VOLUME 91, NUMBER 24 PHYSICAL REVIEW LETTERS week ending 12 DECEMBER 2003

High Temperature Gate Control of Quantum Well Spin Memory

O. Z. Karimov, G. H. John, and R. T. Harley
School of Physics and Astronomy, University of Southampton, Southampton, SO17 1BJ, United Kingdom

W. H. Lau and M. E. Flatté
Department of Physics and Astronomy, University of Iowa, Iowa City, Iowa 52242, USA

M. Henini
School of Physics and Astronomy, University of Nottingham, Nottingham NG7 2RD, United Kingdom

R. Airey
EPSRC Central Facility for III-V Semiconductors, Department of Electronic and Electrical Engineering,
University of Sheffield, Sheffield S1 3JD, United Kingdom

(Received 12 May 2003; published 10 December 2003)

Time-resolved optical measurements in (110)-oriented GaAs/AlGaAs quantum wells show a tenfold increase of the spin-relaxation rate as a function of applied electric field from 20 to 80 kV cm^{-1} at 170 K and indicate a similar variation at 300 K, in agreement with calculations based on the Rashba effect. Spin relaxation is almost field independent below 20 kV cm^{-1} reflecting quantum well interface asymmetry. The results indicate the achievability of a voltage-gateable spin-memory time longer than 3 ns simultaneously with a high electron mobility.

DOI: 10.1103/PhysRevLett.91.246601 PACS numbers: 72.25.Fe, 72.25.Rb, 78.47.+p

The longest possible spin memory and an ability to control the orientation or relaxation of nonequilibrium spin populations in semiconductor quantum wells (QWs) via an applied gate voltage will be the key to many spintronic applications. Recent experiments on (110)-oriented III-V QWs have demonstrated a predicted [1,2] dramatic increase of spin memory at room temperature, up to 20 ns in an *n*-type GaAs/AlGaAs QW [3], but although various possible approaches exist, gate control has hitherto been more elusive. The dependence of carrier spin-relaxation rates on gate-injected electron or hole concentration in QWs has been investigated by optical techniques [4,5]. A second approach exploits the electric field dependence of the electron g factor in parabolic potential wells to control spin precession in an applied magnetic field [6]. Similarly gated ferromagnetism in transition-metal-doped III-V's [7] may allow control of spin orientation without an applied magnetic field. A third proposal is to manipulate the conduction band spin splitting by an applied electric field through the Rashba effect [8]. This permits gate control of the exponential spin relaxation at high temperatures where electrons experience strong scattering, the so-called collision-dominated regime [9], or even coherent spin reorientation under collision-free conditions at very low temperatures [10]. For the collision-dominated case this last approach has the strong advantage of applicability at room temperature.

In this Letter we report a time-resolved optical investigation of electron spin relaxation at high temperatures in undoped (110)-oriented GaAs/AlGaAs QWs. We confirm the existence of a hundredfold increase of spin memory compared to (001)-oriented QWs at 300 K [1] but we now demonstrate a tenfold variation of the spin-relaxation rate with the application of a modest electric field. This is in accord with theoretical expectations [9] for the Rashba effect and strongly indicates the mechanism which currently limits the spin memory in (110)-oriented samples in zero field.

The spin relaxation in our experiments can be interpreted on the basis of the D'yakonov-Perel'-Kachorovskii (DPK) [2,11] mechanism of spin relaxation, as refined in a nonperturbative approach [9,12,13], which dominates zero-field spin dynamics in GaAs/AlGaAs QW systems [13–16]. In this model, spin reorientation is driven by precession of the individual electron spin vectors induced by the effective magnetic field represented by the conduction band spin splitting, which results from spin-orbit coupling and lack of inversion symmetry. The corresponding Larmor precession vector $\mathbf{\Omega}(\mathbf{k})$ varies in magnitude and direction according to the electron's wave vector $\mathbf{k}$ so that scattering results in a randomly fluctuating precession vector [2,11,17]. In the collision-dominated regime, $\langle|\mathbf{\Omega}|\rangle\tau_p^* \ll 1$ with $\langle|\mathbf{\Omega}|\rangle$ the average precession frequency and τ_p^* the momentum scattering time of an electron, spin relaxation is slowed by scattering and has rate [2,11,13]

