Universal spin-induced Time Reversal Symmetry breaking in two-dimensional electron gases with Rashba spin-orbit interaction

F.E. Meijer, A.F. Morpurgo, T.M. Klapwijk, and J. Nitta

1Kavli Institute of NanoScience, Delft University of Technology, Lorentzweg 1, 2628 CJ Delft, The Netherlands
2NTT Basic Research Laboratories, NTT Corporation, Atsugi-shi, Kanagawa 243-0198, Japan
3CREST-Japan Science and Technology Agency

(Dated: November 5, 2021)

We have experimentally studied the spin-induced time reversal symmetry (TRS) breaking as a function of the relative strength of the Zeeman energy ($E_Z$) and the Rashba spin-orbit interaction energy ($E_{SOI}$) in InGaAs-based 2D electron gases. We find that the TRS breaking, and hence the associated dephasing time $\tau_d(B)$, saturates when $E_Z$ becomes comparable to $E_{SOI}$. Moreover, we show that the spin-induced TRS breaking mechanism is a universal function of the ratio $E_Z/E_{SOI}$, within the experimental accuracy.

PACS numbers: 73.23.-b, 71.70.Ej, 72.25.Rb

The spin dynamics in solid state systems is commonly determined by the competition between two energy scales: the Zeeman energy and spin-orbit interaction (SOI) energy. If the Zeeman energy ($E_Z$) is dominant, the spin is always aligned with the applied magnetic field. In contrast, if the spin-orbit interaction is dominant, the spin and orbital dynamics are coupled, and elastic scattering therefore randomizes the spin precession axis. This results in a finite spin relaxation time $\tau_s(0)$. Hence, the "control parameter" for the spin dynamics in diffusive systems is the ratio $E_Z/E_{SOI}$, where $E_{SOI} \equiv \hbar/\tau_s(0)$. Consequently, many proposals and physical phenomena in the field of spintronics depend on the ratio of these two energy scales.

An example where the spin dynamics, and therefore the ratio $E_Z/E_{SOI}$, plays an important role is in phase-coherent transport: quantum interference is qualitatively different for $E_Z/E_{SOI} \ll 1$ and $E_Z/E_{SOI} \gg 1$. For $E_Z/E_{SOI} \rightarrow \infty$ the spin dynamics does not depend on the orbital motion of the electrons (Fig. 1a). The spin is a good quantum number and the interference takes place within each spin-subband separately. For $E_Z/E_{SOI} \ll 1$, the spin is not a conserved quantity, and the spin randomly precesses during the orbital motion (Fig. 1b). This leads to mixing of the spin sub-bands in the interference process (resulting in weak-anti-localization).

Increasing the ratio $E_Z/E_{SOI}$ leads therefore to a crossover between two conceptually different physical conditions.

In the limit $E_Z/E_{SOI} \ll 1$, it was recently shown theoretically and experimentally that increasing the ratio $E_Z/E_{SOI}$ from 0 to a finite value ($\ll 1$), results in dephasing of time-reversed paths, i.e. it induces Time Reversal Symmetry (TRS) breaking. The effect of the interplay between Zeeman and SOI on quantum interference is therefore quite similar to a small perpendicular magnetic field (i.e. a magnetic flux); they both introduce an upper time-scale for interference, which is shorter than the inelastic scattering time. We denote this upper time-scale due to the interplay between Zeeman and SOI by $\tau_d(B)$.

In this paper we investigate experimentally the TRS breaking, due to the competition between Zeeman coupling and Rashba SOI, for the whole range of $E_Z/E_{SOI}$, i.e up to $E_Z/E_{SOI} \gg 1$. We demonstrate that the spin-induced TRS breaking, and hence the associated dephasing time $\tau_d(B)$, saturates when $E_Z/E_{SOI} \approx 1$, i.e. when the spin becomes aligned with the external magnetic field. The saturation value of the dephasing time $\tau_d(B)$ is found to depend exclusively on the spin relaxation time $\tau_s(0)$. Moreover, we show that the quantity $\tau_s(0)/\tau_d(B)$ is a universal function of $E_Z/E_{SOI}$, i.e. it is independent of any details of the quantum well, such as the electron density, elastic scattering time and Rashba spin-split energy $\Delta$. All these conclusions are based on the detailed quantitative analysis of the magnetococonductance as a function of perpendicular and parallel magnetic field.

