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SUPPRESSION OF THE EQUILIBRIUM TUNNELING CURRENT BETWEEN SLIGHTLY DISORDERED TWO-DIMENSIONAL ELECTRON SYSTEMS WITH DIFFERENT ELECTRON CONCENTRATIONS IN A HIGH MAGNETIC FIELD

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Tunnelling between parallel two-dimensional electron gases (2DEG) in accumulation layers formed on both sides of the single doped AlGaAs barrier are examined in both zero and high magnetic field. Accumulation layers are separated from highly n-doped contact regions which freely supply electrons to the 2DEGs via 80 nm thick lightly n-doped spacer layers. Strongly oscillating current with magnetic field along the 2DEG's is absent in this arrangement. Without magnetic field resonant tunneling between 2DEGs with different as grown electron concentration could be settle by application of external voltage bias. High magnetic fields ($\nu < 1$) shift resonant tunnelling to zero external bias and suppresses tunnelling current, creating wide gap in the tunneling density of states at the Fermi level arisen from the in-plane Coulomb interaction in the 2DEGs.

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As have been found during last decade [1 – 7] both resonant and many-body effects play essential role in tunnelling between parallel two-dimensional electron gases (2DEG). In earlier work [1] resonant tunnelling between different two-dimensional (2D) subbands as well as inter and intra Landau level tunnelling in magnetic field normal to the 2D plane were thoroughly investigated. It was shown [2] that in-plane magnetic field also strongly influence resonant tunneling between two 2DEGs as it requires the conservation of both energy and in-plane momentum. The so-called Coulomb gap in the tunneling density of states induced by magnetic field was observed for equilibrium tunneling between 2D electron systems [3 – 6] as the suppression of the tunneling current by magnetic field, and gave rise to intensive theoretical discussions [8 –10]. There is a general agreement that the observed suppression is related to the in-plane Coulomb correlation between 2D electrons in a high magnetic field. Another manifestation of the Coulomb correlation was found in double barrier resonant tunneling devices [7] as the resonance current peak shift to higher voltage bias in a magnetic field. In spite of the large number of works there are still some contradictions even between the experimental findings of the different groups and it seems the current understanding of the phenomena is far from clear.

In this letter we present results of tunneling current measurements on single doped barrier heterostructures GaAs/AlGaAs/GaAs at liquid helium temperatures and in magnetic field up to 23 T. In these kind of structures two-dimensional electron accumulation layers are formed on both sides of the barrier due to its donor doping and are separated from highly n-doped contact regions by lightly n-doped or undoped spacer layers [1, 11]. At first sight our sample resembles the system where two sequential 2D electrons planes are inserted between three-dimensional contact layers with generally unknown potential distribution along the current flow under external bias. To avoid this problem it is necessary to design the structure in such a way that the external voltage will drop mainly on the (AlGa)As barrier. It gives one a sample where 2D and 3D systems are in thermodynamics equilibrium on each side of the barrier with a free supply of electrons to the 2DEG accumulation layer from the parallel planar contact layer under arbitrary external bias. By thorough capacitance-voltage measurement on samples prepared from a number of wafers with different growth parameters we selected the structure which satisfied the condition of thermodynamics equilibrium between 2D accumulation layer and highly doped contact region. The main criterion for this selection was the independence of the capacitance on applied bias and its approximate equality to the geometrical capacitance of the barrier. In this letter we present only results obtained on the selected samples and related in fact with tunneling between 2D electron systems. The arrangement of the structure used essentially distinguishes our measurements from previous work [1, 3 – 6] where strongly oscillating current along 2DEGs in magnetic field was not excluded from the experimental arrangement. Without magnetic field resonant tunneling between 2DEGs with different as grown concentration could be settle by application of external voltage bias. We have found that high magnetic fields ($\nu < 1$) shifts resonant tunneling to zero external bias due to the last Landau level pinning in each 2DEG by contact layer chemical potential. This gives us rise to study magnetic field suppression of the equilibrium tunneling between 2DEGs in the pure vertical arrangement (no current along 2DEGs) and compare our results with recent experimental observations of the magnetic field induced Coulomb gap in the tunneling density of states [4, 5, 7]. We have found linear dependence of the gap parameters on magnetic field in agreement with findings of Ref. [5], which are in contradiction to the results of Ref. [4, 7] where significantly weaker dependence of the gap width on magnetic field were found.

