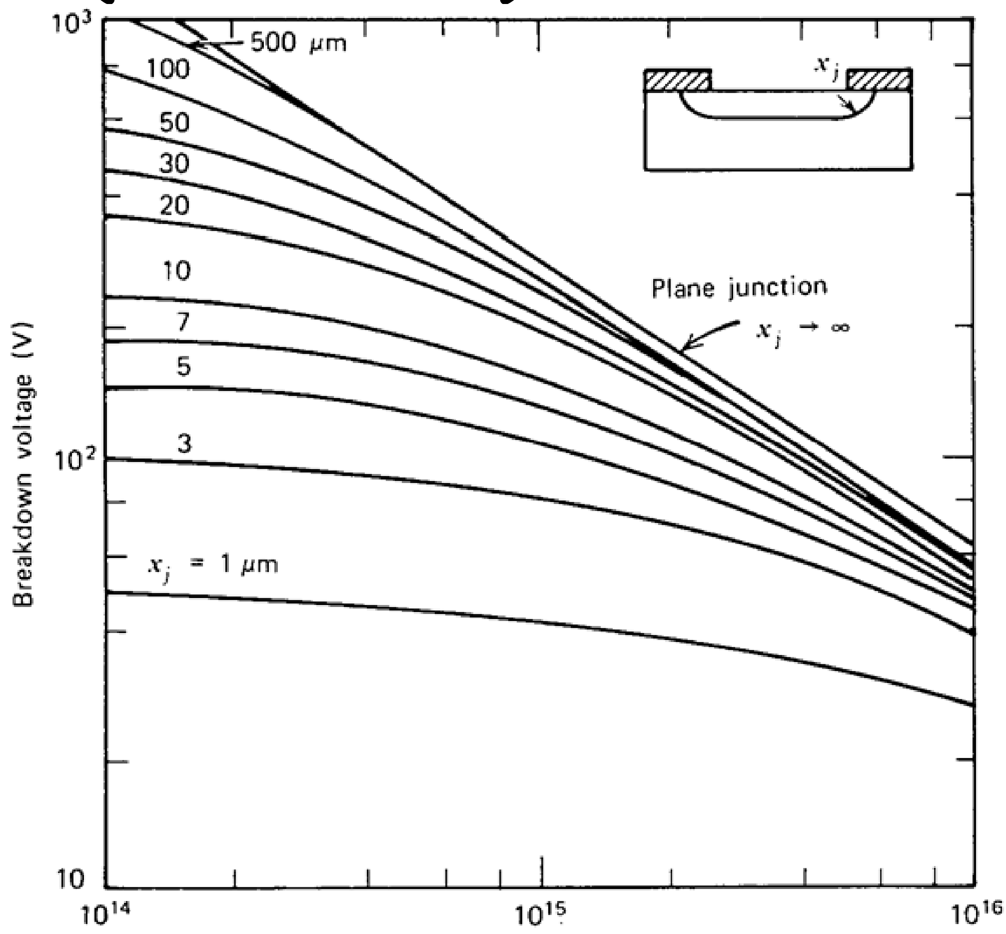
  when $E_{max} = E_{crit}$

  $$BV = \varepsilon (E_{crit})^2/(2qN^-)$$

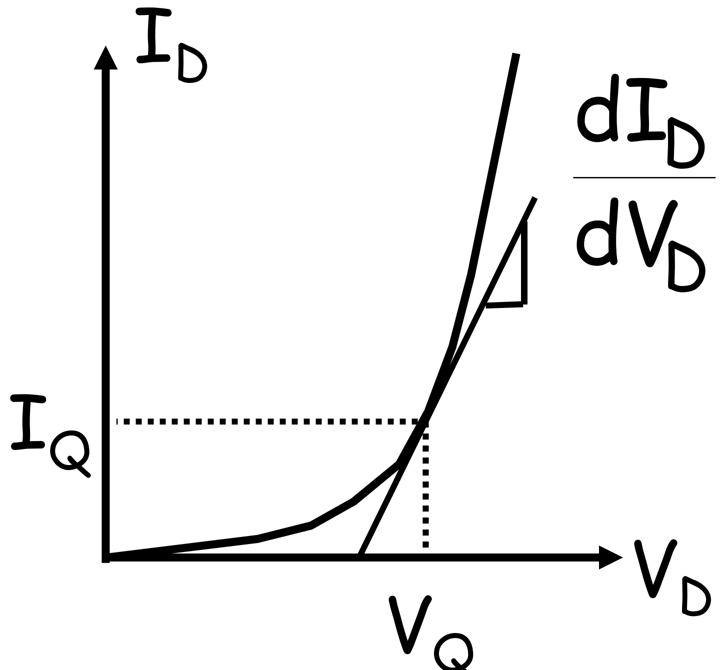
BV for reverse breakdown (M&K**)

