論文 / 著書情報
Article / Book Information

題目(和文)	二重量子ドットと表面弾性波共振器を用いたハイブリッド量子系
Title(English)	Hybrid Quantum System with a Double Quantum Dot and a Surface Acoustic Wave Resonator
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出典(和文)	学位:博士(理学), 学位授与機関:東京工業大学, 報告番号:甲第11040号, 授与年月日:2019年3月26日, 学位の種別:課程博士, 審査員:藤澤 利正,吉野 淳二,上妻 幹旺,笹本 智弘,小寺 哲夫
Citation(English)	Degree:Doctor (Science), Conferring organization: Tokyo Institute of Technology, Report number:甲第11040号, Conferred date:2019/3/26, Degree Type:Course doctor, Examiner:,,,,
学位種別(和文)	博士論文
Category(English)	Doctoral Thesis
種別(和文)	要約
Type(English)	Outline

THESIS ABSTRACT

Hybrid Quantum System with a Double Quantum Dot and a Surface Acoustic Wave Resonator

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February, 2019

A hybrid quantum system is built up by more than two different quantum systems for utilizing advantageous properties or adding new functionalities, which cannot be realized in a single system. One of the schemes to form the hybrid system is cavity quantum electrodynamics (cQED), where a natural atom for static qubit and photons for a flying qubit can be strongly coupled in a resonator. The cQED has been extended to solid-state systems with micro- and nano- fabrication technology for semiconductors, allowing us to study and integrate various hybrid systems on a small chip like circuit-QED. On the other hand, another novel cQED (called acoustic-cQED) is expected by replacing a photon mode with a phonon mode, which essentially exists in solid-state systems. While electron-phonon coupling often causes negative effects in electronic devices like energy dissipation and decoherence, coherent electron-phonon coupling is expected by the cQED scheme and would open up active applications of phonons for the electronic devices. In this thesis, we propose and demonstrate a hybrid quantum system with a semiconductor double quantum dot (DQD) and a surface acoustic wave (SAW) phonon resonator on a GaAs/AlGaAs heterostructure for developing the acoustic-cQED. The system is an appropriate platform for the purpose because a charge qubit of the DQD has a large electric dipole and the high-quality resonator can provide a small mode volume of the SAW field associated with a small wavelength compared to light by five orders magnitude, giving promising estimation for the strong piezoelectric electron-phonon coupling regime, where the coupling strength is much larger than decoherence rate of the qubit and the resonant mode.

For developing acoustic-cQED, we need strong coupling regime by practically realizing a high-quality SAW resonator with a small mode volume. One scheme for the small mode volume is a reducing penetration length of a SAW into the surface periodic metal stripe structure that forms a Bragg reflector. The penetration can be made smaller by increasing the reflection coefficient of the SAW at the boundary between the metalized and free surface. Since the reflection coefficient depends on the material properties of the stripe and the substrate, we investigated the acoustic properties for different metals and demonstrated improvement of the reflection coefficient. The resonator characteristics were performed by comparing experimental electrical reflection spectrum, which is measured through an interdigital transducer (IDT), and simulated one which is numerically calculated from one-dimensional transmission model for a SAW with T-matrix. We find that Titanium is the best material for the SAW resonator among investigated metals, giving a promising estimation for the strong coupling regime. In addition, we studied quality factors and optimal design of the SAW resonator and obtained valuable findings for improving the resonator. Furthermore, we proposed and experimentally performed focusing structure for two-dimensional confinement of a SAW field. The focusing resonator successfully shows the quality factors comparable to the conventional (one-dimensional) structure.

We fabricated and performed the DQD-SAW device. We designed the device to be close to the maximum coupling condition, where the two dots of the DQD is located at anti-nodes of the resonant mode of the SAW. An important measure is a quality factor or finesse of the SAW resonator mode, which characterizes the enhancement of the piezoelectric electron-phonon coupling. This is investigated by measuring the current through a quantum point contact, which is proportional to a local piezoelectric potential around the DQD. This technique allows us to identify the spatial profile of the resonator mode besides the frequency spectrum of the resonator.

The experimental results show that the resonant mode of 3.2225 GHz with the quality factor of about 2400 and the finesse of about 80 is close to the maximum coupling condition. Another important milestone is demonstrating that the DQD couples with the resonant mode SAW, which is the acoustic analogy of a conventional cQED. We successfully observed this as phonon-assisted tunneling current through the DQD under the resonant mode SAW field, where the transition between the charge states is stimulated by absorption or emission of phonons with energy equal to the energy difference between the states. In the experiments above, we extracted the contribution of phonons (or removed that of photons as electromagnetic crosstalk on other words) by combining the measurements with a time-resolved measurement scheme.

The interaction between a two-level system and a bosonic field induce eigenstates called dressed states in the system. The dressed states are often investigated with bosonic spectroscopy for a triplet or doublet associated with a classical coherent or a vacuum field, respectively. While this scheme is successful in various systems, here we propose an alternative novel scheme where the interaction can be investigated from electron transport through a two-electron DQD. Our DQD-SAW device allows us to study the interaction with both phonons at the resonant frequency and photons at an off-resonant frequency by choosing the excitation frequency applied to the IDT. The (piezo-) electric field induces the dressed states for different charge states but does not for different spin states. In this work, we investigated the singlet dressed states by observing phonon/photon assisted transition from the triplet states, which can be used as the energy reference. The system can be initialized into the triplet state by the spin blockade effect, which results from the Pauli exclusion principle. The spin-flip mechanism is provided by inhomogeneous nuclear spin fields under the coherent field. We successfully observed the spin-flip transition current. The results agree with the numerical simulations obtained from the Lindblad master equation. In addition, by considering the Rabi model for the system, we find that permanent dipole coupling, which is associated with the electric dipole of the DQD, plays an important role for a strong coherent field. We believe that this scheme can be extended for studying the interaction with a vacuum filed. Interestingly, this scheme can be applied to a hybrid system with any or multiple bosonic systems such as magnons or plasmons.

In conclusion, we demonstrated the DQD-SAW hybrid system can encourage developing acoustic-cQED. For further study, it is important to realize the strong coupling regime, where non-classical phenomena and novel applications of phonons are expected.