Counting statistics of single-electron capture by a dynamic quantum dot

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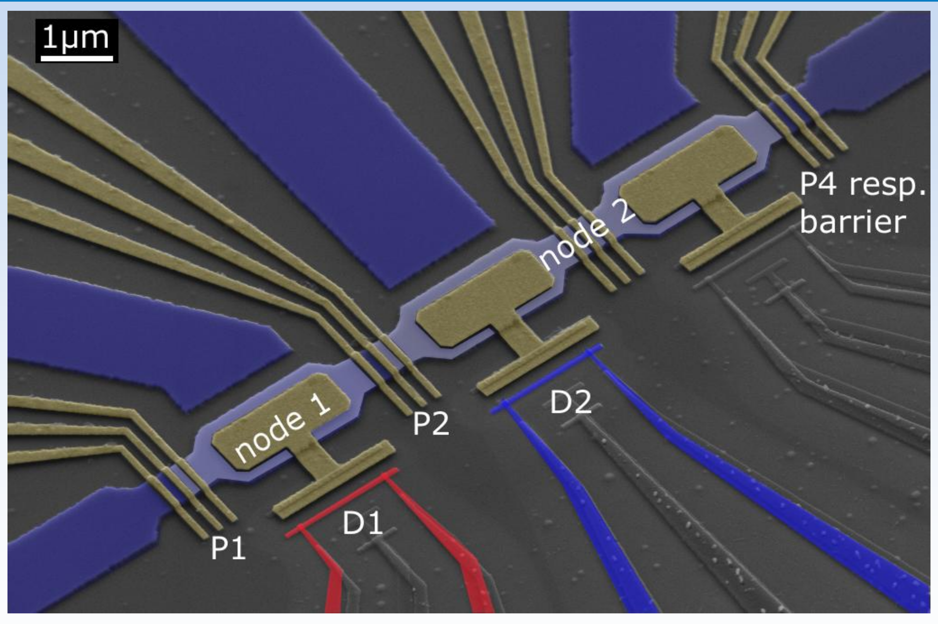
Motivation

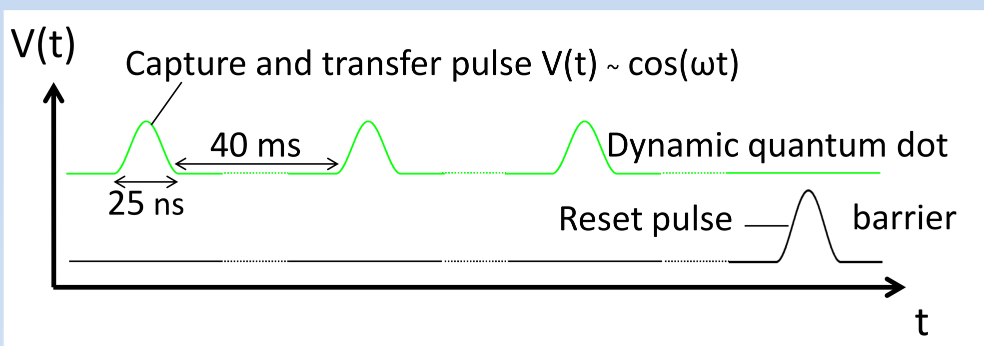
- Quantized-current sources can be employed as on-demand electron sources for quantum-information processing or as a current standard based on the elementary charge *e*.
- A promising candidate for a quantum-based current source is the non-adiabatic electron pump [1], based on a dynamic quantum dot in a semiconducting nanostructure. High current outputs [2], parallelization for further increased currents [3] as well as precision better than 1.2ppm [4] have been demonstrated. A benchmark for transfer fidelity is the decay cascade model [5,6].
- In contrast to macroscopic quantum standards like the Quantum Hall Resistance or the Josephson Voltage, all quantized current sources are based on the manipulation of individual charge carriers and therefore the precision of quantization obeys some probability distribution.
- Here, we directly measure the fidelity of charge capture by counting. Additionally, we propose and demonstrate an architecture consisting of a series of dynamic quantum dots with charge detectors on the interconnecting nodes measuring the number of transfer errors during current output.

