1. Introduction

Single-electron transport (SET) pumps are considered as promising candidates for future quantum current standards [1–3]. The most advanced types of SET pumps, suitable for generating relatively high currents with reasonable accuracy, are based on ‘dynamic’ quantum dots (QD), i.e. ultra-small conducting areas in semiconductors that are defined by energy barriers imposed by electrostatic gate electrodes [3]. Periodic modulation of these barriers causes a clocked transfer of electron, which results in a current $$$I = nef$$$. Here $$$n$$$ is the average number of electrons transferred per transport cycle, $$e$$ the electron charge and $$f$$ the repetition rate of the transport cycles. The use of SET pumps for future metrological current standards, however, will only be possible if they fulfil the qualifications for quantum standards. Besides a level of current of the order of 100 pA that is suitable for practical purposes, the accuracy of the generated current must be sufficiently high so that the new standard can at least compete with the state-of-the-art classical standards. This means that the devices must be tunable to a transport regime in which the current quantization is given in the sense that $$$n$$$ is sufficiently close to an integer. Further, and related to the former requirement, this practically means that the margins of the operating parameters in which quantization is found are sufficiently wide. The invariance of SET pump function (sourced current accuracy) against the variation of driving parameters, in the following also called ‘robustness’, is crucial for practical applications.

This paper is organized in two parts. In the first part, we present improvements to our current measurement technique based on the ultrastable low-noise current amplifier (ULCA) [4–6]. The improvements comprise shortening of the traceability chain (i.e. lowering systematic uncertainties) as well as improving the effective measurement time utilization by optimizing the measurement procedure (i.e. lowering statistical uncertainties). In the second part of the paper, we present parameter robustness investigations on these SET pumps at sub-ppm accuracy level, enabled by our improved measurement technique. These measurements comprise variations of magnetic flux density, bias and gate voltages, and pump driving frequency, all of them being relevant operational parameters for GaAs-based SET pumps. Parts of the data shown here were already used in conference digest papers [7, 8].
2. Pump design and operation

Measurements were performed using a tunable barrier single-electron pump based on a GaAs/AlGaAs heterostructure as shown in figure 1. Starting from a two-dimensional electron system (2DES) 90 nm below the surface, a 1D transport channel was formed by shallow wet etching. Two finger-shaped Schottky gates made from Ti/Au were deposited on top of the channel 250 nm apart (center to center) to allow the formation of a QD. Two devices were patterned from two wafers with similar 2DES properties (carrier densities of $2.09 \times 10^{15} \text{ m}^{-2}$ and $2.18 \times 10^{15} \text{ m}^{-2}$, and mobilities of $280 \text{ m}^2 \text{ V}^{-1} \text{ s}^{-1}$ and $200 \text{ m}^2 \text{ V}^{-1} \text{ s}^{-1}$, respectively). The pumps with the design shown in figure 1(a) were fabricated with an etch depth of about 60 nm, whereas for the design shown in figure 1(b) the heterostructure was etched down to 40 nm. The second design is one under development that focuses on the simplicity of the structure. However, a systematic study of design dependence was not an aspect of the paper.

The setup scheme shown in figure 1(a) was used for driving the pump. Negative voltages applied to the gates generate potential barriers confining the QD. The third gate visible in figure 1(a) was not used and grounded.

