Non-magnetic semiconductor spin transistor

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We propose a spin transistor using only non-magnetic materials that exploits the characteristics of bulk inversion asymmetry (BIA) in (110) symmetric quantum wells. We show that extremely large spin splittings due to BIA are possible in (110) InAs/GaSb/AlSb heterostructures, which together with the enhanced spin decay times in (110) quantum wells demonstrates the potential for exploitation of BIA effects in semiconductor spintronics devices. Spin injection and detection is achieved using spin-dependent resonant interband tunneling and spin transistor action is realized through control of the electron spin lifetime in an InAs lateral transport channel using an applied electric field (Rashba effect). This device may also be used as a spin valve, or a magnetic field sensor. The electronic structure and spin relaxation times for the spin transistor proposed here are calculated using a nonperturbative 14-band $k \cdot p$ nanostructure model.

A number of semiconductor spintronic devices have been proposed in recent years that rely on the energy splitting between electron spin states arising from structural inversion asymmetry \cite{luo2000,garf1,ji2001,ji2002,ji2003} also known as the Rashba effect. Among these device concepts, those involving only non-magnetic materials are especially attractive for application to high-speed, spin-sensitive electronics, since they avoid the complex materials issues and unwanted stray magnetic fields associated with the incorporation of magnetic contacts, and because their operation relies on applied electric fields only, which may be modulated at considerably higher rates than magnetic fields. The 6.1-A lattice constant family of heterostructures (AlSb/GaSb/InAs) offers substantial advantages for such applications because of the high electron mobility of InAs and the extremely large spin splittings characteristic of these heterostructures \cite{lee2000,lee2000a,lee2000b}. However, in devices relying entirely on the Rashba effect, a tradeoff exists between the spin splitting and the spin relaxation time ($T_1$) due to the characteristics of the associated crystal magnetic field. In a III-V semiconductor heterostructure, the magnitude and direction of the wavevector-dependent crystal magnetic field determines the size of the spin splitting and the rate of spin relaxation through precessional decay \cite{ji2003,ji2003a}. The Rashba effective magnetic field lies in the plane of the heterostructure and perpendicular to the electron wavevector \cite{ji2001,ji2002,ji2003}. In this case, regardless of the choice of the non-equilibrium spin orientation to be used within a specific spintronics device, promising designs incorporating a large Rashba spin splitting will suffer from rapid precessional spin relaxation \cite{ji2003a}, placing serious limitations on feasible device architectures.

Here we propose a spin transistor using non-magnetic materials that exploits the unique characteristics of bulk inversion asymmetry (BIA) in (110)-oriented semiconductor heterostructures. Since the BIA crystal magnetic field in (110) symmetric quantum wells is oriented approximately in the growth direction for all electron wavevectors ($k$) \cite{ji2001,ji2002,ji2003} in devices based on such structures there is a natural choice of quantization axis for spin along which precessional spin relaxation is suppressed \cite{ji2003,ji2003a,ji2003b}. In the present work, we demonstrate that large BIA spin splittings are possible in (110) InAs/GaSb/AlSb heterostructures, exceeding reported Rashba spin splittings in this system \cite{ji2001,ji2002,ji2003,ji2003a} and in InGaAs/InAlAs heterostructures \cite{ji2003,ji2003a,ji2003b}. The device, which is depicted schematically in Fig. 1 (a), utilizes spin-dependent resonant interband tunneling (RIT) \cite{ji2003,ji2003a} in a (110) InAs/AlSb/GaSb/AlSb/InAs heterostructure.
The central feature exploited in the device proposed here is the structure of the BIA crystal magnetic field in (110) symmetric quantum wells. As shown in Fig. 1(b)-(c), the salient features of this field are: (i) it is oriented primarily in the growth direction; and (ii) for each spin subband, the carrier spin points in the opposite direction on either side of k-space (about the [00\overline{1}] axis). The calculated field in Fig. 1(b) corresponds to the first heavy hole subband (HH1) in the GaSb/AlSb quantum well within the proposed spin injector/detector, but these primary characteristics are reproduced by both valence and conduction states for any (110) III-V semiconductor quantum well. The crystal magnetic field in Fig. 1(b)-(c) differs fundamentally from the clockwise and counter-clockwise pinwheel structure associated with the Rashba effect, in contrast, for (110) symmetric heterostructures there is a natural choice of quantization axis for spin in the growth direction. In this case, the BIA crystal magnetic field lifts the degeneracy of the electron spin states but induces only very small precessional relaxation, resulting in long spin lifetimes. The strong enhancement of $T_1$ due to the near growth direction orientation of the BIA crystal magnetic field in (110)-oriented heterostructures was recently observed in GaAs/AlGaAs quantum wells and InAs/GaSb superlattices.

Electron spin injection in the proposed device is achieved through spin-dependent RIT. Resonant tunneling has been utilized in both magnetic2,3,4,5 and nonmagnetic2,3,4,5 spintronics device proposals in recent years. As shown in the inset of Fig. 2(a), electrons in the conduction band of the InAs emitter tunnel through the two HH1 spin states of the GaSb quantum well, whose degeneracy is lifted by BIA, to the InAs 2DEG lateral transport channel. Spin independent transport in similar RIT structures has been under investigation for more than a decade because of the advantages of the broken gap band alignment of the InAs/GaSb heterojunction for high speed electronic applications.5,6,7,8,9 The calculated HH1 spin splitting in the GaSb quantum well is shown in Fig. 2(a) for a range of well thicknesses. For thin GaSb layers, the BIA-induced spin splitting exceeds 30 meV, and is larger than that utilized in similar spin filter devices based on the Rashba effect.2,3,4,5 The spin splitting for the first conduction subband of the GaSb quantum well, which is not used in the present device, is $\leq 20$% smaller for the range of in-plane wavevectors shown and is considerably larger than the conduction band Rashba spin splitting in InGaAs/InAlAs heterostructures.8,16,17,22 These large spin splittings, which reflect the strong spin-orbit interaction in GaSb, would permit filtering of electron spins at room temperature with suitably designed emitter and collector regions.