Taken from Figure 4.13, p. 198, M&K**

Breakdown voltage of a one-sided, plan, silicon step junction showing the effect of junction curvature.[4,5]



Diode equivalent circuit (small sig)



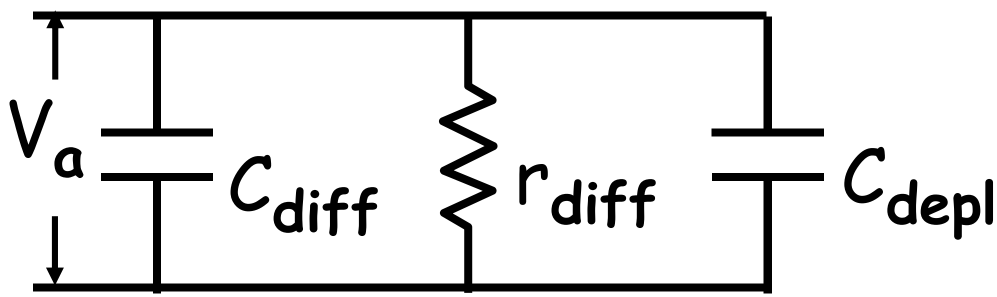
$$\left.\frac{dI_D}{dV_D}\right|_{V_Q} \equiv g_d = \frac{1}{r_d} = \frac{I_Q}{\eta V_t}$$

η is the practical "ideality factor"

$$r_d C_d = \tau, \ (\tau_{tr} \text{ for short, } \tau_{min} \text{ for long})$$

$$C_{diffusion} = \frac{\tau I_Q}{\eta V_t}, \ r_{diff} = \frac{\eta V_t}{I_Q}$$

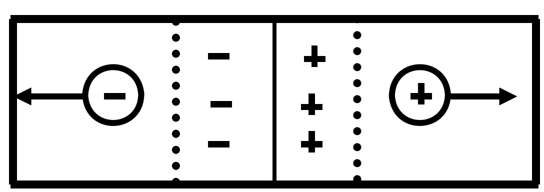
Small-signal eq circuit



C_{diff} and C_{depl} are both charged by

$V_a = V_Q$

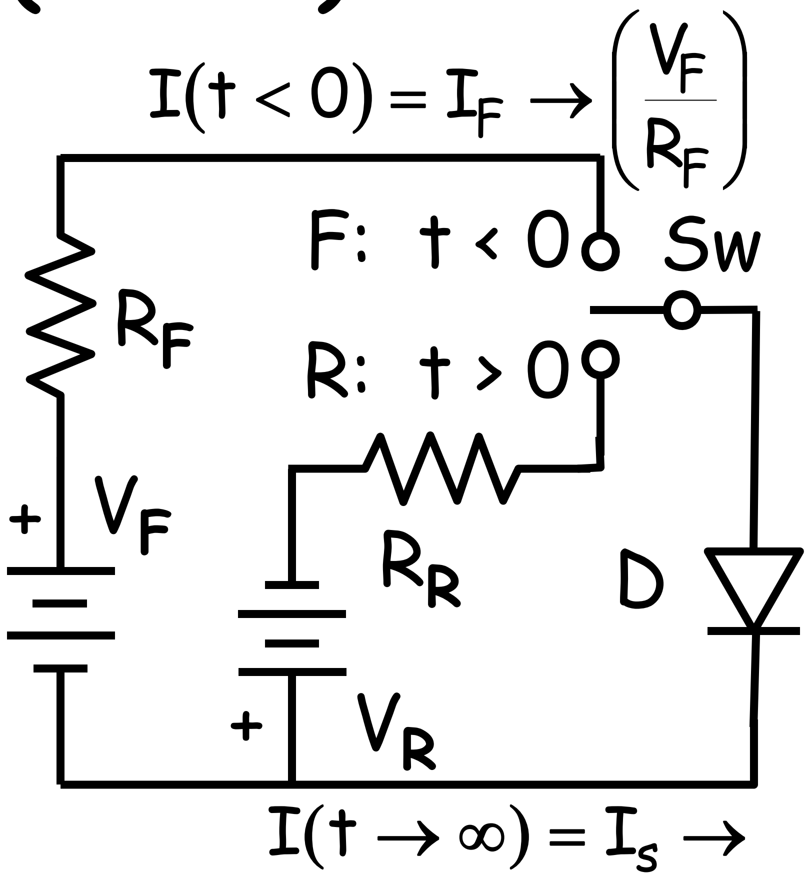
$$C_{depl} = C_j = C_{jo}\left(1 - \frac{V_a}{V_{bi}}\right)^{-1/2}, V_a = V_Q$$



