ECE-305: Spring 2018
Ideal Diodes+Solar Cells

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

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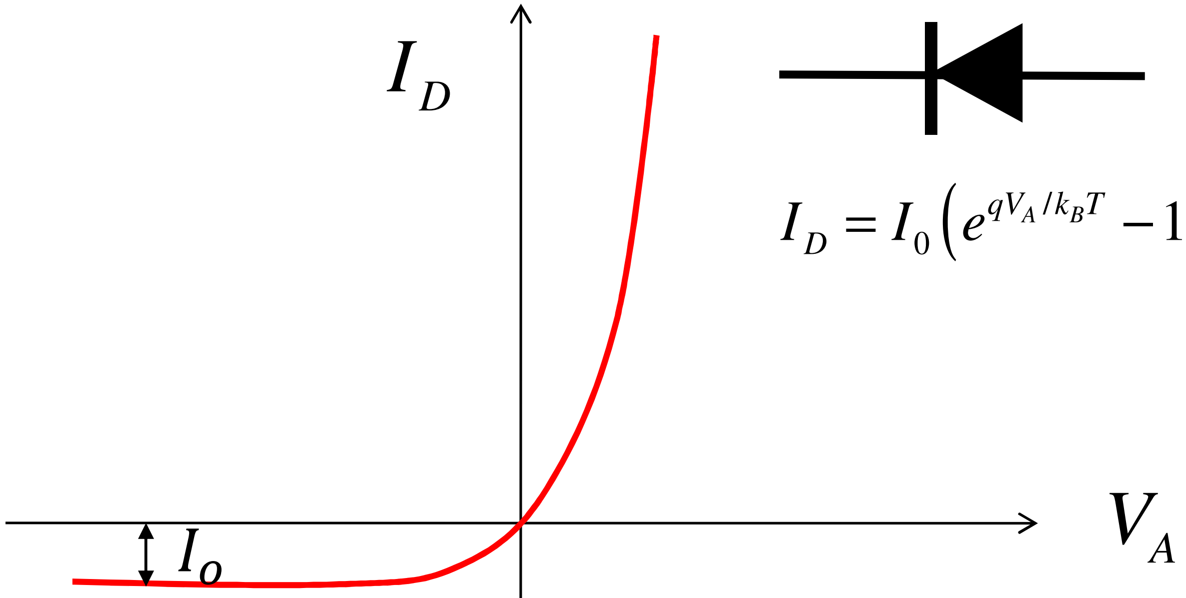
outline

1) Ideal Diode Equation
2) Ideal Diode Example
3) A Primer on Solar Cells
4) Diode Non-idealities

ideal diode equation recap



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

long

$$I_0 = qA\left(\frac{D_n}{L_n}\frac{n_i^2}{N_A} + \frac{D_p}{L_p}\frac{n_i^2}{N_D}\right)$$

short

$$I_0 = qA\left(\frac{D_n}{W_P}\frac{n_i^2}{N_A} + \frac{D_p}{W_N}\frac{n_i^2}{N_D}\right)$$

outline

✓ 1) Ideal Diode Equation

2) Ideal Diode Example

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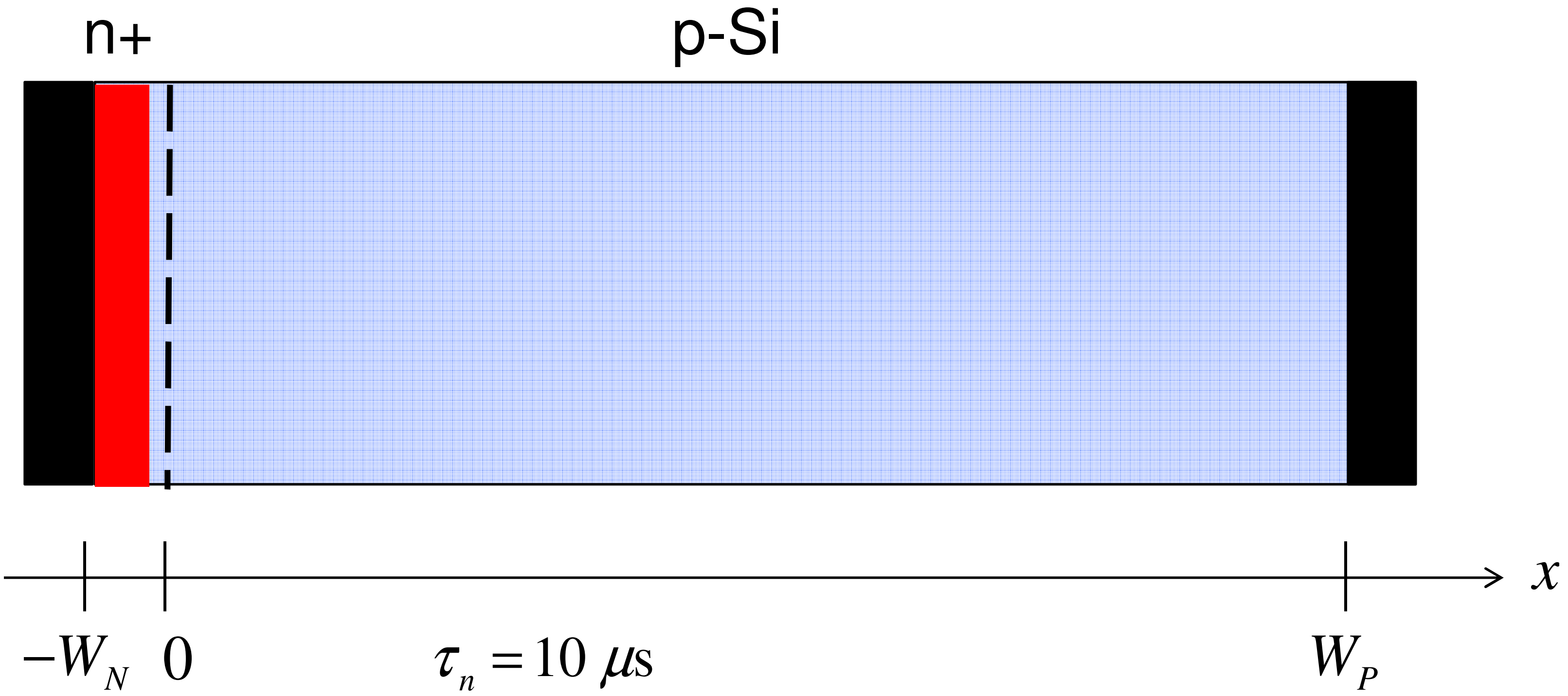
example



$N_D = 10^{20}\ \text{cm}^{-3}$

$N_A = 10^{17}\ \text{cm}^{-3}$

$\tau_n = 10\ \mu\text{s}$

$W_N = 0.1\ \mu\text{m}$

$\tau_p = 1\ \mu\text{s}$

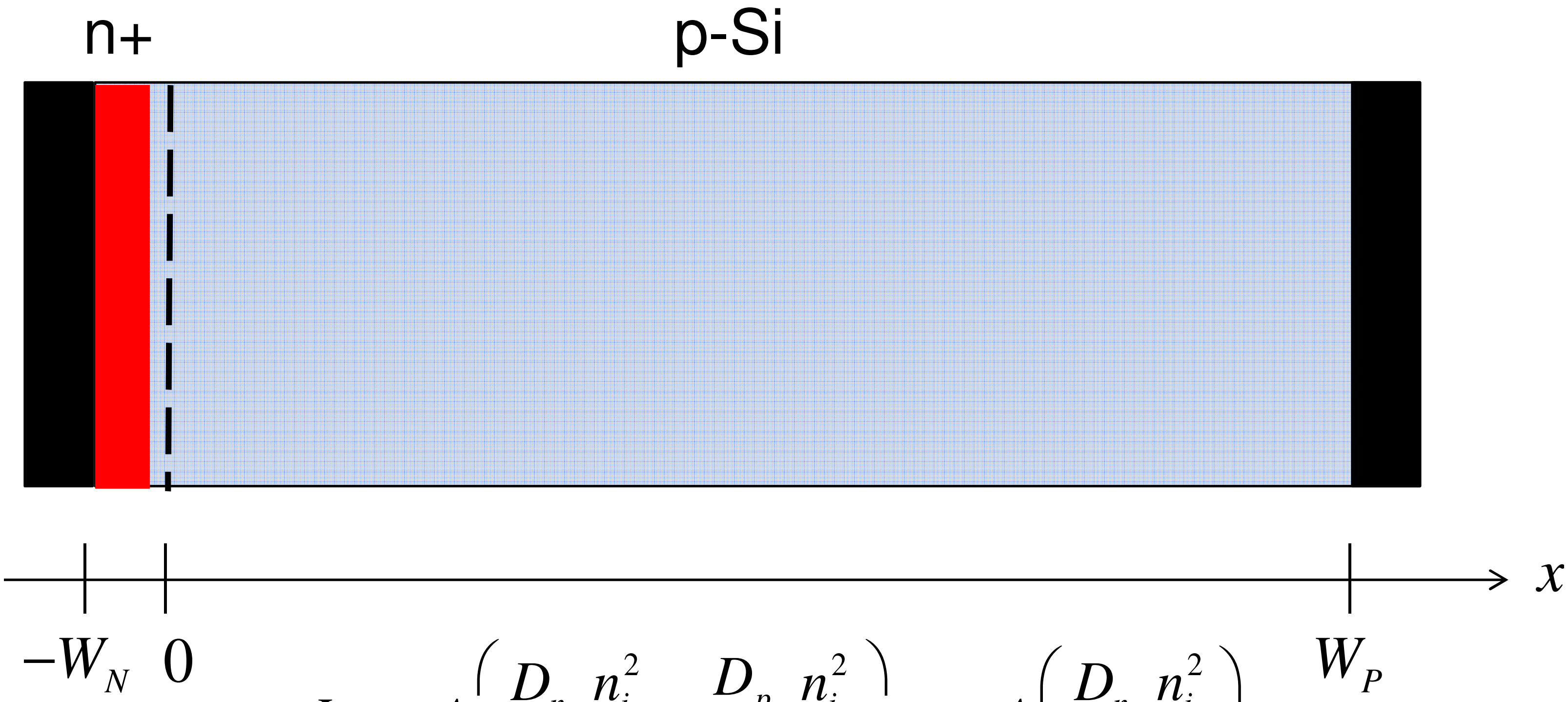
$W_P = 10\ \mu\text{m}$

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

$$I_0 = ?$$

Is this a one-sided diode?

