ECE-305: Spring 2018
Non-Ideal Diodes+Solar Cells

Pierret, *Semiconductor Device Fundamentals* (SDF)
Chapter 6

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outline

1) Recap of Ideal Diodes

2) Diode Non-idealities:
   - Breakdown
   - High forward bias
   - Recombination-generation current

3) Small-signal model

ideal diode + solar cell summary

Ideal diode equation: $I_D = I_0\left(e^{qV_A/nk_BT} - 1\right)$

1) Light is absorbed and produces e-h pairs
2) PN junctions separate e-h pairs and collect the carriers.

3) Current flow in external circuit produces a FB voltage and the FB diode current reduces the total current.

4) Power out $\left|P_{out}\right| = I_{mp}V_{mp} = \quad I_{SC}V_{OC}FF$

5) Unlike integrated circuit chips, where the value added comes from the design/system, manufacturing costs are critical in PV.

outline

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2) Diode Non-idealities:
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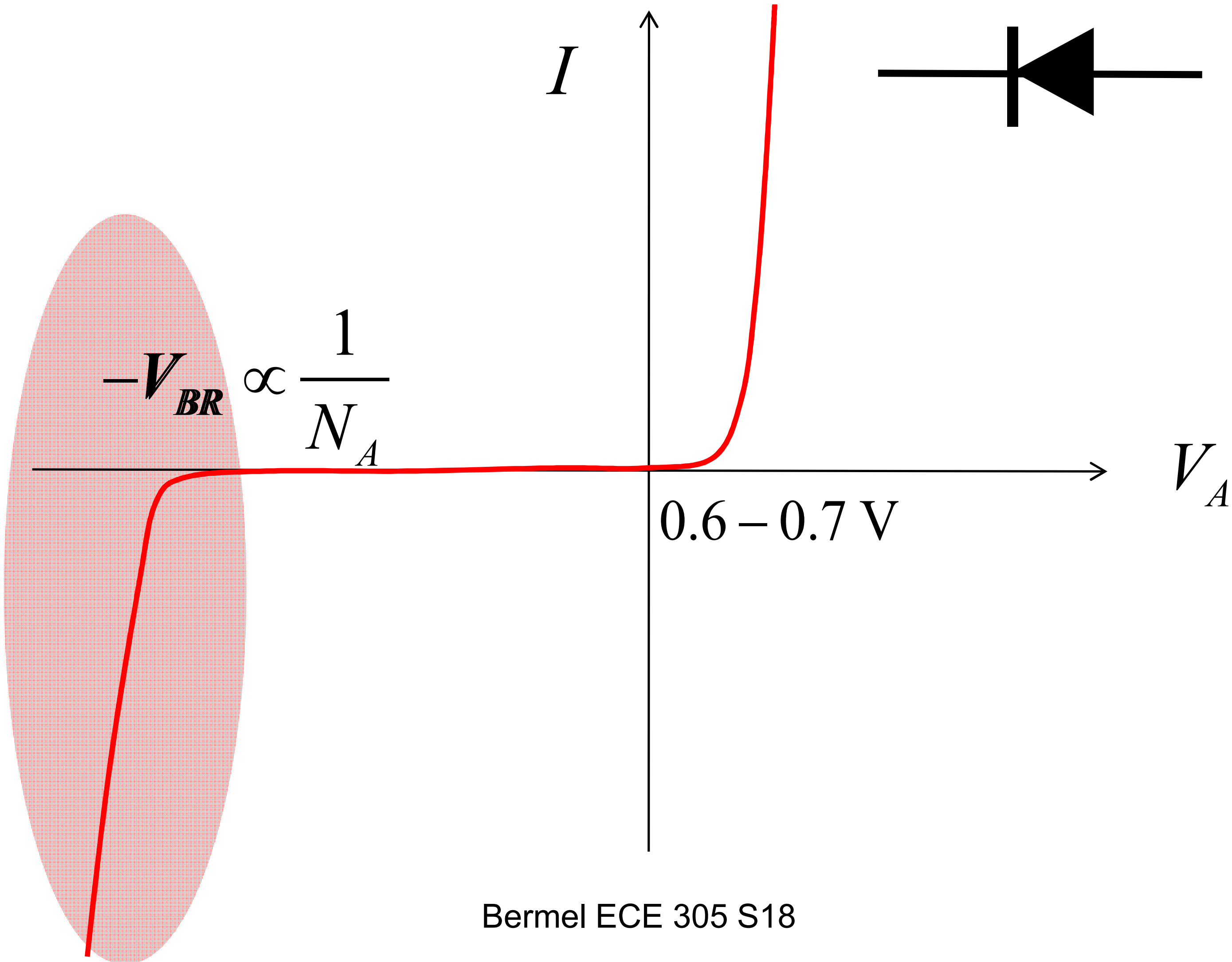
3) Small-signal model

reverse bias breakdown



critical electric field

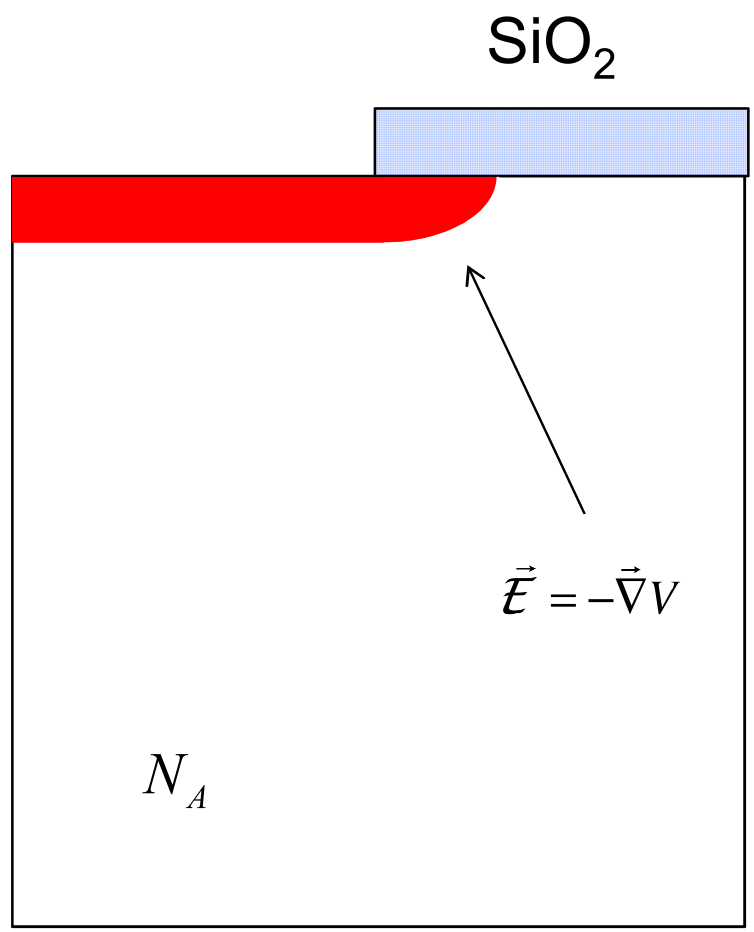
$$\mathcal{E}_{CR} = \sqrt{\frac{2q\left(V_{bi} + V_{BR}\right)N_A}{K_s \varepsilon_0}} \qquad V_{BR} \propto \frac{1}{N_A}$$

$\mathcal{E}_{CR} \approx 3 \times 10^5$ V/cm (Silicon)

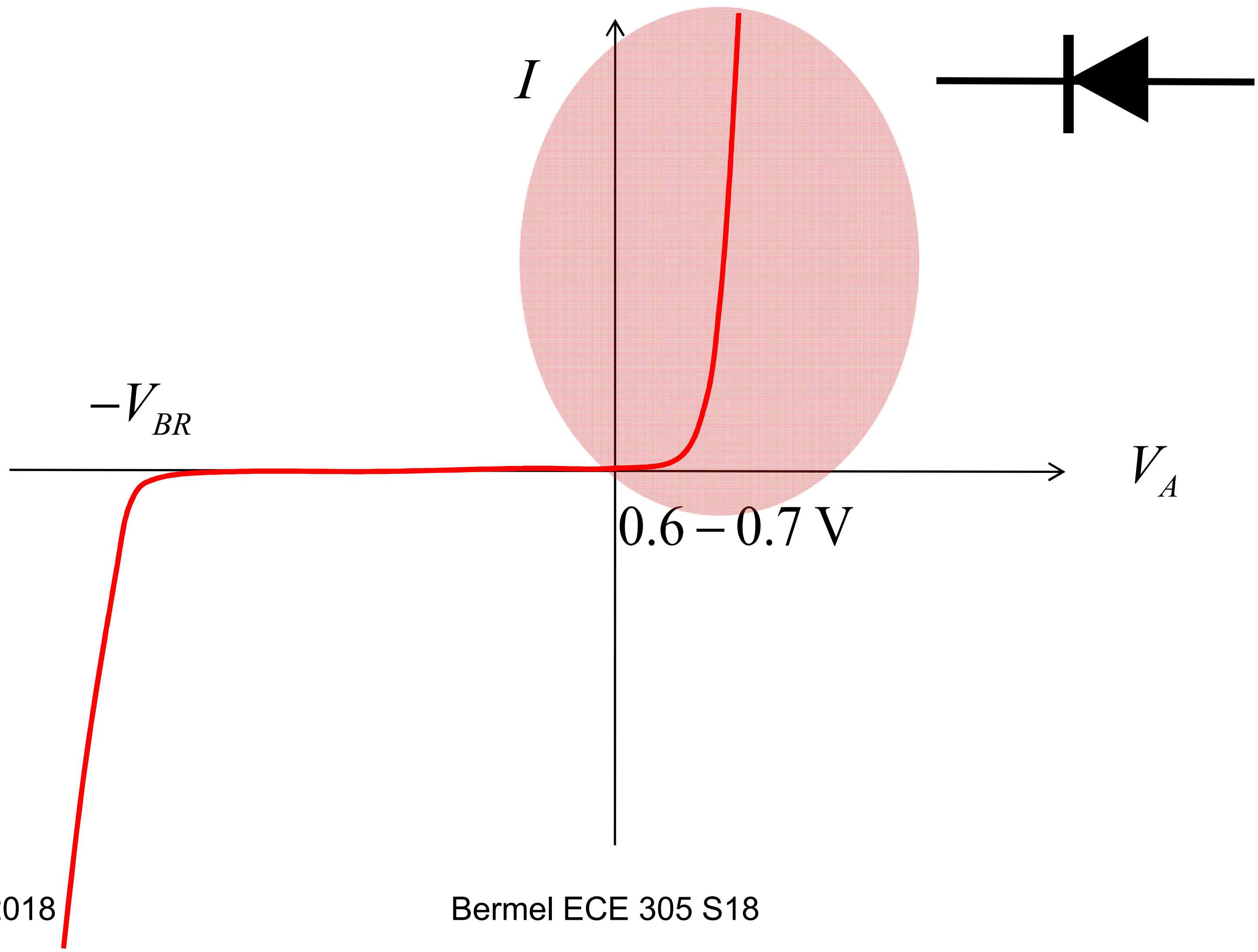
$\mathcal{E}_{CR} \approx 1 \times 10^5$ V/cm (Germanium)