Diode Switching

- Consider the charging and discharging of a Pn diode
  - ($N_a > N_d$)
  - $W_d \ll Lp$
  - For t < 0, apply the Thevenin pair V_F and R_F, so that in steady state
    - $I_F = (V_F - V_a)/R_F$, $V_F \gg V_a$, so current source
  - For t > 0, apply V_R and R_R
    - $I_R = (V_R + V_a)/R_R$, $V_R \gg V_a$, so current source

Diode switching (cont.)

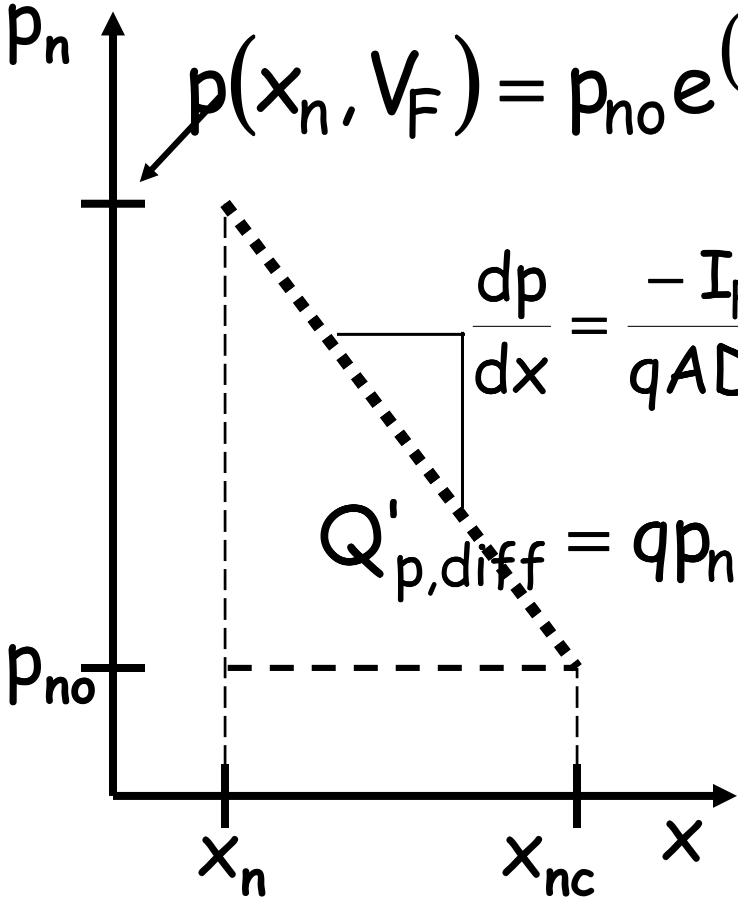


$V_F, V_R \gg V_a$

for $t < 0$,

$$I_Q = \frac{V_F - V_a}{R_F} \approx \frac{V_F}{R_F}$$

Diode charge for t < 0



$$p(x_n, V_F) = p_{no} e^{(V_F / V_t)}, \; p_{no} = \frac{n_i^2}{N_D}$$

$$\frac{dp}{dx} = \frac{-I_F}{qAD_p}, \text{ since } J_p = -qD_p \frac{dp}{dx}$$

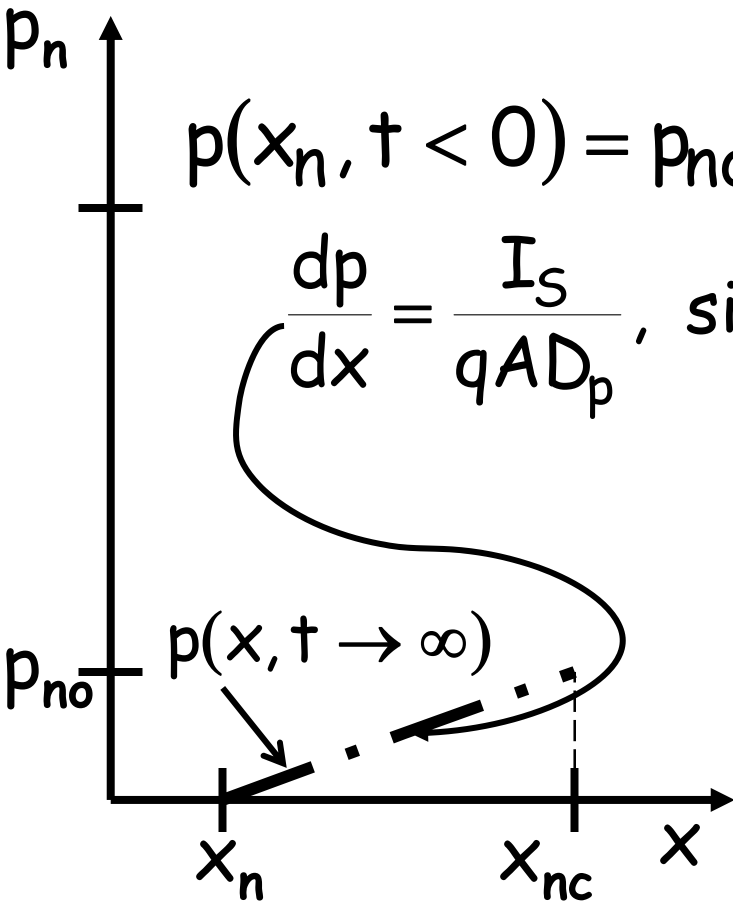
$$Q'_{p,diff} = qp_n(x_n, V_F)W_n = I_F \tau_{TR},$$

