Time-resolved transconductance spectroscopy: Towards all-electrical spectroscopy of a single self-assembled quantum dot

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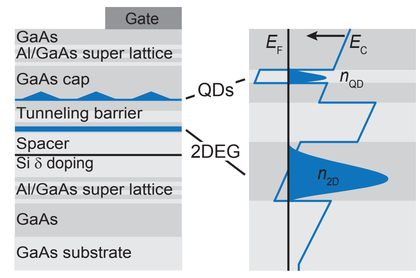
Introduction

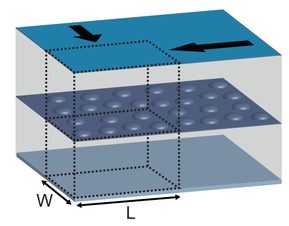
- High confinement energies and long spin lifetimes make InAs self-assembled quantum dots (QDs) ideal candidates for charge, spin and quantum state operations.
- The required control and detection would ideally be done electrically, on a single QD.
- A 2-dimensional electron gas (2DEG) in the vicinity of a QD layer can be used as charge reservoir and detector in transconductance spectroscopy (TCS).

➡ **Goal:** All-electrical single QD read-out and control.

Sample structure

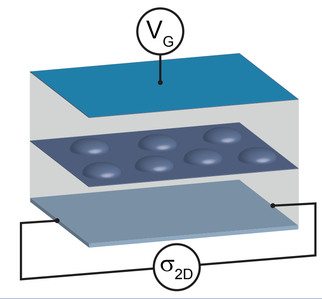
- AlGaAs heterostructure grown by MBE: Inverted HEMT with QDs in gate dielectric.





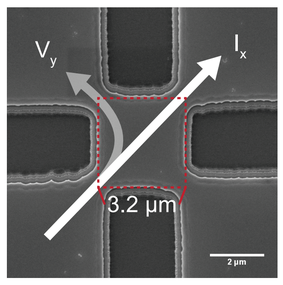
- Proportional scaling preserves conductance.
  ➡ $G = W/L\ \sigma$
  Relative signal given by density ratio n_{QD}/n_{2D}.

- Gate voltage determines QD charge. Detection by transconductance of 2DEG.

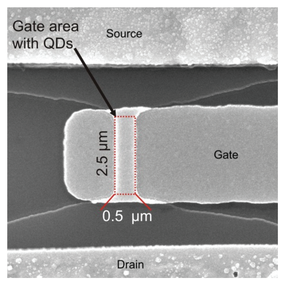


Principle of TCS

- Mesa defined by electron beam lithography and wet etching.
- Densities determined by Hall measurement: $n_{QD} \sim 10^{10}$ cm^{-2}, $n_{2D} \sim 10^{11}...10^{12}$ cm^{-2}.

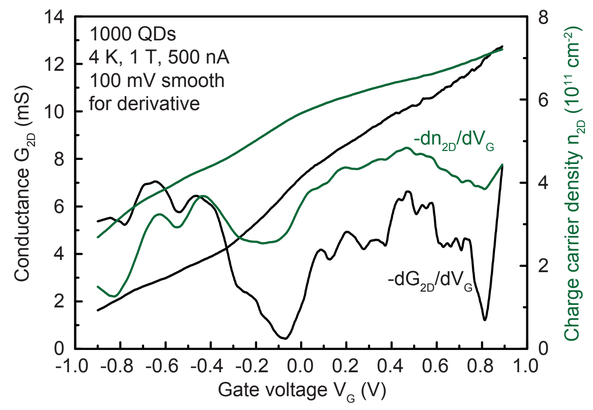


1000 QDs



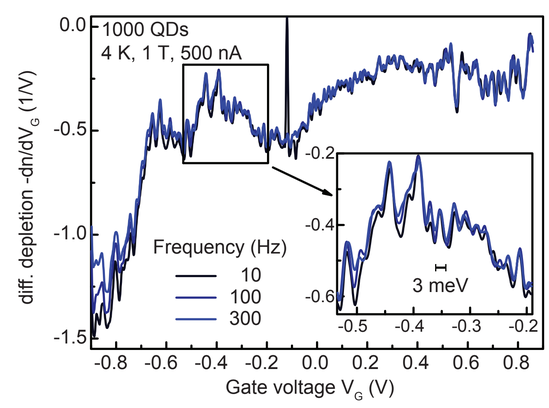
100 QDs

- Screening deplets (almost) one electron per QD charge.
- Constant 2D-density ➡ dn/dV shows QD-DOS.



