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MOONSHOT
RESEARCH & DEVELOPMENT PROGRAM

July 20, 2023

Development of scalable Silicon quantum computer technology

PM Seigo Tarucha

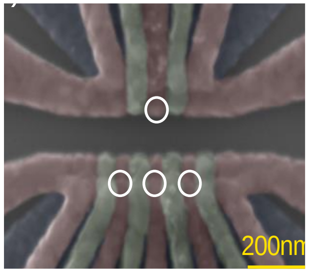
RIKEN Center for Emergent Matter Science
RIKEN Center for Quantum Computing

Performers Takashi Nakajima, RIKEN
Takafumi Fujita, Osaka Univ.
Satoru Miyamaoto, Nagoya Univ.
Michihisa Yamamoto, RIKEN/Tokyo Univ.
Shintaro Takada, AIST

Scenario for Achieving the MS Goal

Milestones

Build technology bases of implementing scalable multi-qubit devices toward development of large-scale QC **in collaboration with semiconductor industries**, and also **demonstrate the proof of quantum error correction** optimized for semiconductor QC.



Challenges

(1) Scale-up: Building blocks of qubit layout
Middle-distance quantum link

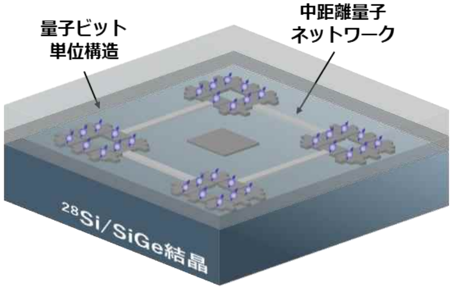
(2) Substrate quality and valley: Interface control of large-area 28Si/SiGe

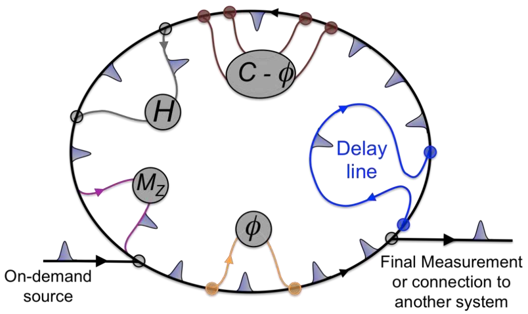
(3) Error correction: Optimized QEC code for biased noise (T1/T2*> $10^{3 \text{ to } 4}$)
…in collaboration with MS theory project

(4) Wiring: Multilayer interconnection, 3D wiring, Integration with cryo-electronics
… in collaboration with industry and MS exp. project

(*) Fridges, Auto-tuning, Cost, Engineers,…

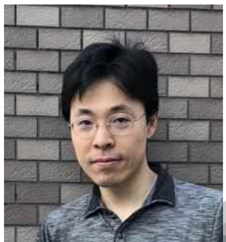
(5) Alternative approach: New method using flying qubits of electron wave packets



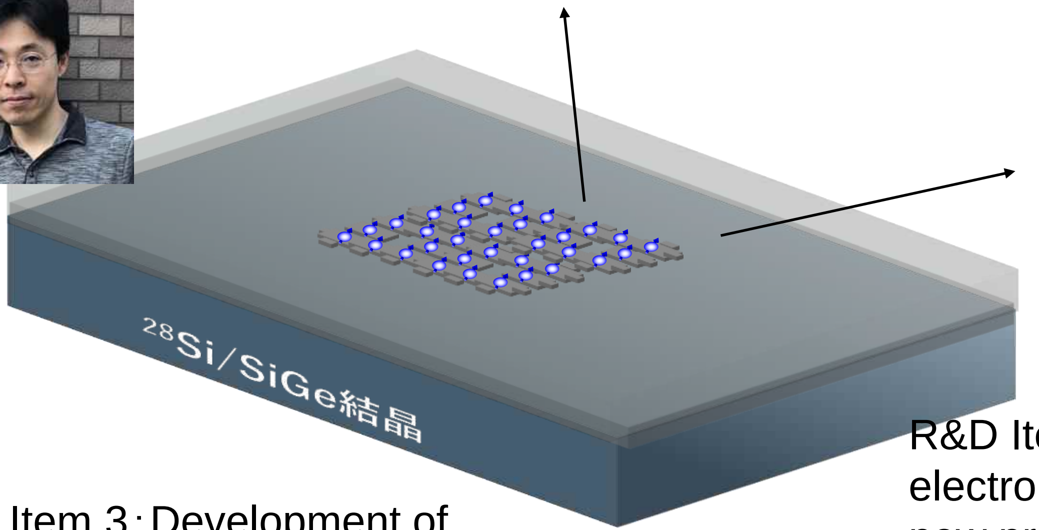


R&D Items in the Project

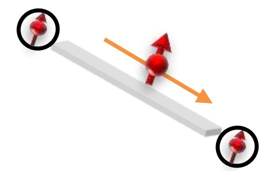
R&D Item 1：Development of scalable technologies for fault-tolerant Si spin qubits
T. Nakajima, RIKEN



Qubit unit cell



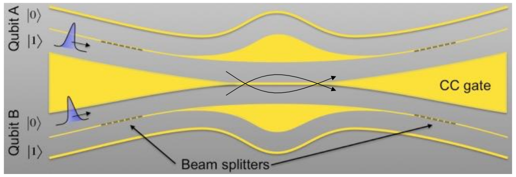
R&D Item 2：Development of middle-distance quantum link
T. Fujita, Osaka-U



Qubit shuttle

R&D Item 3：Development of isotopically controlled Si/SiGe substrate technology
S. Miyamoto, Nagoya-U

R&D Item 4: Development of electron wave-packet qubits with new principle
M. Yamamoto, RIKEN/Tokyo-U
S. Takada, AIST



Progresses since Oct. of 2022

- Installation of large-scale facilities, big dilution fridges, electronics, crystal growth machine,… in end of 2023 through beginning of 2024.

> 100 qubits

- Starting programs in each PI.

T. Nakajima: Developing multi-qubit devices prototypes (4 to 10 qubits) and improving qubit control technology

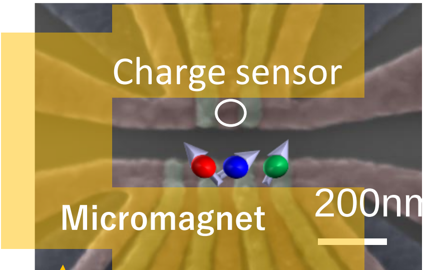
T. Fujita: Fabricating quantum dot arrays for a transport channel

S. Miyamoto: Studying Si/SiGe interface control technology

M. Yamamoto, S. Takada: Developing generation and control technology of wave packet propagation

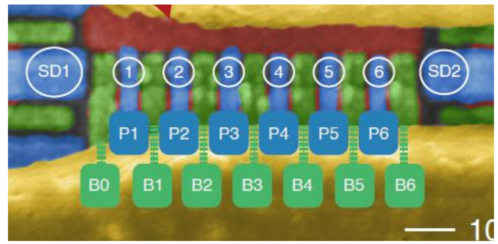
R&D Item 1 Development of scalable technologies for fault-tolerant Si spin qubits

T. Nakajima, RIKEN



microwave

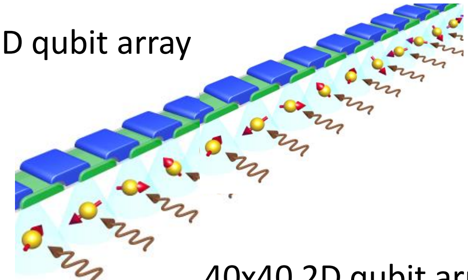
Nat. Nanotechnol. 2021
Nature 2022



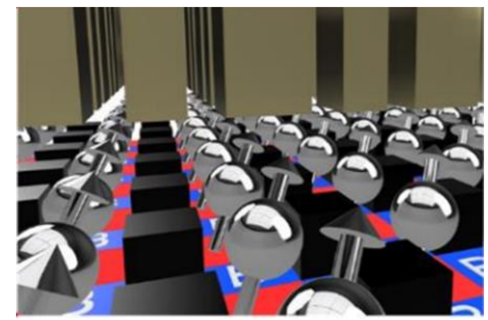
100nm

Nature 2022 (TuDelft)

