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Spin relaxation in n-InSb/AlInSb quantum wells

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Abstract. We have used time resolved spectroscopy to measure the relaxation of spin polarization in InSb/AlInSb quantum wells (QWs) as a function of temperature and mobility. The results are consistent with the D'yakonov–Perel (DP) mechanism for high mobility samples over the temperature range from 50 to 300 K. For low mobility samples at high temperature the Elliott–Yafet and DP mechanisms become comparable. We show that the mobility can in certain circumstances determine which mechanism is dominant, and that above $1\,\mathrm{m^2\,V^{-1}\,s^{-1}}$ in 20 nm wide InSb QWs it is the DP mechanism. We also give a criterion for the maximum spin lifetime in terms of mobility and temperature, and show that for our 20 nm wide QWs this corresponds to 0.5 ps at 300 K and mobility $1\,\mathrm{m^2\,V^{-1}\,s^{-1}}$.

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1. Introduction and theory

Semiconductor quantum wells (QWs) are important components for future spintronic transistor device applications because the method for electrical manipulation of spin polarizations in semiconductors is likely to be the Rashba effect [1]. Recently alternative methods for coherent spin control have been demonstrated using strain gradients [2] or composition gradients [3], without manipulation of QW symmetry. However, most investigations have concentrated on control of the spin-splitting by a gate electric field, and observations of this effect have been made using Shubnikov–de Haas experiments [4], weak-antilocalization [5] and time-resolved optical experiments [6]. These experiments have all been performed on GaAs-based, and more recently on InAs-based [16], structures. In the present work, we investigate the spin lifetime, and hence the ability to control the zero field spin splitting, in alternative, antimonide-based semiconductors. In this case, the spin–orbit coupling and hence the Rashba effect are stronger, resulting in a larger zero field spin splitting and spin relaxation rate. We have measured the spin relaxation rate in InSb/AlInSb QWs, and find that it is significantly faster than in GaAs-based wells, and comparable to the InAs rate.

In bulk n-type semiconductors, two main spin relaxation processes have been found to be important in optical orientation experiments: the D'yakonov–Perel (DP) and the Elliott–Yafet (EY) mechanisms [7]–[9]. Theoretical prediction indicates that for bulk III–V n-type semiconductors the transition temperature from the DP-dominated regime to the EY-dominant regime is at $T \sim 5$ K [8]. In support of this, the EY process has been found to be responsible for the spin relaxation of electrons in bulk InSb at a temperature of $T = 1.3$ K [10, 11], whereas the DP process dominates at room temperature [12].

For QWs, only in the case of DP-dominated scattering will an electric field applied in the growth direction cause a modulation of the strength of the spin–orbit coupling through the Rashba effect and hence also the rate of DP spin relaxation. This is an essential component for spintronic devices requiring modulation of the spin lifetime with an electric field. It is therefore important to establish the conditions in which spin polarization lifetimes are both long and dominated by the DP process.

It has been shown that for the GaAs/AlGaAs QW system at room temperature the DP process is the dominant spin relaxation mechanism (for example, [13]–[15]), as with the bulk materials. This is also true for the narrow gap system InAs/GaSb (for example [6, 16]). On the other hand, in the intermediate bandgap system InGaAs/InP it has been reported, but as yet not fully explained, that the EY mechanism is the strongest process [15]. We show in this work that the *mobility* of the material can be important for determination of which mechanism dominates, at least in narrow gap semiconductor QWs, and that there is an optimum value of mobility (specific to a particular confinement energy) that gives the longest DP-dominated lifetime.

The EY process leads to spin relaxation due to mixing of the valence band states into the conduction band, leading to a nonzero transition rate even for spin-conserving scattering processes. An expression for the spin relaxation rate for the EY process in a QW has been given by [15, 17]

$$\frac{1}{\tau_s^{\mathrm{EY}}} = C_{\mathrm{EY}} \eta^2 \left(1 - \frac{m_e}{m_0}\right)^2 \frac{E_{1e}}{E_g^2} kT \frac{1}{\tau_p}, \tag{1}$$

where m_e/m_0 is the electron effective mass ratio, E_{1e} is the confinement energy for the lowest electron subband, $\eta = \Delta/(E_g + \Delta)$, E_g is the band gap and Δ is the spin–orbit splitting energy.

The orbital momentum scattering time τ_p is related to the mobility μ (assuming the electron–electron scattering rate is low compared with inelastic scattering) by $\tau_p = \mu m_e/e$. $C_{\rm EY}$ is a dimensionless constant and is predicted to be of the order of unity.

