Negative Magnetoresistance in Viscous Flow of Two-Dimensional Electrons

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At low temperatures, in very clean two-dimensional (2D) samples, the electron mean free path for collisions with static defects and phonons becomes greater than the sample width. Under this condition, the electron transport occurs by formation of a viscous flow of an electron fluid. We study the viscous flow of 2D electrons in a magnetic field perpendicular to the 2D layer. We calculate the viscosity coefficients as the functions of magnetic field and temperature. The off-diagonal viscosity coefficient determines the dispersion of the 2D hydrodynamic waves. The decrease of the diagonal viscosity in magnetic field leads to negative magnetoresistance which is temperature and size dependent. Our analysis demonstrates that this viscous mechanism is responsible for the giant negative magnetoresistance recently observed in the ultrahigh-mobility GaAs quantum wells. We conclude that 2D electrons in those structures in moderate magnetic fields should be treated as a viscous fluid.

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In modern high-quality GaAs heterostructure samples with low-temperature mobilities of 2D electrons of the order of 10^6–10^7 cm^2/Vs the electron mean free path for collisions with static defects and phonons, l, can be greater than the sample width w. In this case, the transport properties depend on the character of the electron scattering at the sample edges. If the scattering is *specular* and the sample has the form of a long rectangle, then, after several collisions with the edges, an electron will eventually be scattered by a defect or a phonon. These processes will determine the Drude resistivity $\varrho_D = m/e^2 n\tau$, $\tau = l/v_F$, similar to the usual case when $l \ll w$. Here n is the electron concentration, e and m are the electron charge and the effective mass, and v_F is the Fermi velocity.

If the scattering on the sample edges is *diffusive*, the electron transport will be controlled by the relation between the mean free path for electron-electron collisions, l_{ee}, and the sample width w. When l_{ee} is greater than w, the scattering at the edges dominates and the transport mean free path will be of the order of w. The corresponding "ballistic" resistivity is $\varrho_{\rm ball} = m/e^2 n\tau_{\rm ball}$, where $\tau_{\rm ball} \sim w/v_F$. In the opposite case, $l_{ee} \ll w$, the electron transport should resemble the Poiseuille flow in conventional hydrodynamics with the resistance proportional to the electron shear viscosity $\eta \sim v_F l_{ee}$. This idea was put forward (for three-dimensional metals) by R. N. Gurzhi with co-authors a long time ago [1–3], and more recently it was also applied to various aspects of two-dimensional electron transport [4–10]. The equations describing a flow of a viscous electron fluid in a sample have some common features with the magnetohydrodynamic equations of charge-compensated viscous fluids (e.g., plasma in the hydrodynamic limit) [11,12].

If a sample is placed in magnetic field and the electron cyclotron radius R_c is much smaller than the sample width w, the hydrodynamic regime can be realized even when $l_{ee} > w$ (but herewith $l_{ee} \ll l$) [2]. Indeed, an electron moving along the trajectory similar to the circle with the radius $R_c \ll w$ does not scatter on the sample edges, but undergoes all other types of scattering. The electron viscosity, like other kinetic coefficients, becomes a tensor depending on magnetic field [13,14].

Another type of solid state system with the hydrodynamic mechanism of electron transport was studied in Ref. [15]. The authors of that paper considered a 2D viscous electron flow bypassing the defects located one from another at the distances of the order of $d \gg l_{ee}$. If the electron-electron scattering dominates, a viscous flow in the regions between the defects is formed and the sample resistance is again proportional to the viscosity η.

In this Letter we develop the hydrodynamic approach for the 2D electron transport in a magnetic field [16]. We calculate the electron viscosity tensor in a shortcut way similar to the textbook derivation of the Drude conductivity. The nondiagonal viscosity η_{xy} determines the dispersion law of the 2D hydrodynamic waves in a magnetic field. The decrease of the diagonal viscosity η_{xx} with the magnetic field provides a mechanism for large *negative* magnetoresistance of 2D electrons which is temperature and sample width dependent [17]. We perform detailed calculations of magnetoresistance for the conventional Poiseuille flow in a long rectangular GaAs sample with rough edges. We also qualitatively demonstrate that the hydrodynamic negative magnetoresistance arises in the 2D samples of other types, in particular, in the samples containing large-radius defects.

