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InAs/GaSb/AlSb Resonant Tunneling Spin Device Concepts

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Abstract

We discuss device concepts for creating spin polarized current sources without external magnetic fields, using nonmagnetic 6.1 Å semiconductor resonant tunneling structures. Spin filters, spin pumps, and spin transistors that exploit structural and bulk inversion asymmetries will be examined. © 2003 Elsevier Science. All rights reserved

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1. Introduction

Spin polarized current sources can be made using nonmagnetic semiconductor heterostructures. These devices contain asymmetric quantum wells where quantized states are spin split by the Rashba effect [1], which describes the lifting of Kramers degeneracy due to structural inversion asymmetry (SIA). Spin filtering is accomplished by exploiting the fact that the spin of a resonantly transmitted electron aligns with that of the quasibound state traversed [2,3]. Achieving significant spin filtering with this approach is challenging due to the intrinsic properties of the spin-split quantum well states [4]. This work describes how the properties of the InAs/GaSb/AlSb (6.1 Å) material system could be used to provide effective strategies for spin filtering.

2. Structural Inversion Asymmetry Spin Devices

Spin filtering devices based on asymmetric resonant tunneling diode (aRTD) was first proposed by Voskoboynikov *et al.* [5]. Figure 1(a) shows that the quasibound states in an aRTD are spin split by the Rashba effect. The shaded disks in Fig. 1(b) represent available quasibound states with energy below the Fermi level in the incident electron reservoir in $\mathbf{k}_{\|}$-space. When the spin directions of two spin-split subbands are plotted along the Fermi surface in the $\mathbf{k}_{\|}$-plane, they appear as counter-clockwise (ccw) and clockwise (cw) pinwheels. Quasibound state spin directions are important because transmitted electrons are spin-polarized by them. Although the two subbands have opposite spins, due to spin splitting, the cw disk has a larger radius, resulting in a net

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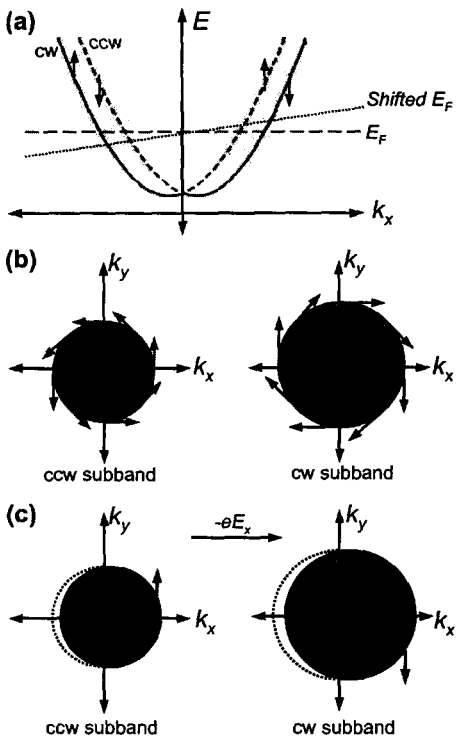

Fig. 1. (a) Lowest conduction subband (cb1) in an asymmetric quantum well showing Rashba spin splitting. (b) Available quasibound states in the cb1 with energy below the emitter Fermi level. Arrows indicate spin directions. (c) Same as (b), but with the Fermi surface in the incidence electrode displaced by the application of a lateral E-field.

"subband current polarization" in favor of the cw subband. But since states with opposite $\mathbf{k}_{\|}$ in a given subband also have opposite spins, the transmitted current still exhibits no net spin polarization. To obtain non-zero net spin polarization, one must create an anisotropy in the lateral momentum distribution of electrons undergoing resonant tunneling. Voskoboynikov *et al.* proposed using a small in-plane electric field in the source region of the aRTD to shift the incident electron distribution towards, say, the positive k_x side in k-space [5]. Figure 1(c) shows that this would result in net $+y$ and $-y$ spin polarizations for resonant tunneling currents transmitted through the ccw and cw subbands, respectively. And since cw subband current contributions are larger, the total transmitted current yields a net $-y$ spin polarization.

