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Optimization of the tunnel Diode for GaAs/Ge Tandem Solar Cell

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Abstract

In two terminals monolithic tandem solar cells, tunnel diode is an important variable to improve conversion efficiency depending on current matching between the top and the bottom cells. Especially, the GaAs/Ge tandem is one of the most interesting cells for its high potential efficiency.

This paper shows that physical analysis about I-V specific character of the GaAs/Ge solar cell, which is grown by MOCVD for GaAs or CVD for Ge, using computer simulation and experimental results, varying with thickness of the tunnel diode layer and concentration.

1. Introduction

Tandem junction solar cells offer higher energy conversion efficiencies than single junction solar cells. A double hetero GaAs tunnel diode which consists of a GaAs tunnel junction sandwiched between $Ga_{1-x}Al_xAs$ layers has been grown by MOCVD. The top layer acts as a window layer for the underlying GaAlAs cell. Under this cell is two heavily doped layers having several functions. These act as a back surface field for the top cell and a front surface field for the lower cell. The width of the depletion region at their junction is very thin and electrons can flow between the conduction and valance band at this junction by quantum mechanical tunneling process. This region consequently acts as the series connection between the cells, as well as an optical window for the underlying GaAs. We take the GaAs/Ge tandem cell structure as the model to figure out activities that tunnel diode layer and I-V character the same as below figure 1. Herewith, tunnel diode layer of the tandem solar cell can be specified by varying with tunnel diode width and doping concentration.

2. Tunnel diode

Tandem cell has the advantage of absorption rate, which is increased by energy band gap. Tandem cell has three layers that top cell, bottom cell and tunnel diode layer, which mono cell does not have. When photon is coming through the window, tunnel diode layers is useful to moving of the electrons passing by emitter and base. Therefore, tunnel diode layers is able to decrease the electrons that is reflected by the base of the top cell or recombination using quantum mechanics property.

The current-voltage characteristics of a tunnel diode consists of three regions. In the reverse bias and low forward bias region, the current is the result of quantum mechanical tunneling, as described by Esaki. The current density, J, in a tunnel diode is given by :

$$J = J_{tunneling} + J_{diode} \qquad (1)$$

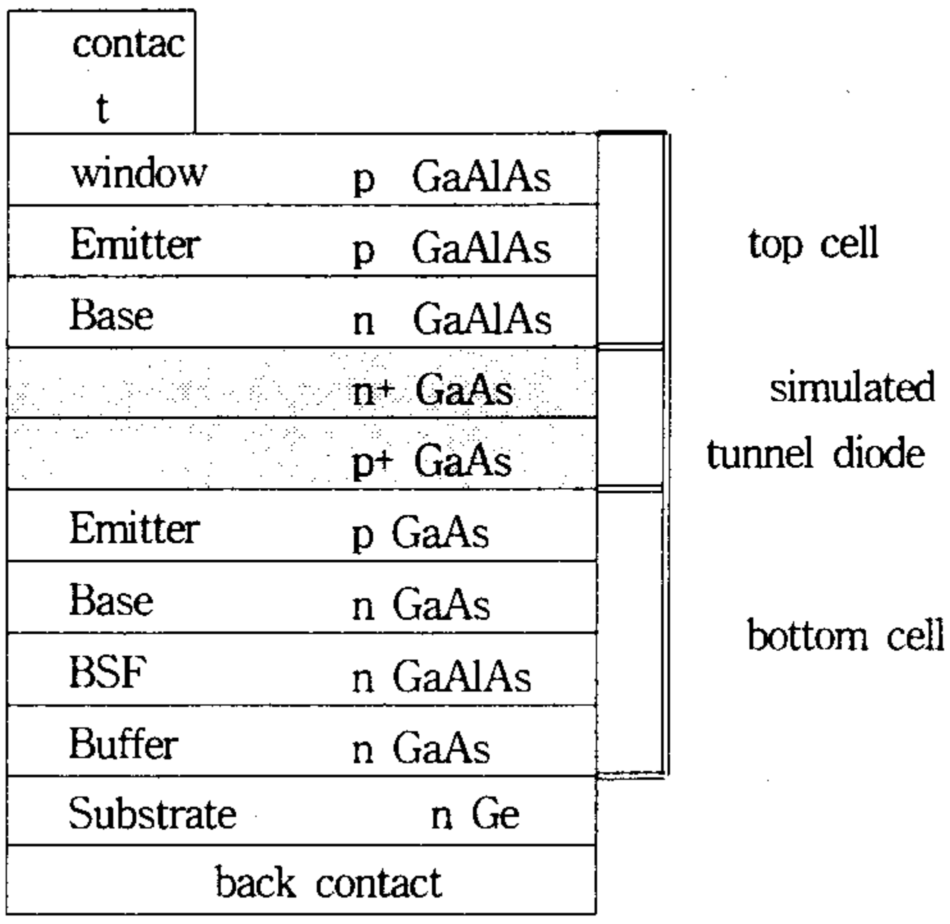

Fig. 1 Structure of GaAs/Ge tandem cells formed by epitaxial processes.

