Electrically Controlled Spin Device Concepts

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Abstract. We discuss spin device concepts that exploit spin-orbit coupling in nonmagnetic semiconductor heterostructures, including the resonant interband tunneling spin filter, the bi-directional spin pump, the bulk inversion asymmetry enhanced spin filter, and resonant spin lifetime devices.

INTRODUCTION

Spin degeneracy in non-magnetic semiconductor heterostructures results from time reversal and spatial inversion symmetries, and can be lifted by the presence of structural inversion asymmetry (SIA) or bulk inversion asymmetry (BIA). SIA- and BIA-induced spin splittings can be described by the Rashba effect [1] and the Dresselhaus term [2], respectively. They can be exploited to build spin devices using only non-magnetic semiconductor heterostructures, without external magnetic fields or optical excitation. In this paper we briefly describe two types of non-magnetic spin devices. The first uses resonant tunneling to filter spins, and can be used to create a source of spin polarized current. The second exploits the interplay between BIA and SIA to control spin lifetimes for device applications. The proposed devices are electrically controllable, potentially amenable to high-speed modulation and integration in optoelectronic devices for added functionality.

RESONANT TUNNELING DEVICES

The resonant tunneling spin filter idea originated with Voskoboynikov *et al.* [3]. It uses an asymmetric resonant tunneling structure in which quantized conduction subband states are spin split by the Rashba effect due to SIA, and relies on resonant tunneling for spin selection. Because Rashba spin split states in a given subband with opposite in-plane momenta have opposite spins, thus yielding no net spin upon subband averaging, a mechanism for lateral momentum selection such as lateral E-field in the emitter [3], one-sided collector [4], and side gating [5] is needed. Rashba spin splittings in the conduction subbands are typically small, and vanish at the zone center. Typical predicted spin filtering efficiencies in the original conduction band based designs are low, although a spin-blockade scheme could be used for improvement [4]. Below we describe additional device concepts.

Resonant Interband Tunneling Spin Filter

The asymmetric resonant interband tunneling diode (aRITD) [6,7] exploits large valence band spin-orbit interaction to provide strong spin selectivity while minimizing the effects of faster hole relaxation. Interband tunneling through the heavy-hole 1 (hh1) subband not only exhibits strong spin-dependent tunneling, but also eliminates tunneling through states near the zone center, where spin splitting vanishes. The spin-filtering efficiency of aRITD has been predicted to be significantly higher than in conduction subband resonant tunneling diodes [6]. A prototype side gated aRITD has been fabricated [5]. An RITD grown on [110] to take advantage of BIA spin splitting has also been proposed [8].

Bi-Directional Spin Pump

The bi-directional resonant tunneling spin pump [9] is similar in structure to resonant tunneling spin filters. In the spin pump, we do not intentionally apply any bias along the growth direction, but apply a small lateral *E*-field in the emitter region only. This results in a forward (emitter to collector) electron (particle) current with one spin polarization, and a backward current with the opposite spin polarization, due to the special properties of the spin filter. 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.

BIA Enhanced Spin Filter

The resonant tunneling spin filter and spin pump concepts were developed to exploit the Rashba effect [1], which is a consequence of spin–orbit interaction and the presence of SIA. The effect on spins due to the presence of BIA in zincblende semiconductors can also be exploited in spin devices. 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]. Best of all, the design changes required to take advantage of this improvement are minimal: we only need to be specific in selecting the direction of one-sided collectors or the lateral E-field [10].

RESONANT SPIN LIFETIME DEVICES

An interesting property arising from the interplay between SIA and BIA effects is that the D'yakonov-Perel' mechanism of spin relaxation becomes suppressed when $\alpha_{SIA}=\alpha_{BIA}$ [11], where α_{SIA} and α_{BIA} are coefficients describing the strengths of SIA and BIA effects respectively. This led us to the concept of a variant of the Datta-Das spin transistor [12] based on [001] grown structures called the resonant spin lifetime transistor (RSLT) [13]. 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 [14], and can be used in non-volatile memories and magnetic readout heads [13]. The RSLT may also be implemented in [110] grown structures, where BIA effects play a dominant role [8]. But perhaps best way to implement the RSLT is to use [111] grown heterostructures where, under the right conditions, the lowest-order-in-*k* component of the spin relaxation tensor can be made to vanish for *all* three spin components at the same time, in contrast to [001] or [110] devices where spin relaxation can be suppressed for one of the three spin components [15].

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