We propose the concept of a quantized single-electron source based on the interplay between Coulomb blockade and magnetic flux-controllable superconducting proximity effect. We show that flux dependence of the induced energy gap in the density of states of a nanosized metallic wire can be exploited as an efficient tunable energy barrier which enables charge pumping configurations with enhanced functionalities. This control parameter strongly affects the charging landscape of a normal metal island with non-negligible Coulombic energy. Under a suitable evolution of a time-dependent magnetic flux the structure behaves likewise a turnstile for single electrons in a fully electrostatic regime.

Synchronized transport of charge quanta has been envisaged since the very beginning of single electronics [1], i.e., circuits where manipulation of single electrons can be performed. So far a number of quantum effects have been exploited in solid-state devices to obtain a fine control over electromagnetic quantities in view of the realization of their quantum standards [2]. This technology has been exploited in a wide range of applications, covering on-chip cooling [3–5], single photons detection [6] and current sources [7]. The performance of single electron current sources is a trade-off between current amplitude and its accuracy [7, 8], and from the high sensitivity of these structures to both background charge fluctuations [9] and residual microwave radiation in the cryogenic setup [10]. Yet, different approaches have been conceived to overcome these limitations. Most of them relies on the so-called Coulomb-blockade effect which can be tuned by a locally-applied electric field through capacitively-coupled gates [7, 8, 11–13], whereas only few schemes are based on a hybrid electric- and magnetic-driven clocking [14, 15]. In this latter context it is also worth mentioning two fully magnetic-field-driven concepts, i.e., a ferromagnetic single-electron pump [16], and a Josephson quantum electron pump [17].

One recent promising proposal is based on the interplay between the superconducting energy gap and the charging energy in hybrid single-electron transistors (HSETs) [7, 11]. The turnstile operation of such a device originates from a time-periodic voltage applied to a gate electrode capacitively-coupled to a small metallic island, the preferential tunneling direction through the structure being guaranteed by a finite source-drain bias voltage. A different approach has been applied to two-dimensional electron gas-based charge pumps. In this context, gate electrodes create the junctions barriers which are shaped in a time-dependent fashion, allowing transport of a single electron per cycle by taking advantage of the Coulombic energy of the island [8]. These charge pumps operate in a zero-bias configuration, the directionality of events being controlled by properly shaping in time the barriers.

On the basis of the above described strategies, and exploiting recent advances in magnetic flux-tunable proximity effect as an effective building block to implement phase coherent superconductor-normal metal (SN) structures [18–21], we put forward the concept of a quantized single-electron turnstile where the flux-dependent proximity gap created in a N nanowire acts as a tunable barrier coupled to a Coulomb-blockaded island. In such a structure the magnetic flux can drive an opaque NIS junction to an NIN one, where I denotes

\[ E_c = \Delta_0. \]
an insulator. Under this premise, this single-charge structure will be referred to as superconducting quantum interference single-electron transistor (SQUIET).

We investigate a simple design for the SQUIET implementation by following Fig. 1(a). In particular, we assume the structure to be symmetrical and composed by two identical superconducting quantum interference proximity transistors (SQUIPTs) [18, 19] pierced by different magnetic fluxes \( \Phi_1 \) and \( \Phi_2 \), which play the role of source (1) and drain (2) electrodes. Furthermore, the SQUIPTs are connected by a normal metal (N) island through two identical tunnel junctions of capacitance \( C \) and resistance \( R_T \). The island is capacitively-coupled to a gate electrode at voltage \( V_g \) via the capacitance \( C_g \) which induces \( n_g = C_g V_g / e \) elementary charges on it. The structure is symmetrically biased with a voltage \( V \), and we suppose the charging energy \( E_C \) of the island to be dominated by the capacitance of the junctions, \( E_C = e^2 / 2C \) where \( C_g = 2C + C_e \approx 2C \). Each SQUIPT is composed by a superconducting loop interrupted by a diffusive N wire of length \( L \), and negligible transverse dimensions [22]. In the following we assume the wire as quasi-one-dimensional, and its contacts with the S ring as perfectly-transmitting interfaces. Moreover, we consider the case of a short \( N \) bridge satisfying the condition \( E_{th} \gg \Delta_0 \), where \( E_{th} = \hbar D / L^2 \) is the Thouless energy, \( D \) is the wire diffusion constant, and \( \Delta_0 \) is the zero-temperature order parameter of the S loops. In such a regime an analytic expression for the wire density of states (DoS) can be derived therefore simplifying the transistor analysis. In addition, the SQUIET performance is optimized in this limit since proximity effect in the N wires is maximized. In this case the DoS \( \nu_i (i = 1, 2) \) in each N proximized region is given by [23]

