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1 Executive Summary

Introduction

The impending revision of the SI, envisaged for 2018, will define the unit of electrical current, the ampere, by fixing the value for the elementary charge *e*. According to the draft of a *Mise en Pratique*[1], the new ampere definition can be realised most directly by using a Single-Electron Transport (SET) device, i.e. a SET pump that enables the controlled transport of single electrons. The lack of suitably accurate methods for this was the motivation for this project, giving rise to its scientific objectives: to provide the means for the practical implementation of the future quantum-based ampere realisation at an accuracy level of about one part in 10^7. The results obtained, advanced SET device instrumentation enabling highly accurate amplification and measurement of the so-generated currents, are substantial contributions to this fundamental metrological task.

The Problem

The SET-based realisation of the ampere faces two main issues related to the pump devices: i) typically, currents sourced by SET pumps are small (about 100 pA); and ii) their accuracy generally is limited by statistical errors due to the stochastic nature of the physical transport mechanisms involved. Also, the validation of SET current sources needed iii) highly accurate, traceable methods for the amplification and measurement of these currents, which, before the project, were not available at the required accuracy level of about one part in 10^7.

The Solution

This project addressed the points above to create a complementary set of SET pump devices and instrumentation required for the described task. Starting from the most promising device concepts, the project systematically pursued the further development of different kinds of SET pumps that enabled quantised current sourcing at the required levels of current and accuracy; and for their accuracy verification, new SET error accounting schemes were developed and realised via error detection circuits integrated on-chip with the SET pumps. Complementary current amplification and metering instrumentation was also supplied via optimisation of amplification setups based on Cryogenic Current Comparators (CCCs) and by the development of a new, innovative type of highly accurate picoammeter.

As key project deliverable, the combination of these new devices and methods enabled the first SET-based quantum-ampere realisation at an excellent accuracy level of 0.2 ppm (5-fold improvement compared to the state of the art before the project), which improved on the best ‘classical’ realisation (based on non-quantum experiments) of the ampere within the present SI.

The Impact

Due to the fundamental nature of the project – to support the implementation of capabilities and methodologies for the realisation and dissemination of an SI unit definition – the key impact is in fundamental metrology. The main impact is an improved basis for the new SI ampere (expected to come into effect in 2018) and other electrical units derived from the ampere. The scientific achievements are highly significant for the implementation of capabilities and methodologies towards the realisation and dissemination of the future ampere unit definition in the re-defined SI.

Ultimately, the development of Single-Electron Transport devices (SET pumps) suitable for metrological application as current standards was highly promoted by the results from this project.

The project research has led to a path-breaking conclusion on SET devices regarding their use as quantum current standards: there is no ‘rapid characterisation’ procedure which enables the prediction of accuracy of a given sample of SET pumps from a series of quick measurements. Instead, for realising future SET current standards reaching uncertainties of 0.1 ppm and better, on-chip error accounting strategies, as pioneered by this project, will have to be applied.

[1] *Mise en pratique for the ampere and other electric units in the International System of Units* (CCEM/09-05)

The project has developed advanced current amplification and measurement instrumentation which brings significant impact on calibration and measurement capabilities in the field of small electrical currents. The successful development of a new, superior picoammeter, excelling former instruments by two orders of magnitudes in accuracy, is considered a revolutionary step forward, also for calibration services and industry branches dealing with small currents. Assessment of the project outputs regarding their potential for licence or patent application resulted in three patents pending; and strategies for the dissemination of the related techniques to relevant stakeholders have been developed and implemented.

Altogether, the research conducted on the accuracy verification of SET pumps currents brought the consortium to the world-wide lead in this field. Fundamental metrological challenges beyond the project are universality tests on quantum electrical phenomena, notably the experimental realisation of the quantum metrology triangle, which represents a consistency test on the electrical quantum effects. Such experiments have so far delivered results at the part-per-million precision level; but the new picoammeter is predestined for application in a quantum metrology triangle experiment at an enhanced accuracy level in the order of 0.1 ppm.

2 Project context, rationale and objectives

Context and rationale

The present system of electrical units is grounded in the base unit of electrical current, the ampere (A), whose definition dates from 1960 and remains defined in terms of mechanical units via the laws of classical electromagnetism. Under this 'classical' definition, the ampere cannot be realised with an uncertainty better than about three parts in 10^7, which is not sufficient to meet the accuracy needs of present and future routine electrical metrology, requiring one part in 10^7, or better. In 1990, this dilemma with the classical ampere definition led to the adoption of a practical unit system based on voltage and resistance standards (represented by the definition of 'conventional values' for the von-Klitzing and Josephson constants) decoupled from the SI.

To ensure worldwide consistency and uniformity of measurements, the *Conférence Générale des Poids et Mesures* (CGPM) adopted the long-term aim of basing the international system for physical units (the SI) entirely on the fundamental constants of nature. Within the forthcoming revision of the SI, envisaged to come into effect in 2018, the ampere will be re-defined in terms of a fixed value of the elementary charge e (the charge of the electron)[2]. This restores coherence to the SI System and enables practical realisations of electrical units via a short, direct traceability chain in accordance with the "*Mise en pratique for the ampere and other electric units in the International System of Units*". According to this, a possible realisation of this new ampere definition is given by applying Single-Electron Transport (SET) devices known as SET pumps or SET turnstiles, which allow the clocked transfer of single charge quanta. SET devices are considered the 'silver bullet' solution for the new quantum-based ampere realisation mainly for two reasons:

- SET allows the most direct ampere realisation via the physical definition of current as the time derivative of electric charge q being transported through the cross section of a conductor, $I = \delta q/\delta t$, thus exploiting the simple and evident relation $I_{SET} = e \cdot f$; and
- such a SET-based ampere realisation involves only one fundamental constant (e), and not two (e and h), as alternative indirect ampere realisations based on a combination of Josephson- and quantum Hall effect would do.

The practical application of SET pumps or turnstiles for future quantum current standards, however, required the following crucial features to be given:

i) sufficiently high output current of the order of 100 pA (corresponding to about 1 GHz repetition frequency for the single-electron transfer) at least; and

ii) sufficiently high single-electron transfer accuracy, in order to guarantee current accuracy in the quantised regime at the level of one part in 10^7 of relative uncertainty, or better. This point becomes important since – due to the stochastic nature of single-charge transport – all kinds of SET devices unavoidably are subject to statistical transfer errors.

2 Resolution 1 of the 24th CGPM from 2011

By the start of the project, three different types of SET devices were known that had the potential to fulfil the requirements of point i:

a) SET pumps made from GaAs-based heterostructures with electrostatic gate structures,

b) Hybrid turnstile devices made from superconductor-insulator-normal-insulator-superconductor (SINIS) structures; and

c) Silicon-based pump devices made from silicon-on-insulator (SOI) material, or from electrostatically gated silicon.

Their common beneficial features were

- that they can be driven by a single rf gate (enhancing the ease of operation),
- that their fabrication technologies allowed the realisation of parallel and series arrays (for increasing the output current, or enhancing accuracy), and
- that they could be driven at high frequencies up to the GHz range (for reaching the necessary minimum current level of 100 pA).

Starting from the most promising different device concepts and technologies a) – c), the project had to systematically pursue their further development and optimisation regarding the required levels of output current and accuracy. The redundancy given by the project work on multiple device concepts also provided failure mitigation for the case of possible technological issues at the different fabrication sites involved.

In order to address the necessary accuracy verification according to point (ii), advanced SET error accounting schemes needed to be developed and realised via error detection circuitry integrated on-chip with the SET quantum current sources. Such circuits rely on nanofabricated ultrasensitive single-electron detectors, i.e. single-electron transistors and quantum point contacts, which enable electric charge detection on a resolution level below *e*. Besides these differences in technological realisation, different concepts of SET error accounting strategies needed to be implemented, investigated and assessed regarding their advantages and limitations: one relies on the counting of every single electron to be transported by the SET device, another relies on the counting of only the errors occurring during SET current generation. The general philosophy of SET accuracy verification in all these methods, however, followed the advice given by the natural scientist and philosopher *Galileo Galilei*:

"Count what is countable,
measure what is measurable,
and what is not measurable, make measurable".

By the start of the project, traceable current metering and amplification instrumentation and methods for input currents of the order of 100 pA, with accuracy of one part in 10^7, were not available. Therefore besides, and complementary to, the development and optimisation of SET circuits themselves, the project had to develop the instrumentation suitable for highly accurate measurements and amplification of SET-generated currents. Again, different concepts were pursued, as the optimisation of amplification setups based on Cryogenic Current Comparators (CCCs) with high winding ratios and an entirely new non-cryogenic picoammeter instrument, the Ultrastable Low-noise Current Amplifier (ULCA), was invented and developed within the project.

Objectives

Following the rationale given above, this project addressed four objectives:

1. Realisation of quantum based current sources (turnstile and pump devices) on the basis of the best existing device candidates, optimised for metrological applications with an output current of 100 pA or higher and a relative uncertainty of 0.1 parts per million or smaller
2. Development and provision of new and advanced concepts for single-electron error accounting in single-electron generating circuits by on-chip detection methods involving different kinds of single-electron charge detectors

3. Realisation of "self-referenced" quantum current standards by integrating the above-mentioned quantum current sources and error accounting technologies
4. Realisation of quantum-based amperemeter and current amplification setups for the calibration of electrical current sources with output currents in the range of 100 pA and for up-scaling of these currents to about 1 µA for practical metrology applications, both at an accuracy in the range of 0.1 ppm.

All together these objectives served a fundamental metrological task: to provide underpinning capabilities for the practical implementation of the *Mise en pratique* for the future quantum-based ampere.

3 Research results

3.1 Objective 1: Quantum based current sources (SET pumps and turnstiles)

The project aimed at the fabrication, characterisation and optimisation of three different types of single-electron current source considered to be the most promising candidates suitable for the generation of output currents of 100 pA or higher with a target uncertainty of 0.1 ppm. These device types were:

- SET pumps made from GaAs-based heterostructures with electrostatic gate structures,
- hybrid turnstile devices made from superconductor-insulator-normal-insulator-superconductor (SINIS) structures; and
- silicon-based pump devices made from silicon-on-insulator (SOI) material.

The work included the fabrication of these devices, their preliminary performance characterisation and verification and finally their optimisation and comparison regarding output current level and accuracy.

Device production activities took place at five of the partner’s institutes and extended throughout almost the whole lifetime of the project. The devices produced were the basis for the further project work towards the overall key objective, i.e. the first successful prototype demonstration of an SET-based quantum-ampere realisation. The certain degree of redundancy implemented in this part of the project, i.e. developing different device concepts at different sites, also provided failure mitigation regarding fabrication issues at the different sites involved and thus paved the way for successful project completion.

Important and significant progress towards the optimisation of the fabrication technologies and of operational procedures for the metrological applications of these devices was made; however, further improvements of various details are considered possible. The pump devices demonstrated current sourcing at the 100 pA level; and the targeted relative uncertainty level of 0.1 ppm (as an order of magnitude) was demonstrated experimentally by a direct current measurement with a best result of 0.2 ppm, limited by experimental conditions (see Section 3.5 of this report). Reaching 0.1 ppm will be possible by straightforward technical improvements. Theoretical estimates have shown that the intrinsic accuracy limits of the pump and turnstile devices investigated are even lower. Thus, this objective was almost fully achieved.

3.1.1 GaAs tunable-barrier pumps

GaAs tunable-barrier pumps had already been pioneered by work of two of the project partners prior to start of the project. These pump devices were fabricated starting from GaAs/AlGaAs heterostructures comprising a two-dimensional electron gas and by applying dc voltages to two electrostatic Schottky gates, dynamic quantum dots were formed in the electron gas. Single electrons were pumped through a transport channel, i.e. from source to drain of these dots, by driving one gate (or both gates) by an rf voltage at a repetition frequency *f* (Figures 1 and 2).

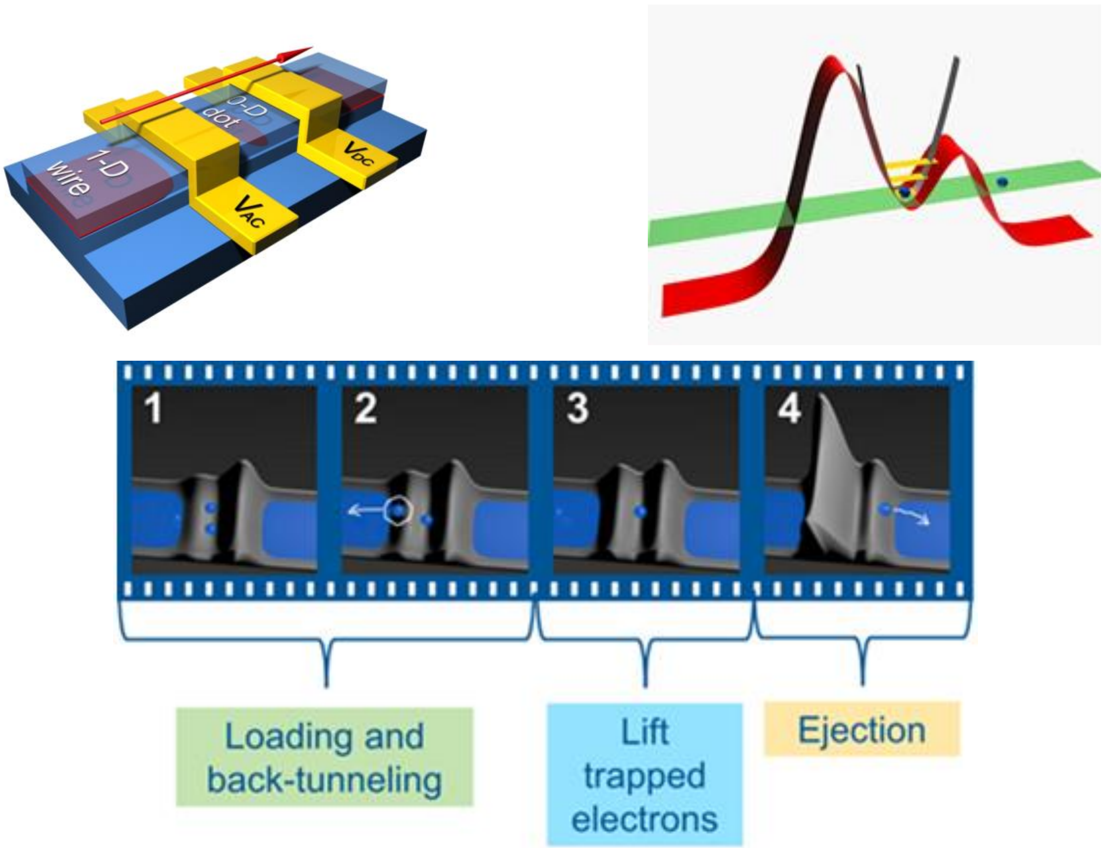

***Figure 1**: Top left side: Schematic view of a GaAs tunable-barrier pump with two electrostatically acting Schottky gates, forming a dynamical (0-D) quantum dot. Top right side: Driving one gate (denoted V_{AC} on the left) with an rf voltage clocks single electrons one-by-one through the quantum dot. The pumping cycle with its different phases is also illustrated by the "movie strip" at the bottom.*

Sample fabrication and investigation activities in the project were carried out by project partners PTB and NPL, with different technological foci: NPL developed pumps with all-gate defined transport channels, while PTB's pumps comprised etched transport channels (Figure 2).