1D qubit array



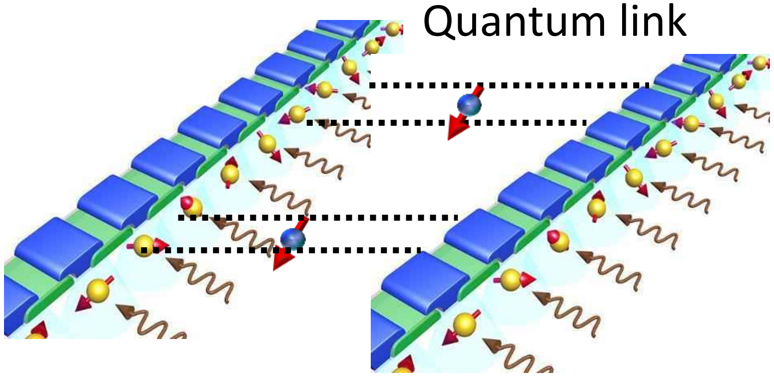
40x40 2D qubit array



Sci. Rep. 2021

Scaling up by interconnecting
1D qubit arrays

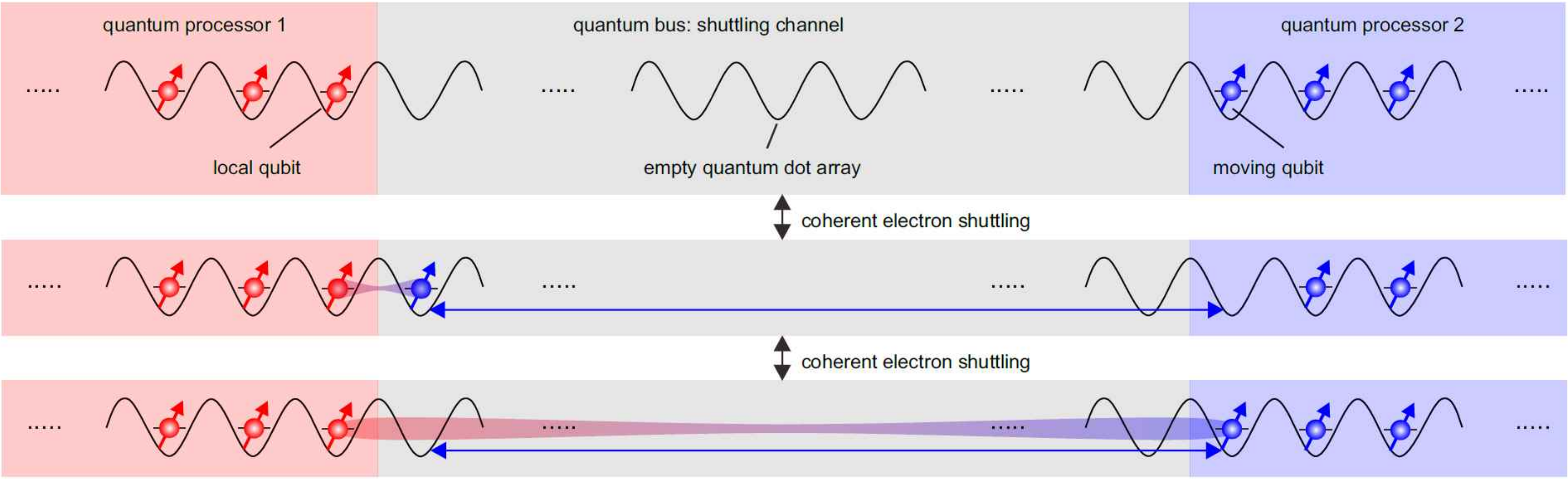
Quantum link



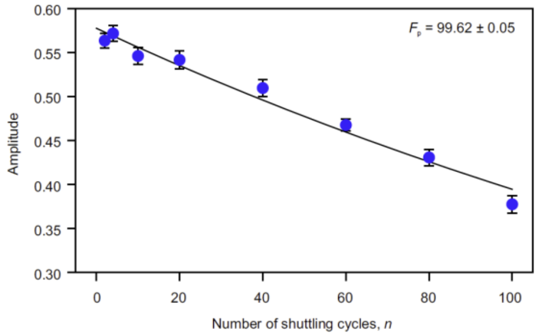
- ➢ Device structure allowing for qubit initialization, readout, and application of microwaves / gate pulses
- ➢ Wiring to dense gate electrodes
- ➢ Demonstration of basic error correction codes

R & D Item 1 Progress

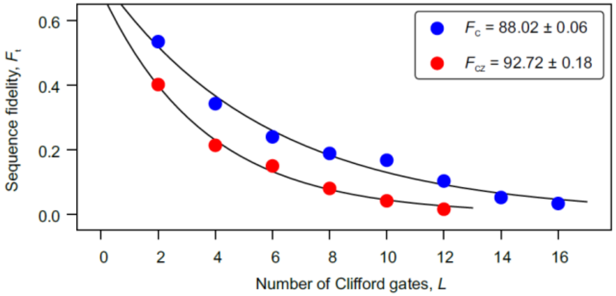
Purpose:
To interconnect qubit arrays, a two-qubit gate is implemented using spin shuttling



Coherent spin shutting



2Q gate fidelity evaluated with randomized benchmarking



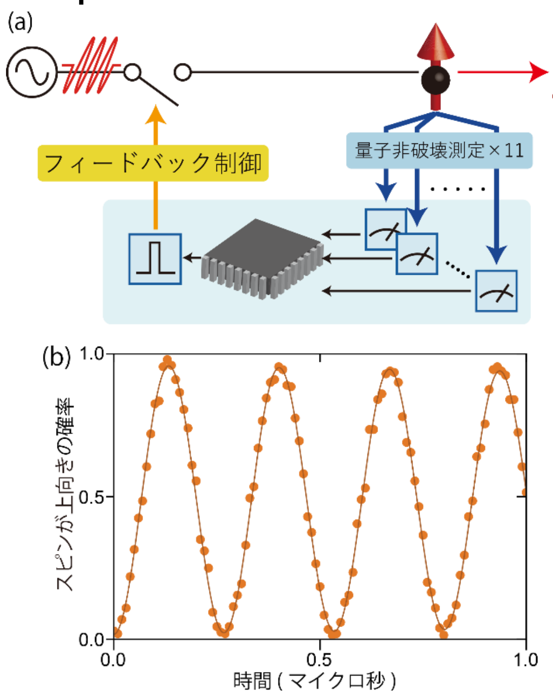
Achievements:

1. Coherent spin shuttling with 99.6% fidelity
2. Shuttling-based CZ gate with 93% fidelity

A. Noiri *et al*., Nature Commun. **13** 5740 (2022)

R & D Item 1   Progress

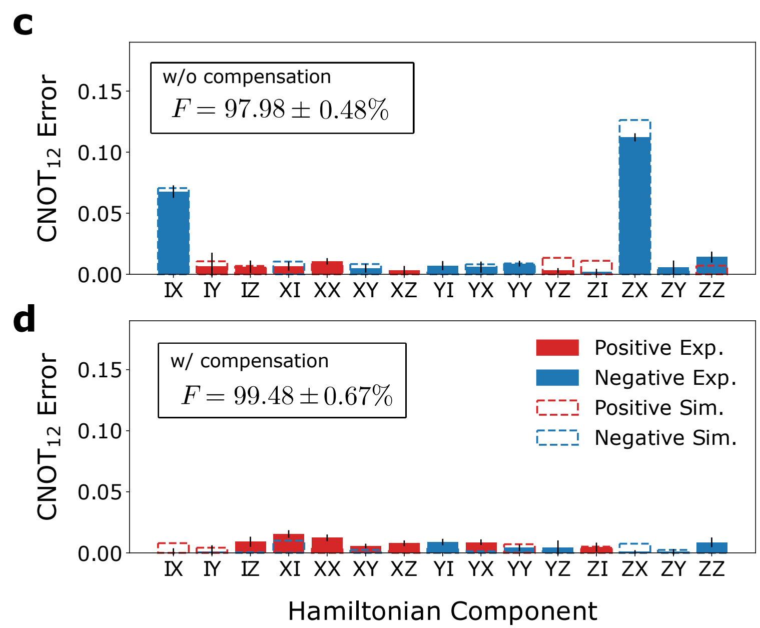
Purpose:
High-fidelity initialization of qubits decoupled from reservoirs