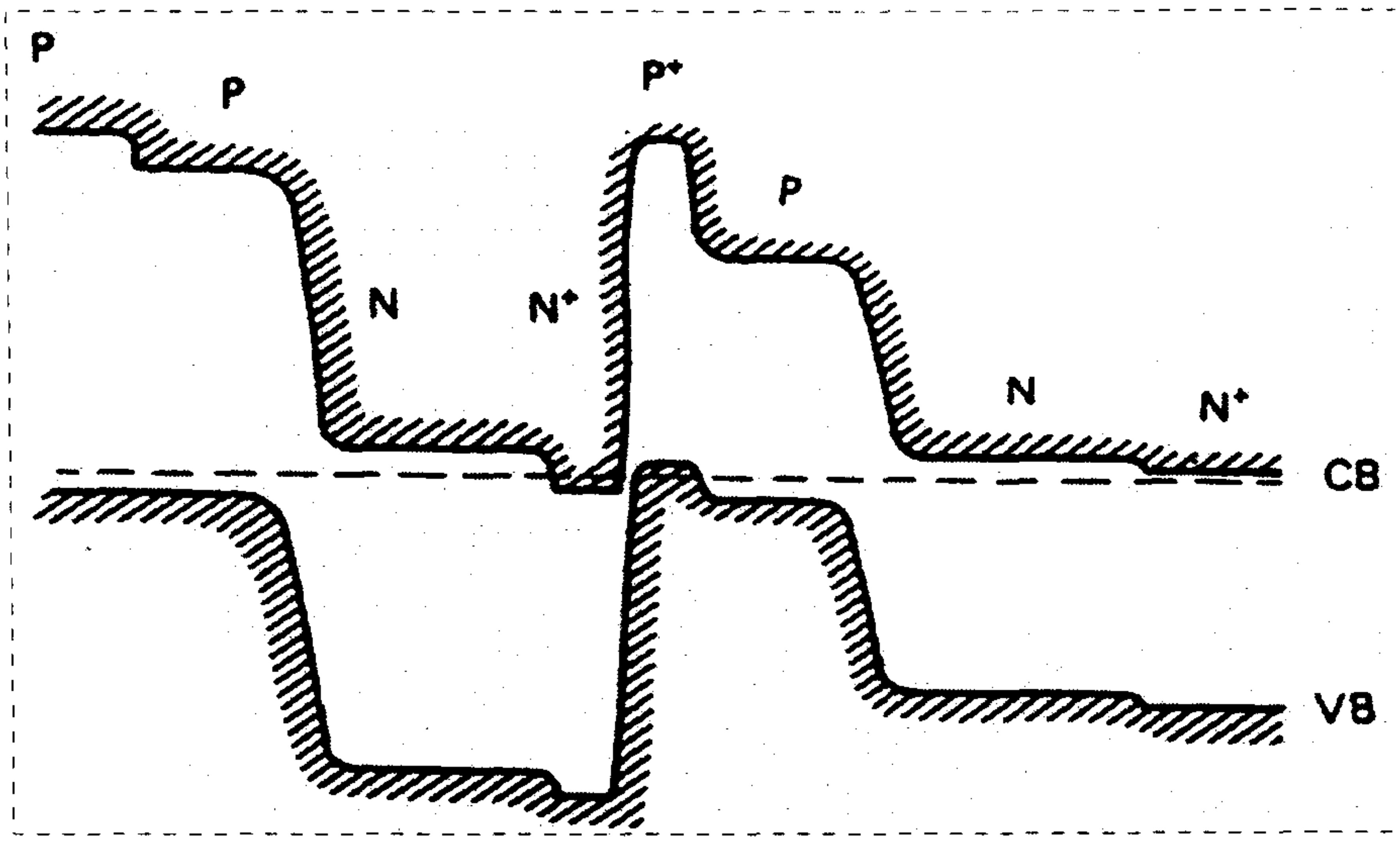

Figure 2. Corresponding energy band diagram

Where $J_{tunneling}$ and J_{diode} are tunneling current density, normal diode current density. In fact, there is an additional tunneling current that becomes important at large forward voltages called the excess current. so that

$$J = J_{tunneling} + J_{diode} + J_{excess} \tag{2}$$

This excess current component is related to the indirect tunneling via states present in the energy gap. These processes typically involve the emission of phonons. A calculation of $J_{tunneling}$ and J_{excess} lead to the following expression for the current-voltage characteristics of a tunnel diode.

$$J_{tunneling} = J_p(V/V_p)\exp(1-V/V_p) \tag{3}$$

$$J_{diode} = J_o\{\exp[qv/(n_{id}k_BT)]-1\} \tag{4}$$

$$J_{excess} = J_v\exp[A_e(V-V_v)] \tag{5}$$

Where V_p is the voltage at maximum forward tunneling current density J_p, V is applied voltage, and J_o is the reverse saturation current density. nid is the diode ideality factor. J_v and V_v are valley current density and voltage. , A_e is a constant.

2-1. The band to band tunneling current

The theory of band to band tunneling current density can be written as follows:

$$J_p = \frac{e\,m^*}{18\,\hbar^3}\frac{E_\perp}{2}D\exp\left\{-\frac{\pi\,m^{*1/2}\;E_G^{\;3/2}}{2\sqrt{2}\,\hbar F}\right\} \tag{6}$$

$$E_\perp = \frac{2\hbar F}{\pi\;M^{*\,1/2}\;E_G^{\;1/2}} \tag{7}$$

$$F=\left(\frac{e^3}{2\varepsilon}\right)^{1/2} n^{*1/2} \quad V_D^{1/2} \tag{8}$$

where D is the density of states factor which describes the distribution of electrons on both sides of the diode and is approximately equal to Vp at maximum tunneling current Jp. If the diffusion potential V_D and the band gap E_G are assumed to be equal. The effective mass M* is the effective mass for tunneling, and is equal to the product of the electron and light hole masses divided by the sum of the two and the reduced impurity concentration n* is equal to $(N_dN_a)/(N_d+N_a)$. The above equation (6) can be rewritten as:

$$J_p = const\ n^{*1/2} D \exp(-const\ m^*\ E_G\ n^{*-1/2}) \tag{9}$$

which shows the exponential dependence of the tunneling current on the effective mass m*, the reduced doping concentration n*, and the band gap E_G [1],[2],[3],[4].

2-2. The thermal current

The thermal minority carrier injection current density can be expressed by the familiar diode relation as follows[3]:

$$J_{Diode} = J_0\left[\exp\left(\frac{qv}{n_{id}kT}\right)-1\right] \tag{4}$$

$$J_0 = q\ \ n_i^{\,2}\left[\left(\frac{D_p}{\tau_p}\right)^{1/2}\left(\frac{1}{N_d}\right)+\left(\frac{D_n}{\tau_n}\right)^{1/2}\left(\frac{1}{N_a}\right)\right] \tag{10}$$

where ni is the intrinsic carrier density, D_p and D_n are the diffusion coefficient in p-type, in n-type. τ_p and τ_n are the hole lifetime, electron lifetime respectively. At large forward biases, the conductance is always dominated by thermal current, that is, by a flow of carriers over some sort of a potential barrier. Consequently, it should depend on voltage as $\exp[qv/(n_{id}k_BT)]$, with $1 \le n_{id} \le 2$ in most common cases.

