Spin–orbit-induced semiconductor spin guides

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Abstract
The tunability of the Rashba spin–orbit (SO) coupling allows us to model semiconductor heterostructures with space-modulated coupling intensities. We show that a wire-shaped SO modulation in a quantum well can support propagating electronic states inside the wire only for certain spin orientations, and therefore it acts as an effective spin transmission guide for this particular spin orientation.

Currently, one of the most challenging issues in condensed matter physics is the injection and control of the electronic spin in semiconductor heterostructures. This is of major interest from the applications point of view, since the electron spin in semiconductor nanostructures has been revealed as a promising candidate for implementing quantum bits, a necessary ingredient of quantum computation [1]. The feasibility of spin-based electronic devices [2–6] also relies on the ability to manipulate the spin carriers.

In recent years, spin polarization has been induced in semiconductors using optical [7] and electrical methods [8, 9]. In the case of electrical injection, the technique relies on external ‘spin-aligner’ elements, such as magnetic semiconductors or ferromagnetic metals, as a previous step that polarizes the current which is injected into the semiconductor. In this work we propose an alternative mechanism that internally selects the propagating spins in the semiconductor by means of a space modulation in the Rashba spin–orbit (SO) coupling for heterostructures with inversion asymmetry.

We consider a two-dimensional electron gas (2DEG) confined to a III–V quantum well whose inversion asymmetry produces an electric field in the perpendicular (z) direction. As a consequence of relativistic corrections, this electric field acts on the 2DEG carriers as an effective SO coupling field known as the Rashba term [10, 11]. The strength of the Rashba coupling depends on the heterostructure’s vertical electric field and has been shown to be experimentally controllable with a tunable gate voltage [12]. We take advantage of this tunability to define a heterostructure with a space-modulated SO coupling intensity, depicted schematically in the upper part of figure 1. In practice, the SO coupling variation would correspond to a modulated electric field in the vertical direction. The well has a constant SO coupling strength $\lambda^{(0)}_{R}$ except within a narrow region (guide) of width $a$, where it takes the ‘internal’ value $\lambda^{(i)}_{R}$.

We model the conduction electrons of this heterostructure using the effective mass Hamiltonian

$$\mathcal{H} = p^{2}_{x} + p_{y}^{2} + \frac{\lambda_{R}(x)}{\hbar} (p_{y} \sigma_{x} - p_{x} \sigma_{y}), \quad (1)$$

where the modulated SO coupling reads

$$\lambda_{R}(x) = \begin{cases} \lambda^{(i)}_{R} & \text{if } |x| \leq \frac{a}{2} \\ \lambda^{(0)}_{R} & \text{if } |x| > \frac{a}{2}. \end{cases} \quad (2)$$

Equation (1) also contains the conduction band effective mass $m^{*}$ and the Pauli matrices $\sigma_{x}$ and $\sigma_{y}$ corresponding to the in-plane electron spin.

Since the Hamiltonian is translationally invariant in the $y$ coordinate its eigenstates have well-defined momentum in that direction. In this representation the Hamiltonian is separable in space coordinates and the eigenstates are composed of a propagating longitudinal plane wave, having $y$ momentum $\hbar k$, and a spinorial transverse profile

$$\begin{pmatrix} \psi_{\uparrow}(r) \\ \psi_{\downarrow}(r) \end{pmatrix} = e^{i\phi_{y}} \begin{pmatrix} \phi_{\uparrow}(x) \\ \phi_{\downarrow}(x) \end{pmatrix}, \quad (3)$$

where the spinorial part is given in the usual $\sigma$ basis.

From the experimental data reported by Nitta et al [12] for an In$_{0.53}$Ga$_{0.47}$As/In$_{0.52}$Al$_{0.48}$As heterostructure, we extract the following parameter values to be used below in the numerical applications: $m^{*} = 0.05 m_{e}$, where $m_{e}$ is the free electron mass; $\lambda^{(0)}_{R} = 0.5 \times 10^{-9}$; $\lambda^{(i)}_{R} = 1.0 \times 10^{-9}$ eV cm; relative dielectric constant of InGaAs $\epsilon = 13.9$; $y$-coordinate wavevector $k = 3.5 \times 10^{6}$ cm$^{-1}$, near the Fermi wavevector of a 2DEG with density $n_{c} \approx 2 \times 10^{12}$ cm$^{-2}$.

