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Spin filtering in asymmetric resonant interband tunneling diodes

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Abstract
We describe the use of an InAs/GaSb/AlSb-based asymmetric resonant interband tunneling diode (a-RITD) as a spin filter. The device exploits the Rashba effect to achieve spin polarization under zero magnetic field using non-magnetic III-V semiconductor heterostructures. We discuss the basic principles of the interband tunneling spin filter, and present calculated spin-dependent current densities and current polarization.

1. Introduction

Recent theoretical studies suggest the possibility of using resonant tunneling in conventional non-magnetic semiconductor heterostructures to polarize electron spins [1,2]. These devices are based on asymmetric double barrier resonant tunneling diodes, in which quasibound states are spin-split by the Rashba effect [3]. In this work we explore an InAs/GaSb/AlSb-based asymmetric resonant interband tunneling diode (a-RITD) for spin filtering. Heterostructures made from the nearly lattice-matched InAs/GaSb/AlSb material system are strong candidates for pronounced Rashba spin splitting because of the large spin-orbit interaction in InAs and GaSb, and the availability of both InAs and GaSb for the construction of highly asymmetric quantum wells. The InAs/GaSb/AlSb material system allows for a variety of band alignments. In addition to conventional intraband resonant tunneling structures, the type-II broken-gap band offset between InAs and GaSb allows us to fabricate resonant interband tunnel diodes (RITDs) [4], where the quasibound states have opposite k-parallel dispersions to those in the electrodes. In the following sections we will discuss spin-dependent tunneling in the interband resonant tunneling structures, and describe how the properties of the a-RITD can be used to improve the design of resonant tunneling spin filters.

2. Rashba Effect Resonant Tunneling Spin Filter

Spin splitting can result from the lifting of Kramers degeneracy [5] through the removal of inversion symmetry. Bulk zinc-blende or wurzite compound semiconductors exhibit microscopic inversion asymmetry in their lattice structures. Dresselhaus [6] has shown that this bulk inversion asymmetry (BIA) in zinc-blendes leads to a spin-orbit induced splitting whose magnitude is proportional to k^3 for small k, where k is the electron wave number. The Dresselhaus mechanism can also lead to an additional splitting linear in k in 2D systems [7]. Bychkov and Rashba showed that structural inversion asymmetry (SIA) could lead to a spin splitting which is also linear in k [3]. It is believed that in InAs/GaSb and InAs/AlSb systems, spin splitting is primarily due to the Rashba rather than the Dresselhaus effect [8,9]. In this work we limit our treatment to SIA effects.

The Rashba effect may be exploited in conjunction with resonant tunneling for spin filtering using, for example, a double barrier heterostructure (DBH) containing an asymmetric quantum well. In our case, we use an asymmetric composite InAs-GaSb well, surrounded by AlSb barriers and InAs electrodes. When designed with appropriate layer widths, this device can be made to operate either, under low bias, in the resonant interband tunneling [4] regime where

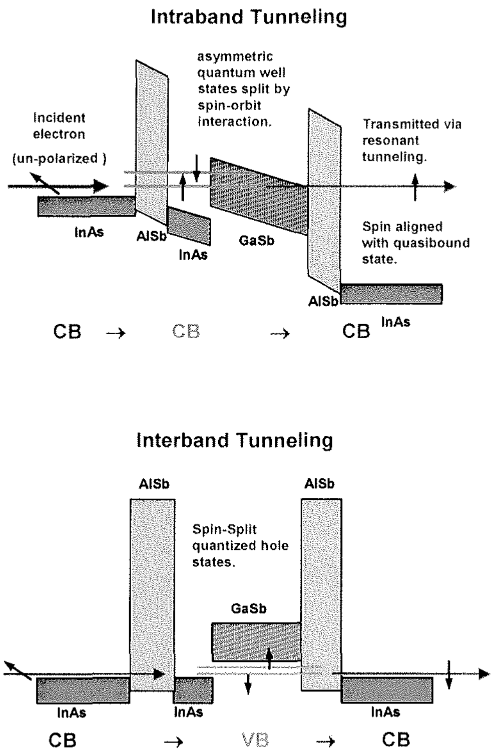

Figure 1. Schematic illustration of an asymmetric double barrier structure undergoing intraband (upper panel) and interband (lower panel) resonant tunneling.

electrons traverse valence subband states in GaSb, or, under moderate bias, in the intraband resonant tunneling regime where electrons traverse conduction subband states in InAs. The quasibound states in this structure are spin-split due to the Rashba effect. Fig. 1 illustrates the asymmetric resonant tunneling diode operating in the intraband and interband modes, depicting that the spin of a resonantly transmitted electron is aligned with that of the quasibound state traversed [1].

