

## Weak localization in $\text{Al}_{0.5}\text{Ga}_{0.5}\text{As}/\text{GaAs}$ $p$ -type quantum wells

S. Pedersen, C. B. Sørensen, A. Kristensen, and P. E. Lindelof

*The Niels Bohr Institute, University of Copenhagen, Universitetsparken 5, DK-2100 Copenhagen, Denmark*

L. E. Golub and N. S. Averkiev

*A.F. Ioffe Physico-Technical Institute, Russian Academy of Sciences, 194021 St. Petersburg, Russia*

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We have experimentally investigated the weak-localization magnetoresistance in an  $\text{Al}_{0.5}\text{Ga}_{0.5}\text{As}/\text{GaAs}$   $p$ -type quantum well. The peculiarity of such systems is that spin-orbit interaction is strong. On the theoretical side it is not possible to treat the spin-orbit interaction as a perturbation. This is in contrast to all prior investigations of weak localization. In this paper we compare the experimental results with a newly developed diffusion theory, which explicitly describes the weak-localization regime when the spin-orbit coupling is strong. The spin relaxation rates calculated from the fitting parameters were found to agree with theoretical expectations. Furthermore, the fitting parameters indicate an enhanced phase-breaking rate compared to theoretical predictions. [S0163-1829(99)12927-8]

The effect of localization in weakly disordered systems can be understood in terms of the quantum interference between two waves propagating by multiple scattering along the same path but in opposite directions. When a magnetic field is applied, the phase pick-ups along the two paths have opposite sign, and as a consequence, a negative magnetoresistance is observed.<sup>1</sup> This effect is normally known as *weak localization*.

Due to the properties of the spin part of the wave function, spin-orbit interaction has been shown to have a dramatic influence on the weak localization. In systems with strong spin-orbit interaction, the magnetoresistance reverses its sign. This is in contrast to the above, known as *weak antilocalization*.

Traditionally, weak antilocalization has been studied intensely in metallic films,<sup>2,3</sup> where spin-orbit interaction occurs at the individual scattering centers. More recently, weak antilocalization has been observed in true two-dimensional systems which lack inversion symmetry, such as  $n$ -type  $\text{Ga}_{0.7}\text{Al}_{0.3}\text{As}/\text{GaAs}$  or Te quantum wells. The lack of inversion symmetry gives rise to a new spin-relaxation mechanism. This has surprisingly led to a completely new physical insight<sup>4-9</sup> (see also Ref. 5).

However, most of all previous works referred to  $n$ -type quantum wells. In the case of a  $p$ -type quantum well, an even more dominating positive magnetoresistance would be expected due to strong spin-orbit interaction in the GaAs valence band.<sup>3</sup>

In recent theoretical works devoted to weak localization in  $p$ -quantum wells,<sup>10</sup> it was shown how the sign of the magnetoresistance depends on the hole concentration. Moreover, anisotropy of the spin relaxation was predicted, which in turn leads to a dependence of the phase-relaxation rate on the spin orientation. Experimental investigations of anomalous magnetoresistance in  $p$ -quantum wells so far did not exist. In this work, the magnetoresistance is studied experimentally in  $p$ -quantum wells and peculiarities of weak localization are discussed in the case where spin and momentum relaxation rates are comparable.

The heterostructures used in the experiment were grown on a [100] oriented GaAs wafer by molecular-beam epitaxy (MBE) technique. A symmetrical quantum well was formed as a 70-Å-wide GaAs channel in a modulation-doped  $\text{Ga}_{0.5}\text{Al}_{0.5}\text{As}$  matrix. The  $\text{Ga}_{0.5}\text{Al}_{0.5}\text{As}$  was homogeneously doped with Be ( $n_{\text{Be}} = 2 \times 10^{18} \text{ cm}^{-3}$ ) in two 50-Å-thick layers separated by 250 Å of intrinsic  $\text{Ga}_{0.5}\text{Al}_{0.5}\text{As}$  from the center of the GaAs channel. The individual samples were mesa-etched into rectangular Hall bars with a width of 0.2 mm and a total length of 4.2 mm. Three voltage contacts on each side were placed in a distance of each 0.8 mm to avoid perturbing significantly the four point measurements. Ohmic contacts to the two-dimensional hole gas were made by a Au/Zn/Au composite film annealed at 460 °C in 3 min. The contacts areas were  $0.6 \times 0.6 \text{ mm}^2$  squares, and bonded to the legs of a nonmagnetic chip carrier. Four point measurements of the resistivity were carried out using standard low-frequency lock-in technique (EG&G 5210). The samples were biased by an ac current signal with an amplitude of 200 nA. The experiments were performed at temperatures between 0.3 and 1.0 K in an Oxford Heliox cryostat equipped with a copper electromagnet. The characterization of the samples with respect to density and mobility were done by Hall measurement at magnetic fields between  $-0.3 \text{ T}$  and  $0.3 \text{ T}$ , while the weak-localization magnetoresistance measurements were performed at fields between  $-100 \text{ Gs}$  and  $100 \text{ Gs}$ . To generate the stable current for the magnetic fields, we used a Keithley 2400. The samples were found to have a hole density of  $p = 4.4 \times 10^{15} \text{ m}^{-2}$ , which is low enough to ensure that only one subband is filled. The mobility was found to be  $\mu = 3.5 \text{ T}^{-1}$ .

