A CMOS silicon spin qubit

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Spin Qubit Virtual Meeting

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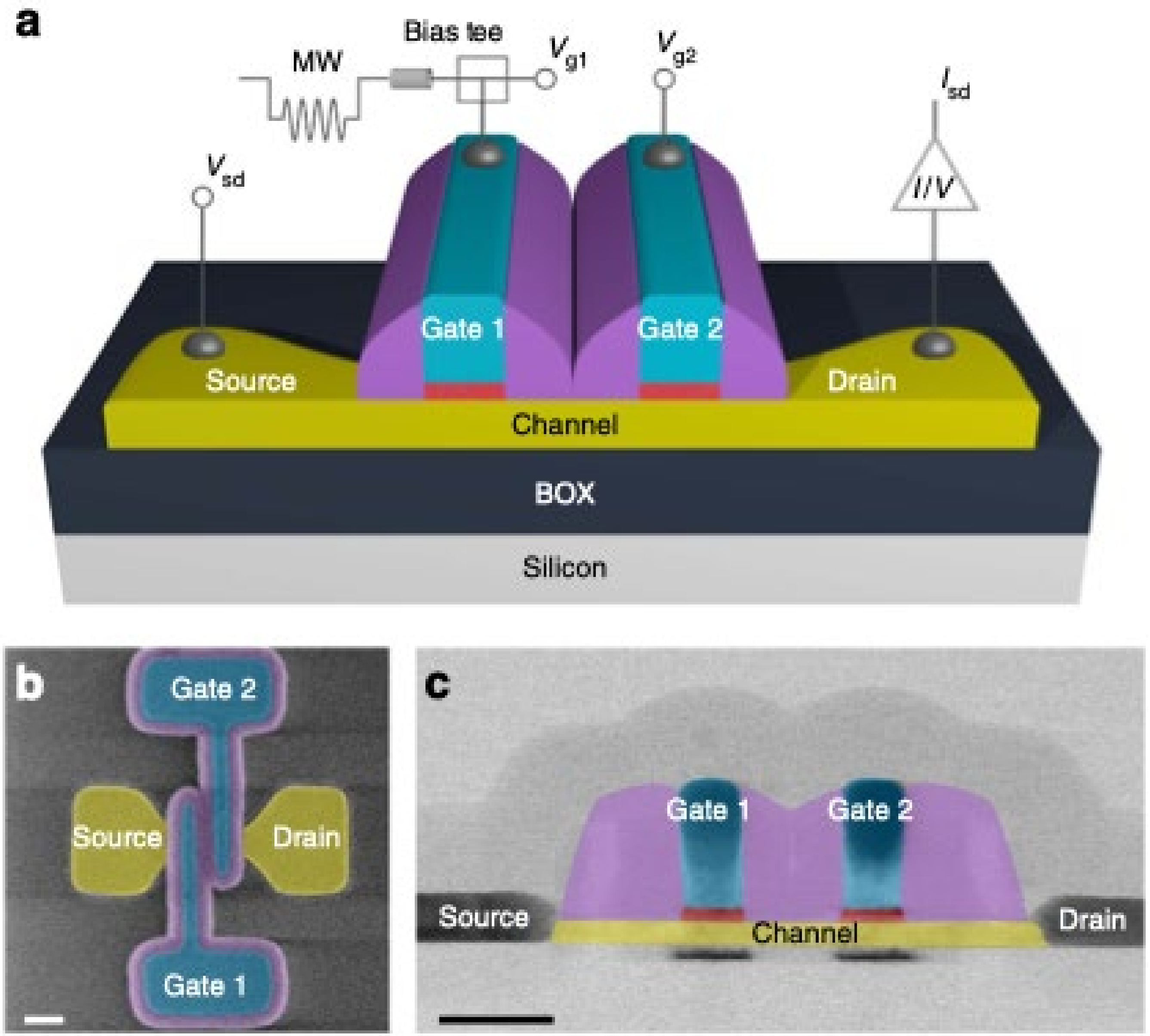
Presentation by Rafael Eggli

Introductory Notes

- Hole spin qubits in silicon double quantum dots
- Etched nanowire field-effect transistor
- 2 Gates
- No single-shot readout
- Demonstrate two-axis qubit control

