NOTES ON SCHOTTKY DIODE :

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- A Schottky contact or Schottky diode is formed when a rectifying contact is formed between a metal and a semiconductor. The rectifying properties of the contact are similar to those of a PN-junction diode. The first semiconductor devices, dating back to the end of the 19th century were rectifying, metal-semiconductor, "point-contact" diodes. The rectifying effect in metal-semiconductor contact diodes was discovered in 1874 by F. Braun and was explained by Schottky and Mott in 1938. A typical semiconductor material used at that time was galena, a naturally occurring lead sulphide crystalline mineral.

SCHOTTKY DIODE CONSTRUCTION AND SYMBOL :

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- The symbol to represent Schottky diode is shown in Fig.1

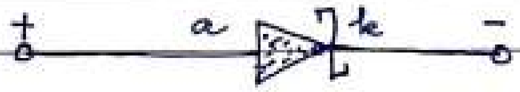

Fig.1. Circuit symbol for Schottky diode.

- Figure 2 shows a simplified circuit diagram of a SCHOTTKY diode in which lightly doped N-type silicon semiconductor

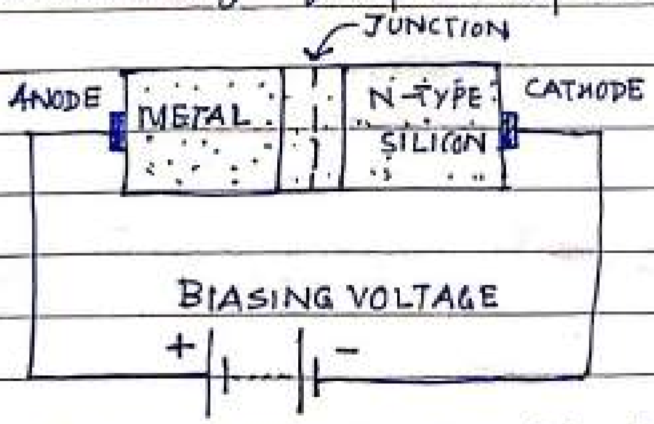

Fig.2 Circuit diagram of Schottky diode

MS = metal-semiconductor

is joined with a metal electrode to produce what is called a "metal-semiconductor junction". The width of MS-junction will depend on the type of metal and semiconductor used, but when forward-biased, electrons move from the N-type material to the metal electrode allowing current to flow. Thus current through the Schottky diode is the result of the drift of majority carriers.

Since there is no p-type semiconductor material and therefore no minority carriers (holes), when reverse biased, the diode conduction stops very quickly and changes to blocking current flow, as for a conventional PN-junction diode. Thus for a Schottky diode, there is a very rapid response to change in bias and demonstrating the characteristics of a rectifying diode.

SCHOTTKY DIODE V-I CHARACTERISTICS:

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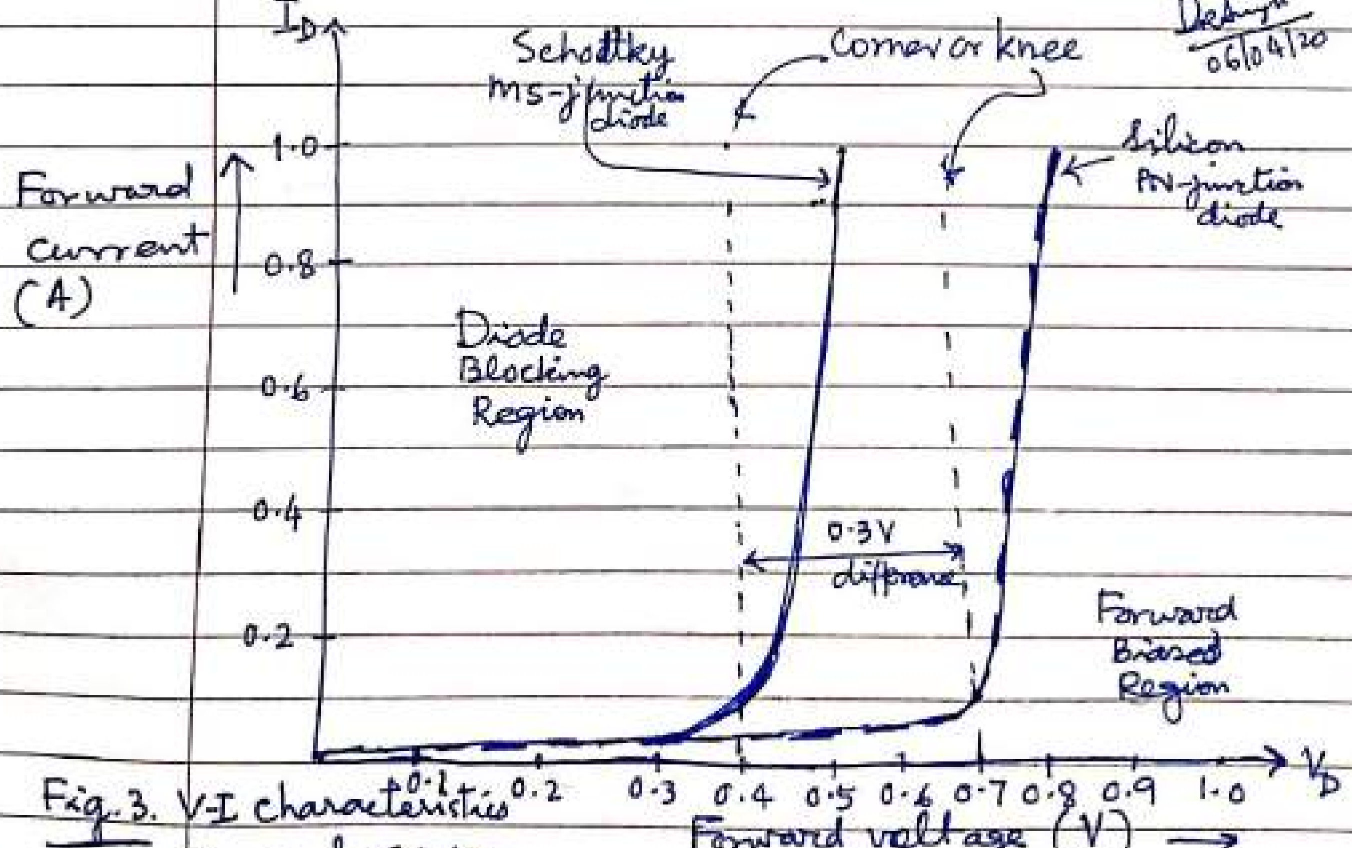

