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LATERAL TUNNELING THROUGH THE CONTROLLED BARRIER BETWEEN EDGE CHANNELS IN A TWO-DIMENSIONAL ELECTRON SYSTEM

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We study the lateral tunneling through the gate-voltage-controlled barrier, which arises as a result of partial elimination of the donor layer of a heterostructure along a fine strip using an atomic force microscope, between edge channels at the depletion-induced edges of a gated two-dimensional electron system. For a sufficiently high barrier a typical current-voltage characteristic is found to be strongly asymmetric and include, apart from a positive tunneling branch, the negative branch that corresponds to the current overflowing the barrier. We establish the barrier height depends linearly on both gate voltage and magnetic field and we describe the data in terms of electron tunneling between the outermost edge channels.

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Recently there has arisen much interest in the lateral tunneling into the edge of a two-dimensional electron system (2DES), which is related not only to the problem of integer and fractional edge states in the 2DES but also to that of resonant tunneling and Coulomb-blockade [1 – 7]. The tunneling regime was identified by exponential dependences of the measured current on either source-drain voltage [1 – 4] or magnetic field [5]. For producing a tunnel barrier a number of methods were used: (i) gate voltage depletion of a narrow region inside the 2DES [1 – 4,7]; (ii) focused-ion-beam insulation writing [6]; (iii) cleaved-edge overgrowth technique [5]. As long as the tunnel barrier parameters are not well controllable values, it is important that using the first method one can tune the barrier on the same sample. In contrast to vertical tunneling into the bulk of the 2DES at a quantizing magnetic field, when the 2DES spectrum shows up [8,9], in the lateral tunneling electrons can always tunnel into the Landau levels that bend up at the edge to form edge channels where they intersect the Fermi level, i.e., the spectrum gaps are not seen directly in lateral tunneling. Instead, it reflects the edge channel structure and density of states. For both the integer and fractional quantum Hall effect, a power-law behaviour of the density of states at the 2DES edge is expected. This can interfere with the barrier distortion at an electric field in the nonlinear regime of response and, therefore, results of lateral tunneling experiments obtained from the measurements of current-voltage curves [5] should be treated with care.

Here, we investigate the lateral tunneling in the narrow constrictions in which, along a thin strip across, the donor layer of a GaAs/AlGaAs heterostructure is partly removed using an atomic force microscope (AFM). A controlled tunnel barrier is created by gate depletion of the whole of the sample. The well-developed tunneling regime is indicated by strongly asymmetric diode-like current-voltage characteristics of the constriction which are sensitive to both gate voltage V_g and normal magnetic field B. The behaviour of the tunneling part of current-voltage curves points to electron tunneling between the outermost edge channels.