An additional periodic modulation of the entrance barrier to the QD is applied using an arbitrary waveform generator (Tektronix AWG 7122C). The rf signal $V_{1}^{ac}$ is low-pass filtered at room temperature (Mini-Circuits VLF-5500+, 5.5 GHz), combined with the dc voltage by a bias $T$ and then attenuated by $-3$ dB. This realizes single parameter driven single electron pumping consisting of the following phases [9, 10]: During the periodic modulation of the left gate, electrons are first loaded from source into the QD, followed by a back-tunneling process initializing the electron number, then they are isolated from the leads, and finally ejected to drain (figure 1(c), panels (i)–(iii)). In certain ranges of the exit gate voltage $V_{2}$ the current–voltage characteristics of the SET pump exhibits flat regions corresponding to $(n) \approx 0, 1, 2, \ldots$ in the following called plateaus [9, 10]. Pumping performance is enhanced by application of a magnetic field perpendicular to the 2DES [11, 12], i.e. if the pump is operated with the 2DES being in the quantum Hall regime. Typically, no significant improvement is reached by further increasing the magnetic field when only the lowest Landau-level of the 2DES is occupied, which in our samples is the case for $B > 8.4 \text{ T}$. Therefore, most of the experiments were carried out at $\sim 9 \text{ T}$.

If not otherwise stated all modulation signals are composed in a similar way as described in [6, 13]. They consist of parts of two sine waves of different frequency, typically of about 150 MHz and 1 GHz, such that the durations of the loading and isolation phases (panels (i) and (ii) in figure 1(c)) are longer than the time for the ejection phase [14]. All measurements were performed in a commercial dilution refrigerator in a magnetic field at a base temperature of 100 mK.

3. Current measurement technique

Our measurement scheme (see figure 1(a)) for the current $I$ being sourced by the SET pump is based on the ULCA as a highly accurate current-to-voltage converter with an effective transresistance $A_{TR}$ of $1 \Omega$, traceable to the quantum Hall effect [4, 5]. Similar to the setup used in [6], two ULCA instruments were used in both source and drain lines connected to the SET pump (ULCA channels A and B in figure 2). For the measurements presented in this paper, the measurement scheme was improved as explained in the following, aimed at further reduction of measurement uncertainty: firstly, improvements of the setup allowed the reduction of systematic (type B) uncertainties. Secondly, the measurement routine was improved for a more effective usage of measurement time, by which the statistical (type A) uncertainty in each measurement was lowered.
Figure 2 shows our improved setup scheme, introducing a programmable JVS system, its output being adjustable in steps of about 140 $\mu$V corresponding to the microwave frequency of about 70 GHz [15]. The JVS was connected in series with two ULCA channels A and B and a commercial 8½ digit voltmeter (Agilent 3458A). The voltage difference signal $U_A - U_B = (A_{TR}^A + A_{TR}^B) \cdot I$ (about 200 mV at 600 MHz pumping frequency) was then compensated by the quantum voltage source, and the remaining difference of less than $\pm 70 \mu$V was measured with the voltmeter. This method significantly reduced the systematic uncertainty attributed to the voltmeter gain factor by more than one order of magnitude to only 0.003 $\mu$A A$^{-1}$ (see table 1) in contrast to 0.08 $\mu$A A$^{-1}$ reported in [6].

A 10 MHz rubidium oscillator was used as frequency reference for the arbitrary waveform generator driving the pump as well as for the microwave generator driving the JVS. Since both the current sourced by the pump and the voltage measured in terms of the JVS are proportional to this frequency, and also the ULCA voltage output signals are proportional to the current, the uncertainty contribution of the frequency reference drops from the uncertainty budget. All remaining systematic uncertainty contributions are listed in table 1. Note that in this paper all uncertainty figures and error bars in graphs represent standard uncertainties, i.e. for a coverage factor $k=1$.

Over the total time span of about five months for the measurement runs discussed in the following, the transresistance values of both ULCA channels were calibrated four times in intervals of about eight weeks with PTB’s 14 bit cryogenic current comparator (CCC) [4, 5]. The standard uncertainty for the CCC calibrations is 0.015 $\mu$Ω Ω$^{-1}$. Linear interpolations between calibration values taken before and after each measurement run were used for the measurement evaluation. The stability of the ULCA transresistance is taken into account by the corresponding uncertainty component in table 1 [4]. Further, small effects stemming from ULCA settling, temperature corrections and nonlinearities [17] are also considered.

