Influence of parallel magnetic fields on a single-layer two-dimensional electron system with a hopping mechanism of conductivity

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Large positive (P) magnetoresistance (MR) has been observed in parallel magnetic fields in a single two-dimensional (2D) layer in a δ-doped GaAs/Al_xGa_{1-x}As heterostructure with a variable-range-hopping (VRH) mechanism of conductivity. Effect of large PMR is accompanied in strong magnetic fields by a substantial change in the character of the temperature dependence of the conductivity. This implies that spins play an important role in 2D VRH conductivity because the processes of orbital origin are not relevant to the observed effect. A possible explanation involves hopping via double occupied states in the upper Hubbard band, where the intrastate correlation of spins is important.

Investigation of the two-dimensional (2D) conductivity of localized electrons in a GaAs/Al_xGa_zAs heterostructure[1–3] showed that at low temperatures and in zero magnetic field the temperature dependence of the longitudinal resistivity $\rho_{xx}(T)$ has the variable-range-hopping (VRH) form

$$\rho(T)=\rho_0 \exp[(T_0/T)^x], \tag{1}$$

where ρ_0 is a prefactor, T_0 is a characteristic temperature, and the exponent x depends on the shape of the density of states (DOS) near the Fermi level. The exponent $x=1/2$ corresponds to the existence of a soft (linear) Coulomb gap in the DOS near the Fermi level.[4–7] This is called Efros-Shklovskii (ES) VRH conductivity. The exponent $x=1/3$ (Mott VRH conductivity) corresponds to a constant DOS at the Fermi level.[8] Mott VRH can be observed if the influence of the Coulomb interaction is negligible, for example, at high temperatures when the optimal hopping energy exceeds the width of the Coulomb gap[9] or at low temperatures in gated samples when the hopping distance became larger than twice the distance to the metallic gate, which results in screening of the Coulomb interaction.[10]

In 3D conductivity, hopping magnetoresistance (MR) has been studied in a large number of publications. The theory of positive hopping magnetoresistance (PMR) developed by Shklovskii[7] is based on the orbital shrinkage of the electron wave function in a magnetic field, causing a reduction in the overlap between states and quadratic field dependence of the logarithm of resistivity,

$$\rho(B,T)=\rho(0,T)\exp[B^2/B_0^2(T)]. \tag{2}$$

Here B_0 is a parameter that depends on temperature $B_0 \propto T^m$, $m=3x$, i.e., $m=3/2$ for ES VRH conductivity.

In 2D, measurements of MR in the VRH regime have been reported for both magnetic field orientations: perpendicular and parallel to the 2D plane. In weak fields, the effect of negative magnetoresistance (NMR) was observed and explained by Nguyen *et al.*[11] and by Sivan *et al.*[12] as due to quantum interference of different hopping paths between initial and final states. Ye *et al.*[13] reported PMR in the high-field limit for both orientations and NMR in the low-field limit for the perpendicular direction. Their sample contained 20 parallel Si-δ layers embedded in GaAs. The PMR in both orientations was explained as being due to orbital shrinkage of the electron wave function. Raikh *et al.*[14] observed a similar effect in δ-doped GaAs with 18 parallel layers. The nonmonotonic NMR in the perpendicular orientation has been explained as being due to a combination of an interference mechanism, which suppresses the effect of weak localization in a magnetic field, and an incoherent mechanism, caused by the influence of the magnetic field on the DOS at the Fermi level, which defines the magnitude of the Mott VRH parameter T_0.[15] Similar results were also reported for a parallel magnetic field by Dötzer *et al.*[16] for a double layer system.

It should be mentioned that, so far, hopping MR in parallel magnetic fields has been observed in multilayered systems. Moreover, in Ref. 17 it was emphasized that 2D MR is not quite negligible only in the case where the structure contains two or more parallel 2D subsystems that are a tunneling distance apart. In this paper, we report on the measurements of MR in the VRH regime in parallel magnetic fields in a single-layer 2D electron system. We observed a large PMR accompanied in strong fields by a substantial change in the character of the temperature dependence of the conductivity.

