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ABSTRACT

A theoretical study of the effect of differences in effective masses for electrodes and well, on the characteristics of tunneling current against bias voltage, in the presence of charge build-up has been done. It is observed that balanced effective mass (i.e. $m_l^* = m_r^*$), where m_l^* and m_r^* are the effective masses for electrode and well respectively, results in the normal expected behaviour of rising current with increased bias voltage. Whereas, a positive difference causes charge saturation and zero current change, while a negative difference invokes excess current flow.

MIRAMARE – TRIESTE
September 1992

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1 Introduction

The influence of internal field emission and circuit oscillations on the current-voltage(I-V) characteristics of double barrier resonant tunneling diodes have been studied by Esaki [1]. This study have stimulated other workers to make observations on the characteristics of the concepts of quantum tunneling. Intrinsic and extrinsic bistabilities have been observed in the I-V characteristics of double barrier diode(DBD) [2]. However, the source of bistability remained a controversy among many contributors. Some say it is due to intrinsic feedback dependence of the energy of the electronic states in the well on the tunneling current [2], while others attribute it to circuit oscillations [3]. Sheard, et al [4] confirmed the presence of electrostatic feedback and space charge in DBD as contributing to the observed bistability. They noted that a region of current bistability is found over a voltage range determined by the maximum space charge. Since then, space charge effect on the I-V characteristics of the DBD have taken some more dimensions for investigation, all based on the fact that tunneling enhances space-charge build-up. Lin, et al [5] observed that carrier trappings (space-charge) contribute to fluctuations in resonant wells. Tunneling is enhanced when unoccupied energy states exist at energy levels on the side to which charges can travel, or there is a reduction in the level of the potential barrier. In this letter we shall try to appropriate the theory of resonant tunneling to include the effect of charge build-up in the well with different effective masses. Ohno and Mendez [6] have experimentally investigated the effect of carrier mass differences on the I-V characteristics of resonant structures, but did not include observations on space-charge effect. Also, MacDonald, et al [7] have observed that differences in effective mass could cntribute to the optimal characteristics of resonant diodes, but only when the well widths are the same.

2 Basic models for theoretical consideration.

There are two theoretical approaches to resonant tunneling. In the first, the current is obtained from the global transmission coefficient calculated for coherent wavefunction throughout the DBD. In the second, the transmission is regarded as two successive transitions(sequential), from the emitter into the bound state of the well and then from the well into the collector contact. In the absence of charge build-up these two approaches lead to the same results for direct current operations [8].

We consider here the sequential model which provides a natural structure for the inclusion and evaluation of charge build up. We shall adopt a simple band structure for the device under forward bias as shown in figure 1. E_f is the Fermi energy in the electrodes, E_o is the resonant band energy measured from the bottom of the well, ΔE is defined as the energy separation between E_o and E_f. Electron tunneling is greatly enhanced when E_o is equal to E_f (that is, when $\Delta E = 0$), allowing tunneling to conserve both energy and momentum [9]. Usually for resonant tunneling diodes the emitter and collector are heavily doped, a procedure which narrows the depletion area. The quantum well becomes

an undoped region of the same piece and supports a quasibound state at energy E_d from the bottom.

3 Mathematical consideration

Let us consider the screening charges in the regions near the barriers (each of width d) and the stored charges in the well, as sheets of very small thickness. Charge field develops at the interface under the application of the bias field. The barrier shape is affected electrostatically, and a structure in the form of two capacitor plates connected in series appears [4]. There is now a kind of dynamic motion of charges between the hypothetical plates of the capacitor. The strength of pairing interactions between the plates preserves the charges as they tunnel through the barrier to re-establish coherence on the opposite side. If we try to establish a relationship between the motion of the charges from the electrodes ψ_l and from the well ψ_r, as time dependent, the we write the time dependent Schrodinger equation for the parameters as

$$i\hbar\frac{\partial\psi}{\partial t} = E\psi \tag{1}$$

where E is the energy depending on the mass difference of the substrate material and $\hbar$ is Plank's constant. Since we are considering transmission through a well between identically doped samples, we have the following set of coupled equations

$$i\hbar\frac{\partial\psi_l}{\partial t} = E_l\psi_l + T\psi_r \tag{2}$$

and

$$i\hbar\frac{\partial\psi_r}{\partial t} = E_r\psi_r + T\psi_l \tag{3}$$

where T is the rate of transfer of the charges between the plates-transmission probability for quasi-particle tunneling. These coupled equations have general time dependent solutions in charge densities $|\psi_l|^2$ and $|\psi_r|^2$. These can be interpreted through the current density J per unit area from Poisson consideration as

