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Doctoral dissertation abstract
"Spin dynamics and decoherence in semiconductor nanostructures"

The subject of the dissertation is the analysis of selected issues regarding evolution of spin states of carriers, electrons and holes, quantum confined in semiconductor nanostructures fabricated by means of self-assembly. The scientific problem that has been solved is providing a theoretical description of selected spin decoherence processes in quantum dots, and their coupled pairs, as well as their manifestations in nonlinear optical spectroscopy. Two types of structures are thus considered: quantum dots and their pairs, double quantum dots, in which carrier tunneling occurs. In such systems, the processes of relaxation and decoherence of carrier spin states are examined in the presence of external fields: electric and magnetic, as well as under pulsed laser optical excitation. The main part of the dissertation consists of the Introduction, seven chapters and Summary.

The first chapter is an introduction to the broad topic of semiconductor nanostructures. The self-assembled quantum dots, which are the main physical system considered, are discussed in more detail. Then, the topic of spin degree of freedom of electrons and holes in semiconductors is discussed and experimental methods are described, thanks to which it is possible to track the evolution of spin of carriers trapped in nanostructures, as well as to initialize spin.

The second chapter contains a description of the mathematical formalism used and elements of the theoretical model that are common to subsequent chapters. The first part defines the formalism and methods used by the author in the research, notation is also established. The presentation of the theoretical model contains extensive descriptions and derivation of elements known from literature, such as the eigenstates of carriers confined in nanostructures, the impact of external fields, the interaction of carriers with acoustic phonons, or the evolution of the system due to interaction with the environment. One of the derivations (higher orders of piezoelectric interaction with phonons) is the author's original result.

The following chapters contain a description of the conducted studies, as well as their results along with interpretation and discussion. The third chapter is devoted to the pure dephasing of the spin of resident carriers in doped nanostructures, which occurs during optical spin initialization. The formulated theoretical model takes into account the excitation of the system with a laser pulse and the interaction of carriers with acoustic phonons. Two channels of spin decoherence over the duration of the pulse are found: one due to the optical excitation itself, and the other resulting from interaction with acoustic phonons that follow the evolution of the system. In both cases, decoherence is interpreted as the result of the information about the spin state of the carrier leaking into the environment, which is a consequence of the fact that the initialization procedure itself depends on making photon absorption dependent on the orientation of the resident spin, so its occurrence is a kind of measurement. The calculations allowed for determination of optimal excitation conditions, at which the loss of coherence is minimal.

The fourth chapter formulates, in the language of the quantum Master equation, and examines the general model of spin and orbital evolution of carriers interacting with acoustic phonons and magnetic field in tunnel-coupled nanostructures. The results obtained via numerical solution of the model are presented, and the effect of system parameters on evolution of spin polarization and coherence are analyzed. It is shown that long-lasting spin polarization can be achieved after optical excitation of the system when the tunneling rate of one of the carriers to the adjacent quantum dot exceeds the intensity of the exciton recombination located in the excited dot. The destructive effect of spin relaxation during tunneling and inhomogeneity of the system on spin polarization in the magnetic field is also investigated. Additionally, the evolution of the system in a magnetic field tilted from the sample plane is discussed. The results are presented in the form of the simulated experimental signal.

The fifth chapter is devoted to calculations of the electron tunneling rate between quantum dots that occurs with a spin flip. The detailed calculations carried out in the multiband model are preceded by a perturbative estimation of the contribution from the main channel considered in the literature. The total effect is divided into contributions from various interactions, and those that dominate in given parameter ranges are indicated, showing the dominant role of spin-orbit interaction. It is shown that at non-zero temperature, due to virtual

tunneling, the effect gives a contribution to spin relaxation in each of the quantum dots, in particular forming a Zeeman-doublet relaxation channel that is active without the magnetic field.

The topic of the sixth chapter is pure spin dephasing occurring during the electron orbital relaxation in a magnetic field between states with unequal Zeeman splittings. The effect and its theoretical description are general. Its detailed analysis is presented on the example of electron tunneling between quantum dots with different effective g-factors. The degree of decoherence in typical, realistically modeled nanostructures is estimated, and a few methods are proposed to control or avoid decoherence. In particular, ways of controlling decoherence over an almost full range of values using an external electric field and a magnetic field gradient are described. It is also shown that at non-zero temperature due to virtual tunneling this effect leads to exponential decoherence at times comparable with those resulting from hyperfine interaction.

Chapter seven describes preliminary studies on the spin-dependent rate of phonon-assisted electron tunneling between quantum dots. It is proposed to use the difference of Zeeman splittings in two dots as the basis for spin filter operation. Calculations carried out in a simplified model show a strong blockade of tunneling of electrons in one of the spin states, which in an electric circuit should result in spin-polarized current of carriers.

The main part of the dissertation ends with a summary, which recapitulates and briefly describes the results presented in chapters 3-7, includes some more general conclusions and outlines a possible plan for further research.