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SINGLE COOPER PAIR ELECTRONICS

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Abstract—Single electron devices are based on small normal metal electrodes called 'islands' separated by tunnel junctions. In such circuits, electrons can be transfered one by one when the energy of thermal fluctuations is less than the electrostatic energy necessary to add an extra electron to an island. We present here experimental results in single electron devices for which all normal-metal electrodes are replaced by superconducting ones. In such devices coherent Cooper pair tunneling (i.e. the DC-Josephson effect) combines with Coulomb blockade. These effects can be tuned in such a way that signatures of the macroscopic quantum coherence between two well-defined charge states become observable. © 1999 Published by Elsevier Science Ltd. All rights reserved

INTRODUCTION

The tunneling of an electron through a tunnel junction corresponds to the creation of an electron-hole excitation, each particle being created on one side of the junction. It is an incoherent and irreversible process. On the contrary, the tunneling of Cooper pairs (i.e. the DC-Josephson effect) is coherent and reversible, since it arises from the coupling of the two superconducting condensates. Such a difference has important consequences for the behavior of devices based on charging effects, in which metal electrodes - called 'islands' - separated by tunnel junctions tend to have a well-defined number of electrons in order to minimize the electrostatic energy. In single electron devices, electron tunneling makes the number of electrons on each island fluctuate quantum-mechanically, and essentially only renormalizes the electrostatic energy towards a smaller value. In superconducting devices, Cooper pair tunneling tends to favor *coherent* quantum superposition of island states with different Cooper pair numbers. When the system is tuned in such a way that two charge states differing by one Cooper pairs have the same electrostatic energy, a coherent superposition of these two charge states can be adopted. We present here experiments supporting this prediction.

THE SUPERCONDUCTING BOX

The superconducting box [1] consists of a small piece of superconductoring island, connected to a superconducting reservoir by a Josephson junction (see Fig. 1). The dimensions of the island and junction are small enough to make the Coulomb energy of one extra Cooper pair comfortably larger than the energy of thermal fluctuations at dilution refrigerator temperatures. The island can be electrostatically polarized by a gate capacitance C_g connected to a voltage source U. This island is characterized by its number n of excess Cooper pairs whose average value $\langle n \rangle$ is measured by an electrometer [2]. The device is fabricated in our laboratory using electron beam lithography and thin-film evaporation of aluminum layers through a suspended mask. The tunnel barrier is obtained by a controlled oxidation of the bottom aluminum layer. Josephson junctions Al/AlOx/Al of typical size 0.1×0.1 μm^2 are obtained. The total capacitance of the island $C_\Sigma = C_j + C_g$ determines the characteristic energy $E_C = (2e)^2/2C_\Sigma$ which corresponds to the cost of a Cooper pair entering the island. The Coulomb energy E_C is here dominated by the capacitance C_j which is of the order of 1fF ($E_C/k_B \sim 1$ K).

The electrostatic Hamiltonian H_{el} associated with the quantum variable n can be modified by varying the voltage U on the gate capacitance C_g:

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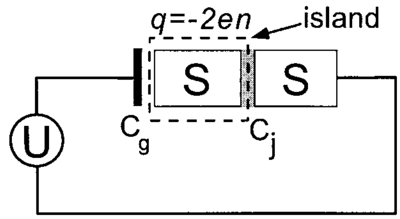

Fig. 1. Schematics of the single Cooper pair box. The island in the dotted frame is characterized by its number n of excess Cooper pairs that have entered the island through the Josephson junction of capacitance C_j. The island can be polarized by the capacitance connected to the voltage source.

$$H_{el} = E_C \Sigma_n (n - C_g U/2e)^2 (|n\rangle\langle n|) \tag{1}$$

The associated eigenvalues can be represented as a function of U by a set of parabolas indexed by the integer n (see Fig. 2(a)). We also have to consider Josephson tunneling, characterized by the energy E_J, which couples neighboring charges states and which gives the following contribution to the total Hamiltonian:

$$H_J = -E_J \Sigma_n (|n+1\rangle\langle n| + |n\rangle\langle n+1|)/2 \tag{2}$$

Note that in standard large-capacitance Josephson junctions, H_J dominates over H_{el}, since E_c is small compared with E_J. This means that the phase of the island is a good quantum number, therefore the Heisenberg uncertainty relation leads to large quantum fluctuations of the island charge n. The ground state of the system is, thus, a coherent superposition of a large number of charge states. In contrast, for small capacitance junctions, H_{el} restricts considerably the effect of H_J. For $E_J \ll E_C$, the island essentially adopts at $T=0$ the number n of extra Cooper pairs which minimizes H_{el}. Except in the vicinity of the degeneracy voltages $U_k = e(2k+1)/C_g$ where k is an integer (parabola crossings in Fig. 2(b)), this number n_0 will be given by the integer part of $(C_g U/2e + 1/2)$ and therefore increases in a stepwise fashion with U.

