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# Strongly-coupled electron and nuclear spin systems in InGaAs epilayers

A E Evdokimov<sup>1</sup>, M S Kuznetsova<sup>1</sup>, M Yu Petrov<sup>1</sup>, R A Potekhin<sup>1</sup>, Yu P Efimov<sup>2</sup>, S A Eliseev<sup>2</sup>, V A Lovtcius<sup>2</sup> and P Yu Shapochkin<sup>2</sup>

<sup>1</sup> Spin Optics Laboratory, Saint Petersburg State University, St. Petersburg, Russia

<sup>2</sup> Saint Petersburg State University, St. Petersburg, Russia

E-mail: evdokimov.artiom@gmail.com

**Abstract.** Photoluminescence (PL) polarization was experimentally studied for the samples with thick InGaAs epitaxial layers with different concentrations of donors in the transverse magnetic field (the Hanle effect). A well-pronounced W-structure observed in the set of samples under study indicate a strong electron-nuclear spin interaction. Analysis of the Hanle curves measured at different pumping powers provided important parameters of the electron-nuclear spin system, such as the Knight field and kinetic local field. We obtained characteristic values of the electron spin relaxation time by modeling the Hanle curves measured with fast modulation of the excitation polarization at different pumping powers,.

## 1. Introduction

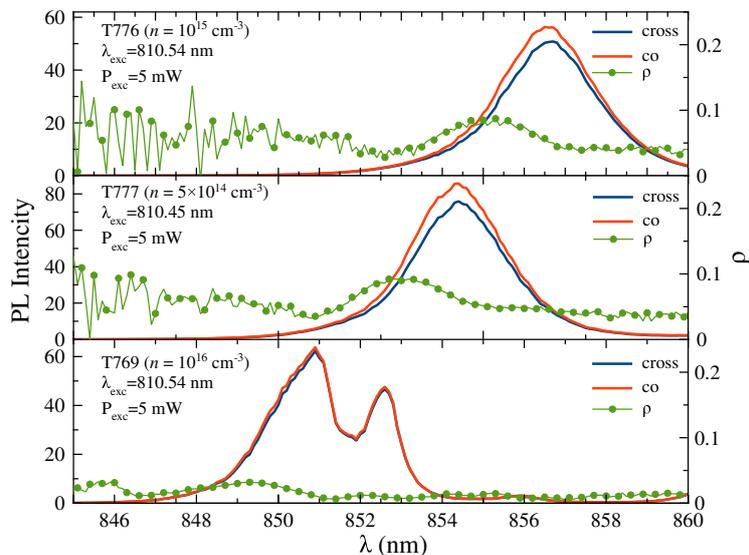
In semiconductor heterostructures, the absorption of circularly polarized light (a process also called optical pumping) leads to the formation of spin-oriented photoelectrons. In this case, the magnetic moments of the crystal lattice of nuclei become polarized due to the hyperfine interaction with polarized electron spins. This process is called the dynamic polarization of the nuclear spin system. Dynamically polarized nuclear spins, in turn, create an effective magnetic field (called the Overhauser field) that can significantly change the spin polarization of photoelectrons. As a result of this interaction, a strongly coupled electron-nuclear spin system is formed, where the polarization of nuclear spins is not only determined by the state of electron spins but also exerts its own influence on the polarization of electron spins. Thus, the electron spins are affected by an effective magnetic field due to oriented nuclear spins, which can reach several kilogauss. Due to the hyperfine interaction, the electron spin and the nuclear spins form a strongly coupled electron-nuclear spin system in bulk GaAs [1,2]. Such systems are believed to be promising for the realization of quantum information processing devices [3-5].

In this paper, we report on an experimental study of the electron-nuclear spin dynamics in thick InGaAs epitaxial layers. The nuclear spin polarization was studied in optical experiments by detection of the electron spin orientation via polarized photoluminescence in epilayers in the transverse magnetic field (the Hanle effect).

## 2. Experimental details

The experiments were performed on samples T776, T777 and T769 with n-doped InGaAs epitaxial layers grown by molecular beam epitaxy on GaAs substrates in the St. Petersburg





**Figure 1.** The PL spectra in co-(red) and cross-(blue) polarization relative to that of optical excitation and the spectral dependence of the PL circular polarization degree (green dots).

