Quantized current of a hybrid single-electron transistor with superconducting leads and a normal-metal island

Antti Kemppinen,1 Matthias Meschke,2 Mikko Mottönen,2,3 Dmitri V. Averin,4 and Jukka P. Pekola2

1Centre for Metrology and Accreditation (MIKES), P.O. Box 9, FIN-02151 Espoo, Finland
2Low Temperature Laboratory, Helsinki University of Technology, P.O. Box 3500, FIN-02015 TKK, Finland
3Department of Applied Physics/COMP, Helsinki University of Technology, P.O. Box 5100, FIN-02015 TKK, Finland
4Department of Physics and Astronomy, Stony Brook University, SUNY, Stony Brook, NY 11794-3800, USA

We discuss the operation of the superconductor–insulator–normal-metal–insulator–superconductor (SINIS) turnstile. This voltage-biased hybrid single-electron transistor (SET) provides current quantization even with only one radio-frequency (rf) control parameter, namely the gate voltage of the single island. We give an overview of the main error mechanisms of the turnstile and consider its feasibility as a quantum current standard. We also present experimental results of pumping with the SINIS structure which show decreased leakage current compared to earlier measurements with the opposite NISIN structure.

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I. INTRODUCTION

A device that can transfer electrons one by one or more generally \( n \) electrons at frequency \( f \) could be used as a quantum current standard with magnitude \( I = n e f \). The first proposals and devices of this kind were based on normal-metal tunnel junctions [1, 2, 3]. The most precise electron pump built to date reached the relative accuracy \( 10^{-8} \). It consisted of a SET structure with seven metallic tunnel junctions and six rf-controlled islands between them [4]. It was used as a quantum capacitance standard [5], but the \( RC \) time constants of the tunnel junctions limited the maximum current on picoampere level which is not enough for a practical current standard. Specifically, at least 100 pA is required for closing the so-called quantum metrological triangle. This experiment compares the electrical quantum standards of voltage, resistance and current against each other via Ohm’s law. It yields a consistency check for the fundamental constants \( e \) and \( h \) [6]. The Josephson voltage standard and the quantum-Hall resistance standard are routinely used in metrology institutes worldwide, but the current standard is the missing link. Devices generating higher currents than the SET pump, based on superconducting devices [7, 8, 9], surface acoustic waves [10] and semiconducting quantum dots [11, 12, 13, 14] have been proposed and realized. However, none of these devices has reached metrological accuracy.

In 2007, a new concept based on a hybrid SET structure was proposed and demonstrated in experiments [15]. The hybrid SET consists of either superconducting (S) leads connected via insulating (I) tunnel barriers to a normal-metal (N) island or vice versa, see Fig. 1. When a constant bias voltage is applied over the SINIS/NISIN structure (e.g. \( V_L = V/2, V_R = -V/2 \)) and the electrical potential of the island is controlled with an rf gate voltage signal, the structure acts as a turnstile. In the first experiments [15], a NISIN turnstile showed robust current quantization. Theoretically, however, the SINIS version promises higher accuracy. Detailed analysis predicts, that metrological accuracy could be reached with the simple SINIS structure with only one rf control parameter and two tunnel junctions [16]. In this paper, we illustrate the principle of operation of the SINIS turnstile. We present an overview of the error mechanisms and discuss the experimental challenges they pose. Finally, we show experimental results of the SINIS turnstile with improved leakage properties.

FIG. 1: Schematic picture of the SINIS turnstile. A constant voltage is applied between the source and the drain. Pumping occurs with a single rf gate voltage control. Turnstile operation is possible also with the opposite hybrid structure with normal-metal leads and a superconducting island.
FIG. 2: Schematic band diagram of the SINIS structure biased with (a) zero voltage and (b) voltage $V$ across the structure. For the superconducting leads, we show the BCS density of states which is zero in the range $E_F \pm \Delta$ where $E_F$ is the Fermi level and $\Delta$ is the BCS energy gap. Close to the edges of the gap, the density of states approaches infinity. The states below the gap are almost perfectly occupied, and those above the gap are empty. In the normal metal, the Fermi function describing the occupancy of the states is shown instead of the density of states, which is roughly constant within the narrow energy range presented here. For these illustrations, the gap has been narrowed for clarity. Applying voltage across the sample changes the Fermi levels of the superconductors by $\pm eV/2$. In (b), $eV$ is slightly below $2\Delta$, and the normal metal cools down.