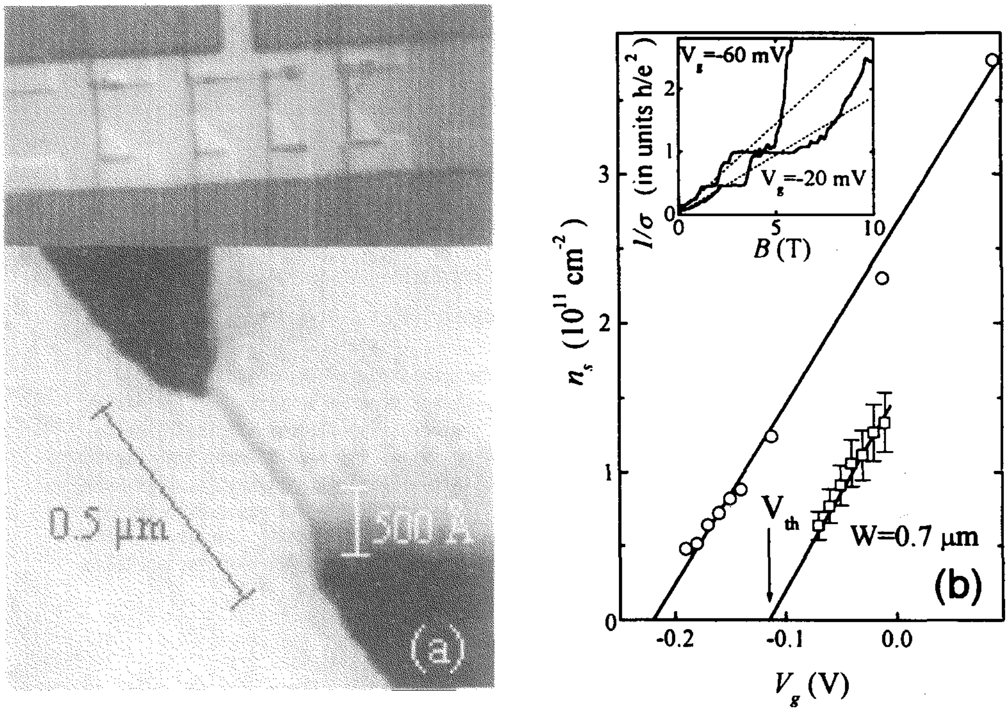

Fig.1. (a) Top view on the sample (top); and a blow-up of one of the constrictions upon etching the oxidized part of the mesa as performed solely for visualization purpose (bottom). (b) Gate voltage dependences of the electron density in the oxidized (squares) and unoxidized (circles) regions of the 2DES. An example of the magneto-conductance in the barrier region is shown in the inset. The value of n_s is extracted from the slope of dashed lines with 10% uncertainty.

The samples are triangular constrictions of a 2D electron layer with different widths $W = 0.7$, 0.4, 0.3, and 0.2 μm of the thinnest part, see Fig.1a. These are made using a standard optical and electron beam lithography from a wafer of GaAs/AlGaAs heterostructure with low-temperature mobility $\mu = 1.6 \cdot 10^6$ cm^2/Vs and carrier density $n_s = 4 \cdot 10^{11}$ cm^{-2}. Within each constriction the donor layer is removed along a fine line by locally oxidizing the heterostructure using AFM induced oxidation [10]. This technique allows one to define 140 Å wide oxide lines of sufficient depth and oxide quality so as to partly remove the donor layer and, therefore, locally decrease the original electron density. The whole structure is covered with a metallic gate, which enables us to tune the carrier density everywhere in the sample. When depleting the 2D layer the oxidized regions get depopulated first, resulting in the creation of tunnel barriers. Potential probes are made to the sample to allow transport measurements.

For the measurements we apply a *dc* voltage, V_{sd}, between source (grounded) and drain contacts of one of the constrictions modulated with small *ac* voltage with amplitude $V_{ac} = 40$ μV and frequency $f = 20$ Hz. A gate voltage is applied between the source and the gate. We measure the real part of the *ac* current, which is proportional to the differential conductance dI/dV, as a function of bias voltage V_{sd} ($I - V$ characteristics) using a home-made $I - V$ converter and a standard lock-in technique. The behaviour of

$I-V$ characteristics is investigated with changing both gate voltage and magnetic field. The measurements are performed at a temperature of about 30 mK at magnetic fields of up to 14 T. The results obtained on different constrictions are qualitatively similar.

To characterize the sample we extract the gate voltage dependence of the electron density from the behaviour of magneto-conductance plateaux in the barrier region and in the rest of the 2DES (Fig.1b). The analysis is made at high fields where the size-quantization-caused effect of conductance plateaux in narrow constrictions is dominated by magnetic field quantization effects [11]. As seen from Fig.1b, if the barrier region is depopulated ($V_g < V_{th}$), the electron density in surrounding areas is still high to provide good conduction. The slopes of the dependences $n_s(V_g)$ in the oxidized region and in the rest of the 2DES turn out to be equal within our accuracy. The distance between the gate and the 2DES is determined to be $d \approx 570$ Å; as the corresponding growth parameter is about 400 Å, the 2D layer thickness contributes appreciably to the distance d. We have found that even in the unoxidized region the electron density at $V_g = 0$ can be different after different coolings of the sample because of insignificant threshold shifts: it falls within the range $2.5 \cdot 10^{11}$ to $4 \cdot 10^{11}$ cm^{-2} and is always higher compared to the barrier region.

