Defense Technical Information Center Compilation Part Notice

ADP013014

TITLE: Interaction Between Landau Levels of Different Two-Dimensional Subbands in GaAs

DISTRIBUTION: Approved for public release, distribution unlimited
Availability: Hard copy only.

This paper is part of the following report:

TITLE: Nanostructures: Physics and Technology International Symposium [8th] Held in St. Petersburg, Russia on June 19-23, 2000 Proceedings

To order the complete compilation report, use: ADA407315

The component part is provided here to allow users access to individually authored sections of proceedings, annals, symposia, etc. However, the component should be considered within the context of the overall compilation report and not as a stand-alone technical report.

The following component part numbers comprise the compilation report:
ADP013002 thru ADP013146

8th Int. Symp. "Nanostructures: Physics and Technology"
St Petersburg, Russia, June 19–23, 2000

Interaction between Landau levels of different two-dimensional subbands in GaAs

D. Yu. Ivanov†, E. Takhtamirov‡, *Yu. V. Dubrovskii*†, V. A. Volkov‡, E. E. Vdovin†, L. Eaves§, P. C. Main§, M. Henini§, D. K. Maude¶, J.-C. Portal¶,*,#, J. C. Maan|| and G. Hill+

† Institute of Microelectronics Technology RAS, 142432 Chernogolovka, Russia
‡ Institute of Electronics and Radioengineering RAS, Moscow, Russia
§ The School of Physics and Astronomy, University of Nottingham, Nottingham NG7 2RD, UK
¶ Grenoble High Magnetic Field Laboratory, MPI-CNRS, BP166 38042 Grenoble Cedex 9, France
|| High Field Magnet Laboratory, Research Institute for Materials, University of Nijmegen, 6525 ED Nijmegen, The Netherlands
+ Department of Physics, University of Sheffield, Sheffield S3 3JD, UK
* Institut Universitaire de France
# INSA, F31077 Toulouse Cedex 4, France

Abstract. Tunneling studies measurements between strongly disordered two-dimensional electron systems in a magnetic field parallel to the current are presented. Two-dimensional electron systems are formed by Si delta doping of GaAs on both sides of the AlGaAs barrier. Strong interaction between Landau levels of different two-dimensional subbands in GaAs have been observed as anticrossing of related peak positions with magnetic field. The splitting of the interacted Landau levels is about 10 meV, which could not be explained by non-parabolicity of the conduction band in GaAs. The possible reasons of the observed interaction are discussed.

In the case of a spherical energy-band model, there is no interaction between Landau levels of different two-dimensional subbands and intersection of two Landau levels is allowed [1]. Interaction between Landau levels was observed previously only in tunneling studies of surface quantization in narrow gap PbTe [2].

In this work we present tunneling studies measurements between strongly disordered two-dimensional electron systems (2DES) in a magnetic field parallel to the current. Due to the strong elastic scattering assisted tunneling in the structures the amplitude of the peaks related to the tunneling between Landau levels was of the same order of magnitude for processes both with Landau level index conservation and without. It gave us chance to study interaction between Landau levels. The main observation was that interaction between Landau levels of different two-dimensional subbands in GaAs is very strong and the observed splitting was about 10 mV, about the same as was observed in PbTe [2]. The possible reasons of the observed interaction are also discussed.

The MBE-grown sample was a single barrier $GaAs/Al_{0.4}Ga_{0.6}As/GaAs$ heterostructure with a 12 nm thick barrier. The barrier was separated from the highly-doped, bulk contact regions by 50 nm thick, undoped GaAs spacer layers. To form the 2DES we used Si donors sheets with concentration of 3×10^{11} cm^{-2} located 5 nm from each side of the barrier. The tunneling transparency of the main barrier was much lower than that of the spacer regions, so that most of the applied voltage is dropped across the barrier. Measurements of the Shubnikov–de-Haas (SdH) like oscillations in the tunnel current gave electron sheet

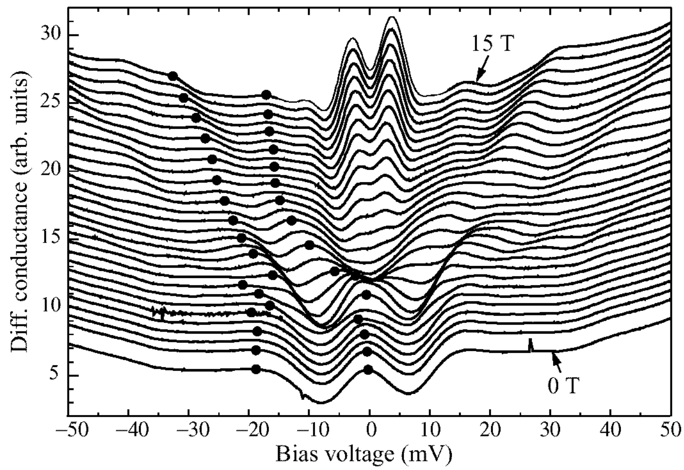

Fig. 1. Tunneling differential conductance at 4.2 K as a function of external voltage in different magnetic fields. The curves are shifted for clarity in vertical direction. The lowest curve is for $B = 0$ T, the top one — for $B = 15$ T. Magnetic field step between curves $\Delta B = 0.5$ T. The curve for $B = 0.5$ T is absent. Circles mark the peaks which evolution with magnetic field are discussed in the paper.