$$J = q\frac{\partial}{\partial t}|\psi_r|^2 = \frac{2}{\hbar}Tnq\sin(\theta_r - \theta_l) \tag{4}$$

where q is electronic charge, $\theta_r - \theta_l$ is phase change between ψ_r and ψ_l with time and n is a constant depending on the doping levels of the electrodes-assumed as 1 for equal dopings. The integral of this equation with respect to the well width gives the total charge. The partial change of the phase angle relates to the energy as follows

$$\frac{\partial}{\partial t}(\theta_r - \theta_l) = -\frac{1}{\hbar}(E_r - E_l) \tag{5}$$

The term $-\frac{1}{\hbar}(E_r - E_l)$ implies energy conservation in the well, which follows from the conservation of transverse momentum wave vector k. The kinetic energy relation between well and electrode is given by

$$\frac{\hbar^2k^2}{2m_r^*} - \frac{\hbar^2k^2}{2m_l^*} = \frac{\hbar^2k^2}{2}(\frac{1}{m_r^*} - \frac{1}{m_l^*}) \tag{6}$$

where m_r^* and m_l^* are the effective masses for well and electrode respectively. If a quasibound level exists, under conservation of transverse momentum and energy, then the emitter charge tunnels and the kinetic energy, $\frac{\hbar^2k^2}{2}(\frac{1}{m_r^*} - \frac{1}{m_l^*})$, involving different effective masses is equal to the total energy of the system. Hence we shall write

$$\frac{\hbar^2k^2}{2}(\frac{1}{m_r^*} - \frac{1}{m_l^*}) = E_d + qV \tag{7}$$

The stored charge equation is obtained after integrating equation(4), and knowing that the tunneling wave vector depends on the stored charge Q, we have

$$Q = \frac{2c}{q}[\frac{\hbar^2k^2}{2}(\frac{m_l^* - m_r^*}{m_l^*m_r^*}) - E_d + \frac{1}{2}qV] \tag{8}$$

where c is the capacitance depending on the barrier and well widths. It is given as

$$c = \epsilon_o\epsilon_r/(d + \frac{1}{2}w) \tag{9}$$

where ϵ_o is the permitivity of vacuum, ϵ_r is relative permitivity, d is barrier width and w is well width. From equations (4) and (8) the final equation for current density J is presented as

$$J = \frac{q}{4\pi d^2}[E_d + \frac{1}{2}q(V - \frac{Q}{c})]\exp[-\frac{2\pi d}{\hbar}(\frac{m_l^* - m_r^*}{m_l^*m_r^*})(E_d + \frac{1}{2}q(V - \frac{Q}{c}))^{\frac{1}{2}}] \tag{10}$$

where all the parameters have their previous meanings.

4 Results and discussion

We have theoretically evaluated the effect of charge build-up in a resonant junction, with different effective masses, on the tunneling current, against the bias voltage. The parameters used for our numerical calculation were selected for a typical GaAs/AlAs resonant junction diode, with relative permittivity 13.1, effective mass 0.067 or 0.082 barrier width 8.5 nm and well width 5.6 nm or 4.6 nm. We assumed room temperature operation for the diode tunnel current density against the bias field is shown in figure 2, for equal effective masses. We notice that there exists a tunnel current even at zero applied bias, which indicates the presence of internal field emission. This result agrees with that observed by Gupta, et al [10] for an aluminium-barium stearate-tin junction. The level of such non-zero current at zero bias however depends on the width of the well. For figure 2, we used a well width of 5.6nm and got a non-zero current density of $1.32 A/m^2$, whereas for a well width of 4.6nm of figure 3, we obtained $1.40 A/m^2$. Again the results compare favourably with the experimental observations of MacDonald, et al [7]. As the applied bias is increased, the tunneling current increase with some kind of oscillations. The oscillations may be due to the instability created by the motion of the space charge in the negative conductivity region. When the effective mass of the electrode is chosen greater than that of the well, $m_l^* > m_r^*$, we observe charge saturation resulting in zero current even when the bias voltage is increased. In the range we find Q = 6.9×10^{17} C. If however, $m_\ell^* < m_r^*$, the current becomes a 'run-away' type, giving us an overflow. Ohno and Mendez [6] have reported that maximum current flows when the emitter effective mass is less than the well effective mass. Our result is in agreement with that observation. In all the calculations the energy difference between the well and the electrode was kept constant. However, we believe that a change in energy difference should affect the level of current as reported by Ohno and Mendel [6].

