PHYSICAL REVIEW B **110**, 045411 (2024)

Magnetic field breakdown of electron hydrodynamics

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(Received 21 March 2024; revised 20 June 2024; accepted 24 June 2024; published 8 July 2024)

Using spatially and temporally resolved microphotoluminescence, the effect of a strong magnetic field on the hydrodynamic properties of an electron-hole fluid is studied. The recombination rate of photogenerated holes is related to the rate of their diffusion. In this way, the electronic Venturi effect is observed in a mesoscopic variable-width GaAs channel and is used as a tool to probe the hydrodynamic response. It is shown that a quantizing magnetic field leads to the disappearance of the Venturi effect, which means that electron-hole fluid becomes nonhydrodynamic. The observed transition from the hydrodynamic regime to the nonhydrodynamic one is due to the magnetic field–induced decrease in the electron-electron scattering rate and is similar in nature to viscous negative magnetoresistance.

DOI: 10.1103/PhysRevB.110.045411

I. INTRODUCTION

Hydrodynamics is an effective description of the long-time and long-distance behavior of a many-particle system, based on conservation laws. Such a system behaves like a fluid, provided that the relaxation of its particles occurs over a time scale that is large compared to the microscopic time associated with collisions of its components. It is assumed that even though fluids are composed of molecules that collide with each other, they are considered as a continuum, which suggests that fluids are continuous rather than discrete. In this case, inside a fluid, frequent interparticle collisions ensure their regular movement in the form of a hydrodynamic flux.

In most conducting materials, momentum-relaxing scattering dominates, leading to nonhydrodynamic electron transport, which is well described by the Drude model. Despite this, the hydrodynamic approach has been successfully applied to describe the flow of electrons in ultraclean two-dimensional electron systems, where the rate of momentum-conserving electron-electron scattering exceeds the rate of momentum-relaxing scattering from disorder (impurities, boundaries, and phonons) [1–4].

The general description of electron hydrodynamics represents the flow of electrons in the form of diffusive transport and is based [5] on three nonlinear partial-differential equations: the continuity, Navier-Stokes, and energy-transport equations, reflecting the conservation of mass, momentum, and energy, respectively. In addition, electron hydrodynamics ignores the fact that electron system consists of discrete particles. It was shown that the hydrodynamic response of electrons arises from the ballistic flow, which is essentially independent particle motion, with a significant increase in the frequency of electron-electron collisions [6–10]. Experimentally, the ballistic-hydrodynamic transition is usually achieved with a change in temperature. Due to Pauli blocking, cooling of the electron hydrodynamic system to the temperature of liquid helium leads to the dominance of electron-phonon scattering over electron-electron collisions and, consequently, to the regime of ballistic electron transport. At the same time, the orbital motion of electrons in a magnetic field effectively reduces the mean free path of electrons, leading to a corresponding decrease in viscosity [11]. As reported in the work of Alekseev [12], this explains giant negative magnetoresistance observed in high-mobility GaAs quantum wells (QWs) [13,14], which is controlled by the ratio of the electron mean free path (limited by electron-electron scattering) to the cyclotron radius. In fact, the cyclotron motion of electrons suppresses the collective hydrodynamic flow, which causes their uncorrelated motion, and therefore, in a strong magnetic field, electron hydrodynamics can be disrupted. Thus, a transition from a hydrodynamic to a nonhydrodynamic (ballistic or Drude) regime, controlled by a magnetic field, can be observed.

We have recently developed a new method for studying diffusion phenomena in mesoscopic hydrodynamic channels built on GaAs/AlGaAs heterostructures [15]. This method is based on measuring the recombination rate of holes photoinjected into a channel, which is proportional to their diffusion rate. The proposed method differs from commonly used electric transport measurements in that it examines charge diffusion rather than charge drift. As a result, a hydrodynamic profile of the Poiseuille diffusion rate, an optical analogue of the Gurzhi effect, and an electronic Venturi effect, in which the diffusion rate increases as the electron fluid passes through the constricted part of the channel, were observed

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[15,16]. In this article, we report on a study of the diffusion of photogenerated holes in a system of hydrodynamic electrons under the action of a strong magnetic field. It is shown that a quantizing magnetic field leads to a disruption of the hydrodynamic response of electrons. Correspondingly, a transition from the hydrodynamic to the nonhydrodynamic diffusion regime is found.

