e-SI-Amp

Publishable Summary for 15SIB08 e-SI-Amp
Quantum realisation of the SI ampere

Overview
Single-electron sources that generate currents by transferring an exact number of electrons per cycle are the most direct methods for the realisation of the new revised ampere. Since they are particularly suited to generate small currents below 1 nA, these sources could enhance metrological capabilities for small current applications. This project developed semiconductor devices and instrumentation technologies which were required to implement direct and practical methods for the realisation of the new ampere, based on the fixed value of the elementary charge i.e. the magnitude of the electric charge carried by a single electron. The project developed high-precision measurement capability for ultra-small currents down to 1 fA and below, which is being used in many other areas of metrology and industrial applications, such as nuclear metrology, gas-particle metrology, semiconductor characterisation, and lighting manufacturing.

Need
Countless electrical measurements are performed as part of device and sensor operations in personal devices (smartphones, tablets, fitness monitors, etc.), medical devices, automotive technology, building management systems, manufacturing, environmental monitoring and security, etc. However, and despite the validity of these measurements relying on a consistent set of electrical standards, in the old International System of Units, SI, which was changed in May 2019, the SI ampere was not realised routinely in National Measurement Institute (NMI) laboratories. This was due to the technical difficulty and the experimental cost involved in its realisation. Instead, the chains of electrical calibration were served by the primary voltage and resistance standards that exploit two quantum effects, the Josephson effect and quantum Hall effect. The traceability to the SI units was maintained indirectly through the agreed values of two constants of proportionality that linked the quantum effects and the electrical units, the volt and the ohm. With the redefinition of the SI units in May 2019, the elementary charge and the Planck constant are fixed, which means volt and ohm can be directly realised by the two quantum effects. However, the ampere lacks a direct method for its realisation.

An electronic device that periodically transfers exactly one electron per cycle would produce an electric current that is equal to the operation frequency multiplied by the value of the elementary charge. Such a “single-electron” current source offers the possibility to directly realise the new ampere, and could serve as a primary standard for electric current. However, for this to become possible, the accuracy of electron transfer must be better than 1 part in 10^7 There are two main issues hampering this: i) accurate measurements are difficult to perform with the small electric currents (~100 pA) produced by single-electron sources are small so it is difficult to perform, and ii) the devices tend to produce higher counts of pump errors if the operation frequency is increased to achieve a larger current. In order to realise single-electron-based quantum current standards, the resolution of small-current measurement technologies must be at the attoampere (10^{-18} A) level. Prior to the start of this project, the best resolution of NMIs’ calibration and measurement capability was limited to several tens of atto-amperes.

For single-electron sources to be trusted as primary ampere standards, their accuracy of operations must be verified, which requires demonstrating their universality, robustness, and reproducibility. Additionally, strict guidelines on how to test/tune the devices need to be developed. Parts of these tests can be performed by comparing the current generated by single-electron sources to a current generated by a measurement system traceable to other quantum standards (by the Josephson and quantum Hall effects). In order to achieve the accuracy required as primary standards, the resolution of this traceable measurement system must be better than 10 aA (for a current of ~ 100 pA) or below, while the accuracy of traceability must be maintained at a level better than 1 part in 10^7.

Objectives

The overall objective of this project was to develop a practical method for the realisation and dissemination of the future SI ampere using semiconductor-based single-electron current sources as primary standards and to develop novel types of portable reference sources as secondary standards.

This project addressed the following scientific and technical objectives:

1. To develop single-electron-based current sources reaching a current level of ≈1 nA with an uncertainty at, or below, 1 part in 10^7. Parallelisation of single-electron sources will be developed and high-frequency operation (above 1 GHz) investigated in order to extend the current level to ≈1 nA. The current quantisation accuracy will also be tested by the consortium's traceable small-current measurement systems.
2. To test the universality, robustness and reproducibility of single-electron-based current sources, which will be used for the practical realisation of the new SI ampere. Long-term stability and invariance in experimental parameters (e.g. RF amplitudes and magnetic fields) will be tested, and inter-device comparisons of current quantisation values performed, with a resolution better than 1 part in 10^7. For this, single-electron sources fabricated both from the same material and from different materials (silicon and gallium arsenide) will be used.
3. To implement high-accuracy current measurement capability across NMIs, suitable for the testing of various types of single-electron devices. Multiple measurement systems, including ultra stable low-noise current amplifiers (ULCA) and null-detectors with calibrated resistors, will be developed and improved for traceable current measurements of single-electron sources (for use as a travelling standard). Multiple reference current sources that, in conjunction, cover a wide range from 1 fA to 10 mA will also be developed. These include a programmable quantum current generator (PQCG) directly realised by Josephson voltage standards and quantum-Hall resistance standards, as well as portable ultra-low DC current sources (ULCS) covering the range 1 fA – 100 pA.
4. To develop guidelines for testing the accuracy of single-electron-based current standards. Towards a *mise en pratique* for the realisation of the new ampere, an agreed method for testing the current-quantisation accuracy will be developed and guidelines published for the verification of single-electron current sources.
5. To facilitate the take up of the technology and measurement infrastructure developed by the project by the measurement supply chain (accredited laboratories, instrumentation manufacturers) and end users (industries where small-current measurements at pico-ampere and femto-ampere levels are required). The consortium will demonstrate to the stakeholders, the calibration of their electrometers using the small-current measurement systems developed in the project and will give training on how to perform these calibrations, e.g. by inviting stakeholders to the partners' laboratories, or at stakeholders' premises using portable systems (the ULCA or ULCS). Some specific stakeholder needs, for example difficulties in making low-activity radiation measurements, have already been identified and will be addressed.