The samples were grown by molecular beam epitaxy (MBE) on a (100)-oriented Si-doped n^+-type GaAs wafer ($N_d = 2 \cdot 10^{18}$ cm^{-3}). The structure consists (in order of growth) of a Si-doped, 50 nm thick GaAs layer ($N_d = 5 \cdot 10^{17}\,\mathrm{cm}^{-3}$); 70 nm lightly doped GaAs layer ($N_d = 2 \cdot 10^{15}\,\mathrm{cm}^{-3}$); 10 nm thick undoped GaAs; 5 nm thick $\mathrm{Al_{0.3}Ga_{0.7}As}$ undoped barrier layer; 10 nm thick Si doped, $\mathrm{Al_{0.3}Ga_{0.7}As}$ barrier layer ($N_d = 6 \cdot 10^{17}\,\mathrm{cm}^{-3}$); 5 nm thick $\mathrm{Al_{0.3}Ga_{0.7}As}$ undoped barrier layer; 10 nm thick undoped GaAs; 70 nm lightly doped GaAs layer ($N_d = 2 \cdot 10^{15}\,\mathrm{cm}^{-3}$); 50 nm thick GaAs layer ($N_d = 5 \cdot 10^{17}\,\mathrm{cm}^{-3}$); Si-doped, 50 nm thick GaAs layer ($N_d = 5 \cdot 10^{17}\,\mathrm{cm}^{-3}$); and a GaAs cap layer ($N_d = 1.5 \cdot 10^{18}\,\mathrm{cm}^{-3}$) which was 300 nm thick. In order to fabricate ohmic contacts an AuGe/Ni/Au metallic film was evaporated on the n^+-type GaAs cap layer. Mesa structure (100μm in diameter) were defined by wet etching (2μm depth) using metal as mask. A second ohmic contact was prepared on the back side of the wafer by In soldering. A standard annealing process (400^{o}C, 2 min in a N_2 atmosphere) gave good ohmic contacts ($10^{-6} - 10^{-5}$ Ohm$\cdot$ cm^{-2}). The schematic band diagram of the structure under zero bias is shown in Fig.1.

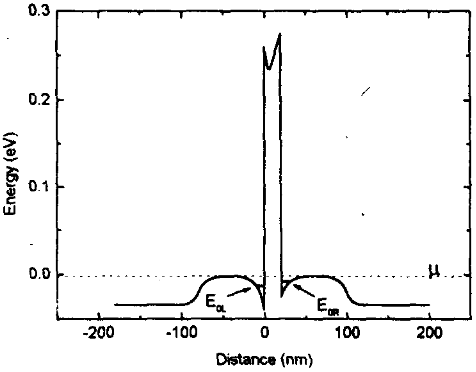

Fig.1 The schematic band diagram of the structure under zero bias. E_{0L} and E_{0R} define the ground states of 2D accumulation layers, μ – chemical potential along the structure under equilibrium condition

The current-voltage IV characteristic of this structure demonstrates negative differential conductance (NDC) (indicated by arrow "a" on Fig.2) at negative bias without magnetic field and some features at positive bias (arrow "b" on the same Figure) at 4.5 K. We argue that as in the Ref. [1] the current peak followed by NDC region is due to the resonance between ground states of 2DEG's (0-0 transition) and rapid increase in current with around 12 mV of positive applied bias to the resonance between ground state of one 2DEG and first excited state of another one (0-1 transition). The accumulation layers have different as grown electron concentration.

We estimated 2D electron concentrations and electron mobility in the layers from measured I-V dependence and Shubnikow – de-Haas like tunnel current oscillations with magnetic field. For this estimation we used procedure described in Ref. [6], and found the 2D electron concentrations $N_{2D-1} \approx 3 \cdot 10^{11}\,\mathrm{cm}^{-2}$, $N_{2D-2} \approx 1.8 \cdot 10^{11}\,\mathrm{cm}^{-2}$, and estimated mobility is about $40000\,\mathrm{cm}^2\mathrm{V}^{-1}\mathrm{s}^{-1}$.

Fig. 2 shows transformations of the IV curves with magnetic field parallel to the current. For fields smaller than 12 T the curves have quite complicated forms which can be described in principal with interplay of resonance tunneling between different Landau levels taking into account also existence of two-dimensional subbands with higher indexes and self-consistent redistribution of the electrons between accumulation layers with density of states modulation by magnetic field.

In this letter we are concentrating on the discussion about the IV curves behaviour with magnetic fields greater than 14 T, leaving the discussion about smaller magnetic field range to our another future publication.