$\mathcal{E}_{CR} \approx 5 \times 10^6$ V/cm (GaN)

$\mathcal{E}_{CR} \approx 3 \times 10^6$ V/cm (air)



forward bias

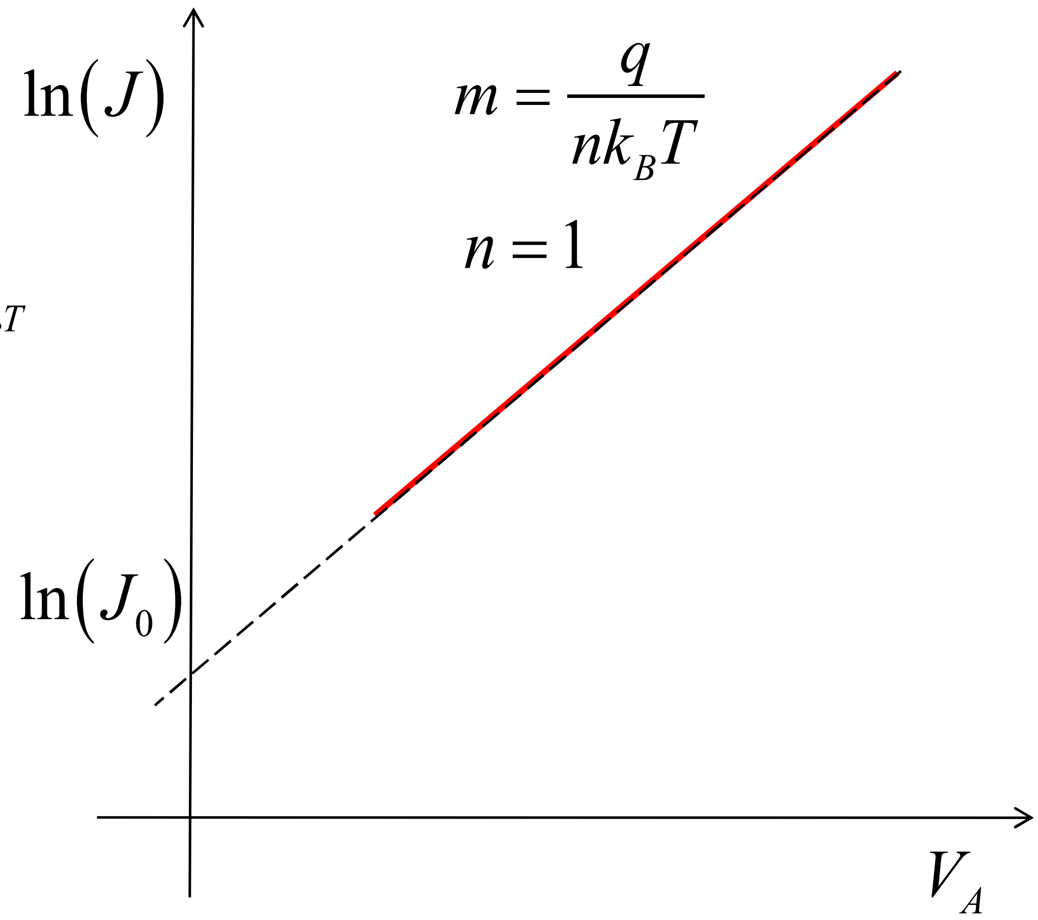


ideal diode current in forward bias

$$J = J_0\left(e^{qV_A/k_BT} - 1\right) \approx J_0 e^{qV_A/k_BT}$$

$$\ln(J) = \ln(J_0) + qV_A / k_BT$$

$$\ln(J) = \ln(J_0) + mV_A$$



real diodes in forward bias

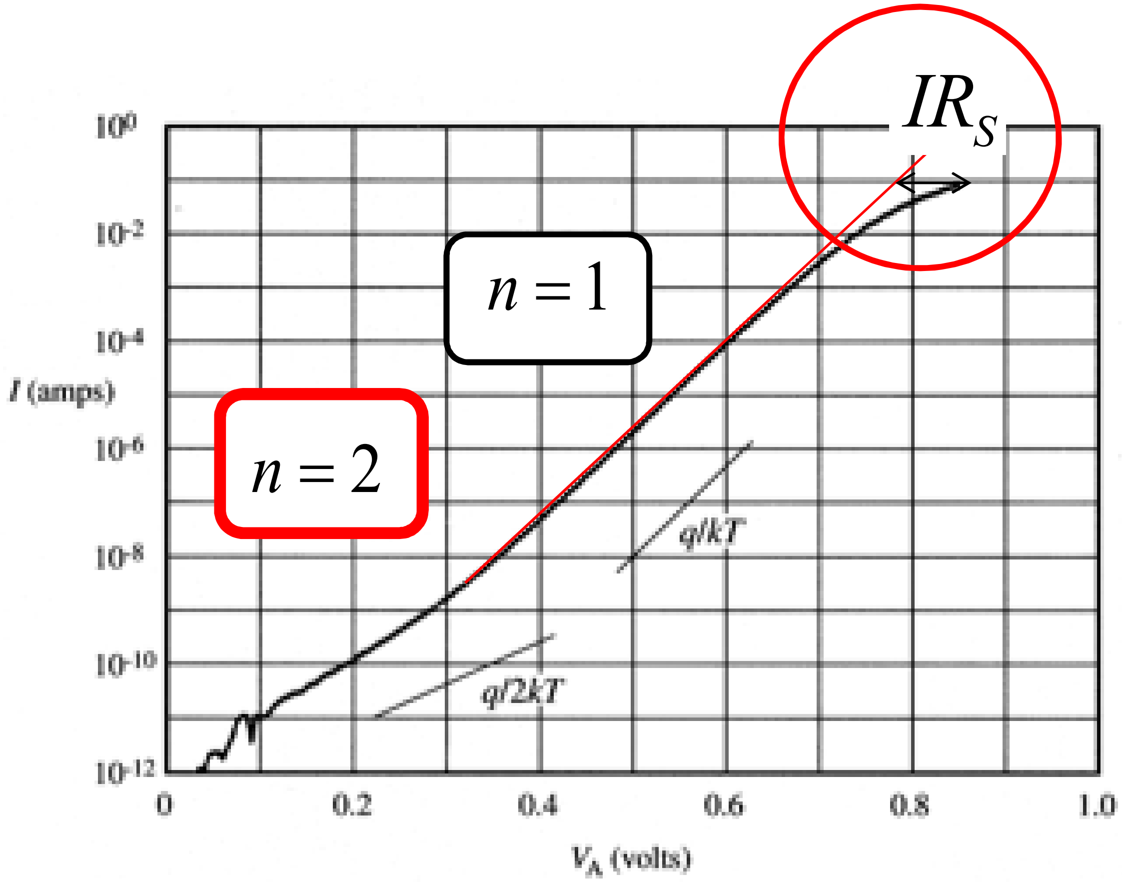
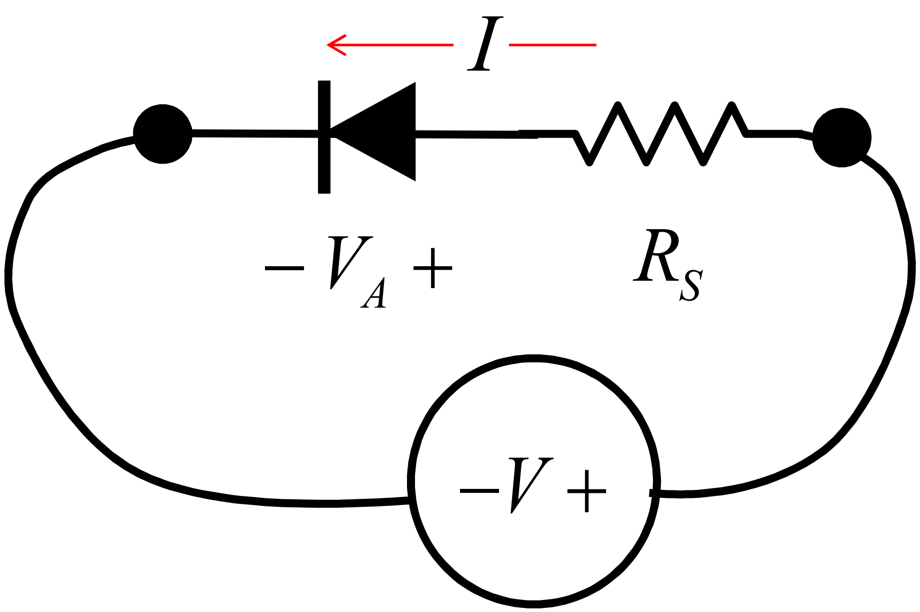


Fig. 6.10(a), Semiconductor Device Fundamentals, R.F. Pierret

high forward bias

1) series resistance



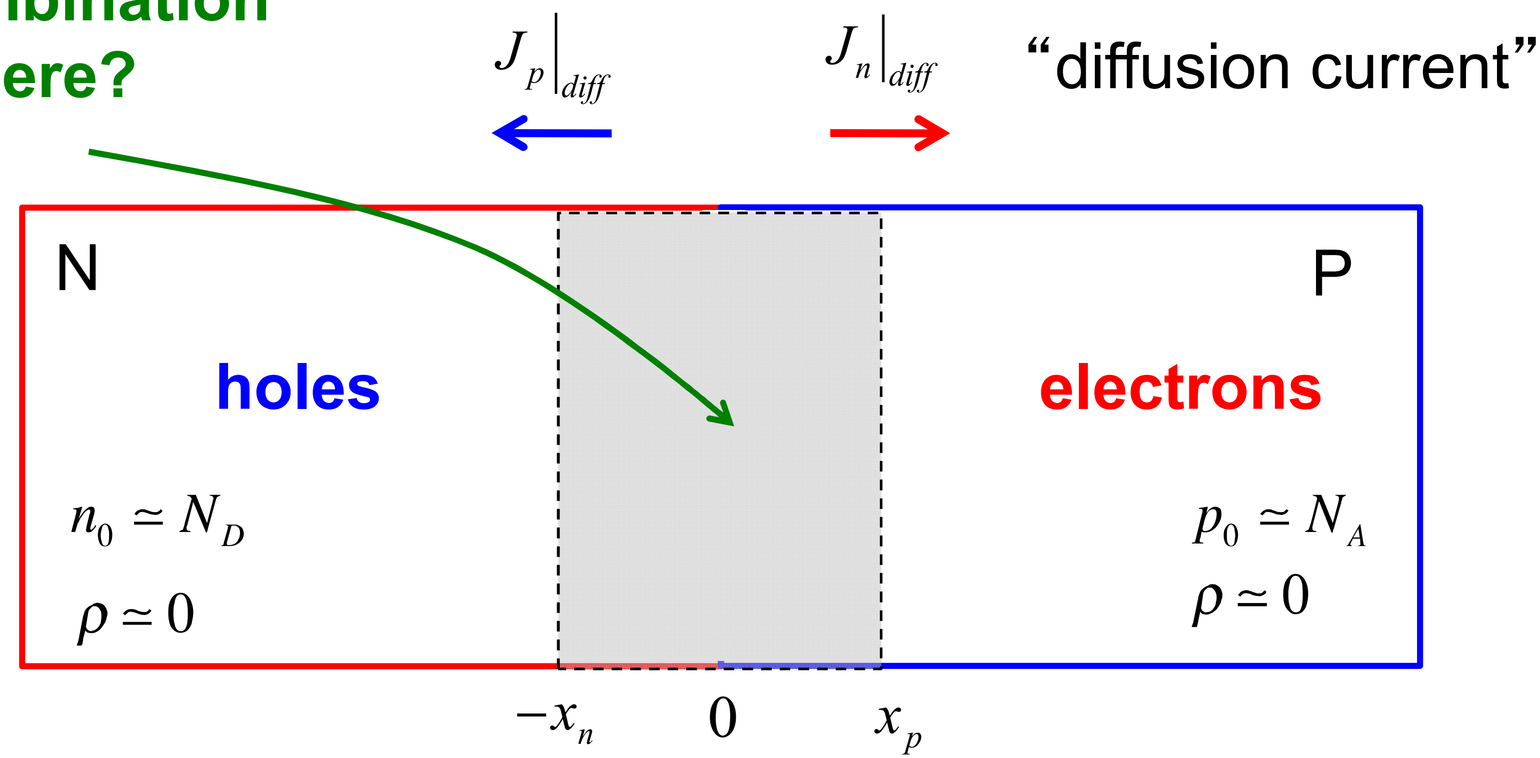
$$I = I_0\left(e^{q(V - IR_S)/k_B T} - 1\right)$$

