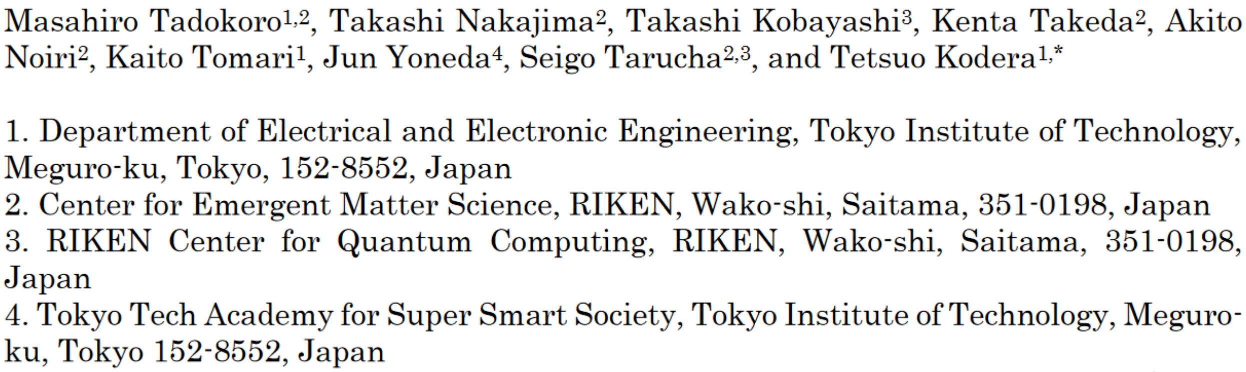
Designs for a two-dimensional Si quantum dot array with spin qubit addressability



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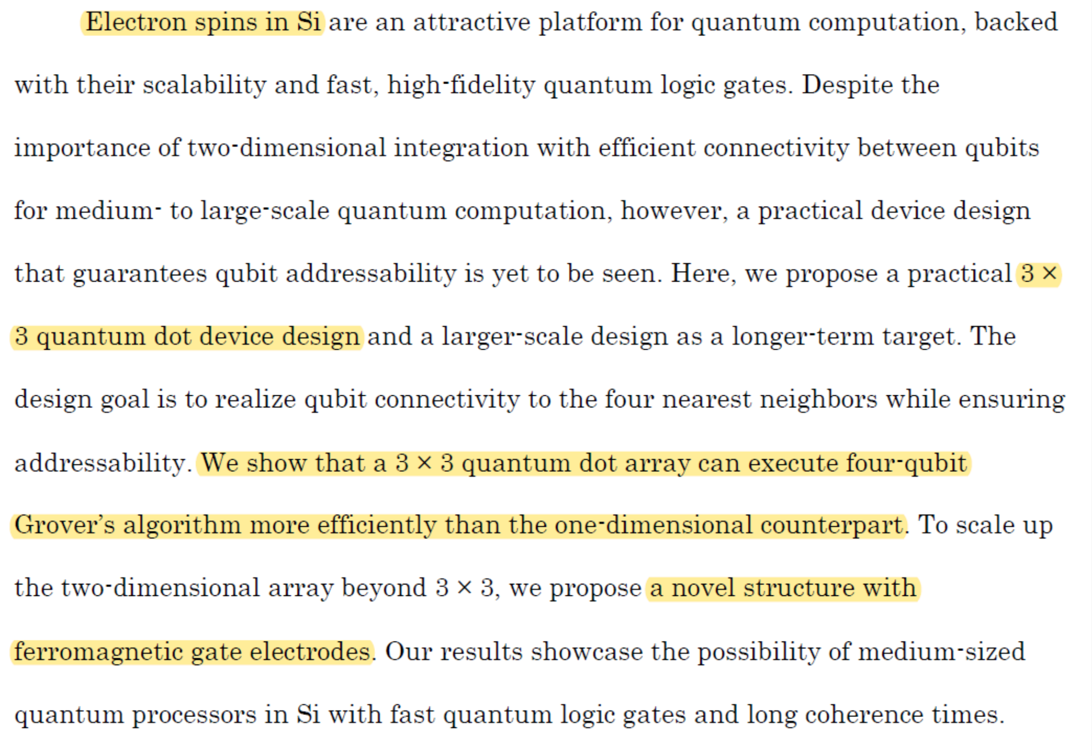
Presenter: Michele Aldeghi

