Metal-Semiconductor Junctions

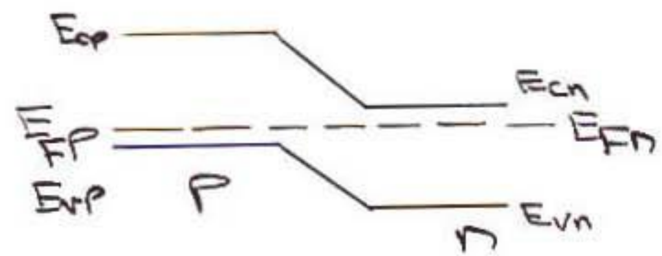
Can get many of the useful p-n junction properties with a metal-semiconductor contact.

Advantage: simpler to make
- high speed rectification

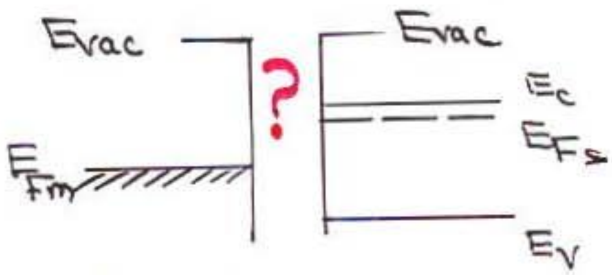
Besides rectifier, metals needed for ohmic contact. (low resistance)

How to draw energy bands?

p-n junction:

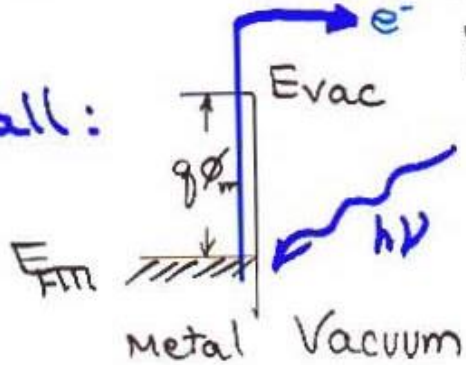


Metal-semiconductor junction:

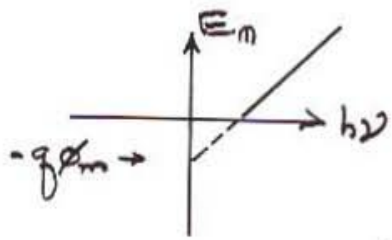


First, line up E_{vac} levels.

Recall:



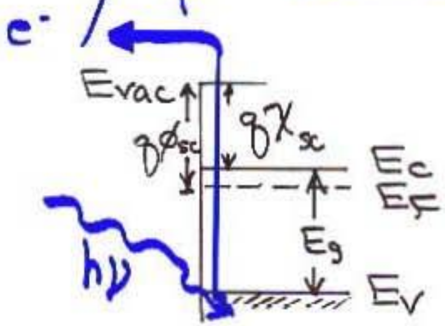
$E = h\nu - q\phi_m$



Photoelectric Effect

$q\phi_m$ = metal work function

Similarly for semiconductor:

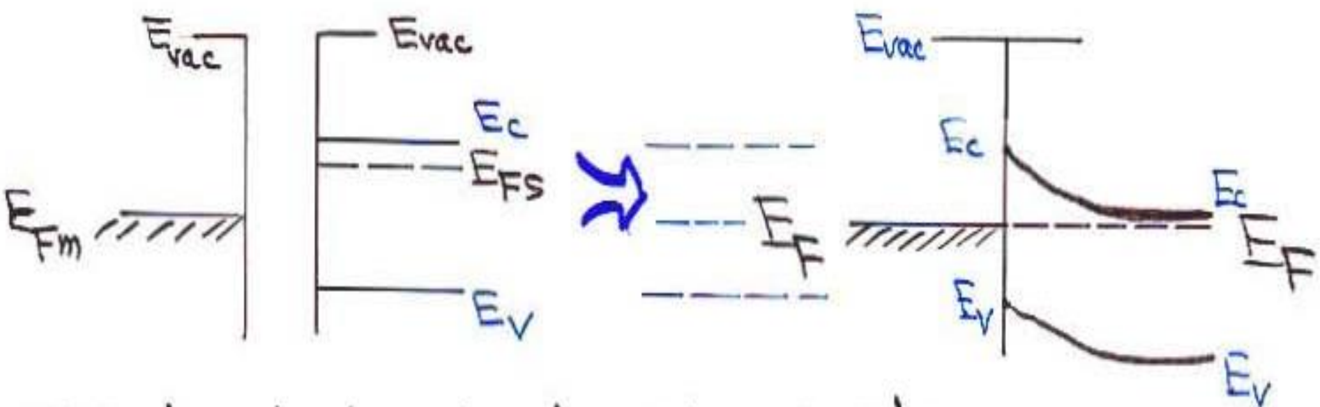


$q\chi_{sc}$ = semiconductor electron affinity

Step 1: Line up E_{vac} levels

Step 2:

→ Bend semiconductor bands



Semiconductor bands stay put.

$E_c - E_F$ in bulk stays the same

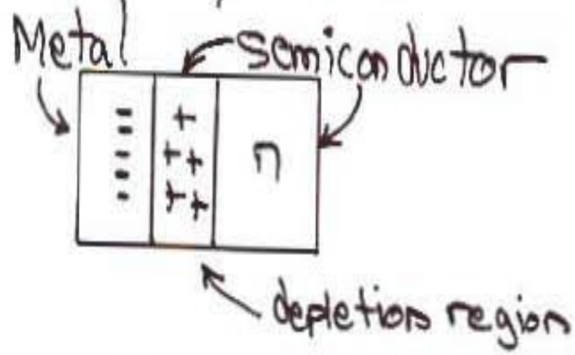
so Bands bend.

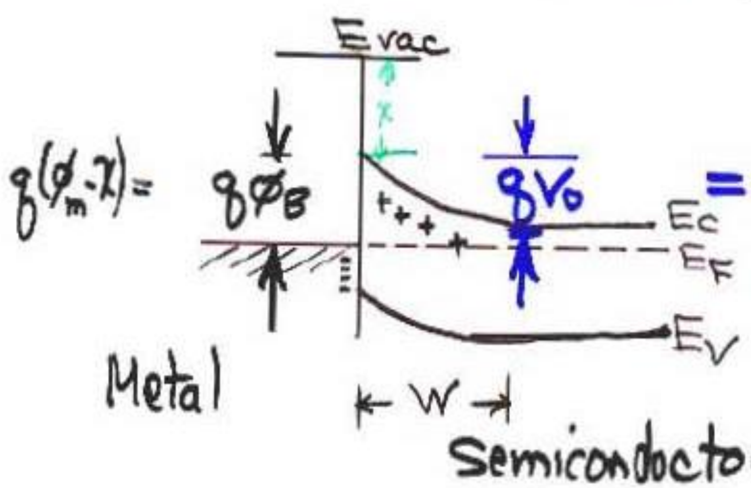
How much do bands bend?

In this example, electrons flow to metal from semiconductor.

They leave behind uncompensated donors.

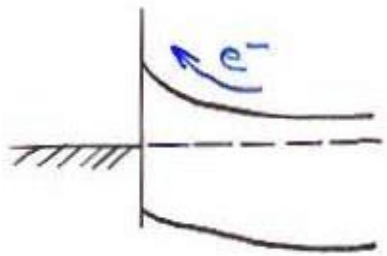
→ positively charged depletion region.



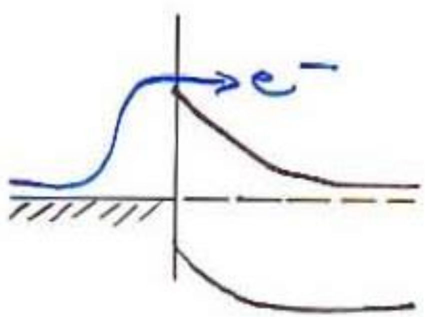


$= q(\phi_m - \phi_{sc})$ Band Bending (contact potential)

(note: $\chi \neq \phi_{sc}$)



contact potential prevents further diffusion into metal



Barrier height to injection

Depletion width W:

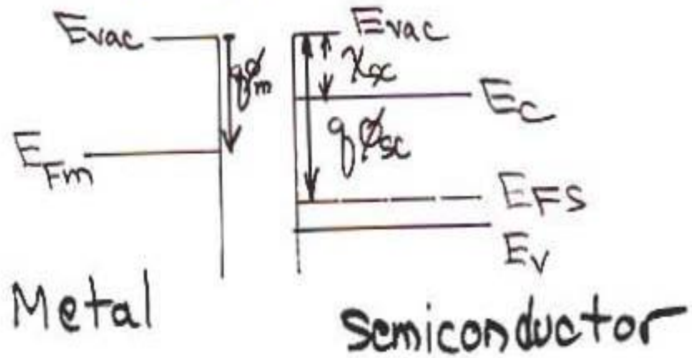
Can get from same formula as in p^+-n junction

$W =$

$\epsilon = \epsilon_{sc} = \epsilon_r \epsilon_o$

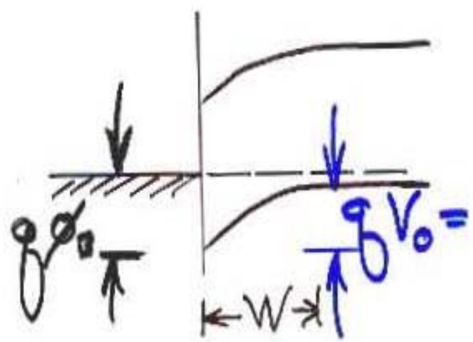
and capacitance $C = \dfrac{\epsilon_{sc} A}{W}$ as in p-n junction

For p-type semiconductor,

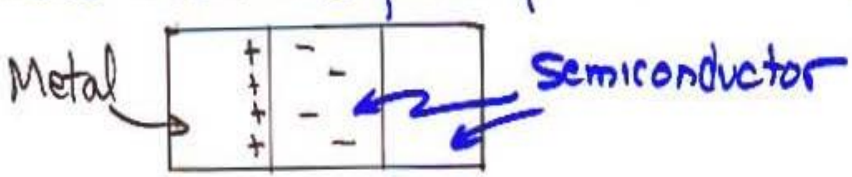


Before Contact

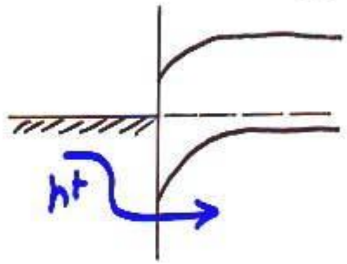
$\phi_{sc} > \phi_m$



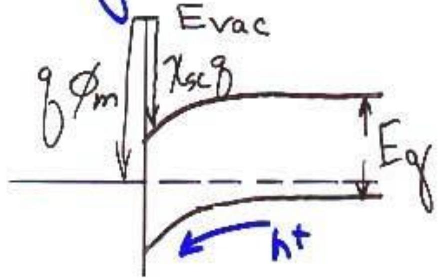
Now electrons flow from metal to Semiconductor



$$W = \left[\frac{2 \epsilon V_0}{q N_a} \right]^{1/2}$$



Injection Barrier



Diffusion barrier

$$qV_0 = q(\phi_{sc} - \phi_m)$$

Reverse of n-type

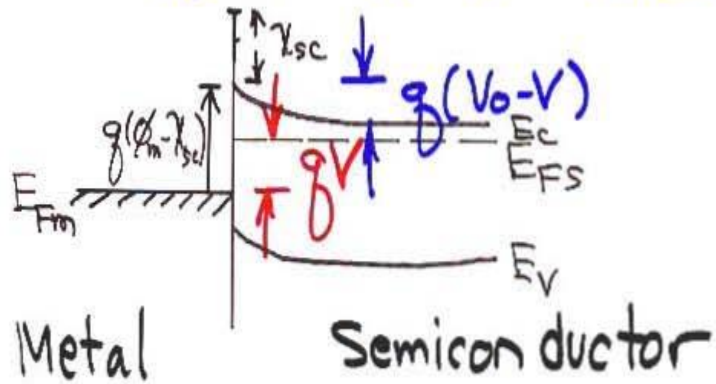
$$q\phi_B =$$

note extra E_g term.