In total, according to table 1 the ULCA contributes with 0.083 $\mu$A A$^{-1}$ (root sum of squares) to the total type B uncertainty of 0.084 $\mu$A A$^{-1}$, and, thus, clearly dominates the budget. Further improvements of the measurement setup

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**Table 1.** Budget of systematic uncertainty components, all given as standard uncertainties from estimates of upper limits for each ULCA channel. For the total type B uncertainty of our setup comprising two ULCA channels, we used an estimate based on the ‘worst case’ scenario: we assumed that all effects listed in the table are fully correlated between the two separate channels. In this case, the total uncertainty figure of 0.084 $\mu$A A$^{-1}$ represents a conservative estimate of the upper limit for the total type B uncertainty of the setup with two ULCA channels.

| Contribution (type B)                  | Relative standard uncertainty in $\mu$A A$^{-1}$ ($k=1$) | Comment                                      |
|----------------------------------------|-----------------------------------------------------------|----------------------------------------------|
| Calibration of $A_{TR}$ (ULCA)         | 0.015                                                     | Calibration with 14 bit CCC                  |
| Stability of $A_{TR}$ (ULCA)           | 0.08                                                      | Including effects of typical short-term fluctuations and drift |
| Other effects on $A_{TR}$ (ULCA)       | 0.014                                                     | Including settling effects, temperature correction, and nonlinearities |
| Voltage measurement                    | 0.003                                                     | Calibration of voltmeter gain versus JVS (interpolation) |
| Leakage current                        | 0.01                                                      | Wire insulation measurements                |
| Total                                  | 0.084                                                     | Root sum of squares                         |

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Figure 2. Schematics of the pump current measurement setup with two ULCA channels and a Josephson voltage standard (JVS) bridge technique. Instrument housings are electrically connected directly, or via the cable shields (omitted for clarity in the figure). The voltage output of the ULCA channels connected in series is compensated using a programmable JVS, the small difference signal is measured by the voltmeter. A frequency reference controls both the arbitrary waveform and the microwave generator.
shown in figure 2 including the use of two JVS systems are envisaged. In such setup, the output signal of each of the two ULCA instruments is measured by a JVS, which then allows a correlation analysis. However, as table 1 shows, this component contributes to the total uncertainty only little.

Reduction of the type A measurement uncertainty was pursued by means of improving the effective measurement time usage, as explained in the following and visualized in figure 3. The first aspect is related to the use of the ‘autozero’ function of the voltmeter involved in the measurement setup. When activated, this function ensures that offset errors internal to the instrument are nulled from subsequent measurements (see [16]). When this function is activated, the voltmeter internally disconnects the input signal and makes a zero reading following every measurement. It then algebraically subtracts the zero reading from the preceding measurement. Consequently, continuous use of the autozero function throughout the measurement will effectively reduce the measurement time to about 50% duty cycle. When the voltmeter is used with autozero disabled, the meter takes one initial zero reading and algebraically subtracts this from subsequent readings. In this way, the duty cycle is maximized; however the measurement will suffer from increased noise. An optimized use of the autozero function hence has to realize a trade-off between these two cases. For the measurements reported in the following, an autozero command was executed after every 75th sample, each taken with an integration time of 40 ms. The effective data acquisition time for each data point was 3.129 s including overhead for the data communication between voltmeter and computer. Similar optimization was reported in [16]. For the precision current measurements, the current from the SET pump was switched on–off periodically in order to suppress offset and drift effects [6]. After each current switching, the first 3 s of acquired data had to be rejected because of the ULCA settling time [4]. In order to use measurement time efficiently the duration of the on–off cycle was prolonged. An upper limit for this was given by intrinsic 1/f-noise of the ULCA. For the cycle time of 131 s chosen for the measurements (see [6], where about 44 s was used), the 1/f-noise contribution of the ULCA to the total noise of the setup was still negligible. Altogether, this resulted in a significant improvement of the effective measurement time utilization: compared to the procedure described in [6], where only about 59% of the measurement time effectively was used, the precision measurements in this paper used about 91%. In comparison, this enabled to reach the same type A uncertainty in about only 2/3 of total measurement duration.
The Allan deviation plot shown in figure 4 from a 20 h precision measurement (for details see next section) corresponds to an effective total current noise level of about 2.3 fA ($\sqrt{\text{Hz}}$)$^{-1}$. Taking into account that the current was measured by two independent ULCA channels in parallel, a total noise level of 2.3 fA ($\sqrt{\text{Hz}}$)$^{-1} \cdot \sqrt{2} = 3.25$ fA ($\sqrt{\text{Hz}}$)$^{-1}$ per channel was derived. Further considering that each ULCA contributes with its intrinsic noise level of 2.4 fA ($\sqrt{\text{Hz}}$)$^{-1}$ gives an effective excess noise level of about 2.2 fA ($\sqrt{\text{Hz}}$)$^{-1}$ per channel. This figure shows a slight improvement compared to the effective excess noise level of 2.5 fA ($\sqrt{\text{Hz}}$)$^{-1}$ per channel as found in [6], attributed to improvements in some parts of the cryogenic cabling.