$$V_A = V - IR_S$$

2) “high level injection” $\Delta n_P = \frac{n_i^2}{N_A}\left(e^{qV_A/k_B T} - 1\right) << N_A$

moderate forward bias diode current

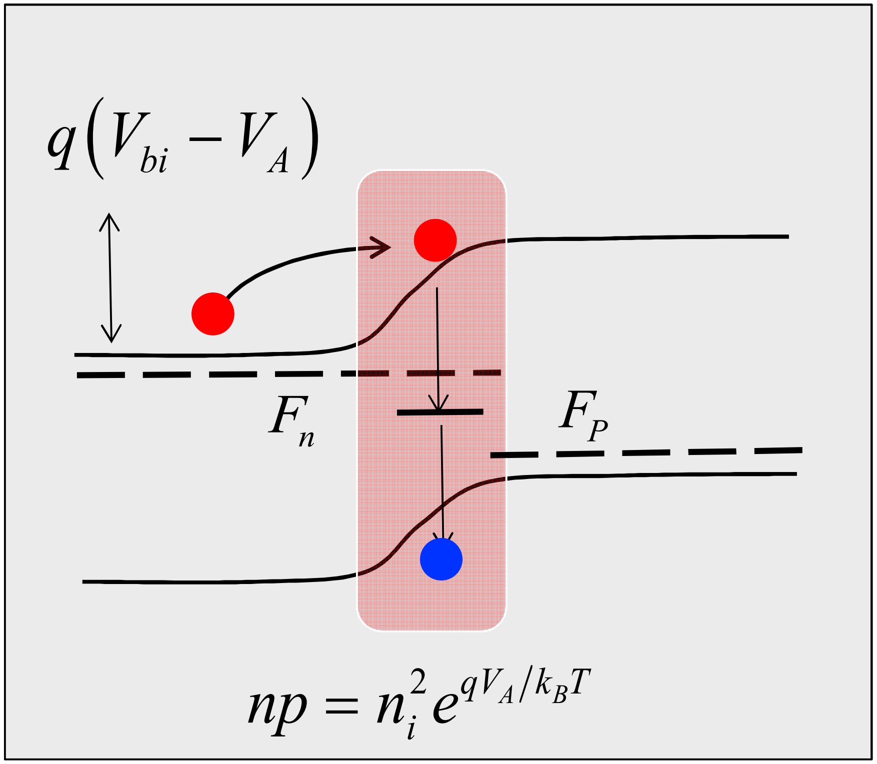
What about recombination here?



transition region

Minority carrier recombination in quasi-neutral regions leads to diode current.

recombination in SCR: forward bias



$$J(V_A) = qR_{TOT}(V_A)$$

Maximum recombination occurs when $n(x) \approx p(x)$

$$n(x)p(x) = n_i^2 e^{qV_A/k_BT}$$

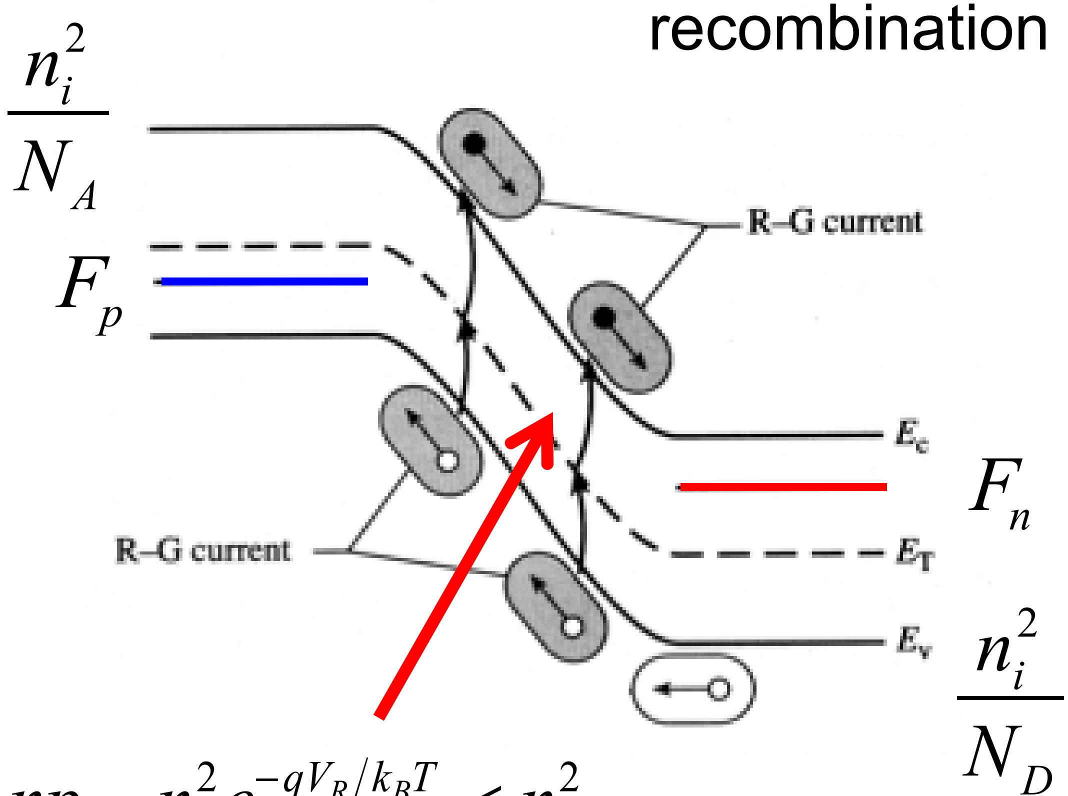
$$\hat{n} \approx \hat{p} \propto n_i e^{qV_A/2k_BT}$$

$$qR(V_A) = \frac{qn_i e^{qV_A/2k_BT}}{\tau_{eff}}$$

Recombination in space-charge regions gives rise to <u>n = 2</u> currents that go as n_i not n_i^2.