5 Conclusion

In conlusion, we have studied theoretically the effect of space charge build-up on the tunneling current-voltage relationship in a junction diode with different effective masses. We report that (i) the internal tunneling current against the bias voltage of a resonant diode depends on the space charge level before the application of the bias.(ii) the effective mass difference between the electrode and the well contribute to the growth or decrease of this current. (iii) well width determines charge intensity in the well.

ACKNOWLEDGMENTS

This work was supported by Grant No. 92TT2919. The authors would like to thank Professor S.K. Adjepong for very useful advice on the paper. They are also grateful to Professor Abdus Salam, the International Atomic Energy Agency and UNESCO for hospitality at the International Centre for Theoretical Physics, Trieste.

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FIGURE CAPTIONS

Fig. 1. Schematic conduction Band diagram of the tunneling diode under forward bias.

Fig. 2. "Tunneling Current-Voltage" characteristics with equal effective masses for well width 5.6nm.

Fig. 3. "Tunneling Current-Voltage" characteristics with equal effective masses for well width 4.6nm.

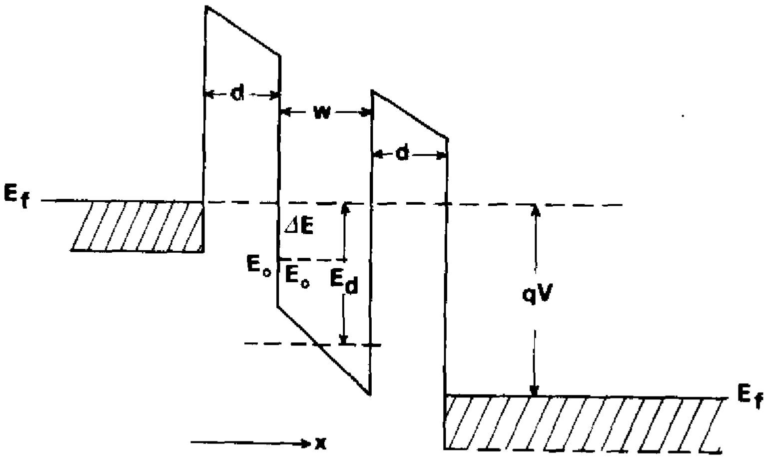
d
w
d
E_f
ΔE
E_o
E_o
E_d
qV
E_f
x

Fig.1

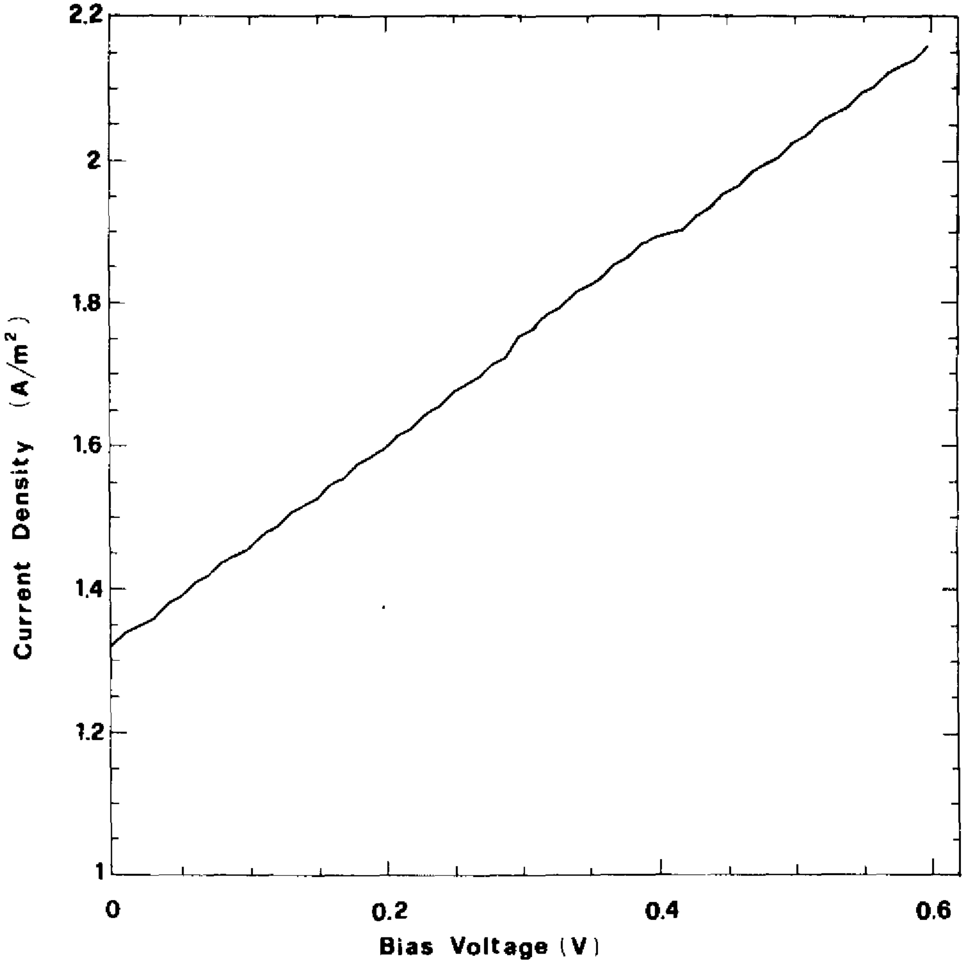
Current Density (A/m²)
2.2
2
1.8
1.6
1.4
1.2
1
0
0.2
0.4
0.6
Bias Voltage (V)

