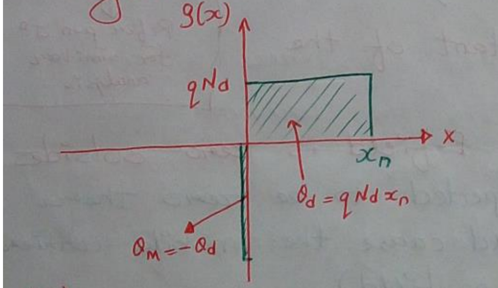
- ## Ideal junction properties :-

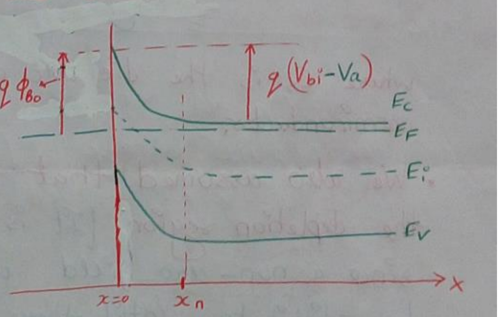
- For a metal - semiconductor junction ($\phi_m > \phi_s$) ie (rectifying contact), we will find the expression for depletion region width (W), E-field and space-charge.
- We will assume "full depletion approximation".

↳ It is obtained by assuming that the semiconductor is fully depleted over distance '$x_n$', called the "depletion region."

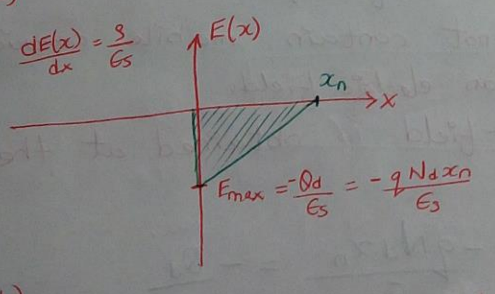
- As the semiconductor is depleted of mobile carriers within the depletion region, the charge density in that region is due to the ionized donors.



(a)



(c)



(b)

fig: (a) Charge density Vs x
(b) Electric field Vs x
(c) EBD as obtained with full depletion analysis
(For Metal-Semiconductor $J^n$) (ntype)
($\phi_m > \phi_s$)

- Outside the depletion region, the semiconductor is assumed neutral. This gives the following expressions for the charge density $\rho(x)$:

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$$\rho(x) = qN_d \quad ; \quad 0 < x < x_n$$
$$\quad = 0 \quad ; \quad x_n < x \qquad \left\{ \text{Fig a} \right\}$$

he charge in the ntype Semiconductor is exactly balanced by the charge in the metal, $Q_M$, so that no E-field exists except around the Metal-semiconductor interface.

Now, using Gauss's law, we obtain electric field as a function of position (fig b)

$$E(x) = \frac{-qN_d}{\epsilon_s}(x_n - x) \quad ; \quad 0 < x < x_n$$
$$\quad = 0 \quad ; \quad x_n \leq x$$

where $\epsilon_s$ is the dielectric constant of the semiconductor.

Analysis

It is similar to a $p^+$-n one-side J$^n$, where p reg$^n$ is heavily doped.
↓
Refer p-n J$^n$ for similar analysis

- We also assumed that the E-field is zero outside the depletion region. (It is expected to be zero there since a non-zero field would cause the mobile carriers to redistribute until there is no field).

→ The depletion region does not contain mobile carriers so that there can be an electric field.

- The largest value of E-field is obtained at the M-S interface as,

$$E_{max}(x=0) = \frac{-qN_d x_n}{\epsilon_s} = -\frac{Q_d}{\epsilon_s}$$

$$\boxed{|E_{max}| = \frac{qN_d x_n}{\epsilon_s}}$$

Here "($x_n$ or W)" or $x_d$ means same.

- Following the similar analysis (as p-n J$^n$), we can next find potential $\phi(x)$ & then find depletion layer width.
- Expression for depletion layer width '$x_n$' or 'W' is

$$x_d = x_n = W = \sqrt{\frac{2\epsilon_s (V_{bi} - 0)}{q N_d}} \quad \text{---- At equilibrium}$$

$$W = \sqrt{\frac{2\epsilon_s (V_{bi} - V_a)}{q N_d}} \quad \text{--- with applied bias "}V_a\text{"}$$

→ Junction capacitance:

In addition, we can obtain the capacitance as a function of the applied voltage by taking the derivative of the charge $Q_d$ w.r.t applied bias '$V_a$',

$$C_j = \left| \frac{dQ_d}{dV_a} \right| \quad ; \quad Q_d = -q N_d x_n = -q N_d W$$

Solving, we get

$$\boxed{C_j = \sqrt{\frac{q \epsilon_s N_d}{2(V_{bi} - V_a)}} = \frac{\epsilon_s}{W}} \text{ — ①}$$

- The last term in the ①, indicates that the expression of a parallel plate capacitor still applies.

$$\left( \frac{C}{A} = \frac{\epsilon}{d} \right)$$

Extra:-

One can understand this once one realizes that the charge added/removed from the depletn layer as one ↓ses/↑ses the applied vtg is added/removed only at the edge of the depletion region.

