EMRP
European Metrology Research Programme
Programme of EURAMET

EMRP Joint Research Project SIB07

EURAMET
European Association of National Metrology Institutes

"Quantum Ampere: Realisation of the new SI ampere"

Motivation

- The new SI ampere definition will be based on a fixed value for the elementary charge *e*

→ Single-electron transport (SET) devices are considered the `silver bullet´ for the new SI ampere realization

Consortium

Partner NMIs *REGs*

PTB – Physikalisch-Technische Bundesanstalt Braunschweig und Berlin
LNE – Sharing a passion for progress
MIKES
NPL – National Physical Laboratory
LATVIJAS UNIVERSITĀTE – ANNO 1919
cea – INAC INSTITUT NANOSCIENCES ET CRYOGÉNIE
Aalto University
UNIVERSITY OF CAMBRIDGE

Project runtime: May 2012 – April 2015

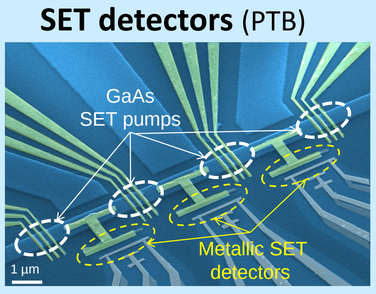
Objectives

To provide:

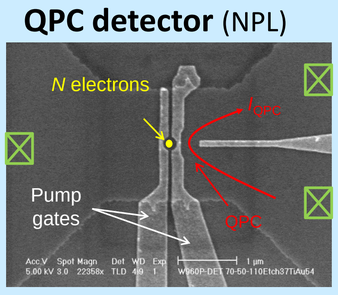
- SET current sources with $I_{SET} \geq 100$ pA
- On-chip integrated SET error detection schemes
- Complementary current amplification & metering instrumentation

to realize SET currents with $u_{rel} \leq 0.1$ ppm

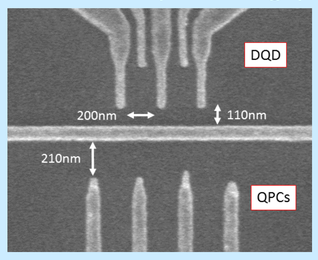
GaAs pumps + SET detectors (PTB)



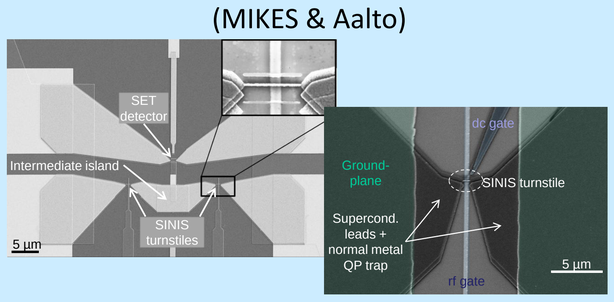
GaAs pump + QPC detector (NPL)



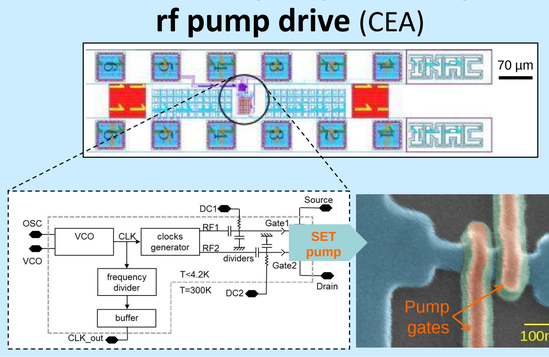
GaAs DQD pump + QPC detectors (Cambridge)



SINIS turnstiles + SET detector (MIKES & Aalto)



SOI CMOS pump + on-chip rf pump drive (CEA)



JRP structure: Technical work packages

WP1: SET current sources

- Nano-scale device fabrication and characterization
- $I_{SET} \geq 100$ pA, with $u \leq 0.1$ ppm, `single parameter´ operation mode

GaAs pumps
SINIS turnstiles
SOI CMOS pumps

WP2: Quantum-based amperemeters and current scaling techniques

- Construction and characterization of ultra-precise ($u \cong 0.1$ ppm) current metering &scaling instruments

1:30 000 CCC
`14-bit´ CCC
ULCA

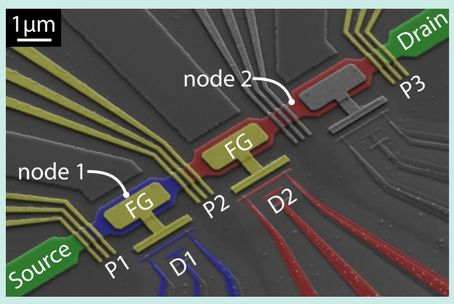
SET current sources
Instruments

WP3: Accuracy verification

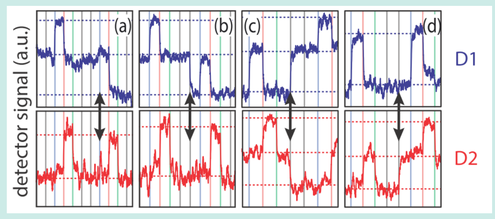
- Development of on-chip SET error detection
- Current accuracy verification by counting SET errors ($u \leq 0.1$ ppm)

