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OBSERVATION OF THE INTERACTION BETWEEN LANDAU LEVELS OF DIFFERENT TWO-DIMENSIONAL SUBBANDS IN GAAS IN NORMAL MAGNETIC FIELD

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Tunnel current measurements between strongly disordered two-dimensional electron systems in a perpendicular magnetic field are presented. Two-dimensional electron accumulation layers are formed by extremely narrow layer of Si donors (Si delta doping) in GaAs on either sides of an AlGaAs tunnel barrier. Strong interaction between Landau levels of the two-dimensional subbands in each accumulation layers is observed as an anti-crossing of the related peak positions in the tunnel current vs. voltage curves as a function of magnetic field. The splitting of the interacting Landau levels is about 10 meV, which cannot be explained by non-parabolicity of the conduction band in GaAs. Possible reason for the observed interaction connected with the collective excitations in the 2DES is discussed.

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In the case of a spherical energy-band model, there is no interaction between Landau levels of different two-dimensional subbands in normal magnetic field and the intersection (crossing) of two Landau levels is allowed [1]. Interaction between Landau levels has been observed previously only in tunnelling studies of surface quantization in narrow gap PbTe [2]. In this case weak coupling can have large effect which leads to the anti-crossing effect observed in tunnelling spectra.

As far as we know a similar effect has not been observed in wide band gap semiconductors, e.g. GaAs. This may be understood as follows: to observe interaction between

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Landau levels in tunnelling experiments it is necessary to detect both tunnelling processes with Landau levels index change and with Landau level index conservation. The former is usually weak in comparison with the latter since it takes place only in the presence of the strong elastic scattering in the tunnel structures. In relatively clean samples, which are mainly used for tunnel current measurements, the experimental features related to tunnelling with or without conservation of Landau level index are quite different in amplitude, and even if they do cross, it is difficult to judge the nature of the interaction between Landau levels.

In this work we investigate the current-voltage characteristics of the heterostructure GaAs/AlGaAs/GaAs with tunnelling between strongly disordered two-dimensional electron systems (2DES) in a magnetic field parallel to the direction of current flow. Due to the strong elastic scattering-assisted tunnelling the amplitude of the peaks related to the tunnelling between Landau levels is of the same order of magnitude for processes both with Landau level index conservation and without. This allows us to study interaction between the Landau level ladders of the two 2DEG. We find that the interaction between Landau levels of the different two-dimensional subbands in GaAs is very strong and the observed splitting is about 10 mV, comparable to the splitting observed in PbTe [2]. Possible reasons for the observed interaction are 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 $3 \cdot 10^{11}\,cm^{-2}$ located 5 nm from each side of the barrier. Samples were fabricated into mesas of diameters $100-400\,\mu m$. The tunnelling transition probability of the main barrier is much lower than that of the spacer regions, so that almost all 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 concentrations approximately equal to the donor doping levels. The schematic band diagram of the structure at zero bias is shown in the insert of Fig.1. The typical electron mobility in the 2DES is estimated to be about $\mu = 1000\,cm^2 \cdot V^{-1} \cdot s^{-1}$ at 4.2 K. In our experiments, electron transport along the layers does not contribute to the measured tunnel current which flows perpendicular to the plane of the barrier.

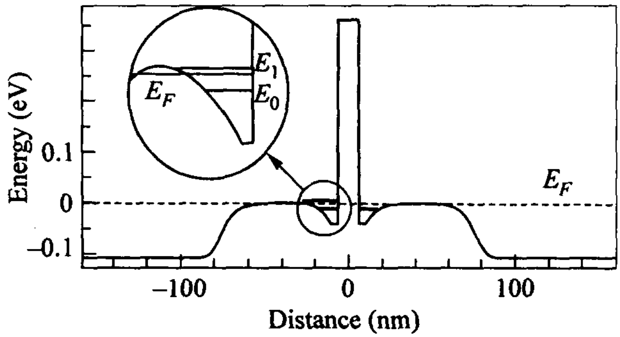

Fig.1. A schematic band diagram of the structure at zero bias. Insert shows the energy levels in the two-dimensional system in more details. E_0 and E_1 are correspondingly the energy of the ground and excited two dimensional states. E_F – Fermi energy

Fig.2 shows the differential tunnel conductance G, at 4.2 K, measured using standard lock-in techniques, versus external bias voltage V_b at various magnetic fields up to 15 T. In zero magnetic field (lowest curve in Fig.2) the differential conductance has a peak at zero bias and two pronounced shoulders at higher voltage for both polarities. We argue