In a magnetic field parallel to the current greater than 14 T ($\nu < 1$) the IV characteristic are drastically changed (Fig.2). Now the NDC appears at both voltage polarities. We assign this behaviour to the magnetic field induced resonance at zero voltage. Indeed, when only one Landau level is occupied in both electron layers the Fermi level in the contact regions pin the Landau levels and both 2DEG's, in spite of the different electron concentration, are brought to the tunnelling resonance. We note that any spin splitting have not been observed in our structures. The IV characteristics in a magnetic field with the current suppressed around zero bias are similar to those which were observed in references [3, 5], but asymmetrical. More obviously the suppression can be seen from

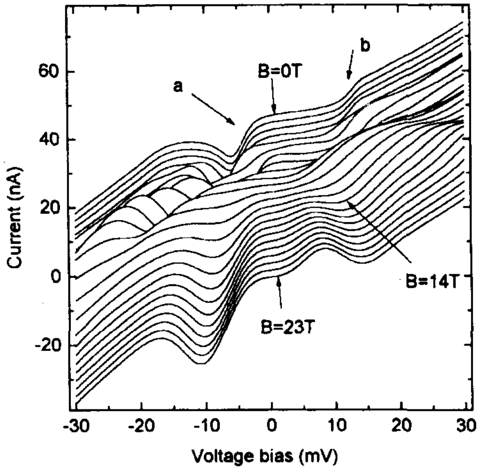

Fig.2 Current-voltage dependences without and in different magnetic fields up to 23 T. Magnetic field step between the curves is 1 T. The curves are shifted verticaly for clarity except 23 T curve. Arrows "a" and "b" indicate pecularities on the IV curve without magnetic field (Details in the text)

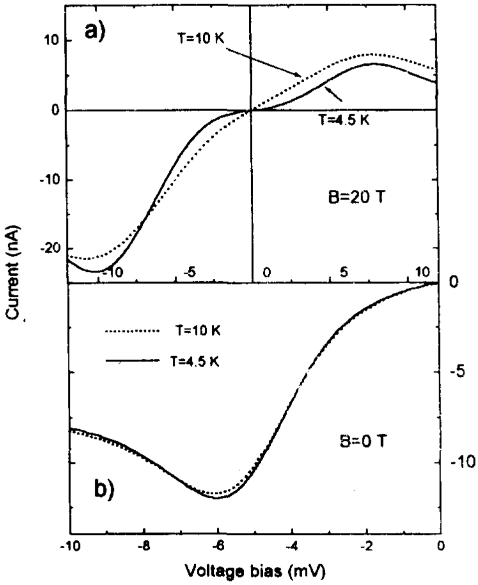

Fig.3 a) Current-voltage dependences in magnetic field 20 T for different temperatures: 4.2 K - solid line, 10 K - dotted line, b) the same without magnetic field

Fig.3a where IV curves are shown for 4.2 K and 10 K in the magnetic field $B = 20\,\mathrm{T}$. For comparison, Fig.3b shows the part of the same curves without magnetic field which clearly demonstrates that influence of temperature on the simple resonant tunneling between 2DEGs is very small. Previously [3] the current suppression around zero bias and wide current peaks at higher biases were interpreted as a manifestation of the gap in the tunneling density of states with broaden final states around the gap.

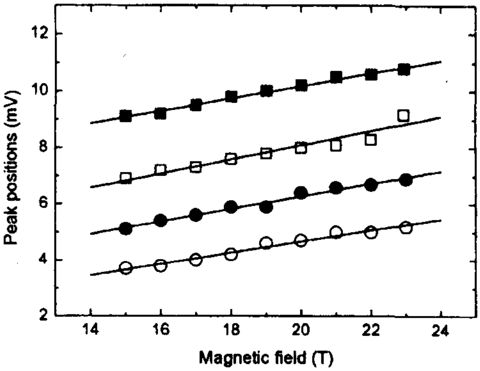

Fig.4 Current peaks and differential conductance maximums position on the voltage scale as a function of magnetic field. Squares are used for current peak positions, circles for differential conductce maximums. Solid squares and circles – for negative bias, open – for positive bias. Averaged dependence of all the data on magnetic field is $\sim (0.14 \pm 0.2)\hbar\omega_c$. Straigt lines are shown only as the guide for the eye

To characterize the gap in our experiments we chose the positions of current peaks and differential conductance maximums on voltage scale as the gap parameters. Fig.4 shows that all of these parameters have linear dependence on magnetic field and from these dependences the gap dependence on magnetic field could be described as $\Delta/2 \approx$ $\approx (0.14 \pm 0.02)\hbar\omega_c$, where $\hbar\omega_c = \hbar eB/m^*$ is the cyclotron energy. We also used 10% onsets of the current to estimate gap width. It is few mV for both positive and negative bias and is the same order of magnitude as the Coulomb interaction energy in the 2D layers.

To compare our results with findings of the previous studies [3 - 7] it is worth first of all to make some remarks here. The reasons of the gap appearance in the tunneling density of states (DOS) is following. In a strong normal to the 2D plane magnetic field, when the Landau level filling factor $\nu = hn/eB$ is less than unity, it is assumed that electron traverses the tunnel barrier between the 2DEGs in a much shorter time scale than the charge rearrangement around the injected electron (or around the hole left behind in the emitter layer). The energies of the injection and extraction processes create a gap in the tunneling DOS. Many-body theories predict [8] that for a fixed filling factor, $\nu < 1$, the width of the energy gap is approximately $0.4e^2/4\pi\varepsilon l_B$ (where $l_B = \sqrt{\hbar/eB}$ is the magnetic length), or if the electron liquid forms a regular lattice [9] the gap energy in classical limit is $e^2/4\pi\varepsilon a$ (where $a = \sqrt{n\pi}$ is the interelectron spacing within layer). At fixed filling factor both predicted forms for the gap have the same $\sqrt{B}$ dependence with magnetic field.

