Accuracy verification of single-electron pumps with 0.2 ppm uncertainty

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***Abstract*—A current source based on clocked single-electron transfer is the natural candidate for the realization of the base unit ampere following a future redefinition by a fixed value of the elementary charge. However, the accuracy depends on microscopic processes and has to be verified for each device. Building on the recent advances on instrumentation we verify the accuracy of the generated current with an uncertainty of 0.16 ppm for one day of averaging.**

***Index Terms*—Single electron devices, Current standard, Semiconductor nanostructures**

I. Introduction

Single-electron pumps (SEPs) generate a nominally quantized current $I_n = nef$ by periodic transfer of n electrons with charge e at a repetition frequency f. The uncertainty of such a current source is generally related to the probability of transfer errors, i.e. cycles in which not exactly n electrons are transferred. Presently the most promising type of SEP for highest possible frequencies at high transfer accuracy is the non-adiabatic tunable barrier pump [1], promising usable working frequencies up to or even above 1 GHz [2]–[5]. However, the single electron transfer relies on the dynamic microscopic processes in the quantum dot used for single electron control and thus the accuracy has to be verified for each device. Reaching a desired accuracy of 10^{-7} is a great challenge. Recently large progress has been achieved for traceable direct current measurements in the sub-nA range [2], [6], [7]. Here the current is measured by conversion to a voltage using a known large (trans-)impedance of order gigaohm which is traced to the quantum Hall effect. The voltage in turn is measured traceable to the Josephson Effect. Assuming the relations $R_K = h/e^2$ and $K_J = 2e/h$ for the characteristic constants of these effects the average number $\langle n \rangle$ of transferred electrons can be deduced from the average direct current $I = \langle n \rangle ef$.

In this paper we assess the accuracy of single-parameter tunable-barrier single electron pumps that are realized by a gate controlled quantum dot in a GaAs/AlGaAs semiconductor wire [8]. It was recently shown that the newly developed ultrastable low-noise current amplifier (ULCA) [6], [7] allows to validate the pump current quantization for a current of about 87 pA with a total uncertainty ($k = 1$) of 0.20 ppm when averaging multiple values across the current plateau. Building on this success we validate the quantization for further pumps. Using a shorter traceability chain allows us to determine the accuracy for a single working point with total $k = 1$ uncertainty 0.16 ppm within one day of measurement time for $f = 600$ MHz. Verifying the accuracy for a modified pump layout more suitable for integration into a self referenced current source [9] we take another step forward to true online error accounting of a quantized current source.

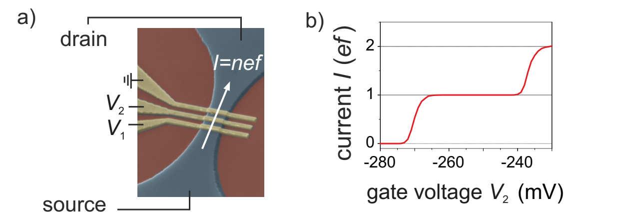

Fig. 1. a) Micrograph of SEP shows quasi-1d semiconductor channel etched from GaAs/AlGaAs heterostructure, crossed by gates to form the quantum dot barrier. b) Normalized pump current as a function of V_2 with shaped RF-signal (cp. Ref. [5]) with $f = 600$ MHz added to V_1 ($ef = 96$ pA).

II. Experiment

The single-electron pumps examined in this paper were patterned from a GaAs/AlGaAs-heterostructure holding a two-dimensional electron system 90 nm beneath the surface. First a shallow etch is used to define a quasi-1d-channel. In a second step metal Schottky gate fingers are added crossing the channel. They allow to generate potential barriers by applying negative voltages. Between two barriers a quantum dot is formed. Driving one barrier with a RF-signal allows to generate a bias-independent pumping current, see Ref. [1] for a detailed discussion of the pumping mechanism. We show data for two devices. The first device following the design used in Ref. [5] has three gates, an etch depth of 65 nm and a layout shown in Fig. 1. The second device has only two gates, shallower 40 nm etch and a layout shown in Fig. 3. This layout was chosen for easier integration with charge detectors [10] for the realization of a self-referenced quantized current source [9].

