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Observation of thermally excited charge transport modes in a superconducting single-electron transistor

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Abstract. – Experiments on a superconducting single-electron transistor are reported. A new structure in the current-voltage characteristics at subgap voltages was observed when temperature was not too low as compared to the superconducting transition temperature T_c of the sample. The strength of the anomalies increases exponentially with temperature. The dominating features arise from matching of singularities in the density of states on two sides of a tunnel junction, and from the Josephson-quasiparticle cycle. Thermal excitations are essential for the former process, and they also make the latter process possible at low voltages.

Charge transport in small capacitance tunnel junctions at low temperatures is influenced by single-electron effects [1], [2]. One of the simplest circuits revealing a great variety of these effects is the so-called single-electron or SET transistor. It consists of a mesoscopic island connected to an external circuit via two tunnel junctions, and of a gate electrode. When thermal and quantum fluctuations are small, the single-electron charging effects show themselves as the suppression of the tunnelling current at voltages below a threshold V_t, which can be modulated by gate charge with a period of the elementary charge e. The maximum threshold for a normal SET transistor is $V_{t,max} = 2E_c/e$, where $E_c = e^2/[2(2C + C_g)]$ is the charging energy, C is the capacitance of a junction, and C_g is the gate capacitance.

In superconducting SET transistors there are several mechanisms responsible for charge transport. First, the usual sequential tunnelling of quasiparticles is fully analogous to the tunnelling of single electrons in transistors made of normal metals. However, there is almost a step-like increase in current at V_t, which is shifted towards a higher voltage by $4\Delta/e$, where Δ is the energy gap of the superconductor. The threshold is smeared due to inelastic cotunnelling [3]. Secondly, pure Cooper pair tunnelling produces a current peak near zero bias [4]. The third current channel is produced by the Josephson-quasiparticle (JQP) cycle [5], [6] and other

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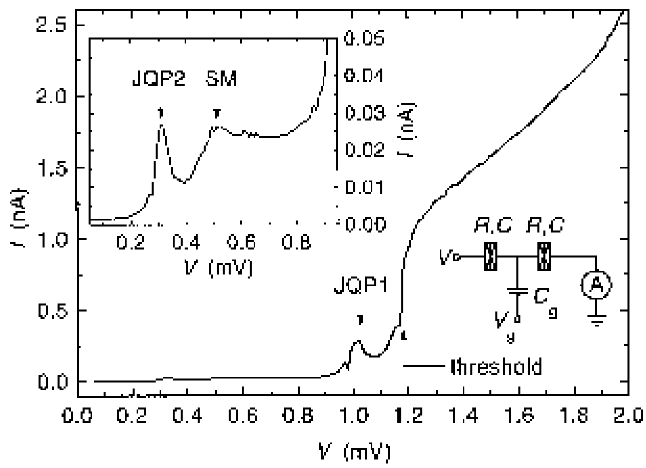

Fig. 1. – The I-V curve of the superconducting (SISIS) SET transistor at $T \simeq 0.52$ K on large current scale (main frame) and on small current scale (left inset). The peaks JQP1 and JQP2 are caused by the Josephson-quasiparticle cycles, and the SM feature is identified as the singularity-matching peak. Right inset: electrical configuration of our experiments.

processes involving combined Cooper pair and quasiparticle tunnelling, with a rich structure in the current-voltage (I-V) characteristics [7].

In this letter we present experimental results on the observation of new features in the I-V characteristics of a superconducting SET transistor. These features, including the ones recently predicted in ref. [8], are associated with charging effects and thermal excitations.

We fabricated the transistor of aluminium in a standard way using electron beam lithography and two-angle evaporation. The sample had a 1 μm × 100 nm central island with two tunnel junctions having resistance $R \simeq 210$ kΩ and capacitance $C \simeq 110$ aF each. The gate modulation measurements in normal state indicated that the capacitances of the two junctions were equal within about 10%. E_c was 0.35 meV and Δ was 0.21 meV at low temperatures. A 100 nm wide finger pointing orthogonally to the centre of the island at a distance of 0.5 μm served as a gate with $C_\mathrm{g} = 14$ aF, yielding a gate modulation period of 11.5 mV. The measurements were made in a dilution refrigerator at temperatures $0.1\ \mathrm{K} < T < 0.8$ K.

