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Determination of the local field in the nuclear spin system of n-type GaAs

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Abstract. The nuclear spin system of a semiconductor can be cooled down to the microKelvin range of spin temperatures using optical pumping with subsequent adiabatic demagnetization. The efficiency of the nuclear spin cooling depends on the local field B_L , which is created by dipole – dipole interaction between nuclear spins. In this work we develop a method of experimental determination of the local field in semiconductor structures by using optical cooling and adiabatic demagnetization of the nuclear spin system, and apply it to measure B_L in n-GaAs.

1. Introduction

Electron spins in semiconductors can be optically oriented by illuminating the semiconductor crystal with circularly polarized light [1]. Recombination of such spin-polarized electrons with holes results in circularly polarized photoluminescence (PL). The degree of polarization of the PL is proportional to the electron spin, and can be used as an indicator of the spin states of electrons. At the same time, optical polarization of electron spins can give rise to nuclear polarization in semiconductors. The reason for this is a hyperfine interaction between electrons and nuclear spins. Such interaction provides a transfer of angular momentum from electrons to nuclei, via flip-flop transitions between electron and nuclear spins. The polarization of nuclear spins leads to appearance of the effective magnetic field created by nuclei upon electron spins. The nuclear field (Overhauser field) B_N can reach several Tesla ($B_{N\ max} \sim 5.3$ T for GaAs [1]), strongly affecting the electron spin state [1, 2]. So, due to hyperfine interaction and, in particular, due to the existence of nuclear field, processes in the nuclear spin system can be studied by measuring the degree of polarization of the PL.

Nuclear spins are also affected by interactions within the nuclear spin system (NSS). In particular, the dipole-dipole interaction creates local fields in which nuclear spins precess with Larmor periods of order of 10^{-4} s. These magnetic fields, created by magnetic moments of nuclei, fluctuate in time due to directional fluctuations of the nuclear spins. The time average of these fields is zero, but the mean squared local field, B_L^2 , is not zero. The dipole-dipole interaction leads to relaxation of nuclear angular momentum with the characteristic time T_2 . During this time a thermodynamic equilibrium is established, so that the NSS can be characterized by a nuclear spin temperature Θ ($\beta = 1/\Theta$ – is the inverse spin temperature). This temperature can be significantly different from the lattice temperature, towards which it would relax with the spin-lattice relaxation time $T_1 \gg T_2$. The NSS can be effectively cooled by circularly polarized optical pumping in an external magnetic field, when the energy flow from optically polarized electrons into the NSS can change nuclear spin temperature by orders of magnitude [1].

Apart of kinetic properties of the NSS, the local field B_L characterizes also its thermodynamic properties, being the measure of the NSS heat capacity [3, 4]. In particular, B_L determines the limit of lowering the temperature of the NSS by adiabatic demagnetization. This



method allows one to obtain extremely low nuclear spin temperatures, reaching 10^{-6} K at the lattice temperature of 4 K [5, 6]. In external fields $B < B_L$ the spin temperature does not depend on B , and the nuclear magnetization is proportional to B and inversely proportional to the spin temperature (Curie law). The Overhauser field created by polarized nuclear spins enhances the external field by hundreds times [1], allowing one to manipulate electron spin polarization in semiconductor structures by applying very weak (microTesla) external fields. So, experimental determination of the magnitude of B_L is vital for planning experiments on deep cooling of the NSS and studying its interaction with electron spins.

