Colossal Magnetoresistance in an Ultraclean Weakly Interacting 2D Fermi Liquid

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We report the observation of a new phenomenon of colossal magnetoresistance in a 40 nm wide GaAs quantum well in the presence of an external magnetic field applied parallel to the high-mobility 2D electron layer. In a strong magnetic field, the magnetoresistance is observed to increase by a factor of $\sim$300 from 0 to 45 T without the system undergoing any metal-insulator transition. We discuss how this colossal magnetoresistance effect cannot be attributed to the spin degree of freedom or localization physics, but most likely emanates from strong magneto-orbital coupling between the two-dimensional electron gas and the magnetic field. Our observation is consistent with a field-induced 2D-to-3D transition in the confined electronic system.

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We report in this Letter the experimental observation of a colossal magnetoresistance (CMR) effect in an ultraclean and (relatively) high-density two-dimensional (2D) electron system. The 2D resistivity of a 40 nm wide modulation-doped GaAs quantum well (QW, with a carrier density $n \simeq 10^{11}$ cm^{-2} and an ultrahigh mobility $\mu \simeq 10^7$ cm^2/V $\cdot$ s) is found to increase by a factor of 10, 30, and 300, respectively, for an applied magnetic field of $\sim$8, 15, and 45 T oriented *parallel* to the 2D plane, i.e., in zero perpendicular field. Our observed CMR phenomenon is unrelated to the earlier observations of 2D parallel-field magnetoresistance [1–16] where either spin polarization or disorder-related localization (or both) play decisive roles. Our high-mobility ultrapure 2D system remains metallic, with metallicity parameter $k_F\lambda \gg 1$ (λ is the transport mean free path) over the whole $B_\parallel = 0$–45 T applied parallel-field range, implying that strong localization effects associated with 2D metal-insulator transition (MIT) play no role in our observation. This contrasts with many recent experiments [1–16] where $k_F\lambda \lesssim 1$ in the high-field regime. Furthermore, due to the relatively high electronic density of our system, the field-induced carrier spin polarization is extremely small, i.e., $\frac{E_z}{E_F} \ll 1$, where $E_z = g^*\mu_B B_\parallel$ is the Zeeman splitting and E_F the Fermi energy, even at our highest applied field; in fact, a full spin polarization of our 2D system would require a field $B_\parallel > 100$ T. To the best of our knowledge, this observation of a two and a half orders of magnitude CMR effect is by far the strongest magnetoresistance ever reported in a metallic 2D electron system without the manifestation of a 2D MIT. We believe that our observed CMR arises from strong magneto-orbital coupling and a parallel-field induced 2D-to-3D transition.

Our main experimental findings, presented in Fig. 1, can be summarized as follows. (i) The 2D resistivity increases with increasing applied parallel field in our 40 nm wide GaAs quantum well with the net increase being very large, and almost a factor of 300 (50) at 45 (15) T. (ii) The magnetoresistance is much weaker in a 30 nm sample. (iii) The system remains metallic throughout; in fact, the metallicity is stronger at higher magnetic fields; i.e., the coefficient $\frac{\partial\rho}{\partial T} > 0$ is larger at high fields. (iv) Even in the most resistive situation, i.e., at the highest applied fields, the measured resistivity remains well below the Ioffe-Regel limit with $k_F\lambda \simeq 4000$–10 in the 0–45 T applied field range, thus keeping our system deep in the effective metallic regime throughout the CMR phenomenon. (v) The spin polarization remains small in our experiment, less than $\sim$10%. Collectively, these observations are unprecedented and intriguing. The observed lack of any obvious insulating phase as well as the high mobility and density of our sample point to our observed CMR phenomenon being of magneto-orbital origin, where the parallel field nonperturbatively couples the 2D dynamics of the system with transverse dynamics (i.e., normal to the 2D plane) leading to a novel 2D-3D transition producing the CMR effect. Since the system most likely remains a relatively weakly interacting Fermi liquid with a dimensionless interaction parameter $r_s \simeq 1.8$ in 2D and $r_s \simeq 1$ in 3D for our GaAs quantum well system, and with the disorder parameter $(k_F\lambda)^{-1}$ and spin-polarization parameter ($\frac{E_z}{E_F}$) both being very small, it is reasonable to assume that interaction, localization, or magnetization phenomena are not responsible for the observed CMR effect, in contrast to the other reported 2D parallel-field experiments [1–16].