$$\tau_s^{-1} = \langle\Omega^2\rangle\tau_p^*. \tag{1}$$

The first factor in this expression is determined by the vector $\mathbf{\Omega}$, which, in a QW, has three contributions, $\mathbf{\Omega}^{\mathrm{SIA}}$, $\mathbf{\Omega}^{\mathrm{BIA}}$, and $\mathbf{\Omega}^{\mathrm{NIA}}$ [13]. The natural interface asymmetry component $\mathbf{\Omega}^{\mathrm{NIA}}$ does not occur in GaAs/AlGaAs QWs and is not considered further here. The most interesting for gating spin relaxation is $\mathbf{\Omega}^{\mathrm{SIA}}$, the Rashba or structural inversion asymmetry (SIA) term. It may arise from some built-in asymmetry of the structure or be induced by an externally applied odd parity perturbation such as an electric field. For field $\mathbf{E}_z$ along the growth axis (z) it has the form $(\mathbf{E}_z \times \mathbf{k})$ [8,13] and so is oriented in the QW plane for all in-plane $\mathbf{k}$. This induces precession of the electron spin away from the z axis and therefore contributes a term to DPK spin relaxation along the axis, which can be varied with applied electric field [9]. However, except in (110)-oriented QWs the effect will be small because $\mathbf{\Omega}^{\mathrm{BIA}}$, which is due to bulk inversion asymmetry (BIA) of the zinc blende structure and is only weakly field dependent, is either wholly or partially in the QW plane, and so swamps $\mathbf{\Omega}^{\mathrm{SIA}}$ [9,10,17]. For the special case of (110)-oriented QWs, illustrated in Fig. 1, $\mathbf{\Omega}^{\mathrm{BIA}}$ lies approximately along the growth axis for all $\mathbf{k}$, causing only weak spin relaxation along the growth axis and thereby leading to greatly enhanced spin memory, as predicted by D'yakonov and Kachorovskii [2] and confirmed experimentally by Ohno *et al.* [1]. Spin relaxation along the growth axis therefore becomes more sensitive to $\mathbf{\Omega}^{\mathrm{SIA}}$ and should be significantly changed by the application of an external electric field [9], an important possibility, which we investigate here.

Equation (1) also shows that the spin-relaxation rate scales with τ_p^* in a way analogous to motional narrowing. For undoped QWs, τ_p^* is closely related to the momentum relaxation time τ_p which determines the electron mobility [2,11,13]. This means that long spin memory and high mobility are, in general, mutually exclusive in low-doped n-type QWs but may be simultaneously achievable in the special case of (110)-oriented QWs.

Samples from three different wafers have been studied, each grown on a semi-insulating (SI) GaAs substrate and each containing twenty 7.5 nm QWs separated by 12 nm barriers with aluminium fraction 0.4. Two wafers consisted only of undoped layers on (001)- and (110)-oriented substrates, respectively. The third wafer was a *pin* structure on a (110)-oriented substrate with the undoped QWs grown between two 0.1 μm undoped buffer layers of AlGaAs and with layers of 2×10^{18} cm^{-3} n^+ doped GaAs and of 1.2×10^{18} cm^{-3} p^+ doped AlGaAs, respectively, below and above. The orientation of the (110)-oriented substrates was accurate to ±0.5°. Measurements were carried out at 300 K on all three wafers as grown and the *pin* wafer was also processed into 400 μm mesa devices [Fig. 2(a)] and used for measurements in variable electric field at 170 K. Although the sequence of layers in the samples does not have inversion symmetry, for flat-band conditions the QWs and barriers possess local inversion symmetry where the confined electron wave functions have significant density. The doped layers of the *pin* structure result in a built-in electric field $\mathbf{E}_z$ of about 25 kV cm^{-1}. Figure 2(b) shows the photoluminescence (PL) spectrum of one of the mesa structures for zero applied bias at 170 K. The width, at 10 K, of the excitonic recombination line was ~6.5 meV in each of our (110)-oriented wafers, and 1.8 meV in our (001)-oriented wafer. Since we expect similar fluctuations in QW width for the two sets of multiquantum wells (MQWs), this suggests that the interfaces of the (110)-oriented QWs are less perfect than for (001) growth and could be further improved by variation of growth conditions.