It is well known that the weak-localization effect on the magnetoconductivity manifests itself more brightly when  $k_F l \gg 1$ , corresponding to a metallic conductivity in the system. Here  $k_F$  is the Fermi wave vector and  $l$  is the mean free path. For our samples this product may be estimated with the help of the two-dimensional Drude conductivity,  $\sigma_D$ ,

$$\sigma_D = \frac{e^2}{2\pi\hbar} k_F l. \quad (1)$$

In the studied samples  $\sigma_D = 2.47 \times 10^{-3} \Omega^{-1}$ , which gives  $k_F l \approx 63$ . The value of  $k_F$  may be determined from the hole concentration,  $k_F = \sqrt{2\pi p}$ , and is equal to  $1.7 \times 10^8 \text{ m}^{-1}$ . This leads to a mean free path  $l = 0.37 \mu\text{m}$  for our samples. The magnetic length is equal to  $l$  in a field  $B_{tr} = \hbar/2el^2 \approx 24 \text{ Gs}$ . For  $B < B_{tr}$ , the diffusion theory may be applied for a description of weak-localization effects.

According to recent theoretical works,<sup>10</sup> the key parameter in a  $p$ -quantum well of width  $a$  is  $k_F a / \pi$ . This product is a measure of heavy-hole/light-hole mixing degree at the Fermi level, which determines the behavior of the anomalous magnetoresistance. For instance, if the carrier concentration is small ( $k_F a / \pi \ll 1$ ), the magnetoresistance does not change its sign and is exclusively negative. On the other hand, if  $k_F a / \pi \gg 1$ , the magnetoresistance is also sign-constant, but positive. This positive magnetoresistance was observed in recent experimental reports.<sup>11</sup> Moreover, the resistance may change its sign as a function of magnetic field at the intermediate values of this parameter. Since in the studied system  $k_F a / \pi \approx 0.37$ , this intermediate regime is in fact realized in our experiments.

Under these conditions the weak-localization correction to the conductivity of our  $p$ -type quantum wells in magnetic fields  $B < B_{tr}$  is given as<sup>10</sup>

$$\delta\sigma(B) = \frac{e^2}{\pi h} \left[ f\left(\frac{B}{B_\varphi + B_\parallel}\right) + \frac{1}{2}f\left(\frac{B}{B_\varphi + B_\perp}\right) - \frac{1}{2}f\left(\frac{B}{B_\varphi}\right) \right], \quad (2)$$

where  $f$  is given by  $f(x) = \ln(x) + \psi(1/2 + 1/x)$ ; here  $\psi(x)$  is a digamma function and  $\delta\sigma(B)$  is the difference between the conductivity with and without magnetic field. The characteristic magnetic fields  $B_\varphi$ ,  $B_\parallel$ , and  $B_\perp$  are given as

$$B_\varphi = \frac{\hbar}{4eD\tau_\varphi}, \quad B_\parallel = \frac{\hbar}{4eD\tau_\parallel}, \quad B_\perp = \frac{\hbar}{4eD\tau_\perp}, \quad (3)$$

where the quantities  $\tau_\parallel$ ,  $\tau_\perp$  refer to the longitudinal and transverse spin-relaxation time with the preferred axis lying normal to the quantum well, and  $\tau_\varphi$  is the phase-relaxation time for the holes. The diffusion coefficient  $D = l^2/2\tau$ , where  $\tau$  is the momentum relaxation time. Equation (2) resembles the expression for metallic films first reported by Hikami *et al.*<sup>2</sup> as well as that by Altschuler *et al.*<sup>3</sup> for diffusive spin-orbit effects in two-dimensional electron systems. However, in our case the spin relaxation cannot be described by one parameter and the expression given by Eq. (2) does only converge into the Hikami expression if  $B_\perp = 2B_\parallel$ , which, as we shall see, is not the case.