Fig. 3. V-I characteristics curve for Schottky Diode

As shown in Fig. 3, the general shape of the metal-semiconductor diode VI-characteristics is very similar to that of a standard PN-junction diode, except the corner or knee voltage at which the ms-junction diode start to conduct is much lower at around 0.4 V.

Due to this lower value, the forward current of a silicon Schottky diode can be many times larger than that of a typical PN-junction diode, depending on the metal electrode used. Remember that Ohm's law tells us that power equals volts times amps (i.e, $P = VI$), so a smaller forward voltage drop for a given diode current, I_D will produce lower forward power dissipation in the form of heat across the junction.

This lower power loss makes the Schottky diode a good choice in low-voltage and high current applications such as solar ~~volt~~ photovoltaic panels where the forward voltage (V_F) drop across a standard PN junction diode would produce an excessive heating effect. However, it must be noted that the reverse leakage current (I_R) for a Schottky diode is generally much larger than for a PN-junction diode.

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NOTE:

However that if the VI-characteristics curve shows a more linear non-rectifying characteristic, then it is an ohmic contact. Ohmic contacts are commonly used to connect semiconductor wafers and chips with external connecting pins or circuitry of a system. For example, connecting the semiconductor wafer of a typical logic gate to the pins of its plastic dual-in-line (DIL) packages.

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SCHOTTKY BARRIER HEIGHT :

o The working of the Schottky diode depends upon how the metal-semiconductor junction behaves in response to external bias. Let us persue the approximation we used for the PN-junction and