Early focus of the project work was on optimisation of the fabrication processes at both institutes, aiming at sample yield and performance optimisation by iterative fabrication-characterisation steps. This work included setup of suitable procedures for sample characterisation at room temperature (pre-characterisation for sample selection) and under cryogenic (millikelvin) conditions, as needed for quantised current generation experiments.

In the initial phase of the project, operation of the GaAs pumps at driving frequencies up to 1 GHz was performed by driving only one gate per pump with a sinusoidal rf voltage. This 'single-parameter' drive mode first was preferred because it is the easiest way of operating an SET pump. However, later during the project, the rf-drive of both gates ('dual gate drive') by two counter-oscillating, slightly phase-shifted sine waves was successfully tested in PTB experiments. Also, starting from experiences collected by NPL, tailored waveforms supplied by arbitrary waveform generators were found to be advantageous for increasing the accuracy of the quantised pump current in a wider range of the control parameters (current plateau width). This technique was successfully adopted by PTB.

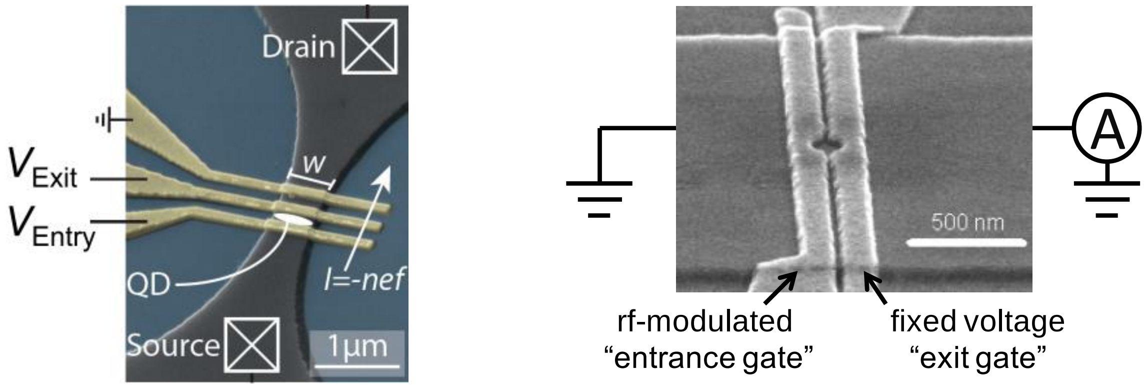

***Figure 2**: Left side: Electron micrograph of a GaAs tunable-barrier pump fabricated at PTB with etched transport channel. The gates V_{Entry} and V_{Exit} define the dynamical quantum dot (QD) of the pump. Right side: SEM picture of a GaAs tunable-barrier pump fabricated by NPL with gate-defined transport channel (the circular ‘dot’ formed between the two gates).*

Pictures from F. Hohls, “Single-electron sources and error accounting towards the new ampere: status of work at PTB”, and S. P. Giblin “Electron loading accuracy in the tunable-barrier pump”, meeting of the TC-EM subcommittee “DC & Quantum Metrology” and Final Dissemination Meeting JRP Qu-Ampere, 27-29 May 2015, Bern (Switzerland).

Furthermore, pump current invariance in the quantised regime as a function of relevant control parameters (exit gate voltage, rf drive waveform shape, dual-gate rf drive, and magnetic field) was investigated by NPL and PTB with ppm resolution, i.e. about ten times more precise than the state of the art before the project.

An important contribution to the understanding of the physical transport mechanisms in tunable-barrier pumps was given by the work from the theory group at the University of Latvia (LatU), cooperating through a Researcher Excellence Grant. This work, fostered by several guestworking visits between the groups, in particular addressed the refinement of theoretical models describing the single-electron transport processes. This enabled the comparison of model predictions with the measurement results and helps improvement of device layout and operation for enhanced accuracy of pump current. New insight was found in the theoretical understanding of error mechanisms limiting the ultimate accuracy of tunable-barrier pumps. Within the scope of this work, experimental data from high-accuracy current measurements collected at NPL and PTB on GaAs pumps was used to advance existing theoretical models beyond the state of the art (i.e. beyond the ‘decay-cascade’ model, Figure 3). In particular, multiple physical mechanisms were studied that may lead to pump performance degradation. Analysis of simulation and experimental data has uncovered a more complex interplay of the physical mechanisms than anticipated earlier.

Additionally, a collaboration between one of the project partners and the University of Hannover achieved new results on high-fidelity splitting of electron pairs generated with the GaAs single electron pumps developed within the project. This research showed that the developed pump devices were ideal for use in the field of quantum information processing, precisely because they can emit electrons on-demand with determined timing. This is an essential building block for employing the quantum state of ballistic electrons in electron quantum optics experiments and was an example of spin-off results from the project that was not anticipated at the start.

The project metrology key targets – the first successful prototype demonstration of an SET-based quantum-ampere realisation and SET error accounting based on single-electron detection – were achieved with GaAs pumps; and these results will be explained in detail in Section 3.8.

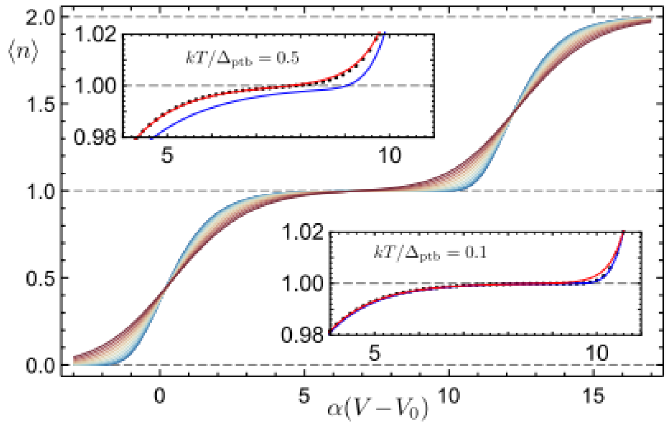

***Figure 3**: Average number ⟨n⟩ of electrons on the island of a tunable barrier pump as function of exit gate voltage V for a uniform set of temperatures kT/Δ_{ptb} = 0 to 1 (blue to red, decreasing steepness). The insets show examples of fitting the pure decay cascade formula (blue, lower curve) and the new fluctuation ansatz (red, upper curve) to the numerical solution (dots). From V. Kashcheyevs, J. Timoshenko, "Modeling of a tunable-barrier non-adiabatic electron pump beyond the decay cascade model", Conference on Precision Electromagnetic Measurements (CPEM) Digest 2014, pages 536-537.*

3.1.2 Hybrid turnstiles

Hybrid turnstile devices are 'hybrid' in the sense that they are fabricated from two metallic nano-scale Superconductor–Insulator–Normal (SINIS) tunnel junctions in series. A single-electron current can be driven through this circuit by applying an rf voltage signal to a gate electrode that is capacitively coupled to the 'Normal' metal island between the 'Insulating' tunnel barriers (Figure 4). Physically, the accurately clocked transfer of single electrons in these devices is enabled by the interplay of the Coulomb blockade gap and the superconducting energy gap. The inherent physical limitations of the tunnelling transport mechanism limits the maximum driving frequency *f* for these devices to about 100 MHz, i.e. to a maximum quantised current of the order of 10 pA per turnstile device. This was about ten times less than GaAs pumps typically had shown to achieve, which consequently meant that parallelisation of about ten turnstile devices on-chip was needed to achieve the required current of about 100 pA.

However, similar to the GaAs tunable-barrier pumps and common for all single-electron current source devices investigated in the project, is the feature that each hybrid turnstile can be driven by only one externally controlled clocking signal. By the start of the project this beneficial feature was considered to facilitate their parallelised operation substantially. Also, the hybrid turnstile was considered easier to fabricate than tunable-barrier pumps and parallel operation of an array of ten pumps had already been demonstrated by the group at Aalto University, pioneer in the field hybrid turnstiles and participating with a Researcher Excellence Grant.

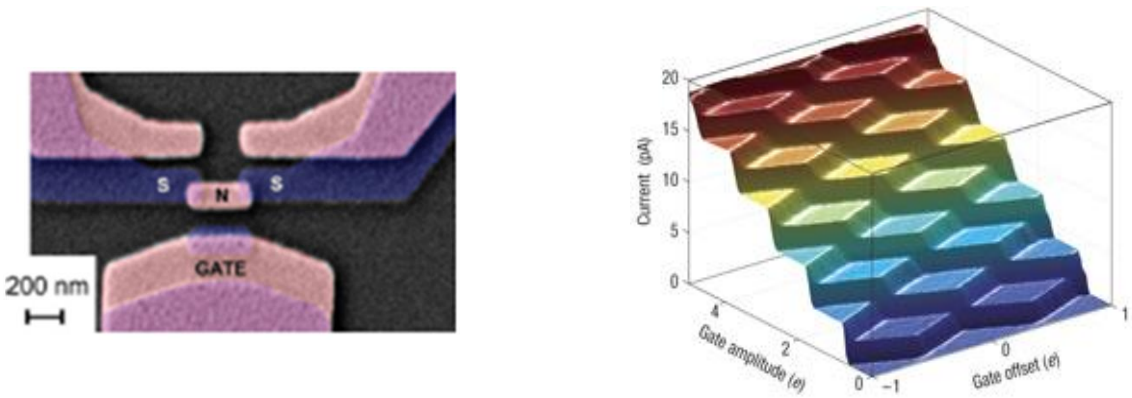

***Figure 4**: Left side: Hybrid turnstile with superconducting leads (S), normal metal island (N), and gate electrode. Right side: Current of a turnstile under rf drive.*

The main aim of one of the project partners was to fabricate, characterise and optimise hybrid turnstiles for parallel operation in arrays of about ten devices to achieve output currents of about 100 pA and to explore the accuracy limits with respect to their metrological application as quantum current standards. However, serious problems with relevant parts of the nanofabrication equipment (the electron beam lithography system and the *e*-gun evaporator) involved in the fabrication line caused drawbacks and delays with the sample fabrication. This strongly impaired the work progress and made significant adjustments to the original work plans necessary. Some of the failures remained non-recoverable during the runtime of the project and the theoretically predicted high performance of the hybrid turnstile as a quantum current standard could not be properly demonstrated before the end. Nevertheless, the work on hybrid turnstiles was successful, showing results beyond the state of the art.

Technological fabrication challenges, such as the reproducibility of the junction sizes and resistances, were solved; and parasitic effects hampering device performance caused by fluctuating background charges were evaluated and analysed. In the improved sample fabrication process, resist residuals were removed by dry-etching, which minimised background charge fluctuations. Also, the dependency of background charge effects on different types of insulator materials was also investigated and compared.

Advanced understanding about the design criteria for optimised turnstiles was achieved in the project. Samples fulfilling these design criteria, among them arrays of 10 parallel turnstiles, were fabricated and showed promising characteristics in room-temperature measurements (Figure 5). Unfortunately, however, mK-temperature experiments and proper quantised current pumping with these devices failed. Thus, the theoretically predicted high-accuracy performance of hybrid turnstiles could not be verified during the project lifetime.

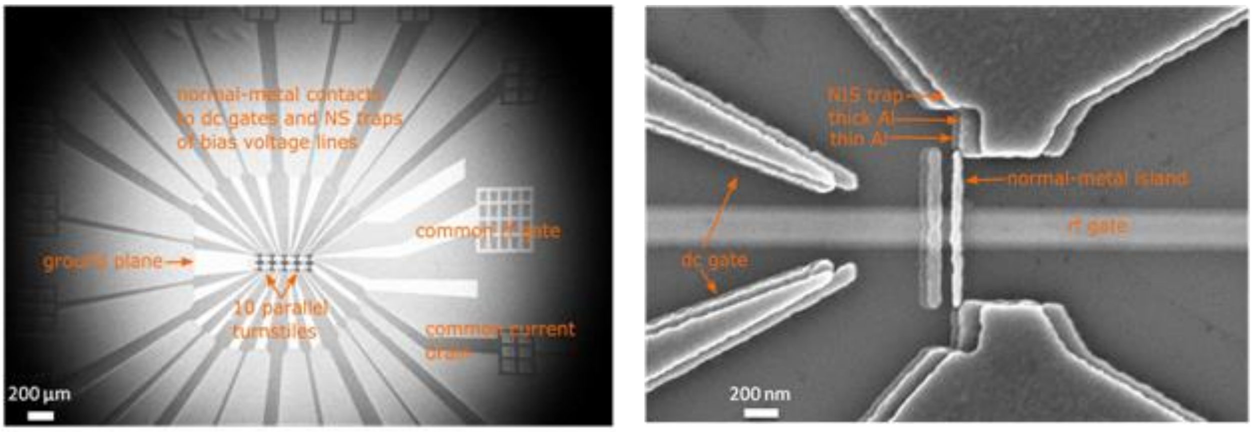

Figure 5: *Microscopy pictures of a hybrid turnstile device (blow-up of a single turnstile on the right side) with 10 turnstiles in parallel, to be driven by a common rf gate. The right panel also shown a structure denotes 'NIS trap' in the leads to the island which serves as a quasiparticle filter. From E. Mykkänen et al., "SINIS turnstile as a quantum current standard", meeting of the TC-EM subcommittee "DC & Quantum Metrology" and Final Dissemination Meeting JRP Qu-Ampere, 27-29 May 2015, Bern (Switzerland).*

Joint research between the Researcher Excellence Grant Researcher at Aalto-korkeakoulusäätiö (Aalto) in Finland and one of the project partners also brought important progress in the theoretical understanding of hybrid turnstiles, with more general impact on physics of electronic quantum devices. Different physical mechanisms impairing turnstile operation were studied theoretically and experimentally and means for minimising these effects were developed (Figures 5 and 6). Excess (non-equilibrium) quasiparticle population was identified as the key problem for achieving ultimate pumping accuracy and this problem was successfully tackled by an optimised design of the on-chip leads contacting the turnstile structures to avoid excess quasiparticle population in the superconductor and to provide a stabilised voltage bias.