example: one-sided diodes



$$I_0 = qA\left(\frac{D_n}{L_n}\frac{n_i^2}{N_A} + \frac{D_p}{L_p}\frac{n_i^2}{N_D}\right) \to qA\left(\frac{D_n}{L_n}\frac{n_i^2}{N_A}\right)$$

$$I_0 = qA\left(\frac{D_n}{W_P}\frac{n_i^2}{N_A} + \frac{D_p}{W_n}\frac{n_i^2}{N_D}\right) \to qA\left(\frac{D_n}{W_P}\frac{n_i^2}{N_A}\right)$$

outline

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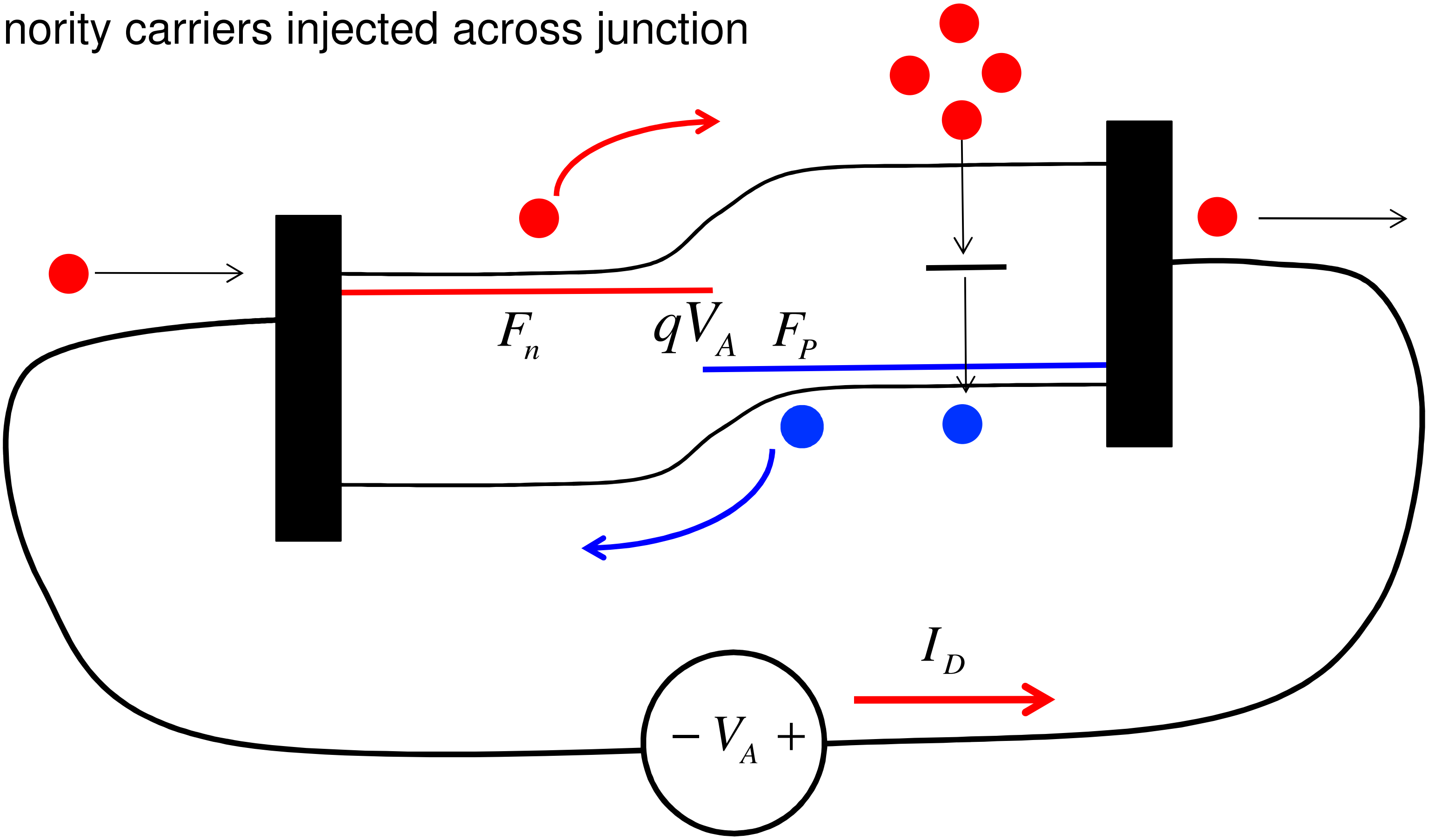
solar cells

SunPower http://us.sunpower.com

recombination and dark current

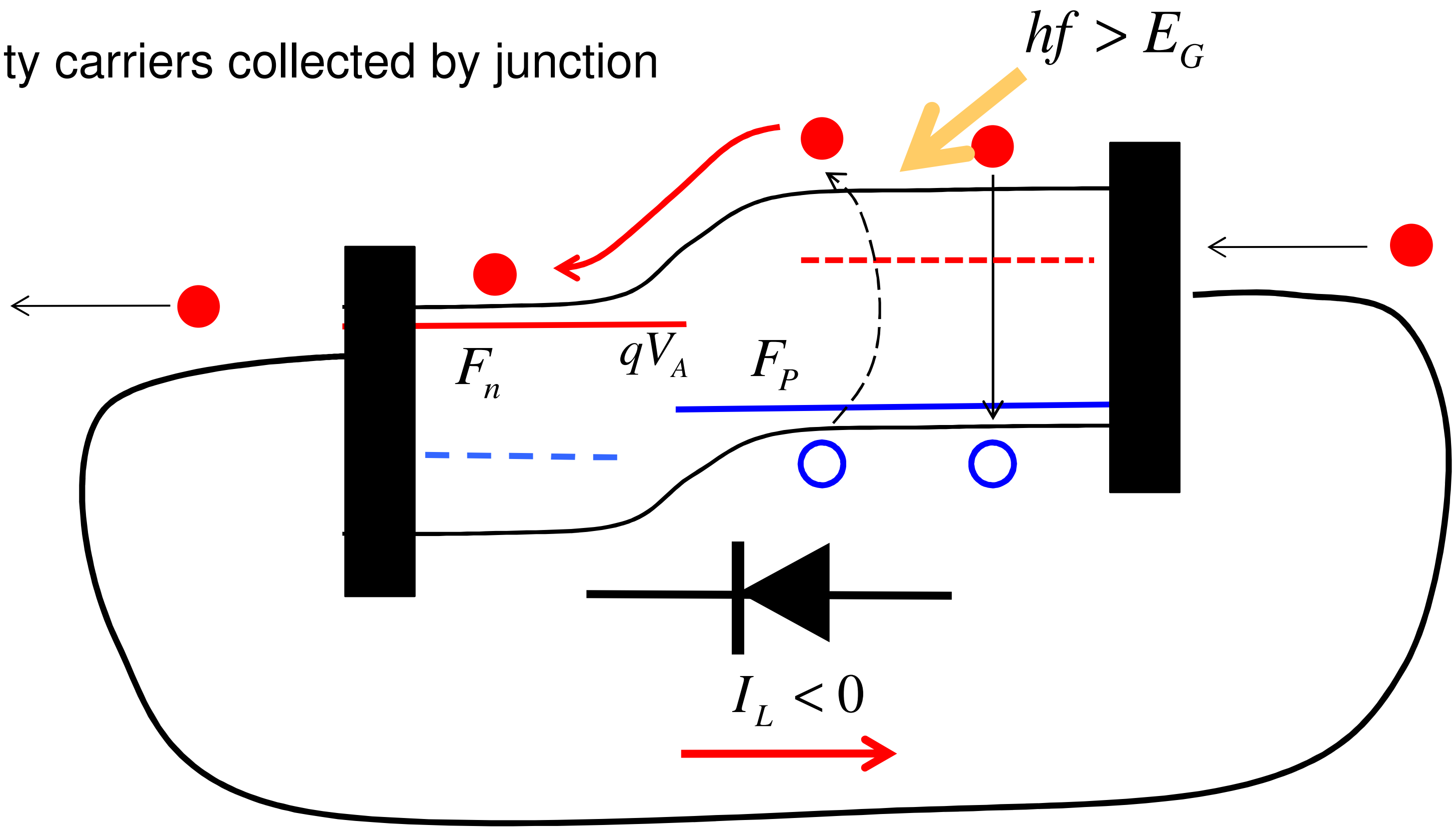
minority carriers injected across junction



Every time a minority electron **recombines** on the p-side, one electron flows in the external current.

generation and current

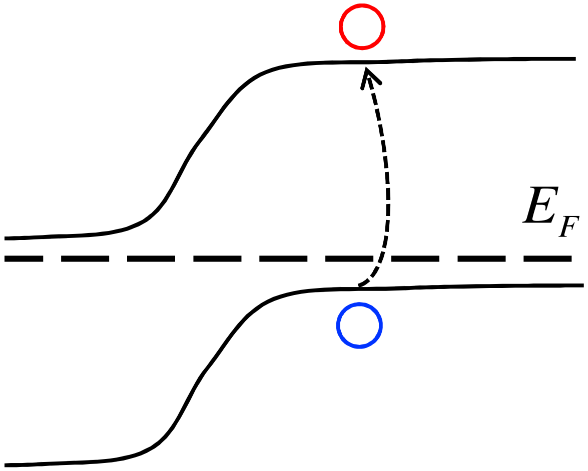
minority carriers collected by junction



Every time a minority electron is generated and collected by the PN junction, one electron flows in the external current.