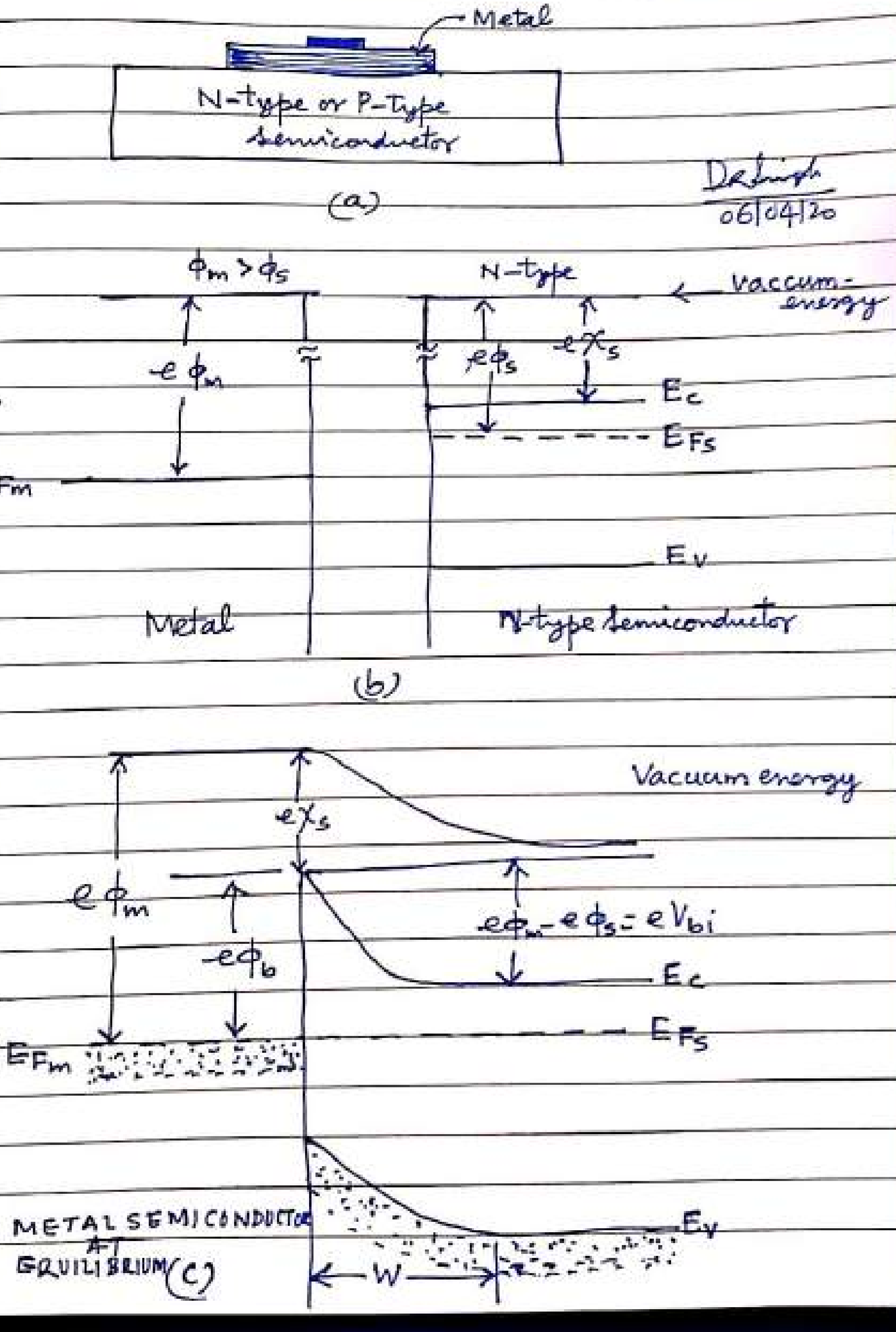

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Fig. 4: (a) A schematic of a metal-semiconductor junction; (b) The various important energy levels in the metals and the semiconductor with respect to the vacuum level. (c) The junction potential described when the metal and semiconductor are brought together. Due to the build-in potential at the junction, a depletion region of width W is created

examine the band profile of a metal and a semiconductor. A metal semiconductor structure is shown in Fig. 4(a). In Fig. 4(b) and Fig. 4(c) the band profiles of a metal and a semiconductor are shown. Figure 4(b) shows that the band profile and Fermi level positions when the metal is away from the semiconductor. In Fig. 4(c) the metal and the semiconductor are in contact. The Fermi level E_{Fm} in metal lies in the band, as shown. As shown in Fig. 4, is the work function $e\phi_m$. In the semiconductor, we show the vacuum level along with the position of the Fermi level E_{FS} in the semiconductor, the electron affinity, and the workfunction.

o We will assume an ideal surface for the semiconductor in the first calculation. Later we will examine the effect of the surface defects. We will assume that $\phi_m > \phi_s$, so that the Fermi level in the metal is at a lower position than in the semiconductor. This condition leads to an N-type Schottky barrier. When the junction between the two systems is formed, the Fermi levels should line up at the junction and remain flat in the absence of any current, as shown in Fig. 4(c). At the junction, the vacuum energy levels of the metal side and semiconductor side must be the same. To ensure the continuity of the vacuum level and align the Fermi levels. Electrons move out from the semiconductor side to the metal side.

NOTE ↔ Since the metal side has an enormous electron density, the metal Fermi level or the band profile does not change when a small fraction of electrons are added or taken out.

As electrons move to the metal side, they leave behind positively charged fixed dopants, and a dipole region is produced in the same way as for the P-N junction diode.

In the ideal Schottky barrier with no bandgap defect levels, the height of the barrier at the semiconductor-metal junction (Fig. 4(C)) is defined as the difference between the semiconductor conduction band at the junction and the metal Fermi level. This barrier is given by [Fig. 4(C)]

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$$e\phi_b = e\phi_m - e\chi_s \longrightarrow (1)$$

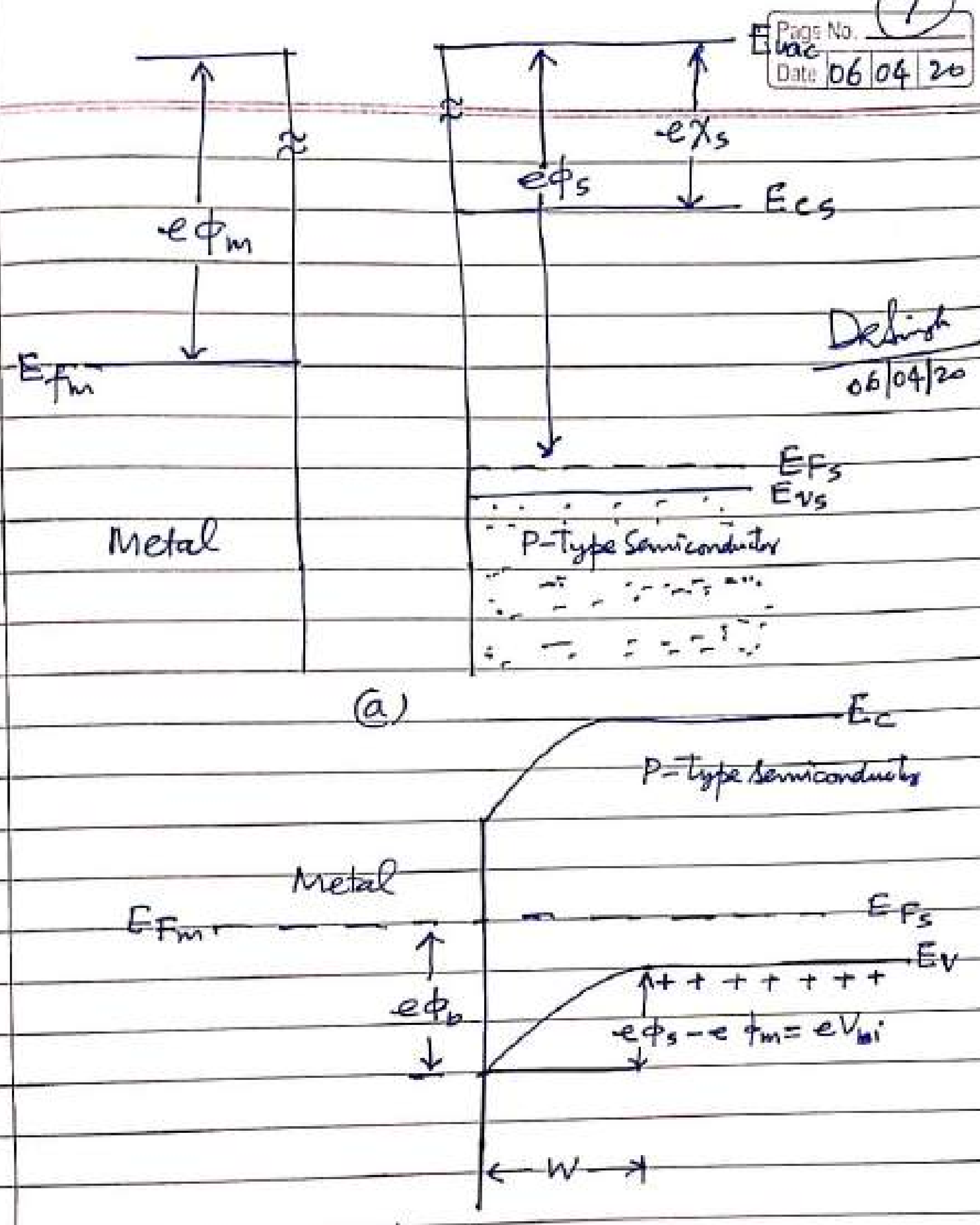
The electrons coming from the semiconductor into the metal face a barrier denoted by eV_{bi} as shown in Fig. 4(C). The potential eV_{bi} is called the build-in potential of the junction and is given by

