Publishable JRP Summary for Project T1 J1.3 (REUNIAM)
Foundations for a Redefinition of the SI Base Unit Ampere

Rationale

In response to a call by the International Committee for Weights and Measures (CIPM) to focus research efforts related to a possible redefinition of the SI system, the project REUNIAM aims at providing important foundations for a redefinition of the SI base unit ampere. In a new SI likely based on fundamental constants, the electrical units will have a pivotal role: macroscopic quantum effects link them directly to the values of the elementary charge e and to Planck's constant h. In the new system the unit ampere could be defined by the product $e{\cdot}f$, relating it to e and to a frequency f. However, the quantum effects used to derive the units volt and ohm from e and h allow a realization of V and Ω much more precise than single charge transport (SCT) effects permit to derive the ampere from e since the relation $e{\cdot}f$ can only be utilized at low frequencies which limits the practical use of such small currents.

The results of the project are intended to provide important input for the redefinition of the SI. As outlined above, all electrical measurements will be based on fundamental constants within a new and coherent SI. But beyond this also the redefinition of the unit of mass, the kilogram, is influenced by the outcome of the project since one of the routes for redefining the kg, the watt balance experiment, relates the kilogram to e and h via the electrical quantum effects.

Project Structure

The project objectives are twofold. A short term objective is the realization of a fundamental experiment known as Quantum Metrology Triangle (QMT, Figure 1). The QMT is an experimental test of the constituting relations of the three quantum effects and its outcome will provide an important foundation for a new SI. The long term objective will

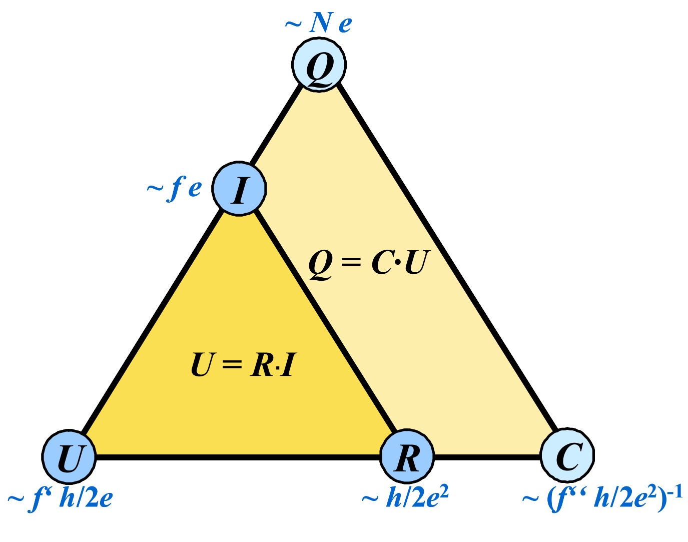

Figure 1:
The $U = RI$ and the $Q = CU$ variants of the quantum metrological triangle

be a high current SCT device of practical relevance: such a device will utilize the relation $e{\cdot}f$ to deliver a high enough current for practical applications. With an operation frequency in the GHz range (as compared to a few MHz in existing approaches) a high current SCT device will allow to directly reference the ampere to a fundamental constant *at practically useful current levels*. Further the SCT effect allows the principal possibility of a room temperature device.

In different work packages of the project two variants of the QMT are pursued by experimentally determining the product $K_J R_K Q_X$. It equals 2 if the theoretical relations $K_J = 2e/h$, $R_K = h/e^2$, and $Q_X = e$ are strictly valid. Any deviation from 2 would indicate new physics, and have direct impact on the planned re-definition of the SI units. In one variant a current $e{\cdot}f$ is amplified, passed through a resistance known in units of R_K, and the voltage drop is compared to a voltage $K_J^{-1}.f'$. In the other variant N elementary charges are collected on a capacitor $C \sim (2\pi f'' R_K)^{-1}$ during N cycles of frequency f. The voltage across C is then compared to a voltage $K_J^{-1}.f'$. Since f, N, f', f'' are known exactly, both variants determine $K_J R_K Q_X$ with high precision, although both are extremely challenging. Existing SCT devices might allow to close the QMT at an uncertainty of around 1 part in 10^7, but already a few parts in 10^7 would constitute clear progress beyond the current state of art.

In a third work package a high current SCT device is the key development goal. Different routes are followed, using new types of super/semiconductor SCT nano-circuits on the one hand and the so-called quantum-phase-slip (QPS) effect on the other hand. The coherent QPS effect is formally an exact dual to the Josephson effect. A corresponding device should have constant current plateaus, similar to the Josephson effect voltage plateaus. For the QPS effect current levels up to a few nA are predicted. The strategy to follow technologically well established routes as well as the unknown, strongly challenging QPS route might even help to arrive at a successfully closed QMT experiment breaking the 10^{-7} uncertainty level, and it should demonstrate perspectives for a quantized current source delivering currents up to the nA range.

