Magnetic field effect on diffusion of photogenerated holes in a mesoscopic GaAs channel

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The effect of the magnetic field on diffusion of the photogenerated holes was studied in a mesoscopic channel formed in a high-mobility GaAs quantum well where the electron-hole plasma reveals hydrodynamic properties. The reported results demonstrate that the magnetic field leads to a significant asymmetry of the diffusion profile, which depends on the direction of the magnetic field. According to the presented results, the observed asymmetry is due to the entrainment of holes by the electron Hall current. As a result, a magnetic-field-induced spatial separation of the diffusion of heavy and light holes was found. The valve effect, which controls the number of photogenerated light holes reaching the collection probes, is observed when the current through the collection probes is varied.

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I. INTRODUCTION

In clean electron systems, where electron-electron collisions with conservation of momentum predominate over scattering of electrons without conservation of momentum, electron transport resembles a classical fluid flow. In this case, the electrons exhibit a collective behavior that can be interpreted using the hydrodynamic approach [1,2]. The fundamental property of electrons is their electric charge, which determines the specific response of hydrodynamic electrons to a magnetic field. For instance, the suppression of viscosity by a transverse magnetic field has been predicted for more than 60 years [3]. More recently, such an effect was observed in high-mobility GaAs/AlGaAs heterostructures [4,5]. Furthermore, many fascinating phenomena caused by the magnetic field have been observed in hydrodynamic electron systems: The Hall viscosity [6–10], the giant negative magnetoresistance [11], and the magnetic resonance at the double cyclotron frequency [12] (see also references in Ref. [13]). Moreover, some new effects were predicted such as the transverse magnetosonic waves [14] and the magnetic-field-induced oscillations of the spin density [15].

We address our investigation to the diffusion processes which take place in the hydrodynamic regime in a high-mobility mesoscopic GaAs channel. In particular, we report the effect of a magnetic field on the diffusion of photogenerated holes in a viscous electron fluid. We found that the magnetic field applied perpendicular to the channel causes a significant change in the diffusion profile (particle concentration as a function of distance), which depends on the direction of the magnetic field. The observed effect was found to be due to the electron Hall current, which blocks the diffusion of light holes, preventing them from reaching the collecting probes, while leaving heavy holes unaffected. As a consequence, a magnetic-field-induced spatial separation of the diffusion of heavy and light holes was observed.

II. EXPERIMENTAL DETAILS

A hydrodynamic two-dimensional electron gas was formed in a single GaAs/AlGaAs quantum well (QW) 14 nm thick, grown on a (100)-oriented GaAs substrate by a molecular beam epitaxy. The sheet electron density and the mobility measured at the temperature of 1.4 K were 9.1×10^{11} cm^{-2} and 2.0×10^{6} cm^2/V s, respectively. In this structure the viscous flow transport was demonstrated in Refs. [16–18], while diffusion of photogenerated holes was studied by measuring photocurrent in Ref. [19]. It should be noted that the high optical excitation conditions, when the concentration of photogenerated holes is comparable to the concentration of background electrons, used for photocurrent measurements, cause strong electron-hole scattering, which suppresses the quantum Hall regime expected in such pure electronic systems. At the same time, the electron-hole fluid continues to exhibit collective fluid behavior due to the momentum-conserving nature of electron-hole scattering.

The energy band structure of the sample studied here, calculated by a one-electron Schrödinger-Poisson equation solver [20], is depicted in Fig. 1 where the relevant electron and hole levels are shown. The band parameters used in the calculations were taken from Ref. [21]. The only lowest-energy fundamental confined level is found in the conduction band below the Fermi energy. Optical excitation in the region of barriers leads to the spatial separation of photogenerated electrons and holes due to the built-in electric field. As a consequence, photogenerated holes tunnel into the QW, where their recombination with background doping electrons causes a decrease in the electron concentration.

