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## Suppression of D'yakonov–Perel spin relaxation in InAs and InSb by *n*-type doping at 300 K

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We have made direct pump-probe measurements of spin lifetimes in intrinsic and degenerate *n*-InAs at 300 K. In particular, we measure remarkably long spin lifetimes ( $\tau_s \sim 1.6$  ns) for near-degenerate epilayers of *n*-InAs. For intrinsic material, we determine  $\tau_s \sim 20$  ps, in agreement with other workers. There are two main models that have been invoked for describing spin relaxation in narrow-gap semiconductors: the D'yakonov–Perel (DP) model and the Elliott–Yafet (EY) model. For intrinsic material, the DP model is believed to dominate in III–V materials above 77 K, in agreement with our results. We show that in the presence of strong *n*-type doping, the DP relaxation is suppressed both by the degeneracy condition and by electron–electron scattering, and that the EY model then dominates for the *n*-type material. We show that this same process is also responsible for a hitherto unexplained lengthening of  $\tau_s$  with *n*-type doping in our earlier measurements of *n*-InSb. © 2003 American Institute of Physics. [DOI: 10.1063/1.1635659]

Utilization of the electron spin has become a focus of interest in semiconductor electronics, or spintronics, in recent years, and it is important to realize a sufficiently long spin lifetime  $\tau_s$  to process information stored in the form of the polarization of spin ensembles.<sup>1–3</sup> To find a way to control  $\tau_s$ , it is necessary to understand the spin relaxation mechanisms in both bulk and low-dimensional semiconductor structures which are designed so that spins can be appropriately confined and/or transferred. In contrast to GaAs-based systems, relatively little attention has been paid to InAs, even although it may be important in future spintronics applications. We previously measured spin lifetimes in narrow-gap semiconductors (NGSs),  $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$  and InSb, at wavelengths between 4 and 10  $\mu\text{m}$  over the temperature range of 4 to 300 K.<sup>4</sup> We have now extended those measurements to include bulk epilayers of InAs as a function of doping at 300 K.

The InAs samples were grown at Imperial College by molecular-beam epitaxy on GaAs (001) substrates<sup>5</sup> with the following 300 K Hall effect characteristics. IC313:  $n = 3.8 \times 10^{16} \text{ cm}^{-3}$ , mobility  $\mu = 3 \times 10^4 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ ; IC311:  $n = 1 \times 10^{17} \text{ cm}^{-3}$ ,  $\mu = 2.5 \times 10^4 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ . The InSb samples used in our previous work<sup>4</sup> were as follows: ME1654:  $n = 1.5 \times 10^{16}$ ,  $\mu = 6.9 \times 10^4 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ ; ME1629:  $n = 2.3 \times 10^{17} \text{ cm}^{-3}$ ,  $\mu = 4.5 \times 10^4 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ . To measure the spin lifetimes, we used the standard polariza-

tion pump-probe method,<sup>4,6,7</sup> which excites spins in the semiconductor with above-bandgap, circularly polarized light, and probes the induced bleaching with either the same or the opposite circularly polarized light (SCP or OCP, respectively). The pump and probe beams are pulsed, and by changing the time delay between the pump and probe, and comparing the SCP and OCP results, we measure the spin decay lifetime. The optical pulses for the experiment, carried out at the University of Surrey, were generated with a solid-state laser system that produces  $\sim 40$  fs pulses from 2.5 to 11  $\mu\text{m}$  wavelength, with a repetition rate of 250 kHz and typical average power of 5 mW. The beams were focused onto the sample with spot sizes of approximately 100  $\mu\text{m}$ , and the transmitted probe light was detected with a liquid-nitrogen-cooled InSb photodiode.

Results for the transmission change in the probe due to the pump are shown for sample IC313 in Fig. 1 for SCP and OCP configurations at a wavelength of 3.4  $\mu\text{m}$ ; that is, just above the absorption edge. The data are in extremely good agreement with the results of other workers.<sup>6</sup> Following Ref. 6, we plot the fractional difference in transmission between SCP and OCP,  $P_{\text{opt}} = (\Delta T_{\text{SCP}} - \Delta T_{\text{OCP}}) / (\Delta T_{\text{SCP}} + \Delta T_{\text{OCP}})$  shown in the inset, and interpret the monoexponential decay time of 20 ps as the spin lifetime  $\tau_s$ . The error in the fitting due to noise in the data is estimated to be  $\pm 10$  ps. In practice, our polarizers were not fully optimized for these long wavelengths, so that the maximum polarization we achieve is somewhat less than the maximum value attainable.