However, in the vicinity of the degeneracy voltages, which can be defined more precisely by the range where the electrostatic energy difference between the two charge states $|n\rangle$ and $|n+1\rangle$ is of the order or smaller than E_J, the ground state of the system will be a superposition of the two charge states. In particular, at $U = U_k$ the ground state wave function is $|\psi\rangle = (|n\rangle + |n+1\rangle)/(2)^{1/2}$.

Theory predicts that the expectation value of $\langle n\rangle$ as a function of U takes the shape of a rounded staircase. At the middle of the transition between steps, the slope is equal to E_C/E_J and directly reflects the interplay between charging and Josephson effects.

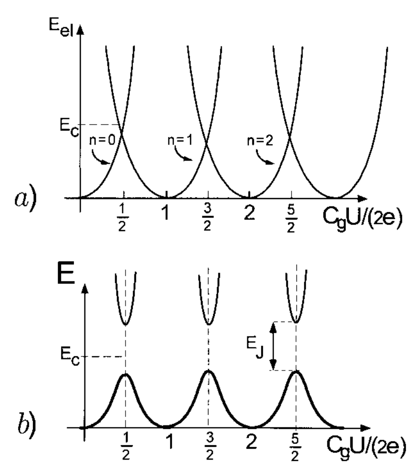

Fig. 2. (a) Electrostatic energy of the box for given numbers n of Cooper pairs in excess in the island as a function of the reduced voltage $C_g U/e$. (b) Energy levels of the total energy of the system when both electrostatic and Josephson Hamiltonians are taken into account. The gap between the ground level and the first excited level is equal to the Josephson energy E_J.

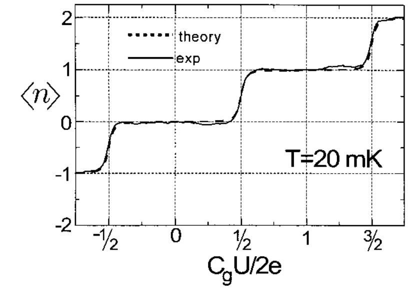

Fig. 3. Time averaged number of excess Cooper pairs in the island as a function of the reduced voltage $C_gU/2e$. The experimental curve (solid line) is compared with the zero-temperature theoretical prediction (dotted line) obtained using Equation (3).

In our experiment, we have measured the time-averaged number of Cooper pairs in the island by coupling it electrostatically to a SET electrometer. The sample was such that $E_C/E_J = 0.3$. The variations of the average value n of the island charge as a function of the reduced voltage $n_g = C_gU/2e$ has indeed the shape of a rounded staircase (see Fig. 3).

At temperatures above 80 mK, the rounding is well explained by thermal fluctuations. Below 80 mK, the curve becomes temperature-independent and the shape of transition steps agrees with the theoretical prediction at $T = 0$ based on the coherent superposition of two states (see Fig. 3):

$$\langle n \rangle = (n_g - 1/2)/((2n_g - 1)^{1/2} + (E_C/E_J)^{1/2})^2. \tag{3}$$

This observation radically differs from the case of a superconducting island connected to a non-superconducting reservoir [3]. In such a case, the slope diverges at low temperature since without Josephson effect, thermal fluctuations remain the only smearing process. The superconducting box experiment demonstrates that the Josephson effect can manifest itself when only two charge states are energetically available.

THE SUPERCONDUCTING TRANSISTOR

In this second type of device, a superconducting island is connected through Josephson junctions to two superconducting electrodes and operated in a transport mode (Fig. 4) [4, 5, 6].

As in the superconducting box, the island is polarized by a gate capacitance C_g and we have, thus, a three-terminal device. This superconducting transistor is biased at dc by a current source. The electromagnetic environment of the transistor (not represented in the figure) is such that the phase difference between the source and drain superconducting electrodes is a classical quantity, allowing a supercurrent flow through the transistor.