recombination-generation in SCR: reverse bias

recombination rate R<0



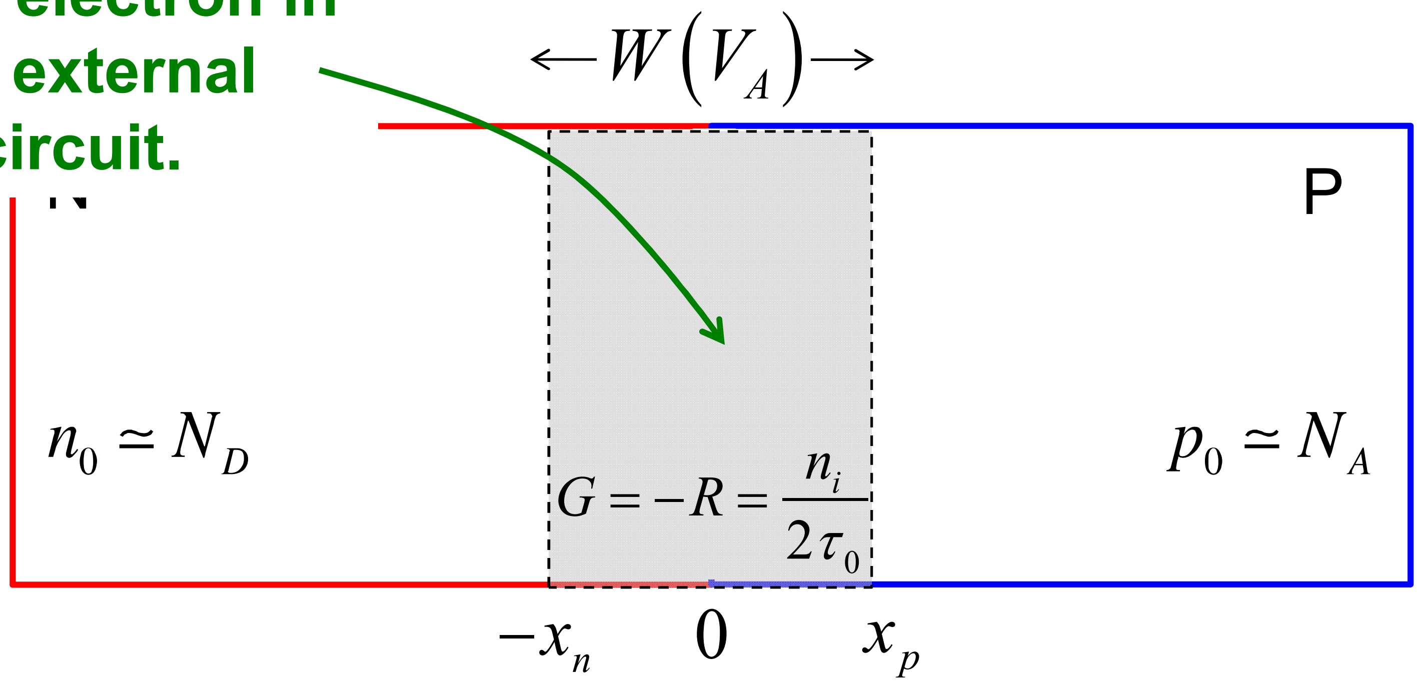
$$np = n_i^2 e^{-qV_R/k_BT} < n_i^2$$

Fig. 6.15, Semiconductor Device Fundamentals, R.F. Pierret

RB diode current

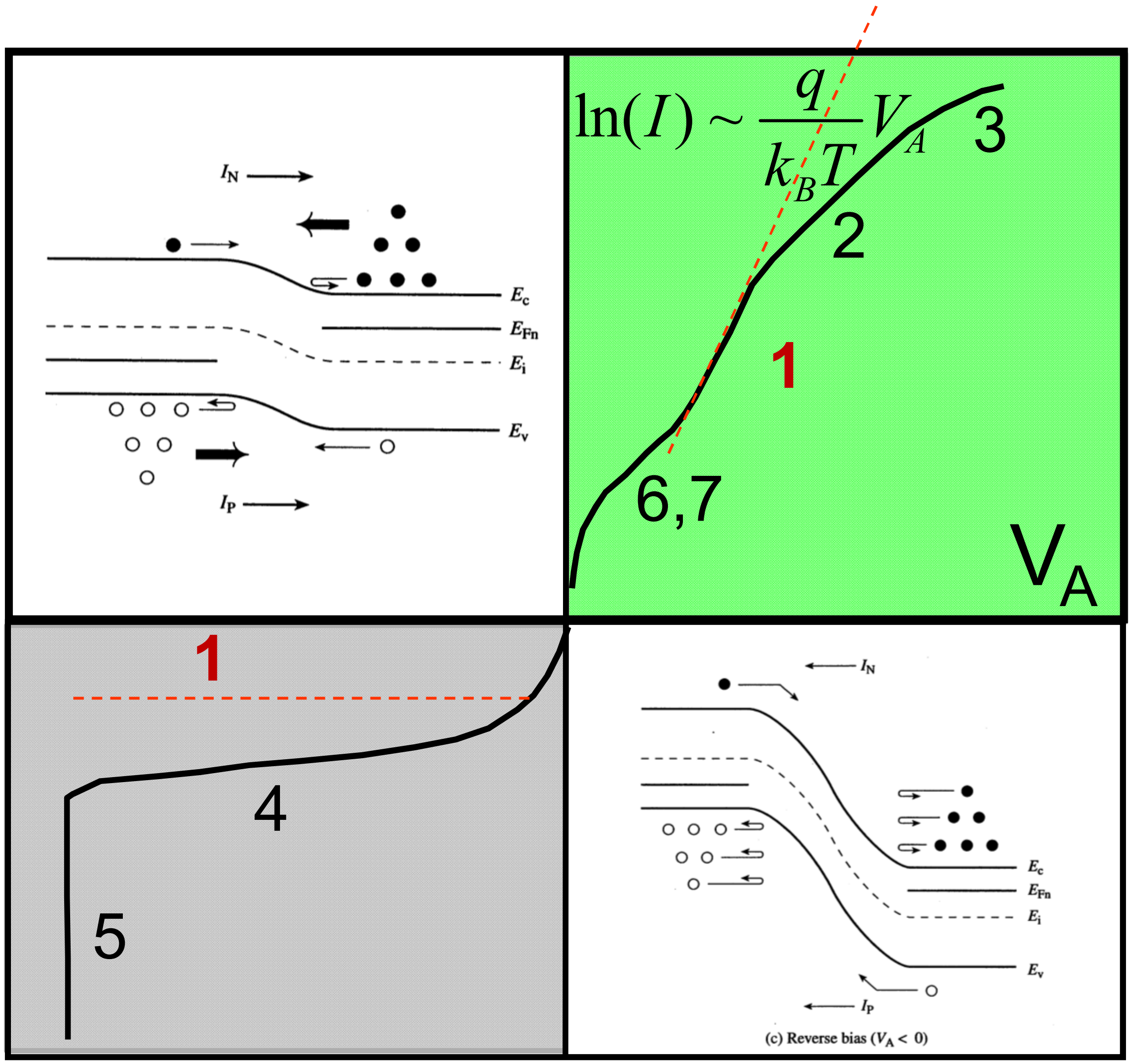
e-h pairs generated here give 1 electron in the external circuit.

recombination rate R<0



$$I = -q \frac{n_i}{2\tau_0} WA \quad W \propto \sqrt{V_{bi} + V_R}$$

Various Regions of I-V Characteristics



1. ***Diffusion limited***
2. *Ambipolar transport*
3. *High injection*
4. *R-G in depletion*
5. *Breakdown*
6. *Trap-assisted R-G*
7. *Esaki Tunneling*

non-ideal diode summary

Non-ideal diode equation: $I_D = I_0\left(e^{q\left(V - I_D R_S\right)/nk_BT} - 1\right)$

1) FB: recombination in quasi-neutral regions give n = 1 current (diffusion current).
2) FB: recombination R>0 in SCR gives n = 2 current
3) RB: constant when dominated by diffusion current
4) RB: increases as W from generation (R<0) in SCR
5) RB: avalanche or Zener tunneling

outline

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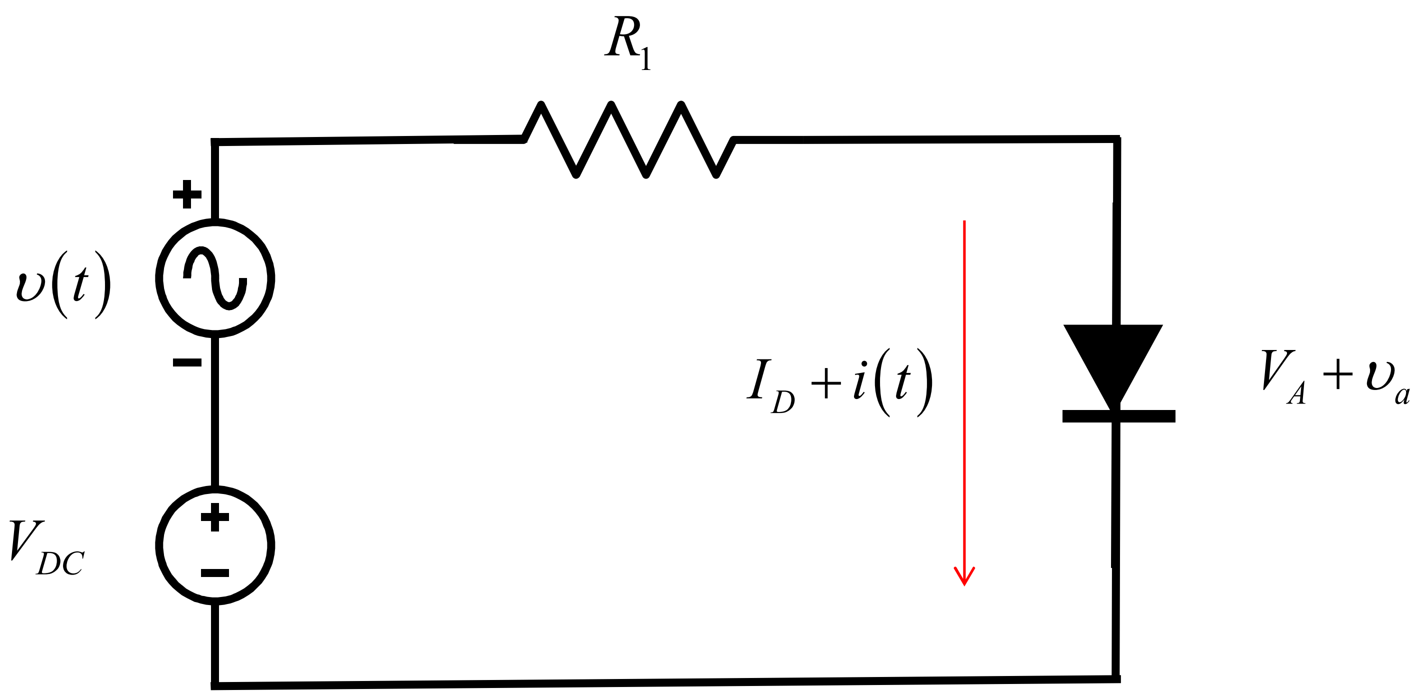
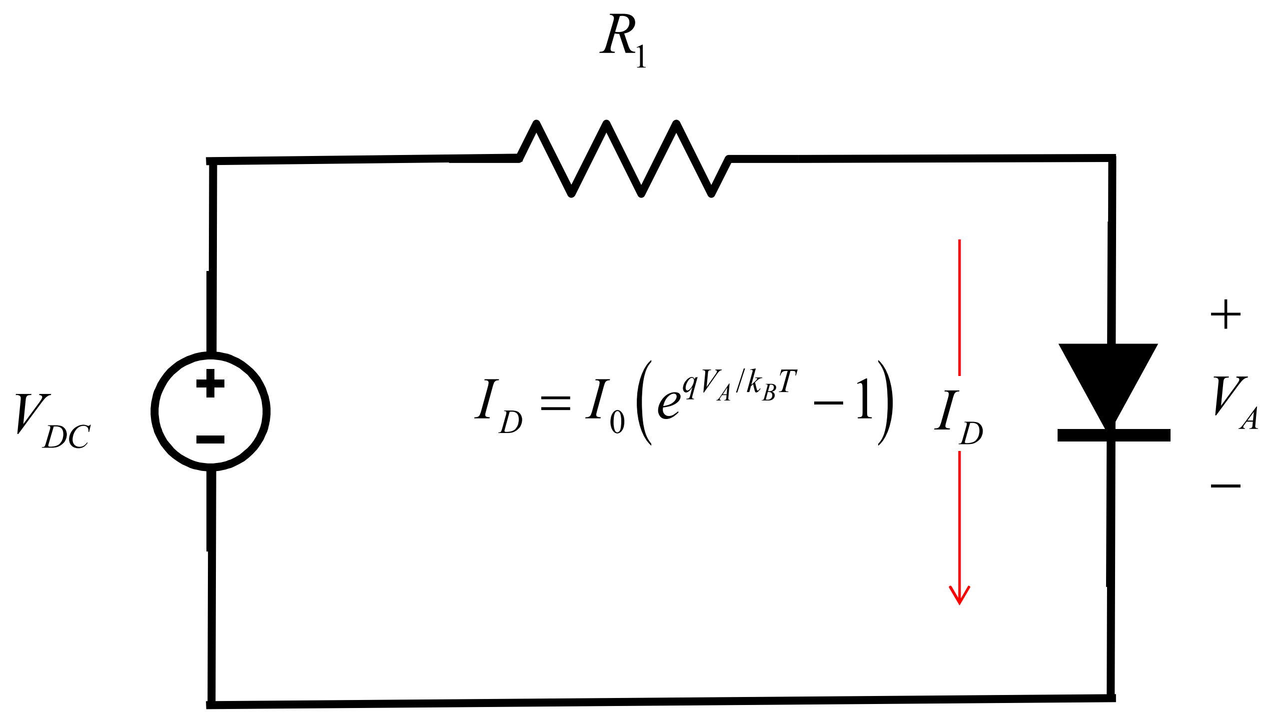
✓ 2) Diode Non-idealities:
   - Breakdown
   - High forward bias
   - Recombination-generation current

