Single charge transport in a fully superconducting SQUISET locally tuned by self-inductance effects

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We present a single-electron device for the manipulation of charge states via quantum interference in nanostructured electrodes. Via self-inductance effects, we induce two independent magnetic fluxes in the electrodes and we demonstrate sensitivity to single charge states and magnetic field at variable temperature. Moreover, our approach allows us to demonstrate local and independent control of the single-particle conductance between nano-engineered tunnel junctions in a fully-Superconducting Quantum Interference Single-Electron Transistor (SQUISET), thereby increasing the flexibility of our single-electron transistors. Our devices show a robust modulation of the current-to-flux transfer function via control currents, while exploiting the single-electron filling of a mesoscopic superconducting island. Further applications of the device concept to single-charge manipulation and magnetic-flux sensing are also discussed.

Superconducting nanoelectronics has continuously grown in the last decades as a flexible and promising platform for the implementation of quantum-based sensors1–3 and quantum-states manipulating circuits4,5, with particular attention to interference-based superconducting devices6 and mesoscopic structures where single charges play dominant roles7,8. Different geometries can be easily combined with standard nanolithography techniques9, opening the field to complex and robust devices embedding multiple control lines and tunable working points in the parameters space. As a consequence, superconducting nanoelectronics technology represents an exceptional research platform for condensed-matter quantum physics experiments as well as for scalable quantum computing10 and photonics applications11.

Normal-metal12, hybrid13 or fully-superconducting14 single-electron devices - fabricated by shadow-mask technique9 - have been so far one of the research topics where nanofabrication technology excelled, leading to device concepts where the detection of charge states approaching their coherent superposition15 has been routinely reached. While rather complex single-electron systems based on local electrical gating have been demonstrated16, the on-chip tunability of their electrodes carriers population has been limited to the semiconductor nanowires17 and the 2D-electron-gas based technologies18, where clear manipulation of Coulomb blockade effects has only been allowed via strong electric fields.

Nanofabricated superconducting electrodes8 introduce an alternative control parameter, the magnetic flux, that can act on the population of quasiparticles charge carriers19 via quantum interference1. Short metallic nanowires have been embedded in superconducting loops7 leaving enough space to be coupled to a Coulombic island through mesoscopic tunnel junctions. The present technology, which is mostly based on aluminum tunnel junctions, is then further extended by an unprecedented level of control and flexibility offered by localized magnetic fluxes. Various approaches exploiting these phenomena demonstrated state-of-the-art magnetic flux sensing capabilities2,3,20 and single charges states manipulation8 but still lack for on-chip control.

Here we demonstrate that two local magnetic fluxes can be used to manipulate the electrodes density of states of a fully superconducting SQUISET and to efficiently modify its electron transport properties. In particular, we show how the typical Coulomb energy of the island can be controlled by the quasiparticle spectra of the source and drain electrodes by exploiting self-inductance effects.