## Ideal Junction properties: "same"

(Derivation for space charge region width and junction capacitance for a metal - ntype semiconductor for contacts)

- The ideal metal-semiconductor junction discussed so far has <u>striking similarities</u> with the pn junction
- The electric-field in the space-charge region is determined using the Poisson's equation, given by

$$\frac{dE}{dx} = \frac{\rho(x)}{\epsilon_s} \quad — ①$$

where $\rho(x)$ is the space-charge volume density
$\epsilon_s$ is the permittivity of the semiconductor.

- Assuming a uniformly doped semiconductor, then by integrating eqn ①, we get ($\rho(x) \approx qN_d$ "ntype SC")

$$E = \int \frac{qN_d}{\epsilon_s}\, dx = \frac{qN_d x}{\epsilon_s} + C_1 \quad — ②$$

where, $C_1$ is a constant of integration.

(Refer fig 1.b),

An important difference w.r.t pn junction appear at this stage. → A metal cannot sustain an electric field in its bulk and, therefore, E-field is <u>zero</u> inside the metal.

"same"
Suppose at $x = x_n$. (refer fig 1.b), represents the point 12 where the E-field is zero at the space-charge region edge in the semiconductor.

- Then using eq$^n$ ②, we have

$$E = 0 = \frac{q N_d x_n}{\epsilon_s} + C_1$$

This leads to,

$$C_1 = \frac{-q N_d x_n}{\epsilon_s} \quad — ③$$

Using ③ & ④, we have

$$\boxed{E = -\frac{q N_d}{\epsilon_s}(x_n - x)} \quad — ④$$

Thus, the electric field is a linear function of distance and has its maximum value at the metal-semiconductor interface.

Since, the E-field is zero inside the metal, a negative surface charge must exist in the metal at the Metal-semiconductor junction.

- The space-charge width 'W' can be expressed as

$$\boxed{W = x_n = \left[\frac{2 \epsilon_s (V_{bi} + V_R)}{q N_d}\right]^{1/2}} \quad — ⑤$$

{Expression similar to one-sided $p^+$-n junction) where, $V_R$ represents the applied reverse-bias.

- Similarly, the junction capacitance (per unit area), $C_j$ is given by,

$$C_j = qN_d \frac{dx_n}{dV_R} \quad - ⑥$$

ie $$\boxed{C_j = \left[\frac{q\epsilon_s N_d}{2(V_{bi}+V_R)}\right]^{1/2}} \quad - ⑦$$

- Evaluating $(1/C_j)^2$ from $eq^n$ ⑦ results in

$$\frac{1}{C_j^2} = \frac{2(V_{bi}+V_R)}{q\epsilon_s N_d} \quad - ⑧$$

- Thus, the slope of the curve obtained using $eq^n$ ⑧ yields semiconductor doping '$N_d$'. The curve can also be used to obtain $V_{bi}$.
- The magnitude of $V_{bi}$ can then yield the Schottky barrier $\phi_{B0}$, ie

$$\boxed{qV_{bi} = q(\phi_{B0} - \phi_n)} \quad - ⑨$$

- The value of $\phi_n$ is the difference $bet^n$ $E_F$ and $E_C$ of the semiconductor.

$$\boxed{\phi_n = \frac{KT}{q} \ln\left(\frac{N_C}{N_d}\right)}$$

1. A metal-semiconductor contact is formed between gold and ntype Si doped to a level $N_d = 5\times10^{16}\,cm^{-3}$ at 300K. Calculate the ideal Schottky barrier height, built-in potential barrier, space-charge width at zero bias, and maximum electric field for zero bias. Assume the work function of gold to be 5.1 eV, $\chi_s = 4.01 eV$ and the effective density of states function $N_c = 2.8\times10^{19}/cm^3$.

Sol$^n$: a) Ideal barrier height $\phi_{B0}$ is

$$\phi_{B0} = \phi_m - \chi_s = 5.1 - 4.01 = \underline{1.09 eV}$$

Also, $\phi_n = \frac{KT}{q}\ln\left[\frac{N_c}{N_d}\right]$ ; $\frac{KT}{q} \simeq 0.0259 V$.

