

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

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8 November 2021



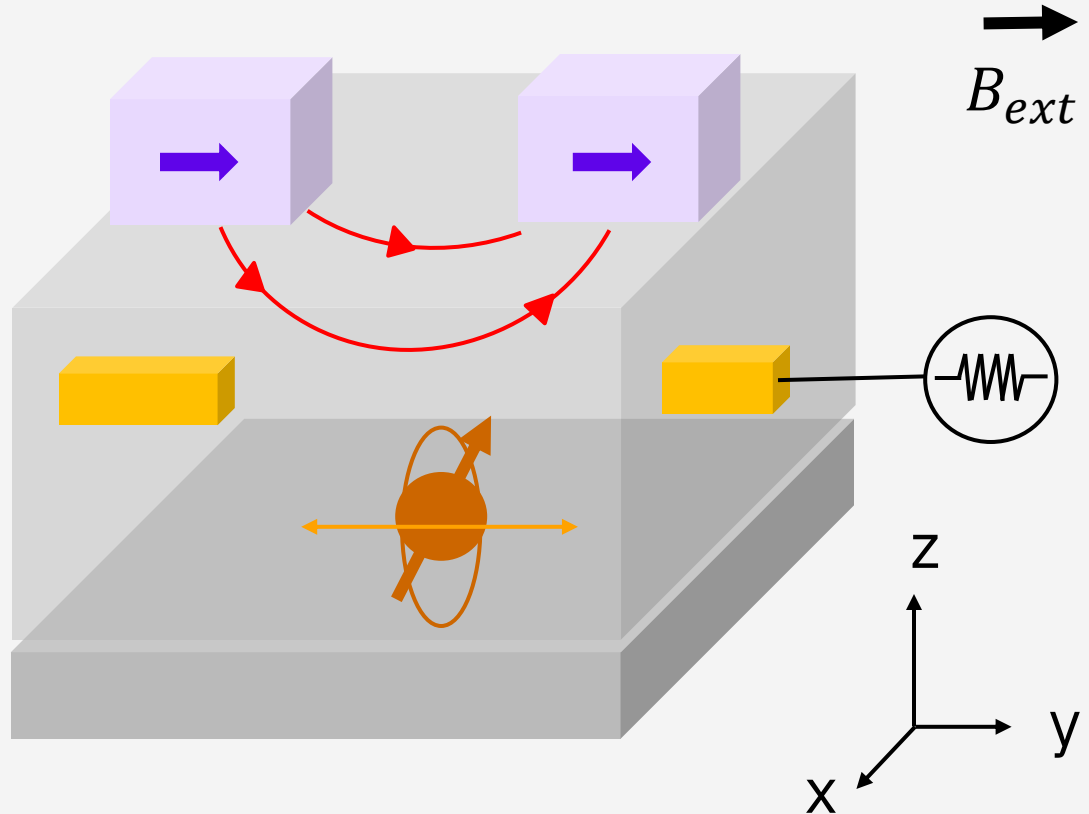
Abstract

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:

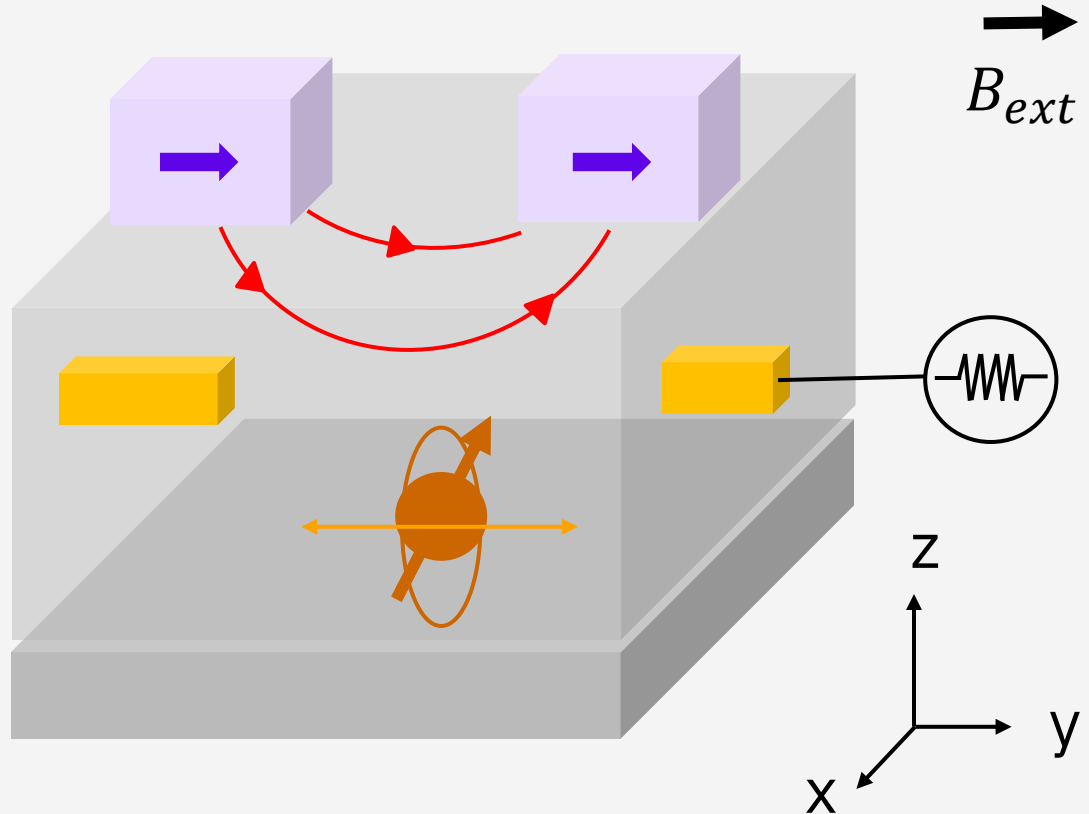
- Stray field gradient
- Electric field



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

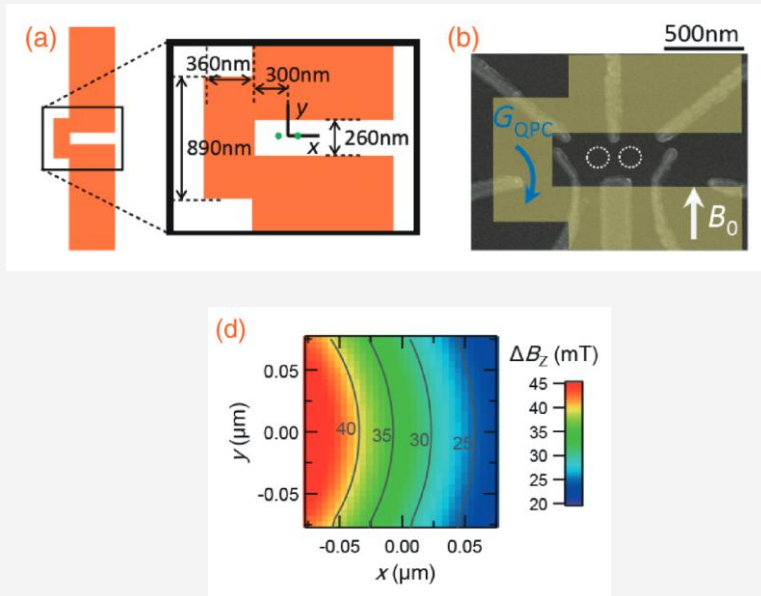
Outline

1) Overcome addressability problem in two dimensional arrays

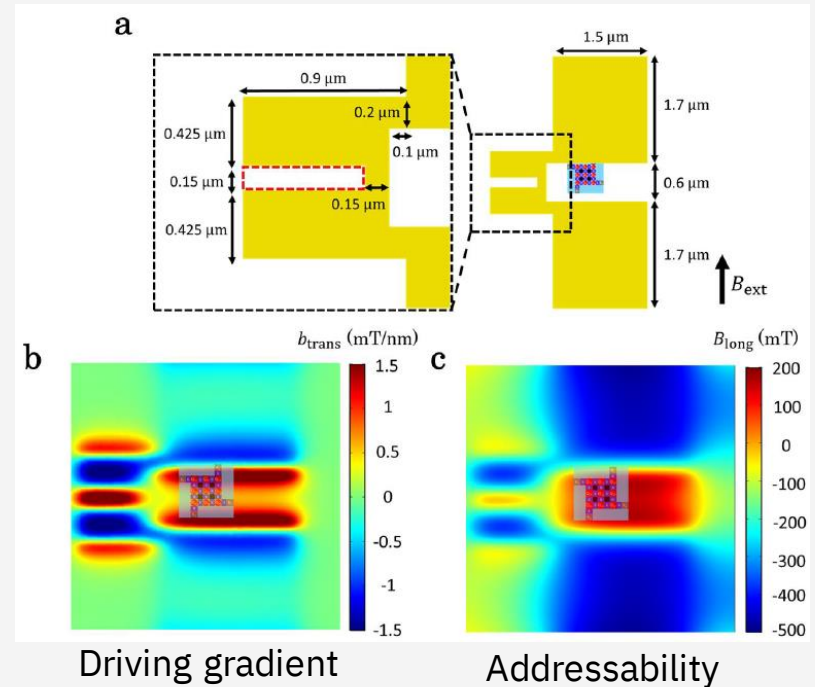
2) Find a scalable path towards thousands of qubits

