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Quantum information devices based on semiconductor quantum dots

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1. Introduction

The quantum coherence in solid-state systems has attracted much attention for quantum information processing. In the quantum computing scheme, quantum state of each particle (qubit) is sequentially manipulated in a programmable manner so that some sorts of information processing can be performed efficiently in a parallel way [1,2]. The advanced quantum information processing has been led by various experiments on natural atoms, such as pulsed nuclear magnetic resonance of molecules and optically manipulated atomic states. Integrating sufficiently large numbers of qubits is essential for realizing a practical quantum computing.

Recent nano-fabrication technology allows us to design artificial atoms (quantum dots) and molecules (double quantum dots), in which atomic (molecular)-like electronic states can be controlled with external voltages [3]. Quantum states of interacting electrons in quantum dots can be well understood in terms of atomic physics language, but now can be controlled with adjustable voltages. High controllability of the artificial quantum system is desired for quantum information technology. Moreover, quantum dot characteristics have been obtained in various kinds of nanostructures, including metallic particles and synthesized molecules. Nano-fabrication capability is useful for large-scale integration as well as for designing a controlled environment surrounding a quantum system. In this talk, I review our recent experimental studies on coherence, dissipation, and decoherence in single-electron charge and spin in quantum dots.

2. Charge qubit in a double quantum dot

Consider two charge states, in which an excess electron occupies an energy state in one of the two dots. When the two localized states are coherently coupled with a tunneling barrier, the eigenstates become delocalized bonding and anti-bonding states [4]. Non-stationary superposition states can be obtained by applying a high-speed voltage pulse to an electrode [5]. This two-level system can be referred to as charge qubit.

When the double quantum dot is adjusted in the Coulomb blockade regime, the direct tunneling between the double dot and the electrode is suppressed, and the qubit is effectively isolated from the electrodes. By contrast, in the transport regime, the tunneling into the electrode significantly decoheres the qubit system. Therefore, strength of decoherence can also be controlled by an external voltage. In the experiment, we switched the double quantum dot from the transport regime to the Coulomb blockade regime to induce coherent oscillations. The quantum information of the charge quantum bit (qubit) can be manipulated by tailoring the pulse waveform. The experiments indicate the potential application for quantum information processing.

However, the charge qubit suffers from other uncontrolled decoherence, which might be originated from background charge fluctuations, higher-order tunneling effects, electron-phonon coupling etc. In future experiments, one has to design quantum dot structures and their parameters to reduce these decoherence problems.

3. Spin qubit in a quantum dot

Electron spin is a natural two-level system, and is considered as a best candidate for qubit, because of expected long decoherence time. In order to investigate relaxation mechanisms of electron spins in a realistic quantum dot, we employed an electrical pump-and-probe measurement to obtain an energy relaxation time [6]. As a reference, typical momentum relaxation time is 3 - 10 ns, which can be well understood by spontaneous emission of acoustic phonons. However, the relaxation involving spin-flip process shows a very long lifetime of about 200 μs, which is 4 or 5 orders of magnitude longer than momentum lifetime. The experiments indicate that the spin and orbital degrees of freedom are well separated in a QD system, which indicates potential applications to spin based information storage.

4. Summary

A double quantum dot provides an artificial charge qubit, which can be controlled with electrical voltages. Electron spin exhibits a long-lived spin state, which is desired for quantum information processing. Useful quantum information devices would be designed by combining charge (orbital) and spin degrees of freedom.

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