II. THEORY OF TUNNELING IN COULOMB BLOCKADED SINIS DEVICES

The tunneling rates of the SINIS turnstile are determined by the effects of the Coulomb blockade and the electronic structures of the superconductor leads and the normal-metal island. The latter effect can be understood qualitatively from the energy band diagram presented in Fig. 2. Voltage $V$ over the structure shifts the Fermi levels of the superconductors by $\pm eV/2$. At low temperatures, the Fermi distribution is almost like a step function. Tunneling can occur between states with same energy. Hence, at low voltages, electrons cannot tunnel from the occupied states of the normal metal to the superconductors, where the corresponding energy levels are either forbidden or occupied. Similarly, there are no free states in the normal metal at occupied energy range of the superconductors. Therefore, the BCS gap $\Delta$ causes a voltage range $-2\Delta < eV < 2\Delta$ where the current through the device is very small.

In Fig. 2(b), the structure is biased close to the edge of the gap. Electrons can tunnel from the left superconductor to the states slightly below the Fermi energy of the normal metal filling cold holes, whereas hot electrons above the Fermi level of the normal metal can tunnel to the quasiparticle states of the right superconductor. The electron-electron interactions maintain the Fermi distribution, but it narrows, which means that the normal metal cools down. Indeed, SINIS structures are routinely used as microcoolers [17]. The Coulomb-blockaded structure used in the SINIS turnstile has also been proposed for a radio-frequency single-electron refrigerator [18] and has been used as a heat transistor [19]. The cooling effect may also improve the accuracy of the turnstile.

The total capacitance of the island is $C_\Sigma = C_L + C_R + C_g + C_0$, where $L$, $R$, and $g$ refer to the left and right tunnel junctions and to the gate, respectively. The self-capacitance of the island is $C_0$. We normalize all energies by the BCS gap. The normalized charging energy of the island is $\epsilon_{ch} = C(n + n_g)^2$, where $n$ is the number of extra electrons on the island and $n_g = C_g V_g/e$ is the amount of charge in units of $e$ induced on the island by the gate. The unit of charging energy is $\epsilon_C = e^2/2C_\Sigma \Delta$. The change in energy for an electron tunneling to (+) or from (−) the island through junction $i$ is

$$\epsilon_n^{i,\pm} = \pm 2\epsilon_C(n + n_g \pm 1/2) \pm (v_i - \theta).$$

Here, $v_i = eV_i/\Delta$ is the normalized bias voltage of the junction (see Fig. 1) and $\theta = (C_L v_L + C_R v_R)/C_\Sigma$ is the offset to the island potential from the bias voltages.

Within the orthodox theory of sequential tunneling [1], the tunneling rates to and from the island are proportional
to the numbers of empty and full states in the leads and on the island:

\[ \Gamma_{L}^{+} = \frac{3}{e^2 R_T} \int d\epsilon n_S(\epsilon) f_S(\epsilon) \left[ 1 - f_N(\epsilon - e\epsilon,\epsilon) \right] \]
\[ \Gamma_{L}^{-} = \frac{3}{e^2 R_T} \int d\epsilon n_S(\epsilon) f_S(\epsilon + e\epsilon) \left[ 1 - f_S(\epsilon) \right]. \]

Here, \( R_T \) is the tunneling resistance of the junction, and \( f_S \) and \( f_N \) are the Fermi distributions of the leads and the island, respectively. The distribution functions are identical, but the island can be at different temperature than the leads. The density of states in the superconductors is ideally \( n_S(\epsilon) = |\epsilon|/\sqrt{\epsilon^2 - \Delta^2} \).