Overcome addressability problem in 2x2 arrays

Old design



New design



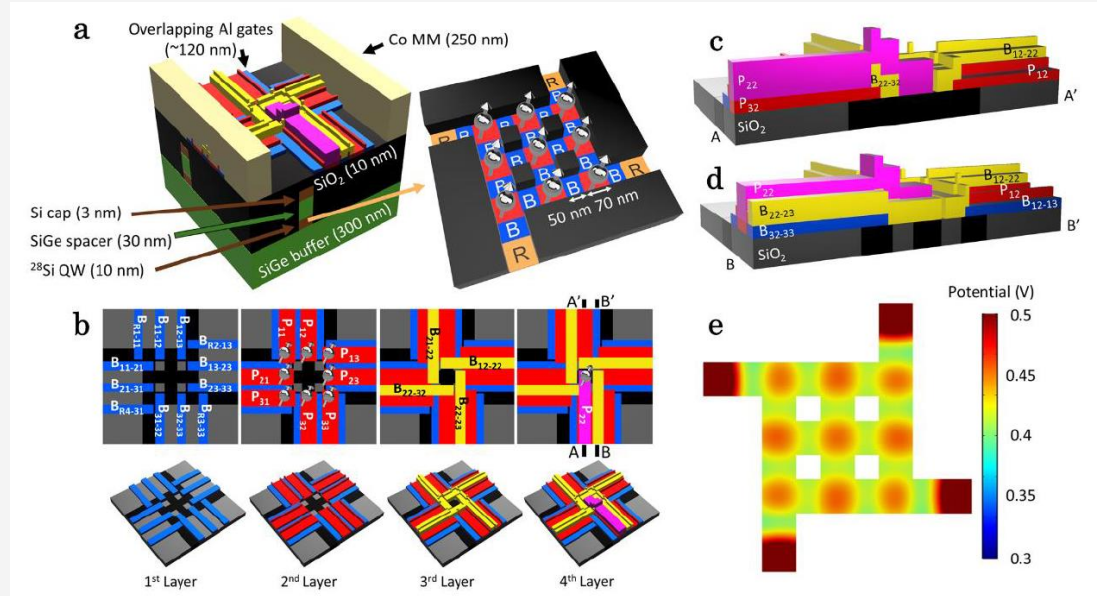
Yoneda et al., Appl. Phys. Express 8, 084401 (2015)

