Efficient switching of Rashba spin splitting in wide modulation-doped quantum wells

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We demonstrate that the size of the electric-field-induced Rashba spin splitting in an 80 nm wide modulation-doped InGaSb quantum well can depend strongly on the spatial variation of the electric field. In a slightly asymmetric quantum well it can be an order of magnitude stronger than for the average uniform electric field. For even smaller asymmetry spin subbands can have wave functions and/or expectation values of the spin direction that are completely changed as the in-plane wave vector varies. The Dresselhaus effect can give an anticrossing at which the spin rapidly flips.

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I. INTRODUCTION

There is presently a strong interest in spin-related phenomena in semiconductors and the prospects of utilizing the spin rather than the charge of the electron for devices have given rise to a new research area called spintronics. One important mechanism that can be used in spintronic devices is called the Rashba effect. An applied electric field is seen in the frame of a moving electron as having a magnetic field component and yields a spin splitting even in the absence of magnetic field or magnetic ions. The Rashba effect is the mechanism behind the Datta-Das spin field effect transistor, which is perhaps the most well-known spintronic device. The spin-orbit coupling in a quantum well gives a subband splitting that is usually described in the Rashba model by

\[ \Delta E = \alpha k = \frac{\hbar^2 \Delta (2E_g + \Delta)}{2mE_g (E_g + \Delta)(3E_g + 2\Delta)} \epsilon k \]  

(1)

where \( \alpha \) is commonly called the Rashba coefficient, \( k \) is the in-plane wave vector and \( \epsilon \) is the electric field. For the expression for \( \alpha \) taken from Ref. 5 we insert the parameters of the well material.

The Rashba coefficient is related to the electric field perpendicular to the quantum well but so far little attention has been paid to the influence of the spatial variation of the electric field. We here find that under certain circumstances insertion of the different kinds of averages, e.g. the expectation value of the electric field, gives incorrect results. In particular we show how modulation-doping can give a strong Rashba effect with an applied field being an order of magnitude smaller than in the case of uniform doping and that it also can give rise to interesting anticrossing phenomena.

II. THEORY

We have gone beyond the Rashba model and performed self-consistent subband structure calculations in the Hartree approximation in a multi-band \( k \cdot p \) envelope function approach. The interaction between the conduction band, heavy-hole band, light-hole band and split-off band is included exactly in an \( 8 \times 8 \) matrix and the contributions from the remote bands are included in perturbation theory. We include terms due to the asymmetry of the zincblende lattice (Dresselhaus effect) and add the macroscopic potential along the diagonal of the matrix. This approach simultaneously gives accurate descriptions of the electron and hole subbands. We have here considered an 80 nm wide \( \text{In}_{0.74}\text{Ga}_{0.26}\text{Sb} \) quantum well (QW) surrounded by \( \text{In}_{0.7}\text{Al}_{0.3}\text{Sb} \) barriers. In this way we essentially retain the strong spin-orbit coupling of InSb and get lattice-matched well and barrier materials with a suitable conduction band offset.

![FIG. 1: (a) Potential and squared wave function and (b) subband dispersion for the lowest subband pair in an 80 nm InGaSb quantum well. The quantum well bias (potential difference between the interfaces) is 36 mV. Dashed lines: uniform electric field, solid lines: modulation-doped quantum well with an electron density of \( 6 \cdot 10^{11} \text{ cm}^{-2} \).]
III. MODULATION-DOPING VS. UNIFORM ELECTRIC FIELD

To illustrate one important effect of ours we compare the situation in a modulation-doped quantum well (MDQW) with that in a QW with a uniform electric field. The potential difference between the interfaces (below denoted quantum well bias, QWB) is the same in both the cases, 36 meV. We here take the wave vector to be in the [10] direction in the two-dimensional Brillouin zone. In this direction the Rashba effect dominates over the Dresselhaus effect. The potentials, squared wave functions and spin-split ground state subbands are shown in Fig. 1. In the modulation-doped case the carrier density was taken to be $6 \cdot 10^{11} \text{cm}^{-2}$. We then have two weakly interacting electron gases in the interface regions.

It is seen that the spin splitting is an order of magnitude larger in the modulation-doped case. Relative to a symmetric QW without Rashba splitting we present a modified mechanism to apply a moderate QWB and take advantage of the much stronger built-in electric field to obtain a substantial Rashba splitting. The reason for this effect is seen from the wave functions. In a symmetric QW the wave functions of the two lowest subbands would be symmetric and antisymmetric, respectively, and thus spread over the entire QW. But for sufficiently large asymmetry each wave function becomes localized to one of the interface regions. There the electric field is quite strong and it is this local field, not any average field, that determines the size of the spin splitting, in contrast to common belief so far.

IV. WAVE FUNCTION DEPENDENCE ON IN-PLANE WAVE VECTOR

Interesting things happen if we consider a MDQW with very small QWB, 1.7 meV. This is comparable to the energy separation at $k_{||} = 0$ between the lowest two subbands, $E_{21} = 1.4 \text{meV}$. This leads to interesting anticrossing phenomena and the influence of the next lowest subband must be seriously considered. We have found that anticrossings can be influenced strongly by the Dresselhaus effect which is stronger when $k_{||}$ is in the [11] direction. From now on we consider $k_{||}$ in this direction.