In fig. 1 we have plotted a typical I-V curve of the transistor at $T \simeq 0.52$ K. One end of the transistor was grounded through a current amplifier, and the voltage V was applied in the other end as shown in fig. 1. In addition to the threshold and the strong Josephson-quasiparticle peak [5] JQP1, two weak features can be observed at low V: a peak JQP2 and a ski-jump–shaped maximum SM. JQP2 and SM get even weaker toward low T, such that at $T < 0.2$ K they are almost unobservable, whereas the magnitude of the JQP1 peak does not change much with temperature. Figure 2 (a) shows the evolution of the I-V curves below $V = 4\Delta/e = 0.84$ mV when the gate voltage V_g is varied. The positions of the various features observable in the traces are plotted as a function of V_g in fig. 2 (b).

To start the discussion about the origin of the new features, let us note that the threshold V_t for "classical" sequential tunnelling through a symmetric superconducting SET transistor is the smallest value of

$$V_\mathrm{s} = \frac{4\Delta}{e} + \frac{4E_\mathrm{c}}{e}\left(\frac{1}{2} + n \pm \frac{Q_0}{e}\right), \tag{1}$$

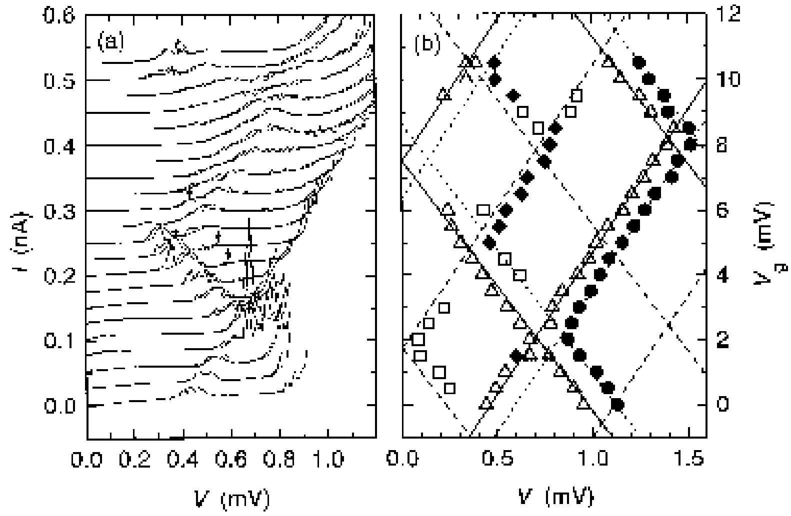

Fig. 2. – (a) I-V characteristics of the superconducting SET transistor at $T \simeq 0.52$ K with several gate voltages. From bottom to top, V_g is varied from 0 up to 10.5 mV with a step of 0.5 mV. Each trace has been shifted up by 0.05 (V_g/mV) nA. Two curves have been plotted for each V_g, one with increasing and one with decreasing bias voltage, in order to show which of the features are reproducible and thus real. The weak maxima in the lower part of the figure ($V_g < 5$ mV) are caused by the JQP processes, whereas the SM peak dominates in the upper part of the figure. The meaning of the small arrows is explained in text. (b) Measured and calculated positions of the features observable in the I-V curves of (a). Different symbols correspond to a different shape of an anomaly: solid circles, threshold voltage (see fig. 1); open triangles, a peak; solid diamonds, a ski-jump–shaped feature with a maximum (see SM in fig. 1); open squares, a kink below which $\mathrm{d}I/\mathrm{d}V > 0$ and above which $\mathrm{d}I/\mathrm{d}V \simeq 0$. The lines are calculated using eqs. (1)-(3) with $n = 0, \pm 1$: dotted line, the threshold voltage V_t and its continuation below $4\Delta/e$ (eq. (1)); dashed line, SM peak (eq. (2)); solid line, JQP peak (eq. (3)). The values of all the parameters used in the calculations were obtained from the V_g-dependence of V_t only: $E_c = 0.35$ meV, $\Delta = 0.21$ meV, $e/C_g = 11.5$ mV, and $Q_b/e = 0.65$.

