

## Anisotropic electron spin lifetime in (In,Ga)As/GaAs (110) quantum wells

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Anisotropic electron spin lifetimes in strained undoped (In,Ga)As/GaAs (110) quantum wells of different widths and heights are investigated by time-resolved Faraday rotation and time-resolved transmission and are compared to the (001) orientation. From the suppression of spin precession as a function of transverse magnetic fields, the ratio of in-plane to out-of-plane spin lifetimes is calculated. While the ratio increases with In concentration in agreement with theory, an unprecedented high anisotropy of 480 is observed for the broadest quantum well at the low In concentration, when expressed in terms of spin relaxation times.

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During the last few years, the manipulation of the electron's spin degree of freedom for information processing was explored in the new field of spintronics.<sup>1</sup> The most prominent proposal for a logic spin device by Datta and Das,<sup>2</sup> the spin-field-effect transistor, is based on the precession of a spin in a variable electric field due to the Rashba effect. Recently, more robust devices have been suggested, which are based on the manipulation of spin relaxation leading to switchable randomization of the spin orientation.<sup>3-5</sup> Some of these proposals exploit the unique characteristics of bulk inversion asymmetry in (110)-oriented zinc-blende semiconductor quantum wells (QWs), for which a large anisotropy of electron spin relaxation time is predicted.<sup>6</sup>

The largest spin relaxation anisotropy was found in a narrow *n*-doped (In,Ga)As/(Al,Ga)As QW grown in the [110] crystal direction.<sup>7</sup> In these zinc-blende semiconductors QWs, the spin relaxation time  $\tau_S$  is mainly governed by the D'yakonov-Perel' (DP) spin dephasing mechanism, for which  $\tau_S^{DP}$  of two-dimensional confined electron spins is proportional to  $T^{-1}E_g d^{-2}E_1^{-2}\tau_p^{-1}$ , where  $T$  is the temperature,  $\tau_p$  the momentum relaxation time,  $E_1$  the quantized kinetic energy of electrons, and  $E_g$  and  $d$  are the band gap and the thickness of the QW layer, respectively.<sup>6</sup> Additionally, the effect of DP spin dephasing strongly depends on the QW's confinement direction as well as on the spin direction:<sup>6</sup> For (001) QWs, the relaxation time of spins pointing in the in-plane direction  $\tau_S^{\parallel}$  and in the out-of-plane direction  $\tau_S^{\perp}$  is given by  $\tau_{S(001)}^{\parallel} = \tau_S^{DP}$  and  $\tau_{S(001)}^{\perp} = \tau_S^{DP}/2$ , respectively, whereas it is  $\tau_{S(110)}^{\parallel} = 4\tau_S^{DP}$  and  $\tau_{S(110)}^{\perp} = \infty$  for (110) QWs, leading to infinite spin relaxation anisotropy for the latter. Indeed, large  $\tau_{S(110)}^{\parallel} > 1$  ns as well as spin relaxation anisotropy were experimentally found in *n*-doped GaAs/Al<sub>0.4</sub>Ga<sub>0.6</sub>As (110) (Refs. 9 and 10) and in *n*-doped In<sub>0.08</sub>Ga<sub>0.92</sub>As/Al<sub>0.4</sub>Ga<sub>0.6</sub>As (110) QWs.<sup>7,11</sup> Additional isotropic spin relaxation mechanisms have to be taken into account: e.g., the Bir-Aronov-Pikus (BAP) mechanism<sup>12</sup> based on randomly oriented hole spins acting on electron spins via exchange interaction is believed to be dominant only at low temperature in undoped and *n*-doped QWs.<sup>10</sup> However, there has been no detailed study of anisotropic spin lifetimes in

shallow and strained In<sub>x</sub>Ga<sub>1-x</sub>As/GaAs (110) QWs yet.

