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Nonmagnetic semiconductor spin transistor

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We propose a spin transistor using only nonmagnetic 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. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1609656]

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,[1–5] also known as the Rashba effect.[6] Among these device concepts, those involving only *nonmagnetic* materials are especially attractive 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 Å lattice constant family of heterostructures (AlSb/GaSb/InAs) offers substantial advantages for such applications because of the high electron mobility of InAs and the large spin splittings characteristic of these heterostructures.[5,7,8] 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 characteristics of the associated crystal magnetic field. In a III–V semiconductor heterostructure, the magnitude and direction of the wave vector-dependent crystal magnetic field determines the size of the spin splitting and the rate of spin relaxation through precessional decay.[9,10] The Rashba effective magnetic field lies in the plane of the heterostructure and perpendicular to the electron wave vector.[5–7] In this case, regardless of the choice of the nonequilibrium spin orientation to be used within a specific spintronics device, promising designs that incorporate a large Rashba spin splitting will suffer from rapid precessional spin relaxation,[11] placing serious limitations on feasible device architectures.

Here we propose a spin transistor using nonmagnetic 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 wave vectors (**k**),[12] in devices based on such structures there is a natural choice of quantization axis for spin along which precessional spin relaxation is suppressed.[12–14] 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[7,15] and in InGaAs/InAlAs heterostructures.[8,16,17] The device, which is depicted schematically in Fig. 1(a), utilizes spin-dependent resonant interband tunneling (RIT)[5,18] in a (110) InAs/AlSb/GaSb heterostructure 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 symmetric InAs two-dimensional electron gas (2DEG) between the injector and detector, which reduces the spin relaxation time through the Rashba effect[6,8,15–17,19] yielding unpolarized carriers following lateral transport. The electronic structure and spin relaxation times are calculated using a nonperturbative 14-band **k·p** nanostructure model,[9] in which BIA is included naturally to all orders of the electron wave vector.

The central feature exploited in this device is the structure of the BIA crystal magnetic field in (110) symmetric

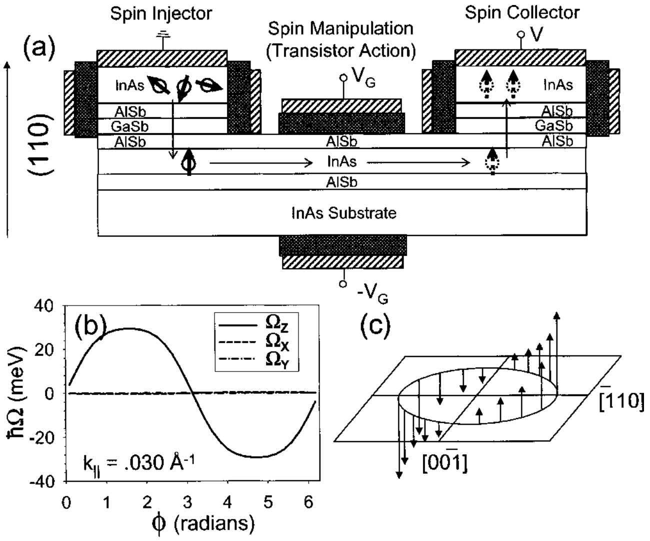

FIG. 1. (a) Schematic diagram of a nonmagnetic semiconductor spin transistor. (b) Calculated crystal magnetic field for HH1 in the GaSb/AlSb quantum well for an in-plane electron wave vector ($\mathbf{k}_{\parallel}$) of 0.03 Å^{-1} vs angle (ϕ). $\phi = 0$ corresponds to the $[00\bar{1}]$ direction. (c) Schematic diagram of the calculated field in (b).

