Universität Basel

Quantum tomography of an entangled three-spin state in silicon

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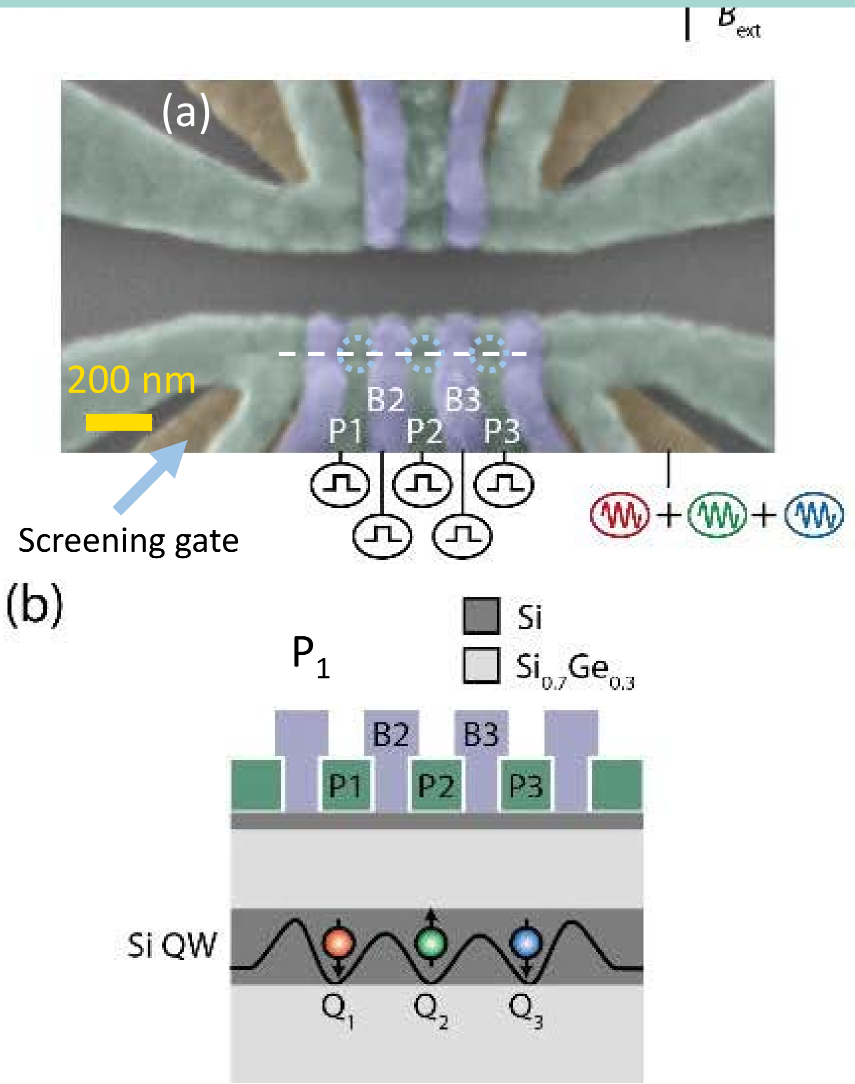
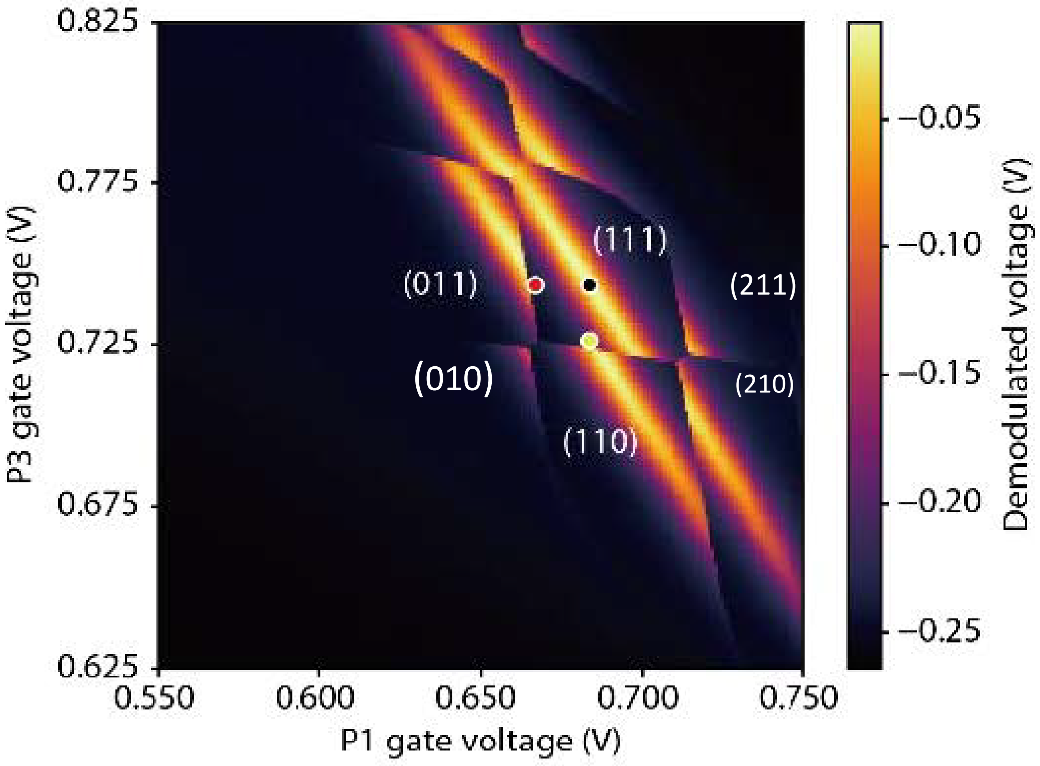
Device architecture



