ECE-305: Spring 2018
Exam 3 Review

Pierret, *Semiconductor Device Fundamentals* (SDF)
Chapters 6, 7, 9, and 14

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Exam 3 Preparation

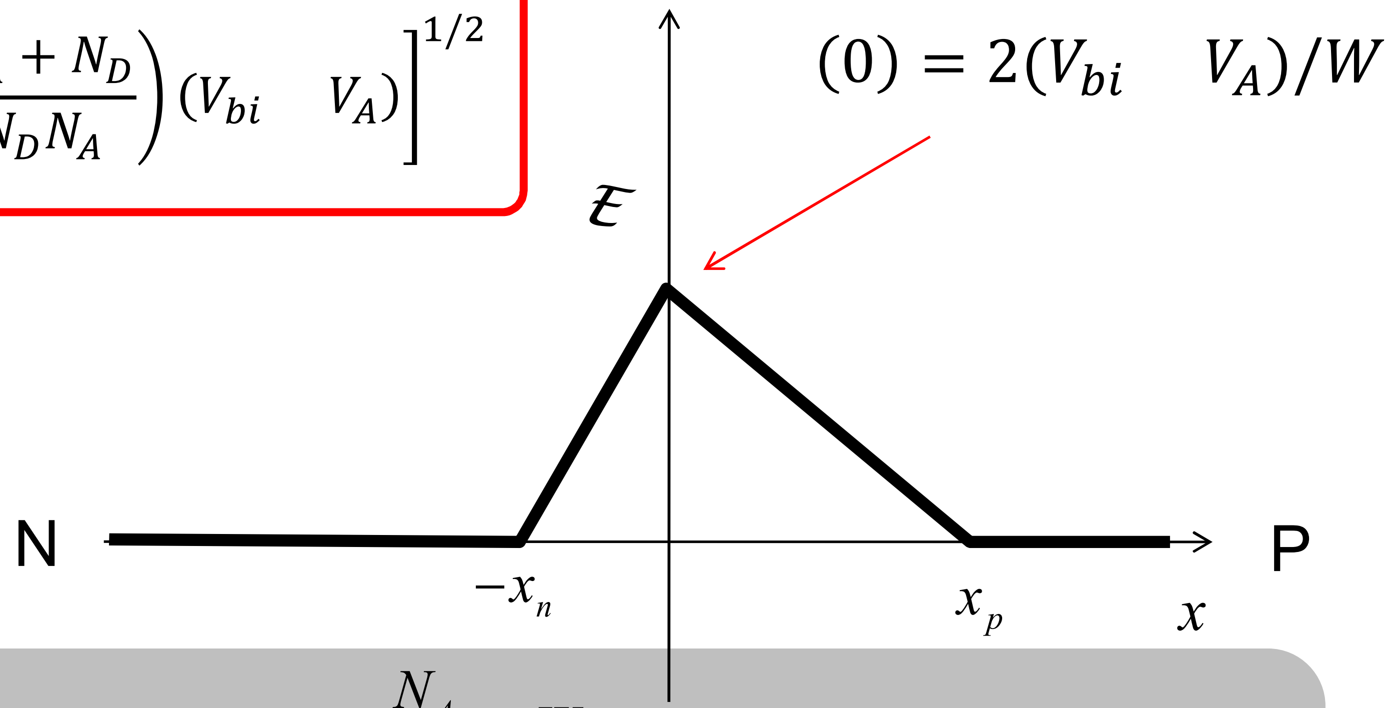
- Chapters 6, 7, 9, and 14
- Exam 3 from Fall 2015-17
- Exams 3, 4, and review session from Spring 2015
- Quizzes 8-10 from Spring 2015
- HW 5-7 from this semester

Exam 3 Preparation

- Ideal & non-ideal diodes
- Small-signal (AC) model
- Metal-semiconductor contacts & diodes

NP junction electrostatics

$$W = \left[\frac{2K_s\epsilon_o}{q}\left(\frac{N_A + N_D}{N_D N_A}\right)(V_{bi} \quad V_A)\right]^{1/2}$$



