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High-Pressure Magnetotransport Measurements of Resonant Tunnelling via X-Minimum Related States in AlAs Barrier

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In this paper, we present the results of magnetotransport experiments performed on a single barrier GaAs/AlAs/GaAs heterostructures. Tunnel current was measured as a function of magnetic field for different values of bias voltage and hydrostatic pressure. We observed that the amplitude of the magnetooscillations of tunnel current quenched when the requirements for resonant tunnelling were met and it recovered in out-of-resonance conditions. This effect was observed both for tunnelling through donor states and through X-minimum related quasiconfined conduction band states. The fact that also in the latter case the amplitude was restored suggests that this process involved X_z subbands and took place without a participation of phonons (the so-called $k_{\|}$-conserving process).

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1. Introduction

Although the tunnel transport through a single barrier in GaAs/AlAs/GaAs heterostructure has already been intensively studied [1, 2], there still remain many interesting unsolved problems. The aim of the studies was to investigate the effect of resonant tunnelling on magnetooscillations of tunnel current.

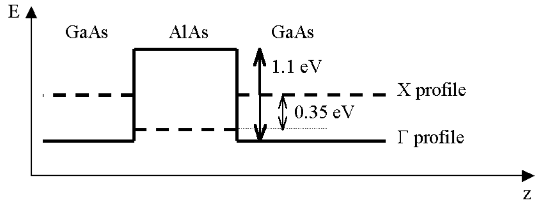

Fig. 1. Schematic conduction band alignment for GaAs/AlAs/GaAs heterostructure when no voltage is applied (in fact there is a small potential bending next to the barrier due to ionised Si donors).

The schematic view of band profile of the structure is presented in Fig. 1. AlAs is an indirect gap material with the minimum of the conduction band at X point of the Brillouin zone, while in GaAs the minimum is at Γ point. The bands are aligned in a way that AlAs layer forms a barrier for the electrons from Γ valley (solid line), and a quantum well (QW) for X-valley electrons (dashed line). The existence of X-valley QW gives rise to quasiconfined X subbands. They can serve as tunnel channels in the tunnelling process. In AlAs layer, beside X-minimum related subbands, there exist also shallow donor states, which are below X minimum in the energy scale. Due to quantum confinement and biaxial strain the orientational degeneracy of X minimum is removed and X_z valley (where z is the growth direction) is no more equivalent to X_x and X_y (X_{xy}) minima and their energies are different [3]. X_z and X_{xy} minima are not equivalent also from the point of view of momentum conservation during tunnelling through AlAs layer. Since there is no translational symmetry in z direction, k_z is not a good quantum number. However, $k_{\|}$ should be conserved in the process. For the tunnelling via states related to X_z minimum, where $k_{\|}$ is small, momentum can be conserved without a participation of additional quasiparticle, whereas for the tunnelling via X_{xy} the assistance of phonons is necessary as for these valleys parallel momentum is very big. Conservation of $k_{\|}$ influences the probabilities of the transfer and the shape of $I-V$ curves.

2. Experiment

The measurements were performed on samples grown by MBE on (001) GaAs substrate. They consisted of: 510 nm of n^+ Si-doped (4×10^{18} cm^{-3}) GaAs, 100 nm of GaAs (2×10^{16} cm^{-3}), 100 nm of undoped GaAs, 10.2 nm of AlAs barrier with the δ-doping layer of shallow donors (Si) in the centre (1×10^{10} cm^{-2}), 100 nm of undoped GaAs, 100 nm of GaAs (2×10^{16} cm^{-3}), 1000 nm of n^+-GaAs (4×10^{18} cm^{-3}).

