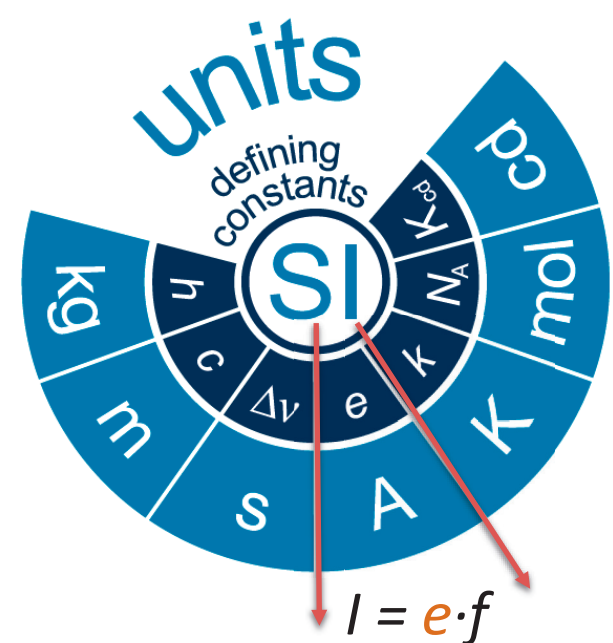


Reproducible single-electron pumps for a quantum current standard

Motivation

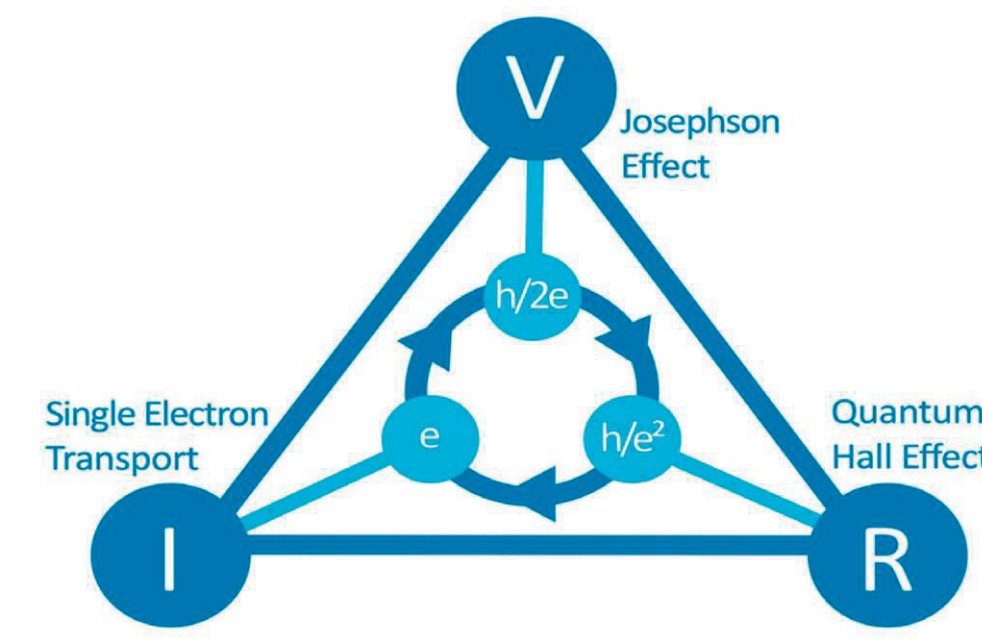
Revised SI-System (2019)¹:



- Fixed values of 7 fundamental constants:
 $e = 1.602\,176\,634 \cdot 10^{-19} \text{ As}$
- 1A: flow of $1/(1.602\,176\,634 \times 10^{-19})$ elementary charges per s

Implementation of a mesoscopic working principle in a robust and reproducible device?!

