Effect of nuclear spins on the electron spin dynamics in negatively charged InP quantum dots.

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Abstract

Kinetics of polarized photoluminescence of the negatively charged InP quantum dots in weak magnetic field is studied experimentally. Effect of both the nuclear spin fluctuations and the dynamical nuclear polarization on the electron spin orientation is observed.

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Introduction

Strong localization of electrons in quantum dots (QDs) may considerably enhance hyperfine interaction of electron spins with those of nuclear\(^1\). Two effects of the interaction are possible. First, due to limited number of nuclear spins interacting with the electron spin in a QD, typically \(n \sim 10^5\), random correlation of nuclear spins may create a fluctuating nuclear polarization, \(\Delta S_N \propto S_N / \sqrt{n}\), where \(S_N\) is the total spin of the polarized nuclei. Fluctuation \(\Delta S_N\) acts on the electron spin as an effective magnetic field, \(\delta B_N\), with random magnitude and orientation\(^2\). Electron spin precession in this field results in the relatively fast dephasing of the electron spins in ensemble of QDs and in the three-fold decrease in magnitude of the total electron spin. Theoretical estimates for the GaAs QDs give rise to sub-nanosecond dephasing times\(^3\). This dephasing may prohibit from realization of the spin memory devices proposed by the so-called ”Spintronics”\(^4\). The fluctuating nuclear polarization may also hinder from study of the electron spin relaxation in steady-state conditions by means of Hanle effect\(^5\). Problem is that the electron spin does not ”feel” any external magnetic field while the field is weaker than the effective magnetic field of the fluctuations\(^2\).

Second effect of the hyperfine interaction appears when the nuclear spins are polarized, e.g., by means of optical orientation of the electron spin in presence of external magnetic field\(^6\). The dynamic nuclear polarization may act as a relatively strong effective magnetic field, \(B_N\), causing Zeeman splitting of the electronic sub-levels\(^7\). Thermalization of the electron spin to the lowest sub-level at the low temperature (freezing effect) may create the electron spin polarization which lives as long as the nuclear spin polarization lives. In this case, the long-lived spin memory can be realized due to the freezing effect rather than to slow electron spin relaxation theoretically justified for QDs by Khaetskii and Nazarov\(^8\).

In this work, we present the experimental study of nuclear field effects on long-lived spin polarization in singly charged InP QDs observed recently\(^9,10\).

I. EXPERIMENTAL

We have studied a sample with the single layer of the QDs grown between the InGaP barrier layers on the n-doped GaAs substrate by the gas source MBE technology. Semi-transparent indium-tin-oxide electrode was deposited on top of the sample to control the charged state of the dots by means of applied bias. It was found previously\(^10\) that the QDs contain one resident electron per dot (in average) at \(U_{bias} = - 0.1\) V.

To polarize spins of the resident electrons, we have used an excitation by the circularly polarized light at the energy which is slightly larger (\(\sim 40\) meV) than the energy of the lowest optical transition in the QDs (intra-dot excitation). Such excitation creates an electron-hole pair at an excited state. After energy relaxation followed by electron-hole recombination, spin orientation of the pair can be transferred to spin of the resident electron and conserved for a time interval much longer than the recombination time. Mechanisms of the spin orientation are widely discussed in literature (see, e.g.,\(^11\)).

II. EXPERIMENTAL RESULTS AND DISCUSSION.

For the QDs under study, spin polarization of the resident electrons can be detected by means of negative circular polarization of photoluminescence (PL) observed in the PL spectrum and kinetics\(^10\). An example of the polarization kinetics is shown in Fig 1. As it is seen, the polarization degree approaches some constant negative value called hereafter as the amplitude of the negative
circular polarization (NCP) of the PL. Mechanism of the NCP formation is discussed in Ref.\textsuperscript{10} where it is shown that the NCP amplitude reflects spin orientation of the resident electrons.

Inset in Fig.1 shows dependence of the NCP amplitude on the relatively small magnetic field applied along the optical axis of the excitation (Faraday configuration). The curve has a pronounced maximum at $B \sim 0$ which is well fitted by a Lorentzian curve with the full width at half maximum (FWHM), $\Delta = 30$ mT. The NCP amplitude at moderate magnetic field ($B > 0.1$ T) is three times larger in absolute value than that in maximum of the dependence. Similar behavior of circular polarization of PL was observed in Refs.\textsuperscript{4,7,8,9}.

In accordance with the theory, three-fold decrease in the NCP amplitude at $B \sim 0$ can be caused by the fluctuating nuclear polarization. For simple explanation of the of the NCP decrease, random orientation of the nuclear spin fluctuations can be replaced by the three types of the fluctuations directed along $x$, $y$, and $z$ axes with equal probabilities. Electron spins directed along $z$ axis will be dephased due to precession in nuclear fields, $\delta B_N$, directed along $x$ and $y$ axes but partly conserved for $z$ component of the field.

In presence of the longitudinal ($z$-oriented) external magnetic field, $B_{\text{ext}}$, electron spin “feels” the total field which is the vector sum of $\delta B_N$ and $B_{\text{ext}}$. Therefore effect of the nuclear spin fluctuations becomes negligible with the $B_{\text{ext}}$ rise. So the dependence $A_{\text{NCP}}(B_{\text{ext}})$ must reveal a singularity near zero value of $B_{\text{ext}}$. FWHM of the singularity allows us to estimate the strength of $\delta B_N$. As it is shown in the inset in Fig. 1, in our case this value is about 15 mT.