\[
\nu_i (E, \Phi_i) = \text{Re} \left[ \frac{E + i\Gamma_i}{\sqrt{(E + i\Gamma_i)^2 - \Delta_i^2 (T) \cos^2 (\pi \Phi_i / \Phi_0)}} \right],
\]

where \( \Gamma_i \) (set to \( 10^{-5} \Delta_0 \) in all the calculations) models the inelastic scattering rate under the relaxation time approximation [24], and \( \Phi_0 \) is the flux quantum. From Eq. 1 it follows that the DoS in the N wires shows a BCS-like shape with a flux-dependent induced gap, \( \Delta_i (T, \Phi_i) = \Delta_i (T) |\cos (\pi \Phi_i / \Phi_0)| \). In particular, for \( \Phi_i = \Phi_0 / 2 \) the gap is fully closed.

Insight into the operation principle of the SQUIET can be gained by looking at Fig. 1(b-d) which shows a sketch of the device clocking cycle via three energy diagrams corresponding to different magnetic flux values. The discrete energy levels generated by \( E_c \) are depicted in the island whereas flux-controllable energy gaps \( \Delta_i (\Phi_i) \) are represented in both source and drain electrodes. By changing the energy distribution of free and occupied states, the magnetic flux can open or close independently tunneling channels in the left and right junction, the bias voltage imposing directionality to single-electron current.

The flux-dependent tunneling rates between the leads and the island can be evaluated within the “orthodox theory” of single-electron tunneling [1] as

\[
\Gamma_{1,n}^{\pm} (\Phi_1) = \frac{1}{e^2 R_T} \int dE \nu_1 (E, \Phi_1) f(E) \left[ 1 - f(E - E_{1,n}^{\pm}) \right],
\]

\[
\Gamma_{2,n}^{\pm} (\Phi_2) = \frac{1}{e^2 R_T} \int dE \nu_2 (E, \Phi_2) f(E + E_{2,n}^{\pm}) \left[ 1 - f(E) \right], \tag{2}
\]

naming \( E_{i,n}^{\pm} = \pm 2E_c (n - n_g \pm 1/2) \pm eV / 2 \) the free energy variation as a consequence of tunneling events through the \( i \)th junction which increase (+) or decrease (−) the number of excess charges on the island. In Eqs. (2) we assume no energy exchange with the environment [25], and we consider both the leads and the island to be in equilibrium at temperature \( T \).

In order to study deterministically the dynamics of the system we focus on the sequential tunneling regime. In this framework, following a Fokker-Planck approach for a particular time-dependent flux driving signal, we can write the master equation in the matrix form for the probability \( p_n (t) \) to store \( n \) charges in excess on the island as a function of time

\[
\frac{d p_n}{dt} = \sum_m \Gamma_{nm} p_m, \tag{3}
\]

being

\[
\Gamma_{nm} = \delta_{m,n-1} \left[ \Gamma_{1,m}^{+} + \Gamma_{2,m}^{+} \right] + \delta_{m,n+1} \left[ \Gamma_{1,m}^{-} + \Gamma_{2,m}^{-} \right] - \delta_{m,n} \left[ \Gamma_{1,m}^{+} + \Gamma_{1,m}^{-} + \Gamma_{2,m}^{+} + \Gamma_{2,m}^{-} \right], \tag{4}
\]
the tunneling rate between \(n\) and \(m\) state. In its stationary version, the master equation can be used to evaluate source-drain charge current as a function of static control parameters \(\Phi_i, V\) and \(n_g\) through the relation \(I = -e \sum \rho_n \left( \Gamma_{1,n}^- - \Gamma_{1,n}^+ \right)\).

