SHUTTLING IN SEMICONDUCTOR SYSTEM

Yang LIU

11/04/2025

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Catalogue

01 Research Background

02 Electron Spin Shuttling in Si/SiGe

03 Hole Spin Shuttling in Ge/SiGe

04 Conclusions and outlooks

What is shuttling?

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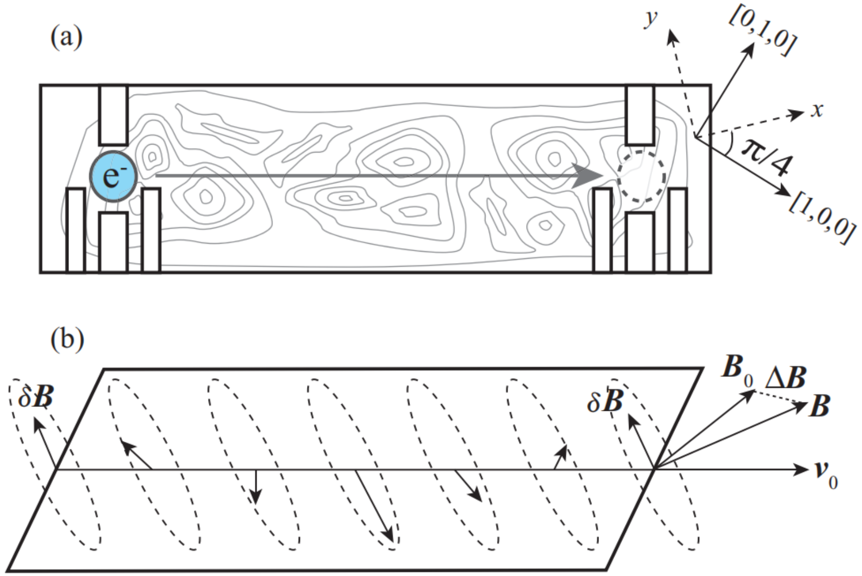
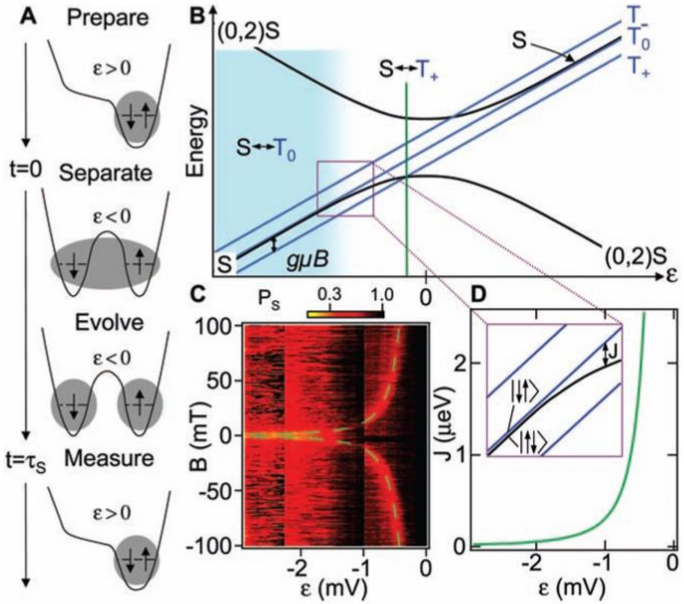




How to couple the qubits?

- Short range(~10nm): SWAP gate
- Middle range (~10μm): surface acoustic wave, **shuttling**, reseonate SWAP gate
- Long range(~100μm): resonator

Advantages of shuttling?

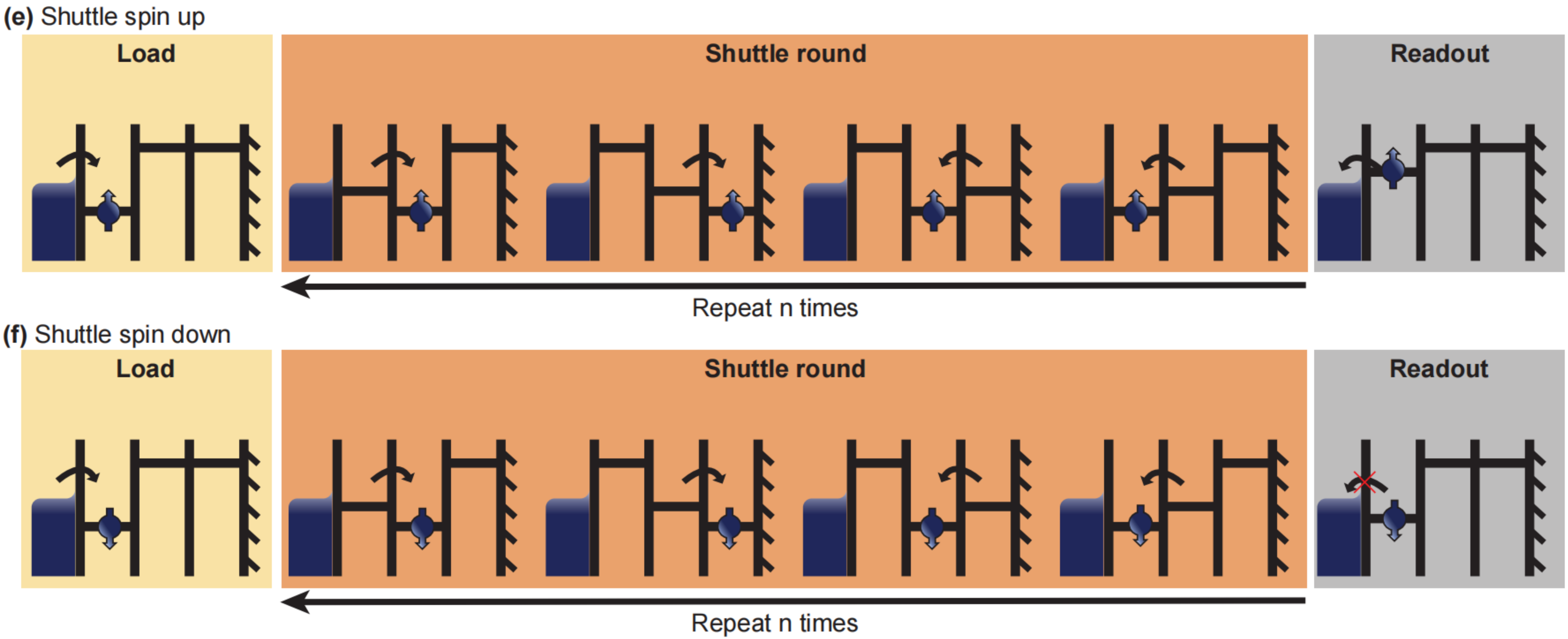
- No need for extra structure in device
- Increase the scalability
- Can be used to tune J between qubits

Petta et al., Science 309, 2180 (2005)
Huang et al., PRB 88, 075301 (2013)

Previous Work

Year	Group	Charge / Spin	Material	QD	Reference
2017	T. Meunier (Grenoble)	Electron spin	AlGaAs-GaAs	Triangle 3 dots	Flentje et al., Nat. Commun 8, 501 (2017)
2019	Petta (Princeton)	Electron charge	$^{28}Si/SiGe$	3*1	Mills et al., Nat. Commun 10, 1063 (2019)
2021	Dzurak (UNSW)	Electron spin	SiMOS	2*1	Yoneda et al., Nat. Commun 12, 4114 (2021)
2022	Tarucha (Riken)	Electron spin	$^{28}Si/SiGe$	3*1	Noiri et al., Nat. Commun 13, 5740 (2022)
2023	Vandersypen (Delft)	Electron spin	$^{28}Si/SiGe$	4*1	Zwerver et al., PRX Quantum 4, 030303 (2023)
2023	Schreiber (Aachen)	Electron spin	Natural Si/SiGe	8*1	Struck, et al., arXiv 2307.04897 (2023)
2024	Veldhorst (Delft)	Hole spin	Ge/SiGe	2*2	Floor van Riggelen-Doelman et al., Nat. Commun 15, 5716 (2024)
2024	Vandersypen (Delft)	Electron spin	$^{28}Si/SiGe$	6*1	De Smet1, Y. Matsumot et al., arXiv:2406.07267 (2024)

Two Types of Shuttling: Bucket-Brigade Mode



Bucket Brigade Mode: qubit shuttles across an array of tunnel-coupled static QDs

Noiri et al., Nat. Commun 13, 5740 (2022)

Previous Work: Bucket-Brigade Mode

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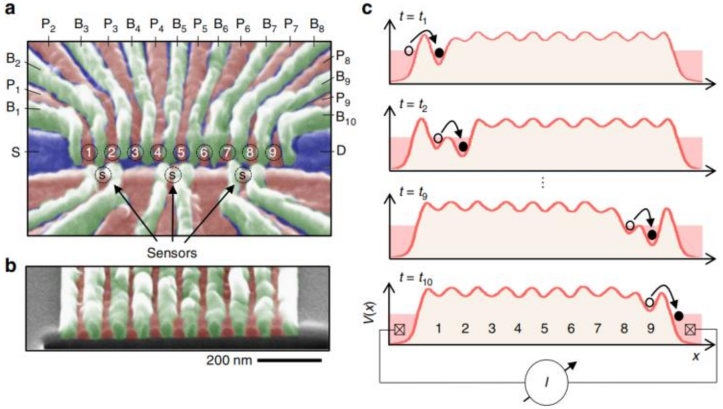
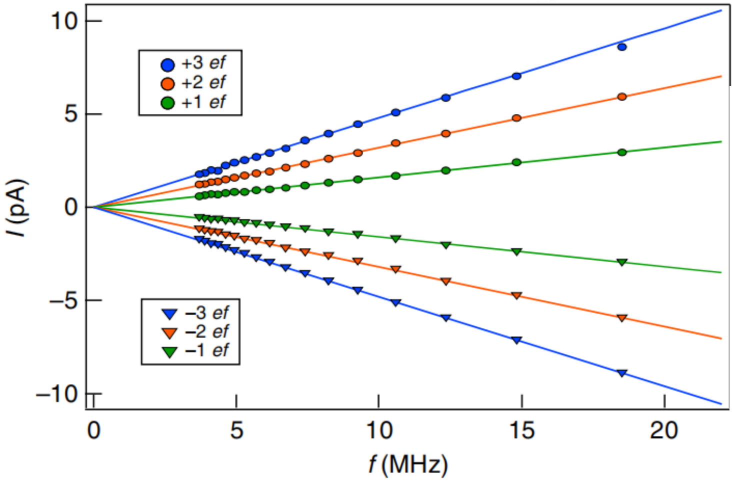
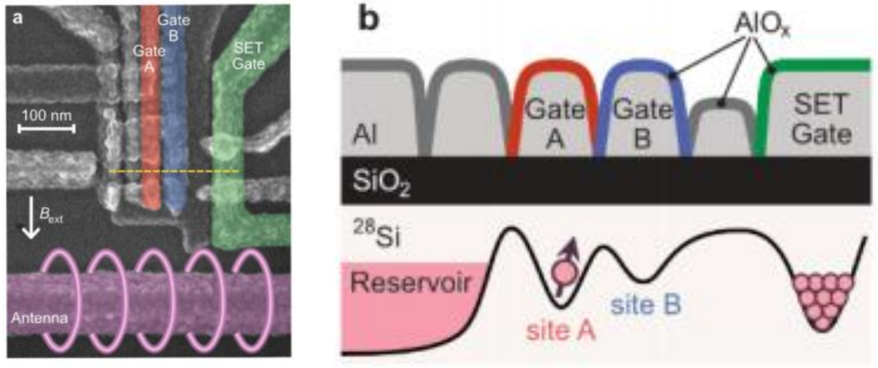


