Theory of Electrically Controlled Resonant Tunneling Spin Devices

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ABSTRACT

We report device concepts that exploit spin-orbit coupling for creating spin polarized current sources using nonmagnetic semiconductor resonant tunneling heterostructures, without external magnetic fields. The resonant interband tunneling spin filter exploits large valence band spin-orbit interaction to provide strong spin selectivity. The bi-directional spin pump induces the simultaneous flow of oppositely spin-polarized current components in opposite directions through spin-dependent resonant tunneling. The efficiency of resonant tunneling spin devices can be improved when the effects of structural inversion asymmetry (SIA) and bulk inversion asymmetry (BIA) are combined properly, and incorporated into device design. The current spin polarizations of the proposed devices are electrically controllable, and potentially amenable to high-speed modulation. In principal, the electrically modulated spin-polarized current source could be integrated in optoelectronic devices for added functionality.

INTRODUCTION

An important component of semiconductor spintronics (spin-based electronics) research is the development of spin-polarized current sources [1]. One interesting approach uses non-magnetic semiconductor heterostructures, without external magnetic fields or optical excitation. The idea originated with the resonant tunneling spin filter proposed by Voskoboynikov *et al.* [2]. Subsequently, a number of new device concepts emerged, including the triple-barrier resonant tunneling diode (TB-RTD) [3], the asymmetric resonant interband tunneling diode (aRITD) [4,5], the bi-directional resonant tunneling spin pump [6], and the [110]-RITD [7]. In this paper we present an overview of some of these concepts, and discuss their prospects.

DEVICE CONCEPTS

We illustrate the concept of nonmagnetic heterostructure spin filters using the asymmetric resonant tunneling structure (aRTS) as an example. In the aRTS the quantized states are spin-split by the Rashba effect [8]. It achieves spin filtering by exploiting the phenomenon that the spin of a resonantly transmitted electron aligns with that of the quasibound state traversed [2, 9]. Figure 1(a) illustrates the properties of quasibound quantum well states in an aRTS. Rashba effect induced spin splitting in the lowest conduction band (cb1) states are shown in the left panel. The shaded disks in the right panel are $\mathbf{k}_{\parallel}$-space representations of available quasibound states with energy below the Fermi level in the incident electron reservoir. These are the states that participate in resonant tunneling, and their spin directions determine the spin polarization of the transmitted electrons in the collector. When the spin directions of two spin-split subbands

