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14. ABSTRACT

The focus of this project was the study of the physics of mesoscopic devices, e.g. single electron devices, related to their use in quantum computation. Theoretical work focused on the design of novel qubit and gate structures using Josephson junctions in the regime of charge dynamics, and theory of mesoscopic quantum measurements including quantum-detector properties of solid-state devices, most importantly, SET transistors. The major experimental effort in this project was the study of the effects of measurement on the periodicity of the Coulomb staircase of a superconducting box. Measuring devices incorporating Josephson junctions operated near or above the gap voltage, even briefly after the period of coherence in the qubit, generate quasiparticles in the qubit which can persist for milliseconds and generate decoherence in subsequent measurements A technique was developed to flush these quasiparticles from the qubit by applying a brief gate pulse to the charge box just before the start of each measurement cycle to invert the potential.

15. SUBJECT TERMS

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Summary

The overall focus of this project was the study of the physics of mesoscopic devices, most particularly single electron or single pair devices, related to their use in quantum computation. The specific areas of research pursued during the project were as follows:

Theoretical work.

The theory work under this grant focused on the two main areas: design of novel qubit and gate structures using Josephson junctions in the regime of charge dynamics, and theory of mesoscopic quantum measurements with the discussion of the quantum-detector properties of various mesoscopic solid-state devices, most importantly, SET transistors.

Experimental work:

The major experimental effort in this project was the study of the effects of measurement on the periodicity of the Coulomb staircase of a superconducting box. The immediate motivation for this work was the problem of "poisoning", i.e. the existence of unpaired electrons in the box, for the use of charge qubits in quantum computation. However, this system also provided an excellent vehicle for a more general study (also applicable to flux qubits) of the effects of measurement on decoherence.

The following **publications** resulted from work supported under this project:

D.V. Averin, ``Quantum computing and quantum measurement with mesoscopic Josephson junctions'', Fortschritter der Physik 48, 1055 (2000).

D.V. Averin, ``Noise properties of the SET transistor in the co-tunneling regime'', in: ``Macroscopic Quantum Coherence and Quantum Computing''} Ed. by D.V. Averin, B. Ruggiero, and P. Silvestrini, (Kluwer, 2001), p. 399.

J.R. Friedman and D.V. Averin, ``Aharonov-Casher-Effect Suppression of Macroscopic Tunneling of Magnetic Flux '', Phys. Rev. Lett. 88, 050403 (2002).

D.V. Averin, ``Quantum Nondemolition Measurements of a Qubit'', Phys. Rev. Lett. 88, 207901 (2002).

D.V. Averin and R. Fazio, ``Active suppression of dephasing in Josephson-junction qubits'', JETP Lett. 78, 1162 (2003).

J. Männik, J. R. Friedman, W. Chen and J. Lukens. "Lifetime of Even-Parity States of a Bloch Transistor", eds. J. Pekola, B. Ruggiero & P. Silvestrini, International Workshop on Superconducting Nano-Electronics Devices, Kluwer Academic/Plenum Publishers, 211-218,(2003).

D.V. Averin and C. Bruder, Phys. Rev. Lett. 91, 057003 (2003).

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D.V. Averin, ``Linear quantum measurements'', in: ``Quantum noise in mesoscopic physics'', Ed. by Yu.V. Nazarov, (Kluwer, 2003), p. 229.

W. Mao, D.V. Averin, R. Ruskov, and A.N. Korotkov, ``Mesoscopic Quadratic Quantum Measurements'', Phys. Rev. Lett. 93, 056803 (2004).

J. Mannik and J. E. Lukens. "Effect of measurement on the periodicity of the Coulomb staircase of a superconducting box". Phys. Rev. Lett. 92, 057004 (2004)

The following **personnel** worked on this project:

> Prof. James Lukens, PI
> Prof Dmitri Averin, Co-PI
> Prof. Konstantin Likharev, Co-PI
> Dr. Alexandre Guillaume, Postdoctoral Associate
> Dr. Vladimir Kuznetsov, Research Scientist
> Dr. Jaan Männik, Graduate Student and Postdoctoral Associate
> Dr. Suma Rajashankar, Postdoctoral Associate
> Ms. Stella Siu, Graduate Student
> Dr. Victor Sverdlov, Research Scientist

The following **thesis** resulted from work done under this project:
Jaan Männik, "Quasiparticle Poisoning in Charge Qubits", Ph. D. thesis, Stony Brook University, August 2003.

