Magnetotunneling Studies in a Pseudomorphic InGaAs/AlAs/GaAs Heterostructure

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We report on magnetotunneling studies in a pseudomorphic $In_{0.1}Ga_{0.9}As$/AlAs/GaAs structure in a magnetic fields perpendicular or tilted to the tunneling current. In a transverse magnetic field, we have observed a shift to higher voltages and a strong broadening of resonant peak in I(V) characteristics. These features are explained by the action of the Lorentz force coupling the parallel and perpendicular motions. In a tilted magnetic field, we have observed structures in I(V) characteristics which corresponds to tunneling in the prewell to the midwell with non-conservation of Landau level index in good agreement with a coherent model in which the effect of the transverse component is treated in a perturbation approach.

I. Introduction

Magnetotunneling in semiconductor heterostructures bas been a subject of considerable interest in the last years. Most of the work has been devoted to the study of magnetotunneling in double barrier structures with the magnetic field parallel ($B_{\|}$) or perpendicular ($B_{\perp}$) to the current. In a parallel magnetic field, oscillations of the resonant current are observed in I(B) curves from which it is possible to deduce the charge build in the well and the dimensionality of the emitter[1−3]. Magnetooscillations are also observed in off-resonant regime[4−6] and arises from elastic and inelastic tunneling process with non conservation of Landau level indexes. Translational invariance in the plane of the layers implies conservation of Landau level indexes for coherent tunneling from the emitter to the well. Nevertheless, elastic and inelastic scattering mechanisms breaks this selection rule. In a perpendicular magnetic field, a shift to higher voltages and a strong broadening of the main peak in I(V) characteristics is observed[7,8]. These effects have been qualitatively explained by the change of transverse momentum as the electron tunnels in the structure induced by the perpendicular magnetic field. Magnetotunneling under tilted magnetic field has been recently investigated[9,10] and leads also to a breakdown of the Landau-level index conservation rule obtained for coherent tunneling in a purely parallel magnetic field. A splitting of the resonant peak in the I(V) characteristics in satellite peaks is observed and corresponds to inter-Landau- tunneling from emitter into the well. This tunneling process can be the dominant contribution to the resonant current for large perpendicular magnetic field component. A coherent

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tunneling model with a perturbational approach have been used to explain both positions and intensities of these satellite peaks[9].

In this paper, we report on magnetotunneling results obtained in a high-quality InGaAs/AlAs/GaAs double barrier in a triple well configuration. We have incorporated a narrow gap InGaAs layer adjacent to the emitter barrier to enhance the two dimensional (2D) character of the injection. The midwell controls the escape process whereas the postwell is introduced to preserve the symmetry of structure. The experimental I(V) characteristics are investigated in the presence of a magnetic field perpendicular or tilted relative to the tunneling current. In a transverse magnetic field, we have observed a shift to higher bias and a strong broadening of resonant peak in I(V) characteristics. In a tilted magnetic field, structures are observed in the I(V) characteristics that corresponds to tunneling from the prewell to the midwell with nonconservation of Landau level indexes.

Our sample was grown by molecular beam epitaxy (MBE) on a GaAs [100] semi- insulating substrate and consisted of the following layers: 500 nm GaAs $n^+(3 \times 10^{18}$ cm$^{-3})$, 10 nm GaAs $n^+(1 \times 10^{17}$ cm$^{-3})$, 5nm GaAs not intentionally doped (nid), 5 nm $In_{0.1}Ga_{0.9}As$ nid well, 0.5nm nid GaAs, 5 nm AlAs nid barrier, 0.5nm nid GaAs, 4 nm $In_{0.1}Ga_{0.9}As$ nid well, 0.5nm nid GaAs, 5 nm AlAs barrier, 0.5nm nid GaAs, 5 nm $In_{0.1}Ga_{0.9}As$ nid well, 5 nm GaAs nid, 10nm GaAs $n^+(1\times10^{17}$ cm$^{-3})$, 500 nm GaAs $n^+(3\times10^{18}$ cm$^{-3})$. A thin layer (0.5nm) of GaAs was introduced between InGaAs and AlAs layers to recover good interface quality. Standard mesa etching techniques was used to define square mesas devices of 60×60 μm^2. Magnetotunneling measurements were performed at 4.2K in magnetic fields up to 12T.