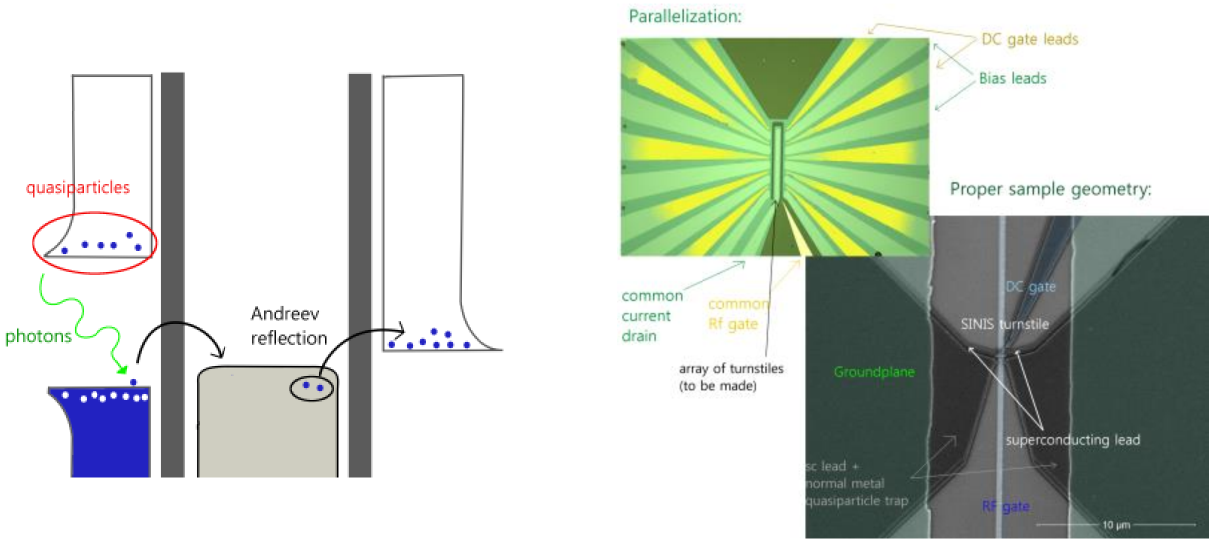

Figure 6: *Dominant error mechanisms in hybrid turnstiles (left side), and solutions for remedy by appropriate device design (right side). Figures provided courtesy of A. Kemppinen and A. J. Manninen (MIKES).*

In one experiment, a turnstile device was studied where the quasiparticle thermalisation was made deliberately poor. The results showed that the single-charge transfer errors revealed a non-equilibrium quasiparticle distribution, i.e. did not obey Fermi distribution. This important investigation significantly helped to understand quasiparticle diffusion and relaxation, not only in SINIS turnstiles, but also in other devices from superconducting quantum electronics.

Other parasitic effects, for instance Cooper-pair-electron (CPE) co-tunnelling caused by Andreev reflections in the superconductor parts of the junctions, were also studied in specially designed turnstile devices. Tunnel resistances and charging energies of these devices were optimised regarding CPE suppression.

3.1.3 SOI-CMOS pumps

First single-electron pumps based on silicon technology had already been pioneered before the start of the project. However, the exploration of their potential (for instance the assessment of current limit and accuracy) for metrological applications had yet to be done and thus was implemented in this project.

Besides the beneficial features of a possible single-gate drive (similar to GaAs pumps and hybrid turnstiles) and high pumping frequencies (0.5 GHz had previously been demonstrated), SET pumps devices based on Silicon-On-Insulator (SOI) technology offered several distinct advantages. Firstly, the ultra-small device structure sizes that could be realised with this technology allowed the fabrication of pumps with charge island sizes in the order of tens of nanometres and less (Figure 7), which elevated the Coulomb charging energy so that SET operation at relatively high temperatures up to few Kelvin seemed realistically possible. This feature was considered very promising because it meant relaxed demands on cryogenic equipment necessary for SET pumping operation. Secondly, the fabrication process was fully compatible with CMOS (Complementary Metal-Oxide-Semiconductor) technology, which allows integration of on-chip error accounting schemes made by state of the art CMOS electronic components. Also, it gaves the opportunity to fabricate pump control electronics (which in all other SET setups consisted of bulky rack-mount units) on-chip with the pump. Last, but not least, it had been shown that silicon-based SET devices are nearly immune to offset charge fluctuations.

However, the SOI process technology required large-scale industry-grade fabrication equipment. Such facilities are typically not available in research laboratories because of costs and expenditure. Therefore, SOI-CMOS fabrication is nearly exclusively found in the semiconductor industry and related foundries, as given for CEA in Grenoble. Within the project, SOI single-electron pumps were developed and investigated in frame of another Researcher Excellence Grant at the Commissariat à l'énergie atomique et aux énergies alternatives (CEA) in France, with part of the measurements being done in collaboration with another project partner.

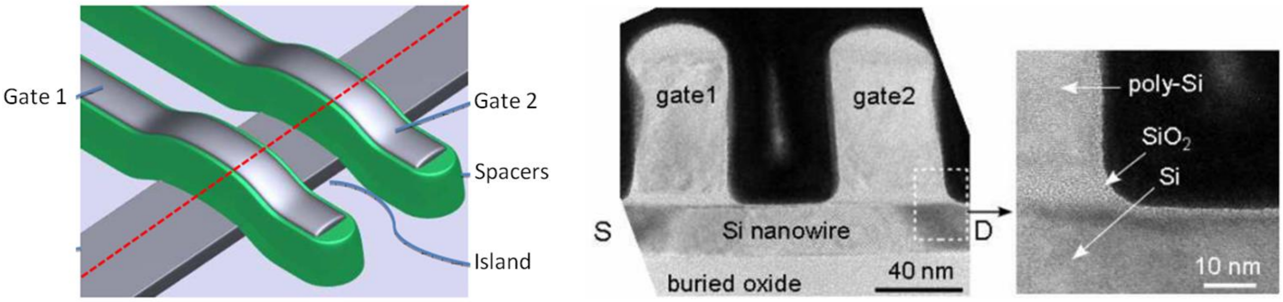

***Figure 7**: Schematics of an SET pump made by CEA in SOI-CMOS technology (left side), and electron micrographs of device structures (right side: cross-section through the device highlighted by the red dotted line on the left side). Pictures adapted from T. Charron et al., "LNE contribution to the JRP Quantum Ampere", meeting of the TC-EM subcommittee "DC & Quantum Metrology" and Final Dissemination Meeting JRP Qu-Ampere, 27-29 May 2015, Bern (Switzerland).*

Within the project, the unique sample fabrication opportunities offered by the SOI-CMOS technology were exploited. Feedback to the device production foundry was provided to allow device layout optimisation in consecutive production batches. Tools and methods for SOI-CMOS pump fabrication (Figure 7), selection and characterisation were established, which included setting up a cryostat and equipment for sample characterisation from 300 K down to a base temperature of 120 mK and establishing a systematic operational procedure for the pumps.

Already with the first SOI pump devices investigated, quantised charge pumping was demonstrated up to 50 MHz pumping frequency with dual-gate drive and at temperatures up to 0.5 K. The flatness of the quantised current plateaus was investigated (however initially with relatively low accuracy corresponding to 1 % resolution) and it was found comparable to GaAs pumps.

The pumping performance was systematically investigated as a function of the source-drain bias voltage, rf signal amplitudes and the phase shift (between the signals on both rf driven gates), as well as on samples with different gate length, channel width, Si layer thickness, doping, and spacer layer thickness. All design parameters then were optimised for maximum pumping accuracy.

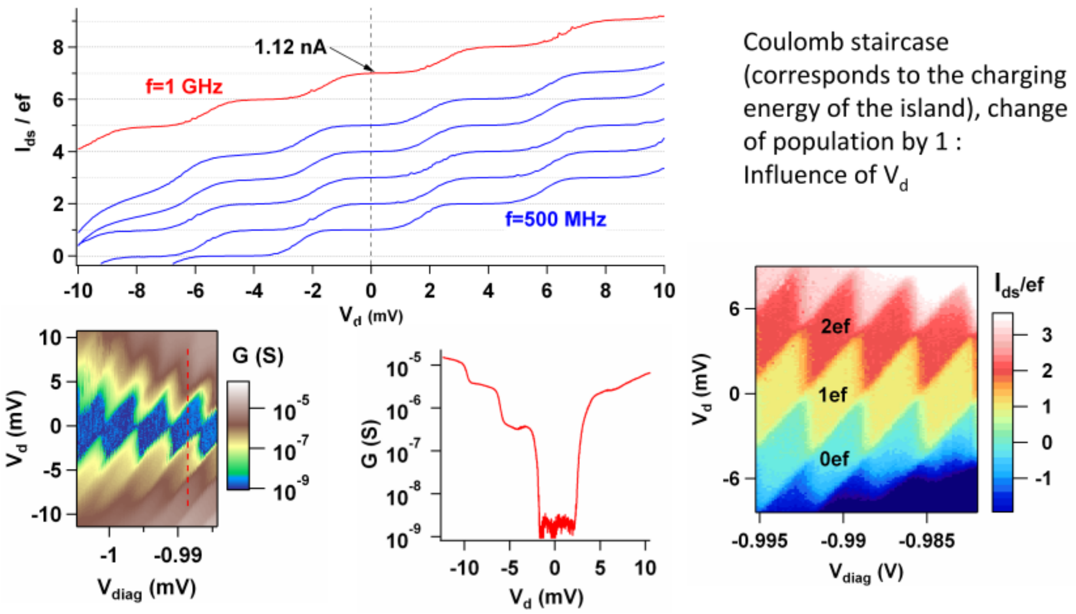

***Figure 8**: Multi- charge pumping (N = 7 electrons per cycle) at 650 MHz. From S. Ray et al., "Single island Silicon single electron pump at 650 MHz and 0.5 K", meeting of the TC-EM subcommittee "DC & Quantum Metrology", 21-22 May 2013, Tres Cantos (Spain).*

Following this, a pumping operation at a frequency of 1 GHz with up to 7 electrons per cycle was demonstrated successfully in first tests (Figure 8). Quantised current operation at pumping frequencies as high as 650 MHz was achieved at T = 500 mK (Figure 9). The stability of the pump current plateaux was investigated as a function of different pumping parameters like dc bias voltage, rf power, and phase shift. At a pumping frequency of 650 MHz, the pumped current was found to be constant over a phase shift range of 6° and rf amplitude of 70 mV for the gate signals, which provided a comfortable and wide region for the operation of the pump (Figure 9). The accuracy achieved in the current measurements was limited by the experimental setup at CEA (accuracy corresponding to 1500 ppm).

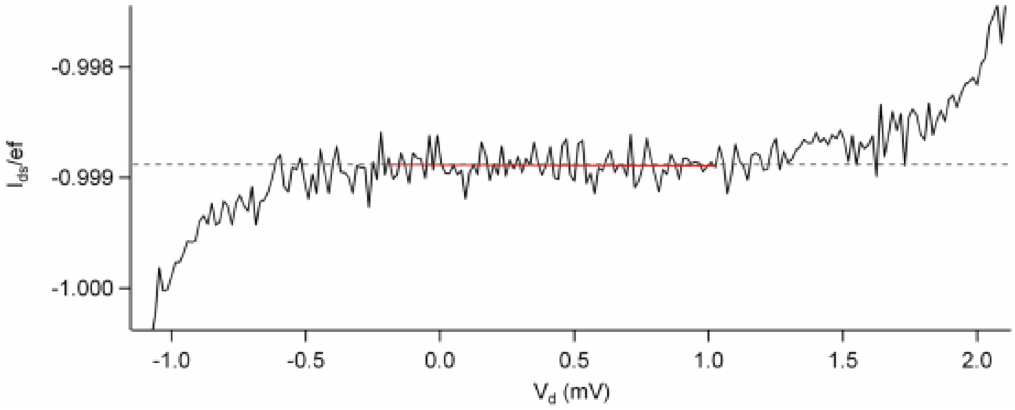

Figure 9: *SET pumping at 650 MHz (N =1). Shown is the pump current, normalised to e·f, as function of source-drain voltage V_d in the quantised regime. From S. Ray et al., "Single island Silicon single electron pump at 650 MHz and 0.5 K", meeting of the TC-EM subcommittee "DC & Quantum Metrology", 21-22 May 2013, Tres Cantos (Spain).*

SOI-CMOS pump current measurements at higher accuracy were then carried using a CCC-based current amplifier setup. The statistical uncertainty achieved within a data acquisition time of 14 hours was 3 ppm.

A completely new, innovative breakthrough in SET pump implementation was achieved by demonstrating on-chip rf pump drive: CMOS electronic circuits based on ring oscillators, integrated on-chip with a SOI pump (Figure 10) were successfully used for the generation of rf gate signals, for driving the pump at cryogenic temperatures down to 1 K (Figure 10). This development clearly represented progress beyond the state of the art and was the advent of advanced device concepts that can highly facilitate the operation of single-electron pump current sources.

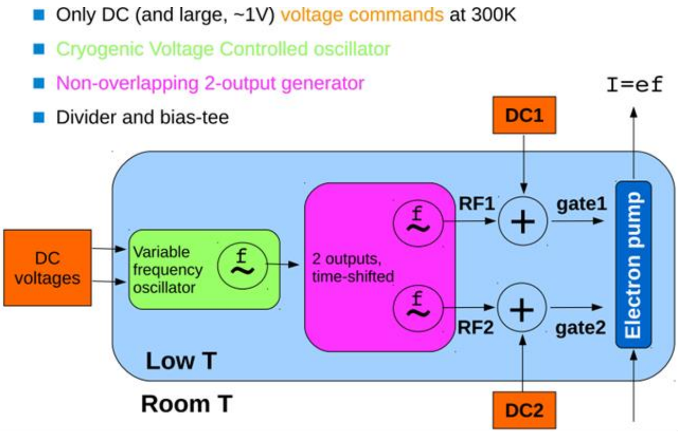

Figure 10: *Circuit principle and features of the on-chip rf pump drive, implemented by CMOS technology. Two dc voltage sources at room temperature are connected to the cryogenic variable frequency oscillator circuit, producing two phase-shifted rf signals for driving the SOI pump (on the right corner). From X. Jehl, "Design and cryogenic operation of an on-chip electron pump rf drive", meeting of the TC-EM subcommittee "DC & Quantum Metrology" and Final Dissemination Meeting JRP Qu-Ampere, 27-29 May 2015, Bern (Switzerland).*

3.2 Objective 2: New and advanced concepts for single-electron error accounting in single-electron generating circuits

The aim of this objective was to develop methods to verify the accuracy of the currents generated by SET pumps with on-chip methods suitable for detecting and counting single-electron transfer errors. In these 'self-referenced' quantum current sources, the current generation is monitored on-chip at the single-electron level, which is referred to as 'error accounting'. Due to the particularly challenging nature of this research, different development routes were pursued in parallel, using different combinations of current source device and error detection circuitry and different error accounting strategies. The concepts developed provided the basis for the development of 'self-referenced' quantum current standards ultimately targeted in objective 3 (Section 3.3). Thus, objective 2 was fully achieved.

3.2.1 Error accounting in hybrid turnstiles

Device layouts for single-electron transfer error accounting in hybrid turnstiles were developed in collaboration with the Researcher Excellence Grant at Aalto. The circuit shown in Figure 11 consists of two turnstiles coupled in series, combined with a metallic SET transistor detecting the charge state of the intermediate island. The work included the improvement of the signal-to-noise ratio of the SET transistor for reliable error counting.