The dependences of tunnel current versus magnetic field ($I-B$ curves) were measured at dc bias, under hydrostatic pressure up to 8 kbar, at liquid helium temperature. When an external bias voltage is applied to the structure, the energy profile changes and so does the energy alignment of the emitter states and the states in AlAs layer and thus for some particular bias conditions, the resonant tunnelling is possible. Under pressure the relative energy distance between X minimum in AlAs and Γ minimum in GaAs decreases. Therefore, X-minimum related states are available in the tunnelling process at lower voltages than at ambient pressure. The application of magnetic field parallel to the growth direction (z) imposes the Landau quantisation on the emitter. When magnetic field is varied, the Landau levels pass through the Fermi level, which in the experiment is seen as oscillations of tunnel current.

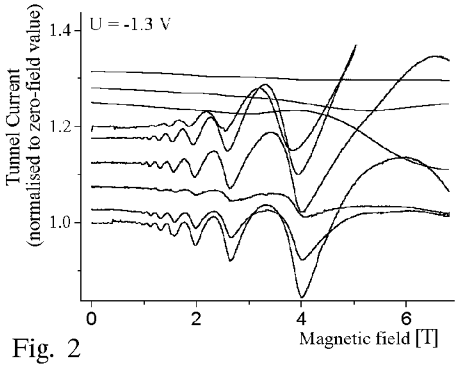

Fig. 2

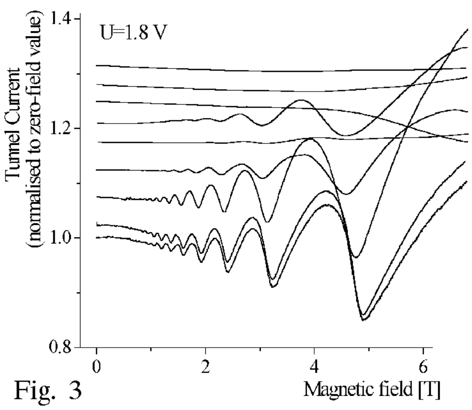

Fig. 3

Fig. 2. Oscillations of tunnel current vs. magnetic field. The experiment was performed at constant bias $U = -1.3$ V for different values of hydrostatic pressure. The sequence of pressures is (from the bottom to the top): 0.0 kbar, 0.5 kbar, 1.5 kbar, 2.5 kbar, 3.5 kbar, 4.0 kbar, 5.0 kbar, 5.6 kbar, 6.3 kbar.

Fig. 3 Oscillations of tunnel current vs. magnetic field. The experiment was performed at constant bias $U = 1.8$ V for different values of hydrostatic pressure. The sequence of pressures is (from the bottom to the top): 0.0 kbar, 0.5 kbar, 1.5 kbar, 2.5 kbar, 3.5 kbar, 4.0 kbar, 5.0 kbar, 5.6 kbar, 6.3 kbar.

The evolution of oscillations for different values of hydrostatic pressure at two different biases is shown in Fig. 2 and Fig. 3. We see that the oscillations occur only up to a certain pressure ($\approx$ 6 kbar); for higher pressures the curves get smooth. Until this pressure is reached, the period of the oscillations as a function of inverse magnetic field remains approximately constant, i.e. the free electron concentration in the emitter does not change with pressure. Another feature is that at some values of pressure the amplitude of oscillations quenches and then, as the pressure is increased, it is restored. These phenomena happen at $\approx$ 1.5 kbar in Fig. 2 (for bias equal to −1.3 V) and $\approx$ 3.5 kbar in Fig. 3 (for bias equal to 1.8 V). Although the amplitude gets much smaller the oscillations are still there.

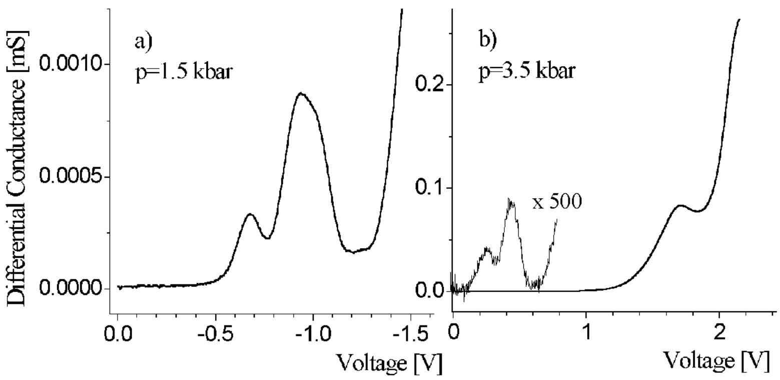

Fig. 4. Differential conductance given in mS as a function of bias voltage for hydrostatic pressure of (a) 1.5kbar and (b) 3.5 kbar. In the inset a magnification of low voltage region is presented where donor-related structures are visible.

