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Characterization of a single Cooper pair box

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Abstract

We have used a radio-frequency single electron transistor to read-out a single Cooper pair box. We observe a Coulomb staircase with 2e periodicity, but with a shorter step corresponding to odd number of charges in the box. From the size of this short step we can extract the even–odd energy difference, $\tilde{\Delta}$, and study its magnetic field dependence. We have also characterized the box with microwave spectroscopy and extracted the charging energy and the Josephson coupling energy to be $E_c/k_B = 1.65$ K and $E_{J0}/k_B = 0.69$ K.

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1. Introduction

The single Cooper pair box (SCB) has been investigated intensively during the last years, mainly due to its properties as a two-level quantum system, which makes it a candidate as a qubit in a quantum computer [1]. Different types of read-out schemes have been used to probe a SCB [2–4]. We have investigated a read-out scheme that uses a radio-frequency single electron transistor (RF-SET) [5] capacitively coupled to the SCB [6,7]. We have characterized the SCB charging energy, E_c, and Josephson coupling energy, E_J, with microwave spectroscopy and determined the odd–even free energy difference, $\tilde{\Delta}$, through the SCBs magnetic field dependence [3,8].

The SCB and the RF-SET are fabricated with the use of electron beam lithography and two-angle shadow evaporation of aluminum. The SCB is designed in a squid-geometry for the ability to tune E_J. A gate line with 50 GHz bandwidth is capacitively coupled to the SCB. The RF-SET is capacitively coupled to the SCB and the RF-SET has a charge sensitivity of $\sim 55\mu e/\sqrt{\text{Hz}}$ and 15 MHz bandwidth.

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2. Characterization of SCB

We have characterized the SCB and RF-SET parameters using both DC and microwave measurements. By ramping the voltage on the SCB gate we induce charge onto the SCB, and with the RF-SET we measure the average charge of the SCB (Fig. 1). From the data we extract the coupling between the SCB and the RF-SET, $C_c/C_{\Sigma q} = 2\%$, where C_c is the capacitance between the SCB and the RF-SET and $C_{\Sigma q}$ is the total capacitance of the SCB.

To determine the characteristic energies E_c and E_J of the box, we have used monochromatic microwaves to induce transitions between the energy levels, Fig. 1 [9]. During the microwave excitation we ramp the box gate and measure continuously with the RF-SET, see inset (b) in Fig. 2. We operate at a magnetic field, $B_{\parallel} = 0.42$ T, parallel with the sample substrate, since both the SCB and the RF-SET have best performance at this field. We have applied microwave frequencies from 27 up to 50 GHz. By inducing two-photon transitions we can retrieve data that corresponds to a level separation of up to 70 GHz. Due to the one electron step near $n_g = 1e$ we are limited to microwave transitions above 27 GHz. From the slope of the lower line in Fig. 2 ($E_J/k_B \approx 0$) we extract $E_c/k_B = 1.65$ K. By slightly changing $B_{\parallel}$, the perpendicular part of the magnetic field that threads the SCB loop changes E_J from zero to E_{J0}, see inset (a) in Fig. 2.

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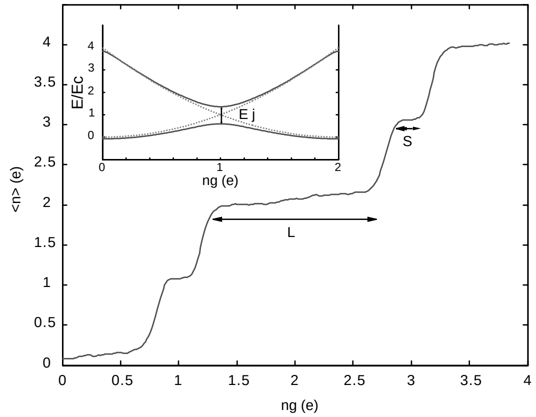

Fig. 1. Average charge on the SCB vs. the induced gate charge and the corresponding energy diagram. The short intermediate step in the Coulomb staircase is presumably due to an odd charge state. S and L are the widths of the short and long step in the staircase.