The DP spin dephasing arises because spin–orbit coupling removes spin degeneracy and provides an effective magnetic field that causes the electron spin to precess at a rate determined by the splitting. For small **k** in bulk crystals this splitting can be written as $\Delta E = \gamma k_3$, where γ is the Dresselhaus spin splitting coefficient [18]. For QWs, the spin splitting is linear in **k** and the Rashba coefficient α_c, related to the spin splitting, is given by [13]:

$$\gamma = \alpha_c \hbar^3 (2m_e^3 E_g)^{-1/2}, \tag{2}$$

where [8]

$$\alpha_c \approx \frac{4\eta}{\sqrt{3-\eta}} \frac{m_e}{m_0}.$$

The DP spin relaxation rate is

$$\frac{1}{\tau_s^{\rm DP}} = C_{\rm DP} \frac{m_e^3 (\gamma E_{1e})^2}{\hbar^8} k_{\rm B} T \tau_p = C_{\rm DP} \frac{\alpha_c^2}{2} \frac{E_{1e}^2}{\hbar^2 E_g} k_{\rm B} T \tau_p, \tag{3}$$

where again $C_{\rm DP}$ is a dimensionless constant, predicted to be 16 [13]. Using equation (2) for InSb, $\alpha_c = 0.045$ which agrees well with other calculations [18].

The scaling of spin relaxation time with electron confinement energy can serve as a criterion for distinguishing between the spin-relaxation mechanisms, assuming the momentum relaxation time can be kept constant. It was shown that $\tau_S \propto E_{1e}^{-2.2}$ for two series of GaAs/AlGaAs QWs, which is consistent with DP being the dominant spin-relaxation mechanism [15]. On the other hand, in the same work for a set of InGaAs/InP QWs, it was found that $\tau_S \propto E_{1e}^{-1}$, indicating dominance of EY. Moreover it was shown that at room temperature the observed magnitude of spin relaxation time in InGaAs/InP QWs is smaller than the estimation based on the DP process [13], as expected for EY. It was suggested that the reason for the change of spin-relaxation mechanism is because the band gap of the InGaAs QWs was about half of that of the GaAs QWs, reducing $\tau_S^{\rm EY}$ via equation (1) [15]. It is clear from later work on narrow gap material (see, for example, [16] and the present work) that this explanation is incomplete. Below we shall show that for InSb QW samples, in spite of the band gap of InSb being more than four times narrower than that of the InGaAs, the DP process dominates at room temperature for high mobility samples (as indeed has been shown previously for InAs QWs [16]).

2. Experiment

We have investigated a set of InSb/$Al_{0.15}In_{0.85}Sb$ single QW samples grown by MBE on GaAs substrates. The mobility of all available QWs was measured by means of the Hall effect. The two samples that exhibit the most strongly different temperature dependence of the mobility, shown in figure 1, were chosen for spin lifetime measurements. These QWs both have a well width of 20 nm, but one was remotely n-doped with Te 20 nm above the well (me1833), and the other was uniformly Te-doped (me1831F).

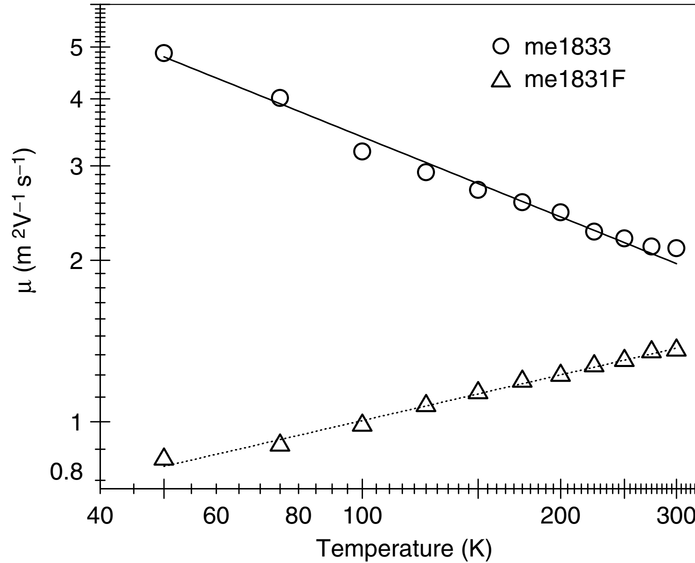

Figure 1. Temperature dependence of the electron mobility for samples me1831F and me1833 (on logarithmic scales).

