RIKEN-Vancouver Joint
WS on Quantum
Computing (RV21)
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High-fidelity Quantum Gates in Silicon Quantum Computing

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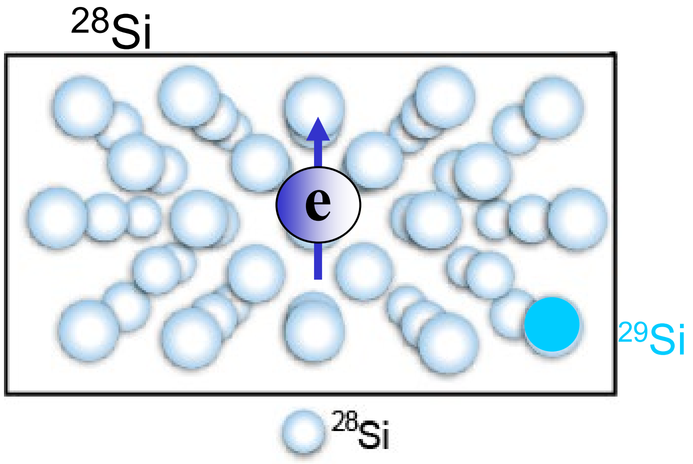
Why Silicon?

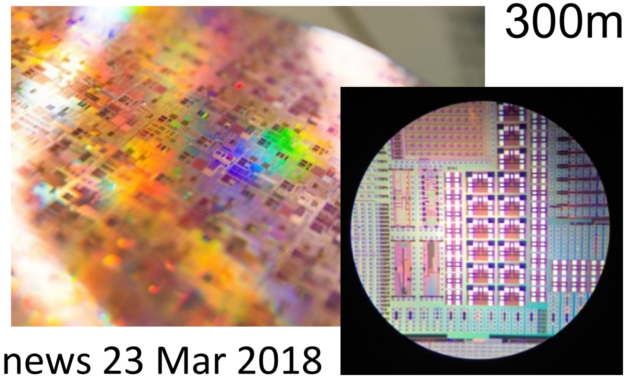


No abundant nuclear spin (^{29}Si)
4.7% in Nat. Si, < 0.1 % in ^{28}Si

→ Long coherence time
> 10 msec

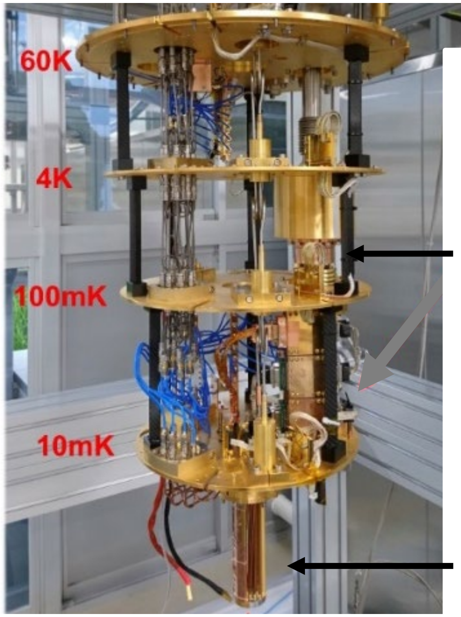
Compatibility of device fabrication with industrial technology

→ 10^9 bits/cm^2 on a chip



300mm QD wafer

LETI news 23 Mar 2018



> 1K

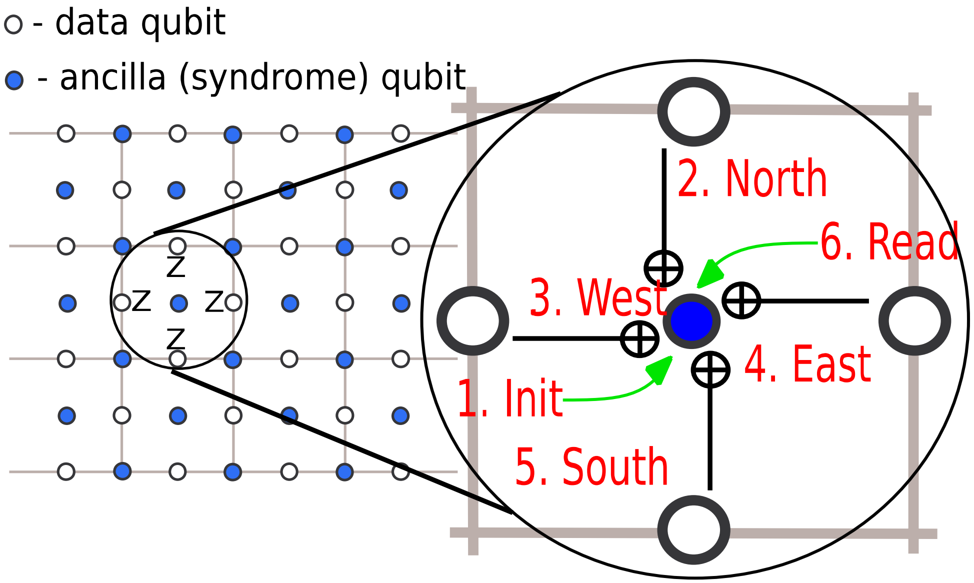
Quantum processor

High temperature operation at > 1K

→ Cooling power at 1 K X100 larger than at < 0.1 K
…. helpful for more qubits and cryo-electronics

Fidelity Thresholds for Fault Tolerant QC

Error Correction in Surface Code



A. G. Fowler et al., Phys. Rev. A (2009)

Error correction thresholds

Fidelity (1 qubit) > 99.9%
Fidelity (2 qubit) > 99%
Initialization F > 99%
Readout F > 99%

Fidelity of Single and Two-qubit Gates

Materials	Single qubit gate Spin-1/2	 Singlet-triplet	Two-qubit gate Spin-1/2
Nat. Si/SiGe	F = 99.6% [1] Limited by magnetic noise	F = 99.6% [2]	F = 98% [3], 75% [5] (ST F ≈ SWAP F = 99.6% [2] Limited by magnetic noise
28Si/SiGe	F = 99.93% [4] Limited by charge noise		
28SiMOS	F = 99.96% [6] Limited by charge noise		$F_{Clifford}$ = 95%, F_{CROT}=98% [7]

[1] K. Takeda et al. Sci. Adv. 2016.
[2] K. Takeda et al. arXiv:1910.00771.
[3] X. Xue et al. PRX 2019.
[4] J. Yoneda et al. Nat. Nanotechnol. 2018.
[5] DM. Zajac et al. Science 2018.
[6] C. H. Yang et al., Nat. Electron. 2019.
[7] W. Huang et al. Nature 2019.