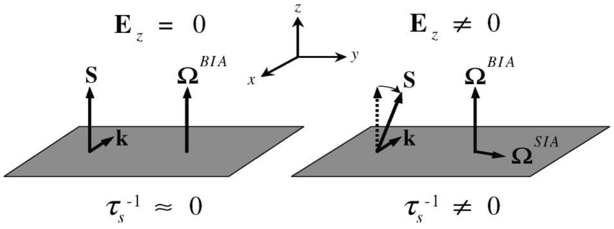

FIG. 1. Precession of photo-injected electron spin population (**S**) in a (110)-oriented QW (shown shaded) due to conduction band spin splitting. For zero growth-axis electric field ($\mathbf{E}_z = 0$) precession vector $\mathbf{\Omega}^{\mathrm{BIA}}$ is almost along the growth axis for all electron wave vectors (**k**) but for $\mathbf{E}_z \neq 0$ an additional in-plane Rashba component $\mathbf{\Omega}^{\mathrm{SIA}}$ causes precession of **S** away from the growth axis. In collision-dominated conditions this leads via Eq. (1) to a longitudinal spin relaxation rate $\tau_s^{-1} \approx 0$ for $\mathbf{E}_z = 0$ and to $\tau_s^{-1} \neq 0$ for finite $\mathbf{E}_z$.

Electron spin evolution was obtained from the change of intensity (ΔR) and polarization rotation ($\Delta\theta$) of optical probe pulses reflected at near normal incidence from the sample surface along the growth axis, at a variable delay following excitation by 10 times more intense, nearly collinear circularly polarized pump pulses [10,14,16]. The pulses were of 2 ps duration from a mode-locked Ti-sapphire laser tuned to the peak of the first electron-

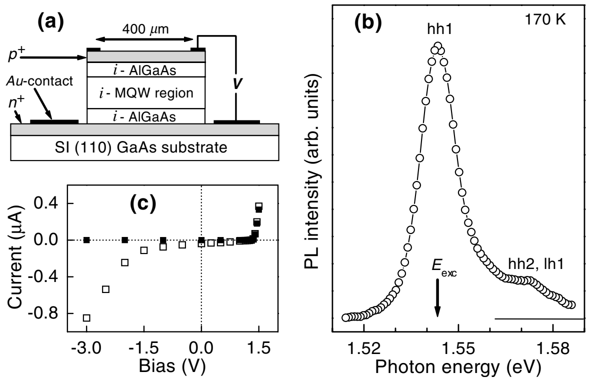

FIG. 2. (a) Cross section of a 400 μm (110)-oriented *pin* mesa device. Pump (circular polarized) and probe (linear polarized) beams for probing spin dynamics are focused on the top of the mesa. (b) PL spectrum of device for applied bias $V = 0$ volts at 170 K; E_{exc} indicates excitation energy for pump and probe measurements. (c) I-V characteristics of mesa device at 170 K in dark (solid squares) and under 350 μW laser illumination (open squares) at peak of hh1 luminescence.

heavy-hole PL transition [Fig. 2(b)] giving excitation density $\sim 10^9$ cm^{-2}. Figure 2(c) shows the I-V characteristics of the device in the dark and illuminated with experimental laser intensity, ~ 350 μW. Such low powers are necessary to avoid screening of the electric field in the MQW region. Since this incident intensity could generate a photocurrent up to 30 μA, the magnitude of the negative bias current shows that in fact a very small fraction, $\sim 2\%$, of the photocarriers is swept out by the bias, but even this may be exaggerated because the rapid increase of current below -1.5 volts indicates avalanche multiplication. The absorbed pump photons thus generate "cold" excitons which dissociate into free carriers on a subpicosecond time scale with spins polarized along the growth axis and which remain confined in the QWs. The hole spins rapidly relax whereas the electron spin relaxation is much slower [14,16]. On a time scale longer than ~ 1 ps, ΔR gives a measure of the population of photoexcited carriers and $\Delta\theta$ a measure of the z component of electron spin so that their ratio gives the pure longitudinal spin dynamics of the electrons [14,16].