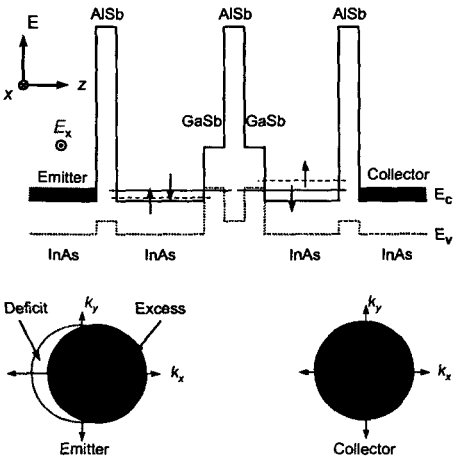

Fig. 2. Schematic energy band diagram of a triple-barrier spin-blockade structure used as a bi-directional spin pump. The bottom illustrates the emitter and collector carrier populations in momentum space.

The aRTD can be implemented in the 6.1 Å material system, where strong spin-orbit interaction in InAs and GaSb can be used to achieve large Rashba spin splitting, which in turn leads to higher spin filtering efficiency. Our calculations show that, using a structure with an asymmetric InAs-GaSb well with optimized Rashba coefficient, modest current spin polarization can be achieved [4].

To improve spin-filtering efficiency, we can strengthen the selectivity between the ccw and cw subbands by using the spin-blockade mechanism proposed by Koga *et al.* [6]. The device consists of a triple-barrier structure containing back-to-back asymmetric wells coupled through a thin central tunneling barrier (see Fig. 2). The two quantum wells have opposite ordering of the ccw and cw subbands. Resonant tunneling is blocked unless the quasibound state spins in the two well are aligned. Either ccw-ccw or cw-cw alignment can be selected by the biasing voltage. This technique has resulted in a calculated subband filtering efficiency of η>99.9% [6], where $\eta=(J_{ccw}-J_{cw})/(J_{ccw}+J_{cw})$, with J_{ccw} and J_{cw} being the resonant tunneling current density components associated with the ccw and cw subband tunneling, respectively. Our calculations show that spin-blockade structures made from 6.1 Å materials, such as the one shown in Fig. 2, also can achieve

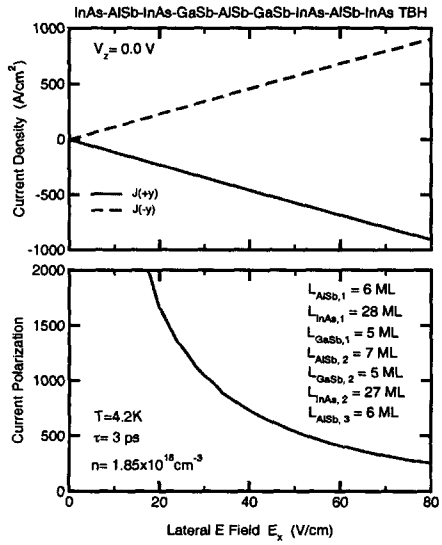

Fig. 3. Spin resolved current density components and current spin polarization as functions of lateral E-field for a triple-barrier spin-blockade bi-directional spin pump.

very high subband filtering efficiency [7]. As an alternative to using the lateral E-field to create anisotropy in the lateral momentum distribution, Koga and co-workers [6] also proposed the use of a one-sided collector, which is placed on, for example, the positive x side to collect only electrons with positive k_x. From Fig. 1(b) we see that for a highly efficient cw spin-blockade device with a one-sided collector on the positive x side, we need to consider only the right side of the cw subband disk, which leads to a net $-y$ spin polarizations in resonant tunneling currents. Note that the individual spins in the cw half disk are not aligned, but rather point in directions given by azimuthal angle ranging from 0° to −180°. This introduces a geometric factor into the calculation of net current spin polarization $P_J=(J_{+y}-J_{-y})/(J_{+y}+J_{-y})$, where J_{+y} and J_{-y} are resonant tunneling current density components spin polarized along the positive and negative y directions, respectively. It can be shown that $P_J=(2/\pi)\eta$, thus limiting P_J to a theoretical maximum of 63.7% for the one-sided collector geometry [7].

We can also improve spin filtering efficiency by exploiting the strong spin-dependent interband tunneling through hole states in asymmetric resonant interband tunneling diodes (aRITDs) [8]. The interband design uses large valence band spin-orbit interaction to provide strong spin selectivity, without suffering from fast hole spin relaxation. Filtering efficiency is enhanced by the reduction of tunneling through quasibound states near the zone center. Current spin polarization of aRITD can approach the theoretical limit of 63.7% in the one-sdied collector geometry, and even higher in the lateral E-field geometry with moderate field strengths [7,8].

