

Electron transport in metallic nanoscale constrictions

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論 文 内 容 の 要 旨

Recent development of information technology is supported by the miniaturization of electronic devices, which consist of the number of integrated circuits. The speed up of the operation in the circuits is challenging issue for modern device technology at the nanometer scale. Significantly, further miniaturization leads to basic changes in the device operation. It is well known that the conventional understanding of the transport phenomena is largely modified because of the existence of the surface boundary when the system size is smaller than its characteristic length such as coherence length, magnetic correlation length. Also, if the wire size is smaller than the mean free path of conduction electron, the ballistic electron transport can be observed with minimal scattering by impurities. In comparison with the bulk, therefore, the Ohm's law is invalid because the travelling distance of an electron is typically much larger than the system size. In this case, the resistance becomes independent of its length. These indicate that the electronic transport in nanosystems attract much attention not only for technical applications but also for advancement and understanding of basic science. This dissertation presents an experimental study of nanometer scale constrictions in various metallic systems.

Chapter 1 describes the motivation and the purpose of this work. Additionally, the theoretical background is presented, which mainly focuses two important keys for the analysis of the electronic correlation effect in nanosystems. First one is the Kondo effect which explains the scattering of impurity magnetic moment by conduction electrons. The Kondo singlet state is formed by shielding the magnetic impurity with the conduction electrons below Kondo temperature. The other is the Andreev scattering in superconducting Josephson junctions. The superconducting energy gap brings about the nonlinear current-voltage character at the normal metal-superconductor interface, which gives rise to the subgap structures (SGS's) inside the superconducting energy gap.

Chapter 2 explains the details of the experimental setup used in this thesis. A metallic nanocontact was prepared by a Mechanically Controllable Break Junction (MCBJ) technique, in which the sample wire was stretched by a mechanical force generated by a piezo element. Our apparatus can control the constriction size from a few 100 nm to atomic sized precisely. Next, differential conductance dI/dV measurements were described. The dI/dV spectra were recorded as a function of the bias voltage using a lock-in technique with a modulation frequency of 1 kHz. The whole experiment was performed at cryogenic environment, enabling to keep a stable contact for a long time by diminishing the thermal fluctuation. Besides, the cryogenic vacuum ($P < 10^{-4}$ Pa) environment prevents any contaminants at the contact during the experiments.

Chapter 3 summarizes the results during the spectroscopy measurements on cobalt (Co) nanoconstrictions by an MCBJ technique to understand the origin of Fano resonance in ferromagnetic atomic sized contacts. In an atomic scale contacts, most of the dI/dV spectra show the anomalies at around zero bias which are well-fitted by the Fano formula. The characteristic temperature, which is introduced as the fitting parameter of that formula, exhibits the log-normal distribution. These indicate that the anomaly is likely caused by Kondo effect. Moreover, the zero bias anomaly is observed even in 2 nm contacts suggesting the coexistence of Kondo effect and ferromagnetism. In this context, the spatial variation of the ferromagnetic moment may play a significant role for the appearance of Kondo resonance not only in atomic contacts but also in large sized constrictions.

Chapter 4 presents the evolution of conductance spectra during the rupture of the nonmagnetic metals of palladium (Pd) and platinum (Pt) constrictions using an MCBJ method by focusing on the ferromagnetic transition due to downsizing. The dI/dV spectra in both of these atomic contacts show zero bias anomalies reproduced by the Fano resonance. The amplitude of the zero bias anomalies increases almost linearly in logarithmic scale of temperature with decreasing the temperature and shows a plateau at lowest temperatures. On the other hand, the dip-like structure disappears at high temperatures. These characteristics indicate that the zero bias anomaly can be described by the Kondo model. From the obtained results in atomic scale contacts of Pd and Pt after the ferromagnetic transition due to downsizing, it is concluded that ferromagnetism is a necessary condition for Kondo effect in single metal.

Chapter 5 focuses the conductance of vanadium nanoconstrictions with the influence of small amount of hydrogen and deuterium impurities for studying the current-voltage (I - V) characteristics in the superconducting state. The results show that the hydrogen isotope environment has a strong effect on nanoconstrictions, which is markedly reflected by the growth of the conductance anomalies at the outside of the superconducting energy gap referred as an over-the-gap structure (OGS) though the only SGS forms inside the superconducting gap in pure vanadium. The temperature dependence of OGS follows the superconducting energy gap, indicates the appearance of OGS is due to the cause of superconductivity. The size dependence of these contacts reveals that the anomaly positions of OGS are reproduced by $1/d$, where d is the constriction size and also identical by plotting IV product. This is consistent with the theoretical model given by Anderson and also similar with the geometrical resonance in lead obtained by Tomasch.

Chapter 6 gives the concluding remarks of this thesis. Moreover, some unsolved problems in the present study are suggested for future studies.