In the steady state, the probability of finding \( n \) extra electrons on the island, \( P(n) \), is constant, and the net probability of transition between adjacent states is zero. Hence, we can solve the steady state from the master equation

\[ [\Gamma_{L}^{+}(n) + \Gamma_{R}^{+}(n)] P(n) = [\Gamma_{L}^{-}(n + 1) + \Gamma_{R}^{-}(n + 1)] P(n + 1). \]

The current through the junction \( L \) is simply

\[ I_L = -e \sum_{n=-\infty}^{\infty} P(n) [\Gamma_{L}^{+}(n) - \Gamma_{L}^{-}(n)]. \]

In the steady state \( I_L = I_R \).

Theoretical current-voltage (IV) curves calculated with these equations are presented in Figs. [a] and [b] for the NININ (normal SET) and SINIS (hybrid SET) cases, respectively. The main difference is that the BCS gap enlarges the areas where the charge states are stable and hence the current is ideally zero. On this scale, the IV curves of the SINIS and NISIN structures are the same. The case of a superconducting (ISIS) SET is not shown here, but it has the significant difference to the presented curves that the supercurrent can pass the structure at zero voltage.

In the literature, the density of states in a superconductor is often written as

\[ n_S(\epsilon) = \text{Re} \frac{\epsilon + i\gamma}{\sqrt{(\epsilon + i\gamma)^2 - 1}}. \]

The physical meaning of the \( \gamma \) parameter is the Cooper-pair breaking rate of the superconductor \[20\]. In the absence of Coulomb blockade, pair breaking yields a finite linear conductance \( G_0 = \gamma/R_T \), and hence a leakage current in the regime \( |eV/\Delta| < 2 \). Ideally, the sub-gap conductance would be zero. In the Coulomb-blockade case with gate open, \( G_0 = \gamma/(2R_T) \). However, there are also other processes that lead to finite conductance, like the Andreev reflection \[16\].

The details of the leakage processes have usually been neglected, and \( \gamma \) has been used as a general phenomenological leakage parameter like in Ref. \[15\]. A typical amount of leakage is \( \gamma = 10^{-4} \ldots 10^{-3} \). Since the extremely low leakage current within the BCS gap is essential for the accuracy of the turnstile, we will discuss the leakage processes in Sec. IV.

III. PRINCIPLE OF OPERATION

The operation of the SINIS turnstile can be explained with the help of Fig. [a]. In the normal case [a], the stability regions arising from the Coulomb interaction barely touch each other. The pumping signal illustrated with the thick line passes the zone outside the stability regions, where current can flow through the device. Without the bias voltage, there would be no preferred direction of tunneling, e.g., transition from the state \( n = 0 \) to \( n = -1 \) can occur by tunneling through the left junction in the forward direction or through the right junction in the backward direction. Hence, the normal SET cannot act as a turnstile even in principle.

In the hybrid case shown in Figs. [b] and [c], the stability regions are expanded by 2 units on the \( eV/\Delta \) axis and by \( \Delta/2E_C \) on the \( n_E \) axis. Hence, the regions overlap. In the overlapping region, the system stays in the initial stable state. Now, let us consider the situation, where the device is biased to \( eV/\Delta = 1 \), and we start to increase \( n_E \) from zero to unity. The device stays in the region, where at least one of the charge states is stable. The transition from the state \( 0 \) to \( -1 \) could happen due to an electron tunneling forwards through the left junction or backwards through the right junction. Because of the bias, we meet the threshold for forward tunneling well before that of backward tunneling. When the gate charge is again reduced to zero, the bias voltage causes a preferred direction of tunneling in a similar fashion.

One can also extend the gate voltage signal to span over several charge states. If, e.g., the path in Fig. [a] is extended to \( n_E = 2 \), the system would transfer from the state \( 0 \) to \( -2 \) by two sequential forward tunneling events through the left
FIG. 3: Theoretical IV curves of a normal (a) and a hybrid (b) SET with \( n_g \) between 0 (closed) and 0.5 (open). Here, \( E_C = \Delta \). The SINIS SET has a high zero-bias resistance even in the gate open state due to the BCS gap. The graph (c) shows the current of the normal SET as a function of bias voltage and gate charge. The diamond-like stability regions with negligible current correspond to charge states -1, 0 and 1. In the hybrid case (d), the stable regions are expanded by the BCS gap and they overlap.

junction, and then back to the state 0 by two forward events through the right junction. In this process, two electrons are transferred per cycle. Current plateaus up to \( I = 10 e f \) were obtained already in the first experiments [15].

