Quantum Transport and Quantum Coherence (Localisation 2002)
J. Phys Soc. Jpn. Vol. **72** (2003) Suppl. A pp. 187–188

Coulomb-blockaded Josephson junction as a noise detector

Julien Delahaye[1,*], Rene Lindell[1], Mika Sillanpää[1], Mikko Paalanen[1], Edouard Sonin[2], and Pertti Hakonen[1,†]

[1] *Low Temperature Laboratory, Helsinki University of Technology, P.O. Box 2200 FIN-02015 HUT, Finland*
[2] *The Racah Institute of Physics, The Hebrew University of Jerusalem, Jerusalem 91904, Israel*

(Received August 14, 2002)

KEYWORDS: Josephson junction, Coulomb blockade, shot noise, noise detector, angle evaporation

1. Introduction

The behavior of a Josephson junction is strongly influenced by the dissipation caused by the resistance R of the surrounding environment.[1)] If dissipation is small ($R > R_Q = h/4e^2$), the phase of the junction becomes delocalized by fluctuations, and Coulomb blockade (CB) of Cooper pair tunneling takes place.[1–3)] In this case, theory predicts a power-law-like increase of conductance, both as a function of temperature and voltage.[1)] The exponent of the power law, $2\rho - 2$, is specified by the parameter $\rho = R/R_Q$. Hence, in the case of large exponents $2\rho - 2 \gg 1$, the conductance is highly susceptible to tiny changes in temperature, or alternatively, there is a high sensitivity to any extra noise sources.

We have investigated if this extreme sensitivity could be turned into use in a high-resolution noise detector. For this purpose, we have experimentally investigated how the CB of a Josephson junction changes in the presence of shot noise induced by a near-by SIN junction. In this brief note, we will discuss just one of our samples and present the basic findings on it. For a more detailed description, we refer to a forthcoming publication Ref.[4)]

2. Experiment

The schematic structure of our sample is displayed in Fig. 1. The circuit consists of: 1) an Al-AlO$_x$-Al Josephson junction (JJ) with a tunnel resistance of $R_T^{JJ} = 8.1$ kΩ, 2) a superconducting-normal Al-AlO$_x$-Cu tunnel junction (SIN) with $R_T^{SIN} = 27.3$ kΩ, and 3) a thin film Cr resistor of $R_C = 22.6$ kΩ (20 μm long), located within a few μm from the Josephson junction.

The sample was patterned using electron beam lithography and four-angle shadow evaporation. The Cr resistor (5 nm thick, 100 nm wide) was evaporated first at an angle of −18°, followed by the Al-island at −38°. After oxidation, the sample holder was rotated by 45° around the z-axis and the JJ was deposited by a second Al-evaporation at +38°. Last, the SIN-junction was formed by a copper deposition at +6°.

The JJ junction was, in fact, made of two 100*100 nm^2 junctions in a SQUID geometry. In all noise studies reported here, the Josephson energy was tuned to its minimum value of $E_J = 22$ μeV. The minimum Josephson coupling energy, E_J^{min}, was obtained from the minimum of critical current $I_C(\Phi)$ as a function of external flux Φ by assuming a linear dependence between E_J and I_C; the maximum value E_J^{max} was calculated using the Ambegaokar-Baratoff relation. The Coulomb energy $E_C = e^2/2C = 65$ μeV was estimated from the asymptotic IV-curves in the normal state. Thus, the ratio $E_J/E_C = 0.34$. The measurement leads were filtered by 1.5 MHz low-pass filters at the top of the cryostat and by 1 m of Thermocoax cable at the mixing chamber temperature.

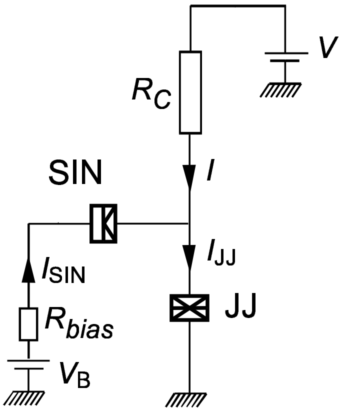

Fig. 1. Scheme of the experimental circuit. The high impedance environment, given by a chrome resistor, is denoted by R_C, the superconductor-normal metal junction by SIN, the Josephson junction by JJ. Symbols for different biasing voltages and the resulting currents are also given in the figure.