Scanning photocurrent (PC) microscopy experiments were performed on a multiterminal Hall bar structure with the 5 μm width and 100 μm length of the active area at the temperature 3.7 K using a helium closed cycle cryostat equipped with a superconducting magnet (Attocube/Attodry1000). The

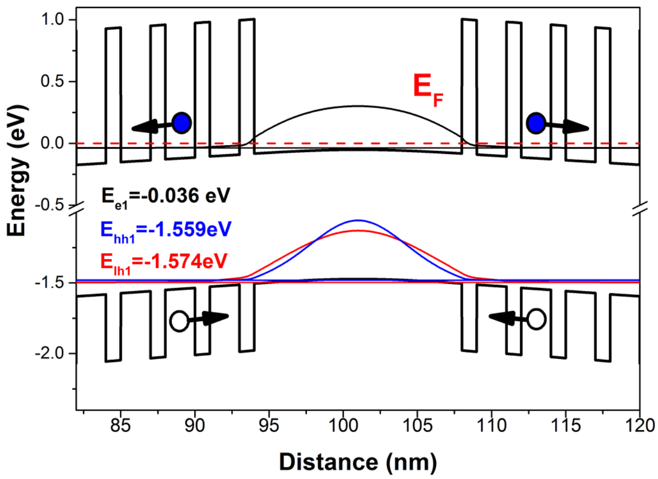

FIG. 1. Calculated energy structure of the 14-nm-thick GaAs/AlGaAs QW. The Fermi energy, shown as a dashed red line, is used as an energy reference.

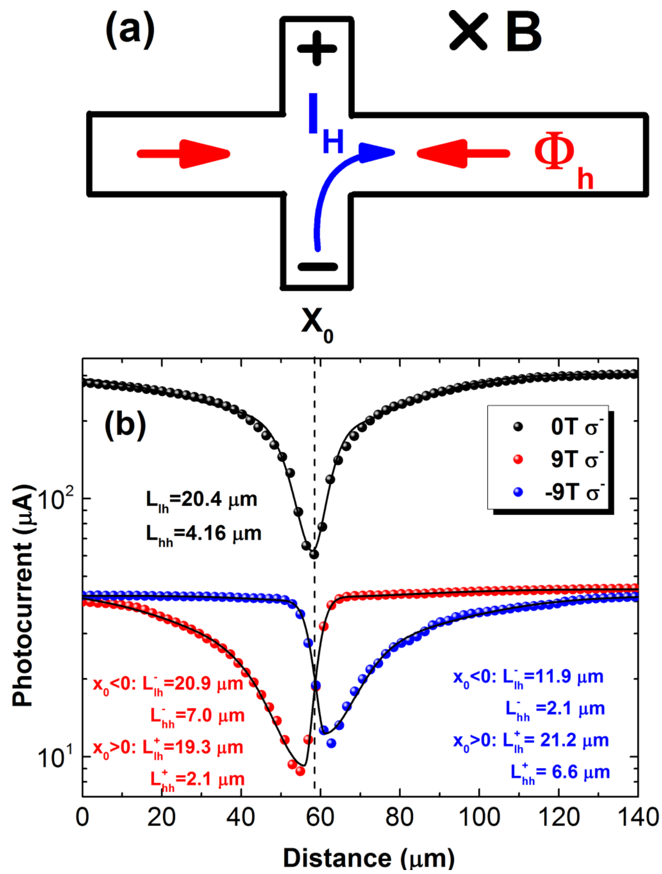

FIG. 2. (a) Scheme of the electron Hall current I_H and the hole diffusive fluxes Φ_h that contribute to the PC measured between the collecting contacts + and − in the magnetic field perpendicular to the QW plane (the positive direction of the magnetic field is shown). (b) PC measured between the collecting contacts at $T = 3.7$ K under σ^- polarized excitation as a function of distance along the channel without the magnetic field and with the magnetic field +9 and −9 T applied perpendicular to the QW. The black solid lines in (b) are the best fits using Eq. (1), while the vertical dashed line indicates the position of the collecting contacts x_0.

photocurrent was generated by circularly polarized light emitted at a wavelength 532 nm (2.33 eV) by a Cobolt series 08 diode laser. The electrically connected sample was placed on top of a stack of *x*-*y*-*z* nanopositioners (Attocube), allowing precise positioning of the laser beam along the channel, focused by an aspherical lens into a spot with a diameter of about 1 μm. The PC measurements were carried out by a source meter Keithley 2400.