State University Resource Center "Nanophotonics". The epitaxial layers are crystal lattices of GaAs with a small substitution of  $\sim 3\%$  of Ga atoms by In atoms. The thickness of epilayers is  $4 \mu\text{m}$  for samples T776, T777 and  $10 \mu\text{m}$  for T769. Samples T776, T777 and T769 are doped with Si to provide different doping densities:  $n = 10^{15} \text{ cm}^{-3}$ ,  $n = 5 \times 10^{14} \text{ cm}^{-3}$  and  $n = 10^{16} \text{ cm}^{-3}$ , respectively.

In our experiments, the PL circular polarization degree was measured as a function of the magnetic field applied perpendicular to the optical axis. The depolarization curves were measured under optical excitation by a continuous-wave (CW) Ti:sapphire laser.

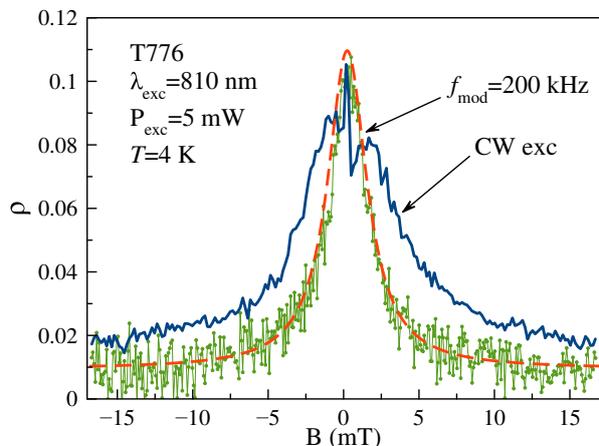
The sample was placed in a closed-cycle cryostat and cooled to a temperature liquid helium temperature ( $T = 4.2 \text{ K}$ ). Helmholtz coils were installed outside the cryostat in order to create a magnetic field perpendicular to the optical axis. The sample was excited with a circularly polarized light with a photon energy  $E = 1.52 \text{ eV}$ . The degree of circular polarization ( $\rho$ ) of photoluminescence is measured by a standard method using a photoelastic modulator operating at a frequency of  $50 \text{ kHz}$  and an analyzer (Glan-Taylor prism). A polarized photoluminescence signal passing through a double monochromator is detected using an avalanche photodiode. The modulation of the polarization of optical excitation between  $\sigma^+$  and  $\sigma^-$  polarizations is created using an electro-optical modulator followed by a quarter-wave plate.

Figure 1 shows the photoluminescence spectra measured for all samples under study in co- and cross-polarization relative to that of optical excitation. The graphs also show the non-monotonic curves of the degree of photoluminescence polarization (the dotted green curve), which is used in further measurements. The wavelength for the detection of Hanle curves was selected precisely because in the experiment we are interested in the range of wavelengths at which the highest polarization of electrons is achieved.

### 3. Results

#### 3.1. Hanle effect with continuous-wave excitation

The classical curve of depolarization of the electron spin in the transverse magnetic field has the Lorentzian shape. Due to a strong interaction between electron and nuclear spin systems

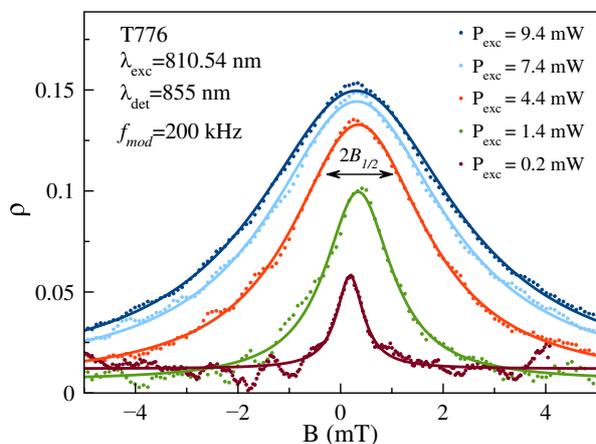


**Figure 2.** Hanle curves measured under CW excitation (blue line) and with modulation of the polarization of optical excitation (the green curve fitted with the Lorentzian shown by red dashes).