Progress beyond the state of the art

Two previous European metrology research projects, iMERA-Plus T1 J1.3 REUNIAM and EMRP SIB07 Qu-Ampere, contributed to improving the accuracy of single-electron sources to 2 parts in 10^7 at a current level of 90 pA. This project built on this to bring the accuracy of single-electron sources to 1.6 parts in 10^7 with a current level of ~100 pA. The error mechanisms under high-frequency operation were studied and fed back to the device design to maximise the operation frequency. This was used to achieve a current level of ≈1 nA. Comparison tests between different devices of different materials were made for the first time to test the universality, robustness and reproducibility of single-electron current sources. The multiple measurement setups and reference current sources developed in this project have enhanced the overall small-current measurement capability across European NMIs.

Results

Single-electron-based current sources reaching a current level of ≈1 nA with an uncertainty at, or below, 1 part in 10^7

More than 10,000 semiconductor-based (GaAs or Si) single-electron sources in total have been fabricated by the consortium in this project. In addition, ~ 30 single-electron devices have been supplied by collaborators. More than 100 single-electron devices have been characterised at low temperatures (4.2 K and below), and more than 3 iterations of improvement to the device design have been made. Over 20 single-electron devices have been selected and detailed tests of their current quantisation have been carried out. Several devices, including one that facilitates a newly-developed error-correction method, have shown promising results for a flat current-quantisation plateau close to our target of 1 part in 10^7 at a current level of 100 – 160 pA. However, best agreement with the value of the product of the elementary charge and the frequency (*ef)* achieved was 1.6 parts in 10^7, only slightly short of the target uncertainty. The main cause for this limitation was the drift of measurement systems during the long integration time (around 24 hours) required to achieve such uncertainty in this current range (~ 100 pA). A trap-based Si electron pump was demonstrated with a 1 nA current level (> 6 GHz operation). This is a promising technology, although this particular device suffered from a pump error of 2 parts in 10^5. The consortium also produced pump arrays for the multiplication of generated currents and multiplexed pumps for faster device screening in a single cooldown process.

As a result of work developed in this objective, accurate semiconductor-based single-electron sources will become available as candidates for primary standards for the new SI ampere. These devices will produce a current level of ≈1 nA by device parallelisation and/or high frequency (> 1 GHz) operations. The pump error rate will be kept at or below 1 part in 10^7.

Universality, robustness and reproducibility of single-electron-based current sources

More than 10 single-electron current sources have been tested for their accuracy and robustness by measuring their current quantisation at or above 1 GHz, generating an electrical current of 160 pA or larger. A GaAs pump device integrated with a new error-correction gate has shown a current-quantisation plateau flatness at 4 parts in 10^7 (limited by the measurement uncertainty), promising to achieve our target uncertainty of 1 part in 10^7, but this particular device suffered from an offset error of ~ 2 parts in 10^6. The origin of this error is still under investigation. So far, the best accuracy demonstrated is 1.6 parts in 10^7 with a GaAs pump, but the device was operated at 600 MHz (96 pA). For a Si pump, the current quantisation has been tested with roughly 2 parts in 10^7 uncertainty operated at 1 GHz (160 pA). Although the target uncertainty has not been achieved by a small margin, the availability of accurate pumps has been increased through the course of this project, which enabled the consortium to perform universality and reproducibility tests. A direct comparison was made for the currents produced by a GaAs and Si pumps, operated at the same frequency (~800 MHz), and agreement within 2 parts in 10^6 was demonstrated. One Si pump was circulated among three partners, each of whom characterised the device with their own traceable measurement system. Agreement within 1 part in 10^6 was achieved. This device achieved high accuracy pumping at a relatively high temperature of 4.2 K, and also showed good reproducibility after a number of thermal cycles, a promising result for a future primary ampere standard.

