

**EFFECT OF MAGNETIC FIELDS ON THE RESONANT TUNNELING IN A  
GaAs/Al<sub>x</sub>Ga<sub>1-x</sub>As DOUBLE BARRIER HETEROSTRUCTURE**

H. Paredes Gutiérrez<sup>(1)</sup>, N. Porras-Montenegro<sup>(1)</sup>, and A. Latgé<sup>(2)</sup>

(1) *Departamento de Física, Universidad del Valle, A. A. 25360 Cali, Colombia*

(2) *Instituto de Física, Universidade Federal Fluminense, Avenida Litorânea sn, 24210-340 Niterói Rio de Janeiro, Brazil.*

**ABSTRACT**

By means of simple one-band tight-binding Hamiltonian and using the diagrammatic techniques for nonequilibrium processes proposed by Keldysh, we investigate the resonant tunneling transport properties through GaAs/Al<sub>x</sub>Ga<sub>1-x</sub>As double-barrier heterostructures under the action of magnetic fields applied parallel and perpendicular to the current direction. We have found that the number of Landau levels that contribute to the resonant tunneling diminishes with the magnetic field applied parallel to the current direction. Also, we have found that the intensity of the resonant peaks increase when the magnetic field is applied parallel to the current direction. The magnetic field applied perpendicular to the current direction leads to a shift to higher voltage and the diminishing of the intensity of the resonant tunneling peak in the characteristic curves of current versus voltage. Also, we have found that the diminishing of the hopping energy between nearest neighbors originates the same effects than the in-plane magnetic field on the current-voltage characteristics. Our results compare quite well with experimental reports.

**1. Introduction**

Electronic transport in semiconductor heterostructures has been extensively studied both theoretically and experimentally, because of the importance of its fundamental quantum mechanics aspect and its technological interest in applications as fast tunneling devices [1]. One of the most important probes has been the application of a magnetic field (B) perpendicular (in-plane) and parallel to the tunneling current through a double-barrier heterostructure (DBH) which permits the study of transport of carriers through the barriers and the analysis of the electronic properties at the interfaces. In DBH's most experimental [2,3] and theoretical [4,5] works devoted to the study of the effects of B applied parallel to the current direction. In these works it has been found the tunneling through the Landau levels located in the resonant region by means of the current-voltage (I-V) characteristic curves. In these studies it has been found that the number of the Landau levels increase with the diminishing of the applied magnetic field and that the intensity of the current increase with the applied magnetic field. The effect of a transverse (in-plane) magnetic field on the tunneling current in a GaAs/(Ga,Al)As DBH has been studied by Eaves et al [6], who showed that the decrease in the tunnel current with an increase in the field arises from an effective increase in the barrier height, due to the diamagnetic energy. The in-plane magnetic field affects considerably the properties of the carriers confined in the QW, such as the charge distribution and the energy dispersion relation, as reported by Oliveira et al [7].

In the present work following the nonequilibrium Green function formalism proposed by Keldysh [8] and describing the system by single-band tight-binding Hamiltonian we are concerned with the study of the IV characteristic curves through a GaAs/Ga<sub>1-x</sub>Al<sub>x</sub>As

DBH under the action of a magnetic fields applied parallel and perpendicular to the current direction.

**2. Theory**

The transport properties of a DBH can be described by a simple one-band tight-binding Hamiltonian with only nearest-neighbor interactions. In the presence of a magnetic field,  $\mathbf{B} = B \hat{\mathbf{i}}$ , perpendicular to the heterostructure growth direction ( $z$  axis). The Hamiltonian can be written as

$$H = \sum_i \epsilon_i c_i^\dagger c_i + \sum_{\langle i, j \rangle} V_{ij} c_i^\dagger c_j, \tag{1}$$

where  $V_{ij}$  is the hopping between neighbor sites  $i$  and  $j$  and  $\epsilon_i$  is the diagonal energy.