Further reduction of type A uncertainties will become possible when new ULCA variants become available, as they are currently under development [17]. For instance, the use of the ‘low-noise’ ULCA variant listed in table 1 of [17] together with optimized cabling and daily calibration of the ULCA will give the possibility to enhance accuracy at given measurement time significantly, as discussed in [17]. Reference [18] demonstrates a suitably improved cabling in the setup can even reduce the cable noise contribution to a negligible level.

4. Measurements and results

Measurements performed at a pumping frequency of 600 MHz, corresponding to a current $I \approx 96$ pA on the first current plateau, and at a magnetic flux density of $B = 9.2$ T are shown in figure 5. Similar to [6, 13] the pump was driven by a shaped waveform signal applied to the entrance gate ($V_1^{\text{ac}}$). Figure 5(a) shows an overview measurement covering the $\langle n \rangle = 0$, 1 and 2 current regions, taken with continuous readout of the current (or voltmeter signal, respectively) while sweeping the exit gate voltage $V_2^{\text{dc}}$ and keeping $V_1^{\text{dc}}$ fixed at $-210$ mV. This value was chosen as the middle of a region being insensitive in the pumping characteristic against $V_1^{\text{dc}}$ [3]. As typical, the $\langle n \rangle = 1$ current plateau shows the largest

![Figure 4. Plot of the Allan deviation of the pump current, generated at a pumping frequency of 600 MHz on the optimal working point, in a precision measurement of 20h total duration. The cycle time of each on-off current switching cycle was 131 s, of which about 119 s of acquired data were effectively used. The data correspond to a white noise signal with 2.29 fA ($\sqrt{\text{Hz}}$)$^{-1}$ indicated by the dashed line in the plot.](image)

![Figure 5. (a) Overview pumping current curve measured at $B = 9.2$ T and $f = 600$ MHz. (b) Close-up around the flat spot in the $\langle n \rangle = 1$ current plateau region (grey area in panel (a)). Current values are plotted as relative deviation from the quantized value $\epsilon f$. Blue data points (open circles) show precision pump current measurements, each about 1 h long. Error bars correspond to type A standard uncertainties. The dotted blue line shows a fit curve calculated according to the heuristic model (see [19]) as a guide for the eye. An extended exit gate voltage range $V_2^{\text{dc}}$ from $-256$ mV to $-238$ mV was consulted for the determination of the fit. The red data points at $V_2^{\text{dc}} = -244$ mV (cross symbols) correspond to 20 subsequently taken measurements, each 1 h long. The inset shows a histogram of all data at $V_2^{\text{dc}} = -244$ mV together with a corresponding normal distribution. The half-width 0.55 $\mu$A A$^{-1}$ of the distribution well agrees to the type A uncertainty of 0.6 $\mu$A A$^{-1}$ for each single current measurement. Averaging the current values from all 21 data points taken at the exit gate voltage $V_2^{\text{dc}} = -244$ mV yields the mean value $(-0.10 \pm 0.16)$ $\mu$A A$^{-1}$. The combined standard uncertainty of 0.16 $\mu$A A$^{-1}$ consists of the type A contribution (0.13 $\mu$A A$^{-1}$) and the type B contribution (0.084 $\mu$A A$^{-1}$) from table 1 (raw data already used in [8]).](image)
Figure 6. (a) Contour plot of the derivative of pump current with respect to exit gate voltage (i.e. slope of current versus $V_2^\text{dc}$, high (lighter color) at steps, negligible (darker color) on plateaus). The numbers (n) mark the plateau regions according to $I = (n)\mu A$.