3) Small-signal model

small signal ac

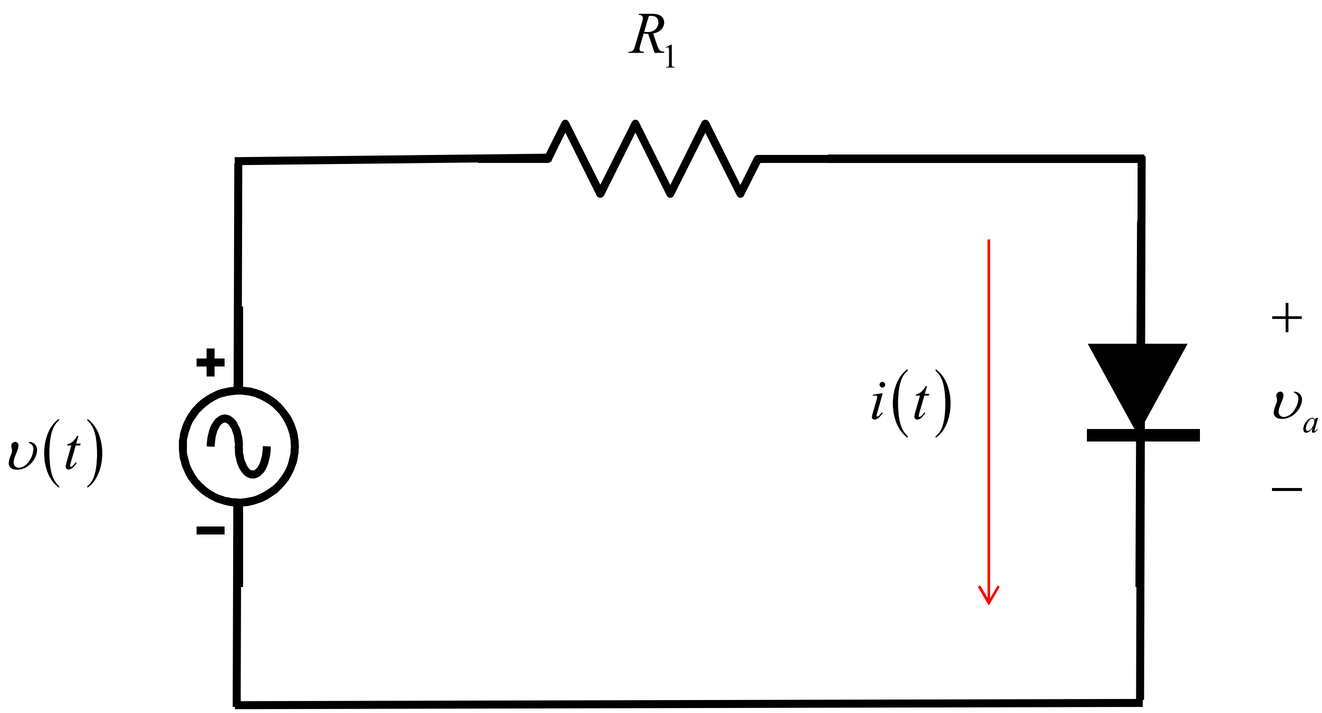


DC solution



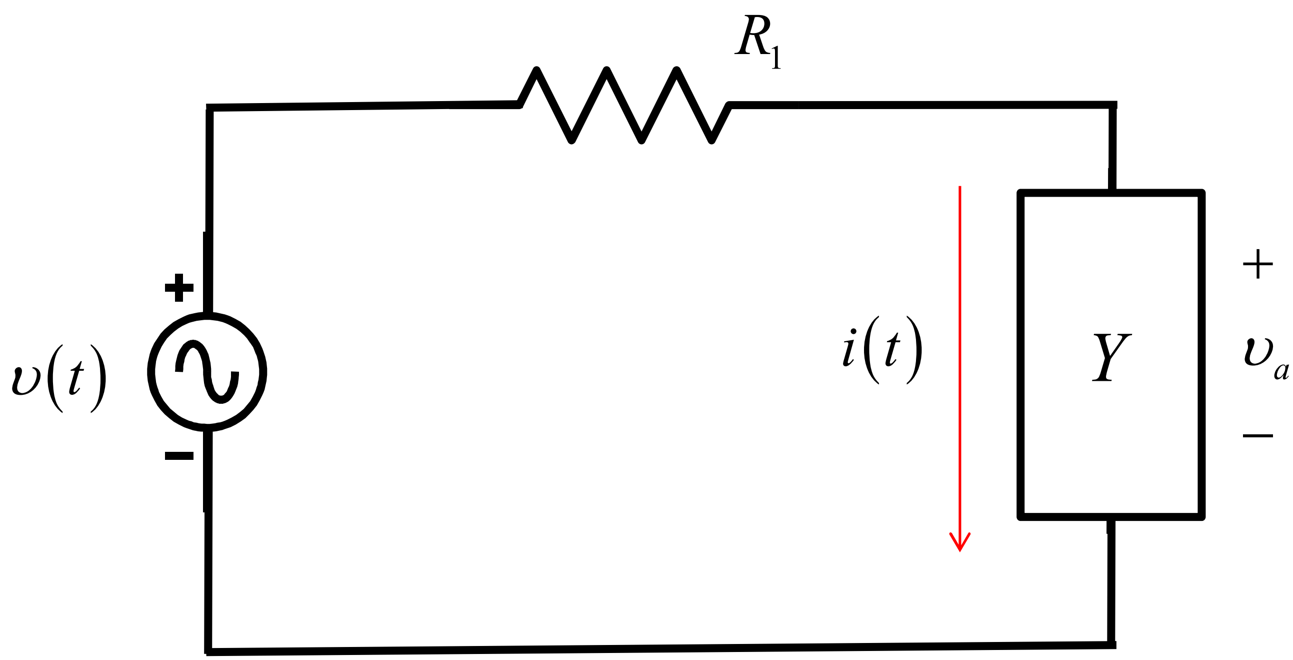
Superposition: 1) DC

small signal ac



Superposition: 2) ac

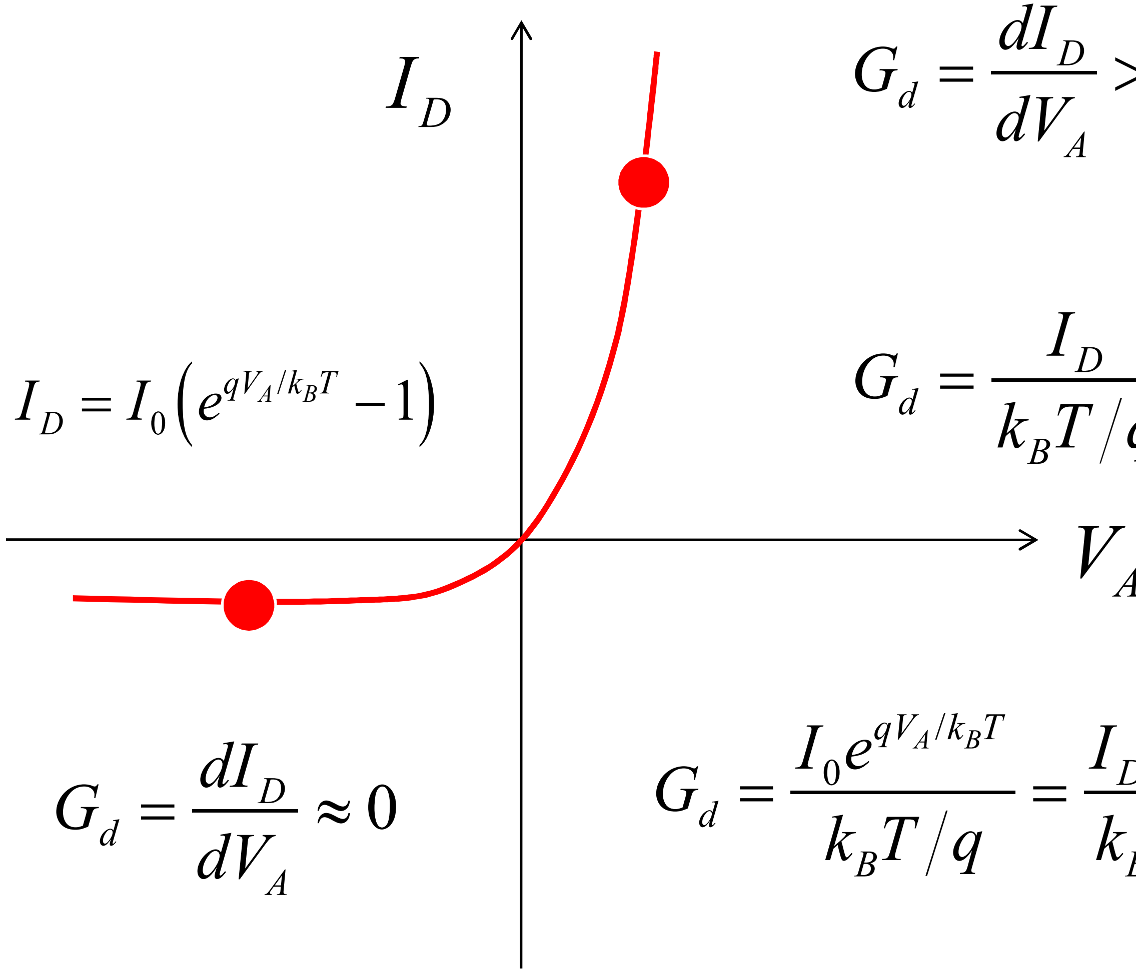
equivalent circuit



$$Y = G_d + j\omega C$$

For low frequencies, $G_d = \dfrac{i}{\upsilon_a} = \dfrac{dI_D}{dV_A}$

Ideal diode equation (DC)