8 November 2021

Abstract

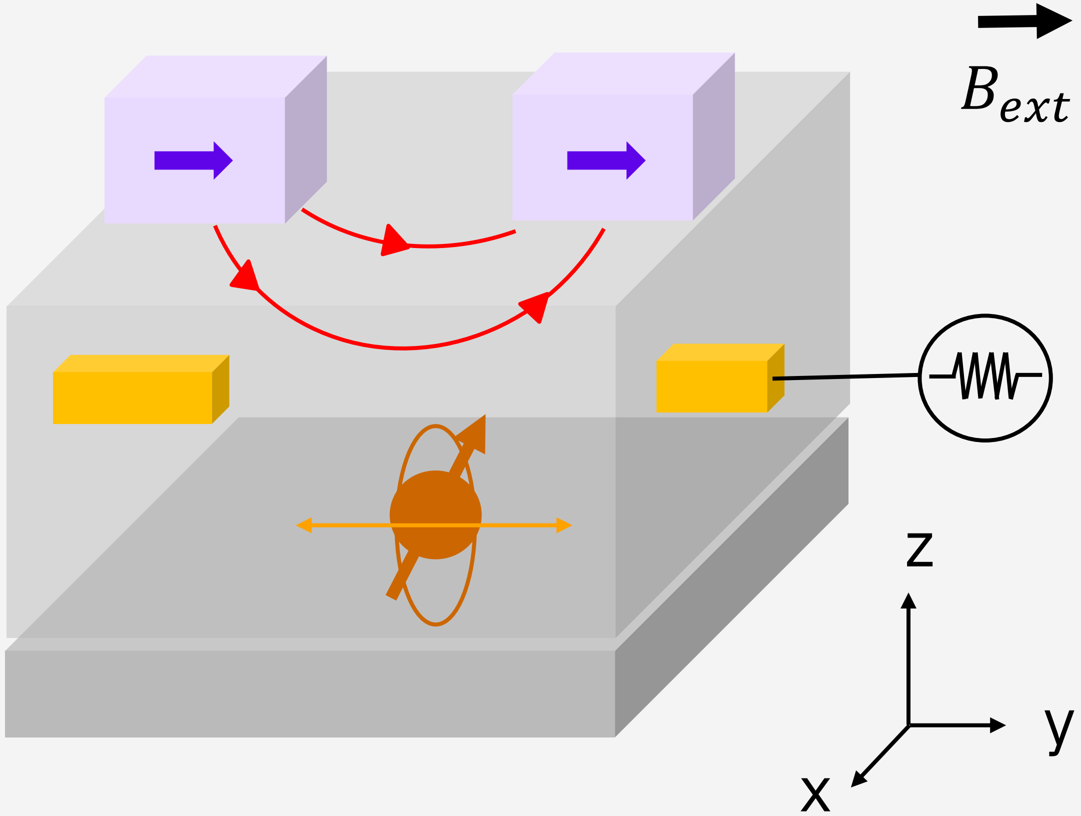


Electron spins in Si are an attractive platform for quantum computation, backed with their scalability and fast, high-fidelity quantum logic gates. Despite the importance of two-dimensional integration with efficient connectivity between qubits for medium- to large-scale quantum computation, however, a practical device design that guarantees qubit addressability is yet to be seen. Here, we propose a practical 3 × 3 quantum dot device design and a larger-scale design as a longer-term target. The design goal is to realize qubit connectivity to the four nearest neighbors while ensuring addressability. We show that a 3 × 3 quantum dot array can execute four-qubit Grover's algorithm more efficiently than the one-dimensional counterpart. To scale up the two-dimensional array beyond 3 × 3, we propose a novel structure with ferromagnetic gate electrodes. Our results showcase the possibility of medium-sized quantum processors in Si with fast quantum logic gates and long coherence times.

EDSR by micromagnets: requirements

Two requirements:

- Stray field gradient
- Electric field

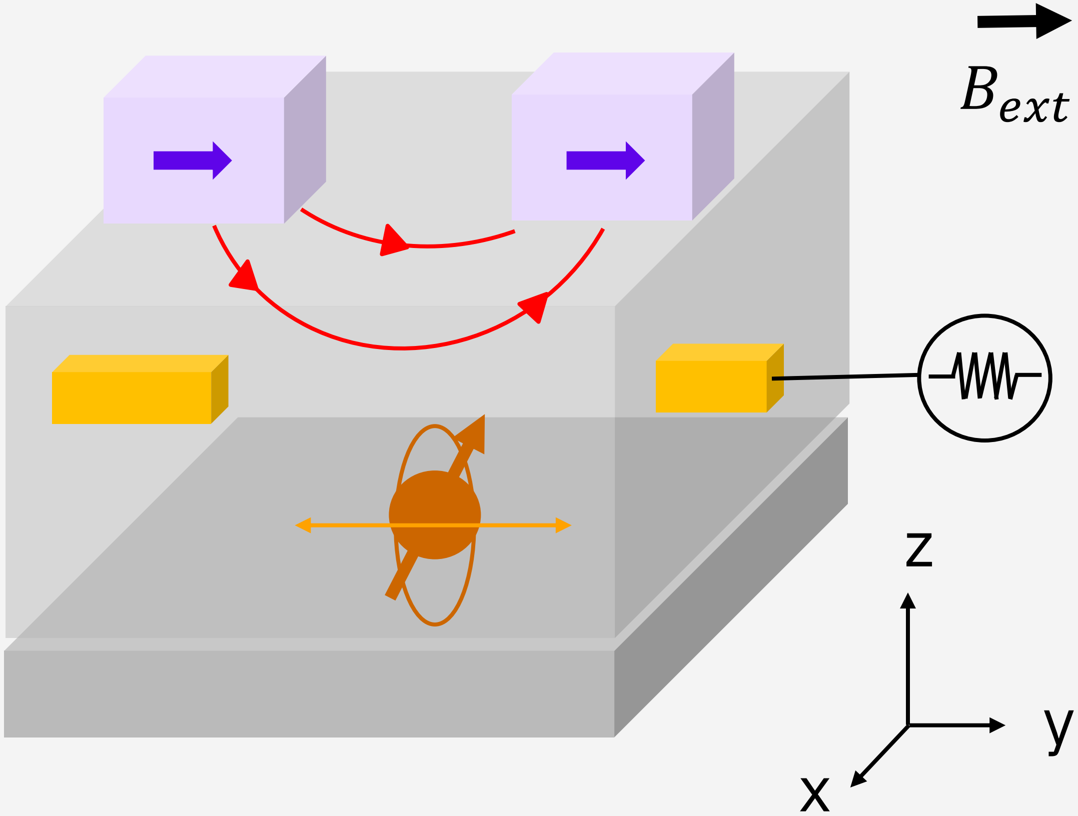


EDSR by micromagnets: goals

Two goals:

- High driving field

- Single qubit addressability



Outline

1) Overcome addressability problem in two dimensional arrays

2) Find a scalable path towards thousands of qubits

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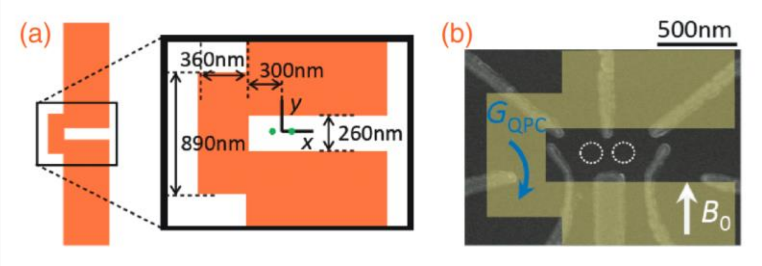
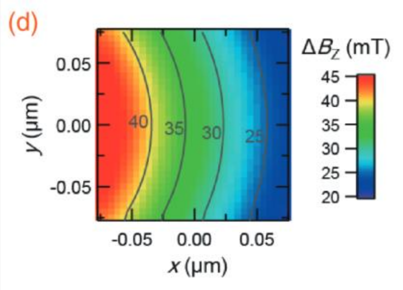
Overcome addressability problem in 2x2 arrays