While this basic concept appears simple, a number of challenges must be overcome. To demonstrate the difficulties involved in designing a resonant tunneling spin filter based on the Rashba effect, we examine the spin directions of the quasibound states. In general, spin-orbit interaction is given by

$$H_{so} = [\hbar/(2mc)^2]\, \boldsymbol{\sigma}\cdot\nabla V\times\mathbf{p} \equiv (g/2)\mu_B \boldsymbol{\sigma}\cdot\mathbf{B}_{\mathrm{eff}}. \quad (1)$$

Spins of quantum well quasibound states align with the effective magnetic field $\mathbf{B}_{\mathrm{eff}}$, and from the form of $\mathbf{B}_{\mathrm{eff}}$ we readily conclude: (1) $\mathbf{B}_{\mathrm{eff}} \perp \nabla V$. Since we consider only SIA, spatial variations of V are along the growth direction, implying that spins are in the plane of the quantum well. (2) $\mathbf{B}_{\mathrm{eff}} \perp \mathbf{p}$, or, since $\mathbf{k}_{\|}$ is a good quantum number, $\mathbf{B}_{\mathrm{eff}} \perp \mathbf{k}_{\|}$. Hence spins are perpendicular to $\mathbf{k}_{\|}$. (3) $|\mathbf{B}_{\mathrm{eff}}| \propto |\mathbf{k}_{\|}|$. Thus spin splitting vanishes at the zone center.

The analysis above reveals the difficulties involved in using the quasibound states in resonant tunneling structures for spin alignment. First, at any given $\mathbf{k}_{\|}$, the two spin-split states have opposite spins. While this is exactly the property we wish to exploit for spin filtering, we also need to ensure that we could resolve the spin-split states so we can preferentially select one of the spin polarizations. The strategy for achieving this is to maximize spin splitting, and use resonant tunneling to resolve the states. Next, the $+\mathbf{k}_{\|}$ and $-\mathbf{k}_{\|}$ states within a given spin-split subband have opposite spins. In a typical resonant tunneling diode, incident electrons come from a reservoir in local thermal equilibrium, occupying $+\mathbf{k}_{\|}$ and $-\mathbf{k}_{\|}$ states with equal probability. Thus the ensemble of transmitted electrons yields no net spin polarization. To solve this problem, Voskoboynikov, Lin, and Lee proposed the application of a small lateral (perpendicular to the growth direction) E-field in the source region of the resonant tunneling diode to shift the incident electron distribution towards, say, the positive k_x side in k-space [2]. The resonantly transmitted currents originating from this non-equilibrium distribution would then show spin polarization. Finally, since spin splitting is linear in k near (and vanishes at) the zone center, resolving the spin-split states there is not feasible. The interband tunneling mechanism can be used to address this issue.

3. Asymmetric Resonant Interband Tunneling Diodes

Fig. 1 illustrates the resonant interband tunneling condition [4]. It shows that a number of valence subband states in the asymmetric quantum well are above the bulk InAs conduction band edge. Under low bias, electrons in the double barrier structure can tunnel from the conduction band of the InAs emitter, through valence subband states localized in the GaSb layer, to the conduction band of the InAs collector.

Fig. 2 shows the spin-dependent transmission coefficient spectra calculated using the multiband quantum transmitting boundary method (MQTBM) [10] for an asymmetric double barrier structure in interband as well as intraband regimes. For this calculation, we intentionally align the incident electron spins to the spin directions of the resonances, which are

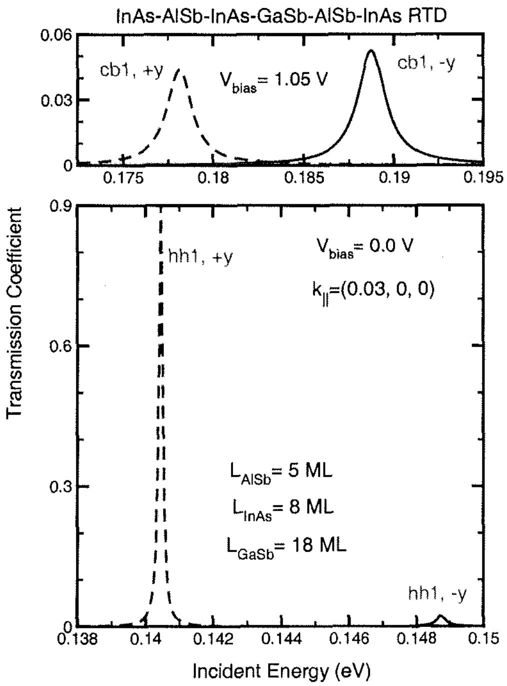

Figure 2. Transmission coefficient spectra for an InAs/GaSb/AlSb double barrier structure with an asymmetric quantum well. The top and bottom panels respectively show results for intraband and interband tunneling regimes, reached under different biasing conditions. The in-plane wave vector is $\mathbf{k}_{\|}$=(0.03, 0,0)(2π/a). The dashed and solid lines represent results for incident electron with +y and −y spin polarizations, respectively.

