Lecture-4 Junction Diode Characteristics Part-II

Q: Aluminum is alloyed into *n*-type Si sample $(N_D = 10^{16} \ cm^{-3})$ forming an abrupt junction of circular cross-section, with an diameter of 0.02 in. Assume that acceptor concentration in the alloyed regrown region is $N_A = 4 \times 10^{18} \ cm^{-3}$. Calculate $V_0, x_{n_0}, x_{p_0}, Q_+$, and ε_0 for this junction at equilibrium. Sketch $\varepsilon(x)$ and charge density ρ_v . Take $n_i = 1.5 \times 10^{10} \ cm s^{-3}$ at 300° K, $\varepsilon_r = 11.8$, 1 in = 2.54 cms. A: From the Eqn.(7) of lecture notes-3 we have

$$V_0 = V_T \times ln \frac{N_A N_D}{n_i^2}$$

where

$$V_T = \frac{\overline{k}T}{q}$$

at room temperature i.e., at $300^{\circ} K V_T = 0.0259 V$

$$\epsilon = \epsilon_0 \epsilon_r = 8.854 \times 10^{-14} \times 11.8 \ F/cms$$

Hence

$$V_0 = 0.00259 \times ln \frac{10^{16} \times 4 \times 10^{18}}{2.25 \times 10^{20}} = 0.85 V$$

from the Eqn.(25) of lecture notes-3, we have

$$W = \left(\frac{2\epsilon V_0}{q} \left(\frac{1}{N_A} + \frac{1}{N_D}\right)\right)^{\frac{1}{2}}$$

= $\left(\frac{2 \times (11.8 \times 8.854 \times 10^{-14})(0.85)}{1.6 \times 10^{-19}} \times (0.25 \times 10^{-18} + 10^{-16})\right)^{\frac{1}{2}}$
= $3.34 \times 10^{-5} \ cm$
= $0.334 \ \mu m$

From the Eqns.(22) and (23) of LN-3 (Lecture Notes-3)

$$x_{n_0} = 0.333 \ \mu m$$

 $x_{p_0} = 8.3 \times 10^{-8} \ cm = 8.3 \ \mathring{A}$

Thus from the above values we can see that $x_{n_0} \approx W$. This shows that depletion or space-charge region, penetrates more in to the lightly doped region than the heavily

doped region. The charge $Q_+ = -Q_-$ can be calculated by multiplying the charge density ρ_v with volume Ax_{n_0} or Ax_{p_0} respectively. Therefore we have,

$$Q_{+} = -Q_{-} = qAx_{n_{0}}N_{D} = qAx_{p_{0}}N_{A}$$
$$A = \pi r^{2} = \pi \times (2.54 \times 10^{-2})^{2} = 2.03 \times 10^{-3} \ cm^{-3}$$
$$\Rightarrow Q_{+} = 1.08 \times 10^{-10} \ C$$

The electric field at the equilibrium, is given by Eqn.(14) of LN-3

$$\varepsilon_0 = -\frac{qN_D x_{n_0}}{\epsilon} = -5.1 \times 10^4 \ V/cm$$



Figure 1: Charge Density graph

1. The p-n junction with bias:

(a) <u>Forward Bias:</u> An external voltage applied with polarity as shown in the Figure-2(a) is called *Forward bias*. This polarity causes the diffusion of majority carriers on either side of the junction. Hence for a forward bias the holes cross the junction from *p*-type into *n*-type region, where they become minority carriers and hence constitute *injected minority current*. Similarly, the electrons cross the junction in the reverse direction and become a minority current in *p*-side. Holes traveling from left to right constitute a current in the same direction as electrons moving from right to left. Due to this bias the space-charge region decreases. Hence the resultant current is the sum of hole and electron currents.

(b) <u>Reverse bias</u>: The battery connected as shown the Figure-2(b) is called *Reverse bias*. The polarity of the connection is such that it causes both holes in the *p*-type and the electrons in the *n*-type to move away from the junction. Consequently the region of negative charge-density is spread to the left of the junction and the positive charge density to the right. In order to have steady flow of holes to the left, these holes must be supplied across the junction from the *n*-type. And there are very few holes in the *n*-type. Hence nominally the current becomes zero.

However there shall be a small current that flows because of generated hole-electron pairs through out out the crystal as the result of thermal energy. The holes so formed in the *n*-type will wander over the junction. A similar remark applies to the electrons thermally generated in the *p*-type. This small current is called *reverse saturation current* and its magnitude is designated by I_0 . This current is dependent on temperature.



Figure 2: p-n junction with bias (a) Forward (b) Reverse

2. Current Components in p-n diode:

- (a) With forward bias applied, we already know that there will be an injected minority carriers on either side of the junction. That is holes in the *n*-side and electrons the *p*-side.
- (b) Under low-level injection conditions, the currents will be minority currents which are almost entirely due to diffusion, so that *minority drift* currents can be neglected.