In order to test the effect of *n*-type doping, the measure-

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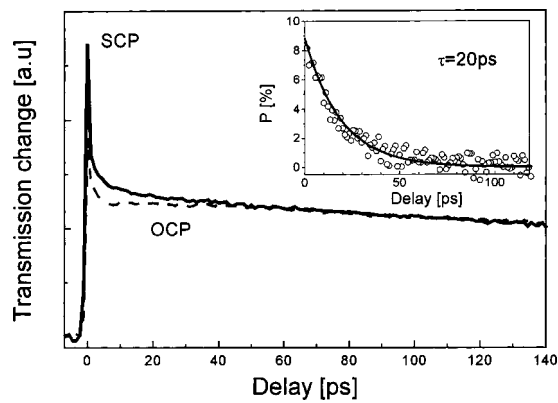


FIG. 1. Pump-probe transmission change as a function of probe delay time for pump and probe having SCP, and OCP, for lightly doped  $n$ -InAs at 300 K (sample IC313,  $n = 3.8 \times 10^{16} \text{ cm}^{-3}$ ). The inset shows the difference of the SCP and OCP signals divided by their sum. The solid curve is a fit of a monoexponential, giving a measured decay constant of  $\tau = 20$  ps. Following Ref. 6, we interpret this as the spin lifetime  $\tau_s$ .

ments were repeated for the near-degenerate sample IC311, and the results are shown in Fig. 2. For this sample, the absorption edge is Moss–Burstein shifted to higher energy by the degenerate doping, and the wavelength used was  $3.2 \mu\text{m}$ . Although the change in polarization  $P_{\text{opt}}$  from SCP to OCP is quite large, the decay times of each are similar to each other in this case and also to the Auger recombination rate. However, there is still an obvious difference in the decays of SCP and OCP, as evidenced by the fact that  $P_{\text{opt}}$  is not flat, and this can still be used to measure a spin lifetime. Clearly the decay of the spin polarization is substantially lengthened, and the decay time of  $P_{\text{opt}}$ , plotted in the inset, now gives a spin lifetime of  $\tau_s = 1.6 \pm 0.5$  ns. A similar and hitherto unexplained lengthening of spin lifetime, was obtained for InSb in our earlier work:<sup>4</sup> ME1654 ( $\tau_s = 16$  ps) and ME1629 ( $\tau_s = 300$  ps) for the undoped and degenerate  $n$ -type samples, respectively. We note that the room-temperature mobilities are very similar for all these samples, so that we have to look elsewhere to explain these large changes in spin lifetime.

In bulk semiconductors, three main spin relaxation processes have been found to be important in optical orientation experiments: the Elliott–Yafet (EY),<sup>8</sup> D’yakonov–Perel,

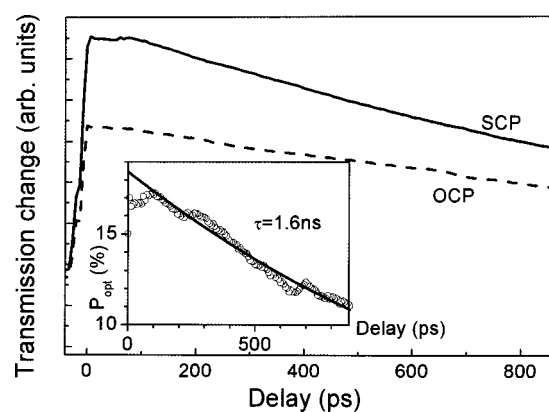


FIG. 2. Same as Fig. 1 for heavily doped  $n$ -InAs at 300 K (sample IC311,  $n = 1.0 \times 10^{17} \text{ cm}^{-3}$ ). The inset shows the difference of the SCP and OCP signals divided by their sum. The decay time of the fit to  $P_{\text{opt}}$  gives a spin lifetime of  $\tau_s = 1.6$  ns.

(DP)<sup>9</sup> and the Bir–Aronov–Pikus (BAP)<sup>10</sup> mechanisms. The BAP mechanism is thought to be particularly important in  $p$ -type wide-gap materials and is based on the electron–hole exchange interaction. By contrast with the other two processes, it depends directly on the concentration of holes, and is not thought to be important in  $n$ -type NGS.

The EY mechanism results from the fact that in real crystals Bloch states are not spin eigenstates because of the strong spin–orbit coupling induced by the lattice ions, so that the spin relaxation is directly related to the orbital relaxation processes. This mechanism has been shown to be important at low temperatures in NGS.<sup>11–13</sup> The EY spin relaxation rate for ionized impurity scattering and degenerate statistics is

$$\frac{1}{\tau_s} \approx \frac{32}{27} \left( \frac{\gamma E_F}{E_G} \right)^2 \left( \frac{1 - \gamma/2}{1 - \gamma/3} \right)^2 \frac{1}{\tau_p}, \quad (1)$$

where  $\gamma = \Delta / (E_G + \Delta)$ , and  $\Delta$  is the spin–orbit splitting of the valence band. In the other limit of lattice scattering and nondegenerate statistics, the EY expression becomes

$$\frac{1}{\tau_s} \approx 2 \left( \frac{\gamma kT}{E_G} \right)^2 \left( \frac{1 - \gamma/2}{1 - \gamma/3} \right)^2 \frac{1}{\tau_p}. \quad (2)$$

The DP mechanism has been shown to dominate at temperatures above 77 K in intrinsic or lightly  $n$ -type NGS,<sup>6,13</sup> where the lack of inversion symmetry in the presence of a  $\mathbf{k}$ -dependent spin–orbit interaction lifts the spin degeneracy even in the absence of a magnetic field.<sup>9</sup> Somewhat counter-intuitively, and in contrast with EY, the spin relaxation rate  $1/\tau_s$  is subject to motional narrowing, and is therefore directly proportional to the orbital (mobility) scattering time  $\tau_p$ .