Theoretical Work.

The theory work under this grant focused on the two main areas: design of novel qubit and gate structures using Josephson junctions in the regime of charge dynamics (1,2), and theory of mesoscopic quantum measurements (3) with the discussion of the quantum-detector properties of various mesoscopic solid-state devices, most importantly, SET transistors (4). The list of specific topic studied within this project includes the following.

1. Charge-flux qubit [1-3].

We have suggested and analyzed the qubit structure: Bloch transistor enclosed in a loop of finite inductance L, that combines dynamics of the electric charge and magnetic flux. An important part of the motivation for studying such a qubit is the fact that the combination of charge and flux is necessary for the qubit to enable access to more than one of the non-commuting observables of the qubit. Such an access is required for most of non-trivial manipulations of the quantum states of the qubit, and was used to develop schemes of non-demolition qubit measurements and error-correction. It also can be used for direct demonstrations of the EPR correlations in coupled qubits.

The physical mechanisms that provides coupling between charge and flux in this structure is interesting in it own right. It is based on the Aharonov-Casher effect and leads to gate-voltage modulation of the flux tunnelling rate out of the loop L that can be directly studied in experiment. This modulation was analyzed in our work quantitatively in several regimes with the emphasis on the effects of the junctions' asymmetry important for all structures employing the interference effects.

2. Controllable coupling of charge qubits [4].

A simple device, the variable electrostatic transformer, that can be used for controllable coupling of charge qubits was suggested and analyzed. The coupling scheme uses the non-linear effective capacitance of an individual Josephson junction in the Coulomb-blockade regime and the possibility to control this capacitance by an external gate voltage. Advantages of this coupling scheme include simplicity of the transformer which essentially consists of only one junction, and the fact that its operating principle is practically the same as the one used in qubit dynamics.

3. Mesoscopic quantum measurements [5-7].

Quantum measurements represent an important part of quantum information processing and evolution of quantum systems in general. Interest to the ``problem of quantum measurements'' is also motivated by counter-intuitive features of the wave-function collapse in the measurement process. The physics of mesoscopic solid-state qubits and detectors provides convenient tools for studying this problem in the most interesting case of quantum systems that are large on atomic scale. We have developed a theory of "continuous" quantum measurements of individual and coupled qubits in which the dynamics of the wave-function collapse manifests itself directly in the evolution of the measured system. Specific observable consequences of the detector-system interaction differ for the linear and non-linear (e.g., quadratic) detectors. In the case of linear measurements, quantum mechanics manifests itself through the constraint on the amplitude of the spectral line representing qubit oscillations in the output spectrum of the detector. Quadratic measurements, which can be realized in many of the typical mesoscopic detectors at special bias points, should make it possible to monitor products of operators of different quantum systems, and can be used, for instance, to entangle non-interacting qubits, and to implement simple schemes of error-correction.

4. Quantum-detector properties of the SET transistor in the co-tunnelling regime [8,9].

The SET transistor is the most frequently used device for measurement of Josephson-junction charge qubits. In contrast to the classical regime of sequential tunnelling, in the co-tunnelling regime, the transistor can operate as a quantum-limited detector. During this project, we extended our previous results for this regime in the case of quantum-dot transistors with discrete energy spectrum to the practically important case of metallic transistors with continuous density of states. Characteristics of the metallic SET transistors as the linear quantum detectors were studied both deep in the co-tunnelling regime (at small bias voltages), and close to the Coulomb blockade threshold. We calculated spectral densities of the output and back-action noise of the SET transistor that determine its characteristics as the linear quantum detector. The obtained energy sensitivity of the transistor approaches the quantum limit, $h/4\pi$, deep in the co-tunnelling regime. The absolute value of the transistor current in this regime is, however, small, making the transistor sensitive to external perturbations. Because of this, it is important to study the crossover regime realized for the bias voltage close to the Coulomb blockade threshold. Theoretical description of the transistor biased at the Coulomb blockade threshold requires the non-perturbative approach incorporating both the co-tunnelling and sequential classical electron

transitions. We developed such an approach and found that the energy sensitivity at the threshold is lower than the quantum limit by a factor of ln(1/g), where g is tunnel conductance of the transistor junctions normalized to the quantum resistance h/e^2.

