RESONANT INTERNAL FIELD EMISSION IN QUANTUM WELLS

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ABSTRACT

A theoretical study of resonant tunneling in quantum wells subject to a constant electric field E_L is presented. The analysis is carried out in the framework of the simplified two-band Kane model. It is shown that the transmission coefficient (TE) as a function of the electron energy exhibits a well defined resonant structure. Some interesting properties of T(E) are reported.

RESUMEN

Se presenta un estudio del tunelaje resonante en pozos cuánticos sometidos a la acción de un campo eléctrico E_L constante. El análisis se lleva a efecto en los marcos del modelo simplificado de dos bandas de Kane. Se pone de manifiesto que el coeficiente de transmisión T(E) como función de la energía del electrón presenta una estructura resonante bien definida. Se reportan además algunas otras propiedades interesantes de T(E).

I N T R O D U C T I O N

During the last years theoretical and experimental researches on tunneling through double barriers [1-4], superlattices [5-6], and multiple quantum wells (MQW) [7], have clarified the mechanisms of current

transport in these semiconductor heterostructures. Two possible mechanisms have been suggested for the underlying physics of the tunneling process: resonant and sequential tunneling [4]. Both are known to lead to negative differential resistance in these structures.

Almost all the investigations developed up to now consider charge carriers moving in the conduction band (electrons) or in the valence band (holes) [8]. Only small attention have been paid to the study of electronic tunneling between states in the valence and conduction bands in MQW structures (Zener Tunneling). As far as we know only in [9] is carried out and experimental study of this important subject, where the observation of resonant Zener tunneling (RZT) in the AlInAs/GaInAs structure is reported.

The purpose of the present paper is to report some characteristic features of RZT in quantum wells (QW) developed in the framework of the simplified two-band Kane model.

2. SIMPLIFIED TWO-BAND KANE MODEL

To study the RZT we will consider a finite QW of width L subject to a constant electric field E_L applied along the positive direction of the well Z (Fig. 1). The QW consists of layers of 1 and 2 host semiconductors with energy gaps given by E_1 and E_2, respectively. The origin of coordinates (energy) is taken at the interface between regions 1 and 2 (at the midgap position of semiconductor 2).

Following [10] to describe the electron dynamics in the framework of the simplified two-band Kane model we will use, in each host material, a Diraclike kinetic energy operator. This leads to a system of four differential equations for the envelope functions that can be transformed in two equivalent decoupled pairs (Eq. (5) in [10]). Under the unitary transformation generated by the operator

$$U = (2)^{-\frac{1}{2}} \begin{bmatrix} 1 & i \\ 1 & -i \end{bmatrix}$$

each one of these pairs of equations takes the form:

$$\begin{bmatrix} H_{11} & E_{eff}(Z) \\ E^{*}_{eff}(Z) & H_{22} \end{bmatrix} \begin{bmatrix} F_1(Z) \\ F_2(Z) \end{bmatrix} = 0; \qquad (1)$$

where $H_{11} = PK_z + V(Z) + FZ - E$; $H_{22} = - PK_z + V(Z) + FZ - E$; $E_{eff}(Z) =$

$E_G(Z)/2 + iPK$; P denotes the interband momentum matrix element, which will be assumed identical in both host materials; E is the energy; $E_G(Z) = E_2$ in the well and equal to E_1 in the barriers; $K_z = -id/dz$; $V(Z) = 0$ in the well and V_0 in the barriers, being V_0 the energy difference between the midgap position in each material; the barrier height in the conduction band (without applied field) is $(E_1 - E_2)/2 + V_0$; $K = (K_x^2 + K_y^2)^{1/2}$, where K_x, k_y are the wave vector components in a plane perpendicular to the growth direction of the QW, which are good quantum numbers; $F = eE_L$, being -e the free electron charge.