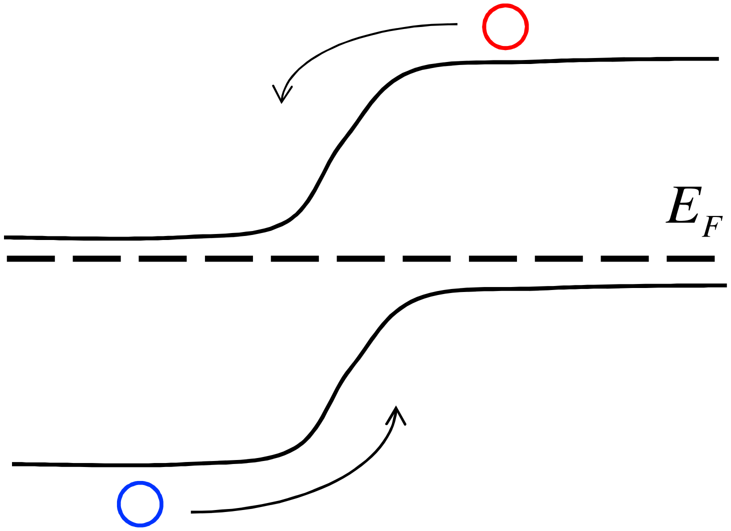
solar cell operation

1) Light generates e-h pairs

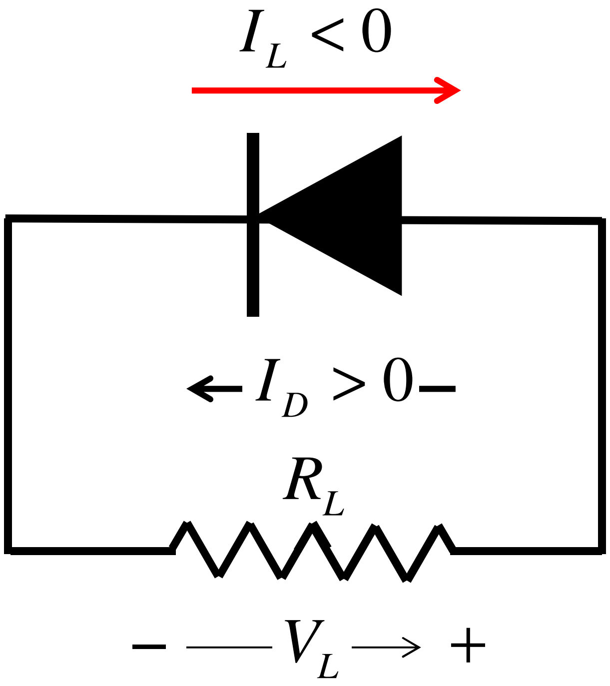


solar cell operation

2) PN junction collects e-h pairs



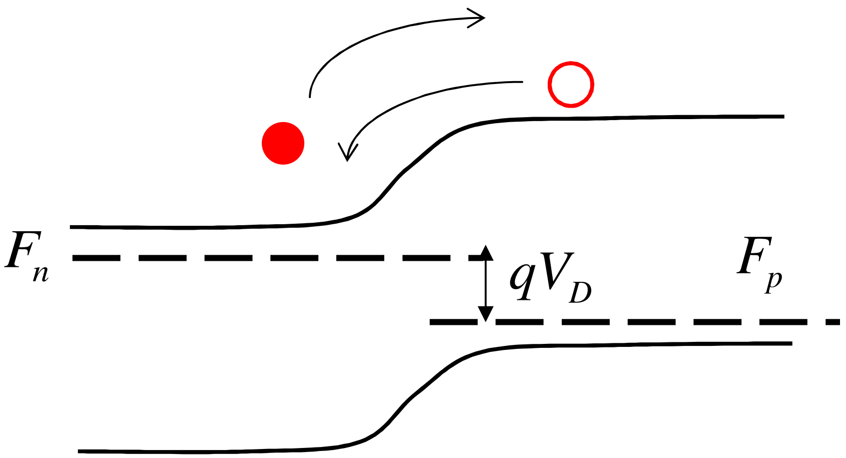
3) Current flows through load



forward bias develops across PN junction

solar cell operation

4) Forward bias reduces current



5) IV characteristic is a superposition

$$I_{TOT} = I_0\left(e^{qV_D/k_BT} - 1\right) - I_{SC}$$

diode (dark) current

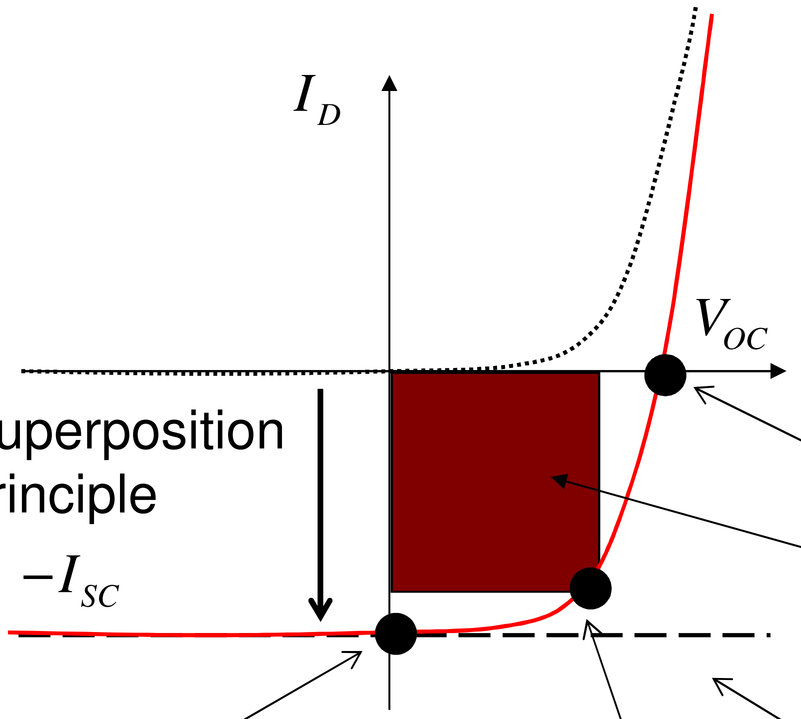
light-generated current

IV characteristic

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

$$I_{TOT} = I_0\left(e^{qV_D/k_BT} - 1\right) - I_{SC}$$

$$\eta = \frac{P_{out}}{P_{in}} = \frac{I_{SC}V_{OC}FF}{P_{in}}$$



Superposition principle

$$P_{out} = I_{TOT}V_{OC} = 0$$

Maximum power rectangle

$$P_{out} = -I_{SC}V_D = 0$$

$$P_D = I_{TOT}V_D < 0$$

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

solar cell efficiency

$$\eta = \frac{P_{out}}{P_{in}} = \frac{I_{SC} V_{OC} FF}{P_{in}}$$

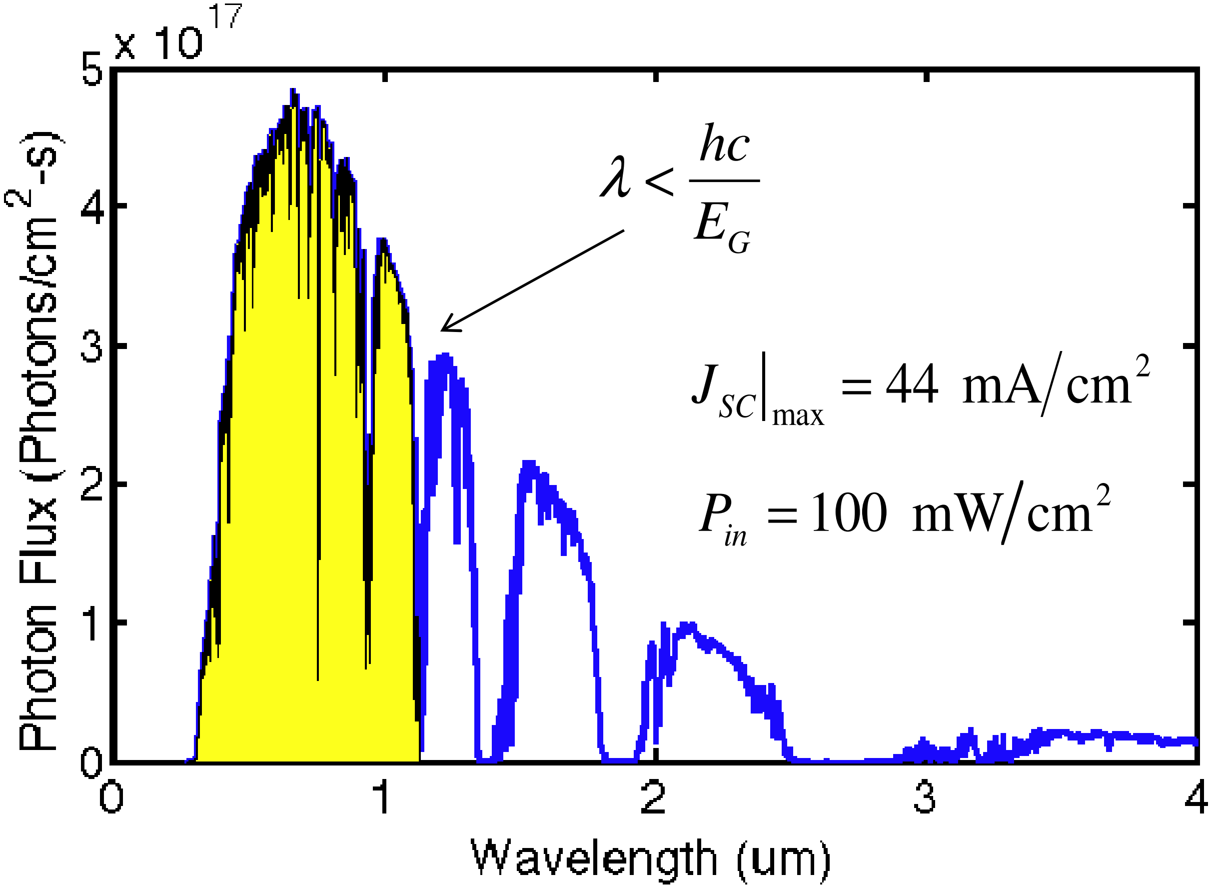
1) Short circuit current

2) Open-circuit voltage

3) Fill factor

maximum short circuit current

Example: Silicon E_g = 1.1eV. Only photons with a wavelength < 1.12 μm will be absorbed.



$$\lambda < \frac{hc}{E_G}$$

$$J_{SC}\big|_{\max} = 44 \text{ mA/cm}^2$$

$$P_{in} = 100 \text{ mW/cm}^2$$

solar spectrum (AM1.5G)

open-circuit voltage and efficiency

$$I_{TOT} = I_0\left(e^{qV/k_BT} - 1\right) - I_{SC} \qquad V_{OC} = \frac{k_BT}{q}\ln\left(\frac{I_{SC}}{I_0}\right) \qquad \eta = \frac{P_{out}}{P_{in}} = \frac{I_{SC}V_{OC}FF}{P_{in}}$$

Example for silicon photovoltaics:

$$I_0 = 1\times 10^{-12}\ \mathrm{A}$$

$$\eta = \frac{P_{out}}{P_{in}} = \frac{40\times 0.63\times 0.8}{100} = 0.20$$

$$I_{SC} = 0.90\times 44\times 10^{-3} = 40\ \mathrm{mA}$$

$$V_{OC} = 0.026\ln\left(\frac{40\times 10^{-3}}{1\times 10^{-12}}\right) = 0.63$$

Increasing the efficiency

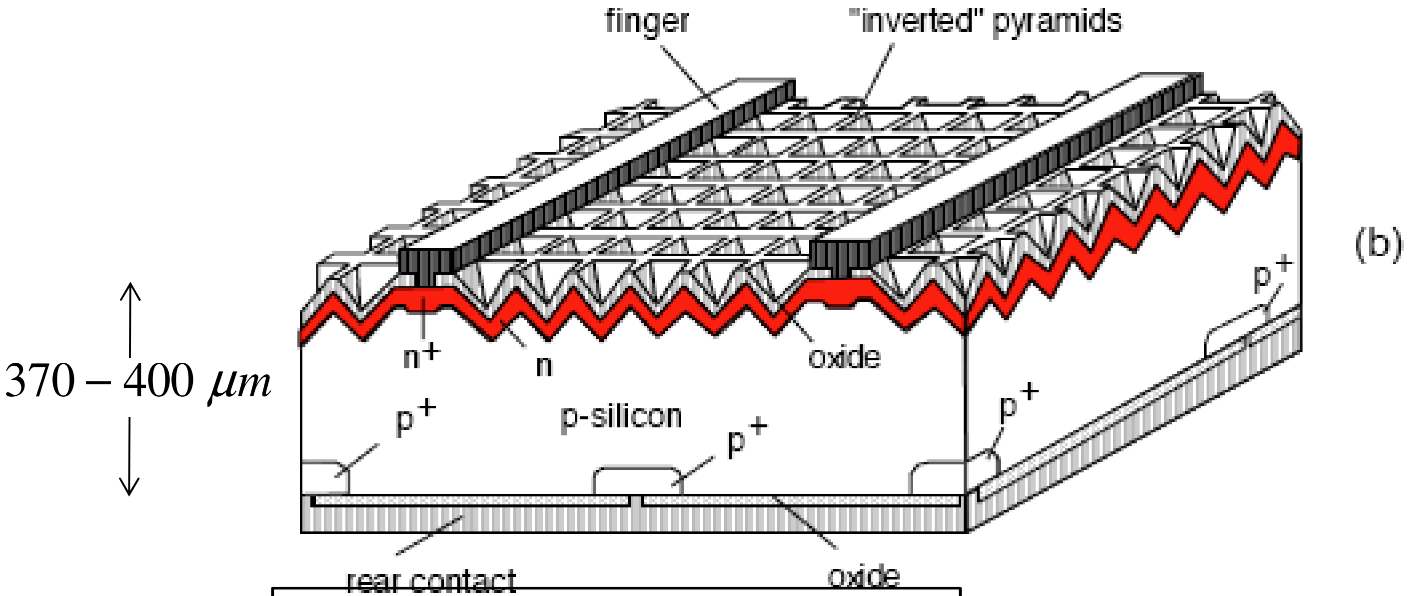
$$\eta = \frac{P_{out}}{P_{in}} = \frac{I_{SC} V_{OC} FF}{P_{in}}$$

