Giant negative magnetoresistance in high-mobility two-dimensional electron systems

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We report on a giant negative magnetoresistance in very high mobility GaAs/AlGaAs heterostructures and quantum wells. The effect is the strongest at $B \simeq 1$ kG, where the magnetoresistivity develops a minimum emerging at $T \lesssim 2$ K. Unlike the zero-field resistivity which saturates at $T \simeq 2$ K, the resistivity at this minimum continues to drop at an accelerated rate to much lower temperatures and becomes *several times smaller* than the zero-field resistivity. Unexpectedly, we also find that the effect is destroyed not only by increasing temperature but also by modest in-plane magnetic fields. The analysis shows that giant negative magnetoresistance *cannot* be explained by existing theories considering interaction-induced or disorder-induced corrections.

Over the past decade, low-field magnetotransport in high-mobility two-dimensional electron systems (2DESs) became a subject of considerable interest, in part, owing to the discovery of many unexpected phenomena.[1–14] While the characteristic features of the majority of these phenomena are now understood reasonably well,[15–27] there still exist many unsolved puzzles. One such puzzle is the recently reported giant microwave photoresistivity peak which emerges in the vicinity of the second harmonic of the cyclotron resonance.[13,14,28] While its origin remains unclear, this peak so far has been observed only in 2DESs which also exhibit giant negative magnetoresistance (GNMR).[13,14] Therefore, investigating the GNMR effect[29] is not only interesting and important in its own right but may also provide clues to account for other phenomena.

The magnetoresistance can be characterized by the ratio $\rho(B)/\rho_0$, where $\rho(B)$ and ρ_0 are the longitudinal resistivities measured with and without perpendicular magnetic field B, respectively. In the present Rapid Communication, we focus on the regime of weak magnetic fields where Shubnikov–de Haas oscillations are not yet developed. In this regime, the characteristic feature of $\rho(B)$ is a broad minimum occurring at $B_0 \simeq 1$ kG. Quite remarkably, the resistivity at this minimum, $\rho(B_0) \equiv \rho_{\min}$, can be significantly lower than ρ_0, i.e., $\rho_{\min}/\rho_0 \ll 1$, in very-high-mobility samples.[13,14] In what follows we will use the value of $\rho_{\min}/\rho_0$ to quantitatively describe the GNMR.

While the negative magnetoresistance effect has been known for nearly three decades,[31–33] systematic experimental studies in very-high-mobility ($\mu \sim 10^7$ cm^2/V s) 2DESs have appeared only recently. More specifically, Bockhorn *et al.*[34] reported that the effect quickly disappears with increasing density; $\rho_{\min}/\rho_0$ increased from ≈ 0.3 to ≈ 0.7 as the carrier density changed from ≈ 2 to $\approx 3 \times 10^{11}$ cm^{-2}.[35] In addition, it was found[34] (for the carrier density of $\approx 2.3 \times 10^{11}$ cm^{-2}) that the minimum resistivity roughly doubles when the temperature is raised from 0.1 to 0.8 K.

In this Rapid Communication we systematically investigate the roles of temperature and in-plane magnetic field on the GNMR effect observed in high-mobility GaAs/AlGaAs heterostructures and quantum wells. In all of our samples,

the effect manifests itself as a well-defined minimum in the longitudinal resistivity emerging at $B_0 \simeq 1$ kG. At low temperatures and low in-plane fields, the resistivity at this minimum is *a small fraction* of the zero-field resistivity. Remarkably, the GNMR is quickly suppressed not only by temperature but also by modest (a few kG) in-plane magnetic fields. Our analysis of the low-field magnetoresistivity shows that the observed GNMR *cannot* be explained by existing theories considering either interaction-induced or disorder-induced corrections to the Drude resistivity.