concentrations approximately equal to the donor doping levels. Samples were fabricated into mesas of diameters 100–400 μm. The typical electron mobility in the 2DES is about $\mu = 1000\,\mathrm{cm^2V^{-1}s^{-1}}$ at 4.2 K.

Figure 1 shows the differential tunnel conductance G, at 4.2 K, measured using standard lock-in techniques, versus external voltage V_b at various magnetic fields up to 15 T. In zero magnetic field (lowest curve in Fig. 1) the differential conductance has a peak at zero bias and two pronounced shoulders at higher voltages of both polarities. We argue that the zero voltage peak reflects resonant tunneling between the ground states of the 2DESs, and that the shoulders are due to resonant tunneling between the emitter ground state (ground 2D subband, $n = 0$) and first exited state (excited 2D subband, $n = 1$) in the collector 2DES. The observation of a pronounced maximum at zero bias in zero magnetic field indicates that, despite the relatively large number of scattering centres in the 2D layers, the conservation of in-plane momentum is important for the tunneling process. The evolving structure in the curves with increasing magnetic field reflects resonant tunneling between different Landau levels, which will be discussed below.

Around $B = 6$ T, which is close to $\nu = 2$ for our sample, experimental $G(V_b)$ curves show (see Fig. 1) a pronounced minimum at zero voltage. With a further increase of the magnetic field, the minimum of the differential conductance at zero bias gradually becomes a maximum. For B higher than 8 T, a dip at zero bias appears within this maximum, reflecting the gap in the tunneling density of states around the Fermi level of the 2D electron systems. The details of the equilibrium tunneling processes around zero bias with magnetic field have been discussed before [3].

In this work, we concentrate on the evolution of the structure related with tunneling between different Landau levels and the appropriate peaks to be considered below are marked by circles in Fig. 1. The fan diagram of the peak positions on the voltage scale versus magnetic field is shown in Fig. 2. For simplicity we only consider peaks at negative bias voltage. In fact, observed structure is perfectly symmetrical around zero bias except

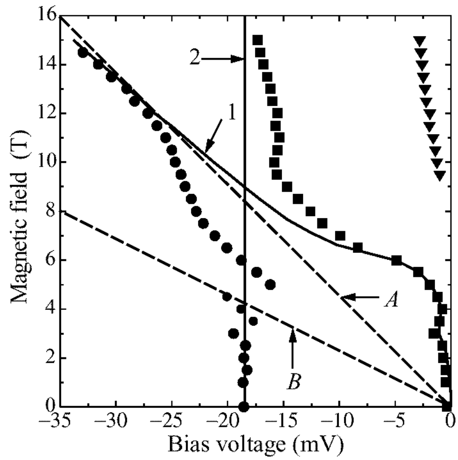

Fig. 2. Peak positions on the voltage scale as a function of magnetic field. Circles, squares and triangles represent experimental data and are discussed in the text. Curves "1" and "2" represent expected peak position calculated in the absence of the interactions between Landau levels. Lines "A" and "B" represent tunneling between Landau levels with $\Delta N = 1$ and $\Delta N = 2$ correspondingly in the case of the ideal Landau level quantization.