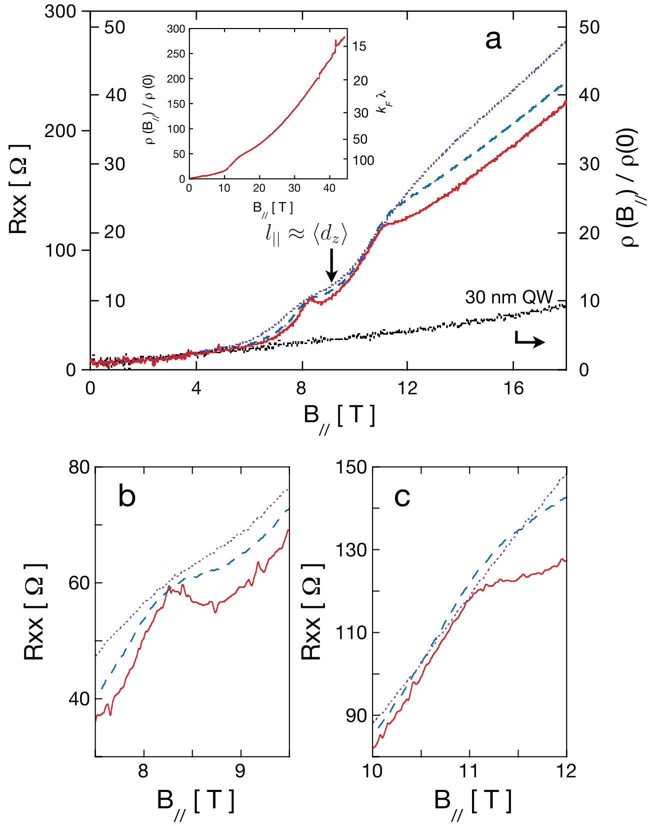

FIG. 1 (color). (a) Longitudinal resistance R_{xx} as a function of the parallel magnetic field $B_{\parallel}$ at temperatures $T = 0.18$ K (solid red line), 0.55 K (dashed blue line), and 1.05 K (dotted purple line). The increase in resistivity $\rho(B_{\parallel})/\rho(0)$ is shown on the right-hand scale, where $\rho(0)$ is the $T = 0.18$ K zero-field resistivity. The black line shows the CMR effect at $T = 20$ mK measured in an ultrahigh mobility 30 nm wide quantum well, shown here plotted on the right-hand y axis, for comparison. Inset: Increase in resistance for fields up to 45 T at $T = 0.51$ K. The right-hand y axis gives the value for the metallicity parameter $k_f\lambda$ estimated from $\rho(B_{\parallel})$. (b),(c) Expanded plot in the vicinity of the 8 and 12 T magnetic field regions.

On the other hand, the width of our quantum well being relatively large ($d = 40$ nm), typically much larger than the magnetic length $l_{\parallel} \equiv \sqrt{\hbar c/eB_{\parallel}}$ associated with the applied parallel magnetic field, leads us to believe that the magneto-orbital coupling [17] induced by the parallel field is producing the CMR effect in our system. This is further corroborated by our measurements on a sample with a quantum well width $d = 30$ nm where the CMR, while still being very large, is much less than in the 40 nm sample (see Fig. 1). This indicates that the well width may well be the decisive parameter leading to the CMR effect reported in this work.

