Localized electrons in the metallic phase of the two-dimensional electron system at (Al,Ga)As-GaAs heterojunctions

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Using the effect of electron focusing we measure the Fermi wave vector of the delocalized electrons in a two-dimensional (2D) electron system. After obtaining the total electron density from the high-field magnetoresistance we are able to determine the density of localized electrons in the metallic phase at zero magnetic field that form the bandtail of the 2D band. The number of localized electrons does not change appreciably over a wide range of total electron densities (down to the point of the metal-insulator transition), in spite of a profound change in the screening properties in the density-range studied. We show that the localized electrons are responsible for the observed shift of the quantum oscillation minima in relatively weak magnetic fields. [S0163-1829(97)50708-9]

According to a scaling hypothesis one expects[1] that a two-dimensional (2D) electron system, at zero temperature, and at zero magnetic field, is localized with finite disorder. Nevertheless, in experiments on actual 2D systems, down to the lowest achievable temperatures, one always observes the occurrence of a metal-insulator transition on lowering the electron density.[2] Regardless of the reason for this discrepancy between theory and experiment (one could think of insufficiently low temperatures in the experiments, or an incorrect treatment of the electron-electron interactions in the theory, etc.), from an experimental point of view it is interesting to determine the density of localized electrons in the metallic phase and to check how this density varies on changing the screening regime by varying the total electron density.

A disorder potential produces a bandtail of localized electrons in the 2D density of states at $E<E_c$ (Fig. 1). The Fermi wave vector is defined by the density of extended electrons at $E>E_c$, and the transport properties of a 2D electron gas (2DEG) in weak magnetic fields are governed by delocalized electrons alone. In a magnetic field applied perpendicular to the plane of a 2D electron system, the Fermi wave vector k_F is proportional to the cyclotron radius $k_F=r_c eB/\hbar$. The k_F value thus can be measured directly in electron focusing experiments[3,4] and converted into the density of delocalized electrons $N_d=k_F^2/2\pi$. In the case of strong magnetic fields, where the cyclotron energy is large compared to the bound state energies of electrons from the bandtail, all electrons should contribute to the value of the Landau level filling factor ν. An analysis of the Shubnikov–de Haas oscillations, a traditional way to characterize a 2DEG, should then yield a value close to the total electron density, N_s, in a 2D band, including localized electrons, via $\nu=hN_s/eB$. Thus, by comparing the results of different experiments one can determine the localized electron density in the metallic phase in zero magnetic field.

Our experiments on electron focusing were performed on small, square mesa-etched samples of dimensions 2.4×2.4

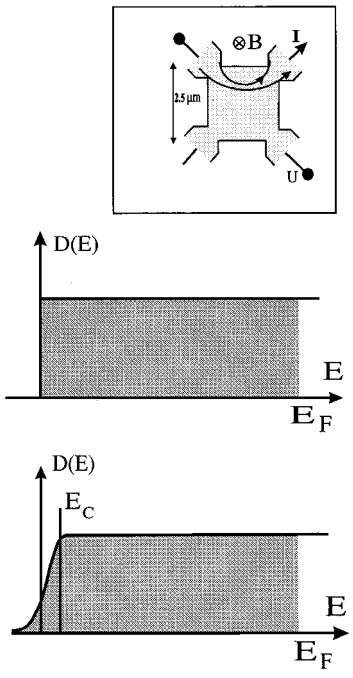

FIG. 1. Density of states in an ideal (top) and disordered (bottom) 2D electron system. The inset shows the layout of the sample.

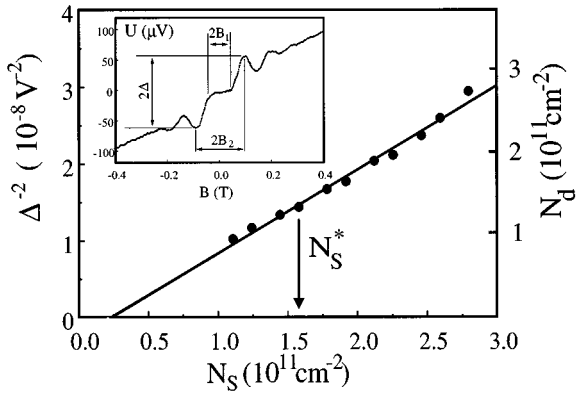

FIG. 2. The dependence of Δ^{-2} on the total electron density. The inset displays an experimental trace of the dependence of the electron focusing response on magnetic field at $N_s = 2.8\times10^{11}$ cm^{-2} and illustrates the definition of the amplitude Δ.