The temperature-dependent giant negative magnetoresistance of 2D electrons in high-quality GaAs quantum wells at low temperatures and moderate magnetic fields, reported in several recent publications [18–20], and especially the "colossal" negative magnetoresistance, observed

in Ref. [21], are not understood at the present time. Several striking features of these experiments, especially, the temperature dependence of magnetoresistance, are in fine agreement with the predictions of our model. Our theory explains the existence of a magnetoresistance peak as well as its broadening and disappearing with temperature [22–26]. Thereby we conclude that 2D electrons in the ultrahigh-mobility GaAs quantum wells in moderate magnetic fields form a viscous fluid [27].

We recall the simple hydrodynamic approach in the extreme case when the electron mean free path l_{ee} is much less than the 2D sample width w, while the mean free path for scattering by phonons and static defects is much greater than w. Also the sample length L is assumed to be much greater than w. The hydrodynamic electron velocity $V(y)$, directed along x, obeys the equation

$$\frac{\partial V}{\partial t} = \eta \frac{\partial^2 V}{\partial y^2} + \frac{e}{m} E, \tag{1}$$

where $\eta = v_F l_{ee}/4$ is the viscosity of the 2D degenerate electron gas and E is the electric field directed along x. In the present work we neglect the compressibility and the thermal conductivity effects.

The conventional boundary conditions require $V = 0$ at $y = \pm w/2$. This implies that the electron scattering at the sample edges is diffusive [28]. In the stationary case, the solution of Eq. (1) gives the parabolic velocity profile $V(y)$. Integrating the current density $j_x(y) = enV(y)$ over y one obtains the resistivity

$$\rho = \frac{m}{e^2 n \tau^\star}, \qquad \tau^\star = \frac{w^2}{12\eta}. \tag{2}$$

Here $\tau^\star$ is the "effective" relaxation time which, in the hydrodynamic regime, replaces the normal momentum relaxation time τ in the formula $\varrho_D = m/e^2 n\tau$.

To be precise, by the electron-electron scattering time $\tau_{ee} = l_{ee}/v_F$ we have to imply the relaxation time $\tau_{2,ee}$ of the second moment of the electron distribution function (i.e., its harmonics $\sim e^{im\phi}$ with $m = \pm 2$, where ϕ is the angle of the single electron velocity). For such a time a calculation was done for an almost ideal Fermi gas and the Debye model for screening of the Coulomb potential. Following the approach of Ref. [35], we obtained

$$\frac{\hbar}{\tau_{2,ee}(T)} = A_{ee} \frac{T^2}{E_F}, \tag{3}$$

where T is the temperature, $E_F = m v_F^2/2$ is the Fermi energy, and $A_{ee} = A_{ee}(E_F)$ is a dimensionless value of the order of 1 for E_F corresponding to typical GaAs samples. However, for these samples the electron-electron interaction energy is of the same order of magnitude as the electron kinetic energy. Calculation of the time $\tau_{2,ee}$ for a system of strongly interacting electrons is very laborious, but it leads to the result, which is quite similar to Eq. (3) (see Refs. [29,36]).

Thus the characteristic features of the ideal viscous electron transport consist in (i) inverse dependence of resistivity on the square of the sample width, $\rho \sim 1/w^2$, and (ii) inverse dependence of resistivity on the square of temperature T, $\rho \sim \eta \sim \tau_{2,ee} \sim 1/T^2$. A weakly pronounced *decrease* of resistance with increasing temperature was recently reported in Ref. [21] in a limited temperature interval below 5 K.