some of the not principal details which we omit to discuss here. To understand presented data, it is better to start the discussion of the data in Fig. 2 from high magnetic fields. In a field higher than 12 T circles correspond to the tunneling between 1st Landau level ($N = 0$) of the ground subband state in the emitter ($n = 0$), and 2nd Landau level ($N = 1$) of the ground subband state in the collector ($n = 0$), without Landau level index conservation, i.e. $(n = 0, N = 0) \to (n = 0, N = 1)$ tunneling. The dash line labeled "A" has a slope equal to $L\hbar\omega_C$, where $\hbar\omega_C$ is the cyclotron energy, L is the leverage factor equal to 1.28 for our structure, and presents position of the peaks for $\Delta N = 1$ tunneling in the case of ideal Landau level quantization, the dash line labeled "B" presents position of the peaks for $\Delta N = 2$ tunneling in ideal case correspondingly. For broadened Landau levels the tunneling differential conductance which was just measured in our studies reflects the joint density of states at the Fermi levels of the emitter 2D electron system. In this case the calculated position of the peaks for $(n = 0, N = 0) \to (n = 0, N = 1)$ tunneling is shown by curve labeled "1". The position of the peaks related with $\Delta N = 0$ processes do not depend on magnetic field. Evidently the peak position for $(n = 0, N = 0) \to (n = 1, N = 0)$ should be presented by vertical line labeled "2", which coincide with position of the peak reflected resonant tunneling between ground 2D state in the emitter and first excited state 2D state in the collector without magnetic field. Without interaction between Landau levels lines described peak positions of the different processes versus magnetic field dependencies should intersect as the curves "1" and "2" do. In contrast, experimental dependencies presented as circles and squares in Fig. 2 exhibit obvious anticrossing, which is a manifestation of the interaction between Landau levels $(n = 0, N = 1)$ and $(n = 1, N = 0)$ of the different subbands in the collector. The Landau level splitting is about 10 meV. Some peculiarities is evident also around point where line labeled "B" intersect vertical line "2". These peculiarities indicate that interaction between Landau levels $(n = 0, N = 2)$ and $(n = 1, N = 0)$ in the collector 2DES also takes place, but details of this interaction is out of the experimental accuracy. For generality we also indicated position of the peaks around zero voltage (triangles in Fig. 2) which appeared due to the development of the tunneling gap at Fermi level in magnetic field by triangles.

Let us discuss possible mechanisms of strong ($\sim$10 meV) anticrossing of the Landau levels $N = 1$ from the ground subband $n = 0$ and $N = 0$ from the excited subband $n = 1$. Naturally, such mechanism should mix longitudinal and transverse motion of electrons in the 2D layer. The first reason is connected with the weak non-parabolicity of the electron spectrum in GaAs, the more so as the qualitatively similar anticrossing was observed in 2D layer of highly non- parabolic material PbTe [2]. But in the latter case the strong anticrossing may be caused by the fact that the main axes of the constant energy ellipsoid of the conduction band minimum (L-point of the Brillouin zone) are not along the direction of the structure growth. It does not take place when concerning GaAs, and the theoretical estimation of contribution of the non-parabolicity yields only $\sim$1 meV—too small a value.

The second reason of the strong anticrossing may be connected with the effect of the chaotic potential $V(\mathbf{r})$ which is not weak in our case. In the two-subband ($n = 0, 1$) approximation after averaging $V(\mathbf{r})$ over the longitudinal motion the contribution of the potential takes the matrix form

$$\begin{pmatrix} V_{00}(r_\parallel) & V_{01}(r_\parallel) \\ V_{10}(r_\parallel) & V_{11}(r_\parallel) \end{pmatrix}. \tag{1}$$

Here the diagonal elements $V_{00}(r_\parallel)$ and $V_{11}(r_\parallel)$ describe chaotic motion in the plane of 2D layer in the subbands $n = 0$ and $n = 1$. It is the functions that correspond the broadening of the Landau levels which is large enough in our "dirty" system ($\sim$10 meV). The non-diagonal elements $V_{01}(r_\parallel)$ and $V_{10}(r_\parallel)$ push the states from the subbands $n = 0$ and $n = 1$ apart. If the characteristic length of variation of $V(\mathbf{r})$ relatively to the normal to 2D layer is of the order of the "width" of 2D layer (which sounds reasonable), the value $V_{01}(r_\parallel)$ is not small, and it may be responsible for the observed effect. One more mechanism of the anticrossing connected with the many-particle interaction is under consideration.

Thus we have investigated tunneling processes between strongly disordered 2D electron systems in a quantized magnetic field parallel to the current. The manifestation of the strong interaction between Landau levels of different two-dimensional subbands in GaAs have been observed experimentally.

Acknowledgements

This work was partly supported by INTAS (97-11475), PICS-CNRS (#628, France), RFBR (98-02-17642, 98-02-22008, 99-02-17592), and National programs "Physics of solid state nanostructures" (97-1057), "Physics of quantum and wave processes" (V.3), "Surface atomic structures" (3.11.99).

References

[1] C. B. Duke, *Phys. Rev.* **159**, 632 (1967); D. J. Ben-Daniel and C. B. Duke, *Phys. Rev.* **160**, 679 (1967); C. B. Duke, *Phys. Lett. A* **24**, 461 (1967); G. A. Barraf and J. A. Appelbaum, *Phys. Rev. B* **5**, 475 (1972).

[2] D. C. Tsui, G. Kaminsky and P. H. Schmidt, *Phys. Rev. B* **9**, 3524 (1974).

[3] Yu. N. Khanin, Yu. V. Dubrovskii, E. E. Vdovin *et al.*, to be published in *Physyca E*.