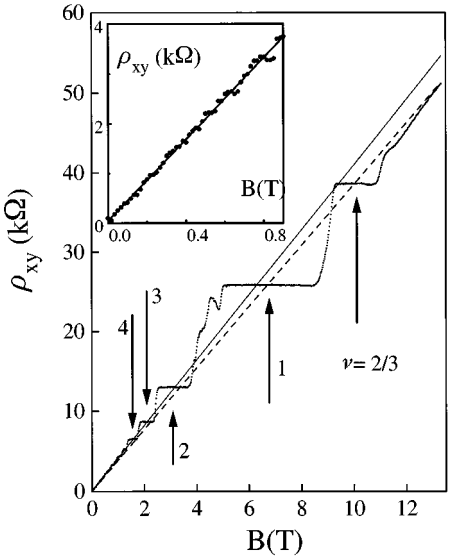

FIG. 3. Hall resistance as a function of magnetic field for a wide Hall bar. The arrows correspond to zeros in the longitudinal resistance. Inset: blow-up of the low-field part of the graph.

μm^2, fitted with four Ohmic contacts in the corners (inset to Fig. 1). The samples were fabricated by electron beam lithography from an (Al,Ga)As heterojunction wafer containing a 2DEG with mobility 1.3×10^6 cm^2/Vs and high field density 1.7×10^{11} cm^{-2}. The electron density could be varied using a gate evaporated on the sample surface. The sample was placed in the mixing chamber of a dilution refrigerator with a base temperature of $\approx$30 mK. Measurements were performed using a standard lock-in technique, at a frequency of 10 Hz. An ac current of 10 nA (small enough to ensure that the experiments were in the regime of linear response) was passed along one of the diagonals of the sample. The electron focusing signal was measured between the probes along the other diagonal, as a function of magnetic field.

A typical electron focusing curve is presented in the inset to Fig. 2. As seen from the figure, in the vicinity of zero magnetic field the Hall voltage vanishes. This effect is known as ''quenching'' of the Hall resistance,[5,6] and can be observed on narrow, ballistic, Hall bridges. When sweeping the magnetic field, the measured signal displays maxima caused by the electron focusing from the current to potential probes, which change sign upon reversal of the direction of magnetic field. The first maximum corresponds to the direct flight of electrons between the neighboring probes, the second one occurs at twice as large a magnetic field, and results from the focusing of electron trajectories that include one specular reflection with the sample boundary, etc. The magnetic fields B_1, corresponding to the onset of the Hall voltage, and B_2, corresponding to the first maximum (electron trajectories for these fields are shown in the inset of Fig. 1) are proportional to the Fermi wave vector and hence can be used for determining the electron density N_d. However, in this case the experimental accuracy is not sufficiently high to reliably deduce the localized electron density.

An experimental observable that is directly related to the number of delocalized electrons, and is defined with better accuracy, is the amplitude Δ of the first focusing maximum. One can easily find