Eisenstein and co-workers [4] argued from the tunneling measurements on the samples with different barrier width that the high field gap energy is mainly determined by the in-plane Coulomb interaction, modified by an interlayer excitonic binding energy. The form of the gap used to fit their data was $\Delta_E = f(\nu)\ e^2/4\pi\varepsilon a - 0.4e^2/4\pi\varepsilon d$, where $f(\nu)$ is some universal function of filling factor, and d is the quantum well center to center separation.

Contrary to Eisenstein et al. findings [3, 4] and current theories predictions [8, 9] Brown et al. [5] found linear magnetic field dependence of the gap, $\Delta \approx 0.44\hbar\omega_c$, that was observed both at fixed filling factors and constant carrier density. They measured gaps of comparable energy in lower mobility, but otherwise similar samples to those used by Eisenstein et al. GaAs/AlGaAs double-layer structures with additional gates to control independently electron concentration in the layers. In addition, at fixed magnetic field 16 T they did not observe noticeable changes in the measured I-V curves when the electron concentration in the layers were varied from 1 to $3 \cdot 10^{11}\,\mathrm{cm}^{-2}$ (Fig.3 in Ref. [5]).

Lok et al. [7] by measurements on different (AlGa)As double-barrier resonant tunneling devices found that at $T = 0$ the additional energy Δ_L required for resonant tunneling in high magnetic fields increases with increasing electron concentration n in the emitter 2DEG from 0.7 to $3.0 \cdot 10^{11}\,\mathrm{cm}^{-2}$ and can be described by the dependence $\Delta_L = \beta e^2/a \sim n^{1/2}$ ($\beta \approx 0.6 - 0.8$). Additional energy Δ_L dependence on magnetic field for single device showed saturation for $\nu < 1$. The results at least qualitatively agreed with ones obtained by Eisenstein et al. [4], but in contradiction to the Brown's et al. findings [5].

Our samples have serious restriction since we were not able to change the electron concentration in the accumulation layers. Nevertheless, Brown et al. mentioned in their paper [5] that the same results, as for equal concentration, were obtained when measuring the magnetic field suppression with different electron concentration in the layers. This allows us to compare our results at least with Browns et al. findings.

Our results imply a linear dependence of the gap on magnetic field, $\Delta \approx 0.28\hbar\omega_c$, which is similar to $\Delta \approx 0.44\hbar\omega_c$ in Brown's et al. paper [5]. The tunneling gap found by Eisenstein et al. [4] due to the prefactor $f(\nu)$ also depends on magnetic field at constant electron concentration. However, as can be seen from Fig.1 in Ref. [3] this dependence is weak and does not exceed $\Delta \approx 0.03\hbar\omega_c$. The main difference between Eisenstein and Brown samples is the difference of the 2DEGs quality. In the Eisenstein experiments the 2DEGs had $\mu \sim 3 \cdot 10^6\,\mathrm{cm}^2\,\mathrm{V}^{-1} \cdot \mathrm{s}^{-1}$ whereas in the Brown experiments only mobilities of $\mu \sim 10^5\ \mathrm{cm}^2\,\mathrm{V}^{-1} \cdot \mathrm{s}^{-1}$. In our samples the mobility in the layers $\mu \sim 4 \cdot 10^4\,\mathrm{cm}^2\,\mathrm{V}^{-1} \cdot \mathrm{s}^{-1}$. It is difficult to judge about the 2DEG mobility in resonant tunneling devices of Ref. [7], but it should be noted that tunneling gap induced by magnetic field was, in this work studied, far away from equilibrium conditions. The magnitude of the gap in all experiments is of the order of Coulomb interaction energy in the layers.

From the above comparison it could be supposed that microscopic nonhomogenities and disorder not only determine the mobility in the 2DEG but also influence the magnetic field induced gap formation in the tunneling density of states giving rise to a different dependence of the gap on magnetic field in comparison with the case of the high quality two-dimensional electron systems. As far as we know this influence has not yet been considered theoretically.

Thus we have investigated the equilibrium tunnelling between 2DEG's in a high magnetic field in the structure with pure vertical transport for the first time. High magnetic field induced resonant tunnelling between 2DEG's with different electron concentration at zero external voltage bias via pinning of the last Landau levels by Fermi levels in contact regions. This gave us opportunity to investigate and compare our data concerning tunnelling current suppression by high magnetic field near zero bias with previous studies.

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