The transport measurements are performed in a 40 nm wide AlGaAs/GaAs/AlGaAs quantum well sample of rectangular shape (with a long-to-short axis ratio ~3:1) using a standard low-frequency lock-in technique at a low excitation current, $I = 100$ nA. Except where noted, all measurements are performed with the current path defined by the contacts set at the edge of the long axis of the rectangle perpendicular to the in-plane magnetic field. Other measurements performed in the orthogonal configuration confirmed that there is no strong anisotropy with respect to the direction of the in-plane field, possibly due to a mixing of R_{xx} and R_{yy}. The 2D electron plane is aligned parallel to the magnetic field direction by using an *in situ* rotation stage to minimize the Hall voltage $V_H = R_{xy}I$ at the highest magnetic field used. In a nonideal Hall bar or van der Pauw geometry, there may be a small R_{xx} mixing into the measurement of R_{xy}, so as a consequence the measured Hall voltage may not necessarily vanish even when $\theta = 90°$ and $B_{\perp} \equiv 0$. To overcome this, we have performed a systematic study where we have measured the longitudinal and Hall resistances on a fine scale in the range $\theta \in [89.6°, 90.4°]$, up to 12 T magnetic field, using a second sample whose Hall voltage allowed a more precise determination of the angle at which the perpendicular field vanishes. In doing so, we have verified that the main observation reported here is not due to a slight misalignment of the magnetic field with the 2D plane. We have also measured the low-field Shubnikov–de Haas oscillations as well as the fractional quantum Hall series in the presence of a large perpendicular field. These measurements confirmed that only one subband is occupied in our 40 nm QW sample. Finally, the carrier density and mobility of the sample were measured with the magnetic field perpendicular to the sample.

The resistance R_{xx} (left axis) and the normalized resistivity $\rho(B_{\parallel})/\rho(0)$ (right axis) as a function of the parallel magnetic field are shown in Fig. 1(a), at temperatures $T \simeq 0.18$ K (solid red line), 0.55 K (dashed blue line), and 1.05 K (dotted purple line). Expanded plots around 8 and 12 T regions are shown in Figs. 1(b) and 1(c). An increasing monotonic magnetoresistance is observed, enhanced by a factor of ~40 at 18 T magnetic field. This colossal magnetoresistance effect shows no saturation in very large fields, manifesting an increase by a factor of ~300 at 45 T at a temperature of 0.51 K, as shown in the inset of Fig. 1 (for this data, the current was chosen to be parallel to the in-plane magnetic field). As a comparison, we also show in Fig. 1 the CMR effect observed at 20 mK in a 30 nm wide sample with an electron density $n \simeq 3 \times 10^{11}$ cm^{-2} and with a very high mobility, $\mu \simeq 2 \times 10^7$ cm^2/(V · s). Albeit considerably weaker, the CMR effect in the 30 nm wide quantum well sample is observed to increase the magnetoresistance by a factor of ~10. The more dramatic CMR effect observed in the 40 nm well is, to our knowledge, the strongest ever reported in a metallic 2D system without the manifestation of a metal-insulator transition.

It is well established [18] that the lifting of the electron spin degeneracy by an in-plane magnetic field can lead to an increase in resistance due to the suppression of the screening of charged impurities. This phenomenon is, however, only important in low electron density systems where a noticeable spin polarization builds up in the presence of an external magnetic field. In the simplest picture, the single particle spin polarization of a 2D electron system at $T = 0$ is proportional to $(m^* g^* B_{\|})/n$, where m^* is the electron effective mass and g^* the electronic g factor. In GaAs where g^* and m^* are relatively small, the single particle spin polarization for our sample with an electron density $n \simeq 10^{11}$ cm^{-2} is less than 4% in a 10 T magnetic field. This modest spin-polarization buildup cannot account for the substantial CMR effect observed here with magnetic fields as low as 10 T. Furthermore, the largest possible spin-polarization induced CMR effect is a factor of 4 [18] in the metallic ($k_F \lambda \gg 1$) phase, much weaker than what we report in this Letter.

The temperature dependence of the longitudinal resistance was also measured from 0.18 to 1.05 K, and is shown in Fig. 2(a) at several values of the magnetic field. The normalized resistivity is shown in Fig. 2(b), with the dotted lines being guides to the eye. In this temperature range, the CMR effect manifests very little temperature dependence for fields lower than 5 T (not shown in Fig. 2). Examinations of other data taken below 5 T exhibit a weak metalliclike temperature dependence with a small coefficient of resistivity $\frac{\partial \rho}{\partial T} > 0$. In contrast to the low-field (or zero-field) absence of any appreciable temperature dependence in our measured resistivity, consistent with the resistivity of high-mobility 2D GaAs systems [19] with density $n \sim 10^{11}$ cm^{-2}, the high-field data ($\gtrsim$10 T) exhibit some complex temperature dependence. The data above 12 T manifest strong metallic temperature dependence with $\rho(T)$ increasing almost linearly with temperature by ~20% or more for $T \simeq 0.2$–1 K. This contrasts greatly with the low-field data (for $B_{\|} \lesssim 5$ T), where $\rho(T)$ changes by less than a few percent in the same temperature range. In between the low- ($\lesssim$5 T) and high-field ($\gtrsim$12 T) regimes, $\rho(T)$ shows a complex and nonmonotonic behavior, as can be readily seen in Figs. 1(b), 1(c), and 2(b).