Since the crystal magnetic field for each of the HH1 spin subbands reverses sign on either side of the [00\overline{1}] axis, net spin injection is achieved by applying a lateral bias along [110] using side gates across the InAs emitter, as depicted schematically in Fig. 1(a). The use of for both the generation and detection of spin-polarized electrons. Spin transistor action is realized through the application of an external electric field to a lateral transport channel formed by a high mobility, symmetric InAs two-dimensional electron gas (2DEG). The applied field reduces the spin relaxation time in the InAs quantum well through the electric field-induced Rashba effect6,8,16,17,18,19,22 yielding unpolarized carriers following lateral transport. The electronic structure and spin relaxation times for the spin transistor proposed here are calculated using a nonperturbative 14-band $k \cdot p$ nanostucture model in which BIA is included naturally to all orders of the electron wavevector.

![Graphical representation of spin filter and detector](image_url)
a lateral bias to generate spin-polarized current was described previously in analogous resonant tunnel spin filter devices employing the Rashba effect. 

Spin transistor action is achieved through control over the spin relaxation time in the 2DEG using the electric field-induced Rashba effect. The calculated $T_1$ for electrons in the (110) InAs/AlSb quantum well is shown in Fig. 3 as a function of the applied electric field. In the absence of the field, the precessional spin lifetime is extremely long because both the injected electron spins and the BIA crystal magnetic field are oriented primarily in the growth direction. For comparison, $T_1$ is more than 3 orders of magnitude smaller for the corresponding (001) InAs/AlSb quantum well, reflecting the in-plane orientation of the BIA magnetic field in (001) heterostructures. $T_1$ in (110) quantum wells is limited only by a very small, in-plane BIA magnetic field component that originates from contributions of higher than 3rd order in the electron wavevector. The applied electric field introduces structural inversion asymmetry that produces an in-plane Rashba magnetic field component, as shown in the inset to Fig. 3. This in-plane magnetic field induces rapid precessional relaxation of the growth-direction-polarized electron spins in the InAs 2DEG, thereby preventing detection at the final RIT spin filter. Because of the strong spin-orbit interaction in the AlSb barriers and the small band gap of the type II InAs/AlSb quantum well, the application of a relatively weak electric field leads to a sharp decrease in spin lifetime: $T_1$ falls by more than 2 orders of magnitude for $E < 5$ kV/cm. This pronounced sensitivity of $T_1$ to the applied field may permit operation of the spin transistor proposed here with a low threshold gate voltage, representing a likely advantage over conventional transistor technology. It should be noted that the gate voltage only controls the spin decay rate associated with precessional relaxation, which is known to dominate in most III-V semiconductors (including InAs/GaSb/AlSb heterostructures) above 77 K. The residual relaxation rate due to other processes

Spin-dependent resonant tunneling in a second GaSb quantum well (see Fig. 1(a)) is used for detection of spin-polarized electrons following lateral transport in the InAs 2DEG channel. As shown in Fig. 2(d), as long as a net spin polarization persists in the 2DEG at the second RIT structure, and the range of energies between the fermi levels of the minority and majority spin electrons is in resonance with the BIA-split spin levels of the GaSb quantum well (a condition which may be controlled through appropriate choice of doping level in the 2DEG channel) a ballistic lateral current will be generated in the final InAs collector due to the preferential tunneling of spins on one side of k-space relative to the [001] direction. In the steady state, this ballistic current will be detected as a voltage at the side gates across the collector. The polarity of this voltage indicates the orientation of the initial spin polarization in the 2DEG. If no spin polarization survives following transport in the 2DEG, the tunnel current will have equal contributions on both sides of k-space, producing no voltage across the collector side gates. As this spin detection scheme relies only on a difference in population between the two spin states, it does not require ballistic transport in the InAs 2DEG channel.
that may become important with the strong suppression of precessional relaxation in this (110) 2DEG (such as the Elliott-Yafet mechanism\textsuperscript{27,28}) will ultimately determine the requirements for the lateral dimension of the 2DEG transport channel and the minimum applied field required to produce the spin transistor action in the device proposed here.

In summary, we have proposed a non-magnetic semiconductor spin transistor that utilizes the characteristics of BIA effects in (110) III-V semiconductor quantum wells. Our demonstration that extremely large spin splittings associated with BIA in 6.1 Å semiconductor heterostructures are possible, together with the long spin lifetimes we calculate for these structures, illustrates the strong potential for applications of BIA in a wide range of (110) semiconductor spintronics device concepts. For example, because of the growth direction orientation of the electron spins in such structures, vertical emission spin-polarized light-emitting diodes\textsuperscript{33} may be realized based on BIA-mediated resonant tunneling spin filters such as that proposed here. A non-magnetic semiconductor spin valve may also be realized using a device similar to that in Fig. 1(a)\textsuperscript{30}, in which the resistivity between the source and drain is controlled by the relative polarity of a bias applied to the side contacts of the injection and detection RIT structures. Due to the large g factor in InAs, the present device may also find application as a magnetic field sensor, in which the phase of coherent spin precession of electrons in the InAs channel in the presence of an external B field would be indicated by the magnitude and polarity of the voltage measured at the collector RIT. We estimate that a magnetic field as low as a few gauss may be measurable using such a device.

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