A report on single-electron sources was produced at the end of this objective following a series of rigorous tests of their electron transfer performance. This report will be used to gauge the suitability of single-electron sources as primary electrical-current standards and for further improvement in the device performance.

Implementation of high-accuracy current measurement capability across NMIs

In this project, 3 types of instrument were developed to enhance the capability of small current measurements at NMIs, academia and industry: ULCA, PQCG and ULCS. 4 new advanced ULCA variants tailored for special applications were developed, different in stability, gain, noise and other features. The ULCA is a highly stable secondary transimpedance standard (i.e. current to voltage converter) calibrated against SI resistance standards, suited to a wider range of currents (up to 1 µA). The commercialisation of 2 versions of these new ULCAs has been agreed with a manufacturer. ULCAs were distributed within the consortium for on-site comparison and calibration experiments. This activity has improved the small-current measurement capabilities of the partners, and has allowed the partners to engage with stakeholders (see the Impact section). Partners have started to use ULCAs for measurements of single-electron current sources, allowing traceable measurements with uncertainty better than 1 part in 10^6 in laboratories where this was not possible before. In addition, the uncertainty of a small-current measurement system using a 1 GΩ standard resistor has been improved by a factor of 4 to 2 parts in 10^7. A realisation of the new ampere through the quantum Hall resistance and Josephson voltage standards has been demonstrated by a PQCG, and reached the target uncertainty of 1 part in 10^8 in the high current regime (from 1 µA up to 10 mA). This has enabled the calibration of a commercial ammeter in this range with uncertainties below 3 parts in 10^7. The development of the ULCSs, a secondary current standard based on linear voltage ramps applied to a capacitor (traceable to SI impedance, voltage and time units) best suited to very low currents, has also been completed. Comparison studies between PQCG and ULCA, and between ULCS and ULCA have been made, and the target uncertainty at a level of 10^{7} and 10^{-5}, respectively, have been reached.

New small-current measurement systems and reference current sources (ULCA, PQCG, and ULCS) were implemented at partner NMIs. These facilities in conjunction cover a wide current range from 1 fA to 10 mA.

They are capable of testing various types of single-electron devices with an uncertainty at, or below, 1 part in 10^7.

Development of guidelines for testing the accuracy of single-electron-based current standards

Even though the accuracy (better than 1 part in 10^7) required for metrological applications has not been achieved and it is not yet possible to construct full guidelines for testing the accuracy of single-electron sources, the consortium has accumulated a substantial body of data describing the behaviour of current quantisation plateaux through this project. Consequently, guidelines were prepared for assessment of the flatness of plateaux and for robust verification procedures for single-electron current sources. The adoption of our guidelines by stakeholders will simplify, promote, and enhance the reliability of comparison studies between different experiments on current quantisation accuracy.

Impact

The consortium has disseminated the results of the project through different routes. 27 papers have been published in peer-reviewed journals. In addition, 8 articles were published in trade/popular press and 64 conference presentations and posters have been given. 14 in-depth training sessions were organised and held to train stakeholders in small-current measurement techniques. In addition, the partners have been engaging in a significant number of activities to promote the uptake of the project's outputs and improve the small-current measurement capability of our stakeholders. In order to provide the stakeholders and the general public information on the importance of small-current metrology, a short video has been created and is available on the project website (http://www.e-si-amp.eu/) and also on YouTube (https://www.youtube.com/watch?v=5WQP0yv-IM4). The Helmholtz Prize 2018, considered the most prestigious award in the field of metrology, in the category "Application" was awarded to a partner NMI for ground-breaking improvements in the field of high-precision traceable measurement and generation of small electrical currents. A contribution from a partner NMI won "the Best Paper of the Conference" award at a major conference for the test and measurement industry (NCSLI, August 2017) and a consortium's paper on the robustness of single-electron pumps at sub-ppm current accuracy level was selected by the journal editors for the category "Highlights of 2017". One paper on the new variant of ULCA was selected as one of the most read editors' highlights of 2017 in the Review of Scientific Instruments. Another paper published in the same journal, studying the noise optimised version of ULCA, was selected as an editor's pick. A paper on the electron counting capacitance standard was selected for "2017 Highlights of Metrologia".

Impact on industrial and other user communities

The manufacturers of instruments that require small current measurements, such as particle counters or radiation dose meters, have benefited from the availability of high accuracy portable current measurement/source systems. The uncertainties of electrical units that propagate through the calibration chains have been improved, and therefore more accurate electrical units have become available to end users. Training and demonstration courses have been held for the stakeholders to exploit the enhanced small-current measurement facilities at partner NMIs and portable current measurement/source systems.