$$G_d = \frac{dI_D}{dV_A} >> 0$$

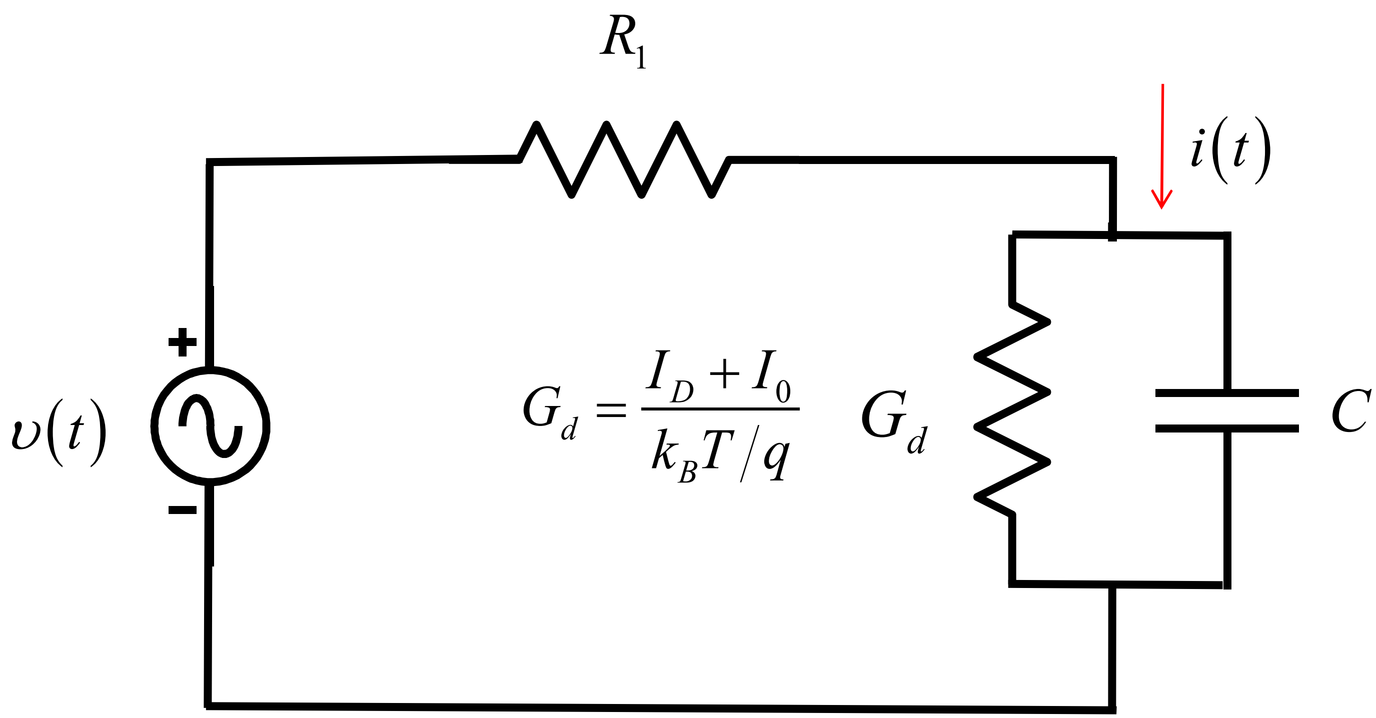
$$I_D = I_0\left(e^{qV_A/k_BT} - 1\right)$$

$$G_d = \frac{I_D}{k_BT/q}$$

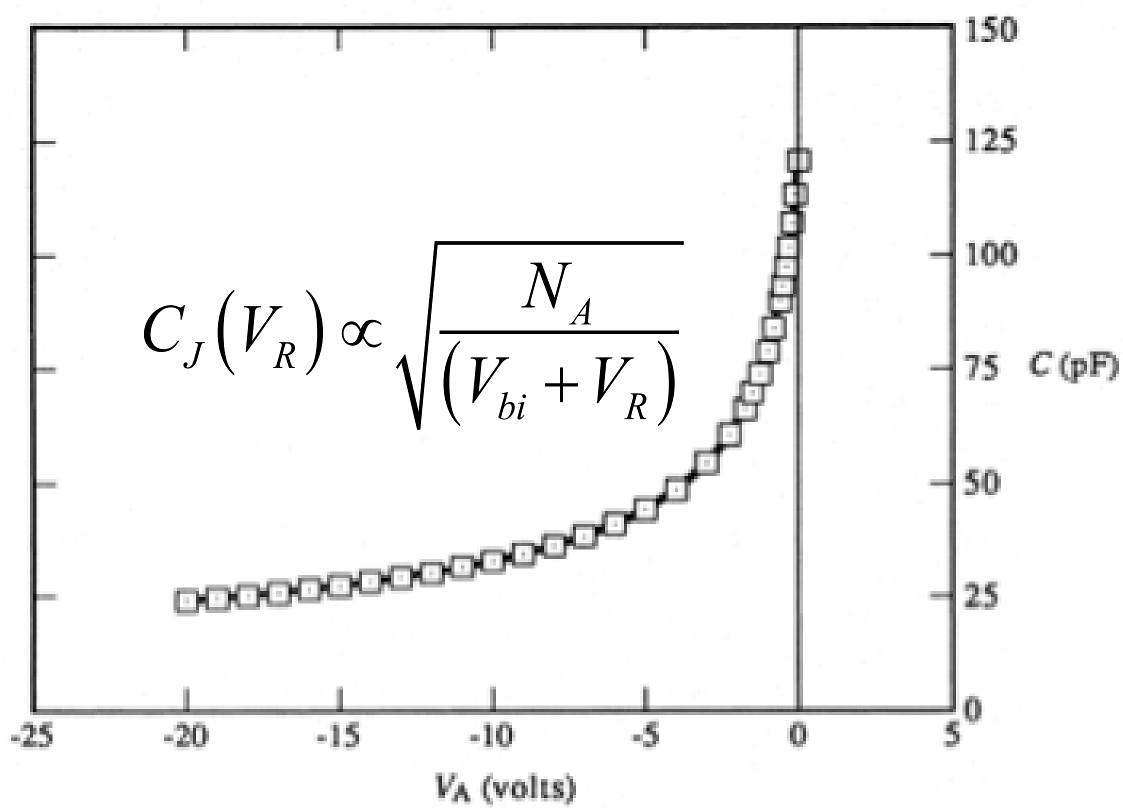
$$G_d = \frac{dI_D}{dV_A} \approx 0$$

$$G_d = \frac{I_0 e^{qV_A/k_BT}}{k_BT/q} = \frac{I_D + I_0}{k_BT/q}$$

small signal ac (capacitance)



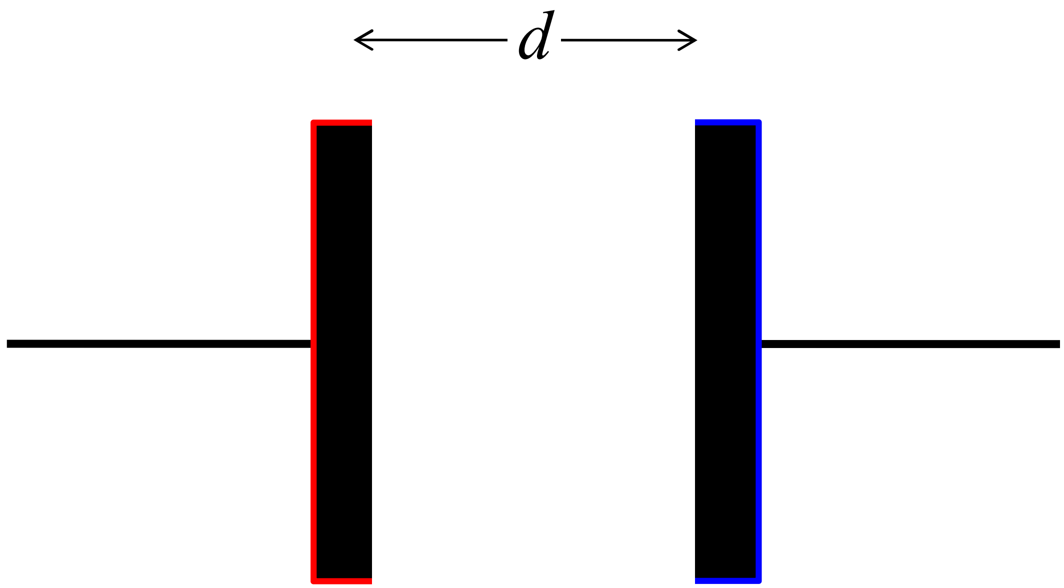
diode capacitance in RB



$$C_J(V_R) \propto \sqrt{\frac{N_A}{(V_{bi}+V_R)}}$$

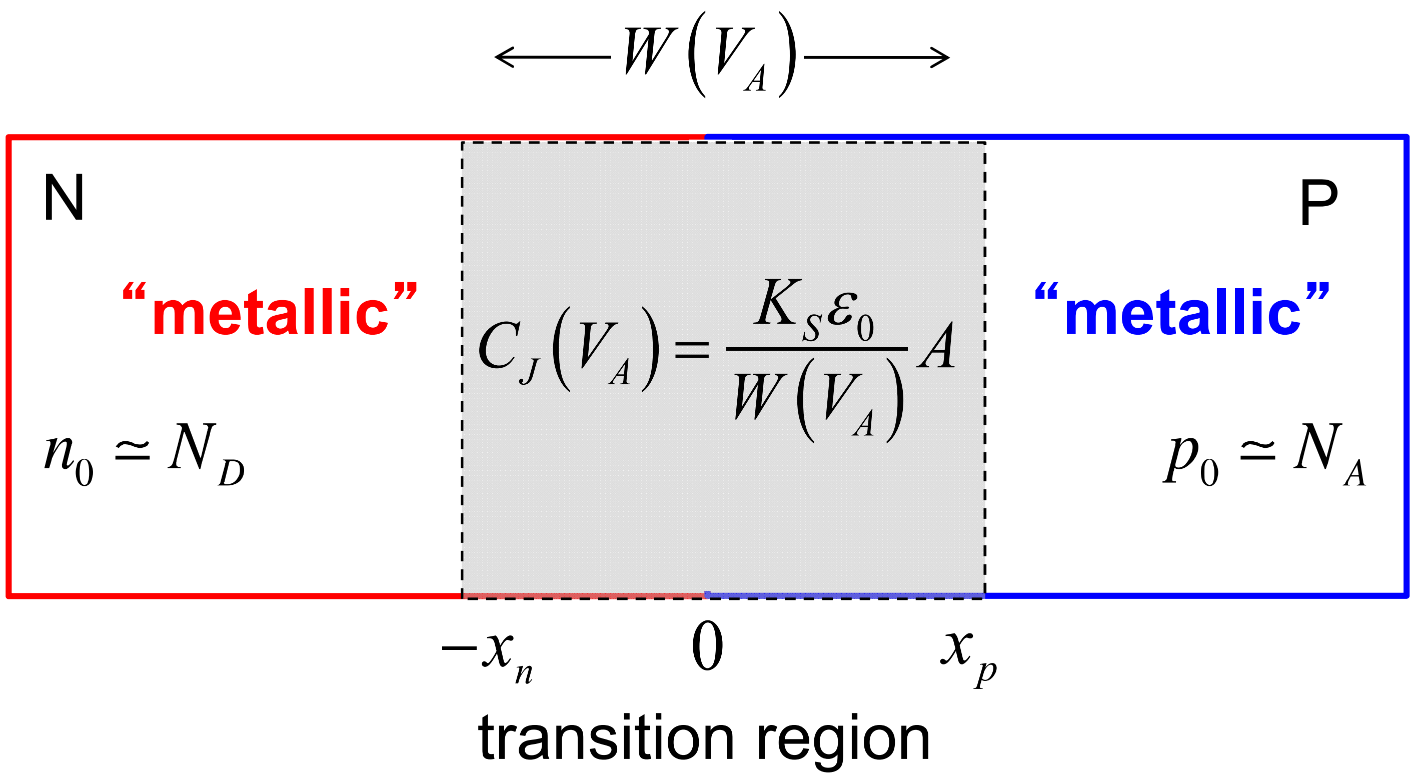
Fig. 7.3, Semiconductor Device Fundamentals, R.F. Pierret

capacitance



$$C = \frac{K_r \varepsilon_0}{d} A$$

reverse bias capacitance



reverse bias capacitance

$$C_J\left(V_A\right) = \frac{K_S \varepsilon_0}{W\left(V_A\right)} A$$

$$W\left(V_A\right) == \left[\frac{2K_S\varepsilon_0}{qN_A}\left(V_{bi} - V_A\right)\right]^{1/2} = \left[\frac{2K_S\varepsilon_0}{qN_A}\left(V_{bi} + V_R\right)\right]^{1/2}$$

$$C_J\left(V_R\right) = \boxed{} \propto \sqrt{\frac{N_A}{\left(V_{bi} + V_R\right)}}$$