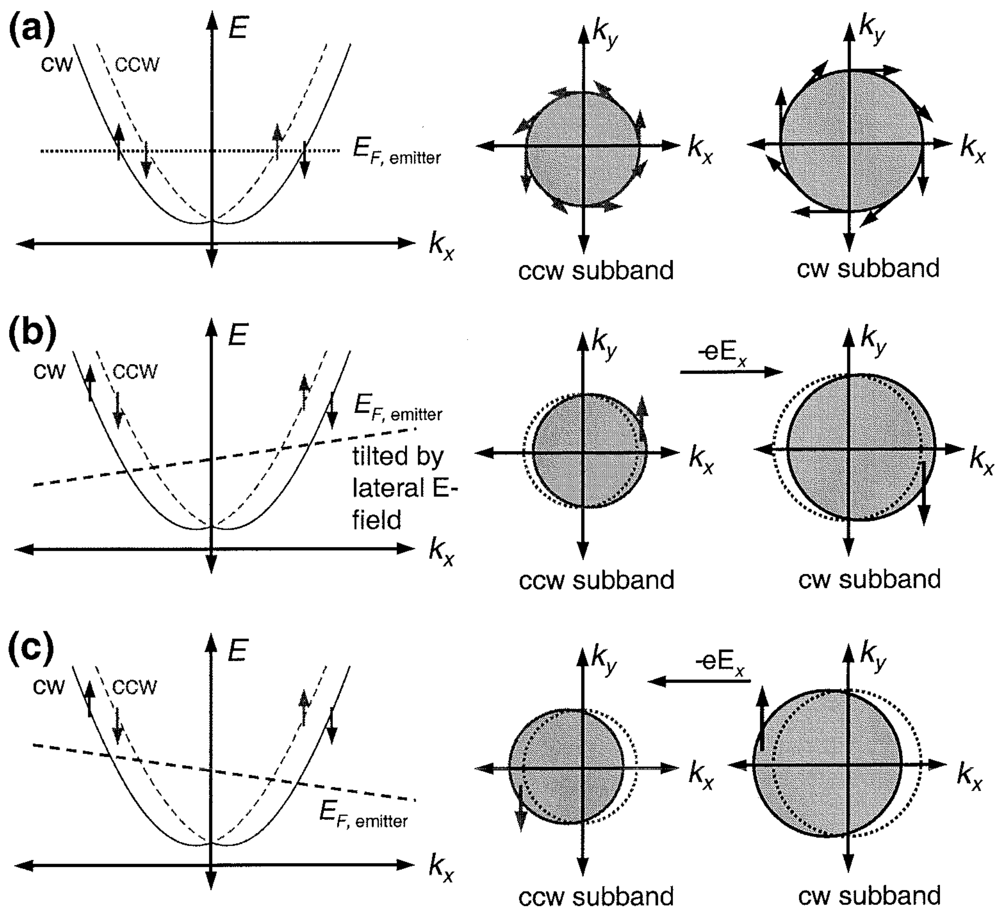

Figure 1. (a) Lowest conduction subband (cb1) in an asymmetric quantum well showing Rashba spin splitting. Available quasibound states in the cb1 with energy below the emitter Fermi level are shown as shaded disks in $\mathbf{k}_{\|}$-space. Arrows indicate spin directions. (b) Same as (a), but with the Fermi surface in the incidence electrode displaced by the application of a lateral E-field along the x direction. (c) Same as (b), but with the lateral E-field in the opposite direction, resulting in the opposite net spin polarization.

are plotted along the disk perimeters, they appear in counter-clockwise (ccw) and clockwise (cw) pinwheel patterns. Therefore we label the subbands "ccw" and "cw." Note that ccw and cw subband states at the same $\mathbf{k}_{\|}$ have opposite spins, and that states with opposite $\mathbf{k}_{\|}$ within a given subband have opposite spins. Thus, to achieve efficient spin filtering we must provide mechanisms for (1) preferentially selecting a particular spin-split subband, and (2) lateral momentum selection.

The subband filtering efficiency is defined as $\eta = (J_{ccw} - J_{cw})/(J_{ccw} + J_{cw})$, where J_{ccw} and J_{cw} are the resonant tunneling current density components associated with the ccw and cw subband tunneling, respectively. The subband filtering efficiency in the aRTS is typically limited by cancellation between the ccw and cw subband contributions. The strategy for optimizing η is to increase spin splitting, thereby enlarging the difference between ccw and cw contributions. One way to strengthen the selectivity between the ccw and cw subbands is to use the spin-blockade mechanism proposed by Koga *et al.* [3]. Their proposed device consists of a triple-barrier structure containing back-to-back asymmetric wells coupled through a thin central tunneling barrier. 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 wells are aligned (spin blockade). Either ccw-ccw or cw-cw alignment can be selected by the biasing voltage. This technique has resulted in a very high calculated subband filtering efficiency of $\eta > 99.9\%$ [3]. 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) [4]. The interband design uses large valence band spin-orbit interaction to provide strong spin selectivity, but does not leave the electrons in valence bands where spin relaxation is fast. Filtering efficiency is also enhanced by the reduction of tunneling through quasibound states near the zone center. Another interband device concept takes advantage of bulk inversion asymmetry (BIA) induced spin splitting in (110) devices to perform spin filtering [7].

Lateral momentum selection can be accomplished in several ways. Voskoboynikov *et al.* proposed using a small in-plane electric field in the source region of the aRTS to shift the incident electron distribution towards, say, the positive k_x side in k-space [2]. Figure 1(b) shows that a lateral E-field along the x direction 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 $-y$ current spin polarization. Note that, as indicated in Fig. 1(c), reversing the direction of the lateral E-field causes the collector current to be spin polarized in the opposite direction. Thus, it is possible to modulate the spin polarization by changing the direction of the lateral E-field. A variant lateral E-field scheme, proposed by Chow and Moon [5], uses lateral side-gates fabricated on the mesa sidewalls of the resonant tunneling structure. The side gates are electrically isolated from the mesa itself, and do not induce a lateral current in the emitter region. An alternative scheme for creating anisotropy in the lateral momentum distribution was proposed by Datta and co-workers [3]. It makes use of a one-sided collector, which is placed on, for example, the positive x side to collect only electrons with positive k_x. It can be shown that for the one-sided collector geometry, the net current spin polarization, $P = (J_{+y}-J_{-y})/(J_{+y}+J_{-y})$, where J_{+y} and J_{-y} are resonant tunneling current density components spin polarized along the positive and negative y directions, respectively, is related to the subband filtering efficiency in a simple manner: $P = (2/\pi)\eta$ [10]. This limits P to a theoretical maximum of $(2/\pi) \approx 63.7\%$ for the one-sided collector geometry.