Before presenting numerical results with the above Hamiltonian and in order to clarify our purpose we consider...
We shall numerically obtain the relevant transverse eigenmodes of the Hamiltonian $\mathcal{H}_c$, from the resolution of the time-dependent Schrödinger equation uniformly discretized in the $x$ coordinate and in time. The procedure is as follows: we evolve in time an initial spinorial wavepacket and, taking advantage of the harmonic time evolution for eigenmodes, we extract the transverse eigenspinors and eigenenergies using Fourier analysis of the time signals. For a certain value of $y$-wavevector $k$ the time evolution of any wavepacket is decomposed as:

$$
\begin{align*}
\left( \psi_{k\uparrow}(x,t) \right) = & \sum_n A_{n,k} \left( \phi_{n,k\uparrow}(x) \right) e^{-i\omega_{n,k}t}, \\
\left( \psi_{k\downarrow}(x,t) \right) = & \sum_n A_{n,k} \left( \phi_{n,k\downarrow}(x) \right) e^{-i\omega_{n,k}t}.
\end{align*}
$$

(5)

Besides the eigenenergies $\omega_{n,k}$ of the different transverse modes $n$, a Fourier transform at each grid point yields the local value of the eigenspinors. This method is appropriate to the present problem since an initial wavepacket inside the guide (see figure 1) will excite the confined transverse modes, if they exist, or it will quickly spread to the bulk surrounding the guide. We use Gaussian-shaped wavepackets in coordinate space with spin oriented in $x$ direction, i.e.

$$
\psi(x,t=0) = \frac{1}{2\sigma\sqrt{\pi}} e^{-\frac{x^2}{2\sigma^2}} \chi_{\sigma}^{(x)},
$$

with the $\sigma_x$ eigenspinors

$$
\chi_{\sigma}^{(x)} = \left( \frac{1}{\pm 1} \right).
$$

(7)

The spatial spread of the wavepacket is chosen to be close to the width of the SO guide because we want a maximum overlap with the confined transverse modes. Gaussian wavepackets are appropriate to excite confined modes, having even parity in the $x$ coordinate, while for odd-parity states it is convenient to use an antisymmetric wavepacket. This can be done by multiplying equation (6) by $x$.

Physically, the input wavepacket represents an electron having well-defined $p_z$ and spin oriented along $x$, injected from a lead with transverse dimensions matching those of the guide. Figure 2 shows the time evolution of the density for initial wavepackets with two different initial spin orientations: $x$-up (up), and $x$-down (down), using a guide width $a = 60$ nm. It can be seen that for down initialization the wavepacket spreads over the transverse dimension in $t \sim 1$ ps, with a complete depletion of density inside the spin guide. For spin up a part of the probability density remains confined to the guide as time evolves. This means that our initial up state was composed of confined and travelling transverse modes, while the down state is only composed of the latter. For a general orientation of the initial spin the confined fraction of the density depends on $\sigma_z$, vanishing if the initial spin points in the $-x$ direction and reaching a maximum for the $+x$ one.

To identify and extract the confined modes present in the time evolution simulation we use the mentioned Fourier analysis technique, focusing on a frequency region of the order $\Delta \lambda_{k}$. This analysis reveals that for our parameter set there is only one confined mode with spin polarization mainly oriented in the $+x$ direction, as was expected from the above discussion. To observe a second...
Figure 2. Time evolution of the density for an initial Gaussian wavepacket with well-defined spin orientation for times up to $\approx 1$ ps. The upper panel corresponds to $+x$ initial spin direction while the lower one corresponds to $-x$. The dotted lines indicate the position of the spin guide.

Confined mode (antisymmetric), maintaining the width of 60 nm, the longitudinal wavevector should be increased up to $k \sim 6 \times 10^6$ cm$^{-1}$. Actually, for a fixed $\Delta \lambda k$, the number of confined states depends only on the product $ka$. The probability and spin densities of the confined mode, related to the wavefunction by

$$
\langle \rho \rangle (x) = |\phi_{nk}^\uparrow (x)|^2 + |\phi_{nk}^\downarrow (x)|^2,
$$

$$
\langle \sigma_z \rangle (x) = 2 \text{Re}\{\phi_{nk}^\uparrow (x)\phi_{nk}^\downarrow (x)^*\},
$$

$$
\langle \sigma_x \rangle (x) = 2 \text{Re}\{\phi_{nk}^\uparrow (x)\phi_{nk}^\downarrow (x)^*\},
$$

are shown in figure 3.

Probability and spin densities clearly show the confining character of the guided mode, the main spin polarization being concentrated in the $+x$ direction. The mode has zero $\langle \sigma_z \rangle (x)$ and a small $\langle \sigma_z \rangle (x)$. This confined mode is not an eigenstate of $\sigma_x$, as the transverse Hamiltonian $\hat{H}_{tr}$ does not commute with this operator but, nevertheless, it has an expectation value $\langle \sigma_z \rangle = 0.99$, very close to the value 1 for eigenstates.

