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Electron correlations and Coulomb gap in a two-dimensional electron gas in high magnetic fields

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We apply tunnel spectroscopy to investigate the two-dimensional electron gas (2DEG) in high-mobility GaAs/Al$_x$Ga$_{1-x}$As heterostructures at very low temperatures. Vertical transport establishes equilibrium between the high-mobility electron system and an n^+-type-doped back electrode separated from the 2DEG by a shallow tunnel barrier. We find that at magnetic fields $B>7$ T and temperatures $T<0.6$ K the tunnel resistance as function of Landau-level filling factor exhibits a camel-back structure centered around filling factor $\nu=1$. We argue that the structure reflects the formation of a classical Coulomb gap at the phase transition from a correlated electron liquid to an insulating phase.

Many-body phenomena can strongly modify the effective density of states for tunnel processes into a two-dimensional electron gas (2DEG) system as, e.g., has been observed in recent vertical transport experiments.[1–5] In Refs. 1 and 2 two effects have been found in a finite magnetic field: In addition to oscillations of the tunneling conductivity with minima at integer filling factors a filling-factor-independent suppression of the tunneling conductivity is observed with decreasing temperature. Both effects have been interpreted as a manifestation of a Coulomb gap. Vertical transport through a barrier between two very high mobility electron systems has been investigated in more recent experiments.[3,4] Again, a magnetic-field-induced suppression of the tunnel current was found at small voltages between the two electron systems. The authors of Refs. 3 and 4 argue that in their samples the behavior of the I-V characteristics reflects the highly correlated nature of their high-mobility electron systems. It has been pointed out[3,6] that the broad gap observed in their samples is distinct from the singular disorder-induced gap observed in the samples of Ashoori *et al.*

In this work we perform experiments similar to those of Ashoori *et al.*[1,2] on single GaAs/Al$_x$Ga$_{1-x}$As heterojunctions with high mobility. The very shallow tunneling barrier in our structures allows us to measure the device capacitance and the tunnel current simultaneously. In our samples the tunnel resistance depends much more strongly on the Landau level filling factor than in the results by Ashoori and co-workers.[1,2] Here we would like to focus on the behavior of the tunnel resistance at high magnetic fields close to filling factor $\nu=1$, where the electron system is spin polarized in the lowest Landau level. As a result of the low disorder in our devices we observe a magnetic-field-induced transition from a correlated electron liquid to the insulating phase. In the latter the classical Coulomb gap forms at the Fermi level.[7] In our experiments we observe an enhanced tunnel resistance which we believe to originate from the formation of the Coulomb gap in the insulating phase near filling factor $\nu=1$ at high magnetic fields.

Our devices are metal-insulator-semiconductor type heterojunctions also successfully employed to generate high-quality one-dimensional electron systems.[8] The epitaxially grown layer sequence of our sample is depicted schematically in the inset of Fig. 2 below. The front gate and the heterojunction barrier are separated from the back electrode by the distances $x_g=142$ nm and $x_w=100$ nm, respectively. Electron transfer across the tunnel barrier brings the electron gas in the back electrode and the 2DEG into equilibrium. The density of the electrons in the 2DEG is controlled by the gate voltage V_g applied between the back electrode and the front gate. The gate area is $A=8700$ μm^2. The gate voltage is modulated with a small a.c. voltage so that an a.c. current is excited through the device. From the active and the reactive, i.e., the real and the imaginary, components of this current we derive information on both the thermodynamic density of states as well as the tunnel resistance between the 2DEG and back electrode.