A bi-directional spin-pump [6] is similar in structure to resonant tunneling spin filters. In the spin pump, we do not intentionally apply any bias along the growth (z) direction, but apply a small lateral E-field only in the emitter region. Consider a spin pump structure where the emitter and the collector are made from the same material and doped to equal carrier concentrations. The application of an in-plane E-field along the x direction displaces the emitter Fermi surface. 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. Assuming the spin filter structure is designed such that resonant tunneling through the cw states dominates over the ccw states at zero bias, then resonantly transmitted electrons on the $+k_x$ and $-k_x$ sides will be spin polarized along the $-y$ and $+y$ directions, respectively. This results in a forward (emitter to collector) electron (particle) current with $-y$ spin polarization, and a backward current with $+y$ spin polarization. The bi-directional spin pump induces the simultaneous flow of oppositely spin-polarized current components in opposite directions through spin-dependent resonant tunneling, and can thus generate significant levels of spin current with very little net electrical current across the tunnel structure, a condition characterized by a greater-than-unity current spin polarization.

The resonant tunneling spin filter and spin pump concepts were developed to exploit the Rashba effect [8], which is a consequence of spin–orbit interaction and the presence of structural inversion asymmetry (SIA). The effect on spins due to the presence of bulk inversion asymmetry (BIA) in zincblende semiconductors can also be exploited for spin device applications. It can be shown that the efficiency of nonmagnetic resonant tunneling spin devices can be improved significantly when SIA and BIA effects are combined properly [10]. The design changes required to take advantage of this improvement are minimal: we only need to be more specific in selecting the direction of one-sided collectors or the lateral E-field [10].

MODELING RESULTS

In this section we present spin filter modeling results, calculated using the multiband quantum transmitting boundary method [11], on an InAs-AlSb-InAs-GaSb-AlSb-InAs asymmetric resonant interband tunneling diode (aRITD). The left panel of Fig. 2 shows the results for the case with applied lateral *E*-field in the emitter. Three different E-field strengths (E_x=0, 33, and 67 V/cm) are used in this calculation. Spin polarized current density components J_{+y} and J_{-y} are shown in the top panel, and the current spin polarization in the bottom. As expected, no spin polarization is found for E_x=0. But significant spin polarization is found for E_x=33 and 67 V/cm for applied biases under 0.05 V. The reason that there is no current spin