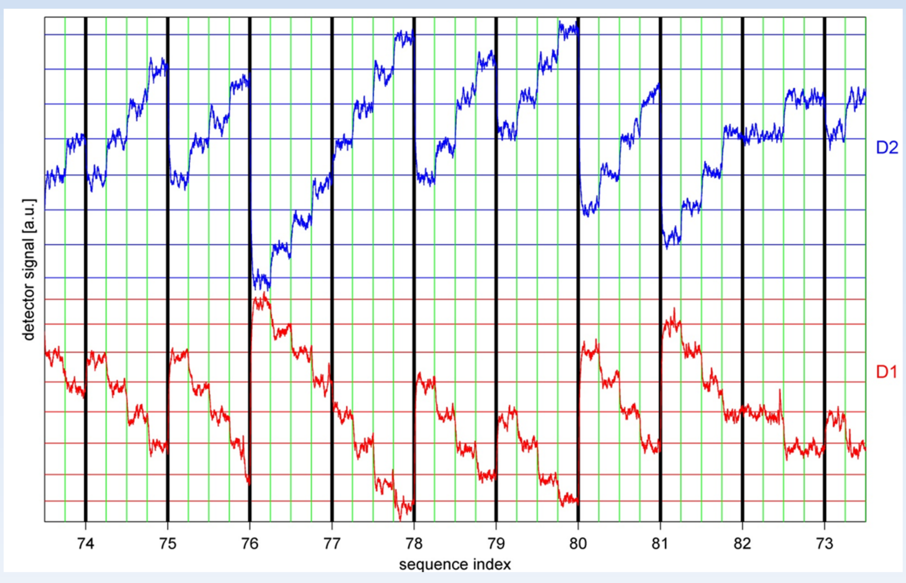
Sample under investigation

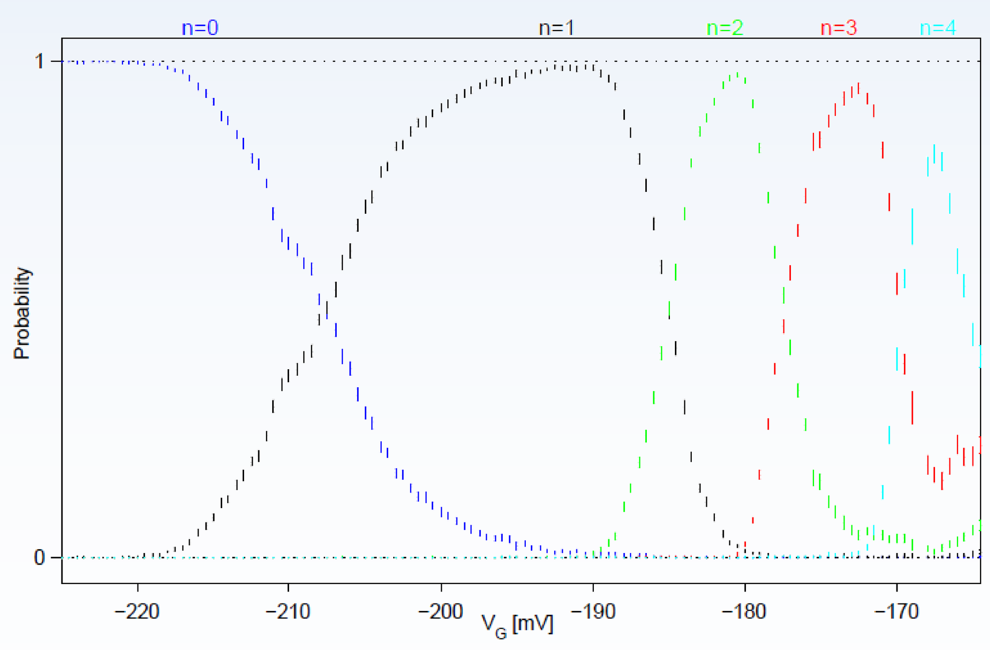


- Hybrid semiconducting (dynamic quantum dots) and superconducting (electrometers) device.
- Dynamic quantum dots:
  - AlGaAs/GaAs heterostructure, 2DEG 90nm below surface.
  - Quasi-1dimensional channel created by wet chemical etching.
  - Charge carrier density locally tunable by Schottky gates (100nm wide each).
- Electrometers:
  - Two-angle evaporation of Al with intermediate oxide barrier formed at controlled oxygen pressure.
- Metallic floating gates are deposited for enhanced capacitive coupling between electrons on the nodes and the electrometers.
- All measurements are performed using a dry dilution refrigerator at nominal temperature of 25 mK.