The I–V characteristic of the transistor is presented in Fig. 5, top panel. It shows a zero-voltage branch which corresponds to a supercurrent flow through the junctions. As the current increases, the system switches to a finite voltage branch for which conduction is dominated by the quasi-particule current. Switching occurs for a current I_s which is the main experimental feature of the device. We have measured the variations of I_s as a function of the gate voltage (Fig. 5 bottom panel). The curve is $2e$-periodic with respect to the charge C_gU on the gate capacitance. It has

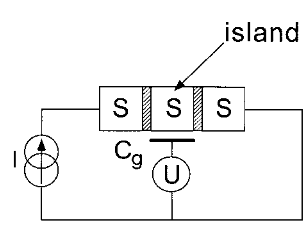

Fig. 4. Schematic diagram of the superconducting transistor. The island is connected to two superconducting electrodes by Josephson junctions. The transistor is biased by a current source. As for the superconducting box, the island can be polarized by a capacitance connected to a voltage source U. Time averaged number of excess Cooper pairs in the island as a function of the reduced voltage $C_gU/2e$.

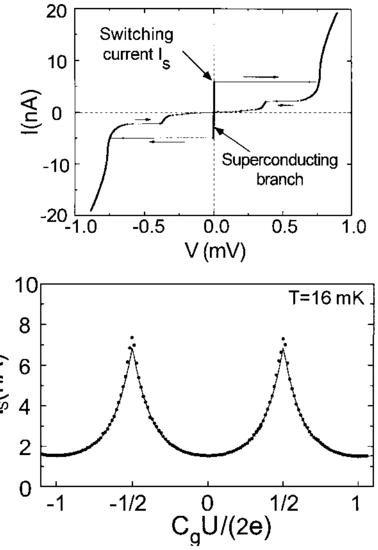

Fig. 5. Top: experimental current–voltage characteristic of the superconducting transistor biased with a quasi-ideal current source The zero voltage branch corresponds to the superconducting state of the transistor. For $I > I_s$ the transistor switches to the finite voltage branch. Bottom: switching current I_s as a function of the reduced gate voltage $C_gU/2e$. Theory corresponding to an environment temperature $T_e = 50$ mK is shown by a continuous line.

sharp peaks whose values would reach the theoretical prediction $I_{max} = \pi e/hE_J$ in the limit where the electromagnetic environment seen by the junction has zero impedance. For a finite but small impedance, corrections to this zero-th order theory are known [7] and the experimental peak shape can be compared directly with the theoretical predictions (continuous line in bottom panel of Fig. 5). The supercurrent peaks occur for voltages $U = (2n+1)e/C_g$ corresponding to the middle of the steps in the superconducting box experiment. The cusp shape of the peaks in the $I_s(U)$ curve provides a signature of the coherent superposition of two charge states for the island and is directly related to the shape of the relationship linking the supercurrent to the phase difference and the reduced gate voltage [6]. Note that the switching current has smooth minima where the charge on the gate is an integer number of Cooper pairs. There, the number of excess Cooper pair in the island can fluctuate quantum mechanically only through a second order effect in the Josephson coupling. The corresponding switching current is given by $I_{min} = I_{max}(E_J/E_C)$.

The value $E_J/E_C = 0.3$ in our experiment accounts for the relatively high value of the switching current at integer values of $C_gU/2e$.

CONCLUSION

We have presented here two experiments which implement, in the solid state, a two-level quantum system using the charge states of a superconducting island in a tunnel junction circuit. The coherence time of a quantum state in such a system is limited by the residual dissipation in the leads and in the dielectrics of the circuits. Direct measurements of this coherence time have still to be performed if one would want to use an array of superconducting islands for quantum information manipulation [8].

REFERENCES

1. M. Büttiker, *Phys. Rev. B* **36,** 3548 (1987).
2. P. Lafarge, H. Pothier, E. R. Williams, D. Esteve, C. Urbina and M. H. Devoret, *Z. Phys. B* **85,** 327 (1991).
3. P. Lafarge, P. Joyez, D. Esteve, C. Urbina and M. H. Devoret, *Nature* **365,** 422 (1993).
4. T. A. Fulton, P. L. Gammel, D. J. Bishop and L. N. Dunklerberger, *Phys. Rev. Lett.* **63,** 1307 (1989).
5. D. B. Haviland, L. S. Kuzmin, P. Delsing, K. K. Likharev and T. Cleason, *Z. Phys.* **85,** 339 (1991).
6. D. Joyez, P. Lafarge, A. Filipe, D. Esteve and M. H. Devoret, *Phys. Rev. Lett.* **72,** 2458 (1994).
7. D. Vion, M. Götz, P. Joyez, D. Esteve and M. H. Devoret, *Phys. Rev. Lett.* **77,** 3435 (1996).
8. Note added in proof: such a measurement has been recently performed indirectly by Nakamura *et al. Phys. Rev. Lett.* **79,** 2328 (1997).