It should be mentioned that the scanning PC measurements are accompanied by specific errors. First, the position of the laser spot is determined within the error of a few μm, which affects the position of the starting point of each scan. Second, PC was measured using two contacts. In this case, the contact resistance, which may vary slightly from one measurement to another, causes uncertainty in determining the PC value. However, neither positional nor amplitude PC errors significantly affect the shape of PC profiles, which determines the corresponding diffusion length.

III. RESULTS AND DISCUSSION

PC was measured under specific conditions when electron-hole pairs were mainly photogenerated in AlGaAs barriers. Optical excitation in the barrier region leads to a spatial separation of photogenerated electrons and holes due to the built-in electric field [22]. As a consequence, holes tunnel into the GaAs QW, while electrons recombine in the barriers. Nonequilibrium holes injected into the QW cause a decrease in the PC due to their recombination with background doping electrons. It was shown that the injection of holes leads to the formation of a hydrodynamic three-component mixture consisting of electrons and photogenerated heavy and light holes [19,22]. In the presented experiments, excitation with circular polarization is used to create spin-oriented photogenerated holes. In this way, diffusion of spin-polarized holes is studied.

In all the experiments presented, PC measurements were carried out when a voltage of 1 V was applied between the potentiometric contacts. PC measured as a function of the distance between the laser spot and the collecting contacts (PC diffusion profile) for circularly polarized light σ^- and different magnetic fields applied perpendicular to the QW plane in different directions (+9 and −9 T) is shown in Fig. 2(b) together with the PC measured without magnetic field.

The observed decrease in the PC magnitude under the influence of a magnetic field is associated with an increase in contact resistance (hot spots) due to the specific topology of the current in the quantum Hall regime [23,24], which is expected in contact areas remote from the illuminated channel. At the same time, in the channel area scattering of electrons by photogenerated holes prevents the quantum Hall effect.

The PC minimum symmetrical with respect to the position of the collecting contacts is observed without a magnetic field. The magnetic field leads to a significant asymmetry of the PC minimum, which depends on the direction of the magnetic field, more precisely, on the direction of the Hall current. Namely, the diffusion profile on the right side of the contacts ($x > x_0$), where the current enters the channel, changes

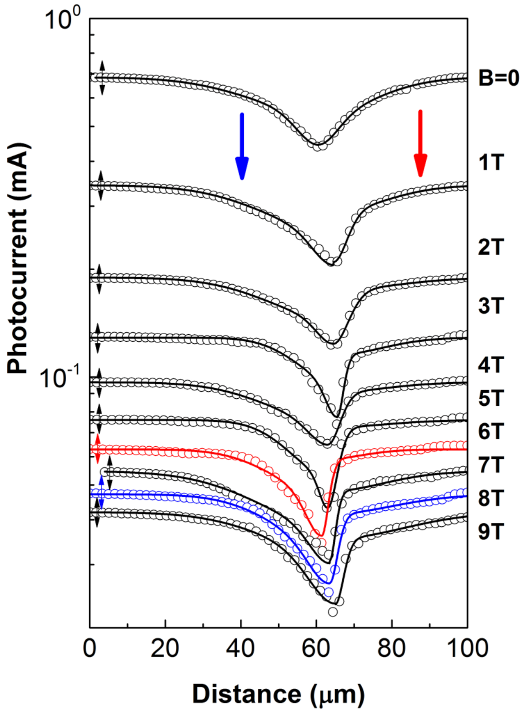

FIG. 3. PC measured at $T = 3.7$ K under σ^- polarized excitation as a function of distance along the channel at various positive magnetic fields applied according to Fig. 2(a). The solid lines are the best fits using Eq. (1). The arrow bars show fitting errors. The vertical arrows indicate the points at which the PL shown in Fig. 4 was measured.