$$\tau_{TR} = \frac{W_N^2}{2Dp}$$

Diode charge for t >>> 0 (long times)

$$p(x_n, t<0) = p_{no} e^{(V_F / V_t)}$$

$$\frac{dp}{dx} = \frac{I_S}{qAD_p}, \text{ since } J_p = -qD_p \frac{dp}{dx} = J_s$$



Equation summary

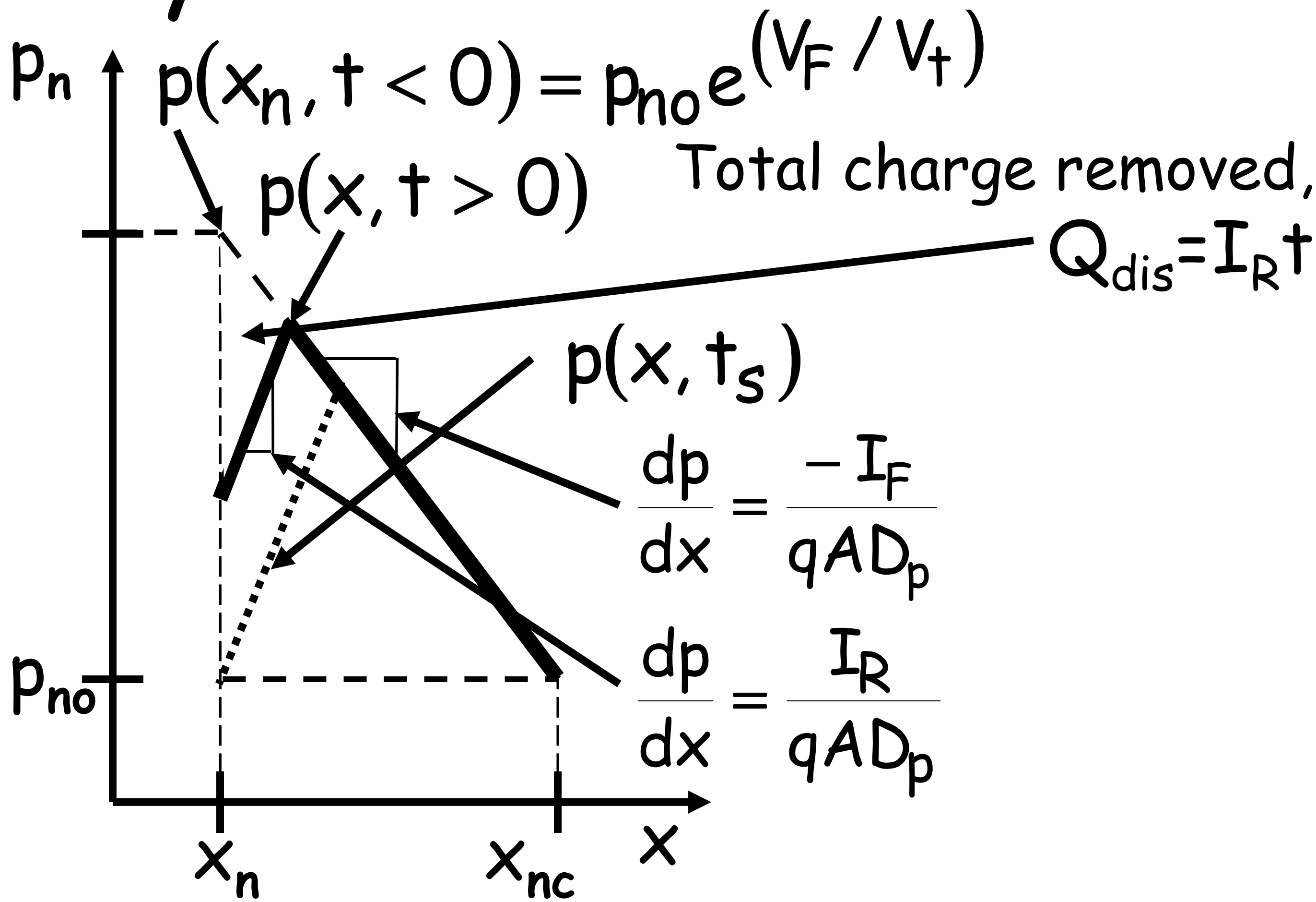
$$\left.\frac{dp}{dx}\right|_{R,t\to\infty} = \frac{1}{qD_p} J_{p,\infty}$$