In Fig. 2(a), the dependence of the NCP amplitude on the magnetic field in Faraday configuration ($B \parallel z$) is compared with that in Voigt configuration ($B \perp z$). In the latter case, the NCP amplitude decreases in the magnetic field due to the electron spin precession around the magnetic field direction (Hanle effect). According to classical theory of the Hanle effect, FWHM of the magnetic field dependence, $\Delta B_H$, should be related to the spin relaxation time, $\tau_s$:

$$\tau_s = \frac{\hbar}{g\mu_B \Delta B_H},$$

where $g$ and $\mu_B$ are the electron $g$-factor and Bohr magneton respectively. Substituting experimentally determined value $\Delta B_H = 10$ mT to the above equation results in unreasonably small value of the spin relaxation time $\tau_s \approx 1$ ns which is approximately five orders of magnitude smaller than that measured in the direct experiment.\textsuperscript{10,11}

At the same time, the FWHM of the magnetic field dependence in Voigt configuration is very close to that in Faraday configuration [see Fig. 2(a)]. So, it is natural to suppose that, in our case, the Hanle effect is the result of competition between the external magnetic field and the fluctuations of nuclear field in the QDs.

In presence of the external longitudinal magnetic field and optical excitation, dynamic nuclear polarization may occur as it is discussed in the introduction. To estimate the effective magnetic field created by dynamical nuclear polarization, $B_N$, we have measured field dependencies of the NCP amplitude in Faraday configuration for two opposite circular polarization of the exciting light. The results of the experiment are shown in Fig. 2(b). The relative shift of the curves corresponds to the value of the dynamical nuclear field $B_N = 15$ mT. This value is the same order of magnitude as that obtained in Refs.\textsuperscript{7,9}.

As it is seen from inset in Fig. 2(b), the value of $B_N$
increases with increasing of the laser beam power, i.e., the nuclear field is really created by optical pumping. It should be emphasized that the power dependence of $B_N$ is clearly superlinear which is an indication of the threshold nature of the dynamical nuclear orientation process. At the same time, the values of $B_N$ optically created in InP QDs are much smaller than those for GaAs QDs presented in Ref. 1. Further studies are needed to understand this strong distinction between two types of QDs.

III. CONCLUSION

In conclusion, we have studied experimentally the effect of the small magnetic fields on the electron spin orientation in InP QDs. The abrupt increase of the spin orientation was found in the longitudinal fields larger than 0.015 T. In the transverse fields, the spin orientation abruptly decreased at the same values of the field. This behavior was explained as a result of competition between fluctuations of nuclear field in the QD and the external magnetic field. Mean value of the fluctuations of the nuclear field and the strength of the effective magnetic field created by the dynamical nuclear polarization are estimated from the experiments to be few tens of meV.

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1 D. Gammon, Al. L. Efros, T. A. Kennedy, M. Rosen, D. S. Katzer, D. Park, S. W. Brown, V. L. Korenev, and I. A. Merkulov, Phys. Rev. Lett. 86, 5176 (2001).
2 I. A. Merkulov, Al. L. Efros, and M. Rosen, Phys. Rev. B 65, 205309 (2002).
3 Semiconductor Spintronics and Quantum Computation, edited by D. D. Awschalom, D. Loss, and N. Samarth, Nanoscience and Technology (Springer, Berlin, 2002).
4 R. I. Dzhioev, V. L. Korenev, I. A. Merkulov, B. P. Zakharshenya, D. Gammon, Al. L. Efros, and D. S. Katzer, Phys. Rev. Lett. 88, 256801 (2002).
5 Optical Orientation. Modern Problems in Condensed Matter, edited by F. Meier and B. P. Zakharshenya (North-Holland, Amsterdam, 1984).
6 A. V. Khatskii and Yu. V. Nazarov, Phys. Rev. B 61, 12639 (2000).
7 R. I. Dzhioev, B. P. Zakharshenya, V. L. Korenev, P. E. Pak, D. A. Vinokurov, O. V. Kovalekov, and I. S. Tarasov, Phys. Solid State 40, 1587 (1998) [Fiz. Tv. Tela 40, 1745 (1998)].
8 R. I. Dzhioev, B. P. Zakharshenya, V. L. Korenev, P. E. Pak, M. N. Tkachuk, D. A. Vinokurov, and I. S. Tarasov, JETP. Lett. 68, 745 (1998) [Pis’ma ZHETF 68, 711 (1998)].
9 R. I. Dzhioev, B. P. Zakharshenya, V. L. Korenev, and M. V. Lazarev, Phys. Solid State 41, 2014 (1999) [Fiz. Tv. Tela 41, 2193 (1999)].
10 M. Ikezawa, B. Pal, Y. Masumoto, I. V. Ignatiev, S. Yu. Verbin, and I. Ya. Gerlovin, Phys. Rev. B (submitted).
11 B. Pal, M. Ikezawa, Y. Masumoto, and I. V. Ignatiev, Appl. Phys. Lett. (submitted).
12 I. E. Kozin, V. G. Davydov, I. V. Ignatiev, A. V. Kavokin, K. V. Kavokin, G. Malpuech, Hong-Wen Ren, M. Sugisaki, S. Sugou, and Y. Masumoto, Phys. Rev. B 65, 241312(R) (2002).