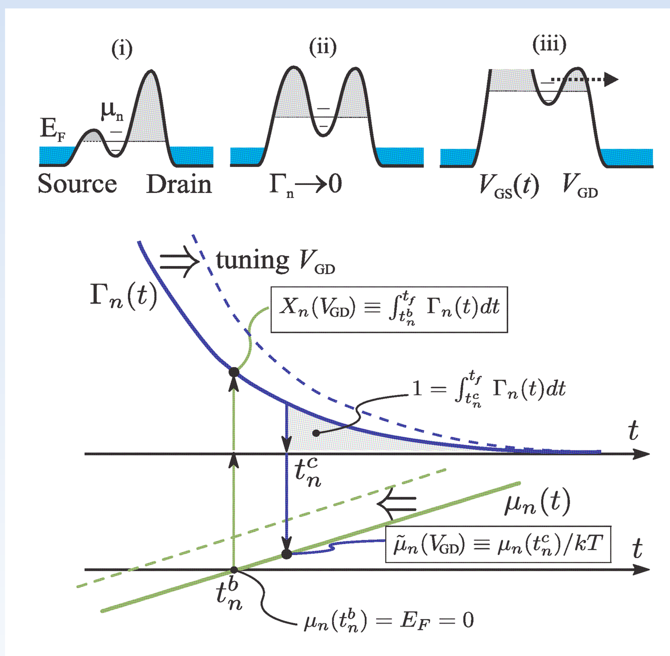
Dynamics of single-electron capture

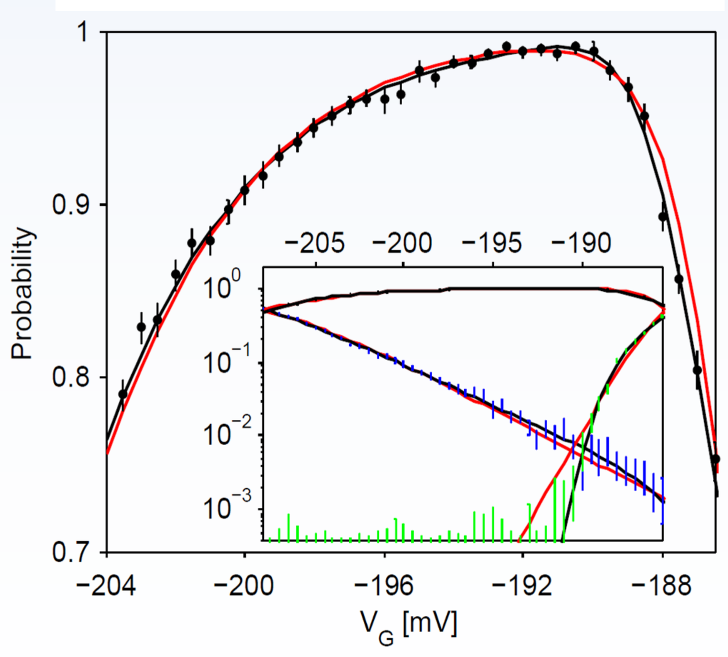






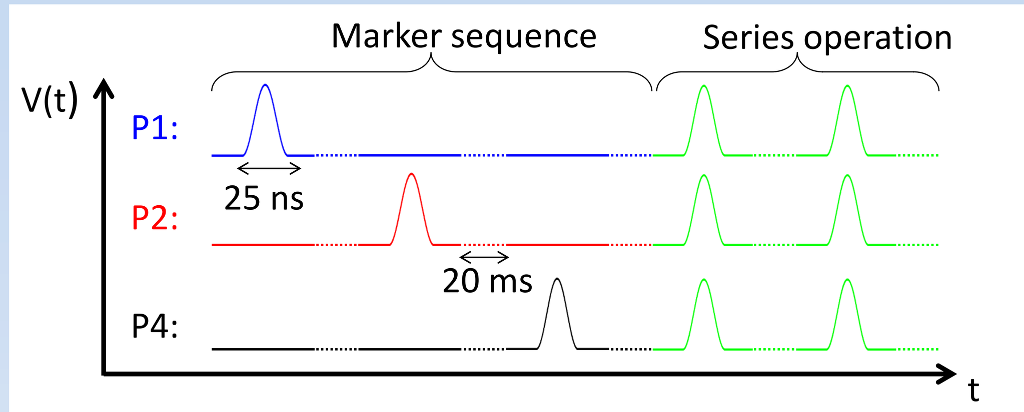
- Reduced back-action of transferred charges onto the quantum dot by periodically opening the node to drain.
- Both detectors are coupled to the same node, therefore correlation of both signals can be performed for reduced uncertainty.
- Alternatively, by applying a phase shift between the detectors the dynamic range can be increased.