In order to ascribe the structures observed in the tunnelling to particular resonant states we performed differential conductance versus voltage ($\sigma - V$) measurements. The results are shown in Fig. 4a and b. We see that at pressures and voltages, at which oscillations quench, there are minima in $\sigma - V$. To explain this behaviour we should recall that each maximum in $\sigma - V$ corresponds to a process of switching on of a new tunnelling channel, whereas the subsequent drop of signal means that the switching on of a new channel has already been completed, i.e. that the probability of the tunnelling has its maximum. This means that the channels are active in the tunnelling process. We identified the structures in Fig. 4a and b as being due to the tunnelling via donor states and via X-minimum conduction band states, respectively [2]. This identification was based on the experimental fact that the structures presented in Fig. 4a were observed only in doped samples, while those from Fig. 4b observed at high voltage were seen in all the samples (doped and undoped).

3. Discussion

The decrease in the amplitude of magnetooscillation for the tunnelling realised via donor states has already been observed by Itskevich et al. [1]. However, in our results we observed the same phenomenon for the tunnelling via quasiconfined states. Quenching of oscillation at resonance can be explained in terms of broadening of the Landau levels, which comes from shortening of electron lifetime in the emitter at resonance.

The fact that the oscillations are restored suggests that the tunnelling channel switches off. As far as donor states are concerned this statement is obvious, since they have well-defined, discrete energy (although it can be smeared by random spatial distribution of donors in the barrier or by thermal excitations). But in the case of X-well states the situation is more complex.

The tunnelling can be realised by two kinds of states: X_z with small $k_{\|}$ and X_{xy}, where $k_{\|}$ is substantial. For the so-called $k_{\|}$-conserving transfer (with no additional quasiparticle involved), the tunnelling starts when not only the energy, but also $k_{\|}$ of both emitter and X-related subband are the same. It continues at a constant rate, as the number of accessible states is constant, until the bottom of X subband is below the one in the emitter [4]. Then the process stops and the tunnel current decreases. This can be the case for the tunnelling via X_z states. For $k_{\|}$-non-conserving tunnelling (an abbreviation describing processes in which needed momentum can be supplied e.g. by an additional quasiparticle) only the energies should be properly matched. Therefore, the tunnelling starts approximately when the bottom of X-well subband reaches the Fermi energy in the emitter. As there is no need of momentum matching between emitter and X-well states, the number of available states increases, and thus the current is bigger and bigger until all occupied emitter states participate in the process. Moreover, there is no such notion as a stop in tunnelling — the tunnelling can be realised via states which are high above the bottom of a subband. Such situation corresponds to the tunnelling via X_{xy} subbands. In our case, as the amplitude of magnetooscillations is restored after its quenching even for resonant tunnelling via X-valley related states, there is a clear indication that this should be the $k_{\|}$-conserving process, so it must be realised via X_z subband.

4. Conclusions

Resonant-tunnelling induced quenching of magnetooscillations of current associated with tunnelling through quasilocalised X-minimum states was observed for the first time. Since the amplitude of the oscillations recovers at higher pressures, it means that this tunnelling channel switches off. This is the clear indication that this process is a $k_{\|}$-conserving one and therefore that X_z-minimum related states are engaged in resonance. Further increase in pressure (or bias voltage) leads to very efficient both resonant and non-resonant tunnelling through X-minimum QW and magnetooscilllations disappear completely.

Acknowledgments

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