T. Kobayashi *et al*., npj Quantum Info. **9** 52 (2023)

Achievements:
99% initialization fidelity with repeated measurements and active reset

Purpose:
Error analysis with GST for high-fidelity 2Q gates

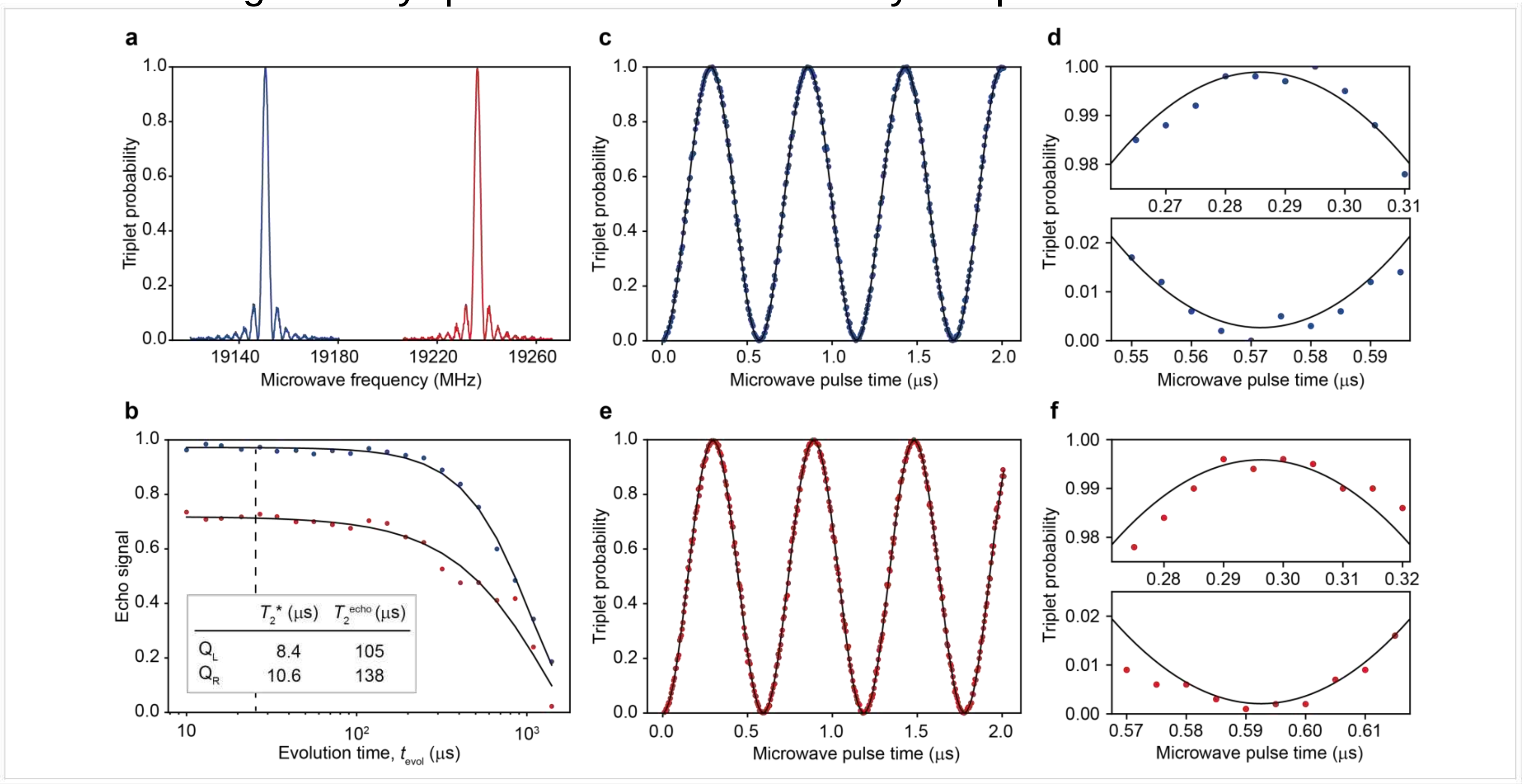


Yi-Hsien Wu *et al*., submitted

Achievements:
99.4% 2Q gate fidelity with systematic error calibrations

R & D Item 1 Progress

Purpose：
Fast and high-fidelity qubit readout is necessary for quantum error correction



K. Takeda *et al.*, submitted

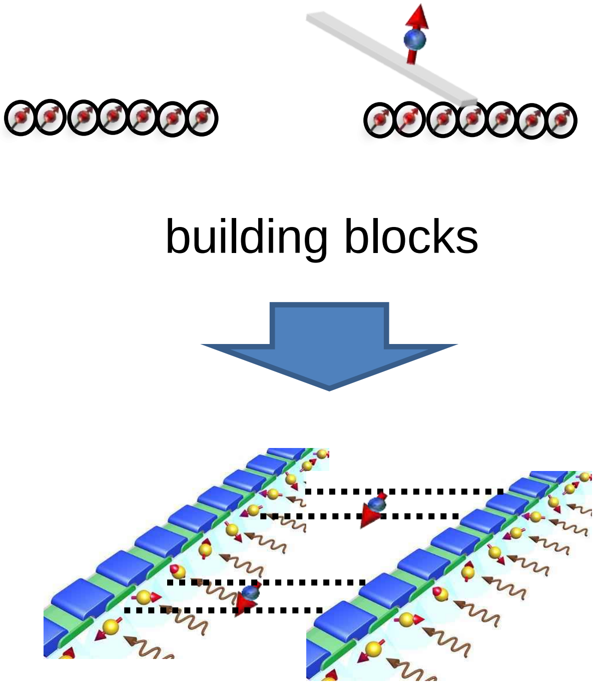
Achievements:
SPAM fidelity 99.8% with 3µs readout time, applicable to QEC

R & D Item 1 Outlook

In FY2023, we aim to

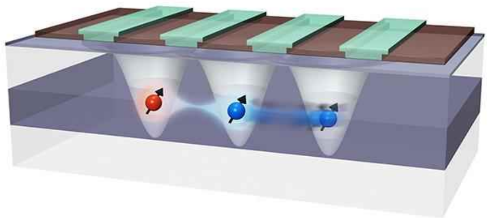
1. Design, fabricate, and characterize building blocks of sparse qubit array structures

2. Start high-fidelity qubit control experiments with more than 4 qubits



T. Fujita, Osaka-U

Shuttling quantum bits and two-qubit gate operation

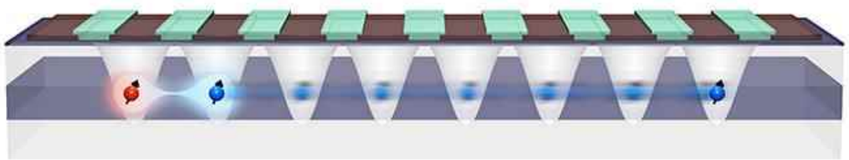


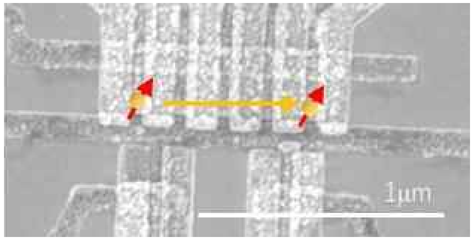
npj Quantum Info. 2017 (T. Fujita, Delft)