Typical experimental traces of the active (lower trace) and reactive a.c. current (upper trace) components are shown as function of gate voltage V_g in Fig. 1. At gate voltage $V_g\leq 0.8$ V the reactive current signal reflects the capacitance between the back electrode and the front gate. At $V_g=0.8$ V the 2DEG is generated and correspondingly the capacitance rises rapidly. A slight overall increase of the capacitance signal at higher gate voltages is caused by a field-induced shift of the center of charge to the front gate. The small thermodynamic density of states at Fermi energies between the Landau levels causes pronounced minima at filling factors close to $\nu=1$ or 2. At filling factors indicated by arrows in Fig. 1 the capacitance signal is enhanced with respect to the overall value. As discussed in previous publications[9–11] this en-

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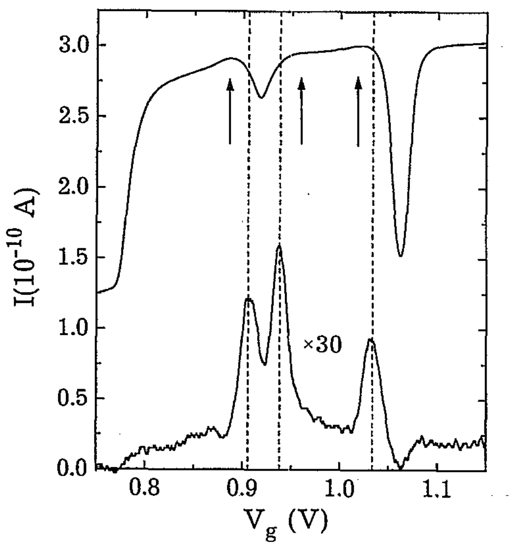

FIG. 1. Imaginary (upper curve) and real (lower curve) parts of the current through the structure as a function of the gate voltage. The current is excited with a modulation voltage of amplitude $U_d = 2$ mV and frequency $f = 1314$ Hz. The real current component is multiplied by a factor 30 for the sake of visibility. $T = 110$ mK, $B = 7$ T.

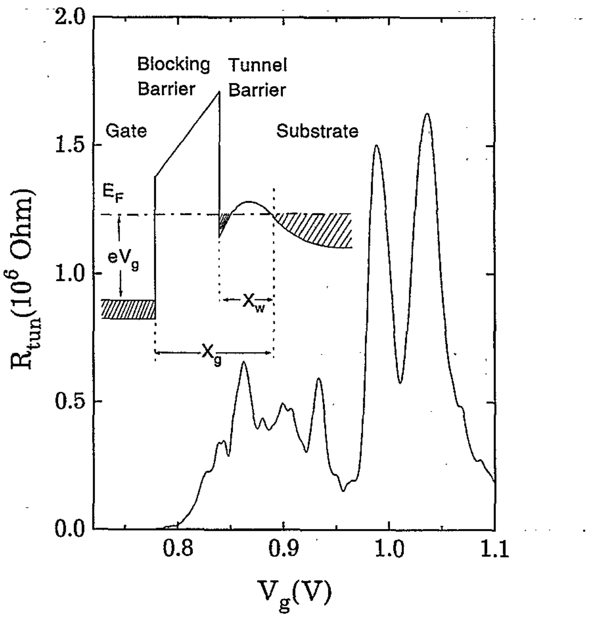

FIG. 2. Tunnel resistances $R_{\rm tun}$ at $B = 11.5$ T as a function of the gate voltage. $T = 110$ mK and the modulation voltage is $U_d = 2$ mV, $f = 1314$ Hz. In the resistance peaks the amplitude of the voltage between the 2D layer and back electrode U is about 3.7×10^{-4} V. In the inset the sample layout is shown schematically.

hancement reflects electron correlations in the two-dimensional electron liquid which effectively result in a negative compressibility. We note that the capacitance enhancement below integer filling factor seems to be always more pronounced than the one above. This asymmetry is not yet well understood.

In the following we focus on the active component of the current. In Fig. 1 it has two symmetrically placed maxima around filling factor $\nu = 1$ whereas only one maximum is observed close to $\nu = 2$. The positions of the maxima correspond to filling factors $\nu = 1 - 0.08$, $\nu = 1 + 0.14$, and $\nu = 2 - 0.15$, respectively. At such filling factors all electron states at the Fermi level are expected to be localized by disorder. Both the minimum of the real current component at $\nu = 1$ as well as the maxima at $\nu \approx 1 \pm 0.1$ and $\nu \approx 1.85$ become visible at the same magnetic field of about 7 T. At fields below 7 T no maxima are observed in the active current component even around factor $\nu = 2$.