1) Increase the short circuit current from 40 towards 44

2) Increase V_{OC} (decrease I_0) $$V_{OC} = \frac{k_B T}{q} \ln\left(\frac{I_{SC}}{I_0}\right)$$

$$I_0 = qA\left(\frac{D_n}{W_P}\frac{n_i^2}{N_A}\right)$$

efficiency



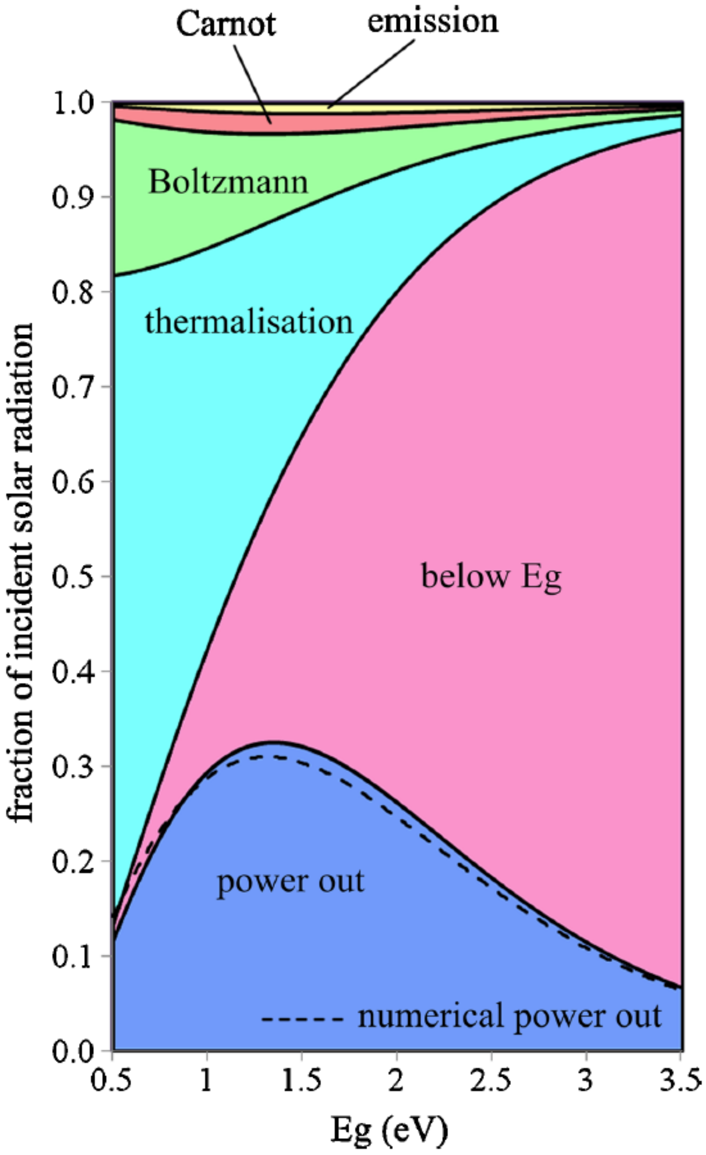
$$J_{SC} = 41.5\ \text{mA/cm}^2 \quad (94\%)$$

$$V_{OC} = 0.703 \qquad FF = 0.81$$

$$I_0 = 0.075 \times 10^{-12}\ \text{A}$$

Martin Green Group UNSW – Zhao *et al.*, 1998 (25% at 1 sun)

J_{SC} – V_{OC} trade-off



1) Smaller bandgaps give higher short circuit current
2) Larger bandgaps give higher open-circuit voltage
3) For the given solar spectrum, an optimum bandgap exists.

"Shockley-Queisser Limit"

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

✓ 1) Ideal Diode Equation

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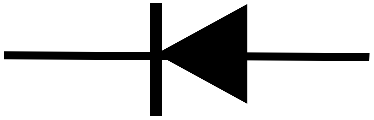
4) Diode Non-idealities:
    - Breakdown
    - High forward bias
    - Recombination-generation current

How large of a voltage can we apply?



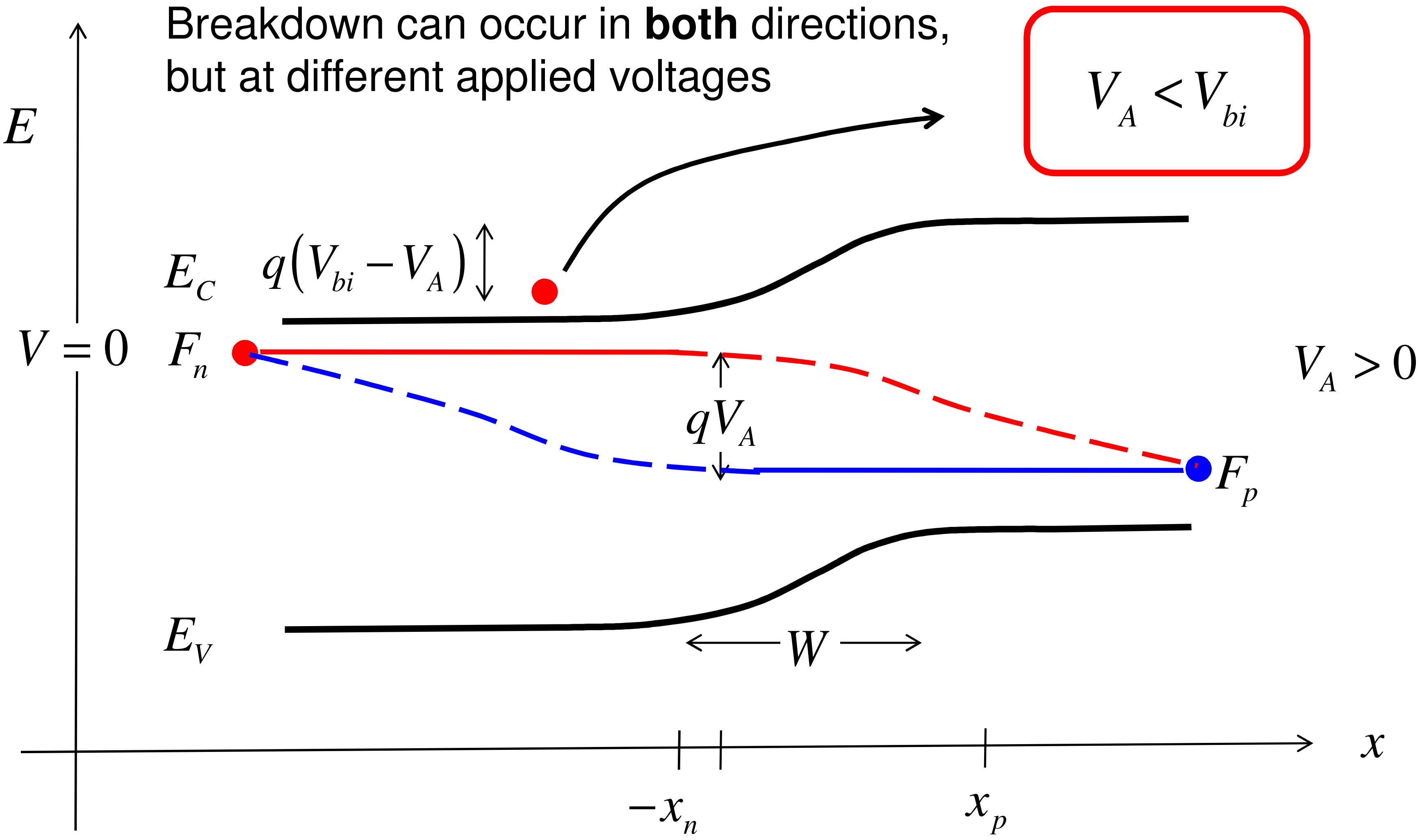
$$I_D = I_0\left(e^{qV_A/k_BT} - 1\right)$$

Reverse bias: breakdown

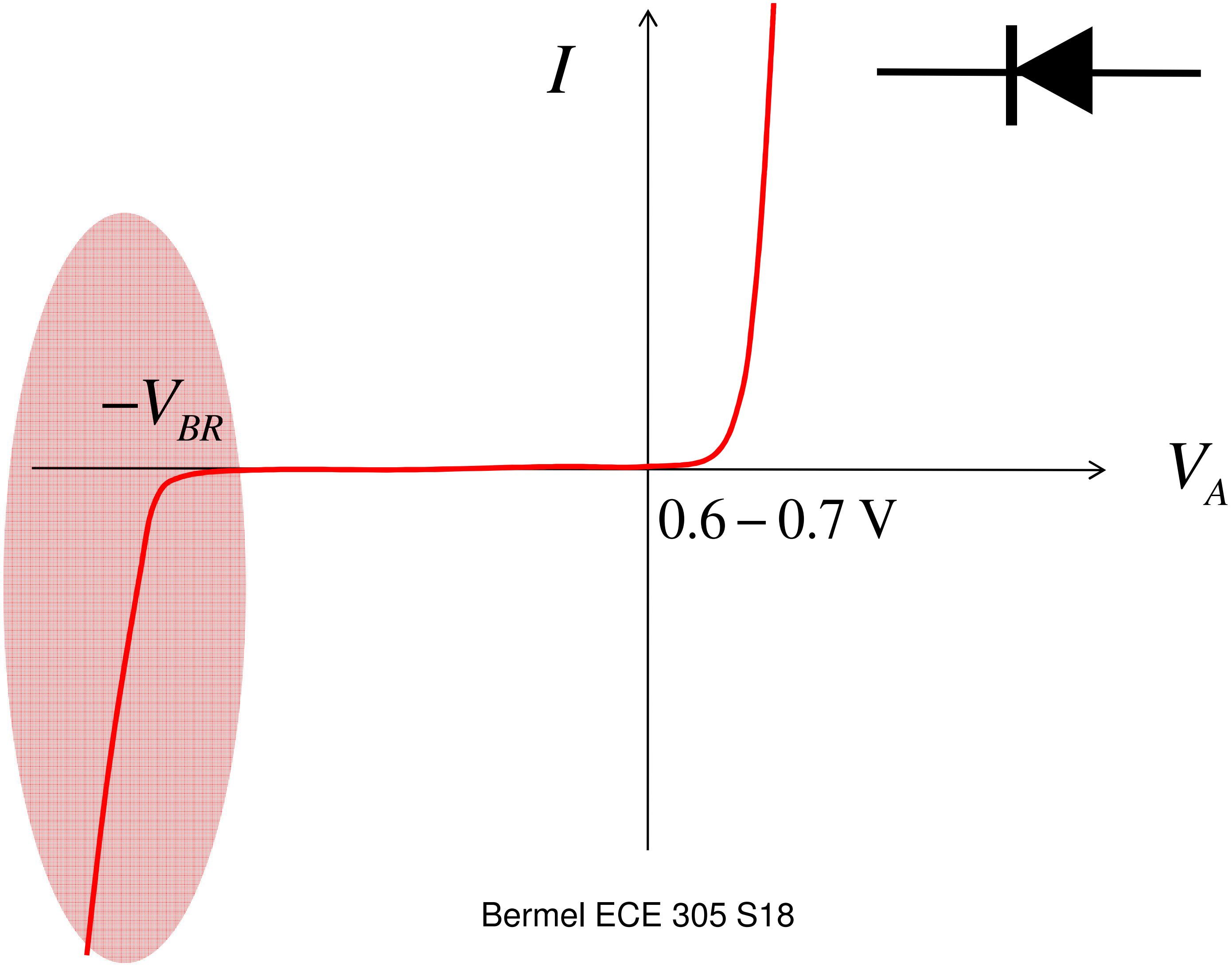
Forward bias: ?