$$eV_{bi} = -(e\phi_m - e\phi_s) \longrightarrow (2)$$

It is possible to have a barrier for hole transport if $\phi_m < \phi_s$. In Fig. 5, we show the case of a metal-p type semiconductor junction where we choose a metal so that $\phi_m < \phi_s$. In this case, at equilibrium the electrons are injected from the metal to the semiconductor, causing a negative charge on the semiconductor side. The bands are bent once again and a barrier is created for hole transport. The height of the barrier seen by the holes in the semiconductor is

$$eV_{bi} = e\phi_s - e\phi_m \longrightarrow (3)$$

The Schottky barrier height for N or P-type semiconductors depends upon the metal and the semiconductor properties. This is true for an ideal



(b)

Fig. 5 : A schematic of the ideal P-type Schottky barrier formation : (a) The positions of the energy levels in the metal and the semiconductor, (b) the junction potential and the depletion width.

case. It is found experimentally that the Schottky barrier height is often independent of the metal employed, as can be seen from Table 1. This

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Table 1. Schottky barrier heights (in V) for several metals on N- and P-type semiconductor

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Schottky Metal	N-Si	P-Si	N-GaAs
Aluminium (Al)	0.7	0.8	–
Titanium (Ti)	0.5	0.61	–
Tungsten (W)	0.67	–	–
Gold (Au)	0.79	0.25	0.9
Silver (Ag)	–	–	0.88
Platinum (Pt)	–	–	0.86
PtSi	0.85	0.2	–
$NiSi_2$	0.7	0.45	–

can be understood qualitatively in terms of a model based upon non ideal surfaces. In this model the metal-semiconductor interface has a distribution of interface states that may arise from the presence of chemical defects from exposure to air or broken bonds etc. We have known that defects can create bandgap states in a semiconductor. Surface defects can create $\sim 10^{13}\,cm^{-2}$ defects if there is 1 in 10 defects at the surface. Surface defects lead to a distribution of electronic levels in the bandgap at the interface, as shown in Fig. 6. The distribution

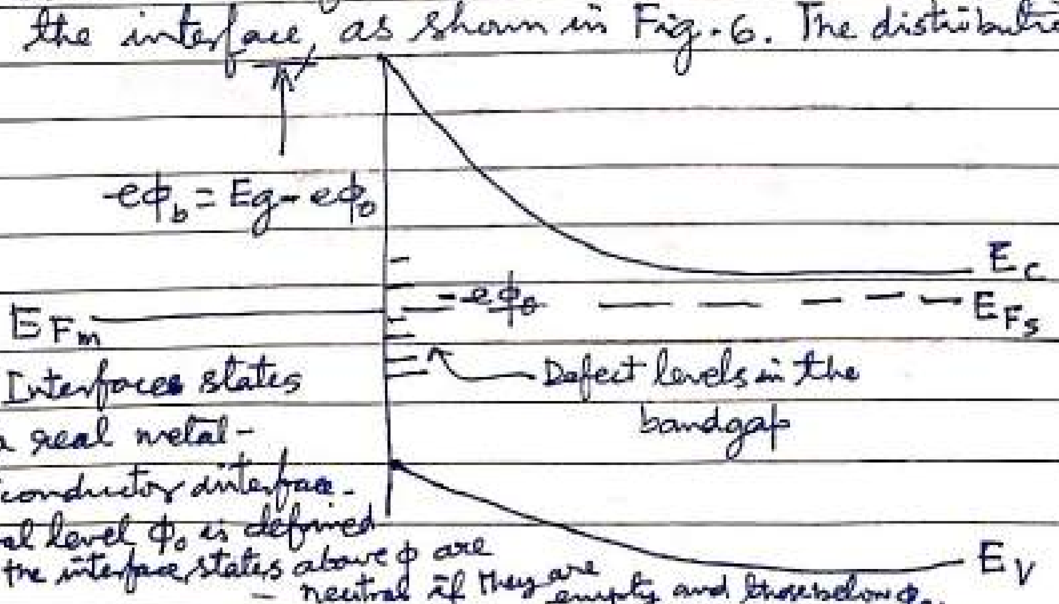

Fig. 6 Interfaces states at a real metal-semiconductor interface. A neutral level ϕ_0 is defined so that the interface states above ϕ are neutral if they are empty and those below ϕ_0.

may characterised by a neutral level ϕ_0 having the property that states below it are neutral if filled and above it are neutral if empty.