which exceeds $4\Delta/e$, with n an integer. Q_0 describes the charge polarisation in the island and can be written for our asymmetric voltage bias as $Q_0 = C_g(V_g - V/2) + Q_b$, where the "background charge" Q_b is caused by the charged impurities near the island. The values of Δ, E_c, C_g, and Q_b can be obtained by comparing eq. (1) to the observed behaviour of V_t as a function of V_g, as shown in fig. 2 (b).

At $T > 0$ there can be a small step in the I-V characteristics at voltages V_s given by eq. (1) even for $V < 4\Delta/e$ [8]. This situation is shown schematically in fig. 3 (a): Tunnelling of quasiparticles from the filled states below the gap in the left electrode into the empty states above the gap in the island becomes possible when $V = V_s$, but tunnelling from the island into the right electrode is possible only because of the thermally excited quasiparticles and quasiholes. Thus, the step can be observed only if T is not too low compared to the transition temperature T_c of the superconductor, so that the number of thermal excitations is not negligible. This feature can be seen in some of the I-V curves of fig. 2 (a) as a weak, smeared step (see the small arrows). In fig. 2 (b) the positions of these features are very close to the continuation of the V_t line, eq. (1), indicated by a dotted line.

A more interesting phenomenon predicted in ref. [8] is the existence of a so-called singularity-

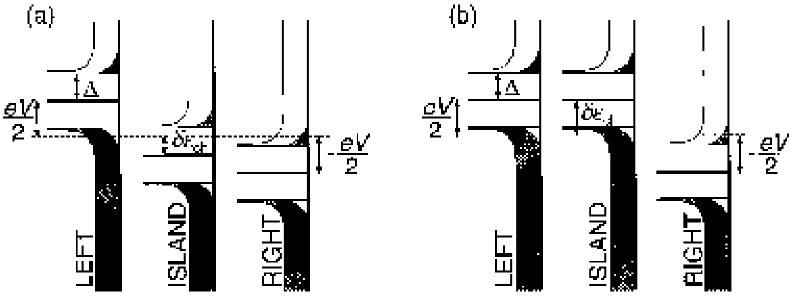

Fig. 3. – Density-of-states diagrams for a superconducting SET transistor at a finite temperature when (a) $V = V_{\mathrm{s}}$ and (b) $V = V_{\mathrm{SM}}$. Tunnelling from the left electrode into the island or from the island into the right electrode is possible along horizontal lines if there are occupied states (grey) on the left side and empty states (blank) on the right side of the junction. To simplify the discussion we assume a symmetric bias voltage (unlike in the experiments), such that the potentials on the left and right electrodes are $-V/2$ and $V/2$, respectively. The energy of the island is shifted by $\delta\varepsilon_{\mathrm{ch}} = 2(N+1/2-Q_0/e)E_{\mathrm{c}}$, which is the change in the Coulomb energy when the number of electrons in the island changes from N to $N+1$. $Q_0 = C_{\mathrm{g}}V_{\mathrm{g}} + Q_{\mathrm{b}}$ for the symmetrically biased transistor. The condition for Josephson tunnelling from the left electrode into the island in the JQP cycle is described by (b), as well, but now $\delta\varepsilon_{\mathrm{ch}} = 2(N+1-Q_0/e)E_{\mathrm{c}}$ is the change in energy per electron when a Cooper pair tunnels into the island. However, for the subsequent tunnelling of single electrons from the island into the right electrode, $\delta\varepsilon_{\mathrm{ch}} = 2(N+1/2-Q_0/e)E_{\mathrm{c}}$ again: for the first (second) electron the energy level of the island is shifted up (down) by E_{c} from that indicated in (b).