$$= \frac{I_s}{AqD_p},\; I_s = J_s A$$

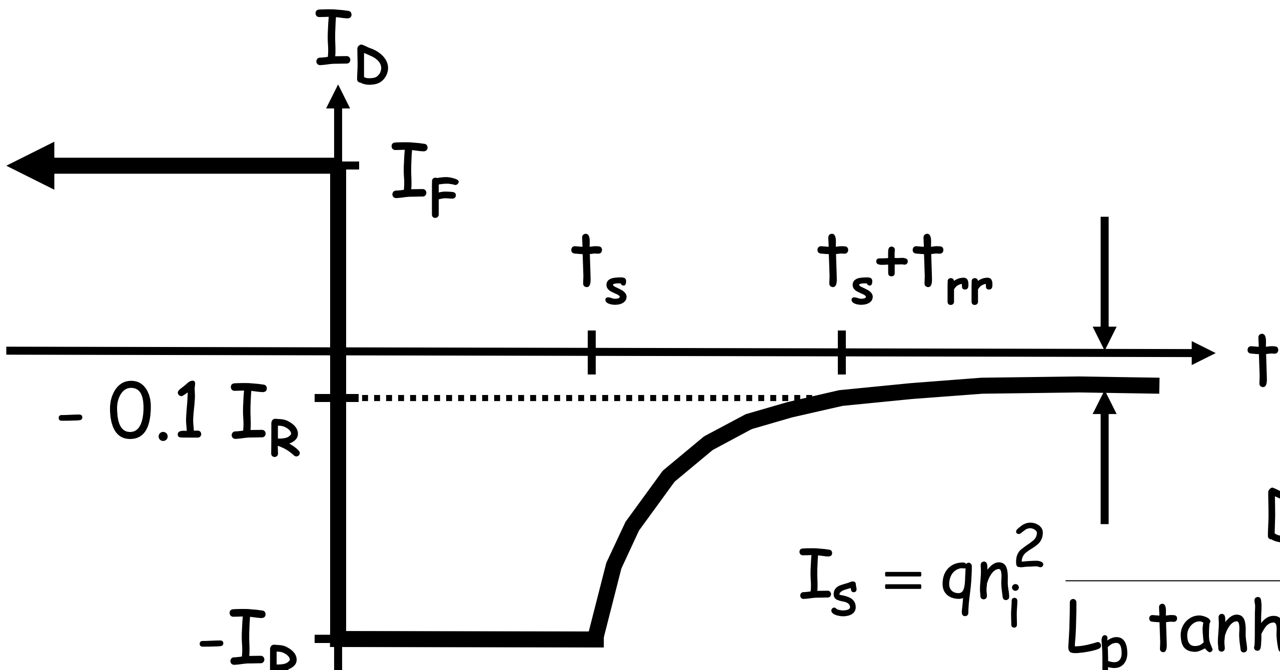
$$-\left.\frac{dp}{dx}\right|_{F,t>0} = \frac{I_F}{qAD_p},\; I_F = \frac{V_F}{R_F}$$