Device setup

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

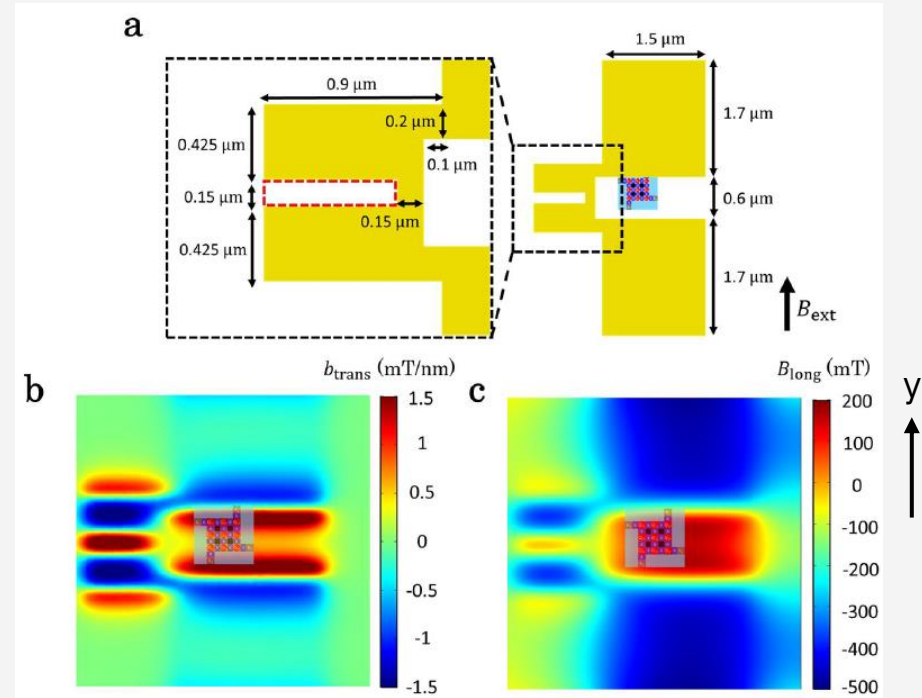
Table 1. Overlapping-layer gate characteristics.

Layer index	Gate name	Gate color	Gate width (nm)	Gate height (nm)
1	B ₁₁₋₁₂ , B ₁₂₋₁₃ ... B _{r1+1} , B _{r2-13} ...	Blue	50	15
2	P ₁₁ , P ₁₂ ...	Red	90	25
3	B ₁₂₋₂₂ , B ₂₁₋₂₂ ...	Yellow	60	40
4	P ₂₂	Magenta	70	60



Performance

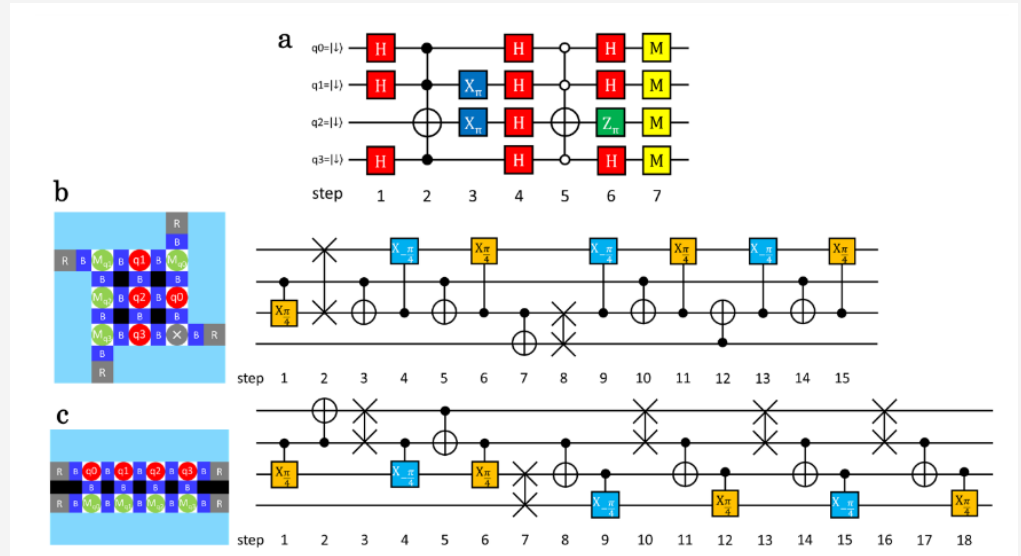
- $f_{\text{Rabi}} = 6.8 - 14$ MHz, assuming wavefunction displacement of 0.43 nm
- Minimum $\Delta B = 6$ mT, which corresponds to $\Delta f = 160$ MHz
- Qubit 143 nm below the magnets
- External field: NA, assumed fully magnetized magnets
- Displacement: along y



Linear vs 2D array performance

Implementation of a 4-qubit Grover's search algorithm

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



Outline

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- 2) Find a scalable path towards thousands of qubits