matching (SM) peak at voltages

$$V_{\mathrm{SM}} = \frac{4E_{\mathrm{c}}}{e}\left(\frac{1}{2} + n \pm \frac{Q_0}{e}\right). \tag{2}$$

When $V = V_{\mathrm{SM}}$, the density-of-states diagrams on both sides of one of the tunnel junctions of the transistor coincide, as shown in fig. 3 (b): thermally excited quasiparticles from the states just above the energy gap in the left electrode can tunnel into the infinite density of empty states in the island (and similarly for tunnelling into the thermally emptied states below the gap in the island). Thus, the origin of the SM peak is the same as that of the peak in tunnelling current between two different superconductors at $V = (\Delta_1 - \Delta_2)/e$ [9]. Because the SM peak is caused by thermal excitations, its strength should increase with increasing temperature, and in BCS it should completely disappear at $T \ll T_{\mathrm{c}}$. The feature should be most pronounced when $2\Delta/e < V < 2(\Delta + E_{\mathrm{c}})/e$ [8].

In the experimental traces of fig. 2 (a) the SM peak is the dominant feature at $V_{\mathrm{g}} > 5$ mV, *i.e.* in the upper half of the figure. It can be seen in fig. 1, as well. The identification of the feature is based both on the temperature dependence of its magnitude (see fig. 4), on its shape which is close to that given by numerical simulations, and on the evolution of its position with V_{g}. In fig. 2 (b) the dashed lines are calculated using eq. (2) with the parameters determined from the V_{g}-dependence of the threshold V_{t}. The position of the features observable at subgap voltages ($V < 0.8$ mV) at $V_{\mathrm{g}} > 5$ mV follows the prediction of eq. (2) reasonably well. The measured locations are systematically at a slightly larger voltage than predicted, probably because of experimental rounding, which tends to shift the measured maximum of the ski-jump–shaped SM features to higher V. When $V_{\mathrm{g}} < 3$ mV, the SM feature can be seen at $V < 0.3$ mV as a weak kink, which is only barely observable on the scale of fig. 2 (a).

The strength of the SM feature increases fast with T in fig. 4 (a), but at the highest

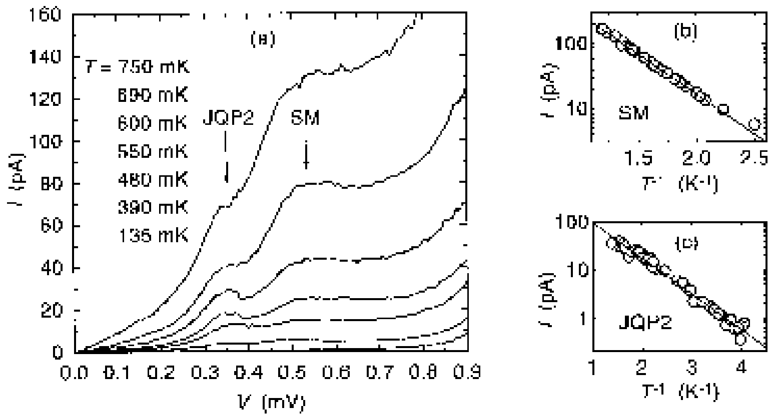

Fig. 4. – (a) Temperature dependence of the I-V curve when both SM and JQP2 are present. Temperatures for each of the traces are shown in the figure. (b) The current level on the maximum or the plateau of the SM feature on a logarithmic current scale plotted as a function of $1/T$ when V_g was the same as in (a). The straight line is $I = 5\ \mathrm{nA} \cdot \exp[(-2.85\ \mathrm{K})/T]$. (c) Temperature dependence of the height of the JQP2 peak from which a linear background was subtracted. V_g was adjusted in such a way that the peak was well separated from other anomalies in the I-V trace. The formula for the line is $I = 0.55\ \mathrm{nA} \cdot \exp[(-1.72\ \mathrm{K})/T]$.

temperatures there is a plateau instead of a maximum at $V_{\mathrm{SM}} \simeq 0.5$ mV. We have plotted the current level on the maximum or the plateau of the SM anomaly as a function of $1/T$ in fig. 4 (b). It follows very well an exponential law of the form $I = I_0 \exp[-\alpha/T]$, as expected for a process which involves thermal excitations. The fitted value of $\alpha = 2.85$ K is only slightly larger than $\Delta/k_{\mathrm{B}} = 2.43$ K, although we would not expect these two quantities to coincide necessarily. The SM feature is possibly also present in the low-temperature data of ref. [10], due to non-thermally excited quasiparticles.