Fig.2

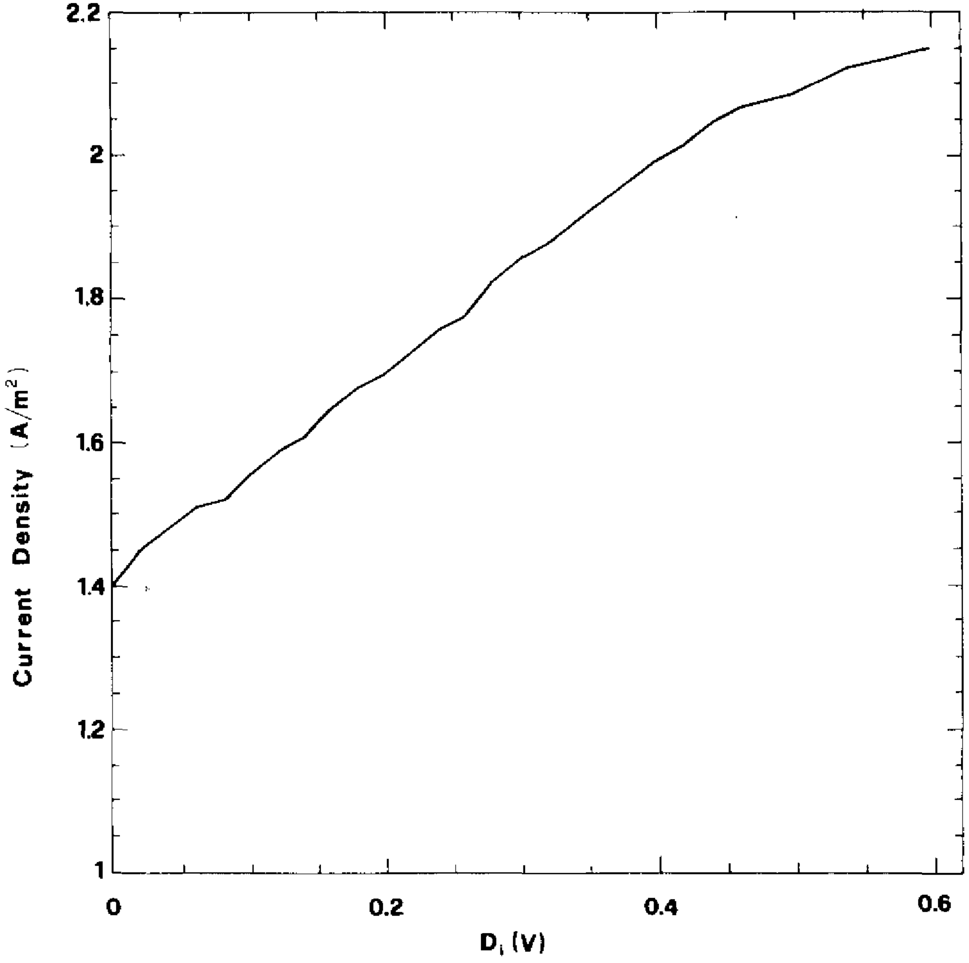

Fig.3