- Si/SiGe heterostructure (2DEG)
- 3 Al layers
- Dilution refrigerator: $T_e \sim 40$ mK
- Inplane magnetic field: $B_{ext} \sim 0.5$ T + a magnetic field gradient (in and outplane) made by a cobalt micro-magnet (on top of the QDs)
- (Radio-frequency) Sensor QD (at top)

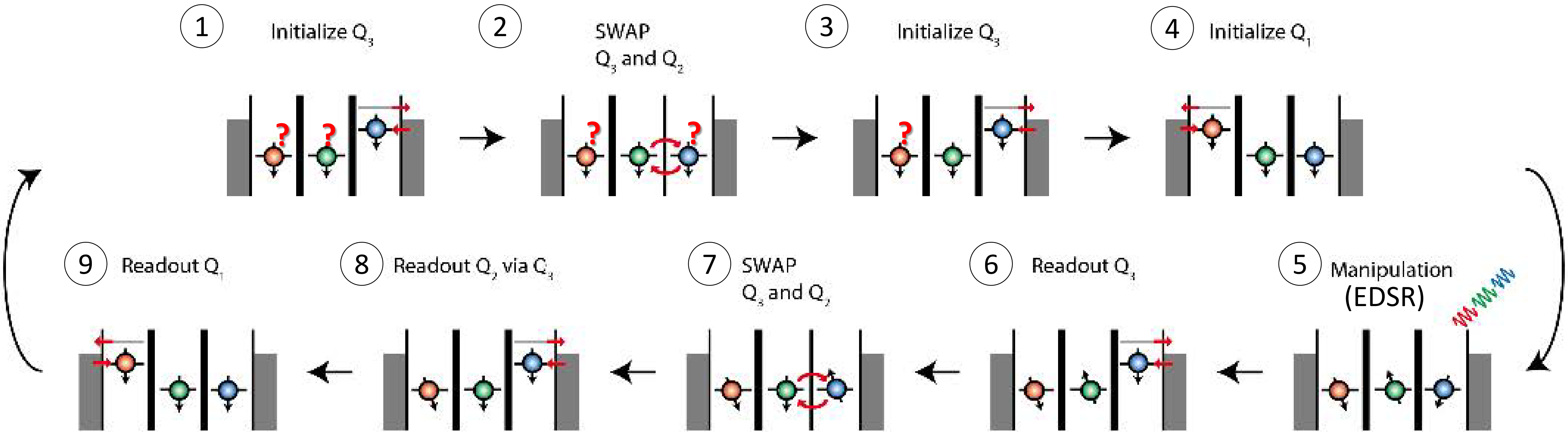
Charge stability diagram

(c)