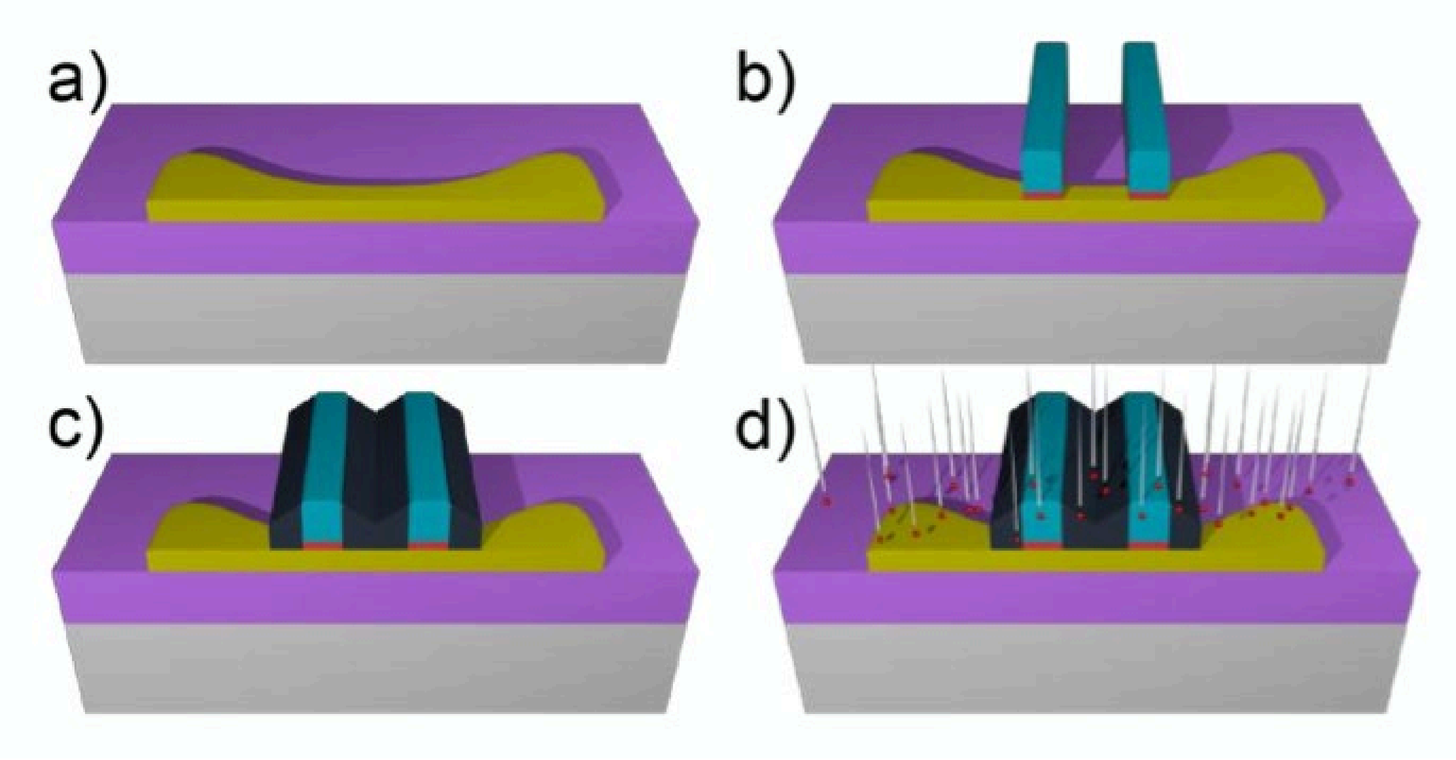
- Accessible style of writing
- Extensive supplementary materials and explanations

The Device



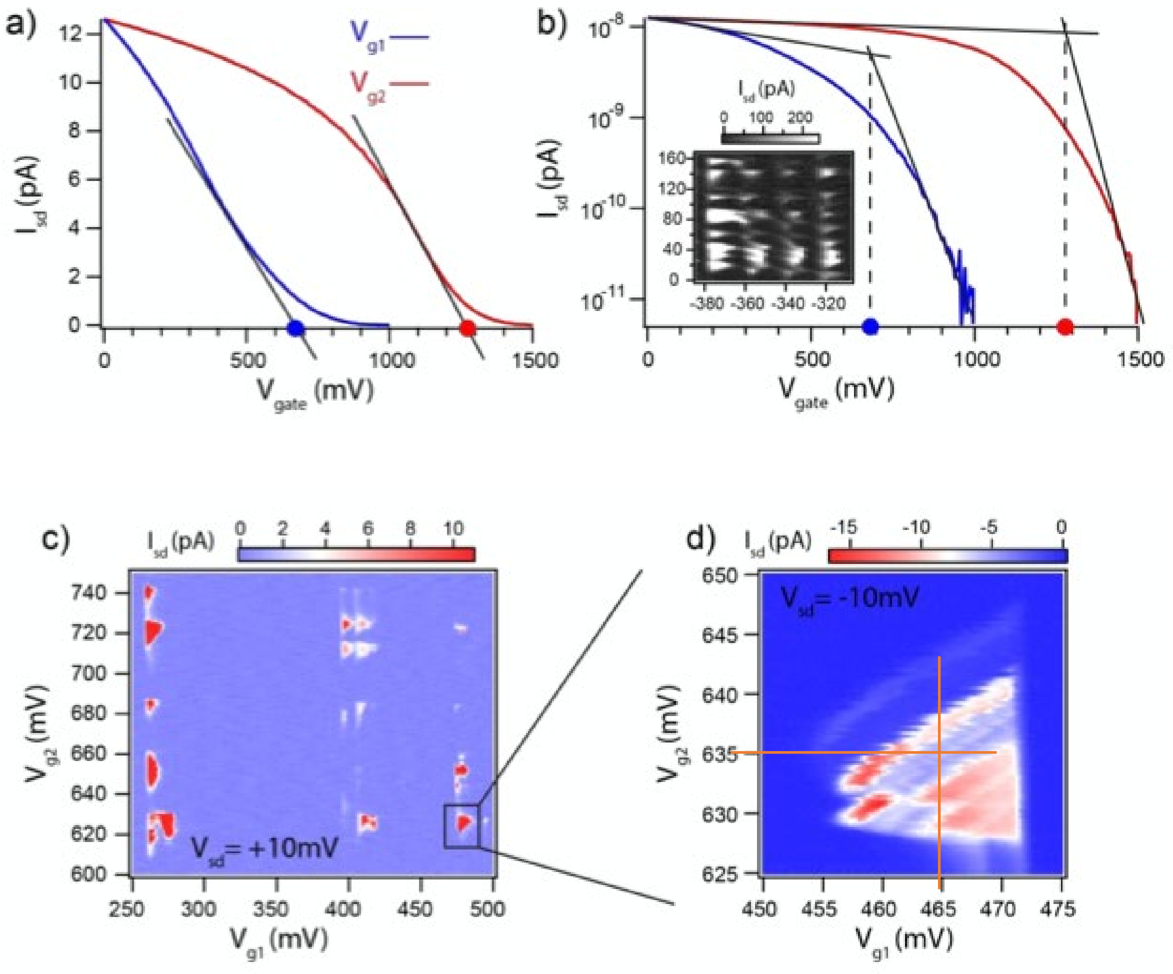
- Two gates:
  - G1 used for qubit operation (EDSR)
  - G2 defines readout-QD
  - 35nm wide and separated by 30nm
  - 5nm TiN (red), 50nm polysilicon (blue)
  - Insulating SiN spacers (purple)
- Channel:
  - Undoped Si (10nm thick, 15-20nm wide)
  - Oriented along [110]-direction
  - Fully covered by gates and spacers
- Source/Drain:
  - Boron ion implantation for p-type doping
  - Low-resistance ohmic contacts