Quantum Metrology Triangle²:

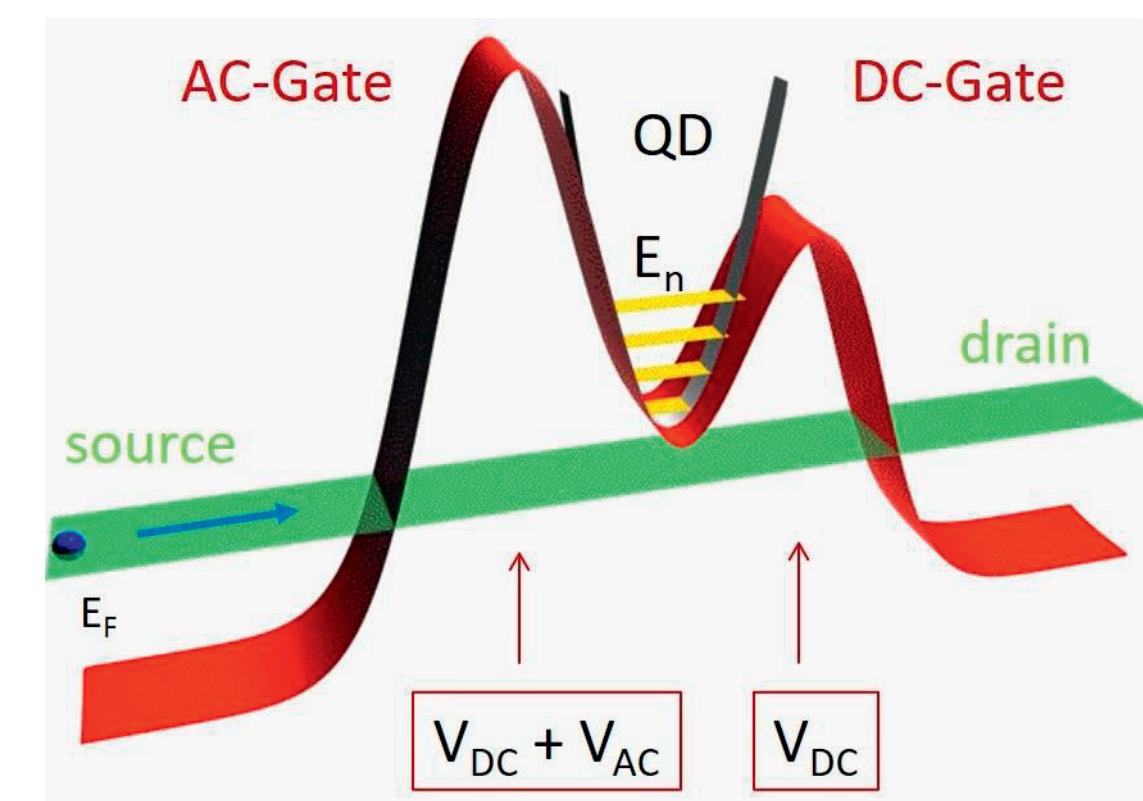


- Test of consistency of Ohm's law
- Electron quantum optics³
- Quantum link for semiconductor spin qubits⁴

Non-adiabatic single-electron pump (SEP)

Single-electron pump: direct correlation between pumping frequency and current

$$I = n \cdot e \cdot f$$



Quantum Dot (QD) with tuneable barriers:

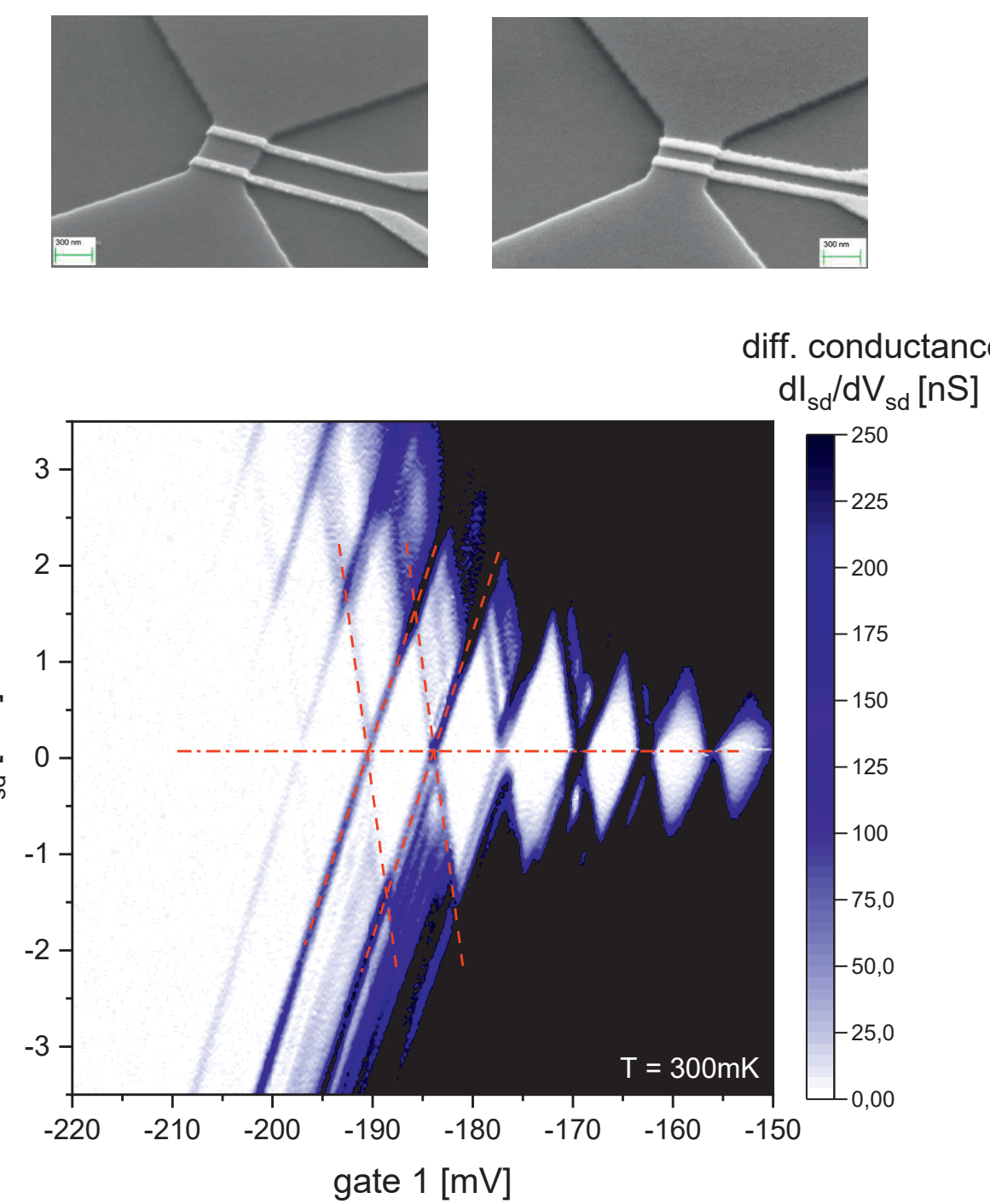
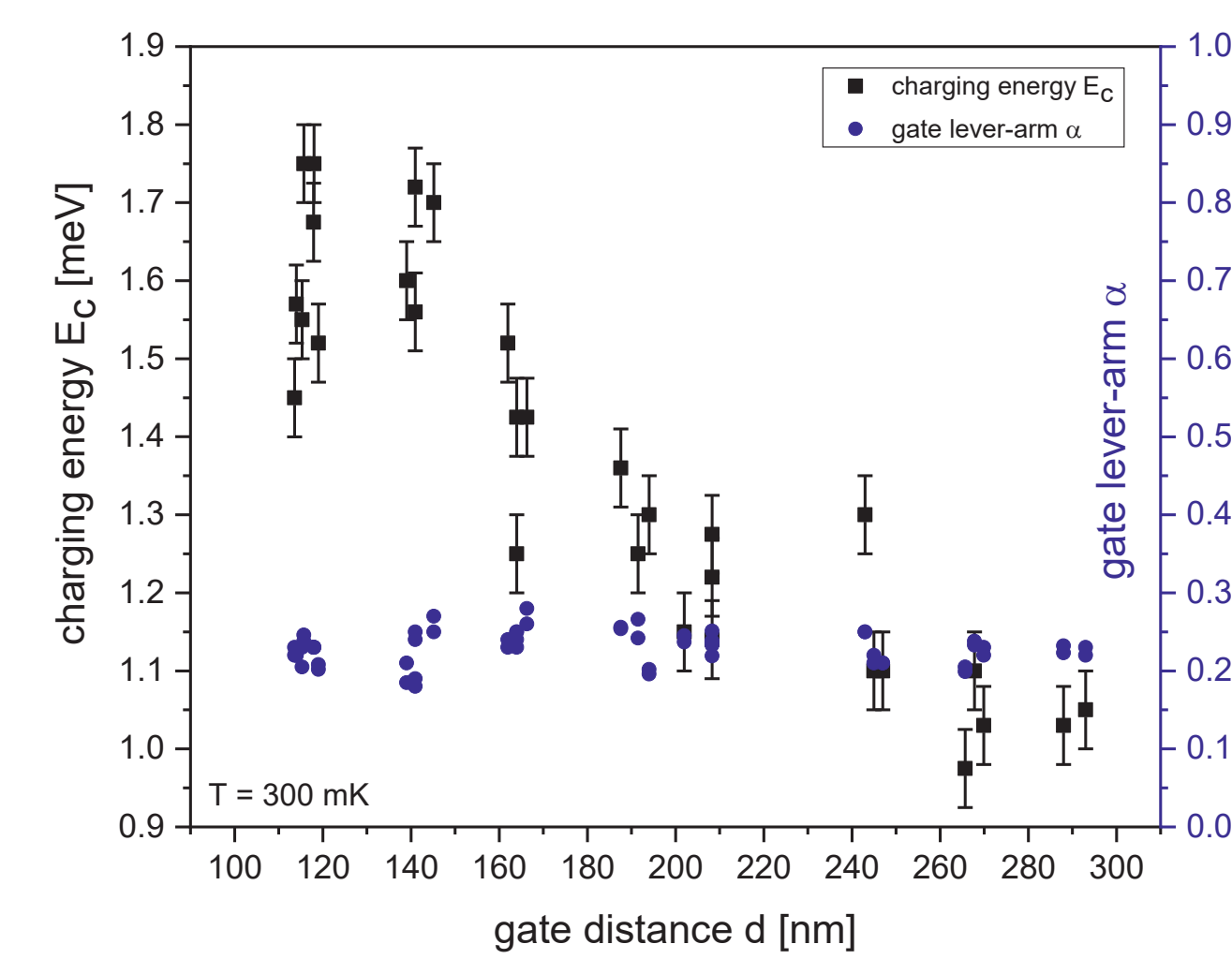
- Modulation of entrance barrier (MHz - GHz)
- Capture of electrons from source and back-tunneling
- Lift electrons over exit gate to drain