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If the density of bandgap states near ϕ_0 is very large, then addition or depletion of electrons to the semiconductor cannot alter the Fermi level position at the surface without large changes in surface charges (beyond the number demanded by charge neutrality considerations). Thus, the Fermi level is said to pinned.

In this case, as shown in Fig. 6, the Schottky barrier height is

$$e\phi_b = E_g - e\phi_0 \longrightarrow (4)$$

and is almost independent of the metal used. The model discussed above provides a qualitative understanding the Schottky barrier heights. However, the detailed mechanism of the interface state formation and Fermi level pinning is quite complex. In Table 1, we show Schottky barrier heights for some common metal-semiconductor combinations. In some materials such as GaN and AlGaN, the surface retains its ideal behaviour and the Schottky barrier is indeed controlled by the metal work function.

CAPACITANCE-VOLTAGE CHARACTERISTICS:

Once the Schottky barrier height is known, the electric field profile, depletion width, depletion capacitance etc. can be evaluated the same way we obtained the values for the P-N junction. The problem for a Schottky barrier diode on an n-type material, is identical for the abrupt p+n diode, since there is no depletion on the metal side. One again makes the depletion approximation; i.e, there is no mobile charge in the depletion region and the semiconductor is neutral outside the depletion region. Then the solution of the Poisson's equation gives the depletion width (W) for an external voltage (V) applied to the metal.

$$W = \left[\frac{2\,\epsilon(V_{bi} - V)}{e N_d}\right]^{1/2} \longrightarrow (5)$$

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Here N_d = doping of the N-type semiconductor

NOTE: → There is no depletion on the metal side because of the high electron density there. The potential V is applied potential, which is positive for forward bias and negative for reverse bias.

CURRENT FLOW ACROSS A SCHOTTKY BARRIER:

THERMOIONIC EMISSION:

Consider the Schottky barrier band diagram shown in Figure 7 at zero bias.

The Schottky barrier between a metal and semiconductor is shown in equilibrium (at zero bias) with the electron distribution shown on the right.

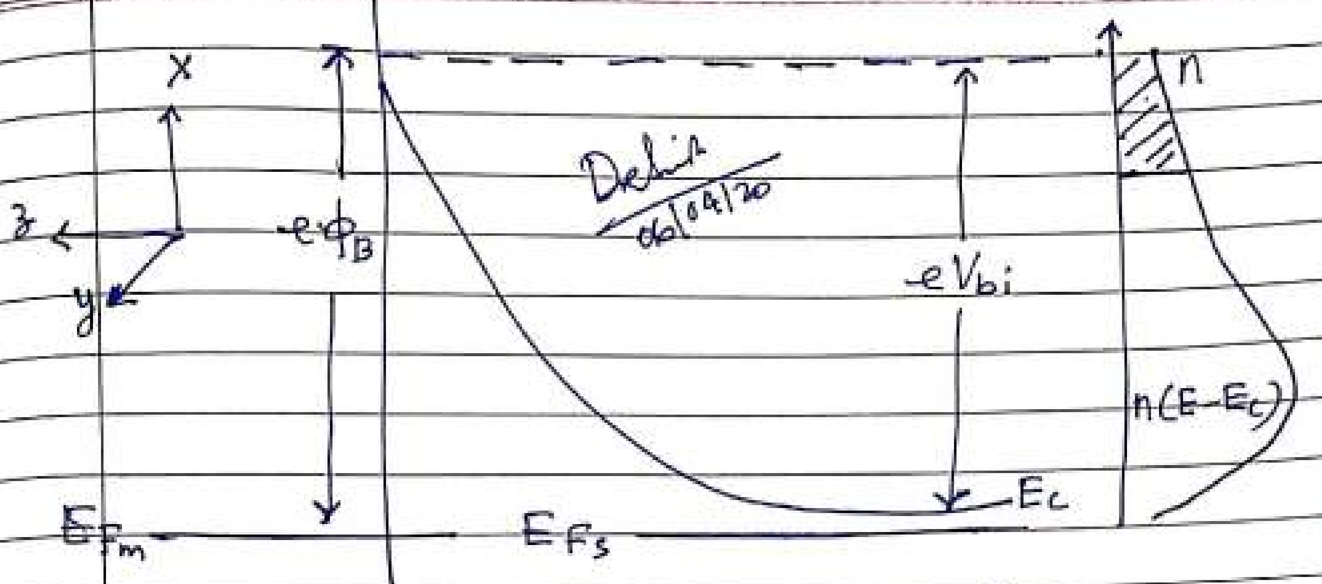

Fig. 7 Schottky barrier in equilibrium

As shown in the electron distribution:

$$n(E-E_c) = 2f(E-E_c) \cdot N(E-E_c) \rightarrow (6)$$

Similar to the case of a P-N junction, the factor of 2 in accounting for electron spin. Thermoionic emission assumes that all electrons in the semiconductor with kinetic energy in the +z direction greater than

$$eV_{bi} \; (E_z > eV_{bi})$$

and $k_z > 0$, are capable of surmounting the barrier and contributing to current flow from the semiconductor to the metal, $J_{s\rightarrow m}$. Note that the total kinetic energy

$$E - E_c = E_x + E_y + E_z \; .$$

At thermal equilibrium the current from the metal to the semiconductor, $J_{m\rightarrow s}$, will be equal in magnitude and opposite in sign to $J_{s\rightarrow m}$ making the net current zero. To calculate $J_{s\rightarrow m}$ one needs to sum the current carried by every allowed electron:

$$J_{s\to m} = e\sum n(E-E_c).v_z \quad \longrightarrow (7)$$

for $E_z > eV_{bi}$ and $v_z > 0$. The methodology employed is to calculate the number of electrons at energy E in a volume of k-space $(dk)^3$, multiply the number with the electron velocity in the direction along the barrier, and sum or integrate over the energy. Assuming a crystal length L, periodic boundary conditions yields allowed k values given by