Figure 3 shows the observed $\Delta\theta$ signals for the three as-grown wafers at 300 K. There is a dramatic difference between the decay for the (001)-oriented wafer (A) and the undoped (110)-oriented wafer (B), which essentially reproduces the findings of Ohno *et al.* [1]. However, the decay for the *pin* (110)-oriented wafer (C), where there is a built-in electric field of about 25 kV cm^{-1} (at 300 K), is significantly faster than for the undoped (110)-oriented wafer (B). Measurements were made at various pump intensities to allow extrapolation to zero power and when the decay of the ΔR signal is also included in each case the spin-relaxation times are found to be 32 ± 1 ps, 3.5 ± 0.2 ns, and 0.85 ± 0.02 ns for A, B, and C wafers, respectively. These figures are consistent with our theoretical predictions [9] if we assume electron mobilities ~ 0.4 m^2 V^{-1} s^{-1}, ~ 0.3 m^2 V^{-1} s^{-1}, and ~ 0.43 m^2 V^{-1} s^{-1}, respectively. Although we do not have direct mobility measurements, these are reasonable room temperature values for such samples where optical phonon scattering and interface roughness are likely to be dominant [14]. Figure 3 therefore gives a strong indication that there is a significant variation of spin-relaxation rate with electric field at 300 K as predicted theoretically [9].

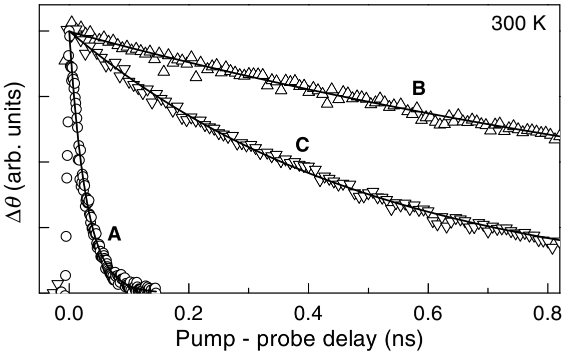

FIG. 3. $\Delta\theta$ signals for three as-grown wafers each containing twenty undoped 7.5 nm GaAs/AlGaAs QWs at 300 K; A, (001)-oriented substrate, all layers undoped; B, as A but on (110)-oriented substrate; C, as B but with $n^+(p^+)$ doped layers below (above) the QWs giving built-in electric field $E_z \approx 25$ kV cm^{-1}. Corresponding values of τ_s are 32 ± 1 ps, 3.5 ± 0.2 ns, and 0.85 ± 0.02 ns, respectively.

Measurements on the mesa devices at different bias voltages at 170 K [Fig. 4(a)] support this conclusion (measurements at 300 K for the same range of voltages were prevented by excessive current in reverse bias leading to destruction of the device). The $\Delta\theta$ signals show single-exponential decay and there is a strong variation of decay rate with voltage. The ΔR signals also decay exponentially and Fig. 4(b) shows the extracted decay times (τ_R) as a function of bias. For large negative bias τ_R increases significantly reflecting the reduced electron-hole overlap at high electric fields and showing that recombination is predominantly radiative [18].