e-band diagram under bias

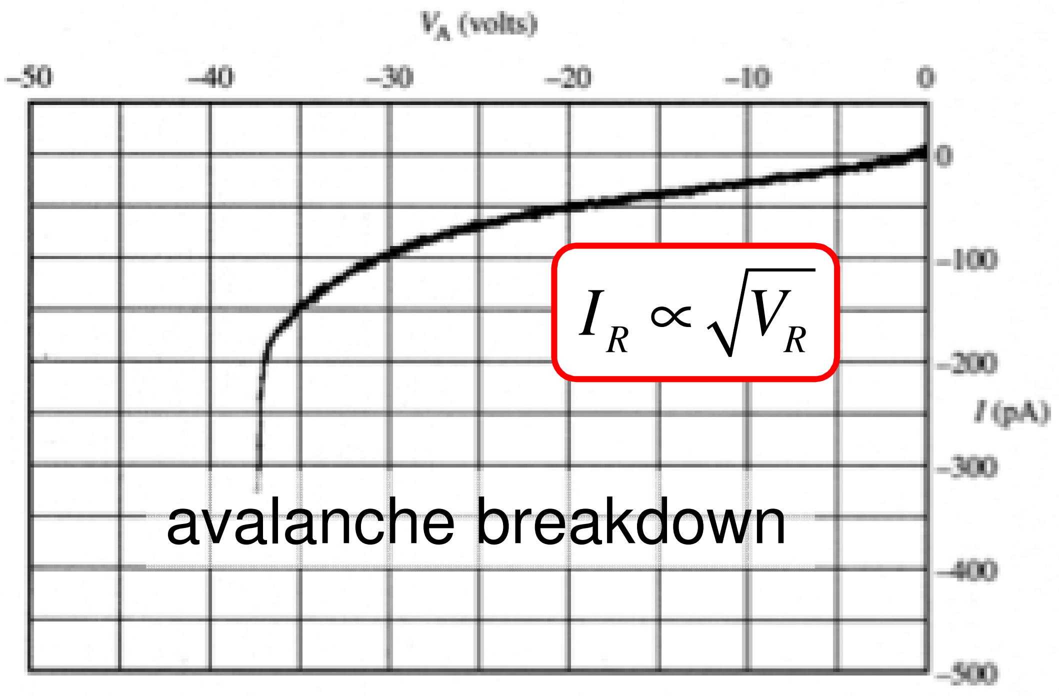
Breakdown can occur in **both** directions, but at different applied voltages



reverse bias breakdown



real diodes in RB

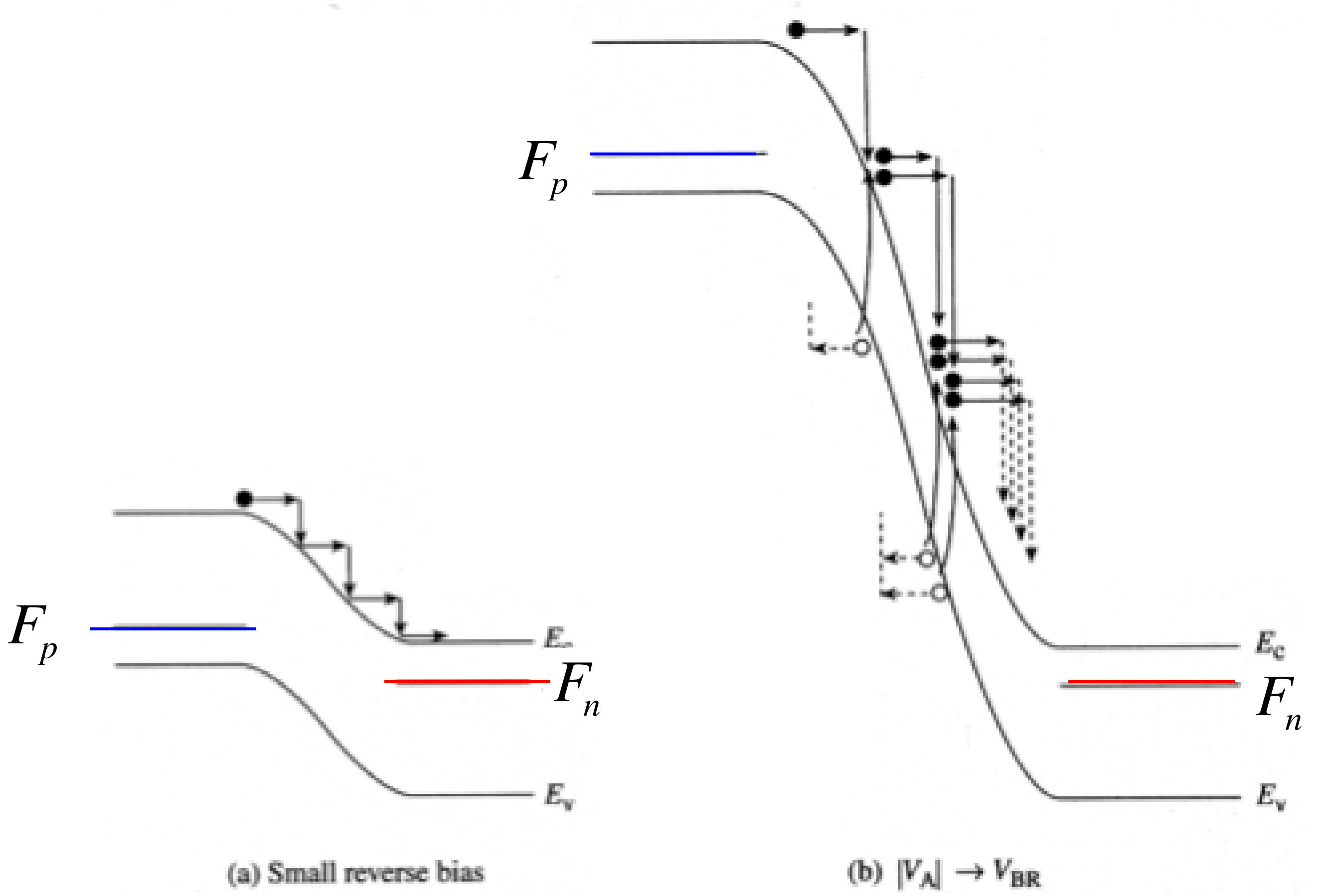


$I_R \propto \sqrt{V_R}$

avalanche breakdown

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

avalanche breakdown

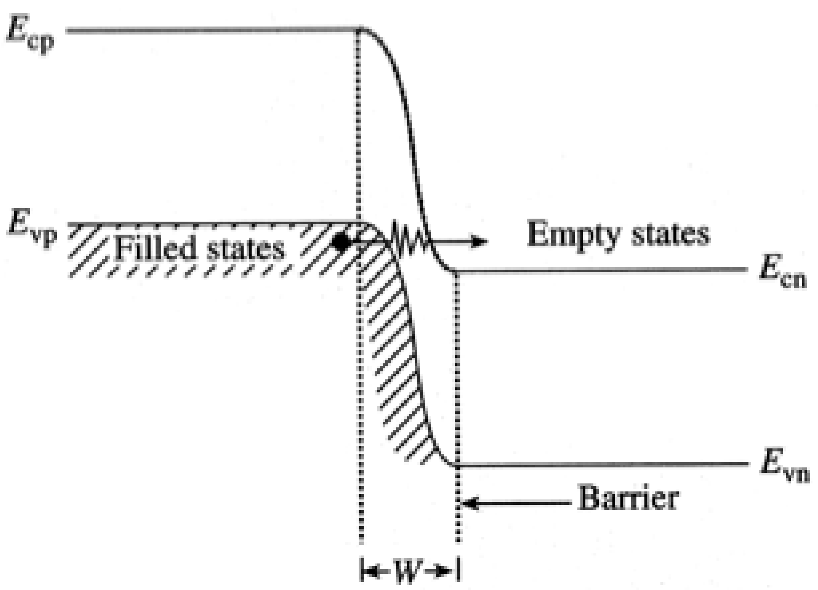


(a) Small reverse bias

(b) $|V_A| \to V_{BR}$

Fig. 6.12, Semiconductor Device Fundamentals, R.F. Pierret

tunneling



$$W = \left[\frac{2K_S\varepsilon_0}{q}\left(\frac{N_A+N_D}{N_DN_A}\right)V_{bi}\right]^{1/2} \approx \left[\frac{2K_S\varepsilon_0}{qN_A}V_{bi}\right]^{1/2}$$