Experimental Work.

The major experimental effort in this project was the study of the effects of measurement on the periodicity of the Coulomb staircase of a superconducting box. The immediate motivation for this work was the problem of "poisoning", i.e. the existence of unpaired electrons in the box, for the use of charge qubits in quantum computation. However, this system also provided an excellent vehicle for a more general study (also applicable to flux qubits) of the effects of measurement on decoherence. As explained later, in detail, the main results of this work are:

- Measuring devices incorporating Josephson junctions operated near or above the gap voltage, even briefly after the period of coherence in the qubit, generate quasiparticles in the qubit which can persist for milliseconds and generate decoherence in subsequent measurements. The density of these quasiparticles in the qubit was shown to be proportional to the number quasiparticle tunnelling events in the measurement electrometer.

- A technique was developed to flush these quasiparticles from the qubit by applying a brief gate pulse to the charge box just before the start of each measurement cycle to invert the potential. Using this technique it was possible to restore the 2e-periodicity of the charge box, i.e. to remove the effects of quasiparticle poisoning.

The superconducting box, e.g. a small island of Al film very weakly coupled to the outside circuitry by Josephson junctions, has shown considerable promise as a qubit for quantum information processing where the two states can be represented by superpositions of 0 or 1 excess Cooper pairs in the box. Measurement of the quantum state of this so-called charge qubit without inducing unwanted decoherence is a significant problem as is quasiparticle poisoning, i.e. the introduction of unpaired electron (quasiparticle) into the box. At temperatures of 10 mK or so, where experiments are commonly done, the number of quasiparticles should, in principle, be negligible. However, such quasiparticle poisoning, due perhaps to the measurement process itself, is commonly observed. A manifestation of this is seen in the so called Coulomb staircase. When a charge, q_g, is capacitively induced on the box, one expects Cooper pairs to tunnel resonantly into or out of the box at $q_g = n_o e$, where n_o is an odd integer, to maintain the lowest energy charge state of the box. This results in the Coulomb staircase of the charge in the box $Q(q_g)$ with period 2e in q_g. On the other hand, if there are quasiparticles in the system, then

maintaining the lowest charging energy state also leads to quasiparticle tunneling. This gives rise to splitting of the steps in the Coulomb staircase, which shifts toward e-periodicity as the number of quasiparticles increases. As a result, the lowest energy state of the box at $q_g=n_o e$, no longer corresponds to a resonant state of the Cooper pair tunneling. For the box qubit, this means that relaxation does not bring the system back to its computational ground state at its operating point. Since the ability to prepare the initial state of the qubit is an absolutely necessary condition for quantum computing, solving this problem in charge qubits is essential.

The purpose of this work was to investigate back-action effects of Single Cooper Pair Transistor (SCPT) electrometer (**E**) on quasiparticle poisoning of the box (**B**) in charge measurements and to develop approaches to minimize these effects. We use two capacitively coupled SCPTs, one of which acts as an electrometer and the other as a superconducting box for this study. The latter gives a good representation of the box and at the same time allows us to study quasiparticle poisoning effects without need to operate the SCPT electrometer. Commonly the charge measurements of the box are done by operating the SCPT electrometer in the voltage modulation mode (VM). In this mode, the SCPT is biased at a sufficiently high voltage that quasiparticles are generated, so it effectively functions as a SET where the source drain voltage is modulated by $q_{g,E}$ with a period of e. However it is known that the switching current of a SCPT, i.e. the current at which it switches hystereticly from the low voltage or phase-diffusion branch to $eV > 2\Delta$, is also charge sensitive and can be used for charge measurement. We refer to this as the switching current mode (SW). The SW mode of operation has been analyzed, but until this work no measurements of the charge on the island of a box using a SW mode electrometer have been reported.