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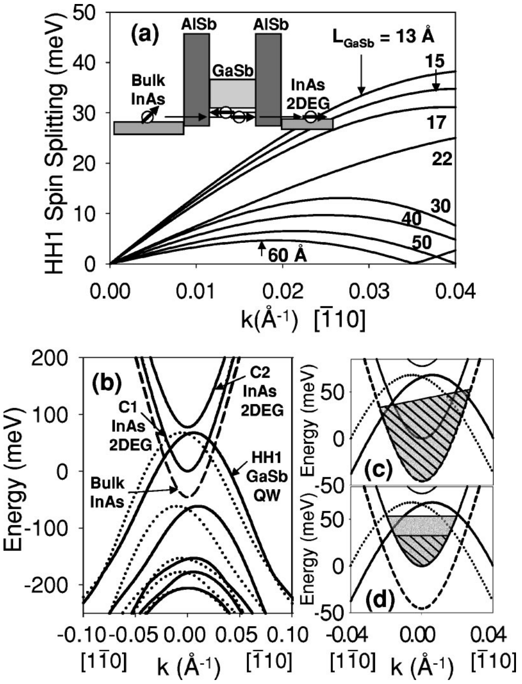

FIG. 2. Spin filter and detector based on RIT in an InAs/AlSb/GaSb heterostructure. (a) Calculated HH1 spin splitting in the GaSb/AlSb quantum well vs well thickness ($L_{\mathrm{AlSb}}=60$ Å). (b) Overlay of the band structure of the 13 Å GaSb/AlSb quantum well, the bulk InAs emitter, and the 215 Å InAs/AlSb 2DEG. For the GaSb quantum well, spin states oriented with $+z$ ($-z$) are indicated by the dotted (solid) curves. States involved in resonant tunneling, under conditions of (c) spin injection and (d) spin detection. $+z(-z)$ polarized electrons are indicated by the shaded (diagonal striped) region. ($+z=[110]$).

quantum wells. As shown in Figs. 1(b) and 1(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 $[00\bar{1}]$ axis). These primary characteristics are reproduced by both valence and conduction states in the vicinity of $\mathbf{k}=0$ for any (110) III–V semiconductor quantum well. (For the GaSb/AlSb quantum well, these characteristics are maintained for in-plane wavevectors beyond $0.1\,\text{Å}^{-1}$.) The crystal magnetic field in Figs. 1(b) and 1(c) differs fundamentally from the Rashba field[5–7] since for (110) symmetric heterostructures there is a natural choice of quantization axis for spin in the growth direction. In this case, the BIA 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 in (110)-oriented heterostructures was recently observed in GaAs/AlGaAs quantum wells[13] and InAs/GaSb superlattices.[14]

Electron spin injection in the proposed device is achieved through spin-dependent RIT.[5,18] Resonant tunneling has been utilized in both magnetic[20,21] and nonmagnetic[2–5] 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. The calculated HH1 spin splitting in the GaSb quantum well is shown in Fig. 2(a). For thin GaSb layers, this spin splitting exceeds 30 meV. (The spin splitting for the first conduction subband of the GaSb quantum well, which is not used in the present device, is $\leqslant 20\%$ smaller and is considerably larger than the conduction band Rashba spin splitting in InGaAs/InAlAs heterostructures.[8,16,17]) These large spin splittings, which reflect the strong spin–orbit interaction in GaSb, would permit filtering of electron spins at room temperature.