Sub-ensemble resolution on 1000 QDs

- Hall measurements on 1000 QDs shows resolution below the inhomogeneous broadening of 30 meV (FWHM).

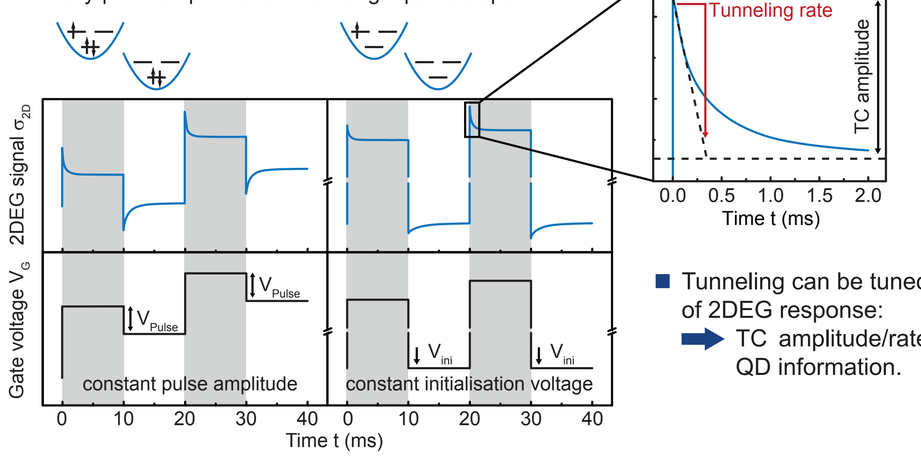


Principle of time-resolved TCS

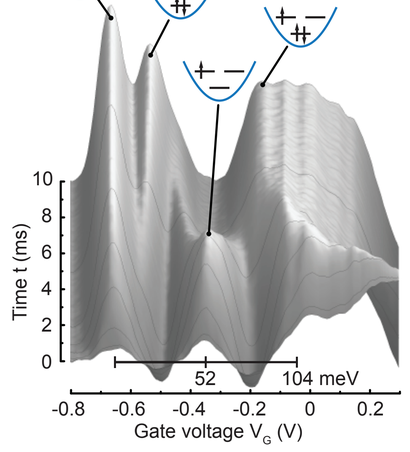
- TCS can be extended into **time-resolved** spectroscopy, to directly observe the tunneling processes.[1,2]
- In a **pulsed** (pump-probe) measurement scheme, excited (e.g. single-particle) levels can be detected; or tunneling rates can be used to distinguish degeneracy of many-particle states.
- Sequentially increasing QD charge **near-equilibrium** allows sensitive detection of charging/emission rates into many-particle states.
- Driving the system further into **non-equilibrium** allows to prepare and detect **excited states**.

Near-equilibrium mode:
Many-particle spectrum/rates

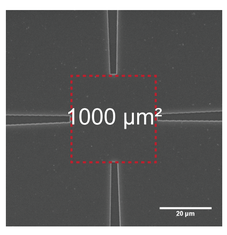
Non-equilibrium mode:
Single-particle spectrum



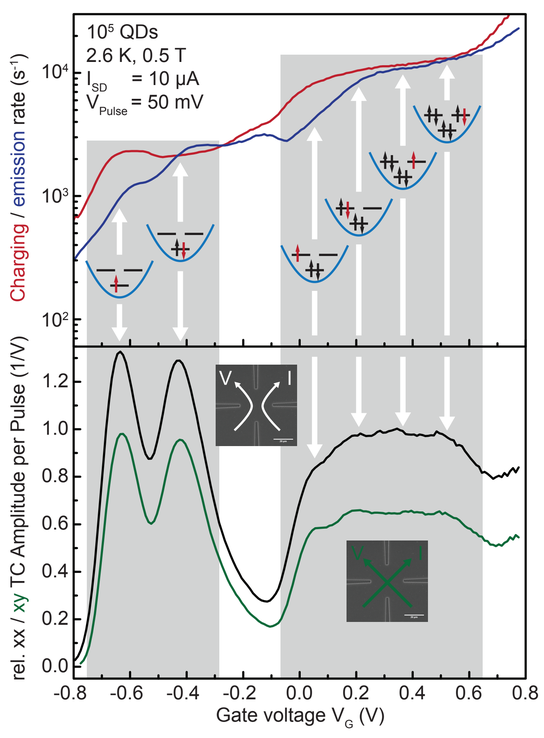
- Tunneling can be tuned independently of 2DEG response:
  ➡ TC amplitude/rate only contains QD information.