Prototype "Quantum Ampere" realization

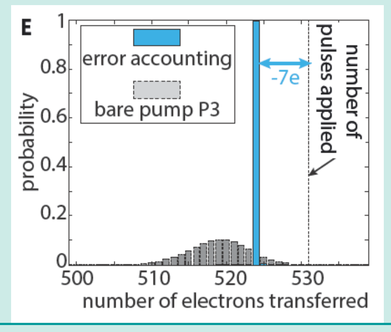
i."Self-referenced" SET pump & accuracy enhancement (PTB)



Self-referenced current source consisting of three pumps (P1…P3) serially connected via charge nodes, whose charge states are monitored by SET detectors D1 and D2

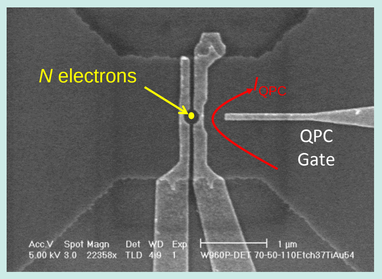


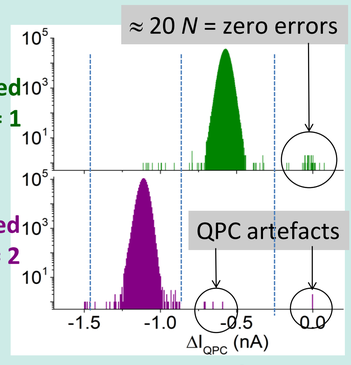
Error signatures of (a) P1 during sequential electron transfer, and errors by P1…P3 (b-d) during simultaneous electron transfer, showing "missing cycles"



Result i: Probability distributions for electron number distribution (pump P3) without (grey) and with (blue) error accounting by charge detection. The comparison shows the accuracy enhancement of the measured current (transferred charges) by a factor of 50.

ii.Number of electrons in the pump measured for error checking (NPL)

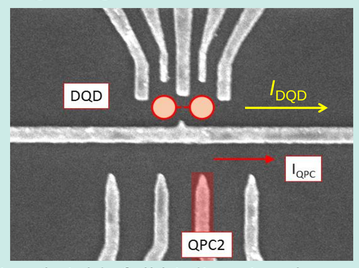




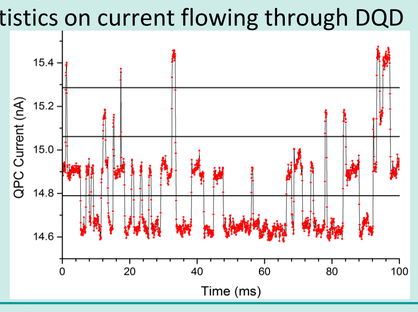
Histograms of QPC current for 10^6 load cycles

Result ii: One possible error in 10^6 loading cycles ↔ ppm-level accuracy

iii.Small currents measured by counting single electrons (Cambridge)



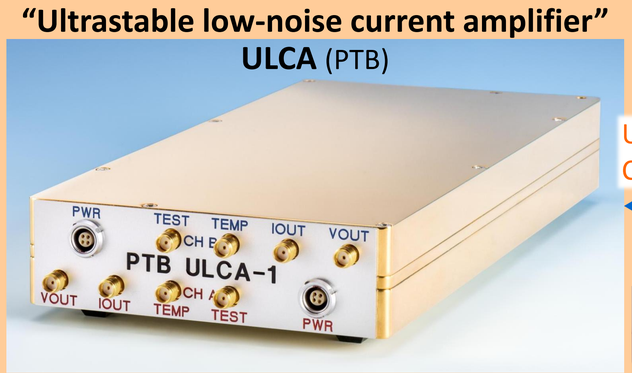
QPC signal yields full bi-directional counting statistics on current flowing through DQD



Result iii: Currents up to 15 aA measured with 0.2 aA uncertainty

1:30000 turns CCC (LNE)

"Ultrastable low-noise current amplifier" ULCA (PTB)



ULCA calibration with CCC, traceable to QHR

14-bit CCC (PTB)

Publications in peer-reviewed journals

- M. Wulf, Error accounting algorithm for electron counting experiments, Phys. Rev. B **87**, 035312 (2013)
- L. Fricke *et al.*, Counting statistics for electron capture in a dynamic quantum dot, Phys. Rev. Lett. **110**, 126803 (2013)
- X. Jehl *et al.*, Hybrid metal-semiconductor electron pump for quantum metrology, Phys. Rev. X **3**, 021012 (2013)
- P. Mirovsky *et al.*, Towards quantized current arbitrary waveform synthesis, J. Appl. Phys. **113**, 213704 (2013)
- L. Fricke *et al.*, Self-referenced single-electron quantized current source, Phys. Rev. Lett. **112**, 226803 (2014)
- H. Scherer *et al.*, Introducing joint research project «Quantum Ampere», online publication in EPJ Web of Conferences, 00004 (2014)
- D. Drung *et al.*, Ultrastable low-noise current amplifier, submitted to Metrologia (2014)
- M. Götz *et al.*, A compact 14-bit cryogenic current comparator, submitted to Metrologia (2014)
- H. Scherer *et al.*, Traceable precision pA direct current measurements with the ULCA, submitted to Metrologia (2014)
- P. Clapera *et al.*, Integration of an on-chip radio-frequency generator with a quantum device, submitted to Appl. Phys. Lett. (2014)