The DP relaxation rate for lattice scattering and nondegenerate statistics is given by

$$\frac{1}{\tau_s} \approx 0.8 \beta^2 \frac{(kT)^3}{\hbar^2 E_G} \tau_p. \quad (3)$$

For the case of degenerate statistics and ionized impurity scattering, the DP expression becomes

$$\frac{1}{\tau_s} \approx \frac{16}{315} \beta^2 \frac{(E_F)^3}{\hbar^2 E_G} \tau_p, \quad (4)$$

where<sup>13</sup>  $\beta \approx [4\gamma/\sqrt{3-\gamma}](m_c/m_0)$ . The relationship of Eq. (4) has recently been confirmed quantitatively for degenerate  $n$ -GaAs at helium temperature.<sup>14</sup> Following others, we neglect the extremely rapid decay of the hole spin polarization in interpreting our experiments.<sup>3,4,6</sup>

In our previous work,<sup>4</sup> we demonstrated that the temperature dependence of the results for  $n$ -type  $\text{Hg}_{0.78}\text{Cd}_{0.22}\text{Te}$  could be explained in terms of the EY model. We also showed a remarkable lengthening of the spin lifetime in InSb from  $\sim 16$  ps for intrinsic material to 300 ps for the degenerate case. The reason for the lengthening was not explained, but we showed that the longer spin lifetime of the degenerate case was consistent with the EY process dominating, as with the  $n$ -HgCdTe.

For intrinsic and lightly doped samples, the DP process [Eq. (3)] dominates for both InAs and InSb [theoretical/experimental values for  $\tau_{\text{DP}}$  are obtained as follows: IC313

(20 ps/20 ps), and ME1654 (10 ps/16 ps)]. The EY process [Eq. (2)] gives  $\tau_{EY} \sim 50$  ps and  $\tau_{EY} \sim 350$  ps, respectively, so that clearly it is not important for this case.

In the presence of significant  $n$ -doping, two points become extremely important with regard to the DP process. In the first instance, it is obvious from the prefactor in Eq. (4) that the onset of degeneracy considerably suppresses the DP process in the case of  $n$ -InSb and  $n$ -InAs, in which the mobilities (and hence  $\tau_p$ ) are relatively constant for the range of samples measured. Thus, for the more heavily doped samples in this limit we obtain theoretical values from Eqs. (1) and (4) as follows: IC311 ( $\tau_{EY} \sim 500$  ps,  $\tau_{DP} \sim 800$  ps) and ME1629 ( $\tau_{EY} \sim 100$  ps,  $\tau_{DP} \sim 100$  ps). However, in addition to this it has been demonstrated recently<sup>15</sup> that for the DP process, the precession of an electron spin can be as effectively randomized by scattering from another electron (i.e., electron–electron scattering)<sup>15,16</sup> via the Coulomb interaction as by scattering from thermal vibrations or defects, and yet this process can affect the mobility only weakly. This would accentuate the difference between the two processes (i.e., lengthen  $\tau_{DP}$  and shorten  $\tau_{EY}$ ). Thus, for both these reasons, we expect the spin relaxation for samples IC311 and ME1629 to be dominated by the EY process, and in fact this is in reasonable agreement with our measured values of  $\tau_s$  given the simplifications of the model [Eq. (1)] [experiment/theory( $\tau_{EY}$ ): IC311, 1.6 ns/500 ps; ME1619, 300 ps/100 ps].

In summary, our results for intrinsic  $n$ -InAs (and earlier,  $n$ -InSb) are in excellent agreement with the predictions of the DP process. However, we have measured a remarkably long spin lifetime ( $\sim 1.6$  ns) in near-degenerate  $n$ -InAs at 300 K. This, together with our earlier result for degenerate  $n$ -InSb ( $\tau \sim 300$  ps),<sup>4</sup> is explained in terms of the suppression of the DP spin relaxation process by the degeneracy condition and by electron–electron scattering. (We note that a similar effect was reported very recently in degenerate  $n$ -type Si.<sup>17</sup>) The EY process then limits the spin relaxation for the  $n$ -type material. The long spin lifetimes are clearly

important from the point of view of devices of the spin transistor type.<sup>1–3</sup>

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