Single-shot readout in graphene quantum dots

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Journal Club Zumbühl Lab; 1.4.2022
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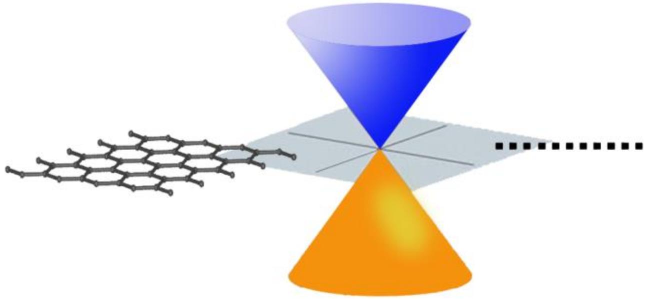
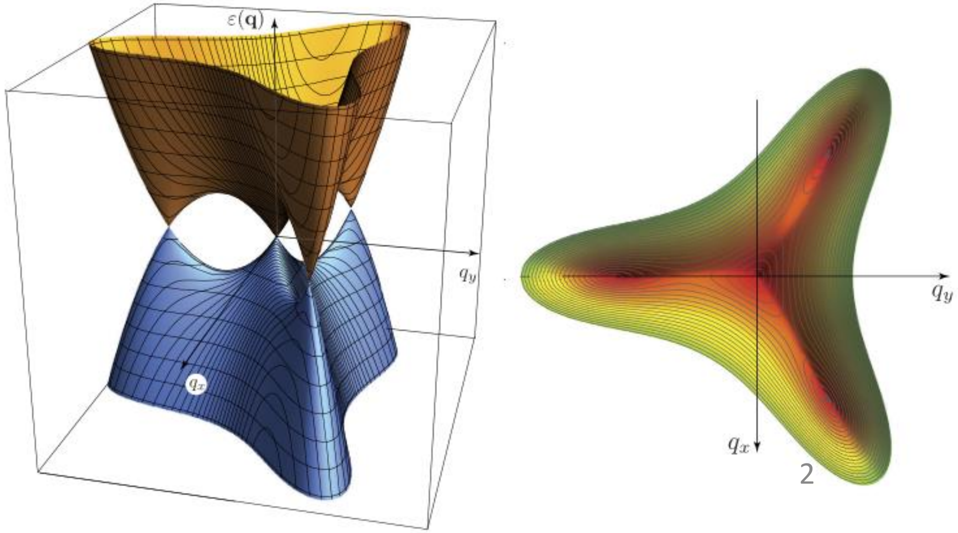
Why Graphene?



- Low nuclear Spin concentration: $^{12}C \sim 98.9\%: s = 0;\ ^{13}C \sim 1{,}1\%: s = \frac{1}{2}$
- Weak SOI: similar strength as in Si
- Strong 2D confinement:
  - Smaller devices (But harder fab…)
  - Stronger coupling to gates etc.

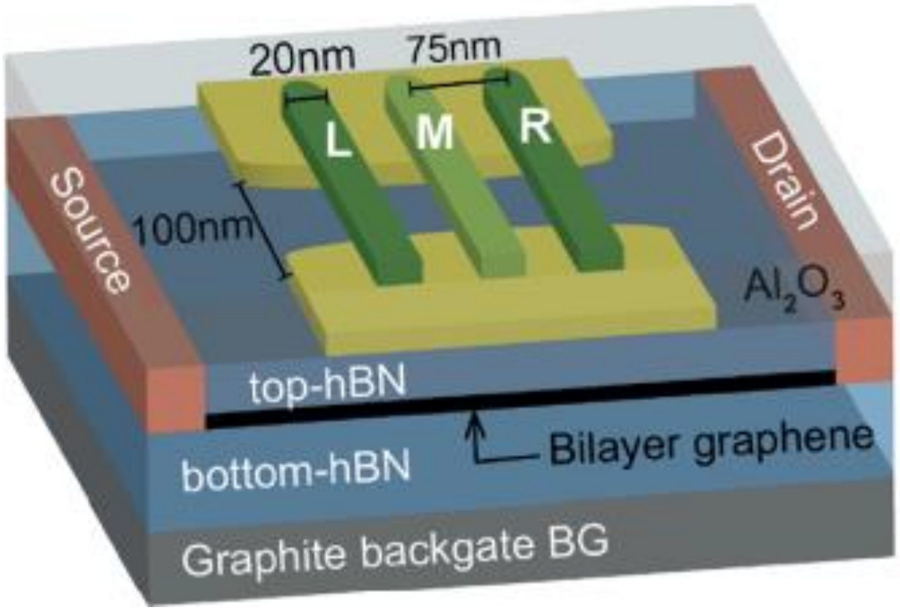
Bilayer Graphene:

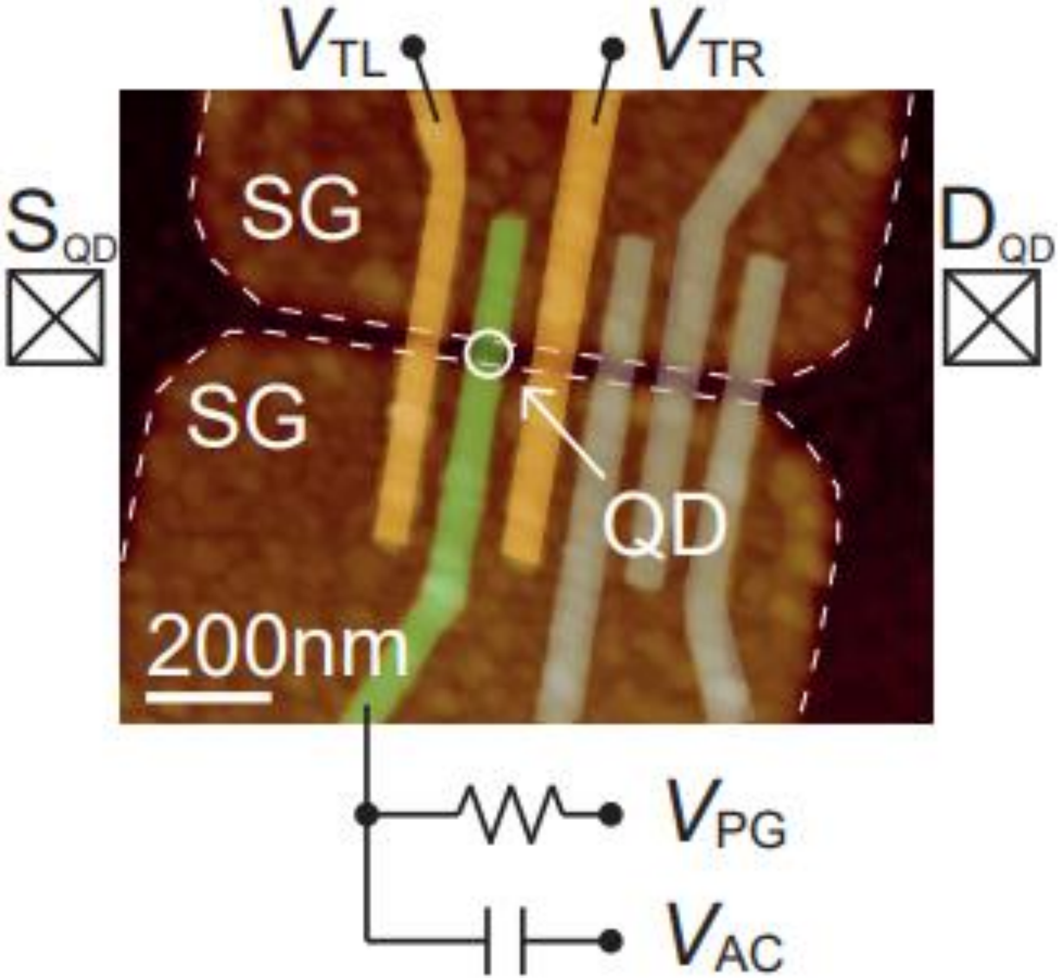
- 4 Atoms in unit cell, 2 directly on top of each other
  - Strongly coupled "dimer sites" due to p_z-orbital overlap
- Band Structure evolution:
  - Single Layer Graphene: Dirac cones, linear dispersion
  - Bilayer: Parabolic dispersion near Dirac points
  - Bilayer: "Weak trigonal wrapping"
  - **Band Gap opens in external electric field!**
  - **In general: 2 degenerate valleys!**