Figure 1 shows the device configuration used in this work along with the charge on the island of **B**, Q_B, measured with **E** in the VM mode and the switching current modulation of **B** measured with the bias current through **E**, I_E, set equal to zero. As can be seen, the switching current modulation of **B** is 2e-periodic as expected at low temperature, but the charge of B, measured by the electrometer, is e-periodic. Similar dependences of Q_B on $q_{g,B}$ were measured with **E** biased in either of its voltage sensitive regions, i.e. near the gap where $V_E \approx 4\Delta/e$ or near the Josephson-quasiparticle peak where $V_E \approx 2\Delta/e$. To determine if the e-periodicity of $Q_B(q_{g,B})$ is due to the back-action of **E** on **B**, the quasiparticle poisoning rate of **B**, γ_B, was measured for a

range of bias conditions of **E**. In addition to this, we studied how the biases of two other SCPTs located on the same chip but coupled more weakly to **B** affected γ_B.

The technique for determining γ_B from switching current distributions was developed during the first year of the project. Briefly, as I_B is linearly ramped in time, the switching current histogram of **B** with its gate biased near $q_{g,B} = n_o e$ exhibits two peaks if the number of quasiparticles on the island changes during the measurement of histogram. One peak, I_{even}, which is close to the maximum of the $I_{sw,B}(q_{g,B})$ characteristic occurs when the island has an even number of electrons (even state) and the other -much lower current- peak, I_{odd}, is near the predicted switching current minimum at $q_{g,B} = 0$ when one quasiparticle occupies the island (odd state). If $I_B > I_{odd}$ and **B** has not switched, it must be in the even state. The entry of a quasiparticle onto the island effectively changes $q_{g,B} = e$ to $q_{g,B} = 0$ which for $I_B > I_{odd}$ will cause **B** to switch rapidly to the running state, giving the time of the quasiparticle tunneling and thus the quasiparticle poisoning rate γ_B. Our studies have shown that γ_B is independent of I_B in the region between the peaks, giving an exponential decay of the even state. Several of these histograms with increasing γ_B as V_E and I_E increase are shown in Fig. 2. The relatively low bandwidth of our filters limits these measurement to $\gamma_B < 10$ ms^{-1}.

First we determine γ_B when all the electrodes of electrometer are disconnected from the measurement circuitry and grounded. In this case we still observe a small residual rate $\gamma^0_B = 0.06$ ms^{-1} for $q_{g,B} \approx n_o e$. This non-zero rate can be caused, e.g., by the presence of impurity levels in the superconducting gap of Al. For the present discussion it is clear this small residual rate is not related to the back-action of **E**. γ_B is unchanged if **E** is biased on its supercurrent branch or when **E** is biased on its return current branch at low voltage $V_E < 200\mu V \approx \Delta/e$ as shown in Fig. 3. For $V_E > 200\mu V$, γ_B decreases rapidly, becoming too short to measure for slightly higher voltages. The modulation characteristics of the current I_E with gate voltage also change at this point from being 2e-periodic for $V_E < 200\mu V$ to e-periodic for $V_E > 200\mu V$

In order to study how γ_B depends on the voltage and current of **E** through its entire operating range, and in particular near $V_E \approx 2\Delta/e$ and $V_E \approx 4\Delta/e$, we use two other SCPTs fabricated on the same chip but much more weakly coupled to **B**. These two SCPTs, which we call **E1** and **E2**, are much more weakly coupled to **B** and therefore allow us to measure γ_B for

bias currents, $I_{E1,2}$, that are several orders of magnitude higher than is possible using **E**. For these devices, we can measure the rate γ_B up to voltages *4Δ/e*. Again, we see a small initial increase of γ_B at $V_E{\approx}200\mu V$ and then sharp increases at voltages $V_E{\approx}2\Delta/e$ and *4Δ/e*. These voltages correspond approximately to the Josephson-quasiparticle tunneling and sequential quasiparticle tunneling thresholds in an SCPT and are accompanied by sharp increases in $I_{E1,2}$.