$$\Delta^{-1} = e^2 D V_F \Theta a I^{-1}, \tag{1}$$

where a is the sample dimension, Θ is a dimensionless geometric factor, V_F is the Fermi velocity, and I is the sample current. Assuming that the density of states D and the factor Θ are constant, the value Δ^{-2} should be proportional to the extended electron density N_d. The dependence of Δ^{-2} on the electron density N_s is displayed in Fig. 2. One can see that this dependence is linear, which indicates that, in the range of N_s used, the localized electron density is constant, as will be discussed below. Although it is impossible to determine the value of N_d by means of Eq. (1) because the factor Θ is unknown, there is another way to convert Δ^{-2} into N_d. Let us consider the screening of a random potential by a 2DEG. In the absence of magnetic field, the screening properties of the 2DEG depend on two parameters:[7] the Thomas-Fermi screening constant $q_{\rm TF}$ and Fermi wave vector k_F. As long as $2k_F < q_{\rm TF}$ (or $N_s < N_s^* \cong 1.6\times10^{11}$ cm^{-2}) the screening of random potential harmonics with $q < q_{\rm TF}$ is very sensitive to the electron density N_s: the disorder potential harmonics with $q < 2k_F$ are screened while those with $q > 2k_F$ are not. In the opposite case of $2k_F > q_{\rm TF}$, the screening by the 2DEG does not depend on N_s because the disorder potential harmonics with $q > q_{\rm TF}$ are not screened at all. Since the critical value N_s^* falls within the experimentally accessed interval of electron densities (Fig. 2), in the high-density limit the number of localized electrons should not change with varying N_s, i.e., in the (N_s, N_d) plane the slope of the experimental dependence in the figure should be equal to 1. Thus, we can determine the factor Θ and restore the N_d axis in Fig. 2. Linear extrapolation of the dependence $N_d(N_s)$ to zero yields a value of $N_s \approx 2\times10^{10}$ cm^{-2} as the density of localized electrons.

In principle, any phenomenon depending on k_F is suitable for measuring the electron density N_d, for instance, the Hall effect in weak magnetic fields. Magnetotransport measurements carried out on standard Hall bars of width 250 μm with mobility 0.5×10^6 cm^2/Vs and density 1.6×10^{11} cm^{-2} yield a similar behavior for N_d. As is evident in Fig. 3, the

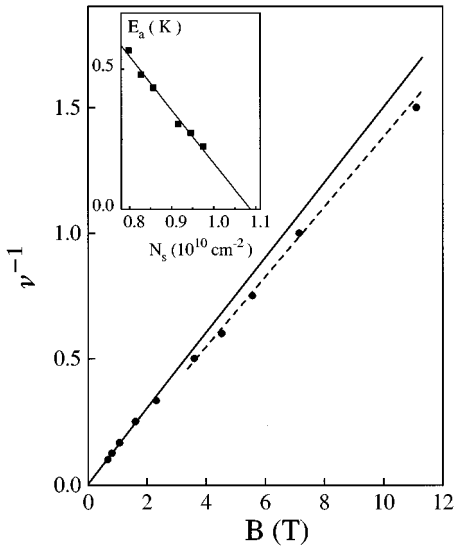

FIG. 4. Dependence of ν^{-1} on magnetic field at $N_s = 1.75 \times 10^{11}$ cm^{-2}. The slopes of the solid and dashed lines correspond to the low and high field data, respectively. Inset: the activation energy in the insulating phase as a function of electron density.

solid line that extrapolates the weak-field Hall resistance ρ_{xy} (inset of Fig. 3) to higher fields deviates from the middles of the quantum plateaus with lowest filling factors so that at $\nu = 2/3$ it is located practically beyond the plateau. A straight line passing through the origin and the points that correspond to the minima in ρ_{xx} at lowest ν (dashed line in Fig. 3) lies beyond the plateaus for the filling factors $\nu = 3,4$ and higher. Hence, the observed deviation of the classical Hall resistance from the middles of the plateaus at small ν can be attributed neither to the asymmetry of a disordered potential in the sample nor to a possible shift of the minimum in ρ_{xx} with respect to the plateau midpoint. This means that the periods of quantum oscillations in strong ($\omega_c \tau \gg 1$) and relatively weak ($\omega_c \tau \gtrsim 1$) magnetic fields, respectively, are different.

Figure 4 shows the positions of the minima in conductivity σ_{xx} on a gated Corbino sample fabricated from the same wafer as the samples for electron focusing. In addition to the positions of the integer filling factors, also the most prominent fractions at $\nu = 5/3, 4/3, 2/3$ are marked in this figure. One clearly observes that for $\nu < 2$ the minima are shifted to higher magnetic fields as compared to the values expected from the larger filling factors. Just as in Figs. 3 and 4, the electron density as defined by the filling factor ''is enhanced'' with increasing magnetic field.

