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Giant negative magnetoresistance of a degenerate two-dimensional electron gas in the variable-range-hopping regime

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We present an experimental study of magnetoresistance of a degenerate, two-dimensional electron gas with a broad range of localization length in the variable-range-hopping regime. At low magnetic fields, a giant negative magnetoresistance of $R(0)/R(H)\sim 7$ is observed and is confirmed to be an orbital mechanism in origin. At high fields, the two-dimensional electron gas shows a contrasting transport behavior of a positive magnetoresistance. We found the transition from negative to positive magnetoresistance is temperature independent and occurs at a magnetic field corresponding to the lowest Landau-level filling factor of $\nu=2$. While we cannot reach a definite conclusion as to the origin of the giant negative magnetoresistance, our experimental data suggest the important role of the Landau-level quantization to the transport properties of a degenerate two-dimensional electron gas in the variable-range-hopping regime.

The phenomena of negative magnetoresistance (MR) is exhibited in various disordered quantum systems in both the weak- and strong-localization regime.[1] The mechanism and the characteristic properties of negative MR are a subject of both experimental and theoretical interest.

In the weakly localized regime, $kl \gg 1$ where k is the electron wave vector and l is the mean free path, the electronic conduction process can be considered as quantum diffusion. The coherence among multiple elastic scattering paths of a single conduction electron leads to an enhancement of the backscattering probabilities. A phase shift in the electron wave function introduced by the magnetic field suppresses the coherent backscattering and produces the negative MR. There are also many well-documented studies.[2] The phenomena of negative MR in the weak localized regime is generally considered to be well understood.

In the strong localization regime, $kl < 1$, the conductance process is known as the variable-range-hopping (VRH) process where an electron hops between localized states through phonon-assisted tunneling. Lee and Fisher[3] were the first to realize a negative MR in a numerical calculation of the conductance of a square lattice in the Anderson model. Because the nature of the hopping process is strictly different from the normal diffusion process, the conventional coherent back-scattering picture for the negative MR is not applicable to the VRH regime. There are theoretical models on the mechanism of negative MR in the VRH regime. One model is based on the coherent interference of the electron path. At low temperature, the tunneling distance can be much larger than the distance between impurities so that an electron undergoes multiple elastic scattering in the course of tunneling. Nguen, Spivak, and Shklovskii[4] predicted that magnetic-field dephasing can suppress the interference between different scattering paths in the hopping process and lead to a negative MR. Medina *et al.*[5] in a recent numerical study pointed out that the coherence in the backscattering gives a negligible contribution to negative MR in the VRH regime and the destructive interference between the forward paths is the major source of the negative MR in the VRH regime. Another numerical simulation by Zhao *et al.*[6] has shown that the negative MR in the VRH regime can be much larger than a factor of 2 unlike the small negative MR in the weak-localization regime. Yet another model, by Raikh, known as the incoherent mechanism model, is based on the increase of the density of the states at the Fermi surface in magnetic field.[7] He proposed the shrinkage of the wave functions of the localized electronic states in magnetic field can reduce the repulsion of the energy levels of the neighboring sites and thus increase the density of states. Experimentally, the negative MR in the VRH regime has been observed in several materials of In_2O_{3-x} film,[8] GaAs field effect transistor,[9] δ-doped Si in GaAs,[10,11] etc. As to the origin of the negative MR, some experiments attribute the effect to interference[8–10] while others support the idea of the change of density of the states.[11] Since those experimental systems are very different, no meaningful comparison can be made as to the general properties of the negative MR in the VRH region. The mechanism of negative MR in the VRH regime remains a subject of debate.

In this paper, we report observation of giant negative MR of a degenerate two-dimensional electron gas (2DEG) in the VRH regime in a well-characterized system in which the localization strength can be adjusted *in situ*. We compare our MR study with theoretical models. Although no definite conclusion can be reached as to the origin of the negative MR, our results illustrate some unique properties of strongly localized, degenerate 2DEG, particularly the importance of the Landau-level quantization to the transport in the VRH regime.

