1) $N_a = 10^{19} \text{ cm}^{-3}$ \hspace{1cm} $N_d = 10^{17} \text{ cm}^{-3}$ \hspace{1cm} $\tau_n = \tau_p = 0.5 \times 10^{-6} \text{ s}$

$W_p = 0.1 \mu m = 1 \times 10^{-5} \text{ cm} \hspace{1cm} W_n = 500 \mu m = 5 \times 10^{-2} \text{ cm}$

$x_d' = \frac{x_d}{10} \hspace{1cm} \mu_n = 1350 \hspace{1cm} \mu_p = 480$

$D_n = \frac{K_T}{2} \mu_n = 34.9 \text{ cm}^2/\text{s} \hspace{1cm} \Rightarrow L_n = \sqrt{D_n \tau_n} = 4.1773 \times 10^{-3} \text{ cm}$

$D_p = \frac{K_T}{2} \mu_p = 12.409 \text{ cm}^2/\text{s} \hspace{1cm} \Rightarrow L_p = \sqrt{D_p \tau_p} = 2.4909 \times 10^{-3} \text{ cm}$

$V_{bi} = \frac{K_T}{2} \ln \left( \frac{N_a N_d}{n_i^2} \right) = 0.9314 \text{ V}$

$n_{po} = \frac{n_i^2}{N_a} = 22.5 \text{ cm}^{-3}$

$P_{no} = \frac{n_i^2}{N_d} = 2.250 \text{ cm}^{-3}$

$x_n = \sqrt{\frac{2 e V_{bi} (N_a/N_d) (1)}{2}} = 1.0918 \times 10^{-5} \text{ cm}$

$x_p = \sqrt{\frac{2 e V_{bi} (N_d/N_a) (1)}{2}} = 1.0918 \times 10^{-7} \text{ cm}$

$W_p < L_n \Rightarrow \text{ Short diode}$

$V_a = 0.6 \text{ V}$ Case

a) $P_n(x_n) = P_{no} \exp \left( \frac{e V_a}{K_T} \right) = 2.70195 \times 10^{15} \text{ cm}^{-3}$

$J_p(x_n) = \frac{D_p}{2 \tau_p} P_{no} \left[ \exp \left( \frac{e V_a}{K_T} \right) - 1 \right] = 2.1566 \times 10^{-2} \text{ A/cm}^2$

b) $J_{rec} = \frac{e}{2 \epsilon_0} n_i^2 \exp \left( \frac{e V_a}{2KT} \right)$

$x_d' = \frac{(x_n + x_p)}{10} = 1.102718 \times 10^{-6} \text{ cm}$

$J_{rec} = 2.9041 \times 10^{-4} \text{ A/cm}^2$

$J_p(-x_p) = J_p(x_n) + J_{rec} = 2.1856 \times 10^{-2} \text{ A/cm}^2$

c) $J_n(W_p) = \frac{D_n}{W_p} n_{po} \left[ \exp \left( \frac{e V_a}{K_T} \right) - 1 \right] = 0.15108 \text{ A/cm}^2$

d) $J_n(W_n) \approx J_{tot}$

$J_{tot} = J_n(W_p) + J_p(x_n) + J_{rec} = J_n(W_p) + J_p(-x_p)$

$J_n(W_n) = 10.1729 \text{ A/cm}^2$
$V_a = 0.3 \, \text{V Case}$

a) $J_p(x_n) = \frac{D}{2} \frac{\partial p}{\partial x} \rho_n \left[ \exp \left( \frac{2V_a}{kT} \right) - 1 \right] = 9.68 \times 10^{-7} \, \text{A/cm}^2$

b) $J_{rec} = q \frac{N_i}{2} \exp \left( \frac{2V_a}{kT} \right) = 8.77 \times 10^{-7} \, \text{A/cm}^2$