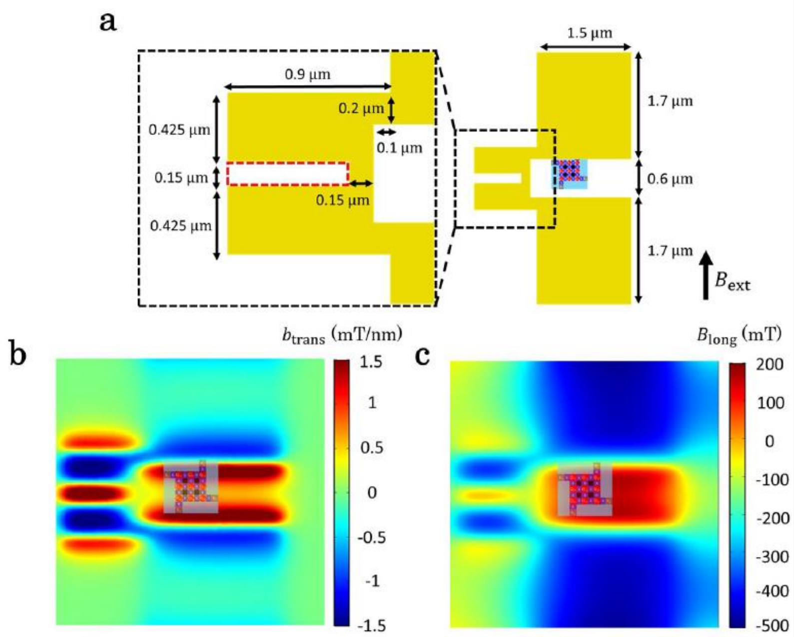
Old design





Yoneda et al., Appl. Phys. Express 8, 084401 (2015)

New design



Driving gradient

Addressability

Device setup

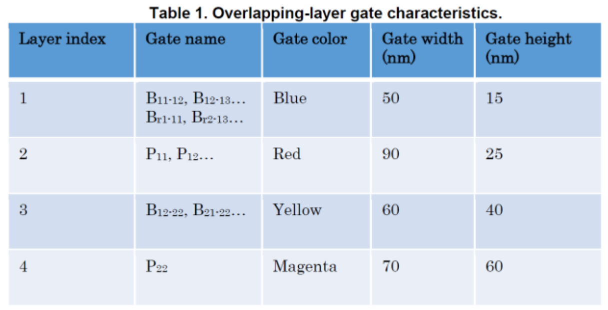
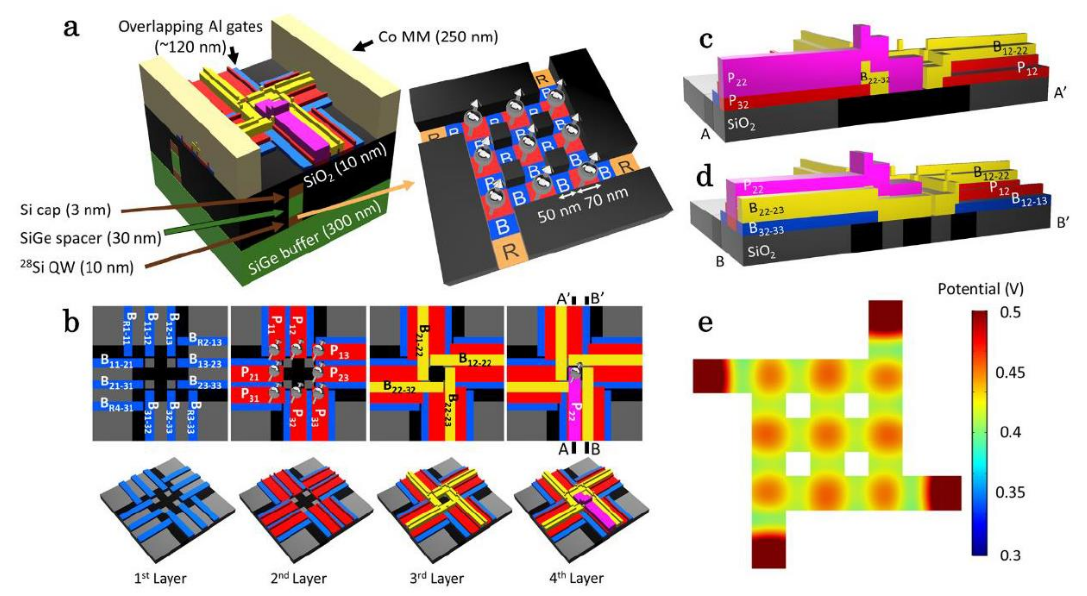


Table 1. Overlapping-layer gate characteristics.