Figure 4(c) shows the spin-relaxation rate vs bias voltage and vs the corresponding electric field at the QWs

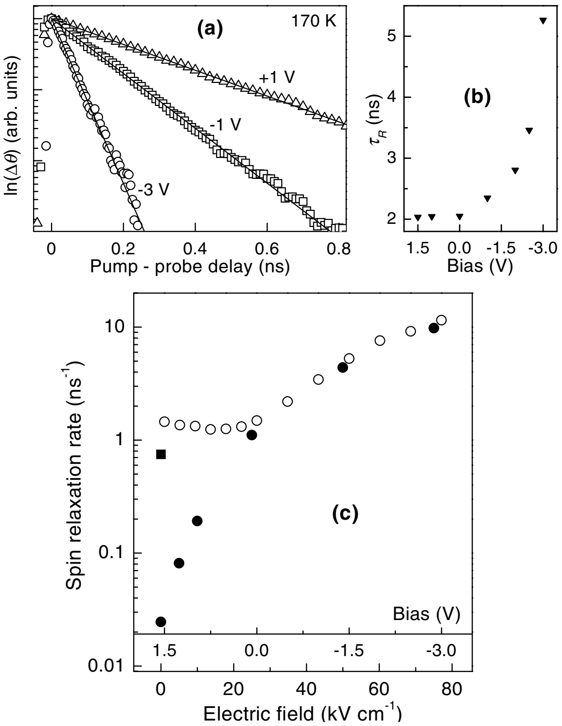

FIG. 4. Spin dynamics for (110)-oriented *pin* mesa device at 170 K: (a) $\Delta\theta$ signals for three applied voltages and (b) decay time for the ΔR signal showing increase of recombination time with applied electric field. (c) Measured spin relaxation rate vs bias voltage and corresponding electric field (open circles) compared with calculation for a symmetrical QW (solid circles) and for a QW with one two-monolayer graded interface (solid square) assuming electron mobility 0.6 m^2 V^{-1} s^{-1}.

obtained using the layer thicknesses in the *pin* structure and the band gap of GaAs at 170 K. Up to 20 kV cm^{-1} the spin-relaxation rate is almost constant but then increases by about a factor of 10 by 80 kV cm^{-1}. The solid dots are results of our nonperturbative calculations [9,12,13] based on the DPK mechanism for a symmetrical (110)-oriented QW. The calculations assumed electron mobility of 0.6 $\mathrm{m}^2\,\mathrm{V}^{-1}\,\mathrm{s}^{-1}$, which is consistent with the assumed 300 K value in the *pin* wafer, $\sim$0.43 $\mathrm{m}^2\,\mathrm{V}^{-1}\,\mathrm{s}^{-1}$, for mobility limited by optical phonon scattering in this temperature range. The variation for electric fields greater than 20 kV cm^{-1} [Fig. 4(c)] is very well fitted by the theory but at lower fields there is clearly a contribution to the spin relaxation not included in the calculations which predict a rate almost 100 times lower than we have observed at zero field.

The measured decay rates in this region were found to increase linearly with pump power, consistent with a small influence of the Bir-Aronov-Pikus (BAP) relaxation mechanism [19] due to exchange interaction with the photo-excited holes as also found by Adachi *et al.* [3]. This does not, however, explain the observed discrepancy with theory since extrapolation to zero power would make a reduction of only about 10%. Nor can it be explained in terms of the BAP mechanism with electrically injected holes; even for flat-band conditions in forward bias, where the injected hole concentration would be greatest, the calculated concentration is at least 2 orders of magnitude too low to explain the additional spin relaxation [19]. Another possible cause of the additional spin relaxation is random built-in asymmetry in the QWs, which would give a field-independent SIA contribution. Such asymmetry could result from alloy fluctuations or from differences of top and bottom interface morphology for the GaAs/AlGaAs QWs and for a given $\mathbf{k}$ would generate an $\mathbf{\Omega}^{\mathrm{SIA}}$ component varying randomly in magnitude and orientation from point to point on a QW with associated nonzero mean square entering Eq. (1). To gauge this possibility, we have repeated our calculation in zero field for a QW with one perfect interface and the other containing a two-monolayer compositional gradient. We describe this compositional gradient simply with a layer of composition $\mathrm{Al}_{0.2}\mathrm{Ga}_{0.8}\mathrm{As}$ extending one monolayer on each side from the nominal interface location and then we calculate the properties of this effective $\mathrm{GaAs/Al}_{0.2}\mathrm{Ga}_{0.8}\mathrm{As/Al}_{0.4}\mathrm{Ga}_{0.6}\mathrm{As}$ QW. The relaxation rate is $\sim$30 times greater than for a perfectly symmetrical QW [solid square in Fig. 4(c)]. Even this small perturbation of the symmetry produces a change approaching our discrepancy between theory and experiment supporting the idea that the spin memory is actually limited by the sample perfection which, as indicated by the width of luminescence lines may be somewhat inferior to that in (001)-oriented samples. At sufficiently high reverse bias the increase of the relaxation rate due to the applied field becomes dominant over this random built-in asymmetry.

