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Analytical Formulation of Dynamic Characteristics of a Diode with Non-linear Contact Characteristics

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***Abstract*—A practical p-n junction diode basically consists of three junctions, one p-n junction at the middle and two metal-semiconductor (M-S) junctions at both ends of the device. In such devices, the contact resistances arise due to contact characteristics of two M-S junctions at the ends of the diode. So, such a device consists of three non-linear elements in series. In the present paper, non-linear characteristics of M-S junctions are used in the analysis of the device characteristics. The device considered is a solar cell and the V-I characteristics of a solar cell are obtained from three non-linear characteristics in a closed form.**

***Index Terms*— Contact problem, metal-semiconductor junction, MJM model, non-linear contact characteristics, solar cell.**

I. Introduction

Studies for understanding of contact problem in a semiconducting device are still in progress [1]-[2]. In this connection, a different approach to explain the problem, following the observation of Ng K. K. [3], has been made in this paper. A p-n junction diode consists of a p-n junction at the middle of the semiconductor sample and two contacts at both ends. But these end contacts are basically metal-semiconductor (M-S) junctions [1]. The V-I characteristic of the said device is determined by computation of three non-linear diode characteristics. However, for a particular case, when the characteristics of non-linear M-S junctions are assumed to be linear with a near vertical slope, the ohmic contact is realised.

Further in this analysis, the p-n junction of the device will be considered to be illuminated and the photovoltaic properties will be examined with M-S junctions at the ends. The output of the cell will be limited by the M-S junctions. This is a model for investigating the contact characteristics of a solar cell. The model is likely to show the role of contacts on the performance of the solar cells.

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II. KVL in Multiple Junctions

In practice it is difficult to obtain a single p-n junction because the metal-semiconductor junctions are at the two ends. So, their influence on p-n junction behaviour is to be considered in the analysis. A model, namely Multiple Junction Model (MJM) is proposed to understand the role of M-S junctions on p-n junction characteristics. According to this model, a p-n junction diode or a solar cell is composed of additional multiple junctions having non-linear contact resistances. Figs. 1 & 2 show three junctions as three building blocks of proposed multiple junction model of a solar cell. In both the figures, the central diode represents the p-n junction of solar cell. The M-S junctions are represented by a pair of diodes connected in back to back fashion [1]. Fig. 1 shows an equivalent circuit for illuminated solar cell and photocurrent density J_L is through D_1 & D_3. The current J_L is in the direction [4] of forward bias current through the contact diodes. In figs. 1, J is the diode current density through the diode D_2 [1]. Again J_L & J are opposite in direction. The resultant current produces a voltage drop V across R_L. Let us determine the V-I characteristics for D_1, D_2 & D_3 in series. Fig. 2 shows the circuit for obtaining V-I characteristics with D_1, D_2 & D_3 in series. V is the applied voltage and the resultant current I is to be determined.

To analyse the circuits, the basic equation for V-I relation of a p-n junction and KVL are used. The equation for the V-I characteristics of a p-n junction without photo generation is given by:

$$I = I_0(e^{\frac{qV}{nkT}} - 1) \tag{1}$$

Symbols having their usual significance. Equation (l) can be rearranged to the following form in terms of current densities as:

$$V = \frac{nkT}{q}\ln(1+\frac{J}{J_0}) \tag{2}$$

In both Figs. 1 and 2, let V_1, V_2 & V_3 denote the respective voltages across the diodes D_1, D_2 & D_3 and V be the net voltage, then from KVL:

$$V = V_2 + V_1 + V_3 \tag{3}$$

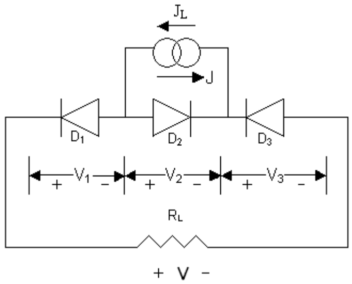

Fig.1. Equivalent Circuit Diagram of a p-n junction diode with photogeneration according to MJM