F > 99% on arXiv
for two electron spins in
28Si/SiGe from TuDelft
and this work
for two nuclear spins in 28Si
from UNSW

Outline

High-fidelity single and two qubit gates

- Single and two qubit gates with fast qubit gating and long dephasing time

High-fidelity readout and initialization

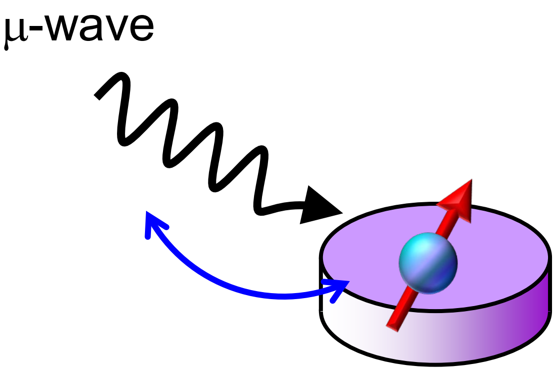
- Quantum non-demolition measurement

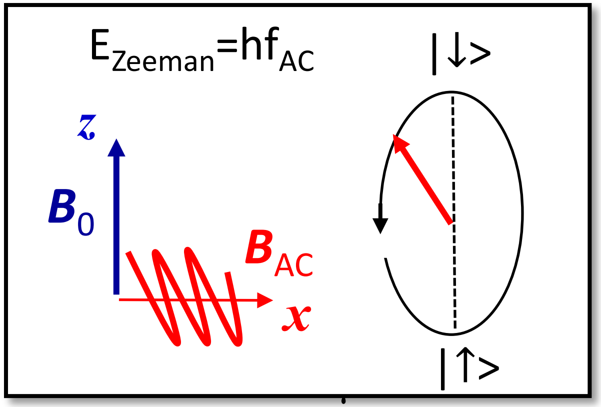
Three qubit entanglement

- Preparation of GHZ state

Physical Implementation of Spin Qubits
: Spin Resonance for Single Electrons in QD

ESR

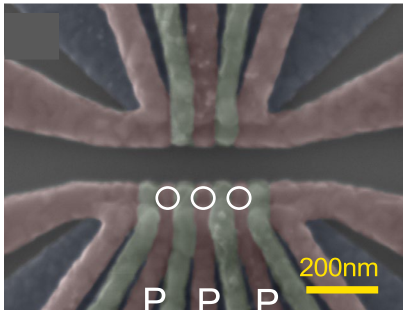


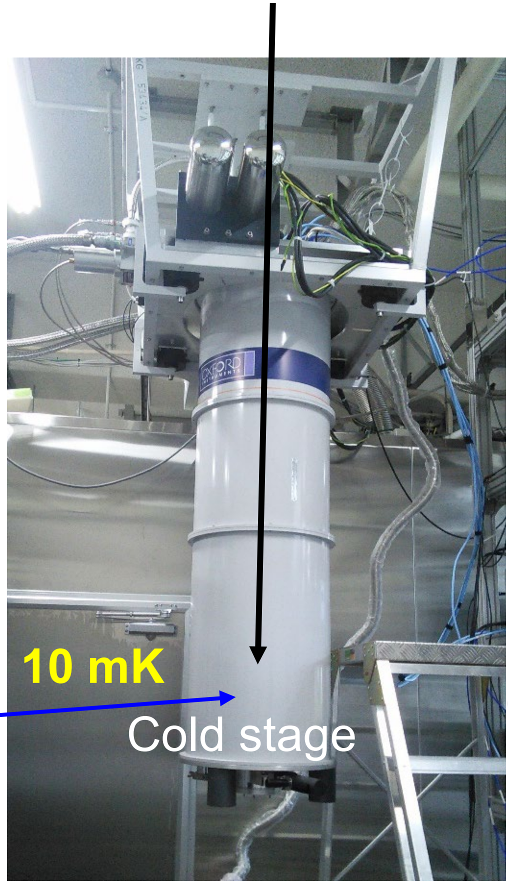


E to B conversion by spin-electric coupling
(μ-magnet, spin-orbit, mini-coil,..)

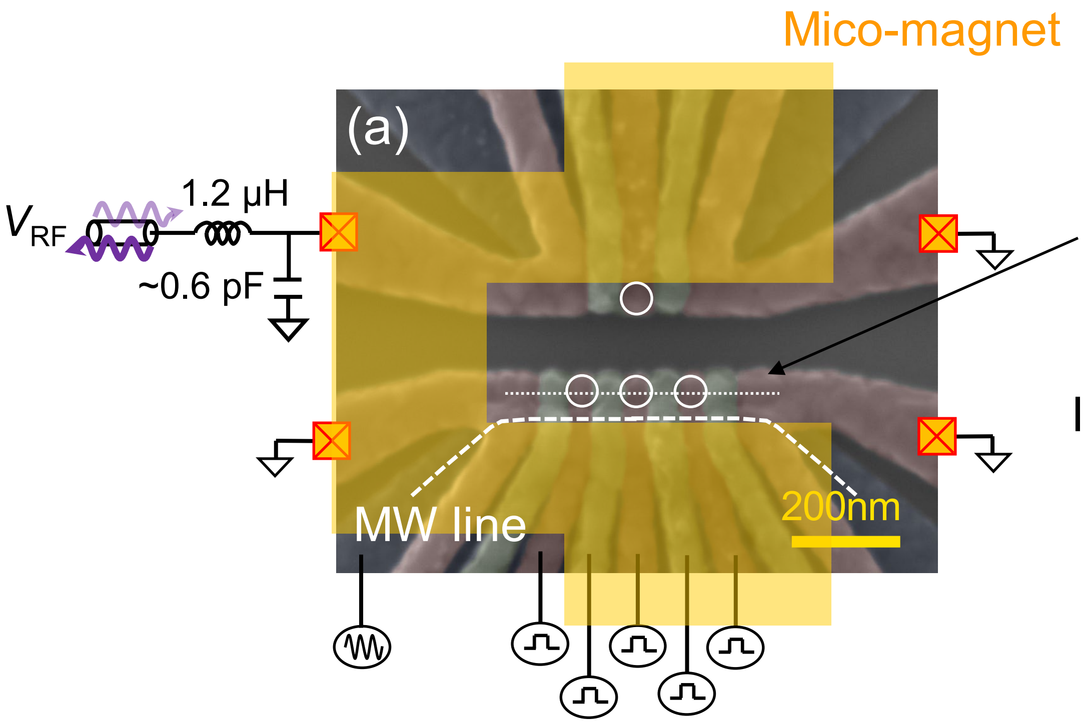
Y. Tokura et al.PRL 2007
MP Ladriere et al. Nat. Phys. 2010
R. Brenner et al. PRL2010
K. Takeda et al. Sci. Adv. 2016
J. Yoneda et al. Nat. Nano. 2018
….

