論文の内容の要旨

Study on Nuclear Spin Manipulation in Single Quantum Dots by Optical Spin Pumping

(光スピン励起による単一量子ドットにおける核スピンの制御に関する研究)

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Semiconductor quantum dot (QD) nanostructures confine individual charge carriers in all three directions, leading to the formation of discrete energy levels, as such earning the moniker of "artificial atoms". QDs have attracted much attention over the last few decades for its potential in lasers, displays, telecommunications, spintronics, as well as for solid-state quantum computing technologies. QDs of III-V semiconductors, especially InAs and GaAs, are the most heavily investigated and thus have been at the forefront for realizing various applications. In particular for quantum computing technologies, the carrier spins trapped in QDs are suitable candidates as qubits and it has been predicted as well as demonstrated that these spins can have long lifetimes. However, as III-V materials have non-zero nuclear spins, the noisy environment from the fluctuation of the mesoscopic nuclear spins becomes a cause for concern as it is a prime source of carrier spin dephasing, which could significantly reduce the carrier spin lifetime. Just as the interaction between the nuclear and the carrier spins causes undesired loss of spin information, researchers have increasingly sought to make use of this interaction as a resource. The hyperfine interaction between the two spin systems allows for the transfer of spin from the carriers to the nuclei. As carrier spins can be optically oriented due to the selection rules of the interband transition, by continuous exciting spin polarized carriers in a QD, spin transfer could effectively align the nuclear spins in a process known of dynamic nuclear spin polarization (DNP). The polarized nuclear spins cause a shift in the energy of the carriers, an effect that can be exploited to measure the degree of nuclear spin polarization.

This thesis presents the study on nuclear spin manipulation by optical spin pumping in single InAs/GaAs self-assembled QDs grown by molecular beam epitaxy. This thesis can be considered to consist of three main works.

In the first work, we showed the contribution to DNP by the first excited state (p-shell) electrons in a QD even at zero external magnetic field. DNP by these excited state electrons manifested itself in the observation of the increase in the degree of nuclear spin polarization along with increase of the excited state population. Furthermore, we measured the nuclear spin polarization time by employing a circular polarization modulation excitation. We observed an abrupt increase in the length of time to polarize the nuclear spins, which we attributed to the increase in nuclear spin decay time due to the excited state electrons.

The second work focuses on the manipulation of the nuclear spin polarization by optical engineering using QDs embedded in photonic crystals. Photonic bandgaps are present in photonic crystals, resulting in modified density of states which in turn affects the radiative rate of the emission of the embedded QD. As DNP requires many repeated cycles of spin transfer, this process is thus limited by the radiative rate. By utilizing photonic crystals, we demonstrated the control of the degree of nuclear spin polarization by varying the radiative rate of QD emission.

We then outline a scheme for optical spin pumping for nuclear spin polarization by twisted light (light with non-zero orbital angular momentum). Due to the tight confinement of light in the cavity, the polarization (spin) and the spatial distribution of the light wave are no longer independently conserved, representing significant optical spin-orbit interaction. By exciting the cavity with a light beam with non-zero orbital angular momentum, we could generate spin polarized electrons in a QD which is coupled to the cavity. This spin polarized electrons can then transfer the spin to polarize the nuclear spins.

The results presented in this thesis provide new insights on the dynamics of nuclear spin in QDs, as well as methods to manipulate the nuclear spin ensemble. These methods could be used together with previously reported schemes of electron spin qubit manipulation, in order to alleviate electron spin dephasing, as well as paving the way for future devices such as nuclear spin based quantum memory and spin-photon interaction for twisted light.