It should be noted that generally the electron viscosity is not necessarily related to electron-electron collisions. Any process providing the relaxation of the second moment of the electron distribution function (e.g., scattering on static defects or, more generally, on disorder) gives rise to viscosity. So the viscosity coefficient η is proportional to the relaxation time τ_2, for which the reciprocal value, $1/\tau_2$, contains the contribution Eq. (3) from the electron-electron scattering as well as the temperature-independent contribution from electron scattering on disorder:

$$\eta = \frac{1}{4} v_F^2 \tau_2, \qquad \frac{1}{\tau_2(T)} = \frac{1}{\tau_{2,ee}(T)} + \frac{1}{\tau_{2,0}}. \tag{4}$$

The result given by Eq. (2) is modified if the momentum relaxation time τ due to interaction with phonons and static defects is comparable to $\tau^\star$. In this case, the usual bulk friction term $-V/\tau$ should be added to the right-hand side of Eq. (1). The modified velocity $V(y)$ profile can be easily found, and integration over y gives the following expression for the resistivity [2,3]:

$$\rho = \frac{m}{e^2 n \tau} \frac{1}{1 - \tanh(\xi)/\xi}, \qquad \xi = \sqrt{\frac{3\tau^\star}{\tau}}. \tag{5}$$

For $\tau \gg \tau^\star$, $\tanh \xi \approx \xi - \xi^3/3$ and the expression for the resistivity in Eq. (5) reduces to Eq. (2). In the opposite case, when $\tau \ll \tau^\star$, $\tanh \xi \approx 1 \ll \xi$ and one recovers the usual Drude resistivity $\varrho_D = m/e^2 n\tau$ defined by the momentum relaxation time τ.

It turns out that the following simple interpolation formula:

$$\rho = \frac{m}{ne^2} \left(\frac{1}{\tau} + \frac{1}{\tau^\star} \right), \tag{6}$$

reproduces the expression Eq. (5) for any value of $\tau^\star/\tau$ with an accuracy better than 11%. Thus the effect of the electron viscosity can be regarded as a *parallel* channel of electron momentum relaxation.

The values of the momentum relaxation time $\tau_{\rm ph}$ for the scattering of a 2D electron by acoustic phonons in the GaAs quantum well were estimated by using the results of Refs. [37]. According to those papers, the momentum relaxation rate is proportional to temperature, $1/\tau_{\rm ph}(T) = A_{\rm ph} T$, at $T \gtrsim 4$ K and to higher powers of temperature at $T \lesssim 4$ K (for the structure studied in

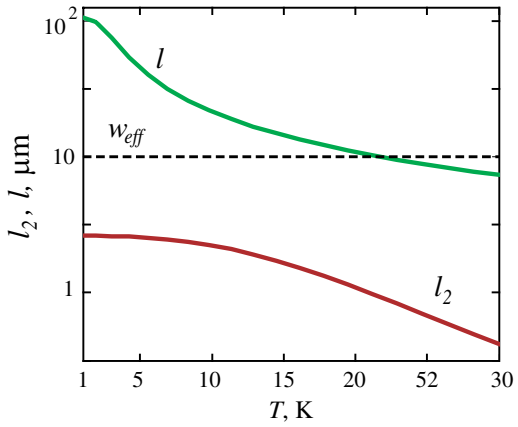

FIG. 1. The mean free paths $l(T)$ and $l_2(T)$ for relaxation of the electron momentum and the second moment of the electron distribution function. Calculations are performed for the sample studied in Ref. [21].