A. V. Rozhkov *et al. Phys. Rep.* **648** (2016)
Y. Zhang *et al. Nature* **459** (2009)

The Device (Pt. 1)

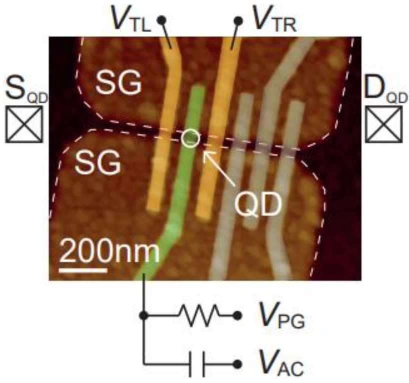


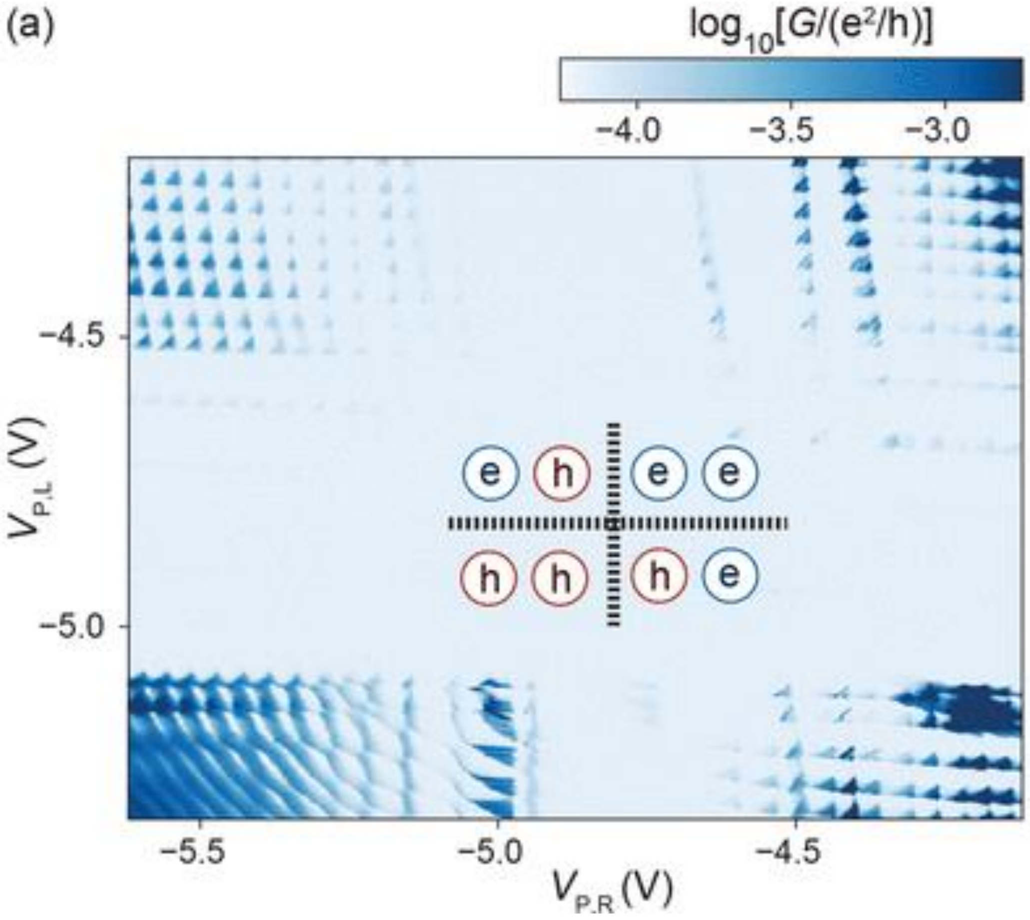


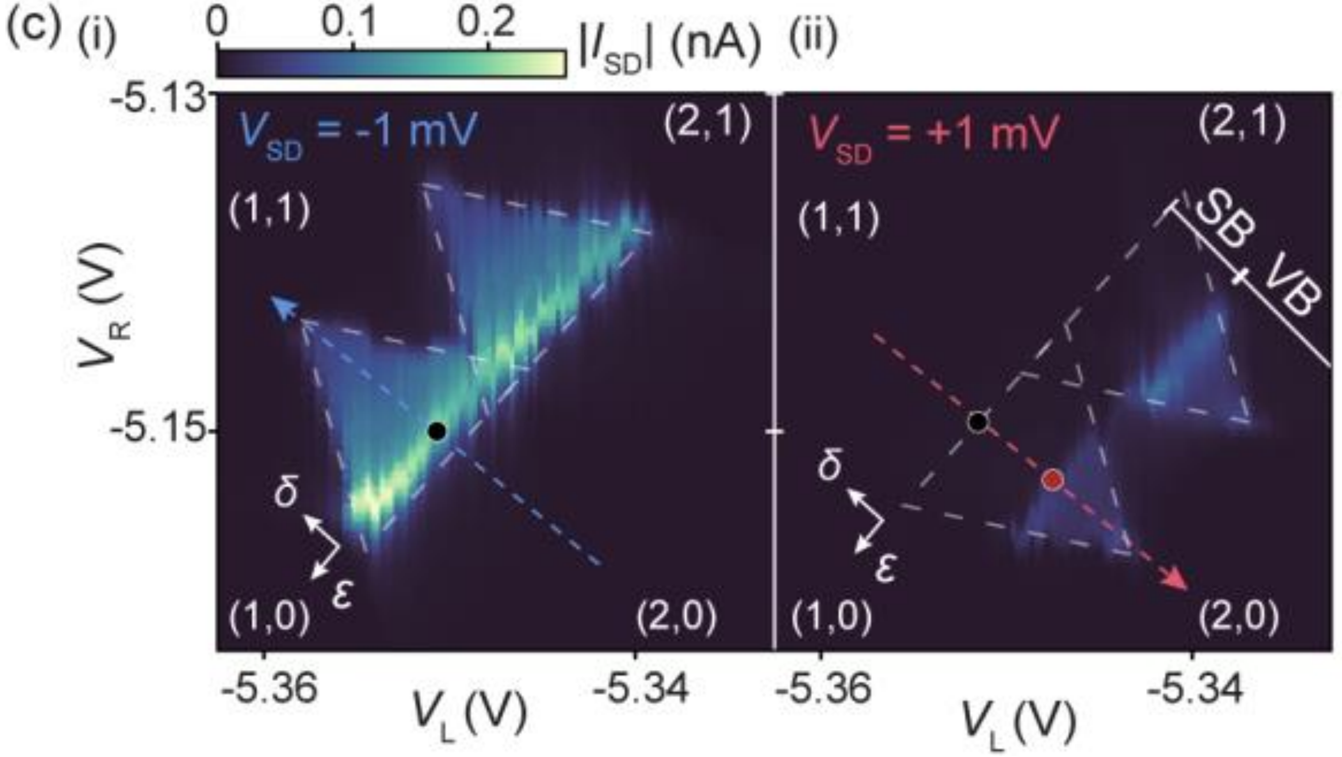
- Bilayer Graphene encapsulated in two hBN layers
- Graphite Backgate
- Two top gate layers:
  - Split gate for channel formation
  - Finger gates
  - Separated by 20 nm ALD Al_3O_2

