Novel mechanism for rapid spin flip with increasing in-plane wave vector in slightly asymmetric modulation-doped quantum wells

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Abstract. We calculate the electric-field-induced spin splittings in wide slightly asymmetric modulation-doped quantum wells. When spin subbands are anticrossing we demonstrate two-step spin flips as the in-plane wave vector along the [11] direction is increased by 0.002 nm⁻¹. At the beginning of this interval the $y$-component flips, at the end the $x$-component. Simultaneously the energy separation stays roughly constant below 1 eV and the wave functions are interchanged. A bias change of about 1 meV is sufficient to move the Fermi level from below to above the anticrossing region.

1. Introduction

In symmetric coupled double quantum wells it is well known that the lowest two states have wave functions that are symmetric and antisymmetric, respectively. We here show interesting phenomena that occur when small asymmetry is introduced. We actually consider an n-type wide modulation-doped quantum well with two weakly interacting electron gases localized near the interfaces. They are separated by a high and wide barrier and the degree of interaction between the electron gases is given by the width of the quantum well and the carrier concentration. The latter can be conveniently regulated by the width of the undoped spacer layers between the donors in the barriers and the interfaces. By choosing these spacer layers unequal we can also adjust the degree of asymmetry of the potential.

An essential difference compared to two square wells is that each electron gas resides in a roughly triangular potential with a strong built-in electric field. It turns out to be essential that the signs of the electric fields are different in the two electron gases. Such structure inversion asymmetry (SIA) gives rise to spin splitting via the Rashba effect [1]. This spin splitting is often taken to be proportional to the expectation value of the electric field. A similar spin splitting called the Dresselhaus effect [2] results from the bulk inversion asymmetry (BIA) in the zincblende crystal structure.

For a symmetric modulation-doped quantum well wide enough that the electron gases are noninteracting it appears that we should have Rashba splitting due to the triangular potentials if we consider each electron gas separately. However, for the whole quantum well the potential is
symmetric. This apparent paradox has previously been sorted out for wide p-type quantum wells [3] and the qualitative features apply also to n-type quantum wells.

2. Spin flips at anticrossings between spin subbands

We here consider 80 nm wide In$_{0.74}$Ga$_{0.26}$Sb quantum wells surrounded by In$_{0.7}$Al$_{0.3}$Sb barriers. Here we have a spin-orbit interaction almost as strong as that in InSb and can expect a strong Rashba effect. The calculations are performed self-consistently in the Hartree approximation using an $8 \times 8$ k·p Hamiltonian [4] in which the interaction between the conduction, heavy-hole, light-hole and split-off bands is included exactly. We thus go beyond the common Rashba model [1]. We consider wave vectors $k$ in the [11] direction in the two-dimensional Brillouin zone for which the Dresselhaus effect [2] becomes significant. From the wave function components we numerically calculate the expectation value of the spin vector [5].

Starting from a symmetric well the wave functions at $k = 0$ gradually become more concentrated to one of the interface regions as the asymmetry increases. For a finite but fairly small asymmetry (36 mV over the quantum well) each wave function becomes localized to one interface region. One can utilize the strong built-in electric field there to obtain a Rashba splitting that is 10 times larger than for a uniform field with a given voltage over the quantum well [6]. The switch energy in a Datta-Das-like spin transistor [7] can then be reduced by two orders of magnitude (if it can be made to function) and become highly competitive compared to present transistors.

In this paper we are interested in quite small asymmetries. Then the energy separation at $k = 0$ between the two lowest subbands becomes comparable to the Rashba splitting. We take $k$ in the [11] direction in the two-dimensional Brillouin zone for which the Dresselhaus effect becomes significant. As $k$ increases interesting anticrossings (avoided crossings) take place. At an anticrossing between two spin subbands they tend to interchange identities. Three fundamental types of anticrossings are identified. If the spin directions of the anticrossing spin subbands are the same we find that the wave function localization (perpendicular to the interfaces!) of a spin subband can move from one interface region to the other as the in-plane wave vector $k$ increases. A second type of anticrossing occurs when the spin subbands are localized at the same interface but have opposite spin directions. We will here focus on the third type of anticrossing where both the effects occur simultaneously. We have designed the structure such that the Fermi level (at $T = 0$) is just below such an anticrossing.

It seems to be an interesting “universal” behaviour of anticrossings of the second and third kind that the spin flip occurs in two steps. In the inset of Fig. 1a it appears that the energy splitting $\Delta E$ stays at zero in the $k$-range $[k_-, k_+]$ during which the spin flip process takes place but a closer examination shows that $\Delta E$ actually is finite but quite small ($< 1 \mu$eV). In Fig. 1b we display the $x$, $y$ and $z$-components of the spin vectors in this $k$-range. This applies to one of the anticrossing spin subbands while the behaviour of the other spin subband (not shown) shows the opposite trend. Where the $y$-component passes zero (at $k_\approx 0.126$ nm$^{-1}$), the $x$ component displays a sharp minimum, and at $k_\approx 0.130$ nm$^{-1}$ the reverse occurs. The $z$-component is usually small, but reaches a high value at $k_\approx$, drops almost linearly in the anticrossing range to reach a similar negative value at $k_\approx$. The behaviour becomes more transparent in Fig. 1c where the projection of the spin vector in the xy-plane is shown for a sequence of closely spaced $k$-values. It is seen that in a narrow range near $k_\approx$ the $y$ component flips and then the $x$ component flips near $k_\approx$. During this process the wave functions are also transferred between the interface regions (cf. [6]).

