# Tunnel spectroscopy of a double superconducting island qubit

P. Lafarge [a,1], D. Schaeffer [b], E. Bibow [b] L.P. Lévy [a]

[a] *Grenoble High Magnetic Field Laboratory, CNRS and MPI-FKF, BP 166, F-38042 Grenoble Cedex 9, France and Université Joseph Fourier, BP 53, F-38041 Grenoble Cedex 9, France*

[b] *Grenoble High Magnetic Field Laboratory, CNRS and MPI-FKF, BP 166, F-38042 Grenoble Cedex 9, France*

**Abstract**

We have probed by tunnel spectroscopy a quantum system consisting of two superconducting islands strongly coupled by an ultrasmall Josephson junction. The Josephson junction allows Cooper pair delocalization between the two islands and gate voltages control the state of the system. Tunnel spectroscopy is made possible by means of two other junctions weakly coupling the islands to measurement leads. We have observed different transport regimes depending on the applied bias voltage.

*Key words:* Josephson effect; Coulomb blockade

Superconducting circuits based on ultra-small Josephson junctions are promizing candidates for implementing quantum bits, or qubits, in solid state devices [1][2][3][4]. We have probed by resonant tunneling spectroscopy a model qubit consisting of two superconducting islands connected by a nanoscale Josephson tunnel junction. For controlling the qubit, each island is capacitively coupled to a gate voltage source.

In superconducting islands, electrons are paired and condensed in the same macroscopic quantum state. The phase and the charge of the island are non commutating quantum variables and can be used alternatively to describe its quantum state. The characteristic energies of the double-island are the charging energy $E_C = e^2/2C$, $C$ being the junction capacitance and the Josephson energy $E_J$ of the junction. In our circuit, charge is a good quantum number since Coulomb blockade suppresses large charge fluctuations. However, the Josephson junction which allows coherent charge transfer between the two islands creates a quantum coupling between charge states. For instance, assuming the double-island contains one extra Cooper pair, the qubit is based on two charge states denoted $|1,0\rangle$ and $|0,1\rangle$ depending whether the extra Cooper pair is on the left or the right island. The natural parameters for controlling the qubit state are the difference $V_d = V_{g2} - V_{g1}$ and the sum $V_s = V_{g2} + V_{g1}$ in applied gate voltages. The condition $E_c \sim E_J$ ensures that significant mixing of the charge states can occur.

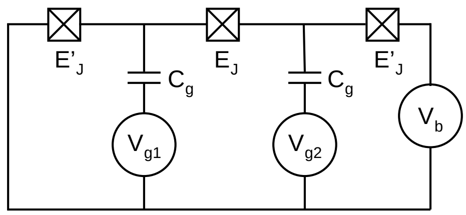


Fig. 1. Schematic of the double-island circuit. The Josephson energy of the middle junction $E_J$ is much larger than $E'_J$, the Josephson energy of the external junctions. We estimate $E_J \sim 43\ \mu V$ and $E'_J \sim 3\ \mu V$.

Practically, the double-island qubit is connected to two reservoirs by weak tunnel junctions as shown on Fig. 1. The sample is fabricated by electron beam lithography followed by shadow evaporation of Al. The whole device consists of three Al/AlOX/Al tunnel junctions in series. Thanks to two different oxidation

[1] Corresponding author. Present address: Grenoble High Magnetic Field Laboratory, CNRS and MPI-FKF, BP 166, 38042 Grenoble Cedex 9, France. E-mail: lafarge@polycnrs-gre.fr

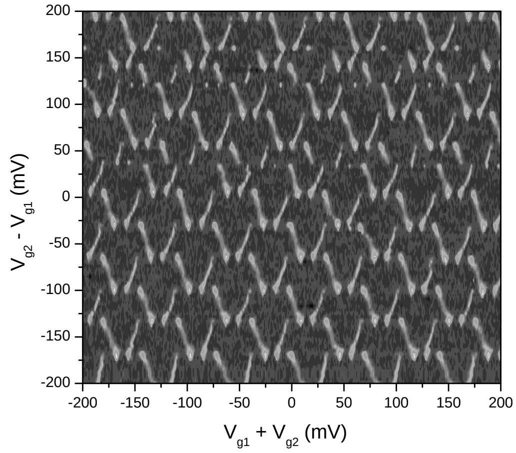


Fig. 2. Contourplot of the current at $V_b = 140\mu V$ measured as a function of $V_{g1} + V_{g2}$ for fixed $V_{g2} - V_{g1}$ values between -200 and 200 mV differing by 4 mV. The maximum current is 0.6 pA. Shifts of the periodic pattern are due to discrete motion of background offset charges.

steps, the middle junction is much more transparent than the junctions connecting the double-island to the reservoirs. We apply a finite bias voltage $V_b$ across the device to inject Cooper pairs in the double-island and we measure a current resulting from transitions between the quantum states of the qubit. The current is enhanced when the transitions are resonant. By tuning the difference $V_d$ in applied gate voltages, we control the energies of the two states whereas the sum $V_s$ sets the potential of the double-island with respect to the reservoirs and controls the total charge.