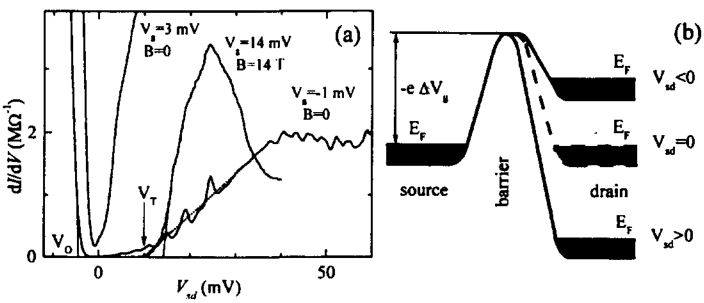

Fig.2. (a) $I-V$ curves at different gate voltages and magnetic fields. The cases of $B=0$ and $B \neq 0$ correspond to two coolings of the sample as compared in Fig.3a. $W = 0.4$ μm. (b) A sketch of the 2D band bottom in the barrier region for different source-drain biases V_{sd}

A typical $I-V$ characteristic of the constriction in the well-developed tunneling regime is strongly asymmetric and includes an overflowing branch at $V_{sd} < 0$ and the tunneling branch at $V_{sd} > 0$, see Fig.2a. The tunneling branch is much smaller and saturates rapidly in zero B with increasing bias voltage. The onset voltages V_O and V_T for these branches are defined in a standard way as shown in the figure. The tunneling regime can be attained by both decreasing the gate voltage and increasing the magnetic field, as is evident from Fig.2a. We check that the shape of $I-V$ characteristics is not influenced by interchanging source and drain contacts. Hence, the tunnel barrier is symmetric and the asymmetry observed is not related to the constriction geometry.

To understand the asymmetry origin let us consider a gated 2DES containing a potential barrier of approximately rectangular shape with width $L \gg d$ in zero magnetic field. The 2D band bottom in the barrier region coincides with the Fermi level E_F of the 2DES at V_g equal to the threshold voltage V_{th}. Since in the barrier region for $V_g < V_{th}$ an incremental electric field is not screened, the 2D band bottom follows the gate potential so that the barrier height is equal to $-e\Delta V_g = e(V_{th} - V_g)$, where $-e$ is an electron charge (Fig.2b). Applying a bias voltage V_{sd} leads to shifting the Fermi level in the drain contact by $-eV_{sd}$. Because of gate screening the voltage V_{sd} drops on the scale of the order of d near the boundary between barrier and drain and so the barrier height on the source side does not practically change, see Fig.2b. If V_{sd} reaches the onset voltage $V_O = \Delta V_g$, the barrier on the drain side vanishes and electrons start to overflow from drain into source.

In contrast, for $V_{sd} > 0$ the electron tunneling through the barrier from source into drain is only possible. With increasing V_{sd} above $-\Delta V_g$, the tunneling distance diminishes and the barrier shape becomes close to triangular. Within the triangular barrier approximation, in the quasiclassical limit of small tunneling probabilities, it is easy to deduce that the derivative of the tunneling current over bias voltage is expressed by the relation

$$\frac{\mathrm{d}I}{\mathrm{d}V} = \sigma_0 \exp\left(-\frac{4(2m)^{1/2}(-e\Delta V_g)^{3/2}L}{3\hbar e V_{sd}}\right) \ll \sigma_0, \tag{1}$$

where $\sigma_0 \approx -(e^2/h)\Delta V_g W/V_{sd}\lambda_F$, $m = 0.067m_0$ (m_0 is the free electron mass), and λ_F is the Fermi wave-length in the source. Obviously, the tunneling current is dominated by electrons in the vicinity of the Fermi level, and the tunneling distance $L_T = -\Delta V_g L/V_{sd}$ should satisfy the inequality $d \ll L_T < L$. In accordance with Eq. (1), the expected dependence of the tunneling onset voltage V_T on gate voltage is given by $V_T \propto (-\Delta V_g)^{3/2}$.