$J_p(-x_p) = J_p(x_n) + J_{rec} = 1.04 \times 10^{-6} \, \text{A/cm}^2$

c) $J_n(W_p) = \frac{D_n}{2} \frac{\partial p}{\partial x} \rho_n \left[ \exp \left( \frac{2V_a}{kT} \right) - 1 \right] = 1.57 \times 10^{-6} \, \text{A/cm}^2$

d) $J_n(W_n) = J_{tot} = J_n(W_p) + J_p(-x_p) = 2.45 \times 10^{-6} \, \text{A/cm}^2$
3) $\varphi_m$ is 4.1 eV

Si: $q \varphi_s = 4.05$ eV

$10^9$ cm$^{-3}$ P doping $\rightarrow$ n-type $\quad T = 300$ K

a) Ignore surface states

before contact:

$$E_F = E_c - kT \ln \left( \frac{N_c}{N_{dl}} \right) = E_c - 0.026 \text{ eV} \cdot \ln \left( \frac{3.2 \times 10^{10}}{10^7} \right) = E_c - 0.15 \text{ eV}$$

In the case of metal-semiconductor contacts you need to consider only the majority carriers of the semiconductor. The minority carriers are negligible.

$$q \varphi_s = q \varphi_m + E_c - E_F = 4.05 \text{ eV} + 0.15 \text{ eV} = 4.2 \text{ eV}$$

$\Rightarrow \varphi_m < \varphi_s$ 

majority carrier: elotions  (n-type semiconductor)

in contact:

$$q \varphi_s = q \varphi_m - q \varphi_s = 0.05 \text{ eV}$$

$$q \varphi_s = q \varphi_s - (E_c - E_F)_{bulk}$$

= 0.05 eV - 0.15 eV = -0.1 eV

Note: $\varphi_B$ is defined as the barrier for majority carriers from $M \rightarrow S$

Equivalent $\varphi_s$: barrier for majority carriers from $S \rightarrow M$
3 a) The contact is ohmic since the barrier $\Phi_B$ is really small 0.05 eV. In the metal there are a lot of carriers and therefore although there is a barrier a large number of carriers (electrons) will make it into the semiconductor

$$n \propto n_e e^{-\frac{\Phi_B}{kT}}$$

@ $T=300K = 0.15$ $\Rightarrow$ factor of 10 reduction.

Another way to think about it. Near the surface will be an accumulation of electrons (Fermi-level close to $E_c$). Therefore this area will have a lower resistance than the bulk. The limiting resistance will come from the bulk and therefore you can consider the contact ohmic.

electrons $S \rightarrow M$ : no problem $\Phi; < 0$ $\checkmark$ $\Rightarrow$ = ohmic

electrons $M \rightarrow S$ : explained above $\checkmark$ $\Rightarrow$ = ohmic
3 b) include large number of surface states (donor & acceptor)

Surface states are trap levels. If they are present in large numbers they pin the Fermi level to the trap level (charge neutrality).

Here: \[ E_t = E_v + 0.35 eV \]

Since they are only present at the surface, their effect is limited to a small distance away from the surface. Far away from surface there is no effect. E.g. \( \Phi_s \) is unchanged from part a) \[ q\Phi_s = 4.2 eV > q\Phi_m \]

\[ q\Phi_b = E_g - 0.35 eV = 0.77 eV \]

\[ q\Phi_i = q\Phi_b - (E_c - E_f)_{bulk} = 0.77 eV - 0.15 eV = 0.62 eV \]

Whether this contact is ohmic or rectifying depends on the nature of the depletion region, which is essentially the thickness of the barrier.

\[ x_d \leq 25-50 \AA = (2.5-5) \text{nm} \]

(see note)
(3b) Thickness of depletion zone

\[ Q = x_d \cdot N_d \cdot q \]

\[ \Phi_E = \frac{Q}{\kappa \varepsilon_0} \quad \Rightarrow \quad E(x) - E(x_0) = \int_{x_0}^{x} \frac{Q}{\kappa \varepsilon_0} \, dx \]

\[ E(x) = \frac{q N_d}{\kappa \varepsilon_0} (x - x_d) \]

\[ E_{max} = E(0) = -\frac{q N_d x_d}{\kappa \varepsilon_0} \]