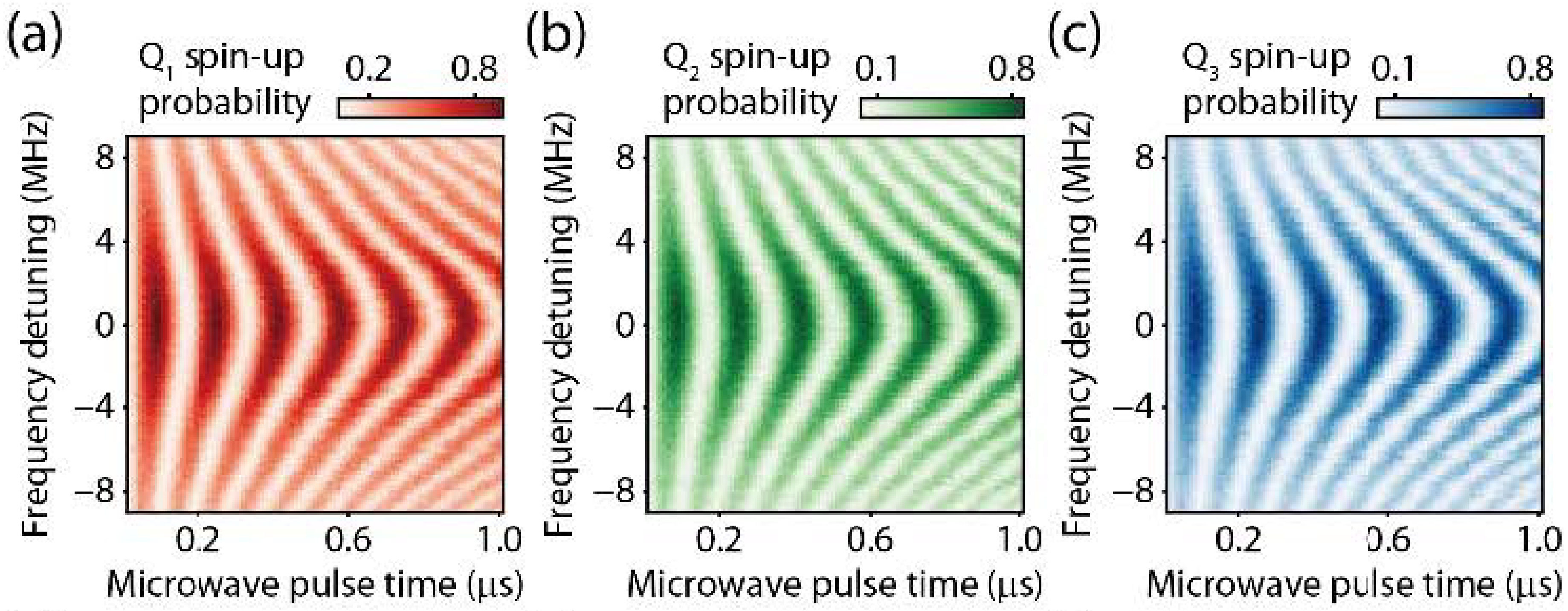


- The background signal variation is due to the sensor dot Coulomb oscillation.
- Red point ● is Q_1 readout/initialization point
- Yellow point ● is Q_2 and Q_3 readout/ initialization point
- Black point ● is the qubit manipulation point