2-3. The excess current

The expression for the excess current density in a tunnel diode as derived by Chynoweth is presented below[1] :

$$J_{excess} = AD\exp\left[-\left(\frac{\alpha_x\ W_1\ q^{1/2}}{2}\{\ E_G - qv + 0.6(\ E_1 + \ E_2)\}\right)\right] \tag{11}$$

where Jexcess is the excess current density at a bias of V volts . E1,E2 are the Fermi level penetrations on n and p sides respectively. q is electron charge.

$$\alpha_x = \frac{4}{3}\left[\frac{(2\ m^*)^{1/2}}{hq}\right],$$

$$W_1 = \left[\frac{2\varepsilon}{q\ n^*}\right]^{1/2}$$

Equation (11) can also be written as,

$$J_{excess} = J_v \exp\left[\frac{4}{3h}\left(\frac{m^{*}\varepsilon}{n^{*}}\right)^{1/2}(V - V_v)\right] \qquad (5)$$

Jv can be obtained from equation (11) by setting V=Vv, but an exact estimation of Jv as a function of n* is not possible from equation (11) because the constant A is not properly defined. Jv and Vv are known for a particular value of n*, the excess current density Jexcess at a bias V can be predicted from equation (5). Jv is closely associated with the mechanism of the band-to-band tunnel current. Hence the equation representating the current density J at a bias V in a tunnel diode including the effects of excess current is given by[6],[7].

$$J = J_p\left(\frac{V}{V_p}\right)\exp\left(1 - \frac{V}{V_p}\right) + J_0\left[\exp\left(\frac{qV}{n_{id}\,k_B T}\right) - 1\right] + J_v \exp\left[\frac{4}{3h}\left(\frac{m^{*}\varepsilon}{n^{*}}\right)^{1/2}(V - V_v)\right] \qquad (12)$$

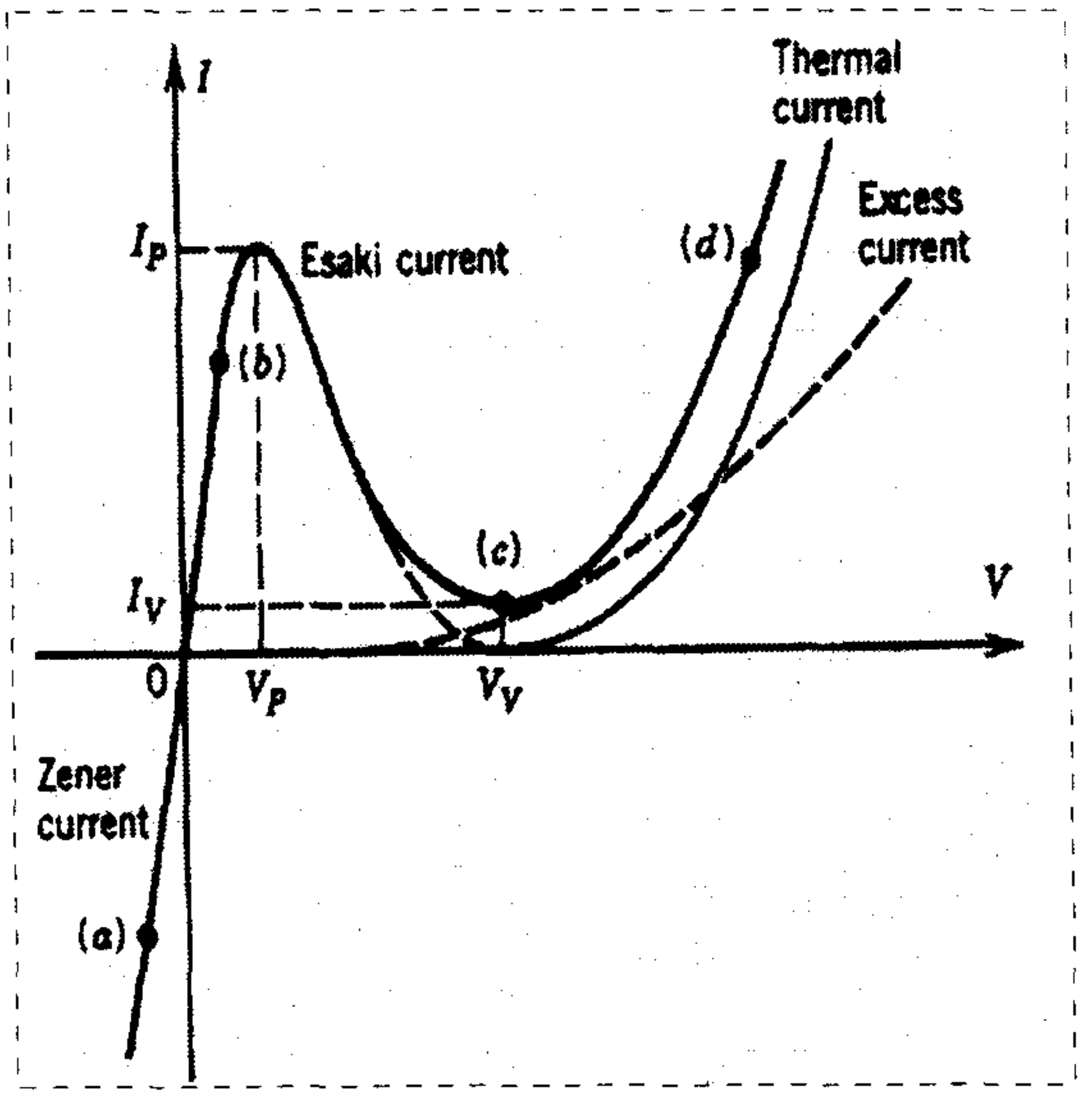

Fig 3. I-V characteristic of a typical tunnel diode showing the various current components.

The contribution of the first term to the total current is significant for V<Vv, that of the second for V≥Vv and the contribution of the third term is significant V>Vv.[Figure 3]

2-4. The tunneling current and junction barrier width

Tunneling theory predicts an exponential dependence of the tunneling current density J on the junction barrier width W of the form[5]:

$$J = AW-1\exp(-BW) \qquad (13)$$

where A and B are material constants. The junction capacity per unit area(Cj/A) is given by the well known relation

$$Cj/A = \varepsilon W\text{-}1 \tag{14}$$

The doping profile at the junction of an Esaki diode can in most cases be represented by a step junction approximation, and the barrier width is then given by

$$W = (2\varepsilon V/qn*)1/2 \tag{15}$$

and the depletion layer width is given by

$$W = \left[\frac{2\varepsilon_s}{q}\left(\frac{N_a+N_d}{N_a N_d}\right)(V_{bi}-V)\right]^{1/2} \tag{16}$$

$$V_{bi}=\frac{kT}{q}\ln\left(\frac{N_a N_d}{n_i^2}\right) \tag{17}$$

where V_{bi} is the bilt-in potential, ε_s is the permittivity in semiconductor, n_i is the intrinsic carrier density. The ratio of peak current density to junction capacity per unit area is dependent only on the doping density and is independent of the junction area.