A partner has agreed with a manufacturer to commercialise two versions of the ULCA variants developed in this project. Also, after the distribution of ULCAs within the consortium, the partners are exploiting their improved small-current measurement capability to engage with stakeholders in a wide range of areas. These activities resulted in an improvement to the traceability of ionisation chambers for medical radiation metrology and nuclear metrology, and also an improvement to the traceability of single-charge aerosol references that are used in the area of health and environment. We have tested the stability of a high-value resistor for its manufacturer. We demonstrated PQCG's capability to a multinational calibration and asset management supplier and made a plan for calibrations of their instruments and later demonstrated a calibration of their multimeter in the presence of the manufacturer's chief corporate metrologist. Also, we have started a new measurement service performing electrical current measurements on prototype semiconductor devices from external customers. Our work with a manufacturer of bespoke cryogenic components and electronics has resulted in a sample enclosure, which is now commercially available from the manufacturer. We demonstrated a calibration of a multimeter using the PQCG in the presence of the manufacturer's chief corporate metrologist. We worked with a large lighting manufacturer to implement a ULCA for optical calibration measurements in their reference laboratory.

Impact on the metrology and scientific communities

The enhanced capability of small-current measurements is expected to have a direct impact on the Calibration and Measurement Capabilities (CMC) of NMIs. Up to one order of magnitude improvement in the range 1 pA – 100 pA has been achieved. In addition, high-resistance (e.g. 100 MΩ and 1 GΩ) calibration has been improved. For scientific communities, the development of single-electron devices will benefit the development of nano-device fabrication technology and the understanding of mesoscopic device physics. The training and demonstration courses described in the “industrial and other user communities” section have been also provided to the metrology and scientific communities.

Four non-partner NMIs have been trained for ULCA usage. Six guest students/scientists from outside the consortium received in-depth training on small-current measurements and electron-pump experiments. We have re-evaluated the uncertainty of the resistance calibration chain to 1 GΩ. A partner NMI had a discussion with a university laboratory working on quantum-limited measurements on ways to control vibration-induced noise in cryogenic systems. Another partner NMI has applied for a CMC entry for the ULCA calibration using cryogenic current comparators. Several international NMIs in Europe, Asia, and America are already using the measurement and calibration capabilities offered by the commercially available ULCA for improved processes or services. Three partners (LNE, VTT and NPL) are preparing to revise CMCs in the high-value resistance and small-value currents following the development of small-current measurement capabilities using ULCA, PQCG, ULCS, and the standard resistor with improved traceability. An international small current comparison (TC Project EM-1380) is taking place between two e-SI-Amp project partners and 5 other European NMIs. A new EMPIR project 17FUN04 SEQUOIA has started, which exploits some of the single-electron device technologies that this project has developed, for applications in quantum information and quantum sensing.

Impact on relevant standards

The progress and results of this project have been reported to European and international committees on electrical measurements such as the EURAMET Technical Committee for Electricity and Magnetism (TC-EM), and Consultative Committee for Electricity and Magnetism Working Groups (CCEM WGs) on Low-Frequency Quantities and on Proposed Modification to the SI.

The consortium has a member of the working group of the CCEM on implementing the revised SI (WGSI), and the project had good visibility in the most relevant standards committees. Two members of partner institutes have given presentations to the CCEM committee, and five partners presented work at two TC-EM DC QM subcommittee meetings. The outcomes of this project will have an impact on international standardisation of electrical units. Improved accuracy and scalability will pave the way for the use of single-electron current sources as primary current standards.

Longer-term economic, social and environmental impacts

In the long term, the improvements in small-current measurement capability will have high impact on society and the environment. The sensitivity of sensors used in environmental or health monitoring, and manufacturing relies on the detection of a small current signal. We have demonstrated that the technology developed in this project equips metrological and industrial laboratories with higher sensitivities in fields such as ionising radiation, particle counting, optical measurements, and material characterisation. The areas covered are likely to expand in the future. The effect of these improvements will eventually permeate into wider society, where more efficient and sensitive devices will allow for more accurate and precise control in products and services, such as environmental protection, medical care, and commercial production of goods.

List of publications

<u>*Articles in peer-reviewed journals*</u>

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Internal Funded Partners: 1. NPL, United Kingdom 2. LNE, France 3. PTB, Germany 4. TUBITAK, Turkey 5. VTT, Finland	External Funded Partners: 6. Aalto, Finland 7. CEA, France 8. UCAM, United Kingdom 9. UoS, United Kingdom	Unfunded Partners: 10. KRISS, Korea, Republic of
RMG: -		