Our samples (A, B, and C) are lithographically defined Hall bars (widths $w_A = 50$ μm, $w_B = 150$ μm, $w_C = 100$ μm). Sample A is fabricated from a GaAs/AlGaAs Sandia-grown heterostructure with density $n_A \approx 1.6 \times 10^{11}$ cm^{-2} and mobility $\mu_A \approx 5.4 \times 10^6$ cm^2/V s. Sample B (C) is made from a Princeton-grown 24(30)-nm-wide GaAs/AlGaAs quantum well with density $n_B \approx 4.3 \times 10^{11}$ cm^{-2} ($n_C \approx 3.4 \times 10^{11}$) and mobility $\mu_B \approx 1.0 \times 10^7$ cm^2/V s ($\mu_C \approx 1.2 \times 10^7$ cm^2/V s). Magnetoresistivity $\rho(B)$ was measured in a ^{3}He cryostat at temperatures up to $T = 6.0$ K using a standard low-frequency lock-in technique.

In Fig. 1(a) [Fig. 1(b)] we present the magnetoresistivity $\rho(B)$ in sample A (sample B) measured at T from 0.5 to 1.75 K (from 0.4 to 1.6 K), in a step of 0.25 K (0.2 K). In addition to Shubnikov–de Haas oscillations, both samples reveal a GNMR effect marked by a pronounced minimum which occurs at $B_0 \simeq 1$ kG and becomes progressively deeper with decreasing T; in contrast to the zero-field resistivity ρ_0, which remains nearly temperature independent, the resistance at this minimum $\rho_{\min}$ decays rapidly and becomes a small fraction of the zero-field resistivity. For example, in sample A, $\rho_{\min}/\rho_0 \approx 0.2$ at $T = 0.5$ K.

To examine the higher T range, we present in Fig. 1(c) the magnetoresistivity $\rho(B)$ in sample A at temperatures from 2 to 6 K, in a step of 0.5 K. Here, we notice that at $T < 4$ K, $\rho(B)$ exhibits phonon-induced resistance oscillations, owing to resonant electron scattering on thermally excited $2k_F$ acoustic phonons.[2,25,26,36–38] The second-order maxima of these oscillations occur at $B \approx 1.3$ kG, as marked by $\downarrow$ next to the trace at $T = 3.0$ K in Fig. 1(c).[39] At $T \gtrsim 4$ K, the position of the resistivity minimum is shifted to a higher field
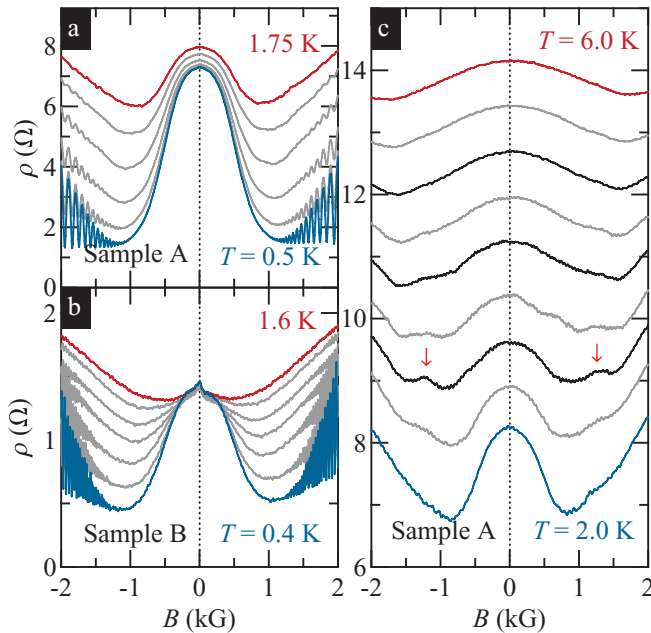
FIG. 1. (Color online) (a) $\rho(B)$ of sample A at 0.5 K $\leqslant T \leqslant$ 1.75 K, with a step $\Delta T = 0.25$ K. (b) $\rho(B)$ of sample B at 0.4 K $\leqslant T \leqslant 1.6$ K, $\Delta T = 0.2$ K. (c) $\rho(B)$ of sample A at 2 K $\leqslant T \leqslant 6$ K, $\Delta T = 0.5$ K. Arrows mark the second-order maxima of phonon-induced resistance oscillations (see text).