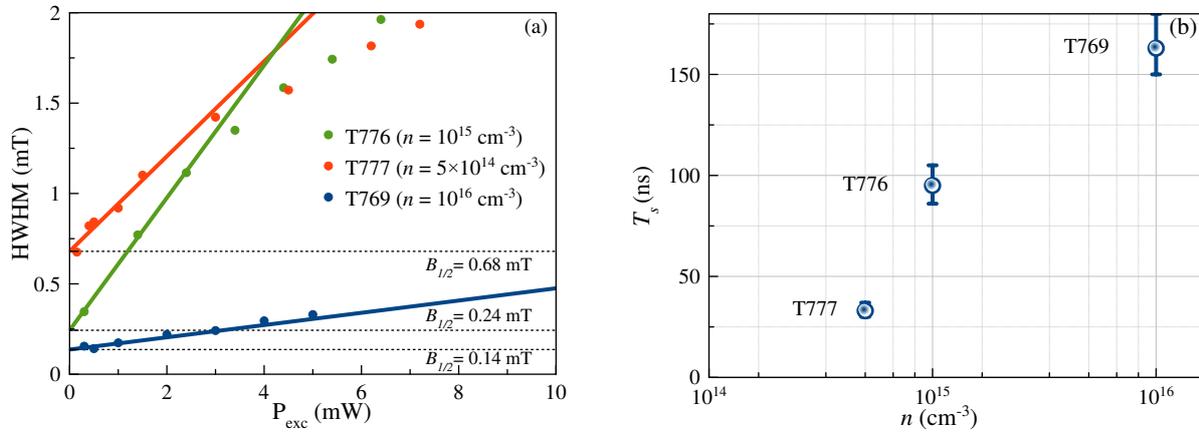
in our structures, the shape of the Hanle curve dramatically changes from Lorentzian to the so-called W-structure. The mechanism of forming such a complex structure is explained in details in [6]. Figure 2 shows the Hanle curves under CW excitation (blue line) with a fixed polarization and with modulation of the polarization of optical excitation (green line), measured for sample T776. A high degree of circular polarization of photoluminescence was observed. This degree of polarization is approximately 3 times higher than that in bulk GaAs with similar doping densities [7]. As seen from figure 2, the Hanle curve measured under CW excitation has a well-pronounced W-structure, which is evidence for a strong nuclear spin interaction. Besides, the Hanle curve measured with fast modulation of the polarization has a Lorentzian shape.

### 3.2. Electron spin relaxation times

In the first part of the research, the behavior of electron spins was studied, which plays an important role in building a complete picture of the interactions between electron and nuclear spin systems. To obtain the electron spin relaxation time, we measured a set of Hanle curves measured with a fast modulation of the polarization of the optical excitation at different pumping powers (figure 3). At sufficiently high modulation frequencies of the exciting light polarization, the nuclear spin polarization does not develop, and the Hanle curves shown in figure 3 can be assumed with good accuracy to have a Lorentzian shape. The analysis of experimental data



**Figure 3.** Hanle curves measured for the fast polarization modulation  $f_{mod}(\sigma^+/\sigma^-)$  for various pumping powers.



**Figure 4.** (a) The dependencies of the half-width at half-maximum (HWHM) of the Hanle curves on the pumping power for three samples (points), approximated to the zero power by a linear function. (b) The spin relaxation time as a function of the doping density.

allowed us to determine the characteristic values of the electron spin relaxation time  $T_s$  for all samples.