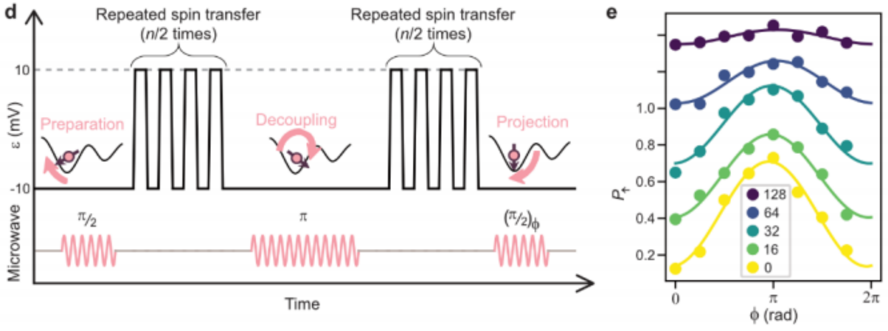


Current I measured as a function of frequency for electron charge shuttling

$I = n\,ef, 3 \le n \le 3$

$V \approx 10\ m/s$



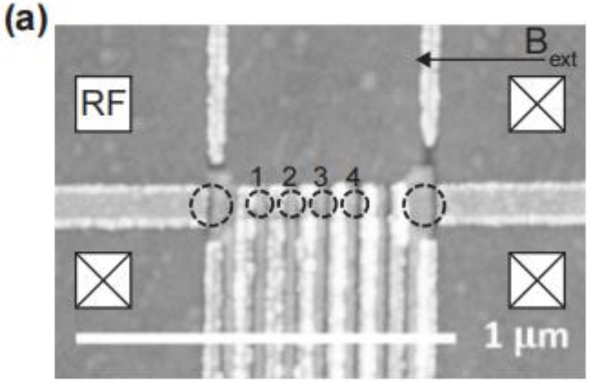


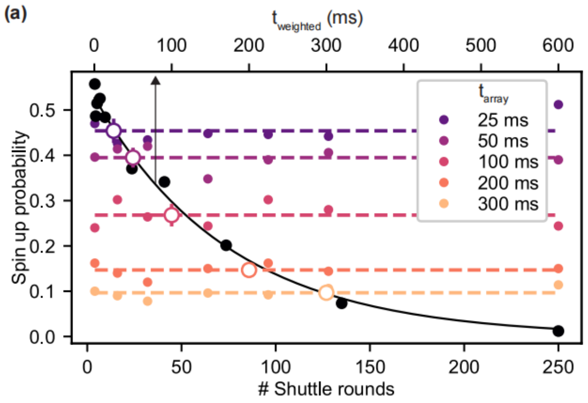
Shuttling through double quantum dots

Polarization transfer fidelity of 99.97%

Average coherent transfer fidelity of 99.4%

$V \approx 0.5\ m/s$





Shuttling through three quantum dots

Spin-flip probability per hop < 0.01%

$V \approx 0.004\ m/s$

Mills et al., Nat. Commun 10, 1063 (2019)

Yoneda et al., Nat. Commun 12, 4114 (2021)

Zwerver et al., PRX Quantum 4, 030303 (2023)

Two Types of Shuttling: Conveyor-Belt Mode

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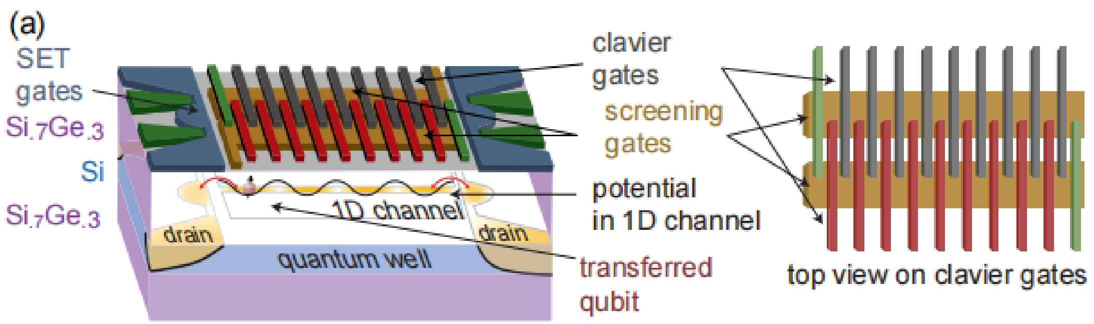
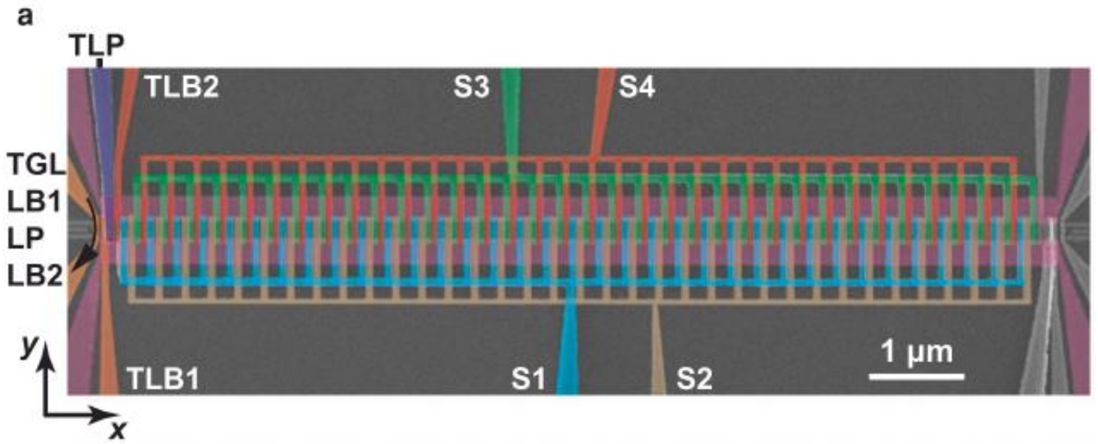
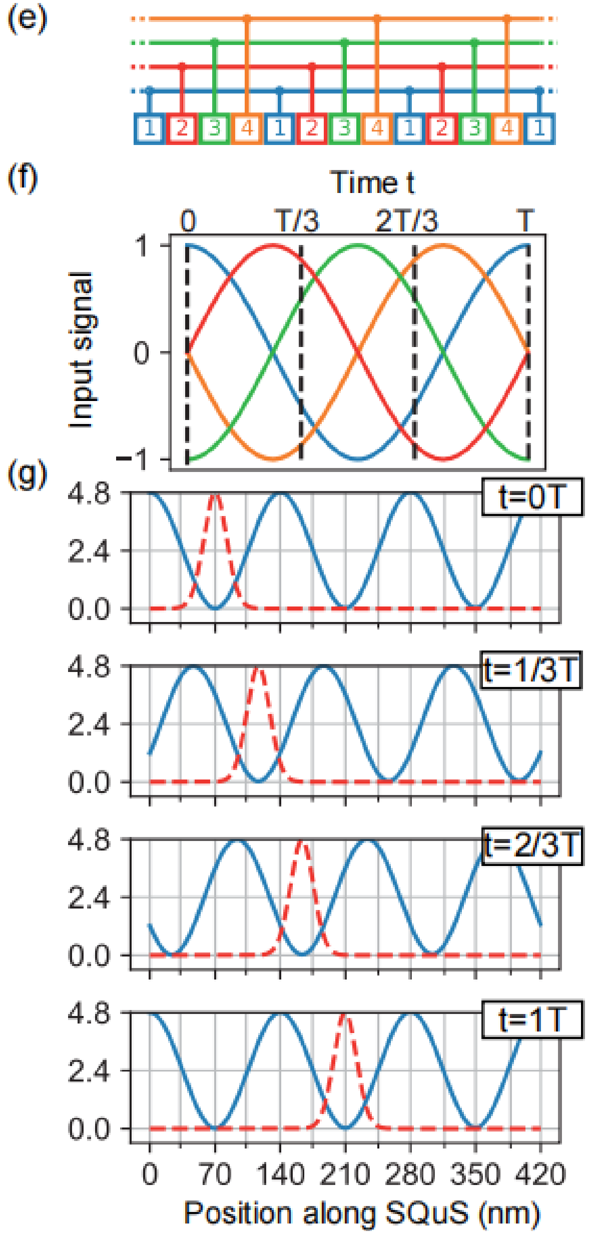






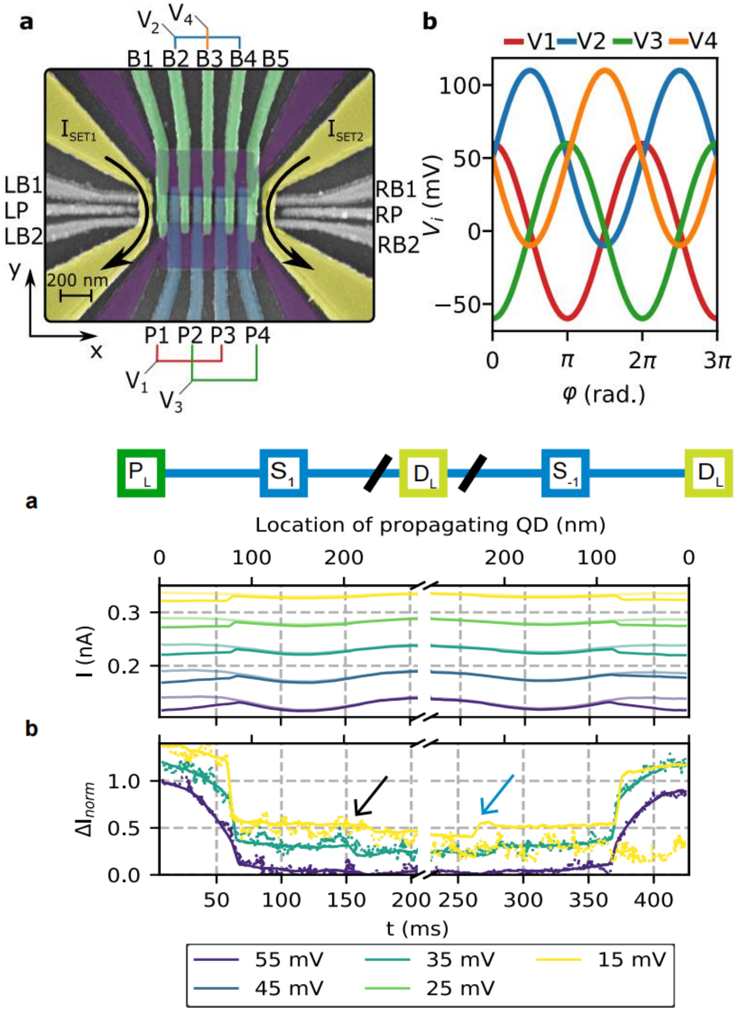
Spin shuttles using a moving potential wave:

- A series of electrostatic gates generate a traveling wave potential that traps and transports electrons sequentially.
- The wave moves at a controlled speed, ensuring electrons are shuttled without losing their quantum state

$$V_{si}(\tau_S) = U_i \cdot \sin(2\pi f \tau_S + \phi_i) + C_i$$

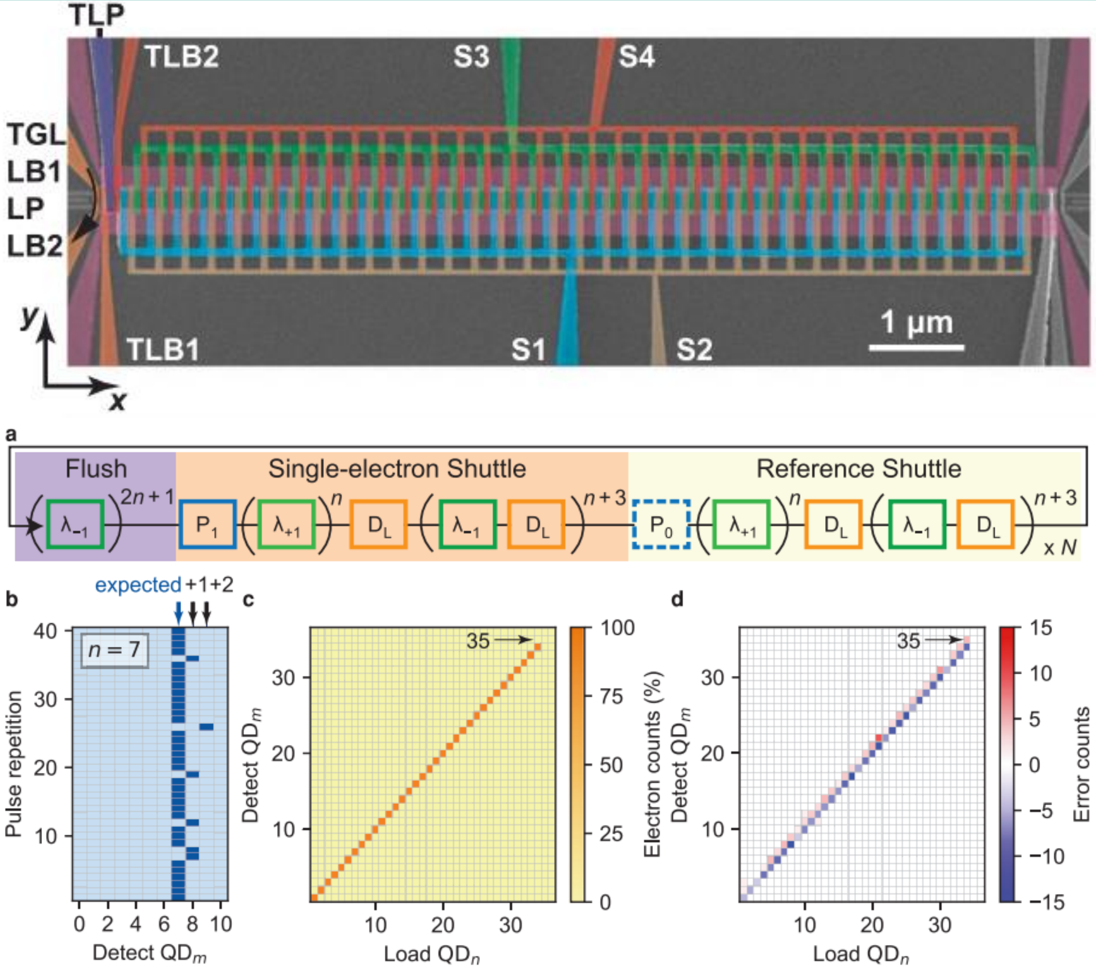
Langrock et al., PRX Quantum 4, 020305 (2023)
Xue et al., Nat. Commun 15, 2296 (2024)