3. Result

For the computer simulation, the value of the tunnel diode concentration is Nd, Na=1.0e+18~1.0e+20cm^{-3}. More over , the constant is the value of the GaAs at normal temperature(300K). We measured the width varying as apply voltage and doping concentration.

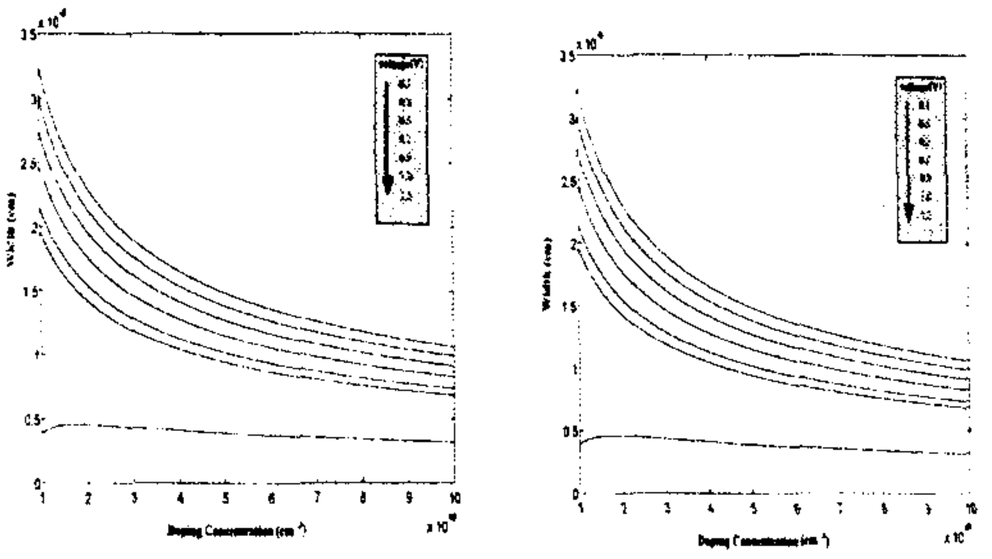

Fig 4. The doping concentration and diode Width are followed by applied voltage.

Figure 4 shows the relation between the doping concentration and width are followed by applied voltage. the doping concentration is from ten to order 18 to ten to order 19 (the left), from ten to order 19 ten to order 20 (the right) respectively. Also this figure shows the minus half dependence of the doping concentration on the width.

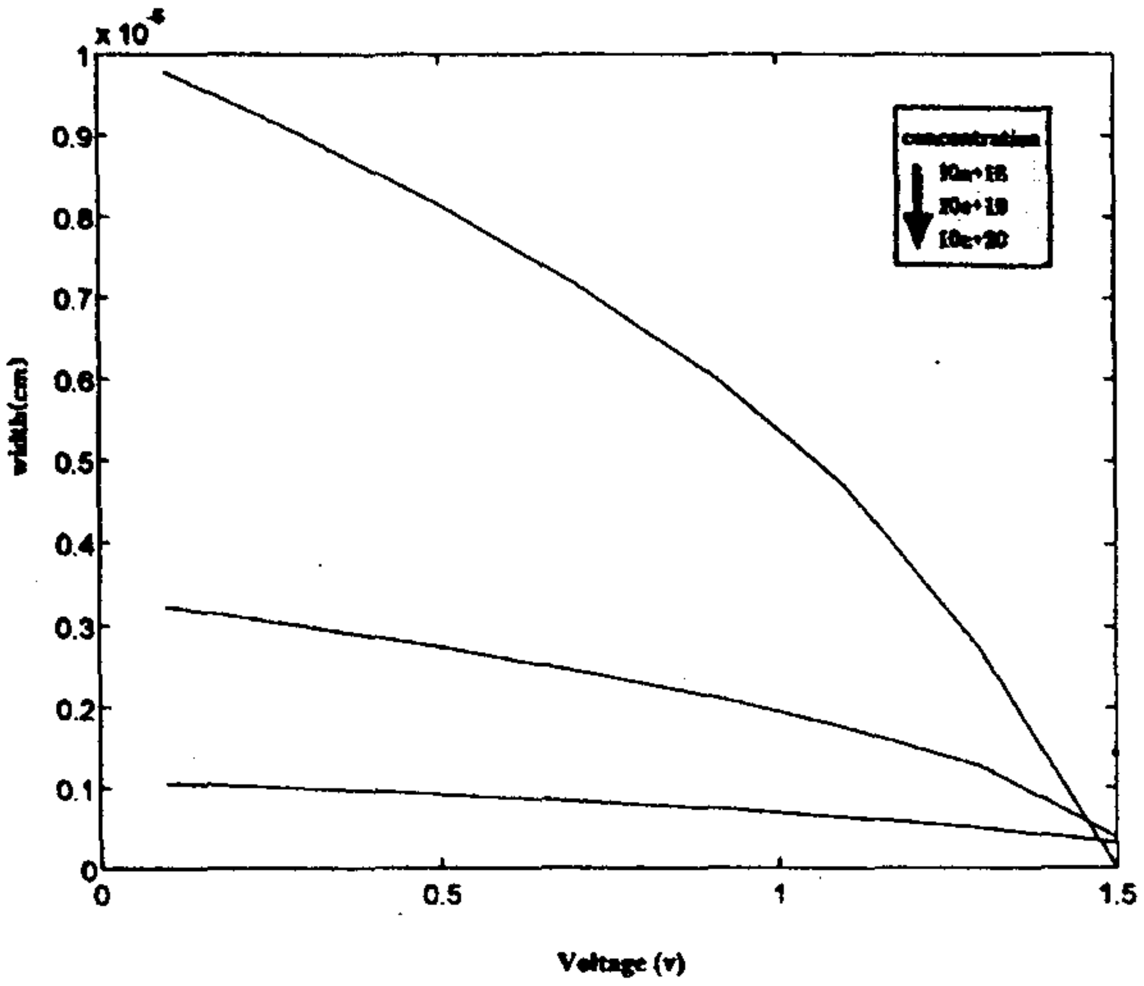

Fig 5. The doping width and applied voltage. (followed by doping concentration)