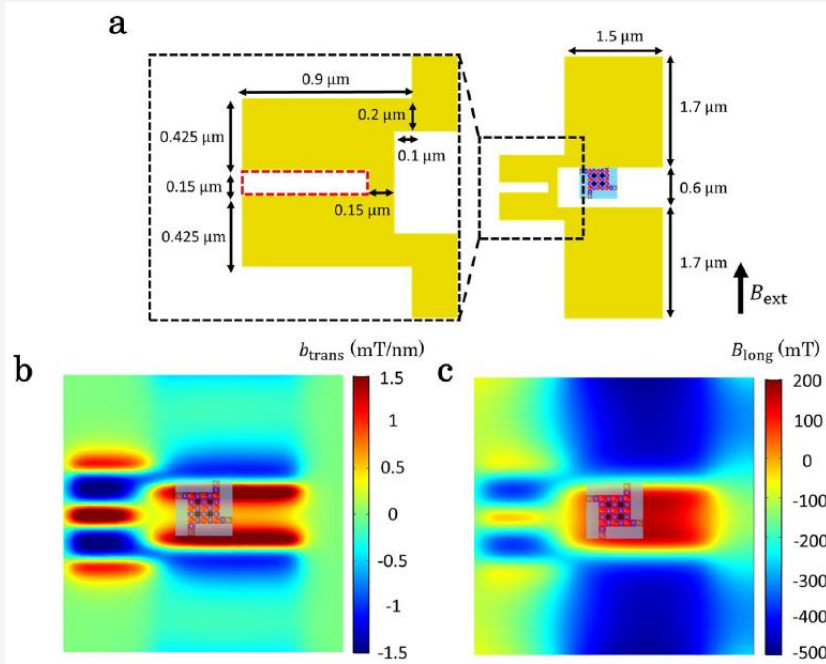
Outline

- 1) Overcome addressability problem in two dimensional arrays
- 2) Find a scalable path towards thousands of qubits**

Find a scalable path towards thousands of qubits

Old design

New idea

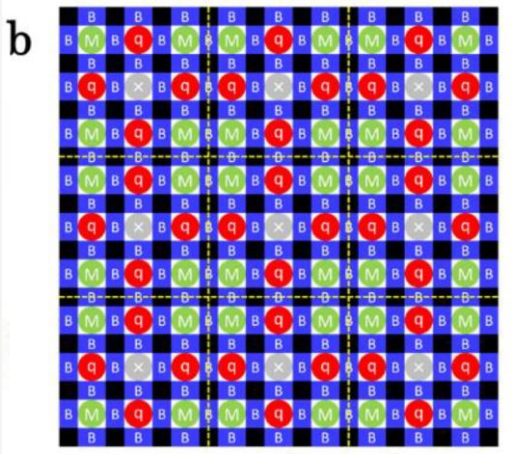
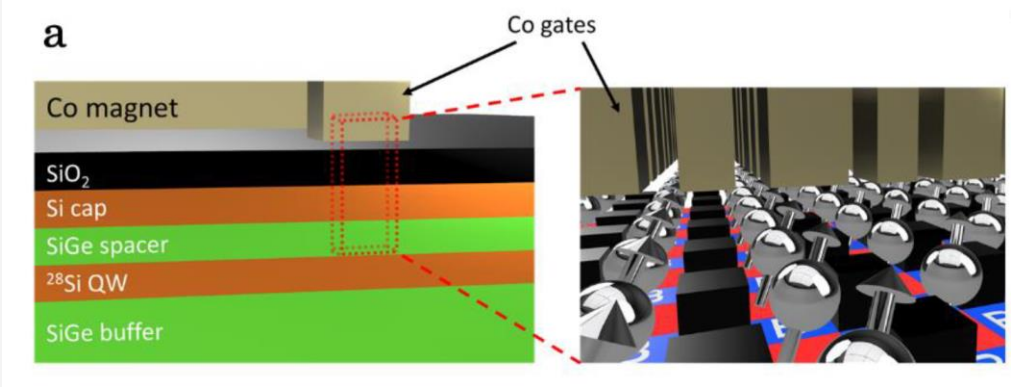


Separate the magnet:

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

Solution: ferromagnetic gates

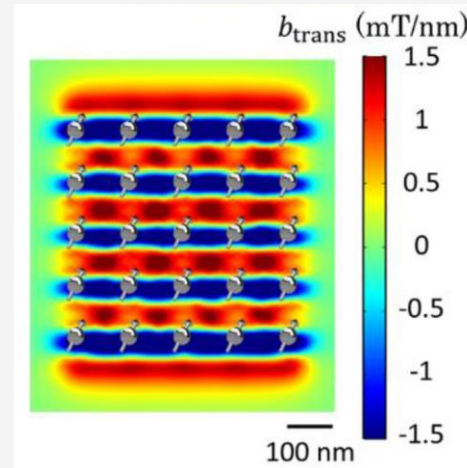
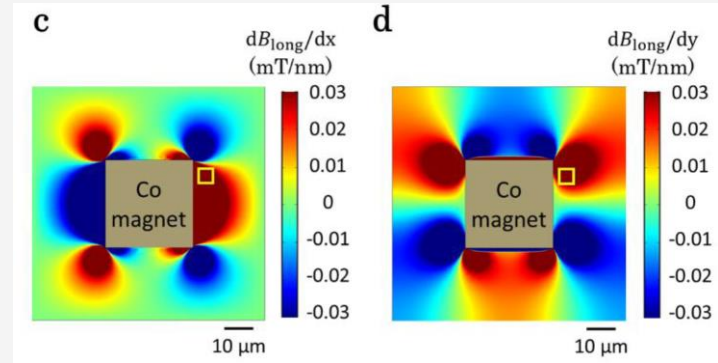
- Plunger and barrier gates are magnetic
- Created as vias
- Size QD=120x120 nm²



Barrier gate
Data qubits
Ancilla qubits

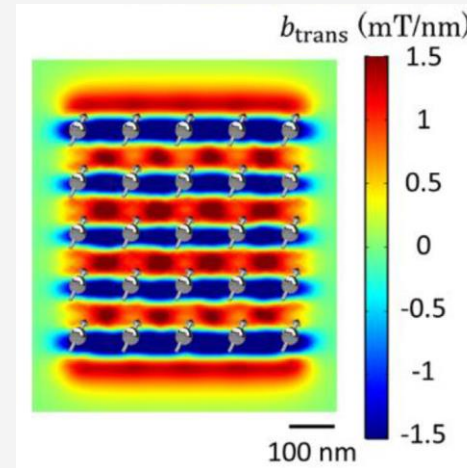
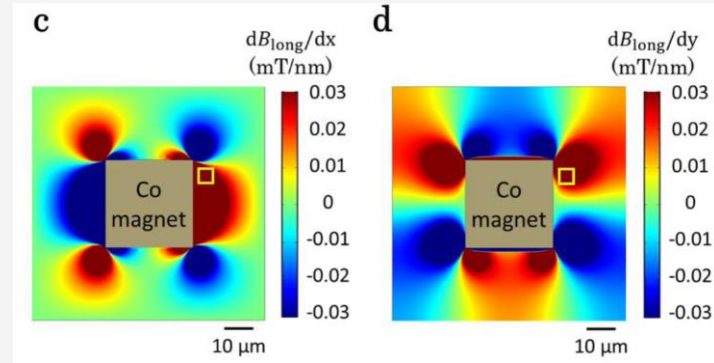
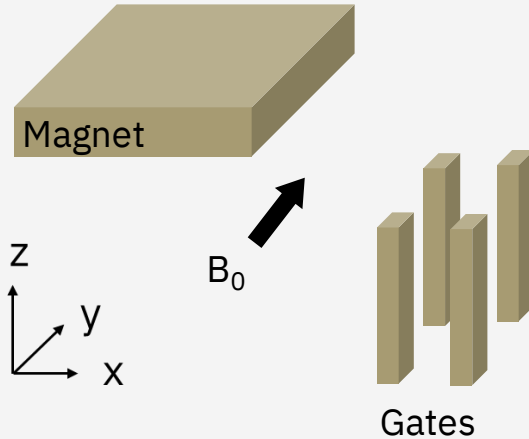
Performance

- $f_{\text{Rabi}} = 39$ MHz, assuming wavefunction displacement of 0.43 nm
- $\Delta f > 100$ MHz
- QD footprint: 120×120 nm²
- Qubit position: NA
- External field: NA, assumed fully magnetized magnets
- Displacement: along y