Figure-of-merit⁵ for accuracy of charge quantization:

$$\delta_2 = \ln \frac{\Gamma_2}{\Gamma_1} + \ln \frac{E_c}{\Delta_{ptb}}$$

Robust und reproducible formation of a QD

32 devices in one batch tested for Coulomb blockade:



Main parameters and deviations:

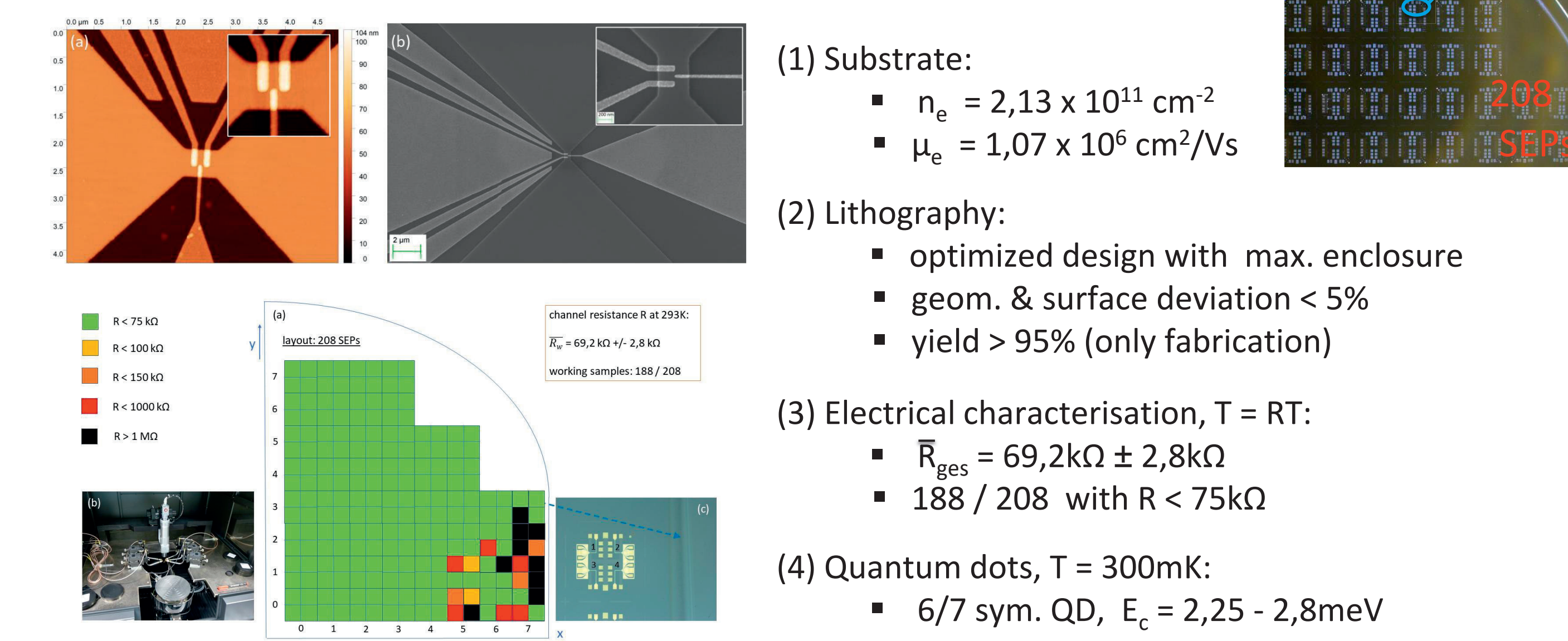
- Lithography (SEM/AFM): < 5%
- Substrate (n_e, μ_e): < 5%
- Charging energy E_c : < 8%
- Gate lever-arms: < 9.7%
- 2 out of 32 devices failed
- No double QD induced by charge traps
- Reproduced on different wafer batches and sample designs

Coulomb blockade realized in GaAs/AlGaAs heterostructure devices is sufficiently robust and underlines the suitability of this material system for mesoscopic devices in metrology⁸