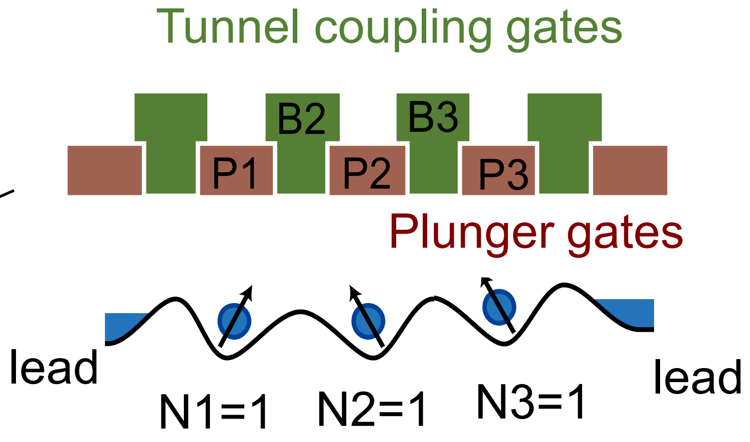
QD device

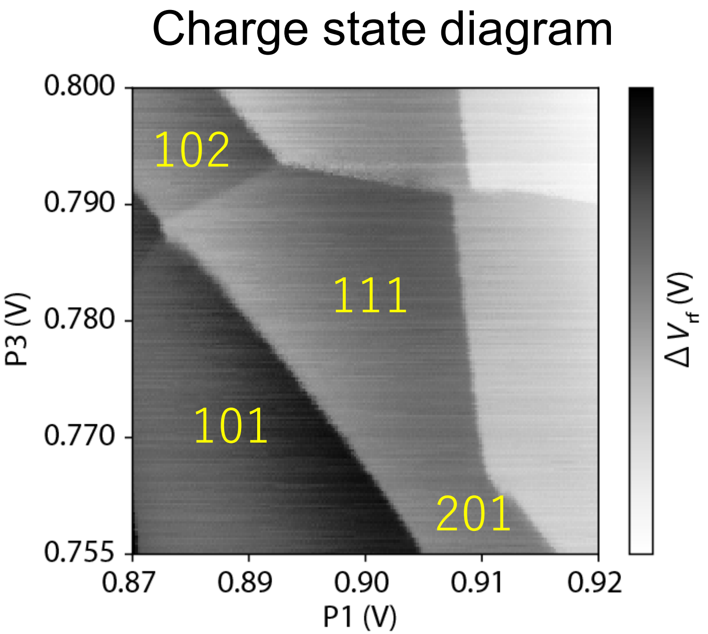




Three Qubit Device with Three QDs



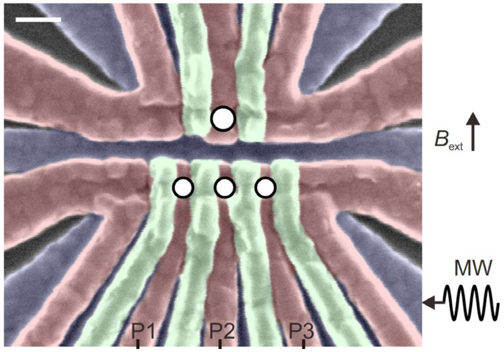




- Three QDs for making qubits and one QD for detecting electron occupations in each QD.
- Co micro-magnet on top

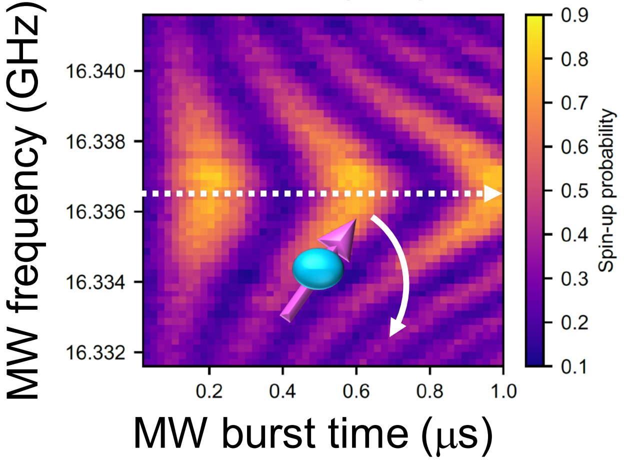
Three Spin Qubits in Si Triple QD

Takeda et al. Nat. Nanotechnol. 2021

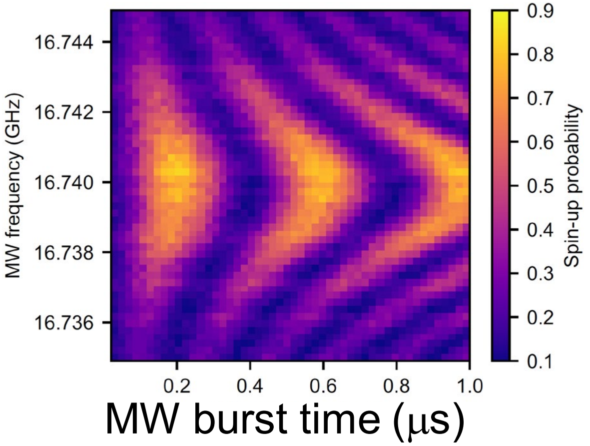


^{28}Si/SiGe from G. Scappucci TuDelft.