Project Progress

In the first 2 project years good progress was made in all work packages. A key achievement was the demonstration of single electron hold times up to 1000 sec in the static mode of the single electron pump used for the $Q=CU$ variant of the QMT. To reduce the still too high error rate in the dynamic mode of that device intense efforts in optimization of the cryo-electronic setup have been made, and a device design with minimised internal cross-capacitances was fabricated and is currently tested.

In the $U=RI$ variant of the QMT the key element is a current amplifying cryogenic current comparator (CCC). A 20,000 winding CCC with current noise of 5 fA/Hz$^{1/2}$, close to the required target performance of 1 fA/Hz$^{1/2}$, is now operating, and type-A measurement uncertainties of 1 part in 10^6 are possible at the few pA level. However, more than one order of magnitude larger reproducible deviations from the expected QMT outcome are observed, and tests are being made to understand their origin. Also work is under way to use the unique performance of the setup to characterise the tunable barrier devices described below.

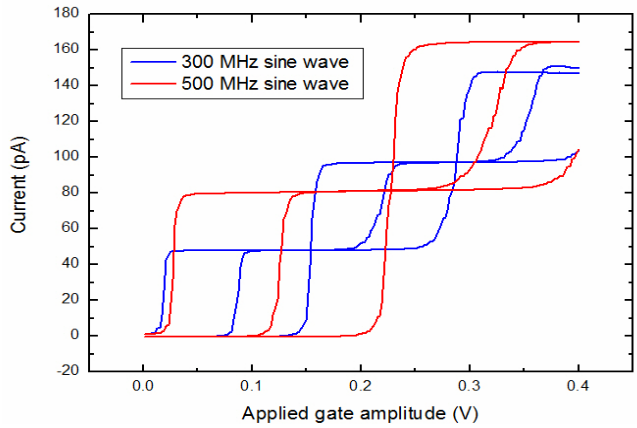

Figure 2:
Current in a hybrid SCT device as a function of applied gate amplitude, with three different dc offsets of the gate drive. Sinusoidal gate drive at 300 MHz (blue traces) and 500 MHz (red traces) has been used. The plateau at 160 pA corresponds to pumping two electrons per cycle at f = 500 MHz.

In the high SCT current work package superconductor-semiconductor hybrid SCT devices were driven at 500 MHz and current plateaux at 160 pA level were obtained. Further the parallelisation of hybrid devices was demonstrated by letting for the first time ever operate ten SCT devices in parallel, producing currents 104 pA and 208 pA at 65 MHz drive frequency. Resistive as well as capacitive shunting of devices was shown to improve the current plateau flatness considerably.

In an alternative development thread SCT devices based on GaAs nano-wires with tunable gates also showed a remarkable increase of performance: Current plateaus of such devices broaden considerably in an external magnetic field, and at the same time the plateaus become flatter. A theory which quantitatively derives the plateau flatness from the plateau shape was published in Physical Review Letters. For the latest batch of devices this theory predicts a relative uncertainty below 1 part in 10^8 over a 10 mV gate voltage range. Such precision is unobtainable with conventional current measurements and the experimental verification of the predictions can only be made using the QMT setup itself.

The direct QMT setup is currently being adapted to accommodate the tunable devices, whose operating conditions differ quite a bit from those of the conventional metal SCT