The family of curves displayed in Fig. 2 represents the static calculation performed for selected values of \(n_g\) and different magnetic flux \(\Phi_0\). We set \(\Phi_1 = \Phi_0 + \Phi_0/2\), and the difference \(\Phi_0/2\) may arise either from geometrical construction of the SQUITT loops or from an applied non-uniform static magnetic field.

For low enough temperature \((k_B T < E_c)\), the current is blocked up to a voltage resulting from the threshold relations \(E^\pm_{1,n} > -\Delta_{1,g}(T, \Phi_1)\) which come from the energy gap induced on the \(i\)th junction. The imposed flux asymmetry yields

\[
E^\pm_{1,n} = -\Delta_{1,g}(0) \cos(\pi \Phi_1 / \Phi_0),
\]

\[
E^\pm_{2,n} = -\Delta_{2,g}(0) \sin(\pi \Phi_1 / \Phi_0).
\]

These equations illustrate a crucial point: the magnetic flux affects only the energy thresholds, and therefore assumes the role of external control parameter. In Fig. 2(a) \((n_g = 0)\), the free-energy variations for a single electron tunneling event are \(E^\pm_{1,g} = \pm 2E_c (n \pm 1/2) \pm eV/2\). By considering the lowest energy contribution coming from \(n = 0\), the voltage thresholds become \(|eV| < 2E_c + 2\text{Max} \left[ |\Delta_{1,g}(0) \cos(\pi \Phi_1 / \Phi_0)|, |\Delta_{2,g}(0) \sin(\pi \Phi_1 / \Phi_0)| \right]\). In the case of Fig. 2(c) \((n_g = 0.5)\), by taking into account that both \(n = 0\) and \(n = 1\) are energetically possible for different magnetic flux values, leads to the opposite situation where the current is blocked for \(|eV| < 2\text{Max} \left[ |\Delta_{1,g}(0) \cos(\pi \Phi_1 / \Phi_0)|, |\Delta_{2,g}(0) \sin(\pi \Phi_1 / \Phi_0)| \right]\).

In the last condition the charging energy is analytically canceled by the effect of the gate which positions the device in a regime where the current is blocked (for each \(\Phi_1\)) by the stronger of the two induced gaps. Therefore the two junctions can be driven alternatively and independently in open or closed states, and the island consequently in \(n = 0\) or \(n = 1\), by the sole operation of the magnetic flux.

Figures 2(b,d) better illustrate the decoupling action of the two gaps caused by the charging energy. For \(n_g = 0.25\) \((n_g = 0.75)\) the decoupling is maximum so that two different thresholds for positive voltage \(0 < eV < E_c + 2\Delta_{1,g}(0) \cos(\pi \Phi_1 / \Phi_0)\|
(0 < eV < E_c + 2\Delta_{g,0}(0) |\sin(\pi\Phi_1/\Phi_0)|), and for negative voltage 
\(-E_c - 2\Delta_{g,0}(0) |\sin(\pi\Phi_1/\Phi_0)| < eV < 0 \) 
\(-E_c - 2\Delta_{g,0}(0) |\cos(\pi\Phi_1/\Phi_0)| < eV < 0 \) can be identified 
with the same procedure. These latter considerations essentially 
lead to an almost rigid voltage shift of the blockaded region represented in Fig. 2(b,d).

Equations (5) are usually represented in a three-
dimensional stability diagram showing the electric current vs 
V and \( n_g \). Although for the SQUISET the control parameter 
(\( \Phi_i \)) would require a further dimension for the stability 
diagram to be fully illustrated, one can easily follow this addi-
tional dependence in Fig. 3 where we have selected three 
representative conditions. Here the current surfaces have been 
colored imposing the red, blue and green color channels pro-
portional to \( p_{-1}, p_0 \) and \( p_1 \), respectively. It clearly appears 
how not just the boundaries are tuned by the flux but also 
the blockade “diamonds” are deformed, and in some way “ro-
tated”, in the \( V-n_g \) space. The three diagrams are essentially 
showing the SQUISET configuration that starts from NNIN-
like state (with \( \Phi_1 = 0 \)), passes through a SINIS-like (at 
\( \Phi_1/\Phi_0 = 0.25 \)) , eventually reaching a SININ-like behavior 
(\( \Phi_1/\Phi_0 = 0.5 \)). While in the regions of current interdiction 
the island charging configuration (\( n \)) is by definition fixed to 
almost unitary values (colored then by a single RGB channel 
color), as soon as a finite current starts to flow the island ex-
periences a time sequence of different \( n \)-states resulting in an 
intermediate color.