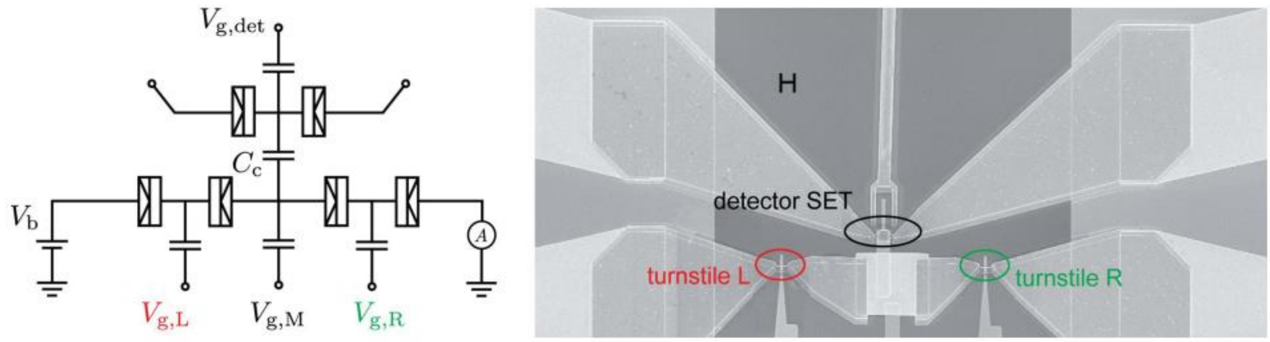

***Figure 11**: Circuit layout for error accounting in hybrid turnstiles (left side) and correspondingly fabricated device (right side). Two turnstiles are coupled in series, combined with an SET detector measuring the charge state of the intermediate island. From E. Mykkänen et al., "SINIS turnstile as a quantum current standard", meeting of the TC-EM subcommittee "DC & Quantum Metrology" and Final Dissemination Meeting JRP Qu-Ampere, 27-29 May 2015, Bern (Switzerland).*

First error counting experiments were performed on (not yet optimised) single hybrid turnstiles (Figure 12). The turnstiles were operated by rapid pumping pulses, each transferring a single electron, separated by a delay for simplifying the readout. In this slow pumping mode, several hundreds of electrons could be pumped without errors. When the pumping frequency was increased to 200 kHz, the error rate exceeded 100 Hz. A rigorous analysis of the results was still under progress by the end of the project. However, already the preliminary analysis indicated the importance of proper screening and optimised device geometry for the implementation of parallelised turnstiles.

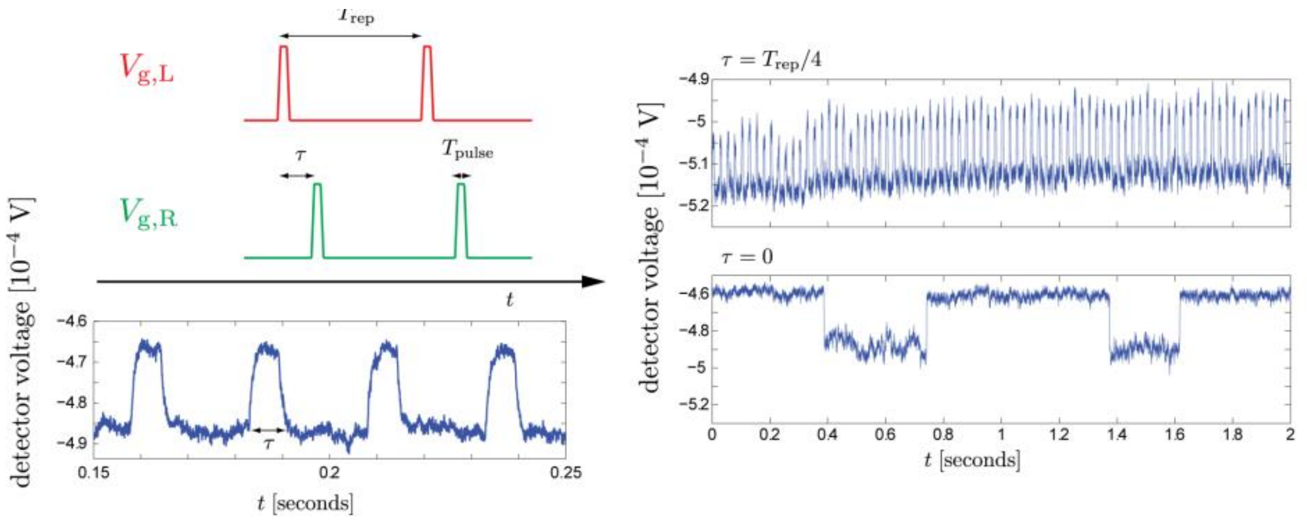

***Figure 11**: Initial measurement of pumping errors in hybrid turnstiles. Left panel: rf drive with low duty cycle, fast driving pulses compared to sampling frequency. Right upper panel: detection of each electron pumped onto/out of the intermediate island. Right lower panel: only transfer errors are detected. From E. Mykkänen et al., "SINIS turnstile as a quantum current standard", meeting of the TC-EM subcommittee "DC & Quantum Metrology" and Final Dissemination Meeting JRP Qu-Ampere, 27-29 May 2015, Bern (Switzerland).*

3.2.2 Error accounting in GaAs devices

Throughout the project, the development and implementation of different on-chip SET error accounting schemes in GaAs-based devices was pursued.

SET error accounting in GaAs double quantum dots

This work was performed within a Researcher Excellence Grant at the University of Cambridge (UCAM), UK in the frame of PhD. thesis[3] work and supported by one of the project partners. The aim was to develop double quantum dot (DQD) devices suitable for the detection of single electron transfer errors in GaAs electron pumps.

The specific technological approach pursued was to integrate GaAs-based DQD devices, fabricated using the same GaAs technology as for the pumps, with quantum point contacts (QPCs) designed to act as single-electron detectors. The function scheme of such integrated circuit is shown in Figure 13.

Initially, the device layout and fabrication was established and optimised and the instrumentation and measurement periphery needed for device characterisation down to sub-Kelvin temperatures was set up. Software algorithms for the statistical analysis of measurement results regarding DQD charge dynamics (DQD state occupation probabilities and transition rates) were developed. This enabled investigations of the noise level, bandwidth and charge sensitivity of the DQD-QPC error detection circuits. An assessment of the errors in 'counting' the electron flow through the DQD was performed. The effect of back-action of the QPC detector on the DQD was investigated, as well as the influence of statistical tunnelling errors and finite detector bandwidth, and an uncertainty budget was set-up. The applicability of the DQD-QPC system for error accounting in GaAs pumps also was assessed. The results from this study are summarised by the following conclusions:

The DQD electron-counter can measure currents as small as a few aA by counting single-electron tunnelling events. The measurement of currents of about 10 aA was demonstrated with an uncertainty of 0.04 aA in 1000 s of measurement time. The DQD electron counter is applicable for probing pump errors at GHz pumping frequency if the difference current produced by two electron GaAs pumps is measured.

[3] J. Waldie, "Electrical current at the single-electron level", PhD thesis, University of Cambridge, Cavendish Laboratory (2015)

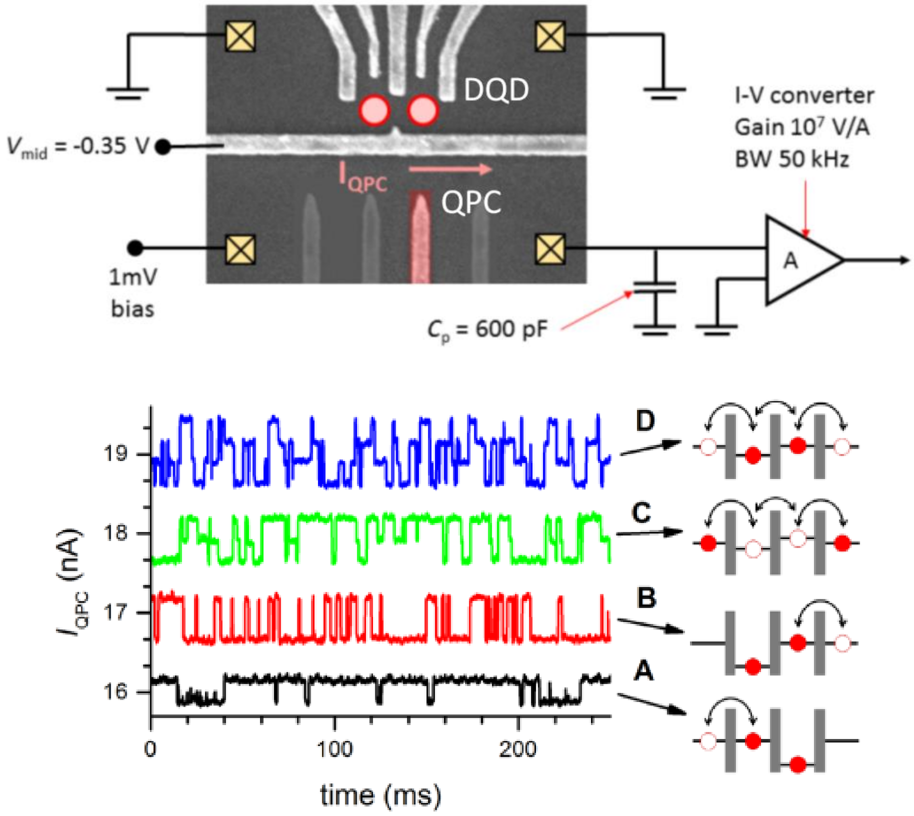

***Figure 13**: The top panel shows a GaAs double quantum dot (DQD) combined with a quantum point contact (QPC). The conductance of the QPC is dependent on the charge state of two dots (bottom panel), thus acting as single-electron detector for monitoring the charge state in the DQD. From J. Waldie, "A double-quantum-dot electron counter for detecting single-electron pump error rates", meeting of the TC-EM subcommittee "DC & Quantum Metrology" and Final Dissemination Meeting JRP Qu-Ampere, 27-29 May 2015, Bern (Switzerland).*

SET error accounting in GaAs pumps by 'electron loading' analysis

This work was based on the postulate that the accuracy of a tunable-barrier pump is determined during the 'loading phase' of the pumping cycle, where electrons are loaded from the source contact into the quantum dot (Figure 14). During this initialisation phase, back-tunnelling of electrons to the source side determined the number of electrons remaining in the dot and then being kicked out into the drain side. After this phase, the charge state of the dot was considered 'frozen' due to the high potential barriers to source and drain contacts, created by the voltages on the gate electrodes.

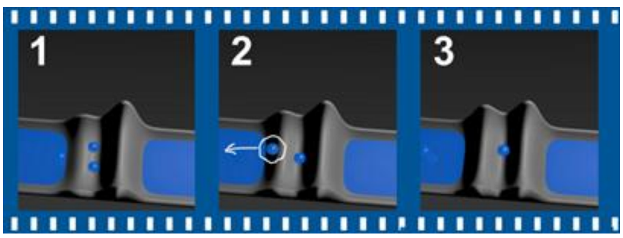

***Figure 14**: Initialisation phase of the dynamical quantum dot in the pumping cycle of a GaAs pump. Frames 1 and 2 show loading (1) and back-tunnelling (2) events of electrons into/from the dot. Frame 3 shows the following 'lifting' of the trapped electrons during further increase of the entrance gate voltage. In this phase, when electrons are trapped, the pumping cycle is paused for a measurement of the dot's charge state with a single-electron resolving detector (not shown in here). From S. P. Giblin, "Electron loading accuracy in the tuneable-barrier pump", meeting of the TC-EM subcommittee "DC & Quantum Metrology" and Final Dissemination Meeting JRP Qu-Ampere, 27-29 May 2015, Bern (Switzerland).*

If the further increase of the entrance gate voltage (the rf driven gate) is stopped right at the moment where entrance and exit gate barriers are close to equal, the electrons in the dot are trapped. The charge state of the dot can be measured by using a charge-sensitive detector nearby the pump island, which in this case was implemented by a QPC detector (Figure 15). This approach was similar to the experiments described in the previous section about the investigations on DQD system dynamics. The implementation of a suitable QPC detector involved expertise from the Researcher Excellence Grant work performed at UCAM.

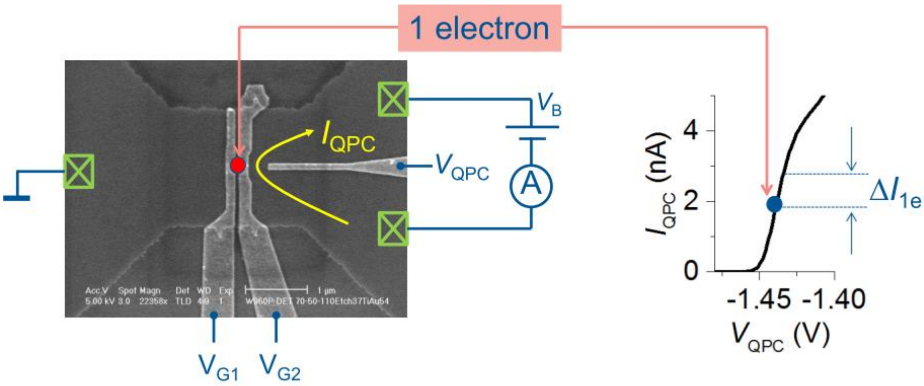

***Figure 15**: Device architecture for investigating loading probability. Monitoring the conductance of a QPC detector nearby a GaAs pump is used to measure the charge state of the initialised island. From S. P. Giblin, “Electron loading accuracy in the tuneable-barrier pump”, meeting of the TC-EM subcommittee “DC & Quantum Metrology” and Final Dissemination Meeting JRP Qu-Ampere, 27-29 May 2015, Bern (Switzerland).*

Charge state measurements on the dot, initialised with trapped electrons, were performed and showed high stability, i.e. dwell times of electrons in the static dot can be more than 10 hours. During each ‘stop phase’ (20 ms duration) consecutively performed, many thousands of pumping cycles, charge state measurements on the pump island were performed, as shown in Figure 16. It is important to note that the initialisation phase of the pump dot was performed at high speed, comparable to the operation of the pump for current generation, i.e. the rf voltage signal applied to the entrance gate of the pump was applied with effective frequencies up to 280 MHz.