FIG. 2. (Color online) (a) ρ_0 (open circles) and ρ_{min} (solid circles) vs T in sample A. (b) ρ_{min}/ρ_0 vs T in sample A (circles) and in sample B (squares). The vertical line "separates" high- and low-temperature regimes in sample A.

(≈ 1.5 kG) and both ρ_0 and ρ_{min} grow at about the same rate, as evidenced by roughly parallel traces in Fig. 1(c). The spacing between adjacent traces remains roughly constant, indicating linear temperature dependence of the resistivity over the entire range of magnetic fields.

For a quantitative analysis of the GNMR we present in Fig. 2(a) the zero-field resistivity ρ_0 (open circles) and the resistivity at the minimum ρ_{min} (solid circles), measured in sample A for each T studied. The data clearly show that at $T \gtrsim 2.5$ K (to the right of the dashed vertical line), the resistivities are close to each other, $\rho_0 \simeq \rho_{min}$, both featuring very similar, approximately linear, temperature dependence. Such behavior is consistent with the electron scattering on thermal acoustic phonons.[37,40]

At lower temperatures, $T \lesssim 2.5$ K (to the left of the vertical line), the T dependences of ρ_0 and ρ_{min} become markedly different. The decrease of ρ_0 gets considerably *slower* as the acoustic phonon contribution becomes irrelevant and the resistivity saturates at a value determined by impurity scattering.[37,40,41] Quite remarkably, in contrast to ρ_0, ρ_{min} not only continues to drop at lower temperatures but also does so at a much *faster* rate. Such a sudden change of the temperature dependence of ρ_{min} is totally unexpected. Quantitatively, once the temperature is lowered from 2.5 to 0.5 K, ρ_0 decreases only by about 20% while ρ_{min} drops by more than a factor of 5.[44]

Using ρ_0 and ρ_{min} shown in Fig. 2(a), we calculate ρ_{min}/ρ_0 and present the result (circles) in Fig. 2(b) as a function of temperature. Results for sample B obtained in the same way using the data in Fig. 1(b) are represented by squares. Both samples show a rapid increase of ρ_{min}/ρ_0 with increasing temperature and eventual saturation at $\rho_{min}/\rho_0 \simeq 1$.
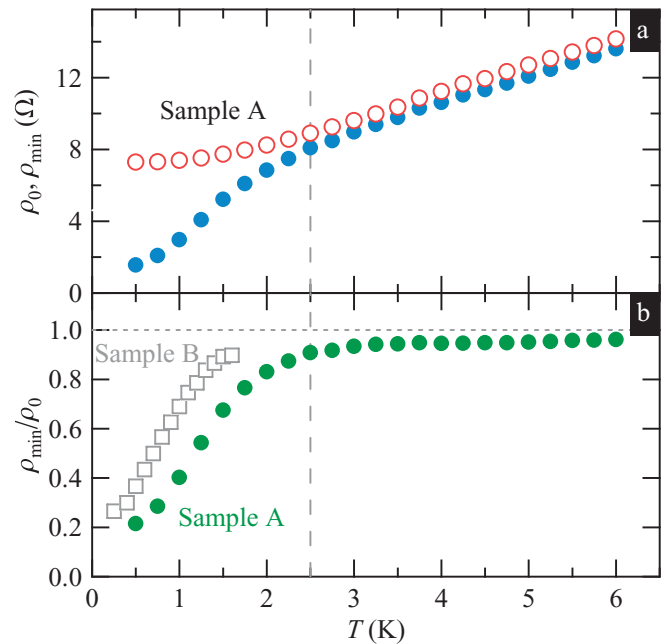
We next examine the effect of an in-plane magnetic field which is introduced by tilting the sample normal by angle θ with respect to the magnet axis. Figure 3(a) shows magnetoresistivity $\rho(B)$ at selected θ from 0° to 89° measured in sample C at $T \simeq 0.3$ K. At $\theta = 0$° we again observe GNMR characterized by $\rho_{min}/\rho_0 \approx 0.14$. With increasing θ the data reveal rather complex behavior; ρ_{min} increases while B_0 becomes smaller, decreasing roughly by a factor of four at the highest angle.