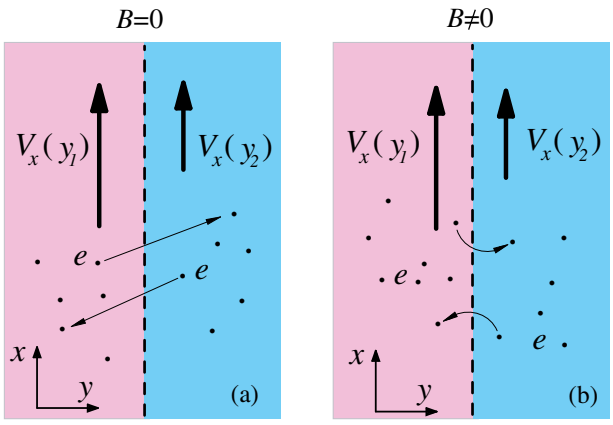

FIG. 2. The physical origin of the decrease of electron viscosity in the magnetic field (schematics). Two adjacent layers of the electron fluid move with different velocities $V_x(y_1)$ and $V_x(y_2)$. The viscous friction is due to the interlayer penetration of electrons. Without magnetic field (a) the penetration length (defining the viscosity) is of the order of l_2. In the strong magnetic field $\mathbf{B} = B\mathbf{e}_z$ (b) this length is limited by the cyclotron radius $R_c \ll l_2$.

Ref. [21]). For the total bulk momentum relaxation rate we should use the expression

$$\frac{1}{\tau(T)} = \frac{1}{\tau_{\rm ph}(T)} + \frac{1}{\tau_0}, \tag{7}$$

where the term $1/\tau_0$ does not depend on temperature and is due to electron scattering on disorder.

Figure 1 shows the temperature dependencies of the mean free paths $l_2 = v_F\tau_2$ and $l = v_F\tau$ calculated according to Eqs. (4), (7), Eq. (1) in Ref. [29], and Refs. [37] with the parameters $\tau_{2,0}$, $A_{\rm ph}$, τ_0, A_{ee}^{Fl} that will be used further in the text to fit the experimental data from Ref. [21].

We now address our main point: the effects resulting from the dependence of the electron viscosity on the magnetic field perpendicular to the 2D layer.

The internal friction between two layers of the electron fluid moving with different velocities is provided by the exchange of electrons between these layers (see Fig. 2). In the absence of a magnetic field, electrons from one layer penetrate into another one on a distance which is of the order of l_2, and this is what defines the viscosity. However, in the presence of the magnetic field this distance is limited by the cyclotron radius R_c. Thus at a strong magnetic field the viscosity should tend to zero.

We derived the following expressions for the electron viscosity tensor η_{ij} [29]:

$$\eta_{xx} = \frac{\eta}{1+(2\omega_c\tau_2)^2}, \qquad \eta_{xy} = \frac{2\omega_c\tau_2\eta}{1+(2\omega_c\tau_2)^2}, \tag{8}$$

where $\omega_c = eB/mc$ is the cyclotron frequency, and η is the viscosity at zero magnetic field introduced above. Dissipation of energy in a viscous flow is related only to the coefficient η_{xx}.

The formula for the dissipative viscosity coefficient η_{xx}, similar to the expression in Eq. (8), was obtained by M. S. Steinberg for a 3D metal in Ref. [38]. The nondiagonal viscosity η_{xy}, to our knowledge, was not considered for 2D electrons in the literature previously.

For the hydrodynamic velocity of a 2D viscous flow in magnetic field we derived the motion equation [29]:

$$\frac{\partial \mathbf{V}}{\partial t} = \eta_{xx}\Delta\mathbf{V} + [(\eta_{xy}\Delta\mathbf{V} + \omega_c\mathbf{V}) \times \mathbf{e}_z] + \frac{e}{m}\mathbf{E} - \frac{\mathbf{V}}{\tau}, \tag{9}$$

where $\Delta = \partial^2/\partial x^2 + \partial^2/\partial y^2$. Since we neglect compressibility of the electron fluid, we must assume that $\mathrm{div}\mathbf{V} = 0$.

In the stationary regime and in the absence of the Hall current, $V_y \equiv 0$, Eq. (9) for a long sample reduces to

$$\eta_{xx}\frac{d^2V}{dy^2} + \frac{e}{m}E_x - \frac{V}{\tau} = 0, \tag{10}$$

$$\eta_{xy}\frac{d^2V}{dy^2} + \omega_c V - \frac{e}{m}E_y = 0. \tag{11}$$

Here $V = V_x$, $E_x(y) = \mathrm{const}$ is the electric field due to the applied voltage, and $E_y(y)$ is the Hall electric field corresponding to the condition $V_y \equiv 0$.