In the JQP process [5], [6] a Cooper pair first tunnels through one junction into (or from) the island, and then two quasiparticles tunnel separately through the other junction. Tunnelling of Cooper pairs from the condensate (thick line in the middle of the energy gap in fig. 3) in the left electrode into the condensate in the island is possible if the energy of the system does not change. That situation corresponds to fig. 3 (b), too, but for Cooper pair tunnelling the change in Coulomb energy per a single electron, $\delta\varepsilon_{\mathrm{ch}}$, differs from the case of single-quasiparticle tunnelling by E_{c}. Thus, the JQP cycle can take place at voltages

$$V_{\mathrm{JQP}} = \frac{4E_{\mathrm{c}}}{e}\left(n \pm \frac{Q_0}{e}\right). \tag{3}$$

In the low-temperature regime, which earlier work has mainly concentrated on [5], [7], [11], the JQP process can only exist if V is high enough so that two quasiparticles can tunnel from the states below the energy gap in the island into the empty states above the gap in the right electrode in the case of fig. 3 (b). Because $\delta\varepsilon_{\mathrm{ch}}$ for tunnelling of the second electron away from the island is smaller by E_{c} from the "Cooper pair value", this gives a condition $V > (2\Delta + E_{\mathrm{c}})/e$ [5]. The "low-temperature JQP" causes the JQP1 peak in the experimental trace of fig. 1. Its height does not depend strongly on T, and its location (open triangles about 0.2 mV below V_{t} in fig. 2 (b)) agrees with eq. (3), plotted as a solid line in fig. 2 (b).

Thermal excitations make tunnelling of quasiparticles from/into the island in a JQP process possible even when $V < (2\Delta + E_c)/e$. Thus, when T is not too much below T_c, the JQP peak should exist at low voltages, too. This "high-temperature JQP peak", JQP2, is clearly observable in the left inset of fig. 1, and it is the dominant feature in the traces in the lower half of fig. 2 (a). As fig. 2 (b) indicates, the gate-voltage dependence of this peak (open triangles below $V = (2\Delta + E_c)/e = 0.77$ mV) follows very well the line calculated using eq. (3). Figure 4 (a) shows that this peak gets stronger with increasing temperature, but upon approaching T_c it becomes indistinguishable from the SM feature. The temperature dependence of the height of the JQP2 peak in the case when it is well separated from the other features is shown in fig. 4 (c). Again, the dependence is of the form $I_0 \exp[-\alpha/T]$, but now $\alpha = 1.72$ K is smaller than that for the SM feature. The high peak at $V \simeq 0.7$ mV on the fifth trace from the bottom in fig. 2 (a) is caused by a $3e$ process [7], [11] and corresponds to crossing of two JQP lines in fig. 2 (b).

In conclusion, we have observed new features in the *I*-*V* curves of a superconducting single-electron transistor at $V < 4\Delta/e$. They originate due to thermal excitations, and their strength increases exponentially with temperature. The dominant ones arise from matching of singularities on two sides of one of the tunnel junctions of the transistor, and from thermally assisted Josephson-quasiparticle cycles. Identification of the features according to the gate voltage dependence of their positions was easy in our sample, in which the charging energy E_c was almost twice as large as the energy gap Δ.

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After we had observed the SM and JQP2 features, we became aware of similar results obtained by Nakamura *et al.* [12]. We thank the NEC group for informing us about their results prior to publication. This work was supported financially by the Academy of Finland, and the work of YuAP and ANK by the Russian Foundation for Basic Research under grants 97-02-17056 and 97-02-16332 and the Russian Program on Nanostructures.

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