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Room-temperature electric-field controlled spin dynamics in (110) InAs quantum wells

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We report the demonstration of room temperature gate control over the electron spin dynamics using the Rashba effect in a (110) InAs/AlSb two-dimensional electron gas. Our calculations predict that the strong spin–orbit interaction in this system produces pseudomagnetic fields exceeding 1 T when only 140 mV is applied across a single quantum well. Using this large pseudomagnetic field, we demonstrate low-power spin manipulation on a picosecond time scale. Our findings are promising for the prospect of nonmagnetic low-power, high-speed spintronics. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1929082]

The prospect of semiconductor-based electronic technologies that would exploit electron spin[1,2] has stimulated considerable research effort in recent years into the spin-related properties of semiconductor materials.[2–18] An essential ingredient for such technologies will be fast, low-power control over the electron spin state in the semiconductor. Spin manipulation schemes that do not require an external magnetic field are attractive for integration into existing semiconductor technologies because they eliminate the need to control stray magnetic fields or to manage the complex materials issues associated with the incorporation of magnetic contacts.

One promising approach to nonmagnetic spin control is to exploit the Rashba effect,[19] by which an electric field applied with a conventional gate contact is experienced by the electron spins as an effective magnetic field through the spin–orbit interaction. The torque from this controllable pseudomagnetic field may be used to modify the electron spin state within the semiconductor. The Rasbha effect is utilized in a wide array of spintronic device concepts[3–6,20] including several proposals for a spin field effect transistor (spin FET).[3,4,20] In a spin FET, the spin state of electrons is modified as they move between source and drain contacts. In these applications, a large pseudomagnetic field is desirable due to the short carrier transport time. The Rashba contribution to the electron spin splitting has been observed in a variety of systems[8–11] and the influence of the Rashba pseudomagnetic fields on the electron spin relaxation time in GaAs quantum wells was recently investigated.[12,13]

In this letter, we report the demonstration of room temperature gate control over the electron spin dynamics using the Rashba effect in (110) InAs/AlSb quantum wells. Our results indicate that, due to the strong spin-orbit effects in the InAs/AlSb system, the electron spin may be manipulated on a picosecond time scale with a very low applied voltage (140 mV for a single quantum well). Using a 14-band $\mathbf{k}\cdot\mathbf{p}$ nanostructure model,[14,15] we calculate momentum-dependent pseudomagnetic fields of 1.1 T at this bias value. Our measured bias-dependent spin lifetimes are in good agreement with our calculated lifetimes, and suggest that nonuniform built-in fields limit the dynamics at zero bias in our structures. Our findings are promising for the development of fast, low-power spintronic devices.

Time-resolved measurements of electron spin dynamics in biased (110) quantum wells provide a sensitive tool to study nonmagnetic spin manipulation using the Rashba effect. This sensitivity derives from the structure of the pseudomagnetic fields, which are generated by the spin–orbit interaction in the presence of electric fields that destroy the inversion symmetry of the crystal. These pseudomagnetic fields are caused by: (i) the internal electric fields associated with the polar bonds in III–V semiconductors, often referred to as bulk inversion asymmetry (BIA); and (ii) extrinsic electric fields introduced through asymmetric layer growth or the application of an electric bias to a gate above the semiconductor quantum well (Rashba effect).[2,14,22] In the special case of (110)-oriented quantum wells, the BIA pseudomagnetic field is approximately in the growth direction for all electron wave vectors, providing a natural quantization axis for electron spin.[21] In the absence of Rashba effects, this preferred quantization axis leads to suppression of precessional spin relaxation for spins aligned with the growth direction.[16,17,21] In contrast, the Rashba contribution to the pseudomagnetic field lies in the plane of the quantum well with no single orientation, and therefore leads to rapid spin relaxation by inducing precession of growth direction-oriented spins. Since the Rashba effects strongly dominate spin relaxation in this case, one gains considerable insight into these effects through studies of spin relaxation kinetics in biased (110) quantum wells.

The InAs/AlSb quantum wells (InAs: 215 Å, AlSb: 200 Å) were grown by molecular beam epitaxy on an *n*-type (10^{16} cm^{-3}) (110)-oriented GaSb substrate [(±)0.1°] in a Fisons VG-80 machine equipped with shuttered EPI group-III evaporators and shuttered EPI valved group-V cracker cells. To provide a sufficient optical response for pump probe

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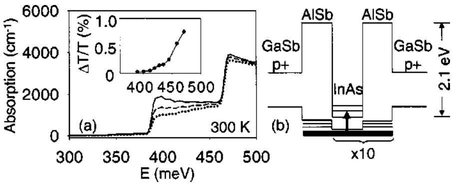