3. Results

The IV-curve of our sample is displayed in Fig. 2 where we plot the current through the chrome resistor I as a function of the full transport voltage V. Near zero-bias, a clear Coulomb blockade of the Cooper pair current is seen. The behavior of the Coulomb blockade follows well the expectations from the theory, *i.e.*, we observe a steep power law as a function of T.[4)] At higher voltages, Zener tunneling up to higher bands sets in, which leads to a decrease in the rate of Cooper pair tunneling. The dashed line displays the IV-curve under the influence of a small base current $I_{SIN} = 0.4$ nA. It is seen to suppress the Coulomb blockade strongly while the Zener tunneling region is only mildly influenced by the added quasiparticle current.

---

[*] Present address: CNRS BP 166 38042 Grenoble, Cedex 9 France
[†] pertti.hakonen@hut.fi.

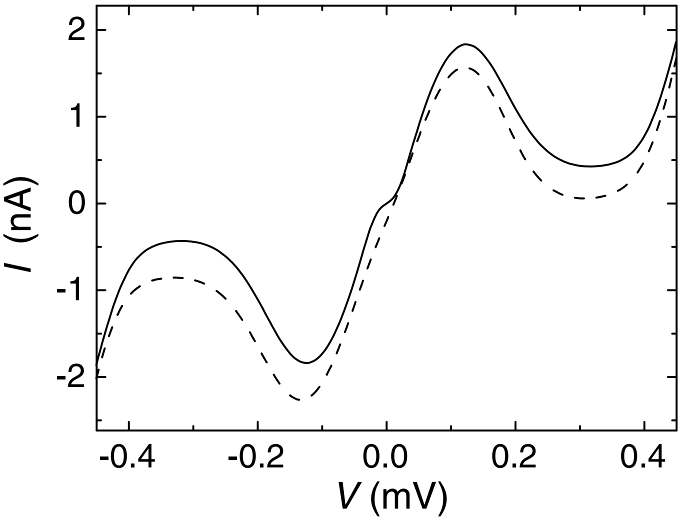

Fig. 2. Solid curve displays an IV-curve measured at $T = 90$ mK. The dashed curve illustrates the IV-curve under otherwise the same conditions but with $I_{SIN} = 0.4$ nA ($R_{bias} = 100$ MΩ).

Experimentally, it is easier to quantify the effect of the base current by measuring the dynamic resistance $R = \frac{dV}{dI_{JJ}}$. This quantity is shown in Fig. 3, where we compare the effect of I_{SIN} to that of T. From the shapes of the RV-curves measured at $T = 90$ and 130 mK, we deduce that a current of $I_{SIN} = 0.1$ nA produces a similar effect as a temperature change of $\Delta T = 40$ mK.