II. EXPERIMENTAL DETAILS

The sample used in this work is a mesoscopic channel of variable width, fabricated based on a single GaAs QW with a thickness of 46 nm, grown on a (100)-oriented GaAs substrate by a molecular beam epitaxy. QW barriers were grown in the form of short-period GaAs/AlAs superlattices. The channel studied here consists of the segments width $w =$ 4, 10, and 50 μm. The sheet electron density and the mobility measured at the temperature of 1.4 K were $6.7\cdot10^{11}$ cm^{-2} and $2.0\cdot10^{6}$ cm^2/V · s, respectively. The electron-hole fluid exhibits hydrodynamic behavior in the temperature window of 4–30 K, with maximum viscosity at 25 K [17]. At a temperature of 25 K, the electronic Venturi effect has been observed up to a magnetic field of 9 T, meaning that even at such a strong magnetic field, collisions between particles control their flow, which is therefore hydrodynamic [15]. To find the conditions for observing a nonhydrodynamic regime, we applied a magnetic field to a practically inviscid electron-hole fluid at a temperature of 4 K. In the following, we will show that in this case, the Venturi effect disappears in a magnetic field of about 5 T, which indicates a violation of the hydrodynamic regime.

The energy structure of the sample studied here is similar to the structure calculated in the work of Pusep *et al.* [16]. The electric field built in the barriers spatially separates the electrons and holes photogenerated in the barriers, which leads to hole injection into the QW. As a result, photogenerated holes move into the QW, where they form a diffusion flow. Holes injected in this way into the GaAs QW lead to the emergence of a multicomponent hydrodynamic fluid formed by background electrons and photogenerated holes.

The time of recombination of photogenerated holes with background electrons was measured in various channel segments using time-resolved photoluminescence (TRPL) at the peak emission energy of the GaAs QW.

Scanning TRPL microscopy experiments were performed at the temperature of 4 K using a helium closed cycle cryostat equipped with a superconducting magnet (Attocube/Attodry1000) with a magnetic field directed perpendicular to the channel plane. TRPL measurements with a temporal resolution of 100 ps were made using the Pico Quant/LDH Series diode lasers emitting 80 MHz pulses at 440 nm (2.82 eV) with a pulse duration of 70 ps. Photoluminescence (PL) emission was dispersed by a 75 cm Andor/Shamrock spectrometer and the PL decay transients were detected by a PicoQuant Hybrid PMT detector triggered with a time-correlated single-photon PicoQuant/PicoHarp 300 counting system. Electron-hole pairs were generated within a laser spot about 1 μm in size. The spatial resolution of the setup is determined by the size of the light collection area, which is estimated at about 10 μm in the spectral range of GaAs QW radiation due to chromatic aberration.

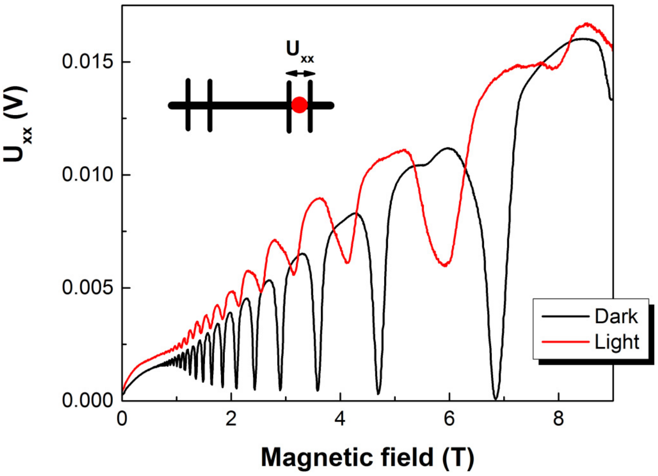

FIG. 1. Magnetoresistance measured on a Hall bar made using a sample of a similar structure in the dark and under laser pumping (light) conditions at T = 4 K. The position of the laser spot on the Hall bar is shown with a red circle.