The two main scattering processes that determine the temperature dependence of the electron mobility are lattice scattering for which $\mu \propto T^{-3/2}$ and impurity scattering for which $\mu \propto^{+3/2}$. Fitting a power law $\mu \propto T^x$ to the experimental mobility reveals that for the remotely doped sample $x = -0.5$, whereas for the uniformly doped sample $x = 0.28$, i.e. consistent with lattice scattering dominating in the former, and ionized impurity scattering dominating in the latter, as expected. The carrier density for me1833 is 5.3×10^{11} cm^{-2} at 300 K and 3.6×10^{11} cm^{-2} at 77 K. For me1831F it is 7.3×10^{11} cm^{-2} at 300 K and 5.7×10^{11} cm^{-2} at 77 K.

We measured the spin relaxation time by means of a circularly polarized pump-probe experiment [9], [12]–[17], [19]–[23]. Our experimental setup is shown in figure 2. The probe beam was circularly polarized using a variable quarter wave plate. A photo-elastic modulator (PEM) was used to modulate the pump, between the same circular polarization (SCP) as the probe to the opposite circular polarization (OCP). The change in transmission of the probe beam due to the modulation (i.e. the circular dichroism, ΔT_{CD}) was detected as a function of the time delay between pump and probe pulses. The recombination time of photo-generated carriers was measured by simply replacing the PEM with an optical chopper. The change in transmission due to the chopping will be referred to as the linear polarization signal (ΔT_{LP}). All measurements were performed using the output of a difference frequency generator (DFG, Coherent Inc.) pumped by both the signal and the idler output of an infrared optical parametric amplifier. The DFG provides pulses shorter than 100 fs duration at a repetition rate of 250 kHz. The wavelength of the laser radiation could be continuously tuned from 3 to 13 μm. In all cases, the pump and probe photon energy was maintained just above the bandgap. The laser power before the beam splitter was 4 mW. The intensity of the probe beam was a few percent of that of the pump beam. In order to obtain the spin relaxation time the ratio $(\Delta T_{\mathrm{SCP}} \Delta T_{\mathrm{OCP}})/(\Delta T_{\mathrm{SCP}} + \Delta T_{\mathrm{OCP}})$, which is equivalent to $\Delta T_{\mathrm{CD}}/\Delta T_{\mathrm{LP}}$, should be fitted with an exponential decay. It was found that the spin relaxation time is significantly shorter than the carrier lifetime obtained from the ΔT_{LP} signal. The carrier recombination proceeds via the Auger process [23] and does not follow a single exponential decay, but the fastest component measured was ∼50 ps. This is much longer than any of our

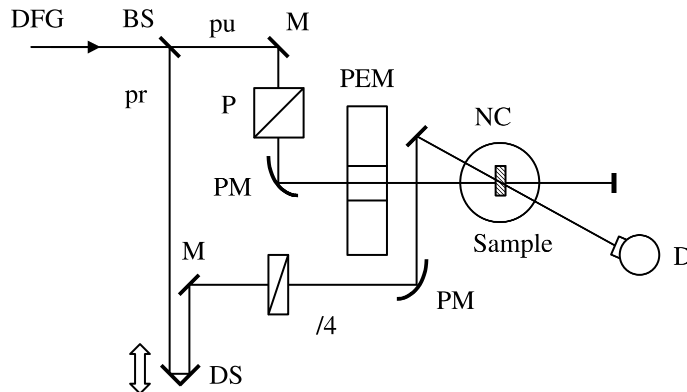

Figure 2. The schematic experimental apparatus: DFG, different frequency generator; BS, beam splitter; pu, pump beam; pr, probe beam; DS, delay stage; M, flat mirror; PM, parabolic mirror ($f = 15$ cm); P, polarizer; $\lambda/4$, quarter wave plate; D, InSb detector cooled with liquid nitrogen; NC, nitrogen cryostat.

observed spin relaxation times and therefore ΔT_{LP} may be considered as a constant. We have extracted spin relaxation times from ΔT_{CD} decay only.

3. Discussion and conclusion

Experimental results for the change in transmission of the probe beam due to the modulation (i.e. the circular dichroism, ΔT_{CD}) was detected as a function of the time delay between pump and probe pulses, as shown in figure 3.

The temperature dependence of the spin relaxation time obtained by fitting ΔT_{CD} with exponential decay is shown in figure 4 for both samples. Also shown on figure 4 are theoretical predictions for the variation of the lifetime with temperature from equations (1) and (3) using the experimentally determined mobility from figure 1 (interpolated using the power law fit described above). The scaling factors C_{DP} and C_{EY} were used as free parameters, though assumed to be sample independent, and the values used for the curves shown in figure 2 were 32 and 7.5 respectively (see below for discussion of this choice). The value of E_{1e} was taken to be 0.08 eV, estimated from k.p calculations.