We introduce the role of the magnetic field perpendicular to the current direction through a linear Landau-gauge for the vector potential  $\mathbf{A} = By \hat{\mathbf{k}}$  and perform a Peierls substitution [9] in the hopping energies, by means of

$$V_{i,i'} \rightarrow V_{i,i'} \exp \left\{ i \frac{e}{\hbar} \mathbf{A} \left( \frac{\mathbf{l} + \mathbf{l}'}{2} \right) \cdot (\mathbf{l} - \mathbf{l}') a \right\}, \tag{2}$$

where  $\mathbf{l}, \mathbf{l}'$ , are the position vectors for the sites  $i$  and  $j$  of the nearest neighbors atoms, in all positions in the lattice.

When the magnetic field is applied parallel to the current direction, in eq. (1)  $\epsilon_i = \epsilon_i^s + \epsilon_i^{\parallel}$ , where  $\epsilon_i^s$  denotes the diagonal energies and  $\epsilon_i^{\parallel} = (n + \frac{1}{2})\hbar\omega_i$ , ( $n = 0, 1, 2, \dots$ ), where  $n$  is the Landau index and  $\omega_i = \frac{eB}{m_i^*}$  is the cyclotron frequency ( $m_i^*$  is the in-plane x-y electronic effective mass,  $e$  the electron charge, and  $B$  is the applied magnetic field).

Using the diagrammatic techniques for nonequilibrium processes proposed by Keldysh, the full system is decoupled in two equilibrium ones [right (R) and left (L)] and the associated Green functions obtained. The current, at  $T = 0$  K, which can be written in terms of the density of states of the two equilibrium subsystem  $\mathbf{r}_{R,L}(\hbar\omega)$  as

$$I = \frac{4p^2 e T^2}{\hbar} \int_{\mu_R}^{\mu_L} \frac{\rho_L(\hbar\omega) \rho_R(\hbar\omega) d(\hbar\omega)}{|\rho(\hbar\omega)|^2}, \tag{3}$$

where  $T = V_{01} = V_{10}$  y  $|\Lambda|^2 = (1 - g_{LL}^a g_{RR}^a V^2)(1 - g_{LL}^r g_{RR}^r V^2)$ , with  $g_{LL(RR)}^{a(r)}$  corresponding to the advanced (retarded) Green function of the left and right subsystem. We have considered  $\mu_R < \mu_L$ ,  $\mu_L$  and  $\mu_R$  being the chemical potentials of the injector and collector located on the left and right-hand sides of the system, respectively. In the present micro-

scopic model we have used the GaAs electronic effective mass,  $m^* = 0.067m_0$ , where  $m_0$  is the free electron mass, and the lattice constant,  $a = 2.82 \text{ \AA}$ .

### 3. Results and Discussion

Figure 1 presents the I-V characteristics curves for a GaAs/Ga<sub>1-x</sub>Al<sub>x</sub>As DBH with different magnetic fields applied in the current direction. When the magnetic field is applied parallel to the current direction the motion in the x-y plane, parallel to the interfaces, is quantized into Landau levels. This fact is reflected in the jumps or peaks of the tunneling current. At low magnetic fields the Landau levels are close together, and several of them may be in resonance with the Fermi sea of the emitter presenting simultaneous tunneling and the number of jumps in the current increases with the diminishing of the magnetic field. With increasing magnetic field the Landau levels are more separated, the number of jumps in the resonant current decrease, the current peaks move to higher voltages and their intensity is increased due to the enhanced of the hopping energy.

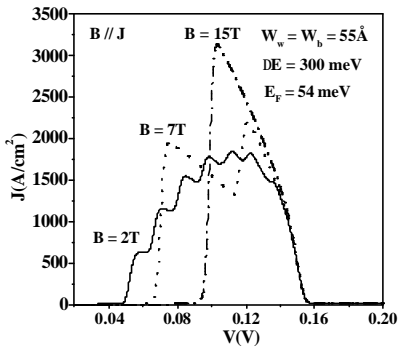


Figure 1. Current densities vs voltage for for a GaAs/Ga<sub>1-x</sub>Al<sub>x</sub>As DBH with different magnetic fields applied in the current direction: B = 2 T, 7 T, 15 T. The barriers width is 50 Å, the well width is 40 Å, and  $\Delta E = 300 \text{ meV}$ . The doping of the emitter and collector contacts is  $n^+ = 10^{18} \text{ cm}^{-3}$  (corresponding to a Fermi energy of 54 meV).