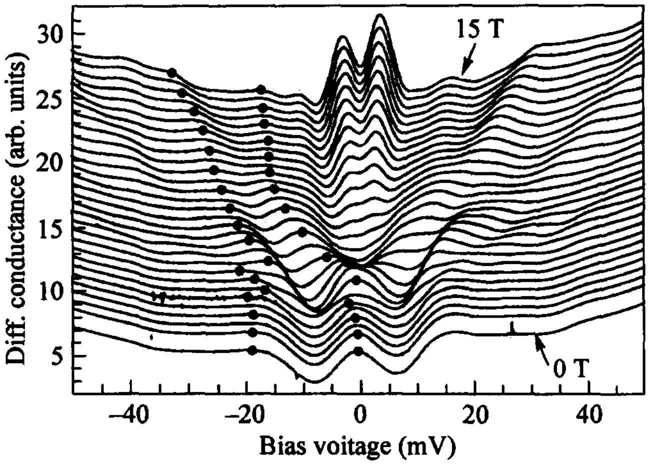

Fig.2. Tunnelling differential conductance at 4.2 K as a function of external voltage in different magnetic fields for a mesa of diameter 400 μm. The curves are shifted for clarity in vertical direction. The lowest curve is for $B = 0$ T, the top one – for $B = 15$ T. Magnetic field step between curves $\Delta B = 0.5$ T. The curve for $B = 0.5$ T is absent. Circles mark the peaks whose evolution with magnetic field are discussed in the paper

that the zero voltage peak reflects resonant tunnelling between the ground states of the 2DESs, and that the shoulders are due to resonant tunnelling between the ground state of the emitter 2DES (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 tunnelling process. The evolving structure in the curves with increasing magnetic field is due to resonant tunnelling between different Landau levels, which we now consider in more detail.

Around $B = 6$ T, which is close to Landau level filling factor $n = 2$ for the 2DES, the measured $G(V)$ curves show (see Fig.2) 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. The details of the equilibrium tunnelling processes around zero bias with magnetic field have been discussed previously [3].

In this work, we concentrate on the evolution of the structure related with tunnelling between different Landau levels. We focus on the shoulders in G which are indicated by circles in Fig.2. Their fan diagram (positions on the voltage scale versus magnetic field) is shown in Fig.3. For simplicity we consider only negative bias; the observed structure is symmetrical around zero bias except for certain details which we will not consider here. To understand the data, it is easiest to begin with the curves at high magnetic fields. At fields higher than 12 T, circles correspond to the tunnelling 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. $(n = 0, N = 0) \rightarrow (n = 0, N = 1)$ tunnelling. The dashed line labelled A has a slope equal to $L\hbar\omega_C$, where $\hbar\omega_C$ is the cyclotron energy, L is the electrostatic leverage factor, equal to 1.28 for our structure. This gives the positions of the peaks for $\Delta N = 1$ tunnelling in the case of ideal Landau level quantization. The dashed line labelled B gives the positions of the peaks for ideal $\Delta N = 2$ tunnelling. For broadened Landau levels the differential tunnelling conductance which we measure 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 $(n = 0, N = 0) \rightarrow (n = 0, N = 1)$ tunnelling is shown by the

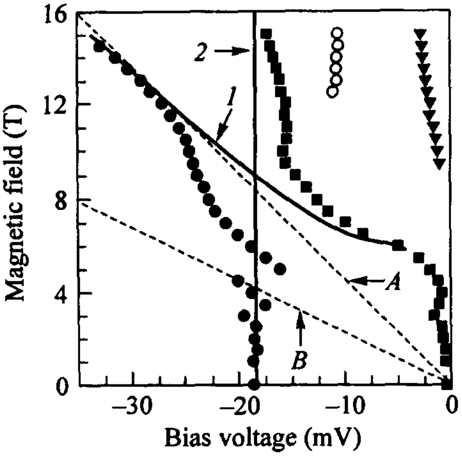

Fig.3. Peak positions on the voltage scale as a function of magnetic field. Circles, squares and triangles represent experimental data and are discussed in the text. Curve *1* is calculated peak positions for the $(n = 0, N = 0) \to (n = 0, N = 1)$ tunnelling process, where n is the main quantum number of the two-dimensional state, N – Landau level index. Vertical line, labelled *2*, represents expected position of the peak for $(n = 0, N = 0) \to (n = 1, N = 0)$ tunnelling process. Both curves *1* and *2* are calculated in the absence of the interaction between Landau levels. Lines A and B has a slope equal to $L\hbar\omega_C$, and $2L\hbar\omega_C$, where $\hbar\omega_C$ – is cyclotron energy, L is the leverage factor in the structure. These lines represent tunnelling between Landau levels with $\Delta N = 1$ and $\Delta N = 2$ correspondingly in the case of the ideal Landau level quantization