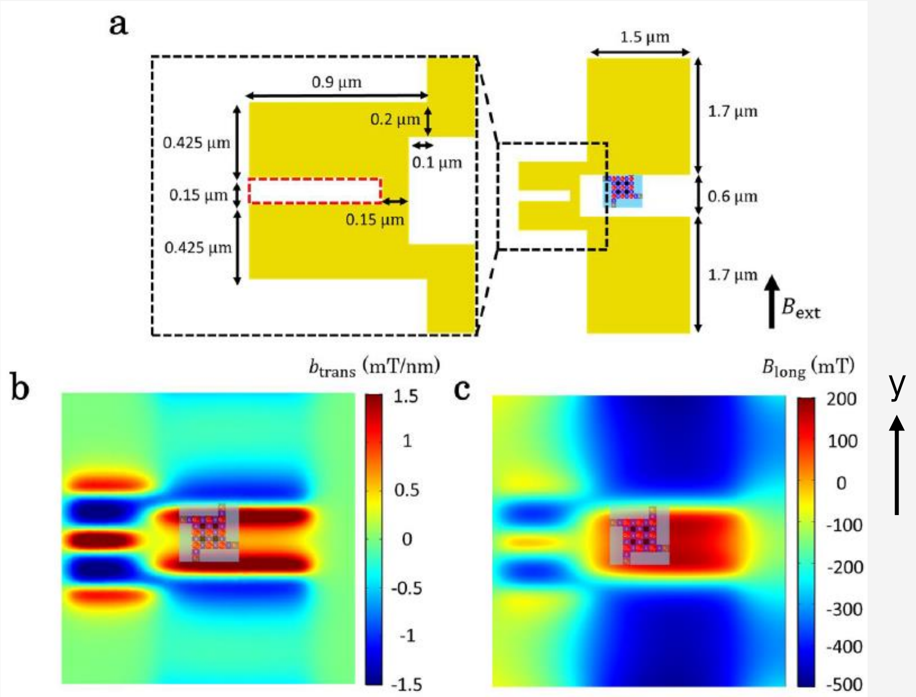
Layer index	Gate name	Gate color	Gate width (nm)	Gate height (nm)
1	$B_{11\text{-}12}$, $B_{12\text{-}13}$… $B_{r1\text{-}11}$, $B_{r2\text{-}13}$…	Blue	50	15
2	P_{11}, P_{12}…	Red	90	25
3	$B_{12\text{-}22}$, $B_{21\text{-}22}$…	Yellow	60	40
4	P_{22}	Magenta	70	60

- ^{28}Si/SiGe heterostructure
- Spin readout via gate-based sensing
- Initialization via relaxation and adiabatic passage
- Manipulation: EDSR



Performance

- f_{Rabi} = 6.8 – 14 MHz, assuming wavefunction displacement of 0.43 nm
- Minimum ΔB = 6 mT, which corresponds to Δf =160 MHz

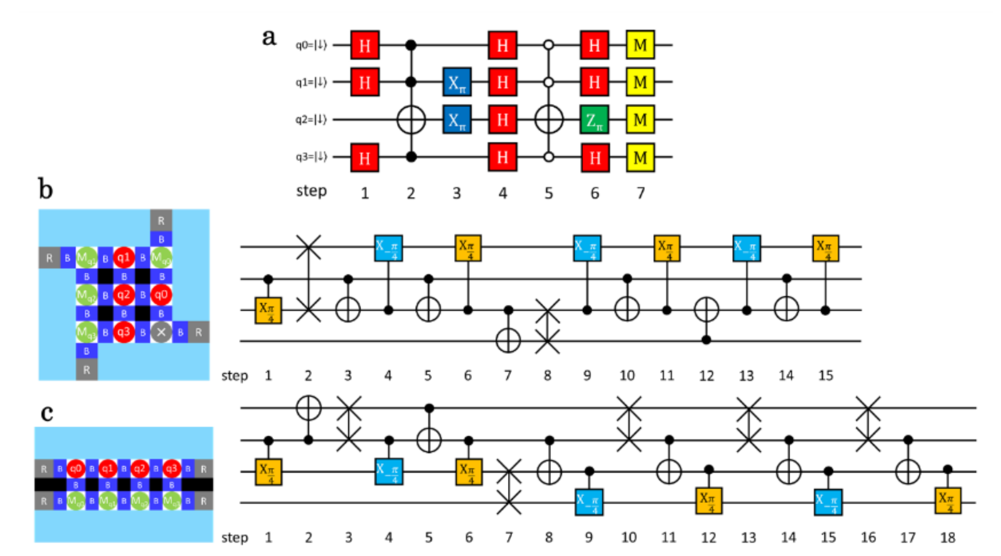


- Qubit 143 nm below the magnets
- External field: NA, assumed fully magnetized magnets
- Displacement: along y

Linear vs 2D array performance

Implementation of a4-qubit Grover’s search algorithm

- 2d: 15 two-qubit gates (2 SWAP)
- Linear: 18 two-qubit gates (5 SWAP)



