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Tunneling between strongly localized two-dimensional electron systems

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Over the last decade, various authors have shown that [1–7] both resonant and many-body effects play an essential role in tunnelling between parallel two-dimensional electron gases (2DEG). In earlier work [ ] resonant tunnelling between different two-dimensional (2D) subbands as well as inter and intra Landau level tunnelling in a magnetic field normal to the 2D-plane were thoroughly investigated. It was shown [ ] that the 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 was observed as the suppression of the tunneling current by a magnetic field for equilibrium tunneling between 2D-electron systems [3–6]. 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 [ ] where the voltage position of the resonant current peak shifted to higher voltage bias in a magnetic field. Recently it was shown [ ] that weak disorder influences the suppression of the tunneling current and gives rise to a linear dependence of the gap magnitude on magnetic field in the ultraquantum limit (filling factor $\nu < 1$) while a square root dependence was observed [,] for high quality 2DEGs.

In this work we present tunneling current measurements between strongly disordered two-dimensional electron systems (2DES) in a magnetic field parallel to the current. To form the 2DES we used Si donors sheets (δ-doped layers) with the donor concentration slightly above metal-insulator transition in the corresponding electron system [,]. In a high enough magnetic field all the electrons in the studied δ-doped layers were strongly localized. In our experiments electron transport along the layers did not contribute to the measured current due to the special structure arrangement [ ] (pure vertical transport). This allows us to measure for the first time the equilibrium current which is proportional to the tunneling density of states of the strongly localized 2D electron systems in a magnetic field.

The sample grown by MBE 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. Si donors sheets with concentration of 3×10^{11} cm^{-2} were located 5 nm from each side of the barrier. Measurements of the Shubnikov–de-Haas like oscillations in the tunneling current gave the same electron sheet

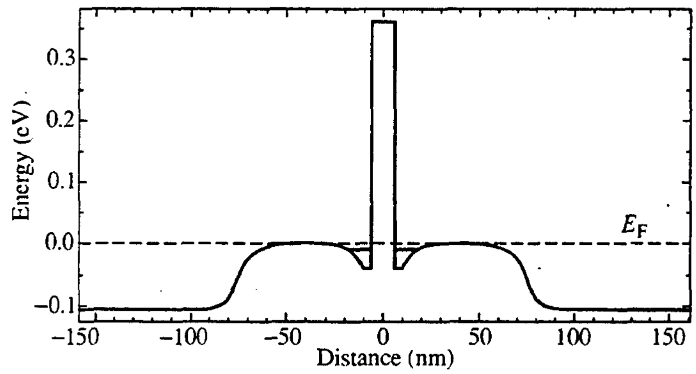

Fig. 1. Schematic band diagram of the structure at zero bias.

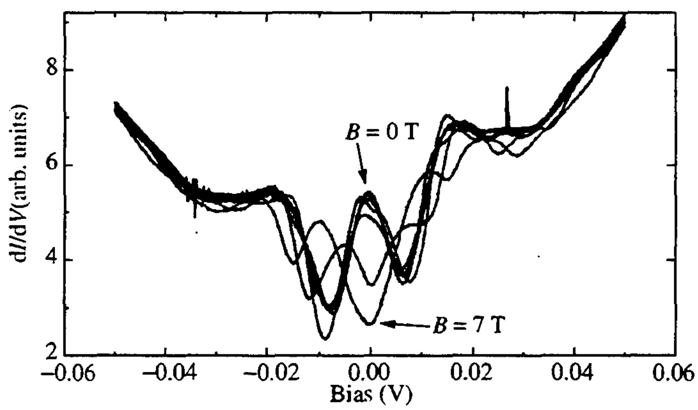

Fig. 2. The tunneling differential conductance as a function of external voltage in different magnetic fields up to 7 T. Magnetic field step between the curves is 1 T.

concentrations as the donor doping levels. Samples studied had 100 μm mesa diameters. The schematic band diagram of the structure under zero bias is shown in Fig. 1.

Figures 2 and 3 show the differential conductance versus external voltage at various magnetic fields. In zero magnetic field the differential conductance has a peak at zero voltage and two pronounced shoulders at higher voltages of both polarities. We argue that the zero voltage peak reflects resonant tunneling between ground states of the 2DEGs, and the shoulders are due to resonant tunneling between subbands of different indexes (0-1 transition). For our structure the metal-insulator transition is expected for a critical field about 5 T when the magnetic length becomes equal to the average donor separation.

The experimental curves could be described in principle on the interplay of resonance tunneling between different Landau levels taking into account the existence of two-dimensional subbands with higher indexes and the self-consistent redistribution of the electrons between accumulation layers as the density of states is modulation by the magnetic field.

In this work we concentrate on the equilibrium tunneling processes around zero bias. In magnetic fields around the critical value, the tunneling differential conductance exhibits a minimum at zero bias. At the same time only the lowest energy Landau levels in the respective layers are occupied (the spin splitting is not resolved) and as the result there is the minimum in the density of states around the Fermi level. The tunneling differential

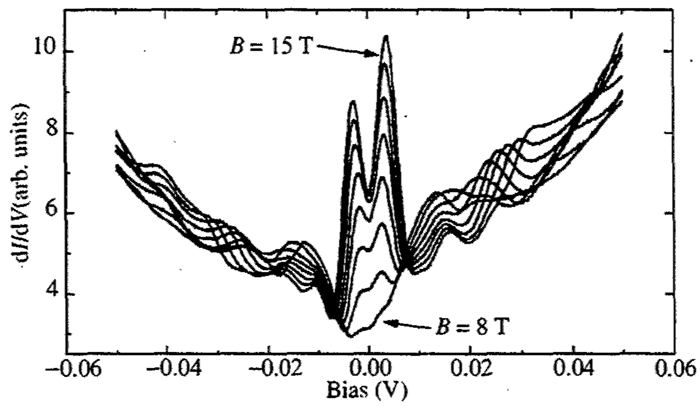

Fig. 3. The tunneling differential conductance as a function of external voltage in different magnetic fields from 8 T to 15 T. Magnetic field step between the curves is 1 T.

conductance at low voltage directly reflects the joint density of states at the Fermi levels in the 2D electron layers. With a futher increase of the magnetic field, the minimum of the differential conductance at zero bias gradually converts to a maximum reflecting again the density of states at the Fermi level. At the same time a dip at zero bias appears which reflects the gap in the tunneling density of states around the Fermi level of the strongly localized 2D electron systems.

The distance between maxima is well described by the expression $\Delta = (0.30 \pm 0.01)\hbar\omega_c$, where ω_c is the cyclotron frequency. It is difficult to compare this value with current theories because as far as we know there are no calculations of the gap dependence on the magnetic field for the strongly localized system. We would like only to emphasise that the measured dependence surprisingly coincides with the gap dependence on the magnetic field found for tunneling between slightly disordered 2D electron systems $\Delta = (0.28 \pm 0.02)\hbar\omega_c$ [ ] for $\nu < 1$.

Thus we have investigated equilibrium tunnelling between strongly localized 2D electron systems in a high magnetic field in the structure with pure vertical transport. High magnetic field suppresses equilibrium tunneling creating a gap in the tunneling density of states which depends linearly on magnetic field.

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