It is apparent from Fig. 1(a) that the 40 nm sample exhibits two kinks in its resistivity at $B_{\|} \sim 8$ and 11 T, with the kink sharpness being stronger at lower temperatures [plotted on an expanded scale in Figs. 1(b) and 1(c)]. No such kink is observed in the data of the 30 nm sample. The measured resistivity, particularly at the lowest temperature (solid curve at $T = 0.18$ K), shows a clear nonmonotonicity as a function of the magnetic field, with the nonmonotonic feature being more pronounced at ~8 T, while being suppressed as the temperature is increased. The expanded scale in Fig. 1(c) also indicates that the temperature dependence of the resistivity is nontrivially affected by the kink feature near ~11 T, however disappearing quickly above this field.

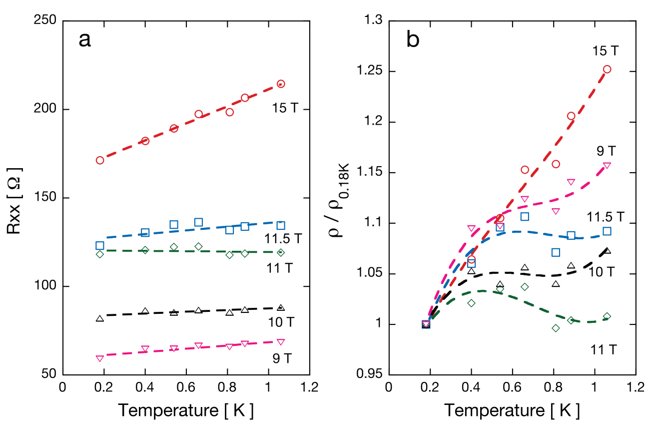

FIG. 2 (color). (a) Longitudinal resistance R_{xx} and (b) normalized resistivity versus temperature. The dotted lines are guides to the eye.

We believe that the observed kinks in the magnetoresistance indicate that they arise from the nonperturbative magneto-orbital coupling between the applied in-plane magnetic field and the subband dynamics of the quantum well carriers. This is most easily seen by comparing the field-induced magnetic length $l_{\|}$ with the confinement width of the 2D electron wave function $d_z \equiv \sqrt{\langle z^2 \rangle}$, with the 2D electron layer and $B_{\|}$ being in the x-y plane. The condition $d_z = l_{\|}$ occurs for our 40 nm quantum well at fields $B_{\|} \simeq 9$ T, and at a field of 20 T in the 30 nm sample. We note that this condition for strong magneto-orbital coupling $l_{\|} \lesssim d_z$ is much more stringent than the condition $l_{\|} \lesssim d$, occurring at a field of only 1 T for both the $d =$ 40 nm and $d = 30$ nm quantum well samples. The true quasi-2D transverse width of the quantum well wave function in the z direction is thus much smaller than the physical well width. The regime $l_{\|} \ll d_z$ involves very strong magneto-orbital coupling between the Landau level and the transverse subband dynamics. In this case, the quasi-2D confinement potential and the applied magnetic field are equally important in controlling the carrier dynamics of the electron system since $\hbar\omega_c \gg E_{ij}$, where $\hbar\omega_c$ is the in-plane cyclotron energy and E_{ij} are the subband energy differences associated with the quantum well confinement in the z direction. In such a situation, realized in our 40 nm quantum well for $B_{\|} \gtrsim 8$ T, the system can no longer be considered a 2D system because of the nonperturbative magneto-orbital coupling.