Previous Work: Conveyor-Belt Mode



Single-electron shuttling fidelity is 99.42 %

$V \approx 1.4\ \mu m/s$



The fidelity of the single-electron shuttle is $(99.7 \pm 0.3)\%$

Total shuttling distance is $19\ \mu m$

$V \approx 10\ \mu m/s$

Seidler et al., npj Quantum Information 8, 100 (2022)

Xue et al., Nat. Commun 15, 2296 (2024)

Summary

	Bucket-Brigade Mode	Conveyor-Belt Mode
Advantage	1. Relatively easy to fabricate 2. Faster speed and higher fidelity compared to CB in short region	1. Relatively low requirement for adiabatic transfer 2. More smooth qubit transfer, higher fidelity in principle 3. No predefined quantum dots
Disadvantage	Potential disorder and non-uniformity make it difficult to ensure tunnel coupling is large enough **Easier for us to achieve BB mode in NW system**	1. Potential disorder and non-uniformity make it difficult to ensure that the potential wells at each location have similar shapes. 2. The process requires strictly on the shuttle path fabrication, such as no defects.

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03 Hole Spin Shuttling in Ge/SiGe

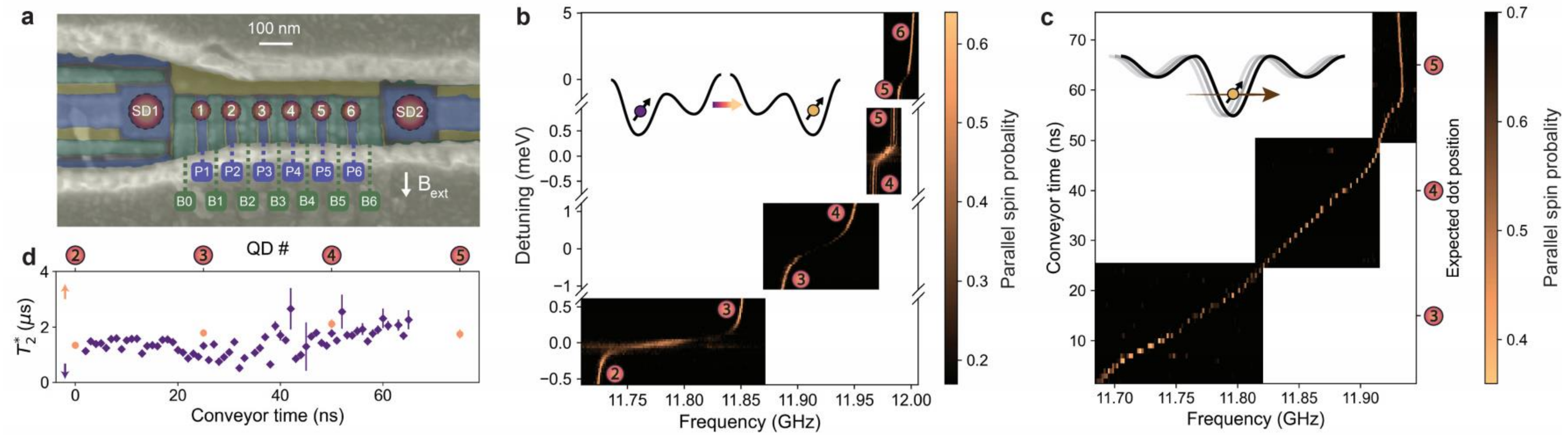
04 Conclusions and outlooks

Electron Spin Shuttling in Si/SiGe

T_2^* increases with decrease of B_{local}

High-fidelity single-spin shuttling in silicon

M. De Smet[1†], Y. Matsumoto[1†], A.M.J. Zwerver[1], L. Tryputen[2], S.L. de Snoo[1], S.V. Amitonov[2], A. Sammak[2], N. Samkharadze[2], Ö. Gül[2], R. N. M. Wasserman[2], M. Rimbach-Russ[1], G. Scappucci[1], and L.M.K. Vandersypen[1*]
[1]*QuTech and Kavli Institute of Nanoscience, Delft University of Technology, Lorentzweg 1, 2628 CJ Delft, The Netherlands*
[2]*QuTech and Netherlands Organization for Applied Scientific Research (TNO), Delft, The Netherlands and*
[†] *These authors contributed equally*
(Dated: June 12, 2024)

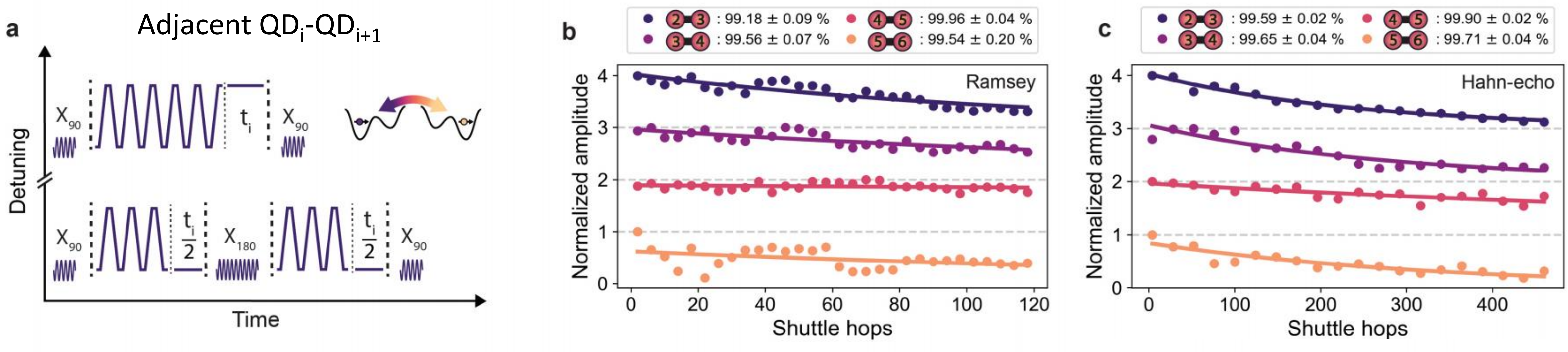


Spin dephasing time in the gate-defined quantum dots and in a static two-tone conveyor.

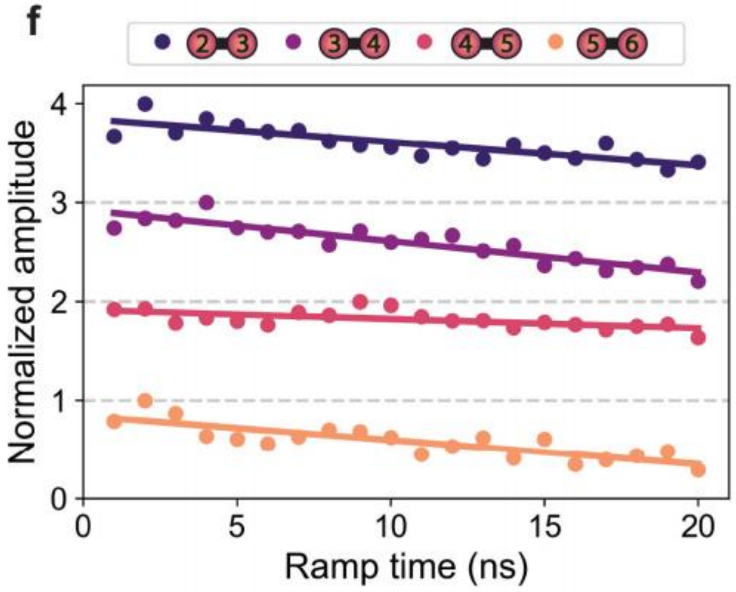
BB mode detuning dependence of spin resonance frequency

CV mode detuning dependence of spin resonance frequency

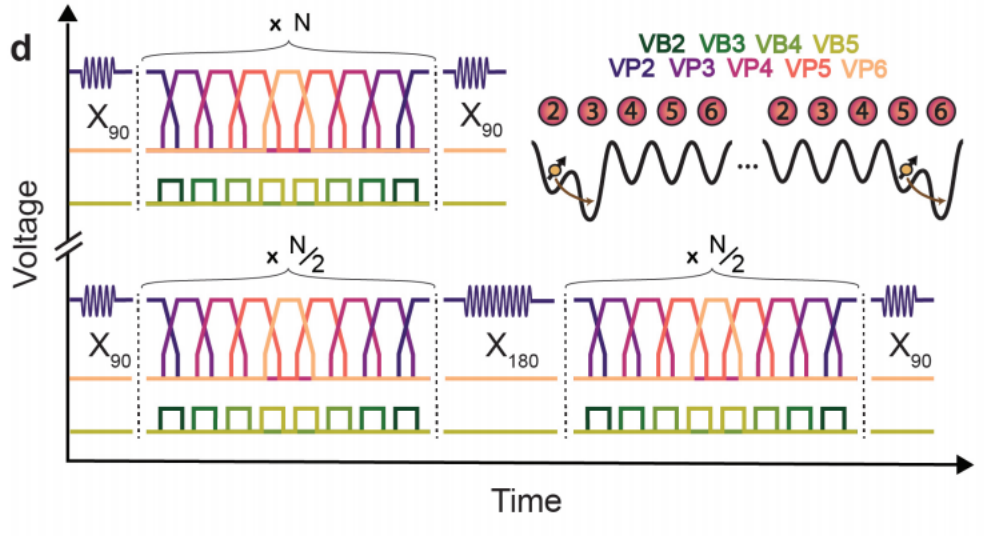
BB shuttling



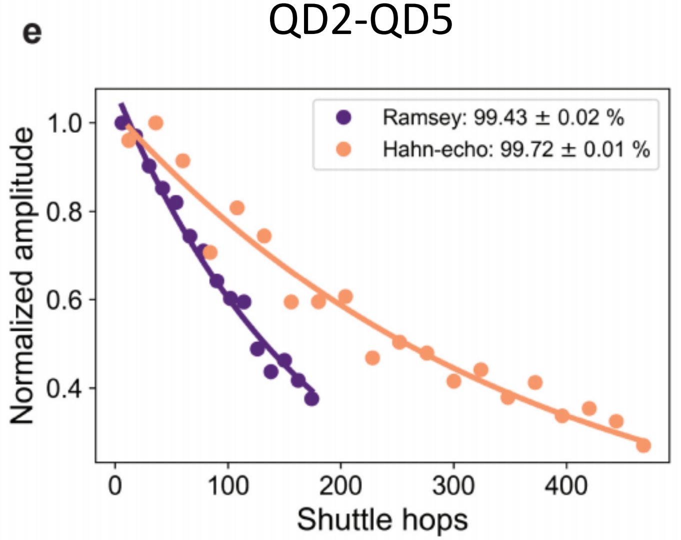
- Ramsey (top) and Hahn-echo (bottom) pulse sequences when shuttling repeatedly between sites of a DQD
- Ramsey and Hahn-echo fringe amplitude for each double dot with increasing number of shuttle hops
- Normalized Hahn-echo fringe amplitude after shuttling forth and back twice through a double dot as a function of the ramp time