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$$k = 2\pi N \quad \longrightarrow (8)$$

where N is an integer and the separation between allowed k's is $\Delta k = 2\pi/L$. The number of electrons in a volume elements dk_x, dk_y, dk_z is therefore

$$dN = 2f(E-E_c)\frac{dk_x dk_y dk_z}{(\Delta k)^3} \quad \longrightarrow (9)$$

Assuming $(E-E_c) >> E_F$ and writting $E-E_F = E-E_c+E_c-E_F$ gives

$$dN = 2\exp.\left(\frac{-((E-E_c)+(E_c+E_F))}{k_B T}\right)\frac{dk_x dk_y dk_z}{(\Delta k)^3} \quad \longrightarrow (10)$$

The current density contributed by these electrons is

$$J_z = -ev_z\frac{dN}{L^3} \quad \longrightarrow (11)$$

If $k_z > 0$ and $E_z > eV_{bi}$. Note that all values of E_x and E_y are allowed as they represent motion in the x-y plane, which is not constrained by the barrier in the +z-direction. Note that

$$(E_x - E_c) = \frac{\hbar^2 k_x^2}{2m^*} \quad \longrightarrow (12)$$

with similar relationships for $(E_y - E_c)$ and $(E_z - E_c)$.

Also employing the condition $(E_z - E_c) > eV_{bi}$ yields a minimum value of

$$k_{min} = \sqrt{eV_{bi}\left(\frac{2m^*}{\hbar^2}\right)} \longrightarrow (13)$$

Also

$$v_z = \frac{\hbar k_z}{m^*} \longrightarrow (14)$$

Therefore

$$J_z = \frac{-e}{(2\pi)^3}\int_{-\infty}^{+\infty} dk_x \int_{-\infty}^{+\infty} dk_y \int_{k_{min}}^{+\infty} \frac{\hbar k_z}{m^*} dk_z$$

$$\left(2\exp\left[-(E_x+E_y+E_z)/k_BT\right]\cdot\exp\left[(E_c-E_F)/k_BT\right]\right.$$

$$\left.\exp\left(\frac{E_c}{k_BT}\right)\right)$$

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$$\Rightarrow J_z = -\frac{2e}{(2\pi)^3}\int_x \cdot \int_y \cdot \int_z \exp\left(-\frac{E_c - E_F}{k_BT}\right) \longrightarrow (15)$$

where

$$\int_x = \int_y = \int_{-\infty}^{+\infty} \exp\left(\frac{\hbar^2 k_x^2}{2m^* k_BT}\right) dk_x$$

$$= \frac{\sqrt{2\pi m^* k_BT}}{\hbar} \longrightarrow (16)$$

$$\int_z = \int_{k_{min}}^{\infty} \exp\left(-\frac{\hbar^2 k^2}{k_BT}\right)\cdot\frac{\hbar k_z}{m^*} dk_z \longrightarrow (17)$$

$$\frac{k_BT}{\hbar}\exp\left(-\frac{\hbar^2 k_{min}^2}{k_BT}\right) = \frac{k_BT}{\hbar}\exp\left(\frac{-eV_{bi}}{k_BT}\right) \longrightarrow (18)$$

Therefore

$$J_2 = \frac{4\pi}{(2\pi\hbar^2)^3} \cdot e m^* k_B^2 T^2 \exp\left(-\frac{(eV_{bi} + (E_c - E_F))}{k_B T}\right) \longrightarrow (19)$$

or $$J_2 = A^* T^2 \exp\left(\frac{-e\phi_B}{k_B T}\right) = J_{s\to m}(V=0) \longrightarrow (20)$$

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where $$A^* = \frac{4\pi e m^* k_B^2}{2\pi \hbar^3} = 120\ A\ cm^{-2} K^{-2} \times \frac{m^*}{m_0} \longrightarrow (21)$$

is Richardson constant and $\phi_B = V_{bi} + (E_c - E_F)$, the barrier seen by the electrons in the metal of the Schottky barrier height. We have calculated $J_{s\to m}$ at $V=0$. The analysis can be easily extended to a forward bias of V_F, the only change being replacing the barrier, V_{bi} by the new barrier $V_{bi} - V_F$. This changes I_3 to

$$I_3 = \frac{k_B T}{\hbar} \exp\left(-\frac{eV_{bi}}{k_B T}\right) \cdot \exp\left(\frac{eV_F}{k_B T}\right) \longrightarrow (22)$$

or $$J_{s\to m}(V=V_F) = J_{s\to m}(V=0) \cdot \exp\left(\frac{eV_F}{k_B T}\right) \longrightarrow (23)$$

Since the current flow from the metal to the semiconductor is unchanged.

$$J(V=V_F) = J_{s\to m}(V=V_F) - J_{m\to s}(V=V_F) \longrightarrow (24)$$

$$= A^* T^2 \exp\left(\frac{-q\phi_B}{k_B T}\right)\left[\exp\left(\frac{eV_F}{k_B T}\right) - 1\right] \longrightarrow (25)$$

Numerical Example

Q In a W–N-type Si Schottky barrier the semiconductor has a doping of $10^{16}\,cm^{-3}$ and an area of $10^{-3}\,cm^2$

(a) Calculate the 300K diode current at a forward bias of 0.3V.