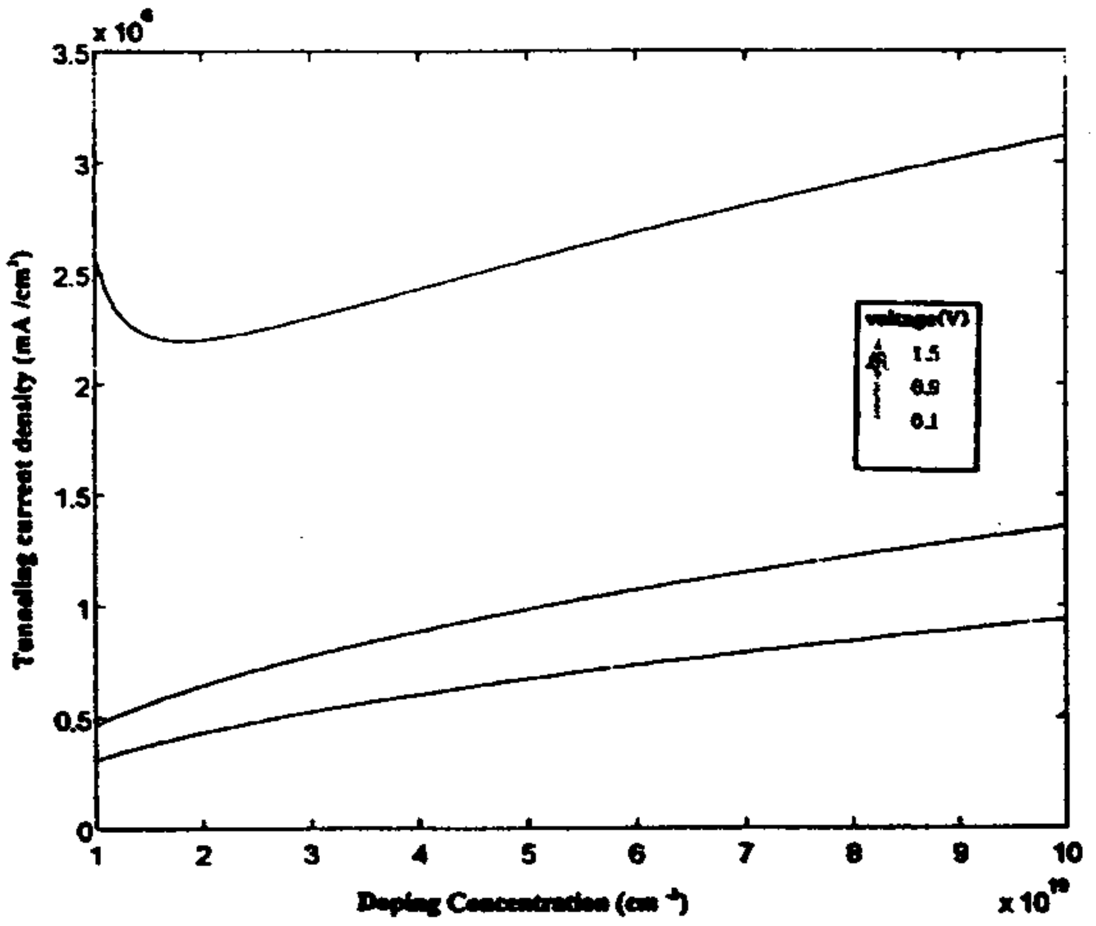

Fig 6. The tunnel current density and doping concentration

Figure 5 is doping width and applied voltage followed by doping concentration and view figure 4 from a different standpoint. These lines are ten to order 18, ten to order 19, ten to order 20 respectively. The below figure 6 and 7 show the relation between tunnel current density, diode width and concentration.

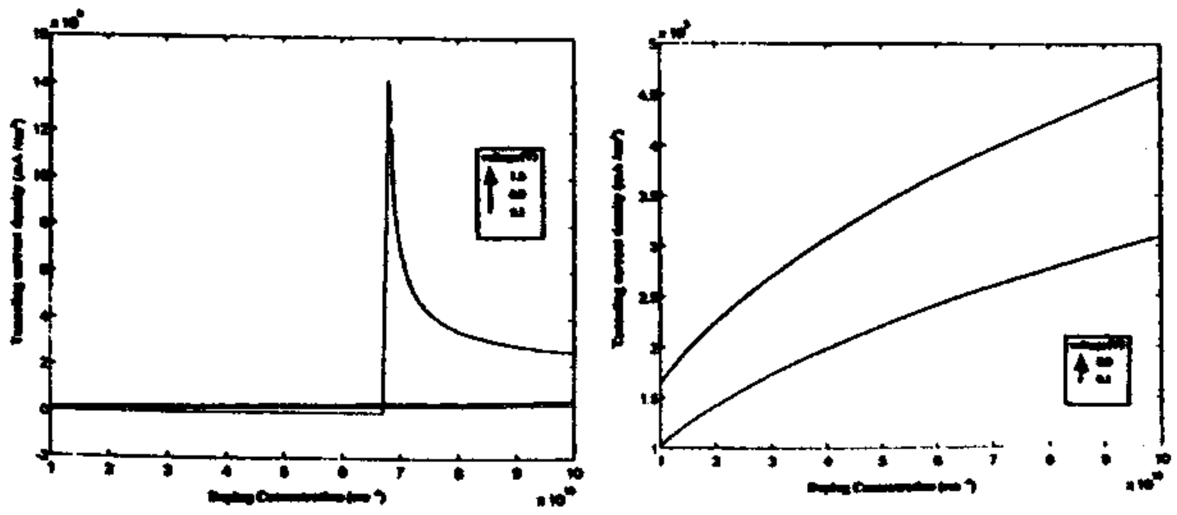

Fig 7. The tunnel current density and doping concentration

The doping concentration is from ten to order 19 to ten to order 20 in figure 6. The doping concentration is from ten to order 18 to ten to order 19 and the right side shows the 0.1 and 0.9 applied voltage scale up the left. This figures show the exponential dependence of the tunneling current on the doping concentration.