(c) From the LN-2 Eqn.(45) we have the injected minority current (i.e holes, since the semiconductor was *n*-type) is given by

$$I_p(x) = \frac{AqD_p}{L_p} \{p(0) - p_0\} e^{-x/L_p}$$

In the above equation p(0) represents the hole concentration at the origin i.e., the left most part of the semiconductor specimen chosen (Refer to the figure-8, LN-2). However this equation has to be modified here because, we have two semiconductors (p and n). Thus we have the following equation

$$I_{p_n}(x) = \frac{AqD_p}{L_p} \{ p(x_{n_0}) - p_{n_0} \} e^{-x/L_p}$$
(1)

where $I_{p_n}(x)$ represents the injected minority hole current present in the *n*-side when no bias is applied. When no bias is applied the depletion region is $W = x_{n_0} + x_{p_0}$. Thus as the *n*-type specimen starts from x_{n_0} , we have $p(x_{n_0})$ instead of p(0) in the Eqn.(45) of LN-2. p_{n_0} represents the hole concentration in the *n*-side under thermal equilibrium. Similarly the injected minority electron current present in the *p*-side becomes,

$$I_{n_p}(x) = -\frac{AqD_n}{L_n} \{ n(-x_{p_0}) - n_{p_0} \} e^{-x/L_n}$$
(2)

- (d) Let us consider an un-symmetrical doping. Let acceptor concentration be much greater than the donor concentration $(N_A > N_D)$. This results in $I_{p_n}(x) > I_{n_p}(x)$, as shown in figure-3. Hence when the bias is applied the penetration of the depletion region on the either side will also be un-symmetrical. That is the depletion region penetrates more into the lightly doped region than into heavily doped. In our case it penetrates more on the *n*-side than the *p*-side as shown in the Figure-2.
- (e) Let $W' = x'_{n_0} + x'_{p_0}$ be the depletion region after the bias is applied. In the case of forward bias W' < W and in reverse bias W' > W as shown in figure-2(a) and (b).
- (f) Hence Eqn.(1) and (2) now becomes

$$I_{p_n}(x) = \frac{AqD_p}{L_p} \{ p(x'_{n_0}) - p_{n_0} \} e^{-x/L_p}$$
(3)

$$I_{n_p}(x) = -\frac{AqD_n}{L_n} \{ n(-x'_{p_0}) - n_{p_0} \} e^{-x/L_n}$$
(4)

As we have assumed $N_A > N_D$, this results in $I_{p_n}(x) > I_{n_p}(x)$

(g) If V_0 is the open-circuited voltage present under no bias, the $V_0 - V_F$ is the voltage present under forward bias and $V_0 + V_R$ is the voltage under reverse bias.



Figure 3: Current Components in p-n junction

From the Eqns. (3) and (4) $p(x'_{n_0})$ and $n(-x'_{p_0})$ can be eliminated using the Eqns.(3) and (4) of LN-3.

$$p_1 = p_2 e^{\frac{V_{21}}{V_T}}$$
$$n_1 = n_2 e^{\frac{-V_{21}}{V_T}}$$

as follows, Under no bias, we have

$$p(-x_{p_0}) = p(x_{n_0})e^{(V_{x_{n_0}} - V_{-x_{p_0}})/V_T}$$
(5)

$$= p(x_{n_0})e^{V_0/V_T} (6)$$

In obtaining the Eqn.(6) we have taken $V_{x_{n_0}} = V_0$ and $V_{-x_{p_0}} = 0$. Let us define $p(-x_{p_0}) = p_{p_0}$ and $p(x_{n_0}) = p_{n_0}$ which represents the concentration of holes in the p and n sides at thermal equilibrium respectively. Thus Eqn.(6) becomes

$$p_{p_0} = p_{n_0} e^{V_0/V_T} \tag{7}$$

Under the forward bias conditions, the Eqn.(5) becomes,

$$p(-x'_{p_0}) = p(x'_{n_0})e^{(V_{x'_{n_0}} - V_{-x'_{p_0}})/V_T}$$

= $p(x'_{n_0})e^{(V_0 - V_F)/V_T}$ (8)

Eqn.(8) is obtained by taking $V_{x'_{n_0}} = V_0$ and $V_{-x'_{p_0}} = V_F$. $p(-x'_{p_0})$ is the hole (which is majority in p-side) concentration at $-x'_{p_0}$ under the bias condition.

We can clearly see that the percentage change in the majority carrier is very less and hence there is hardly any change in the concentration of holes due to the injected minority from the *n*-side due to the bias applied. Therefore $p(-x'_{p_0}) = p_{p_0} = p(-x_{p_0})$. Thus the Eqn.(8) becomes,

$$p_{p_0} = p(x_{n_0})e^{(V_0 - V_F)/V_T}$$
(9)

Equating Eqn.(7) and (9) we get

$$p_{n_0} e^{V_0/V_T} = p(x'_{n_0}) e^{(V_0 - V_F)/V_T}$$

$$\Rightarrow p(x'_{n_0}) = p_{n_0} e^{V_F/V_T}$$
(10)