To emphasize and reinforce the fact that our observed high parallel-field state is a new metallic state in spite of a factor ~300 enhancement in resistivity, we show in Fig. 3 its comparison with data taken in a tilted magnetic field, where a 40 nm sample cut from the same wafer is now subjected simultaneously to a large parallel and a large perpendicular field. Whereas the strict parallel-field case produces a factor of ~300 CMR as shown in Fig. 1, the tilted field case produces a longitudinal magnetoresistance that is several orders of magnitude larger at high parallel magnetic field, indicating a clear insulating state. We have previously identified this tilted field situation as a possible Wigner crystal [20], whereas we identify our currently reported state in the presence of zero perpendicular field as a novel metallic state driven solely by the applied parallel field through magneto-orbital coupling.

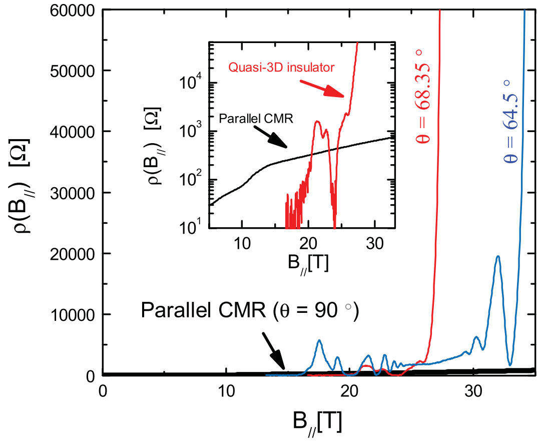

FIG. 3 (color). Comparison of the resistivity versus parallel field between a tilted 40 nm quantum well [20] at $\theta = 68.35°$ (red line), $\theta = 64.5°$ (blue line), and the pure parallel-field case studied in this work, $\theta = 90°$ (black line). The inset shows the same data for the $\theta = 68.35°$ tilt angle and $\theta = 90°$ but on a semilog scale.

Theoretically, calculating the field and temperature dependence of the magnetoresistance in a quasi-2D system with finite thickness is extremely complex and beyond the scope of this experimental work. This complexity arises when the in-plane magnetic field strength is such that the magnetic length becomes comparable or shorter than the 2D thickness, $l_\parallel \lesssim d_z$, and the system becomes quasi-three-dimensional. All resistive scattering processes (both electron-impurity and electron-phonon) are strongly affected by the in-plane field since the scattering matrix elements depend in this case on the quasi-2D confinement wave functions which themselves are affected nonperturbatively by the external magnetic field. In other words, one needs to consider a transport theory in the presence of nonperturbative effects of both the confining quantum well potential and the external in-plane magnetic field, a difficult problem that has not yet been solved in any context. We can, however, crudely estimate the magnitude of the CMR effect by assuming that our extremely high-mobility sample is limited by resistive scattering from background random (unintentional) charged impurity scattering. It is then possible to calculate the matrix elements for electron-impurity scattering incorporating the nonperturbative effect of $B_\parallel$ in the quantum well wave function [21,22], which then immediately leads to an estimate for the CMR effect. We obtain a CMR factor (for the $d =$ 40 nm sample) of 20 for $B_\parallel = 16$ T and 200 for $B_\parallel =$ 45 T, which are in semiquantitative agreement with our experimental observations in Fig. 1.

In conclusion, we can make the following concrete remarks about the physics underlying the magneto-orbital CMR effect. (i) The temperature dependence for $B_\parallel >$ 12 T likely arises from phonon scattering which is strongly affected by the strong magneto-orbital coupling. This is consistent with the linear temperature dependence of the resistivity for $B_\parallel > 12$ T, shown in Fig. 2. (ii) The kink in the resistivity at $B_\parallel \simeq 8$ T most likely arises from a magneto-orbital resonance where the first excited magneto-electric subband (i.e., the quantum well confined levels in the presence of strong magneto-orbital coupling) is pushed down through the Fermi level by the applied field [21], allowing strong intersubband scattering in the 2D system. It is known [23] that such intersubband resonance can produce the kink structure and the associated temperature dependence observed in this work. (iii) The kink at ~11.5 T likely corresponds to the onset of the quasi-3D regime, where the cyclotron energy exceeds all confined energy levels. In this regime ($B_\parallel > 12$ T), the system can be viewed as a quasi-3D electron system with strong scattering from boundaries, impurities, and phonons. (iv) A 2D-to-3D crossover transition is expected as the magnetic field is increased beyond ~11 T. The quasi-three-dimensional dynamics occurring at high magnetic fields is likely to be important for the CMR observed in this work.

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