As mentioned before, under particular circumstances 
(\( n_g = 0.5 \)), the flux parameter can drive the SQUISET into 
a charging state [Fig. 1(b)] or into a discharging state [Fig. 
1(d)] passing through a blocked state [Fig. 1(c)]. In this situa-
tion the control parameters are then reduced to \( \Phi_1 \) and \( V \) only, 
and a new kind of stability diagram can be introduced [see 
Fig. 4(a)]. Here, the green channel is proportional to \( p_0 \) and 
the blue one to \( p_1 \) so that it is clear how the device can settle 
to different stable regions having the bias threshold \(|eV| < 
2\Delta_{g,0}(0) |\cos(\pi\Phi_1/\Phi_0)|, \Delta_{g,0}(0) |\sin(\pi\Phi_1/\Phi_0)|\) intro-
duced before with a flux periodicity of \( 1/2\Phi_0 \). Figure 4(a) 
shows how a closed trajectory in the \( \Phi_1 - V \) space, and result-
ing in a single-electron net current per cycle, can be found.

Apart the above stationary approximation, Eq. (4) allows 
to calculate [see Fig. 4(b)] the time evolution of the rates af-
fecting the state of the island during a particular magnetic flux 
cycle defined, for instance, as

\[
\Phi_1(t) = \Phi_2(t) + \Phi_0 \cdot \frac{\Phi_1}{2} \cdot \left[ \text{tri}(f \cdot t) - 1 \right],
\]

where \text{tri}(x) is the triangular waveform function. \( N_{\Phi} \) denotes 
the peak-to-peak amplitude of the time-dependent modulation 
in units of \( \Phi_0/2 \) [see the red arrow in Fig. 4(a)]. Equation 
(6) is only one of the possible clocking cycles, and it has been 
chosen here for the sake of clarity. It drives the induced gaps 
in source and drain electrodes from a complete closing to the 
situation where the \( N \) wires fully inherit a superconducting 
behaviour from the \( S \) loops. Several flux sequences transfer-
ing one charge per period can be easily found. We note that

FIG. 4. (a) SQUISET stability diagram vs \( \Phi = \Phi_1 = \Phi_2 + \Phi_0/2 \) 
and \( V \) at fixed gate voltage \( n_g = 0.5 \). The surface has been col-
ored having the green and blue channels proportional to \( p_0 \) and \( p_1 \), 
respectively, and shows the periodicity in the blockade regime states 
as a function of magnetic flux. The red arrow represents Eq. (6) with 
\( N_{\Phi} = 3 \). (b) Basic pumping cycle of a SQUISET with \( N_{\Phi} = 1 \) in a 
fully symmetrical configuration having \( \Delta_1(0) = \Delta_2(0) = \Delta_0 = E_c = 
185\mu eV \). Here \( \Gamma_{2,0}^{+} \) and \( \Gamma_{1,1}^{-} \), normalized by \( \Gamma_0 \equiv \Delta_0/e^2R_T \), repre-
sent the dominant rates moving the system between \( p_0 \) and \( p_1 \) states. 
During this particular cycle from Eq. (6) the bias voltage is set to 
\( V = \Delta_0/e \), and \( n_g = 0.5 \). (c) Frequency dependence of the normal-
ized source-drain current for different \( N_{\Phi} \) values. (d) Basic pumping 
cycle of a SQUISET as in (b) with different values of the Dynes 
parameters \( \log(\Gamma_i/\Delta_i) \), respectively \(-7, -6, -5, -4, -3 \) from bottom 
(lighter) to top (darker) curves. (e) Normalized source-drain current 
for \( N_{\Phi} = 1 \) at different values of the Dynes parameters \( \Gamma_i/\Delta_i \).
even time-dependent cycles yielding an incomplete closing of the induced gaps can drive efficiently the single-charge clocking mechanism under suitable biasing conditions. From Eq. (6) the rates are then essentially alternating for the two NIS junctions [see Fig. 4(b)]; moreover, they are almost constant in “closed” states and dominated by the intra-gap leakage of the induced gaps, while in the “open” state they reach a nearly unitary value in unit of $\Gamma_0 \equiv \Delta_0/\epsilon^2 R_T$. The origin the leakage stems from the smeared DoS [see Eq. (1)] modeling the environmental-assisted tunneling.