QDs as candidates for a quantum current standard

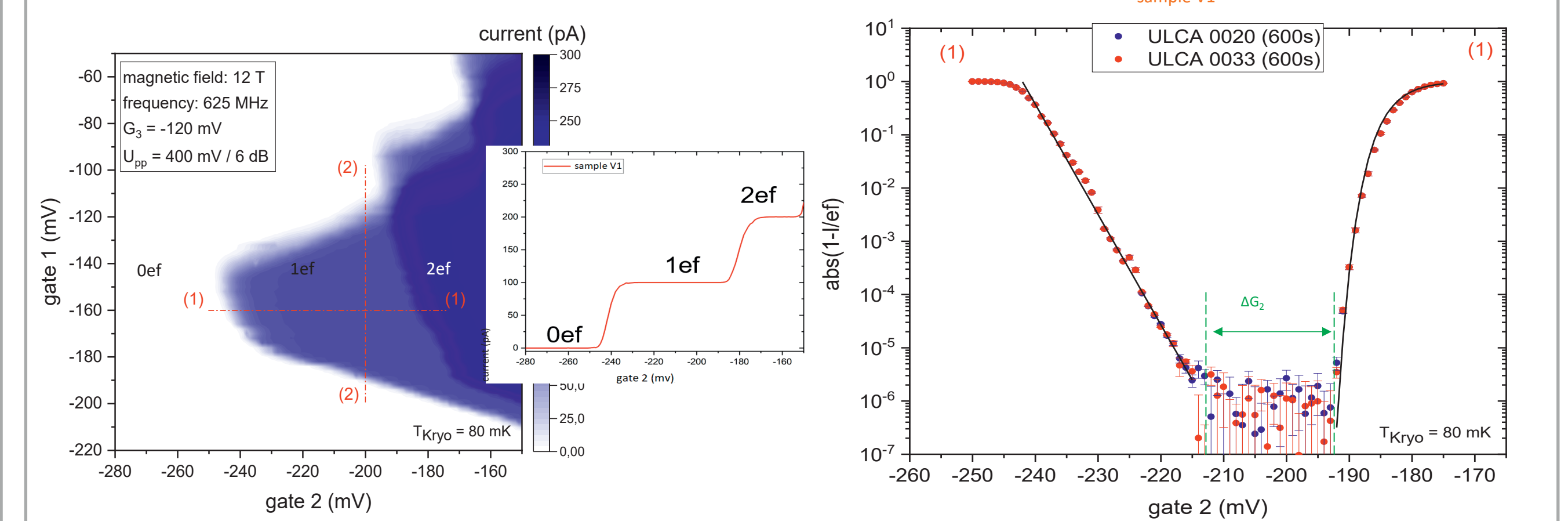
Metrological task : verification and validation concept based on multiple pillars

(a) Sample system: Verification of substrate / lithography / QDs



(b) Individual sample: Verification and validation, 5 samples, no-preselection

- 18h precision measurement⁹ scan, low-noise ULCA¹⁰, I = 100pA, sub-ppm base level
- Expectation: error rates determined by charge capture probabilities in theoretical model¹⁵
- Validation: test agreement with predicted gate dependency



- 5/5 samples successfully validated ($\delta_2 > 26$) out of this sample system, no pre-selection!
- Variations on microscopic scale → validation of each individual pump mandatory!

GaAs/AlGaAs-Technology for robust and reproducible devices for a primary quantum standard for a current in the range of 100pA established

Outlook

23FUN05 AQUANTEC: Advanced quantum technology for metrology of electrical currents

- Develop a continuous wide range of primary quantum current sources: fA - mA
- Explore novel quantum current device concepts
- Develop advanced technologies for devices, control and measurement
- Linking metrology and quantum technology communities



New Work Item Proposal: Single Electron Sources – terminology, metrics, and characterization procedures			
* to be attached to the CIB			
CEN/CENELEC JTC22 – Quantum Technologies			
Secretariat:	Proposal documented in N1 xx		
Date of circulation:	Closing date for voting:		
Decision reference:	Decision date:		

References

- [1] M. Stock et al., Metrologia **56**, 022001 (2019)
- [2] H. Scherer et al., Meas. Sci. Technol. **23**, 124010 (2012)
- [3] N. Ubbelohde et al., Nat. Nano. **18**, 733-740, (2023)
- [4] M. Künne et al., Nat. Com. **15**, 4977, (2024)
- [5] B. Kaestner et al., Rep. Prog. Phys. **78**, 103901 (2015)
- [6] H. van Houten et al., Appl. Phys. Lett. **49**, 1781 (1986)
- [7] Y. Nagamune et al., Appl. Phys. Lett. **49**, 1781-83 (1994)
- [8] T. Gerster et al., Metrologia **56**, 014002 (2019)
- [9] F. Stein et al., Metrologia **54**, S1 (2017)
- [10] C. Krause et al., Rev. Sci. Instrum. **90**, 014706 (2019)



The project 23FUN05 AQUANTEC has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States."