Device Fabrication



- Deep-UV (DUV) lithography and subsequent etching of channel
- Gates added by DUV and e-beam lithography (EBL)
- Self-aligned spacers
- All steps (except for EBL) are CMOS-compatible
- High-precision realignment and multiple patterning allows for DUV to replace EBL steps

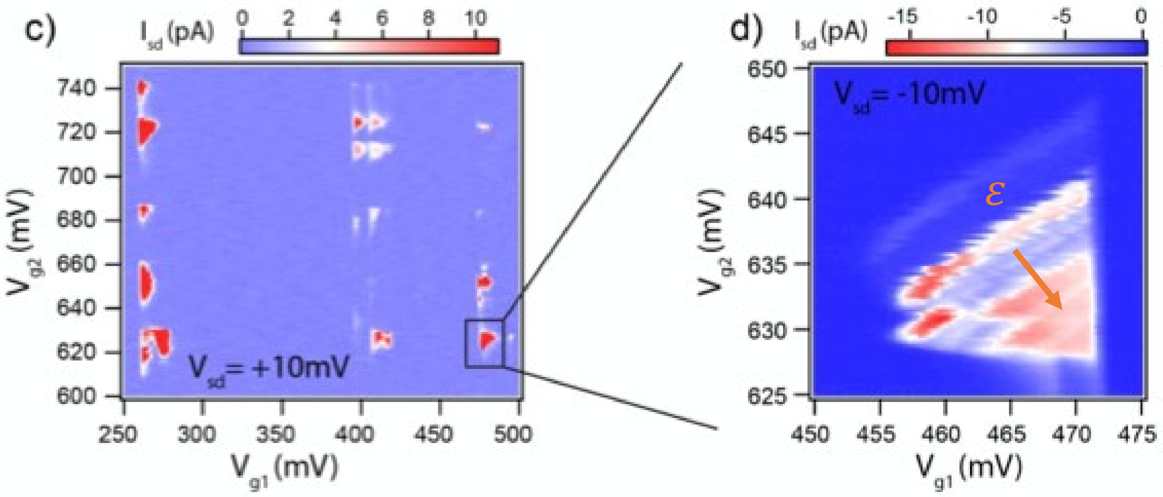
Double-Dot Characterisation: Dot Occupancy