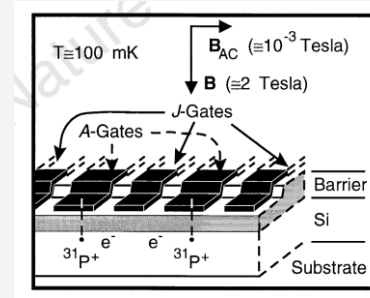
Issues

- Vias fan-out and connection
- Magnetization pattern uniformity

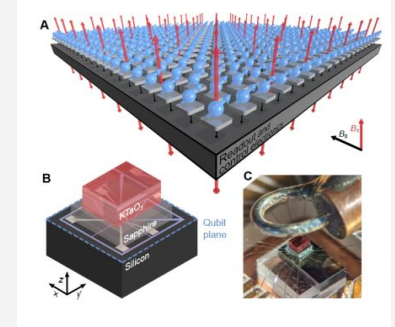


Comparison: global magnetic field

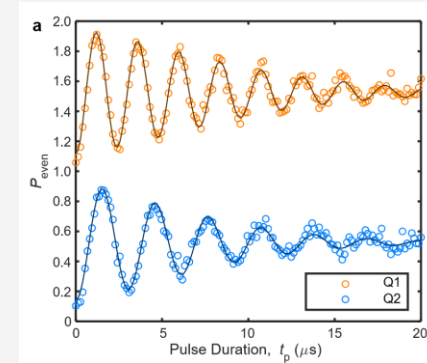
- Deliver of magnetic field through MW dielectric resonator
- Brought in resonance by local voltage (g-factor modulation)
- Demonstrated coherent Rabi oscillation



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



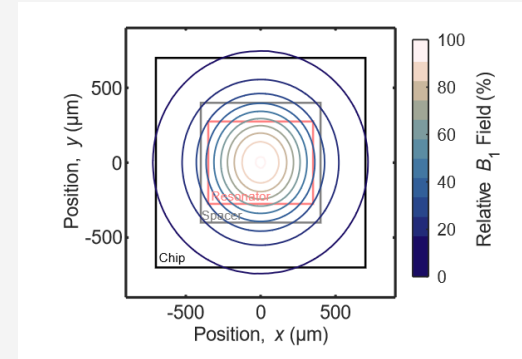
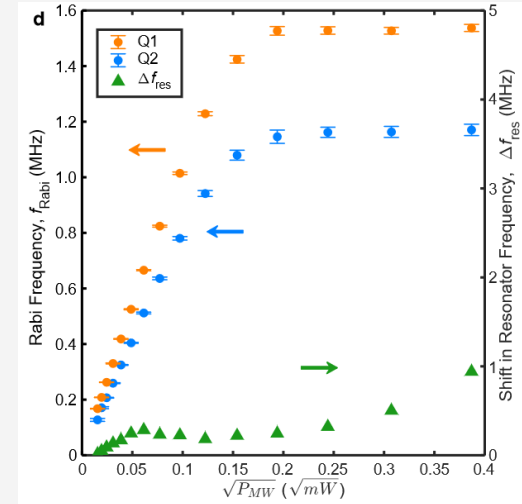
Vahapoglu, E., et al., Science Advances, 7(33), (2021)



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

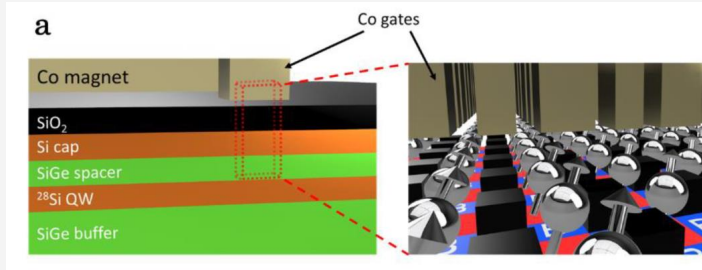
Issues

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



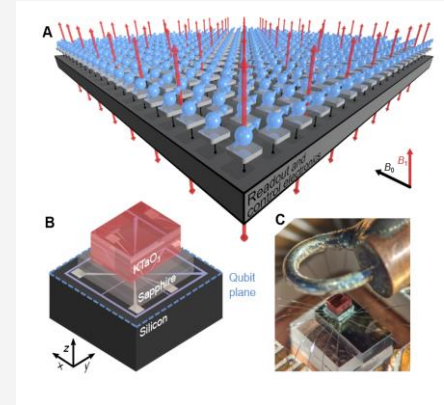
Vahapoglu, E., et al.,
arXiv:2107.14622 (2021)

Comparison



Tadokoro et al. (arXiv:2106.11124)

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



Vahapoglu et al. (arXiv:2107.1462)

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

Conclusion

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