One of the key benefits of the hybrid design is that it allows current quantization with a single island. A pump with \( N \) islands has \( N \) unique fluctuating background charges that must be compensated by applying offset voltages to the gate signals. Employing many rf controls to a dilution refrigerator is also a considerable engineering effort. In the hybrid case, this effort can be used to connect \( N \) turnstiles in parallel which increases the current and decreases the relative statistical error. Also the maximum operation frequency, limited by the \( RC \) time constants, is lowered by the number of junctions. Therefore, the hybrid structures can be used to create roughly \( N^2 \) times the current of an \( N \)-island pump with the same amount of complexity.

Also the normal-state turnstile of Ref. [2] has a dc bias and only one rf gate control. However, it requires at least two junctions on each side of the gate-controlled island. It means that there are at least two extra islands whose charge is either not well defined or they require extra controls. Four junctions cannot be biased optimally with the two control parameters [21]. In the normal-state turnstile, dc bias always leads to self-heating unlike in the SINIS case (see Fig. 2 (b)).
FIG. 4: Schematic picture of pumping (a) with the normal SET, (b) with the hybrid SET with equal charging and BCS gap energies, and (c) with the hybrid SET with $E_C = 2\Delta$. The shaded diamond-like areas are the stability regions of the charge states $n = 0$ and $n = -1$. The edges of the normal SET stability regions are drawn to all figures with dashed black lines. The thin lines represent the transition thresholds from states $n = 0$ and $n = -1$ by tunneling through the left (L) or the right (R) junction in the wanted forward (F, solid line) or unwanted backward (B, dashed line) direction. We define the bias voltage to be positive in the left electrode. Hence, the current flows from left to right, and the forward tunneling direction is from right to left. The thick line corresponds to pumping with constant bias voltage $eV/\Delta = 1$ and the gate charge varying between the values $n_g = 0$ and $n_g = 1$.

IV. ERROR SOURCES

The error mechanisms of the SINIS turnstile have been analyzed theoretically in detail in Ref. [16]. Here, we give a brief overview of them. The error sources can be divided into three categories: errors related to the pumping speed, thermally activated errors in tunneling, and several kinds of leakage processes.

The turnstile can be operated with any gate waveform oscillating around $n_g = 1/2$ with amplitude large enough to pass the tunneling thresholds. An obvious choice is the sine wave, which was used in the first experiments [15], and which is experimentally the easiest to accomplish. However, a square-wave signal would be optimal, because the time spent between the optimal gate charge values increases the probability of unwanted transitions. Also, the time spent at the extreme values decreases the probability of missed tunneling, which is $\exp(-\Gamma_{i,\pm}/2f)$ for the square-wave signal. Here, $\Gamma_{i,\pm}$ is the tunneling rate of Eq. (2) of the wanted transition. At zero temperature, $\Gamma_{i,\pm} = (\Delta/R_T, e^2)\sqrt{(\epsilon_{i,\pm}^n)^2 - 1}$, where the electrostatic energy change $\epsilon_{i,\pm}^n$ of Eq. (1) is roughly proportional to $1/C_S$. Hence, the probability of missed tunneling depends on the $RC$ time constant as in normal-state devices. If the transition speed of the square-wave signal approaches $\Delta/h \approx 50$ GHz, the transistor can be excited to higher energy states, which causes errors. Realistic pumping frequencies are, however, not close to this limit.