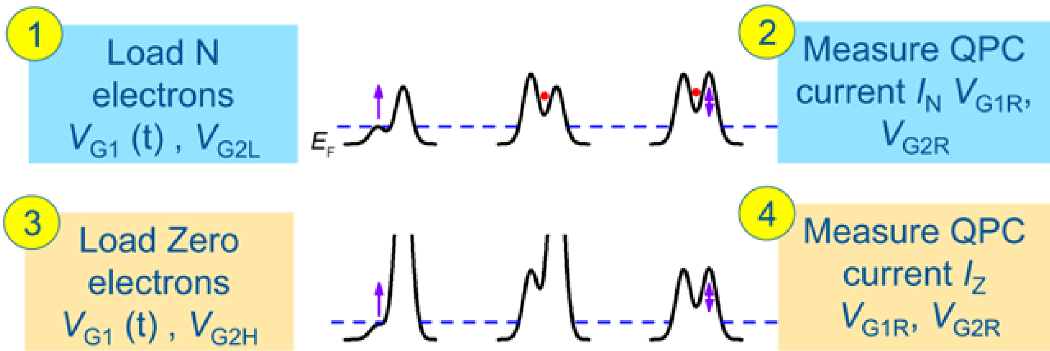

***Figure 16**: Protocol for consecutive measurements of the charge-initialised (‘loaded’) pump island with the QPC detector. From S. P. Giblin, “Electron loading accuracy in the tunable-barrier pump”, meeting of the TC-EM subcommittee “DC & Quantum Metrology” and Final Dissemination Meeting JRP Qu-Ampere, 27-29 May 2015, Bern (Switzerland).*

The results enabled a statistical analysis of the ‘electron loading’ performance. Figure 17 shows the result from such measurements and analysis for about 1 million loading cycles in which the pump was tuned for loading $N = 1$ and $N = 2$ electrons (i.e. the nominal electron number to be trapped on the island in each cycle), at a speed for the loading phase corresponding to 280 MHz pumping frequency. For $N = 1$, about 20 errors events ($N = 0$) were counted, corresponding to a relative uncertainty of about 20 ppm for the initialisation of the pump, i.e. for the expected output current. For $N = 2$, at maximum one such error event was counted, corresponding to a relative uncertainty of 1 ppm for the expected pump output current. The accuracy of this experiment was limited to around 1 ppm by two-level fluctuators, which disrupted the operation of the charge detector.

In summary, the first demonstration of part-per-million pump current accuracy by on-chip single-electron counting has been performed. The investigations focussed on the accuracy with which electrons are loaded into the pump when a fast voltage ramp, equivalent to pumping at 280 MHz, was applied to the entrance gate. Additional devices fabricated on the same GaAs wafer have also shown enhanced two-level fluctuator activity, suggesting that improved results could be obtained in the electron counting experiment just by fabricating the devices on a different wafer.

The best result of one error in approximately one million loading cycles on the $N = 2$ electron plateau represents an improvement of at least two orders of magnitude in electron counting accuracy to that which was state of the art before the project.

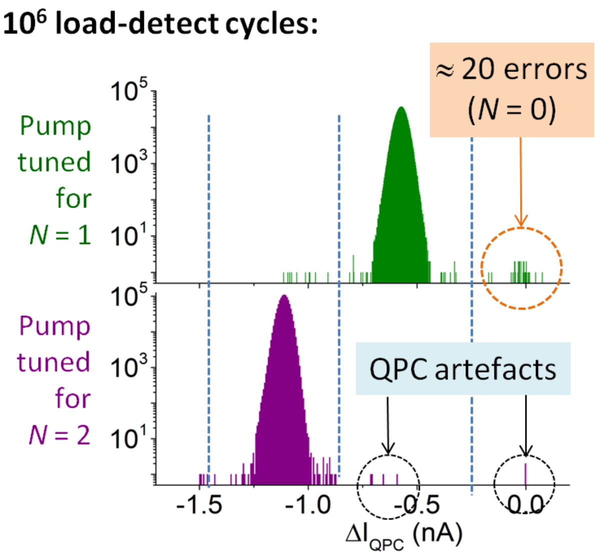

***Figure 17**: Statistical analysis of pump 'loading' performance. About 1 million loading cycles were performed in which the pump was tuned for loading N = 1 (upper panel) and N = 2 island electrons (upper panel), at an effective frequency of 280 MHz for the loading phase. The histograms show the charge state distribution with maxima positions corresponding to the nominally expected 'loading states' (Detector signal $I_{QPC} = 0$ nA for zero island electrons, $I_{QPC} \approx 0.6$ nA for one island electron, and $I_{QPC} \approx 1.2$ nA for two island electrons). Encircled areas highlight in the lower panel measurement artefacts from the QPC detector caused by background charge fluctuations. Figure provided courtesy of S. P. Giblin (NPL)*

In-situ **SET error accounting in GaAs pumps**

This work was based on a concept[4] for *in-situ* SET error accounting in series arrays of tuneable barrier pumps, invented at the start of the project (Figure 18). The circuit architecture involved (N+1) pump devices connected in series, combined with N single-electron charge detectors monitoring the charge states of the island nodes between each two neighboured pumps.

The error accounting concept here was based on the strategy not to count each electron transferred through the pump array, but to only count the transfer error events of the individual pump devices, which occur at much lower rates than the pumping frequency. As shown in the proposal paper[4], this error accounting scheme yielded a corrected error rate Γ_{corr} scaling roughly as $\Gamma_{corr} \approx \Gamma^{(N/2)+1}$, with Γ being the error rate of a single pump device. Thus, higher N improved the corrected accuracy of the current sourced by the pump array. It was shown that a circuit with five pumps can provide current accuracy verification at the level of 0.01 ppm even with SET pumps (or turnstiles) of modest accuracy, i.e. with error rates corresponding to pumping accuracy of about 100 ppm per pump.

[4] M. Wulf, "Error accounting algorithm for electron counting experiments", Phys. Rev. B, Vol. 87, 035312 (2013), http://dx.doi.org/10.1103/PhysRevB.87.035312

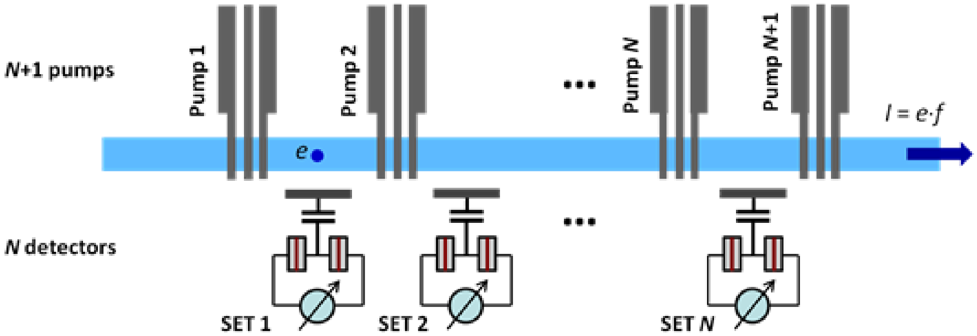

Figure 18: *In-situ pump error accounting scheme, realised by a series array of (N+1) SET pumps combined with (N) single-electron charge detectors monitoring the charge states of the islands between each two neighboured pumps. From F. Hohls, "Single-electron sources and error accounting towards the new ampere: status of work at PTB", meeting of the TC-EM subcommittee "DC & Quantum Metrology" and Final Dissemination Meeting JRP Qu-Ampere, 27-29 May 2015, Bern (Switzerland).*

Within the project, such a scheme was implemented by series arrays of three GaAs pumps, combined with two metallic single-electron charge detectors (SET transistors) capacitive coupled to the charge nodes (Figure 19). Initially, these circuits were used for extensive investigations of the dynamic quantum dot initialisation process, based on single-electron counting experiments. This yielded insight in the electron capture process on the pump islands (full probability distribution of electron number). The data were analysed in the context of different models involving two opposing initialisation mechanisms. The distinction between the capturing mechanisms allowed deriving experimental strategies for optimising the initialisation with respect to improving pump operation.

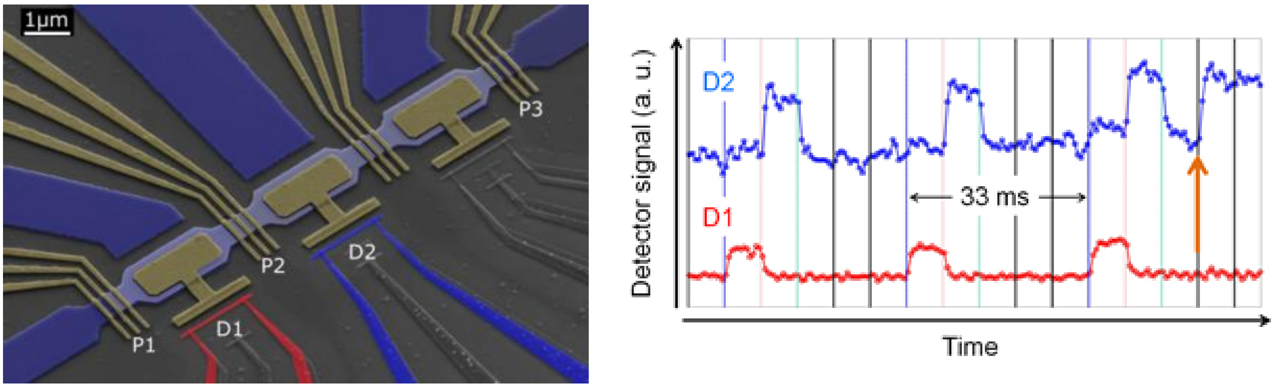

Figure 19: *Left side: Electron micrograph of a series array with three GaAs pumps (denoted P1-P3), combined with two metallic single-electron charge detectors (denoted D1 and D2). Right side: Detector signals during slow pumping (30 e/s), with indicating single electrons entering an leaving the charge nodes between the pumps. The orange arrow indicates a pump error caused by pump P3. From F. Hohls, "Single-electron sources and error accounting towards the new ampere: status of work at PTB", meeting of the TC-EM subcommittee "DC & Quantum Metrology" and Final Dissemination Meeting JRP Qu-Ampere, 27-29 May 2015, Bern (Switzerland).*

In following experiments, the *in-situ* error accounting for accuracy enhancement of the output current was successfully demonstrated. Correlation analysis of the detector signatures during current generation clearly revealed erroneous pumping events (right panel, Figure 19) and enabled determining the deviation of the output current from the nominal quantised value $e{\cdot}f$. As result of a statistical analysis, the error detection yielded a corrected output current value at uncertainty reduced by more than one order of magnitude (about a factor of 50) as compared to an individual single-electron pump (Figure 20). This work represented the first experimental demonstration of an error-corrected ('self-referenced') SET current source with increased accuracy.

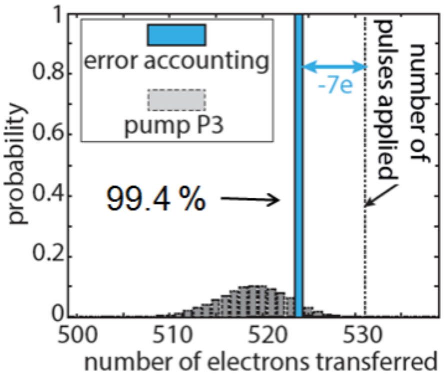

***Figure 20**: Probability distributions of number of electron transferred through the pump array. Grey: distribution of pump P3. Blue: result after applying error accounting, effectively reducing the transfer uncertainty of the single pump by a factor of about 50. From F. Hohls, "Single-electron sources and error accounting towards the new ampere: status of work at PTB", meeting of the TC-EM subcommittee "DC & Quantum Metrology" and Final Dissemination Meeting JRP Qu-Ampere, 27-29 May 2015, Bern (Switzerland).*

Furthermore, the ultimate performance of single-electron error accounting in 'self-referenced' GaAs devices was assessed, including creating an uncertainty budget. The target uncertainty of 0.1 ppm for GaAs pumps driven at 1 GHz corresponds to an error rate of 100 Hz, which is realistically achievable with state of the art devices. Hence, the application of dc-SET single charge detectors with a typical bandwidth of 1 kHz, as used for the study with the results presented above, was chosen for these first experiments. Nevertheless, for further improvements the development of rf-SET detectors with increased bandwidth of about 0.1 MHz will need to be pursued.

3.2.3 Error accounting in SOI-CMOS pumps

In the final phase of the Researcher Excellence Grant work at CEA, on-chip single electron detectors coupled to an SOI pump were implemented and characterised. This development aimed at performing on-chip SET transfer error measurements on SOI pumps. During dc characterisations performed until the end of the grant, it was found that the devices were functional at temperatures down to 100 mK, however they failed under pumping operation. The reasons for this failure were identified, but the remedy required substantial changes in the device layout and fabrication, which could not be completed within the project lifetime.

3.3 Objective 3: Realisation of 'self-referenced' quantum current standards

This research was strongly entangled with the work pursued for objective 2, in detail described in Section 3.2. However, while objective 2 aimed at the provision of error accounting schemes suitable for the realisation of 'self-referenced' single-electron current sources, accomplished by corresponding proof of principle demonstrations, objective 3 aimed further by pursuing the realisation of devices suitable for use as quantum current standards. The latter was a more demanding task since it aimed at accuracy verification by error accounting realised at an accuracy level corresponding to 0.1 ppm uncertainty (for currents at the level of 100 pA, or 1 GHz pumping frequency).

The scheme developed for the in-situ detection of transfer errors in series arrays of several GaAs pumps (Section 3.2) had shown the potential to yield a true 'self-referenced' quantum current standard; however, it was yet only demonstrated at very low currents. Another concept pursued error accounting in GaAs pumps in a 'verification' phase separate from the current generation phase (Section 3.2). This work resulted in the demonstration of part-per-million accuracy verification at higher speed, i.e. corresponding to transfer frequencies of 280 MHz; however still below the GHz frequency level aimed at.

In summary, the advent of a true 'self-referenced' single-electron current standard was accomplished by the development and implementation of promising concepts, but its realisation and establishment in metrology will need more efforts and time. Therefore, this objective was partly achieved.

3.4 Objective 4: Quantum-based amperemeter and current amplification setups

The aim of objective 4 was to develop the instrumentation necessary for measuring single-electron currents of the order of 100 pA at the 0.1 ppm precision level; and also for amplifying these currents by a factor of the order of 10 000. This was needed to provide complementary instrumentation for the high-accuracy verification of SET quantum current sources, not being available before the project start. Two alternative routes of development towards quantum-based amperemeters and current scaling techniques were pursued: the first was the optimisation of existing concepts and setups involving Cryogenic Current Comparators (CCCs) for current amplification; and the second was the completely new development and verification of a non-cryogenic, highly accurate picoammeter. Both concepts aimed at enabling SET-generated current measurements traceable to the Josephson and quantum Hall effects, at an accuracy level exceeding state-of-the-art instruments by more than one order of magnitude.

The key output from this work – at the same time the key result of the whole project – was the first successful prototype demonstration of an SET-based quantum-ampere realisation at an accuracy level corresponding to only 0.2 ppm of uncertainty, better than the best realisation of the ampere within the present SI (Section 3.5). This objective was fully achieved.

3.4.1 CCC-based current amplifier setups

This work was aiming at the development and optimisation of CCC-based amperemeters and current scaling techniques with high current amplification gains of the order of 10 000.

