Precessionless spin transport wire confined in quasi-two-dimensional electron systems

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We demonstrate that in an inversion-asymmetric two-dimensional electron system (2DES) with both Rashba and Dresselhaus spin-orbit couplings taken into account, certain transport directions on which no spin precession occurs can be found when the injected spin is properly polarized. By analyzing the expectation value of spin with respect to the injected electron state on each space point in the 2DES, we further show that the adjacent regions with technically reachable widths along these directions exhibit nearly conserved spin. Hence a possible application in semiconductor spintronics, namely, precessionless spin transport wire is proposed.

Crystallographic-direction-dependence of the Datta-Das transistor and the spin orientation in an inversion-asymmetric two-dimensional electron system (2DES) have been investigated recently. In the ballistic regime, electron spins are expected to precess when propagating in the 2DES, where electrons encounter spin-orbit (SO) couplings due to space inversion asymmetry, including structure and bulk. The former, structure inversion asymmetry (SIA), generates the well-known Rashba spin-orbit (RSO) coupling with strength $\alpha$ being gate-voltage tunable, while the latter, bulk inversion asymmetry (BIA), induces the Dresselhaus spin-orbit (DSO) coupling, with strength $\beta$ being material specific. When an electron with specific spin is ideally injected into the 2DES, the electron state is superposed by the two spin-dependent eigenstates with a phase difference between. As determining the electron spin away from the injection point, the expectation value, in general, differs from the injected one due to interference between the two superposing components, and the spin precession thus occurs.

Recently this spin precession due to individually the RSO and DSO couplings has been mathematically investigated and pictorially introduced. Implications indicated therein had demonstrated the uniqueness of the four crystallographic directions $\pm[1\pm10]$ for a [001]-grown zinc-blend-based 2DES. The spatial behaviors on these four directions are shown to be invariant, regardless of the coupling ratio $\alpha/\beta$, since the effective magnetic fields generated by RSO and DSO are either parallel or antiparallel to each other on these axes. More specifically, the total effective magnetic field directions are always perpendicular to the electron wave vectors when propagating along $\pm[1\pm10]$. Possible applications utilizing these four axes are thus envisioned. In this paper we apply the theoretical method constructed in Ref. [5] to demonstrate that in the 2DES with nonvanishing RSO and DSO couplings, zero spin precession (ZSP) axes, i.e., axes on which no spin precession occurs, can be found when the injected spin is properly oriented. By analyzing the spatially varying spin vectors, i.e., spin expectation values done with respect to the injected spin states, we further show that the adjacent regions with technically reachable widths along these directions own nearly conserved spin. Hence a possible application in semiconductor spintronics, namely, precessionless spin transport wire (STW) is proposed.

We begin by giving two examples of the STW confined in a [001]-grown 2DES. In the upper panel of Fig. 1 we in-
ject a $\pi/4$-polarized spin (polarization angle relative to [100]) on the 2DES where the RSO and DSO coupling ratio is set $\alpha/\beta = 2.15$. Shading the channel with projections between local spin vectors and the injected spin, a narrow precessionless path along [110] is clearly observed. In this case the ZSP axis is definitely [110] since we inject a spin parallel to the effective magnetic field thereon. Note that the longitudinal and transverse positions of the 2DES channel is labeled to the effective magnetic field thereon. Taking the DSO coupling strength as $L_D$ along $\phi = \pm \pi/4$ as a function of $\alpha/\beta$ in Fig. 4, where $L_{RD}^\pm (\alpha/\beta = 2.15)$ are also marked out, showing $L_{RD}^\pm (\alpha/\beta = 2.15) > 0.1$ eVÅ, and $m^*/m_0 = 0.023$. This yields $L_D \approx 0.52 \mu m$, leading to $W^+ \approx 226 \mu m$ and $W^- \approx 83 \mu m$ which are technically reachable scales in current semiconductor industry. As can be seen from Fig. 5 the wire width can even be considerably broaden by properly adjusting the coupling ratio $\alpha/\beta$.

Next we take into account the size effect of the spin injection contact and the possible influence due to the channel boundary. In the former consideration, the electron spin state on the space points inside the wire will be a superposition of every contribution from the spin injection contact, while in the latter modification, additional contribution from the state reflected from the two sides of the wire needs also to be summed. We consider a $0.25 \mu m \times 0.75 \mu m$ [110] channel, using a full side contact with perfect polarization of magnetization. The coupling parameters are set as $\alpha = 0.3 \mu eV \AA$ and $\beta = 0.09 \mu eV \AA$. As shown in Fig. 6 the anisotropy of the spin vectors occurs only in regions near the source contact, whether the boundary effect is taken into account, and hence does not influence the collection of the spin signal at the end of the channel. When comparing with the point injection case, these additional consideration does not raise considerable change, in particular, for channel directions with strong SO strength such as [110]. Therefore, the analysis for point injection cases introduced previously may work well enough.

It is worthy of mentioning that the effect of the boundary scattering on the dynamics of propagating spin in clean systems has recently received increased attention for both regular and chaotic walls. However, such relaxation, namely

\begin{align}
R_0 &\equiv \frac{\pi \hbar^2}{m^* \sqrt{\alpha^2 + \beta^2}}, \\
L_{RD} &\equiv \frac{\pi \hbar^2}{2m^* \sqrt{\alpha^2 + \beta^2 + 2\alpha \beta \sin 2\phi}}, \\
L_{RD}^\pm &\equiv L_{RD} \left( \phi = \pm \frac{\pi}{4} \right) = \frac{L_D}{|\alpha/\beta \pm 1|}
\end{align}

FIG. 2 The half period distances $L_{RD}^\pm$ as a function of the coupling ratio $\alpha/\beta$.