The results of dark magnetoresistance measurements performed on a Hall bar made using a sample of a similar structure, together with data obtained with laser illumination (light) of the area between the potentiometric contacts, are presented in Fig. 1. In this case, the same laser pump power of 7.5 μW was used for light measurements as in the TRPL experiments. These data qualitatively demonstrate the effect of high-intensity laser excitation. They exhibit well-pronounced magnetoresistance oscillations caused by Landau quantization. At the same time, laser excitation apparently reduces the concentration and mobility of electrons.

III. RESULTS AND DISCUSSION

As mentioned earlier, the rate of hole recombination is proportional to the rate of their diffusion. Therefore, micro-TRPL measurements serve as a tool to study the spatial distribution of diffusion velocities of holes photoinjected into a mesoscopic GaAs channel of variable width, which is used as detector of a hydrodynamic response. The absence of a change in the recombination/diffusion rate with a change in channel width indicates a nonhydrodynamic flow, whereas in the case of a hydrodynamic regime, the Venturi effect is expected.

The scheme of excitation/collection process is shown in Fig. 2(a) together with the sample image. Holes injected into the QW at the focus of the lens diffuse to the boundaries of the light collection area at a velocity determined by the properties of the electron-hole fluid. All experimental data presented in the following were obtained at a laser pump power of 7.5 μW, which avoids sample heating.

PL spectra measured in a channel segment 50 μm wide in various magnetic fields are presented in Fig. 2(b). They demonstrate emission due to the recombination of electrons with holes injected into a GaAs QW from an AlGaAs barrier. Without the application of a magnetic field, PL emission is observed in the energy range between the band gap and the

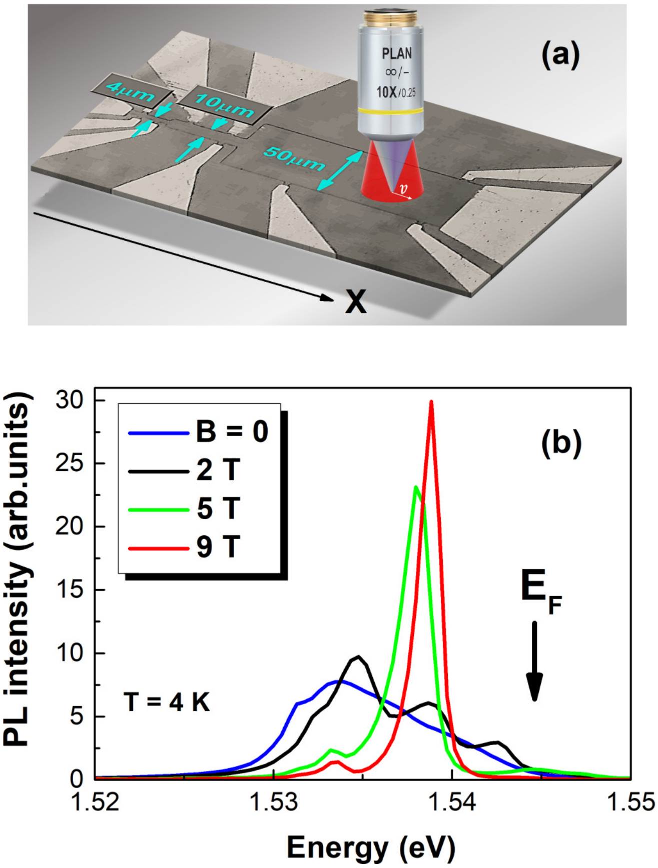

FIG. 2. Sketch of the excitation/collection probe (a), typical PL spectra measured in a channel segment 50 μm wide at T = 4 K, laser excitation at 440 nm (2.82 eV), and at the pump power of 7.5 μW, in various magnetic fields (b).