Rectifying Contacts Under Bias (Schottky Diode)

Forward Bias

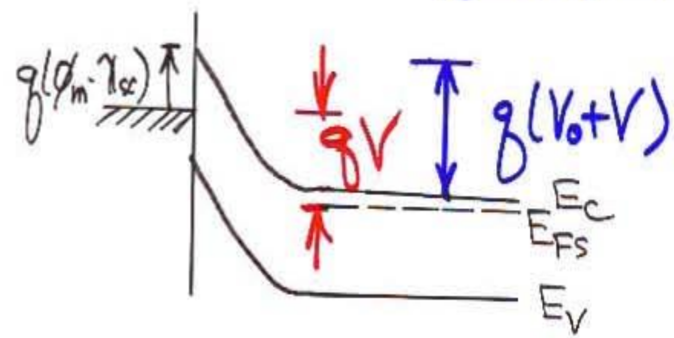
$V_o \longrightarrow V_o - V$ as with p-n junction



n-side goes ↑

Reverse Bias

$V_o \longrightarrow V_o + V$

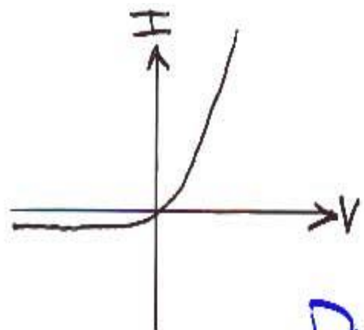


n-side goes ↓

Barrier $q\phi_B = q(\phi_m - \chi_{sc})$ unaffected

Diffusion (forward) much more

Diffusion (reverse) much less (negligible)



Rectifying!

Diode equation similar to p-n junction: $I = I_o\left(e^{qV/kT} - 1\right)$

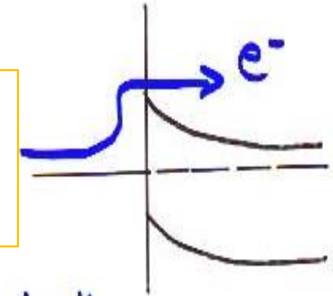
Saturation current depends on ϕ_B.

For large reverse V_r,

$I = I_o\left(e^{qV/kT} - 1\right) \cong -I_o$

depends on getting over $q\phi_B$

depends on getting over $q\phi_B$



$I_0 \propto$

Schottky diodes = "majority carrier device"

No minority carrier injection

(Here, electrons are majority carriers on <u>both</u> sides of junction. Little or no minority carriers in semiconductor

→ No storage delays →

→

Example: Schottky Barrier

An ideal metal–semiconductor contact is made of a metal that has $\Phi_M = 4.75$ eV, and a semiconductor that has $\chi = 4.00$ eV with $n_i = 10^{10}/\text{cm}^3$, $N_D = 10^{16}/\text{cm}^3$, and $E_G = 1.00$ eV; $kT = 0.026$ eV.

(a) Calculate the barrier for electrons in the metal.

(b) Calculate V_{bi}, the barrier for electrons in the semiconductor.

(c) Calculate the value of the depletion region width at thermal equilibrium.

(d) Calculate the maximum electric field.

(e) Sketch the energy band diagram in thermal equilibrium.

$\Phi_M = 4.75$ eV $\chi = 4.00$ eV $E_G = 1.00$ eV $\epsilon = 11.8\epsilon_0$ $(K_S = 11.8)$

