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Coherent transfer of quantum information in a silicon double quantum dot using resonant SWAP gates

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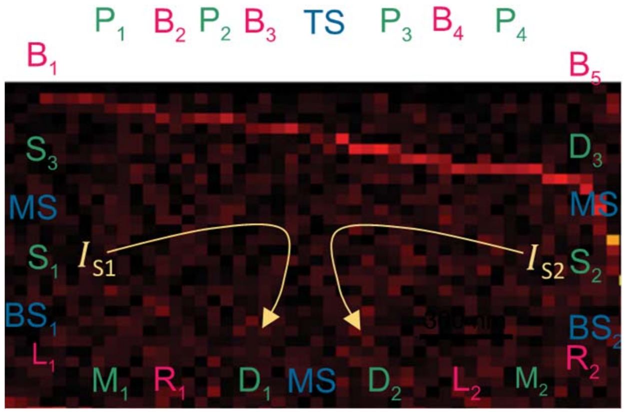
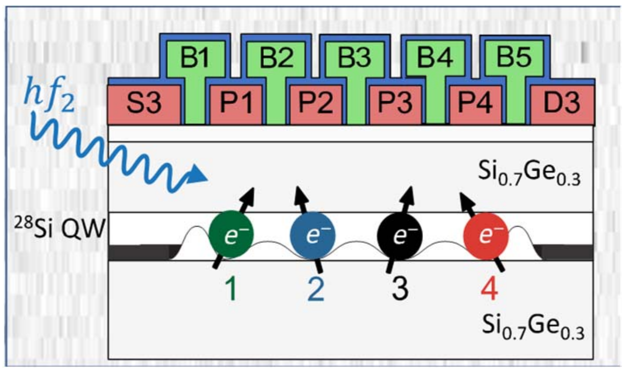
Motivation

- electron spin qubits in Si
- high-fidelity single- and two-qubit (exchange) gates
  - error correction
  - random access memory
  - multiqubit algorithms
- quantum SWAP gate → phase coherent SWAP
  - move spin eigenstates in 100 ns, $\bar{F}^{(p)}_{SWAP} = 98\%$
  - transfer product states in 300 ns, $\bar{F}^{(p)}_{SWAP} = 84\%$
- coupling of non-adjacent qubits

UNI BASEL

Device architecture





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- isotopically enriched ^{28}Si/SiGe
- micromagnet
- electron dipole spin resonance (single spin control)
- qubits Q_3 and Q_4 (under plunger gates P_3 and P_4)
- $(N_3, N_4)=(1, 1)$
- charge sensing with I_{S2} (readout 3 ms)
- measure/initialize Q_4 (via spin-selective tunneling to reservoir under D_3)
- loading fidelity 95% limited by 110 mK

Two-qubit interactions

modulate exchange interaction $J_{3,4}(V_{B4})$

$$V_{B4}(t) = V_{B4}^{(dc)} + V_{B4}^{(ac)}\cos(2\pi f_{SWAP} + \phi)$$

$J_{3,4} \gg \gamma_e |B_3^{tot} - B_4^{tot}|$ - magnetic filed gradient

γ_e - gyromagnetic ratio

No → CPHASE-like evolution

Yes → SWAP oscillations

CPHASE-like evolution → SWAP oscillations

$$2\pi f_{SWAP} = \gamma_e |B_3^{tot} - B_4^{tot}|$$

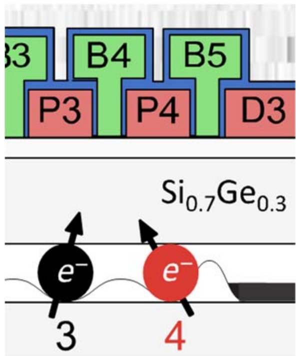
$|\uparrow\uparrow\rangle, |\downarrow\downarrow\rangle$ - unaffected

$|\phi_3, \phi_4\rangle \in \{|\uparrow\downarrow\rangle, |\downarrow\uparrow\rangle\}$