(b) Precision current measurement along exit gate voltage $V_2^\text{dc}$, heuristical fit (orange) according to [6, 19] to guide the eye. (c) Precision current measurement along entrance gate voltage $V_1^\text{dc}$. Error bars show type A standard uncertainties only. Note that the discrepancy of the current values for the data at ($V_1^\text{dc} = -200 \text{ mV}, V_2^\text{dc} = -271 \text{ mV}$) between panels (a) and (c) was caused by a shift of the pump operating point, which occurred during the two weeks between measurement of map (a) and the data point in (c) (raw data partly already used in [7]).

The inset shows the histogram of 21 current measurements taken at this working point together with a Gaussian correlation with the determined statistical uncertainties for each of the single measurements, each 1 h long.

Averaging these current data taken over the total measurement time of 21 h finally yielded the result $(I_{\text{ref}} - 1) = (-0.10 \pm 0.16) \mu A \, \text{A}^{-1}$. This result represents the most accurate direct current measurement ever performed on a SET pump. It excels the former best result of $0.2 \mu A \, \text{A}^{-1}$, consistent with the determined statistical uncertainties for each of the single measurements, each 1 h long.

Next the robustness of this type of SET pumps is examined. The invariance of output signal against the variation of any operating parameters is a fundamental condition of a quantum standard to guarantee the precision and to demonstrate the universality of operation. In order to test the conditions making the SET pump suitable for a true quantum current standard, the dependencies of its output current from relevant operating parameters therefore were investigated. In addition to the measurements regarding the entrance and exit gate voltages $V_1^\text{dc}$ respectively $V_2^\text{dc}$, shown in figure 6, the pump output current was investigated under the variation of magnetic field strength $B$, driving frequency $f$, and bias voltages on source and drain contacts ($U_{\text{Source}}$ and $U_{\text{Drain}}$). If not otherwise stated the measurements were performed on pump devices with the design shown in figure 1(a).

Figure 6 shows pump current characteristics mapped in the $(V_1^\text{dc}, V_2^\text{dc})$ plane taken at $f = 600 \text{ MHz}$ and $B = 12 \text{ T}$. In the center region of the plateau $(n) = 1$, at $V_1^\text{dc} = -182 \text{ mV}$ precision measurements of the pump current versus exit gate voltage $V_2^\text{dc}$ were taken, shown in figure 6(b). An exponential fit according to [19] was applied, from which $V_2^\text{dc} = -271 \text{ mV}$ was derived as the working point with respect to the exit gate voltage. Keeping this voltage fixed, the $I(V_1^\text{dc})$ dependence was investigated in precision current measurements, as shown in figure 6(c). Averaging the current values from the measurements symmetrically around $V_1^\text{dc} = -182 \text{ mV}$ in the range $-192 \text{ mV} < V_1^\text{dc} < -172 \text{ mV}$ yielded $(I_{\text{ref}} - 1) = (0.052 \pm 0.208) \mu A \, \text{A}^{-1}$ combined uncertainty including a type B contribution of $0.13 \mu A \, \text{A}^{-1}$ since the former measurement setup from [6] was used. This excellent agreement with the expected quantized current value over the large entrance gate voltage range of about $20 \text{ mV}$ demonstrates wide margins for working points with respect to $V_1^\text{dc}$.