In each host semiconductor the general solution of Eq(1) can be expressed in terms of Weber's functions $D_n(Z)$[11]. The continuity of these solutions at the interfaces allows to write down the integration constants for $Z > 0$, A_1 and B_1, in terms of the corresponding constants for $Z < -L$, A_3 and B_3:

$$\begin{bmatrix} A_1 \\ B_1 \end{bmatrix} = S \begin{bmatrix} A_3 \\ B_3 \end{bmatrix} \tag{2}$$

In Eq.(2), S is a 2x2 matrix which has the form $S = M_1^{-1}[t_1(0)]M_2[t_2(0)]x$

$$x\ M_2^{-1}[t_2(-L)]M_1[t_1(-L)] \tag{3}$$

where subindexes 1 and 2 characterize the corresponding materials and $M_j[t_j(Z)]$ is a matrix whose elements are:

$$\begin{aligned} \{M_j[t_j(Z)]\}_{11} &= D_{ip_j}[t_j(Z)] \\ \{M_j[t_j(Z)]\}_{12} &= D_{ip_j}[-t_j(Z)] \\ \{M_j[t_j(Z)]\}_{21} &= -b_j D_{ip_j-1}[t_j(Z)] \\ \{M_j[t_j(Z)]\}_{22} &= b_j D_{ip_j-1}[-t_j(Z)] \end{aligned} \tag{4}$$

with $j = 1,2$; and $p_j = [(E_j/2)^2 + P^2K^2]/2FP$; $b_j = p_j(2FPi)^{1/2}/(E_j/2 + iPK)$; $t_j(Z) = (2i/PF)^{1/2}[FZ + V_j - E]$, being $V_1 = V_0$ and $V_2 = 0$.

Let us now assume that under the action of the electric field an electron, with energy E, moves from right to left in the valence band. Then, only a transmitted wave will appear in the conduction band. If under these

conditions the asymptotic behaviour of the solutions for $Z \to \pm\infty$ is calculated, following the criteria that the direction of propagation of a wave for the conduction (valence) band is the one in which its phase increases (decreases), we can obtain the following expression for the transmission coefficient:

$$T(E) = \left| S_{21} - S_{22} \exp(\pi p_1) \right|^{-2} ,$$

where S_{22} and S_{21} are the corresponding matrix elements of S.

3. NUMERICAL RESULTS AND DISCUSSION

In order to obtain some information about the properties of T(E) we will suppose that $(E_1, E_2, V_0) = (0.5, 0.19, 0.1$ eV and $P = 0.561$ eV-nm. A similar model of QW was considered in [12]. From now on we will only deal with the case $K = 0$ and $F > F_0$, being $F_0 = 2 \times 10^5$ eV/cm. With such a set of parameters the p-parameters in the Weber's functions are relatively small, which introduce important simplifications in the numerical calculations of T(E). The energies corresponding to the points A, B, C in Figure 1 will be denoted by $E_A = -(E_2/2) + V_0 = -0.15$ eV, E_B, E_C, respectively.

The logarithm of T(E) as a function of energy for $L = (15, 20)$ nm and $F = F_0$ is presented in Figure 2. From these curves and others not reported here we can draw the following conclusions:

(a) Each curve exhibits a well defined resonant structure (RZT), and the corresponding resonance energies are always greater than $E_B = E_2/2 - FL$. This is obvious from Figure 2 if we note that for $F = F_0$ and $L = (15, 20)$ nm the values of E_B are -0.205 and -0.305 eV, respectively.

(b) In each curve the peak value at the lowest resonance energy (fundamental peak) is greater than the others (secondary peaks).

(c) The study of a given peak (fundamental or secondary) for a fixed F and different L values shows that: (1) its resonance energy E_R decreases when L increases, taking the value E_A for a certain value of L; (2) when $E_R > E_A$ the peak value decreases as $(E_R - E_A)$ increases; (3) for $E_R < E_A$ the fundamental peak can take values near or equal to 1. These results can be illustrated with the following example: for $F = F_0$ and $L = (10, 15, 19.2, 20)$ nm the fundamental peak values are $T(E_R) = (0.05, 0.5, 1, 0.97)$, with $E_R = (0.0299, -0.0712, -0.1546, -0.1705)$ eV, respectively. From these results it is obvious that the optimum values of

T(E) are achieved when $FL > E_2 - V_0 + e_R$ where e_R is the resonance energy measured from E_B.

(d) The resonance energy E_R of a secondary peak can be greater than E_C. This takes place, for example, for the second secondary peak of curve (a) in Figure 2, where $E_C = -0.05$ eV and $E_R = 0.03$ eV.