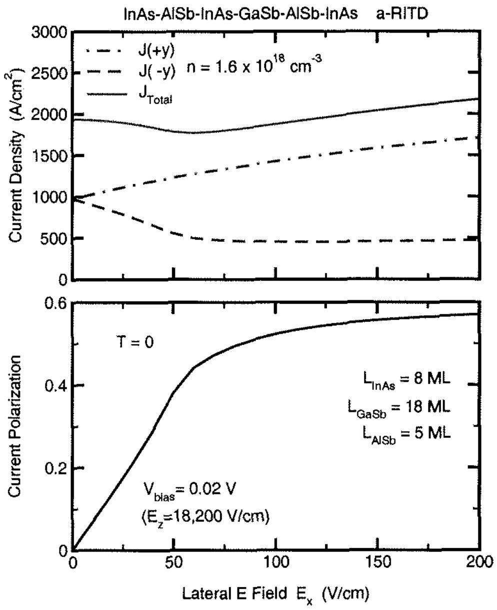

Figure 3. Spin-dependent current densities and current polarization for the a-RITD as functions of applied lateral E-field.

themselves dictated by the $\mathbf{k}_{\|}$-dependent effective magnetic field $\mathbf{B}_{\mathbf{eff}}$. Thus each of the incident spin polarization only couples to one of the spin-split resonances. The top panel shows that in the intraband tunneling case the resonant transmission probability through the two spin-split n=1 conduction subband states (cb1) are approximately equal. On the other hand, in the interband tunneling case shown on the bottom panel, transmission probability through the highest heavy hole (hh1) states is much higher for the $+y$ than the $-y$ spin polarization. The transmission peak strength ($T_{\max}\Delta$E, peak height times peak width) of the $+y$ channel is approximately 17 times larger than that of the $-y$ channel.

The hh1 resonances have a number of attractive features for spin filtering application. The hh1 energies decrease with increasing $k_{\|}$, allowing the selection of states with $\mathbf{k}_{\|}$ away from the zone center by setting the Fermi level in the incoming electrode to be below the energy of the zone center hh1 states. Also, hh1 peak strengths are exceedingly weak near the zone center due to inadequate hole mixing [11]. This also helps to filter out zone-center states. Finally, the pronounced difference in the strengths of the two hh1 spin channels can be exploited for spin filtering.

In contrast to the intraband case, in the interband case we are able to remove contributions from the zone center where spin selectivity is difficult. The interband design improves upon the intraband version in two respects: (1) cancellation between the contributions from the two subbands is reduced since the lower band represents a much stronger transmission channel than the upper subband. (2) Within each subband, spin polarization is stronger since non-spin selective zone center contributions are removed.

Fig. 3 shows the computed current densities and current polarizations as functions of lateral E field for an asymmetric resonant tunneling diode operating in the interband mode at a fixed transverse biasing voltage. We analyze the spins of transmitted electrons along the y-axis, and record separately current densities for spin up and spin down, $J(+y)$ and $J(-y)$, respectively. The current polarization is defined as

$$P = \frac{J(+y) - J(-y)}{J(+y) + J(-y)} \quad . \qquad (2)$$

The doping level of n=1.6×10^{18} cm^{-3} is used for both the emitter and the collector. At a bias of 0.02 V resonant interband tunneling takes place through the hh1 states, but not the lh1 or hh2 states that are blocked by the occupied states in the collector. It shows that as the lateral E-field increases, $J(+y)$ become substantially larger than $J(-y)$. For $E_x > 80$ V/cm, we can obtain values of P exceeding 0.5. Note that the size of the lateral E-field required for achieving $P > 0.5$ is small in comparison with the transverse E-field of 1.82×10^4 V/cm (0.02 V bias applied across the 108Å active region of the tunnel structure).

4. Summary

We examine the basic principles of the Rashba effect resonant tunneling spin filter, point out the challenges, and offer strategies for overcoming these difficulties. In particular, we present modeling results, which demonstrate the advantages of using the InAs/GaSb/AlSb-based asymmetric resonant interband tunneling diode (a-RITD) over the intraband version of the device. In the a-RITD, unpolarized electrons from the InAs conduction band of the emitter electrode tunnels rapidly through the valence subbands of an asymmetric InAs-GaSb quantum well where spin-filtering takes place, then into the InAs conduction band of the collector. The interband design exploits the larger spin orbit interaction in the valence bands for spin filtering, without suffering from fast hole spin relaxation. The a-RITD can effectively exclude tunneling through quasibound states near $\mathbf{k}_{\parallel}=0$ where Rashba spin spitting vanishes, and spin selectivity is difficult. Away from the zone center, a-RITD can provide strong spin selectivity.

The a-RITD requires an emitter capable of k-space selectivity to function as a spin filter. Implementing such an emitter is a major challenge. We have proposed a device structure and the associated processing procedure for accomplishing this task. The successful implementation would allow us to achieve spin filtering in semiconductors under zero magnetic field using only conventional non-magnetic III-V semiconductor heterostructures.

Acknowledgments

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