In our experiments we used molecular-beam-epitaxy-grown $GaAs/Al_xGa_{1-x}As$ heterojunctions. To enhance the interface impurity potential, the $Al_xGa_{1-x}As$ was uniformly doped with Si without a conventional undoped spacer layer between the GaAs and doped $Al_xGa_{1-x}As$. An aluminum strip was evaporated onto the sample to be used as a gate. The distance between the gate and the 2DEG in the interface of the GaAs and $Al_xGa_{1-x}As$ is about 1000 Å. Application of a negative voltage to the gate can deplete the underlying 2DEG as in a capacitor, and reduce the carrier density. The presence of the strong impurity potentials is indicated by the low mobility of the 2DEG of $\sim 1\times 10^4$ $cm^2/V\,s$. The standard low-frequency lock-in technique was used to measure the magnetoresistance. The excitation current was carefully selected to avoid self-heating of the 2DEG. The samples were placed in the liquid of a top-load, ^3He cryostat and its temperature was varied down to 280 mK. A magnetic field up to 15 T was provided by a superconducting solenoid.

A semilogarithmic plot of the normalized resistance of the 2DEG at zero magnetic field as a function of the gate voltage at a fixed temperature is shown in Fig. 1. A striking feature is the rapid increase in the resistivity as the gate voltage was increased. The carrier density at zero gate voltage was determined by both the Shubnikov–de Haas oscillations and quantization in the Hall resistance to be approximately 1×10^{12} cm^{-2}. The carrier density at the lowest gate voltage of -4 V is determined to be about 1.5×10^{11} cm^{-2} from Hall voltage measurement. In the weak localization limit, the resistivity is expected to be nearly density independent, and the factor of 7 increase in resistance is expected from the reduction of the density by a factor of 7. However, the observed change is well over a factor of 10^3. This observation suggests that the gate voltage changes not only the density but also the characteristic behavior of the 2DEG. The resistivity of the 2DEG at the lowest gate voltage reaches as high as 10^7 $\Omega/\Box$. The conductivity, $\sigma = 1/\rho$, is far less than the well-known minimum conductivity for a metal-insulator transition[1] of $\sigma_{\text{min}} \approx e^2/h$ in two dimensions. Therefore, the 2DEG in the high gate voltages is expected in the strongly localized regime. A rapid increase of the resistance at about -3.4 V can be noticed. This change is likely associated with the transition from a weak-localized regime to a strongly localized regime.

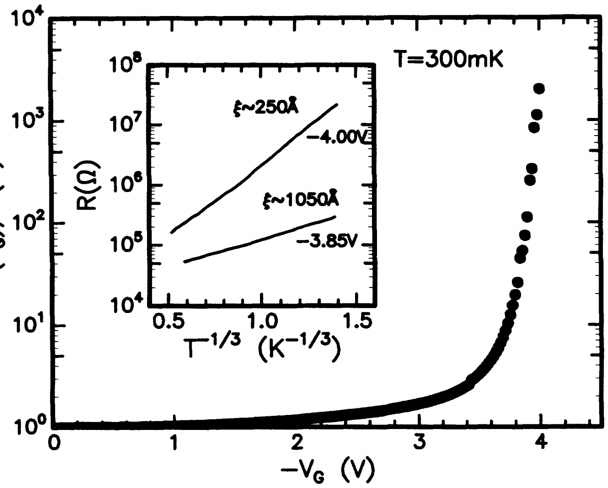

FIG. 1. Semilogarithmic plot of the normalized resistance of the 2DEG as a function of the gate voltage at a fixed temperature of 300 mK. The resistivity increases rapidly as the amplitude of the gate voltage is increased in the vicinity of $V_G = -3.4$ V. Inset: resistance as a function of $(1/T)^{1/3}$ at two gate voltages of -3.85 and -4.00 V. The localization lengths of the electron wave function are estimated to be 250 and 1050 Å, respectively.

We interpret the origin of this variation of localization strength in terms of the picture proposed by Efros.[12] For a given heterojunction, there is a characteristic impurity potential caused by the random positions of the ionized donors in the $Al_xGa_{1-x}As$. With a large undoped $Al_xGa_{1-x}As$ spacer this potential is a long-range fluctuation, and becomes short ranged as the thickness of the spacer approaches zero. The potential seen by the 2DEG is a function of the electron density. At high electron density, the random potential is suppressed by Thomas-Fermi screening and the impurity potential can be considered as a small perturbation in $1/kl$. The reduction of the electron density changes the effectiveness of the screening leading to the change in the localization length of the electron wave function.