In Fig. 2 we present a typical trace of the tunnel resistance computed with Eq. (1), which is discussed below, from the active current component measured at $B = 11.5$ T. The amplitudes of the maxima increase with increasing magnetic field or decreasing temperature. Besides the two maxima at $V_g = 0.99$ V and $V_g = 1.04$ V corresponding to filling factors $\nu \approx 0.9$ and $\nu \approx 1.1$ there are additional maxima observed at $V_g = 0.86$ V and $V_g = 0.93$ V corresponding to fractional filling factors $\nu = 1/3$, $2/3$. The pronounced maxima in the active current component at fractional filling factors start to be observable at $B = 8$ T and have only weak counterparts in the reactive signal. Due to the absence of Ohmic contacts to the 2DEG in our samples it is not possible to determine the electron mobility in the 2DEG with conventional transport measurements. However, the high mobility of our 2DEG is verified by both the observation of signatures of the highly correlated fractional states at magnetic fields $B > 8$ T and the capacitance enhancement close to integer filling factors indicative of electron correlation effects.

If the tunneling barrier is not homogeneous additional lateral currents will flow. At low diagonal conductivity σ_{xx} in the 2DEG lateral transport could contribute a considerable active component to the current signal. Our experimental results, however, show that in our samples the active current component originates essentially from tunneling and not from lateral transport. The prominent features in the active signal in Fig. 1 at $\nu = 1$ and 2 are of the same order of magnitude and vanish at the same magnetic field. This observation is hard to explain with lateral transport effects since the diagonal conductivity at filling factor $\nu = 2$ is expected to be much lower than the one at $\nu = 1$. Furthermore, it is obvious that the minimum of the active current component at filling factor $\nu = 1$ cannot be the result of lateral transport, because $1/\sigma_{xx}$ peaks at integer filling factors. Also, the strong asymmetry observed in the tunnel resistance around filling factor $\nu = 2$ is another indication that the features in the active current component are associated with tunneling phenomena rather than lateral transport.

Hence, we believe that the features in the active current component are associated with properties of the tunnel resistance $R_{\rm tun}$, describing the electron tunneling rate from the back electrode to the 2DEG. If $R_{\rm tun}\omega C \ll 1$ the current excited by an a.c. voltage U_d between the back electrode and the front gate can be described by[2]

$$I = \left(R_{\rm tun} \frac{\omega^2}{\left(\frac{x_g - x_e}{A\varepsilon} + \frac{x_g}{DAx_e e^2} \right)^2} + j\omega C_{\rm low} \right) U_d, \qquad (1)$$

where x_g and x_e are assumed to be the effective distances between the front and back electrodes and between the center of charge in the vertical electron distribution and the back electrode, respectively. We note that the value of x_e is smaller than the thickness x_w of the layer between heterojunction barrier and back electrode. The capacitance C_{low} describes not only the geometrical capacitance but includes also the term associated with the thermodynamic density of states D:

$$C_{\text{low}}=\frac{e^2Dx_e+\varepsilon}{e^2D(x_g-x_e)x_e+x_g\varepsilon}\,\varepsilon A. \tag{2}$$

As expected from Eq. (1) we observe a linear increase of the reactive current component with frequency whereas the active component increases quadratically. The capacitance signal drops at $\nu=1$ only by an amount of about 10% at magnetic fields up to 11.5 T. Thus the thermodynamic density of states D stays sufficiently high at $\nu\approx 1$ so that the real part of the current is proportional to the tunnel resistance and independent of D in a good approximation. With decreasing temperature the camel-back shaped maxima rise and the intermediate minimum becomes more pronounced. On the other hand, the reactive current signal essentially is temperature independent below $T=0.6$ K as long as the frequency is sufficiently low so that $R_{\text{tun}}\omega C\ll 1$. At higher frequencies additional minima arise in the capacitance signal at those filling factors at which the active component exhibits maxima. The suppression of the capacitance signal at these filling factors now reflects the ineffective charging of the 2DEG due to a resistance with a filling-factor dependence that would be extremely unusual for lateral transport effects. We conclude that the features in the active component of the current dominantly originate from the tunnel resistance and thus the single particle density of states in the 2DEG rather than from changes of the capacitance via the thermodynamic density of states.