The experimental current-voltage characteristics obtained for this sample at 4K is shown in Fig. 1. The arrows refer to the effect of bistability and it is not studied in this work. The peak to valley current ratio is about 40 and the current density is 25 A/cm^2. Fig. 2 shows the calculated band structure obtained by a Poisson solver, similar to the model proposed by Fiig and Jauho[11], which combine a semiclassical approximation for electrons in the contacts with a more appropriate treatment of the 2D electrons in the emitter. From this calculation, the resonant tunneling condition is obtained by the anticrossing of the quantized level in the prewell E_{pw} and in the midwell E_w at $V = 0.27$ volt which is in satisfatory agreement with the experimental value of the peak position in the I(V) characteristics. The details of the model used for this theoretical simulation may be found elsewhere[12,13].

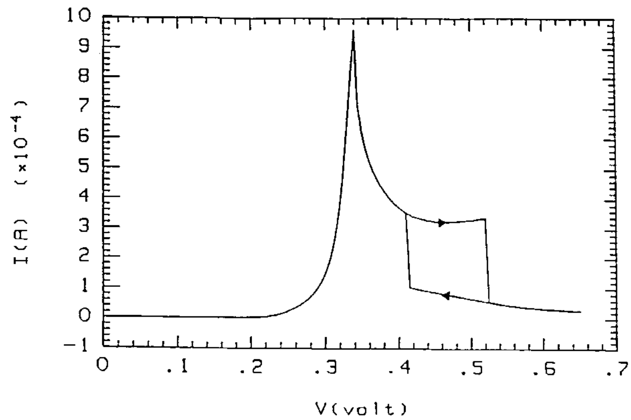

Figure 1. Current-voltage characteristics of the device at 4.2 K.

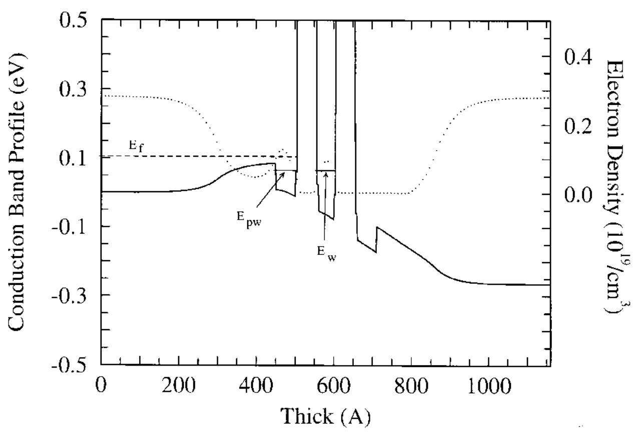

Figure 2. Calculated conduction band profile and electronic density (dotted line). The dashed line indicates the emitter Fermi level.

Fig. 3(a) shows a typical I(V) characteristic at 4.2K in a transverse magnetic field. The I(V) curves are shiftted to higher voltages with strong broadening of the resonant peak. Classicaly, the Lorentz force couples de components of momentum in transverse and longitudinal directions. The transverse wave vector of an electron traveling through the barriers is changed by $\Delta k_\perp = eBd/\hbar$, where d is the travelled distance. Using this semiclassical model, we can show that a resonant peak is observed when the following condition is satisfied[5]: $E_{pw} - E_w = (eB_\perp d)^2/2m_e$. In Fig. 3(b) the experimental peak position is plotted as function of $B_\perp^2$ from which we can deduce $d = 103$Å in good agreement with the expected value $L_b+(L_{pw}+2L_s+L_w)/2 = 100$Å where L_i denotes the width of barrier ($i = b$), prewell ($i = pw$), GaAs layer ($i = s$), and midwell ($i = w$).