In our investigation we have used three gated In-

FIG. 1: Schematic illustration of the relevant time-reversed trajectories contributing to weak-(anti)localization for the case of negligible SOI (a; $E_Z/E_{SOI} \rightarrow \infty$) and strong SOI (b; $E_Z/E_{SOI} \ll 1$). If SOI is negligible the spin remains parallel to itself and interference takes place for each spin-subband separately. If SOI is strong, the spin dynamics has to be taken into account. This changes the nature of time-reversed trajectories and makes them sensitive to the presence of a magnetic field applied parallel to the plane of the two-dimensional electron gas.
AlAs/InGaAs/InAlAs based quantum wells, which were designed to have different values of Rashba SOI strength\cite{12}. At $V_{\text{gate}} = 0\text{V}$, the characteristic spin-split energy $\Delta$ for the different samples are $\Delta \approx 0.5, 1.5$ and 1.8 meV. We will refer to these samples as to samples 1, 2, and 3, respectively (see also \cite{8}). A 14T magnet is used to generate $B_{||}$ (i.e. Zeeman coupling), and split coils mounted on the sample holder are used to independently control $B_{\perp}$. The electron density and mobility at $V_{\text{gate}} = 0\text{V}$ are $n \approx 7 \cdot 10^{15} \text{m}^{-2}$ and $\mu \approx 4 \text{ m}^{2}\text{V}\text{s}^{-1}$, respectively. All measurements have been performed on 20 x 80 $\mu\text{m}$ Hall-bar shaped devices, at $T=1.6\text{K}$.

Experimentally, the values of $\tau_{\phi}(B_{||})$, which quantify the TRS breaking at different values of $E_{Z}/E_{\text{SOI}}$, are obtained from the magnetoconductance as a function of $x \approx 80$. Specifically, from the quantitative analysis of the line-shape of the resulting magnetoconductance curves $\sigma(B_{\perp})$, the values of $\tau_{\phi}(B_{||})$ can be extracted. For all details of extracting $\tau_{\phi}(B_{||})$ we refer the reader to \cite{8}. Here we recall that we use the theory of Iordanskii, Lyanda-Geller and Pikus (ILP) \cite{8}, in which $\tau_{\phi}(B_{||})$ and the spin relaxation time $\tau_{\parallel}(B_{||})$ are the only free parameters\cite{12}.

Figure 2 shows an example of the measured magnetoconductance curves $\sigma(B_{\perp})$ at different values of $B_{||}$ (open dots) for sample 3. The continuous lines superimposed on the data represent the best fit to the ILP theory. We find very good agreement between data and theory for all values of $B_{||}$, or equivalently, for all values of the ratio $E_{Z}/E_{\text{SOI}}$. This kind of analysis has been performed for all samples, and for different values of the electron density, elastic scattering time and SOI strength\cite{14}.

Note that for $E_{Z}/E_{\text{SOI}} \geq 1$ the weak-anti localization is fully suppressed (see Fig. 2). Therefore, in the limit that $E_{Z}/E_{\text{SOI}} \geq 1$, $\tau_{\phi}(B_{||})$ is the only free parameter in the ILP model to fit the data, and can be determined with great accuracy. Only in the narrow region where $E_{Z} \approx E_{\text{SOI}}$, the value of $\tau_{\phi}(B_{||})$ is possibly determined with somewhat less accuracy, due to potential $B_{||}$-induced anisotropies in the spin relaxation time.