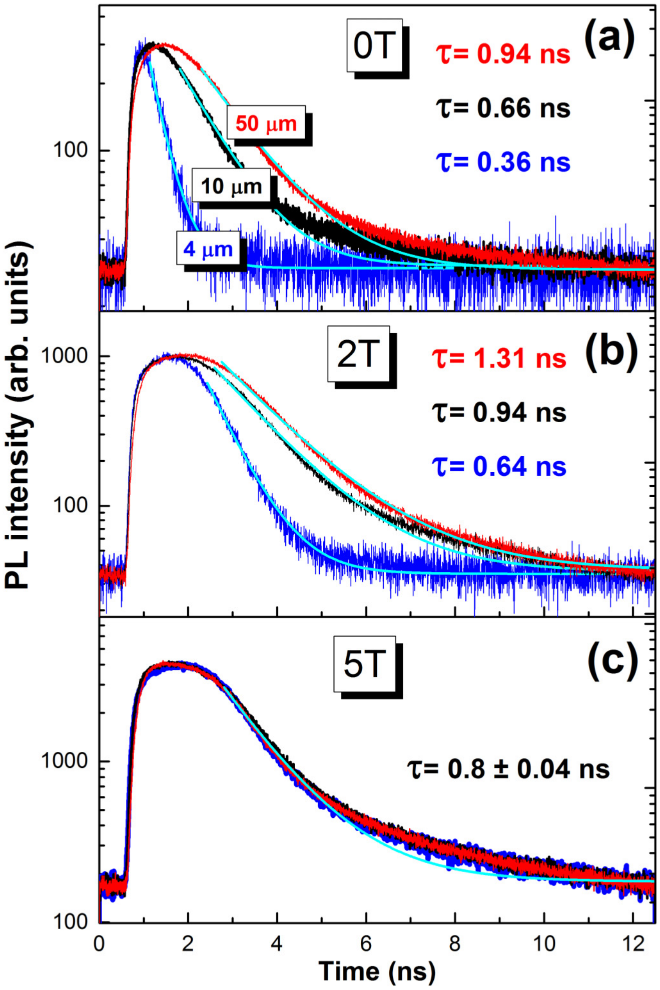

FIG. 3. Typical PL transients measured in various magnetic fields at T = 4 K in channel segments of different widths of 4, 10, and 50 μm.

electron Fermi level E_F. An increase in the magnetic field leads to Landau quantization of the electron and hole energies, observed in the sequence of corresponding PL peaks. In a magnetic field of 9 T, only the lowest electronic Landau levels are populated, resulting in the formation of one strong PL line.

Next, Fig. 3 shows typical PL transients measured in channel segments of different widths in different magnetic fields. The main features of the measured transients are as follows: (i) recombination occurs faster in narrow segments of the channel, and (ii) the magnetic field slows down recombination. Faster recombination in narrow channel segments is due to an increase in the diffusion velocity according to the electronic Venturi effect [15], whereas Landau quantization reduces the probability of recombination, which leads to an increase in recombination time.

It is important to note that in a magnetic field of 5 T, within the error in determining the recombination time, the PL transients measured in different segments of the channel are the same. This implies equal diffusion rates and, as a consequence, the absence of the Venturi effect. As a result, this indicates nonhydrodynamic diffusion flow. The measured PL transients exhibit a mostly monoexponential decay with a characteristic time related to the time of recombination of holes with background electrons. Therefore, a monoexponential fitting procedure was used to extract the corresponding recombination times from the PL transients. The estimated error in determining the recombination time is about ±0.04 ns. The results of the best fits are shown in Fig. 3 by cyan lines.