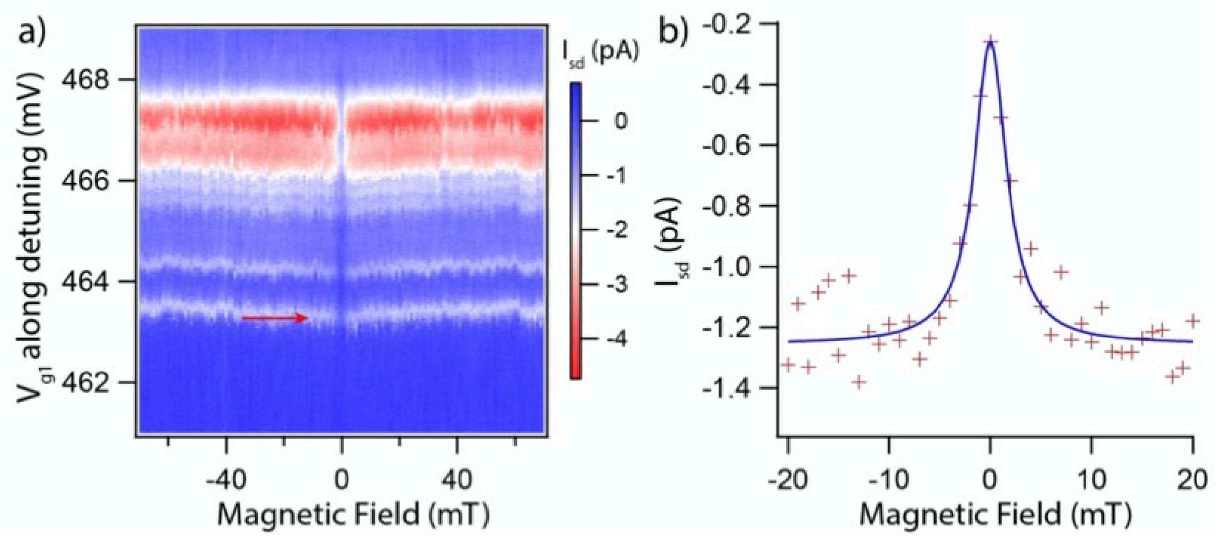


- Room-temperature SD-current vs gate voltage measurements
- Estimate threshold voltages (blue/red dots)
- Few hole regime not accessible
  - Full blockade of transport at estimated threshold for low temperatures
- Assume $N = 0$ at threshold
- Average spacing of two charge states (insert b)): $\sim 20mV$
- Hole occupation estimation (base of bias triangle at $(V_1, V_2) \approx (465{,}635)\ mV$:
  - $N_{QD1} = 12 \pm 5$
  - $N_{QD2} = 33 \pm 5$

Pauli Spin Blockade

- Basis of bias triangle at Vsd = -10mV
- Define detuning-axis ε
- Current drops along ε for $B \rightarrow 0$
- Indication of PSB-relaxation through spin-orbit coupling at nonzero magnetic Field
- Relaxation rate $\Gamma = 1.75\ MHz$ extracted from lorentzian fit
- Blocking of excited states not explained -> unclear to us as well?



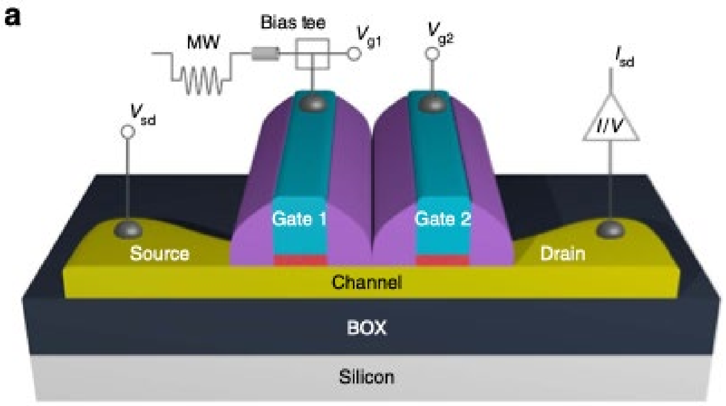


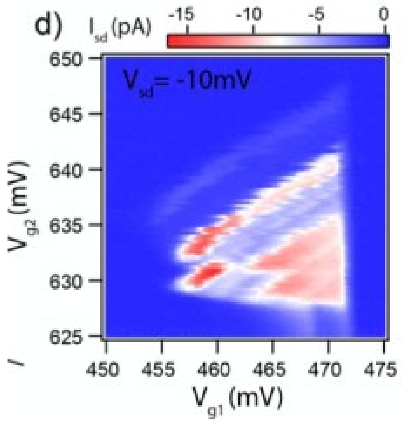
EDSR

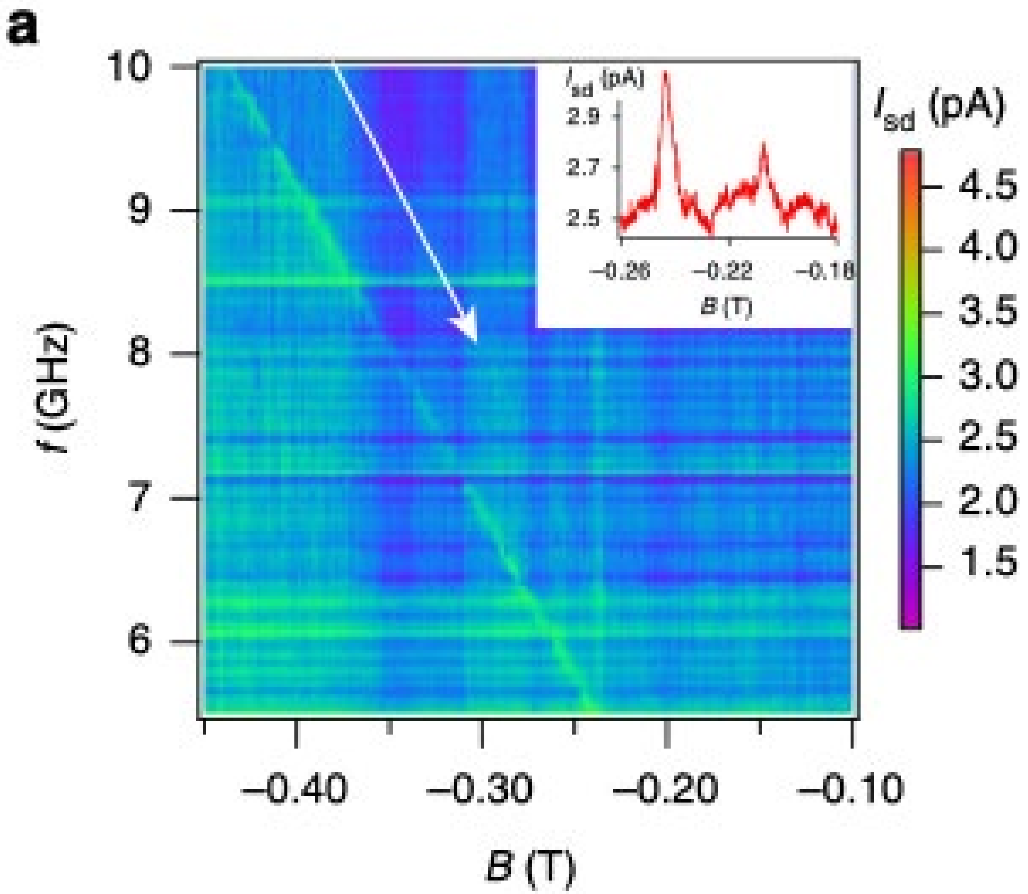
- Operate in spin-blockade regime
- MW signal applied on gate G1
- Observe 2 linear features in I(f,B)-scan
- In line with theoretical expectation:

$$hf = g\mu_B B$$

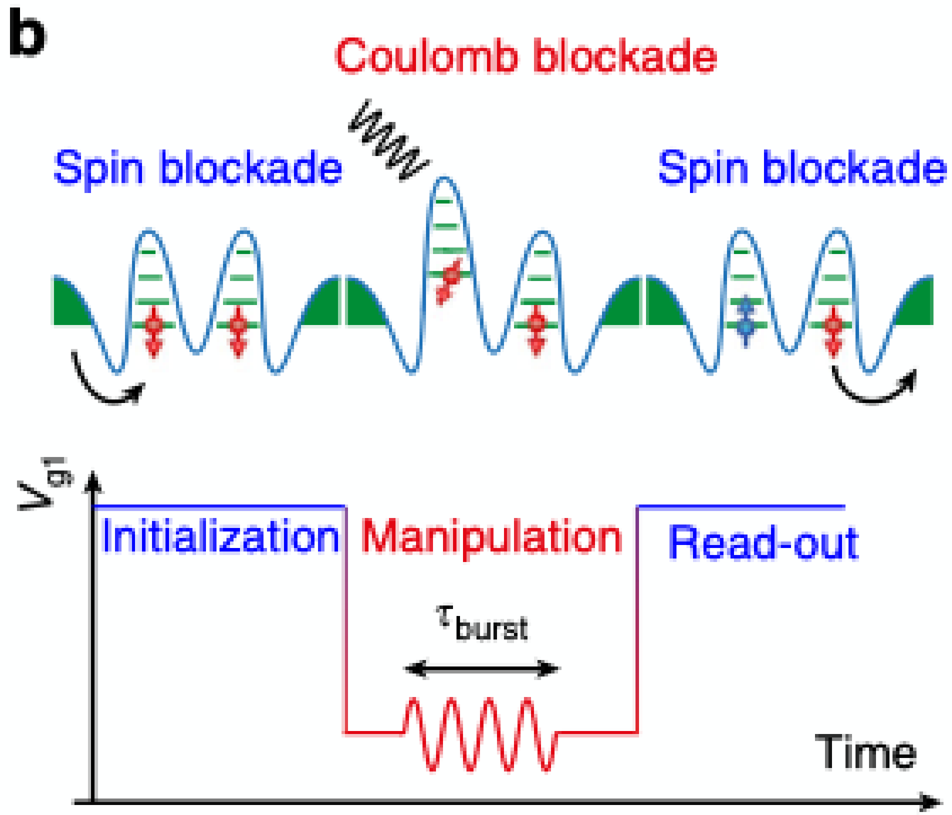
- Bright: QD1, $g = 1.63$
- Faint (white arrow): QD2, $g = 1.92$







Coherent Spin Manipulation



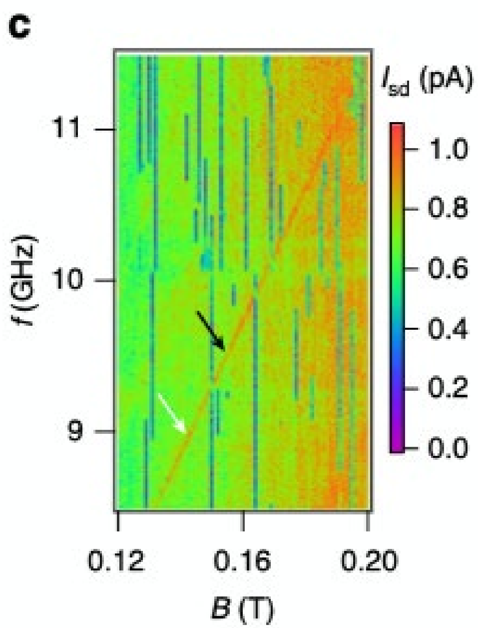
- G1 used to swich to coulomb blockade regime
- After manipulation: »abrupt» return to spin blockade regime for readout
- No single-shot readout