For the case of the absence of momentum relaxation in the bulk, $1/\tau = 0$, Eq. (10) coincides with the stationary version of Eq. (1) if one replaces η by η_{xx}. Thus the resistivity ρ will be given by Eq. (2) with the additional factor $[1+(2\omega_c\tau_2)^2]^{-1}$, describing the giant negative magnetoresistance. For the case of a nonzero bulk momentum relaxation rate, $1/\tau \neq 0$, the resistivity ρ corresponding to Eq. (10) will be calculated by Eq. (5), where

$$\xi = \sqrt{\frac{3\tau^\star}{\tau}[1+(2\omega_c\tau_2)^2]}, \tag{12}$$

or by the approximation formula analogous to Eq. (6):

$$\rho = \frac{m}{e^2 n}\left(\frac{1}{\tau} + \frac{1}{\tau^\star}\frac{1}{1+(2\omega_c\tau_2)^2}\right). \tag{13}$$

It is seen from Eq. (13) that the decrease of τ_2 and fastening of the relaxation rate $1/\tau$ with temperature leads to broadening and a shift upwards of the magnetoresistance curves (see Fig. 3). The increase of $\tau^\star$ with temperature results in the vanishing of negative magnetoresistance. At low temperatures and high magnetic fields, $\omega_c\tau_2 \gg 1$, the Eqs. (7) and (13) yield a finite value of the resistance, $m/e^2 n\tau_0$, which is related only to the electron momentum relaxation on disorder in the bulk.

The Hall voltage can be found by integration of Eq. (11) over y. The first term in the left-hand side of Eq. (11), proportional to the viscosity coefficient η_{xy}, is of the order of $\omega_c(l_2/w)^2 V$ at $\omega_c\tau_2 \ll 1$ or $\omega_c(R_c/w)^2 V$ at $\omega_c\tau_2 \gg 1$, while the second term $\omega_c V$ is much greater. Thus in the calculation of the Hall voltage one should take into account only the second term, and for the Hall coefficient we obtain the usual result: $R_H = 1/nec$.

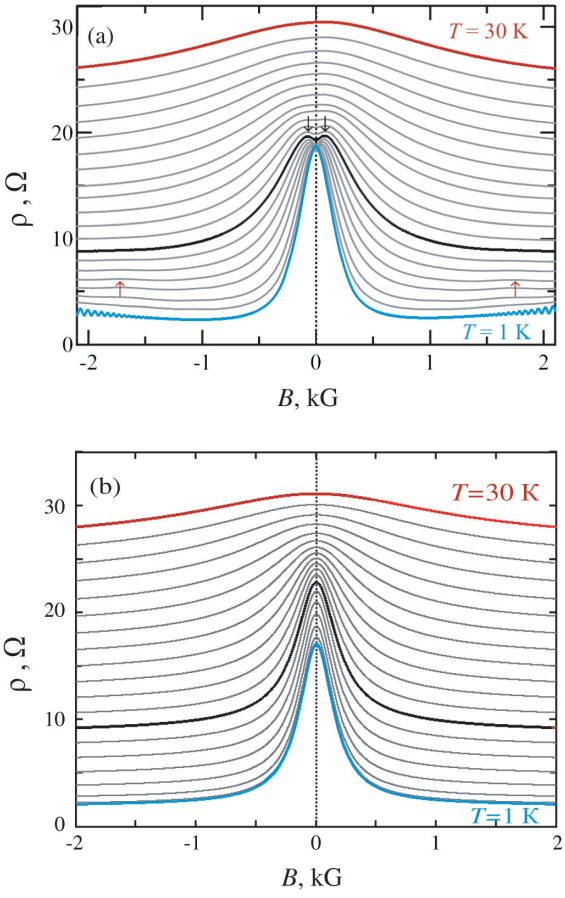

FIG. 3. Temperature-dependent magnetoresistance of high-mobility 2D electrons in the GaAs quantum well experimentally studied in Ref. [21]. Panel (a) is taken from Ref. [21]. The curves in panel (b) are drawn according to Eqs. (5) and (12) with the numerical parameters presented in the main text.