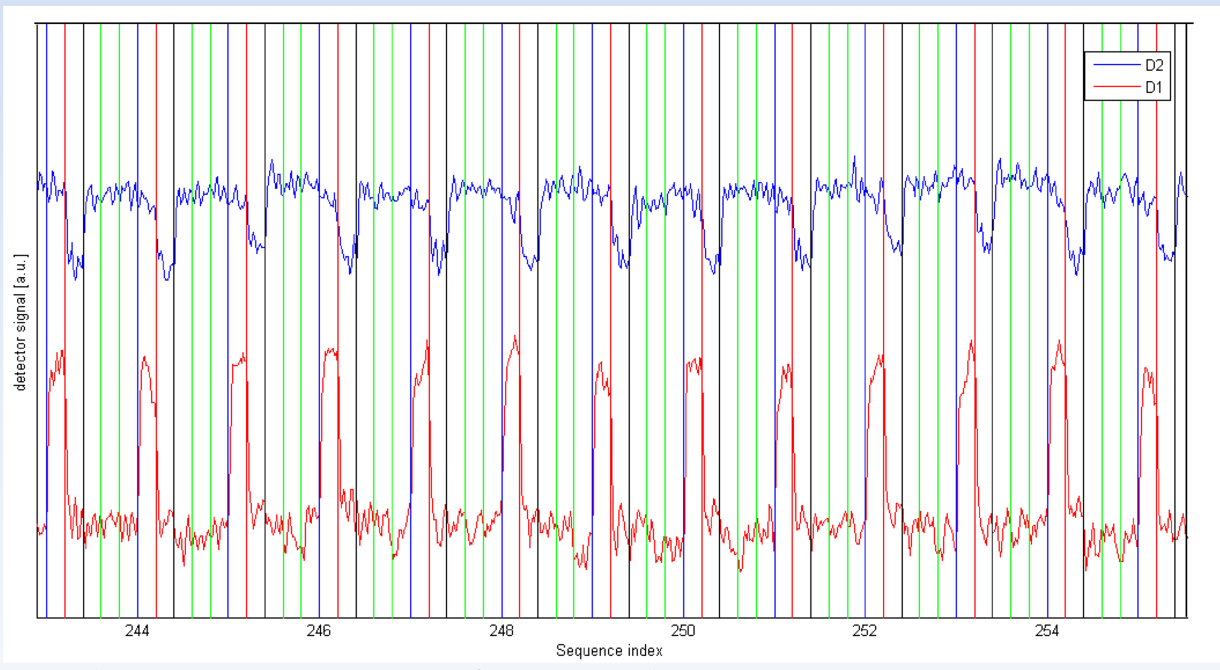


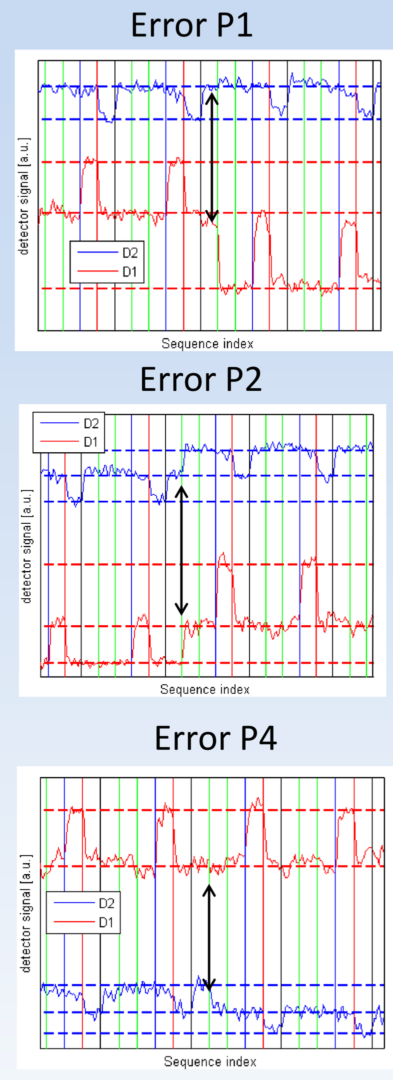


- Fidelity of charge capture at optimal working point P(1e)>0.99 (no magnetic field applied).
- Up to n=4 electrons transferred per cycle can be resolved.
- The high resolution of our data allows for distinction