(b) Consider an Si p^+–n junction diode with the same area with doping of

$$N_a = 10^{19}\,cm^{-3} \text{ and } N_d = 10^{16}\,cm^{-3}$$

and $\tau_p = \tau_n = 10^{-6}\,s$.

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At what forward bias will the PN-junction diode have the same current as the Schottky diode? $D_p = 10.5\,cm^2/s$.

Solution:

From Table 1, the Schottky barrier of W on Si is 0.67V. Using an effective Richardson constant of $110\,A\,cm^{-2}K^{-1}$, we get for the reverse saturation current

$$I_s = (10^{-3}\,cm^2) \times (110\,A\,cm^{-2}K^{-2}) \times (300K)^2 \exp\left[\frac{-0.67(eV)}{0.026(eV)}\right]$$

$$= 6.37 \times 10^{-8}\,A$$

For a forward bias of 0.3V, the current becomes (neglecting 1 in comparison of $\exp\left(\frac{0.3}{0.026}\right)$)

$$I = 6.37 \times 10^{-8}\,A \exp\left(\frac{0.3}{0.026}\right)$$

$$= 6.53 \times 10^{-3}\,A$$

In the case of the PN-diode, we need to know the appropriate diffusion coefficients and lengths. The diffusion coefficient is $10.5\,cm^2/s$ and using a value of $\tau_p = 10^{-6}\,s$, we get $L_p = 3.24 \times 10^{-3}\,cm$. Using the

The results for the abrup p^+—n junction, we get for the saturation current ($p_n = 2.2 \times 10^4\ cm^{-3}$) [Note that the saturation current is essentially due to hole injection into the N-side for a P^+_N diode)

$$I_0 = (10^{-3}\ cm^2) \times (1.6 \times 10^{-19} C) \times \left(\frac{10.5\ cm^2 / S^1}{3.24 \times 10^{-3}\ cm}\right) \times (2.25 \times 10^4\ cm^{-3})$$

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$$= 1.17 \times 10^{-14} A$$

This is an extremely small value of current. At 0.3 V, the diode current becomes

$$I = I_s \exp\left(\frac{eV}{k_B T}\right) = 1.2 \times 10^{-9} A$$

a value which is almost six orders of magnitude smaller than the value in the Schottky diode. For the P-N diode to have the same current that the Schottky diode has at 0.3V, the voltage required is 0.71 V.

This example highlights the important differences between Schottky and junction diodes.

The Schottky diode turns on (i.e., the current is ~ 1 mA) at 0.3V, while the P-N diode turns on at closer to 0.7V.

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SCHOTTKY EFFECT

The height of the potential barrier on the metal side, ϕ_b, is not exactly constant and is slightly affected by the applied voltage. An actual lowering of ϕ_b is observed. It is due to mirror charge produced in the metal by electrons in the semiconductor. Electrostatics tells us ~~about~~ that when a charge is near a

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"perfect" conduct (metal) a mirror charge of same magnitude but opposite sign is created inside the conductor, at a depth equal to the distance between the initial charge and the conductor surface as shown in Fig. 8. As a consequence, the charge