The viscosity coefficient η_{xy} is essential for nonstationary flows. For example, it is seen from Eq. (9) that the term proportional to η_{xy} gives a contribution to dispersion of the hydrodynamic waves, while η_{xx} is responsible for their dissipation. Indeed, if we seek the solution of Eq. (9) in the wave form $\mathbf{V}_\mathbf{k}(\mathbf{r},t) = \mathbf{A}_\mathbf{k}\exp(-i\omega_k t + i\mathbf{k}\cdot\mathbf{r})$, assuming the absence of electric field and bulk momentum relaxation, we easily obtain

$$\omega_k = \pm(\omega_c - \eta_{xy}k^2) - i\eta_{xx}k^2. \tag{14}$$

We now discuss the recent experimental results on the giant negative magnetoresistance of 2D electrons [18–21] in light of our theory. Figure 3(a) demonstrates the experimental magnetoresistance curves obtained in Ref. [21] for an ultrahigh-quality GaAs sample at different temperatures. For the same temperatures and magnetic fields, we calculated magnetoresistance of that sample within our theory [see Fig. 3(b)]. Herewith we used the disorder relaxation times τ_0, $\tau_{2,0}$ and the amplitudes $A_{\rm ph}$, A_{ee}^{Fl} in Eqs. (7) and Eq. (1) in Ref. [29] as fitting parameters.

Although by the appropriate choice of the fitting parameters we are able to perfectly reproduce the form of the experimental curves and their evolution with temperature, it is not possible to obtain, in such a procedure, the absolute values of the sample resistance observed in the experiments. The only way to obtain the measured magnitudes of resistivity within our theory is to replace the sample width w by some *effective* width $w_{\rm eff} < w$. This can be understood in the following way. The sample contains inhomogeneities which result in the formation of the conducting channels in the sample with the widths smaller the sample width w.

Indeed, in the samples where the giant negative magnetoresistance effect was observed there often exist large-radius oval defects arising in the process of growth of the heterostructures [39,40]. The distance d between the defects varies in the range 20–100 μm, while their radii are of the order of 20 μm [39].

In vicinities of the defects the hydrodynamic velocity $\mathbf{V}(\mathbf{r})$ cannot have a component in the direction perpendicular to the defect edge. A slowdown of the flow occurs due to the viscous transfer of the x component of the electron momentum in the y direction from the regions *between* the defects to the regions which are immediately *in front of* the defects (in the x direction). So the large-radius defects lead to momentum relaxation by the mechanism, analogous to the diffusive scattering on rough sample boundaries, as well as to formation of the conducting channels with the widths smaller than w. At the scales of the order of d, the picture of fluid motion is rather similar to the Poiseuille flow in a rectangular sample with the width $w_{\rm eff} \sim d$. The details of the velocity field $\mathbf{V}(\mathbf{r})$ are very complicated, but the relationship for the averaged resistance

$$\varrho \sim \frac{1}{\tau} + \frac{\eta_{xx}}{d^2}, \tag{15}$$

analogous to Eq. (13), will sustain (see Ref. [29] for a qualitative derivation of Eq. (15) and Ref. [34] for its rigorous derivation and analysis).

In Fig. 3(b) we show the magnetoresistance calculated with the following fitting parameters: $\tau_0 = 4.5 \times 10^{-10}$ s, $\tau_{2,0} = 1.1 \times 10^{-11}$ s, $A_{\rm ph} = 10^9\,{\rm s}^{-1}{\rm K}^{-1}$, $A_{ee}^{Fl} = 1.3 \times 10^9\,{\rm s}^{-1}{\rm K}^{-2}$, and $w_{\rm eff} = 10$ μm. Herewith the condition of applicability of the hydrodynamic approach, $l_2 \ll w_{\rm eff}$, is fulfilled at all the temperatures (see Fig. 1). The used values of $A_{\rm ph}$ and A_{ee}^{Fl} are in agreement, by the order of magnitude, with the result of our estimations of the parameters $A_{\rm ph}$ and A_{ee} for the quantum well studied in Ref. [21].