In Figure 3 we first plot the extracted values of $\tau_{\phi}(B_{||})$ as a function of $B_{||}$ (or more precise, $B_{||}^{2}$), since this is the experimentally applied parameter. For each value of $E_{\text{SOI}}$, we find the same qualitative behavior of the $\tau_{\phi}(B_{||})$-curve (results from all three samples are shown). For small values of $B_{||}^{2}$, the slope $\partial(1/\tau_{\phi}(B_{||}))/\partial B_{||}^{2}$ (hereafter called "dephasing-slope") is large, and depends strongly on the value of $E_{\text{SOI}}$. For large values of $B_{||}^{2}$ (or $E_{Z}^{2}$) the dephasing-slope is found to be much smaller. In both limits, we find that the dephasing-slope is constant, i.e. $1/\tau_{\phi}(B_{||}) \propto B_{||}^{-2}$. The value of $B_{||}^{-2}$ (or $E_{Z}^{-2}$) at which the crossover occurs is larger for higher values of $E_{\text{SOI}}$. Anticipating, the crossover occurs when $E_{Z}/E_{\text{SOI}} \approx 1$ (see Fig. 4).

The large dephasing-slope for $E_{Z}/E_{\text{SOI}} \ll 1$ is due to the competition between Zeeman coupling and Rashba SOI\cite{8}. In contrast, the small dephasing-slope in the high field limit can be attributed to the coupling of $B_{||}$ to the orbital motion of the electrons. Hence, Fig. 3 suggests that the spin-induced dephasing of time reversed waves - i.e. the spin-induced TRS breaking - saturates.

To show the spin-induced part of the measured dephasing rate $1/\tau_{\phi}(B_{||})$, we subtract the contribution due to inelastic scattering ($\equiv 1/\tau_{\phi}(0)$), and denote the spin-induced dephasing rate by $\Gamma_{\phi}(B_{||})$, with $\Gamma_{\phi}(B_{||}) = 1/\tau_{\phi}(B_{||}) - 1/\tau_{\phi}(0)$. For $E_{Z}/E_{\text{SOI}} \ll 1$ the spin-induced
dephasing rate of time-reversed waves $\Gamma_\sigma(B) \parallel$ is given by $\tau_s(0)\Gamma_\sigma^\parallel(B) \parallel = (E_z / E_{SOI})^2$. In figure 4 we plot $\tau_s(0)\Gamma_\sigma^\parallel(B)$ for the whole measured range of $E_z / E_{SOI}$ [17]. For all samples, and all different values of electron density, elastic scattering time, Rashba strength, and $E_{SOI}$, the quantity $\tau_s(0)\Gamma_\sigma^\parallel(B) \parallel$ collapses to nearly the same curve (the combined error in the determination of $\tau_s(0)$ and $\Gamma_\sigma^\parallel(B) \parallel$ is typically 10%). We therefore conclude that the spin-induced TRS breaking in quantum wells with Rashba SOI (or more precisely $\tau_s(0)\Gamma_\sigma^\parallel(B) \parallel$) is a universal function of $E_z / E_{SOI}$, within the experimental accuracy.

The spin-induced TRS breaking (or $\Gamma_\sigma^\parallel(B) \parallel$) saturates when $E_z / E_{SOI} \approx 1$. For this strength of the Zeeman coupling the spins start becoming parallel or anti-parallel with $B \parallel$. This conclusion is consistent with the observation that for $E_z / E_{SOI} \approx 1$ the weak-antilocalization is just fully suppressed (see Fig. 2): when the spins become aligned with $B$, only weak-localization is expected, since conceptually this situation is identical to the case where only a small perpendicular field is present, and the spins are aligned with $B \perp$.

Currently, there are no theoretical predictions for the behavior of $\tau_s(0)\Gamma_\sigma^\parallel(B) \parallel$ when $E_z / E_{SOI}$ is not small, i.e. when the Zeeman coupling is not a small perturbation. It has only been predicted, for specific cases, that the magnetoconductance $\sigma(B \parallel)$ saturates when $E_z / E_{SOI} \gg 1$, indicating a saturation of $\tau_s(0)\Gamma_\sigma^\parallel(B) \parallel$ [13]. However, the corresponding behavior of $\tau_s(0)\Gamma_\sigma^\perp(B) \perp$ - in particular its universal character - had not been recognized so far.

