Weak antilocalization in a strained InGaAs/InP quantum well structure

S.A. Studenikin*, P. T. Coleridge, and P. J. Poole
Institute for Microstructural Sciences, National Research Council, Ottawa, Ontario, K1A OR6, Canada

Weak antilocalization (WAL) effect due to the interference corrections to the conductivity has been studied experimentally in a strained InGaAs/InP quantum well structure. From measurements in tilted magnetic field, it was shown that both weak localization and WAL features depend only on the normal component of the magnetic field for tilt angles less than 84 degrees. Weak antilocalization effect showed non-monotonous dependence on the gate voltage which could not be explained by either Rashba or Dresselhouse mechanisms of the spin-orbit coupling. To describe magnetic field dependence of the conductivity, it was necessary to assume that spin-orbit scattering time depends on the external magnetic field which quenches the spin precession around effective, spin-orbit related, magnetic fields.

I. INTRODUCTION

When spin-orbit scattering is strong the weak localization feature in a 2-dimensional system develops an antilocalization structure\(^1,2\). This appears as an additional negative magneto-resistance at very low fields and provides a convenient means of monitoring the spin-orbit interaction\(^3,4,5\) an understanding of which is needed if spins are to be manipulated for spintronic and quantum computing applications in semiconductors\(^6\). Results are presented here for a strained InGaAs/InP quantum well, where the antilocalization feature is prominent, but which cannot be explained using currently available theories.

II. EXPERIMENTAL

The QW structure, grown on a (100) InP semi-insulated substrate, consisted of: 450 nm of undoped InP buffer layer, 10 nm In\(_{0.76}\)Ga\(_{0.24}\)As (with \(x=0.76\)), a 13 nm undoped InP spacer layer, 13 nm of InP doped with Si at \(4 \times 10^{17}\) cm\(^{-3}\) and a 13 nm undoped cap layer. Because the lattice constant of InP is 1.53% less than 76% InGaAs the quantum well is compressively strained in the plane. A gated Hall bar was prepared using standard optical lithography and wet etching techniques. At zero gate voltage the concentration was \(4.9 \times 10^{15}\) m\(^{-2}\) and the electron mobility 7.8 m\(^2\)/Vs. Measurements were made in a He3 system with a split transverse axis superconducting coil.

Figure 1 shows typical magnetoresistance traces at T=0.35 K for various magnetic fields tilted by the angles shown away from the normal to the surface. When plotted against \(R_{xy}\), (which depends only on the normal component of the magnetic field) it can be seen [Fig.1(b)] that the data collapses onto a single curve. That is (at least up to tilt angles of 85\(^0\)) both the weak localization and weak antilocalization (WAL) features depend only on the perpendicular component of the magnetic field and therefore result from orbital motion. This is in contrast to the intuitive expectation that the antilocalization depends on spin and that tilting the magnetic field should decouple the spins from the orbital motion. Similar results have also been observed in an isomorphous (unstrained) sample\(^5\).

Figure 2 shows magnetoconductivity traces for various gate voltages (\(V_g\)) between +0.1 V (corresponding to a density of \(5.4\times10^{15}\) m\(^{-2}\)) and -0.6V (\(1.4\times10^{15}\)m\(^{-2}\)) A feature of these results is that the WAL peak depends non-monotonically on gate voltage: it is absent at positive gate voltages, increases with decreasing \(V_g\) to reach a maximum at -0.3V and then decrease again with further decreases in gate voltage. It is qualitatively evident from Fig. 2 that the spin-orbit scattering parameter \(\beta_{so}\) (defined as \(\tau/\tau_{so}\) where \(\tau\) and \(\tau_{so}\) are respectively the elastic and spin-orbit scattering times) depends non-monotonically on the gate voltage. The maximum at -0.3V corresponds to a density of \(3.4\times10^{15}\) m\(^{-2}\). This behaviour cannot be explained by either the Rasba or the Dresselhaus mechanisms\(^4,7,8\), both of which predict a monotonic dependence on density.

III. DISCUSSION

The solid lines in Fig. 2 are attempts to fit the data using a recent theory for the weak localization effect valid in arbitrary magnetic fields\(^9,10\). The data in Fig. 2 are plotted vs normalized magnetic field \(B/B_{tr}\), where \(B_{tr} = \ldots\)

* sergei.studenikin@nrc.ca
\( \hbar/4eD\tau \) is the characteristic transport field. The theory assumes a single spin-orbit scattering mechanism dominates. For InGaAs structures this is expected to be the Rasba term which should be significantly larger than the bulk (Dresselhaus) term. It should be noted that at low magnetic fields this theory coincides with the exact analytical solution due to Hikami, Larkin and Nagaoka \(^2\). Even under these conditions, that is \( B/B_{tr} < 1 \), the theory is unable to adequately describe the experimental data, which indicates that the current theoretical understanding of the weak localisation phenomena, in presence of spin-orbit scattering, is incomplete.