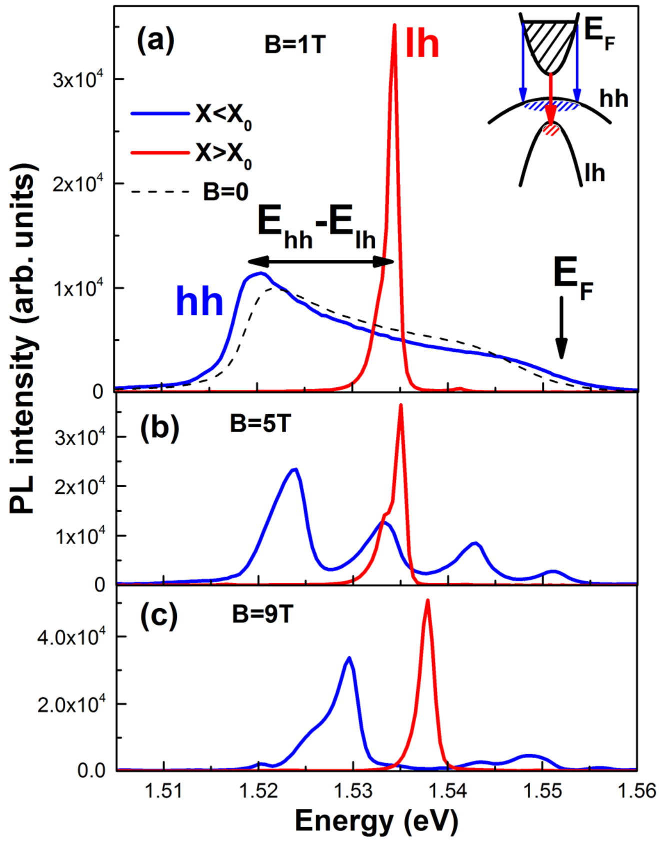

FIG. 4. PL spectra measured under σ^- polarized excitation at $T = 3.7$ K and a voltage of 1 V applied between potentiometric contacts, in different magnetic fields, at $x < x_0$ and $x > x_0$, at points shown by arrows of the same color in Fig. 3. The inset shows a diagram of the relevant optical transitions, where states filled in the conduction and valence bands are indicated by shaded regions.

dramatically, while on the opposite side ($x < x_0$), the diffusion profile remains approximately the same as without a magnetic field.

From Fig. 3, which shows the measured PC diffusion profiles as a function of the magnetic field, it is clearly seen that an increase in the magnetic field increases the observed asymmetry.

The data obtained with both positive and negative magnetic fields, together with the appropriate analysis and a discussion of how specific experimental conditions can affect measurements, are presented in Supplemental Material [25].

Apparently, the observed asymmetry is associated with the influence of the Hall current on the diffusion of photogenerated holes. The diagram of the hole diffusion fluxes Φ_h and the electron Hall current I_H which contribute to the PC measured between collecting contacts is shown in Fig. 2(a). The magnetic field breaks the symmetry of the relevant diffusion fluxes. With a positive direction of the magnetic field indicated in Fig. 2(a), the direction of the corresponding Hall current I_H is opposite to the hole diffusion flow arriving at the contacts from the right. At the reverse (negative) direction of the magnetic field the Hall current is opposite to the hole flow arriving from the left. The Hall current of electrons, which is opposite to the diffusion of holes, can impede the diffusion of holes due to the drag effect and thus lead to hole redistribution in space.

Next, Fig. 4 shows the photoluminescence (PL) spectra measured in various magnetic fields on both sides of the PC minimum, when a voltage of 1 V is applied between potentiometric contacts.

The dramatic difference in the shape of the PL spectra measured on the left and right sides of the PC minimum is due to the magnetic-field-induced redistribution of photogenerated holes along the channel. The broad PL spectrum measured at $x < x_0$ is identical to the spectrum measured in the channel without a magnetic field. In this case, heavy holes dominate the recombination process because of their high density of states and the observed emission reflects the density of states filled between the minimum of the conduction band and the Fermi level. The Fermi energy of 33 meV determined from the PL data is in good agreement with the Fermi energy of 36 meV obtained from the calculated energy structure shown in Fig. 1. An increase in the magnetic field leads to Landau quantization of the electron energy, observed in the sequence of corresponding PL peaks. In a magnetic field of 9 T, only the lowest Landau level is populated. The energy shift of the lowest Landau level is $\Delta E = \hbar eB/2\mu$, where μ is the exciton reduced mass given by $1/\mu = 1/m_e + 1/m_h$ in which m_e and m_h are the effective masses of the electron and the hole, respectively. The reduced heavy-hole exciton mass obtained from the PL spectra shown in Fig. 4 is $0.05m_0$, which is in a good accord with the exciton heavy-hole effective mass in GaAs, equal to $0.06m_0$, calculated with the corresponding electron- ($0.068m_0$) and heavy-hole ($0.51m_0$) effective masses [26].