Measurement sequence: Basic operations

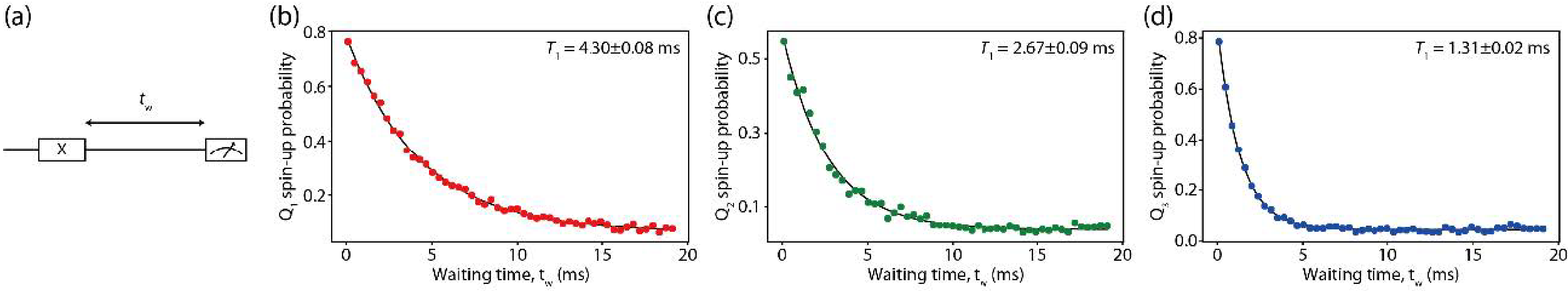


Rabi chevron oscillations of each qubit



- The frequency offsets are 17789.15 MHz (Q1), 18224.5 MHz (Q2), and 18747.7 MHz (Q3).
    - So $\delta E_{12} \approx 435.4$ MHz and $\delta E_{23} \approx 523.2$ MHz
- $f_{rabi} \approx 6$ MHz

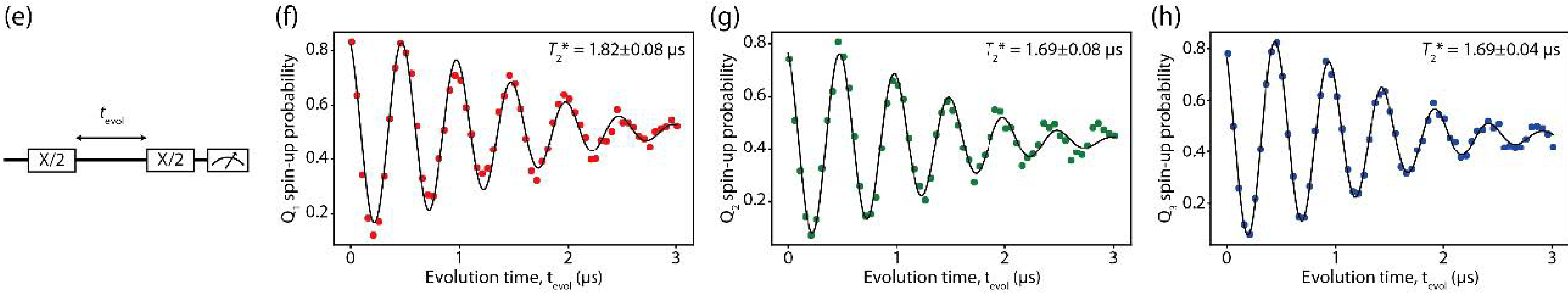
T_1 measurements



- $T_1(Q_1)$ = 4,30 ± 0,08 ms
- $T_1(Q_2)$ = 2,67 ± 0,09 ms
- $T_1(Q_3)$ = 1,31 ± 0,02 ms

- long enough to perform single-shot spin readout
- shorter than typically values for electron spins in silicon (probably due to spin-valley mixing)