π-pulse = SWAP + single-qubit phases

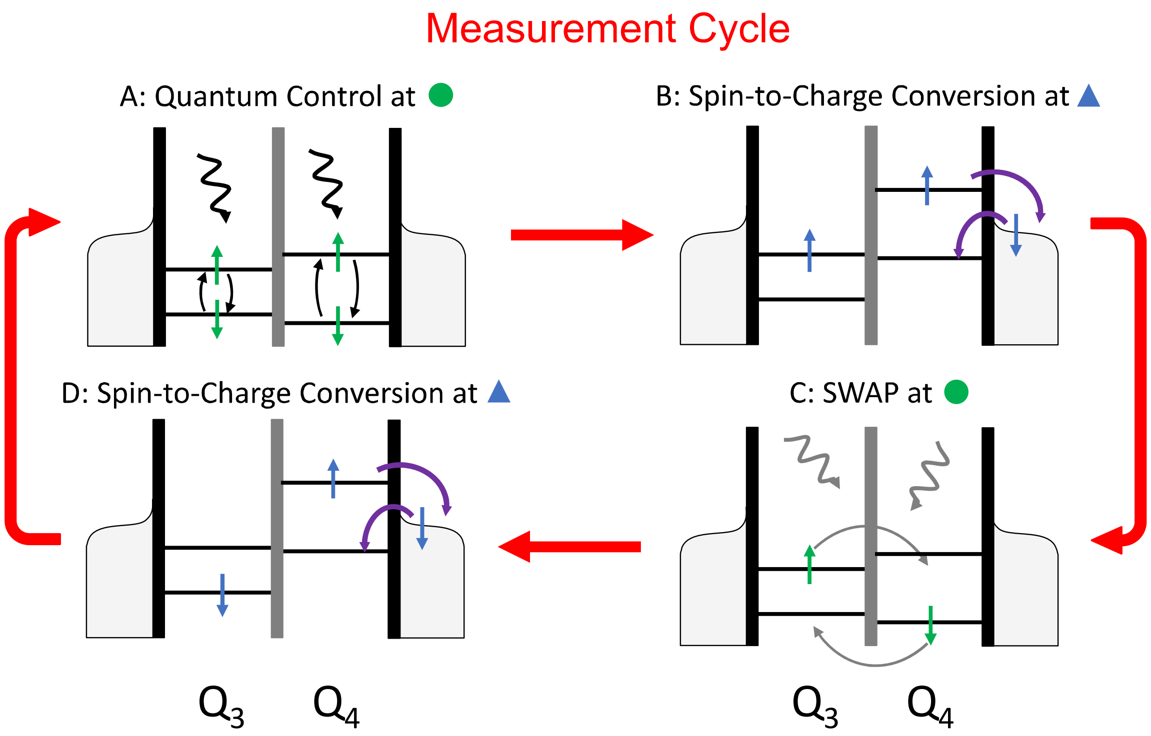
resonant SWAP gate

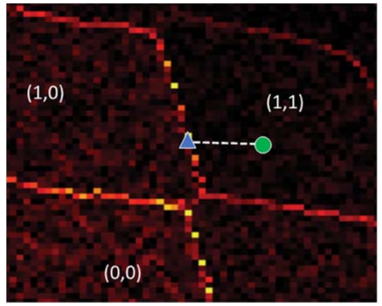
→ *projection*-SWAP —calibration→ *coherent*-SWAP



$$\gamma_e B_3^{tot} = 16.949 \text{ GHz}$$
$$\gamma_e B_4^{tot} = 17.089 \text{ GHz}$$
$$B_{ext} = 410 \text{ mT}$$

