論文の内容の要旨

論文題目　Study on Cavity Quantum Electrodynamics with Single Quantum Dots in High Q Photonic Crystal Nanocavities
(高 Q 値フォトニック結晶ナノ共振器中の単一量子ドットを用いた共振器量子電磁力学に関する研究)

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Cavity quantum electrodynamics (QED) studies light-matter interaction in cavities, especially in situations where quantum nature of the light and the matter is prominent. The study provides a basis for many applications ranging from efficient lasers to future quantum information devices. Recent evolution of nano-fabrication technologies enables the investigation of cavity QED effects in the solid-state. One of the most promising solid-state architectures is based on semiconductor quantum dots (QDs) coupled with photonic crystal (PhC) nanocavities. QDs have quantized energy levels for confined electron-hole pairs and behave as ideal 'atoms' in the solid. PhCs are composed of periodic modulation of refractive index, which provides photonic band gap: defects in the periodic lattice serve as excellent 'cavities'.

In the last decade, the field of QD-based cavity QED has rapidly progressed. Many pieces of interesting physics, including strong coupling between a single QD and a cavity, were observed and proofs-of-principle of several QD-cavity-based devices were done. For realizing such devices and for opening new capabilities, there remain many subjects to be solved: developing higher precision fabrication technologies for better QDs and PhCs, understanding peculiar physics in the solid state cavity QED systems, and so on. In addition, the demonstration of single-photon-level quantum nonlinearities in semiconductors has been considered as a milestone toward fruition of QD-based quantum information processing using single photon qubits. Although a few works on this subject have already been reported, strong breakthroughs are still demanded.

This thesis concerns those research issues and presents original research works on cavity QED effects in coupled QD-PhC cavity systems. By developing fine fabrication technologies, clean QD-PhC cavity QED systems are successfully realized and their interesting physics are discovered.

In chapter 2, bases of the QD-PhC cavity QED are discussed. After discussing fundamentals of QD and PhCs, widely-known Jaynes-Cummings model, a basic of cavity QED, is introduced. With the model, physics of the strong and weak coupling regime is reviewed.

Chapter 3 is devoted to study fabrication and characterization methods of the QD-PhC systems. In the first half part, fabrication techniques for high quality (Q) factor GaAs-based photonic crystal nanocavities are presented. Optimization processes of wafer design, electron beam lithography, and plasma dry etching are shown. A key technique is a sulfur-based surface passivation, which can reduce strong surface absorption loss in the cavities. With these technologies, the highest Q exceeding 60,000 for PhC cavity with QDs operating below 1 μm is demonstrated. In the latter part, several characterization methods optimized for measuring the single-photon-level signals from the coupled QD systems emitting around 1 μm are discussed.

In chapter 4, the application of multiple cavity QED effects on a single QD is examined. The QD was pumped by a cavity resonant excitation technique. At the same time, its emission was enhanced by the Purcell-effect of the weakly coupled cavity mode. Simultaneous utilization of the two effects enables efficient single photon emission from the QD with suppressed background emissions. The overall emission enhancement factor was about 180 compared to a bare QD.

In chapter 5, strong coupling between a single QD and a H1-type PhC cavity is demonstrated. Emission spectra under various detuning conditions were measured by a temperature tuning method. At the resonance condition, clear vacuum Rabi splitting of 124 μeV was observed. Strong coupling with two distinct modes is also investigated. From the QD-cavity coupling constants with the two modes, the location of the QD inside the cavity was extracted.

In chapter 6, solid state features in cavity QED phenomena of coupled QD-cavity systems are studied. First, effects of electron-phonon interaction on a QD-based cavity QED system are investigated both experimentally and theoretically. The vacuum Rabi spectra were strongly modified by the phonon effect and showed strong temperature and detuning dependences. At the resonance condition, the doublet vacuum Rabi spectrum becomes asymmetric and its splitting narrows with increasing temperature. Under detuned conditions, phonon-mediated emissions from the cavity mode were clearly seen. All of these behaviors were well explain by a cavity QED model with non-Markovian phonon bath. Second, peculiar triplet emissions from the strongly coupled QD-cavity system on the resonance condition are investigated. By increasing the pumping power onto the system, the vacuum Rabi spectrum was changed from the doublet to the triplet. Combined with intensity correlation measurements, it is identified that the additional peak arises from a bare cavity mode emission and is driven by background emitters.

In chapter 7, single-photon-level nonlinear optical effects in a strongly coupled QD-cavity system were investigated. One of the interesting experimental observations is cavity enhanced spontaneous two photon emission from a single QD. Emission from a biexcitonic state in the single QD was investigated under various QD-cavity detunings. When the cavity mode was tuned to the center between the exciton and biexciton line, clear emission enhancement from the cavity was observed. This is a result of the two photon resonance of the QD's biexcitonic state to the cavity mode. The behavior was well reproduced by numerical calculations based on a master equation including the two photon contribution. Another nonlinearity discussed in this chapter is so called Jaynes-Cumming nonlinearity in cavity QED systems in the strong coupling regime. Theoretical discussions about how to probe the higher eigenstates, in other words, how to climb the Jaynes-Cummings ladders, are presented. One of the promising methods utilizes a broadband incoherent light illumination on the system for efficient accumulation of photons in the cavity. Using master equation based calculations combined with the input-output theory, it is indicated that climbing the ladder is now possible through QD-cavity systems with achievable Q factors by our state-of-the-art technology.

In Chapter 8, conclusions to this thesis are presented. Implications of the results presented in this thesis are discussed. An outlook for future research and development is also given.