$$(0) = 2(V_{bi} \quad V_A)/W$$

$$W = x_n + x_P$$

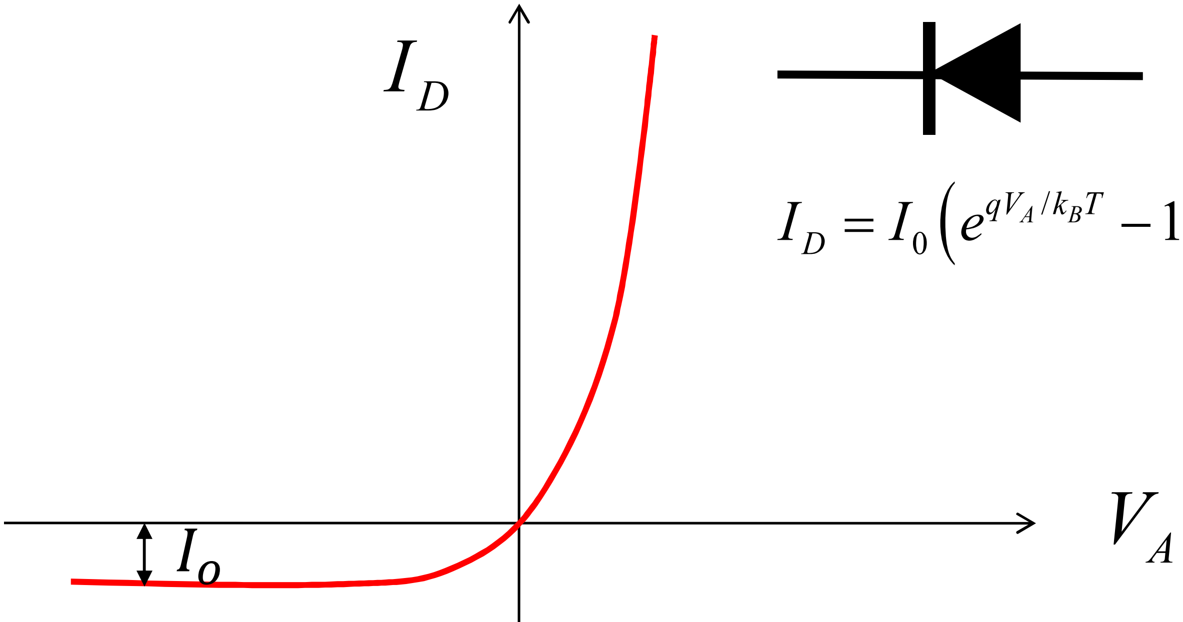
$$N_D x_n = N_A x_P$$

$$x_n = \frac{N_A}{N_A + N_D} W$$

$$x_p = \frac{N_D}{N_A + N_D} W$$

$$V_{bi} = \frac{k_B T}{q} \ln\left(\frac{N_D N_A}{n_i^2}\right)$$

ideal diode equation summary



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

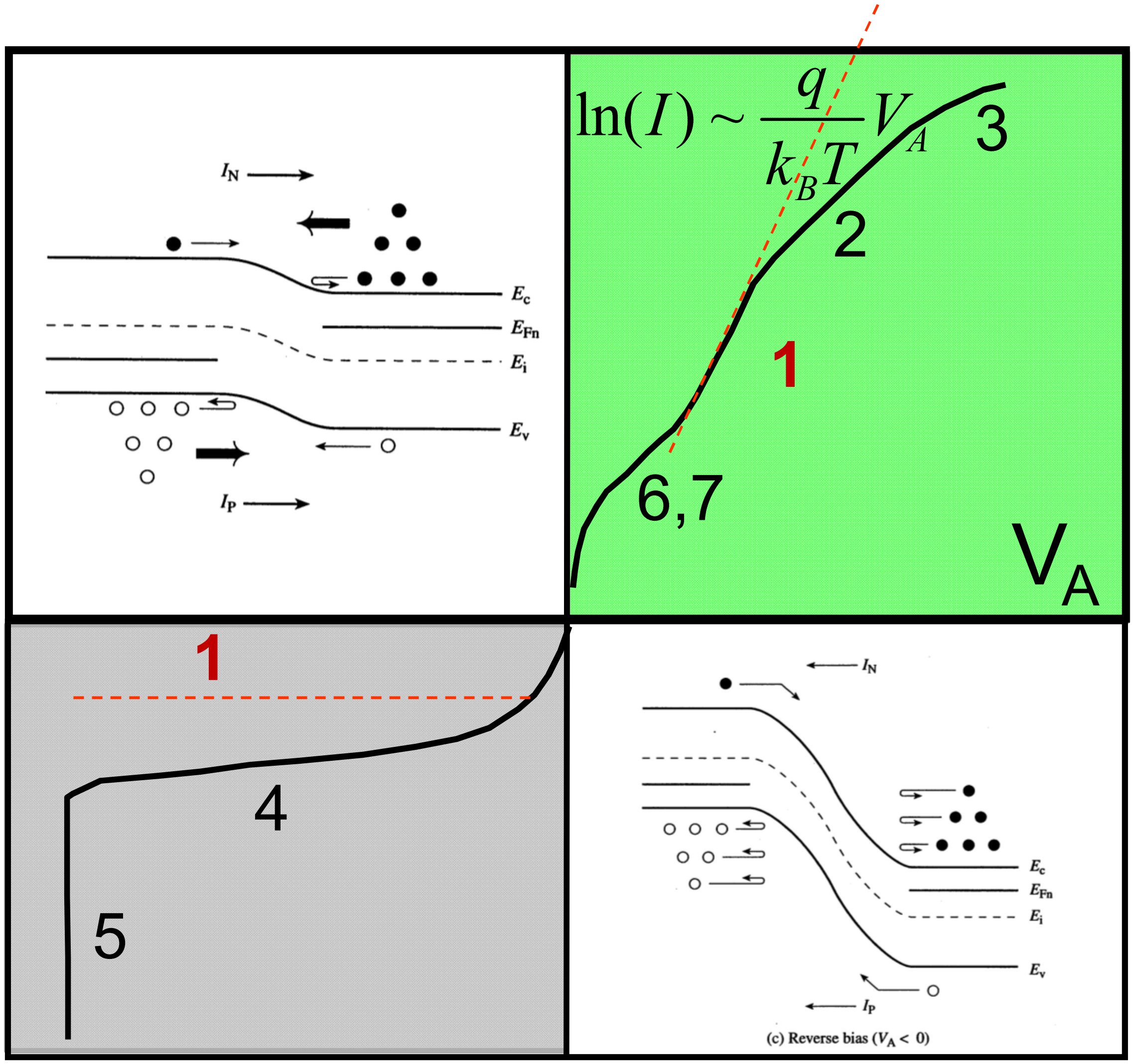
long

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

short

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

Non-ideal diodes



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

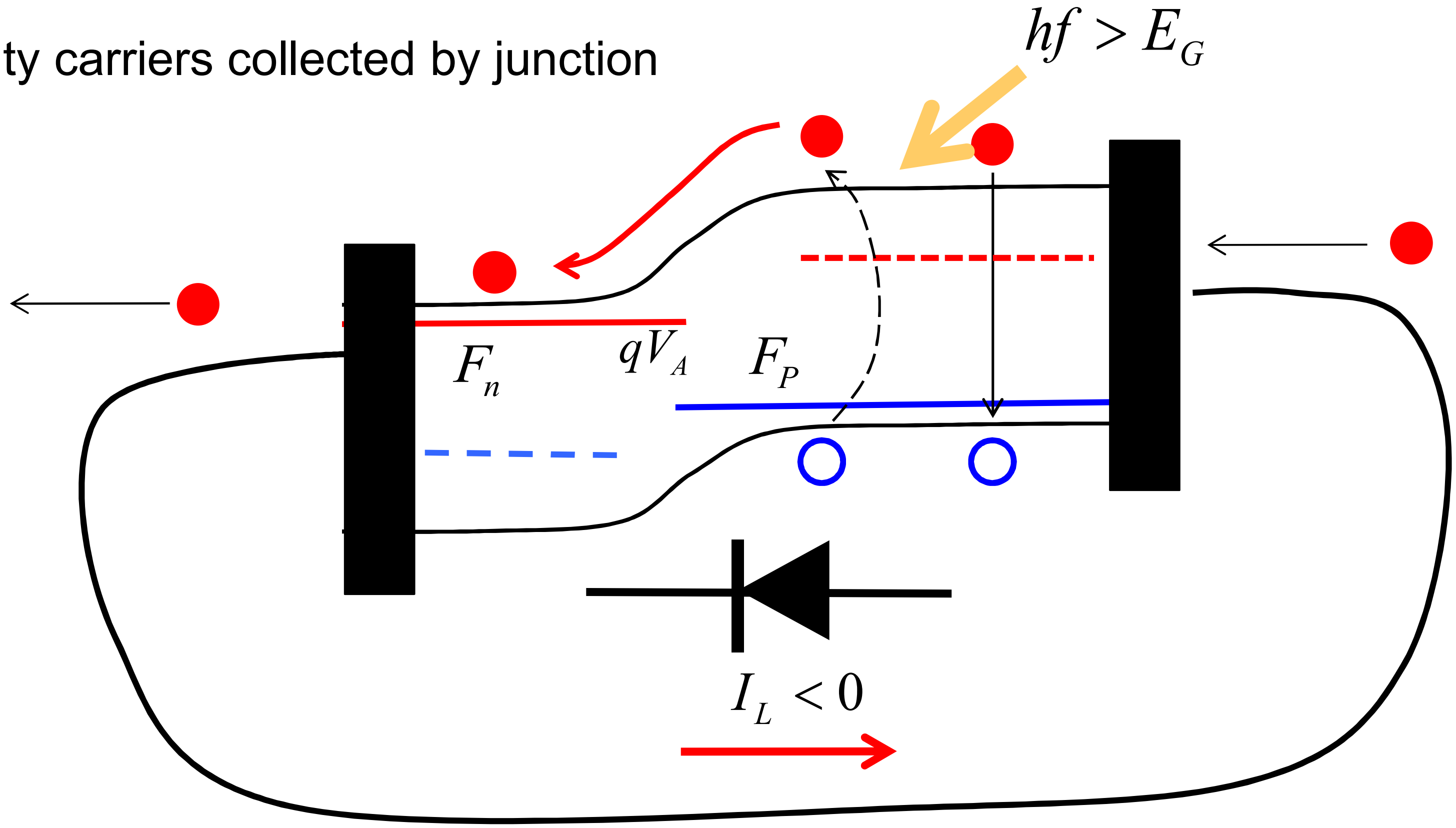
Ideal & Non-ideal diodes

$$I_D = I_0\left(e^{qV_A/nk_BT} - 1\right) \qquad I_D = I_0\left(e^{q\left(V - I_D R_S\right)/nk_BT} - 1\right)$$

1) FB: recombination in quasi-neutral regions give *n* = 1 current (diffusion current).
2) FB: recombination in SCR gives *n* = 2 current
3) RB: constant when dominated by diffusion current
4) RB: increases as *W* for generation in SCR: $I_R \propto \sqrt{V_R}$
5) RB: avalanche or Zener tunneling: $\mathcal{E}_{CR} = \sqrt{\dfrac{2q\left(V_{bi} + V_{BR}\right)N_A}{K_s\varepsilon_0}}$

solar cells: generation and current

minority carriers collected by junction



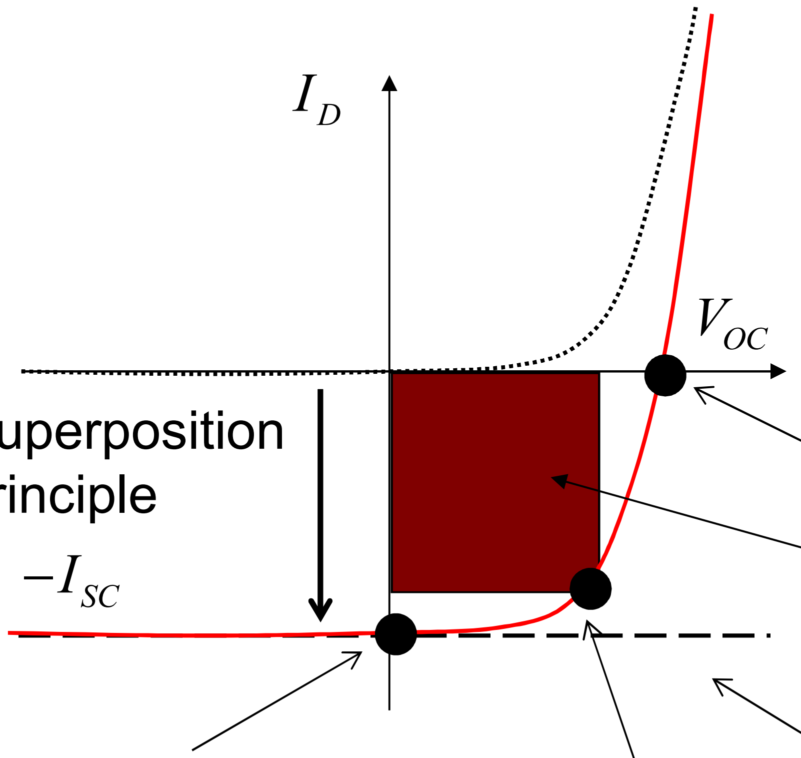
Every time a minority electron is generated & collected by the PN junction, one electron flows in external current.