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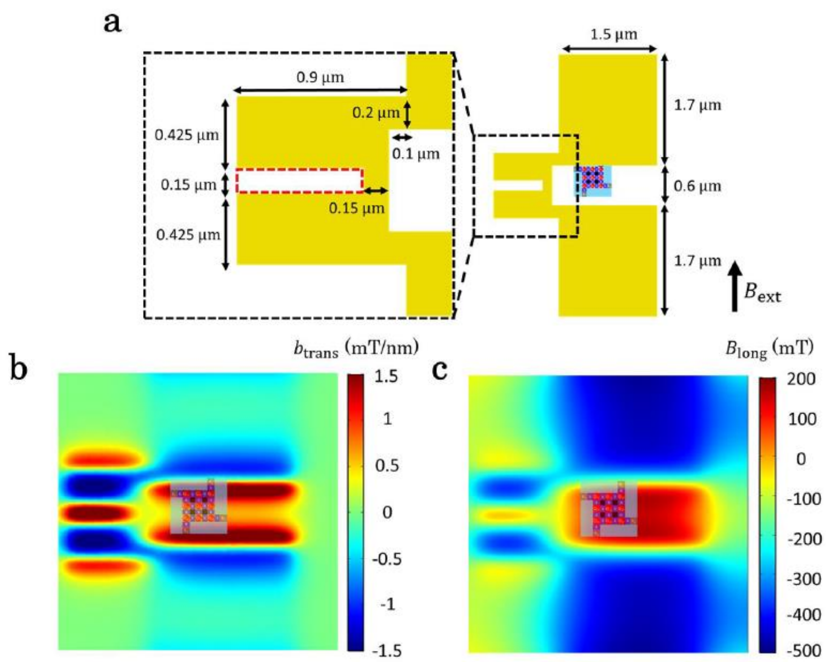
Old design



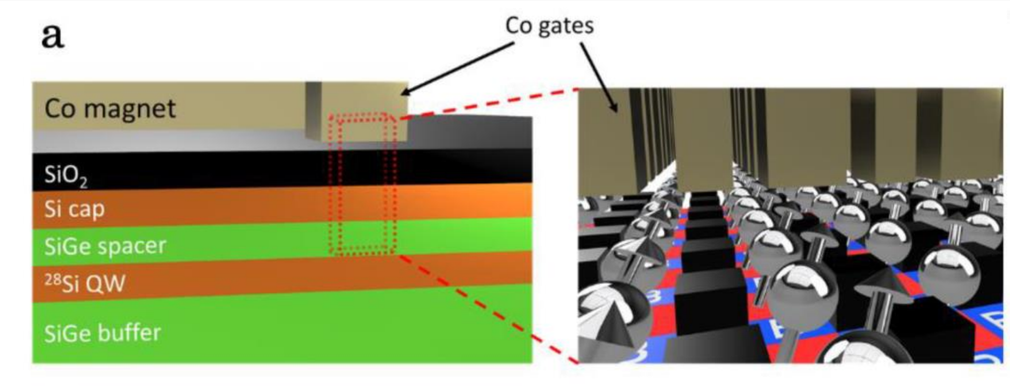
New idea

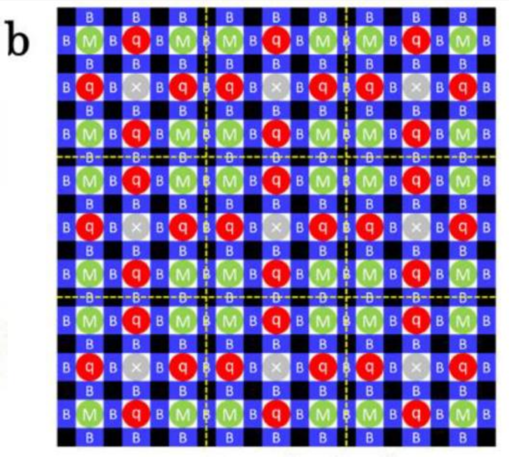
Separate the magnet:

- General magnet for addressability
- One magnet for each qubit for high driving gradient

Solution: ferromagnetic gates

- Plunger and barrier gates are magnetic
- Created as vias
- Size QD=120x120 nm^2