FIG. 1. (a) Calculated absorption spectrum at 300 K of the InAs/AlSb quantum well without optical excitation (solid curve), and for a pump-injected carrier density of 5×10^{16} cm^{-3} (dashed curve), and 1×10^{17} cm^{-3} (dotted curve). Inset: Measured differential transmission spectrum at zero delay, under excitation with 800 nm pulses and probing with a tunable mid-IR pulse (2.63–3.18 μm) at 300 K; (b) band edge diagram of the InAs/AlSb quantum wells, showing the type II band alignment. The optical transition corresponding to the absorption edge in (a) is indicated by the vertical arrow.

experiments, multiple quantum wells were grown (one sample with 10 and one with 20 periods), with 1000 Å p-doped (10^{19} cm^{-3}) GaSb layers grown above and below the quantum wells. The thick AlSb barrier layers and the large conduction band offset between InAs and AlSb (direct offset: 2.1 eV; indirect offset: 1.4 eV) ensure that electrons remain confined in the quantum wells under the full range of bias values used in these experiments. The carrier recombination time measured using pump–probe techniques was 2–3 ns, indicating good quality quantum well growth. For bias-dependent spin relaxation measurements, the quantum wells were processed into square, 100 μm mesas. After patterning with photoresist, the InAs/AlSb quantum well layers were removed using a combination of wet and dry etching, followed by deposition of a nitride dielectric. Contact to the doped GaSb layers was made through vias etched into the nitride layer. The ring-shaped top contact provided optical access to the quantum wells. The processed wafer was epoxied to a sapphire window prior to wire bonding the mesas.

Our calculations of the quantum well absorption spectrum [Fig. 1(a)] indicate that absorption at the fundamental band gap in these quantum wells is negligible due to the low overlap between the electron and hole wave functions associated with the type II band alignment of the InAs/AlSb system. Absorption becomes significant only for photon energies accessing the hole continuum states above the hole barriers in InAs. The experiments were therefore performed under excitation from the hole continuum states to the first conduction subband, as depicted in Fig. 1(b). Results of nondegenerate pump–probe experiments to measure the onset of absorption into the hole continuum are shown in the inset of Fig. 1(a), indicating a small shift of ~60 meV to higher energies relative to theory.

The electron spin dynamics were measured using femtosecond polarization-resolved differential transmission experiments involving 200 fs, 2.5 μm pulses from a tunable mid-IR optical parametric oscillator.[17] The polarization state of the probe pulse was varied between left and right circular at 56 kHz using a photoelastic modulator, and the resulting spin-dependent modulation in the probe transmission was detected using a liquid N_2-cooled InSb detector and a lock-in amplifier. Spatial alignment of the mid-IR pump and probe beams onto the mesa was achieved using a 50 μm pinhole and InSb detectors for spatial overlap, together with a collinear visible alignment laser and a video microscope. The focal spot of the pump (probe) beam had a diameter of 50 μm (40 μm), and the optically injected carrier density was 10^{17} cm^{-3}.

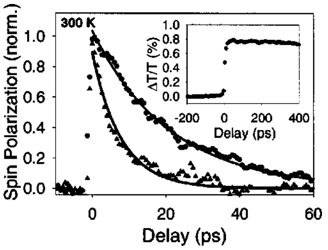

FIG. 2. Measured spin polarization vs time delay between pump and probe pulses at 300 K with no bias (circles) and with an applied bias of 140 mV per quantum well (triangles). Solid curves show single exponential fits to the data, with spin lifetime values of 27 and 8 ps, respectively. Inset: differential transmission for linearly polarized excitation.

The room temperature bias-dependent electron spin dynamics are shown in Figs. 2 and 3. The differential transmission signal under linearly polarized excitation is shown in the inset of Fig. 2, indicating the long carrier recombination time in these quantum wells.[23] The data are shown normalized to the degree of circular polarization at zero delay for clarity: the initial degree of circular polarization is 20% ± 5% for all bias conditions, indicating that the selection rules for optical excitation above the hole continuum are similar to bulk InAs.[18] The spin lifetime is shown as a function of bias voltage in Fig. 3(a), indicating a reduction by more than 70% (to below 10 ps) with the application of a modest electric field of 50 kV/cm, corresponding to a single quantum well bias of 140 mV. As the InAs/AlSb multiple quantum well structure is nominally symmetric, the spin lifetime is expected to be reduced at both positive and negative voltages because only the magnitude of the in-plane component of the pseudomagnetic field (induced by the bias voltage) determines the spin relaxation time in these (110)-oriented quantum wells,[2,13,17] in agreement with the results in Fig. 3(a). However, the asymmetric shape of the spin lifetime data versus applied bias indicates that there are unintentional built-in fields within the structure. The data in Figs. 2 and 3, which were found to be reproducible over multiple cycles of the bias voltage, were taken in the sample containing ten periods of the multiple quantum well. Results for a 20 period structure were similar. These findings demonstrate that we are able to control electron spin through the Rashba effect at room temperature in these InAs/AlSb quantum wells on a picosecond time scale with a low applied voltage.