$n_i = 10^{10}/\text{cm}^3$ $N_D = 10^{16}/\text{cm}^3$ $KT = 0.026$ eV

(a) $\Phi_B = \Phi_M - \chi =$

(b) $q V_{bi} =$

$$E_c - E_F \cong \frac{E_G}{2} - (E_F - E_i)$$

$$= \frac{E_G}{2} - kT \ln \frac{N_D}{n_i} =$$

$V_{bi} =$

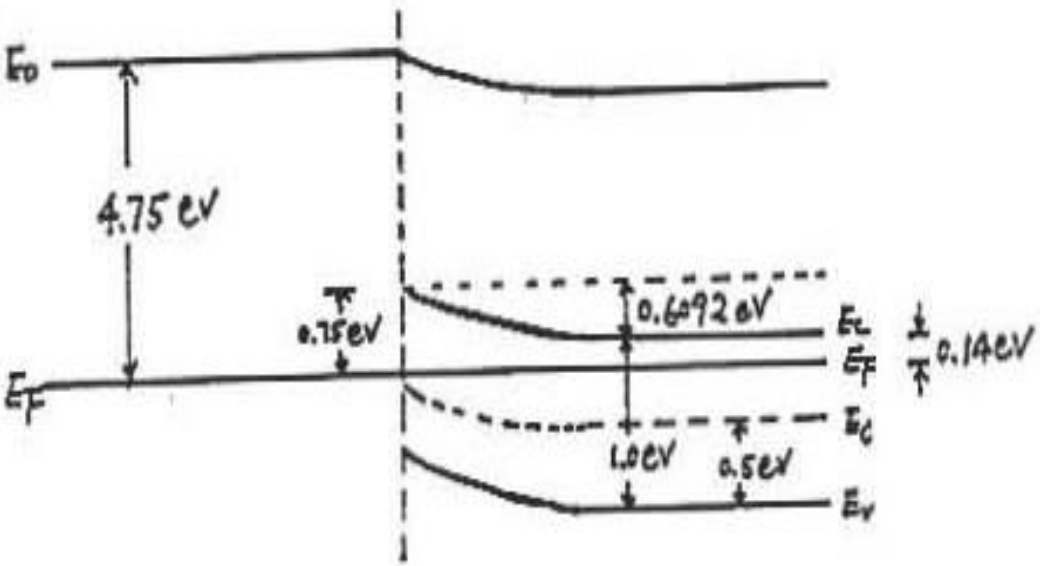
(c) $W = x_n = \left[\frac{2K_S\varepsilon_0}{qN_D}(V_{bi} - V_A)\right]^{1/2}$ $\quad V_A = 0$

$=$

(d) $\mathcal{E}_{max}$ at $x = 0$

$\mathcal{E}_{max} = -q\frac{N_D}{K_S\varepsilon_0}x_n =$

(e)



Junction Capacitance of Schottky Diode

$$C = \epsilon_{sc} A / W$$

$$W =$$

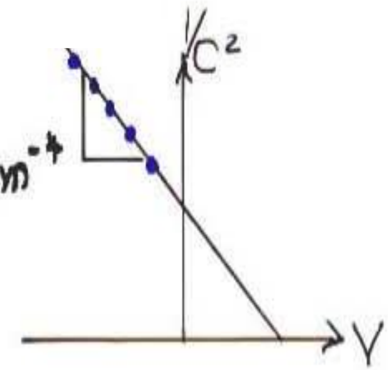
$$C = \epsilon_{sc} A \left[\frac{q N_d}{2 \epsilon_{sc} (V_0 - V)} \right]^{1/2} = A \left[\frac{q \epsilon_{sc} N_d}{2 (V_0 - V)} \right]^{1/2}$$

$$\frac{1}{C^2} = \frac{2 (V_0 - V)}{q N_d \epsilon_{sc} A^2}$$

$$\text{Slope: } \frac{d(1/C^2)}{dV} \cong \frac{\Delta(1/C^2)}{\Delta V} = -\frac{2}{q N_d \epsilon_{sc} A^2}$$

Example: slope $= -4.4\times10^{13}\ F^{-2}V^{-1}cm^{-4}$

$A = 1\ cm^2$



so $N_d = \dfrac{-2}{(1.6\times10^{-19}C)(11.8)(8.85\times10^{-14}\frac{F}{cm})(-4.4\times10^{13}F^{-2}V^{-1}cm^{-4})\cdot 1\,cm^4}$

$=$ $\boxed{}$

Example: Schottky Barrier Properties

OBJECTIVE: To calculate the theoretical barrier height, built-in potential barrier, and maximum electric field in a metal-semiconductor diode for zero applied bias.

Consider a contact between tungsten and n-type silicon doped to $N_d = 10^{16}\ \mathrm{cm}^{-3}$ at $T = 300°\mathrm{K}$.