In order to determine which mechanism dominates the spin decay, we note that from equation (1) $\tau_{\mathrm{S}}^{\mathrm{EY}} T \propto \mu$ assuming that the band gap and the electron effective mass are only slowly varying with temperature, whereas from equation (3), $\tau_S^{\mathrm{DP}} T \propto \mu^{-1}$. A plot of $\tau_S T$ versus μ should therefore reveal which mechanism dominates. The spin relaxation time predicted by the DP and the EY processes as well as experimental results for both samples are shown in figure 5. For sample me1833, $\tau_S T$ is inversely proportional to μ and is perfectly well described by the DP process. The value of C_{DP} obtained from the fit was 32, about twice that predicted by [13]. This may be due to built-in electric fields caused by the remote doping. Similar discrepancies in absolute magnitude with the simple theory have been reported elsewhere [13, 17, 21, 22], and may be resolved by going to a more comprehensive theoretical treatment of the DP process [23]. For sample me1831F, at high temperature and the high mobility end of the range the dependence

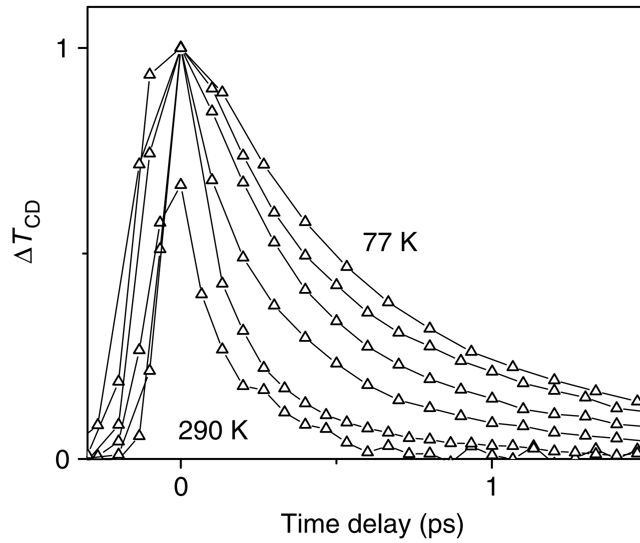

Figure 3. The difference between the transient probe transmission changes for pump and probe having the SCP and OCP measured as a function of time delay between the pump and probe pulses for sample me1831F for temperatures 77, 100, 150, 200, 250 and 290 K.

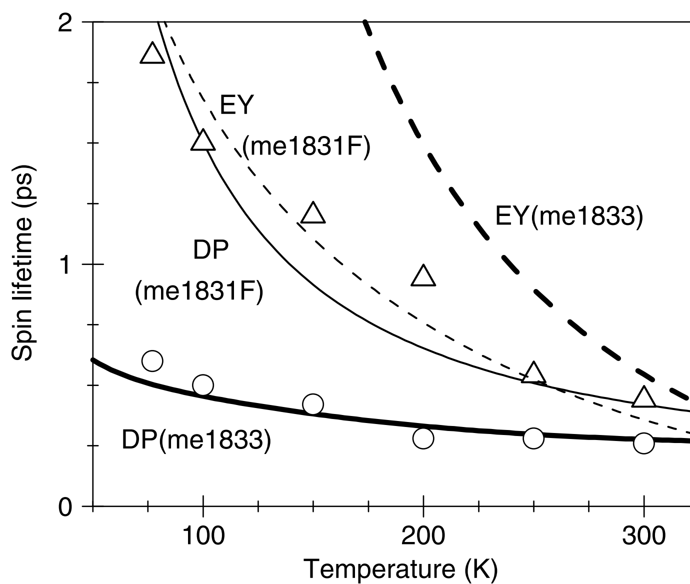

Figure 4. Experimental temperature dependence of the spin relaxation time for samples me1833 (circles) and me1831F (triangles). The labels refer to the lines which represent theoretical predictions for τ_s. The thick lines use the interpolated mobility data of figure 1 for sample me1833, the thin lines use that of sample me1831F. The solid lines are according to the DP model of equation (3) with $C_{DP} = 32$, and the dashed lines use the EY model of equation (1) with $C_{EY} = 7.5$.