The evidence of the strong localization of the 2DEG is revealed more clearly in the temperature dependence of the resistance in the inset of Fig. 1. The data show a characteristic temperature dependence in the VRH regime, $R \sim \exp(T_0/T)^{1/3}$, in two dimensions. This temperature dependence is known as Mott's law for a noninteracting 2DEG.[13] To estimate the localization length of the electron wave function ξ, we have used the theory of Mott, $k_B T_0 = 3/[g(\epsilon_F)^*\xi^2]$, where $g(\epsilon_F)$ is the density of states at the Fermi level. For each curve of $\ln R$ versus $(1/T)^{1/3}$, T_0 can be deduced from the slope and ξ can be estimated. $T_0 = 195$ K, $\xi = 250$ Å at $V_G = -4.0$ V and $T_0 = 10$ K, $\xi = 1050$ Å at $V_G = -3.85$ V were obtained for the curves in the inset of Fig. 1. In the course of the estimation, we have assumed the density of states $g(\epsilon_F)$ is energy independent as in the free-electron case. These localization lengths are on the order of the interelectron spacing of 200 Å indicating strong localization We have demonstrated here clearly the localization length can be varied in a board range by simply changing the 2DEG density by varying the gate voltage.

A typical MR at a fixed temperature in the VRH regime is shown in Fig. 2. The MR was measured when a magnetic field was applied normal to the plane of the 2DEG. The contamination of Hall resistance to the MR was checked to be negligible by the symmetry of the MR curve with opposite field directions. Two main features are observed in Fig. 2: a large negative MR at low fields and a positive MR at high fields. The MR in Fig. 2 drops as much as about a factor of 7 at $H \sim 3.2$ T at 300 mK. The ratio of $R(H)/R(0)$ was found to decrease with temperature, and may change by more than factor of 7 as temperature is decreased below 300 mK. This negative MR was confirmed to be an orbital effect: no negative MR was observed when the magnetic field was applied along the 2DEG plane.

A significant difference between the data in Fig. 2 from those in the literature in the weak-localization regime is

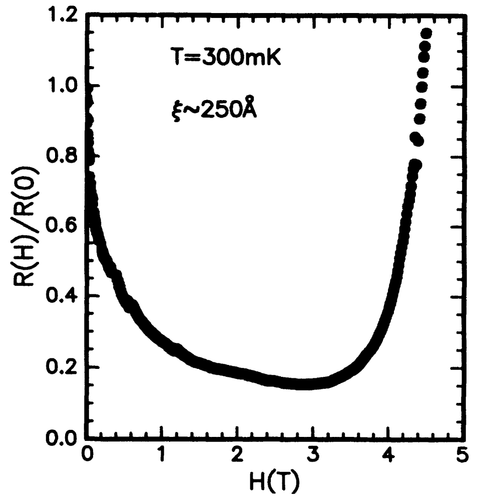

FIG. 2. Magnetoresistance of the 2DEG normalized by its zero-field value at $T=300$ mK at a localization length of $\xi \sim 250$ Å. A giant negative magnetoresistance, $R(0)/R(H) \sim 7$, is observed at low magnetic fields. At high fields, $H > 3.2$ T, the MR is positive.

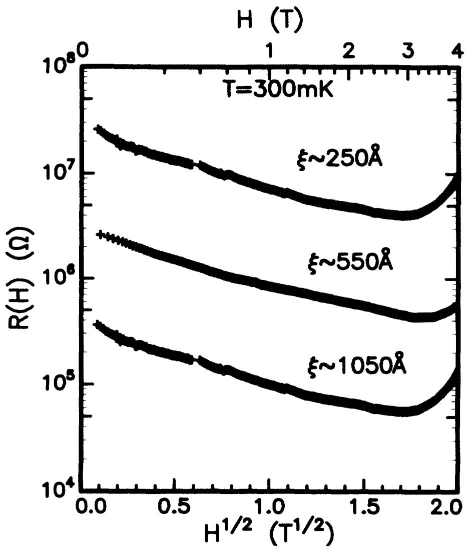

FIG. 3. Semilogarithmic plot of the magnetoresistance as a function of $H^{1/2}$ at a fixed temperature of $T=300$ mK for a sample at three different localization lengths of $\xi \sim 250$, 550, and 1050 Å.