IV characteristics of solar cells and photodetectors

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

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

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



Superposition principle

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

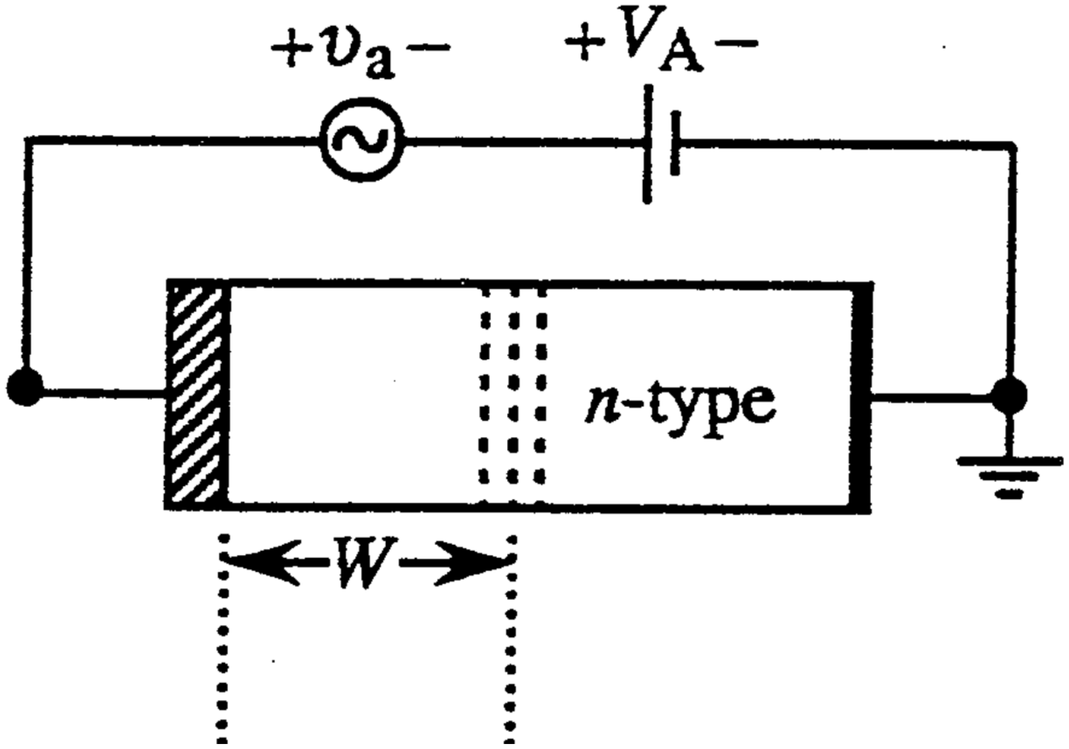
Maximum power rectangle

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

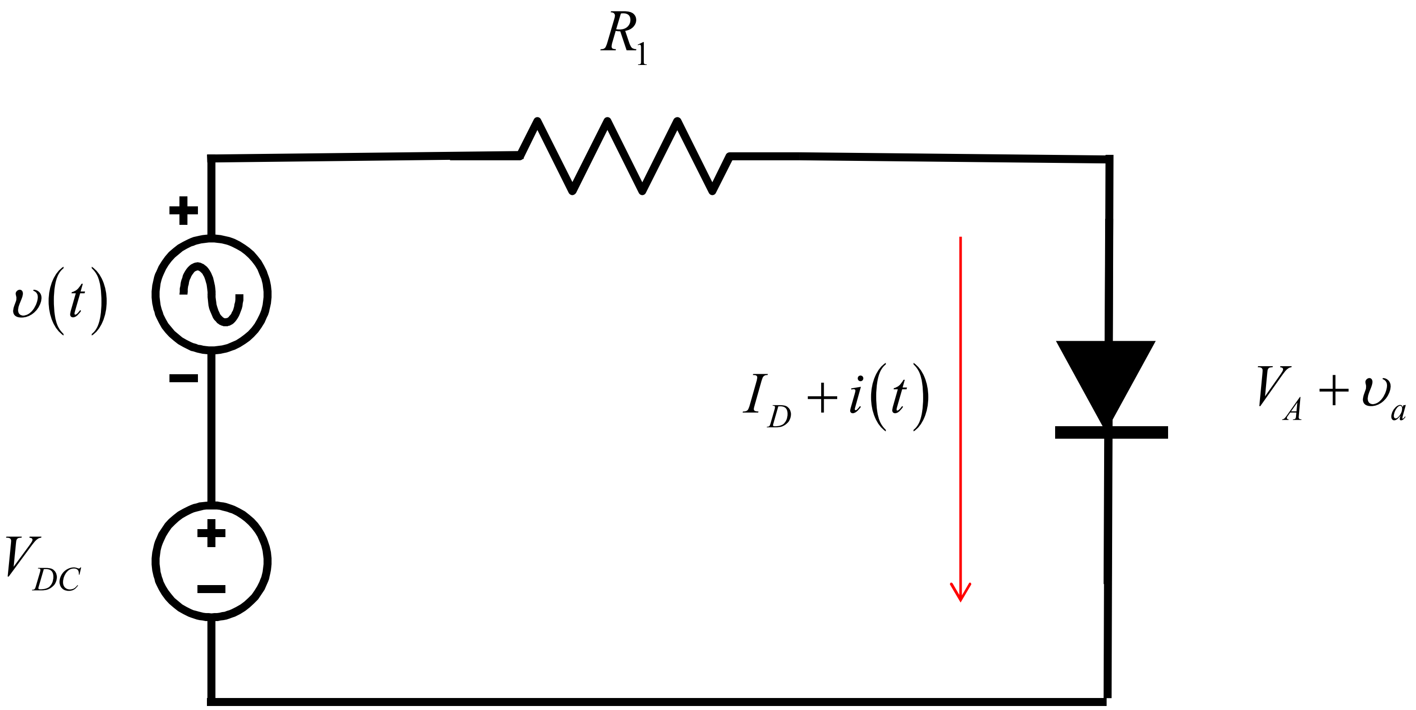
$$P_D = I_{TOT}V_D < 0$$

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

AC response

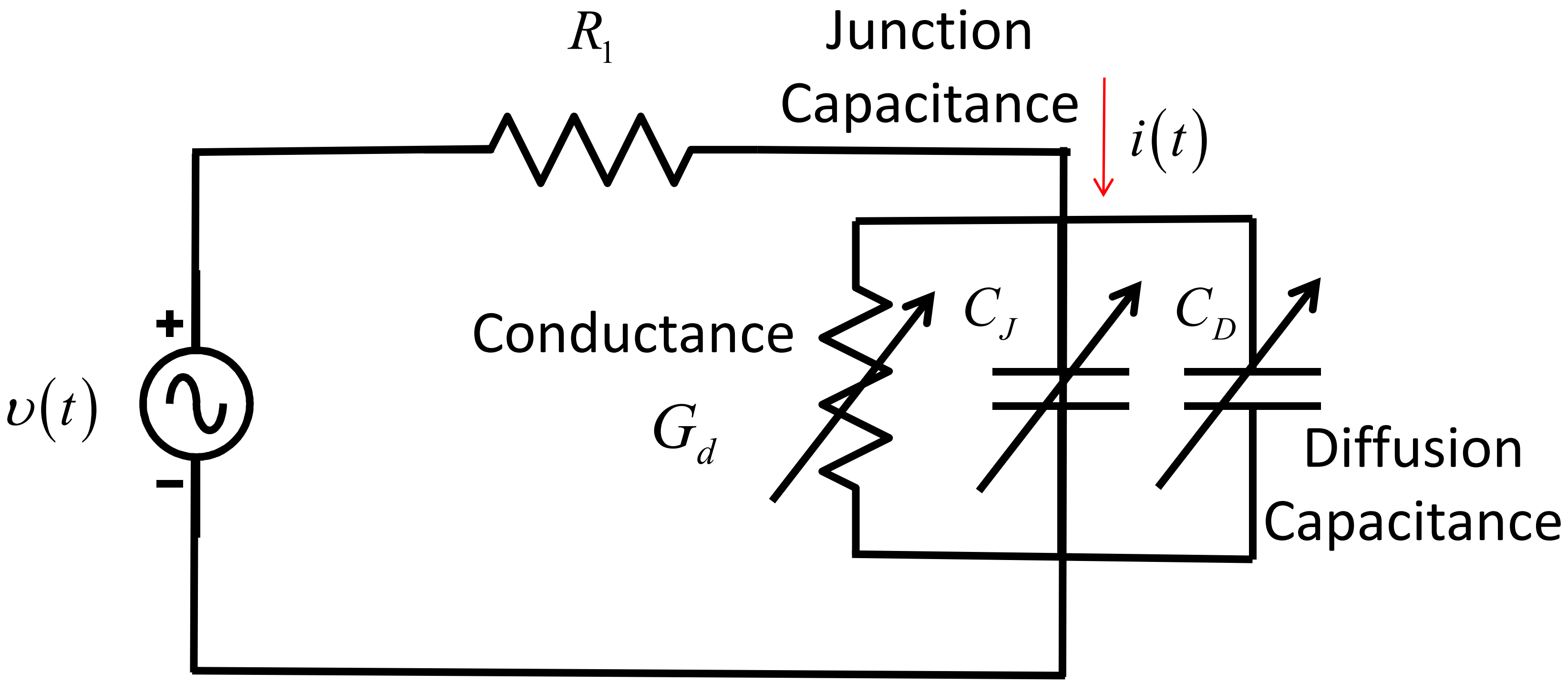


small signal model



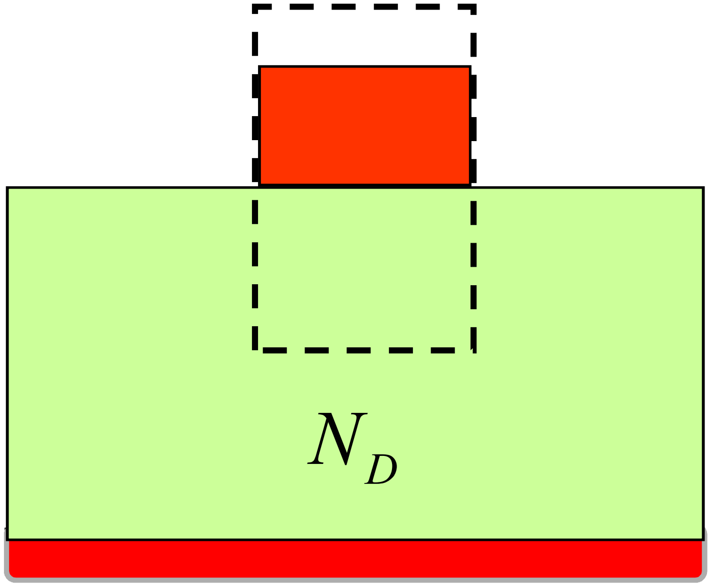
1) Compute the DC bias current
2) Replace the diode with the s.s. a.c. model and do the a.c. analysis.

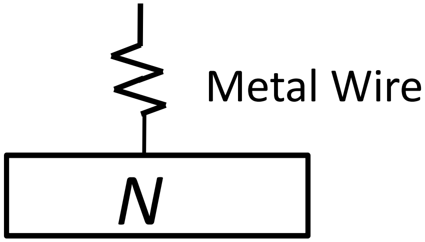
small signal model (NP diode)



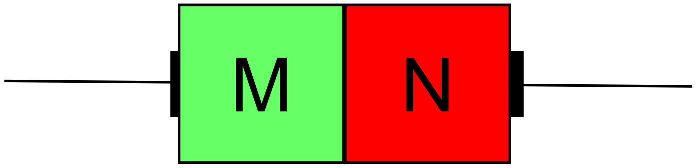
$$G_d = \frac{dI_D}{dV_D} = \frac{I_D + I_o}{kT/q} \qquad C_J(V_A) = \frac{K_S \varepsilon_0 A}{W(V_A)} \qquad C_D = G_d\, \tau_n$$

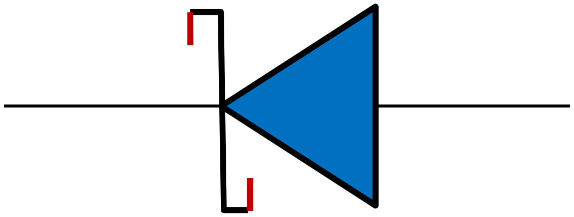
Metal-semiconductor Diode



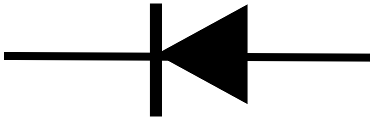


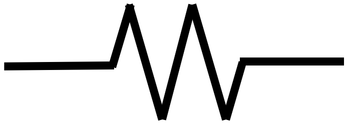
Symbols





MS contacts & diodes



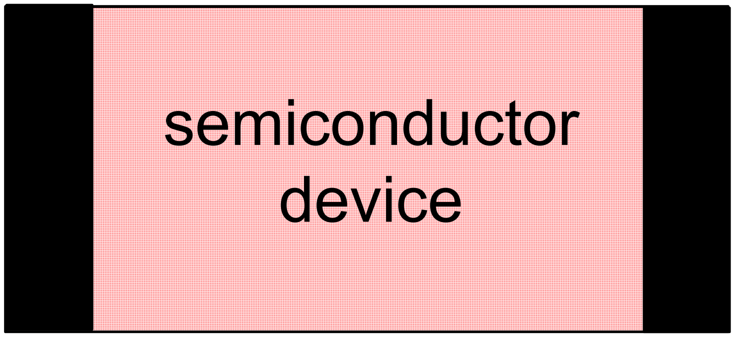


Schottky diode is a majority carrier device.