For t small, but >0, a current, $I_R \approx V_R / R_R$ flows to discharge Q

Snapshot for t barely > 0



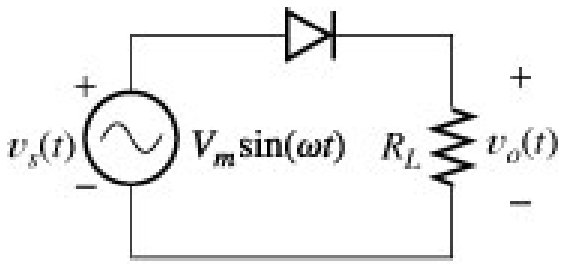
I(t) for diode switching



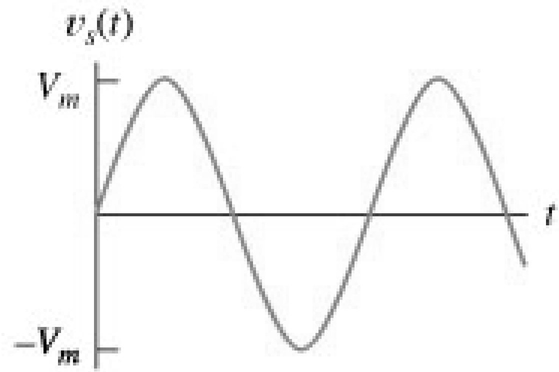
$$I_S = q n_i^2 \frac{D_p}{L_p \tanh(W_n / L_p)}$$