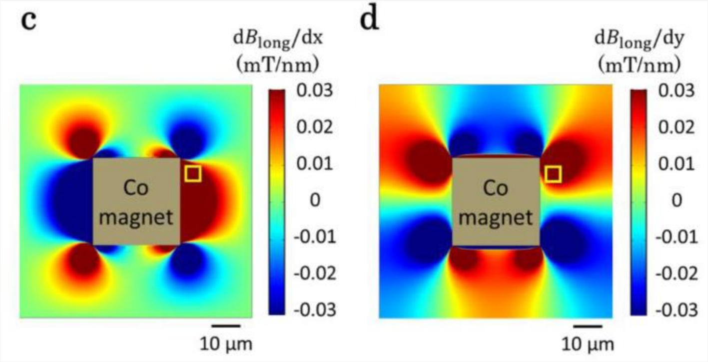


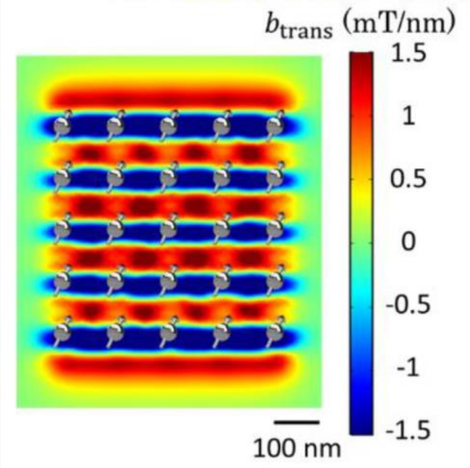


Barrier gate
Data qubits
Ancilla qubits

Performance

- f_{Rabi} = 39 MHz, assuming wavefunction displacement of 0.43 nm
- $\Delta f > 100$ MHz
- QD footprint: 120x120 nm^2

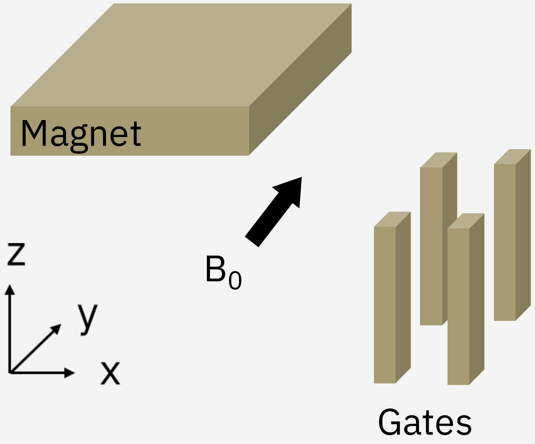


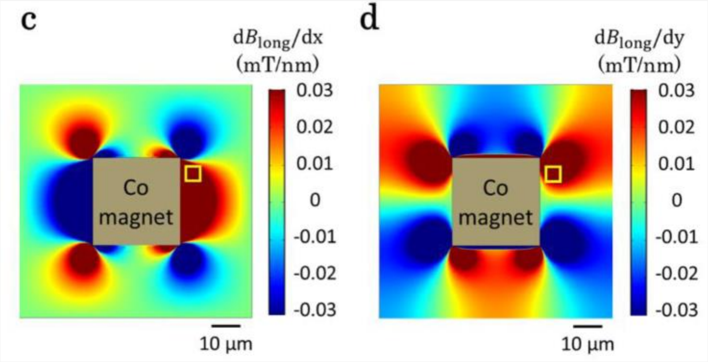


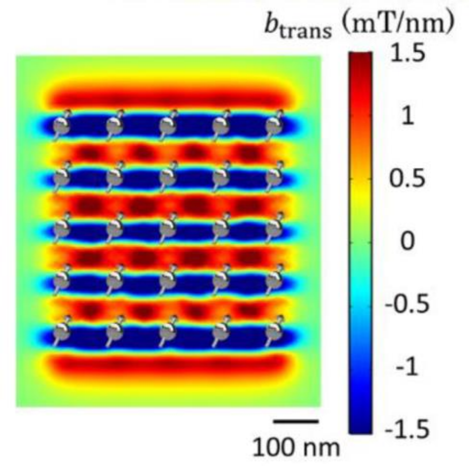
  - Qubit position: NA
  - External field: NA, assumed fully magnetized magnets
  - Displacement: along y

