Linear-response conductance of the normal conducting single-electron pump

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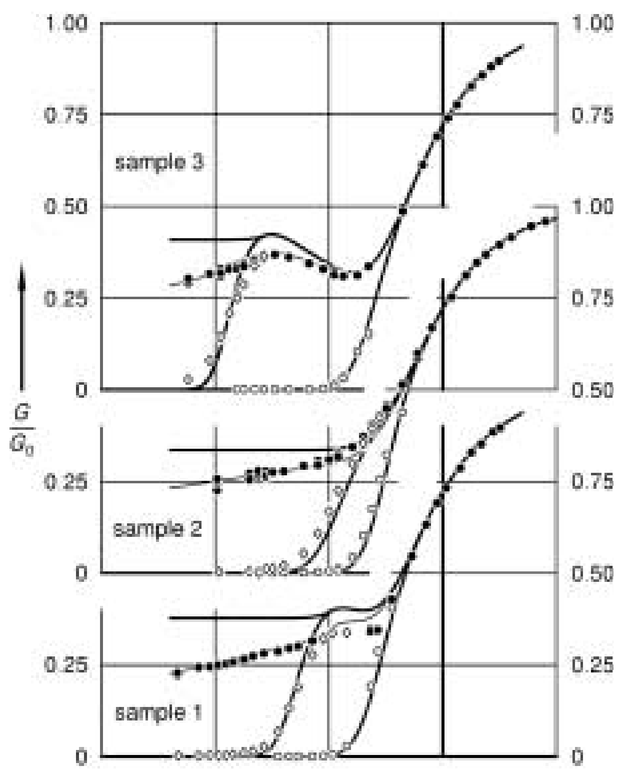
For single-electron devices the model Hamiltonian matches its experimental realization very closely. This has been proven most impressively for the normal-conducting single-electron transistor (SET) with the aid of Quantum-Monte-Carlo methods [1,2]. However, the lowest order perturbation theory, the so called sequential model, gives only a qualitative description in most practical cases. It ignores quantum fluctuations due to the coupling of charge states by the finite conductance of the tunneling contacts, which are fundamental constituents of the devices. Perturbation expansion (PE) has been suggested do deal with the impact of the coupling. Especially if the Coulomb blockade is lifted by lining up the energy of two neighboring charge states a situation arises which calls for sophisticated treatments. PE methods developed by Schöller and König [3,4] as well as by Grabert and Göppert [1,5] have been proven to describe the SET at the degeneracy point quantitatively up to $G = 1.5\ e^2/h$ [2,6]. Despite this success doubts on the applicability of PE in more general cases has occurred lately. Even for the SET, the validity range away from degeneracy is not clear. E.g. in the blockaded regime deviation between PE and experimental results are stronger than at the degeneracy point while the quantum Monte-Carlo data are in full accordance with the experiments. Furthermore, intermediate expressions of the PE calculation are burdened by cut-off parameters. In many expressions for the SET - including the mean charge on the transistor island and the conductance - these cut-offs cancel. But this happens to be somewhat fortunate, since no general rule is known which guarantees the cancellation. E. g. the occupation probability of the individual charge states contain the cut-off parameter explicitly.

To get more insight into the applicability of PE high quality conductance data on single-electron devices other than the SET are desirable. Here we present measurements of the linear response conductance of single-electron pumps (SEP). We have fabricated single-electron pumps with aluminum island and aluminum-oxide tunnel barriers in shadow evaporation technique. Usually single-electron pumps consists of a serial arrangement of three tunneling contacts forming two island; the electrostatic potential on each island can be adjusted via gate electrodes. However, in this simple layout only the serial conductance of the contacts can be measured and the distribution among the individual contacts remains unknown. To make the determination of the conductance of each contact possible, we replaced each outer contacts by two contacts. In the resulting device conductance parameters can be measured along different current paths. From a set of these parameters the individual conductances can be determined. In the final experiments the two outer contacts on the left and the right island are connected in parallel to the source and drain voltage source and act in the same manner as a single contact.

We report the measurements on three well characterized samples with varying asymmetry of the conductance between inner and outer tunneling contacts. In all cases the conductance is of the order of the conductance quantum e^2/h. This results in strong quantum fluctuations of the charge state, which manifest themselves - similar as in the case of the SET - by a logarithmic contribution to the linear-response conductance at low temperatures.

In addition in an easily accessible parameter regime we find a non-monotonic behavior of the conductance on temperature, which is correctly described by the sequential model. Phenomena of this kind are to be expected in all single-electron devices which are more complex than the SET. They can uncover internal characteristics unaccessible by other means - here e.g. the asymmetry of the conductance between the inner and outer tunneling contacts which is not directly measurable in the most natural SEP layout.



Linear response conductance of three SEP as a function of temperature. Shown are the minimal (o) and the maximal (●) conductance, as well as the conductance at a highly symmetric point of the SEP gate voltages (◊). The dashed lines are the result of an analytical solution of the sequential model obtained by restricting the model to four charge states. As solid lines the outcome of the full sequential model with independently determined sample parameters is shown. For the thin solid line a term of the form $\alpha \log(k_BT/E_{co})$ has been added to the maximal conductance as calculated from the sequential model. Here α is a fitting parameter and E_{co} measures the capacitive coupling between the two SEP islands.

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