of different mechanisms of charge capture: The red fit represents a thermal model, the black fit the decay cascade model. The error bars on the data points show the 2σ uncertainty interval.

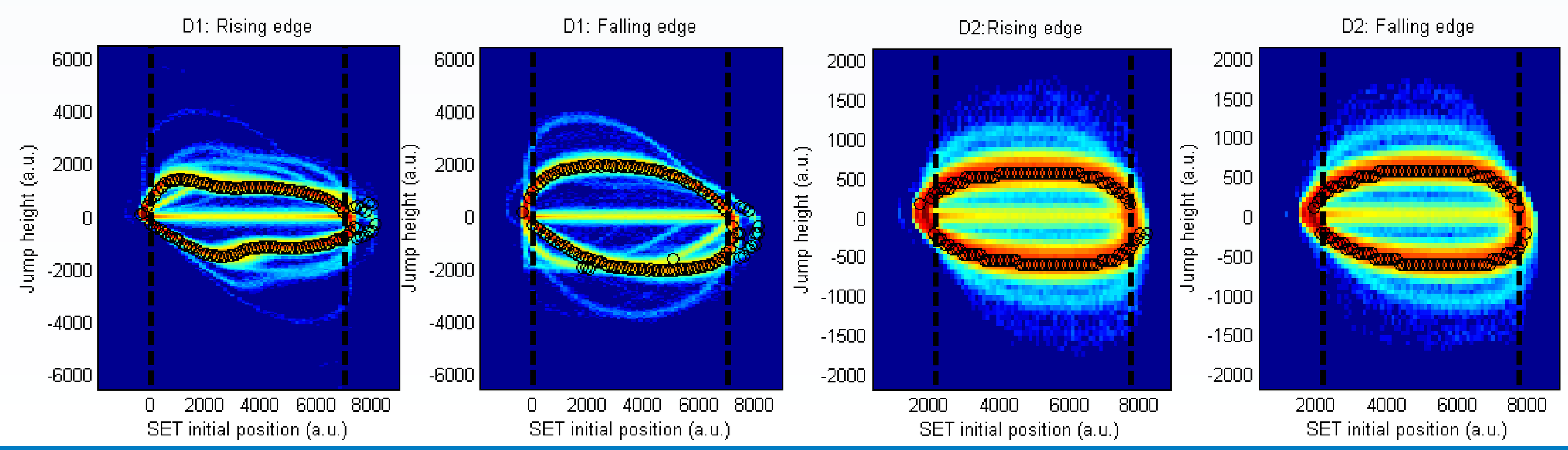
Series operation: Marker sequence and error assignment