Nat. Commun. 2022 (A. Noiri, Riken)

Quantum link using one-dimensional quantum-dot arrays

Basic structure





Linking small-scaled quantum processors

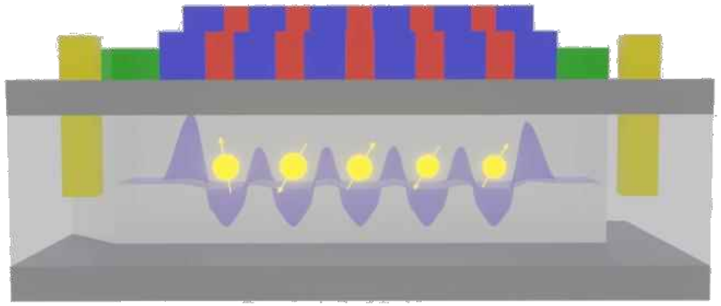
Scale-up ⇩

Middle-distance quantum network

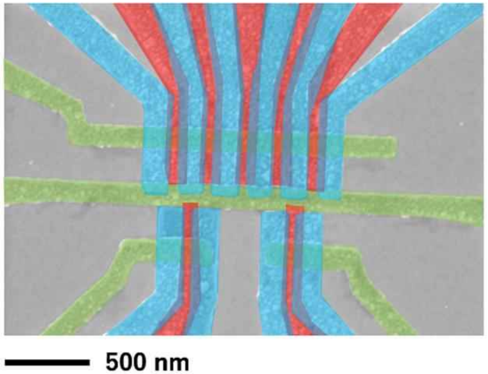
R & D Item 2   Progress

Purpose：
1. Overlapping gate electrode development
2. Simulation of qubit transfer in quantum links

Schematic of dot-array potential, efficiently formed by overlapping gates

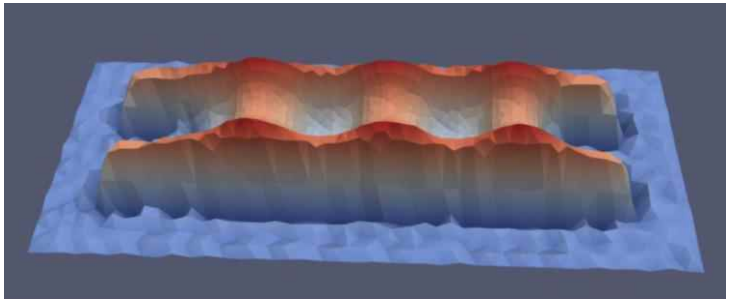


SEM picture of alignment test



1st layer: separation gates
2nd layer: dot gates
3rd layer: barrier gates

Conveyer mode potential simulation

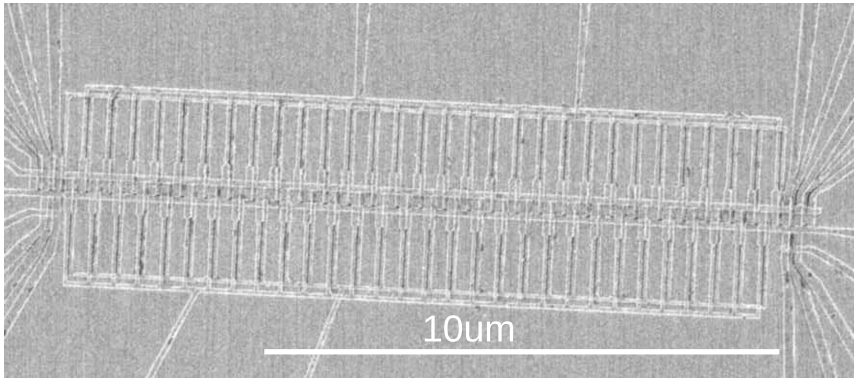


Achievements：
1. Overlapping electrode fabrication using Al gates
2. Calculation of time dependent potential and wavefunction
 (e.g. Conveyer mode, spin chain)

R & D Item 2   Outlook

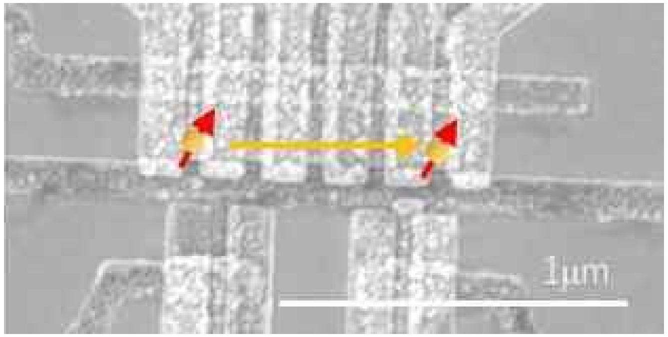
Scopes:
 Increasing number of dots per link
 Benchmarking quantum links
 Distant two-qubit operations

Over-10-dot array link development using periodic gates



Aims for 2023:

Start measurement for qubit transfer in a 5-dot device



Preparing:
 Test-device fabrication (GaAs)
 Setting up equipment for qubit transfer evaluation
 Collaboration for transitioning to Si material

R&D Item 3 Development of isotopically controlled Si/SiGe substrate technology

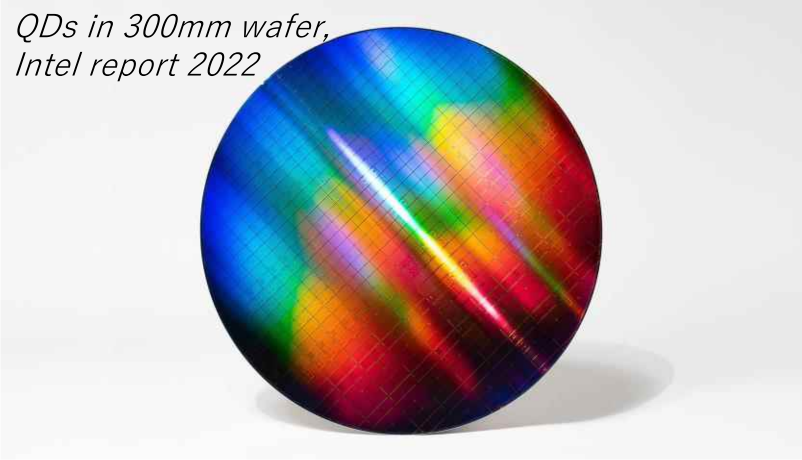
S. Miyamoto, Nagoya-U

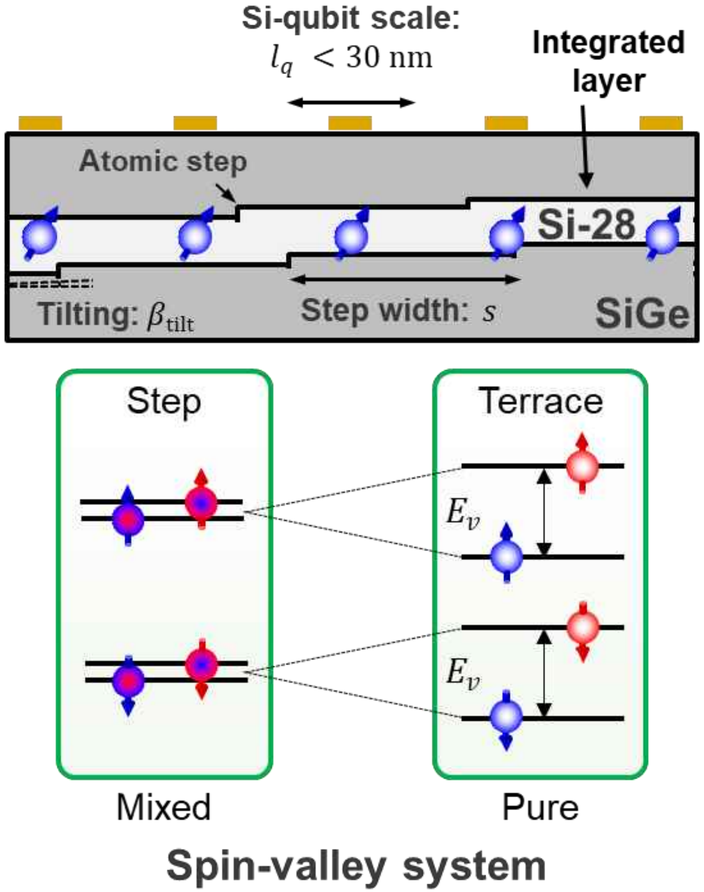
Large-scale implementation of Si quantum platform satisfying fault-tolerance