To estimate the characteristic in-plane field required to suppress GNMR we extract ρ_{min}/ρ_0 from the data in Fig. 3(a) and present the result in Fig. 3(b) as a function of $1/\cos\theta$. We find that ρ_{min}/ρ_0 doubles at $1/\cos\theta \simeq 5$ which gives the scale of the in-plane field $B_\parallel = B_0/\cos\theta \simeq 5$ kG. We note that similar in-plane field values were found necessary to suppress microwave-induced[52] and Hall field-induced[53] resistance oscillations occurring in a similar perpendicular field range. At higher tilt angles ρ_{min}/ρ_0 appears to saturate at ≈ 0.8.

One might think that the increase of ρ_{min} with increasing tilt angle originates from the in-plane field-induced positive magnetoresistance effect, recently reported in very high-mobility 2DEG.[54] However, according to Ref. 54, *an order of magnitude higher* $B_\parallel$ is needed to double the resistance in a 30-nm-wide quantum well. Therefore, further studies are needed to clarify the origin of the $B_\parallel$-induced suppression of the GNMR effect.

In the remainder of this Rapid Communication, we focus on the temperature dependence of the low-field magnetoresistivity preceding the formation of the deep minimum at $B = B_0$. More specifically, we analyze the low B part of the data in
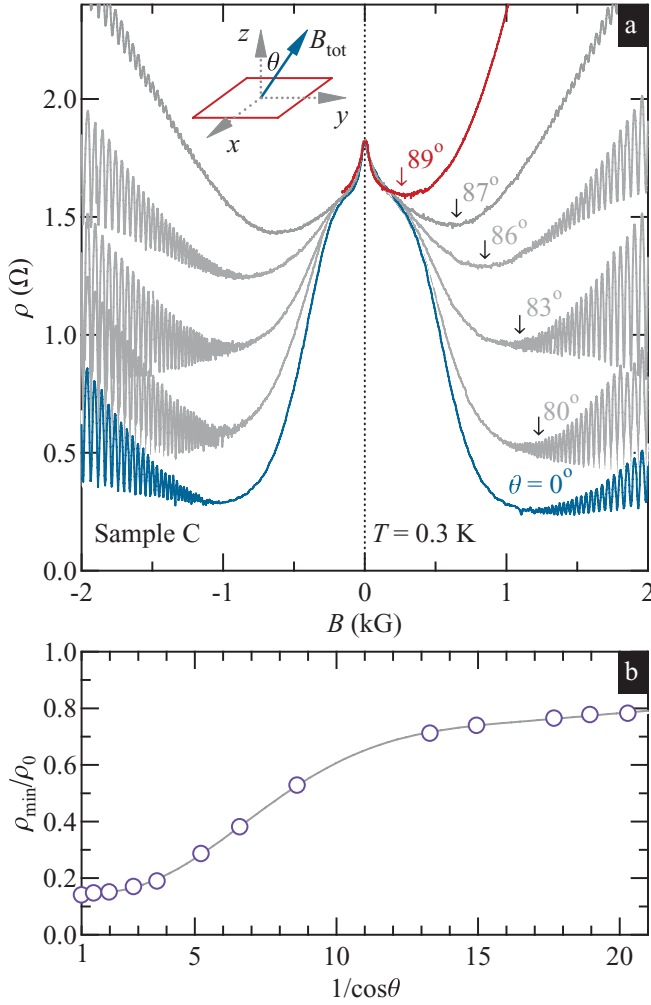
FIG. 3. (Color online) (a) $\rho(B)$ of sample C at $T = 0.3$ K at different tilt angles θ (as marked). (b) $\rho_{\min}/\rho_0$ vs $1/\cos\theta$ (circles). The solid curve is a guide to an eye.