Solution:

The metal work function for tungsten (W) is $\phi_m = 4.55$ volts and the electron affinity for silicon is $\chi = 4.01$ volts. The barrier height is then

$$\phi_B = \phi_{B0} = \boxed{}$$

where ϕ_{B0} is the ideal Schottky barrier height. We can calculate ϕ_n as

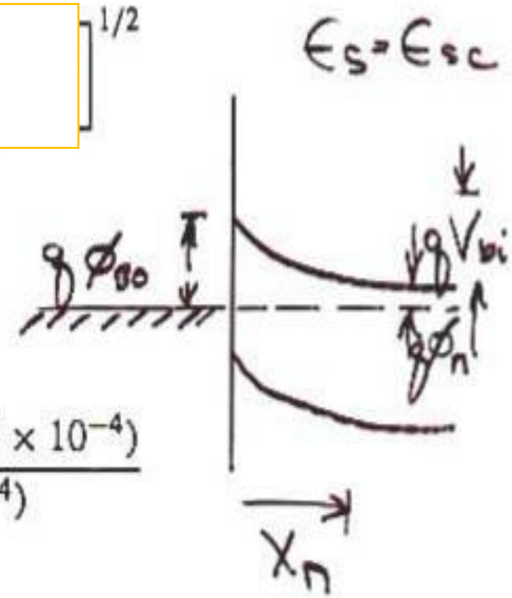
$$\phi_n = \frac{kT}{e}\ln\left(\frac{N_c}{N_d}\right) = 0.0259\ln\left(\frac{2.8\times10^{19}}{10^{16}}\right) = 0.206\ \text{volt}$$

Then

$$V_0 = V_{bi} = \phi_{B0} - \phi_n = \boxed{}$$

The space charge width at zero bias is

$$x_n = \left[\frac{2\epsilon_s V_{bi}}{eN_d}\right]^{1/2} = \left[\qquad\qquad\right]^{1/2}$$



or

$$x_n = \qquad$$

Then the maximum electric field is

$$|\mathrm{E}_{\max}| = \frac{eN_d x_n}{\epsilon_s} = \frac{(1.6 \times 10^{-19})(10^{16})(0.207 \times 10^{-4})}{(11.7)(8.85 \times 10^{-14})}$$

or finally

$$|\mathrm{E}_{\max}| = \qquad$$

Comment:

The values of space charge width and electric field are very similar to those obtained for a pn junction.

Example: Metal Work Function Effect on ϕ_B

The ideal M–S contact has a semiconductor with $\chi = 4$ eV, $n_i = 10^{10}\text{cm}^3$, $N_D = 10^{16}/\text{cm}^3$, $E_G = 1.2$ eV, and $kT = 0.026$ eV. Various metals are applied to the semiconductor with $\Phi_M =$ 4, 4.25, 4.5, 4.75, and 5.0 eV.

(a) Calculate and sketch Φ_B vs. Φ_M

(b) Calculate and sketch qV_{bi} vs. Φ_M

(c) If $K_S = 12$ obtain an equation, with numerical coefficients, for the depletion region width vs. Φ_M if $V_A = 0$

(d) What is the probability that an electron will have an energy equal to Φ_B if $\Phi_M = 4.75$ eV?

(a)

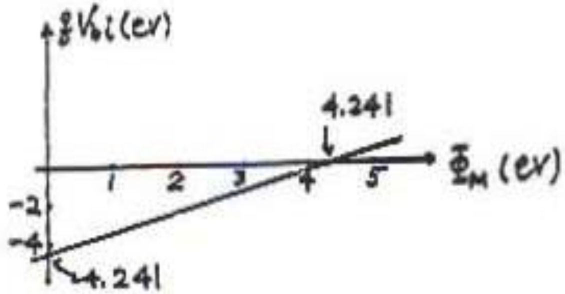
$$\Phi_B = \Phi_M - \chi = \Phi_M - 4\,\text{eV}$$

(b)

$$qV_{bi} = \Phi_M - \chi - (E_c - E_{Fs})_{bulk}$$

$$E_c - E_F \cong \frac{E_G}{2} - kT \ln\frac{N_D}{n_i} = 0.241\ eV$$

$$qV_{bi} = \Phi_M - 4.241\ eV$$



(c)

$$W = x_n = \left[\frac{2K_S\varepsilon_0}{qN_D}(V_{bi} - V_A)\right]^{1/2} \qquad V_A = 0$$

$$= 3.64 \times 10^{-5}\left(\frac{\Phi_M}{q} - 4.241\right)^{1/2}$$

(d)

$$\Phi_M = 4.75\ eV \Rightarrow \Phi_B = 0.75\ eV = E - E_{Fm}$$