Theory on the Coulomb Blockade and Current-Voltage Characteristics in Tomonaga-Luttinger C-SET

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(Dated: March 1, 2003)

Recent experiments of carbon nanotube-based double tunnel junction[1, 2] has opened the way to utilize a new type of self-organized exotic material for single electron devices. In these experiments the single-wall carbon nanotube (SWNT), which is the Tomonaga-Luttinger liquid (TLL) metal, serves as the island connected with Fermi liquid (FL) metal electrodes at the both ends. Under typical experimental setups, the contact between a SWNT and the electrode is not perfect, so the tunnel conductances (currents) show power-laws with different exponents with respect to bias voltage and temperature, depending on the fabrication methods of the contacts; *end-contacted* or *bulk-contacted*. This is due to the peculiarity of the *TLL metal of finite length*. Furthermore, the system exhibits a series of Coulomb oscillations and Coulomb staircases due to Coulomb blockade (CB) at low temperatures at the same time.

Nevertheless, the theoretical study of the transport properties of this kinds of systems has not yet been satisfactory in that there is no theory which can be directly applicable to such systems, because of difficulties in the theoretical treatment arising from both requirements of *an exact description of finite size TLL at arbitrary temperature* and *the consistent incorporation of the charging effect to such systems.* Actually, the power-law behavior of conductance was discussed assuming that the size of the TLL island is *infinite*, which is obviously inconsistent with the presence of charging energy. Furthermore, because of no relevant theory, measured data was arranged for discussion by subtracting temperature dependence expected by CB[2].

We propose a self-consistent microscopic theory on the Coulomb blockade in TLL C-SET (the capacitively coupled single electron transistor structure with TLL island connected with FL electrodes[3, 4]. This is the extention of the theory of FL C-SET[5]. Candidates for the island of TLL C-SET are carbon nanotubes and quantum wires. In this theory, the charging effect as well as the Tomonaga-Luttinger nature are treated in a consistent manner by bosonization technique (BT) with consideration of *zero modes* under *open boundary condition.* Application of the open boundary condition and the incorporation of the zero modes are both indispensable, since we are considering tunneling properties of the ultrasmall but finite TLL system.

Analytical expression of the tunneling current in TLL C-SET is obtained up to the lowest order with respect to the tunneling Hamiltonian for arbitrary environmental impedance. Tunneling current is determined by the effective local spectral density modified by the nature of ultrasmall TLL island (charging effect in the open boundary geometry), as well as by the density of states of the Fermi liquid electrodes. Due to the finiteness of the TLL island, however, the expression for the current (differential conductance) do not have explicit power-law form with respect to bias voltage and temperature in contrast to the infinite TLL system. Assisted by numerical calculations, we show that the theory reasonably describes current-voltage characteristics with Coulomb staircases and Coulomb oscillations as well as contact-nature dependent power-law behaviors. Based on the results, we discuss the exponents of the differential conductance for various conditions (symmetry of the junction, level spacing of the island, charging energy, contact nature, Luttinger parameter and temperature). While, in the infinite TLL, these exponents are determined only by the strength of electron-electron interaction, we will show that the exponents in the finite TLL slightly *depend on the system size* and tend to approach to the limiting values of the infinite system. Finally how to map the obtained general results into the experimental findings in SWNT-based TLL C-SET is briefly discussed.

References

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