At the same time, on the right side ($x > x_0$), the Hall electron current directed against the diffusion flow of holes obstructs the diffusion of light holes, while heavy holes can reach the collecting probes. This leads to the accumulation of light holes on the right side of the collecting contacts and their dominance in the corresponding recombination. In such a case, as shown in the inset to Fig. 4, due to the lower mass of light holes, only states close to the band extrema contribute to recombination, which leads to the observed narrow PL line. The energy difference between the PL maxima measured at $x < x_0$ is in good agreement with the 15 meV difference between the heavy- and light-hole bands $E_{\rm hh} - E_{\rm lh}$ calculated for a 14-nm-wide GaAs QW. Moreover, the observed magnetic field-induced PL line energy shift of about 4 meV due to light holes is in good agreement with the 3 meV light-hole exciton energy shift found in Ref. [27] at 9 T.

Thus, a diffusion flow consisting of heavy and light holes, when encountering an electron Hall current, is separated: Heavy holes reach the collecting probes resulting in the PC minimum, while the accumulation of light holes leads to the absence of their contribution to the corresponding PC diffusion profile and to their dominance in the PL emission. It should be noted that there is no emission from the recombination of heavy holes with electrons at $x > x_0$, where the Hall electron current prevents the diffusion of light holes. This happens because light holes push heavy holes out from the region where they accumulate. Therefore, in the region illuminated by the laser light responsible for PL, there are no heavy holes.

The PC diffusion profile is determined by the net electron concentration at the collecting probes which can be calculated as the difference between the concentrations of the host electrons n_0 and photogenerated holes reaching the contacts according to the expression [19]

$$n(x) = \begin{cases} n_0 - n_{\rm hh}^- e^{-\left(\frac{x-x_0}{2L_{\rm hh}^-}\right)^2} - n_{\rm lh}^- e^{-\left(\frac{x-x_0}{2L_{\rm lh}^-}\right)^2}, & x < x_0, \\ n_0 - n_{\rm hh}^+ e^{-\left(\frac{x-x_0}{2L_{\rm hh}^+}\right)^2} - n_{\rm lh}^+ e^{-\left(\frac{x-x_0}{2L_{\rm lh}^+}\right)^2}, & x \geqslant x_0, \end{cases} \tag{1}$$

where the second and third terms are associated with heavy and light holes arriving at the collecting probes, $n_{\rm hh(lh)}^{-/+}$ is the concentration of heavy (light) holes, x_0 is the position of the PC minimum observed on the collecting probes, while $L_{\rm hh}^{-/+}$ and $L_{\rm lh}^{-/+}$ are the diffusion lengths of heavy and light holes, respectively. The superscript $-/+$ refers to the left and right sides relative to the collecting contacts. Due to the effective mass difference, heavy and light holes contribute near to and far from the collecting probes, respectively. Then the PC as a function of distance can be calculated as $j_{\rm PC}(x) = en(x)v$, where v is the drift velocity of electrons.

Equation (1) represents solutions to simple one-dimensional diffusion equations that describe diffusion in spatially separated regions of the sample at $x < x_0$ and $x \geqslant x_0$. The corresponding diffusion lengths were obtained by fitting the the diffusion profiles calculated from Eq. (1) to the measured diffusion profiles. Regarding the fitting procedure,