Following the system evolution by solving Eq. (3) we have calculated the probabilities $p_n(t)$ during this particular control parameter cycle as a function of frequency for $eV = \Delta_0$ and $n_g = 0.5$, and starting from a reasonable initial condition $p_n(0) = \delta_{n,0}$. After few cycles the system reaches a periodic quasi-equilibrium in which the occupation probabilities clearly oscillate from $p_1$ to $p_0$ state. In full analogy with the turnstile behavior of an HSET driven by a radio-frequency gate voltage, the SQUISET oscillates between $p_1 \sim 1$ state to $p_0 \sim 1$ state, leaving spurious clocking proportional only to exponentially-suppressed tunneling events. This particular cycle is depicted in Fig. 1(b-d) where in Fig. 1(b) the full branch of the drain DoS reaches the $n = 1$ energy level leading to a “charging state” where a single quasiparticle can tunnel into the island. In the intermediate period, shown in Fig. 1(c), both junctions are in a blockaded state due to the interplay between the charging energy and the energy gaps. In Fig. 1(d) the upper, empty branch of the source’s DoS aligns to the occupied island state opening the possibility for a “discharging” condition where a single electron escapes from the island driving it to the initial $n = 0$ state. In this way one electron per cycle is moved from drain to source generating a net current equal to $\langle I \rangle = e f$.

Considering an arbitrary flux modulation amplitude $N \Phi$, the average source-drain current can be obtained by integrating over one control parameter cycle as follows,

$$\langle I \rangle = -\frac{e}{T} \int_0^T dt \sum_n p_n(t) \left( \Gamma_{1,n}^+ (t) - \Gamma_{1,n}^- (t) \right).$$

Figure 4(c) shows clear current plateau in unit of $e f$ for a wide range of flux frequencies up to a cutoff which is inversely proportional to $N \Phi$ in the case of integer values of $N \Phi$. The SQUISET acts thereby in a single-electron turnstile fashion moving $[N \Phi]$ charges each cycle, being $[N \Phi]$ the $N \Phi$ nearest integer. The maximum generated current is limited by the $R_T C$ time constant associated to a single electron tunneling event essentially responsible for the missed tunneling errors. This proportionality holds for the triangular waveform suggested in Eq. (6) which maximizes the cutoff frequency, superimposing an instantaneous current across each junction with a \((f \cdot [N \Phi])^{-1}\) periodicity in the time domain. In this view, under the driving expressed by Eq. (6) the SQUISET realizes the relation $\langle I \rangle = [N \Phi] \cdot e f$.

Figure 4(d) clearly shows the impact of different Dynes parameters on the dominant rates in the turnstile configuration. At higher values the ratio between the unwanted rate and the clocking rate increases proportionally to the Dynes parameter itself leading to a leakage current as shown in Fig. 4(e). As in the case of the SINIS turnstile, the accuracy of our SQUISET device increases by improving the ideality of the superconducting leads DoS.

For the SQUISET implementation we exploited the peculiar behavior of Eq. (1) making the NIS junctions in a HSET-like structure tunable by introducing an additional control parameter, the magnetic flux. The pure quantum nature of flux-tunable phase interference in a proximized nanowire guides the single-electron tunneling in the semiclassical regime. In this view our SQUISET adds new perspectives to metallic single electronics introducing different clocking configurations which can be of interest as building blocks in fields other than quantized current generation, like coherent caloritronics [26–31] or quantum information technology [32]. Further investigation on pumping accuracy is crucial including higher order tunneling processes for which the static condition $n_g = 0.5$ could potentially limit unwanted events to two orders of magnitude lower than in the SINIS turnstile [33]. Eventually, the coupling with the environmental residual radiation as a source of intra-gap leakage [10] and the background charge fluctuation sensitivity of the SQUISET as a fully electro-statical single-electron clocking device [34] are still unexplored phenomena in the field of phase-coherent single electronics.

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