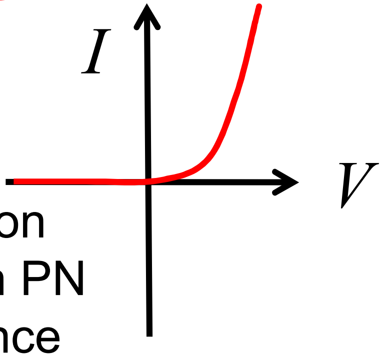
Ohmic contact acts like a series resistor

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

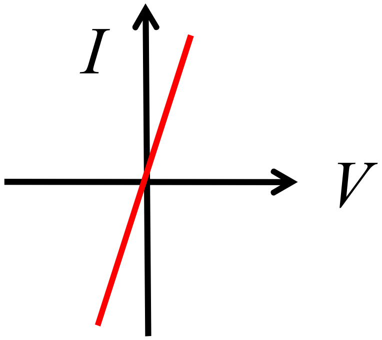
$$J_0 = A^{*}T^{2}e^{-\Phi_{BN}/k_BT}$$



rectifying

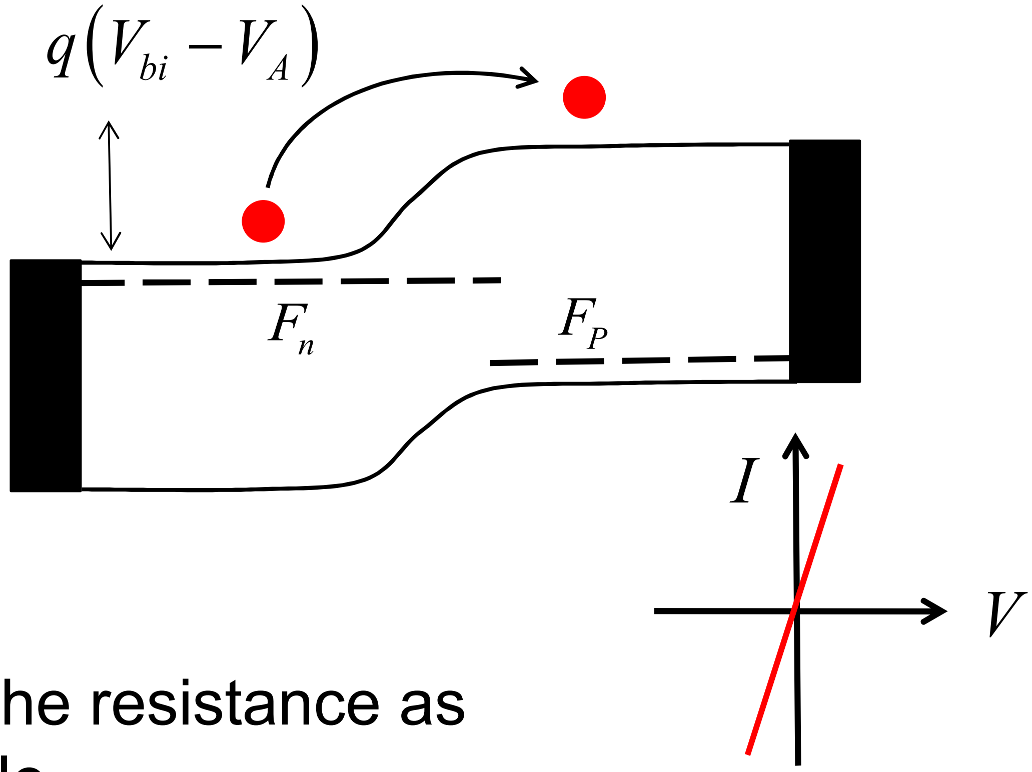


- **much** higher saturation current densities than PN
- no diffusion capacitance



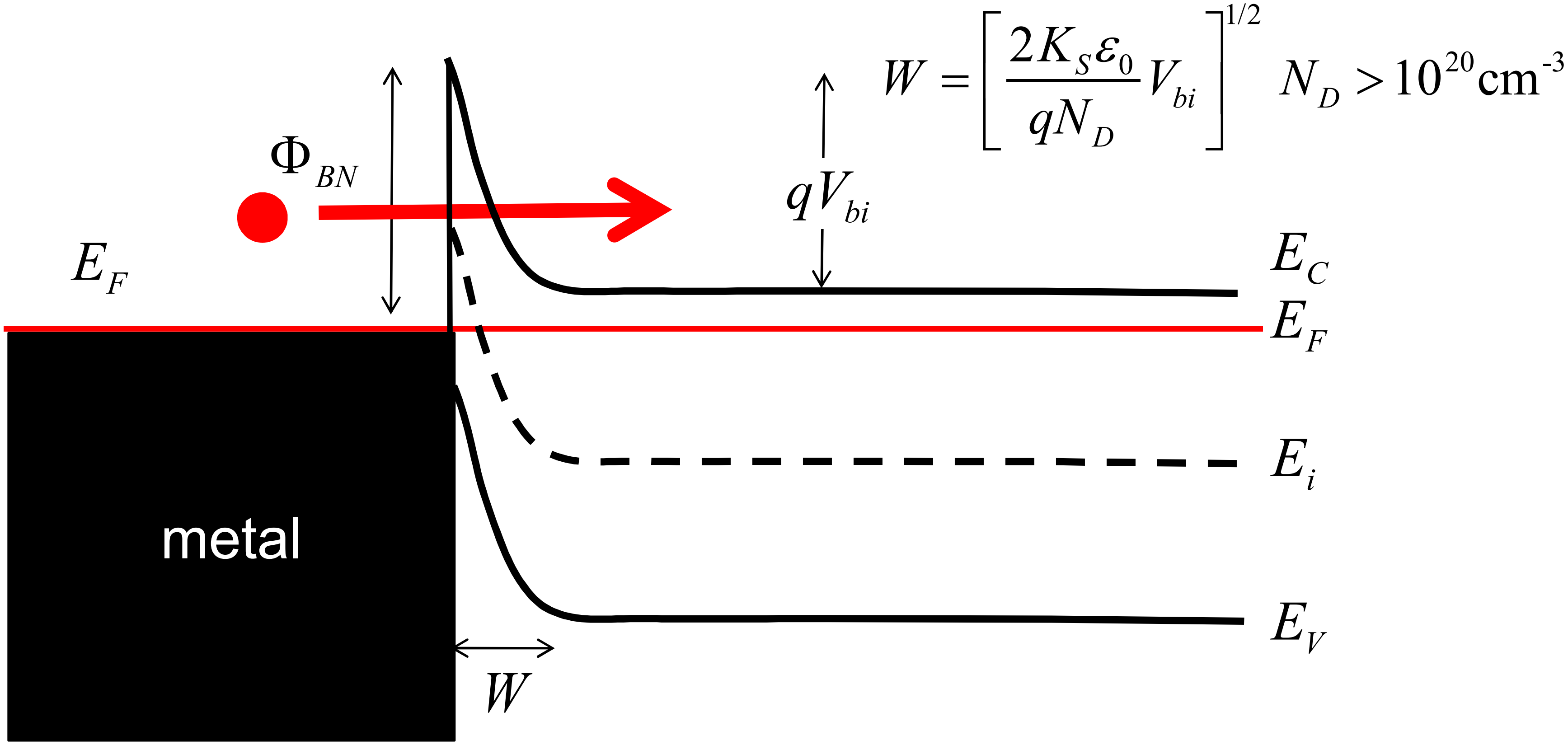
ohmic

MS ohmic contacts: band diagram



Goal: make the resistance as low as possible.

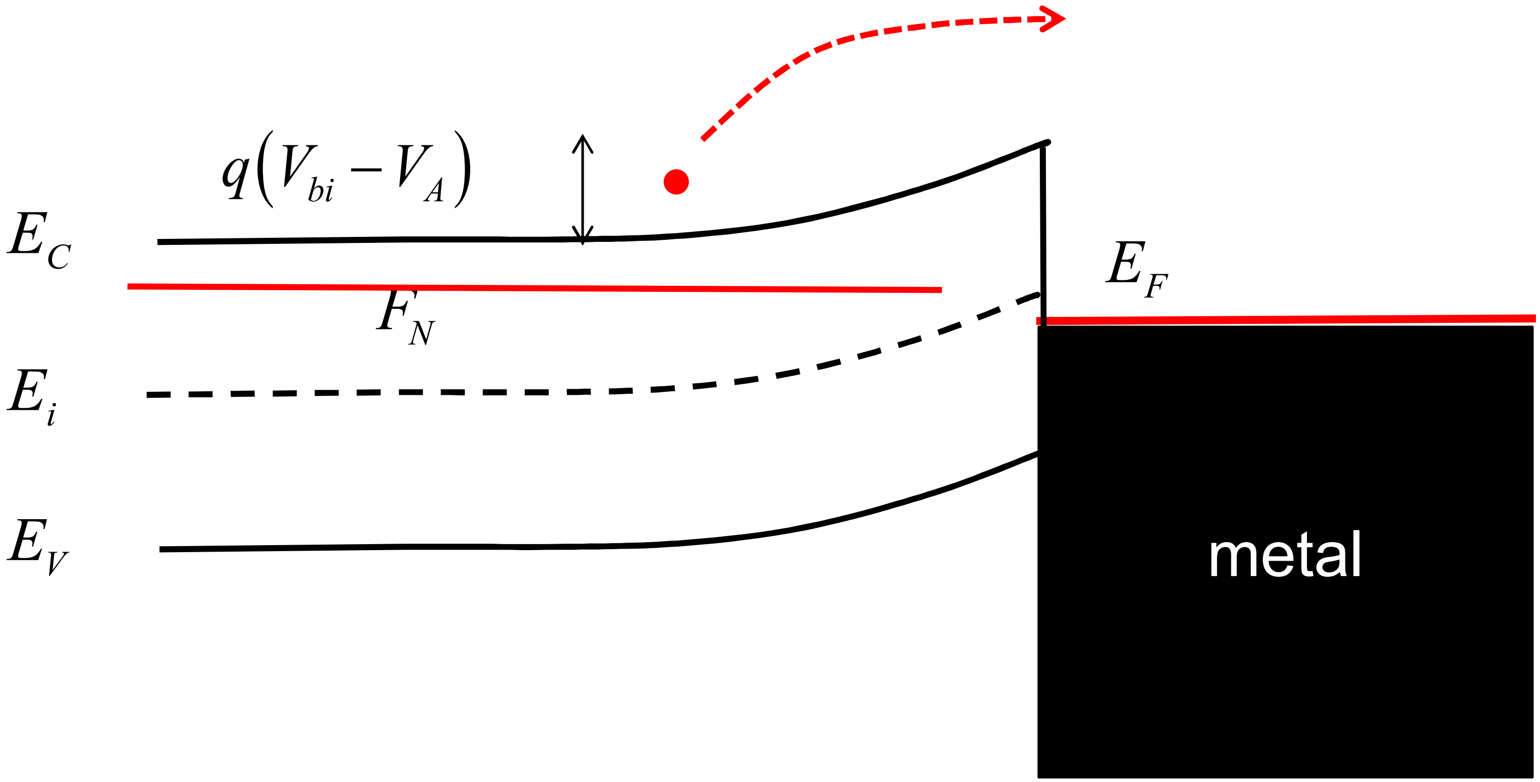
alternative way to make an ohmic contact



$$W = \left[\frac{2K_S\varepsilon_0}{qN_D}V_{bi}\right]^{1/2} \qquad N_D > 10^{20}\,\mathrm{cm}^{-3}$$