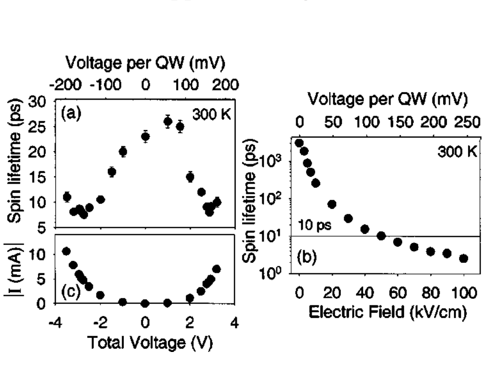

FIG. 3. (a) Measured bias dependence of the spin relaxation time in a (110) InAs/AlSb multiple quantum well at 300 K; (b) theoretical spin lifetimes vs bias calculated using a 14-band nonperturbative $\mathbf{k}\cdot\mathbf{p}$ nanostructure model; (c) hole photocurrent vs applied bias under the same conditions as the data in (a).

The calculated bias dependent spin lifetimes in the InAs/AlSb quantum wells are shown in Fig. 3(b). Our theoretical calculations give good agreement with the experimental voltage required to switch the spin lifetime below 10 ps. A further reduction in spin lifetime is predicted for larger bias values, which is desirable for a spin FET application to provide a high drive current with a minimal channel length.[3] Due to the type-II band alignment of the InAs/AlSb quantum wells [Fig. 1(b)], our spin lifetime measurements were limited to voltages smaller than 200 mV per quantum well due to excessive photocurrent mediated by optically injected holes.[24] This is a limitation of the optical technique used here to study the Rashba effect, and will not affect a spintronic device application relying on *electron* spin transport. We note that the absence of a correlation between the size of the hole photocurrent [Fig. 3(c)] and the spin relaxation time at large bias values indicates that sample heating does not play an important role in our experiments. Our theory predicts a much longer lifetime at zero bias voltage than the maximum observed value in Fig. 3(a) of ~30 ps. We attribute this discrepancy to nonuniform built-in electric fields within the thick (~400 nm) multiple quantum well structure, which was employed to provide a sufficient optical response for pump probe studies. As shown in Fig. 3(b), a nonuniform built-in electric field with an average of 70 mV per quantum well would be sufficient to account for the experimentally observed lifetime. This value is also consistent with the asymmetry in the data of Fig. 3(a). Such built-in electric fields would be much easier to control in a device application in which the spin transport channel would be a single quantum well.

The high sensitivity of the spin relaxation time to the applied electric field is due to the large Rashba effect in the InAs/AlSb quantum well, which arises from the small band gap and strong spin-orbit interaction in this material system. In this case, a large in-plane pseudomagnetic field may be induced with a small applied voltage. For example, for the InAs/AlSb quantum well investigated in this work, our electronic structure calculations indicate that the pseudomagnetic field induced by a gate voltage of 140 mV for a single quantum well for carriers at the fermi energy (30 meV) is 1.1 T.[25] This extremely large pseudomagnetic field has allowed us to switch the spin lifetime in the InAs/AlSb quantum wells below time scales relevant for spin transport in a spin FET ($\leqslant$10 ps) at a practical temperature for device operation (300 K). For comparison, in recent studies of spin relaxation in (110) GaAs quantum wells,[13] approximately twice the applied electric field was required to reduce the spin lifetime to 80 ps, reflecting the much weaker spin-orbit effects in GaAs heterostructures. The large gate-controlled Rashba effect we have observed is promising for developing low-power, high speed spintronic devices. For example, for the nonmagnetic spin transistor recently proposed,[3] our findings suggest that high-speed spin transistor operation will be possible at a much lower threshold voltage than conventional CMOS technology.[26]

In summary, we have demonstrated room temperature gate control over the electron spin dynamics using the Rashba effect in a (110) InAs/AlSb multiple quantum well. Due to the strong spin–orbit interaction and low band gap in the InAs/AlSb system, large pseudomagnetic fields ~1 T may be induced with a low applied voltage (140 mV for a single quantum well). Using this large pseudomagnetic field, we have demonstrated low-power spin manipulation on a picosecond time scale. Our findings support the implementation of nonmagnetic spin control using a conventional gate contact in low-power, high-speed spintronic devices.

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[22] In superlattices involving semiconductors with no common atom, the interface bonding is another source of asymmetry, however, it does not contribute to an in-plane pseudomagnetic field in (110)-oriented quantum wells.

[23] Recombination time is ~1 ns with and without a bias applied to the quantum wells.

[24] Although high electron barriers (~2 eV) prevent electron transport in the growth direction for optical excitation above the hole continuum in these type II quantum wells, holes are free to conduct.

[25] A g-factor of 15 in the InAs quantum well was assumed. The growth direction BIA pseudomagnetic field component is calculated to be 0.5 T, and only depends weakly on applied bias.

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