The samples investigated were fabricated from the wafer used in our previous study, Refs. 1 and 3, where full details of the layer compositions and doping are given. An essential feature of the sample structure is the presence of a δ-doped layer on the Al_xGa_{1-x}As side of the electron gas, 0.6 nm away from the heterojunction. The samples were patterned into 80×720 μm Hall bars, and the as-grown 2D carrier density and low-temperature mobility were $n=4.65\times10^{11}$ cm^{-2} and $\mu=4.5\times10^4$ cm^2/V s. The carrier density n was varied by the application of a negative gate voltage V_g to a surface gate that is $d=90$ nm above the heterojunction;

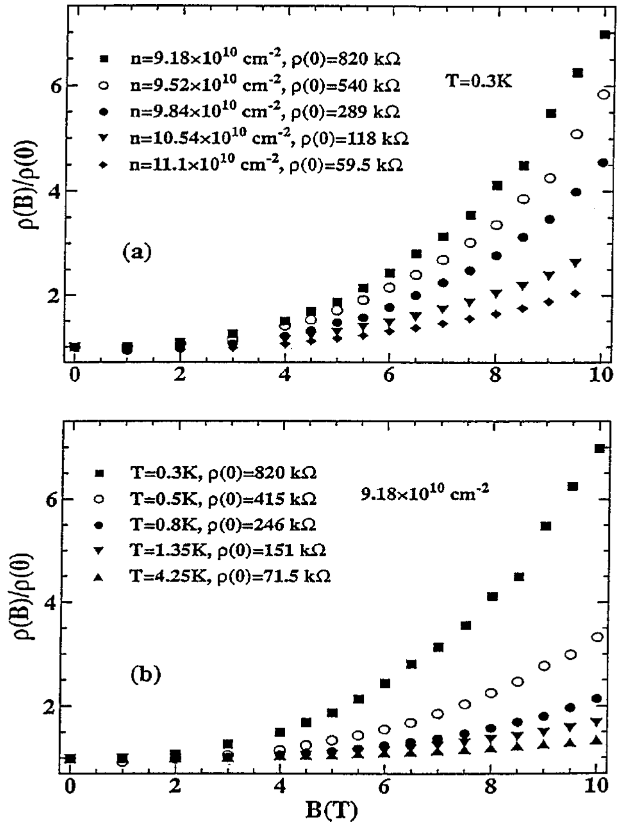

FIG. 1. Normalized resistance $\rho(B)/\rho(0)$ as a function of magnetic field B for different electron densities n at fixed temperature $T=300\,\mathrm{mK}$ (a) and for different temperatures at fixed $n=9.18\times10^{10}\,\mathrm{cm}^{-2}$ (b).

at low temperatures, the electron gas is fully depleted at $V_g=-0.70$ V. MR measurements were carried out in both a ^{3}He cryostat and in a dilution refrigerator. In the ^{3}He cryostat, the sample could be aligned to better than 0.1^0 with the parallel magnetic field by using an *in situ* rotation mechanism. In the dilution refrigerator, the sample was glued to the probe and therefore was susceptible to misalignment. After temperature stabilization, the resistivity (the resistance per square) was measured from the Ohmic part of the four-probe dc I-V characteristics. At higher carrier densities, a four-terminal ac technique was also used with 1 nA current at a frequency of 2–4 Hz. The measurements in fields parallel to the 2D plane correspond to the current being parallel to the field. We have also measured the case where the magnetic field is parallel to the 2D plane but perpendicular to the current. No anisotropy was observed.

Figure 1(a) shows the resistivity $\rho(B)$ normalized by the zero-field resistivity $\rho(0)$ versus the magnetic field for several carrier concentrations at $T=0.3\,\mathrm{K}$. It is seen that $\rho(B)/\rho(0)$ increases with magnetic field. The increase is stronger at lower electron densities. At the carrier density $n=9.18\times10^{10}\,\mathrm{cm}^{-2}$, the increase is almost sevenfold at a field of 10 T. Figure 1(b) shows $\rho(B)/\rho(0)$ at different temperatures for a fixed carrier density $n=9.18\times10^{10}\,\mathrm{cm}^{-2}$. It is seen that the increase is stronger at lower temperatures.