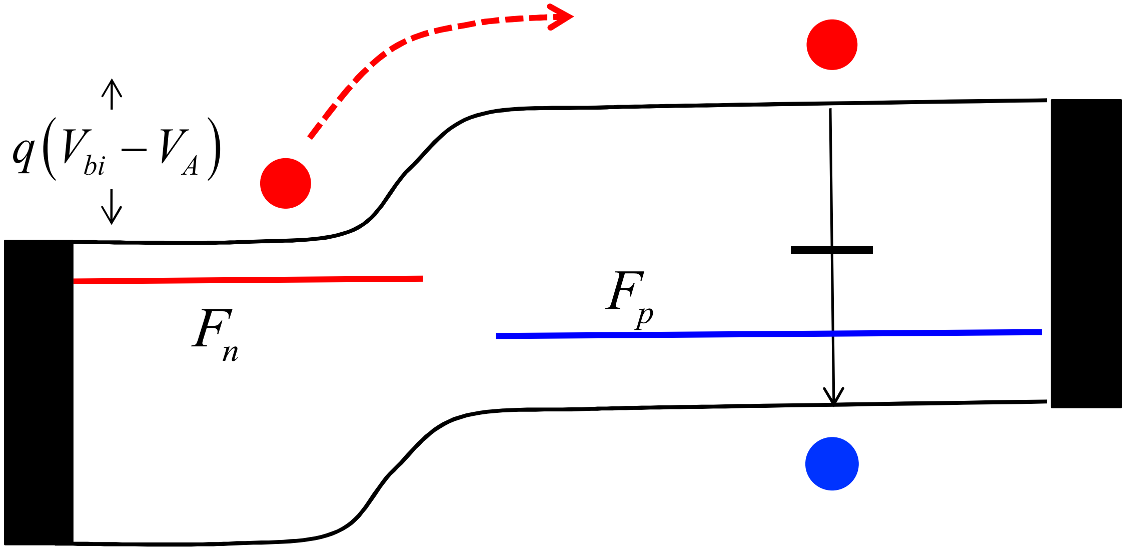
Dope the semiconductor **very heavily** to promote quantum mechanical tunneling.

MS diodes vs. PN junctions



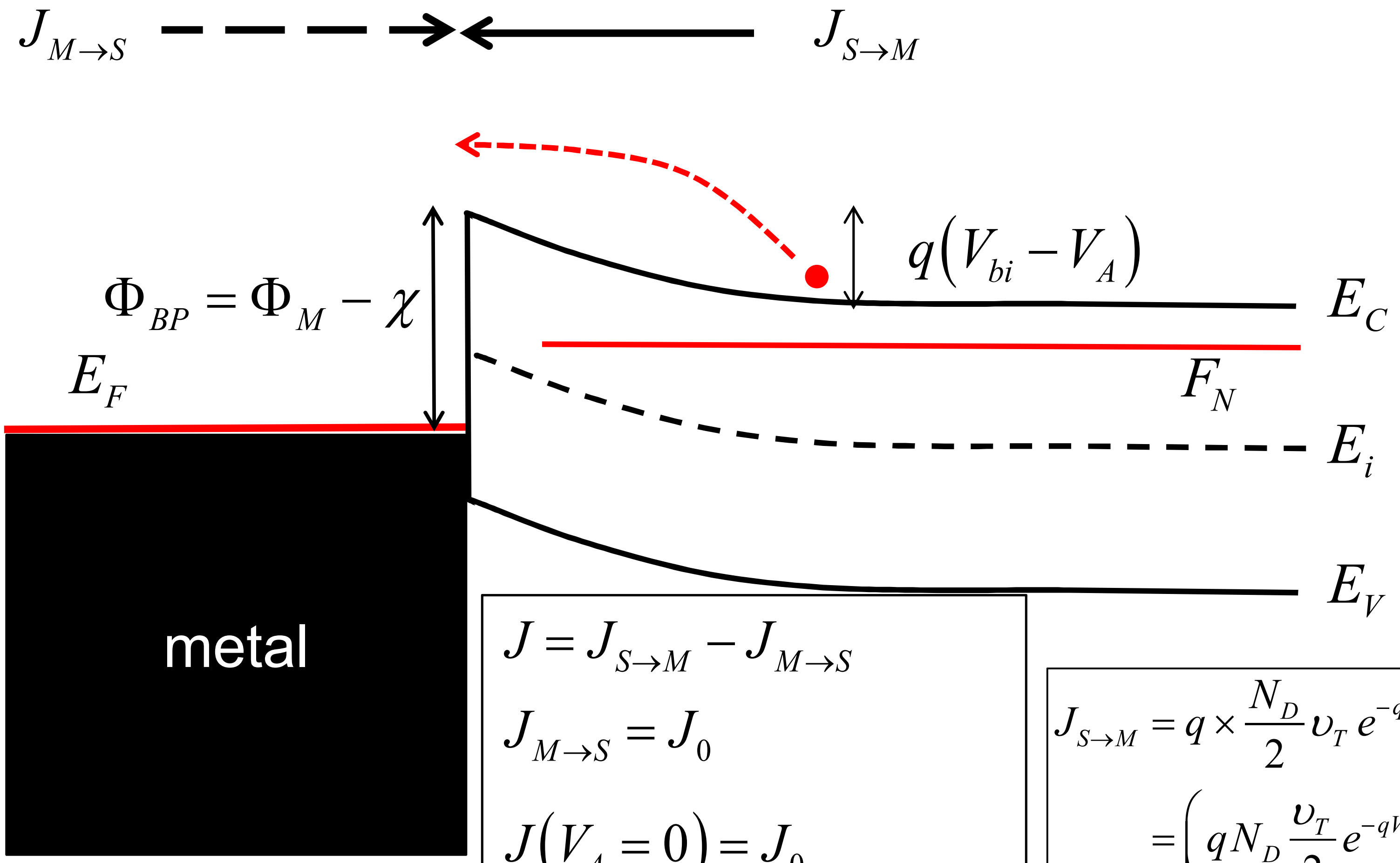
MS diodes are **majority carrier** devices

MS diodes vs. PN junctions



NP junctions are **minority carrier** devices

MS rectifying diodes: band diagram



$$J=J_{S\rightarrow M}-J_{M\rightarrow S}$$

$$J_{M\rightarrow S}=J_0$$

$$J\left(V_A=0\right)=J_0$$

$$J_{S\rightarrow M}\left(V_A>0\right)=J_0 e^{qV_A/k_BT}$$

$$J_{S\rightarrow M}=q\times\frac{N_D}{2}\upsilon_T\, e^{-q\left(V_{bi}-V_A\right)/k_BT}$$
$$=\left(qN_D\frac{\upsilon_T}{2}e^{-qV_{bi}/k_BT}\right)e^{qV_A/k_BT}$$

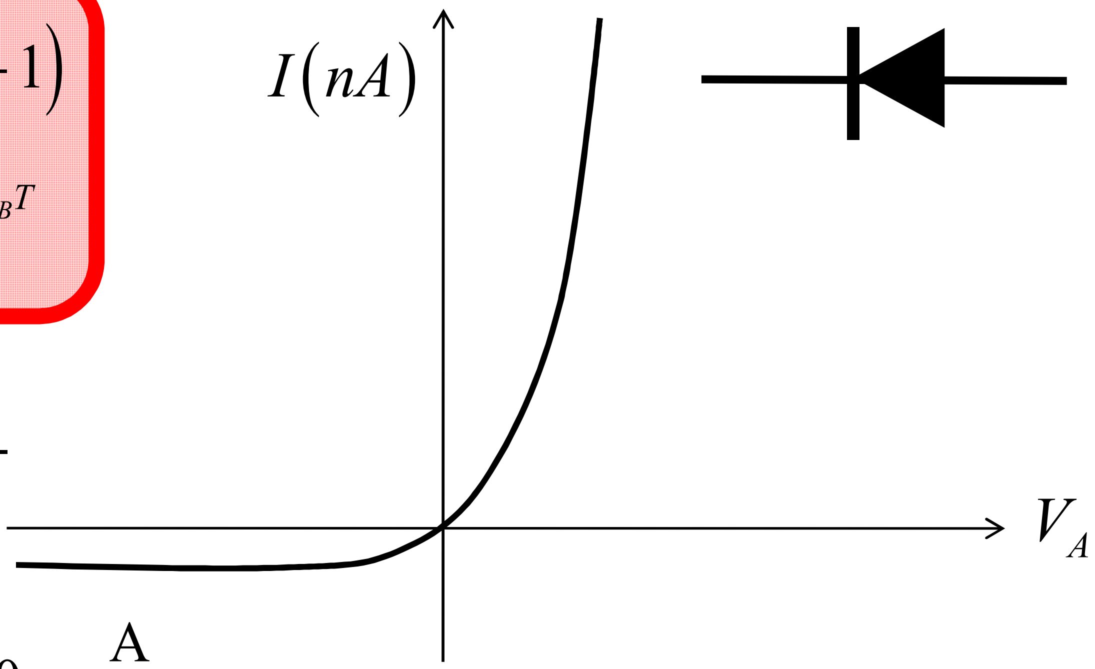
IV characteristics of a Schottky diode

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

$$J_0 = A^* T^2 e^{-\Phi_{BN}/k_BT}$$

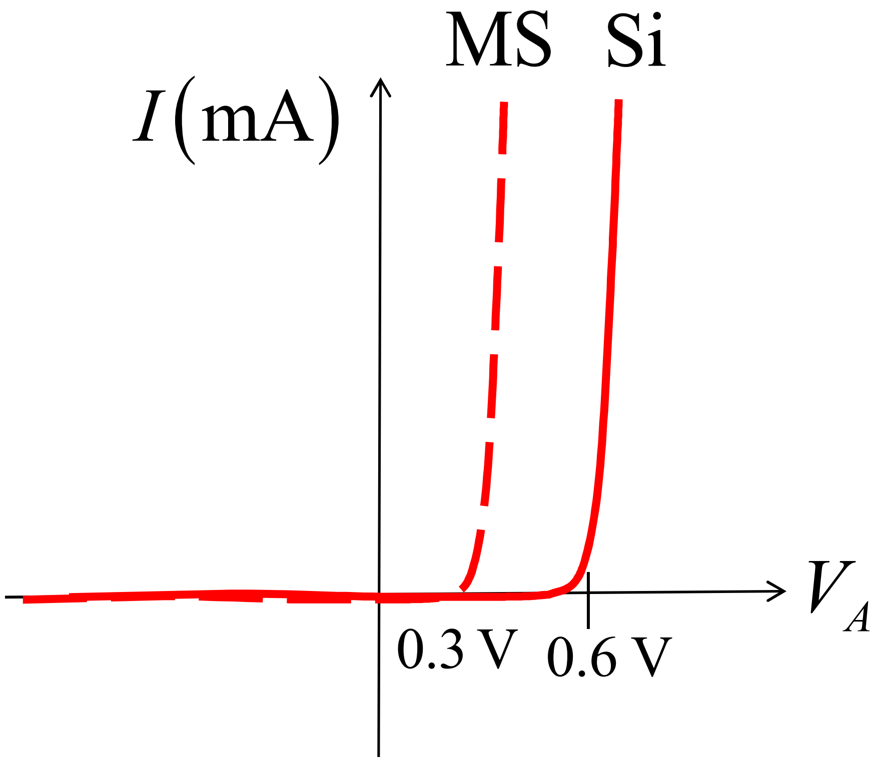
$$A^* = \frac{4\pi q m_n^* k_B^2}{h^3}$$