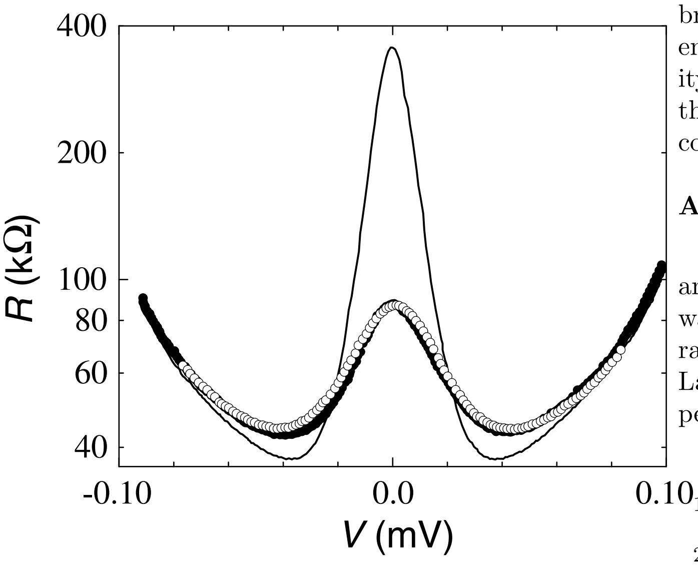

Fig. 3. Influence of I_{SIN} and T on the differential resistance $R = \frac{dV}{dI_{JJ}}$ around the Coulomb-blockaded region. Solid curve – $T = 90$ mK and $I_{SIN} = 0$; open circles – $T = 130$ mK and $I_{SIN} = 0$; filled circles – $T = 90$ mK and $I_{SIN} = 0.1$ nA. Voltage scales of the curves have been slightly modified in order allow for a better comparison.

4. Discussion

At present, there is no well-developed theory for the behavior of a Coulomb-blockaded Josephson junction under the influence of shot noise. Assuming that the shot noise from the SIN-junction can be converted to an equivalent resistive noise source,$^{5)}$ one can estimate the Fano-factor of the current-induced noise:

$$F = \frac{2k_B \Delta T}{eI_{SIN}R_C}. \qquad (1)$$

It can be shown$^{4)}$ using the $P(E)$ formalism for inelastic Cooper pair tunneling$^{6,7)}$ that, in the superconducting phase ($\rho \ll 1$), the above approach is sound whereas in the insulating phase ($\rho \gg 1$) it must be considered as approximative, and one should resort to numerical analysis. The comparison of the data sets in Fig. 3 suggests that $F \sim 3$ for our sample.

Part of the deviation from $F \sim 1$ may be attributed to the fact that a SIN junction is a complicated nonlinear object. In the subgap region, Andreev reflection plays a role, which should lead to $F = 2$ since, instead of single electrons, there is tunneling of Cooper pairs with a charge of $2e$.

5. Conclusions

Altogether, a Josephson junction noise detector provides a serious alternative to be considered for high-resolution noise measurements. Its main virtue, the high sensitivity, comes from the large detector band width: $\sim 1/R_C C$. However, as long as a detailed noise theory for the case under consideration is lacking, a calibration source with a known power spectrum should be employed. A junction detector will surpass the sensitivity of regular high-resolution noise measurements$^{8)}$ when the selection of the parameter values and the operating conditions are properly made.$^{4)}$

Acknowledgements

It is a pleasure to thank L. Roschier, A. Schakel and A.D. Zaikin for useful discussions. This work was supported by the Academy of Finland, by the Israel Academy of Sciences and Humanities, and by the Large Scale Installation Program ULTI-3 of the European Union.

1) See, *e.g.*, G. Schön and A.D. Zaikin, Phys. Rep. **198** (1990) 237.
2) D. B. Haviland, L. S. Kuzmin, P. Delsing, and T. Claeson, Europhys. Lett. **16** (1991) 103.
3) J.S. Penttilä, Ü. Parts, P.J. Hakonen, M.A. Paalanen, and E.B. Sonin, Phys. Rev. Lett. **82** (1999) 1004.
4) J. Delahaye, R. Lindell, M.S. Sillanpää, M.A. Paalanen, E.B. Sonin, and P.J. Hakonen, to be published.
5) This neglects the differences in the power spectra of tunnel-junction noise and Johnson-Nyquist noise.
6) G.L. Ingold and Yu.V. Nazarov, in *Single Charge Tunneling, Coulomb Blockade Phenomena in Nanostructures*, ed. by H. Grabert and M. Devoret (Plenum, New York, 1992), pp. 21-107.
7) G.-L. Ingold, H. Grabert, and U. Eberhardt, Phys. Rev. B **50** (1994) 395.
8) M. Reznikov, R. de Picciotto, T.G. Griffiths, M. Heiblum, and V. Umansky, Nature **399** (1999) 238.