- High-quality Si-28/SiGe isotope crystal*
- Atomic-scale interface control technology

*Pioneering work on Si-28 Crystal (Keio)

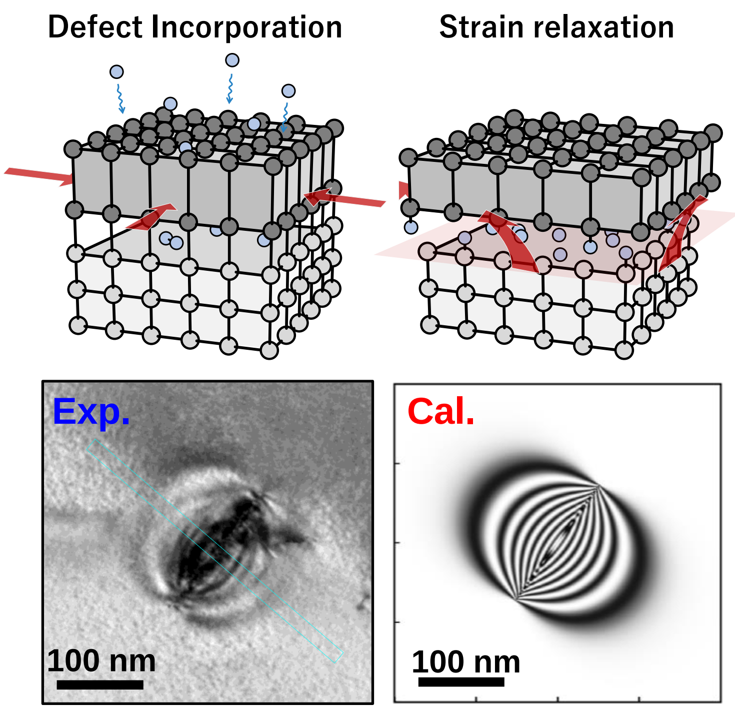
*IEDM Technical Digest 2018
(S. Miyamoto, Keio)

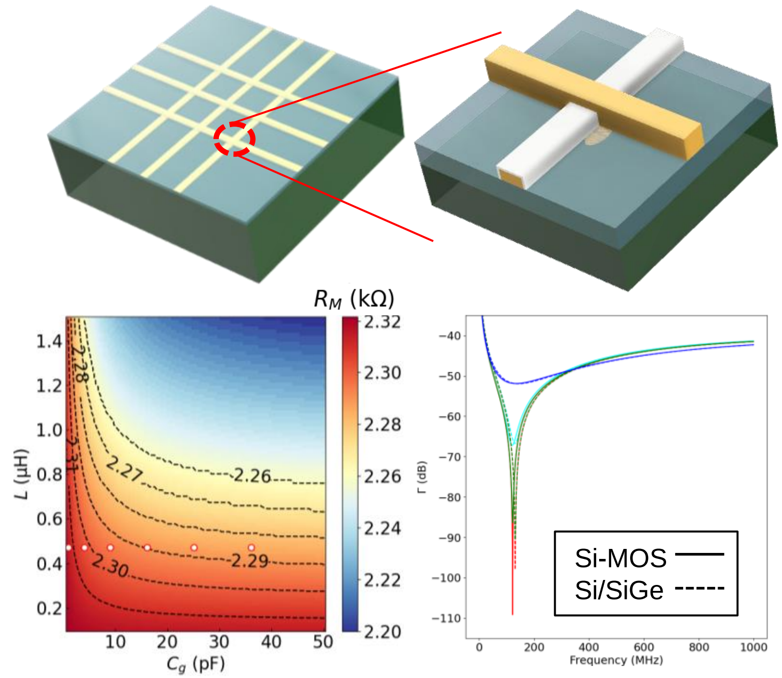




R & D Item 3   Progress

Purpose：
1. Interface control technology
   for high-quality Si-28/SiGe crystals
2. Wafer evaluation technology
   for large-scale isotope crystals



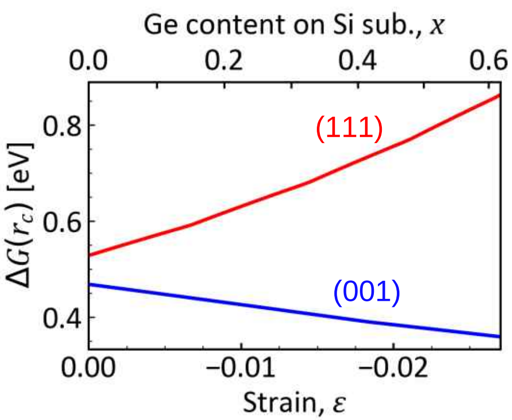


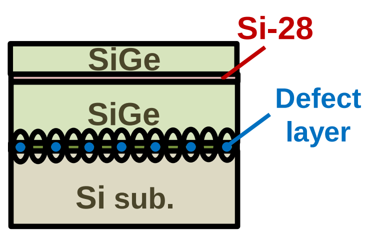
Achievements：
1. Proposal on interface step control
   utilizing defect engineering
2. Exploring high-frequency scheme
   for internal-noise evaluation

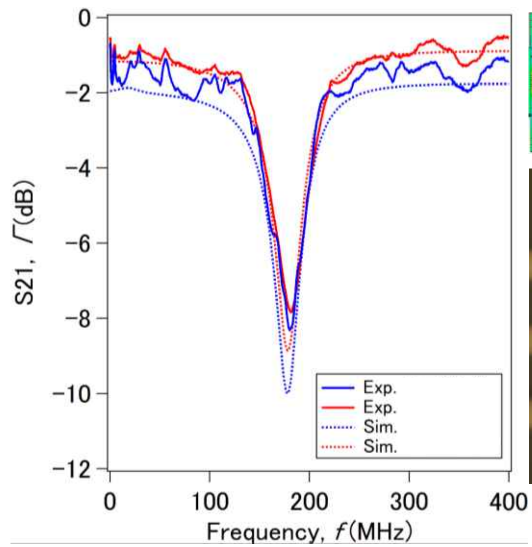
R & D Item 3　Outlook

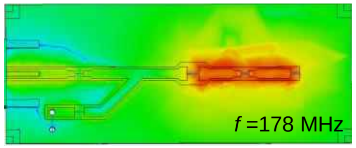
Scopes:

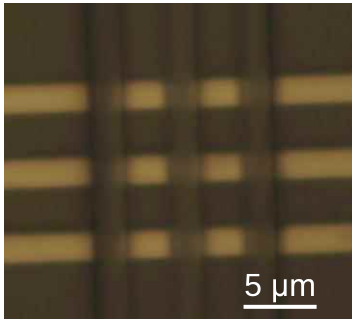
1. Principle verification of interface control technology
2. Foundation building of large-scale process & evaluation technology











Preparing:

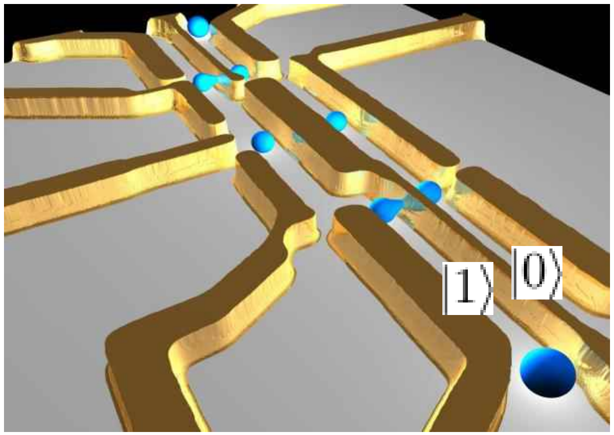
- CVD manufacturing systems enabling Si isotope control
- Prototype design for realizing ultra-flat Si-28/SiGe structure
- Lateral expansion of high-freq. meas. & scalable gate technique

R&D Item 4 Development of electron-wave-packet qubits with a new principle

M. Yamamoto (RIKEN/Tokyo-U), S. Takada (AIST)

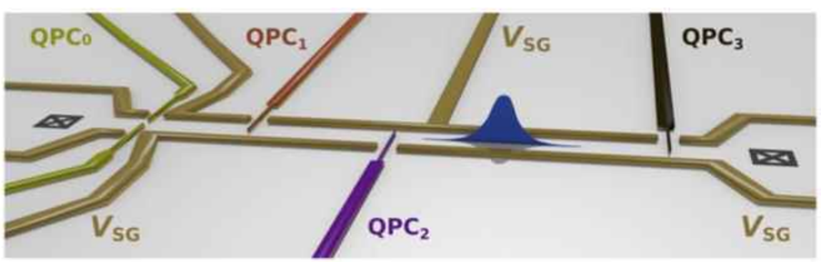
Flying qubits of electron wave packets

2-path interferometer: Quantum operation circuit



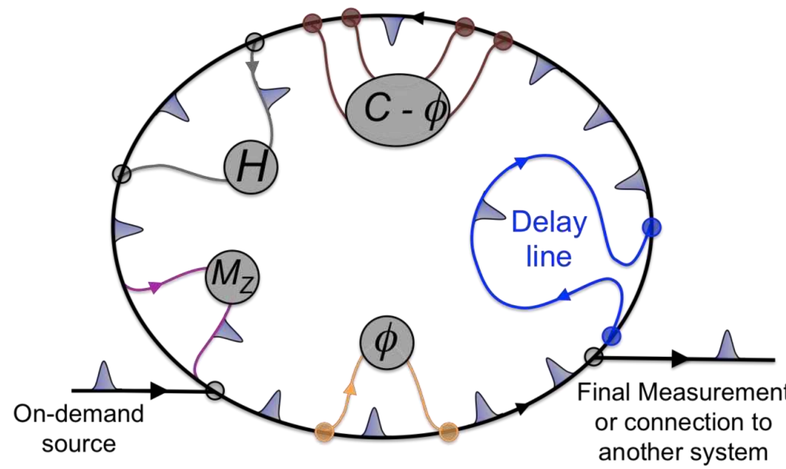
M. Yamamoto et al.,
Nature Nano. 7, 247 (2012)

1D electron wave packets: Low energy relaxation



G. Roussely, S. Takada et al.,
Nature Commun. 9, 2811 (2018)

New-concept quantum computer



Highly efficient hardware (No requirement to wire all individual qubits) → **Possibility to realize a fault tolerant quantum computer with a few thousand wires (in a single dilution fridge)**

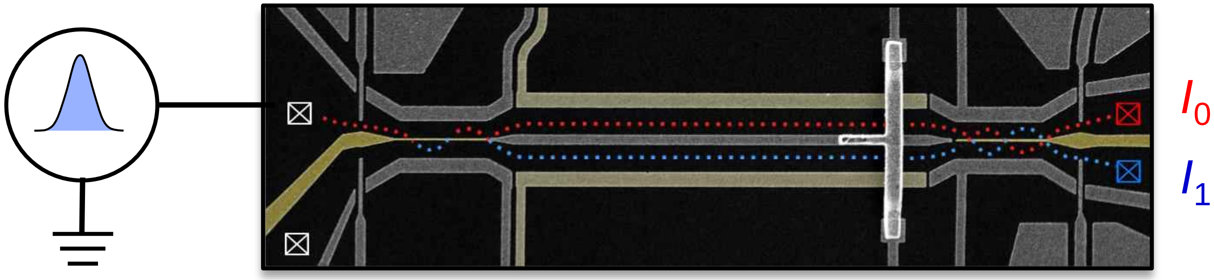
Research topics

- **Demonstration of high-fidelity flying qubit operations**
- **Understanding of properties of electron wave packets**

R & D Item 4   Progress outline

- **Observed suppression of decoherence for injection of short electrical pulses**

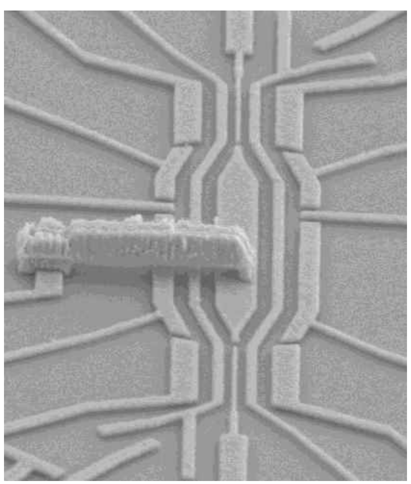
  M. S. Ouacel, et al., in preparation (in collaboration with Institute NEEL, CNRS)

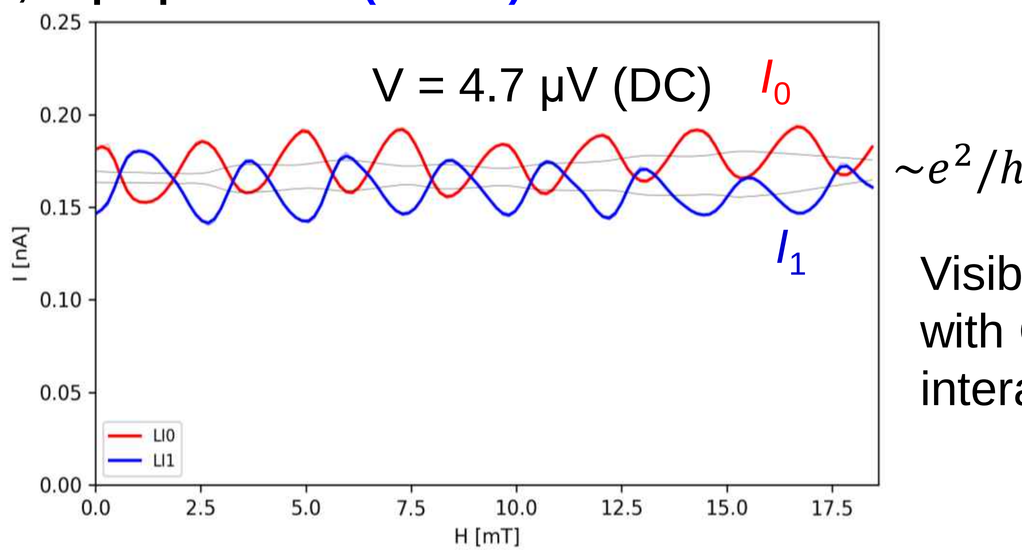


shorter pulse
→ higher visibility
（one order of magnitude)

- **Realizated a scalable two-path interferometer (quantum circuit) consisting of only one transmitting channel with strong Coulomb interaction**

  D. Pomaranski, et al., in preparation. (RIKEN)





Visibility tunable with Coulomb interaction (Vg)