curve labelled *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 corresponds to the vertical line labelled *2*. This coincides with the position of the peak due to resonant tunnelling between ground 2D state in the emitter and first excited state 2D state in the collector with $B = 0$. Without interaction between Landau levels, the lines describing peak positions of the different processes versus magnetic field dependencies should intersect, as do the curves *1* and *2*. In contrast, curves presented as circles and squares in Fig.3 exhibit obvious anti-crossing, 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 observed splitting is about 10 meV. Some deviations are also evident around the point where the line labelled B intersects the vertical line *2*. These deviations indicate that interaction between Landau levels $(n = 0, N = 2)$ and $(n = 1, N = 0)$ in the collector 2DES also takes place, but the resolution of the features is not high enough. For completeness we also indicated the position of the peaks around zero voltage (triangles in Fig.3) which are due to the development of the tunnelling gap at the Fermi level in magnetic field [3]. The origin of the additional peaks, which appear in magnetic fields higher than 12 T around 14 mV (open circles in Fig.3), is not clear. We tentatively propose that they are related to spin splitting in the 2DES.

We now discuss possible mechanisms for the strong (~ 10 meV) anti-crossing of the Landau levels $N = 1$ from the ground subband $n = 0$ and $N = 0$ from the excited subband $n = 1$. Naturally, such a mechanism should mix longitudinal and transverse motion of electrons in the 2D layer. Experiments in tilted magnetic fields have shown that the accuracy of the magnetic field orientation ($\mathbf{B} \parallel \mathbf{J}$) is high enough to rule out the possibility that the anti-crossing is due to effects associated with an unwanted in-plane component of magnetic field. A second possible origin of the anti-crossing is the weak non-parabolicity of the electron spectrum in GaAs. A qualitatively similar anti-crossing was observed in the 2D layer of the highly non-parabolic material PbTe [2]. But in the latter case the strong anti-crossing was caused by the fact that the main axes of the constant energy ellipsoids of the conduction band minimum (L-point of the Brillouin zone) are not along the direction of growth. This is not the case for GaAs, and the theoretical estimation of contribution of the non-parabolicity yields an anti-crossing effect of only $\sim 1\,\mathrm{meV}$ – too small a value to account for our observations.

Alternative explanation of the anti-crossing is connected with the collective excitations. It is necessary to consider possible mechanisms of the energy relaxation of an electron which tunnels onto the excited level in a system with totally discrete spectrum. It is known that if the energy gap between this level and the Fermi level is a multiple of the LO-phonon energy, the energy relaxation will be governed by resonant emission of LO-phonons. This corresponds to the appearance of the phonon replicas on the tunnel spectra. Otherwise, such relaxation is forbidden. Nevertheless, in all cases the relaxation accompanied by emission of 2D magnetoplasmons having the gap equal to the cyclotron frequency (intra-subband magnetoplasmons) or intersubband gap (inter-subband plasmons [4]) is energetically allowed. Note, that conservation of the momentum in these processes is provided with strong electron-impurity scattering in our "dirty" system. The observed anti-crossing occurs at a magnetic field which corresponds to the crossing of the intra- and inter-subband magnetoplasmons. Accordingly, the observed anti-crossing of two peaks may be interpreted as a manifestation of the relaxation on "hybrid" intra-inter-subband magnetoplasmons. In the case $B = 0$ such hybrid plasmons were theoretically investigated in [5, 6]. It could be expected that the anti-crossing in this case would be of the order of Coulomb interaction in the 2DES, which is just have been found in measurements.

In summary we have investigated tunnelling 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. The explanation of the observed anticrossing related with the excitation of inter- and intra-subband magnetoplasmons in the 2DES is proposed.

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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. **A24**, 461 (1967); G.A.Barraf and J.A.Appelbaum, Phys. Rev. **B5**, 475 (1972).
2. D.C.Tsui, G.Kaminsky, and P.H.Schmidt, Phys. Rev. **B9**, 3524 (1974).
3. Yu.N.Khanin, Yu.V.Dubrovskii, E.E.Vdovin et. al., Physica **E67**, 3836 (1991).
4. D.A.Dahl and L.J.Sham, Phys. Rev. **B16**, 651 (1977).
5. R.Z.Vitlina and A.V.Chaplik, ZhETF **81**, 1011 (1981).
6. J.K.Jain and S.Das Sarma, Phys. Rev. **B36**, 5949 (1987).