Graduate School of Pure and Applied Sciences

Summary of Doctor Thesis

Title: Theory of quantum phase manipulation in semiconducting and superconducting nanostructures

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・Abstract

In this thesis, we study the subjects related to quantum phase. In semiconductor nanostructure, electron plays a central role and its quantum phase appears as the argument of its microscopic wave function. The effect of this quantum phase can be verified by for instance the conductance oscillations with respect to magnetic flux penetrating the semiconducting Aharonov-Bohm ring [1]. On the other hand, in superconducting nanostructure, Cooper pair (=a pair of electrons) plays a central role and its quantum phase appears as the argument of its macroscopic wave function (=order parameter). The effect of this quantum phase can be verified by for instance the Fraunhofer pattern of supercurrent in the Josephson junction under magnetic field [2].

By the way, in quantum mechanics, charge and phase are not independent [3]. They are constrained with Heisenberg's uncertain relation. In this thesis, we focus on this relation. Manipulating phase in time and space enables us to control charge. The purpose of this thesis is to demonstrate the basic mechanism of controlling charge by the phase manipulation and propose the new way to manipulate phase of specific phenomena in semiconducting and superconducting nanostructures. In this thesis, we studied two main subjects: (1) Quantum adiabatic pumping [4,5] by manipulating tunnel phase in time in semiconducting quantum dot system, and (2) Quantum phase slip [6,7] by manipulating superconducting phase in space in superconducting loop with a Josephson junction.

(1) Quantum adiabatic pumping in semiconducting quantum dot system:

Electron shows wave-like behavior in the Aharonov-Bohm ring, on the other hand, electron shows particle-like behavior in the quantum dot. In the Aharonov-Bohm ring, two wave functions interfere between upper path and lower path of the ring, and eventually the conductance of the ring oscillates as a function of the magnetic flux penetrating the ring. In the quantum dot, the confinement effect and Coulomb charging effect enable us to control electrons one by one, and eventually the conductance of the dot oscillates as a function of the gate voltage. If we combine these two building blocks into the same system, then interesting phenomena so called Fano effect [8] emerges. This effect reflects both wave and particle properties of electron in such a hybrid system. That is the conductance shows the asymmetry with respect to gate voltage and this asymmetry depends on the magnetic flux penetrating the ring. In these quantum transport in the semiconducting nanostructures, it was clarified that phase degree of freedom of electron wave function is important. Therefore, we focus on the temporal modulation of phase degree of freedom. A phenomenon which is realized by adiabatically changing some control parameters of the nanostructures, so called quantum adiabatic pumping is actively investigated theoretically and experimentally. However, there are only a few previous research focusing on phase degree of freedom as the control parameter. In the former half of this thesis, we summarize our results of quantum adiabatic pumping by temporal modulating electron phase in semiconducting nanostructures (quantum dots) [9].

(2) Quantum phase engineering in superconducting system :

In Josephson effect, Cooper pair tunnels between two bulk superconductors separated with thin insulating barrier, and the phase of Cooper pair is well defined while the charge fluctuates. Recently, active researches are conducted on the quantum phase slip, which is a dual phenomena of the Josephson effect. In quantum phase slip, magnetic flux tunnels between two bulk insulators separated with superconducting nanowire, and the charge is well defined while the phase (magnetic flux) fluctuates. To realize quantum phase slip, inductance should be large because inductance increases phase fluctuations and decreases charge fluctuations. However, to make the superconducting junctions with large inductance is difficult [10]. Hence recent experiments of phase slip are actively performed on the superconducting junction connected with superconducting wire or Josephson junction chains as external environment to realize total large inductance. But these external environments have own excitations. In 1997, Hekking and Glazman studied the superconducting loop closed by single Josephson junction [11]. They showed how the properties of single Josephson junction is modified by the environment. Recent fabrication techniques enable us to choose the parameters of superconducting system from wide range. This offers the possibility to engineer the quantum properties of superconducting junction. We study phase manipulation in inhomogeneous superconducting system and show the possible control of physical parameters, for example, the Josephson energy [12] and phase slip rate [13].

The thesis is organized as following：

In chapter 2, we introduce the two important semiconducting nanostructure building blocks: Aharonov-Bohm ring and quantum dot. And then we introduce quantum pumping and summarize the previous works. In chapter 3, we study the quantum adiabatic pumping by controlling the phase of tunnel coupling and the level energy in quantum dot (QD) systems. We considered two models, (a) a series of two QDs coupled to the leads and (b) three QDs connected forming a ring structure. In chapter 4, we summarize the two important superconducting nanostructure building blocks: Josephson junction and superconducting nanowire. And then we introduce the duality between Josephson effect and phase slip which occur on Josephson junction and superconducting nanowire respectively. Moreover, we review Hekking and Glazman's work for the preparation of the next chapter. In chapter 5, we study quantum phase engineering in superconducting system. We propose a way to control the Josephson energy and the phase slip rate of a single Josephson junction embedded in one-dimensional superconducting metamaterial: an inhomogeneous superconducting loop, made out of a superconducting nanowire or a chain of Josephson junctions. In chapter 6, we conclude our main results and future works.

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