The probability of an electron tunneling through the wrong junction due to thermal activation depends on the energy difference to the zero-bias case with no preferred tunneling direction: $e^{-eV/\kappa_BT}$. This error leads to net charge transferred during the cycle. On the other hand, if the bias point is close to the edge of the stability regions, $eV/\Delta = 2$, an excitation can cause an extra electron to transfer during the cycle. Likewise, this error probability depends on the energy difference: $e^{-(2\Delta - eV)/\kappa_BT}$. Combining these equations, we get $eV/\Delta = 1$ as the optimum bias voltage, and a thermal error probability $e^{-\Delta/\kappa_BT}$. The combined thermal error probability is less than $10^{-8}$ at realistic temperatures of about 100 mK and with the gap of aluminum, $\Delta/\kappa_B = 2.3$ K.

The most severe error source of the turnstile appears to be the different leakage processes. They involve elastic and inelastic higher-order tunneling processes. In the NISIN case, the dominant process is the elastic electron cotunneling that limits the accuracy to about $10^{-7}$–$10^{-8}$. In the SINIS structure, the elastic higher-order processes are negligible.

The simplest inelastic process, cotunneling, is energetically forbidden by the BCS gap in the voltage range $|eV| < 2\Delta$. The next-order processes are the Andreev reflection and Cooper-pair/electron cotunneling. The Andreev reflection causes a higher error rate, but in the case $E_C/\Delta = \epsilon_C > 1$, an optimum pumping sequence exists, where the Andreev reflection vanishes. In the optimum sequence, the bias voltage is $eV/\Delta = 1$, and the gate voltage is a square wave with offset $n_{g0} = 1/2$ and amplitude $A_g$ between $1/4\epsilon_C < A_g < 1/2 - 1/4\epsilon_C$. The amplitude should be closer to the
upper end of this range to increase the tunneling rates. Finally, the leakage is dominated by Cooper-pair/electron cotunneling.

Reference [16] presents estimates for the obtainable error rates of the turnstile with different sample parameters. They are reproduced in Fig. 5. The error decreases significantly, when the charging energy is increased over the BCS gap energy. At $E_C/\Delta = 4$ and with junction resistance 400 kΩ, 30 pA can be reached with the error rate $10^{-8}$. If $E_C/\Delta = 10$ and resistance is 260 kΩ, 100 pA can be reached with the same accuracy. These are still realistic parameters since they were reached, e.g., in Ref. [22].

The optimum resistance of the sample is a tradeoff between low leakage (high resistance) and low $RC$ time constant. The absence of inelastic cotunneling allows to use lower resistance than in normal state devices. Hence, the maximum current can be slightly higher than in normal-state pumps. Also, the capacitance of the island can be very small, since coupling the gate voltage to the island does not create any cross coupling to other islands as in multi-island devices.

The error rates presented in Ref. [16] do not include the Cooper-pair breaking rate $\gamma$ of Eq. (5). However, there seems to be no experimental evidence of $\gamma$ in the case of high-quality aluminum; the leakages observed in experiments can be caused by Andreev reflection, which also causes a linear leakage. In addition, nonidealities in tunnel barriers like pinholes can cause a linear leakage. In this paper, we use a general leakage parameter $\eta = R_T/R_0$ to avoid confusion with $\gamma$. Note the factor of two difference in the Coulomb-blockaded case between the leakage by $\eta$ and that of $\gamma$ presented in Sec. II.

Let us consider also the change of the temperature of the normal-metal island during pumping. The superconducting leads are well thermalized to the base temperature of the cryostat, but the temperature of the electrons on the island can vary significantly. The heat fluxes arising from tunneling are proportional to the energy deposition and extraction rates of incoming and outgoing electrons:

$$
\dot{Q}^{i+} = \frac{\Delta^2}{e^2R_T} \int d\epsilon (\epsilon - \epsilon^{i+})n_S(\epsilon)f_S(\epsilon)[1 - f_N(\epsilon - \epsilon^{i+})]
$$

$$
\dot{Q}^{i-} = \frac{\Delta^2}{e^2R_T} \int d\epsilon (\epsilon + \epsilon^{i-})n_S(\epsilon)f_N(\epsilon + \epsilon^{i-})[1 - f_S(\epsilon)].
$$

(6)

The island can cool down at the first two current plateaus in a frequency range limited by the $RC$ time constant [18]. At higher frequencies, the island is heated, which can increase the error rates. In the case $E_C/\Delta = 10$ and $R_T = 260$ kΩ, cooling is possible up to about 10 GHz, i.e., at all envisioned pumping frequencies. The finite temperature of the island causes a maximum leakage of $\eta(T) = \sqrt{\pi\Delta/2k_B T} e^{-\Delta/k_B T}$ at $n_g = 1/2$, which is, however, negligible at about 100 mK.