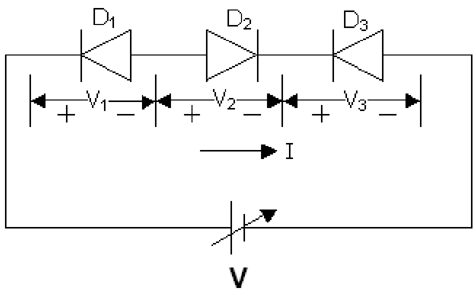

Fig. 2. Circuit to obtain V-I characteristics where V is applied voltage

In Fig. 2, signs of V, V_1, V_2, V_3 are shown explicitly. However, V_2 makes the p-n junction forward biased whereas V_1 & V_3 with the sign in Fig. 2, produce reverse bias on each M-S junction. So, in the exponential V-I relation, V_1 & V_3 are both negative quantities and V_2 is positive [5]. With this observation:

$$V_1 = \frac{n_1 kT}{q}\{\ln(1+\frac{J}{J_{01}})\} \quad (4)$$

$$V_2 = \frac{n_2 kT}{q}[\ln\{1+(\frac{J+J_L}{J_{02}})\}] \quad (5)$$

$$V_3 = \frac{n_3 kT}{q}\{\ln(1+\frac{J}{J_{03}})\} \quad (6)$$

Putting (4)-(6) in (3), one gets:

$$V = \frac{kT}{q}[\ln\{1+(\frac{J+J_L}{J_{02}})\}^{n_2} - \ln(1+\frac{J}{J_L})^{n_1} - \ln(1+\frac{J}{J_{03}})^{n_3}] \quad (7)$$

which on simplification yields:

$$(J+J_{01})^{-n_1}(J+J_{02}+J_L)^{n_2}(J+J_{03})^{n_3} = J_{01}^{-n_1} J_{02}^{n_2} J_{03}^{-n_3} e^{\frac{qV}{kT}} \quad (8)$$

Note, in (7), kT/q $\ln(1+J/J_{01})^{n1}$ is $-V_1$ as per (4). So, (4) is still

$V = V_2 + (V_1 + V_3)$. Equations (7) & (8) give the closed forms to get the analytical solution of the equation for the V-I characteristics.

Equation (7) is the required expression for V-J characteristics considering the non-linearity of contact M-S junctions for the devices.

A. Verification of Result under Linear Boundary Condition

To justify the correctness of (7), it will be shown that under different boundary conditions, (7) reduces to standard forms. Let us consider that both the contact resistances are linear i.e. V_1 and V_3 are linear with J. Under this case (8) becomes:

$$(J+J_{02}+J_L)^{n_3} = J_{02}^{n_2} e^{\frac{q\{V-(V_1+V_3)\}}{kT}} \quad (9)$$

Here, V_1 & V_3 are actually contact drops. Simplifying (9), we get:

$$V-(V_1+V_3) = \frac{n_2 kT}{q}\ln\{1+(\frac{J_L}{J_{02}})\} \quad (10)$$

If the contact drops V_1 & V_3 are both zero, (10) becomes (5) which is the standard equation for the solar cell. For resistive contacts, V_1 & V_3 are both linear. So, (8) is also valid under this boundary condition.

B. Open-circuit Voltage (V_{oc})

In this condition, J=0 & $V=V_{oc}$. Putting these values in (8), we get:

$$V_{oc} = \frac{n_2 kT}{q}\ln(1+\frac{J_L}{J_{02}}) \quad (11)$$

Here, current is zero and hence the question of contact drops do not arise. So, (8) converts to the standard form of (10).

C. Short-circuit Current Density(J_{sc})

Let us discuss J_{sc} under the assumption that diode D_3 is ideal, i.e. $V_3 = 0$ and D_1 gives nonlinear contact resistance. For short-circuit condition, V=0, $J=J_{sc}$ & $V_3=0$. Equation (7) gives:

$$[1+(\frac{J_{sc}+J_L}{J_{02}})]^{n_2} = (1+\frac{J_{sc}}{J_{01}})^{n_1} \quad (12)$$

As a special case when $n_1=n_2$, (12) becomes:

$$J_{sc} = -\frac{J_L}{(1-\frac{J_{02}}{J_{01}})} \quad (13)$$

Since D_1 & D_2 are back to back connected, for individual diodes, reverse saturation current of one is opposite in direction to the reverse current of the other.
Since J_{01} & J_{02} are of opposite signs, (13) shows:

$$J_{sc} = -\frac{J_L}{(1+\frac{J_{02}}{J_{01}})} \quad (14)$$

Equation (14) depicts that J_{sc} is less than J_L as J_{02}/J_{01} is a finite positive quantity. This is similar to the decrease in J_L with linear contact resistance. Equation (14) shows with increase in leakiness i.e. for larger J_{01}, J_{sc} also increases though J_L remains the same. Further, as expected, (14) shows that large J_{01} makes J_L nearly equal to J_{sc}. This corresponds to a very low contact resistance.