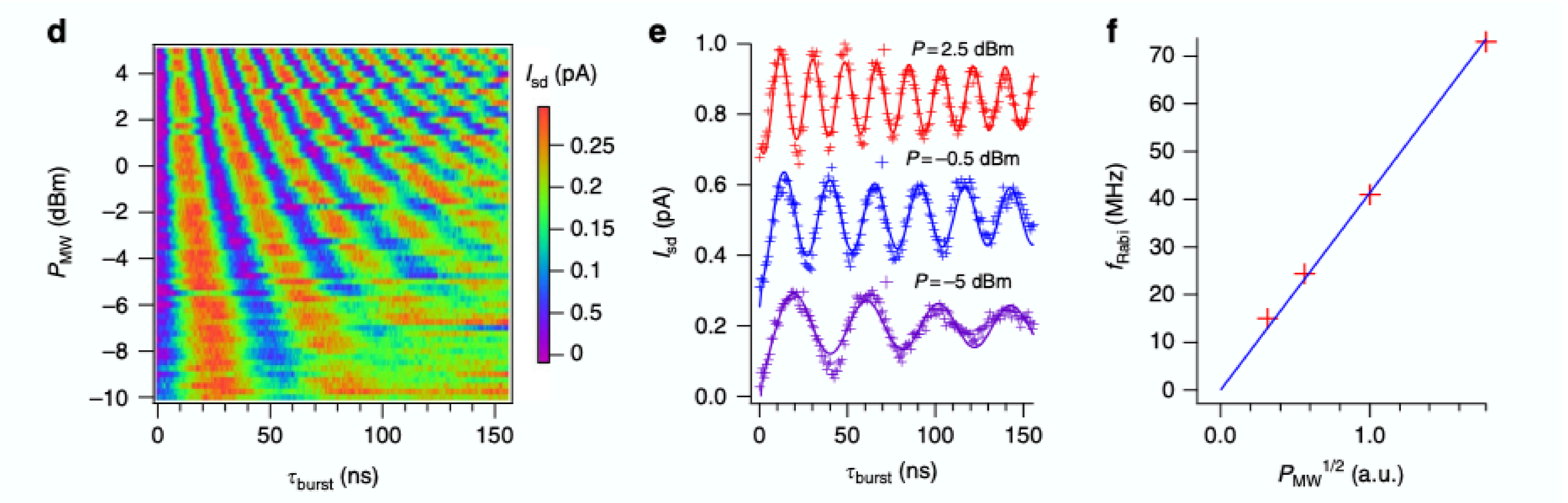
Rabi Oscillations

- Current as function of different pulse length and MW power
- Operated with $B = 0.144T$ and $f = 8.938\ GHz$ (white)