At the gate voltages of the maxima in the active current component in Fig. 2 below and above $\nu=1$ there are about $n\sim 3\times 10^{10}$ cm^{-2} holes in the almost filled lower spin polarized Landau level or about the same number of electrons in the almost empty upper spin level, respectively. We expect that at such small deviations from integer filling factors the holes or electrons are localized. Their average in-plane distance is equal to $\sim$50 nm which is much larger than the magnetic length $l_H=(\hbar/eB)^{1/2}$. Under such conditions and neglecting screening by the gate it is predicted that there exists a classical Coulomb gap in the tunneling density of states $g_s=dN_s/dE$ centered at the Fermi energy E_F:[7]

$$g_s(E)=\alpha|E-E_F|, \tag{3}$$

where α is a proportionality constant and the energies are close to the Fermi energy: $|E-E_F|<\Delta$; Δ is the width of the Coulomb gap. The tunnel resistance in the presence of the classical Coulomb gap is equal to

$$R_{\text{tun}}(U,T)=U\left(\beta\int g_m g_s(E)[f(E-eU)-f(E)]dE\right)^{-1}, \tag{4}$$

where β is a proportionality coefficient, $f(E,T)$ is the Fermi function, g_m is the density of states in the substrate contact, and U is the potential difference between the 2D layer and substrate. We assume the single particle density of states in the back contact to be featureless even at high magnetic fields because of the low mobility in the highly doped layer.

The dependence of the tunnel resistance R_{tun} on the voltage across the tunnel barrier $U\simeq U_d\,\text{Re}(I)/\text{Im}(I)$ and temperature T of the 2DEG can be calculated from Eqs. (3) and (4) by using only one fitting parameter $\gamma=\alpha\beta g_m$ if we assume $eU<\Delta$. The comparison of the measured current-voltage characteristic with the calculated one is shown in Fig. 3. According to Eqs. (3) and (4) the Coulomb gap should result in a parabolic current-voltage characteristic if $\Delta>eU>k_BT$. As verified in Fig. 3 the experimental data can indeed be quite accurately described by a parabola.

The temperature dependence of the measured tunnel resistance (Fig. 4) is only qualitatively similar to the result of our calculations: in both cases the tunnel resistance R_{tun} at first grows with decreasing temperature and saturates in the low-temperature limit at a value that depends on the modulation voltage amplitude. On the other hand, the experimental curve is considerably steeper than the calculated one. This fact could be interpreted as an indication that the gap rapidly narrows with increasing temperature.

Within the above model the filling-factor dependence of the tunnel resistance with a camel-back shape exhibiting a minimum at $\nu=1$ is very intriguing. We have to conclude from the experiment that the observed dependence of $R_{\text{tun}}(V_g)$ is associated with the appearance of the Coulomb gap at filling factor $\nu\approx 0.9$, its disappearance around $\nu=1$, and reappearance of this gap at $\nu\approx 1.1$. Presently, we do not have a model that clearly explains this behavior.