FIG. 4. (Color online) (a) The solid curves represent $\rho(B)/\rho_0$ measured in sample A at T from 0.5 to 2.0 K, as marked. The dashed curves are fits to the data, $\rho(B)/\rho_0 = 1 - \beta B^2$, at $|B| \leqslant 0.5$ kG. (b), (c) β vs T. The solid lines are fits to the data (see text) and the dashed lines are β_i^{sm} calculated using Eq. (3).

terms of

$$\frac{\rho(B)}{\rho_0} = 1 - \beta B^2, \qquad (1)$$

and then examine β as a function of temperature. In Fig. 4(a) we plot the normalized magnetoresistivity $\rho(B)/\rho_0$ measured in sample A at T from 0.5 to 2.0 K, in a step of 0.5 K.[55] To extract β we fit the data using Eq. (1) over the range $|B| \leqslant 0.5$ kG (cf. dashed lines) and observe that the curvature of the low-field resistivity β *decreases* with increasing temperature.

After repeating the fitting procedure for all other T studied, we present extracted β in Figs. 4(b) and 4(c) using log-log and log-linear scales, respectively. First, we notice that at $T \lesssim 1$ K, β shows a sign of saturation and can be well described by $\beta \approx 1.5(1 - T^2/T_0^2), T_0 \approx 2.0$ K [cf. the solid curve in Fig. 4(b)]. At higher T the data can be described by either $\beta \propto T^{-2.6}, T \gtrsim 2.5$ K [cf. the solid line in Fig. 4(b)], or by $\beta \propto \exp(-T/T_{1,2})$, where $T_1 \approx 1.0$ K for 1.0 K $\lesssim T \lesssim 3.5$ K and $T_2 \approx 1.9$ K for 3.5 K $\lesssim T \lesssim 6.0$ K [cf. the solid lines in Fig. 4(c)]. It is clear that the temperature dependence of β is rather complex, which is likely a result of one or several crossovers between different regimes. In what follows we examine $\beta(T)$ in terms of existing
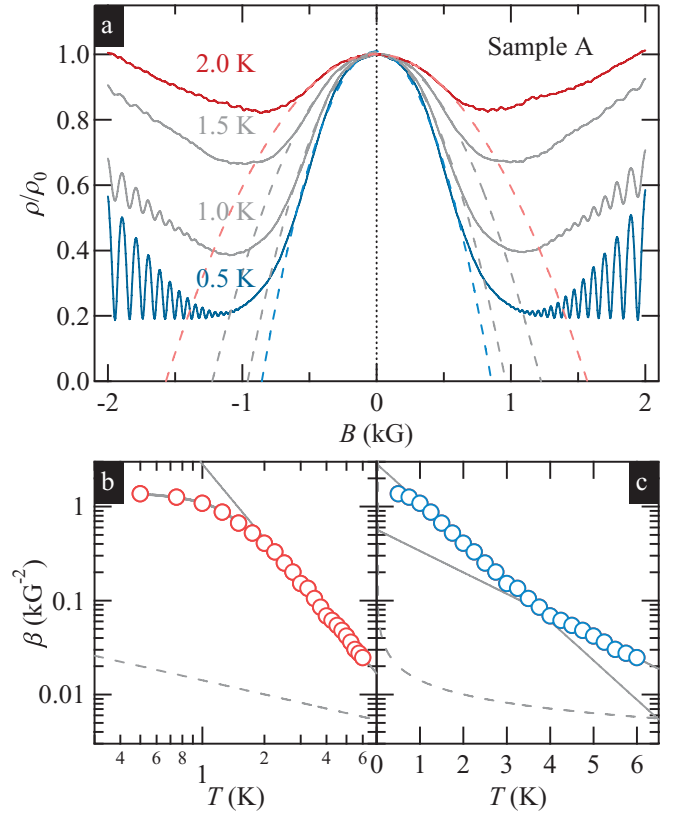
theoretical models and compare the results of our analysis to other experimental studies.[13,34]