Fig. 6.14, Semiconductor Device Fundamentals, R.F. Pierret

breakdown vs. doping

$$V_{BR} \propto \frac{1}{N_A}$$

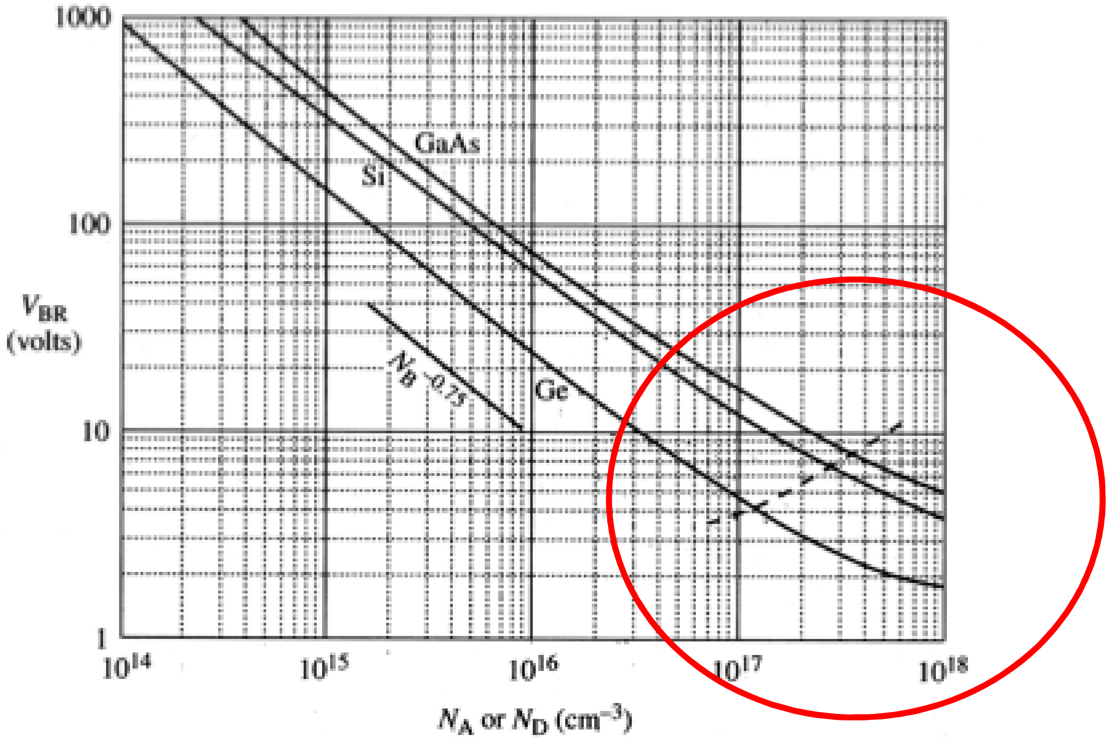


Fig. 6.11, Semiconductor Device Fundamentals, R.F. Pierret

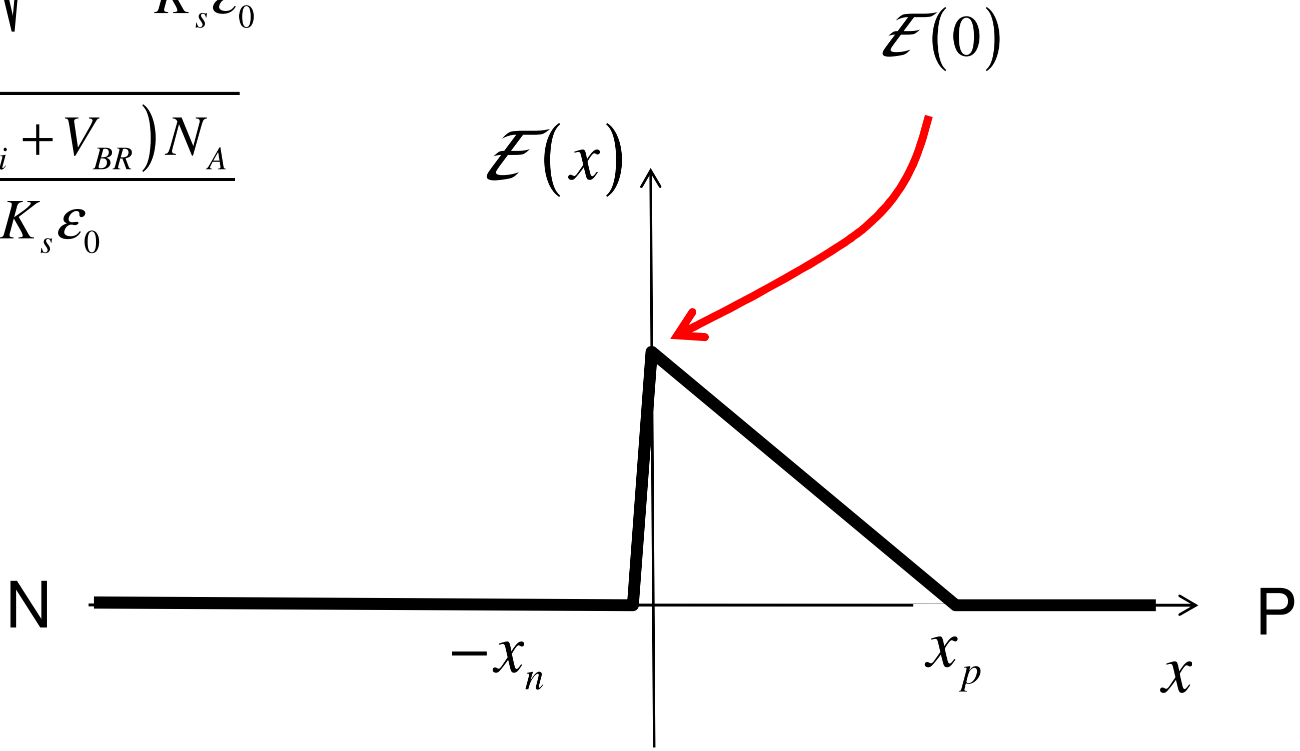
breakdown voltage and critical electric field

$$N_D >> N_A \Rightarrow \mathcal{E}(0) = \sqrt{\frac{2q\left(V_{bi}+V_R\right)N_A}{K_s\varepsilon_0}}$$

$$\mathcal{E}(0) = \mathcal{E}_{CR} = \sqrt{\frac{2q\left(V_{bi}+V_{BR}\right)N_A}{K_s\varepsilon_0}}$$

$$V_{BR} = \frac{K_s\varepsilon_0}{2qN_A}\mathcal{E}_{CR}^2 - V_{bi}$$

$$V_{BR} \propto \frac{1}{N_A}$$



critical electric field

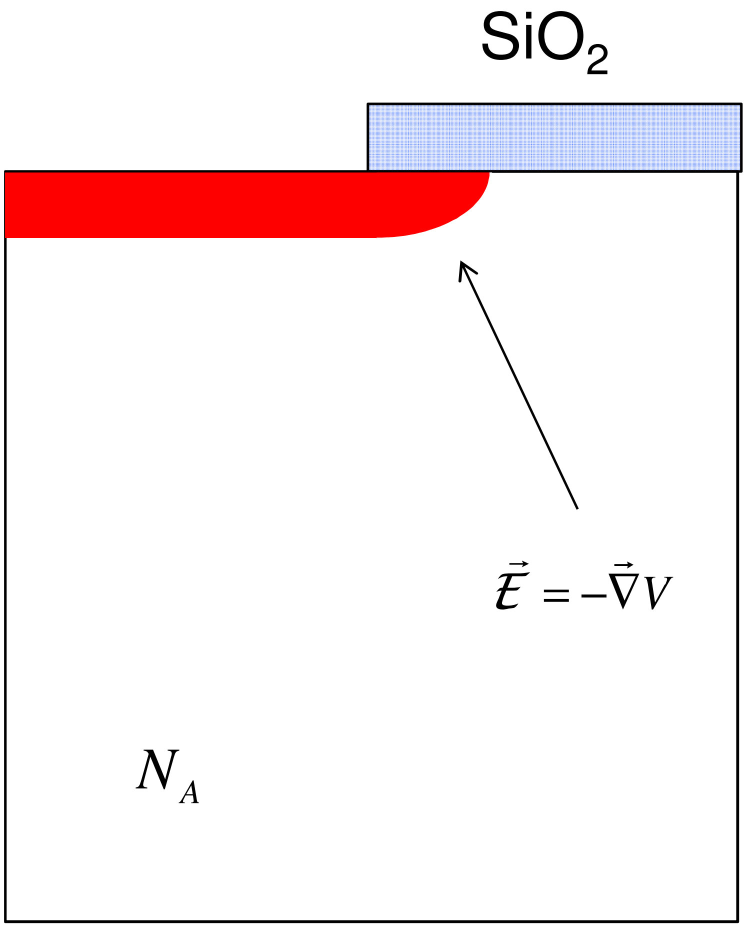
$$\mathcal{E}_{CR} = \sqrt{\frac{2q\left(V_{bi} + V_{BR}\right)N_A}{K_s\varepsilon_0}} \qquad V_{BR} \propto \frac{1}{N_A}$$

$\mathcal{E}_{CR} \approx 3\times10^5$ V/cm (Silicon)

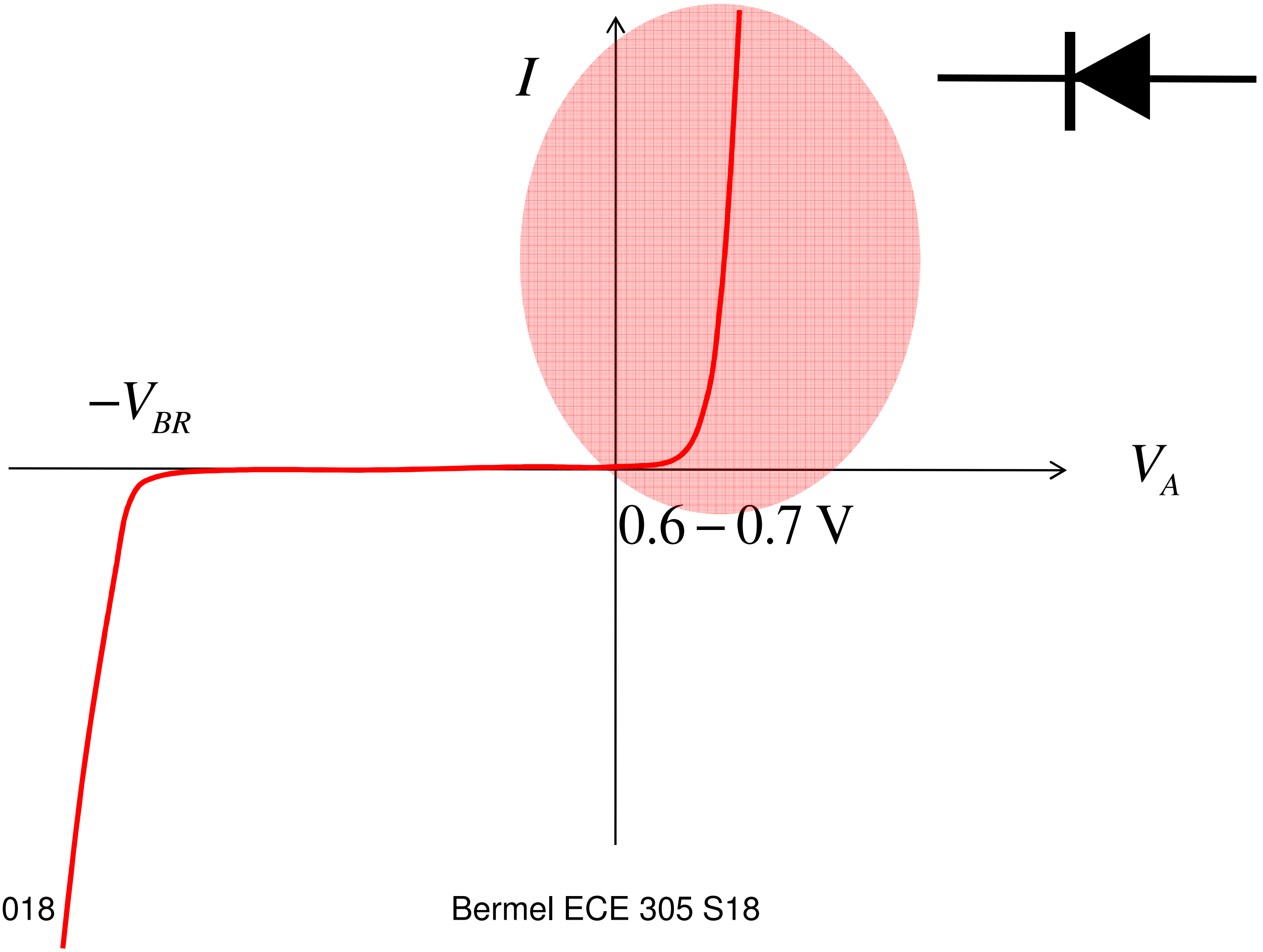
$\mathcal{E}_{CR} \approx 1\times10^5$ V/cm (Germanium)

$\mathcal{E}_{CR} \approx 5\times10^6$ V/cm (GaN)