A bi-directional spin-pump is similar in structure to resonant tunneling spin filters. However, we do not apply any bias along the growth (z) direction, but only apply a small lateral E-field in the emitter region. The application of an in-plane E-field displaces the emitter Fermi surface. As depicted in Fig. 2, the displacement creates an excess of carriers on the $+k_x$ side, which can tunnel to the collector, and a deficit of carriers on the $-k_x$ side, which becomes available to receive electrons tunneling back from the collector. The slightly asymmetric spin-blockade structure in Fig. 2 is designed such that resonant tunneling through the cw states dominates over the ccw states at zero bias. So considering the cw subband only, resonantly transmitted electrons on the $+k_x$ and $-k_x$ sides will be spin polarized along the $-y$ and $+y$ directions, respectively. Our calculations in Fig. 3 show that this results in a forward (emitter to collector) electron current with $-y$ spin polarization, and a backward current with $+y$ spin polarization. The bottom panel of Fig. 3 shows that the bi-directional pumping condition is characterized by the condition of $|P_J|>1$. Note that the aRITD can also be used as a bi-directional spin pump.

3. Bulk Inversion Asymmetry Effects

The devices presented so far focused on the effective use of SIA for spin filtering, and have neglected bulk inversion asymmetry (BIA) effects [9,10]. Under the right conditions, BIA can be used to enhance the efficiencies of spin filters. Figure 4 shows the conduction subband spin directions for a [001] quantum well structure, calculated using a two-band Hamiltonian containing both SIA [1] and BIA [11] terms, for various combinations of α_{SIA} and α_{BIA}, which are the coefficients measuring the strengths of SIA and BIA effects, respectively. Comparison

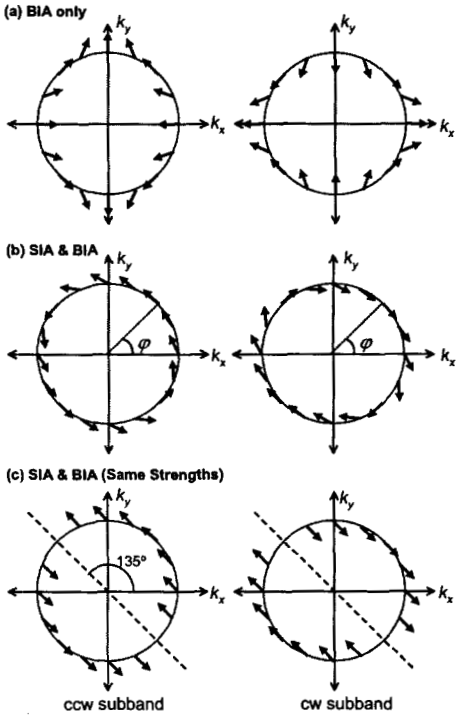

Fig. 4. Schematic illustration of quasibound state spin directions for two spin-split subbands on a constant k_{ij} contour for (a) $\alpha_{SIA}=0$, $\alpha_{BIA}\neq 0$, (b) $\alpha_{SIA}/\alpha_{BIA}=2$, and, (c) $\alpha_{SIA}/\alpha_{BIA}=1$.

between Fig. 1(b) and Fig. 4 shows how BIA modifies quantum well state spin directions anisotropically. In particular, at the azimuthal angle of φ=+45°(–45°), SIA and BIA effects reinforce (work against) each other. Thus if we apply the lateral E-field (or put the one-sided collector) along φ=45° instead of along the x direction (as we did when considering SIA effects only), we obtain noticeably higher current spin polarization. This is most pronounced for the special case of $\alpha_{SIA}=\alpha_{BIA}$ in Fig. 4(c), where directions of states on either side of the 135°-axis (shown as dashed lines) are completely aligned or anti-aligned with the axis, allowing a one-sided collector at φ=45° to collect an ensemble of spin-aligned transmitted electrons. In that case we obtain $P_J=\eta$ for the one-sided collector geometry, instead of $P_J=(2/\pi)\eta$ as discussed earlier when BIA effects were neglected.

An interesting property arising from the interplay between SIA and BIA effects is that the D'yakanov-Perel' mechanism of spin relaxation becomes suppressed when $\alpha_{SIA}=\alpha_{BIA}$ [12]. This led us to the concept of a variant of the Datta-Das spin transistor [13] called the resonant spin lifetime transistor (RSLT) [14]. In RSLT the switching action is accomplished by electrically controlling the spin lifetimes of electrons in the channel, where the size of α_{SIA} can be tuned by gate biasing while α_{BIA} remains essentially fixed. The RSLT is similar in concept to the non-ballistic spin-field-effect transistor [15], and can be used in non-volatile memories and magnetic readout heads [14].

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