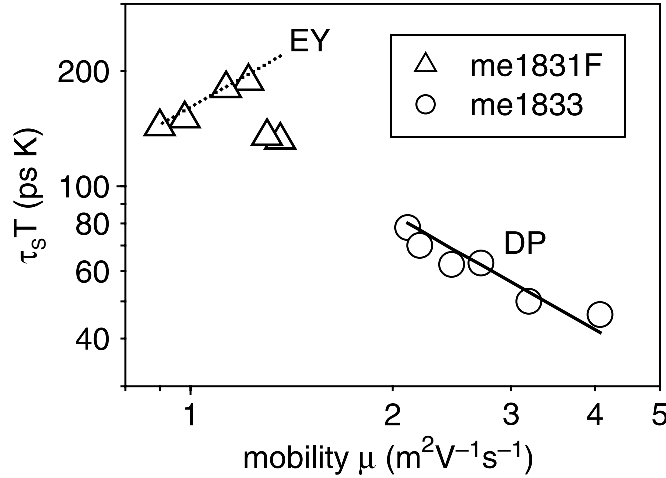

Figure 5. The comparison of experimental (open symbols) and theoretical (lines) dependence on mobility, μ, of the product of spin relaxation time with temperature, $\tau_s T$ (on logarithmic scales). Solid line: DP process using equation (3) using $C_{\rm DP} = 32$ as a fitting parameter; dotted line: EY process of equation (1) with $C_{\rm EY} = 7.5$ as fitting parameter.

of $\tau_S T$ is again inversely proportional to μ and the DP process dominates (again with $C_{\rm DP}$ about twice that predicted, as for me1833). At lower temperature and mobility, the EY process appears to become comparable to the DP process and a clear distinction cannot be made.

In the light of their experimental results, in [13] it was suggested that the efficiency of EY process could become much more significant in narrow band gap semiconductors, as can be seen from equation (1). However, DP also becomes faster from equation (3), and the cross-over from EY to DP dominated regimes occurs when

$$\tau_X = \left(\frac{C_{\rm EY}}{C_{\rm DP}}\frac{3-\eta}{8}\frac{\hbar^2}{E_{1e}E_g}\right)^{1/2}\left(\frac{m_0}{m_e}-1\right), \tag{4}$$

which is not explicitly temperature-dependent. At this point, the spin relaxation lifetime is maximum

$$\tau_{s\,\max} = \frac{1}{\sqrt{2C_{\rm DP}C_{\rm EY}}}\frac{\sqrt{3-\eta}}{2\eta^2}\frac{m_0}{m_e}\left(1-\frac{m_e}{m_0}\right)^{-1}\left(\frac{E_g}{E_{1e}}\right)^{3/2}\frac{\hbar}{k_{\rm B}T}. \tag{5}$$

For our 20 nm wide InSb wells the optimum mobility is about $\mu_X \sim 1\,{\rm m^2\,V^{-1}s^{-1}}$ (from figure 5), very similar to sample me1831F, and if this is achieved at room temperature then $\tau_{s\,\max} \sim 0.5$ ps (since $\tau_{s\,\max}T = 150$ psK also from figure 3). Because $E_{1e} \propto L^{-2}$, $\tau_{s\,\max}$ scales with L_3 (from equation (5)) so strong increases in spin lifetime can be achieved with small increases in well width. Similarly, changing from InSb wells to InAs wells is predicted to increase the maximum spin lifetime by about an order of magnitude. From equation (4), DP can be expected to dominate at room temperature even in narrow gap QWs unless the mobility is low.

We would like to stress that the DP lifetime can be tuned by application of a vertical electric field (in a way that depends on growth direction [25]), which changes the magnitude of the

structural (Rashba) inversion asymmetry and hence also C_{DP}. The attractiveness of narrow gap semiconductors for spintronics comes from the large predicted Rashba effect, i.e. the strong tuning of τ_s with field, and the consequent faster switching and lower power consumption [26].

In conclusion, we have investigated the temperature and mobility dependence of spin relaxation time in narrow gap antimonide single QWs. It was found that simple models of spin-relaxation processes give good agreement between theory and experimental results and allow us to conclude that the DP process is the dominant spin-relaxation mechanism for the temperature range from 290 to 77 K for high mobility material. This is important for spintronic applications since in this case an electric field applied in the growth direction causes a modulation of the strength of the spin–orbit coupling and hence also the rate of DP spin dephasing. However, the EY process begins to become important with low mobility material at low temperature. EY spin-flip scattering is not modulated strongly by the electric field, and it is therefore important to establish the conditions in which spin polarization lifetimes are both long and dominated by the DP process. We show in this work that it is the mobility of the material that is important for the determination of which dominates in narrow gap antimonide QWs, and that there is an optimum value of mobility that gives the longest DP-dominated lifetime.

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