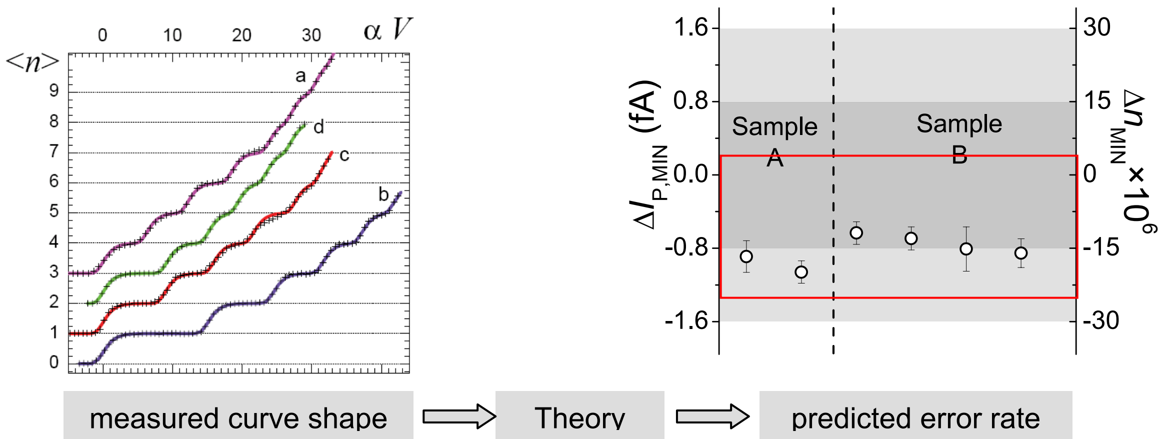

Figure 3:
For GaAs tunable-barrier pumps a theoretical model predicts error rates from the measured pump gate voltage characteristic. Comparison of measured with predicted errors are used verify the theory, which however predicts so low uncertainties that they cannot be resolved with conventional current measurements. The CCC current amplifier of the U=RI QMT is a way to test the theory against experiment.

devices used before. The CCC-based current amplifier in the direct QMT setup should allow a current measurement with high enough resolution. If the expected excellent performance of the new SCT devices should be confirmed, a direct closure of the QMT can then be attempted.

The most risky but at the same time most promising approach to an $e{\cdot}f$ type current source delivering high current levels tries to exploit the quantum phase slip effect. In this work package the material niobium silicide, Nb_xSi_{1-x} is now used for the fabrication of nano-wires after nano-wires made from Aluminium and Titanium had shown no clear superconducting behaviour. First Nb_xSi_{1-x} wires of 25 nm width have been made and have shown superconducting transitions temperatures in the expected range 1.2-2.5 K. A method of joining the NbSi nano-wires to on-chip chromium resistors (a necessary ingredient for a QPS device) has been developed, although reproducibility is currently still poor.

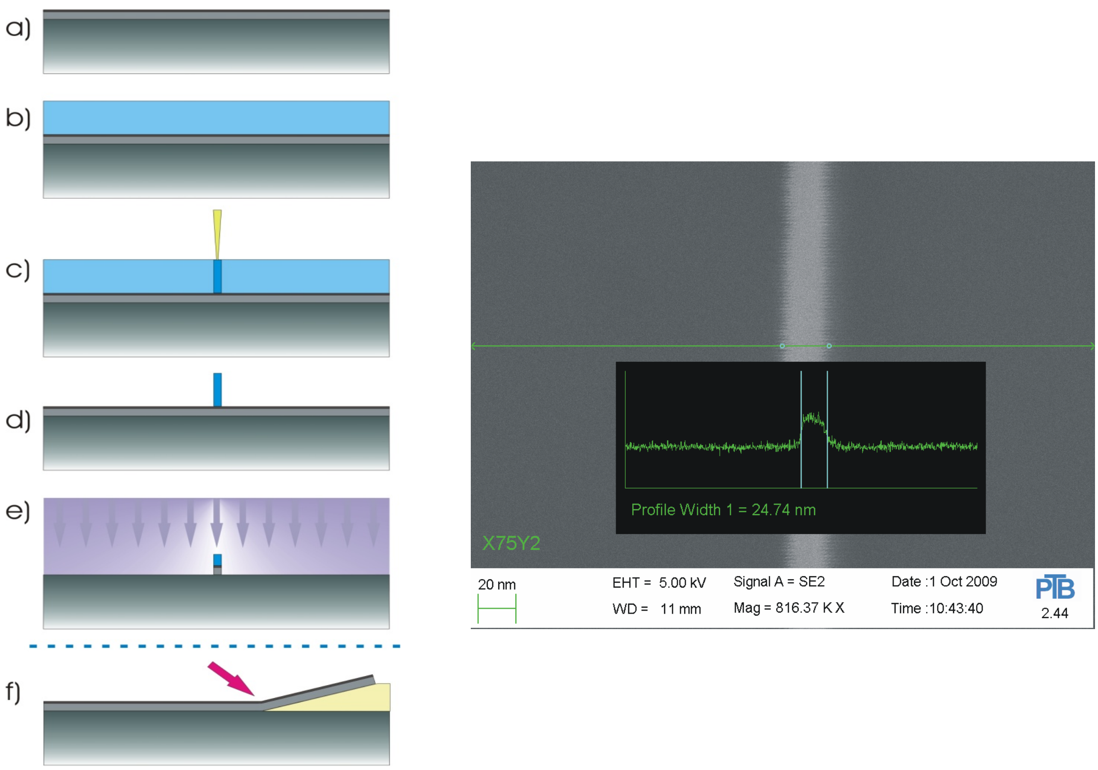

Figure 4:
Schematic processing steps for making NbSi nano-wires (left, a to f). Step f indicates a wedge structure which is used to contact the nano-wire. A scanning electron microscope image demonstrates the achieved line width of 25 nm (right) .

REUNIAM

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