In conclusion, we have demonstrated that the enhanced high-temperature electron spin memory in (110)-oriented QWs may be varied by at least a factor 10 by application of modest gate bias voltages. The variation is consistent with the Rashba effect and the DPK spin-relaxation mechanism. On the basis of this mechanism, the measurements for low electric fields indicate that a further significant enhancement of spin memory may be achieved by modification of the growth techniques to optimise the interface morphology. This may be expected to give at 300 K spin memory longer than 10 ns [3,9] and straightforward voltage bias control simultaneously with high electron mobility. This combination of properties will facilitate a variety of spintronic devices.

We wish to thank Professor E. L. Ivchenko, Mr. M. M. Glazov, and Dr. K.V. Kavokin for many illuminating discussions. This work was supported by EPSRC and DARPA/ARO.

[1] Y. Ohno *et al.*, Phys. Rev. Lett. **83**, 4196 (1999).
[2] M. I. D'yakonov and V. Yu. Kachorovskii, Sov. Phys. Semicond. **20**, 110 (1986).
[3] T. Adachi *et al.*, Physica E (Amsterdam) **10**, 36 (2001).
[4] M. J. Snelling *et al.*, J. Lumin. **45**, 208 (1990).
[5] J. S. Sandhu *et al.*, Phys. Rev. Lett. **86**, 2150 (2001).
[6] G. Salis *et al.*, Nature (London) **414**, 619 (2002); for review, see D. D. Awschalom and N. Samarth, in *Semiconductor Spintronics and Quantum Computation*, edited by D. D. Awschalom, D. Loss, and N. Samarth (Springer, New York, 2002), Chap. 5.
[7] H. Ohno *et al.*, Nature (London) **408**, 944 (2000).
[8] Y. A. Bychkov and E. I. Rashba, J. Phys. C **17**, 6039 (1984).
[9] W. H. Lau and M. E. Flatté, J. Appl. Phys. **91**, 8682 (2002).
[10] S. Datta and B. Das, Appl. Phys. Lett. **56**, 665 (1990); M. A. Brand *et al.*, Phys. Rev. Lett. **89**, 236601 (2002).
[11] M. I. D'yakonov and V. I. Perel', Sov. Phys. JETP **33**, 1053 (1971).
[12] W. H. Lau, J. T. Olesberg, and M. E. Flatté, Phys. Rev. B **64**, 161301 (2001).
[13] For review, see M. E. Flatté, J. M. Byers, and W. H. Lau, in *Semiconductor Spintronics and Quantum Computation*, edited by D. D. Awschalom, D. Loss, and N. Samarth (Springer, New York, 2002), Chap. 4.
[14] R. S. Britton *et al.*, Appl. Phys. Lett. **73**, 2140 (1998).
[15] R. Terauchi *et al.*, Jpn. J. Appl. Phys. **38**, 2549 (1999).
[16] A. Malinowski *et al.*, Phys. Rev. B **62**, 13 034 (2001); R. T. Harley *et al.*, J. Phys. D **36**, 2198 (2003).
[17] B. Jusserand *et al.*, Phys. Rev. B **51**, 4707 (1995).
[18] H.-J. Polland *et al.*, Phys. Rev. Lett. **55**, 2610 (1985).
[19] G. L. Bir, A. G. Aronov, and G. E. Pikus, Sov. Phys. JETP **42**, 705 (1976); G. Fishman and G. Lampel, Phys. Rev. B **16**, 820 (1977); for review, see *Optical Orientation*, edited by F. Meier and B. P. Zakharchenya (North-Holland, Amsterdam, 1984).