Final Publishable JRP Summary for SIB07 Qu-Ampere
"Quantum ampere: Realisation of the new SI ampere"

Overview

Electric current, measured in the unit ampere, is the flow of electrons, each carrying the elementary charge *e*. The impending revision of the international system of units (SI) will base the ampere definition on a fixed value of *e*. The realisation of this new unit definition needs: i) methods and devices enabling the controlled, clocked transport of single electrons at frequency *f* (so-called single-electron pumps or turnstiles); and ii) instrumentation enabling highly accurate amplification and measurement of the so-generated currents.

This project has developed highly accurate single-electron pump devices and instrumentation, beyond the state of the art, for providing the practical means for a future realisation of the quantum-based unit of electric current.

Need for the project

According to the "*Mise en pratique for the ampere and other electric units in the International System of Units*" (CCEM/09-05), a possible way for realising the new quantum-based ampere definition is given by applying Single-Electron Transport (SET) devices, which allow the clocked transfer of single charge quanta.

SET devices are considered the 'silver bullet' solution for the new ampere realisation mainly for two reasons:

- SET allows the most direct ampere realisation via the physical definition of current as the electric charge q being transported through the cross section of a conductor per unit of time, $I = \Delta q/\Delta t$, thus exploiting the simple and evident relation $I = e \cdot f$; and
- SET-based ampere realisation involves only one fundamental constant (*e*), whereas alternative indirect ampere realisations based on a combination of Josephson and quantum Hall effects have two (*e* and *h*).

Possible SET-based ampere realisations are, however, subject to two device-related issues:

i) typically, currents sourced by SET quantum current source devices are small (about 100 pA); and
ii) their accuracy is generally limited by statistical errors due to the stochastic nature of the physical transport mechanisms involved;

Hence, validation of SET current sources needs highly accurate, traceable methods for the amplification and measurement of these currents.

The project has addressed these issues to create a complementary set of SET quantum current source devices and related instrumentation, which were not previously available at the required accuracy level of about one part in 10^7.

Scientific and technical objectives

Derived from the needs above, the project addressed four scientific and technical objectives:

1. Realisation of quantum based current sources (pumps and turnstiles) 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 (ppm) or smaller

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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, implemented by integrating the quantum current sources with the advanced error accounting schemes
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.

Results

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

Starting from the most promising concepts for SET current source devices, the project systematically pursued further development of different kinds of SET pumps to enable quantised current sourcing at the required levels of current and accuracy. These were:

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.

Sample fabrication technology for all three kinds of devices was established and optimised at specialised partner sites. Different modes for driving the pumps and turnstiles by radio-frequency (rf) signals up to 1 GHz were investigated with respect to optimisation of the current sourcing performance.

Error mechanisms spoiling the accuracy of the single-electron transport in pump and turnstile devices were studied both theoretically and experimentally, and theoretical models of the transport mechanisms in these devices were developed, with both yielding important clues to further device optimisation.

For the first time ever, functional rf drive electronics integrated on-chip with a pump was demonstrated: CMOS ring oscillators were successfully used for the on-chip generation of rf signals, driving a silicon-on-insulator SET pump at cryogenic temperatures. This represented considerable progress beyond the state of the art, which will highly facilitate the operation of future SET current sources.

The project achievements made on GaAs based pumps and hybrid turnstiles has extended the world-wide lead of the consortium in these fields; and by their innovative developments on SOI-based pump devices, CEA Grenoble has become one of the world-wide leading institutes in this field.

In summary, quantum based current sources on the basis of the three best existing device candidates were developed, fabricated and characterised. 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 have demonstrated current sourcing at the 100 pA level. The targeted relative uncertainty level of 0.1 ppm (as order of magnitude) has been demonstrated experimentally by a direct current measurement with a best result of 0.2 ppm, limited by experimental conditions. Reaching 0.1 ppm is 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 nearly fully achieved.

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

Advanced schemes and concepts for the accuracy verification of the SET current sources were developed and investigated, which enable monitoring the charge transfer at the single-electron level. This was accomplished by ‘error accounting’ circuits fabricated on-chip with the current sources. Due to the particularly challenging nature of this research, different development routes were pursued in parallel by the project, using different combinations of current source device and error detection circuitry and different error accounting strategies.