The wave function at $k_{||} = 0$ for the next lowest subband is mainly localized at the right interface region where the electric field is reversed (cf. Fig. 1a) and therefore we have the opposite order between "spin-up" and "spin-down" subbands. In order of increasing energy at small $k_{||}$ it is therefore appropriate to label the lowest four spin subbands $1 \downarrow$, $1 \uparrow$, $2 \uparrow$ and $2 \downarrow$. For such a small asymmetry the wave functions at $k_{||} = 0$ also have a non-negligible amplitude in the other interface region (Fig. 2). Another type of anticrossing takes place between the spin subbands $1 \downarrow$ and $1 \uparrow$ around $k_{||} = 0.168 \text{nm}^{-1}$ (Fig. 3). It is seen that in a narrow range of $k_{||}$-values, 0.166 to 0.17 nm$^{-1}$, the wave functions are interchanged and, simultaneously, the expectation value of the spin for a given spin subband is flipped.

V. ANALYSIS OF ANTICROSSING PHENOMENA

The interchange of properties is typical for anticrossing of subbands. For uncoupled spin subbands the Rashba
model (Eq. (1)) predicts a linear increase of the energy splitting with \( k_{\parallel} \) and it is clear that eventually it would exceed \( E_{2\lambda} \) and the spin subbands 1 \( \uparrow \) and 2 \( \uparrow \) would cross. In our multi-band approach an anticrossing takes place around \( k_{\parallel} = 0.03 \text{ nm}^{-1} \) between these spin subbands instead. This anticrossing takes place over a rather wide range of \( k_{\parallel} \)-values. Since these subbands have parallel spins no significant modification of the spin expectation values takes place.

The first anticrossing described above makes the character the second anticrossing possible. Between the anticrossings the next lowest spin subband (1 \( \uparrow \)) has the opposite wave function localization and spin direction compared to the lowest spin subband 1 \( \downarrow \). Fig. 3 displays a different mechanism compared to the gradual spin precession utilized in the Datta-Das spin transistor. The weak interaction between these two spin subbands makes it possible to reach an energy separation of only 0.4 meV and have such a rapid interchange of properties as \( k_{\parallel} \) increases. Inclusion of the Dresselhaus effect is essential to get this behavior. Although the spin flip here occurs as \( k_{\parallel} \) increases it should be possible to design a structure where the spin direction at the Fermi level of a spin subband is reversed when the bias is changed slightly.

It is clear that the wave vector range during which the anticrossing takes place strongly depends on the spin directions of the anticrossing spin subbands. The anticrossing can be conveniently controlled by well width, spacer layer widths, carrier density and applied bias.

One may argue that our results could be explained within the common Rashba model provided that we insert into Eq. (1) the expectation value of the electric field, which can be expected to be enhanced by the localization of the wave function. This procedure would be well-defined if both the spin subbands had the same expectation value of the electric field. However, for small electric fields we find that the expectation values averaged over the filled states (or evaluated at the Fermi energy) can be quite different for the different spin subbands as a result of the strong wave vector dependence of the wave functions.

VI. DEVICE ASPECTS

The strong enhancement of the Rashba splitting described in Fig. 1 due to modulation-doping can be expected to have important implications for spintronic devices like the spin transistor proposed by Datta and Das. For its performance it is essential that one can achieve a large wave vector splitting \( \Delta k \) of a spin-split subband with a small bias. Utilizing the built-in electric field one can achieve a given \( \Delta k \) with a QWB that is an order of magnitude smaller than with a uniform electric field. We have previously approximated the switch energy for n-type and p-type spin transistors by \( CV^2 \), where \( C \) is the capacitance of a QW structure surrounded by two gates and \( V \) is the applied bias between them. We then concluded that n-type spin transistors with the original design would have problems to become competitive with conventional transistors unless fundamentally new ideas were presented. If we only consider the lowest spin subband pair and follow the approach of Ref. 3 we obtain a switch energy of 0.4 aJ in the modulation-doped case and 35 aJ in a spin transistor with the same length and uniform electric field. The former figure compares very well with present state-of-the-art transistors where 3 aJ has been projected.

However, a complication with our design is that the second subband pair with the opposite sign of \( \Delta k \) and spin precession direction is also filled. This does not prevent the possibility that the spins at the interfaces can have made a precession by the angle \( \pi \) but in opposite directions on the arrival to the drain. Furthermore the matter is complicated by the \( k_{\parallel} \)-dependent wave functions and the redistribution of carriers in the QW. Still it is clear that interesting possibilities occurring from the controllable properties open up for the design of modified spin transistors, especially if one manages to contact the electron gases in the interface regions separately. Such considerations will be presented elsewhere.

VII. DISCUSSION

The effects described here also apply to p-type QWs. However, we have recently demonstrated that for p-type spin transistors the optimal choice is quite a small electric field (\( \sim 2 \) \text{-} 5 kV/cm) which is remarkably efficient to create a huge Rashba splitting \( \Delta k \).

We have implicitly assumed coherence of the wave function across the 80 nm QW with a high and broad barrier in the middle. Whether this coherence actually prevails should depend on the sample quality. This system with our predicted effects seems ideal for further studies of this fundamental problem.

VIII. SUMMARY

In conclusion we have demonstrated that the non-uniform electric field in wide modulation-doped quantum wells gives interesting and useful effects. One can use a bias corresponding to a moderate average electric field and still get a Rashba splitting typically enhanced by an order of magnitude due to the built-in local electric field in the interface region. The switching mechanism is based on localization of the wave function to one interface region with a barely sufficient bias. For very small bias the wave functions and spin directions can become strongly dependent on the in-plane wave vector. At anticrossing of spin subbands the wave function moves towards the opposite interface as \( k_{\parallel} \) increases and sometimes the spin is also flipped. The device prospects are promising but require further analysis.
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