From these data one can conclude that the quasiparticle current of electrometer is the source of back-action noise leading to quasiparticle poisoning and an e-periodic Coulomb staircase of **B** when measured by **E**. Further, the quasiparticle generation in **B** is proportional to the total number of quasiparticle tunneling events per second through **E**. This relationship could indicate that the back-action of **E** results from the shot noise of tunneling quasiparticles. On the other hand, this back-action could also be the result of the recombination of quasiparticles in **E** into pairs. This quasiparticle recombination produces phonons and to a smaller extent photons of energy *~2Δ*. These phonons/photons, which propagate from **E** to **B** without energy relaxation could generate quasiparticles in **B**. Determining the details of the interaction between **E** and **B** will require further work..

Quasiparticle poisoning of **B** due to the measurement of its charge can, in principle, be eliminated by the operation of **E** in the SW mode, where its voltage remains well below Δ/e until the measurement is made. The SW mode of operation of the electrometer is illustrated in Fig. 4, which shows its switching current vs. gate charge transfer-function. To measure Q_B as a function of $q_{g,B}$, we bias **E** near point "0", where the switching current is very sensitive to variations of external charge, and record several hundred switching events of **E** for each value of $q_{g,B}$. These switching data are then corrected for the measured nonlinearity in the transfer function of **E** and averaged.

The effects which result from the residual rate $\gamma^0{}_B$ have been nearly eliminated by flushing the quasiparticle from the island of B before each measurement. To prepare the even parity state, we apply a voltage pulse V_B across **B** just prior to each measurement. The amplitude of V_B is chosen such that $2E_{c,B} < V_Be < \Delta$, in order to release the quasiparticle from the electrostatic potential of the island but yet not to generate any new quasiparticles by the pulse . Switching histograms of **B** show that this procedure prepares the even state with a probability of about 85%. Immediately after **B** is flushed, the measurement ramp of I_E begins.
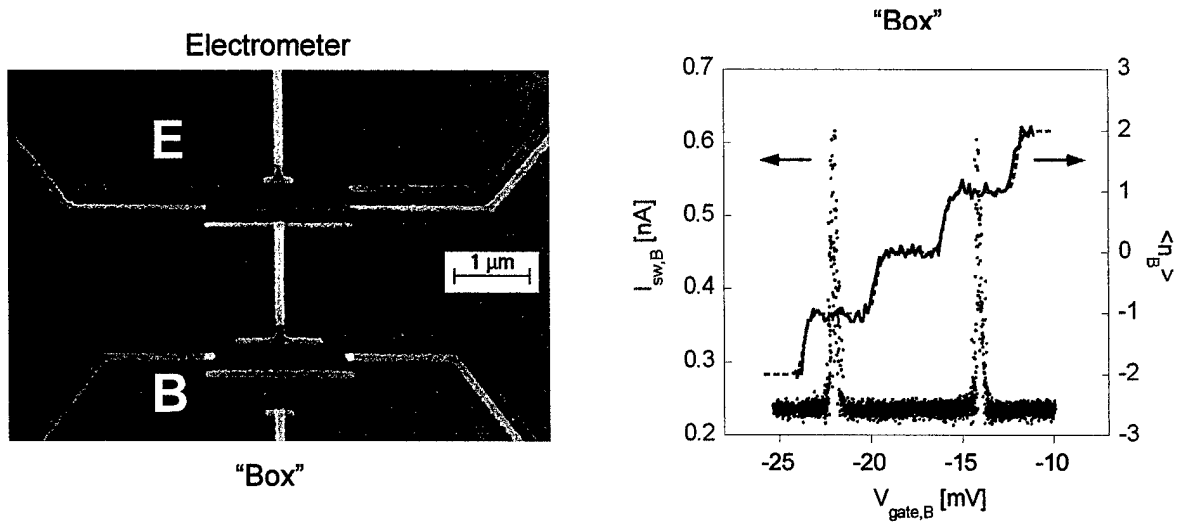
Figures.