The below figures show the physical parameter for tunnel diode of table 1. [fig8,9,10,11,12,13,14,15]

	(a)	(b)	(c)	(d)	(e)
doping concentration	1.9e+19	5.0e+19	1.0e+20	1.9e+19	1.9e+19
thickness	500Å	500Å	500Å	200Å	90Å

Table 1. Thickness and doping concentration of tunnel diode

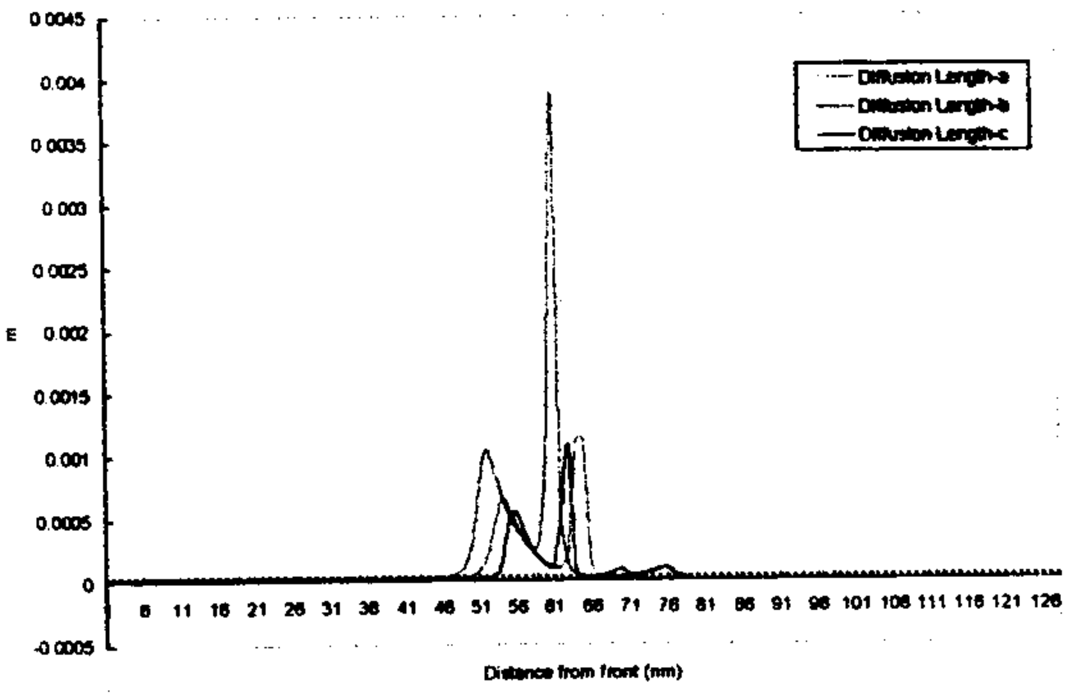

Fig 8. Diffusion Length(tunnel diode a,b,c)

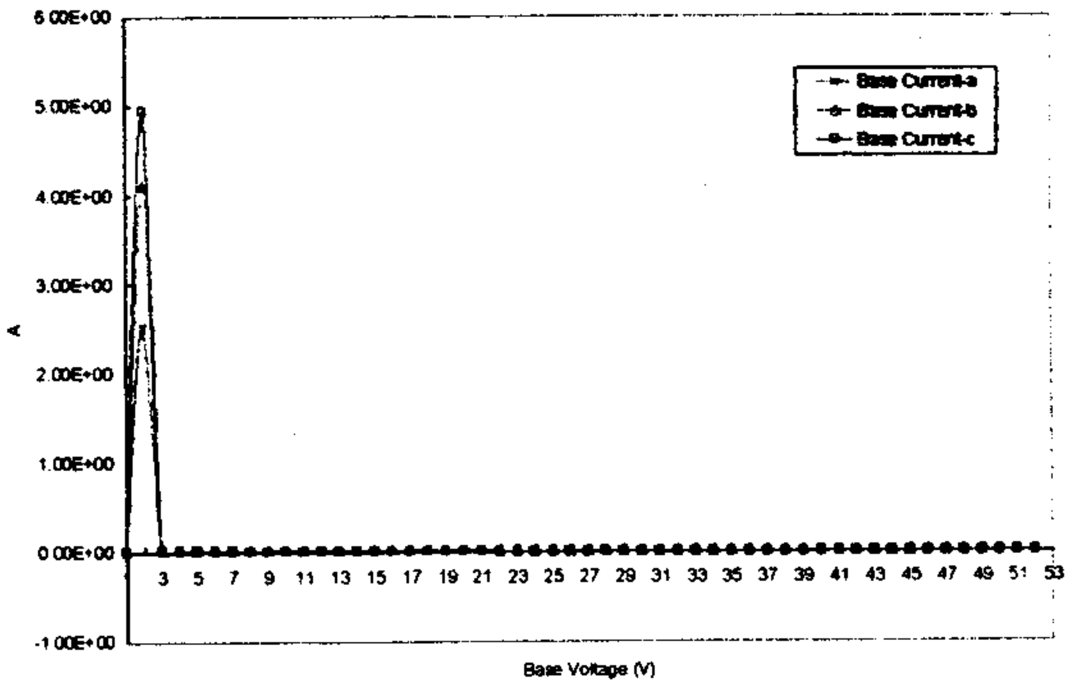

Fig 9. Base Current(tunnel diode a,b,c)

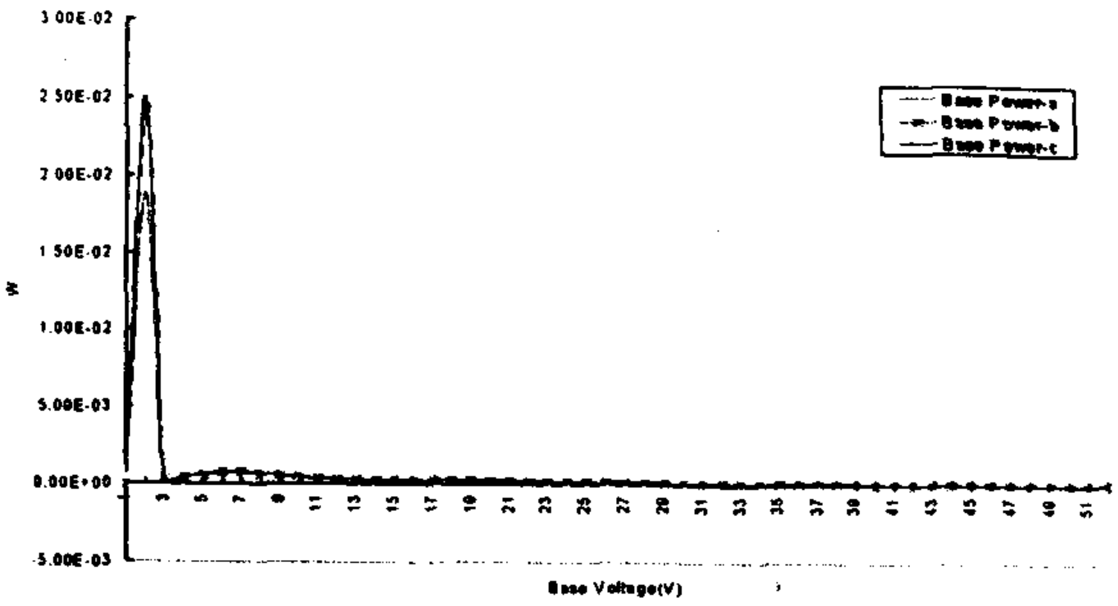

Fig 10. Base Power(tunnel diode a,b,c)