$1/C^2$ vs. V_R

$$C_J(V_R) = \frac{K_S \varepsilon_0 A}{\left[\frac{2K_S\varepsilon_0}{qN_A}(V_{bi}+V_R)\right]^{1/2}}$$

$$\frac{1}{C_J^2(V_R)} = \frac{2}{qN_A K_S \varepsilon_0 A^2}(V_{bi}+V_R)$$

1/C^2 vs. V_R

$$\frac{1}{C_J^2(V_R)} = \frac{2}{qN_A K_S \varepsilon_0 A^2}(V_{bi} + V_R)$$

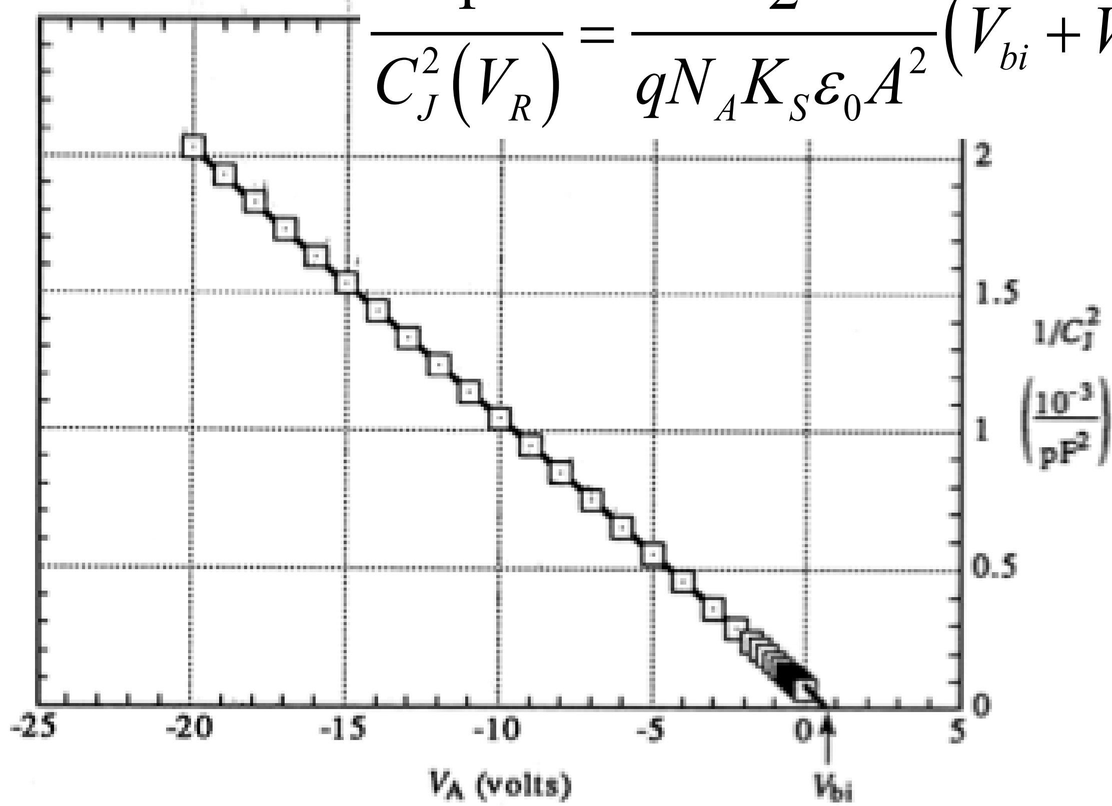
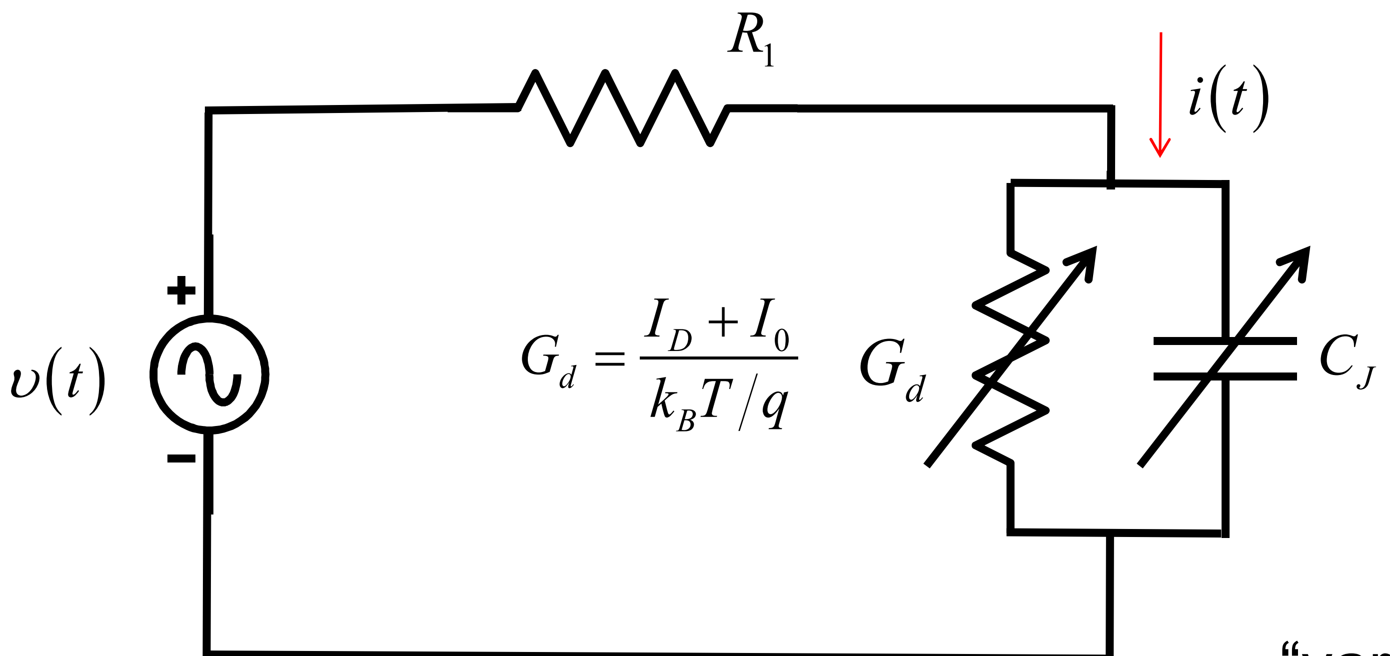


Fig. E7.2, Semiconductor Device Fundamentals, R.F. Pierret

equivalent circuit (reverse bias)

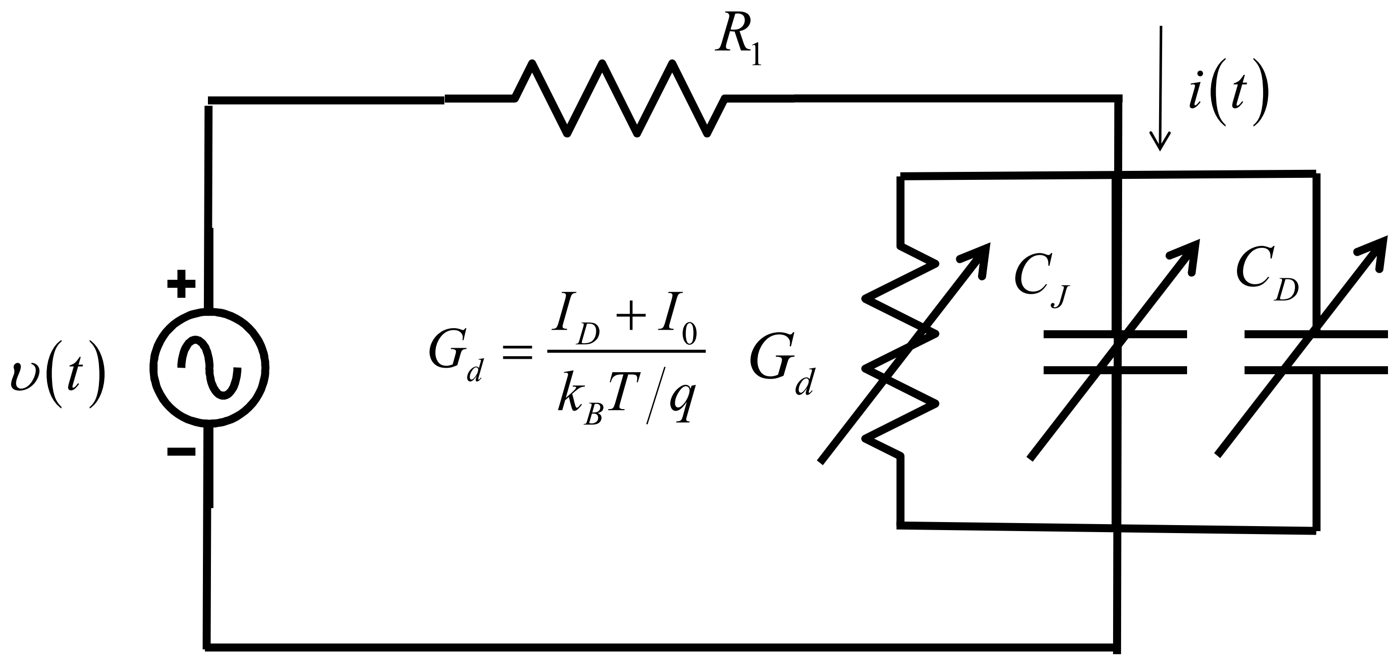


$$G_d = \frac{I_D + I_0}{k_B T / q}$$

"varactor"

$$C_J(V_R) = \frac{K_S \varepsilon_0 A}{\left[\frac{2K_S\varepsilon_0}{qN_A}(V_{bi} - V_A)\right]^{1/2}}$$