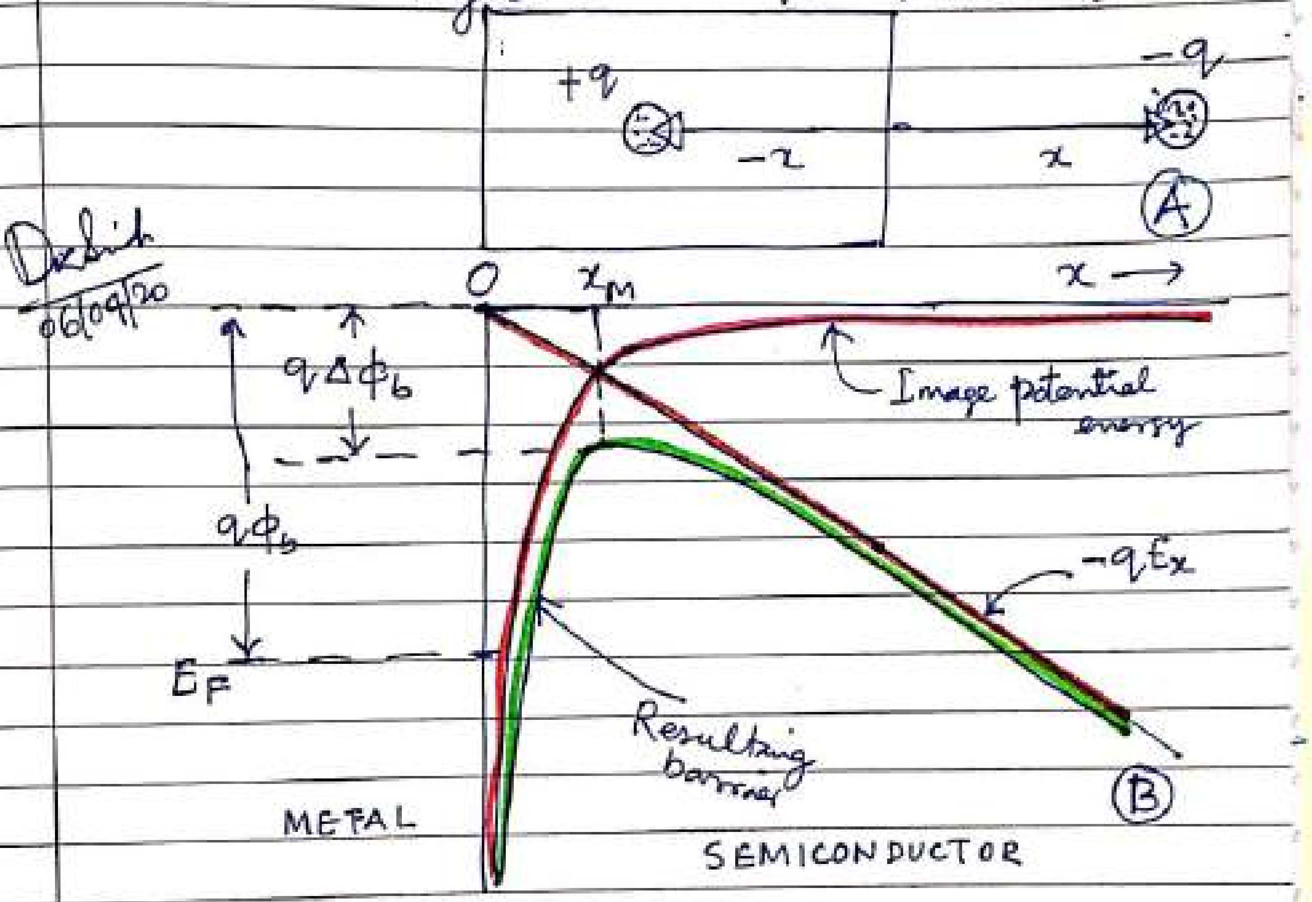

Fig. 8. (A) Mirror charge in a metal
(B) the resulting lowering of the potential barrier

is attracted by the metal, and in the case of the metal-semiconductor contact, the potential barrier is lowered.

The attraction exerted by the metal on an electron can be calculated as follows:

Assuming the distance between the electron and the metal surface is x, the mirror charge bearing a charge $+q$ is located at a distance $-x$ inside the metal. Therefore, the Coulomb attraction force between two charges is equal to

$$-\frac{q^2}{16\pi\varepsilon_{sc}x^2}$$

The force is equivalant to that exerted on an electron by an electric field $E_m(x)$ obeying the relationship:

$$-qE_m(x) = \frac{-q^2}{16\pi\varepsilon_{sc}x^2} \longrightarrow (26)$$

The resulting potential energy of the electron is equal to

$$P(x) = -qV(x) = \int_x^\infty -\frac{q^2}{16\pi\varepsilon_{sc}x^2}\,dx = \frac{-q^2}{16\pi\varepsilon_{sc}x} \longrightarrow (27)$$

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the reference potential being $P(x=\infty)=0$

To find the total energy of the electron this potential energy must be added to the potential energy of the electron inside the semiconductor. In the depletion region the electric field is equal to

$$-\frac{qN_d}{\varepsilon_{sc}}(W-x).$$

This field gives the electron in the conduction band a potential energy which is equal to

$$-\frac{q^2N_d}{2\varepsilon_{sc}}(W-x)^2+E_c.$$

To simplify the problem we will assume that the electric field in the depletion region is constant. The field is noted E and gives the electron a potential energy $-qEx$. The sum of the two potential energies (from the mirror charge and from the depletion ~~layer~~ region) yields the total potential energy $PE(x)$ of the electron:

$$PE(x) = -\frac{q^2}{16\pi\varepsilon_{sc}x^2} - qEx + E_c \longrightarrow (28)$$

The maximum potential energy can be found by writting

$$\frac{d\,PE(x)}{dx} = 0,$$

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which yields the maximum at

$$x = x_m = \sqrt{\frac{q}{16\pi \epsilon_{sc} E}}$$

The potential energy at $x = x_m$ is equal to

$$PE(x_m) = -q\sqrt{\frac{qE}{4\pi \epsilon_{sc}}} < 0$$

which corresponds to an effective lowering of potential barrier $\Delta\phi_b$ equal to:

$$\Delta\phi_b = \sqrt{\frac{qE}{4\pi \epsilon_{sc}}} \longrightarrow (28)$$

Using the value of the electric field at the semi-conductor surface given as

$$E(0) = -\sqrt{\frac{2qN_d}{\epsilon_{sc}}(V_i - V_a)} \longrightarrow (29)$$

we find the magnitude of the potential barrier lowering, which constitutes by Schottky effect

$$\Delta\phi_b = \sqrt[4]{\frac{q^3 N_d}{8\pi^2 \epsilon_{sc}^3}(V_i - V_a)} \longrightarrow (30)$$

The resulting potential barrier height is equal to

$$\phi_b' = \phi_b - \Delta\phi_b \longrightarrow (31)$$

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COMPARISION OF SCHOTTKY DIODE AND NORMAL PN-JUNCTION DIODE

	SCHOTTKY DIODE	PN-JUNCTION DIODE
1.	Junction is formed between N-type semiconductor to Metal plate	Junction is formed between P and N type semiconductors
2.	It has low forward voltage drop.	Compare to Schottky diode it has more forward voltage drop.
3.	Reverse recovery time and reverse recovery loss are very-very less.	The reverse recovery time and reverse recovery loss are more.
4.	They are used in high frequency applications like SMPS circuits.	They can be used in high frequency applications also.
5.	It is unipolar device i.e, current conduction is happening due to movement of electrons only.	It is bipolar device i.e. current conduction is due to movement of both holes and electrons.