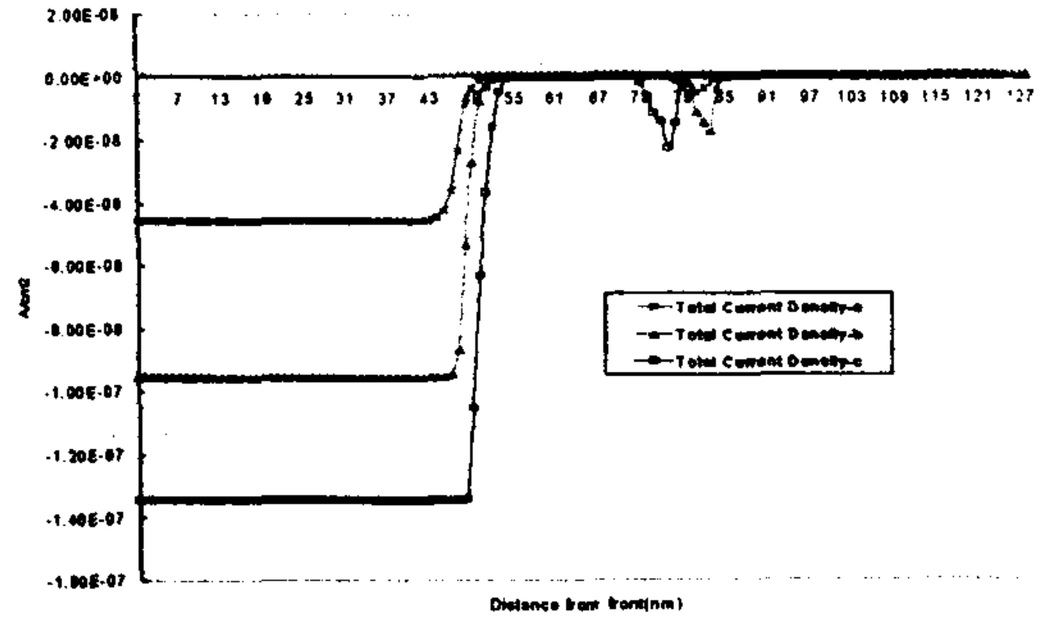

Fig 11. Current Density(tunnel diode a,b,c)

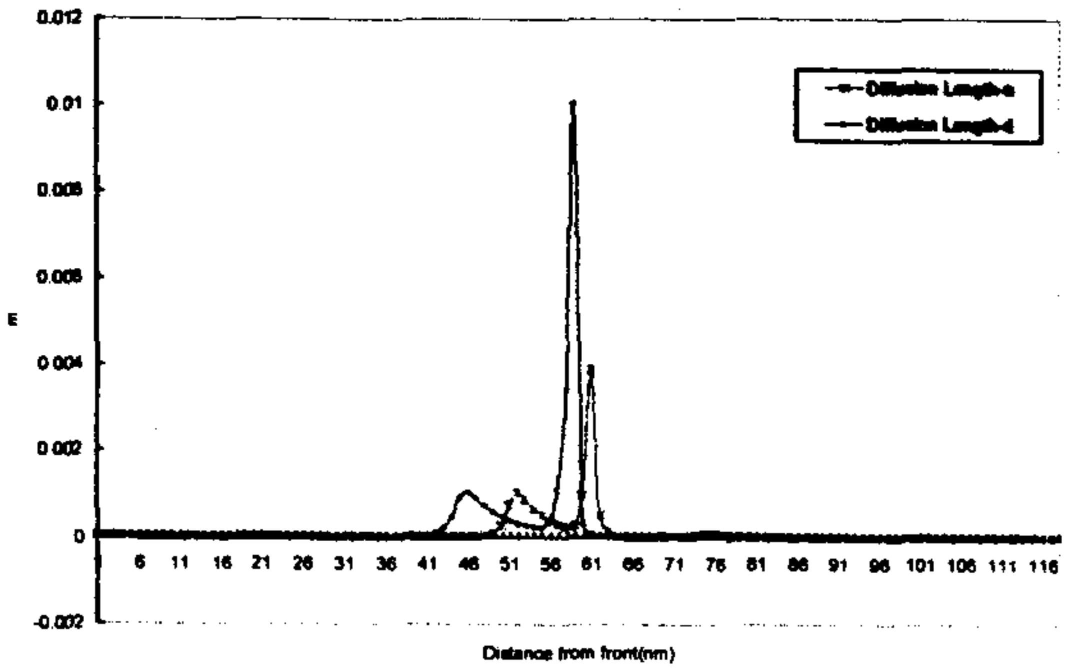

Fig 12. Diffusion Length(tunnel diode a,d)