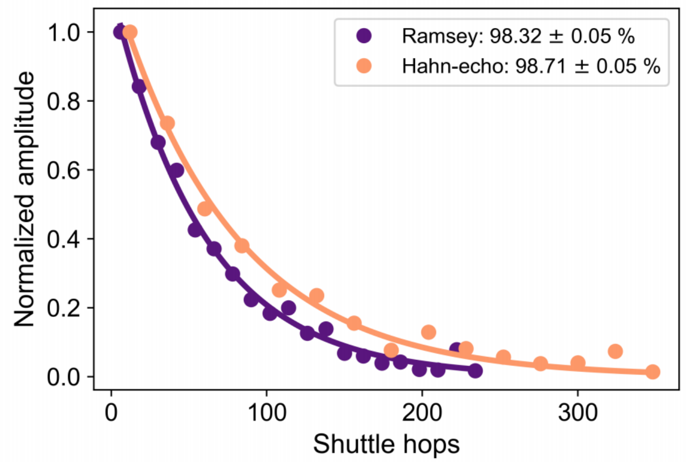
BB shuttling



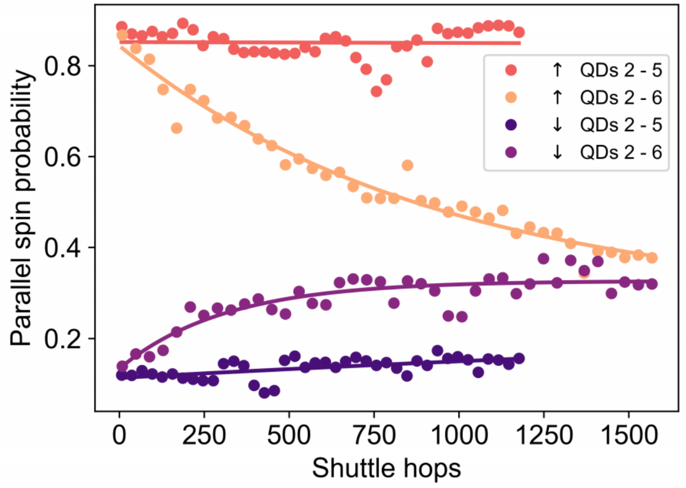
QD2-QD5



QD2-QD6



- B5 has a low lever arm of gate B5 and a small charging energy in QD5, needs more voltage to tune.
- Speculation: the small orbital energy could induce diabatic charge excitations. The artificial SOI from the micromagnet also affects the spin dephasing rate and spin relaxation rate during shuttling

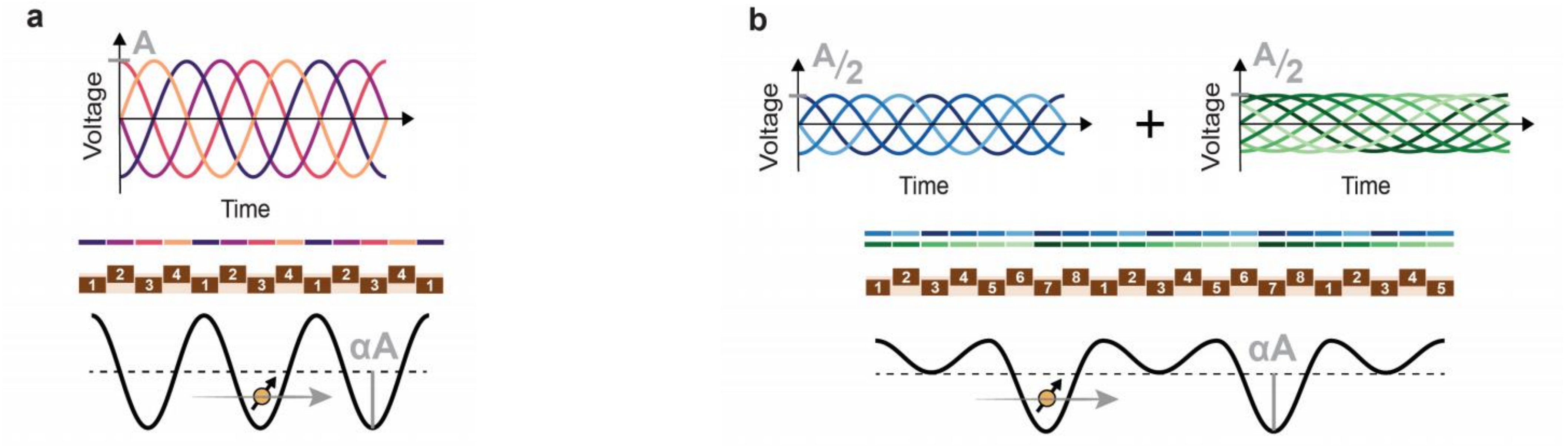


T_2^* of BB shuttling: 1.04 µs, average T_2^* = 1.75 µs in the static dots.

Several ways to increase the dephasing time:

- Shorter ramp time
- Higher detuning region, resonance frequency is highly sensitive to detuning fluctuations
- Lower the magnetic field, the loss of phase coherence increases with the Zeeman splitting difference.

CB Shuttling



Conventional conveyor approach:

$$V_n(t) = V_n^{DC} - Asin(2\pi f t - \phi_n)$$

$$\phi_n = \phi' + (n\ mod\ 4) \times \frac{\pi}{2}$$

V_n^{DC}: DC voltage offset

f: conveyor frequency

ϕ' : phase offset

Two-tone conveyor approach:

$$V_n(t) = V_n^{DC} - \frac{A}{2}[sin(2\pi f t - \phi_n) + \sin(\pi f t - \theta_n)]$$

$$\phi_n = \phi' + (n\ mod\ 4) \times \frac{\pi}{2}$$

$$\theta_n = \frac{\phi'}{2} + (n + 1\ mod\ 8) \times \frac{\pi}{4}$$

- Destructive interference at every second potential minimum strongly suppresses charge leakage to neighbouring moving dots during shuttling
- Amplitude applies on barriers should be 1.4 times larger that of plungers

CB Shuttling

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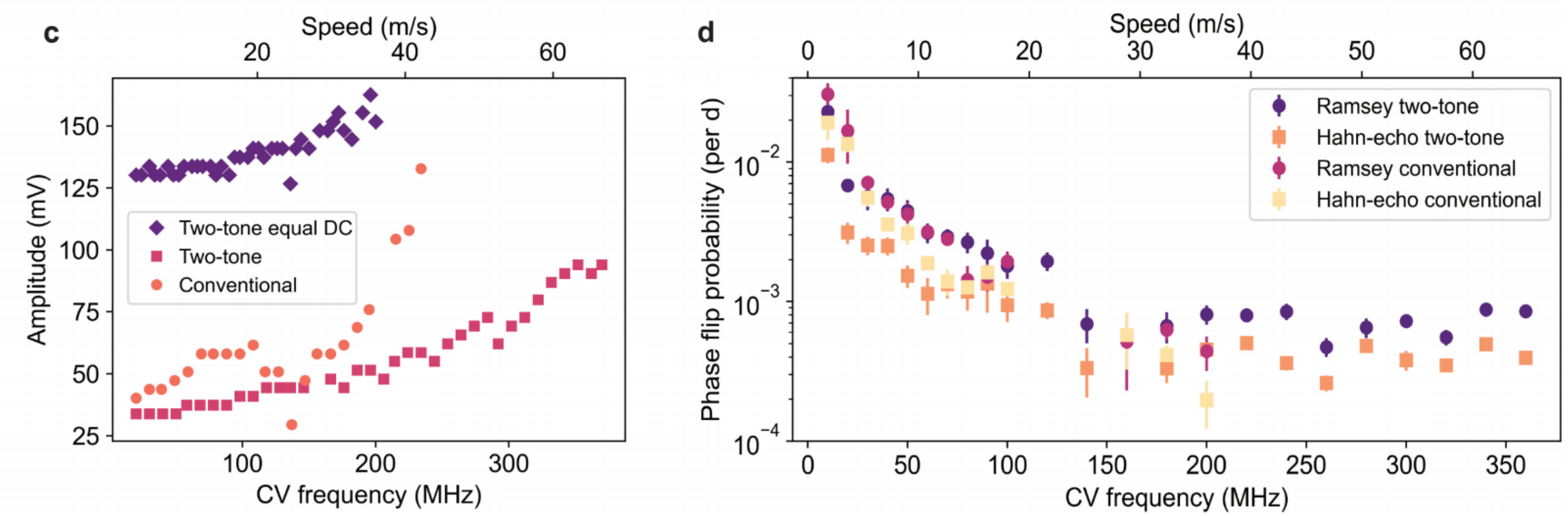
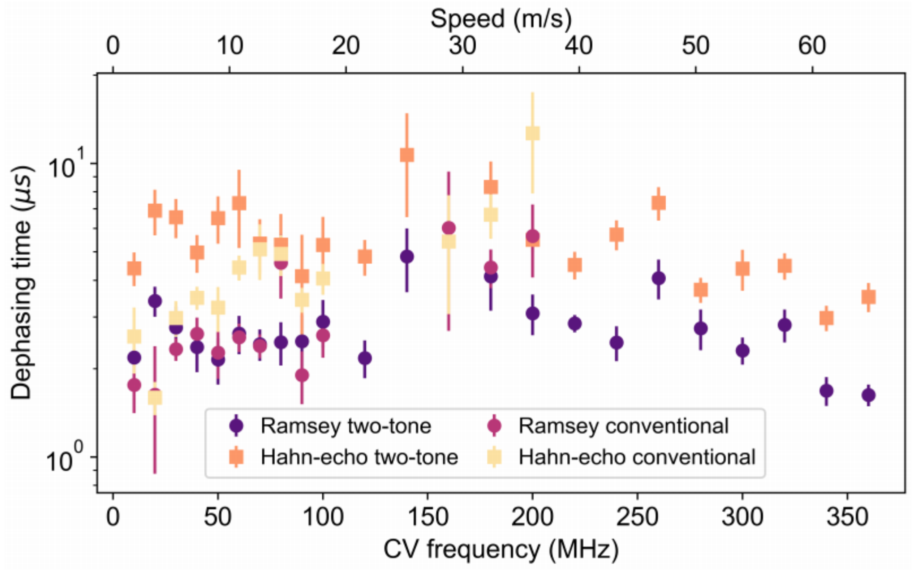


Conventional: $V_n(t) = V_n^{DC} - A\sin(2\pi f t - \phi_n)$

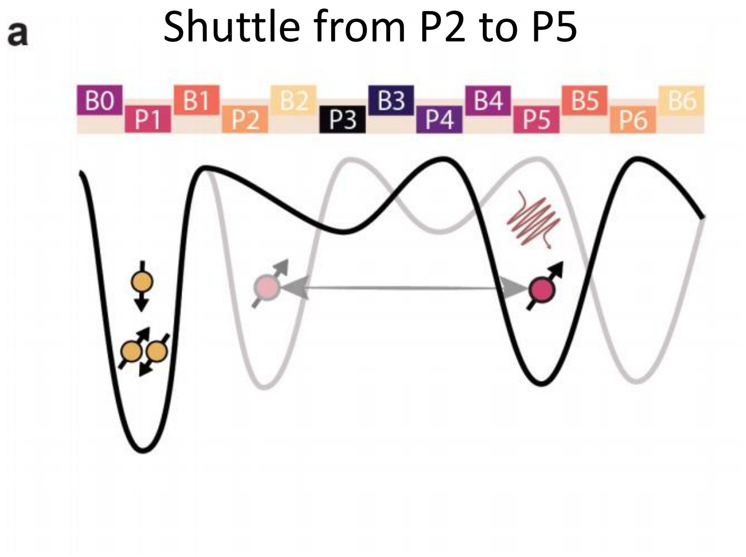
Two-tone: $V_n(t) = V_n^{DC} - \frac{A}{2}[\sin(2\pi f t - \phi_n) + \sin(\pi f t - \theta_n)]$

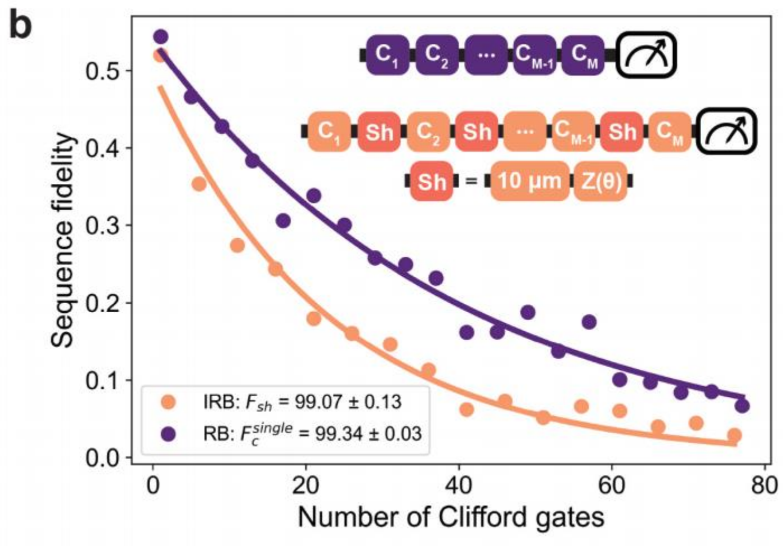
Two-tone equal DC: $V_n(t) = V^{DC} - \frac{A}{2}[\sin(2\pi f t - \phi_n) + \sin(\pi f t - \theta_n)]$

Faster transfer means the spin has less time to dephase while transferring.
The reason why P saturates after 150MHz is still unclear