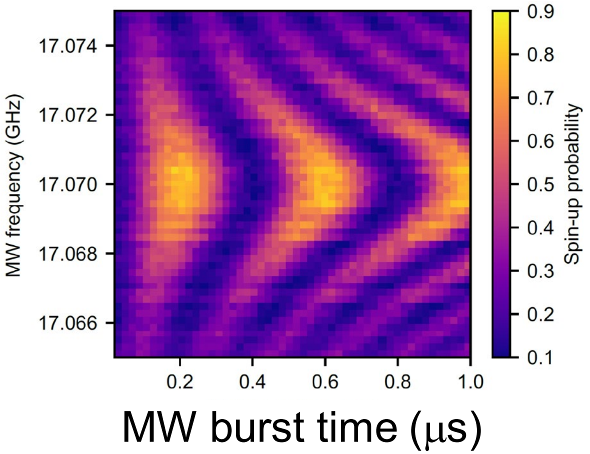
Left dot (Q1)



Center dot (Q2)



Right dot (Q3)

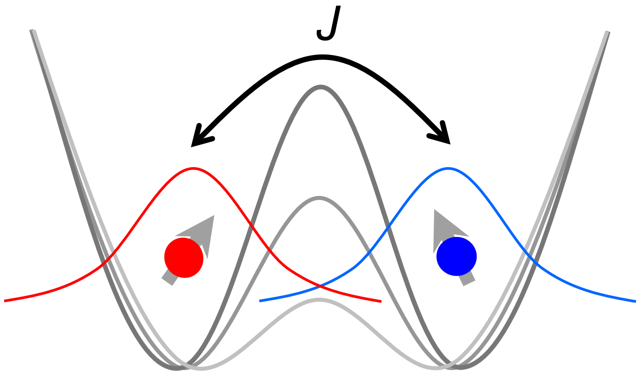


Single-qubit gate fidelity characterized by randomized benchmarking

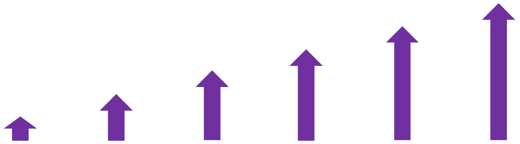
	Q1	Q2	Q3
nat. Si	99.43 %	99.57 %	99.91 %

Two-Qubit Experiments using Two-spin States

Exchange coupling controlled by tunnel coupling



Q1 (target)　Q2 (control)

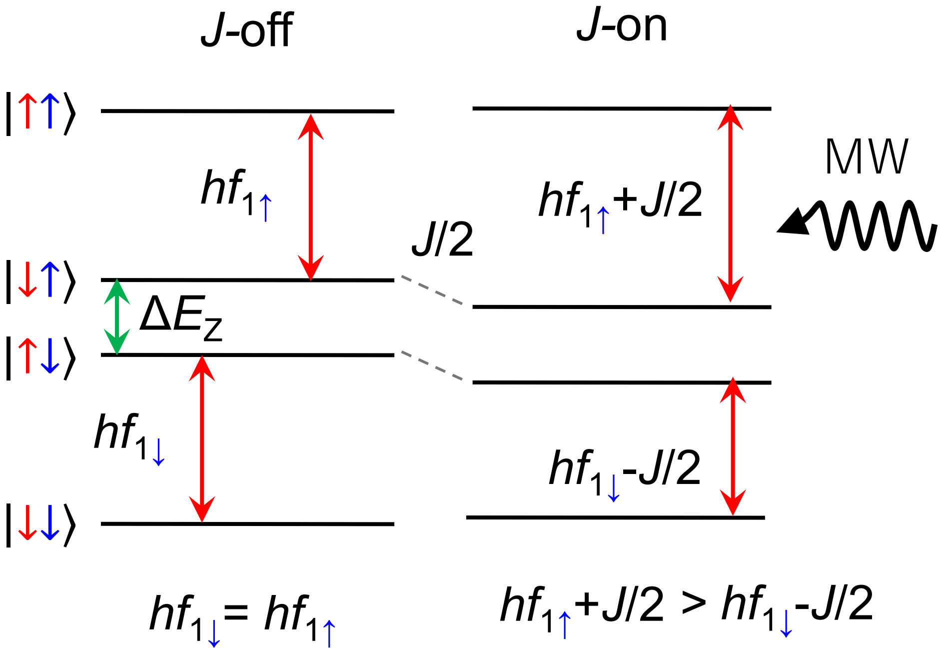


Magnetic field gradient (ΔE_Z) induced by MM

ΔE_Z ~ a few 100MHz >> J~ 10 MHz

"Heisenberg"　***"Ising"***

$$H_{\text{int}} = \frac{J}{4}\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2 \approx \frac{J_{12}}{4}\sigma_{z1}\sigma_{z2}$$