On the other hand , it is not difficult to show that the energy level and the resonance width of quasibound states are the complex roots the equation:

$$S_{21}(E) - S_{22}(E)\exp(\pi p_1) = 0$$

To prove that these roots determine the resonance energies and the corresponding peak widths of T(E), it is neccesary to solve numerically this equation. This is a hard task because S_{21} and S_{22} are expressed through the Weber's functions of complex arguments and indexes. Hence, we followed another approach to find approximatelly the position of the quasibound levels. First, these levels were obtained in the parabolic band approximation using the approach reported in [13], but assuming that the effective masses inside and outside the well are different; and second, corrections due to nonparabolicity effects were included. The latter point was carried out calculating the differences between the corresponding energies obtained in the parabolic and nonparabolic (Eq. (1)) band models without electric field.

With this approach the fundamental quasibound levels for $F = F_0$ and L = (15, 20, 30) nm are (-0.085, -0.186, -0.386) eV, respectively; while the corresponding resonance energies associatted with the fundamental peaks are (-0.071, -0.170, -0.371) eV, respectively. A comparison of these results shows a reasonable agreement and, therefore, suggests that resonances in the transmissivity versus electron energy curve correspond to quasibound levels in the well.

Finally, the peak widths can be used to estimate the lifetime τ associated with the quasibound states. For the fundamental peaks shown in Figure 2 $\tau \sim 10^{-13}$ s .

In conclusion, the results obtained by means of the simplified two-band Kane model confirm the occurence of RZT in QW, and could be useful to analyze other situations where more complicated band models are required. Although all numerical calculations were carried out for high electric field, we believe that the obtained conclusions remain valid for $F < F_0$, especially those related to the optimum value of T(E). It is obvious that the study of RZT in MQW needs both theoretical and experimental further efforts. A more detailed analysis of this important topic is left for a subsequent publication.

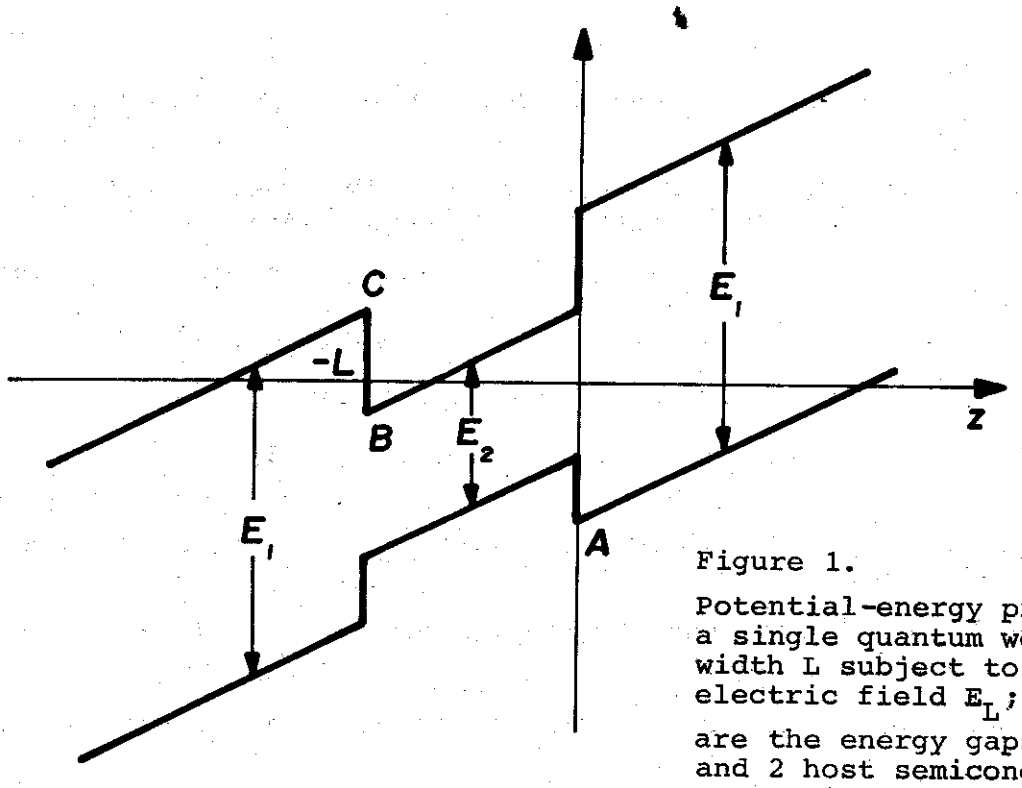

Figure 1.