In the present work, we therefore investigated spin precession as a function of transverse magnetic fields of three In<sub>x</sub>Ga<sub>1-x</sub>As/GaAs (110) QWs with different QW widths and In concentrations  $x$  employing the time-resolved Faraday rotation (TRFR) technique. The QWs were not intentionally doped, allowing us to separate the magnetization loss due to electron spin relaxation in the conduction band characterized by the spin relaxation time  $\tau_S^{\perp,\parallel}$  and the carrier recombination processes described by the carrier lifetime  $\tau_R$ . The decay of electron spin magnetization as observed by TRFR is then given by the spin lifetime  $T_S^{\perp,\parallel}$ ,<sup>13,14</sup>

$$(T_S^{\perp,\parallel})^{-1} = (\tau_S^{\perp,\parallel})^{-1} + \tau_R^{-1}, \quad (1)$$

when hole spins are considered to be already relaxed. Carrier lifetimes were measured using time-resolved transmission (TRTR) simultaneously to TRFR, in order to determine electron spin relaxation times from the measured spin lifetimes. All measurements were performed using a picosecond-pulsed laser with energies tuned to the lowest QW electron-hole transition confirmed independently by TRTR and photoluminescence (PL) at each temperature. The small spectral width of the picosecond laser (full width at half maximum of 0.5 nm) reduces the energetical width of occupied states and thus lowers the effect of inhomogeneous dephasing on  $\tau_S^{\perp}$ ,<sup>15</sup> which otherwise may mask the anisotropy caused by the DP mechanism. In this way, investigating our broadest In<sub>x</sub>Ga<sub>1-x</sub>As/GaAs (110) QW, we observed the highest spin relaxation anisotropy ever reported. We observed an increase of anisotropy with the increase of In concentration which is consistent with DP and confirmed that the anisotropy does not vanish at 10 K, as has been previously observed for a *n*-doped (In,Ga)As/(Al,Ga)As (110) QW.<sup>7</sup>

For all samples, the QW is formed by a single undoped and strained In<sub>x</sub>Ga<sub>1-x</sub>As layer sandwiched between intrinsic GaAs barriers grown by molecular-beam epitaxy. Three samples with different In<sub>x</sub>Ga<sub>1-x</sub>As layer thicknesses  $d$  and In concentrations  $x$  were grown on (110)-oriented semi-insulating GaAs substrates: samples A and B have the same  $d$

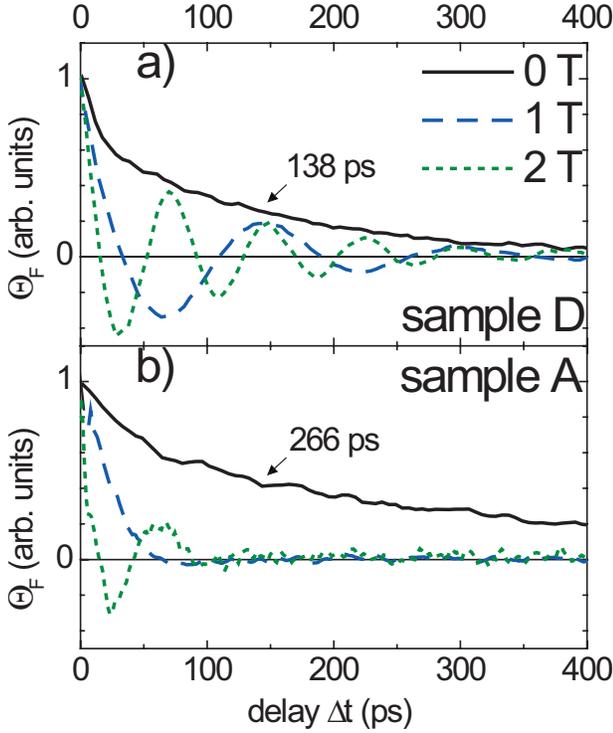


FIG. 1. (Color online) Faraday rotation angle  $\theta_F(\Delta t)$  of (a) (001)-oriented (sample D) and (b) (110)-oriented (sample A) samples for various transverse magnetic fields  $B_{ext}$  measured at 70 K.