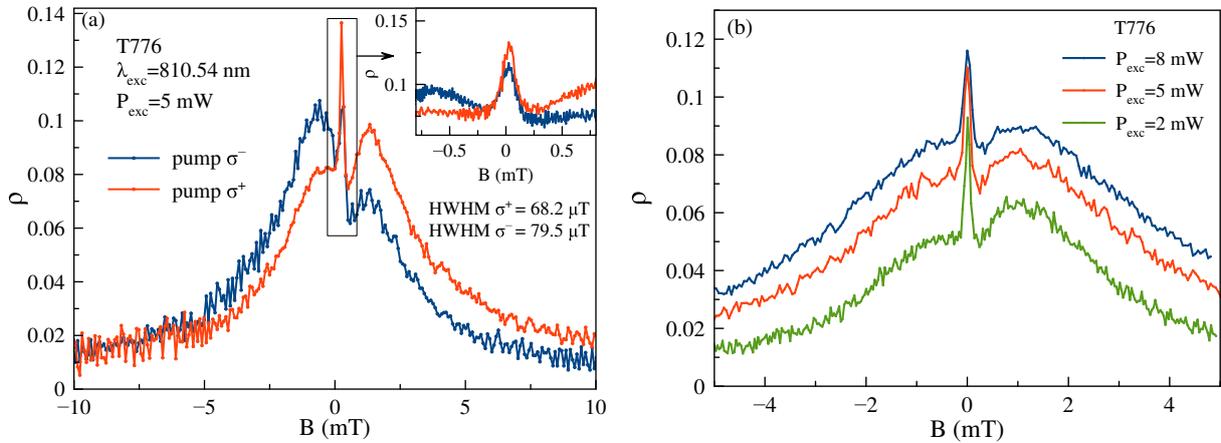
By fitting the Hanle curves by Lorentzians, we extracted the half-width at half-maximum (HWHM) for all measured curves at different pumping powers. Figure 4(a) shows the dependencies of the HWHM on the pumping power for all samples under study. The longest electron spin relaxation time should be observed at the minimum excitation power due to the suppression of electron scattering. We used the fitting to obtain the values of  $B_{1/2}$  for all samples.

The electron spin relaxation time can be found as  $T_S = \hbar/(\mu_B|g|B_{1/2})$ , where  $B_{1/2}$  is the HWHM of the curve,  $\mu_B$  is the Bohr magneton, and  $g$  is the electron g-factor. The g-factor of bulk GaAs is  $g = -0.44$  and  $g = -0.55 \div -1.5$  for InGaAs quantum dots, depending on the indium concentration. We used the g-factor value equal to  $-0.5 \pm 0.05$  to calculate the electron spin relaxation time, assuming that the g-factor value for our structure lies in between the g-factor of bulk GaAs and the g-factor of InGaAs quantum dots with the lowest indium concentration. Figure 4(b) shows the dependence of the calculated effective spin relaxation times on the doping density of the samples under study. We obtained relatively long electron spin relaxation times from the calculation:  $T_S = 33 \text{ ns}$  for sample T777,  $T_S = 95 \text{ ns}$  for sample T776 and  $T_S = 163 \text{ ns}$  for sample T769 (see figure 4(b)). The last value is comparable with that observed for bulk GaAs with an optimal doping [8].

### 3.3. Electron-nuclear spin-spin interaction

In the second part of the work, the interaction of the electron-nuclear spin system was studied. Figure 5(a) shows the Hanle curves obtained with CW excitation for the sample T776. The Hanle curves were measured at different signs of circular polarization of excitation. The inset shows the central parts of the Hanle curves. From the analysis of the central peaks of the Hanle curves, we obtained the HWHM  $\delta B = 68 \mu\text{T}$  (co),  $79 \mu\text{T}$  (cross) for sample T776. Such narrow central peaks of the Hanle curves indicate the high quality of the structures under study.

Figure 5(b) shows a set of Hanle curves measured at different optical excitation powers. We analyzed these data to obtain the value of the kinetic local nuclear field and the magnitude of the Knight field. For these calculations, we used the model described in detail in [6], where the parameter  $\Lambda$  was introduced. The values of  $\Lambda$  could be extracted from experimental data using