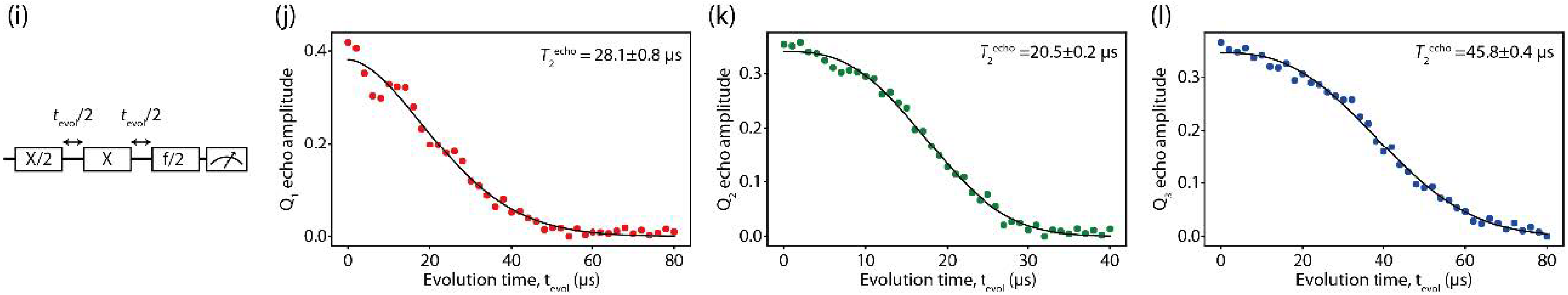
Ramsey interferometry measurements



- $T_2^*(Q_1)$ = 1,82 ± 0,08 μs
- $T_2^*(Q_2)$ = 1,69 ± 0,08 μs
- $T_2^*(Q_3)$ = 1,69 ± 0,01 μs

- Typical value for natural silicon spin-1/2 qubits
- Probably limited by the fluctuation of 4.7% ^{29}Si nuclear spins in natural silicon

Hahn echo measurements

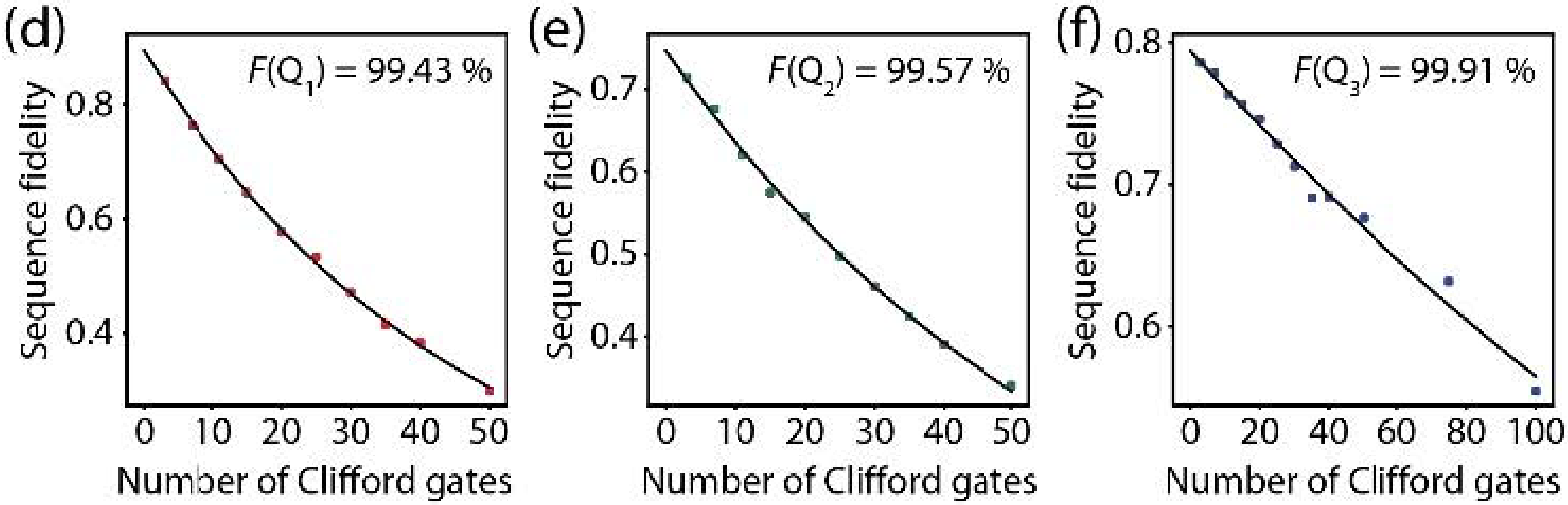


- $T_2^{echo}(Q_1)$ = 28,08 ± 0,08 μs
- $T_2^{echo}(Q_2)$ = 20,5 ± 0,02 μs
- $T_2^{echo}(Q_3)$ = 45,8 ± 0,04 μs

- Hahn echo extends the dephasing times to ~1 order of magnitude

Single-qubit control fidelities

Clifford-based randomized benchmarking



- high enough to perform the quantum state tomography measurements

Goal of this experiment

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=>Let's make a GHZ (~~GigaHertz~~ Greenberger–Horne–Zeilinger) state (because it is useful for quantum error correction)