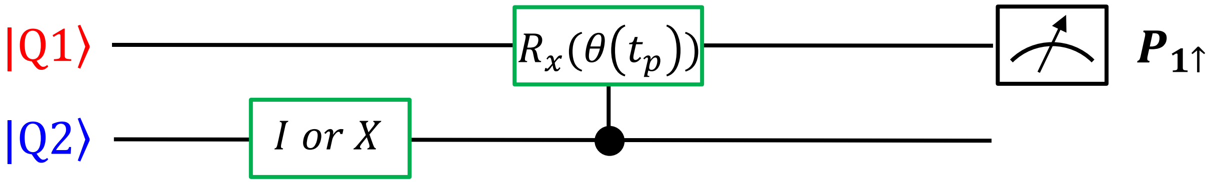


$hf_{1\downarrow} = hf_{1\uparrow}$　　$hf_{1\uparrow}+J/2 > hf_{1\downarrow}-J/2$

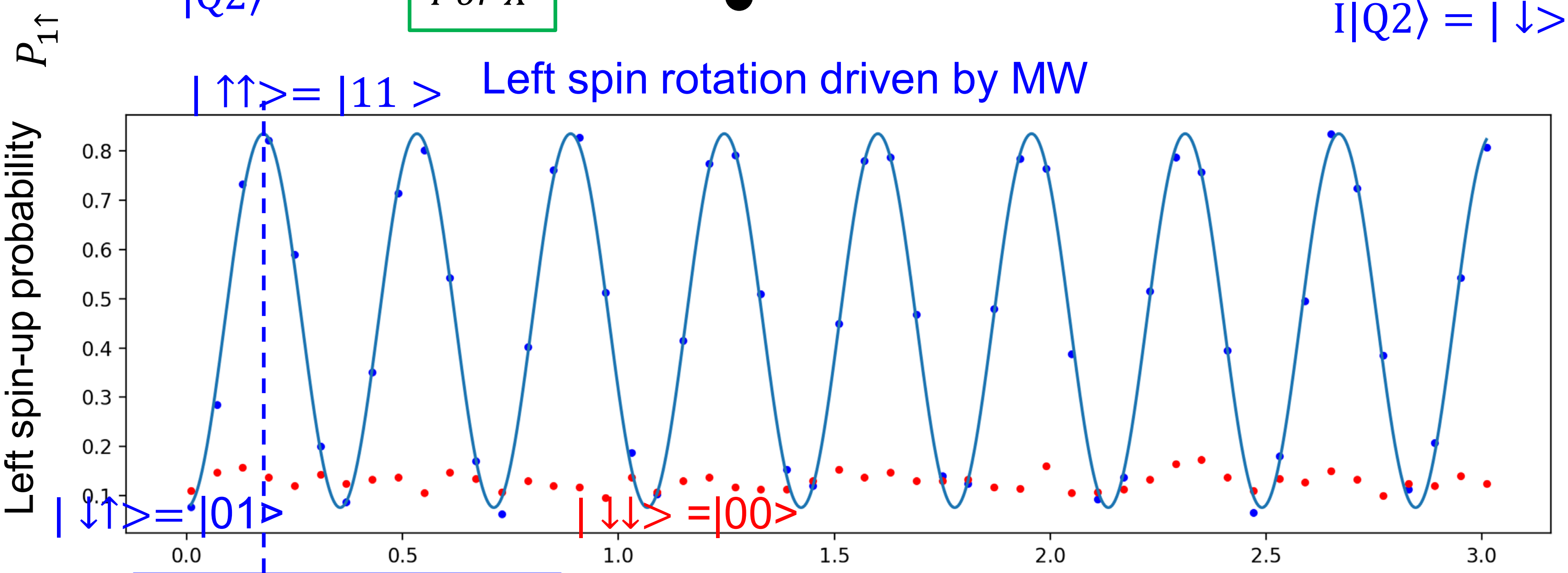
Useful for making $\sqrt{SWAP}$, CPHASE (CZ), and CROT (CNOT)

CROT:
When the upper transition is resonantly excited by MW, the left spin flips with the right spin up but not with the right spin down.

Resonant-CROT



$X|Q2\rangle = |\uparrow\rangle = |1\rangle$
$I|Q2\rangle = |\downarrow\rangle = |0\rangle$

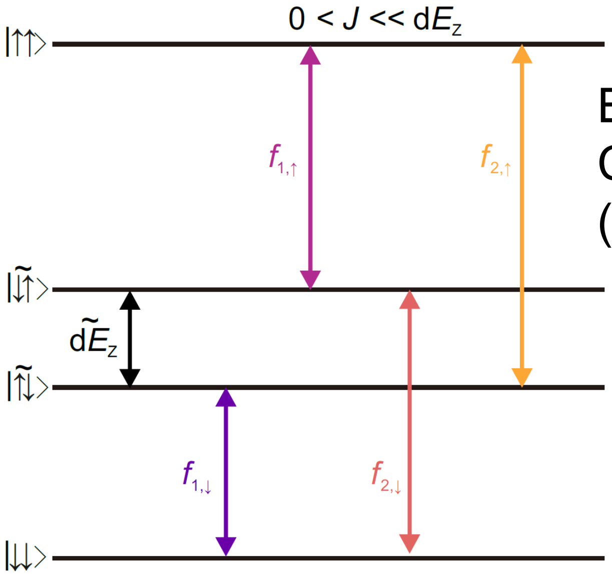


CNOT
: $\theta=\pi$ at $t_p = 0.15\mu s$

- Repeated flips of the left spin when the right spin up, while no flips when the right spin down.

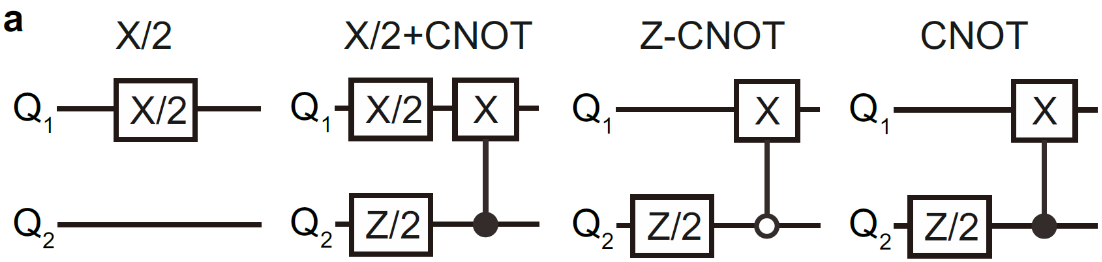
* up to single-qubit local phases

Two-qubit Gate Fidelity Assessed by Clifford-based Randomized Benchmarking



EDSR:
Controlled-rotation
(Rabi frequency < J)

- All of the Clifford gates constructed from 8 primitive gates (controlled-rotation) and single-qubit phase gates under an exchange interaction.