We understand the saturation of $\Gamma_\sigma^\parallel(B) \parallel$ for $E_z / E_{SOI} \gg 1$, and the dependence of the saturation value of $\Gamma_\sigma^\parallel(B) \parallel$ on spin relaxation time $\tau_s(0)$, in the following intuitive way. Imagine first that the Zeeman splitting is large and SOI is absent. At the Fermi energy, the spin-split subbands are then well separated in k-space, and are fully decoupled. In that case each subband contributes separately to the interference, and the upper time-scale for interference is the inelastic scattering time, independent of the size of the Zeeman splitting. In the presence of SOI, the spin subbands become weakly coupled, i.e. a particle can be scattered from one spin subband to the other (flip its spin). Imagine there is a spin-flip center at a certain position along the path. Both time-reversed waves will then flip their spin at that position, and hence at different times in general. The waves spend therefore different amounts of time in each spin subband before they interfere, and obtain a large phase difference, since $k_{F \perp} - k_{F \perp}$ is large (large Zeeman splitting). This implies that waves do no longer contribute to the interference (on average) if a spin-flip event takes place along the path. The upper time-scale for quantum interference is therefore reduced to (roughly) the spin relaxation time $\tau_s(0)$, independent of the Zeeman splitting, as long as $k_{F \perp} - k_{F \perp}$ is large enough. This simple picture is in qualitative agreement with our experiments.

Finally, we focus in more detail on the remaining small, but finite, dephasing-slope for $E_z / E_{SOI} \gg 1$ (see Figs. 3 and 4). To show the remaining dephasing rate for $E_z / E_{SOI} \gg 1$ most clearly, we subtract the spin-induced dephasing rate in this limit - which equals the saturation value $1 / \tau_\sigma(E_z / E_{SOI} = 1)$ - and denote the resulting dephasing rate by $\Gamma_\sigma^\text{orb}(B)$). Fig. 5 shows the extracted values of $\Gamma_\sigma^\text{orb}(B) \parallel = 1 / \tau_\sigma(B) - 1 / \tau_\sigma(E_z / E_{SOI} = 1)$ for sample 1 (weakest SOI), for different values of the electron density [19]. Note that the $B \parallel$-field scale in this graph is much larger than in Figs. 3 and 4, i.e. $E_z / E_{SOI} \gg 1$). We find that the dephasing slope is larger for larger values of the electron density. In particular, we find that the remaining dephasing slope scales about linearly with the Fermi velocity (see inset).

The finite thickness of the quantum well makes that $B \parallel$ does not only couple to the electron spin (Zeeman coupling), but also to its orbital motion. It has been shown that this orbital coupling can also break TRS, via various mechanisms [21, 22]. These mechanisms depend on the specific (non-universal) details of the quantum well, such as surface roughness, z-dependence of the scattering potential in the 2DEG, and the asymmetry of the confining potential. The linear dependence of $\Gamma_\sigma$ (or $1 / \tau_s(B) \parallel$) on $B \parallel$ together with the linear dependence of the dephasing-slope on $v_F$, indicates that the (small) remaining slope for $E_z / E_{SOI} \gg 1$ is caused by surface roughness [21]. The resulting dephasing-slope is given by $\partial(1 / \tau_\sigma(B) \parallel) / \partial B \parallel \approx \sqrt{\pi} \varepsilon^2 d^2 L v_F / h^2$, where $d$ is the mean roughness height and $L$ is the correlation length of the roughness. For our quantum well we find $dL \approx 0.4 \text{ nm}$. 