The parabolic current-voltage characteristics observed in our experiment can be explained by the existence of a classical Coulomb gap at filling factors at which all electrons at the Fermi level are localized. In contrast to results of earlier works[1-4] the gap observed in our samples disappears at the

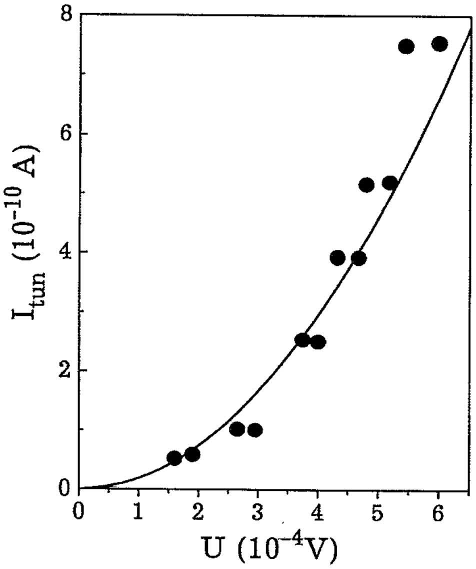

FIG. 3. Experimental dependence of the tunnel current I_{tun} in maxima at $\nu\sim 1$ on the amplitude of the voltage across the tunnel barrier. The magnetic field is $B=11.5$ T, the temperature $T=110$ mK. The solid line represents the calculated dependence $I_{\text{tun}}(U)$ by the use of one fitting parameter.

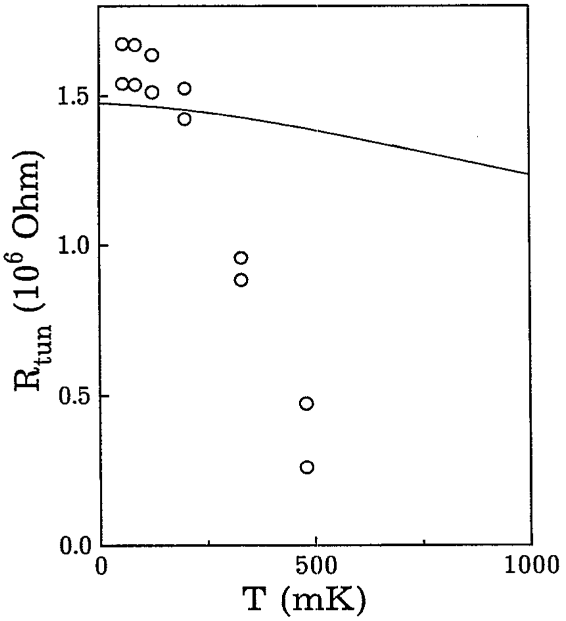

FIG. 4. Dependence of the tunnel resistance maxima at $\nu \sim 1$ on temperature. The magnetic field is $B = 11.5$ T. The amplitude of the excitation voltage between back electrode and 2DEG is determined to $U = 3.75 \times 10^{-4}$ V. The solid line is calculated according to the model of Eqs. (3) and (4) with the same fitting parameter as used in Fig. 3.

transition from the insulating to the metallic phase. Our present view is that our investigation extends the works of Ashoori *et al.*[1,2] to the case of high magnetic fields and/or to samples of higher mobility. Indeed, the fingerprints of the effect described above can be found in Fig. 5 of Ref. 2. The relation to the gap observed in the work by Eisenstein and co-workers[3,4] in the metallic phase is hard to establish from present data. There tunneling between two very high-mobility two-dimensional electron systems is investigated so that at filling factors where the systems are in the insulating phase lateral transport effects dominate the observations.

In conclusion, we have investigated the vertical transport between a metallic back electrode and the 2DEG of high-mobility GaAs/$Al_xGa_{1-x}As$ heterostructures. From the observed dependence of the active current component on temperature and magnetic field as well as from the form of its current-voltage characteristics we infer the existence of a classical Coulomb gap in the insulating phase near filling factor $\nu = 1$. On the other hand, in the metallic phases near the same filling factors we observe the enhancement of the reactive current component typical for the highly correlated electron liquid. Thus we have observed on the same sample the effects of electron-electron interaction in the metallic as well as in the insulating phases. Intriguingly, we find in the insulating phase a camel-back shaped filling-factor dependence of the tunnel resistance. Presently, we lack a clear model to describe this observation.

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