C. Tong *et al. Nano Lett.* **21** (2021)

Previous Results

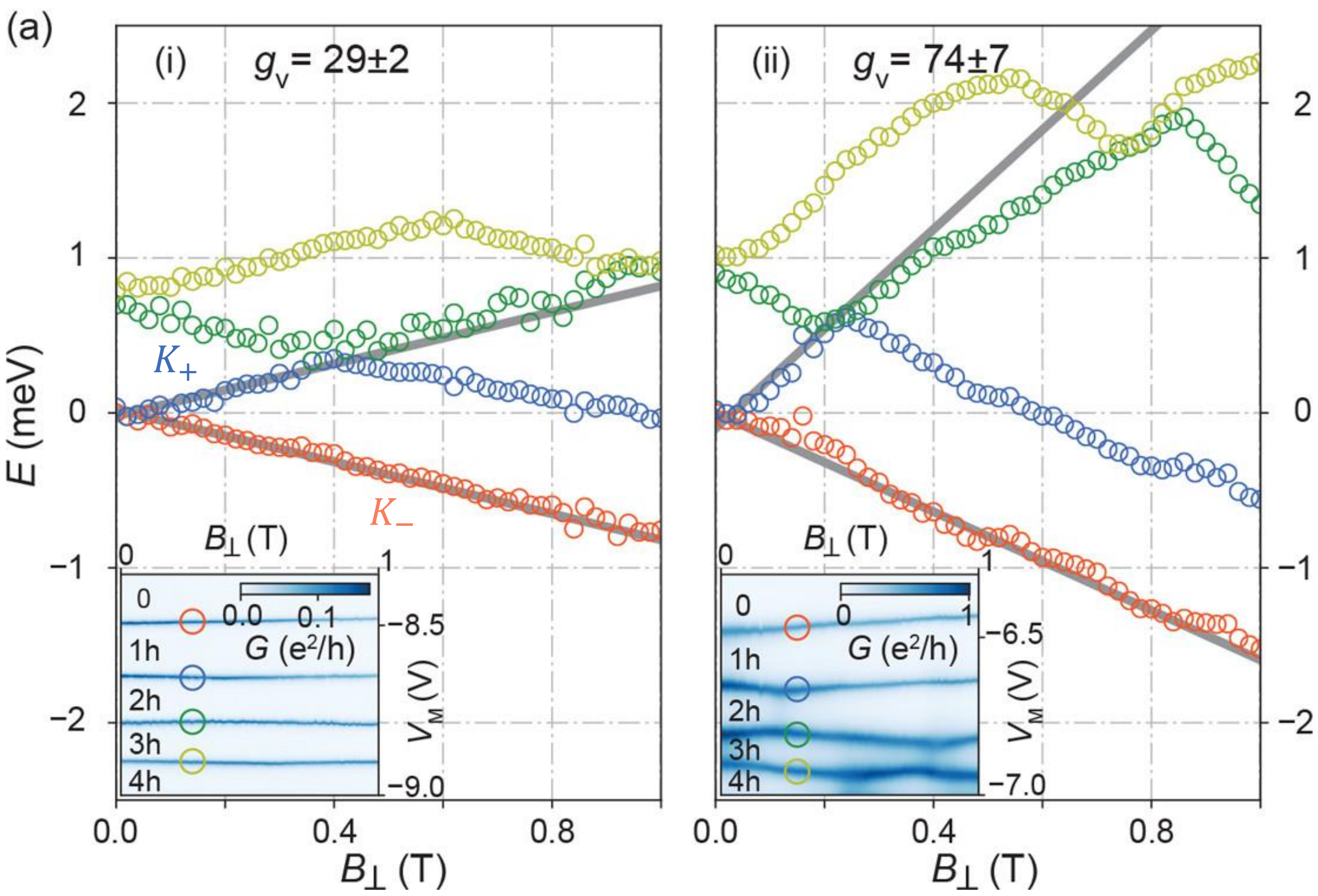


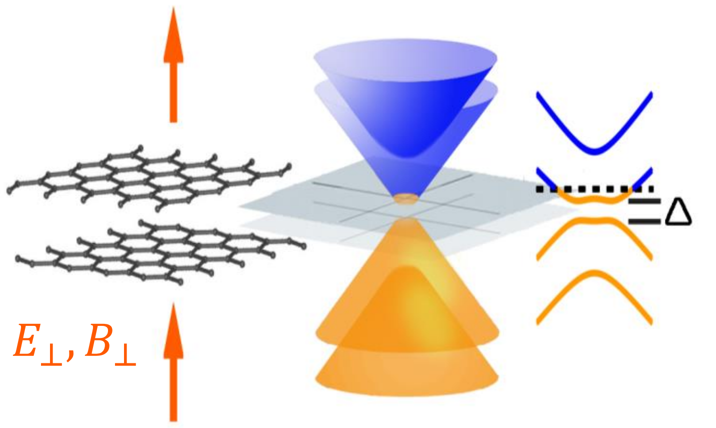




H. Overweg *et al. Nano Lett*. **18** (2018)
C. Tong *et al. Nano Lett.* **21** (2021)
C. Tong *et al.* arXiv:2106.04722v2