It is worth mentioning that since time-reversal symmetry is conserved by the Hamiltonian of equation (1), Kramers degeneracy must hold. Therefore, a counterpart to the confined mode discussed above exists. This complementary state is also confined to the guide but its spin polarization and longitudinal momentum $(p_x)$ are inverted, i.e. it is mainly oriented in the $-x$ direction and has $k' = -k$.

The ability of the guide to confine additional modes is enhanced by increasing the guide width $a$. Figure 4 shows the evolution with $a$, maintaining $k$ at the same value as before. Confined modes should lie between the energy edges of the guide, marked in figure 4 by dotted lines. We note that the second and third modes appear for guide widths of $a \approx 80$ and 150 nm respectively, with probability densities having an additional node for each successive mode. As the first $n = 0$ state these higher modes have spin almost completely oriented in the $+x$ direction.

The confining energies of the guide are of order $\Delta \lambda k$, which takes a value of $\sim 2$ meV for our parameter set. Consequently, the practical operation of the proposed guide is limited to low temperatures, since the coupling with phonons in the meV range would reduce the efficiency of the guiding effect. In this sense, it has to be pointed out that the assignment

![Figure 3](https://example.com/figure3.png)

Figure 3. Charge and spin densities corresponding to the guide-confined mode. As in figure 2 the dotted lines mark the edges of the spin guide. Note the enlarged scale for $\langle \sigma_z \rangle (x)$.

![Figure 4](https://example.com/figure4.png)

Figure 4. Confined mode energies as a function of the guide width $a$. Label $n$ indicates successive modes for a given $a$. The dotted curves show the confinement edge energies. The small plots on the right display the probability densities $\langle \rho \rangle (x)$ for two selected modes labelled ‘a’ and ‘b’.
Spin–orbit-induced semiconductor spin guides of a lower SO constant to the guide region is not arbitrary, because, as reported by Khaetskii and Nazarov [13], SO coupling induces an admixture of pure up and down spin orientations in the eigenstates that causes spin decay through phonon emission, shown to be the dominant source of spin decoherence for quantum dots. To minimize the effects of this mechanism the confining structure needs to have the minimum SO coupling. It should also be mentioned that the scattering by impurities could affect the device operation beyond the pure ballistic regime of this work. Nevertheless, the guided modes can already stand a certain distribution of transverse momentum (as large as a fraction of the Fermi momentum) due to the confinement effect.

In summary, we have shown that a guide structure in a semiconductor quantum well, defined by a spatially modulated Rashba SO coupling, gives rise to transverse-confined and longitudinal-propagating modes only for a given spin orientation. This feature characterizes the proposed structures as spin guides that constitute natural paths to distinguish and drive the spin of the carriers within semiconductors. The feasibility of this spin-guiding mechanism is limited to low temperatures as the energies of the Rashba effect are in the range of a few meV.

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References

[1] Loss D and DiVincenzo D P 1998 Phys. Rev. A 57 120
[2] Wolf S A, Awschalom D D, Buhrman R A, Daughton J M, von Molnár S, Roukes M L, Chichkov B A and Treger D M 2001 Science 294 1488
[3] Datta S and Das B 1990 Appl. Phys. Lett. 56 665
[4] Koga T, Nitta J, Takayanagi H and Datta S 2002 Phys. Rev. Lett. 88 126601
[5] Governale M, Boese D, Zilicic U and Schroll C 2002 Phys. Rev. B 65 140403
[6] Wang X F, Vasilopoulos P and Peeters F M 2002 Appl. Phys. Lett. 80 1400
[7] Kikkawa J M and Awschalom D D 1998 Phys. Rev. Lett. 80 4313
[8] Fiederling R, Keim M, Reuscher G, Ossau W, Schmidt G, Waag A and Molenkamp L W 1999 Nature 402 787
[9] Ohno Y, Young D K, Beschoten B, Matsukura F, Ohno H and Awschalom D D 1999 Nature 402 790
[10] Rashba E I 1960 Fiz. tverd. Tela 2 1224 (Engl. transl. 1960 Sov. Phys.–Solid State 2 1109)
[11] Knap W, Skierbiszewski C, Zduniak A, Litwin-Staszewska E, Bertho D, Kobbi F, Robert J L, Pikus G E, Pikus F G, Iordanskii S V, Mosser V, Zekentes K and Lyanda–Geller Yu B 1996 Phys. Rev. B 53 3912
[12] Nitta J, Akazaki T, Takayanagi H and Enoki T 1997 Phys. Rev. Lett. 78 1335
[13] Khaetskii A V and Nazarov Y V 2001 Phys. Rev. B 64 125316