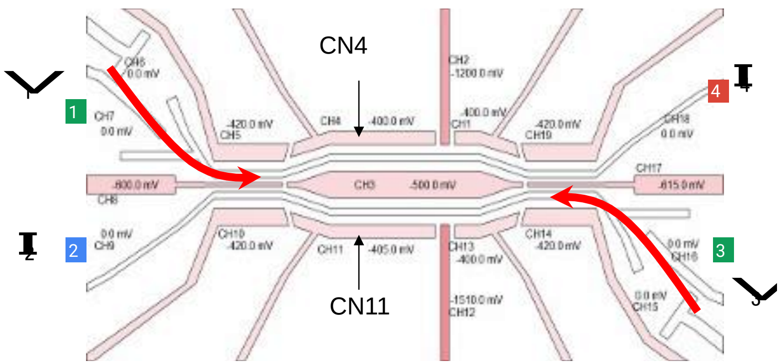
- **Tuned the plasmon velocity by *local* gates**

  S. Takada, et al., in preparation. (AIST)

R & D Item 4 Progress

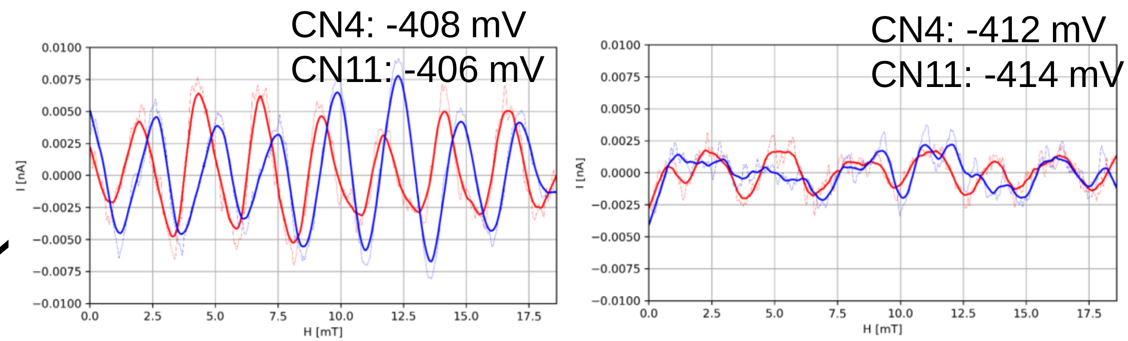
1. Developed highly controllable quantum circuit consisting of a single channel (shown in the previous slide)
2. Investigated Coulomb interaction between electrons in the circuit, which is useful for two qubit gates made out of crossing wave packets.
3. Developed new method to control the velocity of electron wave packets v_p

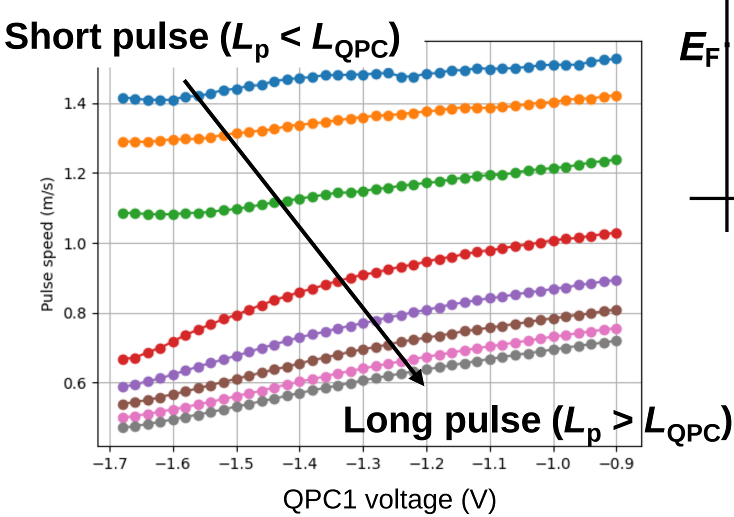
2-particle injection



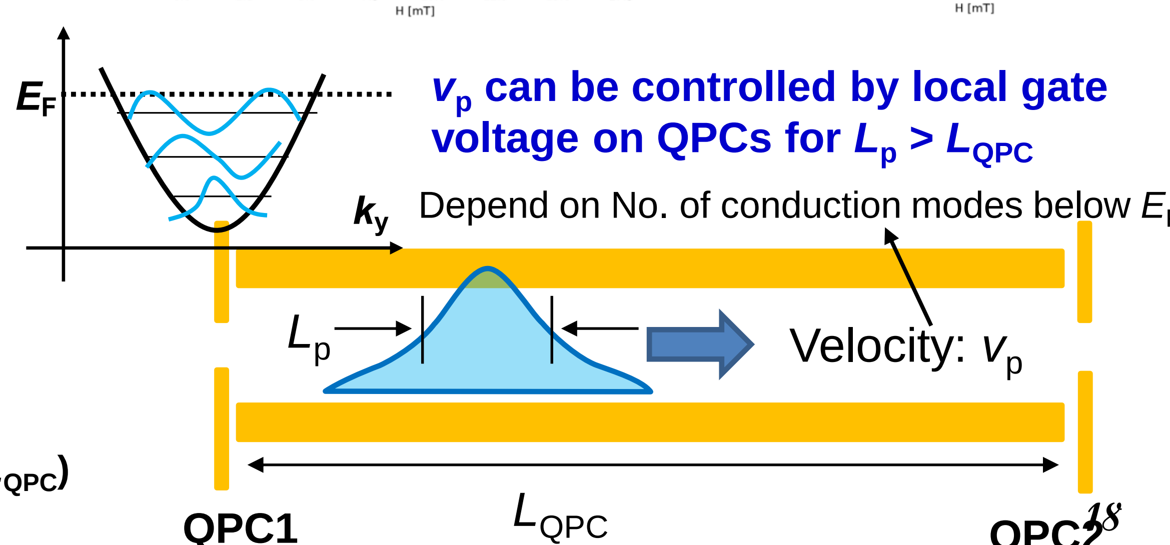
Visibility change by the channel width (via Coulomb)

(only phase shift expected for the non-interacting case)