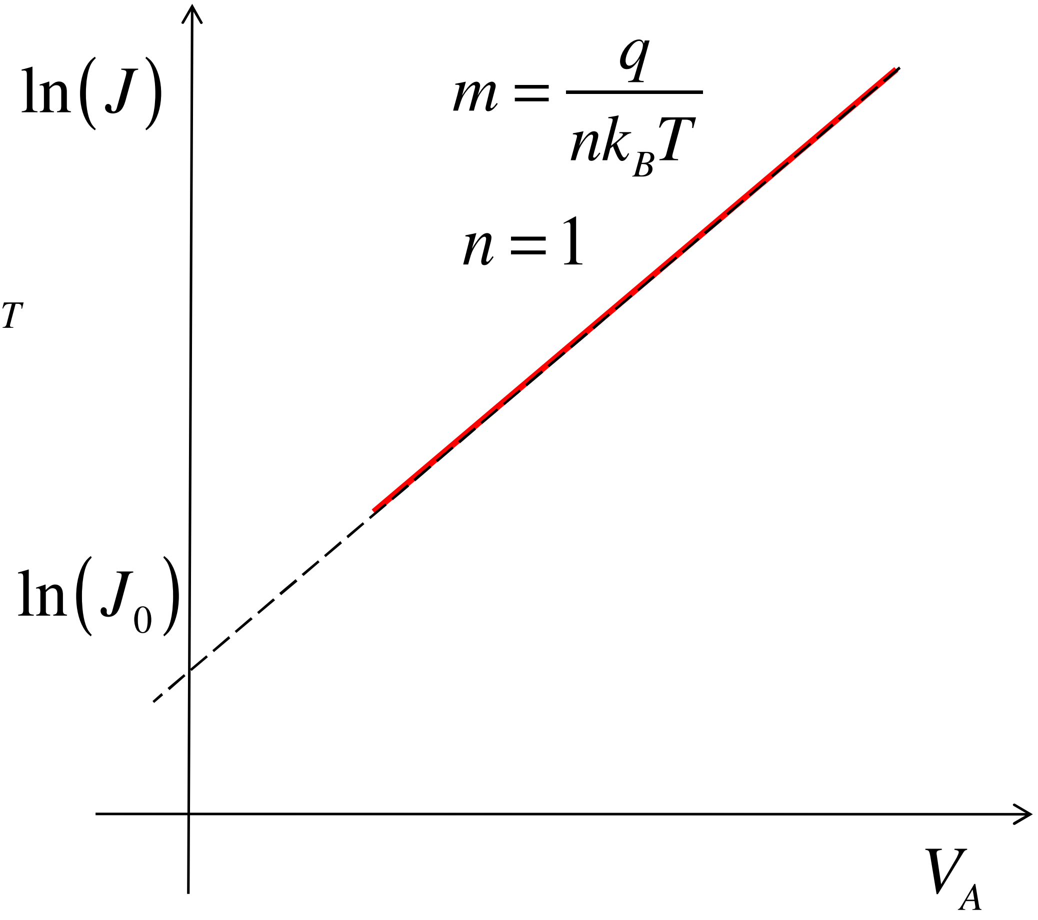
$\mathcal{E}_{CR} \approx 3\times10^6$ V/cm (air)



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

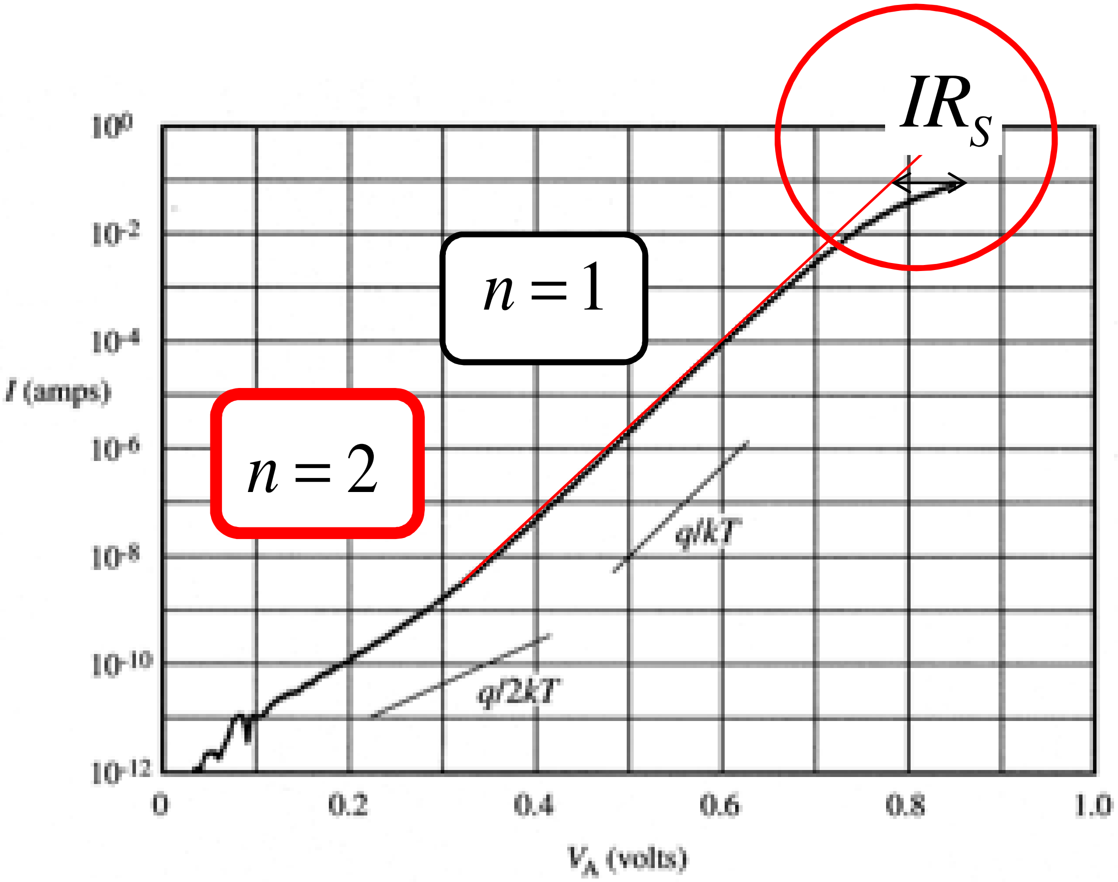
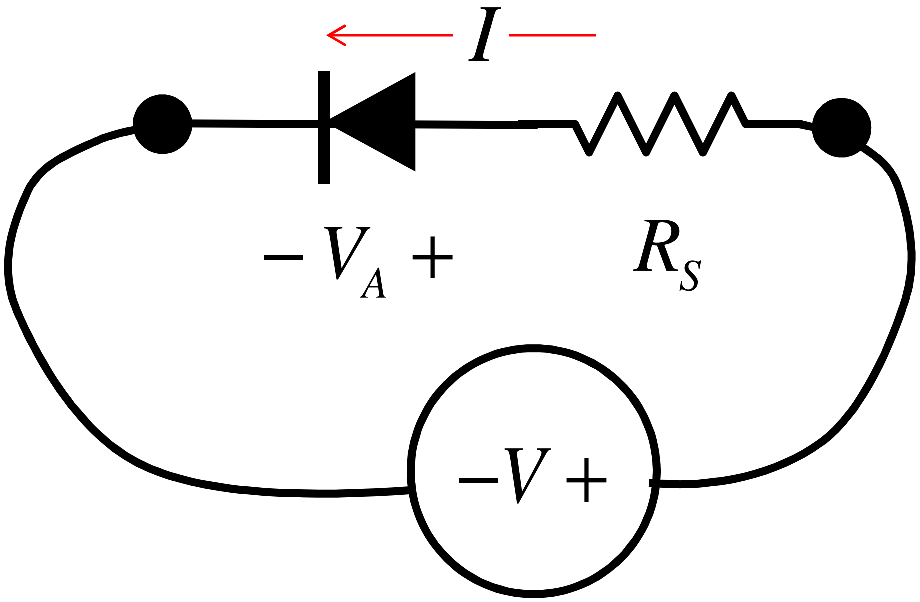


Fig. 6.10(a), Semiconductor Device Fundamentals, R.F. Pierret

high forward bias

1) series resistance

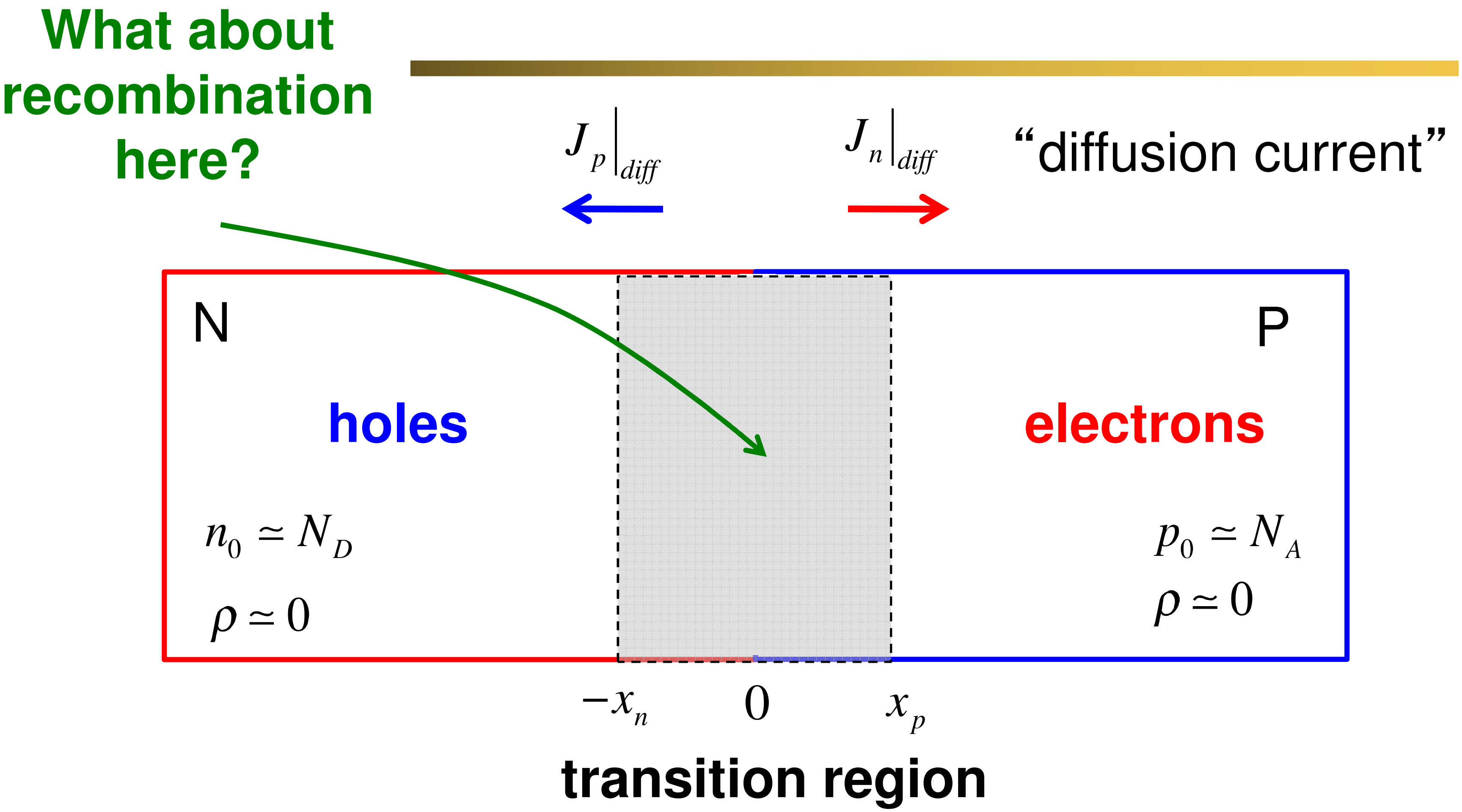


$$I = I_0\left(e^{q(V-IR_S)/k_BT} - 1\right)$$

$$V_A = V - IR_S$$

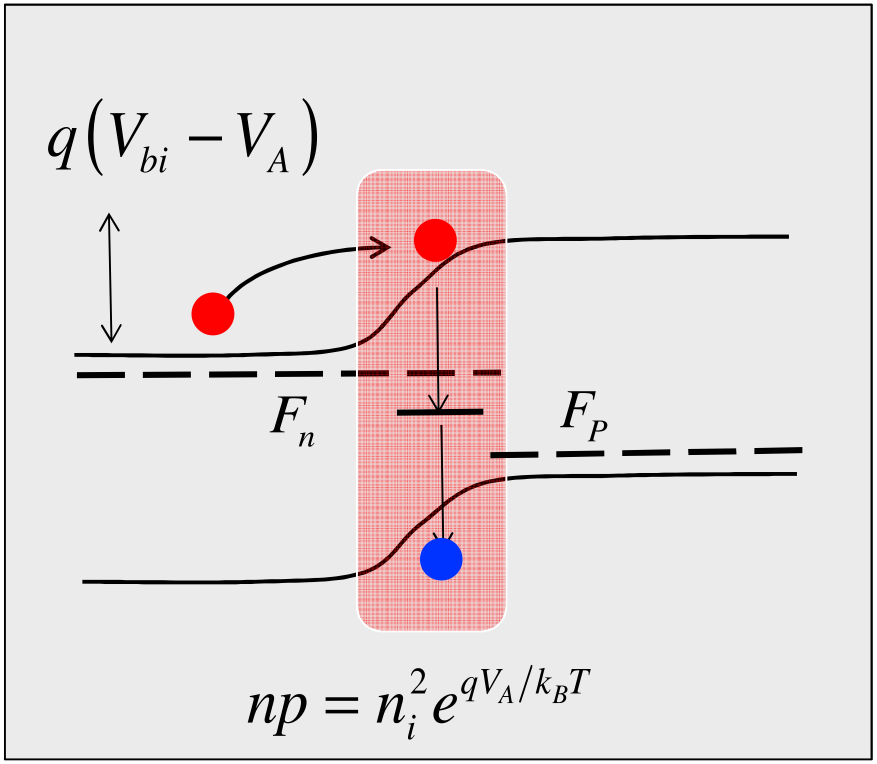
2) “high level injection” $\Delta n_P = \dfrac{n_i^2}{N_A}\left(e^{qV_A/k_BT} - 1\right) << N_A$