![FIG. 4: (Color online) The spin-induced dephasing rate $\Gamma^\parallel(0)$ multiplied by $\tau_s(0)$, as a function of $(E_z / E_{SOI})^2$, with $\Gamma^\parallel(0) = 1 / \tau_\sigma(B) - 1 / \tau_s(0)$, and $\tau_s(0)$ is the inelastic scattering time. Results from all three samples are shown, illustrating that irrespective of sample, electron density, SOI strength, etc., the data collapse on nearly a single curve.](image-url)
which is a small value in comparison to other reports.\footnote{In our measurements.}

In general, the orbital mechanism will break the universality of the experimentally measured TRS breaking in systems with SOI, since it adds to the (universal) spin-induced TRS breaking mechanism. In our samples, the orbital TRS mechanism is very small an hence unimportant, so it affects the universality only minorly. This allows us to observe the universal behavior of the spin-induced TRS breaking for all values of the ratio $E_Z / E_{SOI}$.

In conclusion, we have demonstrated that the TRS breaking rate $\Gamma_{\phi}(B_{||})$, caused by the competition between Rashba and Zeeman, saturates when $E_Z \approx E_{SOI}$. This is because for $E_Z \geq E_{SOI}$, two Fermi surfaces start being formed with well-defined spin direction, pointing either parallel or anti-parallel to $B_{||}$. Moreover, we have shown that the scaled dephasing rate, $\tau_{s}(0)\Gamma_{\phi}(B_{||})$, is a universal function of the ratio $E_Z / E_{SOI}$, within the experimental accuracy. Finally, we have shown that this universality is broken by the coupling of the magnetic field to the orbital motion of the electrons.

We would like to thank T. Koga for the sample fabrication, and Y. M. Blanter, Y. V. Nazarov, and H. Takayanagi for stimulating discussion and support.

---

\footnote{Electronic address: f.e.meijer@tnw.tudelft.nl}

\footnote{Present address: Department of Materials Science, Tohoku University, Sendai 980-8579, Japan.}

\[1\] M.I. Dyakonov and V.I. Perel, Sov. Phys. JETP \textbf{33}, 1053 (1971); Sov. Phys. Solid State \textbf{13}, 3023 (1972)

\[2\] I.L. Aleiner and V.I. Falko, Phys. Rev. Lett. \textbf{87}, 256801 (2001); M. Governale, Phys. Rev. Lett. \textbf{89}, 206802 (2002); D.M. Zumbuhl, J.B. Miller, C.M. Marcus, K. Campman, and A.C. Gossard, Phys. Rev. Lett. \textbf{89}, 276803 (2002); V. M. Apalkov and M.E. Raikh, Phys. Rev. Lett. \textbf{89}, 096805 (2002); I. Zutic, J. Fabian, and S. Das Sarma, Rev. Mod. Phys. \textbf{76}, 323-410 (2004).

\[3\] V.A. Froltsov, Phys. Rev. B \textbf{64}, 45311 (2001); R. Raimondi, M. Leadbeater, P. Schwab, E. Caroti, and C. Castellani, Phys. Rev. B. \textbf{64}, 235110 (2001); Y. Yu, Y. Wen, J. Li, Z. Su, and S.T. Chui, Phys. Rev. B \textbf{69}, 153307 (2004); S.Q. Shen, M. Ma, X.C. Xie, and F.C. Zhang, Phys. Rev. Lett. \textbf{92}, 256603 (2004); D. Frustaglia and K. Richter Phys. Rev. B \textbf{69}, 235310 (2004).

\[4\] J. Nitta, F.E. Meijer, and H. Takayanagi, Appl. Phys. Lett. \textbf{75}, 695 (1999); J.N.H.J Cremers, P.W. Brouwer, and V.I. Falko, Phys. Rev. B \textbf{68}, 125329 (2003); F.E. Meijer, A.F. Morpurgo, T.M. Klapwijk, T. Koga, and J. Nitta, Phys. Rev. B \textbf{69}, 35308 (2004).

\[5\] See e.g. G. Bergmann, Solid State Comm. \textbf{42}, 815 (1982).

\[6\] S.V. Iordanskii, Y.B. Lyanda-Geller, and G.E. Pikus, Sov. Phys. Solid State, \textbf{3}, 199 (1960).

\[7\] A.G. Malshukov, K.A. Chao and M. Willander, Phys. Rev. B \textbf{56}, 6436 (1997).