The work function is area under the curve

\[ \Phi_i = \frac{1}{2} x_d |E_{max}| = \frac{1}{2} \frac{q N_d}{2 \kappa \varepsilon_0} x_d^2 \]

\[ x_d = \sqrt{\frac{2 \kappa \varepsilon_0}{q N_d}} \Phi_i \quad \Rightarrow \quad \Phi_i = 0.62 \, V \]

\[ x_d = 8.95 \times 10^{-6} \, \text{cm} = 89.5 \, \text{nm} \]

This is a thick barrier and therefore tunneling won't work anymore.

\[ x_d \gg (2.5 \text{-} 5) \, \text{nm} \]

\[ \Rightarrow \text{rectifying contact} \]
c) Sketch band-diagrams of a) and b) with applied bias of +0.3 V
4) Gold deposited on p-type \( \phi_B = 0.4 \text{V} \) (Schottky barrier)

\[ N_a = 10^{17} \text{cm}^{-3} \]

\[ E_F = E_V + kT \ln \left( \frac{N_V}{N_a} \right) = E_V + 0.135 \text{eV} \]

\[ N_V = 1.8 \times 10^{19} \text{cm}^{-3} \]

\[ \text{answer: } \phi_m < \phi_s \]

\[ E = E_G - q \phi_B = 1.12 \text{eV} - 0.4 \text{eV} = 0.72 \text{eV} \]
1) Si p-type  \( \phi_b = 0.4V \) Au-Si contact

Since Si is p-type \( \Rightarrow \) Au acts like a heavily doped n-type material.

\[ N_a = 10^7 \text{ cm}^{-3} \]

\[ E_F = E_V + kT \ln \left( \frac{N_V}{N_a} \right) \]

\[ = E_V + 0.14eV \]

\( T=300K \)

\[ N_V = 1.8 \times 10^{17} \text{ cm}^{-3} \]

\( \phi_s = X_s + 0.98V = 5.03V \)

\[ \phi_b = X_b \]

\[ \phi = 0.65V \]

Now \( \phi_b \) is given \( \phi_b = 0.4V \)

\[ q\phi_{bn} = E_g - 0.4eV = 0.72eV \]

Barrier for electrons \( S \rightarrow M \): \( q\phi_s = 0.72eV - 0.14eV = 0.58eV \)
46) Reverse bias $T=300K \Rightarrow 10^8 A$

How to bias contact to pass 0.1 mA

Need to increase current by factor of $10^4$

Inst $\alpha \left( \exp \frac{\phi_i}{kT} - 1 \right)$

$10^4 = \exp \frac{\phi_i}{kT} \Rightarrow \frac{kT \phi_i \cdot 10^4}{q} = 0.24V$

$\Rightarrow$ need to apply forward bias of 0.24 V

c) barrier height unchanged $\phi_i = 0.58V$

What doping is necessary to reduce the depletion region to 4 nm in equilibrium?

\[ \begin{align*}
\phi_i &= \frac{1}{2} X_d |E_{max}| \\
E(x) &= \left[ \frac{\phi_i}{X_d} \right] = \frac{x}{X_d} \\
E(x) &= \frac{-qN_a}{kT} (X - X_d) \\
E_{max} &= \frac{qN_a}{kT} X_d \\
\phi_i &= \frac{1}{2} \frac{qN_a}{kT} X_d^2 \\
N_a &= \frac{2kT \phi_i}{q X_d^2} \\
N_a &= 4.69 \cdot 10^{19} \text{ cm}^{-3}
\end{align*} \]

Note: $N_v = 1.8 \cdot 10^{19} \text{ cm}^{-3} \Rightarrow$ degenerate material

($N_v < N_a$)