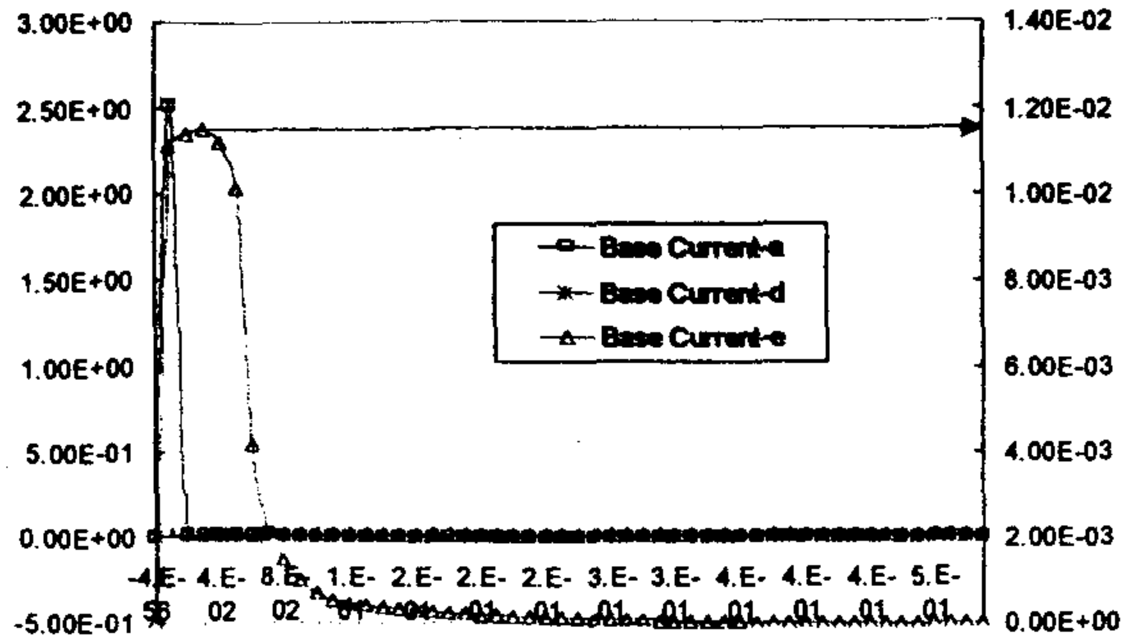

Fig 13. Base Current(tunnel diode a,d,e)

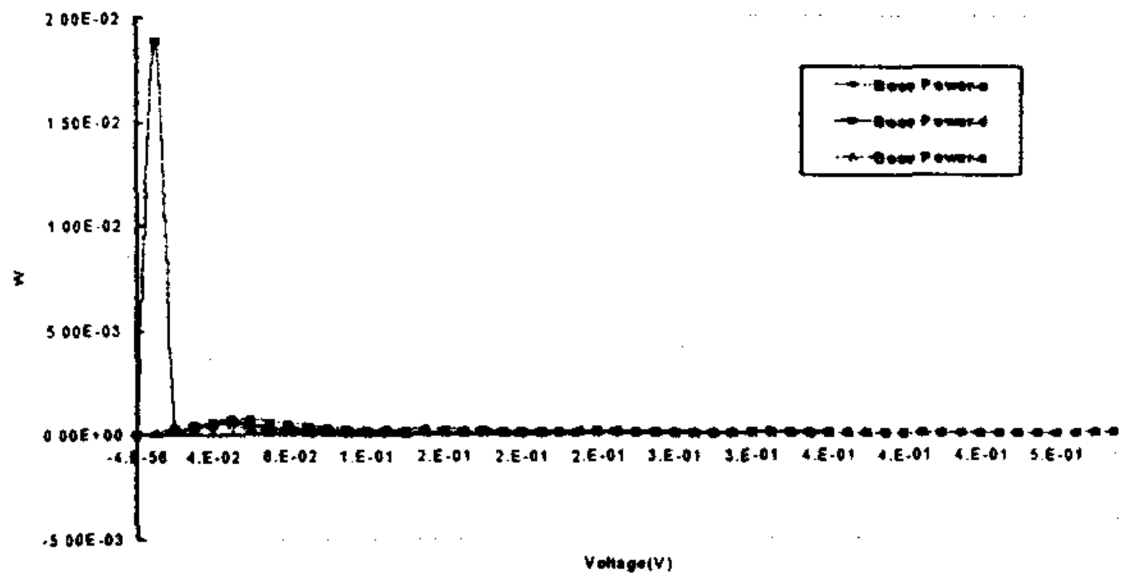

Fig 14. Base Power(tunnel diode a,d,e)

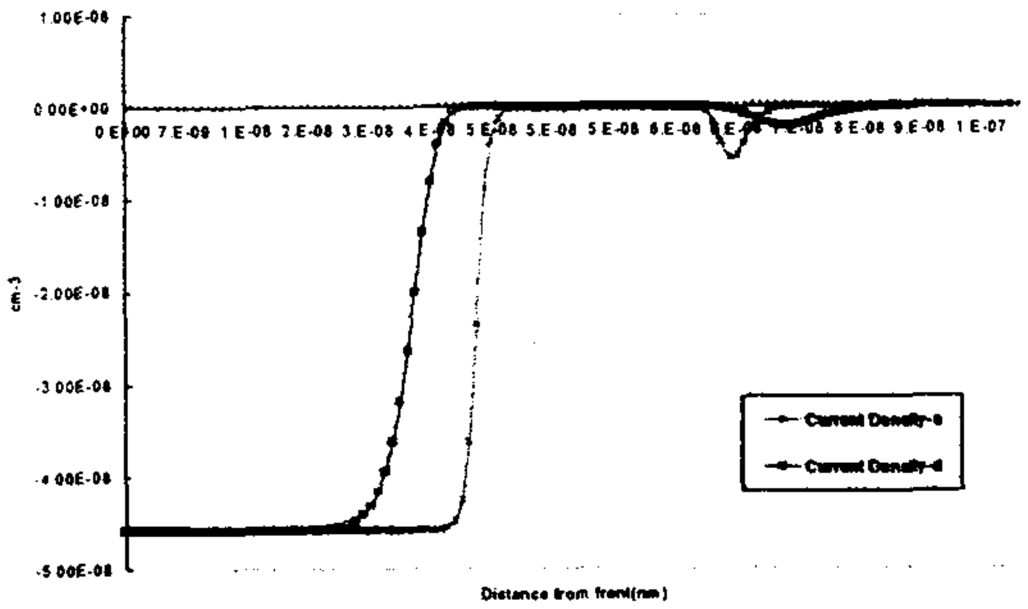

Fig 15. Current Density(tunnel diode a,d)

4. Conclusion

So far we studied the character of tunnel diode. In two terminals monolithic tandem solar cells, tunnel diode is an important variable to improve conversion efficiency depending on current matching between the top and the bottom cells. Especially, the GaAs/Ge tandem solar cell is one of the most interesting cells for its high potential efficiency. The tunnel diode layer that is essential in the tandem cell can prevent the reflection of electrons and prevent the ross of the effectiveness caused by recombination. Also, current density of the tunnel diode depend on doping concentration and width we can make the high efficiency tandem solar cell that is tunnel diode with appropriate width and doping concentration by the specific character.

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