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=> Let's characterize it by quantum state tomography

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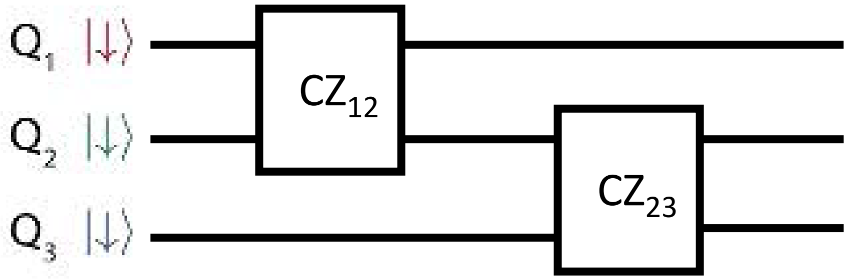
- In theory:



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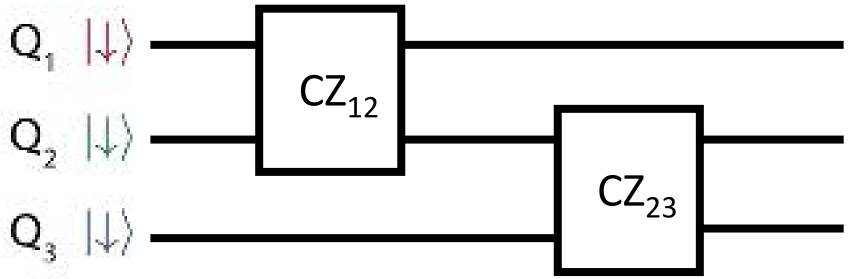
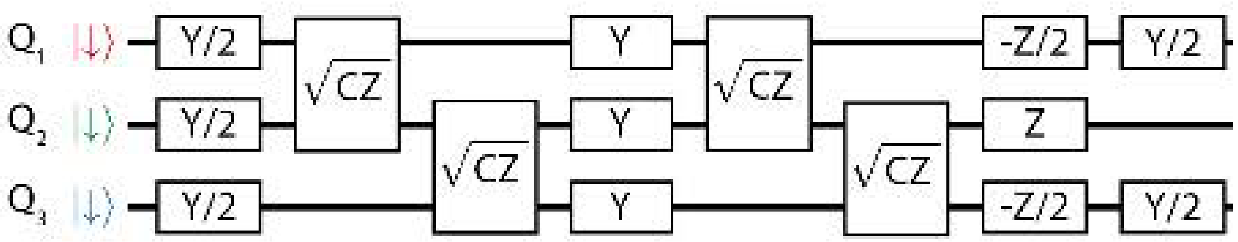


= GHZ state

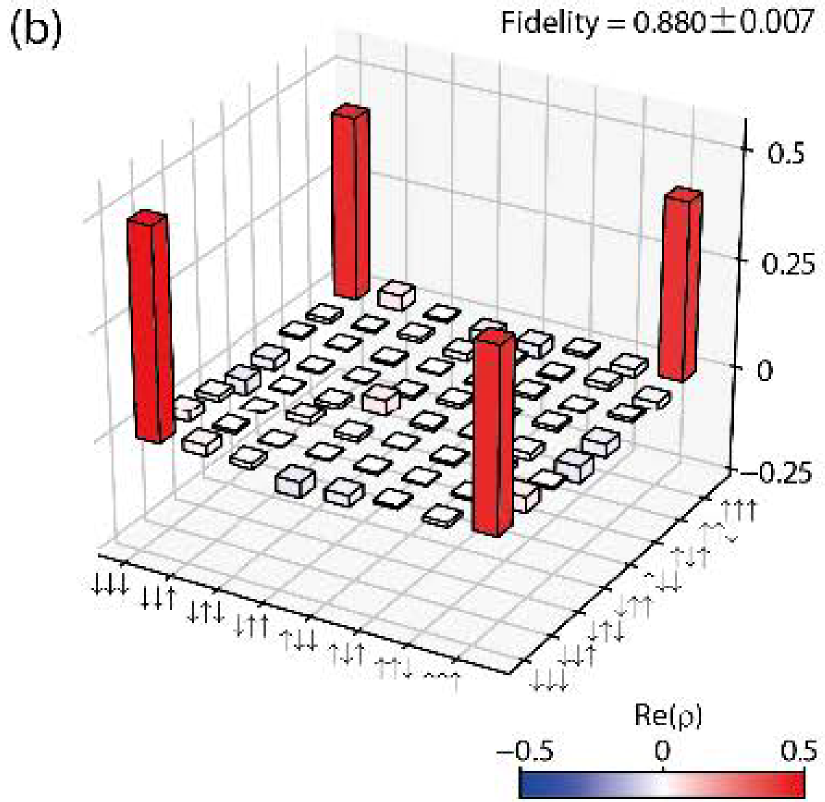
- But, to avoid low-frequency noise, it becomes:

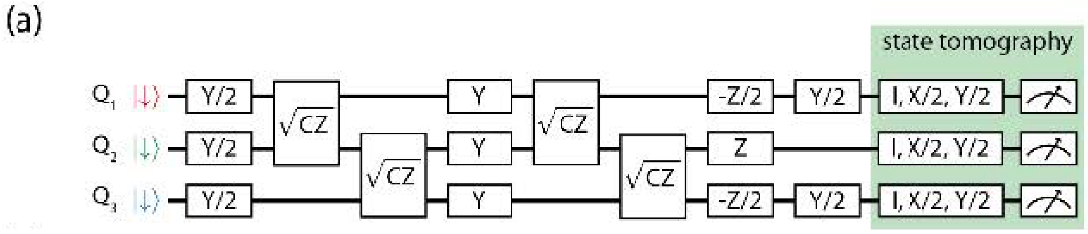


= GHZ state

=> It is same principle as Hahn echo

State tomography





- measured density matrix => Fidelity F_{GHZ}=⟨GHZ|ρ|GHZ⟩=0.880±0.007

- Same order of magnitude that the first time this state was realized (with superconducting device)

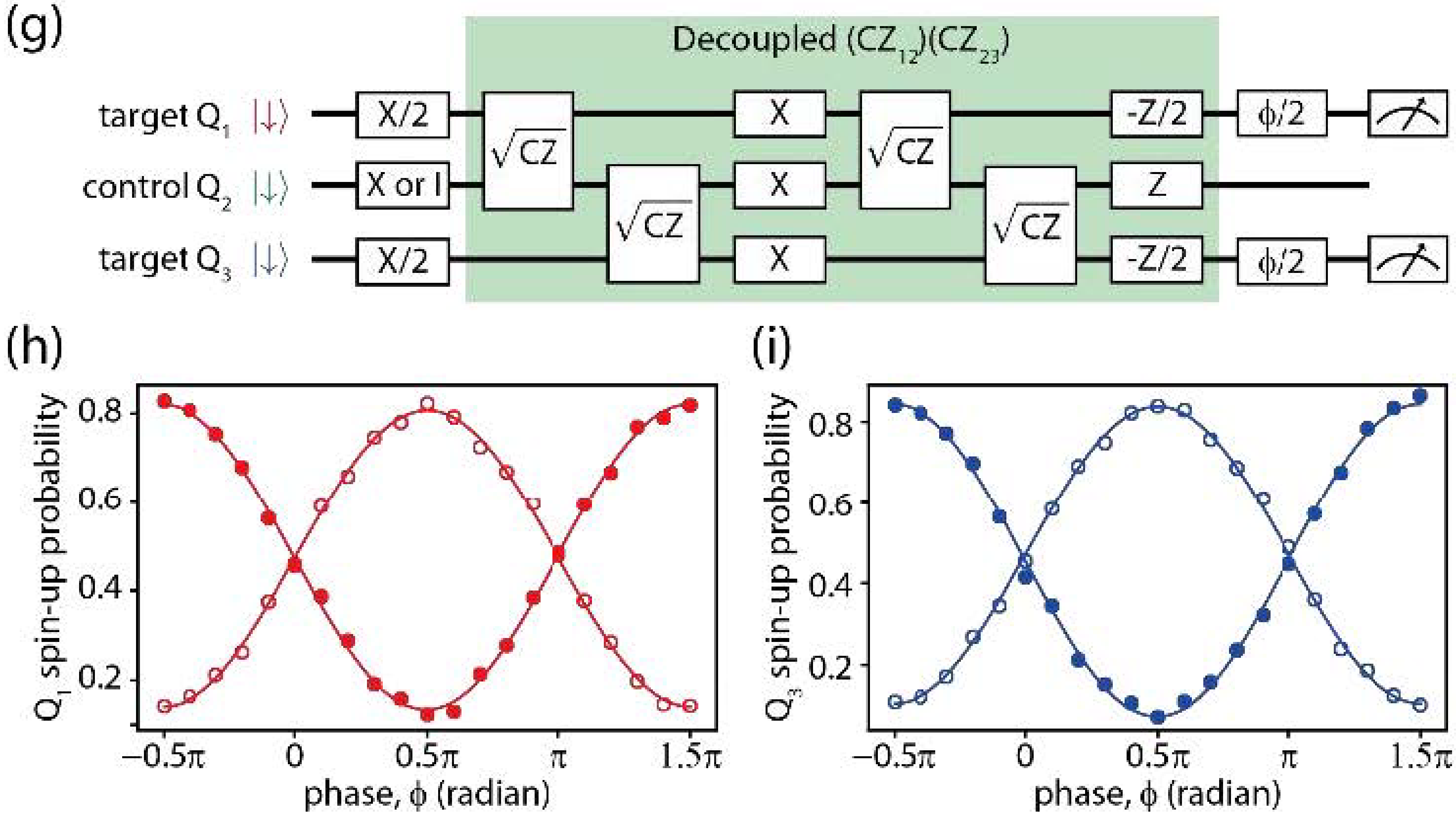
Conclusion

- Shown operation of a three-qubit device in silicon
  - Generation and measurement of a three-qubit GHZ state
- Characterized by quantum state tomography
  - “high” fidelity
- Overall, result that can lead of multi-qubit algorithms such as quantum error correction in scalable silicon-based quantum computing devices.

Thanks

Thank you for your attention!