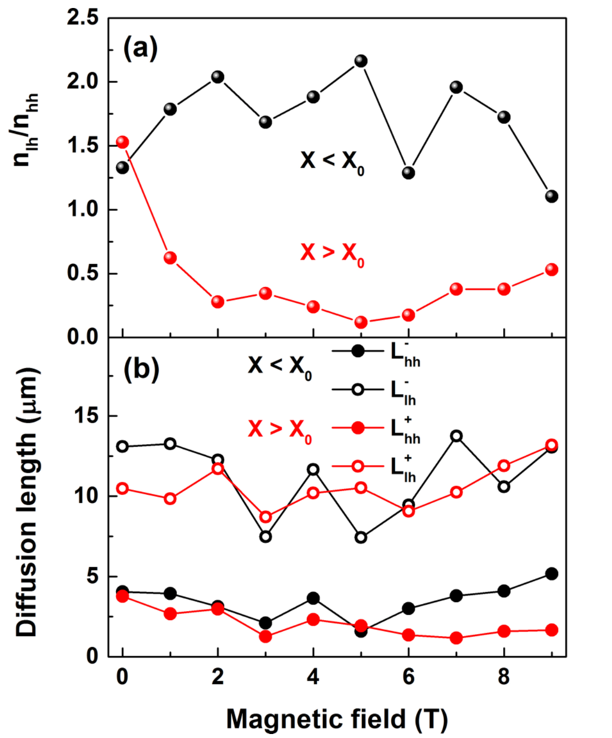

FIG. 5. Ratio of concentrations of light and heavy holes $n_{\rm lh}/n_{\rm hh}$ (a), and the corresponding diffusion lengths $L_{\rm hh}$ and $L_{\rm lh}$ (b) obtained at $x < x_0$ and $x > x_0$ by fitting of the PC profiles shown in Fig. 3 as a function of the magnetic field applied according to Fig. 2(a).

the important fitting parameters are two diffusion lengths and two hole concentrations, which determine the diffusion of holes in each region relative to the collecting probes. In these regions the diffusion profile consists of the diffusion of heavy and light holes with very different diffusion lengths, which spatially separates their contributions. Thus, the fitting parameters influence the diffusion profiles over different ranges of x, and therefore the fitting result of each diffusion profile is unique. The corresponding fitting errors are shown by arrow bars in Fig. 3.

The best fits of PC profiles calculated according to Eq. (1) to experimental diffusion profiles are shown in Figs. 2(b) and 3 by solid lines. As a result, we obtained the diffusion lengths and concentrations of heavy and light holes entering the collecting probes from $x < x_0$ and $x > x_0$, which are depicted in Fig. 5.

The results obtained show that with increasing magnetic field, the concentration of light holes arriving at the collecting probes decreases significantly compared to heavy holes from the side of the Hall current input into the channel ($x > x_0$), and within the experimental error, it does not change on the opposite side ($x < x_0$) sides. As can be seen in Fig. 5(b), the magnetic field does not have a noticeable effect on the diffusion length of light holes. At the same time, the Hall current of electrons probably leads to a decrease in the diffusion length of heavy holes: In a magnetic field above 6 T, the diffusion length of heavy holes on the right side of the channel is smaller than on the left.

These data are in good agreement with the above interpretation of the observed asymmetry of the PC diffusion profile

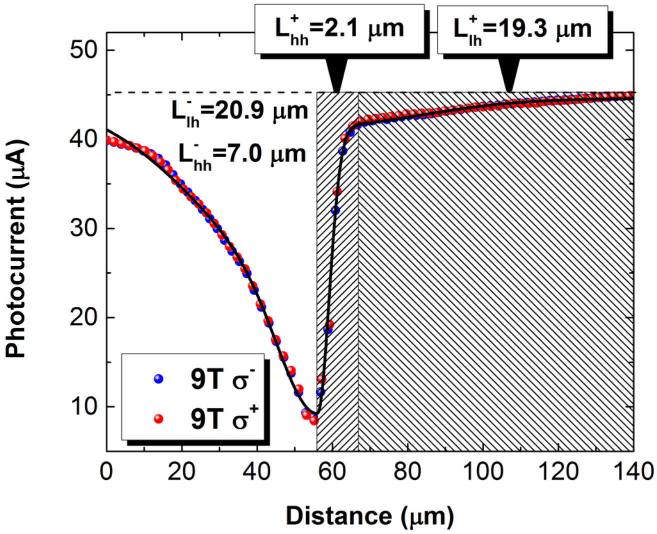

FIG. 6. Diffusion profiles measured at $T = 3.7$ K in the magnetic field 9 T with different circularly polarized excitations. The black solid lines are the best fits using Eq. (1). The hatched areas indicate the regions of diffusion against the Hall current, where the diffusion of heavy and light holes predominates.