CB Shuttling Fidelity





$$f_{CV} = 300\ MHz$$
$$t_{sh} = 4\ ns$$
$$N = 23$$
$$T_{total} = 184\ ns$$
$$D_{sh} = 2N f_{CV} t_{sh} 2d = 9.936\ \mu m$$

Over a plunger-to-plunger distance: $F =\ 99.99\%$
Calculation:
Single qubit gate fidelity: $F =\ 99.34\%$
Shuttling fidelity over $10\mu m$: $F =\ 99.07\%$
Shuttling fidelity: $N = \frac{10\mu m}{90nm} \sim 100$, every hop F $>\ 99.99\%$

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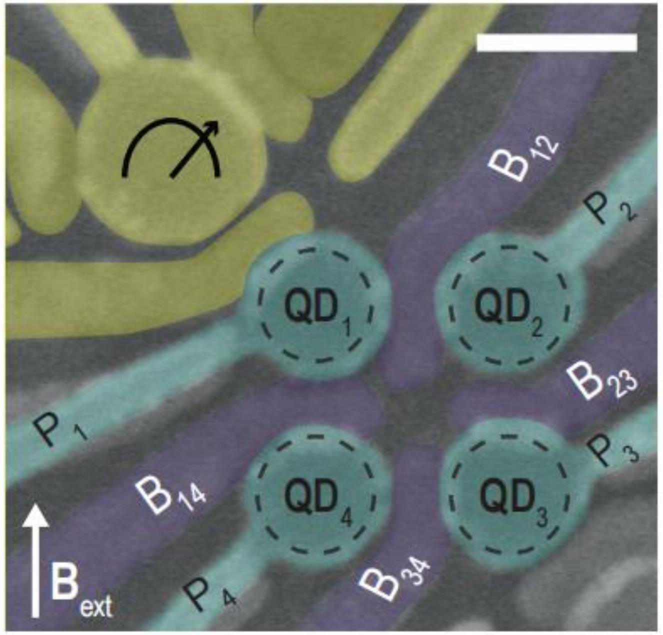
Hole Spin Shuttling in Ge/GeSi



	T_1 (ms)	T_2^* (ns)	T_2^{Hahn} (μs)
Qubit1	0.84	201	4.3
Qubit2	7.6	146	5.5
Qubit3	16.1	446	3.8
Qubit4	11.5	150	2.9

QD distance = 140 nm

Ge has small effective mass and high uniformity

Hendrickx et al., Nature 591, 580–585 (2021)

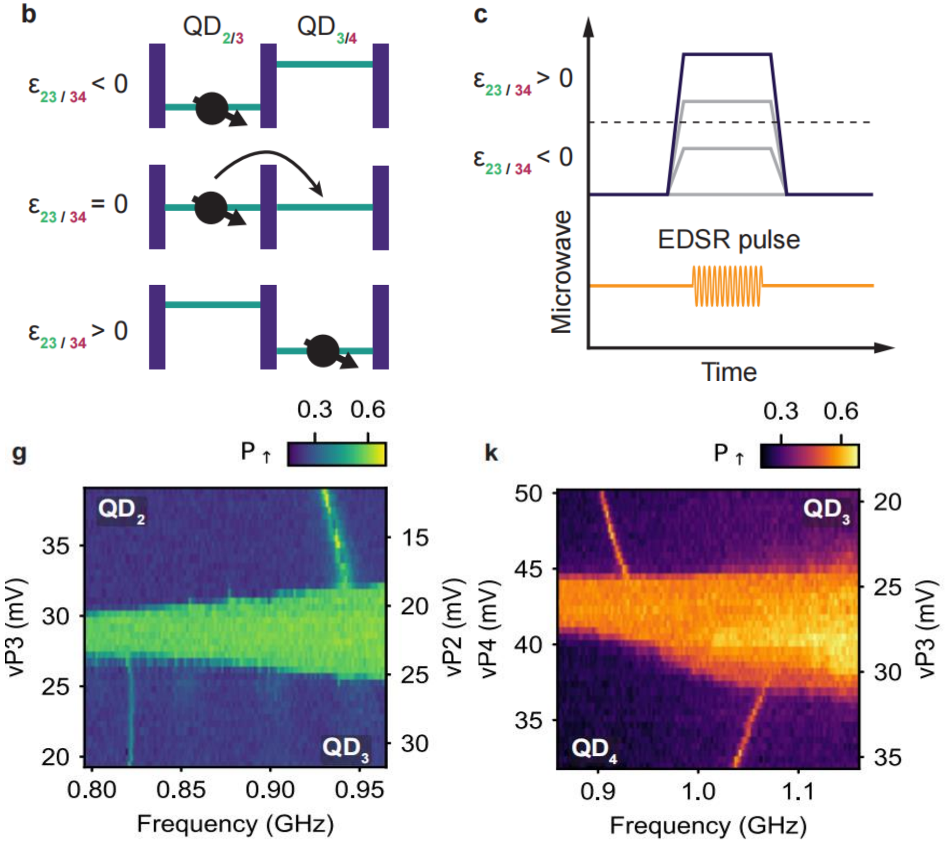
Coherent spin qubit shuttling through germanium quantum dots

Floor van Riggelen-Doelman,[1] Chien-An Wang,[1] Sander L. de Snoo,[1] William I. L. Lawrie,[1] Nico W. Hendrickx,[1] Maximilian Rimbach-Russ,[1] Amir Sammak,[2] Giordano Scappucci,[1] Corentin Déprez,[1] and Menno Veldhorst[1]

[1] *QuTech and Kavli Institute of Nanoscience, Delft University of Technology, PO Box 5046, 2600 GA Delft, The Netherlands*

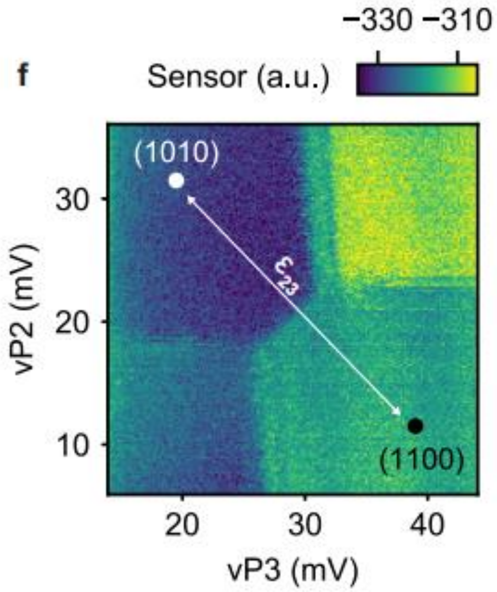
[2] *QuTech and Netherlands Organisation for Applied Scientific Research (TNO), Delft, The Netherlands*

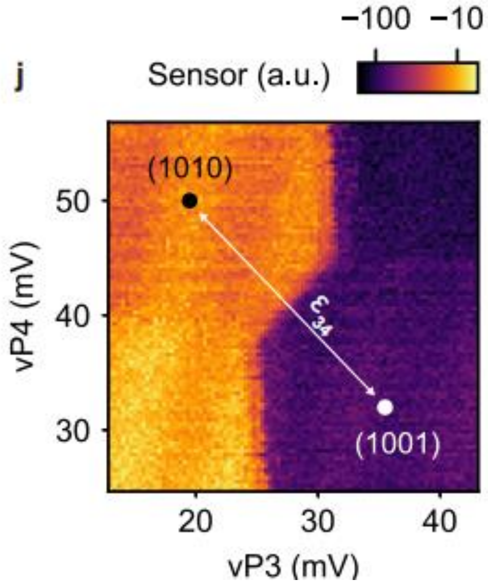
(Dated: August 7, 2023)

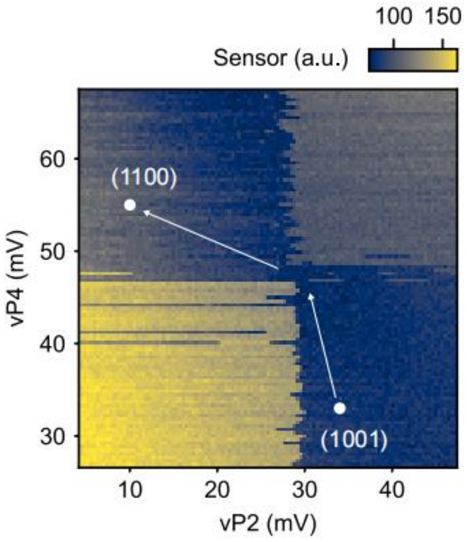


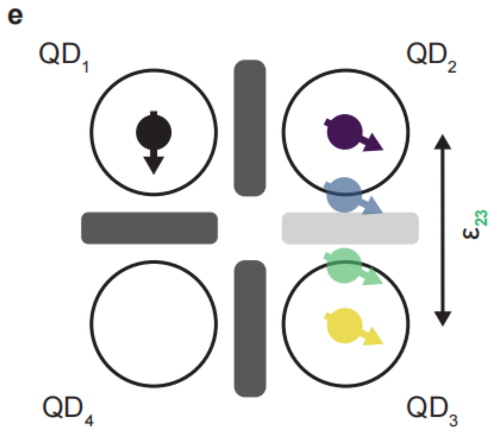
- Change the detuning between two QDs to shuttle holes
- Pulses used for the shuttling, EDSR pulse lasts 4 μs
- We use the change of Larmor frequency to confirm the hole shuttles from one QD to another. The resonance frequency near the charge transition cannot be resolved due to a combination of effects