Valley-Splitting and Valley-g-Factor

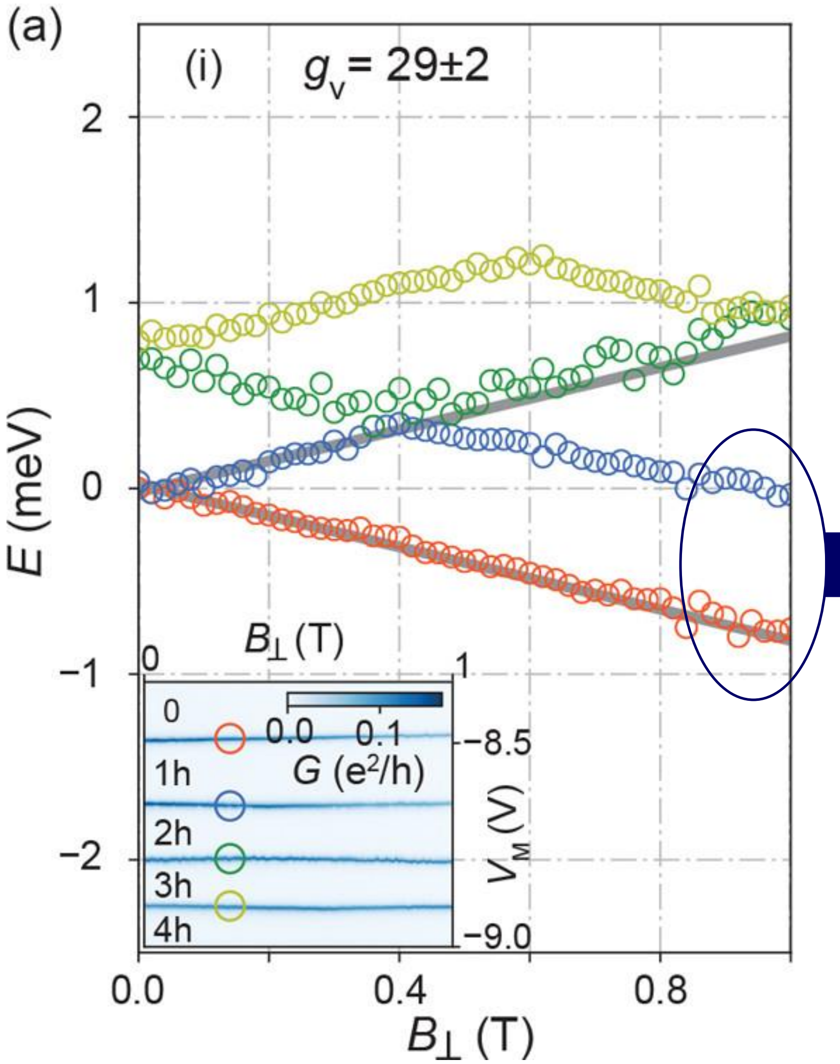




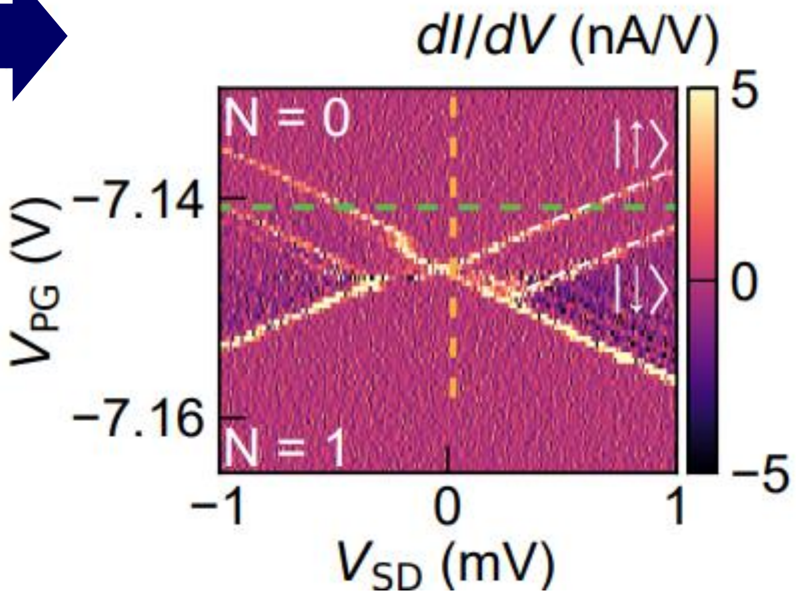
- Operation as a hole-SQD
- Ground state splits in perpendicular magnetic field $B_\perp$
- Valley-g-Factor $g_v = \frac{\Delta E_{K^+,K^-}}{\mu_B B_\perp}$
- Strong tunability of valley-g Factor through dot size

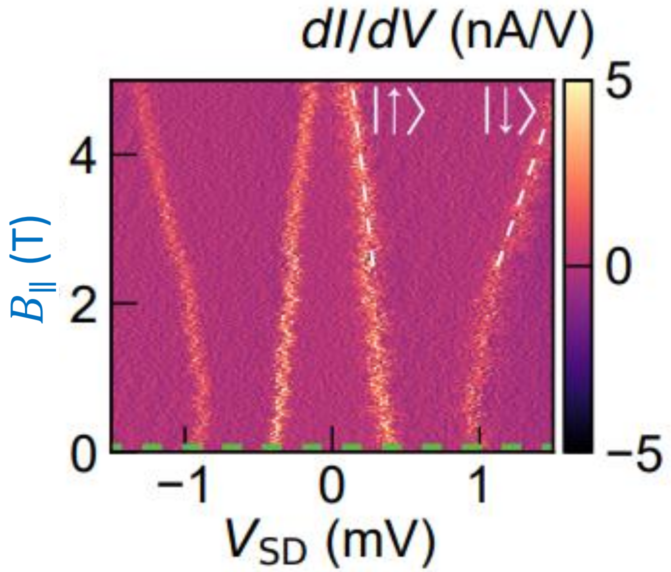
H. Overweg *et al. Nano Lett*. **18** (2018)

Creating an effective Two-Level-System



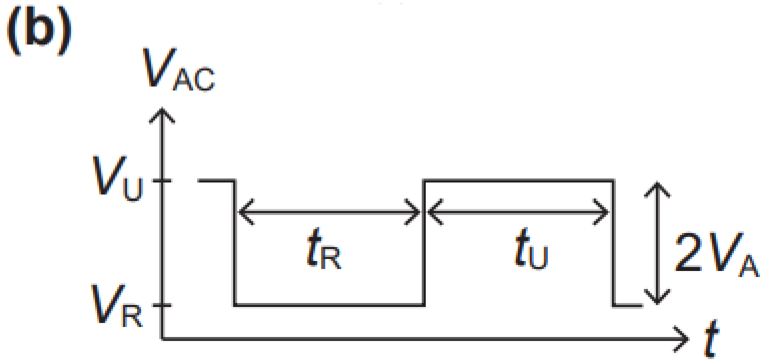
- Operation as a hole-SQD at 9 mK
- Valley-polarized ground $|K' \uparrow\rangle = |\uparrow\rangle$ & 1st excited $|K' \downarrow\rangle = |\downarrow\rangle$ state for $B_\perp = 1.75\ T$
- Splitting as seen in coulomb diamond
- Additional in-plane $B_\parallel$ **only couples to spin!**
- Observe $g_s = 2$ and $\Delta_{SO} = 60\ \mu eV$