Initially the work concentrated on the optimisation of an existing CCC system with a maximum winding ratio of 20 000:1 (i.e. maximum current gain = 20 000) that was installed in a dilution refrigerator. This system was operated with internal feedback mode (IFM) of the superconducting quantum inference device (SQUID) null-detector, which meant the CCC gain of about $3.1 \cdot 10^8$ V/A needed independent calibration. The sensitivity of this CCC was 26.2 µA·turns/Φ_0, and the white noise level was about 7 fA/√Hz with a 1/*f*-noise corner at 0.3 Hz. This CCC amplifier was used in measurement campaigns on SOI pumps from CEA. However, unrecoverable problems with the CCC appeared (degradation of the toroidal superconducting shield).

Therefore, the fabrication, installation and characterisation of a new 30 000:1 CCC current amplifier system in a dilution refrigerator was initiated and performed (Figure 21). This new system had impressive features, excelling the formerly used 20 000:1 CCC system: the sensitivity was about 9.4 µA·turns/Φ_0, and its gain was about $1.45 \cdot 10^9$ V/A. The white noise level was about 2 fA/√Hz within the frequency band from 1 Hz to 350 Hz, with a 1/*f*-noise corner below 1 Hz (in external feedback mode, see Figure 22).

Extensive analytical simulations were performed on the frequency dependence of the CCC performance. The results from these simulations confirmed qualitative estimates on the self-resonance frequency caused by L-C-oscillations in the CCC windings. Also, the frequency induced error was estimated to be about 0.01 ppm at 0.3 Hz (for winding ratio 30 000:1).

This work included cooperation between two of the project partners. Through guest working visits, CCC experts from one of the partner NMIs consulted the other on the use of an advanced stabilisation method implemented in the electronics for the SQUID null-detector (‘internal wide-band feedback’) and also on the optimisation of the CCC operation in external feedback mode.

Figure 21: *Elements of the 30 000:1 CCC current amplifier system developed within the JRP: CCC torus with lead shield (top left), installation of the CCC torus and SQUID (bottom left) in the dilution refrigerator (bottom right).*

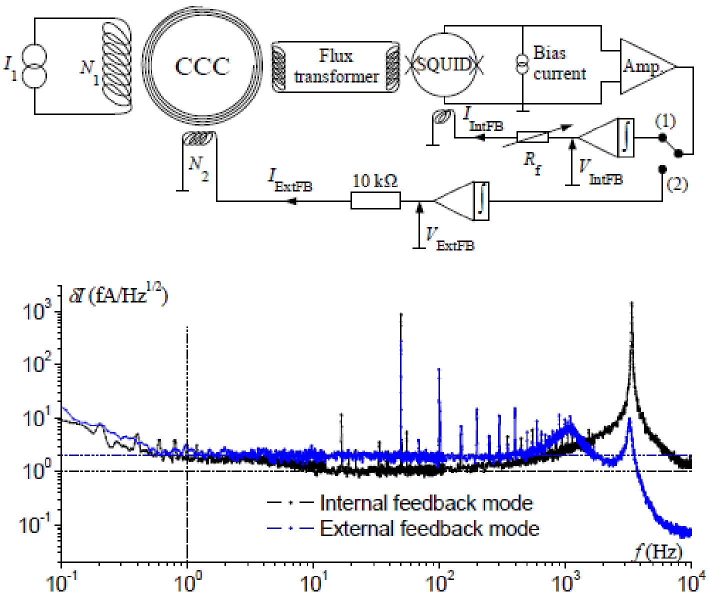

Figure 22: *Top: Simplified block diagram of the CCC operated in (1) internal feedback mode, and (2) external feedback mode. Bottom: Current resolution (current PSD) with SQUID null-detector operated in the two feedback modes working modes (3 windings of each 10^4 turns connected in series).*

Pictures from T. Charron et al., "LNE contribution to the JRP Quantum Ampere", meeting of the TC-EM subcommittee "DC & Quantum Metrology" and Final Dissemination Meeting JRP Qu-Ampere, 27-29 May 2015, Bern (Switzerland).

3.4.2 A new modular & mobile quantum amperemeter

Complementary, and alternative, to the development of a CCC-based amperemeter setup installed in a fixed refrigerator setup, one of the other partners pursued the development of an easy to transport and easy to handle “single box” high-precision picoamperemeter suitable for operation at room temperature. The resulting novel Ultrastable Low Noise Current Amplifier (ULCA), based on conventional electronics, is a non-cryogenic table-top instrument with unparalleled performance and stability features (patents pending). In its original use as a picoammeter, the ULCA represents a dual-stage current-to-voltage converter (transimpedance amplifier) with an effective transresistance of 1 GΩ. A binary CCC setup, also developed by the same partner within the project, was used to calibrate the transfer coefficient of the ULCA (its transresistance) traceable to the quantum Hall effect. The total uncertainty of this calibration is better than 0.1 ppm. The ULCA’s versatility also allows the traceable generation of small currents and the calibration of high-value resistors.

Key features of the ULCA in the standard variant are its low noise of 2.4 fA/√Hz with a very low 1/*f*-corner of about 1 mHz (Figure 23). The ULCA’s transresistance is highly stable versus time, temperature and input current amplitude within the full dynamic range of ±5 nA. Within one week after calibration, the transresistance uncertainty due to short-term fluctuations is about 0.1 ppm, and the long-term drift is better than 5 ppm per year. The input impedance of the ULCA is about 1 Ω and its temperature coefficient is typically less than 0.2 ppm/K; temperature effects can be corrected by an internal temperature sensor.

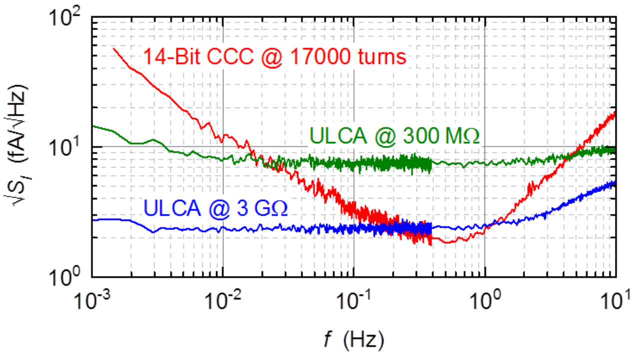

***Figure 23**: Left side: Photographs of a dual-channel ULCA prototype with copper housing and SMA connectors. Right side: Input current noise of two ULCA variants (3 GΩ and 300 MΩ total transresistance) in comparison with the noise of PTB’s 14-bit CCC (input coil with 17 000 turns).*

A special feature of the ULCA is that its transresistance can be directly calibrated with a CCC, providing traceability to national standards. At PTB, the calibration is performed with a state of the art resistance bridge involving a 14-bit CCC developed within the project (Figure 24). The comparator comprises 20 separate windings (2^0 to 2^{13} turns) with in total 18 276 turns. The noise level at 0.05 Hz is 5 fA/√Hz (Figure 25). The calibration of the ULCA transresistance is done in two steps, and a total uncertainty of 0.06 ppm is routinely achieved.

Extensive tests and characterisation measurements have proven that the ULCA provides a hitherto unrivalled accuracy, even when compared to the best sub-nA current measurements reported so far. Within an averaging time of about one day, a total measurement uncertainty of 0.1 ppm is feasible for a current of 100 pA. The accuracy of commercial instruments is, thus, outperformed by about two orders of magnitude.

The ULCA performance was also verified by a comparison with the to-date state of the art method for high precision current generation, i.e. employing pA currents generated by the voltage-ramp-to-capacitor method. It was confirmed that the achievable uncertainty of the ULCA at pA current levels is substantially lower than that of the capacitor charging method. Also, the effect of the frequency dependence of the capacitors involved and limiting the accuracy of this method was investigated.

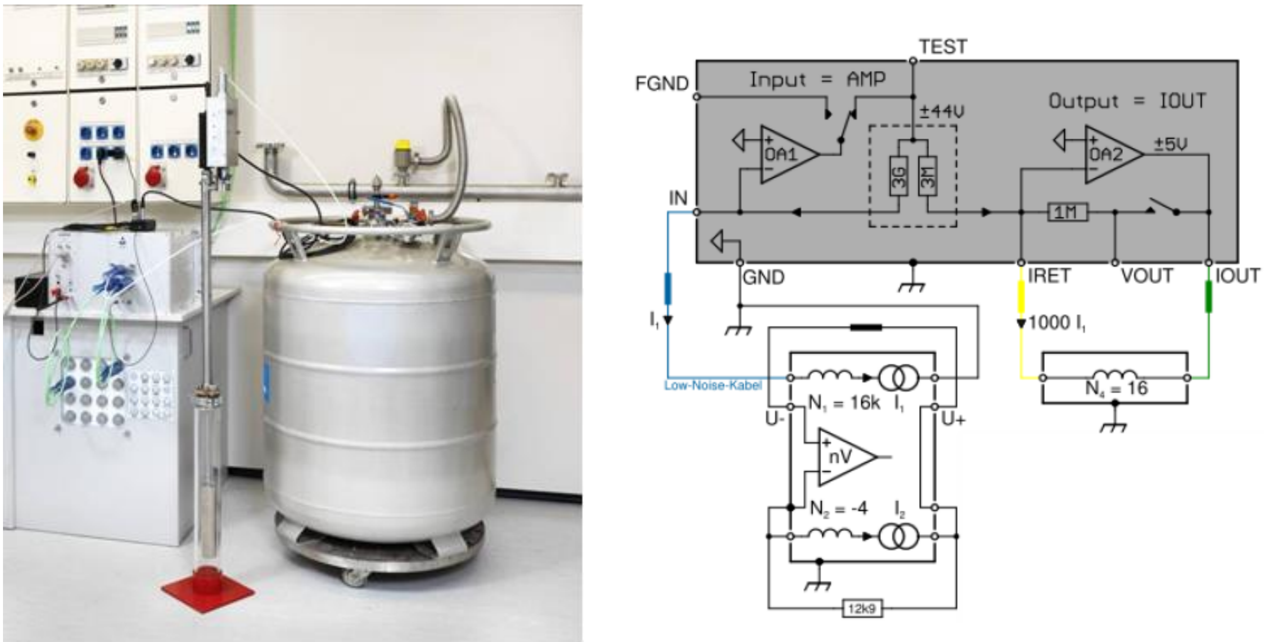

Figure 24*: CCC resistance bridge setup at PTB (left side) and scheme of the calibration of an ULCA (input stage with a 3-GΩ/3-MΩ resistor network) with the 14-bit CCC (right side). From M. Götz et al., "Use of Binary CCCs for the Calibration of ULCAs", meeting of the TC-EM subcommittee "DC & Quantum Metrology" and Final Dissemination Meeting JRP Qu-Ampere, 27-29 May 2015, Bern (Switzerland).*

A further example of the excellent partner cooperation during this project was the validation of the ULCA as a travelling standard for small direct currents. An interlaboratory comparison of the small-current generation and measurement capabilities at three of the partner NMIs was performed using the ULCA as travelling standard (**Error! Reference source not found.**Figure 25). Various measurements at direct currents ranging between 0.16 nA and 13 nA were done to verify the degree of agreement between these three NMIs. Consistency of the results was found well within 1 ppm, which is a factor of ten better than the best comparisons in this field ever performed before. The results from this comparison were a consequence of the superior stability properties of the ULCA, in particular regarding its excellent performance as a travelling standard for small electric currents. In particular, the investigations helped to improve the small-current experimental setups at two of the NMIs, e.g. at one NMI, scientists discovered and quantified short-term instabilities of commercially available high-value thick-film standard resistors, which was useful information for the resistance metrology community.

In conclusion, the superior ULCA instrument is setting new benchmarks and is considered to become a new cornerstone in metrology and calibration applications dealing with small currents. Using the ULCA as travelling standard also enables interlaboratory comparisons of SET pumps at highest accuracy, valuable for universality tests towards the implementation of true SET-based quantum current standards.

Within the lifetime of the project, the commercialisation of the instrument was initiated by the German NMI PTB. This resulted in a license agreement with a German SME instrumentation manufacturer and corresponding know-how-transfer activities from PTB to that company.

An on-site application of the ULCA at PTB regarding the first successful prototype demonstration of an SET-based quantum-ampere realisation is presented in the following section.

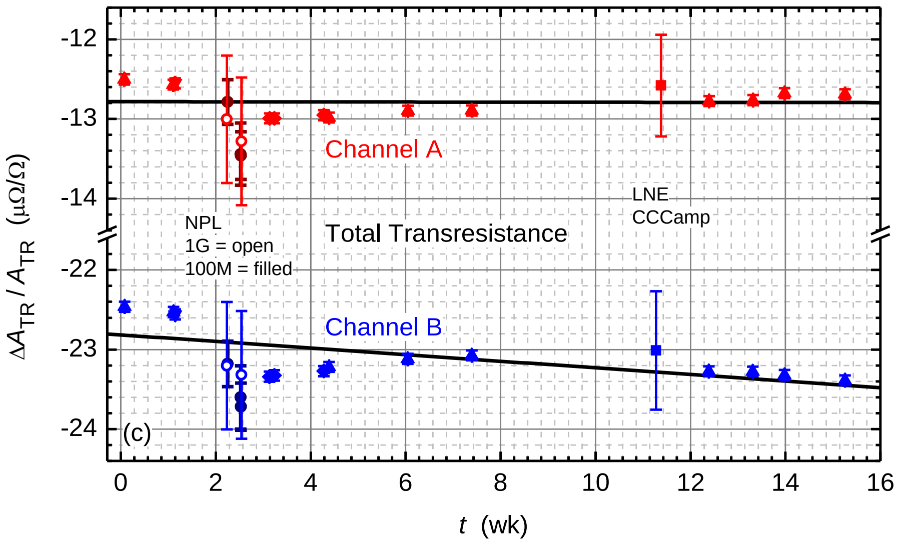

Figure 25*: Calibration values for transresistances A_{TR} of two ULCA channels A and B performed at three different sites (NMIs). Shown is the relative deviation of A_{TR} from the nominal value of 1 GΩ versus time. Error bars show total standard uncertainties. Directly before and after each shipment, the ULCA was calibrated with the 14-bit CCC at PTB (points with small error bars). Measurements at NPL (calibration via NPL's 100 MΩ and 1 GΩ standard resistors) were performed between weeks 2 and 3. Calibrations at LNE via LNE's CCC-based current amplifier were performed between weeks 11 and 12. Solid lines are linear fits through the PTB calibrations. From D. Drung, "Ultrastable Low-Noise Current Amplifier: A Novel Concept For Small Direct Currents", meeting of the TC-EM subcommittee "DC & Quantum Metrology" and Final Dissemination Meeting JRP Qu-Ampere, 27-29 May 2015, Bern (Switzerland).*

3.5 Project key result: Accuracy verification by direct current measurements on GaAs pumps

This work performed at PTB brought together the GaAs tunable barrier pump devices presented in Section 3.1.1 and the ULCA picoammeter presented in Section 3.4.2. Its result was the validation of SET-generated currents with pump frequencies up to 1 GHz at an accuracy level of few parts in 10 million, accomplished by direct current measurement traceable to the electrical quantum effects (Josephson- and quantum-Hall effect).