Electrometer

"Box"

Figure 1. Left, micrograph of sample showing single Cooper pair box (**B**) and measurement electrometer (**E**). Right, measured variation of the switching current of **B** (measure with V_E = 0) along with its island charge (measured with **E** in VM mode) as a function of its gate voltage and the measure. Note that the period of the switch current modulation is twice that of the island charge.
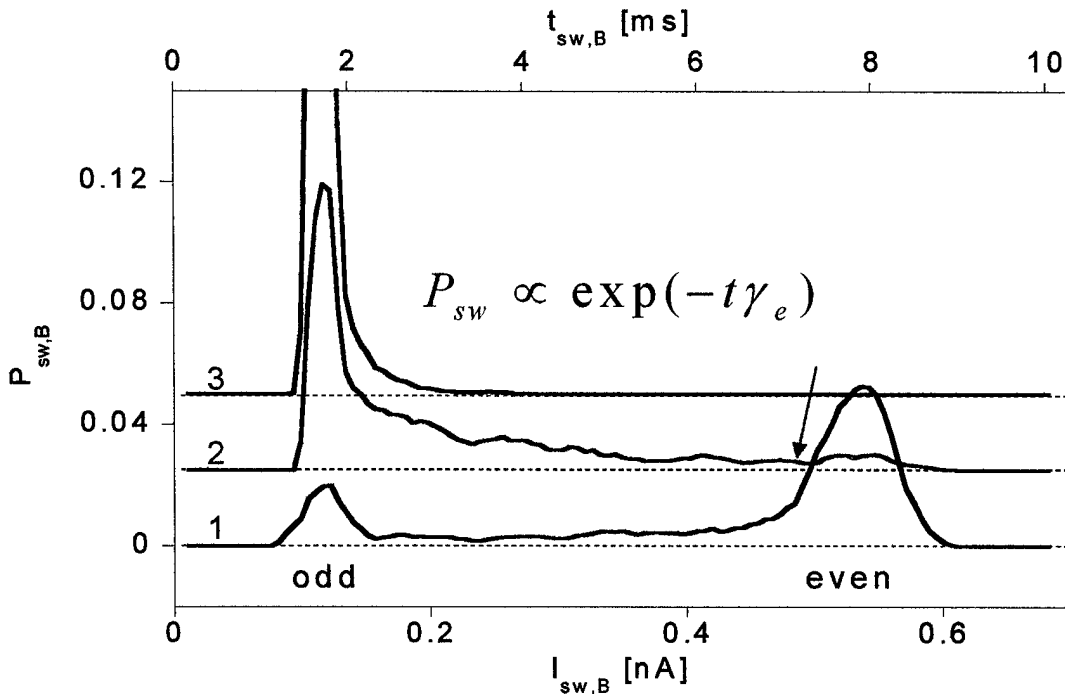