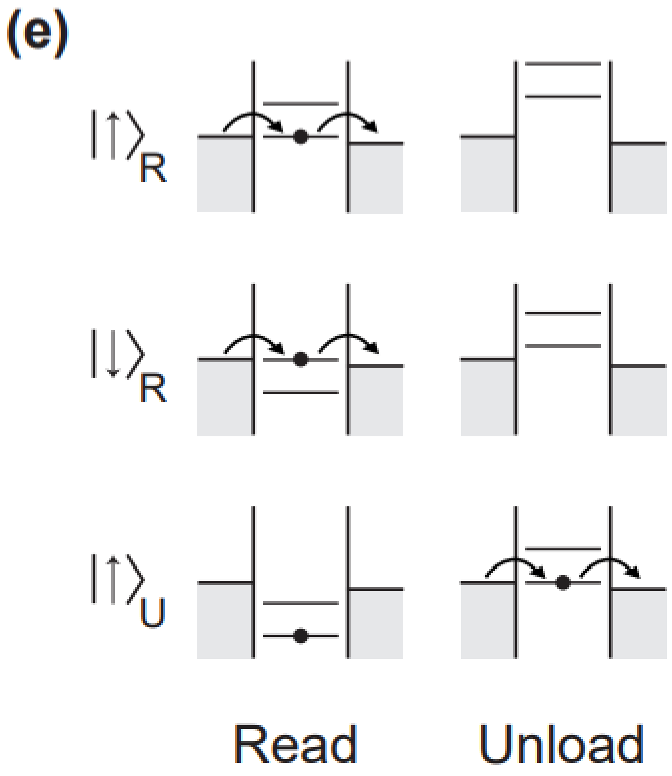


H. Overweg *et al. Nano Lett*. **18** (2018)

Pulsed Transient Current Spectroscopy

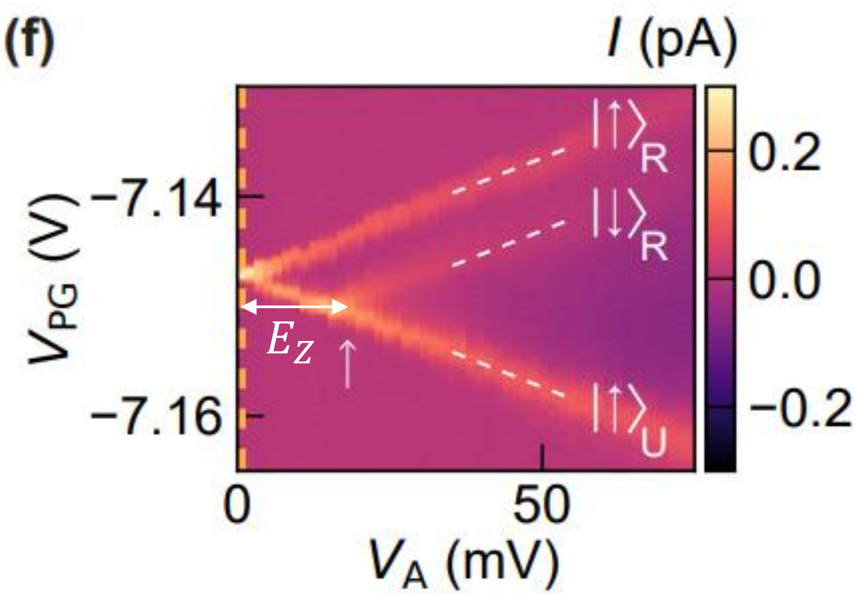


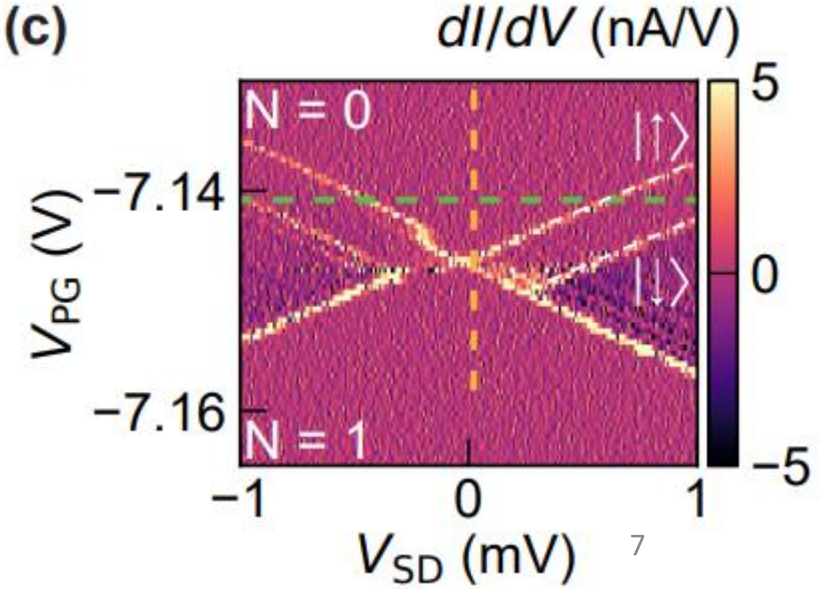
- Constant bias: $V_{SD} = 40uV$
- 2-Level pulse scheme on plunger
- Current observed either during read (R) or unload (U) phase:
  - Resonant tunnelling during R (excited state only at high B)
  - Relaxation during R blocks current, observed in U



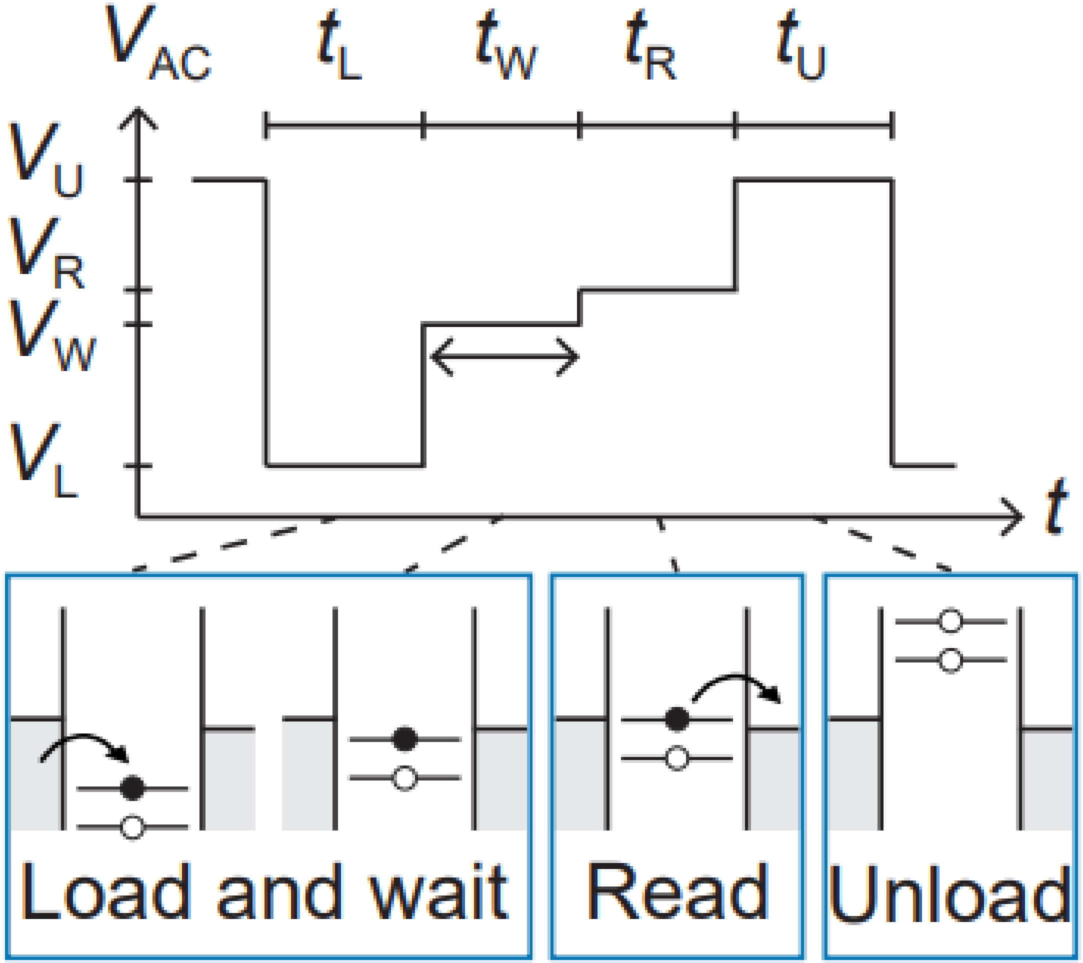
- Pulse amplitude lever arm: $\alpha_{att} = 0.21 \quad \alpha_{PG} = 0.05$