$$f_{Rabi} \propto \sqrt{P_{MW}} \propto V_{MW,amplitude}$$

- Highest P_{MW} leads to $f_{Rabi} \approx 85\ MHz$

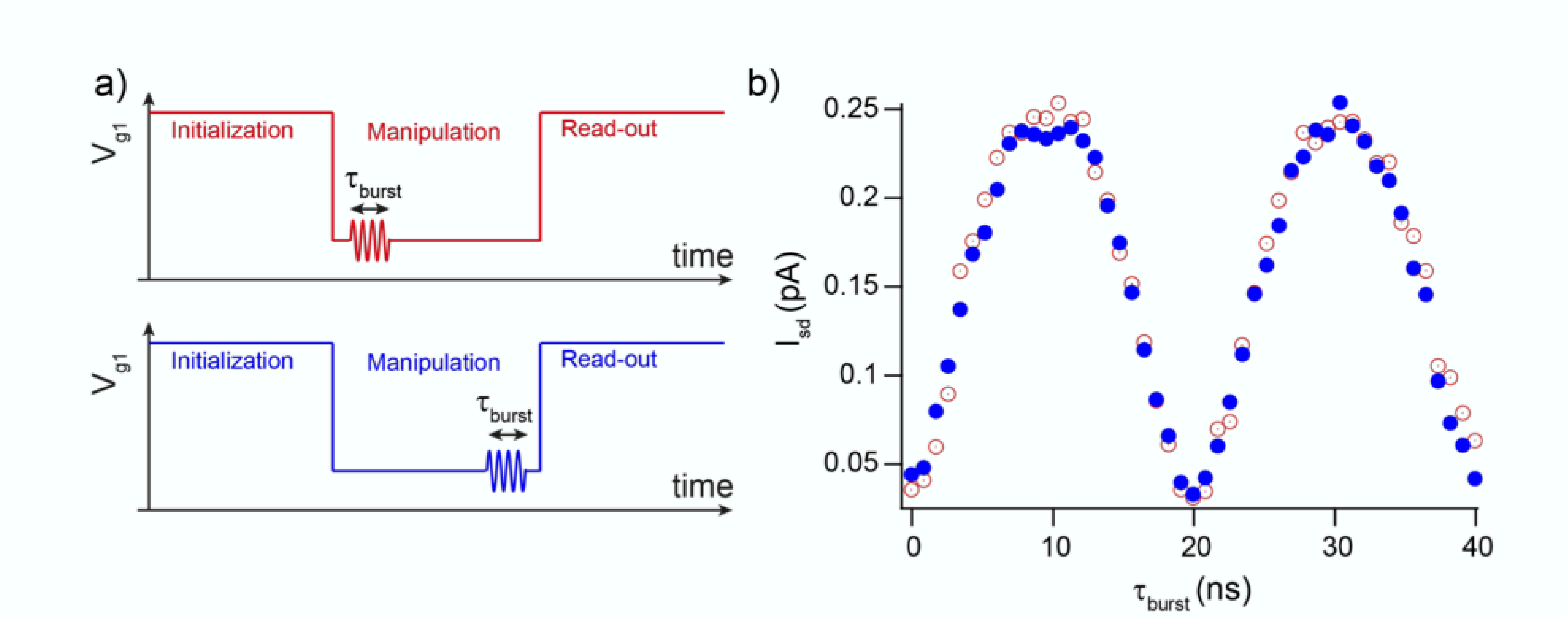




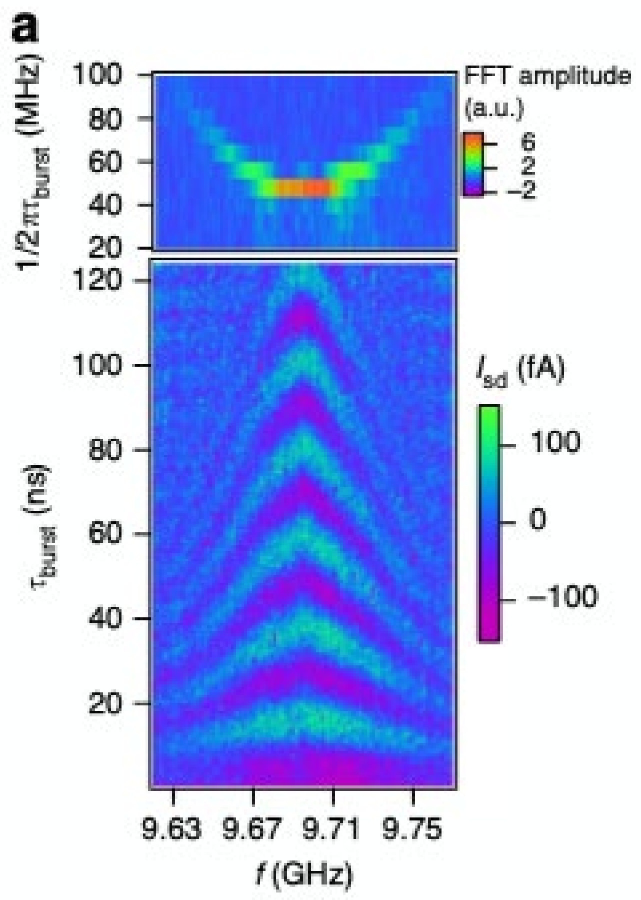
Spin Relaxation during Manipulation

- Rabi experiments with MW pulse at start/end of manipulation phase
- No changes in burst-duration dependence observed

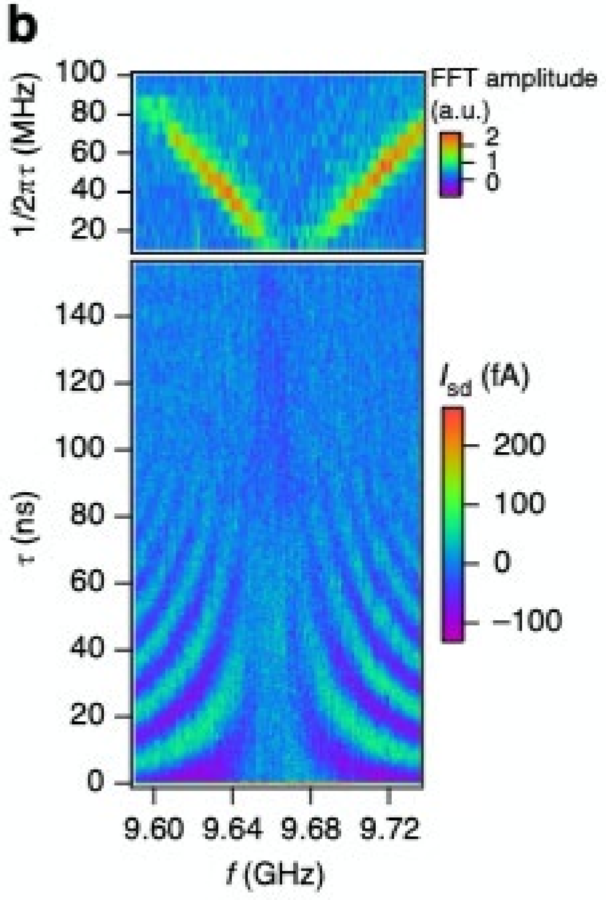
$$\Longrightarrow \; T_1 \gg 175\, ns \text{ (= manipulation time)}$$