projection-SWAP





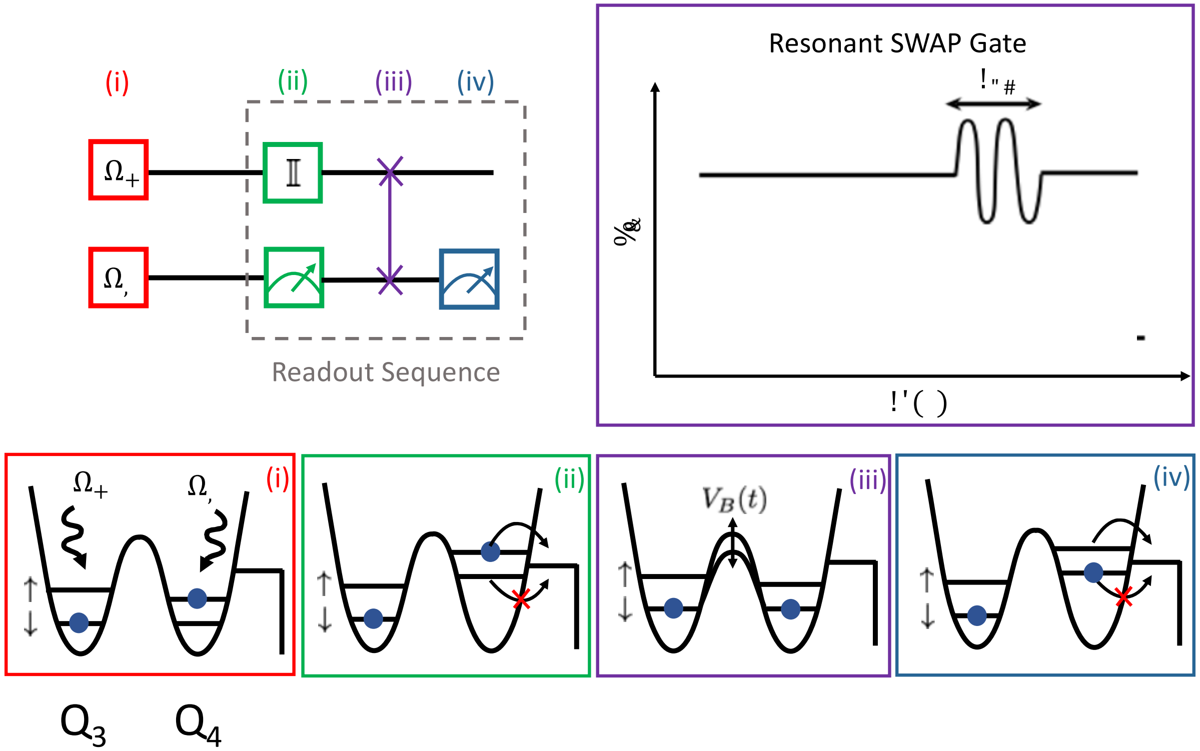
A: individual manipulation

B: spin-selective tunneling
leaves Q_4 in the state $|\downarrow\rangle$

C: modulate the exchange
interaction, map Q_3 to Q_4

D: read out "Q_3"
leaves Q_3 and Q_4 in state $|\downarrow\rangle$

projection-SWAP



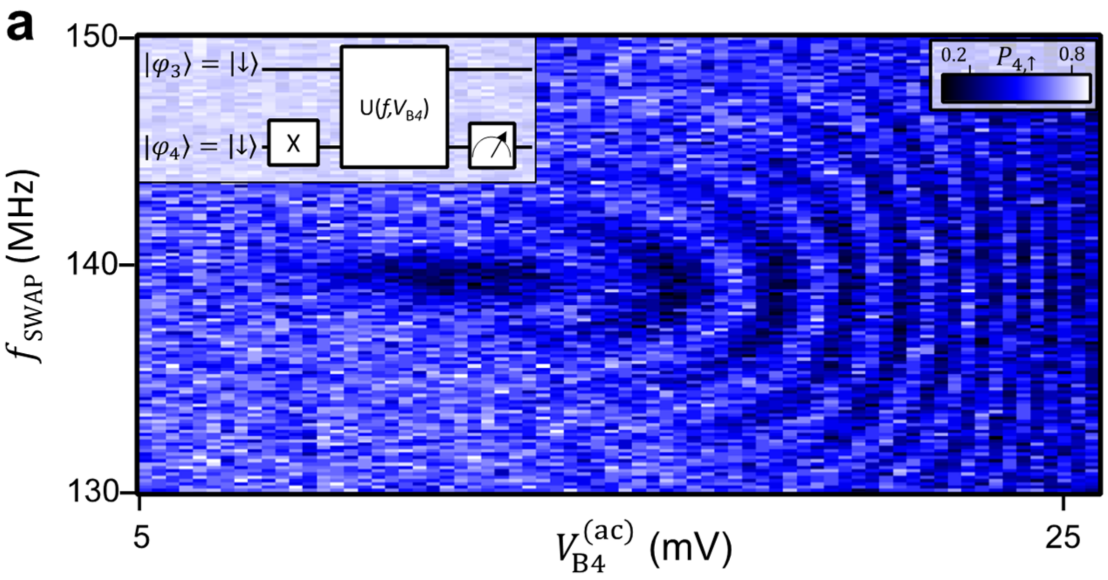
i: state preparation

ii: measurement

iii: resonant SWAP

iv: read out ”Q_3”