v_p can be controlled by local gate voltage on QPCs for $L_p > L_{QPC}$

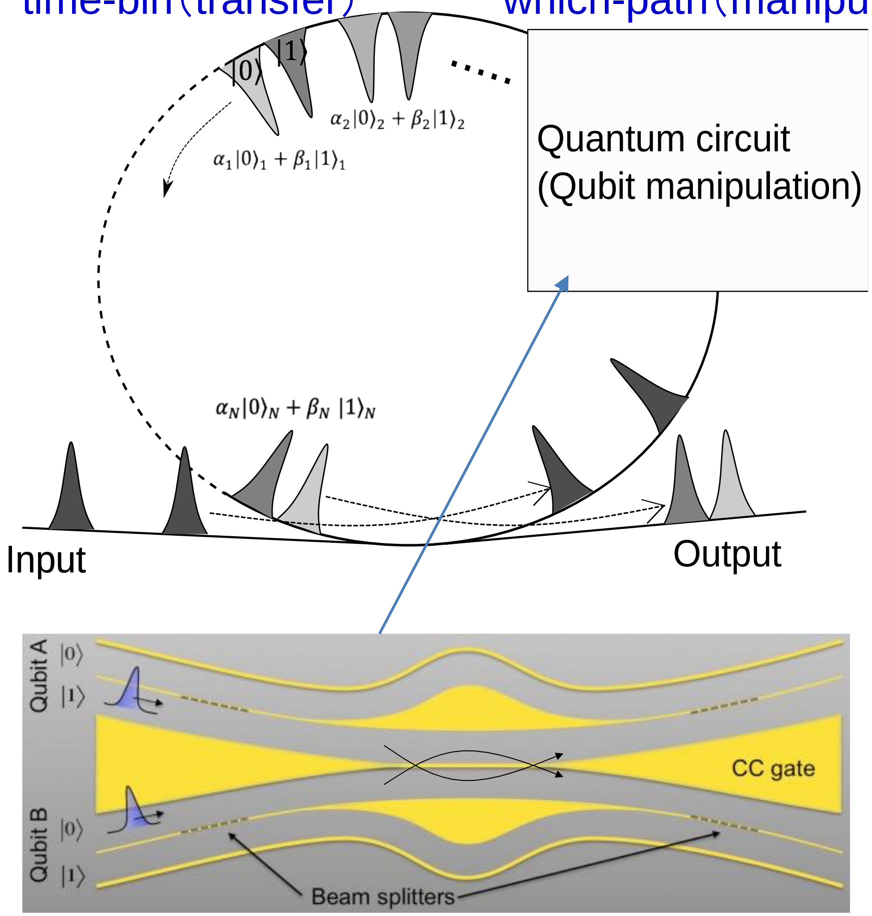


R & D Item 4 Outlook

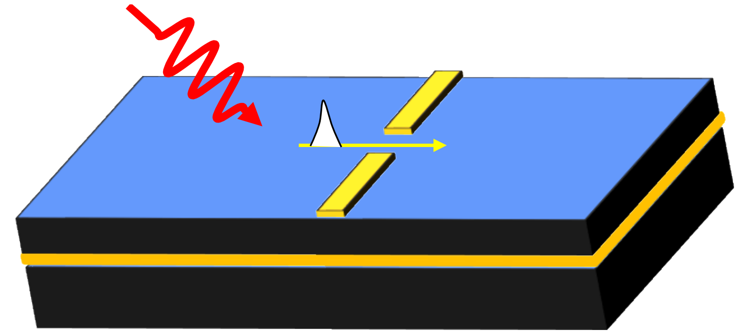
PCT/JP2023/025244 (submitted on 7th July)

"A universal quantum computer using time-bin encoding of electron wave packets in loop circuits"

time-bin（transfer） which-path（manipulation）

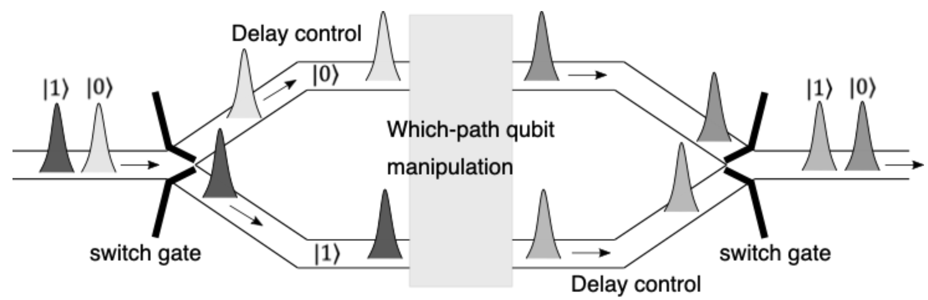


1. Generate ultrashort electron wave packet by converting light pulse to electron pulse

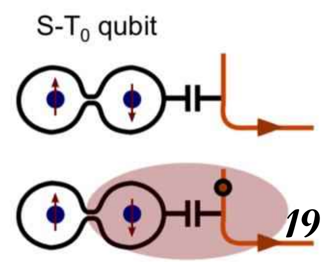


2. Realize high fidelity quantum operation

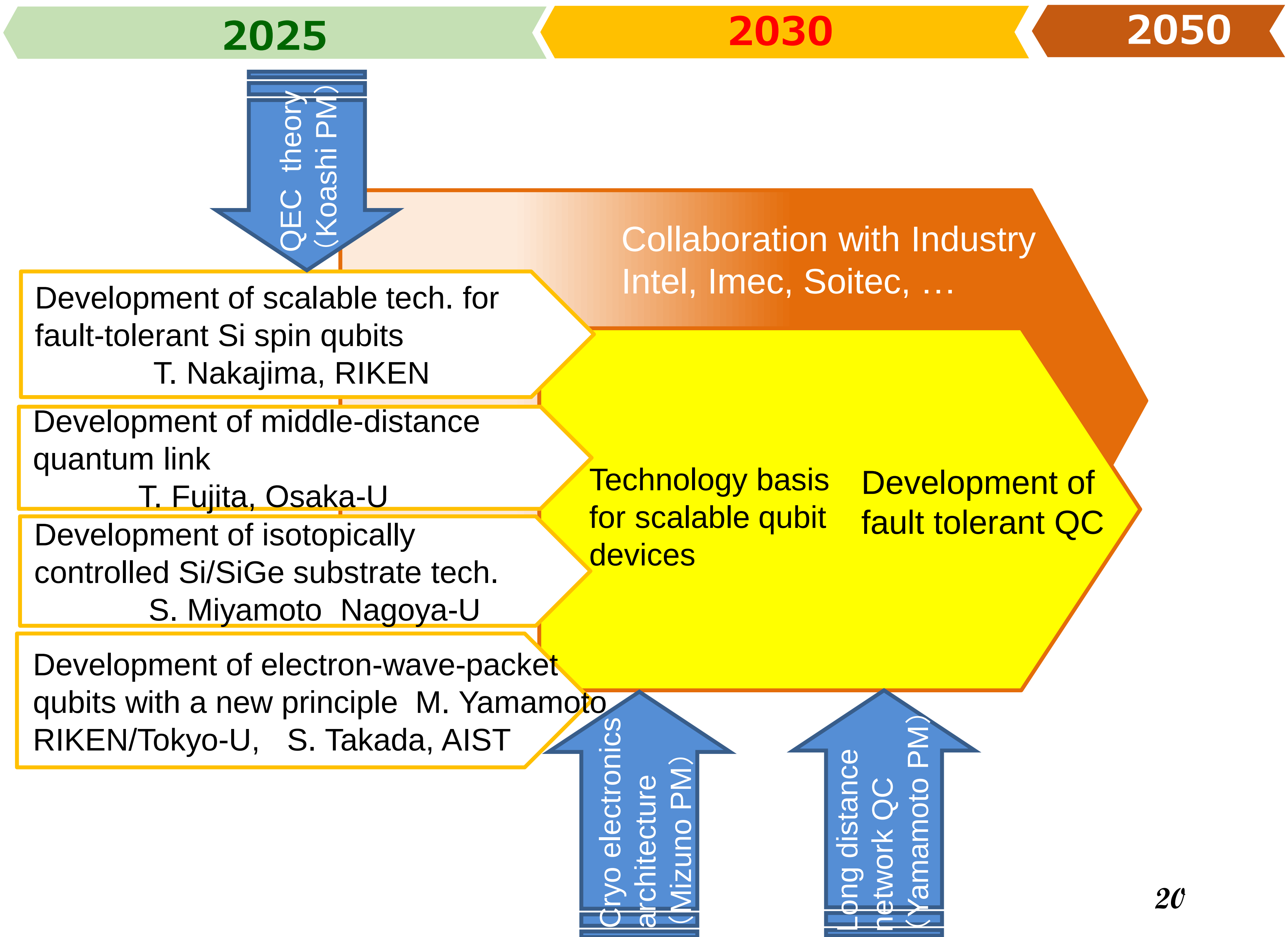
3. Demonstrate long coherence of a time-bin qubit of an electron wave packet



4. Readout a single wave packet using a spin qubit



Summary


2025
2030
2050
QEC theory (Koashi PM)
Collaboration with Industry
Intel, Imec, Soitec, …
Development of scalable tech. for fault-tolerant Si spin qubits T. Nakajima, RIKEN
Development of middle-distance quantum link T. Fujita, Osaka-U
Development of isotopically controlled Si/SiGe substrate tech. S. Miyamoto Nagoya-U
Development of electron-wave-packet qubits with a new principle M. Yamamoto RIKEN/Tokyo-U, S. Takada, AIST
Technology basis for scalable qubit devices
Development of fault tolerant QC
Cryo electronics architecture (Mizuno PM)
Long distance network QC (Yamamoto PM)