In Fig. 1 we present the magnetoconductivity measurements at different temperatures. An example of a fit obtained with Eq. (2) is also shown for  $T = 360 \text{ mK}$ . The fitting was done by the Levenberg-Marquardt method, implemented in  $C^{++}$  by standard nonlinear least-squares routines. The parameters of the fitting procedure are  $B_\varphi = 2.6 \text{ Gs}$ ,  $B_\parallel = 17.2 \text{ Gs}$ , and  $B_\perp = 4.6 \text{ Gs}$ .

We have shown theoretically<sup>10</sup> that spin-flip probabilities depend differently on the value of Fermi quasimomentum for hole spin oriented along the grown axis and lying in the quantum-well plane. For instance, for scattering from the short-range potential  $B_\parallel \sim k_F^4$  and  $B_\perp \sim k_F^6$ . This leads to ar-

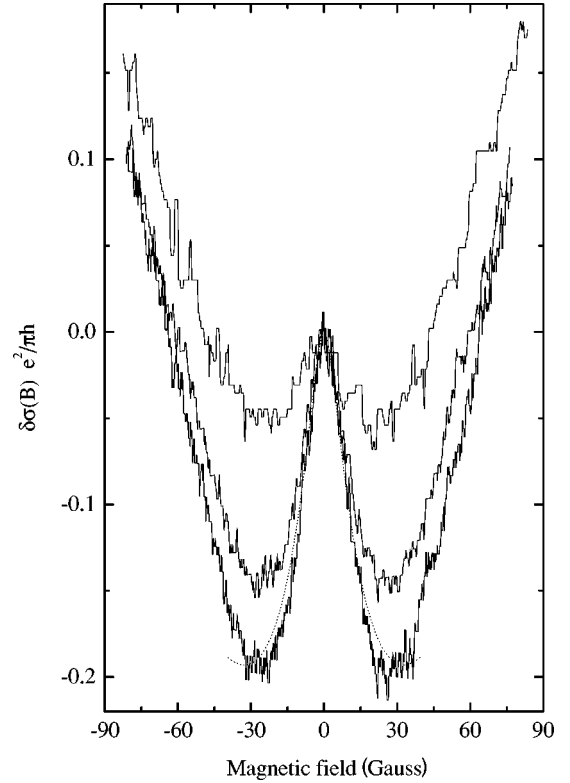


FIG. 1. Magnetoconductivity  $\delta\sigma(B)$  of a  $\text{GaAs}/\text{Ga}_{0.5}\text{Al}_{0.5}\text{As}$   $p$ -type quantum well at three different temperatures (from above  $T = 820 \text{ mK}$ ,  $T = 560 \text{ mK}$ , and  $T = 360 \text{ mK}$ ). The best theoretical fit (dotted line) is shown for  $T = 360 \text{ mK}$ .

bitrary small hole concentrations to the inequality  $B_\parallel > B_\perp$  which is observed in the experiment.

Since  $B_\varphi < B_{tr}$ , the wave-function phase breaks after many collisions with impurities and one can apply the diffusion theory for experiment fitting. In magnetic fields  $B \sim B_{tr}$  the wave-function phase breaks after a few collisions. Weak-localization theory for this region of fields is derived in Ref. 12 and 13 for systems with weak spin-orbit interaction only. Below, we consider the case of strong spin-orbit interaction in magnetic fields  $B \sim B_{tr}$ .

The Cooperon equations for particles with different absolute value of spin projection can be separated at  $B \geq B_{tr}$ .<sup>10</sup> Thus the expression for  $\delta\sigma$  has three terms and each of them depends only on one characteristic magnetic field, similar to Eq. (2). The Cooperon equations, which take into account strong spin-orbit interaction, are complicated integral equations and have to be solved numerically. However, it is clear that the absolute value of each term in the expression for  $\delta\sigma$  decreases in comparison with the diffusion approximation. Hence Eq. (2) describes qualitatively the dependence  $\delta\sigma(B)$  even at  $B \geq B_{tr}$ . The maxima and the subsequent decrease in magnetoconductivity seen in Fig. 1 are in fact caused by the first term in Eq. (2), which dominates in these fields.