Since the crystal magnetic field for each of the HH1 spin subbands reverses sign on either side of the $[00\bar{1}]$ axis, net spin injection is achieved by applying a lateral bias[2,5] along $[\bar{1}10]$ using side gates across the InAs emitter. This situation is depicted in Figs. 2(b)–2(d). The spin of electrons that resonantly tunnel from the bulk InAs emitter to the InAs 2DEG will be aligned with the resonant states in the quantum well,[2,3,5] i.e., in the $\pm z$ direction ($+z=[110]$). As shown in Fig. 2(c), under the application of a lateral bias to the bulk InAs emitter, the requirements of conservation of energy and in-plane momentum for the tunneling electrons lead to the dominance of tunnel current that involves electrons of one spin ($+z$ is shown; the direction of spin polarization is determined by the polarity of the lateral bias). The situation in Fig. 2(c) corresponds to 100% spin-polarized injection, leading to a partially spin-polarized distribution in the lightly doped ($N_d=1\times10^{17}\,\mathrm{cm}^{-3}$; Fermi energy 30 meV) InAs 2DEG channel. Spin-dependent RIT is also used for detection of spin-polarized electrons. As shown in Fig. 2(d), a net spin polarization in the 2DEG produces a ballistic lateral current in the collector due to the preferential tunneling of spins on one side of **k** space relative to the $[00\bar{1}]$ direction, thereby generating a voltage at the side gates across the collector. (This occurs if the range of energies between the Fermi levels of the minority and majority spin electrons is in resonance with the BIA-split levels of the GaSb quantum well, realized through appropriate choice of doping level in the 2DEG.) The polarity of this voltage indicates the orientation of the 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, and produce no voltage across the collector side gates. Because 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.

Spin transistor action is achieved through control over the spin relaxation time in the 2DEG using the electric field-induced Rashba effect.[6,8,15–17,19] T_1 for electrons in the (110) InAs/AlSb quantum well is shown in Fig. 3 vs. electric field strength (E). For $E=0$, T_1 is extremely long because both the injected electron spins and the BIA crystal magnetic field are oriented primarily in the growth direction. [T_1 in (110) quantum wells is limited only by a small, in-plane BIA magnetic field component due to contributions of higher than third order in the electron wave vector.] For comparison, T_1 is more than three orders of magnitude smaller for the corresponding (001) InAs/AlSb quantum well, thus reflecting the in-plane orientation of the BIA magnetic field in (001) heterostructures. The electric field applied introduces structural inversion asymmetry that produces an in-plane Rashba magnetic field component,[19] as shown in the inset of Fig. 3. This in-plane magnetic field induces rapid precessional relaxation of the growth-direction-polarized electron spins in

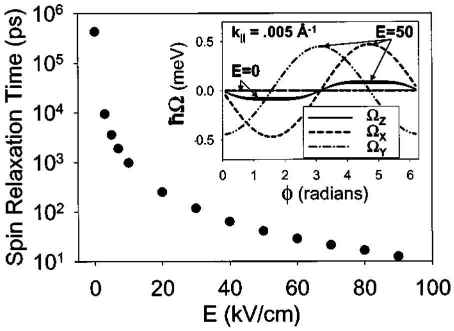

FIG. 3. Calculated T_1 in the (110) InAs/AlSb 2DEG vs growth direction electric field (E) at 77 K. A momentum relaxation time of 100 fs was assumed. Inset: Calculated crystal magnetic field for applied fields of $E=0$ and 50 kV/cm.

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, T_1 falls by more than two orders of magnitude for a small applied field ($E < 5$ kV/cm). This feature will likely lead to a much lower threshold gate voltage compared to conventional transistor technology. We note that the gate voltage only controls the spin decay rate associated with precessional relaxation, which dominates in (001) III–V semiconductors[9,22–25] above 77 K. The residual relaxation rate due to other processes that may become important with the strong suppression of precessional relaxation in this (110) 2DEG (such as the Elliott–Yafet mechanism[26,27]) will ultimately determine the requirements for the lateral dimension of the 2DEG transport channel and the threshold applied field.

In summary, we have proposed a nonmagnetic 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[28] may be realized based on a BIA-mediated resonant tunneling spin filter such as that proposed here. A nonmagnetic semiconductor spin valve may also be realized 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.[29] Due to the large g factor in InAs, this device may also find application as a sensitive magnetic field sensor, able to detect fields as low as a few gauss. In this case the phase of coherent spin precession of electrons in the InAs channel is indicated by the magnitude and polarity of the voltage measured at the collector RIT.

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