2. Experimental results

We study n-type GaAs doped by silicon with concentration $n \sim 10^{15} \text{cm}^{-3}$ at the liquid helium temperature. Samples under study were pumped by circularly polarized light from a semiconductor laser, and we measured the degree of circular polarization of the luminescence ρ which is proportional to electronic spin $\langle S_z \rangle$, where z is the direction along the excitation beam. For our sample, the maximum degree of the PL circular polarization was $\rho_{max} = 4\%$. We realized a precise (limited by the photon statistics) method for measuring the PL polarization, using a photoelastic modulator combined with a two-channel photon counter [5]. PL was detected by an avalanche photodiode. The geomagnetic fields were compensated to the level below 0.005 G by three pairs of Helmholtz coils. Our experiments were conducted in three stages. First, the NSS was prepared in the equilibrium with lattice temperature (optical excitation and magnetic fields were turned off). Secondly, the NSS was cooled by circularly polarized light in the longitudinal magnetic field $B_z = 100$ G during the time $t_{cooling} = 10$ s. Flip-flop transitions with optically spin-polarized electrons provided the energy flow into the NSS that resulted in decreasing the absolute value of the nuclear spin temperature. Depending on mutual orientation of \vec{B}_z and \vec{S}_z , positive (at $B_z \uparrow \uparrow S_z$) or negative (at $B_z \uparrow \downarrow S_z$), nuclear spin temperatures could be obtained. At the third stage, longitudinal magnetic field B_z was adiabatically slowly turned off and the transverse magnetic field was switched on. The cooled NSS was adiabatically re-polarized in the transverse field, with nuclear spin polarization obeying the dependence [5]:

$$p_N = \langle I \rangle / I = \frac{I+1}{3k_B \theta_N(0)} \hbar \gamma_N B_{\perp} \sqrt{\frac{B_L^2}{B_{\perp}^2 + B_L^2}}, \quad (1)$$

where I is the nuclear spin, $\langle I \rangle$ is the mean nuclear spin, γ_N is the nuclear gyromagnetic ratio averaged over all the isotopes (^{71}Ga , ^{69}Ga , ^{75}As) present in GaAs, k_B is the Boltzmann constant, B_{\perp} is the transverse magnetic field, and $\theta_N(0)$ is the nuclear spin temperature immediately after adiabatic demagnetization.

The nuclear spin polarization then relaxed with the spin-lattice relaxation time T_1 . We could trace the dynamics of nuclear polarization by measuring the Overhauser field [1], acting upon electron spins:

$$B_N = b_N \cdot \langle I \rangle / I, \quad (2)$$

where b_N is the maximum value of the Overhauser field corresponding to complete polarization of nuclei; for GaAs, $b_N = 5.3$ T [1].

To this end, we continued to pump the sample with circular-polarized light, and detected the PL polarization ρ . The value of ρ was affected by electron spin depolarization in the effective transverse magnetic field B_{eff} (Hanle effect [1]). As in our case, the time dependence of reflected the dynamics of nuclear spin polarization. A typical experimental curve is presented in figure 1 (blue line).

We fit the experimental time dependence of $\rho(t)$ by the following Eq. (3) (figure 1, red dashed line):

$$\rho(t) = \rho(0) \cdot \frac{B_{1/2}^2}{B_{1/2}^2 + (B_{\perp} + B_N(t))^2}, \quad (3)$$

where $\rho(0) = \rho_{max}$, $B_{1/2}$ is the half-width at half maximum of the Hanle curve [1] and

$B_N(t) = B_N(0) \cdot e^{-\frac{t}{T_1}}$. The value of parameter $\rho(0) = 0.04$ is the maximum polarization degree of the PL for our sample, and $B_{1/2} = 100$ G were taken from the experiment on depolarization of electron spin in transverse magnetic field (Hanle curve) in absence of nuclear effects.