This electron-density-''enhancement''-effect can be seen in previously published experimental data, including samples of rather high quality, for example, Fig. 3.7 from Ref. [8]. Only for the most perfect samples (e.g., Ref. [9]) is this effect negligible. We note that while the larger slope of the Hall resistance in weak magnetic fields might be attributed to a possible admixture of ρ_{xx} into ρ_{xy} owing to sample inhomogeneities, the whole set of experiments on samples of different design (made from different wafers, of different sizes, with and without gate) excludes such a trivial origin of the effect.

It is interesting to compare the density of localized electrons in the metallic phase with the electron density at metal-insulator transition. The metal-insulator transition point can be defined as a point of vanishing activation energy of the conductivity in an insulating phase.[2] The dependence of the activation energy on electron density N_s in zero magnetic field is displayed in the inset to Fig. 4 for the Corbino geometry sample. The observed linear dependence indicates that in the range of N_s studied, the thermodynamic density of states can be regarded as constant. The straight line in the figure intercepts the x axis at $N_s \approx 1.1 \times 10^{10}$ cm^{-2}, which is close to the value determined from the change of the oscillation period (Fig. 4). This points to a localization origin of metal-insulator transition, and excludes the occurrence of Wigner crystallization. Similar results have also been obtained on the electron-focusing sample.

Thus, in the metallic phase the bandtail of localized electron states does not change within experimental uncertainty with varying electron density, despite a change in the screening properties of the 2DEG. This is likely to be due to the relatively large binding energies of the bandtail electrons. That this binding energy is relatively large is clear when one realizes that it should correspond to a spatial extent of bound electron states smaller than $2\pi/q_{\mathrm{TF}}$. The actual characteristic binding energy can be estimated from Fig. 4 as a half of the cyclotron energy in a magnetic field of ≈ 3 T, corresponding to the change of the slope of the experimental dependence. The resulting estimated value of the binding energy of about 3 meV is in agreement with a theoretical prediction.[10]

In summary, we have measured the density of extended electrons in a 2DEG by means of the electron-focusing effect and found that it is smaller than the total electron density obtained from the quantum conductivity oscillations at high magnetic fields. The difference yields the number of localized electrons that form the bandtail of a 2D metallic band. This number has been found to remain approximately constant on reducing the total electron density down to metal-insulator transition, which points to a large binding energy of these bandtail electrons. The results are confirmed by magnetotransport measurements on standard Hall bars and Corbino samples.

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[1] P. Lee and T.P. Ramakrishnan, Rev. Mod. Phys. **57**, 287 (1985).
[2] A.A. Shashkin, V.T. Dolgopolov, G.V. Kravchenko, M. Wendel, R. Schuster, J.P. Kotthaus, R.J. Haug, K. von Klitzing, K. Ploog, H. Nickel, and W. Schlapp, Phys. Rev. Lett. **73**, 3141 (1994).
[3] V.S. Tsoi, J. Bass, and P. Wyder, Adv. Phys. **41**, 365 (1992).
[4] H. van Houten, C.W.J. Beenakker, J.G. Williamson, M.E.I. Broekaart, P.H.M. van Loosdrecht, B.J. van Wees, J.E. Mooij, C.T. Foxon, and J.J. Harris, Phys. Rev. B **39**, 8556 (1989).
[5] M.L. Roukes, A. Sherer, S.J. Allen Jr., H.G. Craighead, R.M. Routen, E.D. Beebe, and J.P. Harbison, Phys. Rev. Lett. **59**, 3011 (1987).
[6] C.J.B. Ford, S. Washburn, M. Büttiker, C.M. Knoedler, and J.M. Hong, Phys. Rev. Lett. **62**, 2724 (1989).
[7] T. Ando, A.B. Fowler, and F. Stern, Rev. Mod. Phys. **54**, 437 (1982).
[8] G.S. Boebinger, in *The Physics of the Two-Dimensional Electron Gas*, edited by J.T. Devreese and F.M. Peeters (Plenum Press, New York, 1987).
[9] T. Sajoto, Y.W. Suen, L.W. Engel, M.B. Santos, and M. Shayegan, Phys. Rev. B **41**, 8449 (1990).
[10] J. Serre, A. Ghazali, and A. Gold, Phys. Rev. B **39**, 8499 (1989).