In conclusion, a hydrodynamic mechanism for 2D electron transport in a magnetic field has been studied. We have demonstrated that this mechanism is responsible for the giant negative magnetoresistance recently observed in the ultrahigh-mobility 2D electrons in GaAs/AlGaAs heterostructures.

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[1] R. N. Gurzhi, Sov. Phys. JETP **17**, 521 (1963).
[2] R. N. Gurzhi and S. I. Shevchenko, Sov. Phys. JETP **27**, 1019 (1968).
[3] R. N. Gurzhi, Sov. Phys. Usp. **11**, 255 (1968).
[4] L. W. Molenkamp and M. J. M. de Jong, Phys. Rev. B **49**, 5038 (1994).
[5] R. N. Gurzhi, A. N. Kalinenko, and A. I. Kopeliovich, Phys. Rev. Lett. **74**, 3872 (1995).
[6] H. Buhmann *et al.*, Low Temp. Phys. **24**, 737 (1998).
[7] H. Predel, H. Buhmann, L. W. Molenkamp, R. N. Gurzhi, A. N. Kalinenko, A. I. Kopeliovich, and A. V. Yanovsky, Phys. Rev. B **62**, 2057 (2000).
[8] A. Tomadin, G. Vignale, and M. Polini, Phys. Rev. Lett. **113**, 235901 (2014).
[9] M. Mendoza, H. J. Herrmann, and S. Succi, Scientific reports **3**, 1052 (2013).
[10] A. V. Andreev, S. A. Kivelson, and B. Spivak, Phys. Rev. Lett. **106**, 256804 (2011).
[11] L. D. Landau and E. M. Lifshitz, *Electrodynamics of Continuous Media* (Pergamon Press, Oxford, 1960).
[12] S. Childress, J. Fluid Mech. **15**, 429 (1963); A. V. Chechkin, J. Exp. Theor. Phys. **89**, 677 (1999); W. A. Manyonge, D. W. Kiema, and C. C. W. Iyaya, Int. J. Pure and Appl. Math. **76**, 661 (2012).
[13] E. M. Lifshitz and L. P. Pitaevskii, *Physical Kinetics* (Pergamon Press, Oxford, 1981).
[14] Yu. M. Aliev, J. Appl. Mech. Tech. Phys. **3**, 11 (1965).
[15] M. Hruska and B. Spivak, Phys. Rev. B **65**, 033315 (2002).
[16] A part of the results of this work was obtained together with Professor M. I. Dyakonov and reported at the conferences: *Workshop: Disorder and its Role in Transport in 2D Systems, Okinawa, Japan, January* (2015), https://groups.oist.jp/ja/dirt2d/program; *Workshop: Quantum transport in 2D systems, Luchon, France, May* (2015), http://www.quantware.ups-tlse.fr/ecoledeluchon/sessionw2/program.html;*Russian Conference on Semiconductor physics, Zvenigorod, Russia, September* (2015), http://semicond-2015.lebedev.ru/ru/programme.
[17] For the first time, the hydrodynamic mechanism for negative magnetoresistance of 2D electrons was discussed in Ref. [5]. However, the authors of Ref. [5] believed that such a mechanism is unlikely for existing GaAs quantum wells.
[18] A. T. Hatke, M. A. Zudov, J. L. Reno, L. N. Pfeiffer, and K. W. West, Phys. Rev. B **85**, 081304 (2012).
[19] R. G. Mani, A. Kriisa, and W. Wegscheider, Scientific reports **3**, 2747 (2013).
[20] L. Bockhorn, P. Barthold, D. Schuh, W. Wegscheider, and R. J. Haug, Phys. Rev. B **83**, 113301 (2011); L. Bockhorn, A. Hodaei, D. Schuh, W. Wegscheider, and R. J. Haug, J. Phys. Conf. Ser. **456**, 012003 (2013).
[21] Q. Shi, P. D. Martin, Q. A. Ebner, M. A. Zudov, L. N. Pfeiffer, and K. W. West, Phys. Rev. B **89**, 201301 (2014).
[22] Other existing mechanisms for strong negative magnetoresistance (see Refs. [23–26]) cannot explain the experiments [18–21]. Indeed, the mechanisms proposed in Refs. [23,24] are based on the memory effects in scattering of 2D electrons on disorder, and therefore the resulting magnetoresistance is independent on temperature in contrast to the experimental data. The work [25] deals with the quasi-two-dimensional systems in a quantizing magnetic field, which are significantly different from the GaAs systems studied in Refs. [18–21].
[23] A. D. Mirlin, D. G. Polyakov, F. Evers, and P. Wolfle, Phys. Rev. Lett. **87**, 126805 (2001).
[24] A. Dmitriev, M. Dyakonov, and R. Jullien, Phys. Rev. B **64**, 233321 (2001).
[25] P. Goswami, J. H. Pixley, and S. Das Sarma, Phys. Rev. B **92**, 075205 (2015).