For each of the following measurements regarding the $B, f, U_{\text{Source}}$ and $U_{\text{Drain}}$ dependencies of the pump current, preliminarily the working points in the $(V_1^\text{dc}, V_2^\text{dc})$ plane were determined in a similar fashion as explained above: first, scanning measurements similar to those shown in figure 6(a) were
Figure 7. Results of pump current measurement at the center of the first quantized current plateau with variation of magnetic flux density and bias voltage on source and drain electrodes, respectively. Measurements in each panel were taken during the same cooling cycle. Error bars correspond to combined standard uncertainties \((k = 1)\). Precision points on the plateau yield the averaged current. Hereby, the plateau region is defined by the fit criterion introduced in [6] in order to select data points for averaging. This criterion defines an interval as the area in which the deviation of the heuristic fit [19] from the quantized value corresponds to 0.01 \(\mu A\) \(A^{-1}\) or less, if not otherwise stated.

Figure 7 shows the results of measurements with variations of \(B\), \(U_{\text{Source}}\) and \(U_{\text{Drain}}\). Figure 8 shows measurement results from experiments with variation of driving frequency \(f\) at different values of \(B\) and with differently shaped gate voltage pulses. For the latter measurements, a pump device with the new design shown in figure 1(b) was used. This device measurements with pumping frequencies exceeding 500 MHz showed deteriorations of the first plateau \((\langle n \rangle = 1)\) and, thus, could not be considered for the data evaluations at sub-ppm accuracy level.

The results shown in figures 7 and 8 agree with \(I = ef\) within their expanded uncertainties \((k = 2)\), and their statistical scatter is in accordance with the distribution at \(k = 1\) confidence level.

Six of eight pumps investigated in total showed sub-ppm level accuracy. Completely non-working pumps suffered from technical problems such as broken gates or loose contacts. Working pumps delivered results at sub-ppm accuracy level in every second cooldown. The decision whether a thermal cycling is appropriate was based on characterization maps as shown in figure 6(a) and the analysis of cuts down to \(10^{-4}\) accuracy level.

5. Conclusion and outlook

Future SET-based quantum current standards demand reliable SET pumps sourcing output currents of at least 100 pA. Also, high accuracy corresponding to uncertainties of 0.1 \(\mu A\) \(A^{-1}\) or better is needed in order to enable SET pumps replacing classical state-of-the-art methods for ampere realizations in current metrology through combinations of watt, ohm and volt realizations [6, 20]. The improved measurement scheme presented in this paper enables approaching this uncertainty level for semiconductor SET pumps based on ‘dynamic’ quantum dots already very closely. Further improved ULCA instruments [17, 18] in the near future may enable exceeding this accuracy benchmark level. It is further expected that the
presented improvements in current measurement technique will allow the verification of theoretical models for transport processes in SET pump devices with unprecedented accuracy and precision [21].

As a matter of principle, the accuracy verification of true quantum current standards for the direct ampere realization in future metrology must not be dependent on current measurements itself. Instead, independent means are needed to determine and quantify possible deviations from $I = \text{ef}$, as offered by using ‘self-referenced’ pump schemes based on single-electron transfer error counting [2, 22]. Such schemes require several pumps to be operated simultaneously on one chip, which sets high demands on their reliability and stability under varying operating parameters. Particularly, there are global parameters that cannot be tuned individually for each pump device on a chip, as for instance the magnetic field or (depending on the setup) the pumping frequency. Also, charge accumulation on the intermediate islands in ‘self-referenced’ pump circuits (comprising several pumps in series) can cause source–drain voltages. The results reported in this paper show that the single-parameter SET pumps in this sense offer sufficient parameter insensitivity and, thus, are suitable for the realization of self-referenced quantum current schemes and current enhancement by parallel pumps [23, 24].

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