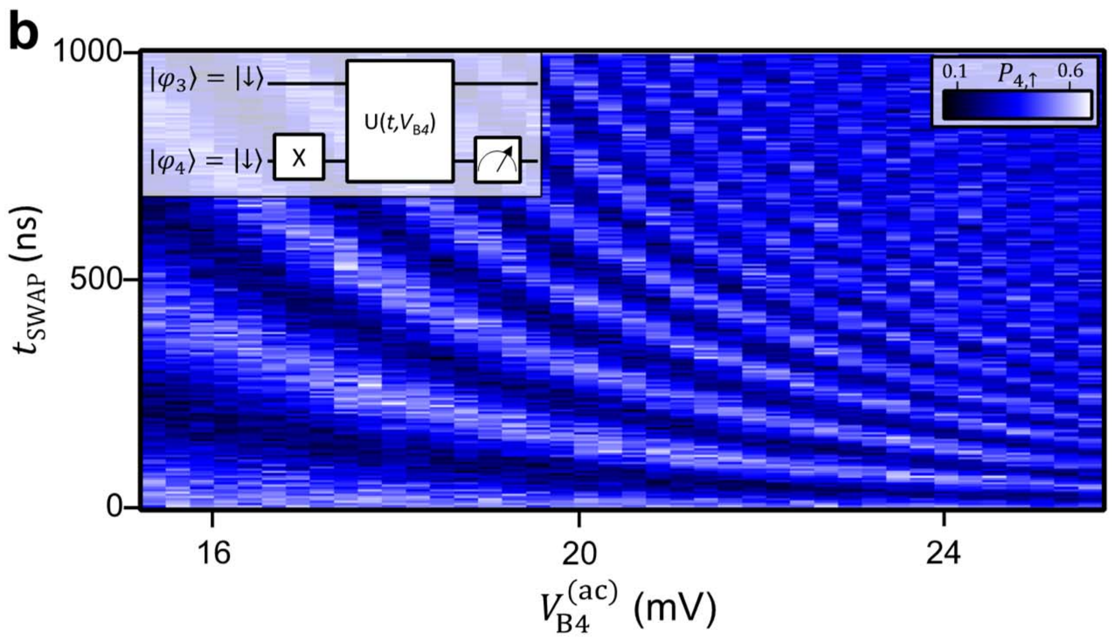
SWAP gate calibration



- initialize $|\phi_3, \phi_4\rangle = |\downarrow\downarrow\rangle$
- flip Q_4 using X gate
- f_{SWAP} burst on B_4 for 600 ns

- no oscillations at small $V_{\mathrm{B4}}^{(\mathrm{ac})}$
- SWAP at $V_{\mathrm{B4}}^{(\mathrm{ac})} = 10\ \mathrm{mV}$
- pattern is symmetric about $f_{\mathrm{SWAP}} = 140\ \mathrm{MHz}$

Minimize SWAP time

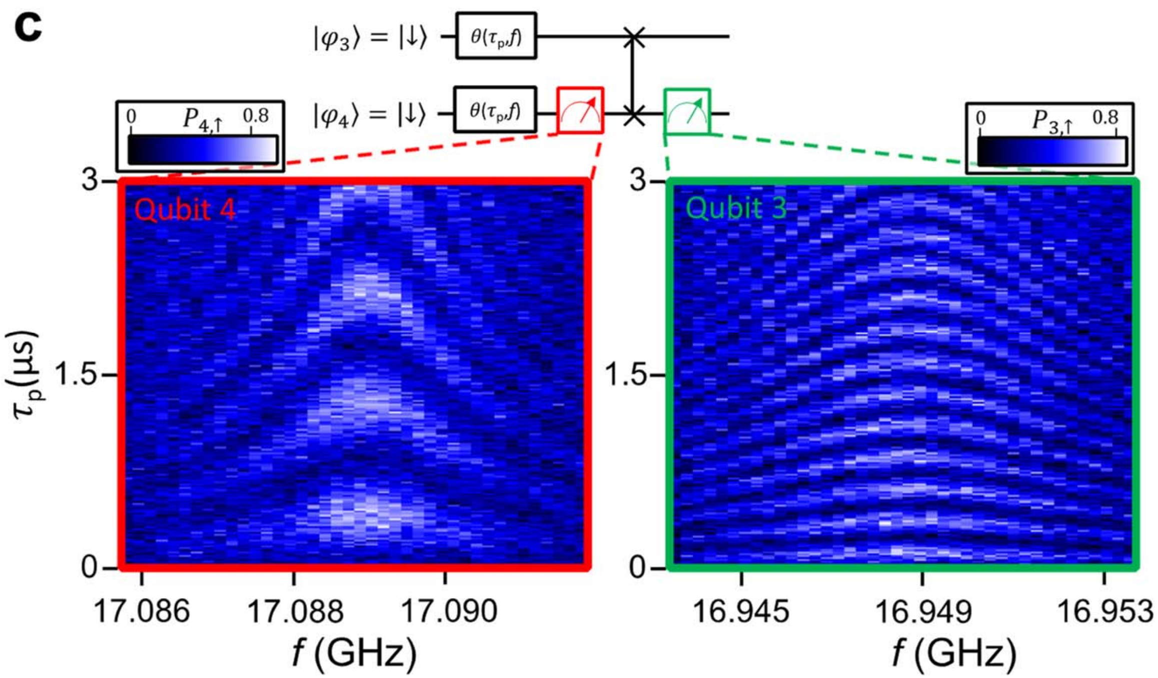


- fix $f_{SWAP} = 140$ MHz
- change burst time and ac amplitude

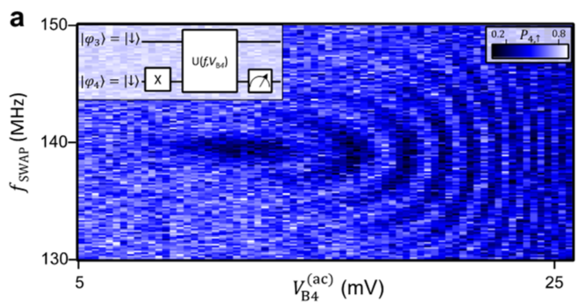
- bright fringe – even number of SWAPs
- Minimum $t_{SWAP} = 23$ ns (limited by control electronics)