The *quasiclassical disorder model*[50] predicts a parabolic negative magnetoresistance [see Eq. (1)], with β given by

$$\beta_d = \frac{e^2}{2\pi n_S p_F^2} \left(\frac{\tau_L}{2\tau_S}\right)^{1/2}, \quad 0 < \tau_L^{-1} \ll \tau_S^{-1}. \qquad (2)$$

Here, τ_L^{-1} and τ_S^{-1} are long- and short-range disorder momentum relaxation rates, $\tau^{-1} = \tau_L^{-1} + \tau_S^{-1}$,[56] n_S is the areal density of short-range scatterers, and p_F is the Fermi momentum. Equation (2) is valid for $\beta_d B^2 \ll 1$, and at higher B the resistivity is expected to saturate at $\rho_{\min} \simeq \rho_0 \times (\tau_S/\tau_L) \ll \rho_0$.[50,51]

While the *disorder model* can, in principle, lead to GNMR, it clearly fails to explain our experimental findings. First, as shown above, β exhibits strong dependence on temperature which does not enter Eq. (2). Second, we believe that the assumption of $\tau_L^{-1} \ll \tau_S^{-1}$ is not satisfied in our samples. Indeed, the analysis of Hall field-induced resistance oscillations in sample A[57] suggests an opposite relation, $\tau_L^{-1} \simeq 5\tau_S^{-1}$. We finally notice that while Ref. 13 concluded that the GNMR in their samples can be consistently described by Eq. (2),[59] neither the temperature dependence nor the validity of the $\tau_L^{-1} \ll \tau_S^{-1}$ condition has been examined.

The *electron-electron interaction model*,[33,60,61] on the other hand, predicts a temperature-dependent magnetoresistance. In the ballistic regime, $\hbar/\tau \ll k_B T$, and for smooth disorder potential this model also leads to Eq. (1), with β given by[61]

$$\beta_i^{\text{sm}} = \mu^2 \frac{\rho_0}{R_K} \frac{c_0}{\pi} \left(\frac{\hbar/\tau}{k_B T}\right)^{1/2}, \quad \tau_S^{-1} = 0. \tag{3}$$

Here, $R_K = h/e^2$ is the von Klitzing constant and $c_0 = 3\zeta(3/2)/16\sqrt{\pi} \simeq 0.276$. However, Eq. (3) also fails to describe our findings. Indeed, taking $T = 1$ K as an example, our experiment gives $\beta \approx 1.1$ kG^{-2}, which is nearly *two orders of magnitude larger* than $\beta_i^{\text{sm}} \approx 0.014$ kG^{-2} obtained from Eq. (3). A comparison of β_i^{sm} obtained using Eq. (3) [cf. the dashed line in Figs. 4(b) and 4(c)] with our data shows that the discrepancy remains significant over the whole range of T studied. Moreover, it this clear that the interaction model fails to explain our data even on a qualitative level. We also notice that significant disagreement with Eq. (3) was found in Ref. 34 reporting low-temperature β which is roughly 30 ($n \approx 2 \times 10^{11}$ cm^{-2}) to 150 ($n \approx 3 \times 10^{11}$ cm^{-2}) times larger than β_i^{sm}.[62]

We next consider several scenarios for the observed discrepancy. First, in a realistic high-mobility 2DEG, sharp disorder, which is not present in Eq. (3), plays a crucial role in many of the low-field magnetotransport phenomena.[3,9–11,22–24,36,50,51,58,63–66] For the case of mixed disorder potential Eq. (3) is generalized to[61]

$$\beta_i^{\text{mix}} = \left(4 - \frac{3\tau}{\tau_L}\right) \sqrt{\frac{\tau_L}{\tau}} \beta_i^{\text{sm}}. \tag{4}$$

If $\tau_L^{-1} \ll \tau_S^{-1}$, there appears a parametrically large factor $4(\tau_L/\tau)^{1/2} \gg 1$ which leads to $\beta_i^{\text{mix}} \gg \beta_i^{\text{sm}}$. However, in our sample A, as mentioned above, $\tau_L^{-1} \simeq 5\tau_S^{-1}$ from which we estimate $(4 - 3\tau/\tau_L)\sqrt{\tau_L/\tau} \approx 1.5$. Such a small factor is clearly not sufficient to explain the discrepancy.