the size of the negative MR. In the weak-localization regime, the correction of the conductance due to the coherent backscattering is $-(1/\pi k l)\ln(\tau_i/\tau_0)$ where τ_i and τ_0 are the inelastic and elastic lifetimes.[1] This correction is very small for $1/kl \ll 1$ and $R(0)/R(H)=2$ is the ultimate limit.[2] Most experiments performed in the weak-localization regime showed only a few percent variation of the MR.[2] In the VRH regime, the magnitude of the negative MR observed was larger, but $R(0)/R(H)$ was still less than a factor of 2 in most experiments [very recently, a large negative MR of $R(0)/R(H) \gg 2$ was observed by Milliken and Ovadyahu[14] in an In_2O_{3-x} film]. Our observation of the giant negative MR is consistent with the prediction that the negative MR in the VRH regime can be much larger than a factor of 2 in the coherent interference model.[5,6]

In the coherent interference model, the field dependence of the MR is expected to be $\ln[R(H)/R(0)] \sim H^{1/2}$, in the weak magnetic-field limit.[6] Inspired by this prediction, we have plotted our data in a semilogarithmic plot of the MR as a function of $H^{1/2}$ at a fixed temperature of $T=300$ mK for a sample at three different localization lengths of $\xi \sim 250$, 550, and 1050 Å (Fig. 3). In this rather broad range of localization length, no clear inconsistency is found with this theoretical dependence.

It is commonly believed that at high magnetic-field limit, the MR is expected to be exponentially positive due to the shrinkage of the electron wave function.[15] The transition from the negative to positive MR is model dependent, but it is expected to be a good manifestation of the origion of the negative MR. We show two interesting experimental facts in Fig. 4. First, the transition point is practically unchanged at different temperatures for a sample with a fixed gate voltage despite the large change in MR. We also found that the magnetic field at which the transition occurs corresponds to the lowest Landau-level filling factor of $\nu = nH/\phi_0 = 2$, where n is the electron density and $\phi_0 = hc/e$ is the flux quantum. In the coherent interference model the transition is expected to take place when $l_H \sim l_s$, where $l_H = (c\hbar/eH)^{1/2}$ is the magnetic length and l_s is the sign memory length.[6] The discrepancy of our result with this picture is that the sign memory is a function of disorder and there is no apparent significance for any Landau-level filling factor. Our temperature-independent result also contradicts the

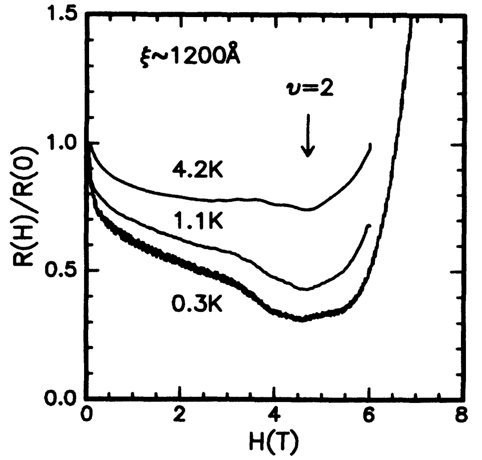

FIG. 4. Normalized magnetoresistance for three different temperatures of $T=0.3$, 1.1, and 4.2 K for a sample with localization length of $\xi \sim 1200$ Å. The transition from the negative to positive magnetoresistance is independent of the temperature, and is at a magnetic field corresponding to the lowest Landau-level filling factor of $\nu=2$.

incoherent mechanism model[7] in which the magnetic field for the transition is temperature dependent.

In the weak-localization limit, it is well known that both the localization length and the density of states depend critically on the Landau-level filling factors.[16] In all the theories mentioned,[3–7] neither of those two parameters as a function of Landau-level filling factors was included. It is not clear whether the ideology used in the weak-localization regime is applicable at all to the VRH regime. Nevertheless, our data show unambiguously that the Landau-level quantization plays a significant role in the MR in the VRH regime. We believe it is essential to extend the theoretical models to the magnetic quantum limit in order to understand the transport of a degenerate 2DEG in the VRH regime.

In conclusion, we demonstrated experimentally the gated GaAs/$\mathrm{Al}_x\mathrm{Ga}_{1-x}$As system as a localization length tunable 2DEG system. We observed giant negative MR of a strongly localized 2DEG with a broad range of localization lengths. Some circumstantial evidence is consistent with the coherent interference model. However, the coherent interference cannot be considered as the ultimate origin of the giant negative MR. Our finding of the negative to positive MR transition at the lowest Landau-level filling factor demonstrated the importance of Landau-level quantization to the transport of a degenerate 2DEG in the VRH regime.

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