$T_2^* \approx 10$ μs for both dots (T_1 = 134 / 52 ms)

Simultaneous control, initialization, and readout

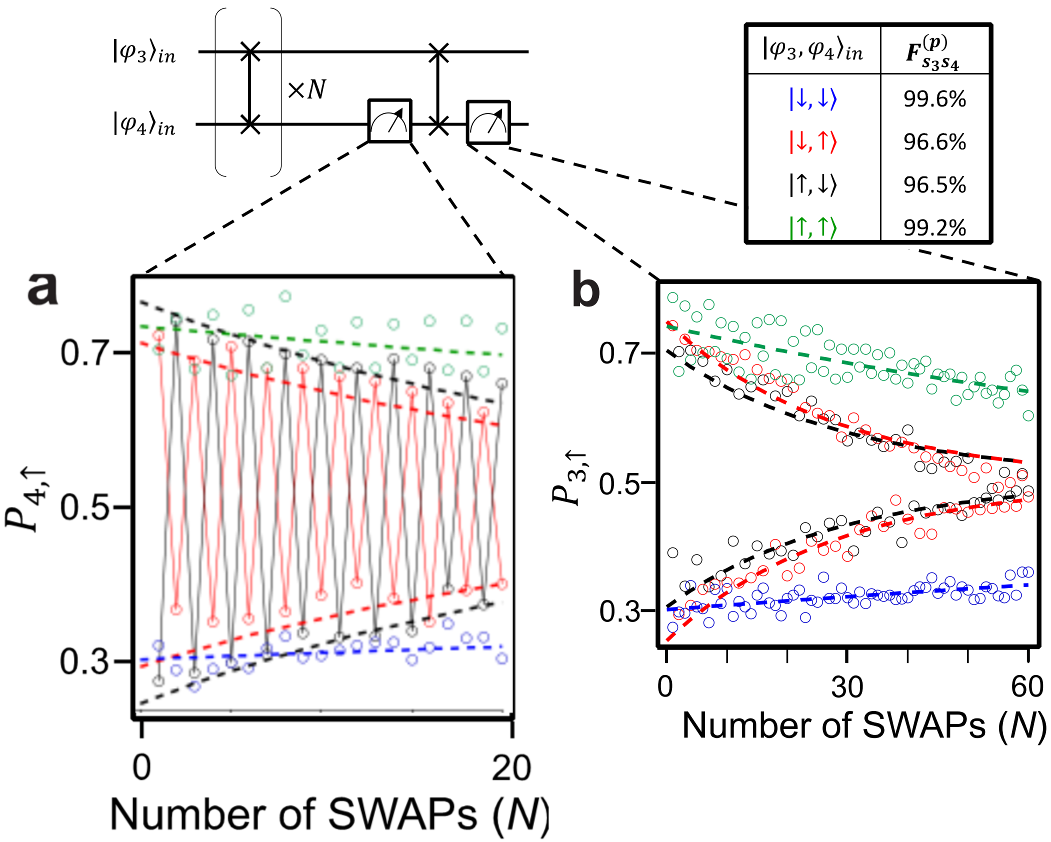


- initialize $|\phi_3,\phi_4\rangle = |\downarrow\downarrow\rangle$
- RF burst
- measure Q_4
- projection-SWAP
- measure "Q_3" (measure Q_4 infer Q_3)



- Rabi oscillations (spacing largest on resonance)
- qubit difference frequency 140 MHz
- Initialize, control, and readout DQD with Q_4

