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論 文 要 旨

THESIS SUMMARY

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要旨（英文 800 語程度）
Thesis Summary（approx.800 English Words ）

Electron-phonon coupling in solid-state systems essentially plays an important role in their properties. While the coupling causes negative effects such as energy dissipation or decoherence process, a coherent electron-phonon coupling is expected by considering the acoustic analogy of cavity quantum electrodynamics (cQED), indicating positive applications of phonons for electronic devices. For developing acoustic-cQED, we propose and demonstrate a hybrid quantum system, a semiconductor double quantum dot (DQD) embedded in a surface acoustic wave (SAW) phonon resonator on a GaAs/AlGaAs heterostructure. The system is a favorable platform to investigate coherent electron-phonon coupling 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. Acoustic-cQED has a unique feature that the coupling strength is characterized by material constants such as the electromechanical coupling coefficient, in contrast to conventional cQED, where the corresponding one is characterized by the fine-structure constant. If acoustic-cQED is successfully developed, such a novel research field is expected.

In this work, 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.

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. 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. 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.

For developing acoustic-cQED, we need strong coupling regime by practically realizing a high-quality SAW resonator with a small mode volume. In the case of the SAW resonator formed by Bragg reflectors made of periodic surface metal stripes, the mode volume is determined by penetration length of a SAW into the periodic stripe structure. The penetration can be made smaller by increasing the reflection coefficient of the SAW at the boundary between the metalized and free surface. Then we investigated the acoustic properties for different

metals and demonstrated improvement of the reflection coefficient. Here the resonator characteristics were performed by comparing the experimental electrical reflection spectrum, which is measured through an interdigital transducer, 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 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.

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.