It should also be noted that at higher current steps, the system should have enough time to set to each charge state between the extremes. A staircase-like waveform that waits at each integer gate charge would be equally good as the square wave that can be used at the first current plateau. However, the staircase-like waveform is not experimentally an obvious choice. Thus, the first step is the most promising for metrology in this respect.
V. EXPERIMENTAL RESULTS

The sample presented in Fig. 6 was fabricated by electron beam lithography and two-angle evaporation on oxidized silicon wafer. We use the standard PMMA and copolymer as resists. First, we evaporate the aluminum superconducting leads. Next, we let oxygen in the vacuum chamber of the evaporator to oxidize the surface of the aluminum. The aluminum oxide acts as the tunnel barrier. Finally, we evaporate copper in a different angle, and we get the same image of the mask as in the aluminum case, but shifted on the axis of the angle change. Tunnel junctions with lateral size below $100 \times 100 \text{ nm}^2$ take form where the copper island touches the oxidized aluminum leads. Due to the two-angle technique, we also get copper leads and an aluminum island, but the first ones are not connected, and the latter one touches the copper end of the gate line and thus becomes a part of the gate capacitor lead.

The resistance of the sample was 475 kΩ and the gate capacitance was 14 aF. The charging energy was 2.2 K, which is of the order of the BCS gap. Hence, the Andreev reflection was still present, and metrological accuracy would not be possible with the present device. In the future, our process must be improved to be able to fabricate smaller junctions with high yield. One possibility is to use a germanium mask between PMMA and the copolymer [22].

The sample was cooled down in a dilution refrigerator to a base temperature of about 60 mK. We used Thermo-coax [23] as the dc lines between the sample stage and the 1.5 K plate of the refrigerator. This is to avoid sub-gap leakage caused by photon-assisted tunneling arising from the high-frequency thermal noise that always exists in the higher temperature parts of the measurement circuit. Furthermore, we added 550 Ω resistors on the sample stage on each side of the sample to reduce noise at lower frequencies. The gate couples to the sample only via weak capacitances. Hence, the noise properties of the gate line are not as critical as those of the dc lines.

The measured dc IV curve of the sample is presented in Fig. 7. The $\eta$ parameter of the sample is clearly below $10^{-5}$, which is a significant improvement to the previous measurements with $\eta = 1.3 \times 10^{-4}$ [12]. In the SINIS coolers with large junctions, the leakage is typically between $10^{-4}$ and $10^{-3}$ even with highly filtered dc lines similar to ours. The Coulomb blockade suppresses the leakage caused by the Cooper-pair breaking only by a factor of two. Hence, our measurement supports the judgement of the theoretical work [16] that the leakage is usually caused by the Andreev reflection. Large junctions might also have pinholes that are statistically less probable in our case with small junctions.

The measurement presented in Fig. 7 shows clearly that verifying the extremely low leakages, promised by the theory, will be an experimental challenge. Already at the present stage we are limited by the noise of the current measurement.

Pumping results of the SINIS turnstile at 10 MHz are presented in Fig. 8. We observe broad quantized current plateaus as in Ref. 15, but this time with a SINIS structure. However, the high-frequency gate line did not function perfectly in the present measurement. Above 20 MHz, the gate signal was significantly weakened by the line. Even at lower frequencies, the gate signal appeared to heat the sample, which rounds the edges of the current plateaus to some extent. Since the square-wave signal suggested in Ref. 16 requires a broad bandwidth for the higher harmonics of the pumping frequency, we did not try to employ it here. A sinusoidal signal $n_g(t) = n_{g0} + A_g \sin(2\pi ft)$ was used instead. The improvement in the accuracy by optimizing the shape of the signal would be very small at the present
FIG. 7: Magnified measured dc IV curve of the sample with resistance 475 kΩ and $E_C/k_B=2.2$ K. The inset shows the IV curve of the sample on large scale. The gate voltage was swept with constant speed during the IV measurement. Hence, at high voltages, the IV curve shows zigzag between the gate open and the gate closed states. At voltages $|eV| < 2\Delta$, the gate periodicity disappears due to the BCS gap. No sub-gap leakage can be seen at a noise level of about 10 fA. The lines correspond to sub-gap leakages $\eta = 10^{-4}$ and $10^{-5}$.

