Review
of the Ph. D. thesis of Maria Kuznetsova
entitled "Nuclear spin effects in self-assembled quantum dots"
submitted for the degree of Doctor of Philosophy in Physics
at the St. Petersburg State University

The dissertation consists of 35 pages of text, list of references and 4 published articles.

The PhD thesis of M.S. Kuznetsova is performed in a relevant branch of physics, which is rapidly developed in the last decade. This area was specifically named "spintronics" because of the actively discussed possible applications to be used in systems of memory and logic for the new generation of computers. In this thesis several scientific problems on the dynamics of coupled electron-nuclear spin system was formulated and successfully solved for an interesting class of objects called quantum dots. In quantum dots, due to the strong localization of electrons, the hyperfine interaction with the nuclear system is much stronger than in the bulk material, which leads to a variety of new interesting effects. The study of these effects, however, is troubled by the quantum dot parameters spread, even grown the most perfect method, such as molecular beam epitaxy. The usual way to overcome this difficulty is to study a single quantum dot, which is associated with technical problems. In this work, M.S. Kuznetsova develops the original methods, which have yielded new data on the dynamics of the spin system for the inhomogeneously broadened ensemble of quantum dots. This is extremely promising for widespread use in the field.

The dissertation consists of an introductory chapter and of three original chapters. The object of study and the methods of experimental research are reviewed in the introductory chapter. The structures with (In, Ga)As/GaAs self-assembled quantum dots, grown by molecular beam epitaxy, were chosen as an object of study. Structures are n-doped by silicon, so the significant amount of quantum dots contains resident electrons. This allows one to study the spin dynamics of the system in the time range, which is not limited by the carrier lifetime. The investigation of a series of samples containing quantum dots, annealed at a variety of temperatures, is the original approach used in this work. Annealing allows one to change the hyperfine interaction strength in a controlled manner by changing the localization volume of the resident electron. The studies also revealed that the annealing leads to a change of the quadrupole splitting of the nuclear spin states, which was effectively used in the research described in the last chapter.

Experimental methods of the spin dynamics studies are based on the measuring of the polarized luminescence of quantum dots in a transverse magnetic field. The base variant of this method has been used for many decades, and the luminescence depolarization effect in a transverse field was named the Hanle effect. In the PhD thesis two original concepts, which allowed author to study the dynamics of the spin system, are used. First, effect of the negative circular polarization is studied, which allows one to monitor the polarization of resident electron, as well as the polarization of electron-nuclear spin system due to the connection with the nuclear spin polarization. Second, the investigation of the Hanle effect with time resolution of a fraction of a microsecond is realized in the work. This allowed author to study the dynamics of the system in a fairly wide range of time, and also to perform the resonant pumping of nuclear spin polarization.

The first original chapter (Chapter 2) describes a series of experiments of the Hanle curve measurements, including the sample excitation with short pulses of the circularly polarized light and the polarized luminescence registration after a dark interval of various duration. The strong modification of the Hanle curve is found in the experiments, which depends on excitation and registration protocols. In particular the narrowing of the Hanle curve is observed, as well as the disappearance of the so-called W-structure, which is usually observed in case of the dynamic nuclear spin polarization. The experimental results are interpreted in terms of a model, which considers the dynamic behavior of the longitudinal and transverse components of nuclear spin polarization. The latter component behavior is due to the quadrupole splitting stabilization of the nuclear spin states polarization. There is a question on this chapter. Why does the rise time of transverse polarization component differs from its decay time in a weak field and pretty close in a strong field?

In the chapter 3 the role of the spin fluctuations in the spin polarization destruction of the resident electrons is investigated. To that end the original method of compensation or, on the contrary, enhancement of the Knight field, acting on the nucleus from the resident electron, was used in experiment, applying the additional longitudinal magnetic field of small magnitude. In the experiments the strong modification of the Hanle curve is also observed, which is interpreted in the framework of the standard nuclear spin system cooling model, which was generalized by including the nuclear fluctuation field. In addition, the components of the electron and nuclear field directed along both the external field and the optical pump direction are considered in the theory. Generalization led to a rather complex system of equations, which was solved numerically. As a result a good description of the main experimental dependencies was obtained; in addition the parameters of the effective field of the nuclear spin fluctuations were defined. Apart from that, the analysis allowed author to visualize the field dependence of the Knight field vector and the effective nuclear field vector. I have one question to this part. Author wrote: "These numerical results, however, are in strong contradiction to our experimental observations; see Fig. 10.The central peak of the measured Hanle curves is higher than the other parts of the Hanle curve at any negative $B_z$… this contradiction is of principal importance…"

Could the low additional peaks on experimental curves in Fig.10 be explained by the inhomogeneous distribution of nuclear field in the QD ensemble (e.g. different leakage factor and/or electron mean spin), thus lifting the exact compensation with the external field? Similarly, could the presence of W structure at any B_z external field value come from the inhomogeneous distribution of the Knight field within the QD ensemble?

The final chapter describes a large series of experimental data covering the observation and systematic study of the nuclear magnetic resonance in the quantum dots ensemble. It should be emphasized that both the initiation of resonances and their detection was performed by purely optical methods. For this purpose, the circularly polarized excitation light is modulated at some frequency. It has been found that if the modulation frequency corresponds to the frequency of the nuclear spin sublevel transition in a magnetic field, a change (resonance) of the luminescence polarization is observed. Detection of such resonances outside the Hanle contour, defined only by the electron spin polarization subsystem, is the new result. These resonances are significantly enhanced, when the radio frequency field is applied with magnetic component directed along the optical axis. The theoretical analysis allowed author to identify resonance transitions in nuclei of different isotopes of atoms in the quantum dot. In particular, it was found that the strongest resonances are caused by transitions between the quadrupole split-off nuclear states. I have a question about the shape of resonance signal: modeling the observed peaks by Gaussian curves contradicts with the conventional dispersion-like shape during the resonant nuclear cooling. Did you try to fit the data with the dispersion-like curves?

In general, the work is done at a good professional level. The author is widely citing the literature on the topic. It should be noted that the results of this work have been reported at many international conferences.

Based on the foregoing, I do believe that the work of M. Kuznetsova is a complete scientific work, which contains whole series of important results on the subject of research. M. Kuznetsova deserves the award of the Ph. D. degree.

D. Sc. Vladimir L. Korenev

Laboratory of Optics of Semiconductors

Ioffe Physical Technical Institute,

Russian Academy of Sciences