moderate forward bias diode current



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 $n(x) \approx p(x)$

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

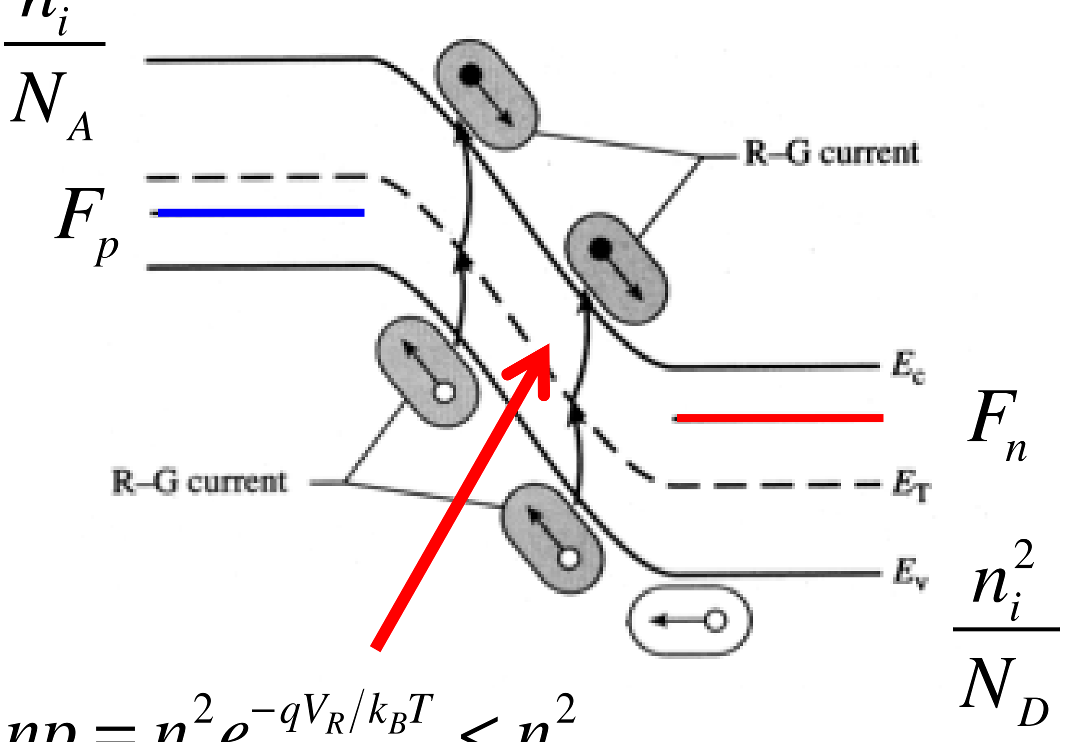
$$\hat{n} \approx \hat{p} \propto n_i e^{qV_A/2k_BT}$$

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

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

recombination-generation in SCR: reverse bias

recombination rate R<0



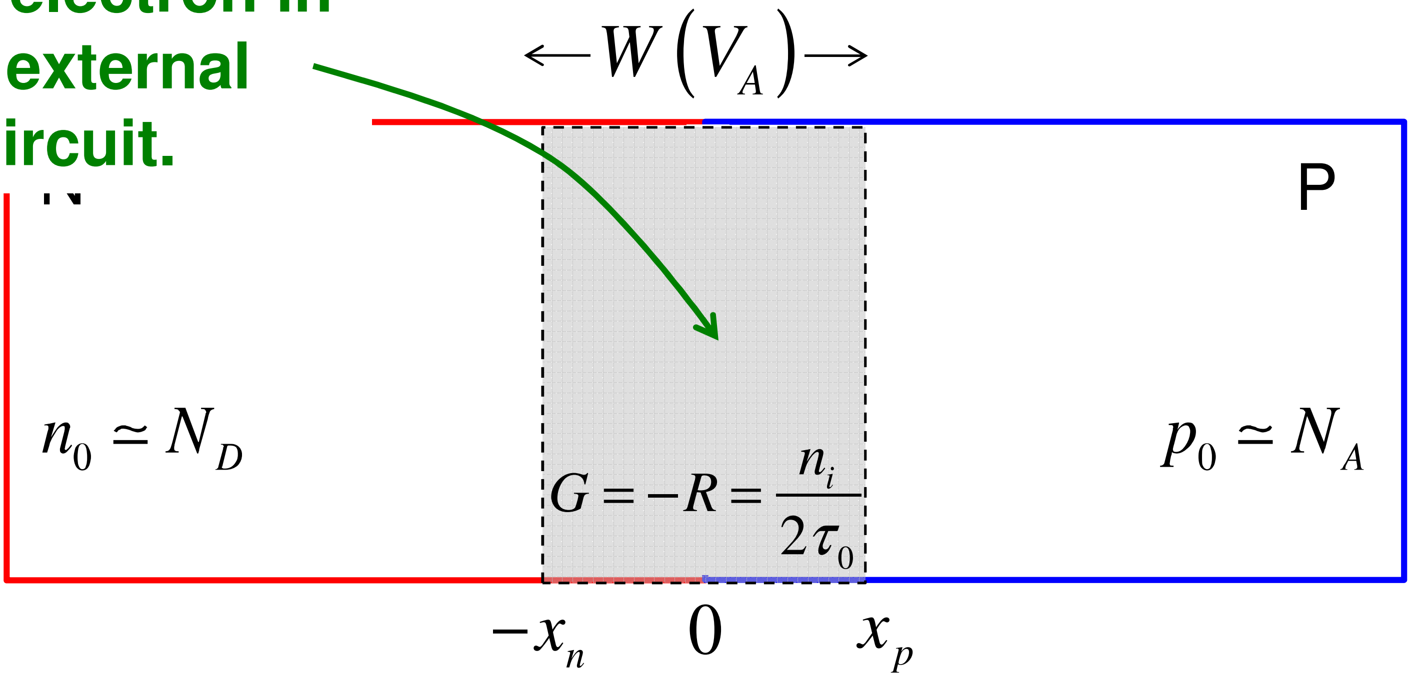
$$np = n_i^2 e^{-qV_R/k_BT} < n_i^2$$

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

RB diode current

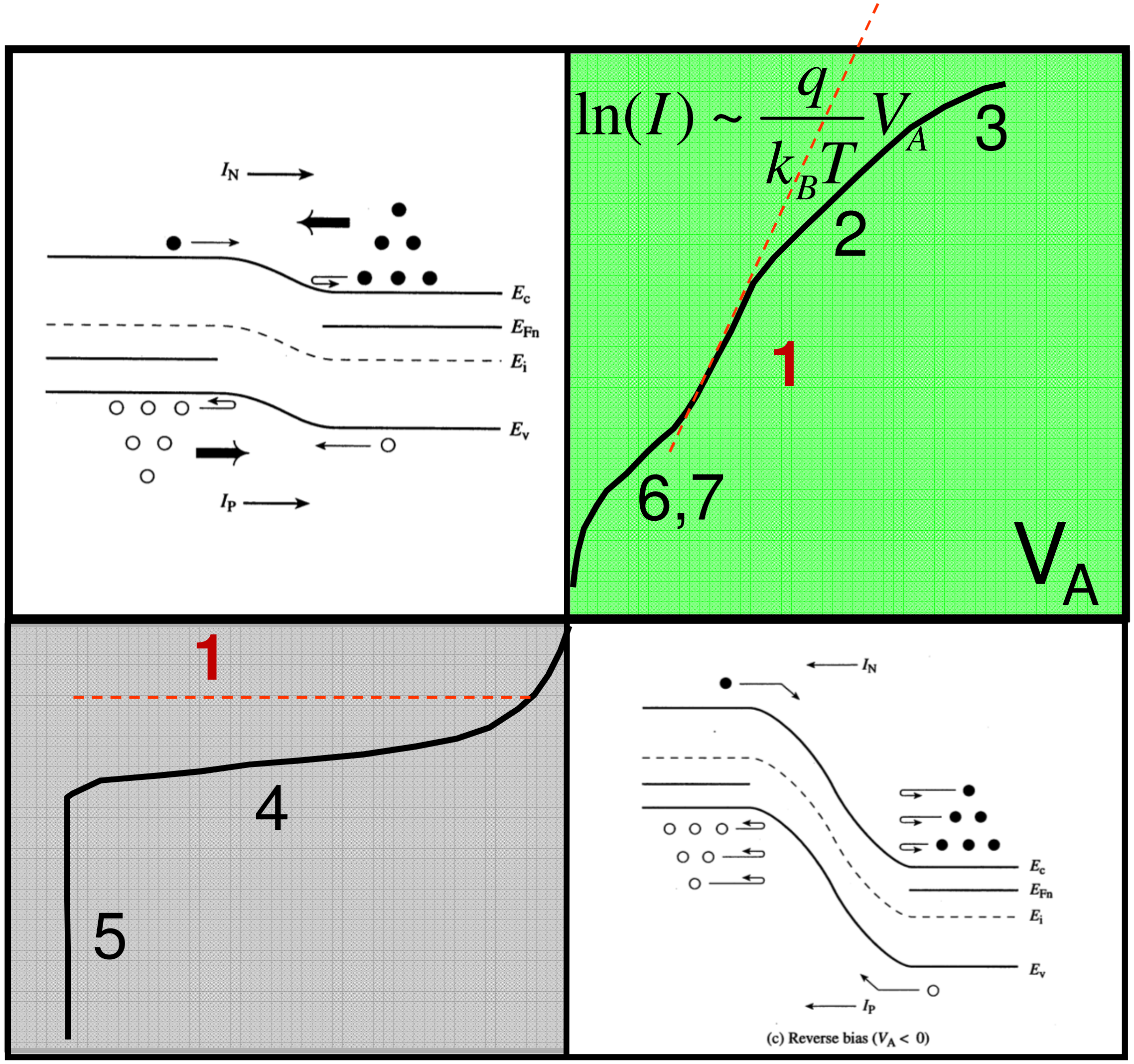
e-h pairs generated here give 1 electron in the external circuit.

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*

outline

✓ 1) Ideal Diode Equation

✓ 2) Ideal Diode Example

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✓ 4) Diode Non-idealities

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