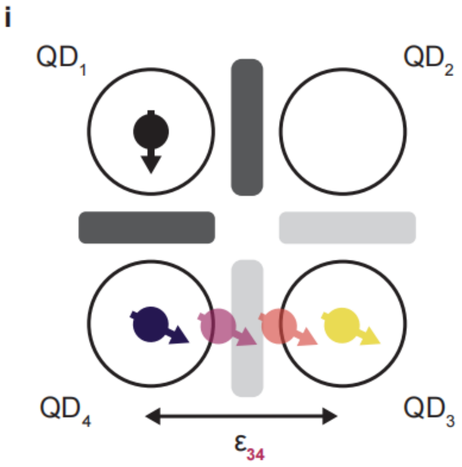
Detuning Between QDs





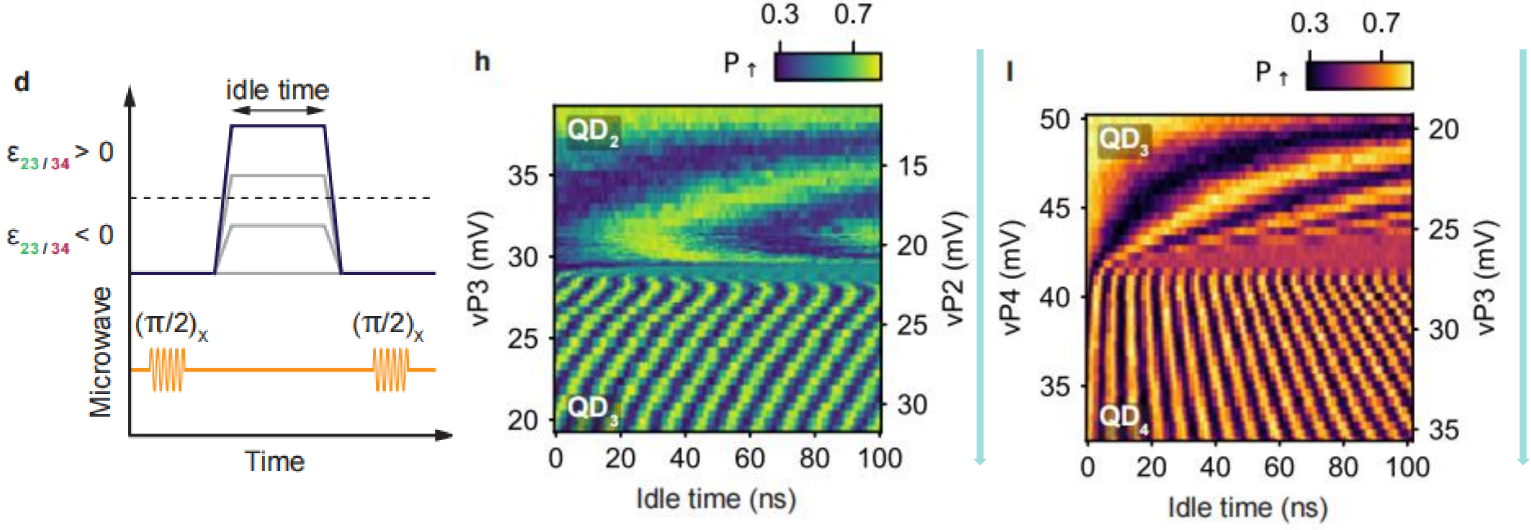




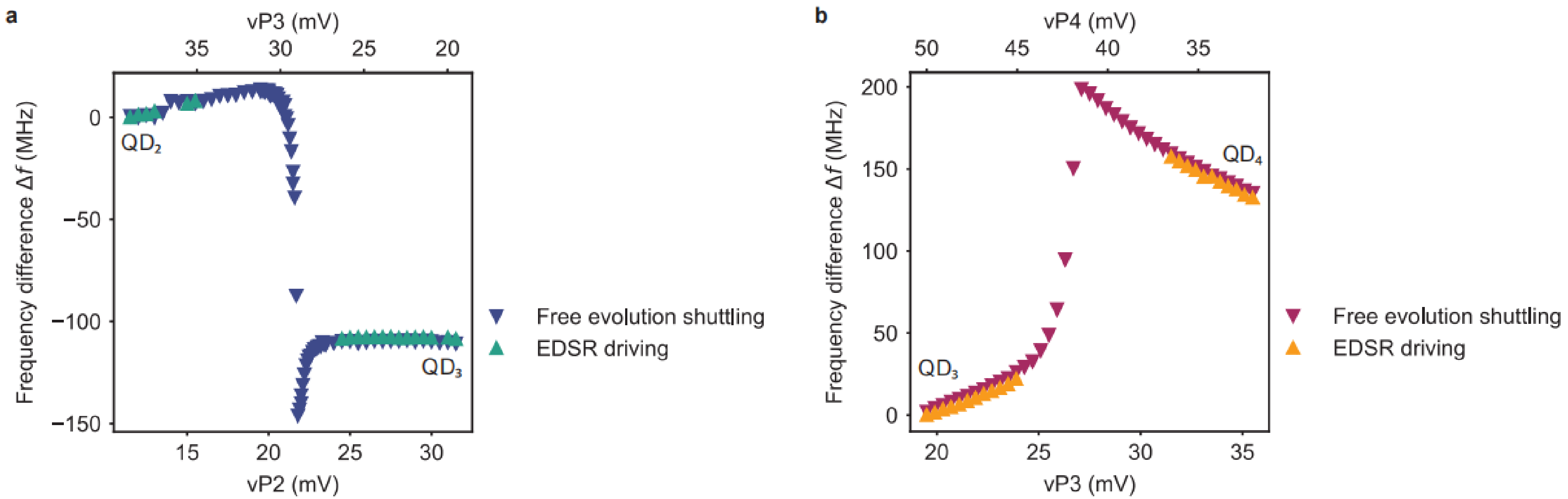


- No clear interdot transition can be distinguished between QD2-QD4, the coupling between QD2 and QD4 is low
- We separately the pulse to two part to reduce the probability of exciting the (1,1,0,1) charge state during transition from (1,1,0,0) to (1,0,0,1)

BB Shuttling

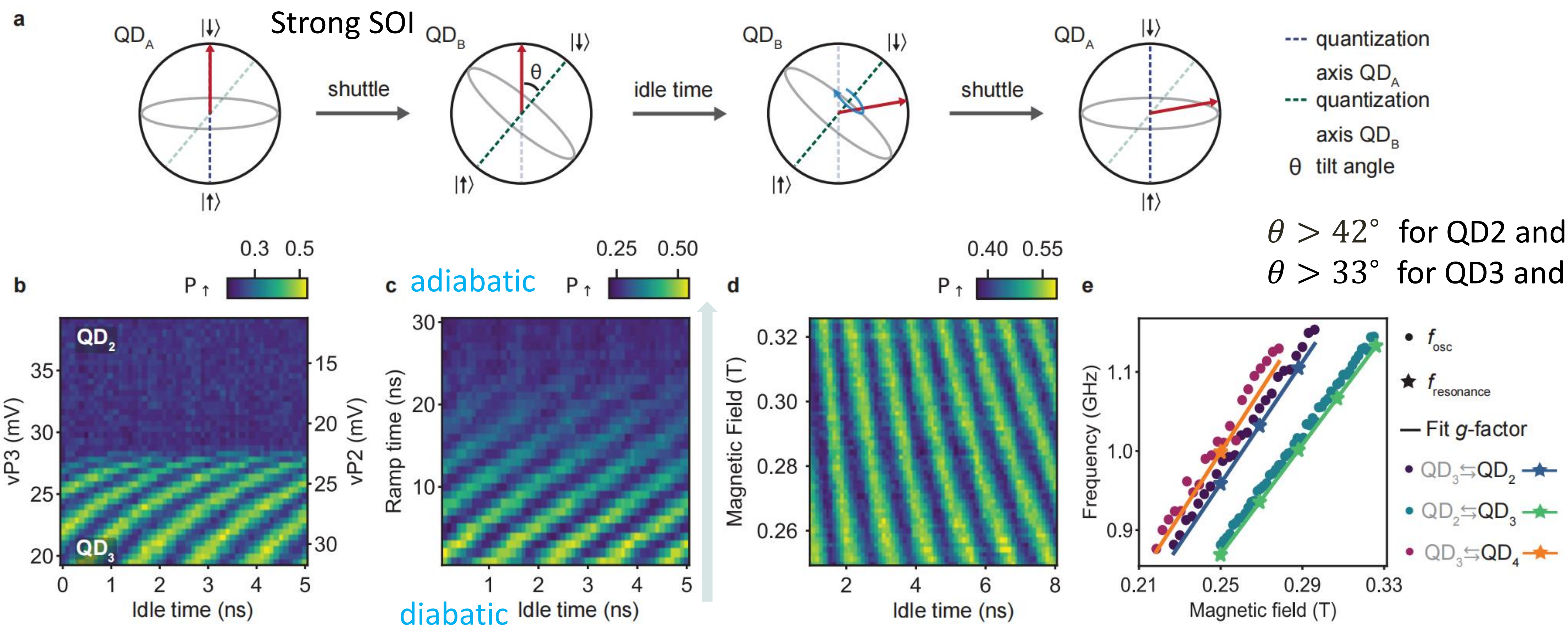


- Oscillation stripes: superposition state phase accumulation during idle time
- f_{osc} changes with the difference in resonance frequency between the starting and end point in detuning



Evolution of the Larmor frequency for shuttling in DQD

SOI Induced Quantization Axis Change

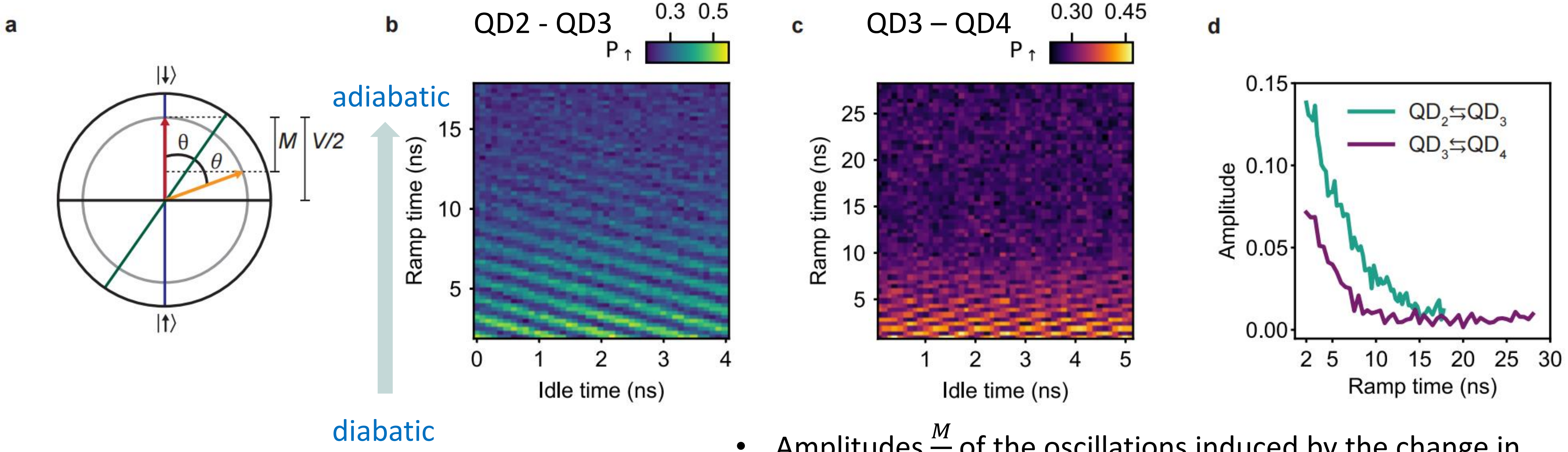


$\theta > 42^\circ$ for QD2 and QD3

$\theta > 33^\circ$ for QD3 and QD4

- Shuttle a spin down qubit between QD2 and QD3 diabatically ($t_{ramp} = 4\ ns$), phase accumulates from the change of quantization axis
- Detuning is fixed, we increase the ramp time and the oscillation vanishes as increasing adiabatic.
- Magnetic-field dependence of the oscillations. f_{Larmor} increases linearly with magnetic field
- f_{osc} increase linearly with magnetic field, matches Larmor frequency in QD

Estimation of the Tilt Angle: Visibility



- Blue axis: quantization axis of QD1
- Green axis: quantization axis of QD2
- When spin down qubit shuttles to QD2, it will evolute freely around the green axis
- Orange arrow: after half a period, the state projection on the quantization axis of the QD1 differs maximally from that of the initial state
- M: oscillation visibility
- V: Rabi oscillation visibility

- Amplitudes $\frac{M}{2}$ of the oscillations induced by the change in quantization axis as function of the pulse ramp time t_{ramp}

$$\theta = \frac{1}{2}\arccos\left(1 - 2\frac{M}{V}\right), \qquad 0 \leq \theta \leq \pi$$

	QD2-QD3	QD3-QD4
V	0.61	0.48
M	0.28	0.14
θ	$\geq 42^\circ$	$\geq 33^\circ$

Estimation of the Tilt Angle: Four Level Model

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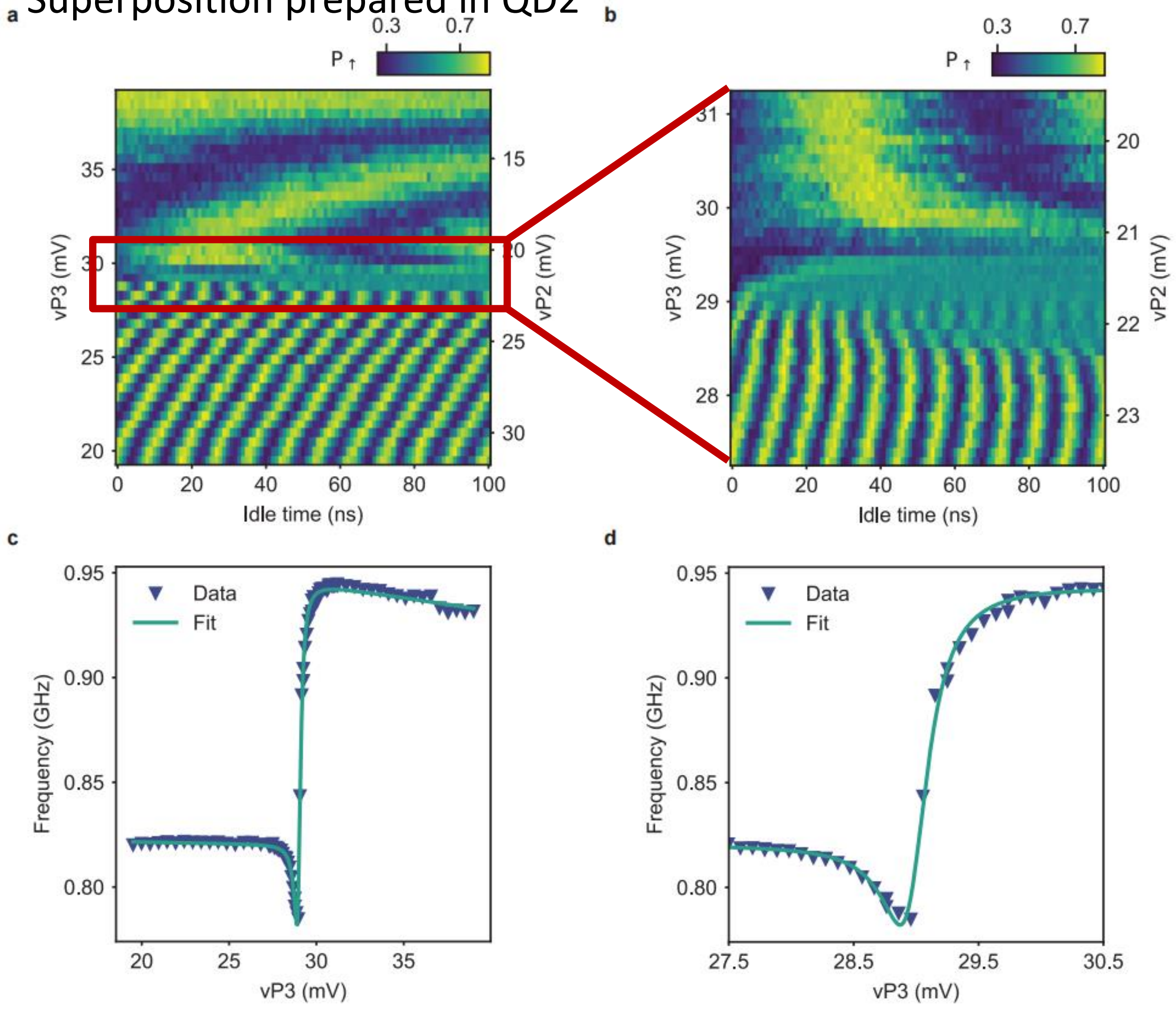
Superposition prepared in QD2



