Spin dynamics in (1 1 0)-oriented quantum wells

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Abstract

Quantum structures of III–V semiconductors grown on (1 1 0)-oriented substrates are promising for spintronic applications because they allow us to engineer and control spin dynamics of electrons. We summarise the theoretical ideas, which are the basis for this claim and review experiments to investigate them.

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Some essential or likely requirements for realisation of spintronic devices such as the spin-FET [1] or the spin-LED [2] working at room temperature are efficient injection of spin-polarised electrons into semiconductors, extended spin-memory within the semiconductor and ability to gate the spin dynamics with externally applied voltage. In this paper, we review recent experiments on (1 1 0)-oriented III–V semiconductor quantum wells, which demonstrate the latter two attributes.

The theoretical background is as follows. Relaxation of a spin polarised population of conduction electrons in intrinsic or n-type III–V semiconductor is not driven, as might be expected intuitively, by spin-dependent scattering of the electrons—the so-called Elliott–Yafet (EY) mechanism [3]. Instead the dominant process—due to D'yakonov, Perel' and Kacharovskii (DPK) [3–5]—is the simultaneous action of ‘in-flight’ Larmor precession of each electron’s spin in the effective magnetic field which represents its spin–orbit interaction together with scattering which randomises its momentum. Randomisation of momentum also randomises the precession because the latter is strongly momentum-dependent. The result is relaxation of the average spin component of a population of electrons along a particular axis \(S_i\) at a rate given by [3,4]

\[
\tau_s^{-1} = \langle \Omega^2 \rangle \tau_p^* \tag{1}
\]

where \(\langle \Omega^2 \rangle\) is the mean squared component of the Larmor precession vector \(\Omega\) perpendicular to the \(i\)-axis and \(\tau_p^*\) is the mean momentum relaxation time for an electron. Eq. (1) contains the interesting feature that the spin-relaxation rate is reduced as the scattering increases—so-called motional slowing. This effect has been observed directly in high mobility two-dimensional electron gases [6]; some very long spin-relaxation times in semiconductors may be assigned to effects of strong scattering and consequently low electron mobility. More effective control is possible by ‘engineering’ \(\langle \Omega^2 \rangle\); this can enable simultaneous high mobility and long spin-relaxation time and also voltage gating of spin dynamics.

The origin of the in-flight precession of an electron spin is a combination of the spin–orbit interaction with inversion asymmetry of the structure [3]. The latter may arise in several ways; (i) in the III–Vs the crystal structure itself lacks a centre of inversion (bulk inversion asymmetry, BIA), giving a contribution \(\Omega_{\text{BIA}}\) to the precession vector (also known as the Dresselhaus term); (ii) from built-in or externally induced structural inversion asymmetry (SIA) such as different alloy composition of barriers of a quantum well or applied odd-parity perturbation such as electric field (Rashba effect [7]), giving a term \(\Omega_{\text{SIA}}\); (iii) from intrinsic or natural asymmetry of the interfaces (NIA), giving a term \(\Omega_{\text{NIA}}\). The orientation and magnitude of each contribution to the vector \(\Omega\) for an electron has a characteristic dependence on the electron’s momentum vector. To a first approximation in a quantum well the
magnitudes are each linear in in-plane momentum; confinement of the momentum leads to the facts that in general $\Omega_{\text{NIA}}$ and $\Omega_{\text{NIA}}$ are oriented in the plane, whereas $\Omega_{\text{BIA}}$ may have any orientation. Thus, the SIA and NIA contributions will always produce spin relaxation along the growth axis, whereas the BIA term usually does.

The case of a (1 1 0)-oriented quantum well is special because $\Omega_{\text{NIA}}$ vanishes [3,8] and $\Omega_{\text{BIA}}$ is oriented perpendicular to the well plane [5]. Therefore, in a symmetrical quantum well with zero applied field, so that $\Omega_{\text{SIA}}$ is zero, the DPK spin-relaxation rate along the growth axis should in principle become zero, as first predicted in Ref. [5]. Since $\Omega_{\text{SIA}}$ is linear in electric field an increase quadratic in field should occur for the spin-relaxation rate [9].