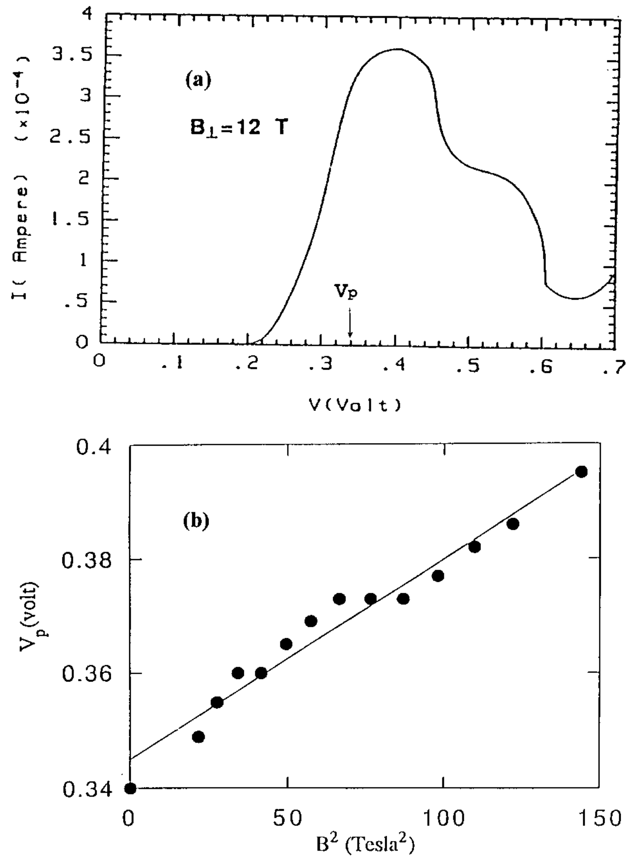

Figure 3. (a) Current-voltage characteristic at 4.2 K for $B_\perp$ =12 T (b) Resonant peak position as function of transverse magnetic field.

Fig. 4 shows a typical I(V) characteristics measured at 4K under tilted magnetic field. Such measurements have been realized for several values of parallel and perpendicular magnetic field components by varying the total magnetic field (**B**) and the angle θ between **B** and **J**. We have observed structures in I(V) characteristics which correspond to tunneling with variation of Landau level index Δn equal -1, -2, 0, 1, 2. The positions of these observed structures are independent on $B_\perp$. The effect of component $B_\perp$ is to induce tunneling transitions in which Landau level index is changed resulting in the splitting of resonance peak into sattelite peaks. The intensities and positions of these structures are explained in terms of a coherent model where the perpendicular magnetic field is treated in a perturbation approach[9]. In this model, a satellite peak is observed in the I(V) characteristics when $E_{pw} - E_w \approx (n' - n)\hbar\omega_c$, where n is the Landau level index of an electron in the prewell that can tunnel into n'th Landau level of the midwell and $\hbar\omega_c$ is the InGaAs cyclotron energy. The relative intensities are given by: $I_m/I_0 = \alpha^{|m|}/|m|!$ where $\alpha = e[< z >_w - < z >_{pw}]^2 B_\perp^2/2\hbar B_\parallel$, $m = n' - n$ and $< z >_j$ denotes the mean electron position in the midwell ($j = w$) and prewell ($j = pw$). We have fitted[9] the experimental relative intensities of the satellite peaks and we have obtained $d =< z >_w - < z >_{pw} \approx 106$Å in good, agreement with the expected value 100Å.

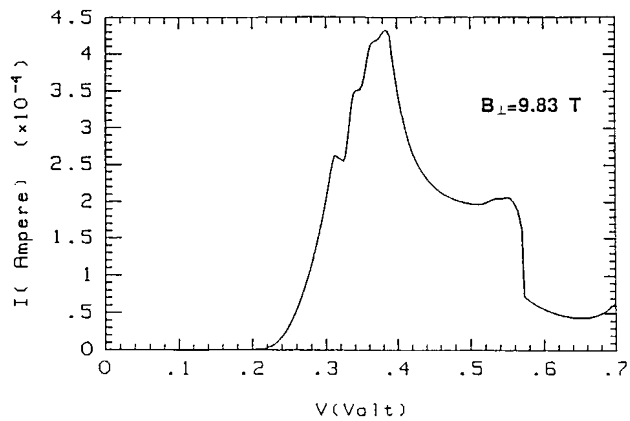

Figure 4. Typical current-voltage characteristics at 4.2K for $B_\perp$ = 9.83 T and $B_\parallel$= 6.9 T.

In conclusion, we have performed magnetotunneling measurements in a high quality InGaAs/GaAs/AlAs triple well structure. In a perpendicular magnetic field, a broadening and a shift of resonant peak with $B_\perp^2$ dependence is observed and are explained by the action of the Lorentz force coupling the parallel and perpendicular motions. Finaly, we have observed a splitting of the resonant peak in the current-voltage characteristic under tilted magnetic field which corresponds to coherent tunneling from the prewell into the well with nonconservation of Landau level indexes. The positions and intensities of these structures have been explained in terms of a coherent theory in which the transverse magnetic field component is treat in a perturbation approximation.

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