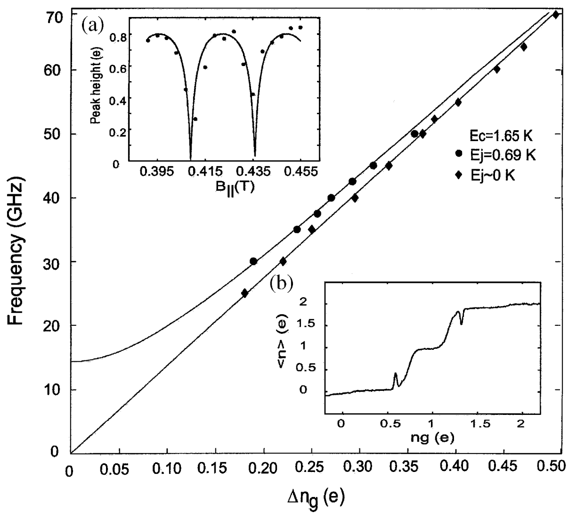

Fig. 2. The applied frequency vs. resonance peak position in Δn_g, for two different E_J, the top curve corresponds to a fit with $E_J/k_B = 0.69$ K and the lower line to $E_J/k_B \approx 0$ K. Δn_g is the charge difference between the peak location and $n_g = 1e$. Inset (a) Modulation of E_J, shown as spectroscopy peak height vs. magnetic field. Inset (b) Coulomb staircase with 50 GHz microwaves applied on the SCB gate.

We obtain an $E_{J0}/k_B = 0.69$ K by fitting the corresponding energy band to the data.

By analyzing the relation between the width of the short, S, and the long, L, step in the Coulomb staircase (Fig. 1) at different applied magnetic fields, $B_{\|}$, we can gain information about the odd–even free energy difference, $\tilde{\Delta}$, which can easily be extracted from the relation $\tilde{\Delta}(B_{\|}) = E_c(L-S)/(L+S)$ [8,10].

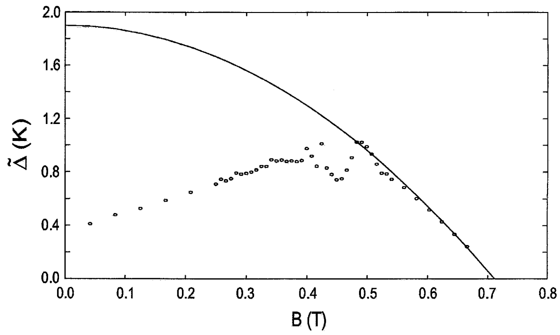

Fig. 3. $\tilde{\Delta}$ vs. parallel magnetic field $B_{\|}$.

We vary $B_{\|}$ from 0 up to 0.7 T. In Fig. 3 one can see that from $B_{\|} = 0$ up to 0.5 T, $\tilde{\Delta}$ increases but above 0.5 T $\tilde{\Delta}$ decreases and at $B_{\|} = B_c = 0.7$ T, $S = L$ and $\tilde{\Delta} = 0$. For $B_{\|} > 0.5$ T the step widths behave as expected and we can fit the data to $\tilde{\Delta}(B) = \tilde{\Delta}(1-(B/B_c)^2)$. From this fit we can extrapolate $\tilde{\Delta}$ from $B_{\|} \approx 0.5$ T down to $B_{\|} = 0$. In this manner we retrieve $\tilde{\Delta}(0)/k_B \approx 1.9$ K. The deviation from the BCS gap below $B_{\|} = 0.5$ T is discussed in Ref. [3] and explained to be due to the presence of discrete quasiparticle states in the gap. However in our case it may also be due to the back-action from the RF-SET.

To summarize, we have demonstrated a continuous read-out of a SCB with a RF-SET and extracted the characteristic energies for the SCB with microwave spectroscopy and Coulomb staircase dependence. We also shown the ability to control E_J of the SCB.

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