A prototypical device is depicted in Figure 1. A superconducting island is connected to the source and drain electrodes via tunnel junctions. Both source and drain consist of a superconducting nanowire embedded in a superconducting loop. Each ring has two contact pads for the injection of the source-drain current and the currents for the independent control of the fluxes. The entire structure is realized via three-angle-deposition (42°/20°/0°) of aluminum (15 nm/20 nm/100 nm) through a suspended mask on a Si/SiO2 (300 nm thick oxide) substrate (see Figure 1a). The polymeric mask has been obtained via electron beam lithography, whereas thin films deposition has been performed via electron beam evaporation. Tunnel junctions were created between the first and the second deposition step by oxygen exposure (5 × 10−3 mbar for 5 min). One of the tunnel junction across the nanowire and the island is visible in the inset of Figure 1a. The device configuration defines three main current path IS, ID and ISD. The first two act as control currents flowing along parts of the source and drain loops, while the last is the effective current flowing through the Coulombic island (Figure 1b). The entire chip is pierced by an uniform magnetic field, B, generated by an external magnet inducing a flux \( \Phi_B = A \times B \) in both the identical loops of area A. The combined effect of B and the local currents gives rise to two magnetic fluxes at the source and drain loops, \( \Phi_S = \Phi_{SD} + M_S \times I_S + m_S \times I_D \) and \( \Phi_D = \Phi_{SD} + M_D \times I_S + m_D \times I_D \), respectively. M_S and M_D are the self-inductances, m_S and m_D are the mutual inductances between opposite loop. The electrodes are biased via an external voltage source (VSD), and the island is exposed to a con-
control electric field via a capacitively-coupled gate that induces $n_G = C_G V_G/e$ quantized charges, being $C_G$ the gate-island capacitance, $V_G$ the gate voltage and $e$ the electron charge. This device architecture is designed to act essentially as a fully superconducting single electron transistor (SSET) with two identical tunnel junctions (total series resistance $R_T$$\approx 1.75\,\text{M} \Omega$). In the absence of a magnetic field, this is confirmed by the differential conductance stability diagram in Figure 1c clearly showing the effect of the charging energy, evaluated to be $E_C =75\,\text{µeV}$ from the Coulomb diamonds and confirmed by the Josephson-quasiparticle peaks (JQPs) \cite{ref1, ref2}. In particular, dark and sharp JQPs conductance peaks clearly visible in the blocked region of Figures 1c and 1d result to be unaffected by the small magnetic field applied since they depend on the island superconducting gap $\Delta_I$ and $E_C$ only. Therefore, from the JQPs we have estimated $\Delta_I$$\approx 216\,\text{µeV}$. When the SQUISET is uniformly pierced by $B$, the condition $\Phi_S = \Phi_D = \Phi_B = \Phi_0/2$ can be reached, as shown in Figure 1d, and the superconducting gaps of the the two nanowires are reduced to their minimum via quantum interference. This effect can be appreciated by the reduction of the voltage threshold separating the conducting region, where the transport is dominated by quasiparticles tunneling and not JQP cycles, respect the blocked one ($V_1 = 2\Delta_I + \Delta_{S,0} + \Delta_{D,0}$ in Figure 1c and $V_2 = 2\Delta_I + \Delta_{S,1/2} + \Delta_{D,1/2}$ in Figure 1d). It’s worth mentioning here that $V_1$ and $V_2$ have been selected as reference thresholds, for which the independence by the charging energy $E_C$ is guaranteed by their position respect the coulomb diamonds. From there, the zero magnetic field and the $\Phi_0/2$ superconducting gaps of the electrodes have been deduced ($\Delta_{S,0} = \Delta_{D,0}$$\approx 235\,\text{µeV}$ and $\Delta_{S,1/2} = \Delta_{D,1/2}$$\approx 84\,\text{µeV}$). The effect of local magnetic flux biasing via $I_S$ and $I_D$ is shown in Figure 2, where the source-drain current $I_{SD}$ is monitored at fixed bias $V_{SD} = V_1$ as a functions of the currents flowing in the loops. The non-symmetrical behavior shown in Figure 2 suggests an asymmetry in the dynamical conductance of the two tunnel junction involved. From the analysis of maxima and minima fitted positions in this diagram, represented by

FIG. 1. (a) Scanning electron micrography of a typical SQUISET device. The two currents paths ($I_S$ and $I_D$) generating the two magnetic fluxes ($\Phi_S$ and $\Phi_D$) are indicated. The latter pierce the two superconducting loops of the source and drain electrodes (orange). A mesoscopic island (light green) is in tunnel contact with two superconducting nanowires (red) and it is capacitively coupled to a gate electrode (green). Few elements of the device can be attributed to fabrication or measurement details. In particular, the cross-like structure reported by the inset near the nanowire is its unavoidable duplicate coming from the shadow deposition technique used to fabricate the structure. Always in the shadow technique context, the fork-like structure of the gate electrodes guarantees a fixed distance between the island and the gate at every deposition angle. The structure with sharp angles composing the current biasing wires acts as mirrors for high frequencies components of the electrical field generated by the external magnetic field $B$. Black arrows indicating $2V_1$ and $2V_2$ represent the voltage region where the current is blocked by either the superconducting gaps of the island and the electrodes or the charging energy.
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tive devices. These offsets where removed by referring to the
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SD presents sharp and periodic peaks on top of
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metry existing between local conductances of the source and
drain tunnel junctions.26 The S’ISIS’ structure of our device
expresses here strong asymmetrical behavior respect the the
symmetrical geometry, simply due to the local action of un-
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wider respect the sharp peaks of the island-drain junction due
to the asymmetric voltage bias of the circuit (see Figure 1(b).
In order to quantify the flux-to-current transfer function we
show in Figure 4(b) the numerical derivative of
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two different superconducting gaps, moreover the effect
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responsiveness of our device to magnetic flux variation. As
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siveness of the SQUIDET to magnetic field is a consequence
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In summary, we have reported the fabrication and character-
ization of a fully-superconducting SQUIDET demonstrating
local manipulation of charge and magnetic flux sensing via
independent current and voltage control lines. We discuss in
detail the dependencies on external magnetic field, gate volt-
age, flux bias currents and temperature, which is possible due
to the multiple-electrodes design of the device. On one side,
this proof-of-concept device opens up to an unprecedented
 tools to superconducting charge control, with quantum
interference based nanostructured electrodes, to be used in quan-
tum electronics and metrology. Moreover, straightforward
integration with present quantum technologies based
on aluminum nanostructures is worth considering. On the
other side, the enhanced and flexible sensitivity to magnetic
fields envisage our device concept for the implementation of
energy-filtered single charge magnetometers.
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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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