Error accounting schemes in single-electron transport devices based on GaAs were developed, implemented and investigated, deploying quantum point contacts (QPCs) and metallic SET transistors as single-electron detectors. The main outcome from the research was the first demonstration of part-per-million pump current accuracy, validated on-chip with a QPC detector at high speed corresponding to transfer frequencies of 280 MHz. This best result represented an improvement of at least two orders of magnitude in electron counting accuracy.

Some of the work involved series arrays of several GaAs pumps in combination with SET transistors as single-electron detectors. The main outcome from this research was the first proof of principle of a ‘self-referenced’ SET pump with *in-situ* detection of transfer errors, initially performed at low transfer frequencies. It was demonstrated that this scheme of error accounting can be applied to significantly enhance the accuracy of the current generating pump array; and this work was awarded with the Helmholtz prize, the most significant award in metrology.

Error accounting schemes for hybrid turnstile devices, involving metallic SET transistors as single-electron detectors, were also developed and initial error counting investigations were performed.

In summary, new and advanced concepts for single-electron error accounting in single-electron generating circuits were developed, based on on-chip detection methods and involving different kinds of single-electron charge detectors. They provide the basis for the development of ‘self-referenced’ quantum current standards ultimately targeted at. Thus, the objective was fully achieved.

Objective 3: Realisation of ‘self-referenced’ quantum current standards

This research was strongly entangled with the work pursued for objective 2, but 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. This meant, accuracy verification by error accounting needed to be realised at an accuracy level corresponding to 0.1 ppm uncertainty for currents at the level of 100 pA (1 GHz pumping frequency).

The scheme developed for the *in-situ* detection of transfer errors in series arrays of several GaAs pumps 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. 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, the objective was partly achieved.

Objective 4: Quantum-based amperemeter and current amplification setups

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.

Fabrication and installation of a CCC current amplifier system with a maximum winding (respectively current amplification) ratio of 30 000:1 in a dilution refrigerator was performed. The system characterisation showed impressive performance features (for instance regarding noise), excelling similar systems formerly deployed. Analytical simulations performed on the frequency dependence of the CCC performance showed ways for further possible improvements in the field of CCC-based current amplifiers.

As a complementary and alternative approach to CCC-based amperemeter setups, the development of a highly accurate 'single box' picoamperemeter was pursued based on conventional electronics and suitable for operation at room temperature. This resulted in the innovation of the ULCA (Ultrastable Low-noise Current Amplifier) with unparalleled performance and stability features (patents pending). In its designated original use as a picoammeter, the ULCA represents a dual-stage current-to-voltage converter with an effective transresistance of 1 GΩ. A binary CCC setup was also developed within the project and was used to calibrate the transfer coefficient of the ULCA (the transresistance) traceable to the quantum Hall effect, with an uncertainty better than 0.1 ppm. Due to the excellent performance features, the ULCA can measure a 100 pA current at an accuracy corresponding to 0.1 ppm of relative uncertainty within an averaging time of about one day. Its versatility also allows the traceable generation of small currents and the calibration of high-value resistors. The instrument was successfully validated regarding its applicability as a travelling standard for small direct currents by an interlaboratory comparison. By a direct current measurement performed with the ULCA within the project, the quantisation of a current sourced by an SET pump (driven at $f = 545$ MHz, $e \cdot f \approx 87$ pA) was verified with an unparalleled uncertainty of only 0.2 ppm. This is a 5-fold improvement compared to the state of the art before the project. The experiment represents the first successful prototype demonstration of an SET-based quantum-ampere realisation at an accuracy level, better than the best ampere realisation based on 'classical' (non-quantum) experiments within the present SI.

In conclusion, the superior ULCA instrument is setting new benchmarks and is considered to become a new cornerstone in small-current metrology and calibration. The innovation has brought the German National Metrology Institute (NMI) to the world-wide lead in the field of ultra-accurate small current measurement instrumentation. The objective was fully achieved.

Actual and potential impact

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 institutes, with strong interests in the project outputs.

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 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.

Throughout the project lifetime the project outputs also resulted in three patent applications and one invention report on the ULCA.

Uptake by end-users and early 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.

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. 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.

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 the 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; but the ULCA picoammeter is predestined for application in a quantum metrology triangle experiment at an enhanced accuracy level in the order of 0.1 ppm.

List of publications

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For a full list of publications and *in press* publications please see the SIB07 Final Publishable JRP Report.

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