[26] D. T. Son and B. Z. Spivak, Phys. Rev. B **88**, 104412 (2013).
[27] Recently, I became aware of the work P. J. W. Moll, P. Kushwaha, N. Nandi, B. Schmidt, and A. P. Mackenzie, Science **351**, 1061 (2016), in which negative magnetoresistance in the high-mobility 2D metal $PdCoO_2$ was reported and interpreted within the hydrodynamic approach, analogous to one developed in the present Letter.
[28] Electron scattering on the edges can be treated as diffusive when the sample edges are rough or when the conducting subregion of the sample has a complicated geometry; see some discussion of this topic further in this Letter and in Refs. [29,34].
[29] See Supplemental Material at http://link.aps.org/supplemental/10.1103/PhysRevLett.117.166601, which includes Refs. [30–33], for temperature dependencies of the 2D electron relaxation times in the cases of strong electron-electron interaction and strong interaction with disorder, for a Drude-like derivation of the 2D hydrodynamic equations in magnetic field, and for a qualitative consideration of a viscous flow in a sample with the large-radius defects.
[30] L. D. Landau and E. M. Lifshitz, *Fluid Mechanics* (Pergamon Press, Oxford, 1987).
[31] I. A. Dmitriev, A. D. Mirlin, D. G. Polyakov, and M. A. Zudov, Rev. Mod. Phys. **84**, 1709 (2012).
[32] M. G. Vavilov and I. L. Aleiner, Phys. Rev. B **69**, 035303 (2004).
[33] A. M. Dykhne, Sov. Phys. JETP **32**, 63 (1971).
[34] P. S. Alekseev, A. P. Dmitriev, I. V. Gornyi, and D. G. Polyakov (to be published).
[35] Z. Qian and G. Vignale, Phys. Rev. B **71**, 075112 (2005).
[36] D. S. Novikov, arXiv:cond-mat/0603184v1.
[37] V. Karpus, Sov. Phys. Semicond. **20**, 6 (1986); P. S. Alekseev, M. S. Kipa, V. I. Perel, and I. N. Yassievich, JETP **106**, 806 (2008); M. S. Keepa, P. S. Alekseev, and I. N. Yassievich, Semiconductors **44**, 198 (2010).
[38] M. S. Steinberg, Phys. Rev. **109**, 1486 (1958).
[39] R. Haug, *Negative Magnetoresistance in High-Mobility Heterostructures, Workshop: Quantum Transport in 2D Systems, Luchon, France, May, 2015*, http://www.quantware.ups-tlse.fr/ecoledeluchon/sessionw2/program.html.
[40] L. Bockhorn, I. V. Gornyi, D. Schuh, C. Reichl, W. Wegscheider, and R. J. Haug, Phys. Rev. B **90**, 165434 (2014).