The recombination times measured along the channel in various magnetic fields are depicted in Fig. 4. As shown, without a magnetic field, the recombination time increases with increasing channel width. This is a direct consequence of the Venturi effect: the recombination time is inversely proportional to the diffusion flow rate of photogenerated holes, which decreases with increasing channel width. To simulate the flow of photogenerated holes, the diffusion rate was calculated for the case of a two-dimensional fluid using the ANSYS R19.2 code, as in prior work [15]. The recombination time is defined by $\tau = C/v$, where it is assumed that C = constant. Simple considerations support this statement. According to Fermi's golden rule, the recombination rate r of a transition between two energy states is determined by the number of final states N_h, which in the case under consideration are holes in the valence band: $r \sim N_h = pdvt$, where p, d, v, and t are the concentration of photogenerated holes, laser spot size, diffusion velocity of holes, and integration time used in TRPL measurements. Consequently, an increase in the hole diffusion

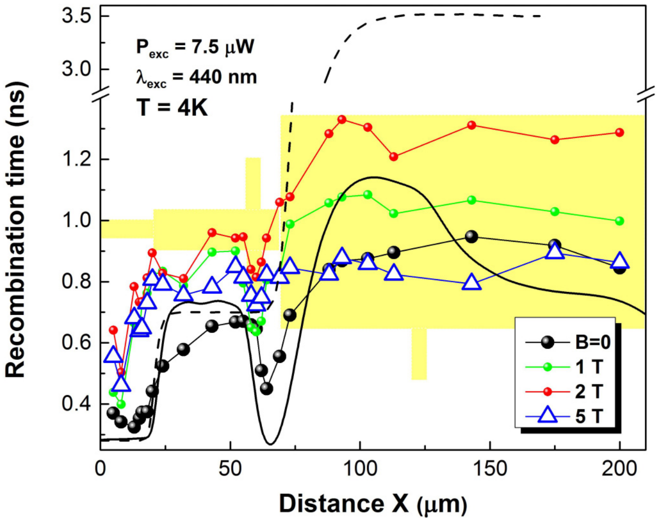

FIG. 4. The recombination time measured along the channel at 4 K at an excitation energy of 2.33 eV (440 nm) and in various magnetic fields. The black solid and dashed lines show the recombination times calculated without a magnetic field for the inviscid fluid as described in the text, for the channel with and without contact pins, respectively.

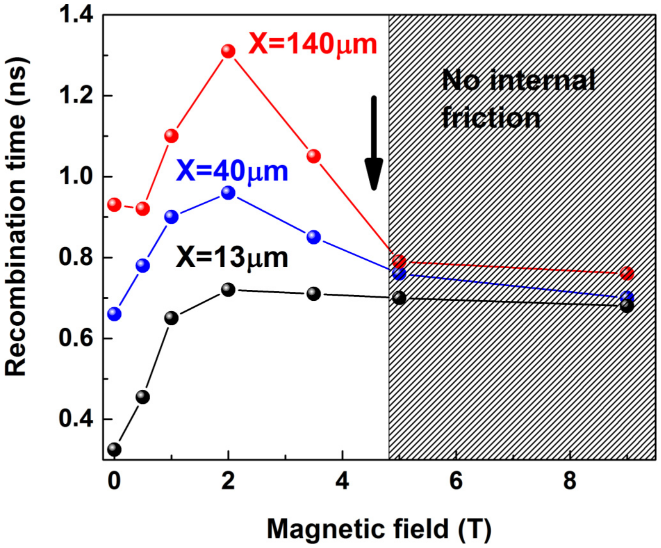

FIG. 5. The recombination times measured at 4 K as a function of the magnetic field in the narrow (at x = 13 μm), middle (at x = 40 μm), and wide (at x = 140 μm) segments. The arrow shows the magnetic field at which the transition from hydrodynamic to nonhydrodynamic diffusion occurs. The shaded area indicates the nonhydrodynamic region.