High-accuracy current measurements with a dual-channel ULCA were performed on a GaAs pump driven with a rf signal with tailored waveform, applied to the entrance gate (shaped-waveform single-gate drive) at repetition frequency $f = 545$ MHz ($I = e{\cdot}f \approx 87$ pA). The excellent performance features of the ULCA, in particular its temporal gain stability, enabled stable measurements of the pump current in the current plateau region over a period of one week (Figure 26**Error! Reference source not found.**). Combined (statistical and systematic) standard uncertainties of down to 0.6 ppm per point were achieved.

The measured values in the plateau region were then averaged. Two different criteria were applied for the definition of the 'plateau region', corresponding to the regions in the dashed boxes denoted (i) and (ii) in **Error! Reference source not found.**. Independent of these criteria, the averaged currents determined were well consistent with $e{\cdot}f$ with their total standard uncertainties of 0.2 ppm (figure based on uncertainty budget developed for these measurements).

A similar experiment was performed on another GaAs pump device, driven at higher pump frequency $f = 1$ GHz ($I = e{\cdot}f \approx 160$ pA). This experiment revealed a significant slope in the plateau region of pump current, which prohibited performing a similar averaging analysis as for the previously presented measurement. However, the inflection point in the plateau region was consistent with $I = e{\cdot}f$ at an uncertainty level of about 0.3 ppm.

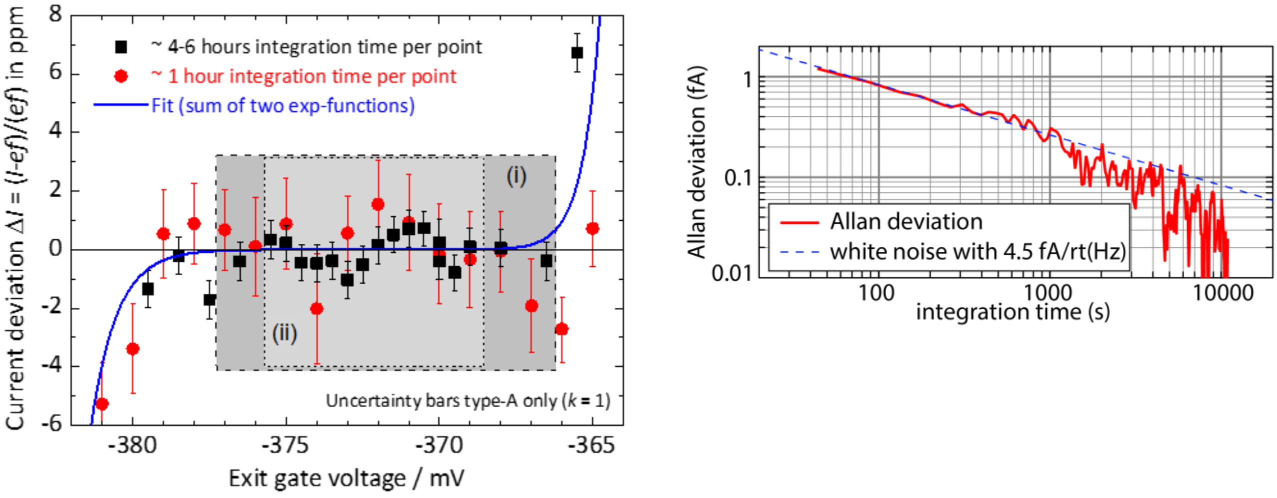

***Figure 26**: Left panel: Two sets of pump current measurements performed with the dual-channel ULCA on a GaAs pump driven at $f = 545$ MHz ($I = e{\cdot}f \approx 87$ pA). Error bars correspond to statistical (type-A) uncertainties only. The blue line results from a model fit. Right panel: Allan deviation of the current measurement data. The dashed line shows white noise with 4.5 fA/√Hz.*

Regarding the accuracy achieved, these results represents the world-record for SET current source validation at a current level of 100 pA, and excels former best results by about a factor of 5. This is the best quantum ampere realisation so far, demonstrated in accordance with the existing draft of the *Mise en Pratique*. In particular, the uncertainty achieved in this prototype experiment is better than the best 'classical' ampere realisation within the present SI: such realisation had been possible (but, to our knowledge, never was realised) indirectly by combining 'non-quantum' SI realisations for resistance and voltage, as there are: i) the realisation of the Ohm via the Thompson-Lampard calculable capacitor, demonstrated with a total uncertainty of 0.02 ppm, and ii) realisations of the volt via a mercury electrometer or via a voltage balance, both demonstrated with total uncertainties of 0.27 ppm, which also limits the achievable accuracy for this indirect SI ampere realisation.

The uncertainty budget developed showed that further enhancement of the accuracy to 0.1 ppm is possible (a calibration uncertainty of the ULCA of 0.06 ppm can be reached at best). Reaching this accuracy level will require further reducing i) type-A (statistical) contributions by considerably longer measurement times (in principle limited by sample stability), and ii) also reducing type-B uncertainty contributions from the voltage measurements.

3.6 Conclusions

The main conclusions from the project work are presented. First, an illustration on the progress in SET current generation accuracy over the last two decades highlights the state of the art advances created by the project. The next following section conclusively reflects on the potential use of SET devices for quantum current standards, and on their perspectives for their future applications in metrology, taking into account the findings from the work accomplished in the project.

3.6.1 Advancement in current generation accuracy with SET current source devices

Figure 27 shows a plot of the relative accuracy achieved in current generation with different kinds of SET devices versus time over the past two decades. The device kinds comprise GaAs pumps, hybrid turnstiles and silicon-based devices (all three kinds further optimised within the project), as well as surface acoustic wave devices (abandoned before the project because of insufficient potential for accuracy improvement).

The most recent results from 2015 (pink and red arrows) were achieved within this project. This is the work using a silicon –based device from NTT, measured at NPL (in the figure denoted “NTT/NPL”), and a work on GaAs pumps from PTB[5] (denoted “Stein”). This highlights the significant scientific impact of the project.

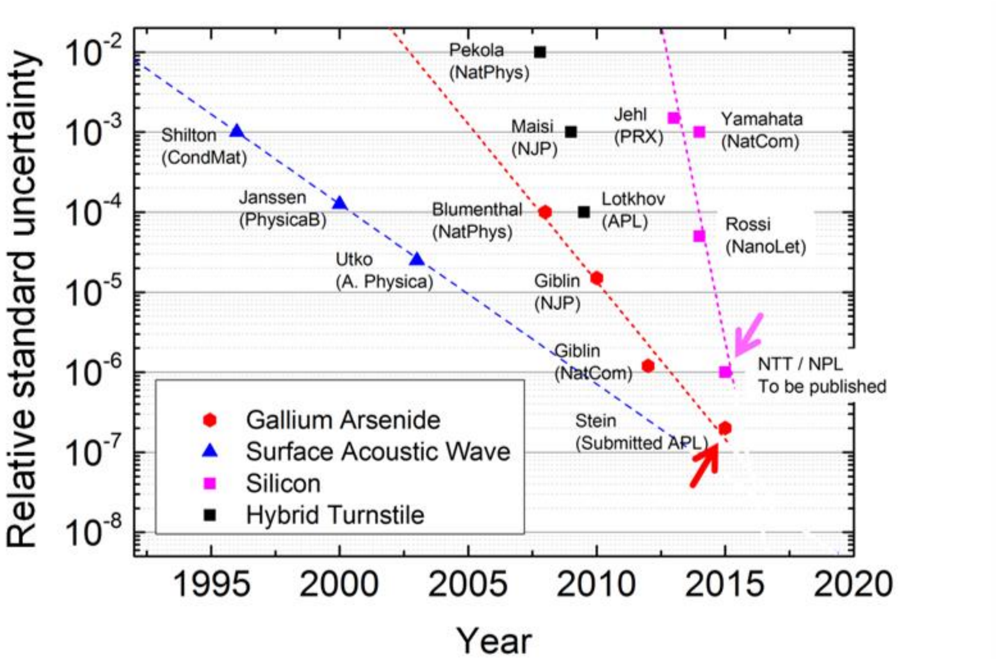

Figure 27*: “Moores-Law”-alike plot of the relative accuracy achieved in current generation with different kinds of SET devices versus time over the past two decades. First author names and journals for according publications are given by the labels. Arrows indicate results from work fully or partly conducted in the frame of the JRP. Figure provided courtesy of S. P. Giblin and J. T. Janssen (NPL).*

3.6.2 On the use of quantum current standards and the perspectives for their future applications in metrology

The most promising and well known types of SET devices considered suitable for future applications in metrology, in particular for the future SET-based realisation of the ampere, are

- SET pumps made from GaAs-based heterostructures with electrostatic gate structures,
- Hybrid turnstile devices made from superconductor-insulator-normal-insulator-superconductor (SINIS) structures; and
- Silicon-based devices made from silicon-on-insulator (SOI) material, or from electrostatically gated silicon

Common beneficial features of all these kinds of devices are that

- they can be driven by a single rf-gate (enhancing the ease of operation),
- their fabrication technologies allows the realisation of parallel and series arrays (for increasing the output current, or enhancing accuracy); and
- they can be driven at high frequencies up to the GHz range (for reaching the required current level of 100 pA at least).

Among these three kinds, GaAs-based SET pumps are to date considered the most advanced and best studied devices with respect to their future application as quantum current standards. On-chip integration with error accounting schemes already was demonstrated within this project. This allowed quantification of

[5] F. Stein *et al.*, “Validation of a quantized-current source with 0.2 ppm uncertainty”, submitted to Appl. Phys. Lett (2015), http://arxiv.org/abs/1506.05965)

statistical transfer errors in GaAs pumps, with preliminary results that confirmed a 1 ppm transfer accuracy. Also, the theoretical understanding of the single-electron transport and error processes in these devices is quite advanced. However, there are indications from investigations done that the current accuracy at pumping frequencies exceeding about 0.5 GHz abruptly deteriorates for typical samples. This point needs further investigations, which are – besides applying error accounting methods – for instance possible by current measurements in the current plateau region with the new ULCA picoammeter at an accuracy level of few parts in 10 million.

The theoretical understanding of error mechanisms in SINIS hybrid turnstiles improved largely during the lifetime of the project. It was found that careful device layout and rf filtering was needed to suppress the dominant error processes sufficiently. However, the transport in SINIS turnstiles relies on quantum tunnelling, with the consequence that the statistics of the physical effects involved do not allow pumping frequencies beyond about 100 MHz for the required accuracy margins. For a future quantum current standard, this would require the SINIS turnstiles to be arranged and operated in parallel arrays, which was also pursued within this project.

Silicon-based SET devices offer the advantage of very small structure sizes, and thus, very high Coulomb energy. This leads to enlarged quantisation effects and enables operating these devices at temperatures in the range of a few Kelvin, i.e. under relaxed demands on operating temperature. Also, current quantisation at very high pumping frequencies of up to several GHz (corresponding to 1 nA of current) has already been demonstrated in the project. However, the fabrication technology is very demanding and required the involvement of industry-grade fabrication lines, i.e. state of the art process techniques from semiconductor industry. Since this automatically provides compatibility with CMOS techniques, the integration of silicon-based SET devices on-chip with CMOS electronic components is highly facilitated. Besides the possible integration of advanced error accounting schemes on-chip, this offers completely new perspectives, for instances realising rf drive components on-chip together with the SET pump. In the project, a successful example for the latter was given: fabrication and operation of integrated ring oscillator circuits for the pump drive, functional at low temperature, was accomplished. In summary, the potential of silicon-based SET devices for applications in metrology is considered very high.

A very important practical point regarding the perspectives of SET-based quantum current standards for metrology is the question of accuracy verification or quantification, respectively. For a practical application of SET devices as quantum current standards, guidelines will be needed which describe the proper preparation of the SET device. This means the tuning of its working point with respect to external control parameters together with measureable criteria which – after fulfillment – ensure current quantisation within certain margins. As an example from contemporary electrical quantum metrology, such guidelines exist and are applied for the quantum Hall resistance: they exactly describe which parameters have to be measured in what manner; and which criteria have to be fulfilled in order to ensure resistance quantisation.

One of the targets of the project was the development of a ‘rapid characterisation procedure’ which would enable the prediction of the accuracy of a given sample of SET pump from a series of quick measurements. It was envisaged that a theoretical model would be developed which could be fitted to data, thus predicting the pump accuracy without the need for high-resolution current measurements. As more high-resolution data have accumulated during the project lifetime, it became clear that the initial target was based on naïve assumptions: even SET pumps fabricated with nominally identical processes display a rich variety of behaviour, especially when driven fast ($f >$ about 500 MHz) to generate high currents. Advances in theoretical understanding have been made throughout the project, but no single theoretical model applies to all samples of pump over the whole range of drive frequencies. Most importantly, comparisons between high-precision data and rapid characterisation data show that the rapid characterisation data are a poor predictor of the true accuracy, no matter which theoretical model is used. Rapid characterisation can be used to eliminate bad samples of pump, but it cannot guarantee accurate operation (in particular when aiming at better than 1 ppm accuracy). Therefore - with the pumps in their current stage of development - such procedure is not considered appropriate for a future *Mise en Pratique*. In order to quantify and ensure current accuracy, other methods have to be applied which rely on high-precision measurements of the pump current. Based on the results presented in Section 3.8 of this report, three possible routes are envisaged:

1. **High-precision measurements of the plateau flatness**. By analogy with the quantum Hall effect, it can be argued that if the current is invariant when a control parameter is changed, it must be exactly quantised. Thus, high-resolution measurements of the pump current (for instance performed by the ULCA) as a function of control parameters could be used to ensure quantisation accuracy. The

measurements would have to be with respect to a reference current, with the requirement that this reference be stable over the time-scale of the measurement to the desired accuracy. However, the reference current does not need to be accurately calibrated – i.e high precision but not accuracy is required. If this procedure was followed, and the current indeed found to be invariant in the control parameters, the pump current would be assumed equal to $e{\cdot}f$ exactly.

2. **Dual-phase electron counting**. This technique exploits the ability to count electrons one at a time using on-chip charge detectors. For this, the pump is operated in two modes (two consecutive phases): in the counting mode, the electrons loaded into the pump island are counted one at a time, with the pump running at a low repetition rate constrained by the time required for the charge detector to resolve the electrons with sufficient fidelity. In pumping mode, the repetition rate is increased to generate the reference current.
3. ***In-situ* counting of single-electron transfer errors**. Instead of counting electrons in the pump in a preliminary counting phase (Method 2), here only the failure events in the single-electron transfer are counted in real time while the pump is generating the reference current. As demonstrated during the JRP, it is possible to count failure events occurring during the single-electron passage through a series array of pumps if suitable on-chip charge detectors are used. The current generated by the pump can then be corrected for these errors accounted.