For $0 < t < t_s$, $\frac{dp}{dx} = \frac{I_R}{qAD_p}$ is a constant,

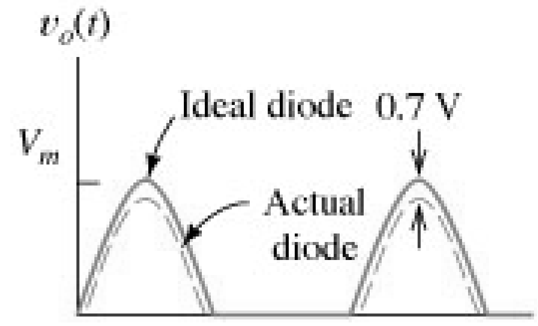
$$Q_{discharge} = I_R t_s$$



(a) Circuit diagram

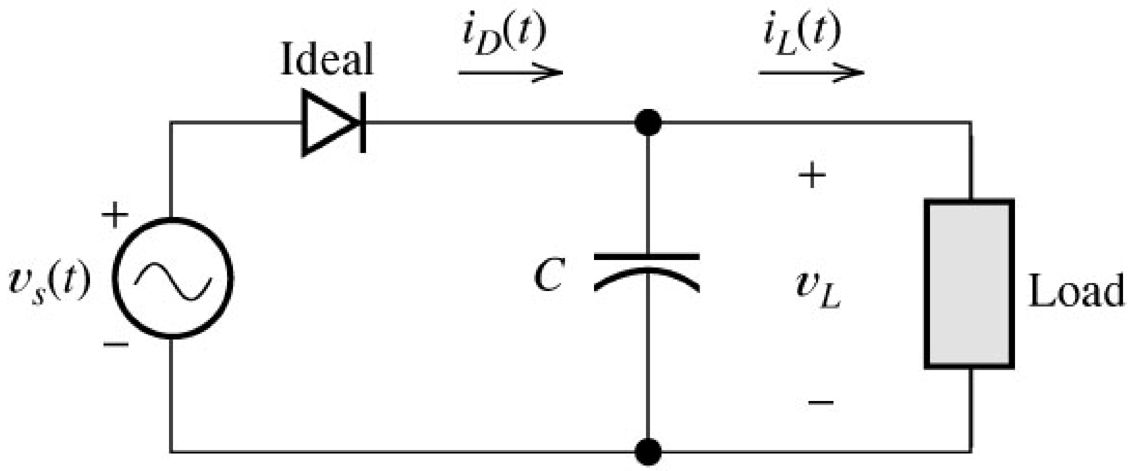


(b) Source voltage versus time



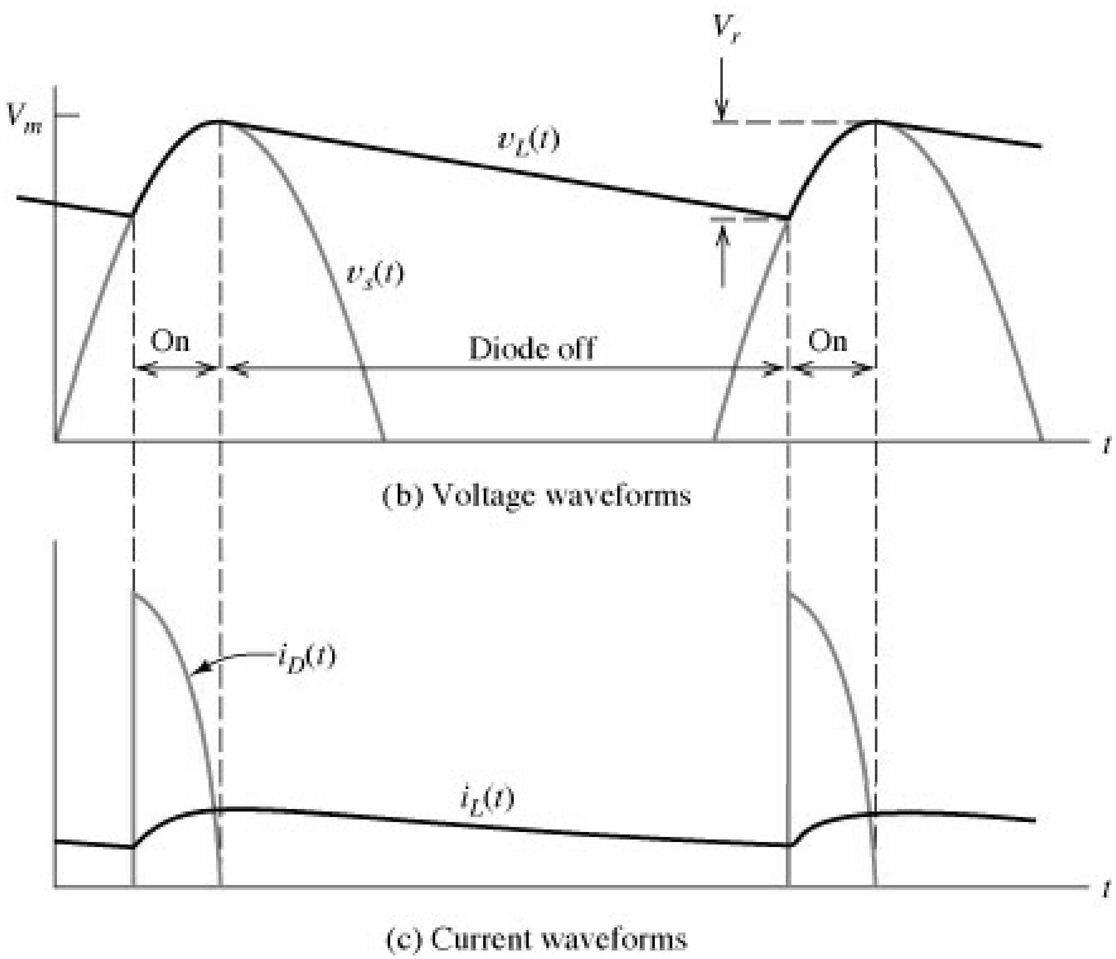
(c) Load voltage versus time

Figure 3.11 Half-wave rectifier with resistive load.