Thus the effect of PMR is stronger for lower densities and lower temperatures, which corresponds to ES VRH conductivity $(x=1/2)$.[3] At higher densities and higher temperatures,

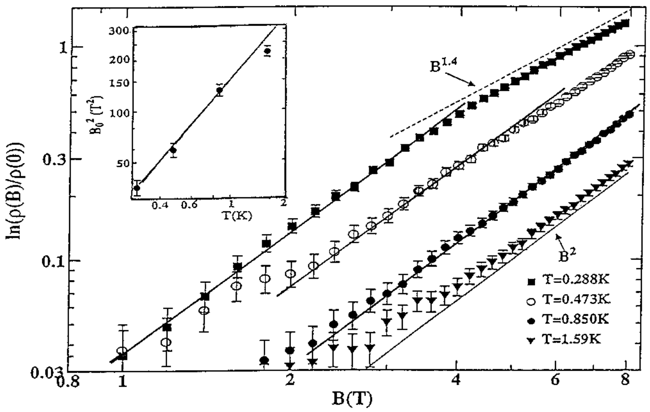

FIG. 2. Magnetoresistance $\ln[\rho(B)/\rho(0)]$ for $n=9.52\times10^{10}\,\mathrm{cm}^{-2}$ versus B on a log-log scale. The solid and the dashed lines correspond to $\ln\rho\propto B^2$ and $\ln\rho\propto B^{1.4}$, respectively. The insert shows B_0^2 vs T on a log-log scale. The solid line corresponds to $B_0^2\propto T^{1.2}$.

which corresponds to Mott VRH conductivity $(x=1/3)$, the effect of PMR is much weaker. Moreover, a negative effect (NMR) can be seen in the low-field regime $(B<2\ \mathrm{T})$. Measurements of Hall voltage at fixed n and low B show that there is a misalignment of $\sim1^0$ with the parallel magnetic field. To check the existence of NMR in parallel fields, we measured samples in a ^{3}He cryostat having an *in situ* rotation mechanism. By monitoring the Hall voltage, we could align the sample to better than 0.1^0 with the parallel field. These measurements showed that there is no NMR in parallel fields at all temperatures. The ^{3}He cryostat was supplied by a superconducting magnet with relatively weak magnetic field, therefore all data in strong fields were obtained in the dilution refrigerator. Weakness of the PMR and entanglement with NMR in the case of Mott VRH leads one to stress ES VRH in further discussion, while the influence of a parallel magnetic field on the Mott VRH is qualitatively the same.

To determine the functional form of $\rho(B)$, we plot in Fig. 2 the values of $\ln[\rho(B)/\rho(0)]$ versus B on a log-log scale for carrier density $n=9.52\times10^{10}\,\mathrm{cm}^{-2}$. It can be seen that, at higher temperatures, the data follow a B^2 law, Eq. (2) up to $B=8$ T (deviations at low fields reflect the interference with NMR), whereas at low temperatures, the B^2 law is observed only at fields up to 2–3 T. For $B>4$ T a weaker field dependence is valid. Similar behavior has been observed for other carrier densities. From B^2 dependences, one can determine the parameter B_0. The inset of Fig. 2 shows B_0 vs T on a log-log scale. The straight line corresponds to $B_0^2\propto T^m$, where $m=1.2$ is a little bit less than the predicted value $m=1.5$ for 3D ES VRH.

Let us now discuss the temperature dependence of the resistivity $\rho(T)$ in fixed magnetic fields and carrier density. Figure 3(a) shows the resistivity at different magnetic fields versus $T^{-1/2}$ for $n=9.52\times10^{10}\,\mathrm{cm}^{-2}$. At zero field, the low-temperature part of the curve fits the straight line, which shows that the conductivity obeys the ES VRH law, Eq. (1) with $x=1/2$. It is remarkable that in our δ-doped GaAs/$Al_xGa_{1-x}As$ heterostructure, the hopping prefactor ρ_0 at electron densities in the vicinity of the crossover from ES to Mott VRH is temperature independent at zero field and equal to $(h/e^2)=25.8\,\mathrm{k}\Omega$ [Fig. 3(a), see also Ref. 3]. The same temperature-independent prefactor for ES VRH at zero