Thus the magnetoconductivity dependence in small magnetic fields is approximately given by

$$\delta\sigma(B) = -\frac{e^2}{48\pi h} \left(\frac{B}{\bar{B}}\right)^2. \quad (4)$$

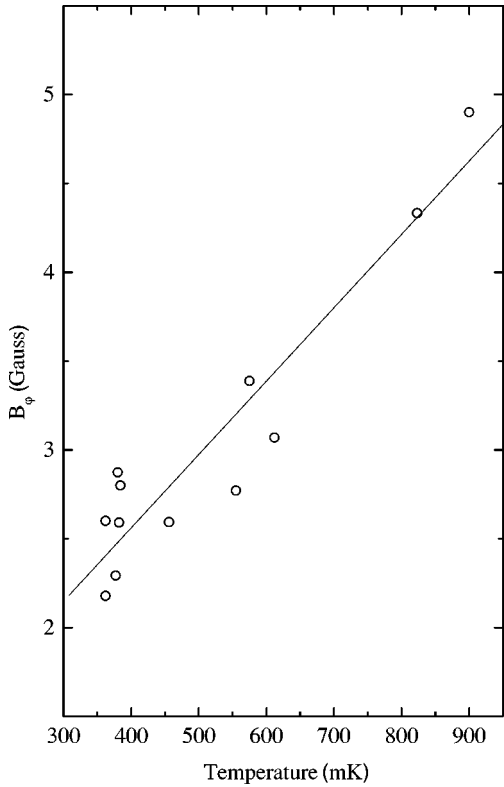


FIG. 2. Temperature dependence of the parameter  $B_\phi$  of a GaAs/Ga<sub>0.5</sub>Al<sub>0.5</sub>As *p*-type quantum well. Experimental results are shown by open dots. The solid line shows the best linear fit to the data points.

One can show that  $\tilde{B} \approx B_\phi$  if  $B_\parallel, B_\perp > B_\phi$ . At  $T = 360$  mK, this inequality is valid. The spin-relaxation times,  $\tau_\parallel$  and  $\tau_\perp$ , are temperature independent because the studied system is degenerate and charge transport is realized by the carriers near the Fermi surface.

The temperature dependence of  $B_\phi$  is shown in Fig. 2. One can see that it is roughly linear. A least-squares fit gives

the approximation  $B_\phi(T) = 4.1 \text{ Gs K}^{-1} T + 0.91 \text{ Gs}$ . As an estimate, we use the Nyquist noise formula for the electron phase-breaking time as an approximation for  $B_\phi$ :<sup>14</sup>

$$B_N = B_{tr} \frac{k_B T}{\hbar k_F v_F} \ln(k_F l), \quad (5)$$

where  $v_F$  is the hole velocity at the Fermi surface. It is related to the mean free path by equality  $l = v_F \tau$ . In this approximation  $B_N = 0.9 \text{ Gs K}^{-1} T$ , where an effective hole mass  $m_h = 0.23 m_0$  was used ( $m_0$  is the free-electron mass). Hence the observed phase-breaking rate is approximately four times larger than what is expected from this simple Nyquist noise estimate. A possible explanation for this discrepancy could be found in the nonparabolic dispersion relation which would tend to decrease  $v_F$ . It is, however, difficult to make any further analysis due to the fact that there have been no theoretical attempts to discuss the phase-breaking rate in hole systems.

In conclusion, we have presented experimental studies of the magnetoconductivity caused by weak localization in Ga<sub>0.5</sub>Al<sub>0.5</sub>As/GaAs *p*-type quantum-well system, where the spin-orbit coupling is strong. We observe that the magnetoconductance changes sign from negative to positive as the magnetic field is increased. This is due to the intermediate degree of heavy-hole/light-hole mixing in these samples. The phase relaxation times were determined as a function of temperature. The spin-relaxation rates are found to be in agreement with theory. The phase-coherence relaxation rate was found to be significantly larger than the Nyquist behavior previously found to explain the values for electron systems.

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