III. CROSSOVER PHENOMENON

In [1], the role of contacts on V-I characteristics of solar cell is discussed. However, it is stated that 'crossover is a less understood phenomena'. Let us obtain the V-I characteristics from (8) with a simplifying assumption that one contact resistance is non-linear and the other one is linear and ideal. This ideal condition means that the drop V_3 equal to zero in (3). Using V_3=0 in (8), we get:

$$(J + J_{01})^{n_1}(J + J_{02} + J_L)^{n_2} = J_{01}{}^{n_1} J_{02}{}^{n_2} e^{\frac{qV}{kT}} \qquad (15)$$

Let us plot (15) with the values of the parameters shown in Table-1. For n1 & n2 in Table-1, vide [2], without p-n junction, a solar cell becomes a metal-semiconductor-metal (MSM) device. Again, "MSM photo detectors usually consist of two rectifying contacts" [6]. Under bias, one of these MS diodes is reverse biased. But, large amount of leakage current passes through the reverse biased junction under illuminated condition. Thus one may assume that leakage current increases with illumination. Note that in row four of Table-1, two values of J_{01} are used, one for the dark condition and other for the illuminated condition. Even the value under dark condition is kept at a higher level indicating a leaky MS junction.

Fig. 1 shows that under illumination, D_1 & D_3 are biased simultaneously by J_L and V_1 & V_3. Further, both V_1 & V_3 biases D_1 & D_3 in reverse direction; but current bias J_L is in a forward direction for them. Under this condition, let us assume that effect of illumination is to increase the reverse bias saturation currents of D_1 & D_3 to an extent; probable cause may be injection of photogenerated carriers in MS junctions.

Fig. 3 is plotted from (15) using MATLAB (V 5.0), with the parameter values shown in Table-1. The crossover has been obtained in Fig. 3 between illuminated characteristics I and dark characteristics D. Plot of (5) which is an ideal form of (10) under dark and illuminated conditions do not show any crossover. So, it appears that variation of non-linear contact resistance with illumination, introduced in (15) automatically shows crossover characteristics.

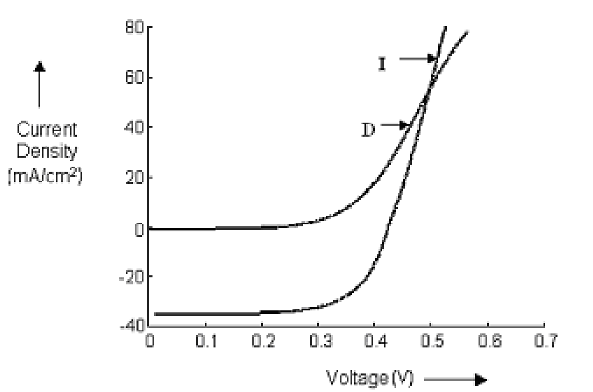

Fig. 3. Cross over Phenomenon shown from Theoretical Analysis (Here I & D respectively denote characteristics under Illuminated and Dark Conditions)

Table I : Values of the parameters used in (15) to plot Fig. 3

Sl. No.	Parameter	Value under illuminated condition	Value under dark condition
1.	n_1	2.5	2.5
2.	n_2	2.0	2.0
3.	J_{02}	0.01 mA/cm^2	0.01 mA/cm^2
4.	J_{01}	175 mA/cm^2	100 mA/cm^2

A. Physical Explanation of crossover shown by (15)

Figs. 1 & 2 show both the diodes are loaded by contact resistance. Under dark condition, both D_1 & D_3 are reverse biased and has high resistance. But D_1 & D_3 have photocurrents through them under illuminated condition. So, D_2 is relatively lightly loaded by D_1 & D_3 under illuminated condition than in dark condition. This produces different dynamic load characteristics of D_2 under illuminated and dark conditions, which may intersect under certain conditions. If the contact resistance is very low under dark condition, then no crossover is expected as both are equally lightly loaded.
Further, if contact resistance is linear, then the question of variation of contact resistance under dark and illuminated conditions does not arise and consequently the question of crossover does not arise.

IV. CONCLUSION

A p-n junction diode inherently consists of one p-n junction and two M-S junctions at both the ends of the device. Thus in the closed form, a p-n junction is loaded by two non-linear elements i.e. M-S junctions. An analytical solution of the dynamic characteristics of p-n junction under such condition is obtained. The result is applied to explain solar cell characteristics. Further, the result may be used to explain the crossover characteristics often observed in some reported solar cell characteristics. In a similar way, this analytical solution may provide some useful applications in other fields. A study to understand the possibility of enhancement of J_{01} & J_{03} under illumination is in progress.

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