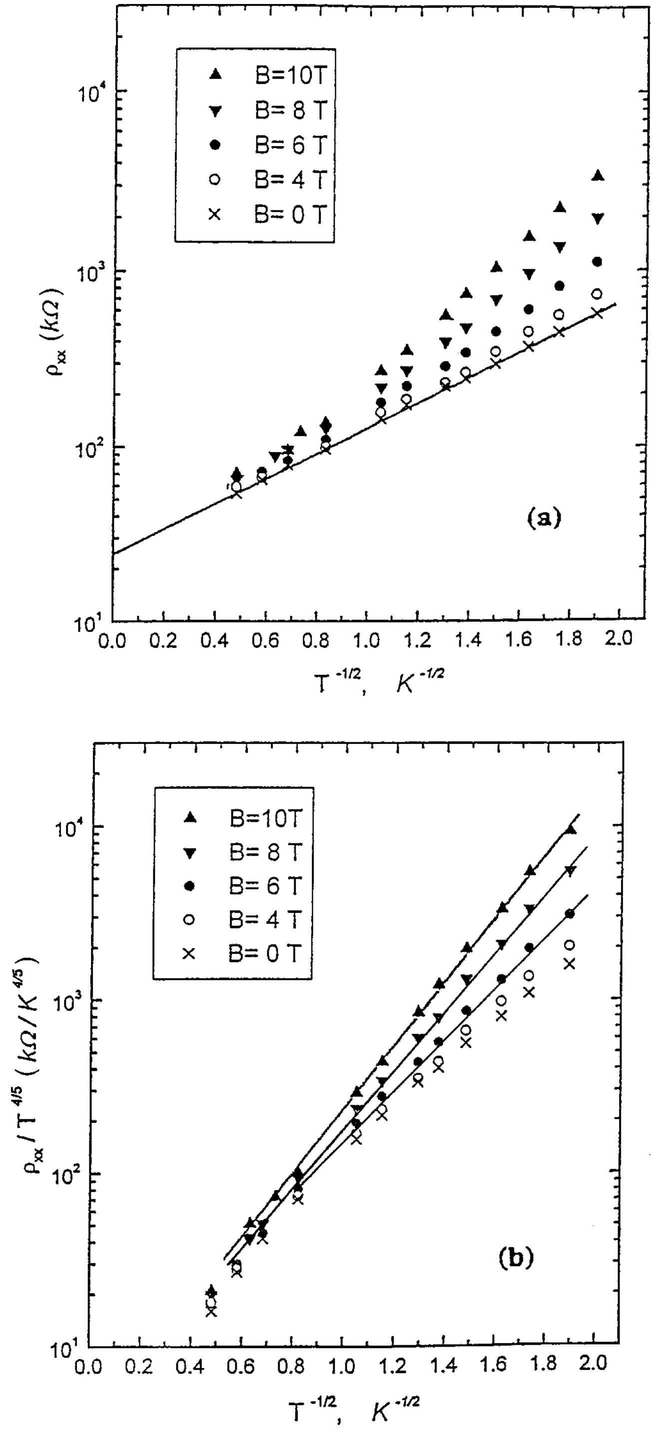

FIG. 3. Temperature dependence of ρ_{xx} (a) and $\rho_{xx}/T^{0.8}$ (b) versus $T^{-1/2}$ for $n=9.52\times10^{10}\,\mathrm{cm}^{-2}$ at $B=0$, 6, and 8 T. The straight lines are guides to the eye.

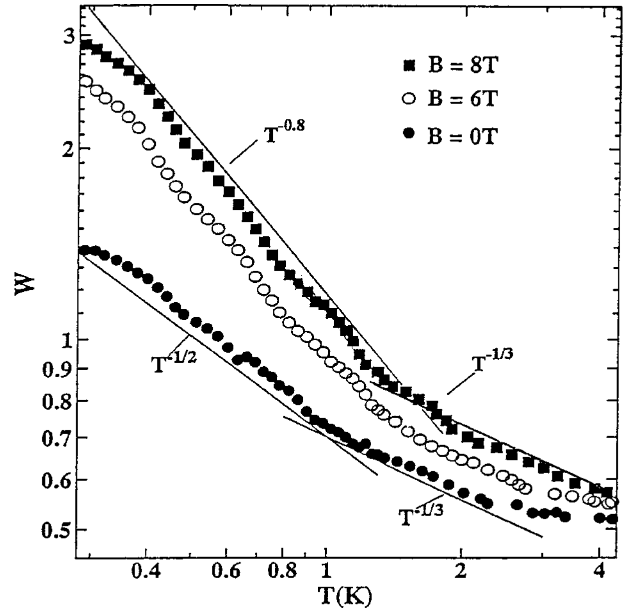

FIG. 4. The derivative $w=-\partial[\ln\rho(T)]/\partial(\ln T)=x(T_0/T)^x$ as a function of T on a log-log scale for $B=0$, 6, and 8 T, $n=9.52\times10^{10}\,\mathrm{cm}^{-2}$. The exponent x is given by the slope of the curve. The solid lines show different temperature dependences of the resistivity $\ln\rho\propto T^{-x}$.