=8 nm and In concentrations of  $x=11.5\%$  and  $x=19\%$ , respectively. Sample C has a much broader QW layer of  $d=14$  nm, but the same In concentration as sample A. Reference sample D was grown under the same conditions as sample A, but on a (001)-oriented GaAs substrate. For simultaneous TRFR and TRTR measurements, we employed a mode-locked Ti:Al<sub>2</sub>O<sub>3</sub> laser generating 1 ps optical pulses with 80 MHz repetition frequency. Normal-incident pump pulses, which were alternatingly left and right circularly polarized by a photoelastic modulator (PEM) working at 42 kHz and chopped at 1600 Hz frequency, excite spin-polarized electrons and holes along the growth direction. The evolution of the corresponding magnetization projected along this direction was determined by means of the Faraday rotation angle  $\theta_F$  of transmitted linear-polarized probe pulses, which were delayed by a variable time  $\Delta t$  with respect to the pump pulses. A balanced diode bridge was employed to measure  $\theta_F$  and the output was locked to the PEM frequency. The evolution of the filling of the QW is determined by the change of transmission  $\Delta\zeta(\Delta t)$  of the probe pulse and recorded by the sum of the intensities on the diode bridge locked to the chopper frequency of the pump beam.

Figure 1 displays  $\theta_F(\Delta t)$  for (001)-oriented (sample D) and (110)-oriented (sample A) samples at various transverse magnetic fields  $B_{ext}$ . Data were taken at 70 K, at which the longest electron spin lifetime as a function of temperature was found for sample A. Fitting the curves for zero magnetic field starting from  $\Delta t=50$  ps reveals a single-exponential decay reflecting the electron spin lifetime  $T_S^\perp$  to be 138 and 266 ps for samples D and A, respectively. An additional fast

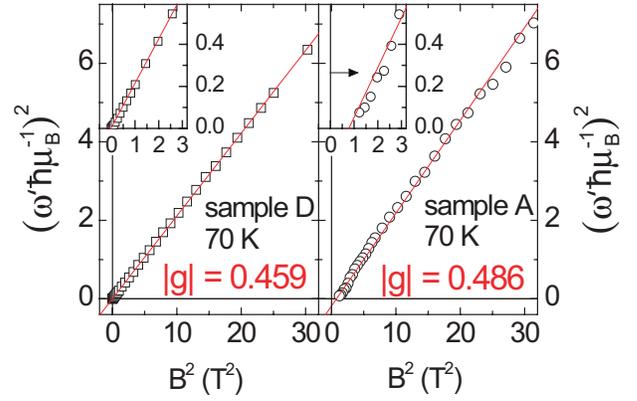


FIG. 2. (Color online) Square of measured Larmor frequency  $\omega'^2(B_{ext}^2)$  for (001)-oriented (sample D) (squares) and (110)-oriented (sample A) (circles) samples measured at 70 K; solid lines are linear fits; zoom near  $B=0$  T in the insets.

decay ( $<10$  ps at 70 K) might be caused by hole spin relaxation.<sup>16</sup> In a transverse magnetic field  $B_{ext} \neq 0$ , spin precession is observed in the control sample (sample D) for all  $B_{ext}$ , whereas spin precession is not observed at  $B_{ext} \lesssim 1$  T for the (110)-oriented sample (sample A). Additionally, the electron spin lifetime of sample A is dramatically reduced when a transverse magnetic field is applied similar to Refs. 7 and 11. The corresponding carrier lifetimes  $\tau_R$  at 70 K (not shown) turned out to be independent of the applied  $B_{ext}$  and are 600 and 675 ps for samples D and A, respectively, which reflects the fact that  $\tau_R$  does not depend on the electron-spin direction.

In order to model the complex  $B_{ext}$  dependence for the anisotropic sample A, the magnetization of electrons spins normal ( $S_\perp$ ) and parallel ( $S_\parallel$ ) to the QW plane has to be considered separately. The time evolution of  $\vec{S}$  in an in-plane magnetic field is given by<sup>10</sup>

$$\frac{\partial}{\partial t} \begin{pmatrix} S_\parallel \\ S_\perp \end{pmatrix} = - \begin{pmatrix} \Gamma_\parallel & -\omega \\ \omega & \Gamma_\perp \end{pmatrix} \begin{pmatrix} S_\parallel \\ S_\perp \end{pmatrix}, \quad (2)$$

where  $\omega = g\mu_B B_{ext}/\hbar$  is the Larmor frequency. For undoped QWs, the total relaxation rates  $\Gamma_{\perp,\parallel} = (T_S^{\perp,\parallel})^{-1}$  are the sum of the anisotropic electron spin relaxation rates  $\gamma_{\perp,\parallel} = (\tau_S^{\perp,\parallel})^{-1}$  and the isotropic carrier recombination rate  $(\tau_R)^{-1}$  in the QW:  $\Gamma_{\perp,\parallel} = \gamma_{\perp,\parallel} + (\tau_R)^{-1}$  in accordance with Eq. (1). The solution for  $S_\perp$ , which is measured by TRFR, is given by