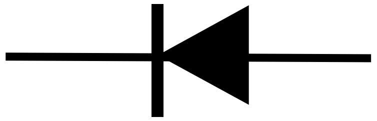
$$A = \frac{4\pi q m_0 k_B^2}{h^3} = 120\ \frac{\mathrm{A}}{\mathrm{cm}^2\text{-}\mathrm{K}^2}$$



How does an MS diode compare to an NP junction?

IV characteristics





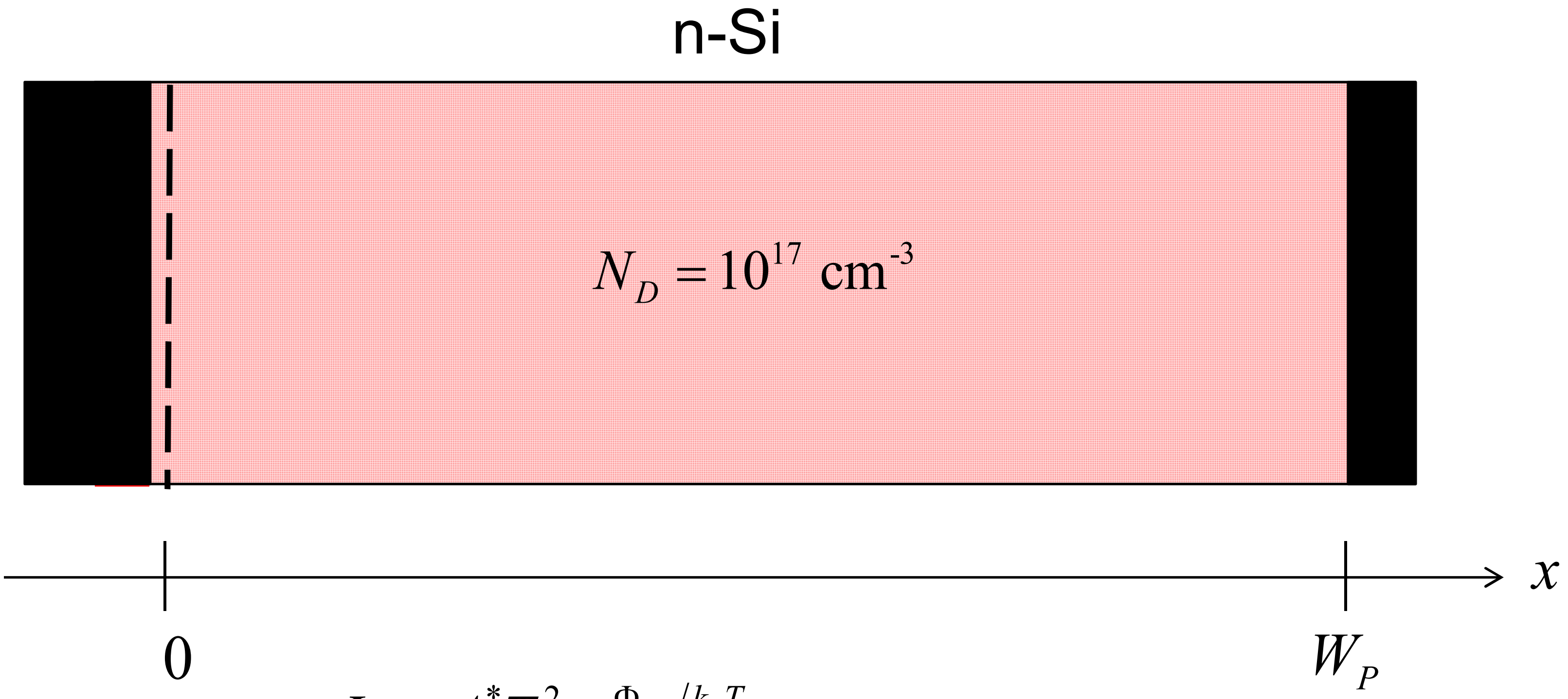
$$J = J_0\left(e^{qV_A/k_BT} - 1\right)$$

$$J_0 = A^*T^2e^{-\Phi_{BN}/k_BT}$$

$$\boxed{J_0\left(MS\right) \gg J_0\left(NP\right)}$$

Strongly controlled by SB height.

example: MS junction



$$J_0 = A^* T^2 e^{-\Phi_{BP}/k_B T}$$

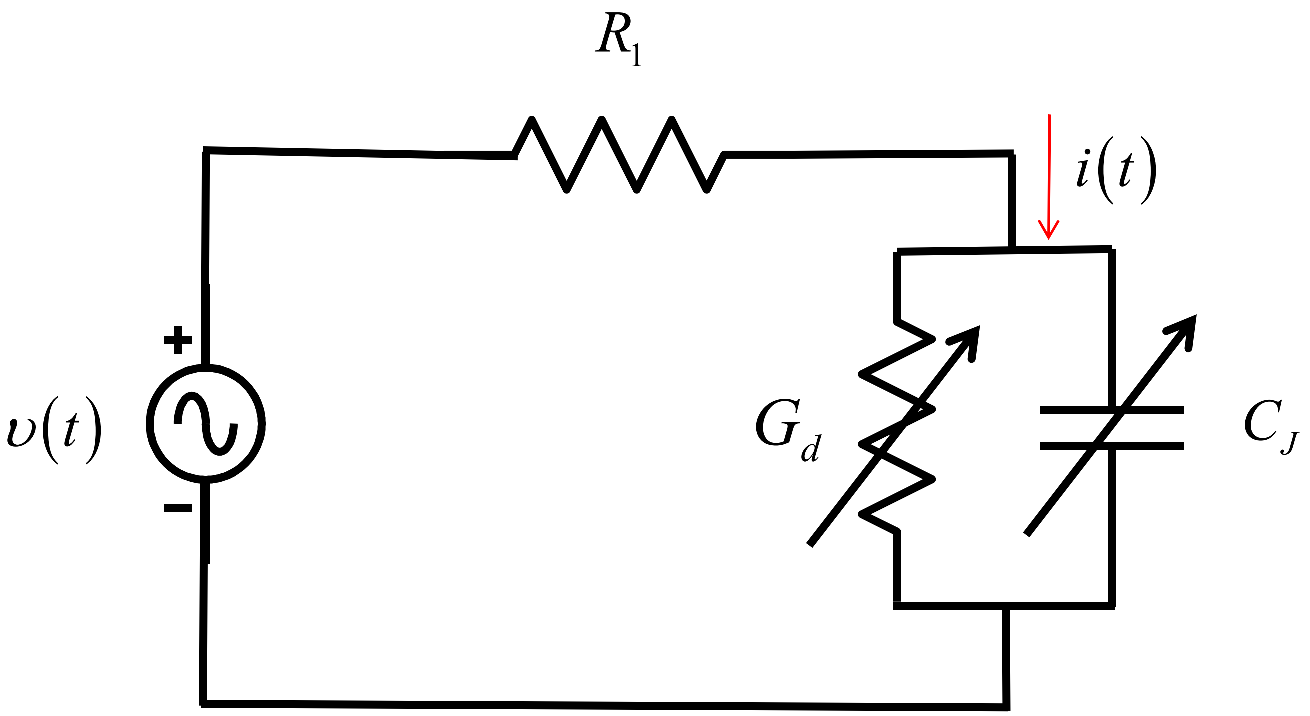
$$I_D = I_0\left(e^{qV_A/k_B T} - 1\right)$$

$$m_n^*/m_0 = 1.18$$

$$I_0 = 0.2 \times 10^{-3}\ \mathrm{A}$$

$$\Phi_{BN} \approx 0.65\ \mathrm{eV}$$

small signal model (MS diode)



No diffusion capacitance!

$$G_d = \frac{dI_D}{dV_D}$$

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

summary

1) PN diodes can be described with a combination of ideal diode law and non-idealities like breakdown, generation/recombination, high injection, series resistance
2) Solar cells are a practical application of PN diodes, whose efficiency can be predicted by a combination of photocurrent + diode current
3) AC response can be predicted with small-signal approximation, in which diode has conductance, junction, and diffusion capacitance
4) Metal-semiconductor junctions can be Ohmic contacts (resistors) or Schottky diodes
5) A Schottky diode is a metal-semiconductor majority carrier device, like a one-sided pn junction
6) M-S diodes typically have much higher saturation current, no diffusion capacitance, and act fast

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1 (8 points). Which of the following is the Schottky barrier height?

a. The difference between the conduction band at the MS junction of an n-type semiconductor and the Fermi level in the metal

b. The difference between the valence band at the MS junction of an n-type semiconductor and the Fermi level in the metal

c. The difference between the conduction band at the MS junction of a p-type semiconductor and the Fermi level in the metal

d. The difference between the valence band at the MS junction of an p-type semiconductor and the Fermi level in the metal

e. a and d

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2 (8 points). The depletion and potential drop in the metal side of the Schottky diode is?

a. Very small, negligible
b. Small, but not negligible
c. Large
d. Must know doping of metal
e. Under steady-state conditions