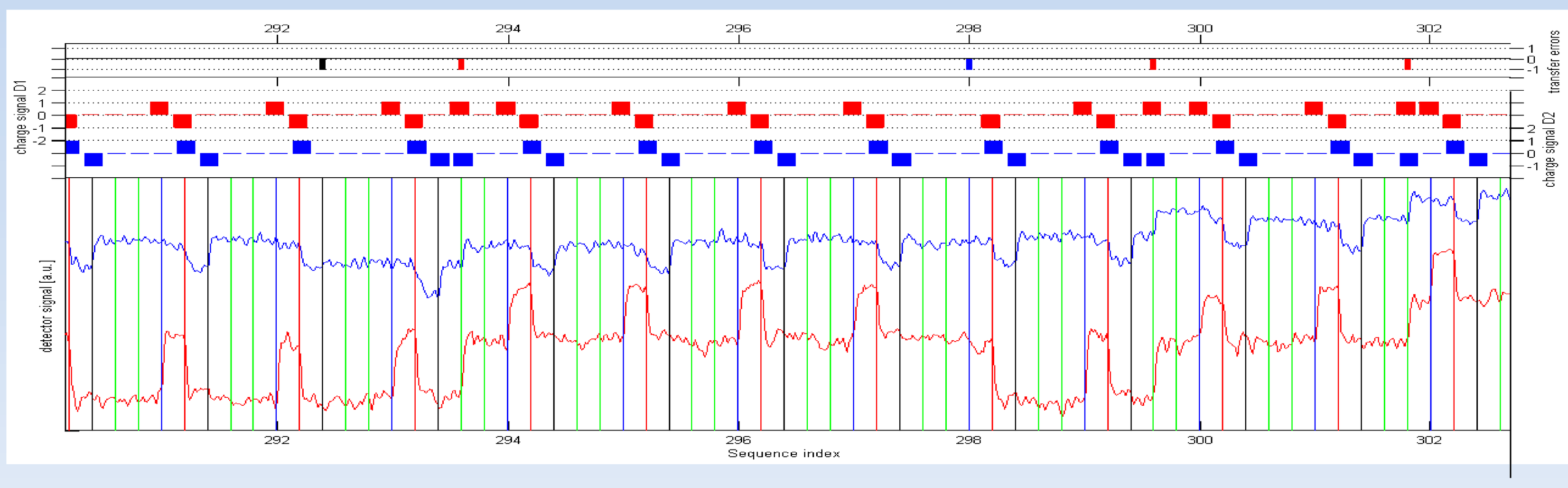


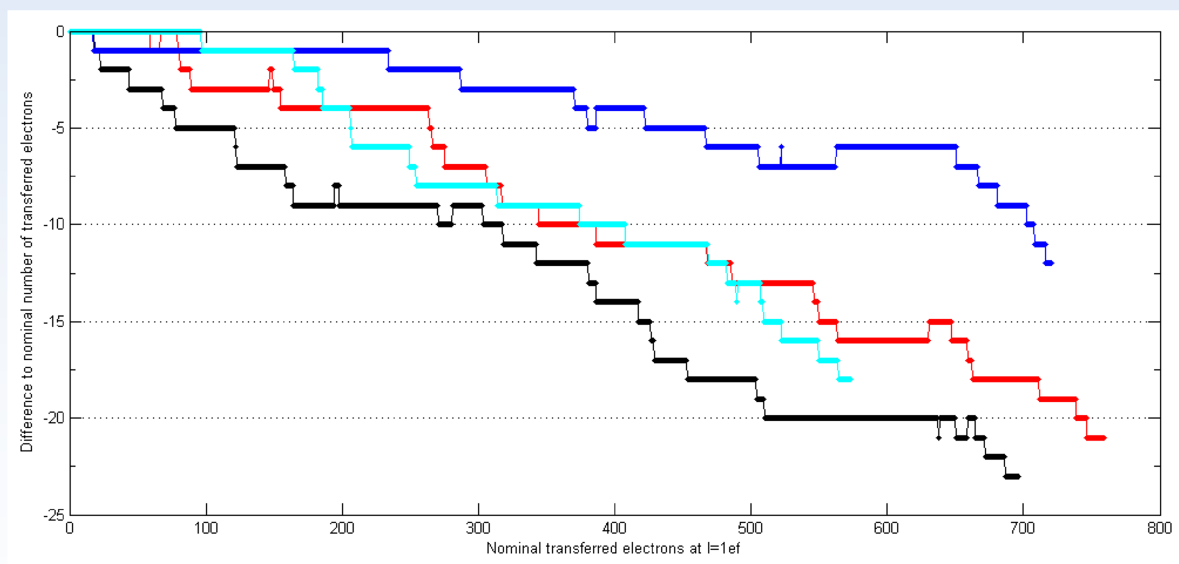


- Marker sequence contains information about:
  - Individual pump fidelity at this working point
  - Rising or falling edge of the SET
  - Amplitude of the SET's response
- By correlation of both electrometers the errors can be attributed to a specific dynamic quantum dot
- These errors can be accounted for [7], the residual error rate is given by the probability of higher order error events (indistinguishability of two pumps missing one cycle from one pump transferring one more electron)



Self-referenced current output





Blue: Individual pump fidelities (derived from marker pulses):
P1: 0.935 (4401 events)
P2: 0.960 (1665 events)
P3: 0.962 (2211 events)
Series: 0.924 (4422 events)

By series operation of the three pumps the uncertainty is reduced from ≈ 0.05 for the individual pump to 2.5E-3 at a current of I=30 *e*/s.

Black: Transferred across P4: 673electrons (696 electrons).
Red: Transferred across P4: 738electrons (759 electrons).
Cyan: Transferred across P4: 555electrons (573 electrons).
Blue: Transferred across P4: 708electrons (720 electrons).
The lengths of the traces are limited by the requirement of both SETs being sensitive.

Conclusion