- Allows conversion of Pulse amplitude to energy





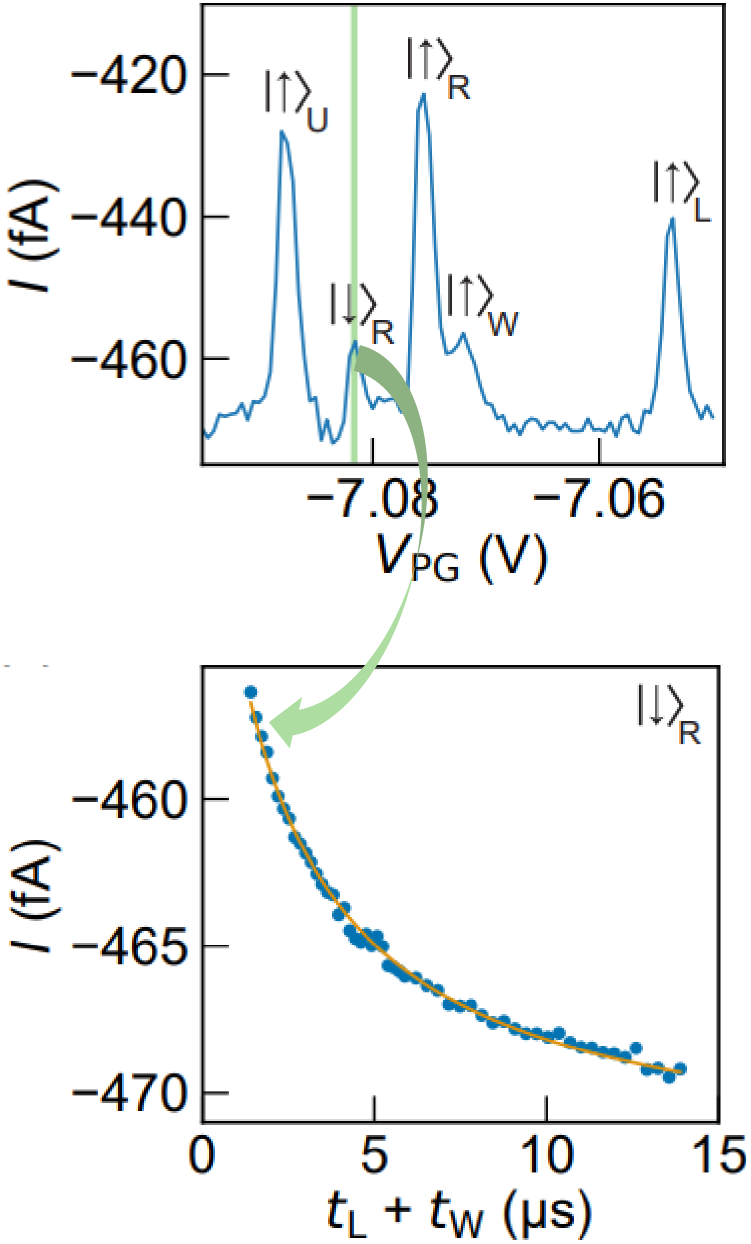
Measuring T_1



Time-integral of 4-level scheme kept at 0

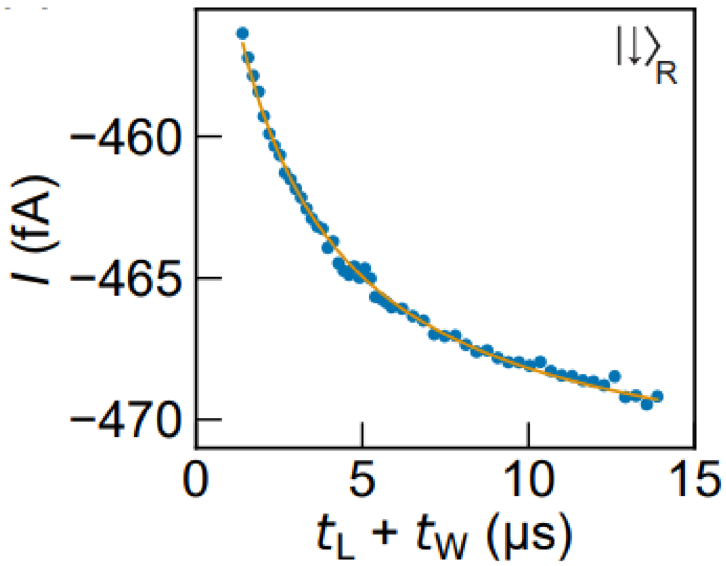
Choosing correct peak in plunger trace

Increasing $\tau = t_L + t_W$ results in decay of observed current



- Can be done through $I_{|\downarrow\rangle_R}(t_R)$ measurement
- But only gives lower bound!
- **Better 4-level pulse scheme**