ishes the overlapping between the nearest neighbor orbitals and consequently the hopping energy. Effectively, one effect of the in-plane magnetic field is to reduce the spatial extent of the electronic wave functions in the z-direction, decreasing the hopping energy in the z-direction. About this matter in Fig. 2(b) we display the current as a function of the voltage for different values of the hopping energy. Here also, it can be observed the diminishing of the intensity and the shifting to higher energies of the current peak with the diminishing of the hopping energy.

The I-V, in a 3D GaAs/Ga<sub>1-x</sub>Al<sub>x</sub>As DBH for different magnetic fields applied perpendicular to the current direction is presented in Fig. 2(a). We can observed that the presence of the transverse magnetic field has two effects on the resonant tunneling peak: its shift to higher bias voltages and the diminishing of its intensity. Eaves et al [6] has presented similar experimental results on the intensity of the tunneling current through a barrier potential in a system made of GaAs-Ga<sub>1-x</sub>Al<sub>x</sub>As-GaAs, where the authors argue that the diminishing in the current intensity is due to an increase in the barrier height due to the diamagnetic energy. However, the shifting to higher energies can be understood by means of the lateral energy the carriers do not use for tunneling [9], originated by the in-plane magnetic field, which must be compensated by a higher bias to reach the resonant energy. On the other hand, the in-plane magnetic field diminishes the overlapping between the nearest neighbor orbitals and consequently the hopping energy.

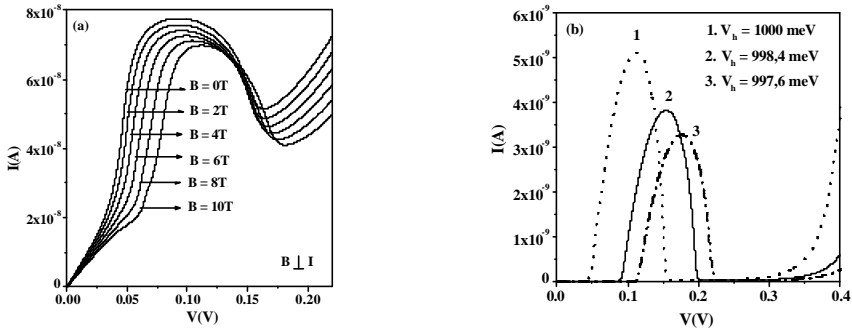


Figure 2. (a) Current as a function of the voltage, in a 3D GaAs/Ga<sub>1-x</sub>Al<sub>x</sub>As DBH for different magnetic fields  $\mathbf{B}=0\text{T}, 2\text{T}, 4\text{T}, 6\text{T}, 8\text{T}$  and  $10\text{T}$ . The barriers and well are  $55\text{ \AA}$  wide, and  $\Delta E = 300\text{ meV}$ , which correspond to an Al concentration  $x = 0.4$ . (b) Current as a function of the voltage, for the same structure, and for different values of the hopping energy.

#### 4. Conclusion

We have presented a study of resonant tunneling in DBH under the action of magnetic fields applied parallel and perpendicular to the current direction. We have followed a theoretical description based on Keldysh's nonequilibrium Green functions, which are adequate to describe transport properties. The presence of the in-plane magnetic field in the I-V characteristic curves leads to a shift to higher voltage and to the diminishing of the intensity of the resonant tunneling. Our results are in good agreement with experimental results. Also, we have found that the diminishing of the hopping parameter also originates the diminishing of the intensity of the resonant tunneling peak. On the other hand, we have found that the intensity of the resonant peaks increase when the magnetic field is applied parallel to the current direction, result that would be expected due to the increasing values of the magnitude of the hopping energy with the magnetic field.

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