To analyze this two-step process we note that with pure Rashba effect the spin vector is always perpendicular to the wave vector [5], which was taken to be in the [11] direction. It is seen that this holds for $k < k_\approx$ and $k > k_\approx$. However, in the anticrossing region the spin vector is antiparallel to $k_\approx$, which indicates that here the Dresselhaus effect dominates.
Fig. 1a. Energy separation between the two lowest spin subbands near their anticrossing at 0.128 nm\(^{-1}\). The inset shows the energy separation on a larger scale. The feature near 0.3 nm\(^{-1}\) is due to anticrossing between spin subbands 2 and 3.

Fig. 1b. Components of the expectation value of the spin vector [5]. In the upper figure the \(x\)-component has a local minimum when the \(y\)-component (middle figure) changes sign, and vice versa. The \(z\)-component (lower figure) is small except from in the anticrossing region, where it varies almost linearly.

Fig. 1c. Projection of the spin vector in the \(xy\)-plane for a sequence of \(k\)-values in the anticrossing range. During the anticrossing the spin vector is antiparallel to the wave vector which would not occur if only the Rashba effect was active.
3. Discussion

We next discuss the possibilities that this interesting two-step spin flip can be observed experimentally. It should be noted that during an anticrossing a change in one spin subband is accompanied by the reverse process in the other spin subband. Measurements that average over both the subbands would not reveal these effects. Since the structure was designed such that Fermi level is just below the anticrossing one can envision an electron travelling adiabatically in a spin subband beyond the anticrossing region and thus flipping the spin. However, since the spin subbands get very close to each other at the anticrossing and the wave functions are mixed there, it seems more likely that it tunnels to the other spin subband and keeps its spin direction.

In the present case one can also change the gate voltage perpendicular to the quantum well slightly such that the Fermi level moves to above the anticrossing region and the spin direction in each subband is reversed. Here the spacer layer widths have been modified to 99.4 and 100.6 nm such that the voltage across the quantum well has changed by about 1 mV. This switching mechanism is of another kind than the gradual spin precession in the Datta-Das spin transistor. In ref. [6] we found a switch voltage of 35 mV and here it can be even lower. The main reason is that the switching occurs quite rapidly as the in-plane wave vector or the gate voltage is changed slightly.

However, it can still be queried if such a switching can be observed at finite temperatures. At first sight the electrons could easily be thermally excited from the lower to the higher spin subband, where $\Delta E$ is less than 1 $\mu$eV at the anticrossing. One interesting aspect is that a small distance away from the anticrossing the wave function of one spin subband is localized to the other interface region than that of the other spin subband. Thus a thermal excitation should be accompanied by the transfer of the electron to the other interface for which there is a high and wide barrier. In this case one cannot rule out nonequilibrium situations and hysteresis effects. Exactly what happens requires further studies, but the spatial separation of wave functions in wide modulation-doped quantum wells may open a possibility to enhance the temperature stability which is often a problem for spintronic devices.

Wide modulation-doped quantum wells also appear to be a good system to study the fundamental issue under which conditions a wave function can be considered as coherent across a wide quantum well with a wide barrier in the middle. In our calculations we have implicitly assumed that the wave functions are coherent.

4. Summary

We have considered spin flip phenomena in slightly asymmetric modulation-doped quantum wells. Here we have two weakly interacting electron gases subject to strong built-in electric fields of opposite signs giving rise to substantial Rashba spin splitting. Inclusion of the Dresselhaus effect turns out to be important to obtain anticrossing phenomena with rapid spin flips as the in-plane wave vector or the applied gate voltage is changed slightly. A remarkable feature is that the spin flip generally seems to occur in two steps where the $x$ and $y$ components flip for slightly different $k$-values. This is tentatively explained in terms of the $k$-dependent relative strengths of the Rashba and Dresselhaus effects. Consideration of temperature effects is essential to evaluate the possibility to observe the predicted effects experimentally. It is argued that the high barrier separating the interface regions may enhance the temperature stability.

References

[1] Y.A. Bychkov and E.I. Rashba, J. Phys. C 17, 6039 (1984).
[2] G. Dresselhaus, Phys. Rev. 100, 580 (1955).
[3] U. Ekenberg, Phys. Rev. B 38, 12664 (1988).
[4] A.M. Cohen and G.E. Marquez, Phys. Rev. B 41, 10608 (1990).
[5] R. Winkler, *Spin-Orbit Coupling Effects in Two-Dimensional Electron and Hole Systems*, Springer Tracts in Modern Physics, Vol. 191 (Springer, Berlin, 2003).
[6] D.M. Gvozdić and U. Ekenberg, Appl. Phys. Lett. 90, 053105 (2007).
[7] S. Datta and B. Das, Appl. Phys. Lett. 56, 665 (1990).