We show the analysis of the pump fidelity at single shots based on charge counting using highly-sensitive single-electron transistors revealing P(1e)> 0.99 (without magnetic field applied) and the ability to discriminate different models of charge capture based on our results. These findings pave the way for efficient optimization strategies for enhanced capture fidelity.
Additionally, we demonstrated the minimum set of a self-referenced single-electron current source: A mesoscopic compound device employing a series of semiconducting dynamic quantum dots in combination with metallic single electron transistors (SET) able to monitor and attribute the changes of electrostatic potentials due to transfer errors between the dots on the single-electron level.
We acknowledge support in clean-room processing by P. Hinze.

References

[1] B. Kaestner et al., Phys. Rev. B 77, 153301 (2008)
[2] M. D. Blumenthal et al., Nat. Phys. 3, 343 (2007)
[3] P. Mirovsky et al., Appl. Phys. Lett. 97, 252104 (2010)
[4] S. Giblin et al., Nat. Comm. 3, 930 (2012)
[5] V. Kashcheyevs and B. Kaestner, Phys. Rev. Lett. 104, 186805 (2010)
[6] V. Kashcheyevs and J. Timoshenko, Phys. Rev. Lett. 109, 216801 (2012)
[7] M. Wulf, Phys. Rev. B 87, 035312 (2013)

Part of this work:
Phys. Rev. Lett. 110, 126803 (2013)