\[8\] F.E. Meijer, A.F. Morpurgo, T.M. Klapwijk, T. Koga and J. Nitta, Phys. Rev. B \textbf{70}, 201307 (2004).

\[9\] G.M. Minkov, A.V. Germanenko, O.E. Rut, A.A. Sherstobitov, L.E. Golub, B.N. Zvonkov, and M. Willander, Phys. Rev. B \textbf{70}, 155323 (2004).

\[10\] For a perpendicular field this upper time-scale is often denoted $\tau_B$, and is given by $\tau_B = h / 2 e B D$, with $D$ is the diffusion constant.

\[11\] E.I. Rashba, Fiz. Tverd. Tela (Leningrad) \textbf{2}, 1224 (1960) [Sov. Phys. Solid State \textbf{2}, 1109 (1960)]; Yu.A. Bychkov and E.I. Rashba, J. Phys. C \textbf{17}, 6093 (1984).

\[12\] T. Koga, J. Nitta, T. Akazaki, and H. Takayanagi, Phys. Rev. Lett. \textbf{89}, 46801 (2002).

\[13\] In the ILP model, the magnetoconductance is assumed to be determined by 2D interference, i.e. $\sqrt{D \Gamma_{\phi}(B_{||}) / 3}$ must be much larger than the sample thickness. This condition is satisfied for all values of $B_{||}$ in our measurements.

\[14\] Notice that due to the relatively large electron density and small effective mass ($m^* \approx 0.041m_e$) the electron gas is far from being spin-polarized, even at $B_{||} = 14T$. Also, due to the large SOI strength in our samples, together with $r_s < 1$, the magnetoconductance is essentially only determined by interference corrections, and not by $B_{||}$-induced electron-electron interaction effects. We do find a small quadratic enhancement of the Drude resistivity with $B_{||} (< 4\%$ at $B_{||} = 14T$), the discussion of which is beyond the scope of the present paper.

\[15\] For a recent review see I.V. Gornyi and A.D. Mirlin, Phys. Rev. B \textbf{69}, 45313 (2004).

\[16\] The Rashba SOI strength $\Delta$ and $E_{SOI} \equiv \hbar / \tau_{s}(0) = \Delta^2 \tau / 2\hbar$ can be modified by a gate voltage. See e.g. J. Nitta, T. Akazaki, H. Takayanagi, and T. Enoki, Phys. Rev. Lett. \textbf{78}, 1335 (1997); G. Engels, J. Lange, T. Schäpers, and H. Lüth, Phys. Rev. B \textbf{55}, R1958 (1997); T. Schäpers, J. Appenzeller, H. Hardtdegen, and H. Lüth, J. Appl. Phys. \textbf{83}, 4324 (1998); D. Grundler, Phys. Rev. Lett. \textbf{84}, 6074 (2000).

\[17\] The g-factor is obtained experimentally from the TRS }
breaking for $E_Z/E_{SOI} \ll 1$, as shown in [3].

[18] A.G. Malshukov, V.A. Frolov, and K.A. Chao, Phys. Rev. B 59, 5702 (1999)

[19] In order to obtain the highest possible accuracy in determining $\tau_\phi(B \parallel)$, as it is needed to determine the weak $B \parallel$-dependence for $E_Z/E_{SOI} \gg 1$, we have (also) used the theory of Kawabata and Dyakonov [20] to extract $\tau_\phi(B \parallel)$. Note that this theory can not be used for $E_Z/E_{SOI} \ll 1$, as weak-antilocalization due to Rashba SOI is neglected.

[20] A. Kawabata, J. Phys. Soc. Jpn. 53, 3540 (1984); M.I. Dyakonov, Solid State Comm. 92, 711 (1994)

[21] H. Mathur and H.U. Baranger, Phys. Rev. B 64, 235325 (2001);

[22] J.S. Meyer, A. Altland, and B.L. Altshuler, Phys. Rev. Lett. 89, 206601 (2002); V.I. Fal’ko and T. Jungwirth, Phys. Rev. B 65, R81306 (2002)