field was previously observed in a different material, Si-MOSFET (metal-oxide-semiconductor field-effect transistor) (Ref. 18) in a narrow interval of electron densities near the metal-insulator transition. This was understood in Refs. 3 and 18 as a hint that the VRH conductivity at zero magnetic field at given electron densities is not determined by the conventional phonon-assisted scattering, because in this case, the prefactor must be material and temperature dependent.[7] As a possible alternative, a mechanism of hopping conductivity via electron-electron scattering, discussed by Fleishman *et al.*,[19] was suggested in Ref. 10. Comparison of the low-temperature conductivity data in different GaAs/Al$_x$Ga$_{1-x}$As heterostructures[2,3] leads to the conclusion that existence of a δ-doped layer in the close vicinity of the 2D conducting plane favors the conductivity mechanism with universal prefactor $\rho_0=(h/e^2)$. Indeed, the VRH in GaAs/Al$_x$Ga$_{1-x}$As heterostructures without additional δ-doped layer is characterized by a temperature-dependent prefactor of the form $\rho_0=AT^m$, $m=0.8$ or 1.0 (Refs. 2, 20 and 21), which is peculiar for the conventional phonon-assisted mechanism of VRH conductivity.

For analysis of $\rho(T)$ dependences, it is useful to plot the derivative of the curves $w=-\partial[\ln\rho(T)]/\partial(\ln T)=x(T_0/T)^x$ versus T on a log-log scale, because the slope of the lines on this scale gives directly the value of index x in Eq. (1). The result of this analysis is presented in Fig. 4. One can see that at zero field and low temperatures (below 1 K), the power x in Eq. (1) is indeed equal to 1/2, which corresponds to ES VRH. Increasing T leads to a crossover to Mott VRH ($x=1/3$), caused by the increase of the optimal hopping band over the width of the Coulomb gap.[9] Figure 4 shows that in strong magnetic fields 6 and 8 T, the value of x at low temperatures increases up to $x\approx0.8$. The same value of x was obtained for $B=10\,\mathrm{T}$. There is no theoretical justification for VRH conductivity with $x=0.8$. Therefore, one suspects that a stronger temperature dependence of the resistivity is caused by the temperature-dependent prefactor. Following Ref. 2, we assume that the prefactor becomes temperature dependent of the form $\rho_0=AT^{4/5}$, and plot $\ln(\rho_{xx}/T^{4/5})$ versus $T^{-1/2}$ in Fig. 3(b). It is seen that on this scale, the low-temperature data for $B=6,8$, and 10 T again fit to a $T^{-1/2}$ behavior. This result could be interpreted as the restoration of the conventional phonon-assisted hopping mechanism in strong parallel magnetic fields. It would be interesting to continue these measurements at higher magnetic fields to answer the question of whether or not x saturates at the value of 0.8.

In this experiment, the processes of orbital origin are not relevant to the observed effect, because the magnetic field, applied parallel to the single 2D conducting layer of electrons, couples only to the electron spins. This implies that spins play an important role in 2D hopping conductivity. Meanwhile, there is no reason for this effect unless the doubly-occupied states of the upper Hubbard band are not involved in the hopping motion. The two electrons at the site should have opposite spins. Thus, the spin alignment by the magnetic field decreases the occupation numbers for the upper Hubbard band, which leads to PMR. For 3D VRH conductivity, the corresponding mechanism was considered by Kurobe and Kamimura.[22] Agrinskaya and Kozub,[23] analyzing the data on magnetic-field dependence of activation energy for 3D nearest-neighbor hopping conductivity, have concluded that in many occasions it is related to the upper Hubbard band. Then, they also observed the features predicted by Kamimura *et al.* in VRH conductivity that evidences an admixture of the upper Hubbard band states at the Fermi level.

One should realize that the localization length in the upper Hubbard band is much larger than for the lower band making the upper band dominant for the hopping process. Moreover, it can in principle allow delocalization, even if the states in the lower Hubbard band are strongly localized. Note that with an account of energy dependence of the density of states in the upper Hubbard band and greater degree of delocalization, the temperature dependence of VRH appears to be more complex as predicted by Kamimura *et al.* and can lead to the activationlike law.[24]

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