$$S_\perp(t) = \frac{S_0}{\cos(\phi)} \exp\left(-\frac{\Gamma_\perp + \Gamma_\parallel}{2}t\right) \cos(\omega't - \phi), \quad (3)$$

with  $\tan(\phi) = (\Gamma_\perp - \Gamma_\parallel)/(2\omega')$  and the modified Larmor frequency

$$\omega' = \sqrt{\omega^2 - \left(\frac{\Gamma_\parallel - \Gamma_\perp}{2}\right)^2}. \quad (4)$$

In order to calculate the spin lifetime anisotropy, the square of the measured modified Larmor frequency  $\omega'^2$  of samples A and D is plotted as a function of  $B_{ext}^2$ , as displayed in Fig. 2. In the inset, a right shift of the plot for sample A is

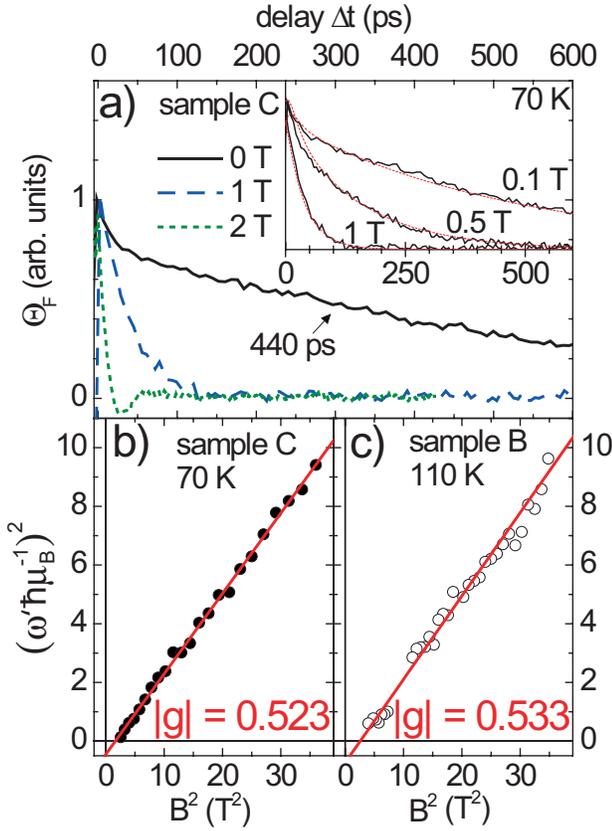


FIG. 3. (Color online) (a) Faraday rotation angle  $\theta_F(\Delta t)$  for the broad (110) QW (sample C) at various transverse magnetic fields  $B_{ext}^2$ ; inset: measurements (line) and simulations (dotted line) for imaginary  $\omega'$ ; Larmor frequency  $\omega'^2(B_{ext})$  for (b) (110) QW (sample C) and (c) (110) QW (sample B) measured at 70 and 110 K, respectively; solid lines are linear fits.

obvious and indicates the suppression of precession in the (110)-oriented QW. According to Eq. (4), this shift is caused by the difference of the total spin relaxation rates  $\Gamma_{\parallel} - \Gamma_{\perp}$  and thus by the spin lifetime anisotropy. From the right shift and the slope of the linear fit, both the difference of the relaxation rates  $\Gamma_{\parallel} - \Gamma_{\perp}$  and the absolute electron  $g$  factor can be determined, respectively. Using  $\Gamma_{\parallel} - \Gamma_{\perp}$  and assuming  $T_S^{\perp} = 266$  ps to be independent of  $B_{ext}$ ,<sup>7</sup> the in-plane spin lifetime of sample A is calculated to be  $T_S^{\parallel} = (13 \pm 2)$  ps. Thus, the anisotropy of the spin lifetime  $T_S^{\perp}/T_S^{\parallel}$  turns out to be  $21 \pm 2$  for sample A. The last assumption is justified, since the exponential decay in Eq. (3) is observed to be independent of the magnetic field in the oscillatory regime and simulations using constant  $T_S^{\perp}$  fit well in the nonoscillatory regime, which is demonstrated here for sample C in Fig. 3(a).