Figure 3a shows how it is possible to fit either the low field (central) part of the magnetoconductivity, or the high field tails, but not both parts simultaneously. Satisfactory fits to the high field region can be made assuming negligible spin-orbit scattering (i.e. \( \beta_{so} = 0 \)). Interestingly, this fit (curve 3) yields the same dephasing rate (\( \beta_{\phi} \)) as that obtained from fitting the low field WAL peak (curves 1 and 2) where both \( \beta_{so} \) and \( \beta_{\phi} \) are allowed to vary. This implies that while the dephasing rate is field independent (as expected) the spin orbit scattering rate decreases quite markedly as the magnetic field increases.

If the main mechanism of spin-orbit relaxation is the spin precession around the effective k-dependent crystal magnetic field that results from the bulk or structural inversion asymmetry \(^{11,12,13}\) then it would be reasonable to assume that this precession will be affected by external magnetic fields larger than the effective spin-orbit field \( B_{so} \). \( B_{so} \) is typically smaller than 1 mT so one might expect the spin precession to be disturbed by external fields of this order. We have been unable to find any theoretical discussion of this effect in the literature and have therefore used an empirical approach. We postulate that the spin orbit scattering rate decreases with increasing field in a Lorentzian fashion, i.e that \( \beta_{so} = \tau/\tau_{so} = \beta_{so}^0/(1 + aB^2) \). Using this expression, with the introduction of an additional fitting parameter \( a \), allows quite satisfactory fits to the experimental data (see Fig. 3(b)). Due to space limitations discussion of the parameters determined in the fits must be deferred to another publication but it can be noted that the values of \( a^{-1/2} \) correspond to fields of order of 0.1 mT.

IV. CONCLUSION

In contrast to intuitive expectation it is found that experimental weak antilocalization and weak localization peaks respond in the same way to tilted magnetic fields and depend only on the normal component of field. To fit the shape of the peaks it was found necessary to assume that the spin-orbit scattering parameter decreases with increasing magnetic fields. Although this can be understood qualitatively in terms of quenching of the precession around internal, spin-orbit related, magnetic fields an improved theoretical treatment is needed if an understanding of the electron transport properties and microscopical spin dynamics in gated semiconductor structures is to be achieved.

A. Acknowledgements

S.A.S acknowledges support of The Canadian Institute for Advanced Research (CIAR). We would like to thank Chandre Dharma-wardana for helpful discussion.

\(^1\) B.L. Altshuler, and A.G. Aronov, in Electron-Electron Interactions in Disordered Systems, edited by A.L. Efros and M. Pollak, North Holland, Amsterdam, 1985, p.1.
\(^2\) S. Hikami, A. Larkin and Y. Nagaoka, Prog. Theor. Phys. 63,707 (1980).
\(^3\) T. Koga, J. Nitta, T. Akazaki, and H. Takayanagi, Phys. Rev. Lett. 89, 046801 (2002).
\(^4\) J. B. Miller, D. M. Zumbuhl, C. M. Marcus, Y. B. Lyanda-Geller, D.Goldhaber-Gordon, K. Campman, A. C. Gossard, Phys. Rev. Lett. 90, 076807 (2003).
\(^5\) S. A. Studenikin, P. T. Coleridge, N. Ahmed, P. Poole, and A. Sachrajda, cond-mat/0206323 (to be published in PRB).
\(^6\) S. A. Wolf, D. D. Awschalom, R. A. Buhrman,4 J. M. Daughton, S. von Molnir, M. L. Roukes, A. Y. Chtchelkanova, and D. M. Treger, Science 294, 1488 (2001).
\(^7\) P. D. Dresselhaus, C. M. A. Papavassiliou, R. G. Wheeler, and R. N. Sacks, Phys. Rev. Lett. 68, 106 (1992).
\(^8\) S. A. Studenikin, P. Coleridge, P. Poole, A. Sachrajda, JETP Lett. 77, 311 (2003).
\(^9\) V. M. Gasparyan, and A. Yu. Zyuzin, Sov.Phys.Solid State 27, 999 (1985).
\(^10\) A. Zduniak, M. I. Dyakonov, and W. Knap, Phys. Rev. B 56, 1996 (1997).
\(^11\) M.I. Dyakonov, and V.Yu.Kachorovskii, Sov. Phys.Semicond. 20, 110 (1986).
\(^12\) W.H.Lau, J.t. Olesberg, and M.E. Flatte, Phys.Rev. B 64, 161301R (2001).
\(^13\) R. Winkler, cond-mat/0305315
FIG. 1: Weak antilocalization feature in a strained InGaAs/InP quantum well in tilted magnetic fields: (a) as a function of total magnetic field and (b) as a function of the Hall resistance $R_{xy}$ which depends only on the perpendicular component of the field.
FIG. 2: Experimental traces of the magnetoresistance for different gate voltages at T=0.36 K. Solid lines are best theoretical fits to the experiment using theoretical equations from 10.
FIG. 3: (a) WAL effect for two gate voltages with fitted curves through either the central WAL peak or the WL tails using same phase relaxation parameter $\beta_\phi$. (b) Same experimental data as in part (a) but fitted with an assumption that spin-orbit relaxation time changes with the magnetic field as $\beta_{so} = \tau / \tau_{so} = \beta_{so0}^0 / [1 + a (B/B_{tr})^2]$.