rate leads to an increase in the recombination rate/decrease in the recombination time. The parameters required for these calculations were obtained in a similar mesoscopic GaAs channel with a width of 5 μm in other works [16,17]. These include the diffusion coefficient/kinematic viscosity $D_{hh} = \nu_{hh} = 0.17\ \mathrm{m}^2/\mathrm{s}$ and the diffusion length attributed to heavy holes measured at T = 4 K, equal to $L_{hh} = 4$ μm. According to these data, in a segment 4 μm wide, the diffusion flow velocity is $v = 3D_{hh}/L_{hh} \simeq 7.5 \cdot 10^4$ m/s. As would be expected from the Venturi effect, the recombination time calculated for the two-dimensional channel without a contact pin is directly proportional to the channel width. However, according to the data shown in Fig. 4, experiments reveal a much weaker change in recombination time with channel width. The black solid and dashed lines show recombination times calculated without a magnetic field for the inviscid fluid as a function of the distance x along the channel, for the channel with and without contact pins, respectively. Adding contact pins considerably reduces the corresponding flow velocity and allows the calculated recombination time to be adjusted to the experimental one. Thus, taking into account the contact pins allows one to achieve agreement between the calculated and observed recombination times without using any fitting parameters. The best fits were obtained with contact pins to the middle (10 μm width) and wide (50 μm width) segments, as shown by the dotted lines in Fig. 4. However, the addition of contact pins to a narrow segment worsens the agreement between the calculated and experimental recombination times. In a segment 4 μm wide, the diffusion length of heavy holes is about its width. In this case, the rapid decay of PL at the channel boundary prevents the contribution of the contact pins.

At the same time, the recombination times measured in the narrow, middle, and wide segments as a function of the magnetic field are shown in Fig. 5. As mentioned earlier, as the magnetic field increases to 2 T, the recombination time increases due to Landau quantization, which is the same in all segments of the channel. In this case, the Venturi effect does not change with a change in the magnetic field. However, in a strong magnetic field of 5 T, the Venturi effect disappears—equal recombination times were obtained in all channel segments. According to Alekseev [12], viscous friction is reduced due to a magnetic field–induced decrease in electron penetration between adjacent layers in a moving hydrodynamic electron fluid. Moreover, as reported by Kempa *et al.* [18], a strong magnetic field can suppress electron-electron scattering. Consequently, momentum-relaxing electron scattering can prevail over momentum-conserving electron-electron collisions and a hydrodynamic diffusion flux is not formed. Therefore, the hole diffusion velocity remains independent of the channel width.

It is important to note that in the presented experiments, the diffusion of photogenerated holes occurs in a viscous electron fluid, which determines the hydrodynamic properties of the electron-hole system under study. When a magnetic field disrupts the hydrodynamics of electrons, the entire electron-hole fluid becomes nonhydrodynamic.

IV. CONCLUSIONS

In summary, the effect of a magnetic field on the diffusion of holes photoinjected into a hydrodynamic electron system formed in a mesoscopic channel of variable width has been studied. In such a channel, an increase in the diffusion rate was detected when holes flow through a narrowed segment of the channel, which is the Venturi effect. Thus, the Venturi effect was used as a tool to probe the hydrodynamic properties of the electron-hole fluid. It was shown that a quantizing magnetic field leads to the disappearance of the Venturi effect, which means that the diffusion flow becomes nonhydrodynamic. The observed hydrodynamic–nonhydrodynamic transition is caused by a magnetic field–induced decrease in the electron mean free path length and is similar in nature to viscous negative magnetoresistance. It should be noted that such a magnetic field–induced hydrodynamic–nonhydrodynamic transition is difficult to observe in electrical transport measurements, since a quantizing magnetic field applied to a clean hydrodynamic electron system leads to the quantum Hall effect, which radically changes the topology of electron diffusion. At the same time, holes photogenerated in the experiments described lead to significant scattering of electrons, which interferes with the quantum Hall effect.

ACKNOWLEDGMENTS

Financial support from the Brazilian agencies FAPESP (Grants No. 2021/12470-8, No. 2022/10340-2, No. 2022/02132-0) and CAPES (Grant No. PNPD 88887.336083/2019-00) are gratefully acknowledged.

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