projection-SWAP fidelity



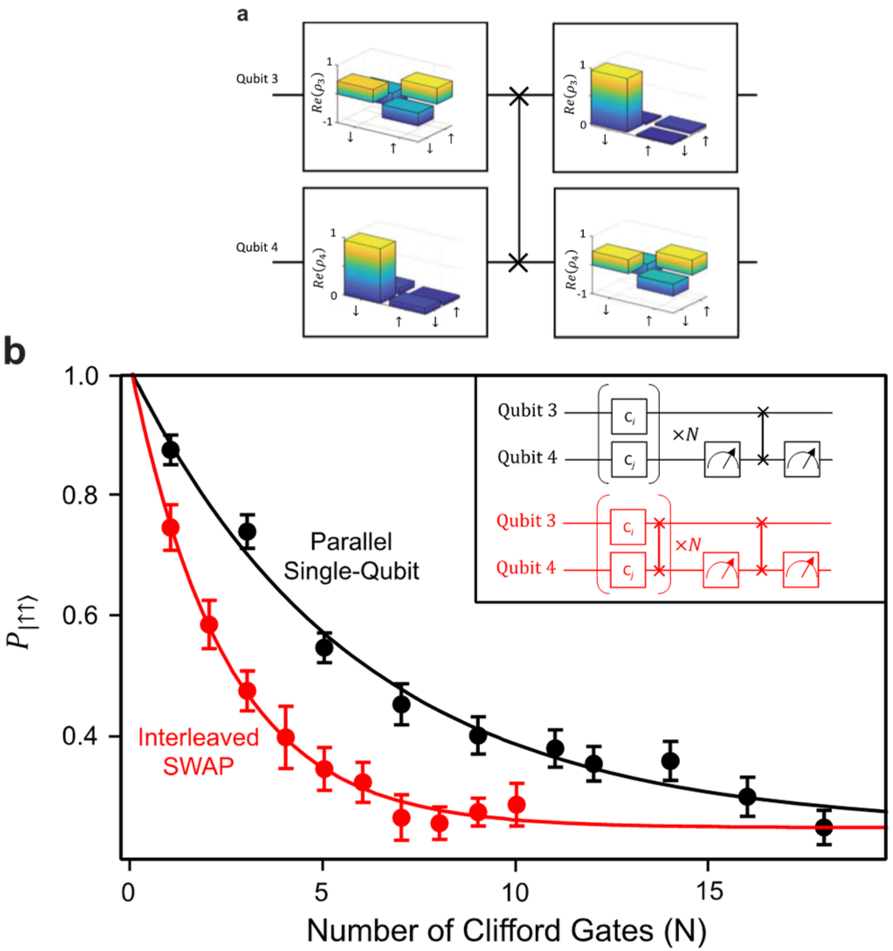
$\lvert\varphi_3,\varphi_4\rangle_{in}$	$F^{(p)}_{s_3 s_4}$
$\lvert\downarrow,\downarrow\rangle$	99.6%
$\lvert\downarrow,\uparrow\rangle$	96.6%
$\lvert\uparrow,\downarrow\rangle$	96.5%
$\lvert\uparrow,\uparrow\rangle$	99.2%

- experiment insensitive to state preparation and measurement (SPAM) errors
- initial states:
  $|\phi_3,\phi_4\rangle_{\text{in}} = |\downarrow\downarrow\rangle, |\downarrow\uparrow\rangle, |\uparrow\downarrow\rangle, |\uparrow\uparrow\rangle$
- execute SWAP gate N times

- $|\downarrow\uparrow\rangle$ and $|\uparrow\downarrow\rangle$ flip-flop for each SWAP
- decay envelope is given by fidelity
- $\mathrm{F}^{(\mathrm{p})}_{\downarrow\uparrow} = \mathrm{F}^{(\mathrm{p})}_{\uparrow\downarrow} = 96.5\%$,
  $\mathrm{F}^{(\mathrm{p})}_{\downarrow\downarrow} = 99.6\%$, $\mathrm{F}^{(\mathrm{p})}_{\uparrow\uparrow} = 99.2\%$

- $\bar{F}^{(p)}_{SWAP} = 98\%$

coherent-SWAP fidelity



- state tomography before and after SWAP of the superposition state Q_3 and spin down state Q_4.

- additional calibration
- $(\alpha_1|\uparrow\rangle + \beta_1|\downarrow\rangle) \otimes (\alpha_2|\uparrow\rangle + \beta_2|\downarrow\rangle) \longrightarrow$
  $(\alpha_2|\uparrow\rangle + \beta_2|\downarrow\rangle) \otimes (\alpha_1|\uparrow\rangle + \beta_1|\downarrow\rangle)$