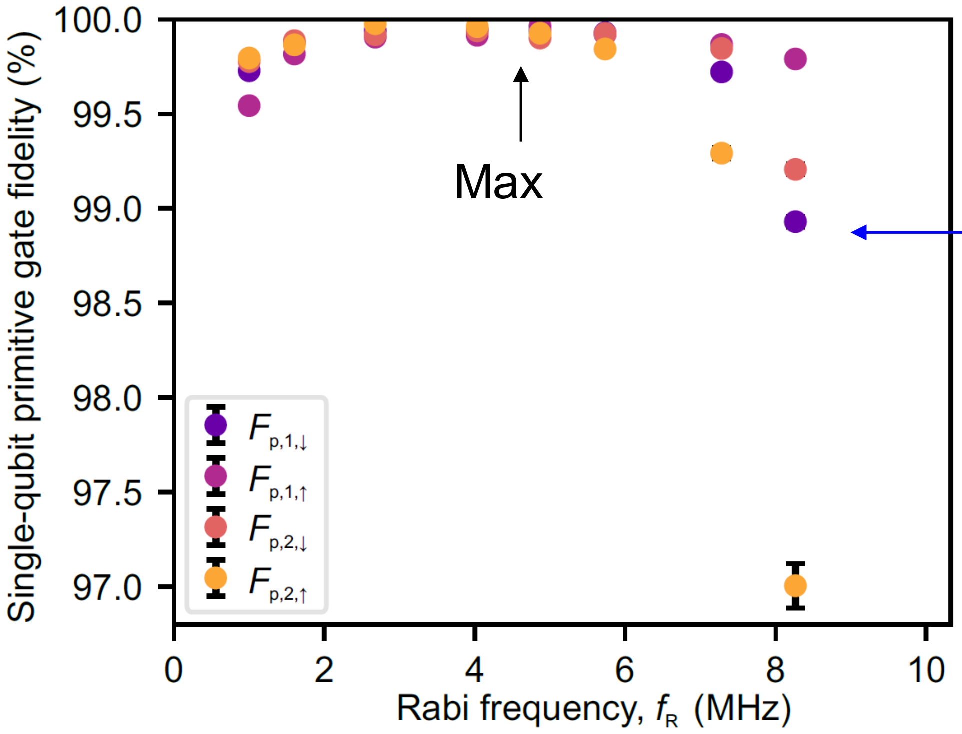


All operated by single spin rotations

W. Huang et al., Nature 569, 532–536 (2019).

Single-qubit Gate Fidelity for Two Qubits

A. Noiri et al. arXiv: 2108.02626 (2021)



> 99.9%

Max

Local heating or population leakage

K. Takeda et al. Sci. Adv. 2016

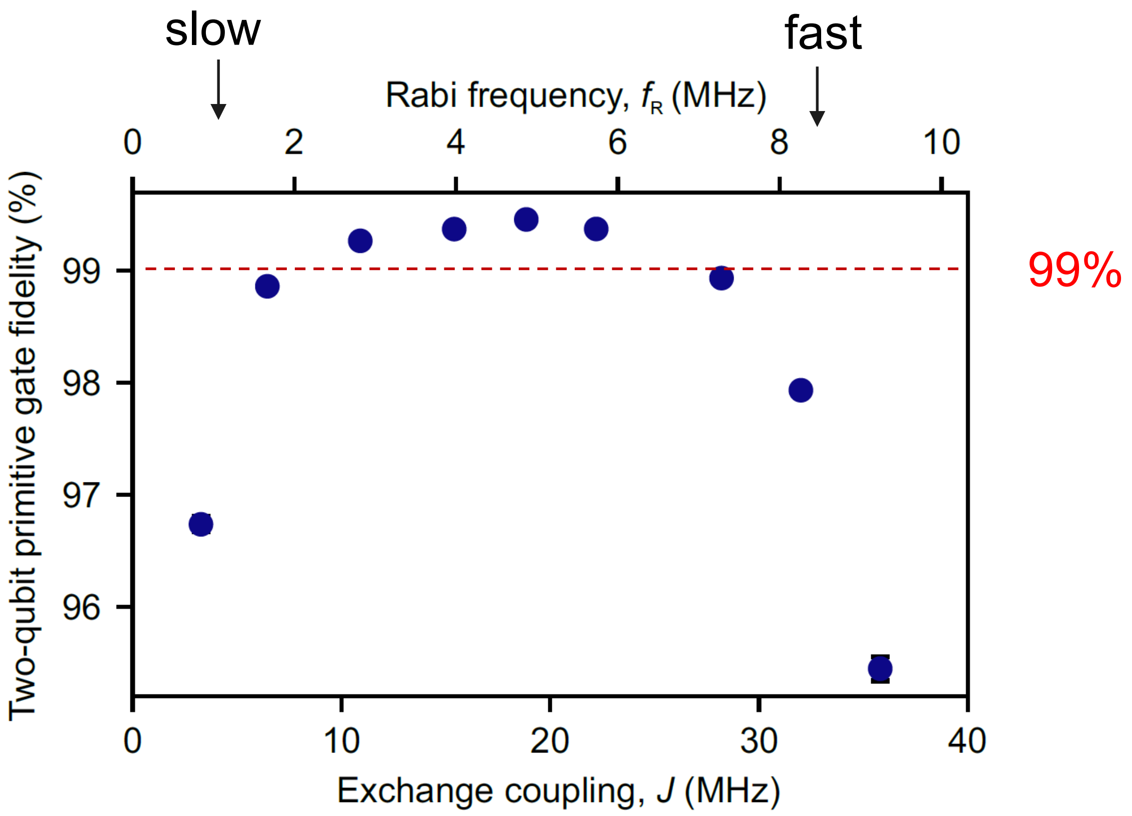
- Single qubit gate fidelity: increases as f_R increases because of the fast gating, but decreases for f_R > 5 MHz because of the heating.
  ⇨ The maximum fidelity > 99.9% at f_R~ 5MHz.

Optimization of Two-qubit Gate Performance

A. Noiri et al. arXiv: 2108.02626 (2021)

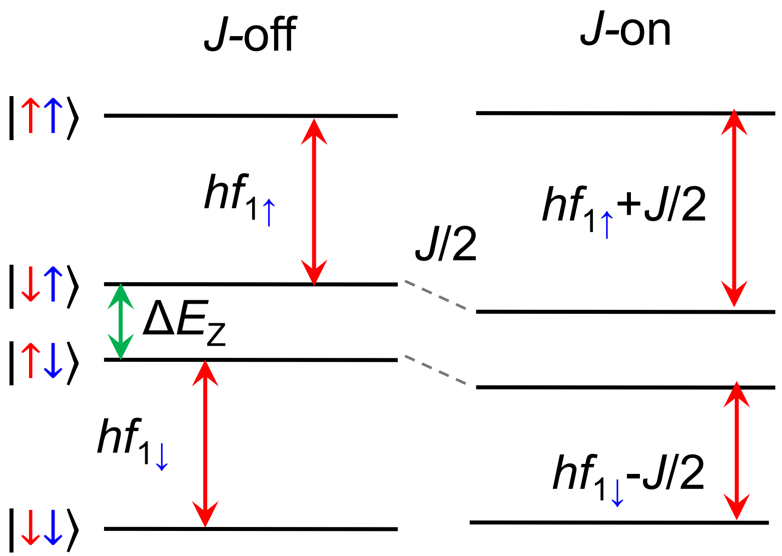
$f_{\mathrm{R}} = J/\sqrt{15}$

Russ et al. PRB
97. 085421 (2018)



- Dependence of the two-qubit gate fidelity is similar to that of the single qubit gate.
- The dephasing time only weakly depends on the exchange coupling.