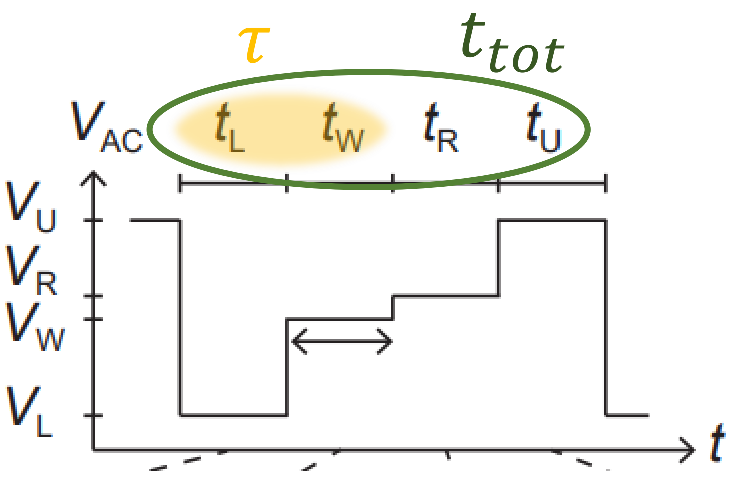
Measuring T_1

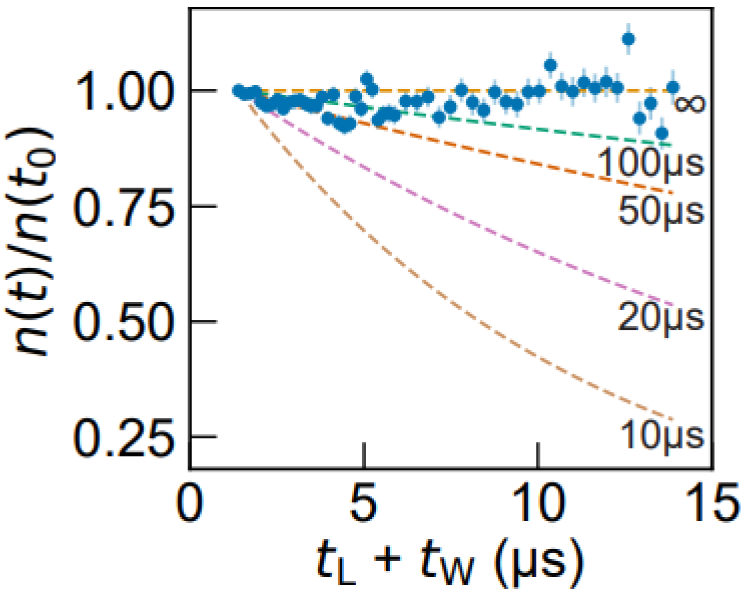


- Problem: long τ -> long t_{tot}

$$I = \langle n \rangle \frac{e^{-\tau/T_1}}{t_{tot}}$$

Carriers per pulse cycle



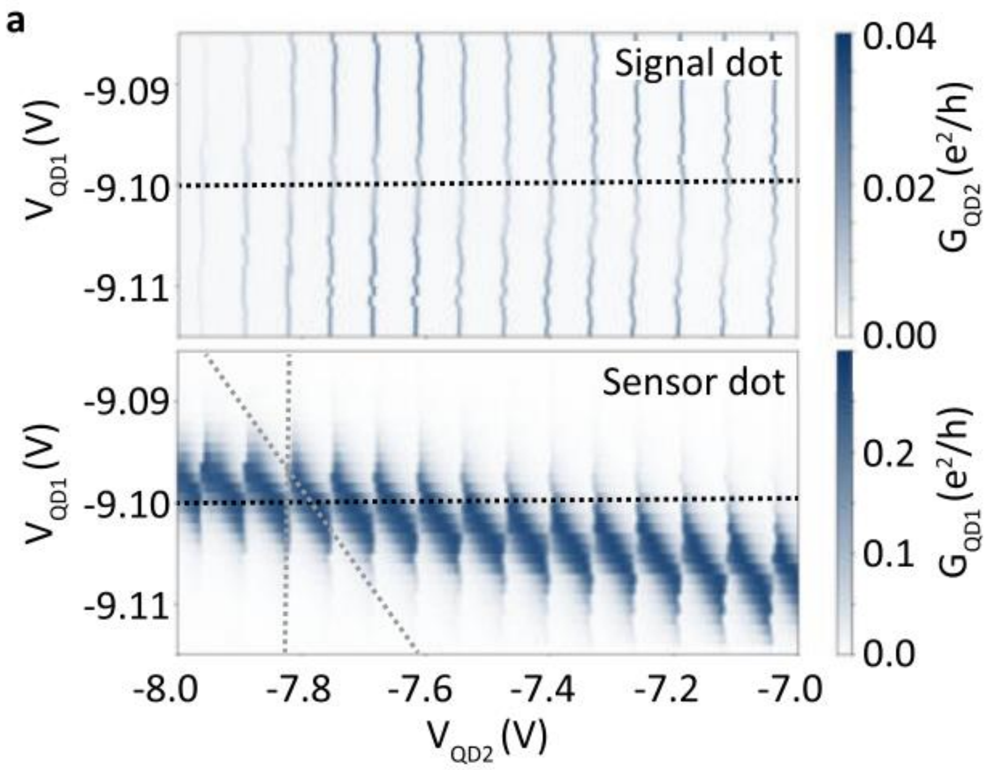


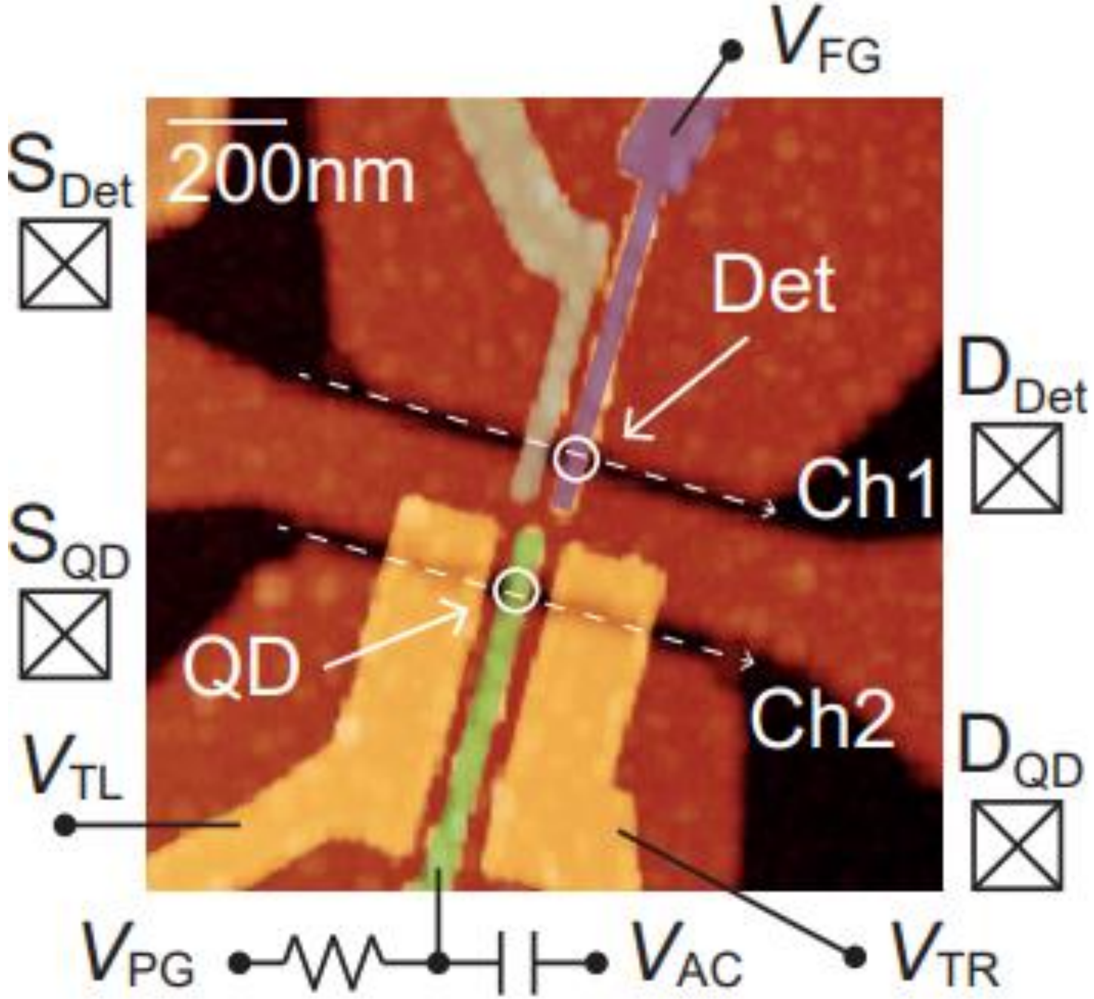
- Current decreases as pulse scheme gets longer!
- Limited by background noise on order 0.1 fA (!!) on hours-timescale