Four basis states $\{|A,\uparrow_A>\}$, $\{|A,\downarrow_A>\}$, $\{|B,\uparrow_A>\}$, $\{|B,\downarrow_A>\}$

A, B: position of hole in QD_A or QD_B

$\uparrow_A$ and $\downarrow_A$: spin states in the frame of QD_A

ϕ is tilt angle between 2 quantization axis

$$H_{\text{model}} = H_{\text{charge}} + H_{\text{Zeeman}} = \begin{pmatrix} \epsilon & 0 & t_c & 0 \\ 0 & \epsilon & 0 & t_c \\ t_c & 0 & -\epsilon & 0 \\ 0 & t_c & 0 & -\epsilon \end{pmatrix} + \frac{1}{2}B\mu_B \begin{pmatrix} g_A(\epsilon) & 0 & 0 & 0 \\ 0 & -g_A(\epsilon) & 0 & 0 \\ 0 & 0 & g_B(\epsilon)\cos(\theta) & g_B(\epsilon)\sin(\theta)e^{i\varphi} \\ 0 & 0 & g_B(\epsilon)\sin(\theta)e^{-i\varphi} & -g_B(\epsilon)\cos(\theta) \end{pmatrix}$$

$$f_L = \frac{\mu_B B}{h}\frac{\sqrt{(2\epsilon^2+t_c^2)(g_A(\epsilon)^2+g_B(\epsilon)^2)+2\epsilon(g_B(\epsilon)^2-g_A(\epsilon)^2)\sqrt{\epsilon^2+t_c^2}+2g_A(\epsilon)g_B(\epsilon)t_c^2\cos(\theta)}}{2\sqrt{\epsilon^2+t_c^2}},$$

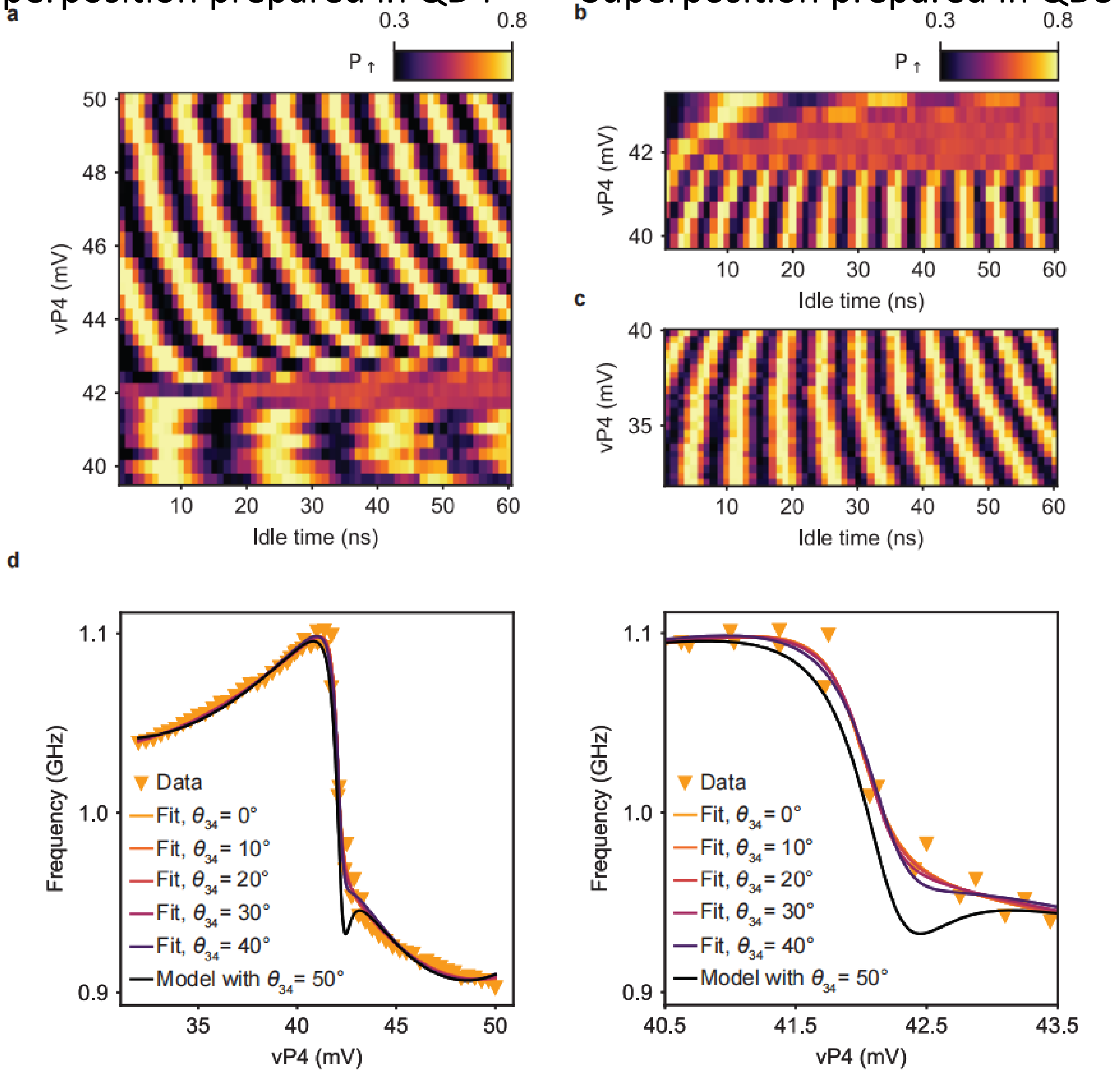
A linear dependence of g factor with vP3 in QD3

$$t_c = 8.7 \pm 0.3\ GHz$$

$$\theta_{23} = 51.8^\circ \pm 0.7^\circ$$

Estimation of the Tilt Angle: Four Level Model

Superposition prepared in QD4 | Superposition prepared in QD3

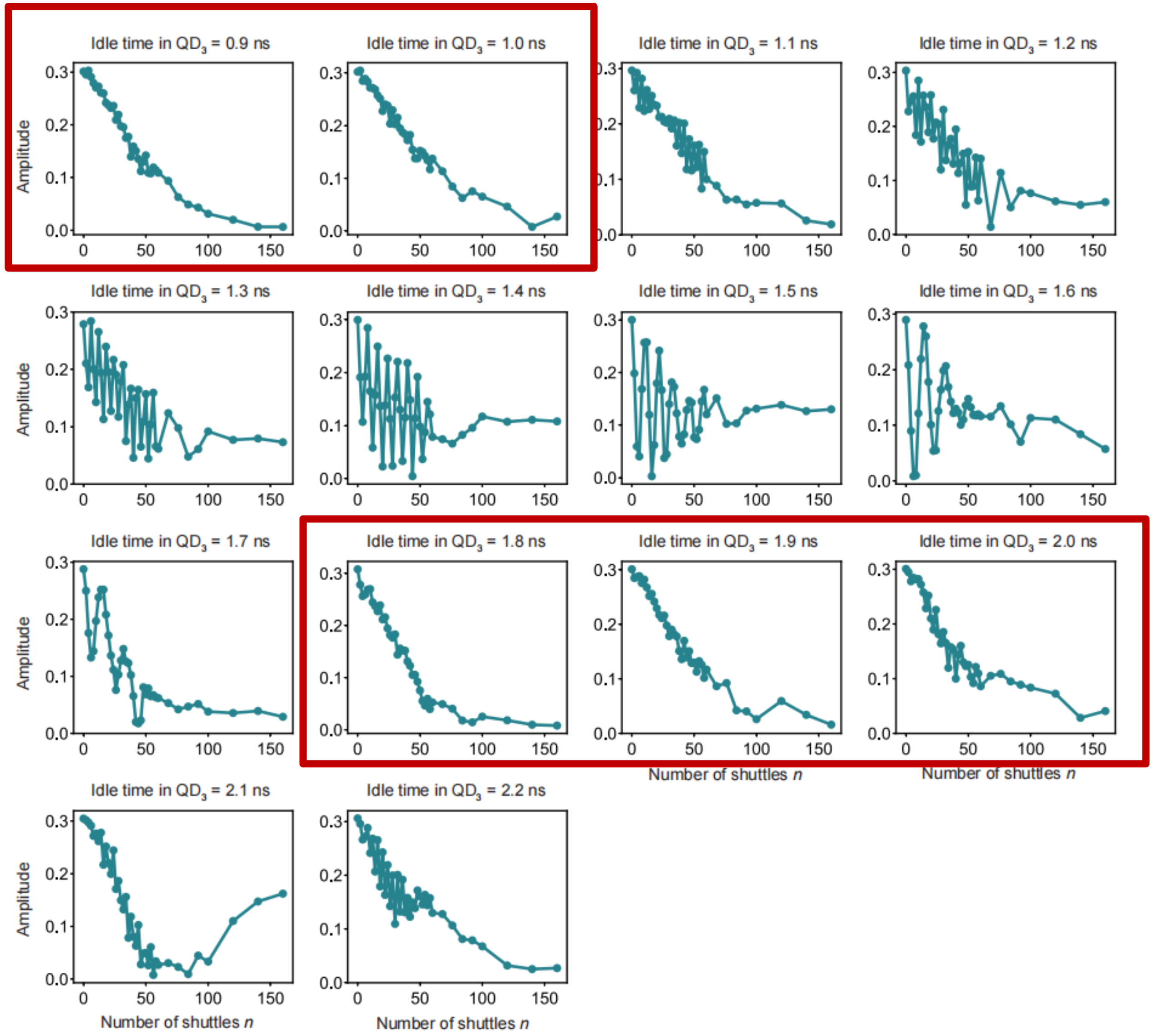


$$f_L = \frac{\mu_B B}{h} \frac{\sqrt{(2\epsilon^2+t_c^2)(g_A(\epsilon)^2+g_B(\epsilon)^2)+2\epsilon(g_B(\epsilon)^2-g_A(\epsilon)^2)\sqrt{\epsilon^2+t_c^2}+2g_A(\epsilon)g_B(\epsilon)t_c^2\cos(\theta)}}{2\sqrt{\epsilon^2+t_c^2}},$$

- Assume a quadratic dependence of the *g*-factor with the gate voltage
- $0^\circ \leq \theta \lesssim 40^\circ$, the shape of f_L curve is nearly only determined by the tunnel coupling and the variation of the g-factor with vP4. This angles all fit well, cause large uncertainty.
- When $\theta_{34} \geq 50°$, we see a minimum value in simulation but not in experiment

$$\theta = 40^\circ, t_c = 15 \pm 2\ GHz$$
$$\theta = 30^\circ, t_c = 12 \pm 2\ GHz$$

Optimization of the Shuttling Pulses

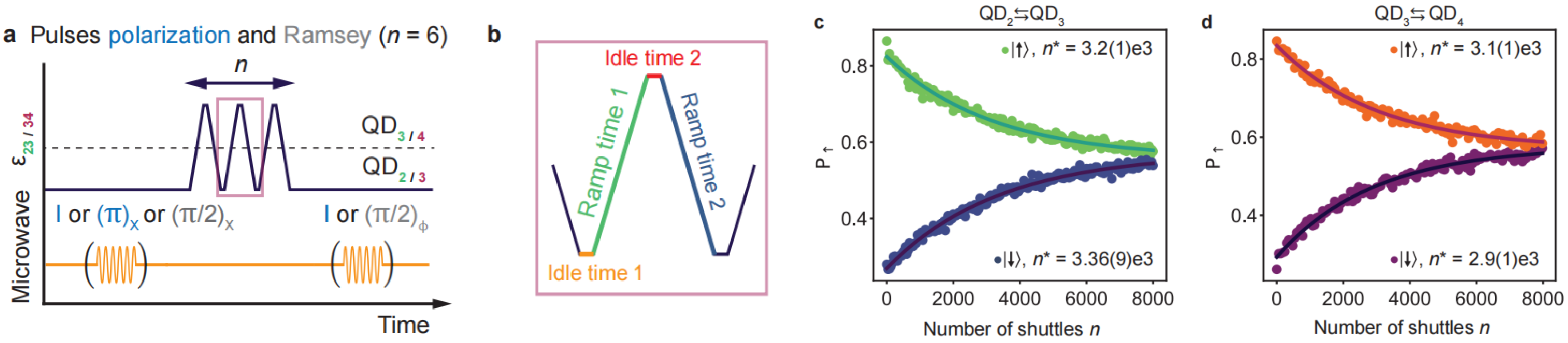


- Results of coherent shuttling experiments between QD2 and QD3 obtained using Ramsey sequences.
- For non-optimized idle times: oscillations of the amplitude and the amplitude can saturate to a non-zero value at large n.

