**Radio-frequency transport of single electrons in superconductor–normal-metal tunnel junctions and the quantum metrological triangle**

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## Abstract

We are developing a single-electron turnstile based on a nanoscale superconductor–insulator–normal-metal–insulator-superconductor (SINIS) structure. The goal is to obtain the frequency to current conversion $I = ef$ with a relative uncertainty $< 10^{-8}$ which would be sufficient for a quantum-based standard of electric current. Finally, the quantum current standard will be compared against the quantum standards of voltage and resistance via Ohm's law in the quantum metrological triangle experiment.

## 1 Introduction

James Clerk Maxwell suggested already in 1870 that the definitions of the units of measure should be based on physical phenomena and fundamental constants [1]. However, an important part of the SI unit system is still based on an artefact, namely the prototype of the kilogram.

The development of a voltage standard based on the Josephson effect in 1960s and a resistance standard based on the quantum Hall effect in 1980s introduced a new concept, quantum metrology, as a promising way to realize units. Two decades ago, new ideas for manipulating single electrons with tunnel junctions [2] raised hope in developing a quantum standard for the SI base unit ampere, too. Besides the use as a current standard, single electronics could provide a consistency check for the quantum standards of voltage and resistance via the quantum metrological triangle [3].

The goal of the triangle experiment is to check whether the Ohm's law $V = RI$ is valid with an uncertainty $< 10^{-8}$ for the three standards. Such an accuracy is routinely reached in Josephson voltage and quantum Hall resistance standards. The uncertainty of about $10^{-8}$ has also been demonstrated in one type of electron pump, but only at the level of 1 pA [4]. However, to be able to reach the low uncertainty in the comparison, the current magnitude should be at least about 100 pA. It corresponds to the electron transport frequency $I/e \approx 600$ MHz.

## 2 The SINIS turnstile

We are developing the SINIS turnstile, which is a promising candidate for the quantum current standard [5,6]. It has the structure of the single-electron transistor (SET), but with superconducting leads and a normal-metal island, see

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Fig. 1. There is a tradeoff between the magnitude and the uncertainty of the current, but theoretically, about 10 pA should be possible with the uncertainty of $10^{-8}$ [7,8]. However, the operation of the device is so simple that, unlike for most other candidates for the current standard, parallelization of the SINIS turnstile is experimentally feasible and has already been demonstrated for 10 devices [9].

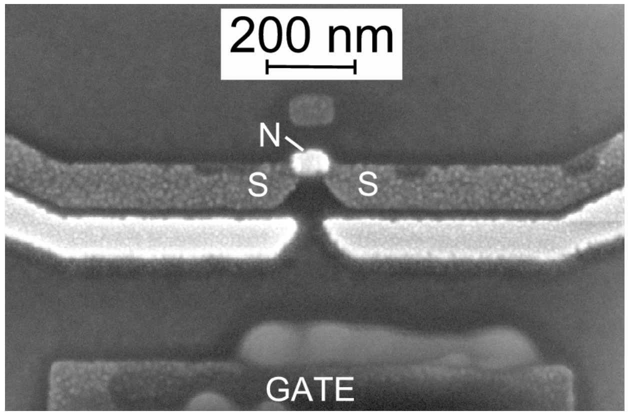


Figure 1: SINIS turnstile sample with superconducting (S) leads and a normal-metal (N) island. The charge on the island can be controlled by the gate electrode. A quantized current $I = ef$ can be generated by applying a dc bias voltage to the leads and an rf signal with frequency $f$ to the gate electrode.

As most single-electron devices, the SINIS turnstile requires a temperature below about 100 mK to suppress thermally excited errors. Such temperatures can be routinely reached in $^3$He–$^4$He dilution refrigerators. However, the electron–phonon coupling is weak at low temperatures, and thus the electron system can in general be at higher temperature than the base temperature of the refrigerator. Also, the transport of electrons can induce self-heating. One of the benefits of the SINIS turnstile is that it can actually work as a single-electronic radio-frequency refrigerator where the transport of electrons cools down the normal-metal island [10].

An uncertainty of about $10^{-3}$ was reached in early experiments with the SINIS turnstile [8]. The main error source was leakage current. Ideally, the electric current should be zero at small bias voltages $|V_{\mathrm{bias}} < 2\Delta/e$, where $\Delta$ is the BCS gap of the superconductor (aluminum). However, experiments showed a resistive slope with a conductance suppressed by a factor of about $10^4$ compared to the conductance at high bias voltages.

In Ref. [11] the sub-gap leakage was reduced by placing on-chip resistors near the sample. In Refs. [12–13] it was shown that the origin of the leakage is environment assisted tunneling. It means that an electron can tunnel in an energetically forbidden direction if it gains energy from a thermal noise photon. The energy of the photon has to be bigger than the energy cost of tunneling. Hence the relevant frequency scale for the leakage processes is $f \gtrsim \Delta/h \approx 50$ GHz.

It is important to note that Johnson noise is white only up to the cut-off frequency at $hf = k_B T$. Above that, it vanishes exponentially. Hence the leakage current is caused by noise arising from the higher temperature parts ($T \gtrsim \Delta/h \approx 2.5$ K) of the measurement setup. In Ref. [12], this noise was filtered by shunting the sample capacitively with an on-chip ground plane. This was sufficient to reach the conductance suppression ratio of about $10^6$.

Recently, we have built a carefully designed wiring and casing to our new cryostat that is dedicated for the quantum metrological triangle experiment. There, we have reached the same conductance suppression ratio of about $10^6$ without any on-chip filtering. When the careful wiring, shielding, and on-chip filtering are combined, we expect that the voltage noise seen by our sample will be of the order of 100 fV/$\sqrt{\mathrm{Hz}}$ in the relevant frequency scale $\gtrsim 50$ GHz. For comparison, it is about 75 dB below the thermal noise of a 50 $\Omega$ resistor at room temperature.

## 3 The quantum metrological triangle experiment

The key ideas of our plans for the direct closure of the quantum metrological triangle have been reported in Ref. [14]. All the components, $V$, $R$, and $I$, will be placed in our new cryostat which is dedicated for the triangle experiment. Here, $V$ corresponds to the Josephson voltage, $I$ to the SINIS turnstile, and $R$ to a 1 M$\Omega$ cryoresistor [15] that will be calibrated against the quantum Hall standard. The setup is practically ready except for a null detector. In the first experiments, we will magnify the current difference $V/R - I$ by a transformer and use a SQUID as the null detector, but we are studying other possible null detectors as well.

The required averaging time is $t = I_n/(\delta I)^2$ where $I_n$ is the current noise and $\delta$ is the required relative uncertainty. Hence the magnitude of the quantized current, $I$, is crucial for the experiment. In the first experiments, $I_n$ will be dominated by the SQUID null detector which we expect to have noise of about 100 fA/$\sqrt{\mathrm{Hz}}$. Then the averaging time to reach an uncertainty of 10 ppm will be about 3 hours.

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