Potential-energy profile for a single quantum well with width L subject to a constant electric field E_L; E_1 and E_2 are the energy gaps in 1 and 2 host semiconductors, respectively.

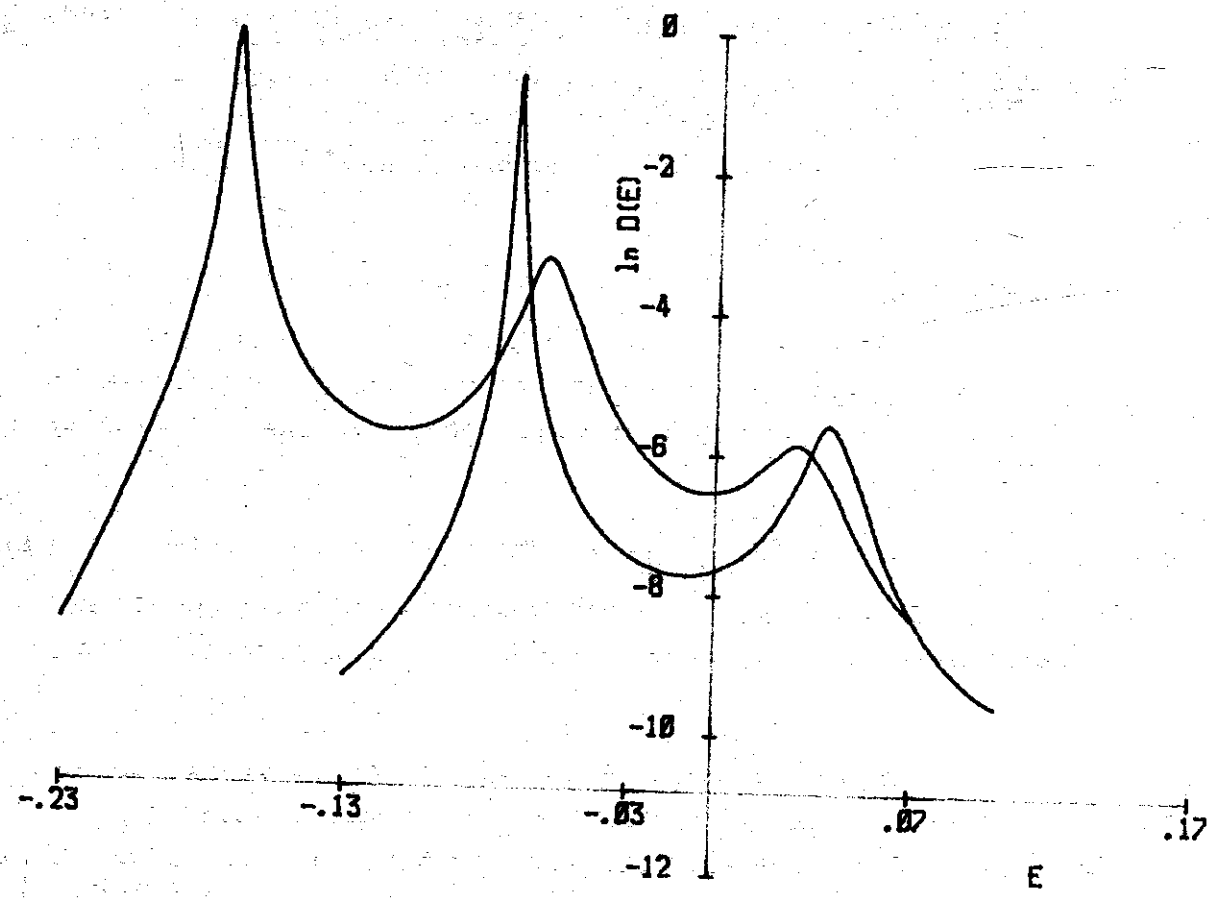

Figure 2. Logarithm of the transmission coefficient as a function of incident electron energy for $F = 2 \times 10^5$ eV/cm and L equal to 20 nm (curve a) and 15 nm (curve b), respectively. The arrows indicate the fundamental peaks.

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