CPHSE (CZ) with Two Qubits



$hf_{1\downarrow} = hf_{1\uparrow}$

$hf_{1\uparrow}+J/2 > hf_{1\downarrow}-J/2$

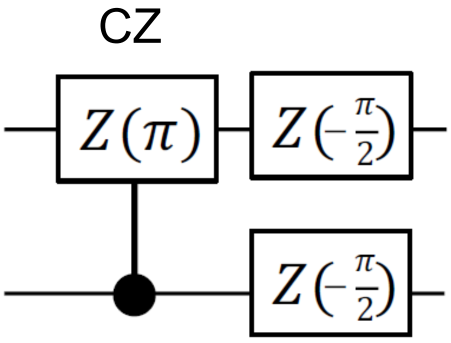
Energy shift ΔE=J/2 for time t generates a phase accumulation:

$$| \uparrow\downarrow> \to e^{\frac{iJt}{2\hbar}}| \uparrow\downarrow>= i| \uparrow\downarrow>$$

for Jt= $\frac{\pi}{\hbar}$

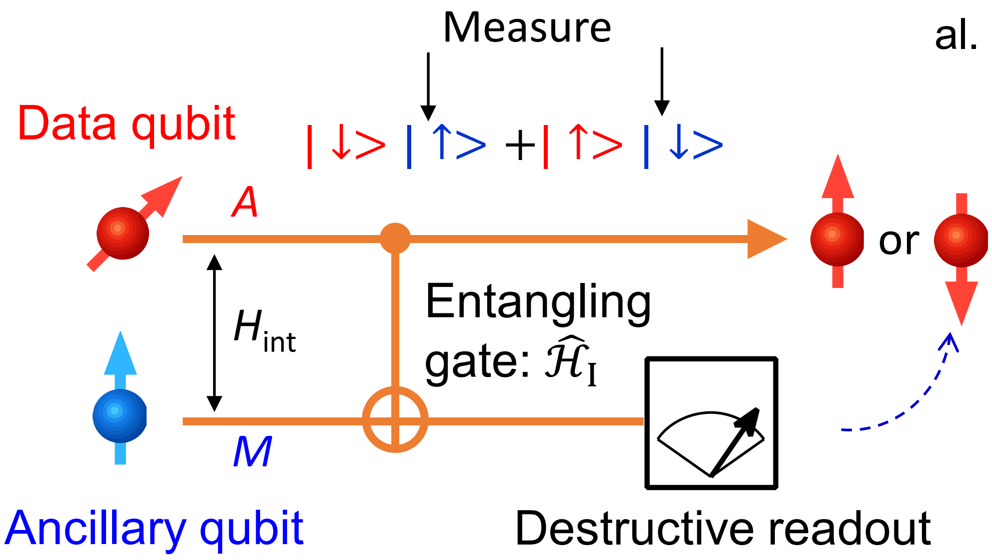
In	Out
$\|\uparrow\uparrow\rangle$	$+\|\uparrow\uparrow\rangle$
$\|\uparrow\downarrow\rangle$	$i\|\uparrow\downarrow\rangle$
$\|\downarrow\uparrow\rangle$	$i\|\downarrow\uparrow\rangle$
$\|\downarrow\downarrow\rangle$	$+\|\downarrow\downarrow\rangle$

$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & i & 0 & 0 \\ 0 & 0 & i & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \stackrel{\text{def}}{=}$$



Quantum Non-demolition Measurement Scheme

T. Nakajima et al. Nat. Nanotechnol. 2018; J. Yoneda et al. Nat. Commun. 2019



Measure

$|\downarrow\rangle|\uparrow\rangle + |\uparrow\rangle|\downarrow\rangle$

Data qubit

A

H_{int}

M

Ancillary qubit

Entangling gate: $\hat{\mathcal{H}}_{\mathrm{I}}$

Destructive readout

or

Backaction through the spin exchange int.

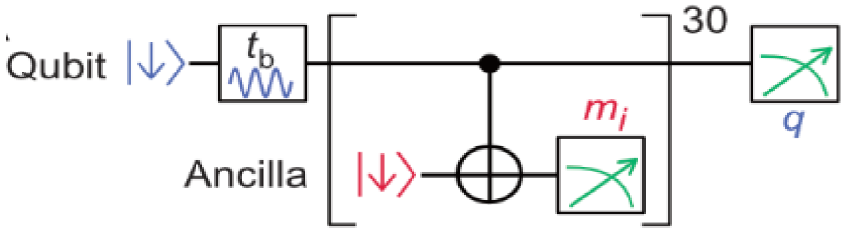
Minimized when the interaction is Ising type.

$$H_{\text{int}} = \frac{J}{4}\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2 \approx \frac{J_{12}}{4}\sigma_{z1}\sigma_{z2}$$