All measurements were taken at a temperature $T = 0.1$ K. We always use single parameter drive applied to the first gate with a shaped waveform [2] similar to the one used in Ref. [5]. An applied magnetic field of $B = 9$ T improves the quantization. The current is measured using the ULCA with linear interpolation between regular calibrations. Optimizing the voltage traceability a total systematic uncertainty of 0.1 ppm for the current measurement is achieved. The measurement is performed using repetitive on/off cycles of the pump to remove offsets. Cycle time and instrument readout has been optimized for reduced type A uncertainty.

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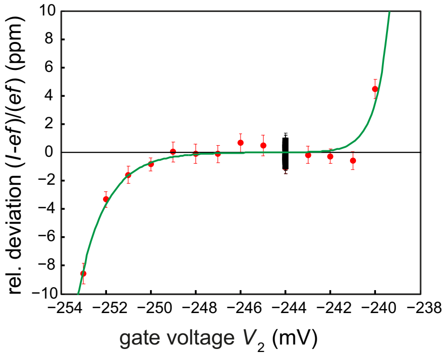

Fig. 2. Precision measurement of device shown in Fig. 1 with same working conditions ($f = 600$ MHz). Each point results from one hour measurement time. Shown is the deviation from quantized pump current $I = ef$. Red points are used to determine the expected point for $I = ef$ using the fit (green line) introduced in Ref. [5]. 21 overlapping black squares show the result of measurements at this point; averaging yields (0.10 ± 0.16) ppm ($k = 1$ total uncertainty).

Fig. 1b shows the SEP current for the first device ($f = 600$ MHz). We observe clear quantization shown as plateaus of the current as a function of the control gate voltage V_2. The precision measurement at the $I = ef$ plateau is shown in Fig. 2. First the plateau is sampled with high resolution as function of V_2 (red points, range larger than shown). The optimal working point is determined as the inflection point of a fit of two exponential functions, see Ref. [5]. Using one day of measurement time at this point we determine the value of the current to agree with $I = ef$ within the total $k = 1$ uncertainty of 0.16 ppm. This is presently the best verification of the quantization of an SEP at a directly usable current level.

We now turn to the second device. Here the modified design has to be tested to ensure that it does not sacrifice accuracy. A slightly reduced frequency of $f = 400$ MHz is used. Fig. 3 shows the result of a precision measurement over a weekend. Here we follow Ref. [5] to verify the accuracy using a plateau average with a criteria determined from the afore mentioned fit. We find an agreement of the plateau current with ef within the total $k = 1$ uncertainty of 0.21 ppm.

For both devices we have only about 100 error events per

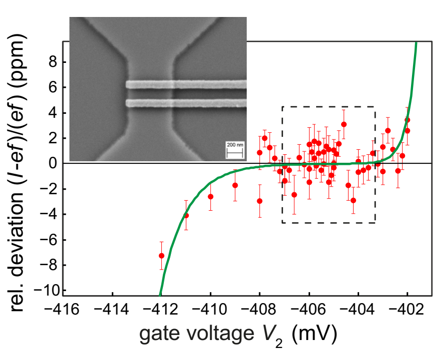

Fig. 3. Precision measurement of device with modified layout as shown in the inset micrograph. $f = 400$ MHz, shaped waveform added to V_1, one hour measurement time per point. Dashed box shows expected plateau range with deviation < 0.1 ppm from ef derived from fit (line). Average in this range yields (0.07 ± 0.21) ppm ($k = 1$ total uncertainty).

second or even less for which the SEP pumps a number of electrons that differs from $n = 1$. For such error rates we can anticipate the realization of a self-referenced current source using single-electron transistors (SETs) for error detection [9]. Such a realizations requires the series operation of at least three SEPs with SETs detecting any change of charge on the nodes in between the pumps.

III. Outlook

For the anticipated self-referenced quantized current source the accuracy verification of the single-electron transfer process would be inherently realized by counting of transfer errors online during current generation, independently of any other realization of electrical properties, i.e. the resistance and the voltage needed for the present verification by direct current measurement using the ULCA. Furthermore, it could allow to account for such errors and determine the amount of charge quanta transferred in a certain time with an uncertainty below the error rates of the pumps [11].

Acknowledgment

We thank Christoph Leicht and Niels Ubbelohde for help with the device fabrication, Lukas Fricke for help with the data analysis and Dietmar Drung, Hansjörg Scherer and Franz J. Ahlers for stimulating discussions.

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