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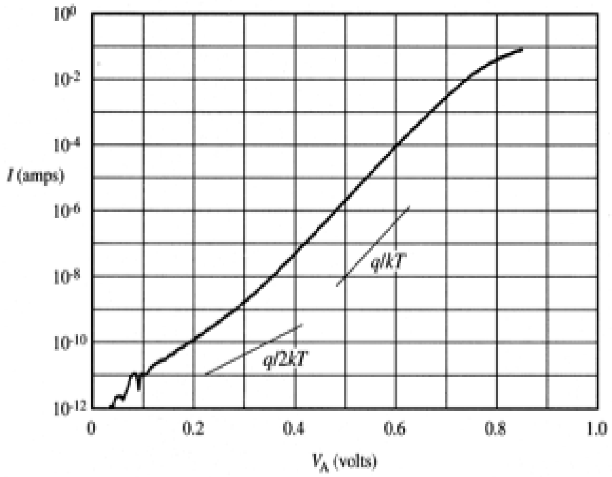
3 (8 points). In the following diagram, what non-ideality accounts for the current roll-over at large forward biases ($V > 0.7$ V)?



a. Recombination in the space-charge region

b. Avalanche diode

c. Quantum-mechanical tunneling

d. Recombination in the quasi-neutral region

e. Series resistance

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4 (8 points). For a metal-semiconductor diode, which of the following is true?

a. The saturation current density is much larger than a PN junction with the same bandgap semiconductor
b. The n=2 current is absent
c. The diode turn-on voltage is reduced compared to a PN junction made from the same semiconductor
d. All of the above
e. None of the above

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5 (8 points). Which is true of the junction capacitance in both PN and MS diodes?

a. It is proportional to $1/\sqrt{V_{bi} \quad V_A}$

b. It is proportional to $\sqrt{V_{bi} \quad V_A}$

c. It is proportional to $1/(V_{bi} \quad V_A)$

d. It is proportional to $V_{bi} \quad V_A$

e. It is proportional to $\exp(qV_A/kT)$

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Part III (Free Response, 30 points)

Assume that we have a solar cell with dark current per unit area $J_o = 2$ nA/cm^2, short circuit current per unit area $J_{sc} = 30$ mA/cm^2, and ideality factor $n = 2$.

a. Calculate the open-circuit voltage and fill factor of this cell. Hint: use $\mathrm{FF} = \frac{z_{oc} - \ln(z_{oc}+0.72)}{z_{oc}+1}$, where $z_{oc} = qV_{oc}/nk_BT$ is the reduced open-circuit voltage.

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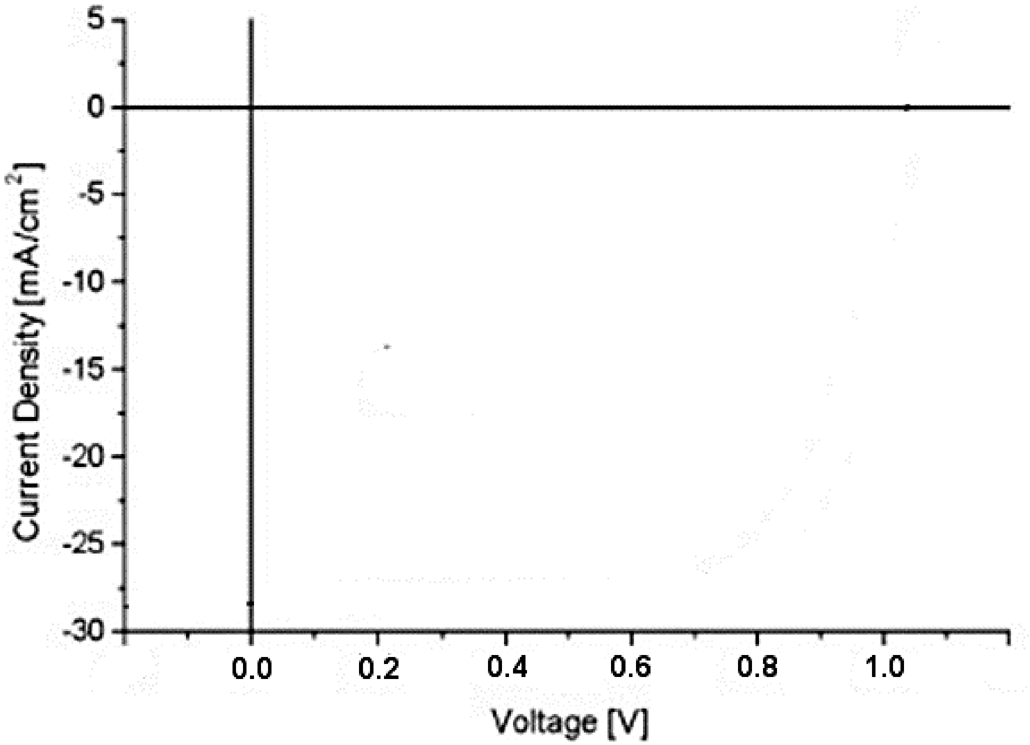
b. Draw the current-voltage relation for this cell, for voltages between 0 and 1 V. Label the x- and y-intercepts.



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c. Assuming that the cell is illuminated by the AM1.5 solar spectrum ($P_{in} = 100$ mW/cm^2), calculate the maximum power conversion efficiency.

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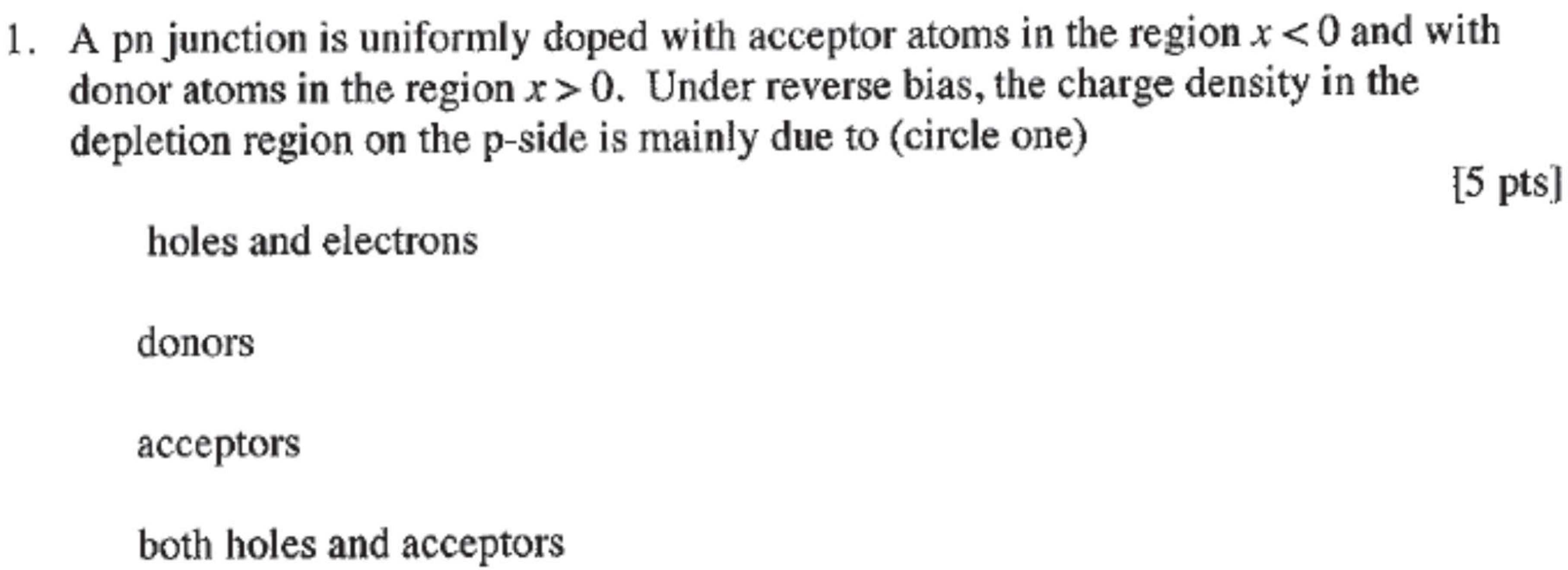


1. A pn junction is uniformly doped with acceptor atoms in the region $x < 0$ and with donor atoms in the region $x > 0$. Under reverse bias, the charge density in the depletion region on the p-side is mainly due to (circle one)

[5 pts]