The gate voltages modulate periodically the amplitude of the measured current (see Fig. 2). We have identified different transport regimes depending on the value of the bias voltage $V_b$ with respect to $\Delta/e = 200$ $\mu V$, where $\Delta$ is the superconducting gap. For $V_b < 200\mu V$, the transport properties are fully 2e periodic with the gate induced charges. In this regime, transport occurs by resonant Cooper pair tunneling between the leads and the quantum states of the double-island [5]. The dissipation is provided by the electromagnetic environment. The lines observed in Fig. 2 are located at points where the energy of charge states of the double-island is aligned with the chemical potential of one of the reservoirs. At lower bias voltages, we have observed resonance peaks in the $V_s - V_d$ plane on the degeneracy line of charge states $|1,0\rangle$ and $|0,1\rangle$ [6]. We interpret these peaks as the result of a double resonant tunneling process involving superposition of the $|1,0\rangle$ and $|0,1\rangle$ states.

At bias voltages between 200 $\mu$V and 400 $\mu$V, the observed pattern is e-periodic in the $V_s$-$V_d$ plane. The e-periodicity indicates the presence of residual unpaired quasiparticles in the islands but transport is still due

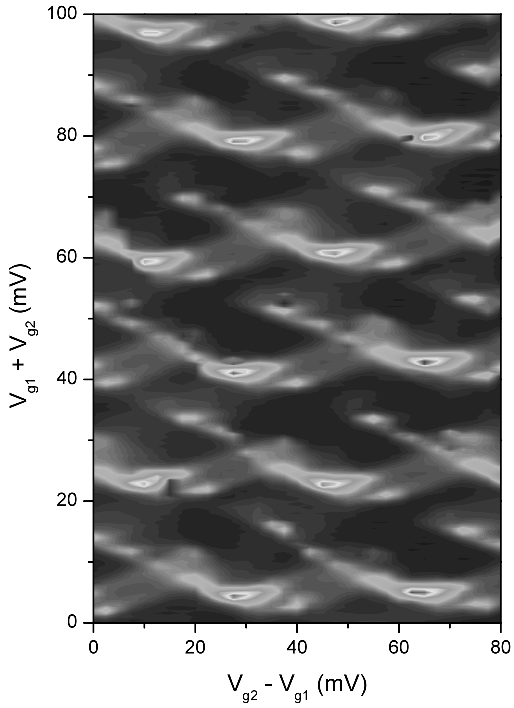


Fig. 3. Contourplot of the current at $V_b = -300\mu V$ measured as a function of $V_{g1} + V_{g2}$ for fixed $V_{g2} - V_{g1}$ values between 0 and 80 mV differing by 2.5 mV. The maximum current is 9 pA.

to Cooper pair tunneling since the applied bias voltage is not large enough for breaking Cooper pairs. Energy differences between charge states vary linearly with the gate voltages, therefore resonances involving pure charge states should appear as lines in the $V_s$-$V_d$ plane. The non linear structure of the pattern in Fig. 3 suggests that the states involved in the resonant processes are quantum superposition of charge states. Calculated peak positions based on a resonance through an eigenstate of the double island are in qualitative agreement with the experimental results.

## References

[1] Y. Nakamura, Yu. A. Pashkin, J.S. Tsai, Nature **398** (1999) 786.

[2] C. H. van der Wal, et al., Science **290** (2000) 773.

[3] Y. Makhlin, G. Schön, A. Shnirman, Rev. Mod. Phys. **73** (2001) 357.

[4] D. Vion, A. Aassime, A. Cottet, P. Joyez, H. Pothier, C. Urbina, D. Esteve, M.H. Devoret, Science **296** (2002) 886.

[5] D.B. Haviland, Y. Harada, P. Delsing, C.D. Chen, T. Claeson, Phys. Rev. Lett. **73** (1994) 1541.

[6] E. Bibow, P. Lafarge, L.P. Lévy, Phys. Rev. Lett. **88** (2002) 017003.