FIG. 3 (Color online) Spin vectors inside a [110] channel with size $0.25 \times 0.75 \mu m^2$, using a wide and perfectly polarized source contact for spin injection, (a) in the absence and (b) in the presence of channel boundary effects.
the D’yakonov-Perel’ (DP) spin relaxation, is suppressed in narrow wires (18) and essentially in strictly single channel quantum transport (19). Thus the DP spin relaxation, neglected in our calculation, does not destroy our analysis on the STW. In fact, it’s relaxation in magnitude of the spin vectors appears insignificant for spin transport within the order of micrometer from Monte Carlo simulation (20).

We now turn back to the point injection case and consider the same geometry but in three different channel directions [100], [110], and [1-10]. Defining the averaged spin signal collected at the end of the wire as the sum of the components along the drain contact magnetization direction (assumed transverse here) of all the spin vectors calculated theret divided by the wire width (0.25 µm in this case), we examine the gate-voltage dependence of these three wires, i.e., we examine the collected spin signal by varying the Rashba coupling strength α. As can be seen in Fig. 4, the spin signal oscillates with the increasing Rashba field for the [100] wire, which is obviously not precessionless. For the two promising cases [1±10], only the [110] exhibits precessionless behavior. This is because the width of the precessionless region along [1-10] is much narrower than the [110] case (mentioned previously) and thus the spin signal is averaged down when summing the spin vectors away from the [1-10] axis. With the above analysis, we also suggest the corresponding experimental setup to inspect the applicability of our precessionless STW.

In conclusion, we have demonstrated that the electron spin may be maintainably and perpendicularly transported along ±[1±10] in a zinc-blend-based [001]-grown 2DES within a reasonable width. Such a significant property of the inversion-asymmetric 2DES can be designed to be a precessionless spin transport wire or channel with widths depending on the coupling ratio of Rashba and Dresselhaus terms. In general, one can determine the effective field direction for a specific wave vector by measuring α/β precisely, inject spins polarized either parallel or antiparallel to the corresponding field, and then obtain precessionless spin transport. In such cases the spin polarization is even not necessarily perpendicular to its propagation. However, we emphasize that our results reveal that the spin transport along the four axes ±[1±10] are always precessionless when injecting perpendicularly polarized spins, regardless of the magnitudes of the RSO and DSO coupling strengths. In particular, [110] is recommended in the case of αβ > 0 for having wider precessionless region and being more robust against the influence due to finite-size spin injection and the channel boundary reflections (21). Such precessionless STW, if successfully fabricated, may be a basic component in the future spin-related devices. For example, the precessionless STW may serve as the lead between the spin source contact and the semiconductor-based transport channel to lower the loss of polarization of spin injection. Hence a modified version of the Datta-Das spin-field-effect transistor can also be proposed.

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FIG. 4 The averaged spin signal (in units of h/2) collected at the end of the 0.25 µm ×0.75 µm wire for [100], [110], and [1-10] cases. The calculation is done within the single injection method.

References

1. A Łusakowski, J. Wróbel, and T. Dietl, Phys. Rev. B 68, R081201 (2003).
2. David Z.-Y. Ting and Xavier Cartoixà, Phys. Rev. B 68 235320 (2003).
3. S. Datta and B. Das, Appl. Phys. Lett. 56, 665 (1990).
4. R. Winkler, Phys. Rev. B 69, 045317 (2004).
5. Ming-Hao Liu, Ching-Ray Chang, and Son-Hsien Chen, Phys. Rev. B 71, 153305 (2005).
6. E. I. Rashba, Sov. Phys. Solid State 2, 1109 (1960);
7. Yu. A. Bychkov and E. I. Rashba, JETP Lett. 39, 78 (1984).
8. J. Nitta, T. Akazaki, H. Takayanagi, and T. Enoki, Phys. Rev. Lett. 78, 1335 (1997).
9. G. Dresselhaus, Phys. Rev. 100, 580 (1955).
10. G. Lommer, F. Malcher, and U. Rüssler, Phys. Rev. B 32, 6965 (1985).
11. M. I. D’yakonov and V. Y. Kachorovskii, Sov. Phys. Semicond. 20, 110 (1986).
12. S. D. Ganichev, V. V. Bel’kov, L. E. Golub, E. L. Ivchenko, P. Schneider, S. Gigberger, J. Eroms, J. De Boeck, G. Borghs, W. Wegscheider, D. Weiss, and W. Prettl, Phys. Rev. Lett. 92, 256601 (2004).
13. John Schliemann, J. Carlos Egues, and Daniel Loss, Phys. Rev. Lett. 90, 146801 (2003).
14. W. Knap, C. Skierbiszewski, A. Zduniak, E. Litwin-Staszewska, D. Bertho, F. Kobli, J. L. Robert, G. E. Pikus, F. G. Pikus, S. V. Jordanski, V. Mosser, K. Zeke, and Yu. B. Lyanda-Geller, Phys. Rev. B 53, 3912 (1996).
15. Ming-Hao Liu and Ching-Ray Chang, cond-mat/0507495.
16. Cheng-Hung Chang, A. G. Mal’shukov, and K. A. Chao, Phys. Rev. B 70, 245309 (2004).
17. Oleg Zaitsev, Diego Frustaglia, and Klaus Richter, Phys. Rev. Lett. 94, 026809 (2005).
18. Branimir K. Nikolić and Sotofumi Souma, Phys. Rev. B 71, 195328 (2005).
19. A. G. Mal’shukov and K. A. Chao, Phys. Rev. B 61, R2413 (2000).
20. A. A. Kiselev and K. W. Kim, Phys. Rev. B 61, 13115 (2000).
21. Sandipan Pramanik, Supriyo Bandyopadhyay, and Marc Cahay, cond-mat/0403021.