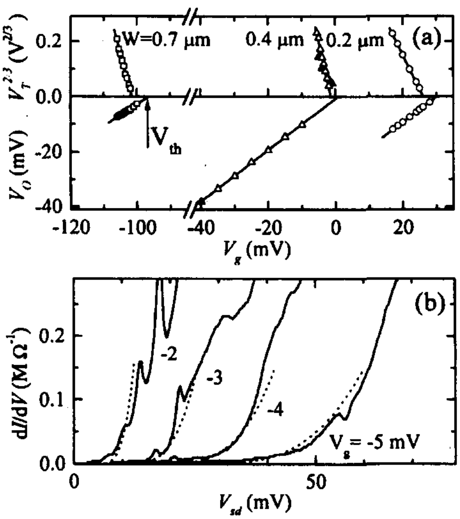

Fig.3.(a) Change of the onset voltages V_O and V_T as defined in Fig.2a with V_g at $B = 0$; and (b) the fit (dashed lines) of $I-V$ curves (solid lines) by Eq. (1) with the parameters $L = 0.6$ μm, $\sigma_0 = 38$ $M\Omega^{-1}$, $V_{th} = -0.4$ mV; $W = 0.4$ μm. In case (a), the data marked by filled triangles are obtained for the same cooling of the sample as the ones at $B = 0$ in Fig.2a and in case (b), whereas the open triangles correspond to the $B \neq 0$ data of Figs.2a and 4 as measured for the other cooling

As seen from Fig.3a, the expected behaviour of both V_O and V_T with changing V_g is indeed the case. The dependences $V_O(V_g)$ and $V_T^{2/3}(V_g)$ are both linear; the slope of the former is very close to one. Extensions of these straight lines intercept the V_g-axis at slightly different voltages, which points out that the triangular barrier approximation is good. The threshold voltage V_{th} for the 2DES's generation in the barrier region, which is defined as a point of vanishing V_O (Fig.3a), is coincident, within experimental uncertainty, with the value of V_{th} determined from the analysis of magneto-conductance plateaux (Fig.1b).

Fitting the set of $I-V$ characteristics at different V_g by Eq. (1) with parameters L, V_{th}, and σ_0 is depicted in Fig.3b. The dependence of σ_0 on ΔV_g and V_{sd} is ignored on the background of the strong exponential dependence of dI/dV. Although three parameters are varied, the fit is very sensitive, except for σ_0, to their variation because of the exponential behaviour of $I-V$ characteristics. One can see from Fig.3b that the above model describes well the experiment at zero magnetic field. As expected, the determined parameter $L = 0.6$ μm is much larger than d, i.e. the barrier shape at $V_{sd} = 0$ is approximately rectangular, and the value of V_{th} is close to the point where V_O (and V_T) tends to zero (Fig.3a). The similar results are obtained on the other two constrictions. Besides, we find that the coefficient σ_0 for different constrictions does not scale with the constriction width W. This probably implies that the tunnel barriers even with submicron lengths are still inhomogeneous, which, however, does not seem crucial for the case of exponential $I-V$ dependences.

Having tested that we deal with the controlled tunnel barrier we investigate the tunneling at a normal magnetic field that gives rise to emerging the tunnel barrier in a similar way to gate depletion (Fig.2a). At constant $V_g > V_{th}$, where there is no tunnel barrier in zero B, the magneto-conductance σ obeys the $1/B$ law at weak fields and drops exponentially with B in the high-field limit, signaling the tunneling regime. Fig.4a presents the magnetic field dependence of the onset voltage V_O that determines the barrier height. As seen from the figure, the change of the barrier height $-eV_O$ with B is very close to $\hbar\omega_c/2$, which points to a shift of the 2D band bottom by half of the cyclotron energy.

For describing the tunneling branch of $I-V$ characteristics we calculate the tunneling probability in the presence of a magnetic field. This is not so trivial as at $B=0$ because electrons tunnel through the magnetic parabola between edge channels at the induced edges of the 2DES. In the triangular barrier approximation one has to solve the Schrödinger equation with the barrier potential

$$U(x) = \frac{\hbar\omega_c}{2l^2}(x-x_0)^2 - eV_{sd}\frac{x}{L} - e\Delta V_g, \; 0 < x < L, \tag{2}$$

where ω_c is the cyclotron frequency, l is the magnetic length, and eV_{sd} is larger than the barrier height in the magnetic field. An electron at the Fermi level in the source tunnels through $U(x)$ from the origin to a state with orbit centre x_0 such that $0 < x_0 < L$. If the barrier potential is dominated by the magnetic parabola (i.e., the magnetic length is the shortest), the problem reduces to the known one to find energy levels in the shifted parabolic potential as caused by the linear term in Eq. (2). The value of x_0 is determined from the condition of coincidence of a Landau level in the potential $U(x)$ with the Fermi level in the source. If the lowest Landau level is regarded only and the spin splitting is ignored, we get the minimum tunneling distance to the outermost edge channel in the drain

$$x_0 = L_T = \frac{l}{2}\left(\frac{\hbar\omega_c L}{eV_{sd}l} - \frac{2\Delta V_g L}{V_{sd}l} - \frac{eV_{sd}l}{\hbar\omega_c L}\right) \gg d. \tag{3}$$