- Conservative estimate: $T_1 \geq 100\ \mu s$

- **Need better readout!**

The Device (Pt. 2)

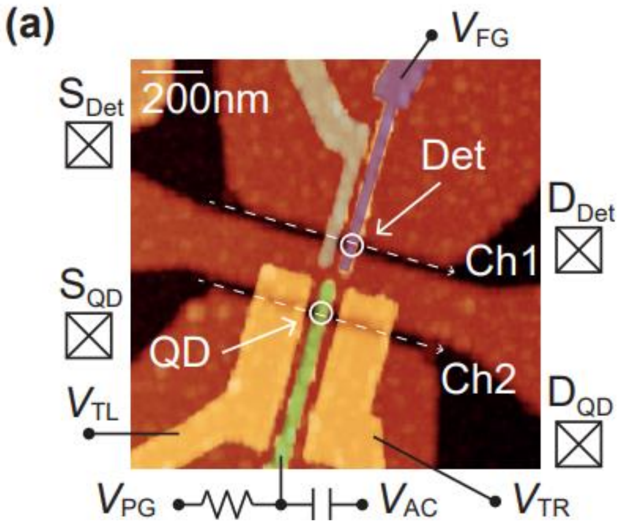




- Sensor dot next to target QD
- Separated by 150 nm wide depletion gate
- Much wider barrier gates than in device 1
- Charge sensing described in previous work

A. Kurzmann *et al. Nano Lett.* ***19*** (2019)

Single-Shot Readout (Pt.1)

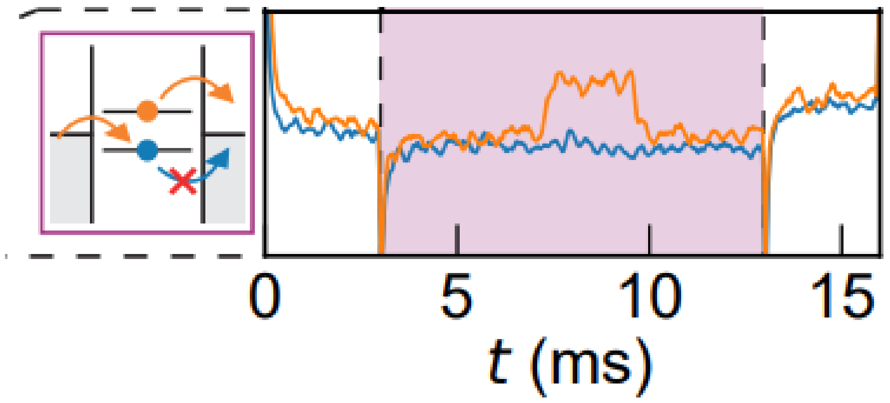


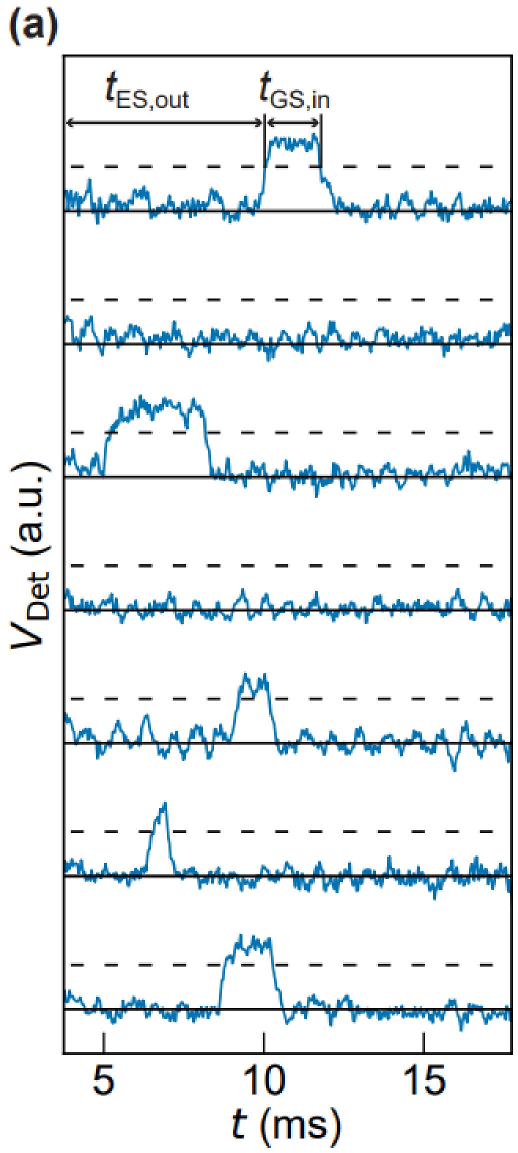
- Tune to valley-polarized spin-2LS:
  $B_\perp = 2\ T$
- No need for in-plane $B_\parallel$ (?)

- Elzerman-readout:

- Monitoring voltage across sensor
- 3 different plunger voltage regimes:
  - Single step: both levels above reservoir
  - Multiple blips: Sequential tunnelling to GS
  - Single blip/none: Good for “qubit”-readout

Single-Shot Readout (Pt.2)





- 10’000 single-shot traces:
- Extract tunnel times:
  - Unloading of excited state: $t_{ES,out}$
  - Reloading of ground state: $t_{GS,in}$
- Detector-Voltage histogram shows 2 peaks
- Fits to tunnel times yield:
  - $\tau_{ES,out} = 4{,}64\ ms$
  - $\tau_{GS,in} = 0{,}66\ ms$

- Readout fidelities & state visibility:
  - $F_{ES} = 90{,}1\ \%$
  - $F_{GS} = 97\ \%$

$V = 87.1\ \%$

Conclusions

- Excited state lifetime in bilayer graphene
- $T_1 \sim ms$ Comparable to other electron spin qubit systems

- Single-shot readout realized using DC-sensor dot

Outlook:

- Improve readout speed using RF-sensor dot or dispersive sensing
- Readout of DQD system with spin/valley blockade
- Driving the qubit?