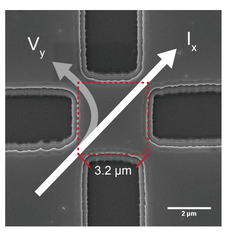
100,000 QDs



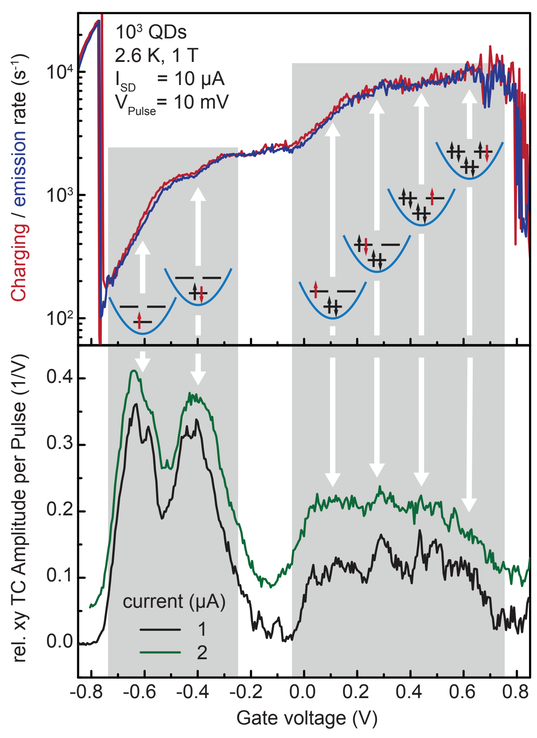
- Sample with **100,000 QDs**.
- Spectral distribution of 30 meV (FWHM) from inhomogeneous broadening of QD ensemble.
- Degeneracy visible in tunneling rate: Many-particle states distinguishable.



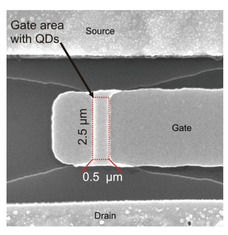
1,000 QDs



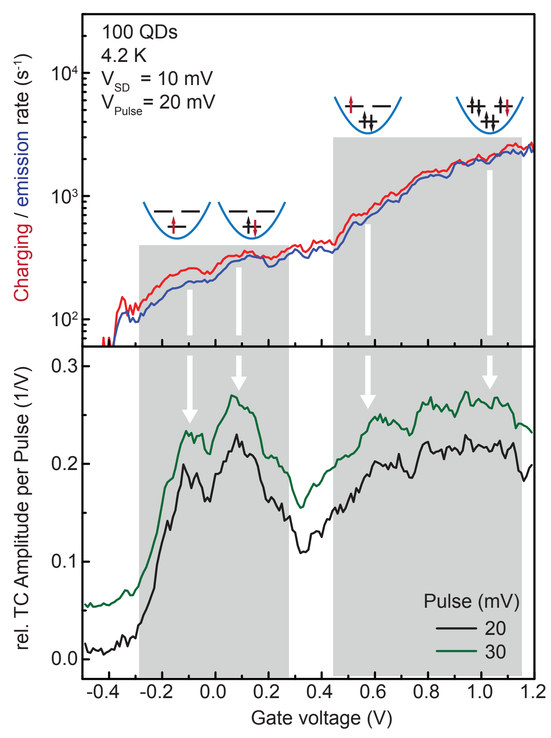
- Sample with **1,000 QDs**.
- Spectrum sensitive to pulse amplitude and current. Reproducible features for low currents.
- Shell structure visible in tunneling rates and many-particle spectrum.



100 QDs



- Sample with **100 QDs**.
- Shell structure distinguishable in tunneling rates and many-particle spectrum.
- Technique sensitive to detect sub-ensembles within 100 QDs.



Conclusion

- Demonstrated sensitivity of TCS for resolutions beyond the inhomogeneous broadening of the QD ensemble.
- Demonstrated capability of time-resolved TCS to detect sub-ensembles within 100 QDs.

➡ Sensitivity sufficient to reduce QD density.

Outlook

- Reducing QD density (~ 10 QDs/µm²) to separate individual QD spectrum.

➡ Single-particle spectrum of a singe self-assembled QD.

References

Non-equilibrium dynamics
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Tunneling dynamics
[3]S. L. Chang et al., Appl. Phys. Lett. **80**, 1270 (2002)
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