Dephasing and Decoherence

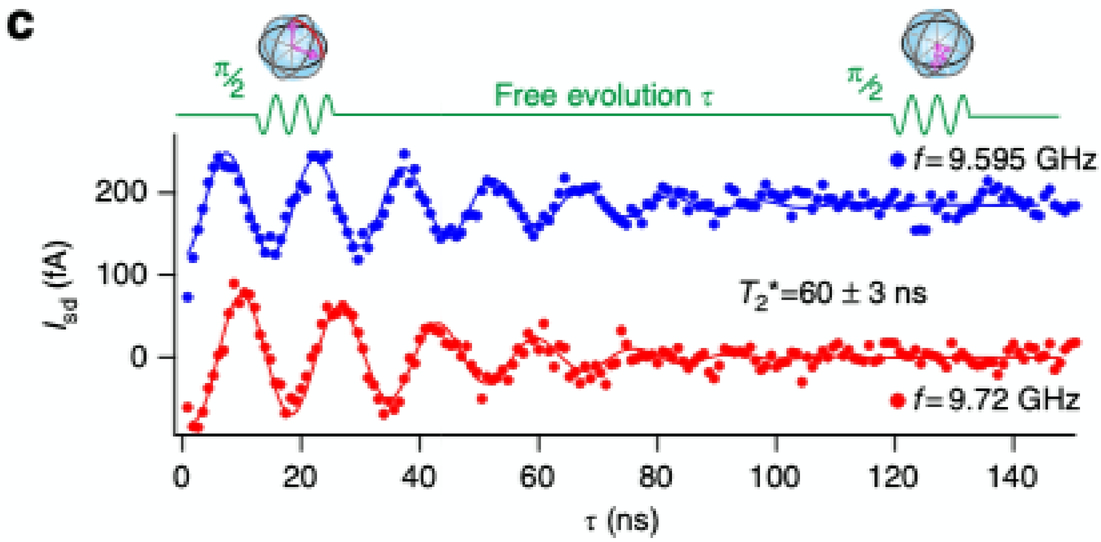


$B\ =\ 0.155\,T;\,P_{MW}\ =\ 3dBm$
Average over 600 ms



$B\ =\ 0.155\,T;\,P_{MW}\ =8dBm$
Average over 2 s

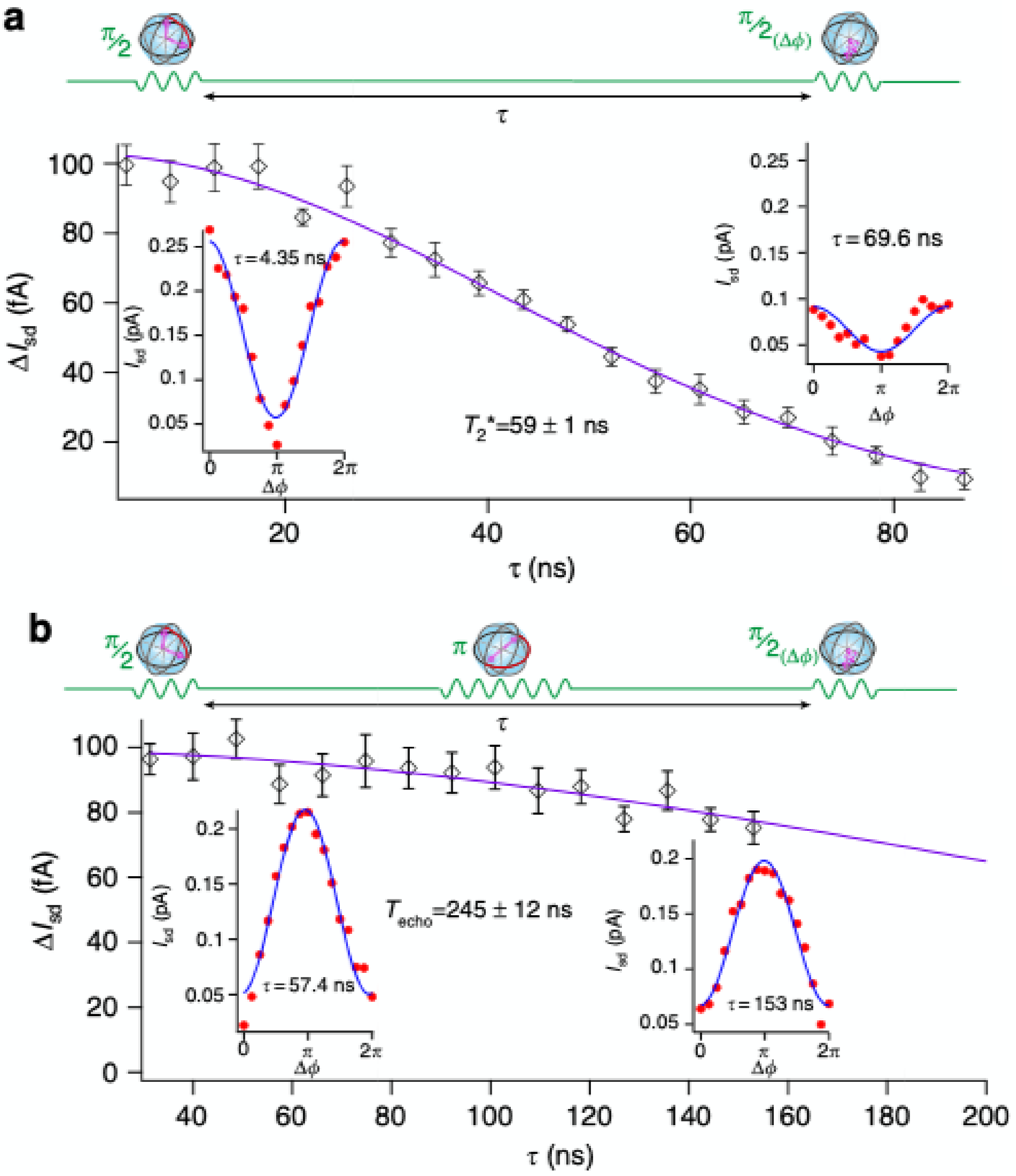
- Rabi (left) and Ramsey patterns (right) with FFT (top)
- Subtract average current
- $T_2^* \approx 60\ ns$



Spin Echo

- Ramsey sequences with varying phase of second pulse
- Extract ΔI_{SD} from sin
- π-Pulse after $\frac{\tau}{2}$ leads to an increase in T_2^* to $T_{echo} \approx 245\ ns$

- Possible explanations for short decoherence times:
  - Paramagnetic impurities, charge noise or hyperfine interaction with boron dopants



Conclusion and Outlook

- First demonstration of a hole spin qubit
- CMOS compatible fabrication
- Demonstrate coherent control of the qubit

- Next steps:
  - Implementation of single-shot readout (charge sensing)
  - Investigation of other pulse sequences (different echos?)
  - Investigation of the reasons for short decoherence times
  - Potentially overcome need for doping?