The first step at 2 MHz as a function of the bias voltage is presented in Fig. 9. The result is an average of 30 IV measurements. The data points of each IV measurement were measured in randomized order to prevent a slope due to a possible drift of the current amplifier. The whole measurement lasted for almost two hours. There is no observable slope in the range 0.9–1.2 $eV/\Delta$: $\eta = (-1.2 \pm 3.4) \times 10^{-6}$ ($k = 2$, 95% confidence). This supports the deduction that the slope of the step observed in Ref. [15] was due to the sub-gap leakage. In Ref. [15], the slope was almost constant over a broad bias range $0.5 < eV/\Delta < 1.5$. Here, the heating effect rounds the edges and thus narrows the step. At higher frequencies, there is a slope even at the optimum bias $eV/\Delta = 1$, presumably due to heating. At 10 MHz, the slope corresponds to $\eta \approx 1.3 \times 10^{-8}$, which is about the same as in Ref. [15].

The theoretical value of the current is about 0.32 pA, but the absolute accuracy of the current amplifier is very poor at this level. A traceable measurement with higher accuracy is planned could be performed e.g. by using an electrometer with an external feedback by a standard air capacitor [24].

VI. CONCLUSIONS

We have demonstrated the current quantization of the SINIS turnstile. We observe no leakage within the BCS gap, which supports the optimism of the theoretical error calculations of Ref. [16]. The upper limit of the ratio between the asymptotic resistance and the sub-gap resistance is clearly below $10^{-5}$, which is a significant improvement to the earlier measurements of the turnstile in Ref. [15].

Theoretically, 100 pA current with a relative accuracy $10^{-8}$ appears to be possible even with a single turnstile with only one island. The fabrication process must be improved to be able to make samples with higher charging energies and more transparent junctions. The demands are realistic, since such sample parameters have been achieved by other research groups [25].

The theoretical potential of the SINIS turnstile has already been studied quite thoroughly. However, lots of
FIG. 8: Current plateaus at $f = 10$ MHz as a function of (a) bias voltage $V$ and applied gate offset, and (b) gate amplitude $A_g$ and applied gate offset. In (a), $A_g \approx 0.5$, which is suitable for pumping one electron in a cycle. When the total offset charge due to the applied offset and the background is about 0.5, the gate varies between the charge states 0 and -1. Then, at voltages $eV/\Delta \approx 1$ and $eV/\Delta \approx -1$, we observe the current plateaus $I = e\Delta \approx 1.6$ pA, and $I \approx -1.6$ pA, respectively. When the total offset is an integer number, the gate amplitude is not large enough to change the charge state, and we observe a zero current plateau. In (b), the sample is biased to $eV/\Delta = 1$. When the total offset is a half integer, we obtain the odd current plateaus $I = e\Delta$, $I = 3e\Delta$ etc. by increasing the gate amplitude. The even steps $I = 0$, $I = 2e\Delta$ etc. occur at integer offsets.

FIG. 9: First quantized current step as a function of the bias voltage at 2 MHz pumping frequency. Slopes corresponding to sub-gap leakages $\eta = 10^{-4}$ and $10^{-5}$ are presented with the lines.
experimental work is still to be done, e.g., a more conclusive experimental study of the leakage processes is necessary. The present pumping accuracy can be improved quite easily in an improved set-up as regards to the gate rf line. The progress from the idea of a hybrid turnstile to considerable experimental results has been fast, though, and the SINIS turnstile is a promising candidate for the quantum current standard.

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