$$t_{idle} = 0.95\ ns$$

Dephasing

$$P_\uparrow = P_0 \exp(-n/n^*) + P_{sat}$$



How to avoid unintended rotations:

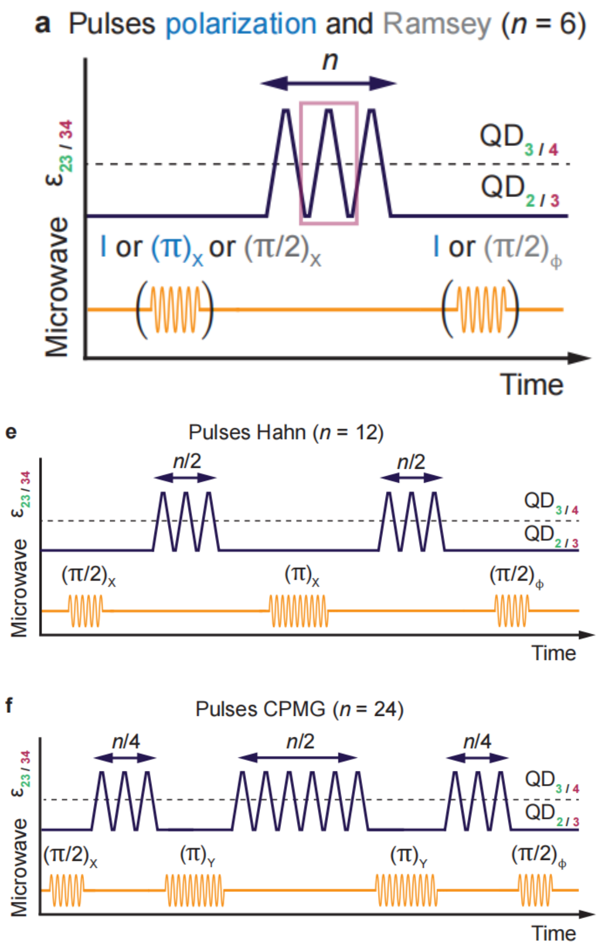
- Transfer the qubit adiabatically. Ramp time can be up to tenths of ns, which are significant with respect to the decoherence time
- Qubit performs an integer number of 2π rotations around the quantization axis of the respective quantum dot. This allows fast shuttling, ramp time 4ns and waiting time 1ns

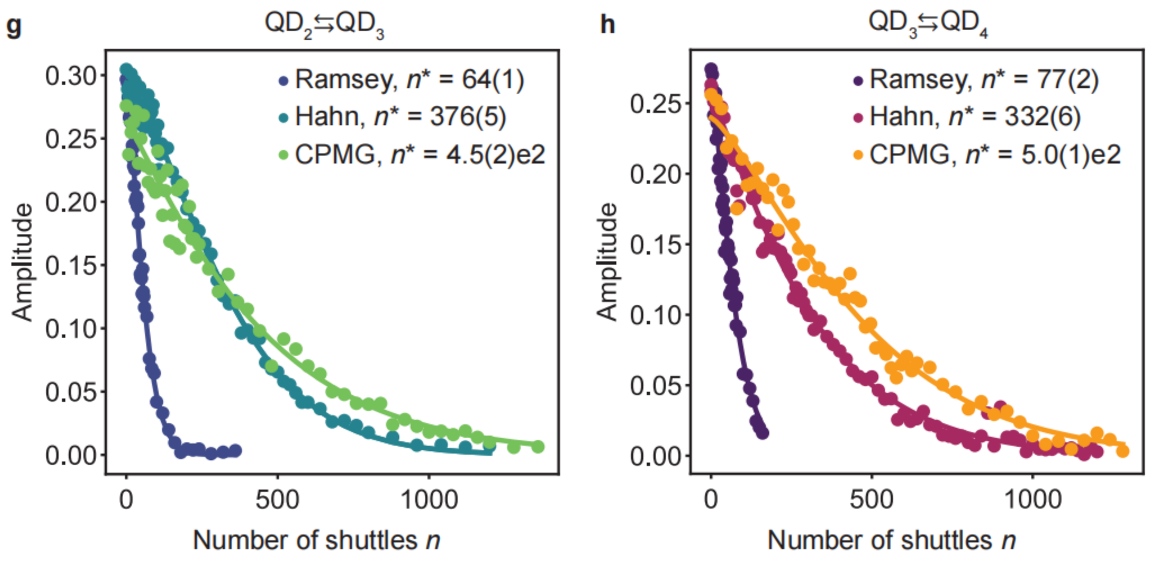
Fidelity for per hop: $F = P_0 exp\left(-\frac{1}{n^*}\right) \approx 99.97\ \%$

This is similar to the fidelities reached in silicon devices [1,2], despite anisotropic g-tensors induced by strong SOI in Ge

[1] Noiri et al., Nat. Commun 13, 5740 (2022)
[2] Yoneda et al., Nat. Commun 12, 4114 (2021)

Decoherence





$$A(n) = A_0 \exp\left(-\left(\frac{n}{n^*}\right)^{\alpha}\right)$$

$$\alpha_{23} = 1.36 \pm 0.05\ ,\ \alpha_{34} = 1.28 \pm 0.06$$

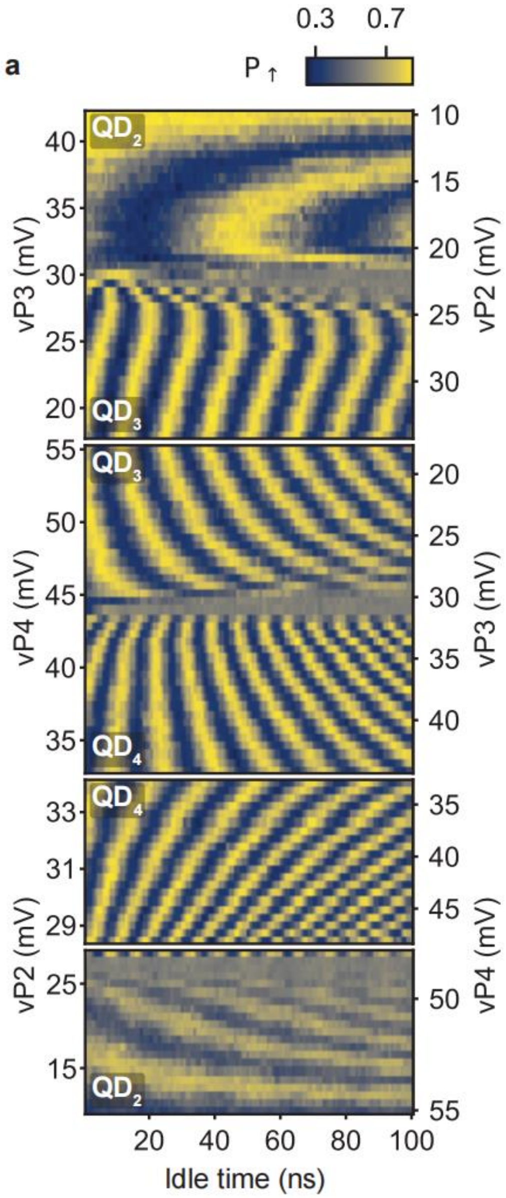
In SiMOS system[1] which has weaker SOI,
$n^* \approx 50$

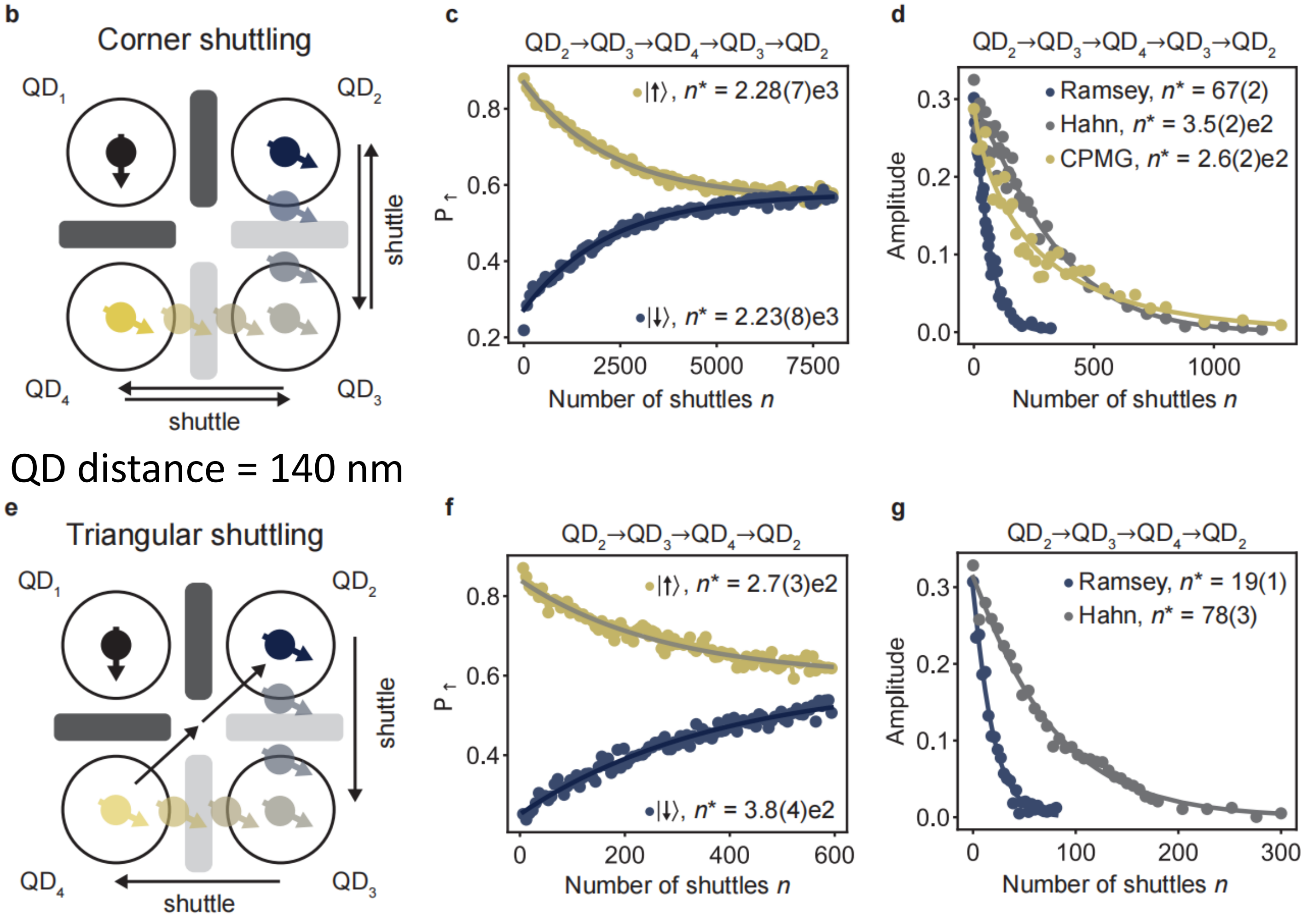
	n^*	Effective length
Basis states	2230	$312\ \mu m$
Coherent states	67	$9\ \mu m$
Using echo pulse	350	$49\ \mu m$

[1] Yoneda et al., Nat. Commun 12, 4114 (2021)

Coherent Shuttling

Free evolution experiments





QD distance = 140 nm

- Fidelity per shuttling step: 99.96% (CS) and 99.63% (TS)
- The infidelity arises from systematic error per shuttling: low coupling between QD2 and QD4, $t_{ramp} = 36\ ns$

Catalogue

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01 Research Background

02 Electron Spin Shuttling in Si/SiGe

03 Hole Spin Shuttling in Ge/SiGe

04 Conclusions and outlooks

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Summary:

- Introduce the background of shuttling
- Characterize BB mode and CB mode shuttling in Si/SiGe
- Achieve BB mode shuttling in Ge/SiGe with strong SOI

Outlook:

- Further research on shuttling theory
- The methods to do shuttling in NW system