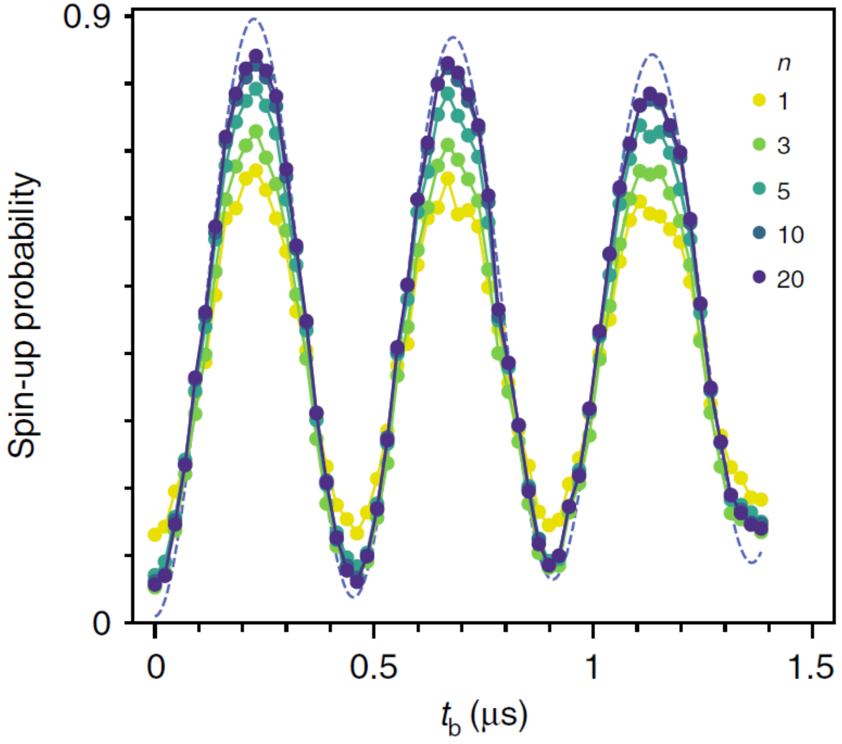
Cumulative QND Readout of a Data Qubit

J. Yoneda et al. Nat. Commun. 2019

Repeatedly measure the ancilla to non-demolitionally read out the data bit Rabi



Data qubit Rabi



n=1 : F = 88% for | ↓ > and 73% for | ↑ >
n=20: F = 96% for | ↓ > and 95% for | ↑ >

⇨ QND readout fidelity: 99.9% for | ↓ > and 97.7% for | ↑ > in the limit.

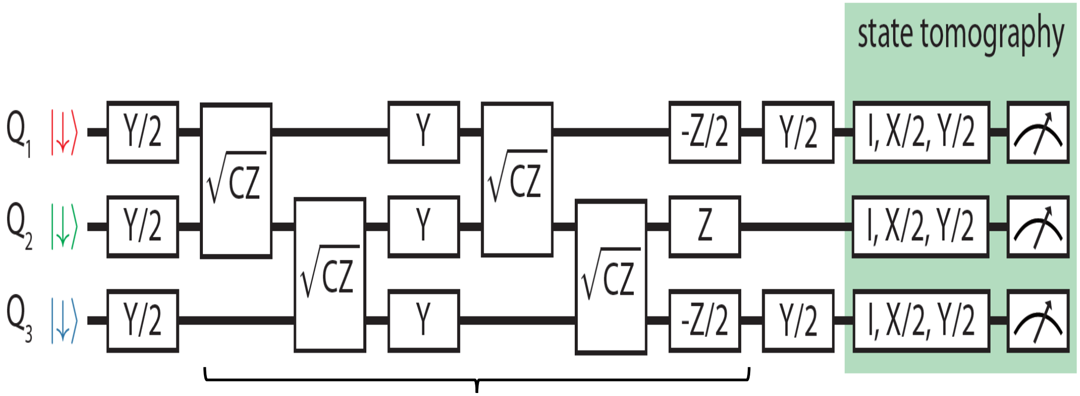
Measurement cycle = 60 μsec

Note: data qubit T1 = 78 ms and 2.5 ms for down-spin and up-spin, respectively.

Three-qubit Entanglement Generation

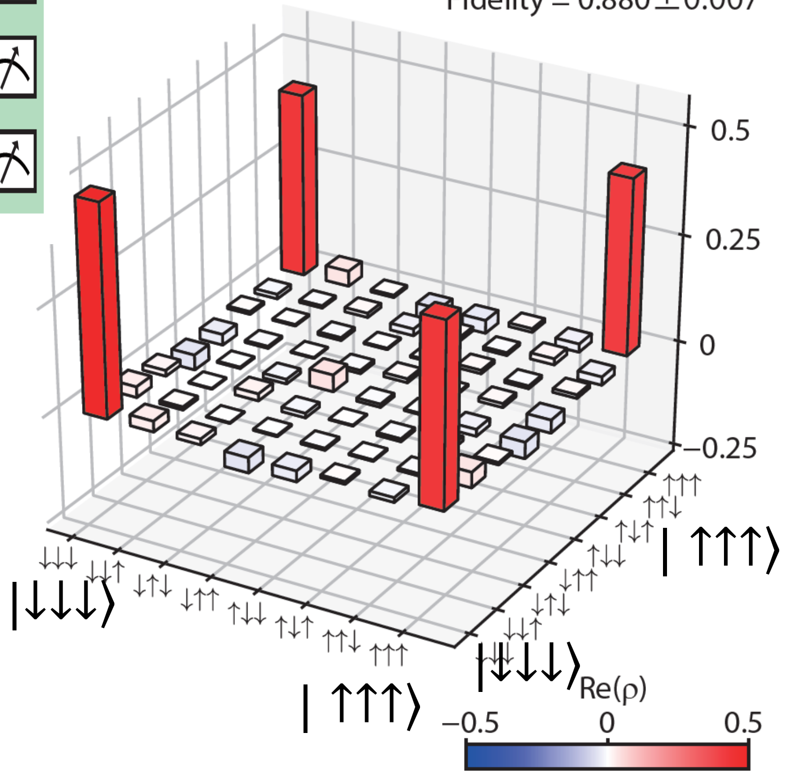
K. Takeda et al. Nat. Nanotechnol. 2021

$|\mathrm{GHZ}\rangle = (|\uparrow\uparrow\uparrow\rangle + |\downarrow\downarrow\downarrow\rangle)/\sqrt{2}$



$(\mathrm{DCZ}_{12})(\mathrm{DCZ}_{23})$

Fidelity = 0.880±0.007



- $F = 0.88$ derived from quantum state tomography > (biseparable limit $= 0.5$ and W-state limit $=\ 0.75$)
- Violation of 3-qubit Bell's inequality: $|\langle\mathrm{XXX}\rangle - \langle\mathrm{YYX}\rangle - \langle\mathrm{YXY}\rangle - \langle\mathrm{XYY}\rangle| > 2$

Summary

Single qubit gate

- Fidelity > 99.9% in 28Si/SiGe using a MM tech. for speeding up Rabi

Two qubit gates

- Fidelity > 99% in 28Si/SiGe by optimizing Rabi speed and using a long dephasing time

Readout and initialization

- Fidelity > 99% possible using QND measurement

Three qubit device

- Three qubits with fidelity > 99.9 % in 28Si/SiGe
- Three qubit entanglement, GHZ state with 88% fidelity

Collaboration

Riken RQC, CEMS
T. Nakajima
K. Takeda
A. Noiri
T. Kobayashi
J. Yoneda (TIT)
C-Y. Chang

D. Loss
P. Stano

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28Si/SiGe
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