Tuning of the CZ gates

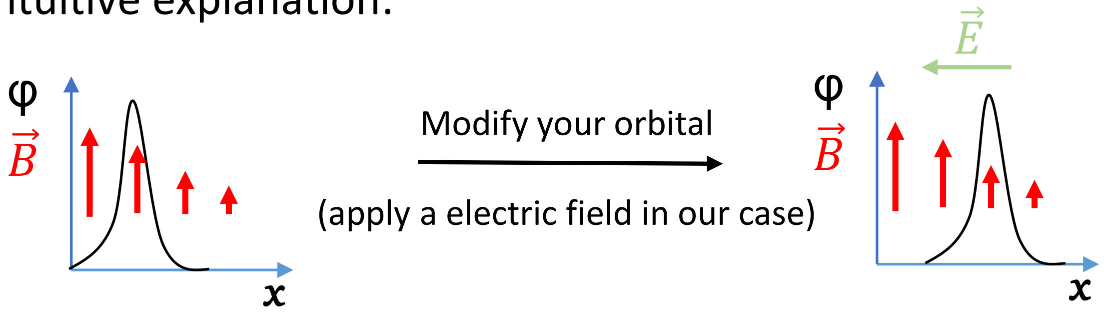


Electric-Dipole Spin Resonance (EDSR)

- Gradient of B outplane ($B_{outplane}$) is used to couple electron's spin and orbital degrees of freedom

(in other words: allows the ESR)

Intuitive explanation:



Different effective magnetic field

- Gradient inplane is used to give different Larmor frequencies for spin in each QD. Hence, we can selectively rotate S_R or S_L (resonant frequency $\propto B_{inplane}$)

- Typical values*: $\delta B_{outplane} >$ 0.8 mT/nm and $\Delta B_{inplane} >$ 18 mT

*Yasuhiro Tokura, Wilfred G. van der Wiel, Toshiaki Obata, and Seigo Tarucha, Phys. Rev. Lett. 96, 047202 (2006).