Method 1 is limited by the long averaging times required to resolve the small pump currents to sufficient precision. With a pump generating 100 pA, averaging times of order 10 hours are required to resolve the current to 0.1 ppm. Such characterisation would require measuring the current at several values of the pump operating points, requiring several days. Obviously, if pumps were developed which could generate nA-level currents, the averaging times would be much shorter and this type of characterisation would become more practical.

Method 2 relies on counting, with the advantage of employing a relatively simple single-electron detector circuit. 1 ppm counting accuracy has already been demonstrated using this method in the project. However, it demands the assumption that pump dynamics are the same during the pumping and counting phases of pump operation. It also suffers from an averaging time constraint during the counting phase, and times of a few hours are likely to be required. In contrast to Method 1, however, the counting only needs to be performed at one value of the operating parameters.

The *in-situ* error counting Method 3 is similar to Method 2, but the pump errors are not quantified in a separate ‘counting’ phase, but counted in real time during reference current generation. This method benefits from the fact that the error events occur at much slower rate than the electron transfer rate. It has the advantage that the validation of pump current accuracy is more reliable than in Method 2 since no crucial assumptions on temporal stability between current generation and validation phases have to be made. Also, in principle it can validate the pump accuracy much faster, on a time-scale of minutes instead of hours, independently of the pump output current. A more fundamental advantage of this method is that, because errors are accounted for in real time, the pumps no longer need to be error-free, which relaxes the constraints on device fabrication. However these advantages come at the expense of considerable circuit and fabrication process complexity. The principle of error accounting while pumping slowly has been successfully demonstrated during the project. Error accounting at realistically fast pumping speeds, however, requires the solution of a number of engineering challenges. This has yet to be realised; however, these challenges are considered solvable. In summary, applying *in-situ* error accounting is considered the most rigorous way towards the implementation of single-electron current standards.

The general advantage of ‘counting methods’ over methods based on ‘measuring’ is also be pointed out by the following quote from *Galileo Galilei*:

*“**Count what is countable**,*
measure what is measurable,
and what is not measurable, make measurable.”

Prototype ampere realisations developed within the project have demonstrated uncertainties on par with those achievable via the present electro-mechanical definition. Operating a single-electron pump is technically challenging, but the level of the challenges (and the man-power required to solve them) are less than those required to construct and operate, for example, an electro-mechanical balance to realise the ampere according to its present ‘classical’ definition. Furthermore, the cryogenic infrastructure required to operate electron pumps is already present in many NMIs. Thus, in their current stage of development, electrons pumps are considered competitive candidates for primary realisations of the ampere.

4 Actual and potential impact

Metrology achievements and impact beyond the end of the project

Due to the fundamental nature of the project – to support the implementation of capabilities and methodologies for the realisation and dissemination of an SI unit definition – the key impact is in fundamental metrology. In particular, with respect to the forthcoming new SI unit definitions, the impact will be an improved basis for new SI ampere and other electrical units derived from the ampere. However, during the project lifetime the implementation of the SI redefinition by CIPM has been postponed until 2018. Therefore, and due to the rapid progress in the field also promoted by the project work, concrete impact on corresponding high-level metrology regulations and directives (as, for instance, the *Mise en Pratique for the ampere and other electric units in the International System of Units*) did not occur during the project lifetime. The scientific achievements of the project, presented in detail in Section 3, are highly significant for the implementation of capabilities and methodologies towards the realisation and dissemination of the future ampere unit definition in the re-defined SI.

The project research has led to a path-breaking conclusion on SET devices regarding their use as quantum current standards: there is no 'rapid characterisation' procedure which enables the prediction of accuracy of a given sample of SET pumps from a series of quick measurements. Instead, for realising future SET current standards reaching uncertainties of 0.1 ppm and better, on-chip error accounting strategies, as pioneered by this project, will have to be applied. This is in accordance with a classical quote from *Galileo Galilei*: *"Count what is countable, measure what is measurable, and what is not measurable, make measurable."*

Further significant tangible impact has already arisen from the new instrumentation, invented and developed within the project: The ULCA is a superior tool for highly precise traceable measurement and generation of small currents. With its excellent features, the ULCA sets new benchmarks, and is expected to become a new cornerstone in metrology and calibration applications dealing with small currents, including high resistance calibrations.

Other significant achievements of the project are the development and application of concepts for on-chip single-electron error accounting in SINIS hybrid turnstile devices and the application and verification of GaAs tuneable barrier pumps at output currents of 100 pA and higher, with accuracy verification at an uncertainty level of down to 0.2 part per million (yielding a quantum ampere prototype demonstration according to the existing draft for the *mise en pratique* for the ampere). Together with the UCLA, these achievements are highly significant for the implementation of capabilities and methodologies towards the realisation and dissemination of the future ampere unit definition in the re-defined SI. Following the pending SI re-definition, the need for the supply of quantum current standards devices is expected. To meet this demand, the consortium is now exploring the possibility of providing a supply of single-electron current standard devices.

Altogether, the research conducted on the accuracy verification of SET pumps currents brought the consortium to the world-wide lead in this field.

Fundamental metrological challenges beyond the project are universality tests on quantum electrical phenomena, notably the experimental realisation of quantum metrology triangle, representing a consistency test on the electrical quantum effects. Such experiments have so far delivered results at the part-per-million precision level. The application of the ULCA picoammeter, resulting from the project, has been suggested[6] for a quantum metrology triangle experiment targeting at an enhanced accuracy level of the order of 0.1 ppm.

Dissemination activities and stakeholder engagement

Stakeholders from the high-level metrology community were the bodies and committees of the CIPM and the BIPM, in particular the CCEM and its working groups, NMIs and their Regional Metrology Organisations. Other stakeholders included industry SMEs, such instrumentation producers and calibration service

[6] D. Drung, M. Götz, E. Pesel, H. Scherer, "Improving the Traceable Measurement and Generation of Small Direct Currents", published open-access at IEEE Trans. Instrum. Meas. (2015), http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=7132759

institutes, with strong interests in the project outputs. Key stakeholder engagements throughout the project lifetime were:

- The 28th Meeting of the CCEM in March 2013 at the BIPM in Sèvres/Paris, France where a review talk was given on the progress in the development and application of SET devices.
- The EURAMET DCQM meeting held in Tres Cantos, Madrid, Spain in May 2013. About 50 participants from NMIs, research institutes and academia from Europe and abroad attended the meeting, which was used to disseminate information on the progress and preliminary results of the project via several oral and poster contributions by the project partners.
- The EURAMET TCEM contact person meeting at GUM Warsaw Poland in October 2013 where national progress reports and poster presentations were given and contact persons were informed about the project progress.
- The Annual Meeting of the TC-EM in Ljubljana, Slovenia in October 2014 where relevant contact people from CIPM, BIPM and EURAMET TCs were informed of the project results to date.
- The 29th Meeting of the CCEM in Sèvres/Paris, France in March 2015. Representatives from the project partners' NMIs attended and relevant issues related to the project were discussed and national progress reports were provided.

The final project dissemination meeting was held in line with the EURAMET DCQM experts meeting in Bern, Switzerland in May 2015. This incorporated the main European experts from the field of single-electron devices and their metrological application, representatives from European metrology bodies, and also international scientific experts from countries such as Korea and USA. This meeting allowed the project to address all the major stakeholders.

Further engagement to a wider stakeholder network occurred via scientific journal publications (more than 20 peer-reviewed publications were published during the project lifetime, including a paper published in *Nature Nanotechnology*) and knowledge dissemination during international conferences (more than 70 presentations were given at international conferences). Major conference events were the "*Conference on Precision Electromagnetic Measurements*" 2014, where 10 oral and poster presentations from the project were given; and the "*International Congress of Metrology*", 2013, where the project and its preliminary results were presented by an oral talk given by the project coordinator. Further practical specialist knowledge from particular fields from the project was disseminated during two workshops for external audiences. The first of these was held in France in 2012, on "SQUID in metrology"; and a second on the calibration and measurement capabilities offered by the ULCA held in 2015 in Germany. Throughout the project, dissemination was also made to public media and popular press by several radio interviews, articles in trade journals and public exhibitions.

The impact potential of the project has also been reflected by:

- An article summarising some of the achievements of the project published as a leading story in *Nature* in January 2014 ("*Ampere to get rational redefinition - Single-electron flow measured in bid to overhaul SI base unit*", http://www.nature.com/news/ampere-to-get-rational-redefinition-1.14512)
- PTB researchers being awarded the "*Helmholtz Prize*" (the most significant prize in metrology) in March 2014 for the first experimental demonstration of the concept of a 'self-referenced' single-electron current source, accomplished within the project, (http://www.ptb.de/en/aktuelles/archiv/presseinfos/pi2014/pitext/pi140331.html)

Uptake by end-users and intermediate impact

The project has already created impact on practical sectors, including uptake from calibration services and instrumentation manufacturers interested in the ULCA instrument (considered to be the superior tool for highly precise traceable measurement and generation of small currents). Commercialisation of the instrument has been pursued, resulting in a license agreement with a German SME instrumentation manufacturer. Regarding end user application of the ULCA, first contacts with a large German calibration service company, one of Europe's leading and most modern metrology laboratories have been made; and it is expected that the ULCA will, in the near future, be disseminated within the international community of electrical calibration service providers for small currents and high-value resistors.

During measurements with the ULCA at one of the partner NMIs (Section 3.4.2, **Error! Reference source not found.**), NPL scientists have discovered and quantified short-term instabilities of commercially available high-value thick-film standard resistors. This is useful information for the resistance metrology community and the resistance standard manufacturing sector. Corresponding knowledge will be disseminated.

5 Website address and contact details

The address of the JRP website is: http://www.ptb.de/emrp/qu_ampere.html

The contact person for all questions about SIB07 Qu-Ampere is:

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Email: hansjoerg.scherer@ptb.de

6 List of publications

Peer-reviewed publications (status 30 April 2015):

1. M. Wulf
Error accounting algorithm for electron counting experiments
Phys. Rev. B, Vol. 87, 035312 (2013)
http://dx.doi.org/10.1103/PhysRevB.87.035312

2. L. Fricke, M. Wulf, B. Kaestner, V. Kashcheyevs, J. Timoshenko, P. Nazarov, F. Hohls, Ph. Mirovsky, B. Mackrodt, R. Dolata, Th. Weimann, K. Pierz, H. W. Schumacher
Counting Statistics for Electron Capture in a Dynamic Quantum Dot
Phys. Rev. Lett., Vol. 110, 126803 (2013)
http://dx.doi.org/10.1103/PhysRevLett.110.126803

3. X. Jehl, B. Voisin, T. Charron, P. Clapera, S. Ray, B. Roche, M. Sanquer, S. Djordjevic, L. Devoille, R. Wacquez, M. Vinet
Hybrid Metal-Semiconductor Electron Pump for Quantum Metrology
Phys. Rev. X, Vol. 3, 021012 (2013)
http://dx.doi.org/10.1103/PhysRevX.3.021012

4. P. Mirovsky, L. Fricke, F. Hohls, B. Kaestner, Ch. Leicht, K. Pierz, J. Melcher, H. W. Schumacher
Towards quantized current arbitrary waveform synthesis
J. Appl. Phys., Vol. 113, 213704 (2013)
http://dx.doi.org/10.1063/1.4807929

5. L. Fricke, M. Wulf, B. Kaestner, F. Hohls, Ph. Mirovsky, B. Mackrodt, R. Dolata, Th. Weimann, K. Pierz, U. Siegner, H. W. Schumacher
Self-referenced single-electron quantized current source
Phys. Rev. Lett., Vol. 112, 226803 (2014)
http://dx.doi.org/10.1103/PhysRevLett.112.226803

6. H. Scherer, S. P. Giblin, X. Jehl, A. Manninen, F. Piquemal, D. A. Ritchie
Introducing Joint Research Project «Quantum Ampere» for the realisation of the new SI ampere
Online publication in EPJ Web of Conferences (2014):
http://dx.doi.org/10.1051/epjconf/20147700004

7. P. Clapera, S. Ray, X. Jehl, M. Sanquer, A. Valentian, S. Barraud
A quantum nanoelectronic device driven by on-chip CMOS circuit
Online publication in IEEE (2014):
http://dx.doi.org/10.1109/WOLTE.2014.6881029

8. N. Ubbelohde, F. Hohls, V. Kashcheyevs, T. Wagner, L. Fricke, B. Kästner, K. Pierz, H. W. Schumacher, R. J. Haug
Partitioning of on-demand electron pairs
Nat. Nanotechnol. (01 Dec 2014):
http://www.nature.com/nnano/journal/vaop/ncurrent/full/nnano.2014.275.html

9. E. Mykkänen
Traceable measurement for a quantum current source
MSc Thesis, Aalto University, December 2013
urn:NBN:fi:aalto-201312198152
https://aaltodoc.aalto.fi/handle/123456789/11882

10. F. Piquemal
Métrologie électrique quantique: de l'impédance du vide à la charge élémentaire
Habilitation thesis, Ecole Normal Supérieur de l'ENS Cachan, April 2013

11. F. Rengnez, O. Seron, L. Devoille, D. Placko, F. Piquemal
A femto ampere current amplifier based on a 30 000:1 cryogenic current comparator
Conference on Precision Electromagnetic Measurements (CPEM) Digest 2014, IEEE Catalog Number: CFP14PEM-CDR, ISBN: 978-1-4799-2478-3, pages 296-297
http://dx.doi.org/10.1109/CPEM.2014.6898376

12. T. Charron, L. Devoille, S. Djordjevic, O. Seron, F. Piquemal, P. Clapera, S. J. Ray, X. Jehl, R. Wacquez, M. Vinet
Characterization of hybrid metal/semiconductor electron pumps for quantum metrology
Conference on Precision Electromagnetic Measurements (CPEM) Digest 2014, IEEE Catalog Number: CFP14PEM-CDR, ISBN: 978-1-4799-2478-3, pages 442-443
http://dx.doi.org/10.1109/CPEM.2014.6898449

13. S. J. Ray, P. Clapera, X. Jehl, T. Charron, S. Djordjevic, L. Devoille, E. Potanina, G. Barinovs, V. Kashcheyevs
Modeling of an adiabatic tunable-barrier electron pump
Conference on Precision Electromagnetic Measurements (CPEM) Digest 2014, IEEE Catalog Number: CFP14PEM-CDR, ISBN: 978-1-4799-2478-3, pages 446-447
http://dx.doi.org/10.1109/CPEM.2014.6898451

14. D. Drung, Ch. Krause, U. Becker, H. Scherer, F. J. Ahlers
Ultrastable Low-Noise Current Amplifier
Conference on Precision Electromagnetic Measurements (CPEM) Digest 2014, IEEE Catalog Number: CFP14PEM-CDR, ISBN: 978-1-4799-2478-3, pages 656-657
http://dx.doi.org/10.1109/CPEM.2014.6898556

15. H. Scherer, G.-D. Willenberg, D. Drung, M. Götz, E. Pesel
Traceable precision generation and measurement of pA direct currents
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