# Broadening of the charge state transition in a single-electron box

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**Abstract**

We report measurements on a sample consisting of two roughly identical single-electron transistors the islands of which are coupled capacitively. One transistor at a time is operated as an electron box. The remaining transistor is used as an electrometer to measure the charge on the box gate. While ramping up the box gate voltage transitions occur periodically between states which differ in the charge on the box island by the elementary charge $e$. This shows up in jumps of the electrometer current. The coupling between the box and the measuring device causes a broadening of the transition width not included in the formulae for an isolated box. This is evident in our data as well as from a thorough analysis of the system in the framework of the sequential tunneling model. The sample is studied in the superconducting as well as in the normal state.

*Key words:* single-electron transistor; single-electron box; charge qubit

## 1. Introduction

The single electron box in the superconducting state has gained considerable attention recently as it might serve as a qubit where the two quantum states differ by one cooper pair on the box island (e. g. [1]). These two states can be brought to degeneracy by tuning the gate voltage of the single-electron box to an appropriate value. Of course, qubit physics requires first of all $2e$ periodicity in the Coulomb staircase. So far, only a few experiments have succeeded to fulfill even this basic requirement (e. g. [2]) showing the outstanding demand of qubit experiments in the field of Josephson contacts. In this paper we point out that studies of the readout problem can be performed at a lower level yielding a deeper understanding of the individual parts a quantum computer might be built upon in far future. To read out the charge state of the single-electron box a sensitive electrometer is desirable. The most sensitive electrometer known today is the single-electron transistor, which is a close cousin of the single-electron box. In fact, a single-electron transistor with vanishing source-drain voltage is equivalent to a box.

We have fabricated a sample consisting of two nominally identical single-electron transistors by means of the well established shadow evaporation technique from aluminum with aluminum-oxide barriers. The islands of the two transistors are coupled capacitively. The sample parameters of the transistors are: charging energy $\sim 2\,\mathrm{K}$, tunnel conductance $\sim e^2/8h$, gate capacities $\sim 70\,\mathrm{aF}$, stray capacities $\sim 25\,\mathrm{aF}$, coupling energy $\sim 0.06E_c$. By choosing an appropriate magnetic field, the sample can be operated in its superconducting as well as in the normal-conducting state. The two contacts of one transistor are grounded thus operating it as a single-electron box. The second transistor is biased slightly above the threshold of the Coulomb blockade and is used to read out —via the coupling— information about changes of the charge state on the box island which occur at low temperature periodically as a function of the box-gate voltage. The sample does not include quasiparticle traps which were essential in most former experiments to get the $2e$ periodic ground state behavior. Therefore it is not surprising that we find a purely $e$ periodic Coulomb

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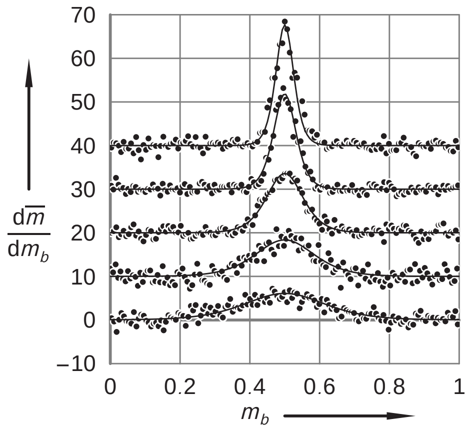


Fig. 1. Experimental data in the normal-conducting state (dots) and fits of Eq. 1 (solid lines) to the data. From top to bottom: $T = 26\,\mathrm{mK} - T_{\mathrm{eff}} = 70\,\mathrm{mK}$; $T = 50\,\mathrm{mK} - T_{\mathrm{eff}} = 85\,\mathrm{mK}$; $T = 100\,\mathrm{mK} - T_{\mathrm{eff}} = 140\,\mathrm{mK}$; $T = 160\,\mathrm{mK} - T_{\mathrm{eff}} = 230\,\mathrm{mK}$; $T = 250\,\mathrm{mK} - T_{\mathrm{eff}} = 315\,\mathrm{mK}$;

staircase in the superconducting as well as in the normal-conducting case, although we have taken especially care of filtering of high frequency as well as low frequency noise[3].

## 2. Result and Discussion

In Fig. 1 we show as dots experimental results for the derivative of single steps in the Coulomb staircase at different temperatures. For the isolated box the stair case should be described by

$$f(m_b) = 1/\left(1 + \exp\left(\beta E_b(1 - 2m_b)\right)\right), \qquad (1)$$

where $E_b$ is the charging energy of the box, $m_b$ labels the dimensionless box gate charge, and $\beta = 1/k_B T$. Eq. 1 has been used in Fig. 1 to fit the date, but $\beta$ has been replaced by $\beta_{\mathrm{eff}}$ as a fitting parameter. We find a significant enhancement of $T_{\mathrm{eff}}$ above the bath temperature $T$ as apparent from Fig. 2. However, in the normal-conducting case the transition width as expressed by $T_{\mathrm{eff}}$ continues to decrease to the lowest temperatures used in our experiment while in the superconducting state it tends to saturate at about 160 mK.

The temperature at which the transition width in the superconducting state saturates can be identified with $T^* = \Delta/k_b \ln N_{\mathrm{eff}}$, a temperature scale introduced by Tuominen et al.[4] as the temperature where switching from $e$ to $2e$ periodic behavior is expected. We do not observe switching to $2e$ periodicity, which simply tells us that we are dealing with a non-equilibrium situation below $T^*$. In thermal equilibrium the number of quasiparticles is exponentially small ($\propto \exp(-\Delta/k_B T)$). In our case it saturates at a small but finite number of the order unity (which is enough to stay at $e$ periodic behavior). As soon as the number of quaiparticles stays approximately constant with falling temperatures the transition width saturates, too.

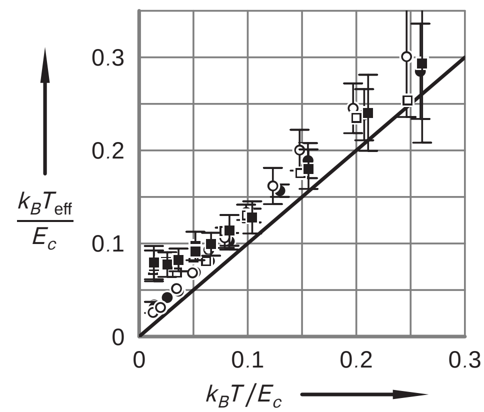


Fig. 2. Effective temperature in the Coulomb staircase $T_{\mathrm{eff}}$ as a function of bath temperature $T$ in the superconducting (squares) and the normal-conducting (circles) state. Open and closed symbols reference the two possibilities for choosing one of the transistors as single-electron box.

The enhancement of $T_{\mathrm{eff}}$ is harder to understand. The limited space of this publication allows for a brief statement only: It is straightforward to solve the sequential tunneling model for the present experimental situation of two capacitively coupled transistors[5]. Even this simple model predicts a broadening of the transition width, which is in a fairly good agreement with the experimental results at low temperatures. At temperatures of about 100 mK the broadening as predicted by the sequential model is far too small to explain the total additional broadening found in the experiment. In this regime a study of the influence of higher order terms is desirable.

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