$$P_{sw} \propto \exp(-t\gamma_e)$$

Figure 2. The switching probability of **B** as its bias current is varied linearly with time. Curves 1—3 were measured for difference bias voltages of **E** ranging from V = 0 (1) to V = Δ (3). Curve 1 shows separate peaks due to the even and odd states of B. Note the increase decay rate with the increasing V_E.
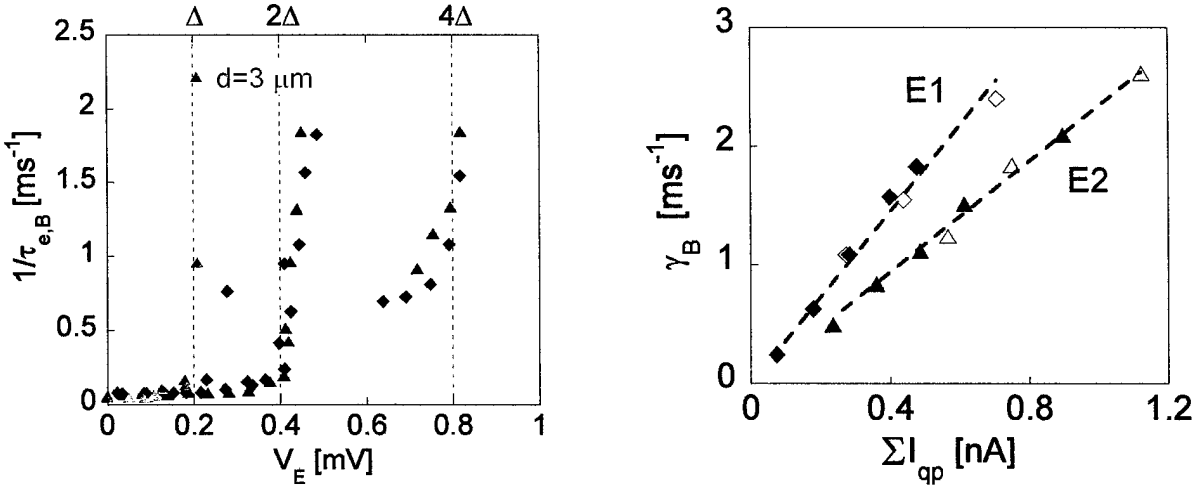
Figure 3. Left, the measured decay rate for the even (unpoisoned) state of B vs. the bias voltage of several electrometers at various distances from B. Right, Decay rate of B vs. the number of quasiparticle tunneling events in the two electrometers, E1 and E2, furthest from B. Solid and open symbols are for biases near the JQP peak and the gap respectively.
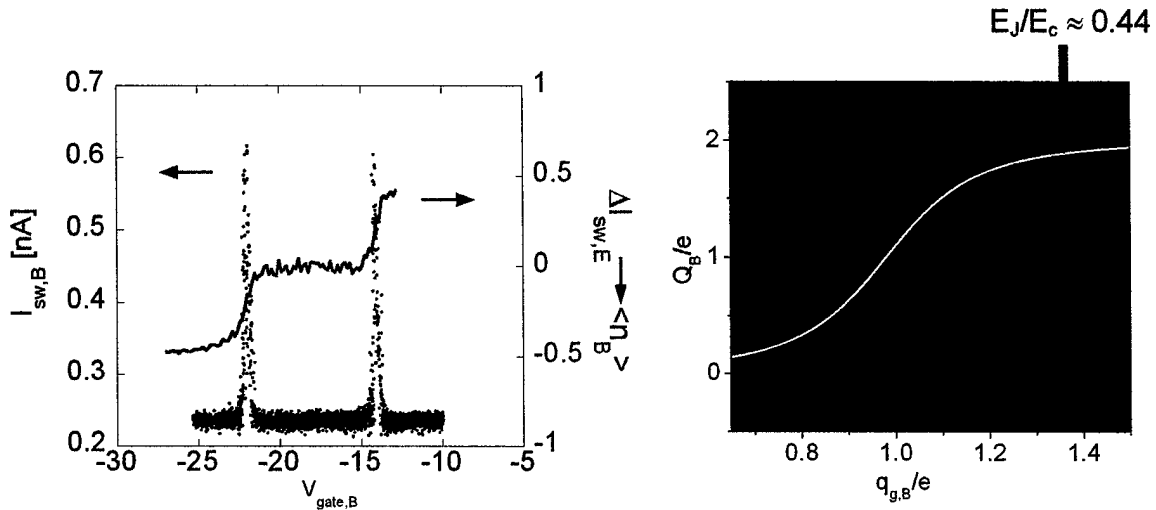

Figure 4. Left panel. The modulation of the switching current and island charge Q_B of the box measurement using the switching current mode of the electrometer. The modulation of Q_B is now 2e-periodic in contrast to the data of Fig. 1 where the electrometer was operated in the VM mode, giving rise to strong poisoning. In order to eliminate that small residual poisoning, present with VE = 0, the box was "flushed" just before each measurement (see text). Right panel. The relative probability (color level) of measuring a given charge on the box vs. the gate bias on the box. The width of the distribution is consistent with that expected due to Josephson coupling between the 0 and 1 pair states of the box.

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