In the following, this result is compared to the other (110)-oriented QWs. Figure 3 shows  $\theta_F(\Delta t)$  at various  $B_{ext}$  for sample C as well as  $\omega'^2(B_{ext})$  for samples C and B. Data were taken at 110 and 70 K for sample B and sample C, respectively, at which the maximum of  $T_S^{\perp} = 335$  ps and  $T_S^{\perp} = 440$  ps was measured. Comparing  $\theta_F(\Delta t)$  of sample C to sample A [see Fig. 1(b)],  $T_S^{\perp}$  of sample C is found to be longer, but spin precession turns out to be even more suppressed, which indicates a higher anisotropy. The same can

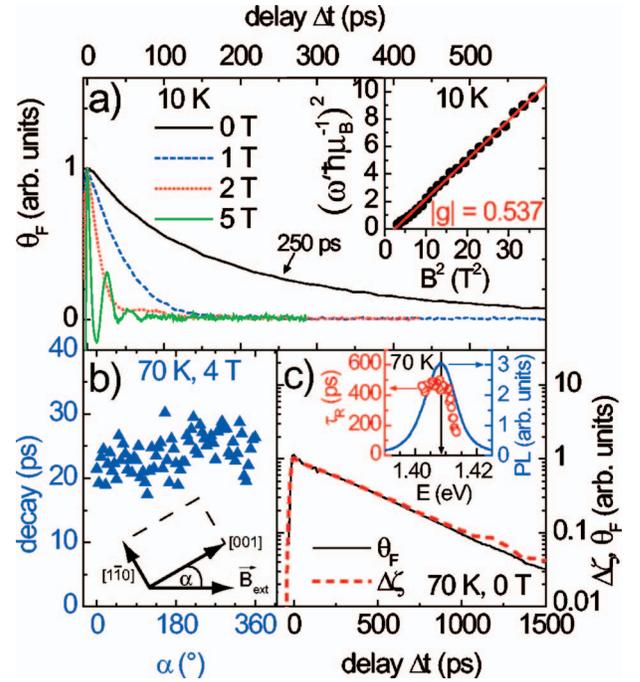


FIG. 4. (Color) (a) Faraday rotation angle  $\theta_F(\Delta t)$  and fitted Larmor frequency  $\omega'^2(B_{ext})$  (inset) for the broad (110) QW (sample C) at various transverse magnetic fields  $B_{ext}$  measured at 10 K; (b) fitted decay of  $\theta_F(\Delta t)$  measured as a function of angle  $\alpha$  between  $B_{ext}$  and [001] crystal direction at 4 T and 70 K for sample C; (c) comparison of  $\theta_F(\Delta t)$  and  $\Delta\zeta(\Delta t)$  for sample C at 0 T and 70 K measured with laser energy  $E$  as marked in the inset, where the PL spectrum is compared to  $\tau_R(E)$ .

be concluded from the pronounced right shift of  $\omega'^2(B_{ext}^2)$  [see Fig. 3(b)]. Using the derivation explained above, the anisotropy of the spin lifetime  $T_S^{\perp}/T_S^{\parallel}$  follows to be  $52 \pm 10$  and  $54 \pm 6$  with  $T_S^{\perp} = (6.5 \pm 0.8)$  ps and  $T_S^{\parallel} = (8.2 \pm 0.5)$  ps for samples B and C, respectively. Compared to the calculated value of sample A, the result for the deeper QW (sample B) has the correct tendency, since DP is more dominant for the latter according to theory. However, the high anisotropy for the broadest QW (sample C) is surprising and needs further discussion. The effectiveness of DP should be reduced for sample C, since  $\tau_S^{DP} \propto d^{-2} E_1^{-2} \propto d^2$ . The increased spin lifetime as well as the higher anisotropy compared to sample A might then be explained by a reduction of an isotropic spin relaxation channel. Scattering at the barrier interfaces, which has not been considered yet, might be a suitable candidate, since it can be assumed to be dependent on the volume-to-interface ratio and thus less pronounced for the broadest QW (sample C).