The first term in brackets in Eq. (3), which is dominant, is large compared to one. Knowing the wave function of the lowest Landau level in the potential $U(x)$ and neglecting the last term in Eq. (3) we obtain for the shape of $I-V$ characteristics near the onset, where the tunneling probability is small,

$$\frac{\mathrm{d}I}{\mathrm{d}V} = \sigma_B \exp\left(-\frac{(\hbar\omega_c/2 - e\Delta V_g)^2 L^2}{e^2 V_{sd}^2 l^2}\right) \ll \sigma_B. \tag{4}$$

Here σ_B is the pre-factor which can be tentatively expected to be of the same order of magnitude as σ_0. From Eq. (4) it follows that at sufficiently strong magnetic fields the tunneling onset voltage V_T is related to the barrier height as $V_T l \propto \hbar\omega_c/2 - e\Delta V_g$, which is consistent with the experiment (Fig.4a). The solution (4) includes the case $e\Delta V_g > 0$ when a tunnel barrier is absent at zero magnetic field but arises with increasing B. This occurs apparently because of depopulation of the barrier region in the extreme quantum limit of magnetic field.

Fig.4b displays the fit of $I-V$ characteristics at different magnetic fields by Eq. (4) with parameters L, V_{th}, and σ_B. The optimum values of $L = 0.6$ μm and $V_{th} = -1.5$ mV are found to be very close to the ones for the $B=0$ case as determined for the same range of barrier heights, see Fig.3b. Although this fact supports our considerations, these are not quite rigorous to discuss the considerable discrepancy between the fore-exponential factors with and without magnetic field.

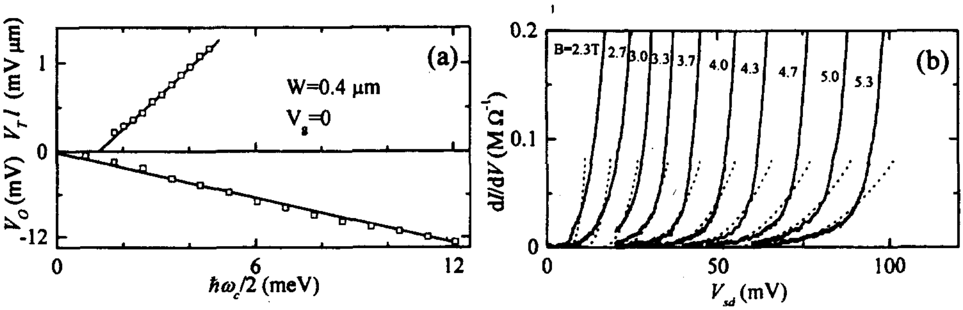

Fig.4. (a) Behaviour of the onset voltages V_O and V_T with magnetic field; and (b) the fit (dashed lines) of $I-V$ curves (solid lines) by Eq. (4) with the parameters $L = 0.6$ μm, $\sigma_0 = 1.3\,\text{M}\Omega^{-1}$, $V_{th} = -1.4$ mV; $W = 0.4$ μm, $V_g = 0$

The observed behaviour of $I-V$ characteristics with magnetic field in the transient region where their asymmetry is not yet strong (Fig.2a) is similar to that of Refs. [4,5]. Over this region, which is next to the scope of the exponential $I-V$ dependences at higher magnetic-field-induced tunnel barriers, our $I-V$ curves are close to power-law dependences, as was discussed in Ref. [5]. There is little doubt that it is very difficult to analyze and interpret such $I-V$ curves without solving the tunneling problem strictly. We note that the peak structures on the tunneling branch of $I-V$ characteristics (see Figs.2a and 3b) persist at relatively low magnetic fields and are very similar to those studied in Ref. [4]. These may be a hint to resonant tunneling through impurity states below the 2D band bottom.

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