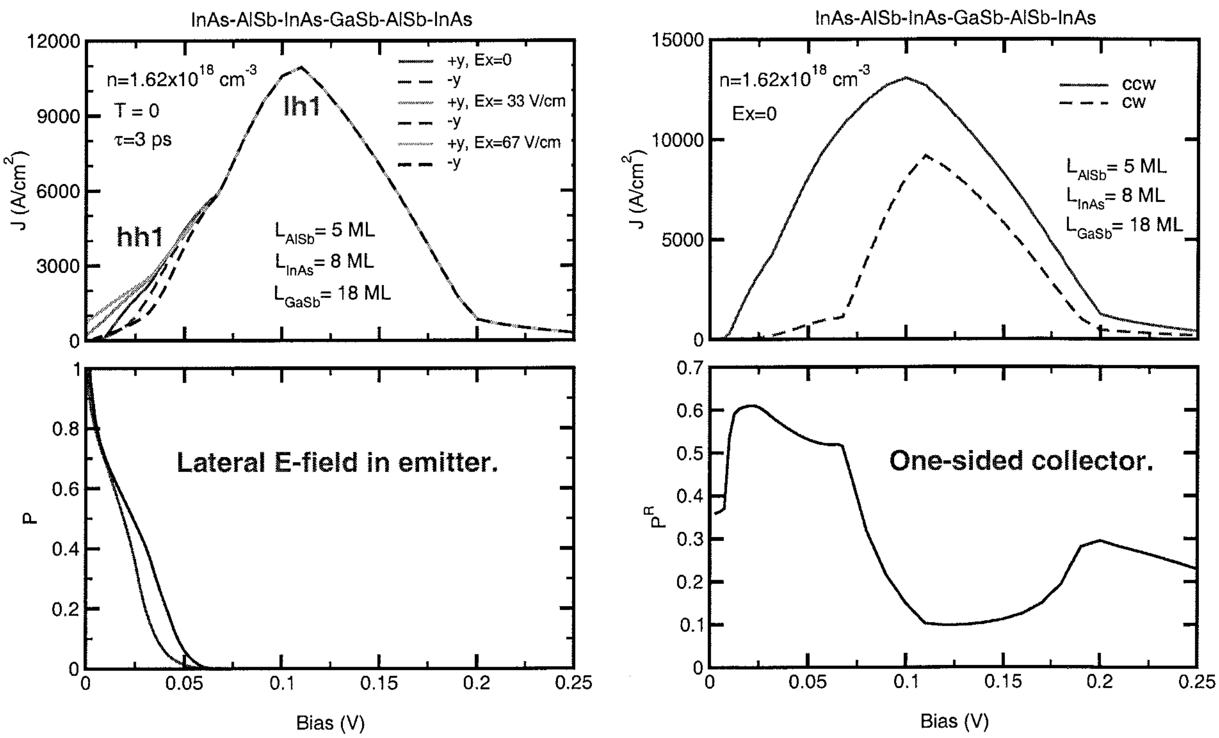

Figure 2. Calculated current density components (top) and current polarization efficiencies (bottom) in an aRITD, as functions of applied bias. The left and right panels show the results for the lateral E-field and the one-sided collector geometries, respectively.

polarization at the peak of the J-V curves near 0.11 V is because the peak is dominated by light-hole 1 (lh1) resonant tunneling. The lh1 tunneling process favors contributions from the zone-center, where Rashba spin splitting vanishes. At below 0.05V, heavy-hole 1 (hh1) tunneling dominates. Here the away-from-zone-center resonant tunneling processes, which show strong spin dependence, are favored. Note that as the applied bias approaches 0, the E_x=33 and 67 V/cm cases show collector current spin polarization greater than 1. This is a manifestation of the bi-directional spin pump effect [6]. The right panel of Fig. 2 shows the computed subband current densities J_{ccw} and J_{cw}, and one-sided collector current spin polarization P as functions of applied bias for the same aRITD. It shows that the aRITD can be a highly efficient spin filter, with P approaching the theoretical maximum of 63.7% at relatively large current density levels.

DISCUSSIONS

The concept of non-magnetic heterostructure spin filters is still being refined. Here we point out a few areas that are under development. A common assumption used in the resonant tunneling spin filter models thus far is coherent tunneling. This preserves the lateral momentum anisotropy during the resonant tunneling process, so that net spin polarization can be obtained in the collector. Coherent tunneling is more likely to occur when resonant tunneling lifetimes are shorter than typical scattering times in the quantum well. For the aRITD structure studied in Fig. 2, the typical tunneling lifetime is on the order of 10 ps. Studies in designing spin-dependent tunneling devices with shorter tunneling lifetimes are ongoing. There has been indirect evidence for the demonstration of coherent tunneling in large-current density resonant tunneling devices [12]. It should be noted that coherent tunneling is a sufficient, but not a necessary requirement for the resonant tunneling spin filter. More detailed studies of the dynamics of spin transport in resonant tunneling spin filters are needed for better understanding.

Another issue being study currently is the effect of higher order k terms. We have shown that BIA effects can be used to enhance spin filtering efficiencies using a model Hamiltonian that describes linear-in-k spin splitting for states near the zone center [10]. The recent work of Winkler points out that the quantum well state spin directions can be more complex when higher-order k terms are included [13], and we expect the higher-order k terms to have important effects for transport as well. These effects are being studied using a band structure model that incorporates BIA effects in the eight-band effective bond orbital model (BIA-EBOM) [14].

A salient feature of the non-magnetic semiconductor heterostructure spin devices is that they do not need magnetic elements (e.g. Mn), and are compatible with conventional semiconductor growth technology. This means that they can be grown, for instance, in the same molecular beam epitaxy machine that is used to grow lasers, detectors, or transistors. However, the need for lateral momentum selection means that they require sophisticated device design and processing technology, such as those used in the fabrication of the split side-gated resonant interband tunneling devices [15].

A resonant tunneling spin filter implemented using the lateral E-field geometry (including split side gate) offers us the ability to control the current spin polarizations electrically, as illustrated in Fig. 1(b) and 1(c). Therefore it is potentially amenable to high-speed spin modulation through electrical means, such as side-gate voltage modulation. A possible application for a spin polarized current source, capable of being modulated electrically at high speeds, is the electrically pumped spin VECSL [16]. In the "spin laser" light polarization follows modulation in injected carrier spin, and can carry information in both light polarization and intensity.

SUMMARY

We reported progress on the development of device concepts that exploit spin-orbit coupling for creating spin polarized current sources using nonmagnetic semiconductor resonant tunneling heterostructures, without external magnetic fields. These spin polarized current source are potentially capable of being modulated electrically at high speeds, and could be useful for spintronics and spin-optoelectronics applications.

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