We now check the consistency of our results with our simple model and with DP theory by varying the temperature and the direction of the magnetic field. Since for the derivation of  $\Gamma_{\parallel} - \Gamma_{\perp}$  and the  $g$  factor only the oscillatory curves are considered as explained above, consistency of raw data with Eq. (3) is checked for imaginary  $\omega'$ . With only the amplitude  $S_0$  as a free parameter left, the simulations fit well to the measured  $\theta_F(\Delta t)$  curves of sample C, as can be seen from the inset of Fig. 3. Furthermore, we measured the anisotropy of sample C at 10 K, at which the isotropic BAP mechanism is

considered to be dominant and thus the anisotropy of spin lifetimes should be reduced. Indeed, a lower anisotropy of  $T_S^\perp/T_S^\parallel=39\pm 9$  is found for sample C at 10 K.<sup>16</sup> Since the anisotropy does not vanish, DP is still present at 10 K as was already observed for an (In,Ga)As/(Al,Ga)As (110) QW.<sup>7</sup> Finally, we checked for any in-plane anisotropy of the spin lifetime by rotating the sample *in situ* around the growth direction in a transverse magnetic field. Figure 4(b) displays no systematic changes of the decay for sample C at 70 K in the oscillatory ( $B_{ext}=4$  T) regime. Thus, in consistency with theory,<sup>6,8</sup> spin relaxation is equivalent for all spin directions in the plane of the QW.

In the end, we express the calculated anisotropy of spin lifetimes in terms of spin relaxation times using the carrier lifetime  $\tau_R$ . Since  $\Delta\zeta(\Delta t)$  is found to be independent of the transverse magnetic field (not shown) and thus  $\tau_R$  does not change with the spin direction, we can use Eq. (1) for our undoped QWs. The difference of the in-plane and out-of-plane electron spin relaxation rates  $\gamma_\parallel - \gamma_\perp = \Gamma_\parallel - \Gamma_\perp$  can be easily seen from the right shift of the linearly fitted  $\omega'^2(B_{ext}^2)$  leading to the anisotropy of spin relaxation times. For sample C,  $\Delta\zeta(\Delta t)$  and  $\theta_F(\Delta t)$  are measured simultaneously at zero magnetic field, 70 K, and with a laser energy  $E=1.409$  eV, as displayed in Fig. 4(c). Fitting  $\Delta\zeta(\Delta t)$  and  $\theta_F(\Delta t)$ , we determine  $\tau_R=(450\pm 20)$  ps and  $T_S^\perp=(440\pm 20)$  ps leading to  $\tau_S^\perp > 4$  ns. Data were taken in an energy region of the PL peak of the QW, where both  $\tau_R$  and  $T_S$  are found to be con-

stant [see inset of Fig. 4(c)]. Since  $\tau_R \gg T_S^\parallel$ , the limitation of the carrier lifetime for the calculation of  $\tau_S^\parallel$  is negligible according to Eq. (1). Expressing the anisotropy in terms of spin relaxation times, we thus obtain  $\tau_S^\perp/\tau_S^\parallel > 480$  for sample C at 70 K. This lower limit of the anisotropy is by a factor of 8 higher than the maximum anisotropy observed so far.<sup>7</sup> As the carrier lifetime  $\tau_R=675$  ps of sample A is considerably higher than its out-of-plane spin lifetime  $T_S^\perp=266$  ps, there is not much difference found when the anisotropy is expressed instead of spin lifetime in terms of spin relaxation time:  $\tau_S^\perp/\tau_S^\parallel=34\pm 7$ .

In conclusion, we observed anisotropic electron spin lifetimes in strained and undoped InGaAs/GaAs (110) QWs by the suppression of spin precession. Increasing the In concentration enhances the dominating DP mechanism and leads to a higher anisotropy consistent with theory. The broadest QW exhibits longest  $T_S^\perp$  as well as an unprecedented large anisotropy, which in terms of spin relaxation times exceeds 480 and does not vanish at low temperatures, when the isotropic BAP is most relevant. No in-plane anisotropy was found and the suppression of spin precession can be described by  $T_S^\perp, T_S^\parallel$  and the electron  $g$  factor in a transverse magnetic field.

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<sup>16</sup>Curve fitting is more complex at low temperatures, since the additional decay time in  $\theta_F(\Delta t)$ , increases with the decrease of the temperature. However, this decay is too short to determine its anisotropy.