Issues

- Vias fan-out and connection
- Magnetization pattern uniformity

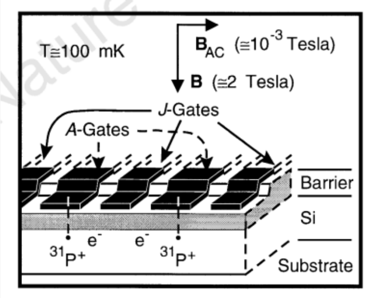




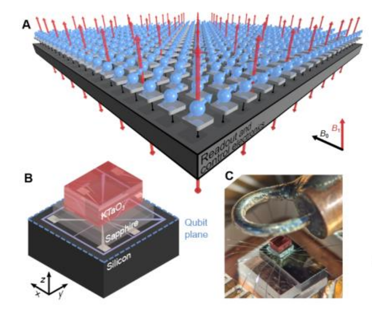


Comparison: global magnetic field

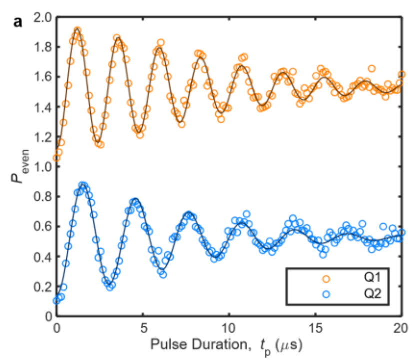
- Deliver of magnetic field trough MW dielectric resonator
- Brought in resonance by local voltage (g-factor modulation)
- Demonstrated coherent Rabi oscillation



Kane, B. E. Nature 393, 133–137 (1998).



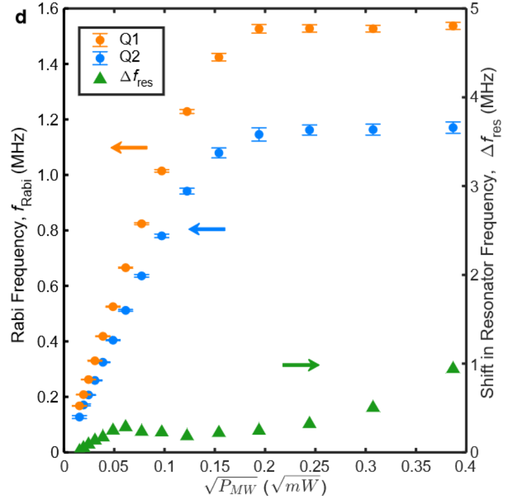
Vahapoglu, E., et al., Science Advances, 7(33), (2021)

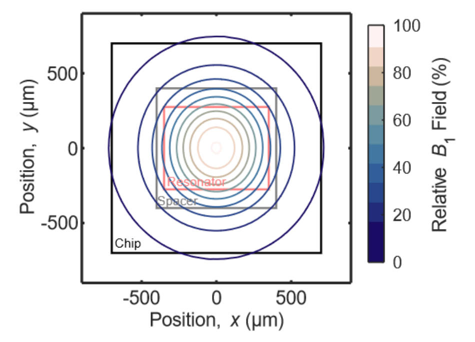


Vahapoglu, E., et al., arXiv:2107.14622 (2021)

Issues

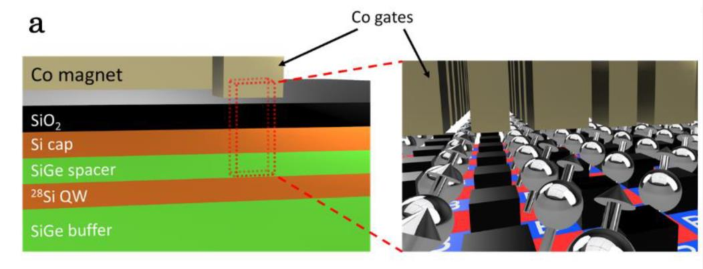
- f_{Rabi} = < 2 MHz (saturation with increasing MW power)
- Unwanted additional drive
- Low quality factor for the resonator



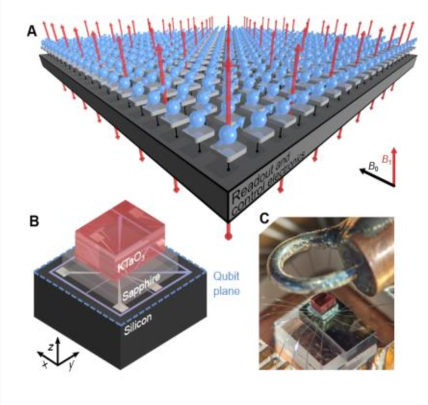


Vahapoglu, E., et al., arXiv:2107.14622 (2021)

Comparison



Tadokoro et al. (arXiv:2106.11124)



Vahapoglu et al. (arXiv:2107.1462)

- $f_{Rabi} = 39$ MHz
- Addressability via magnetic gradient
- Simulation

- $f_{Rabi} = 1.5$ MHz
- Addressability tunable by voltage
- Experiment

Conclusion

- Proposal for EDSR drive up to thousand qubits
- Based on splitting magnet role between driving and addressability