Now substituting Eq.(10) in (3) we get

$$I_{p_n}(x) = \frac{AqD_p}{L_p} \{ p_{n_0} e^{V_F/V_T} - p_{n_0} \} e^{-x/L_p}$$

= $\frac{AqD_p}{L_p} \times p_{n_0} \{ e^{V_F/V_T} - 1 \} e^{-x/L_p}$ (11)

Similarly we can obtain the following equation

$$n(-x'_{p_0}) = n_{p_0} e^{V_F/V_T} \tag{12}$$

substituting Eq.(12) in (4) we get

$$I_{p_n}(x) = -\frac{AqD_n}{L_n} \times n_{p_0} \{ e^{V_F/V_T} - 1 \} e^{-x/L_n}$$
(13)

Thus the total diode current is now given by,

$$I = I_{n_p}(0) - I_{p_n}(0) \tag{14}$$

Therefore observing the Eqns.(11) and (13) we have, total current as,

$$I = \frac{AqD_p}{L_p} \times p_{n_0} \{ e^{V_F/V_T} - 1 \} - \left(-\frac{AqD_n}{L_n} \times n_{p_0} \{ e^{V_F/V_T} - 1 \} \right)$$

= $\left(\frac{AqD_p}{L_p} \times p_{n_0} + \frac{AqD_n}{L_n} \times n_{p_0} \right) (e^{V_F/V_T} - 1)$ (15)

$$= I_0(e^{V_F/V_T} - 1) \tag{16}$$

where

$$I_0 = \left(\frac{AqD_p}{L_p} \times p_{n_0} + \frac{AqD_n}{L_n} \times n_{p_0}\right) \tag{17}$$

$$p_{n_0} = \frac{n_i^2}{N_D} \tag{18}$$

$$n_{p_0} = \frac{n_i^2}{N_A} \tag{19}$$

Thus I_0 becomes,

$$I_0 = qA \left(\frac{D_p}{L_p N_D} + \frac{D_n}{N_A L_n}\right) n_i^2 \tag{20}$$

In the case of reverse bias Eqn.(16) becomes,

$$I = I_0(e^{-V_R/V_T} - 1)$$
(21)

But $e^{-V_R/V_T} \ll 1$ and hence we have the current flowing in the diode during the reverse bias as $-I_0$. Negative sign shows that this current is opposite to the direction of current during the forward bias condition. Also this current is a constant as long as temperature is constant. Hence I_0 is called *reversesaturation current*.

In general for any bias we can write the current in the diode as

$$I = I_0 (e^{V/V_T} - 1) (22)$$

Thus for forward bias $V = V_F$ and for reverse bias $V = -V_R$. This derivation is based on the assumption that there is no carrier generation and recombination in the space charge region. Such an assumption is valid only in the case of germanium. Thus the most general diode equation is given by

$$I = I_0 (e^{V/\eta V_T} - 1)$$
(23)

where $\eta = 1$ for Ge, and 2 for Si.

Majority currents I_{n_n} and I_{p_p} can also be calculated as

$$I = I_{n_n}(x) + I_{n_p}$$

$$\Rightarrow I_{n_n}(x) = I - I_{n_p}(x)$$
(24)

Figure-3 shows all the current components flowing in the *p*-*n* junction diode for $N_A > N_D$.

3. The Volt-Ampere Characteristic: We have seen in the p-n junction diode

the current and the voltage are related by the equation,

$$I = I_0 (e^{V/\eta V_T} - 1)$$
(25)

This equation is plotted as shown in the figure-4. In figure-4, V_D is the diode voltage V and $I_S = I_0$. This figure-4(b) shows a dasehed portion of the curve indicates that, at a reverse biasing voltage V_Z , the diode characteristic exhibits an abrupt and marked departure from the Eqn.(25). At this critcal voltage a large reverse current flows, and the diode is said to be in the *breakdown* region. The Cutin Voltage V_{γ} : In both Si and Ge, there exists a voltage called Cutin Voltage V_{γ} . The current in the diode is very small if the bias voltage is less than V_{γ} . This is also called *cutin*, offset, break-point or thershold voltage. Below this voltage the current is less than 1 percent of maximum rated value.Beyond V_{γ} the current rises rapidly.



Figure 4: V-I Characteristics of p-n junction

4. Temperature Dependence of V/I characteristics: The volt-ampere relationship given in Eqn.(25) contains a temperature dependence in two terms i.e., V_T and I_0 . Theoretical study shows that the reverse-saturation current approximately 7 percent/°C for both Si, and Ge. Since $(1.07)^{10} \approx 2.0$, we conclude that I_0 approximately *doubles* for every $10^{\circ}C$ rise in temperature. Thus if $I_0 = I_{0_1}$ is the current at temperature $T \equiv T_1$, then at temperature T_2 $I_0 \equiv I_{0_2}$ is given by,

$$I_{0_2} = I_{0_1} \times 2^{(T_2 - T_1)/10} \tag{26}$$

The voltage dependence with temperature is given by,

$$\frac{dV}{dT} \approx -2.5 \ mV/^{o}C \tag{27}$$