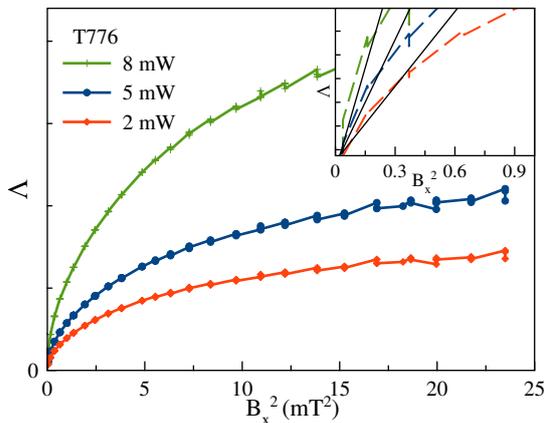


**Figure 5.** (a) The Hanle curves measured in co-(red) and cross-(blue) polarization relative to that of optical excitation, the inset shows the central parts of the Hanle curves. (b) The Hanle curves measured at different pumping powers.

the equation [6]:

$$\Lambda = \frac{B_x}{B_{1/2}} \frac{\langle S_z \rangle}{\langle S_0 \rangle} \left( \frac{\langle S_0 \rangle}{\langle S_z \rangle} - 1 \right)^{1/2} = \frac{B_x^2 + \xi B_L^2}{B_e^2}.$$

Figure 6 shows the dependence of the calculated parameter  $\Lambda$  on  $B_x^2$ . However, unlike the linear dependence obtained in [6] the measured dependence turned out to be linear only in a small range of external magnetic fields. This can be attributed to the long spin relaxation time of electrons obtained in our experiments and presence of residual quadrupole interaction. The quadrupole splitting of nuclear spin states occurs in our system due to the deformation of the crystal lattice. Therefore, we believe that the existing model should give a reasonable approximation for the values of the Knight field and the kinetic local field in the region of small magnetic fields. We obtained the values of the kinetic local field  $\xi B_L^2 = 2.6$  and  $2.9 \text{ G}^2$  for samples T776 and T777 respectively. The values that were calculated theoretically and obtained experimentally in [6] equal to  $4.6$  and  $6.2 \text{ G}^2$  for bulk GaAs, which corresponds in



**Figure 6.** Dependence of the parameter  $\Lambda$  on the squared transverse magnetic field  $B_x^2$ . The inset shows the same dependences in the region of small external magnetic fields. The linear approximation is shown by solid lines.

order of magnitude to the values measured for our systems. In addition, we obtained the values of the Knight field for different pumping powers from the analysis of the parameter  $\Lambda$ . For sample T777, the Knight field turned out to be:  $B_e$  (2 mW) = 1.96 mT, (5 mW) = 2.43 mT, (8 mW) = 2.66 mT. For sample T776, the Knight field turned out to be  $B_e$  (2 mW) = 1.37 mT, (5 mW) = 2.05 mT, (8 mW) = 2.48 mT.

#### 4. Conclusion

As has been repeatedly mentioned, the physical nature of the interactions between electron and nuclear spin systems is quite complex. The reasons for this is that, at first, our structures contain several types of nuclei, and when indium atoms fit into gallium sublattice, the structure becomes strained and, as a result, the quadrupole splitting of nuclear spin sublevels occurs. Second, due to the inhomogeneity of the electron wave function on different nuclei, the nuclear spins feel the effect of the Knight field of various magnitudes. Because of this inhomogeneity, it turns out to be quite difficult to polarize the nuclear system evenly.

A high degree of polarization luminescence up to 15% was observed in the studied samples. Long times of electron spin relaxation were experimentally obtained:  $T_S = 33$  ns for sample T777,  $T_S = 95$  ns for sample T776 and  $T_S = 163$  ns for sample T769. The central peaks of the Hanle curves have an extremely narrow width.

The analysis of the experimental measured at different optical excitation powers allowed us to receive important parameters of the electron-nuclear spin system such as the kinetic local field  $\xi B_L^2 = 2.6$  G<sup>2</sup> and  $\xi B_L^2 = 2.9$  G<sup>2</sup> for samples T776 and T777, respectively, and the Knight field values ranged from 1.96 to 2.66 mT for sample T777 and from 1.37 to 2.48 mT for sample T776 with pumping powers varied from 2 to 8 mW.

All these results allowed us to conclude about the high quality of the structures under study and to consider these samples as promising for further study of electron-nuclear interactions and the creation of a magnetically ordered nuclear spin system.

#### Acknowledgments

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