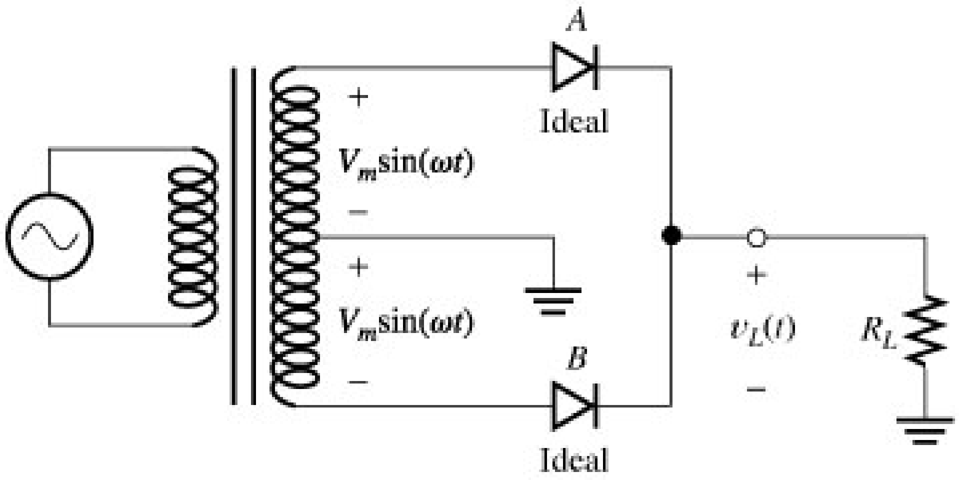


(a) Circuit diagram

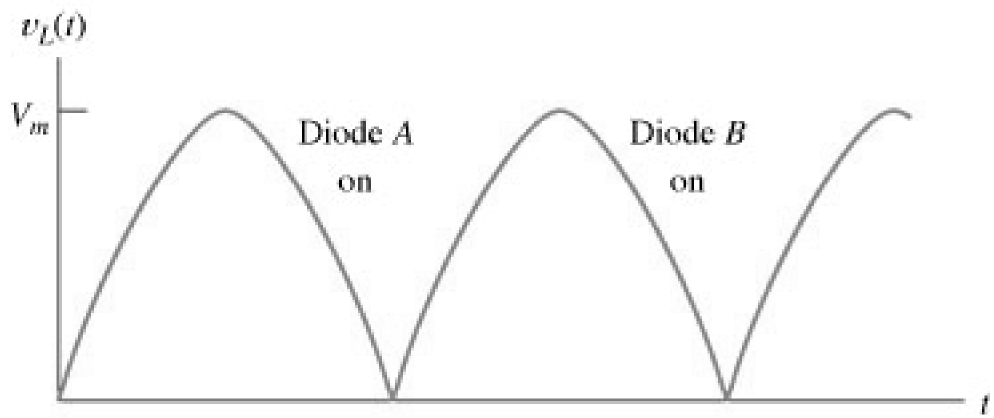
Figure 3.12a Half-wave rectifier with smoothing capacitor.



L07, Feb 11 **Figure 3.12b & c** Half-wave rectifier with smoothing capacitor.



(a) Circuit diagram



(b) Output voltage

Figure 3.13 Full-wave rectifier.

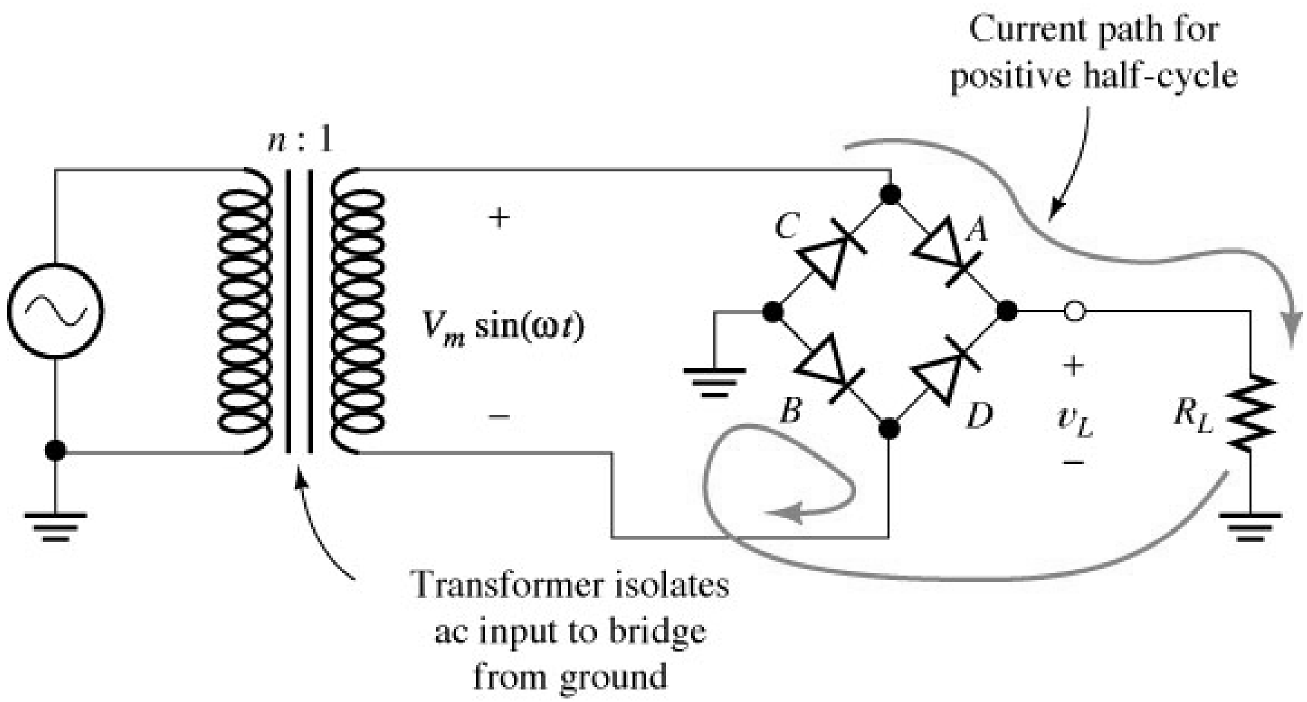


Figure 3.14 Diode-bridge full-wave rectifier.

References

* *Semiconductor Physics and Devices*, 2nd ed., by Neamen, Irwin, Boston, 1997.

***Device Electronics for Integrated Circuits*, 2nd ed., by Muller and Kamins, John Wiley, New York, 1986.

- Where not otherwise noted, Figures not done by RLC are taken from:
  - Electronics, 2nd edition, by Allan R. Hambley, Prentice Hall, Upper Saddle River, NJ, © 2000.