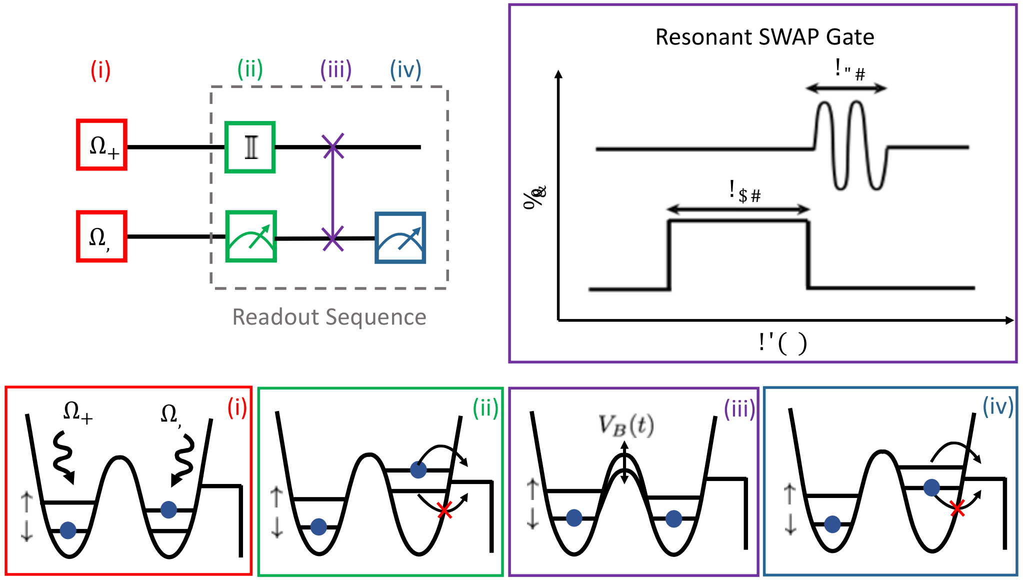
- $\bar{F}_{SWAP}^{(c)} = 84\%$

Gate calibration

$$U = Z_3(\theta_3)Z_4(\theta_4)\mathrm{SWAP},$$

$$\theta_3 = \frac{(\Delta_3^{\mathrm{dc}} + \Delta_4^{\mathrm{dc}})t_{\mathrm{dc}}}{2} - \frac{\Delta_{34}^{\mathrm{dc}}}{2}t_{\mathrm{dc}} + \frac{(\Delta_3^{\mathrm{ac}} + \Delta_4^{\mathrm{ac}})t_{\mathrm{ac}}}{2} + \phi,$$

$$\theta_4 = \frac{(\Delta_3^{\mathrm{dc}} + \Delta_4^{\mathrm{dc}})t_{\mathrm{dc}}}{2} + \frac{\Delta_{34}^{\mathrm{dc}}}{2}t_{\mathrm{dc}} + \frac{(\Delta_3^{\mathrm{ac}} + \Delta_4^{\mathrm{ac}})t_{\mathrm{ac}}}{2} - \phi.$$



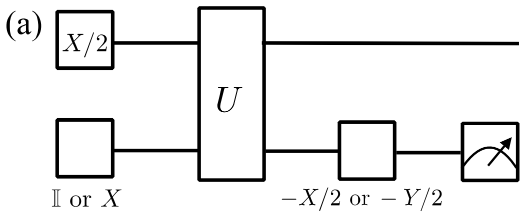
$\Delta_i = B_i - 2\pi f_i$ - magnetic field detuning

$\Delta_{34} = \Delta_3 - \Delta_4$ - shifted magnetic field gradient

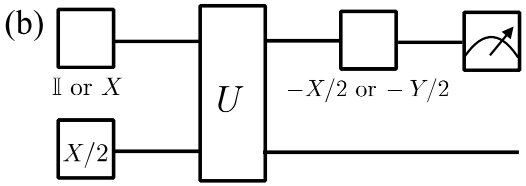
ϕ is the phase of this ac

Calibration of the gate requires a precise measurement of $J_{34}^{dc/ac}$ and $\Theta_{3/4}$

Gate calibration



change t_{dc}



$$p_\uparrow = \frac{1}{2} + \frac{1}{2}\sin\left[\left(\Delta_3^{\mathrm{dc}} - \frac{J_{34}^{\mathrm{dc}}}{2}\right)t_{\mathrm{dc}} + \frac{\Delta_3^{\mathrm{ac}} + \Delta_4^{\mathrm{ac}}}{2}t_{\mathrm{ac}} - \frac{J_{34}^{\mathrm{ac}}}{2}t_{\mathrm{ac}} - \phi\right],$$

$$p_\uparrow = \frac{1}{2} - \frac{1}{2}\sin\left[\left(\Delta_3^{\mathrm{dc}} + \frac{J_{34}^{\mathrm{dc}}}{2}\right)t_{\mathrm{dc}} + \frac{\Delta_3^{\mathrm{ac}} + \Delta_4^{\mathrm{ac}}}{2}t_{\mathrm{ac}} + \frac{J_{34}^{\mathrm{ac}}}{2}t_{\mathrm{ac}} - \phi\right],$$