In (1 1 0) GaAs/AlGaAs quantum wells, Ohno et al. [10] first demonstrated long spin-memory along the growth direction and investigated its dependence on temperature and n-type doping; Döhrmann et al. [11] investigated anisotropy and temperature dependence of spin dynamics. Hall et al. [8] demonstrated suppression of $\Omega_{\text{NIA}}$ in (1 1 0) InAs/GaSb quantum wells. Our results [12] on GaAs/AlGaAs (described below) have confirmed the work of Ohno et al., and also demonstrated the effect of applied electric field and importance of interface perfection in achieving the theoretical spin-relaxation times.

These experiments have all been carried out on MBE-grown samples. Fig. 1 shows the low-temperature photoluminescence (PL) spectra of three different MBE-grown GaAs/AlGaAs wafers. Each is nominally an undoped multi-quantum well (MQW) structure with 20 repeats of 7.5 nm wells and 12 nm barriers with Al fraction 0.4. Wafers 1 and 2 were grown, respectively, on (1 0 0) and (1 1 0) substrates using standard growth conditions which optimise growth on (1 0 0); it is clear from the line widths that these conditions do not allow satisfactory growth on (1 1 0). Wafer 3 was grown on (1 1 0) with reduced substrate temperature of 490 °C and with rates 0.5 and 0.33 monolayer s$^{-1}$ for GaAs and AlAs, respectively, and As/(Ga,Al) beam-equivalent pressure ratio $\sim20:1$. These conditions produce acceptable layer quality but from comparison of the PL widths the interfaces are considerably less perfect than those for (1 0 0) growth.

Our measurements of spin dynamics were made using a polarised ultrafast optical pump-probe reflection technique described elsewhere [13]. It directly determines the time-evolution of $\langle S_z \rangle$, the average component of spin of a photoexcited electron population along the growth direction. Fig. 2 shows the observed signals for three as-grown wafers at 300 K. They are each nominally 7.5 nm GaAs/AlGaAs MQWs. The spin-relaxation times, $32 \pm 1$ ps, $3.5 \pm 0.2$ ns and $0.85 \pm 0.02$ ns for A, B and C, respectively, are qualitatively as expected; there is a dramatic increase of decay time between (0 0 1) and (1 1 0) wafers (A compared to B and C) and the decay for the (1 1 0) pin wafer (C), where the MQW is grown in the centre of the insulating section, is significantly faster than for the simple (1 1 0) wafer (B), reflecting the built-in electric field of about 25 kV cm$^{-1}$ in the pin.

Fig. 3a shows measurements at different bias voltages at 170 K on a mesa device (Fig. 3b) fabricated from the pin wafer (measurements at 300 K for the same range of voltages were prevented by excessive leakage current). Fig. 3c shows the spin-relaxation time vs. electric field. Up to about 20 kV cm$^{-1}$ the time is essentially constant but...
then decreases by about a factor 10 up to the highest fields applied. At the higher fields the spin-relaxation rate is accurately quadratic in electric field (Fig. 4) as expected on the basis of the Rashba effect and field-independent scattering in Eq. (1). This encourages the assumption that as the field is reduced the scattering remains constant and further reduction of the rate is prevented by a field-independent contribution to $\Omega_{SIA}$, perhaps due to imperfection of the hetero-interfaces; the PL linewidths for our (110) samples (Fig. 1) indicate interface roughness on the scale of one to two monolayers. The solid circles in Fig. 4 are the results of calculations [9,12] of the DPK rate for an ideal symmetrical MQW sample with abrupt interfaces. The points deviate from a straight line at low field due to the inclusion in the calculation of effects of penetration of the electron wavefunctions through the barriers. The open circle is a calculation for a similar MQW with one two-monolayer stepped interface in each well. Note that the calculation is for a regular but asymmetric structure giving a uniform built-in SIA component, whereas interface roughness in the as-grown sample will be random and give rise to a corresponding random distribution of SIA components. The calculation indicates that interface asymmetry is capable of explaining the observed low field behaviour.

In conclusion, based on clear theoretical principles and experiments (110) oriented quantum wells are showing very great promise as systems in which the spin dynamics of electrons can be engineered and gate-controlled. There is still much to be done. It is highly desirable to improve the growth of such layers, ideally to the point where the quality is as good as for (100) growth. This might be achieved in material systems that may not yet have been tried, for example GaAs/InGaAs, or by techniques other than MBE.
The spin-dynamics of (110)-grown two-dimensional electron gases are theoretically very interesting and remain to be fully investigated. Finally, there is great potential for engineering spin dynamics in appropriate quantum wires. It seems possible that such wires may be fabricated more readily on (110) than (100) substrates.

References