Another possible cause for large β is the disorder-induced T-independent correction, similar to that given by Eq. (2). Assuming that the contributions are additive, one has $\beta = \beta_d + \beta_i$, where $\beta_d(\beta_i) \propto T^0(T^{-1/2})$. It is clear, however, that the experimentally obtained $\beta(T)$ cannot be described by such dependence.[67]

Theoretically, it would be interesting to consider a possibility that the low-temperature magnetoresistance originates primarily from the quasiclassical disorder mechanism which, however, is significantly altered by the electron-electron interactions with increasing temperature.[68] However, such a theory remains a subject of future work.

In summary, a giant negative magnetoresistance effect in high-mobility GaAs/AlGaAs heterostructures and quantum wells is marked by a pronounced minimum of the longitudinal resistivity appearing at $B \simeq 1$ kG. The temperature dependence clearly reveals a crossover between two distinct regimes. In the high-temperature regime, the zero-field resistivity and the minimum resistivity both exhibit linear temperature dependence, due to scattering on thermal acoustic phonons. In the low-temperature regime, however, zero-field resistivity quickly saturates, but the minimum resistivity continues to decrease at an even faster rate, eventually becoming a small fraction of the zero-field resitivity. Unexpectedly, we also find that the GNMR is destroyed not only by temperature but also by very modest (a few kG) in-plane magnetic fields. Finally, our analysis of the low-field magnetoresistivity demonstrates that the GNMR effect cannot be understood by existing theoretical models considering either interaction-induced or disorder-induced corrections, even on a qualitative level. Taken together, these findings provide important clues for emerging theories and should help to elucidate the origin of the GNMR in very-high-mobility 2DES.

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[55]In order to improve the fitting procedure, a slight asymmetry of the raw data in Fig. 1(a) was eliminated by subtracting a linear in B component to ensure $\rho(B_0) = \rho(-B_0)$.

[56]The limiting cases of $\tau_L^{-1} = 0$, known as Lorentz gas, and of $\tau_S^{-1} = 0$ have been studied in Refs. 45–47 and Refs. 48 and 49, respectively.

[57]The approach of Ref. 58 yields $\tau_\pi/\tau \approx 6$, where τ_π^{-1} is the electron backscattering rate off short-range disorder. With $\tau_S \simeq \tau_\pi$ one obtains $\tau_S^{-1} \approx (1/6)\tau^{-1}$ and $\tau_L^{-1} \approx (5/6)\tau^{-1}$. This analysis assumed isotropic scattering off short-range disorder, which might not be exactly the case.

[58]A. T. Hatke, M. A. Zudov, L. N. Pfeiffer, and K. W. West, Phys. Rev. B **79**, 161308(R) (2009).

[59]Reference 13 assumed $\tau_S/\tau_L \simeq \rho_{min}/\rho_0$, and using Eq. (2) found that in their samples (with μ ranging from 0.9×10^7 cm^2/Vs to 3.0×10^7 cm^2/V s) n_S varies between $(2.6 \ \mu m)^{-2}$ and $(8.0 \ \mu m)^{-2}$. These values correspond to $n_S^{(3D)} \sim n_S/a_B \sim 10^{13}$ cm^{-3} and 10^{12} cm^{-3} ($a_B \simeq 10$ nm is a Bohr radius in GaAs). The same procedure applied to the data from sample A at $T = 0.5$ K leads to $n_S \simeq (1.6 \ \mu m)^{-2}$.

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[61]I. V. Gornyi and A. D. Mirlin, Phys. Rev. B **69**, 045313 (2004).

[62]The disagreement with Eq. (3) is not only in the magnitude of β but also in its much stronger density dependence.

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[67]Fitting the data with $\beta = \beta_0 + bT^{-1/2}$ leads to $\beta_0 < 0$ at any temperature.

[68]D. G. Polyakov (private communication).