$$p_\uparrow = \frac{1}{2} + \frac{1}{2}\sin\left[\left(\Delta_4^{\mathrm{dc}} - \frac{J_{34}^{\mathrm{dc}}}{2}\right)t_{\mathrm{dc}} + \frac{\Delta_3^{\mathrm{ac}} + \Delta_4^{\mathrm{ac}}}{2}t_{\mathrm{ac}} - \frac{J_{34}^{\mathrm{ac}}}{2}t_{\mathrm{ac}} + \phi\right],$$

$$p_\uparrow = \frac{1}{2} - \frac{1}{2}\sin\left[\left(\Delta_4^{\mathrm{dc}} + \frac{J_{34}^{\mathrm{dc}}}{2}\right)t_{\mathrm{dc}} + \frac{\Delta_3^{\mathrm{ac}} + \Delta_4^{\mathrm{ac}}}{2}t_{\mathrm{ac}} + \frac{J_{34}^{\mathrm{ac}}}{2}t_{\mathrm{ac}} + \phi\right],$$

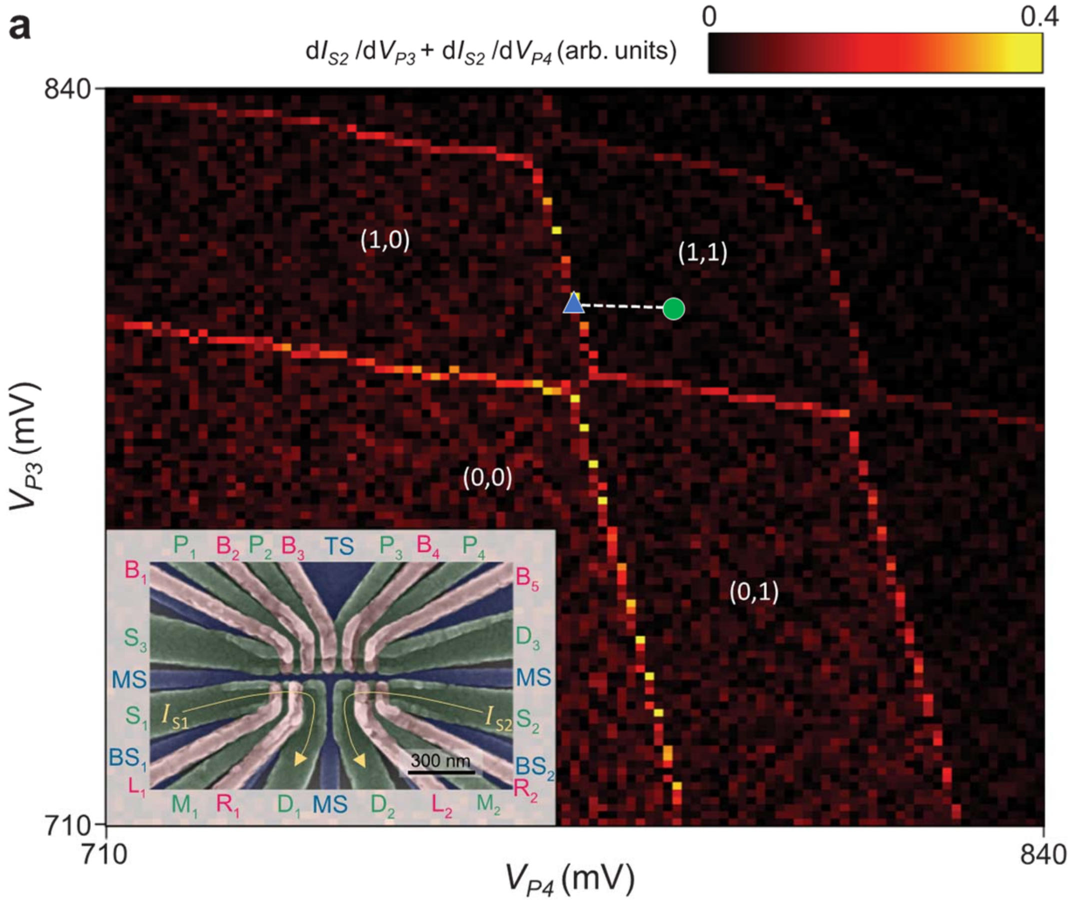
$\Delta_{3/4}^{dc}, J_{34}^{dc/ac}$,
$(\Delta_3^{ac} + \Delta_4^{ac})/2, \phi$

Conclusion and outlook

- coherent spin transport in an array of quantum dots
- transfer arbitrary two-qubit states between spins
- no moving charges

- shuttle a spin projection across nine-dot array with 85% fidelity
- compatible with singlet-triplet and cavity dispersive readouts

Charge stability diagram



Experimental setup