ie $\phi_n = 0.0259 \ln\left[\frac{2.8\times10^{19}}{5\times10^{16}}\right] \simeq \underline{0.165 V}$ $(\phi_n \simeq 0.165 eV)$

b) Built-in potential barrier, $V_{bi}$ is

$$V_{bi} = \frac{\phi_{B0} - \phi_n}{q}$$

ie $V_{bi} = \frac{(1.09 - 0.165)eV}{\cancel{q}} = \underline{0.925 V}$

c) Space-charge width $x_n$ at Zero bias is,

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

$$= \left[\frac{2\times11.7\times 8.854\times10^{-14}\times0.925}{1.6\times10^{-19}\times 5\times10^{16}}\right]^{1/2}$$

$$x_n = \underline{0.155\times10^{-4}\,cm}$$

• The maximum electric field $|E_{max}|$ at zero bias is,

$$|E_{max}| = \frac{q N_d x_n}{\epsilon_s}$$

$$= \frac{1.6\times10^{-19}\times 5\times10^{16}\times 0.155\times10^{-4}}{11.7\times 8.85\times10^{-14}}$$

$$|E_{max}| = 11.98\times10^{4}\ V/cm$$

2. Consider a contact between tungsten and ntype Si doped to $N_d = 10^{16}\ cm^{-3}$ at $T = 300K$. Find the Schottky barrier height, built-in potential barrier, and maximum E-field for zero applied bias.

Given: Metal work function for tungsten is $\phi_m = 4.55V$ and $\chi = 4.01$. , $N_c = 2.8\times10^{19}\ /cm^3$

Solution: a) Barrier height ($\phi_{B0}$) is

$$\phi_{B0} = \phi_m - \chi = 4.55 - 4.01 = 0.54\,V$$

b) $\phi_n = \frac{KT}{q}\ln\left[\frac{N_c}{N_d}\right]$

$$\phi_n = 0.0259\ln\left[\frac{2.8\times10^{19}}{10^{16}}\right] = 0.206\,V$$

$$\therefore V_{bi} = \phi_{B0} - \phi_n = 0.54 - 0.206 = 0.33V$$

c) Space-charge width at zero bias,

$$x_n = \left[\frac{2\epsilon_s V_{bi}}{q N_d}\right]^{1/2} = \frac{2\times11.7\times8.85\times10^{-14}\times0.33}{1.6\times10^{-19}\times10^{16}}$$

$$x_n = 0.207\times10^{-4}\,cm$$

d) Maximum E-field is

$$|E_{max}| = \frac{q N_d x_n}{\epsilon_s}$$

$$= \frac{1.6\times10^{-19} \times 10^{16} \times 0.207\times10^{-4}}{11.7 \times 8.85 \times 10^{-14}}$$

$$|E_{max}| = \underline{3{,}2 \times 10^{4}\ V/cm}$$

3. Consider an ideal chromium to ntype silicon Schottky diode at $T = 300K$. Assume the semiconductor is doped with $N_d = 3 \times 10^{15}\ cm^{-3}$.

Determine a) ideal Schottky barrier height

b) Peak electric field with an applied reverse bias voltage of 5V.

c) Junction Capacitances or Depletion layer capacitance per unit area for a reverse bias voltage of 5V.

(Given: Work function for chromium $\phi_m = 4.5\ eV$, electron affinity for Si $\chi = 4.01\ eV$)

Solution:

a) Schottky barrier height ($\phi_{B0}$) is

$$\phi_{B0} = \phi_m - \chi = (4.5 - 4.01)\ eV = 0.49\ eV$$

b) $$|E_{max}| = \frac{q N_d x_n}{\epsilon_s}$$

where, $$x_n = \left[\frac{2\epsilon_s (V_{bi} + V_R)}{q N_d}\right]^{1/2}$$

· Assuming the built-in potential barrier 'Vbi' to be very small as compared to applied R.B of 5V and hence ignoring it, we get

$$x_n = \left[\frac{2\epsilon_s(\cancel{V_{bi}} + V_R)}{qN_d}\right]^{1/2} \quad , \text{ Neglecting } V_{bi}$$

$$x_n = \left[\frac{2\times 11.7\times 8.854\times 10^{-14}\times 5}{1.6\times 10^{-19}\times 3\times 10^{15}}\right]^{1/2}$$

$$x_n = \underline{1.469\times 10^{-4}\text{ cm}}$$

$$\therefore\ E_{max} = \frac{qN_d x_n}{\epsilon_s}$$

$$= \frac{1.6\times 10^{-19}\times 3\times 10^{15}\times 1.469\times 10^{-4}}{11.7\times 8.85\times 10^{-14}}$$

$$\approx \underline{6.807\times 10^{4}\text{ V/cm}}$$

c) Junction Capacitance '$C_j$',

$$C_j = \left[\frac{q\epsilon_s N_d}{2(V_{bi}+V_R)}\right]^{1/2} \quad , \text{ Neglecting } V_{bi}$$

$$= \left[\frac{1.6\times 10^{-19}\times 11.7\times 8.854\times 10^{-14}\times 3\times 10^{15}}{2(5)}\right]^{1/2}$$

$$\approx \underline{6.928\times 10^{-9}\text{ F/cm}^2}$$