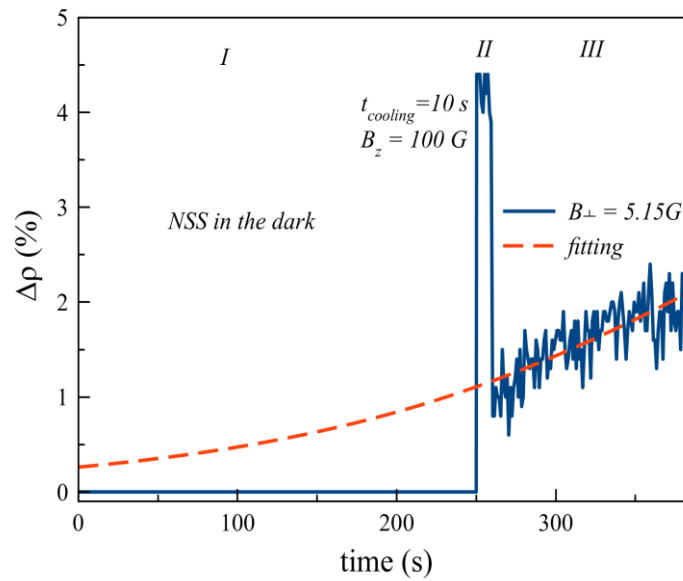


Figure 1. Time dependence of the PL circular polarization in n-GaAs (blue line): I) the NSS in the dark during 250 s; II) optical cooling of the NSS in the longitudinal magnetic field $B_z = 100$ G during 10 s; III) nuclear warm up at transverse magnetic field $B_{\perp} = 5.15$ G. The red dashed curve is the fit by Eq. (1).

Using $B_N(0)$ as the adjustable parameter, we fit experimental curves for each transverse magnetic field, and obtain values of $B_N(0)$ for different values of transverse magnetic field B_{\perp} . The nuclear field $B_N(0)$ just after adiabatic cooling depends on the external magnetic field B_{\perp} , local field B_L and on the inverse spin temperature $\beta(0)$:

$$B_N(0) = \frac{b_N \hbar \gamma_N I(I+1)}{3k_B} B_{\perp} \beta(0) \sqrt{\frac{B_L^2}{B_L^2 + B_{\perp}^2}}. \quad (4)$$

Based on experimental data and fitting of warm up of the NSS, we obtain the experimental dependence $B_N(B_{\perp})$ shown by circles in figure 2. After fitting experimental curve in figure 2 by Eq. (4) with the adjustable parameter B_L (figure 2, solid lines), we obtained the value of the local field $B_L = (6 \pm 2)$ G.

It is worth to note that the value of the squared local field determined in our experiments is larger than the value $B_L^2 = (2.1 \pm 0.1) \text{ G}^2$ calculated for GaAs by D. Paget [2]. This difference may be a

result of the quadrupole splitting of nuclear spin levels due to small residual strains in the structure; increased local nuclear fields in GaAs structures were earlier inferred from the experimental magnetic field dependences of the spin-lattice relaxation time T_1 [7, 8].

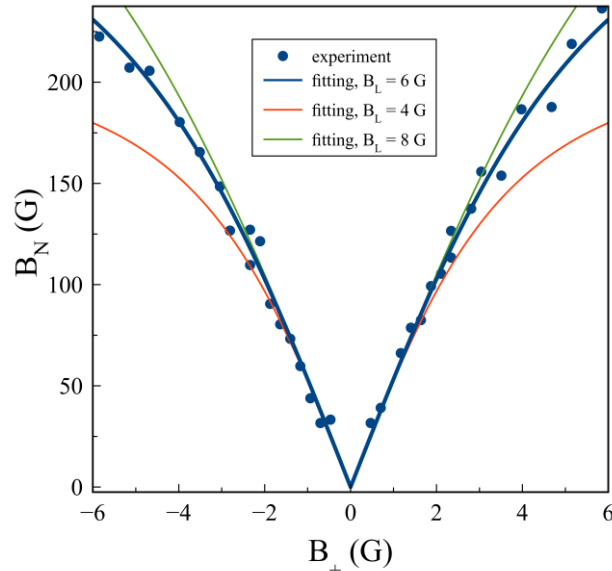


Figure 2. Experimental dependence $B_N(B_{\perp})$ for cooling time equal to 10 s (circles). Solid red, blue and green lines are calculated using Eq. (4) with the adjustable parameter $B_L = 4, 6$ and 8 G, respectively.

3. Conclusion

To conclude, in this work we presented an experimental method for determination of the local field B_L in the nuclear spin system of a semiconductor, exploiting optical cooling combined with adiabatic demagnetization of the NSS, and apply it to n-GaAs. The measured value of B_L in n-GaAs is larger than expected from purely dipole-dipole nuclear spin interaction, and most likely originates from strain-induced quadrupole splitting in our sample.

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