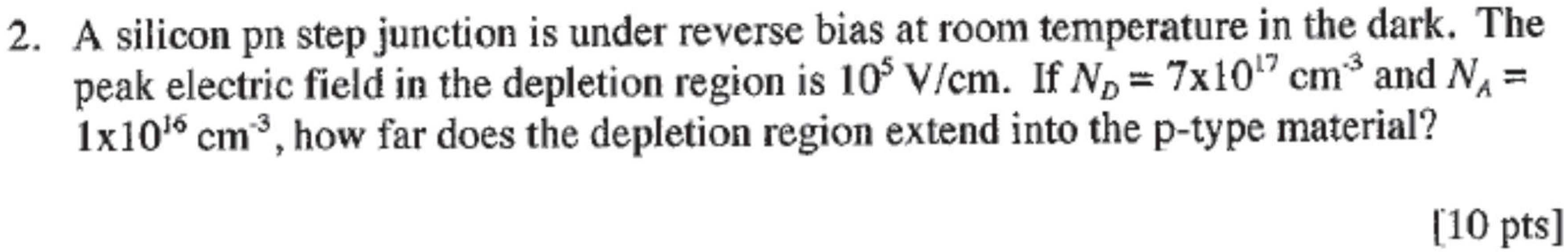
holes and electrons

donors

acceptors

both holes and acceptors

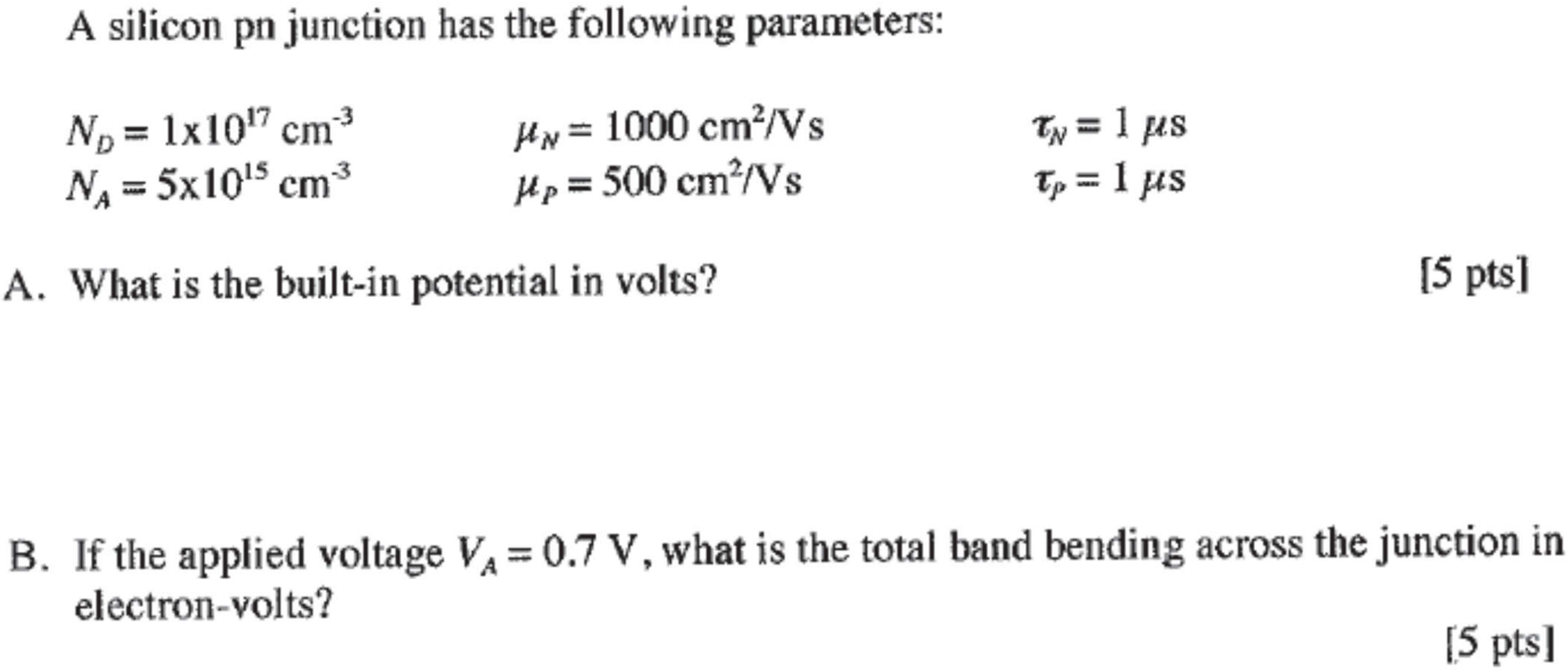
exam 3 review problem



2. A silicon pn step junction is under reverse bias at room temperature in the dark. The peak electric field in the depletion region is 10^5 V/cm. If $N_D = 7x10^{17}$ cm^{-3} and $N_A = 1x10^{16}$ cm^{-3}, how far does the depletion region extend into the p-type material?

[10 pts]

exam 3 review problem



A silicon pn junction has the following parameters:

$N_D = 1\text{x}10^{17}\ \text{cm}^{-3}$ $\mu_N = 1000\ \text{cm}^2/\text{Vs}$ $\tau_N = 1\ \mu\text{s}$

$N_A = 5\text{x}10^{15}\ \text{cm}^{-3}$ $\mu_P = 500\ \text{cm}^2/\text{Vs}$ $\tau_P = 1\ \mu\text{s}$

A. What is the built-in potential in volts? [5 pts]

B. If the applied voltage $V_A = 0.7\ \text{V}$, what is the total band bending across the junction in electron-volts? [5 pts]

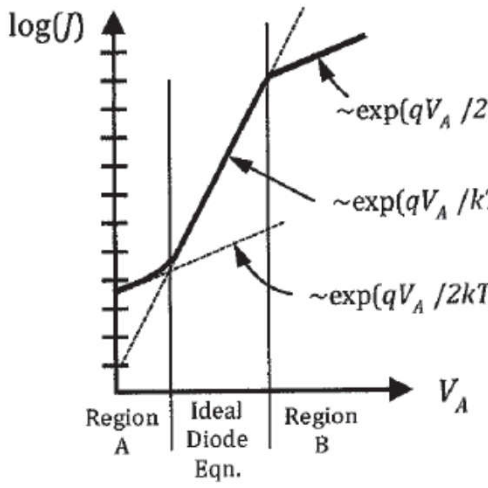
exam 3 review problem

C. Assuming low-level injection, calculate the “ideal” current density if $V_A = 0.7$ V.

[10 pts]

exam 3 review problem

4. Experimentally, the current in a pn diode is found to deviate from the ideal diode equation at both low and high current, as shown in the plot below.



A. The deviation at low currents (region A) is due to (circle one answer): [5 pts]

generation in the neutral regions

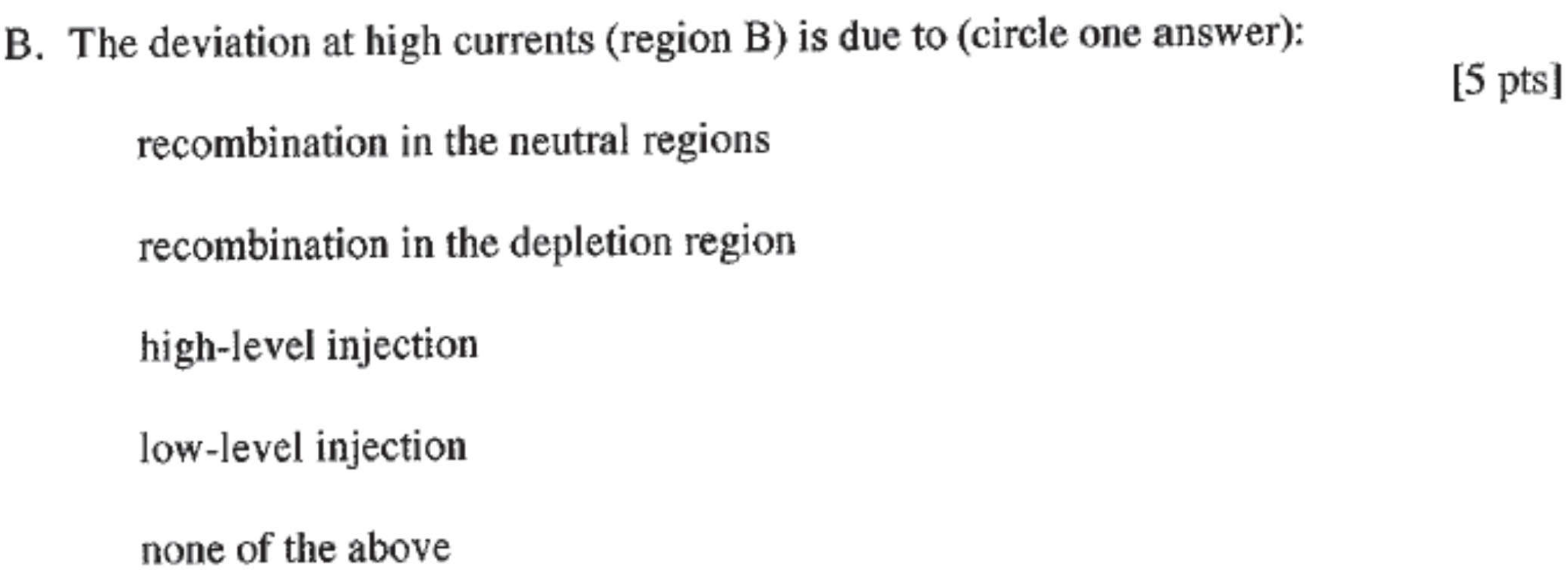
generation in the depletion region

recombination in the neutral regions

recombination in the depletion region

none of the above

exam 3 review problem



B. The deviation at high currents (region B) is due to (circle one answer):

[5 pts]

recombination in the neutral regions

recombination in the depletion region

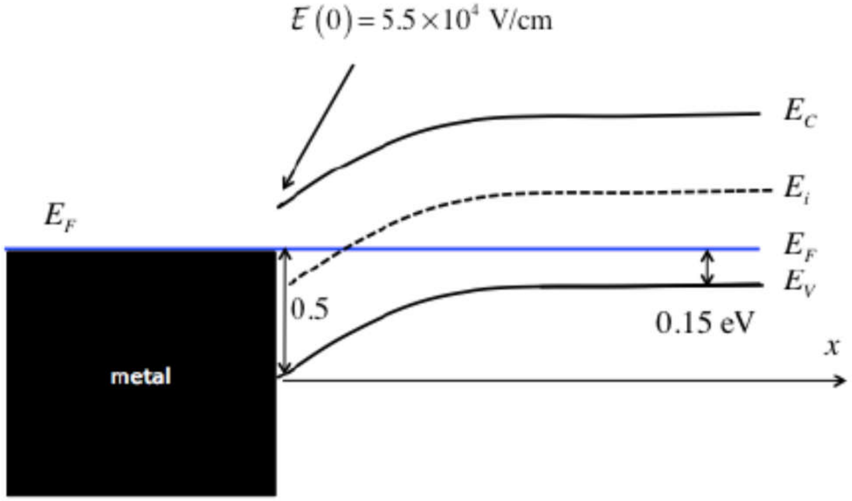
high-level injection

low-level injection

none of the above

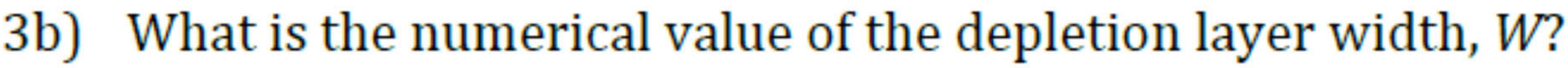
exam 3 review problem

3) Consider an ideal metal-semiconductor junction with the band diagram shown below. The semiconductor has a relative dielectric constant of 12 and an electron affinity of 4.0 eV. Answer the following questions.

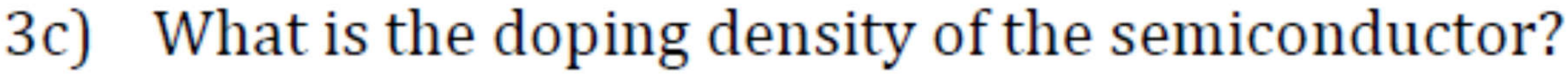


3a) What is the built-in potential of this junction?

exam 3 review problem



3b) What is the numerical value of the depletion layer width, *W*?



3c) What is the doping density of the semiconductor?

exam 3 review problem

3d) What is the numerical value of the small signal capacitance measured under zero d.c. bias? You may assume that the area of the diode is $200\ \mu\text{m} \times 200\ \mu\text{m}$.

3e) The metal is grounded ($V = 0$), and a voltage of $V = -0.35$ is applied to the right side of the P-type semiconductor. Draw the energy band diagram and label the important quantities such as Fermi levels, bandbending, etc.