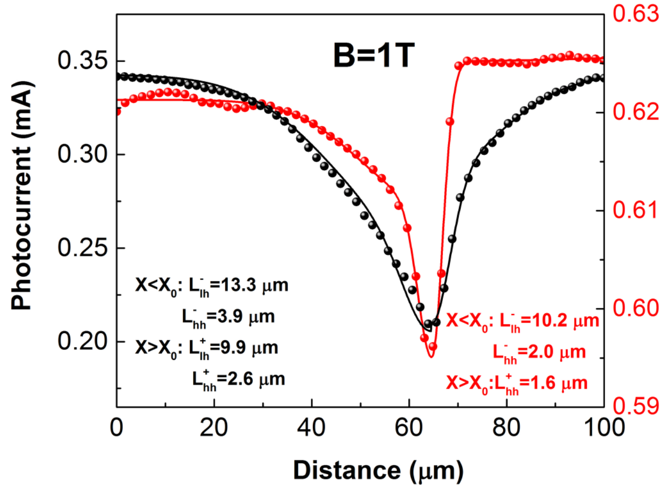

FIG. 7. Diffusion profiles measured under σ^- polarized excitation at $T = 3.7$ K in a 1 T magnetic field with different currents through potentiometric contacts. The solid lines are the best fits using Eq. (1).

caused by the magnetic field, according to which the Hall current of electrons, directed opposite to hole diffusion, prevents hole diffusion due to the drag effect. In this case, Hall electrons have a greater influence on the diffusion of light holes than on the diffusion of heavy holes. The observed effect leads to a spatial separation of light and heavy holes, which mainly occurs in a magnetic field $B < 2$ T.

The diffusion profiles measured for different circularly polarized excitations and in the same magnetic field are shown in Fig. 6. These results indicate the same diffusion of holes with different spin polarizations. In addition, the PC, presented on a linear scale, shows well that diffusion occurring against the Hall current reveals regions in which the diffusion of heavy or light holes predominates. Thus, the Hall current directed against the diffusion flow of holes serves as a filter for the diffusion of heavy and light holes, which leads to a clear spatial separation of heavy and light holes.

The absence of a spin effect on the diffusion of photogenerated holes is explained by fast spin relaxation compared to the recombination process. The spin relaxation time in GaAs quantum wells is expected to be in the range of 30–60 ps, as reported in GaAs QWs [28–30]. While the electron-hole recombination time measured in the same sample as here is about 300 ps [19]. Therefore, spin relaxation occurs on a timescale much faster than diffusion.

It is worth noting that the PC profiles shown in Fig. 3 were measured later than the profiles shown in Figs. 2 and 6. As explained above, due to unstable contact resistance, two-probe measurements result in slightly different PC profiles. Therefore, the corresponding diffusion lengths are somewhat different. However, this difference does not affect the conclusions drawn.

The influence of the PC magnitude is demonstrated in Fig. 7 which shows the diffusion profiles measured in a magnetic field of 1 T with different currents through potentiometric contacts.

A higher PC current results in a higher electron Hall current, which more effectively prevents the diffusion of light holes. In this case, the PC value remains unchanged in the region to the left of the collecting contact, where the diffusion of light holes is expected. Thus, a corresponding contribution from light hole diffusion was not detected. As shown in Fig. 7, increasing the PC current by approximately two times completely stops the diffusion of light holes.

IV. CONCLUSION

In summary, the effect of the magnetic field on diffusion of the photogenerated holes was studied by means of a scanning PC microscopy carried out on a mesoscopic channel formed in a high-mobility GaAs quantum well where the electron-hole plasma reveals hydrodynamic properties. In the case under consideration, photogeneration creates a two-component system of holes, consisting of heavy and light holes. Therefore, the observed diffusion profile consists of the diffusion of heavy and light holes with short and long diffusion lengths, respectively, and, in the absence of a magnetic field, is symmetrical with respect to the collecting probes. It was found that the magnetic field leads to a significant asymmetry in the diffusion profile, which depends on the direction of the magnetic field. According to the presented results, the observed asymmetry is caused by the electron Hall current. The Hall current, directed against the diffusion flow of holes, acts as a filter, allowing heavy holes to pass to the collecting probes and preventing the diffusion of light holes. The valve effect is observed: Changing the current through the collection probes allows one to control the number of photogenerated light holes contributing to the PC.

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