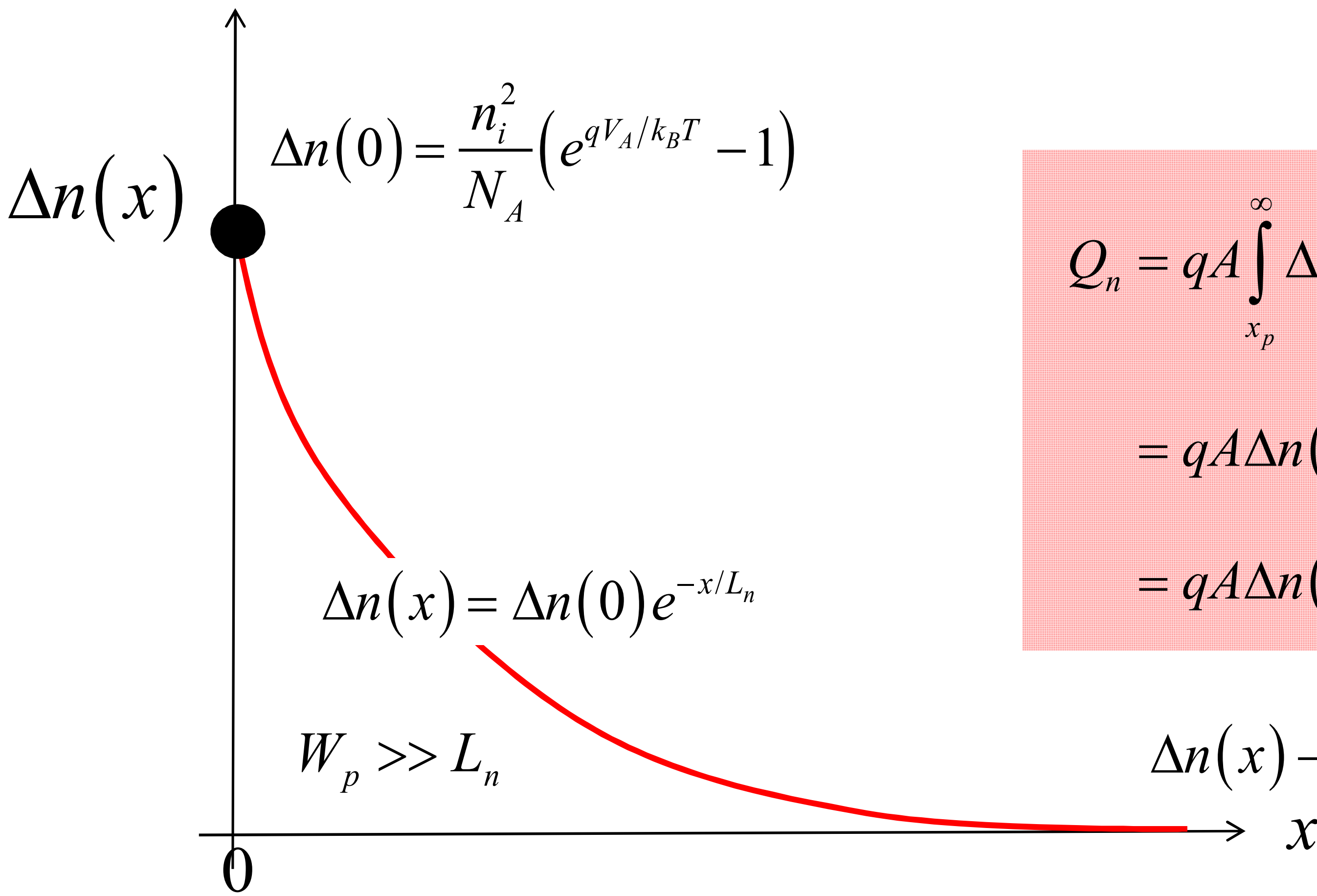
equivalent circuit (forward bias)



$$C_J(V_R) = \frac{K_S \varepsilon_0 A}{\left[\frac{2K_S \varepsilon_0}{qN_A}(V_{bi} - V_A)\right]^{1/2}}$$

$$C_D \propto e^{qV_A/k_BT} >> C_J$$

stored minority carrier charge



$$Q_n = qA\int_{x_p}^{\infty} \Delta n(x)\,dx$$

$$= qA\Delta n(0)\int_{0}^{\infty} e^{-x/L_n}\,dx$$

$$= qA\Delta n(0) L_n$$

stored minority carrier charge

$$Q_n = qA\Delta n(0)L_n \qquad \Delta n(0) = \frac{n_i^2}{N_A}\left(e^{qV_A/k_BT} - 1\right)$$

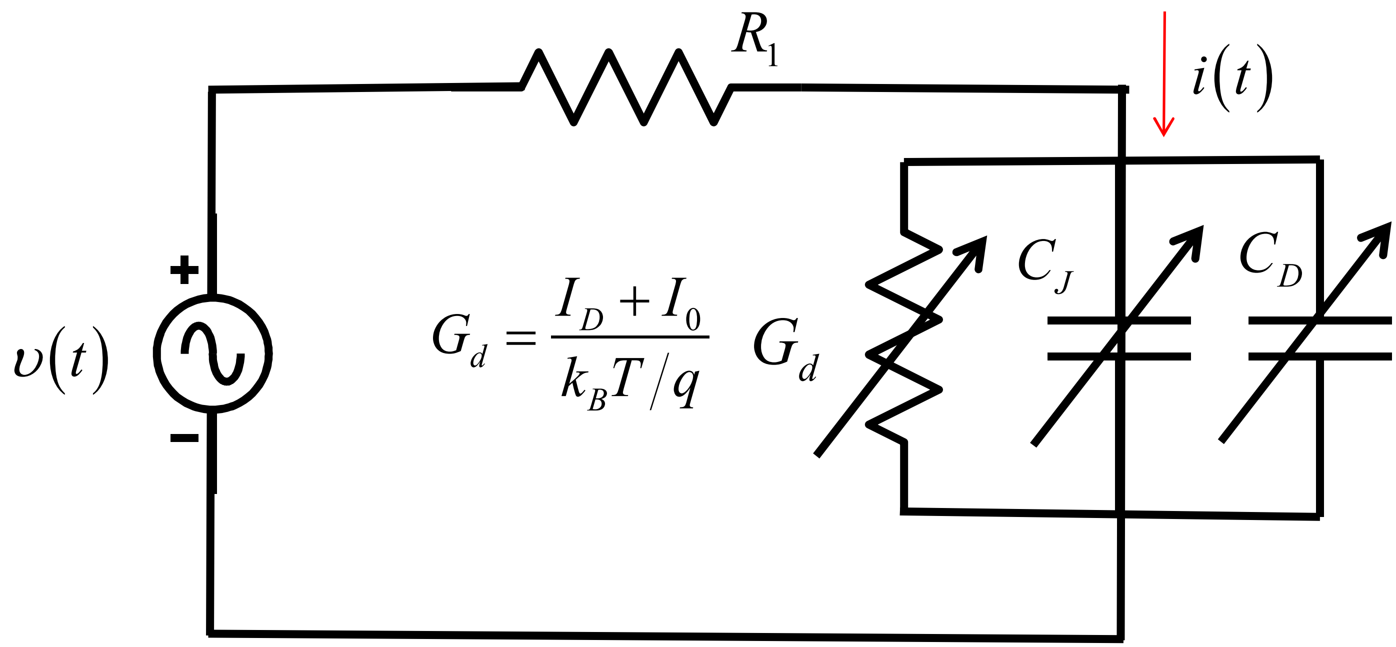
$$C_D = \frac{dQ_n}{dV_A} = A\frac{q}{k_BT/q}\frac{n_i^2}{N_A}L_n e^{qV_A/k_BT}$$

$$G_d = \frac{I_0 e^{qV_A/k_BT}}{k_BT/q} = \frac{qA}{k_BT/q}\frac{D_n}{L_n}\frac{n_i^2}{N_A}e^{qV_A/k_BT}$$

$$C_D = G_d\ \tau_n$$

Check units:

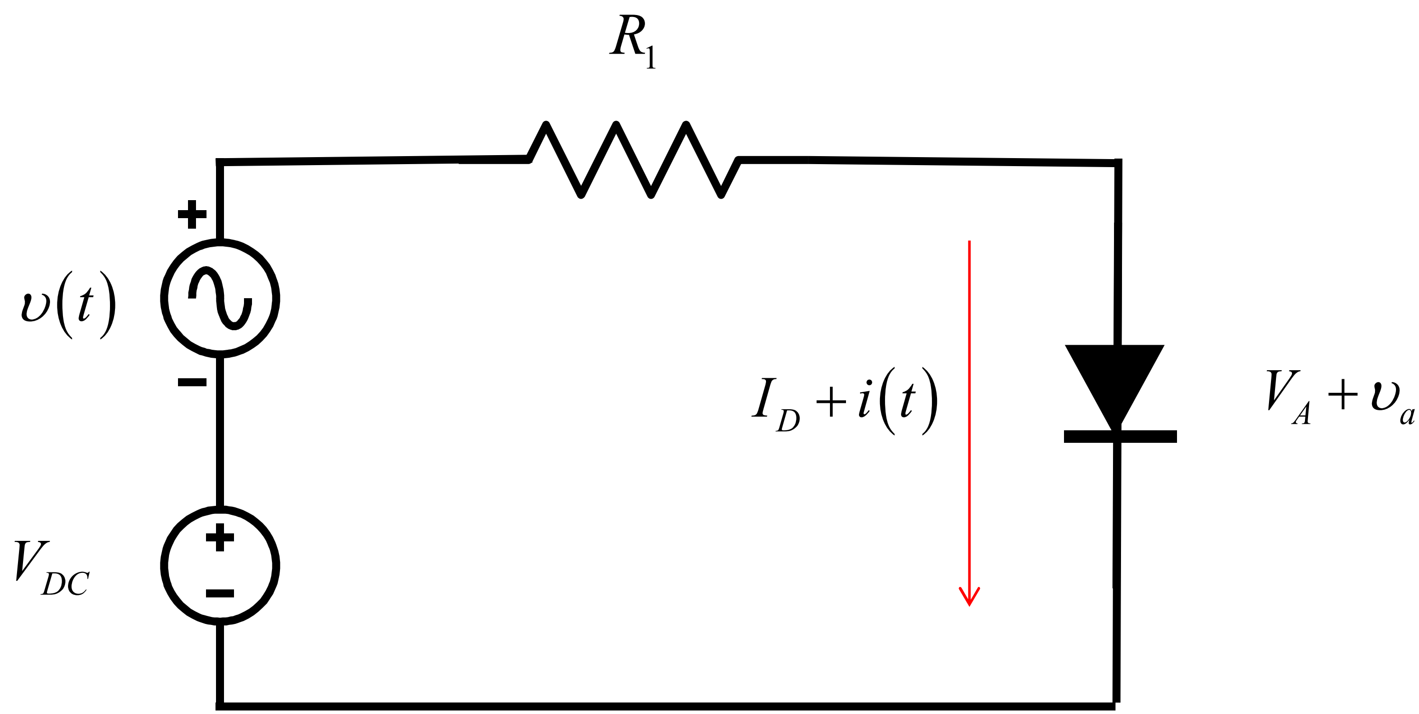
equivalent circuit (general)



$$C_J(V_R) = \frac{K_S \varepsilon_0 A}{\left[\frac{2K_S\varepsilon_0}{qN_A}(V_{bi} - V_A)\right]^{1/2}}$$

$$C_D = G_d\ \tau_n$$

small signal ac



1) Compute the DC bias current
2) Replace the diode with the s.s. a.c. model and do the a.c. analysis.

Summary of Small Signal Model

- In small signal approximation, can treat AC response of pn junction as small perturbation to DC ideal diode equation
- In reverse bias, we find a variable complex impedance (varactor): a junction capacitance and conductance in parallel, i.e., $Y_{eq} = G_c + j\omega C_J$
- In forward bias, we also have a diffusion capacitance, so: $Y_{eq} = G_c + j\omega\left(C_J + C_D\right)$