Coherent control and readout of a coupled quantum dot-donor in silicon

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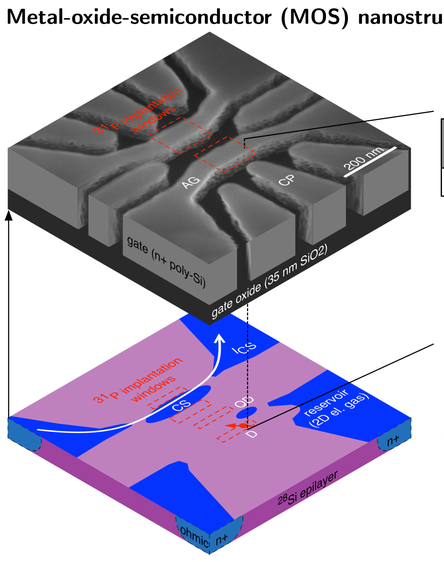
Abstract

Individual donors and quantum dots in silicon chips are used as bits of quantum information with different but complementary advantages. In this work, we show that these two qubit systems can be combined by demonstrating the **coherent interaction** of a ^{31}P **donor** electron with the electron of a metal-oxide-semiconductor **quantum dot**. We form a logical qubit encoded in the spin singlet and triplet states of the two-electron system. We show that the donor **nuclear spin** drives **coherent rotations** between the electronic qubit states through the contact hyperfine interaction. This provides every key element for compact two-electron spin qubits requiring only a single dot and no additional magnetic field gradients, as well as a means to interact with the nuclear spin qubit. This system furthermore introduces an engineered path to couple donors together, alleviating the need for challenging atomic-precision fabrication and providing a scalable path to multi-donor qubit systems.

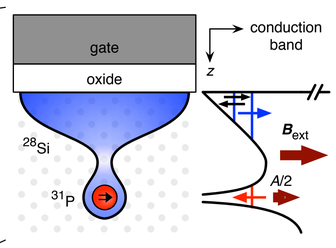
We also discuss our advances in **engineering the valley splitting** and the shell filling of QDs to overcome the system's challenges. We present a scheme for **high fidelity spin readout** that combines the advantages of the Pauli blockade and spin 1/2 readouts.

1. Experimental system

Metal-oxide-semiconductor (MOS) nanostructure



Filled-shell valley configuration

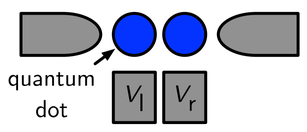


effective (2,0)-(1,1) system

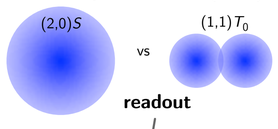
- Isotopically purified Si: low magnetic noise
- Poly-Si gate technology: metal-free, CMOS industry standard

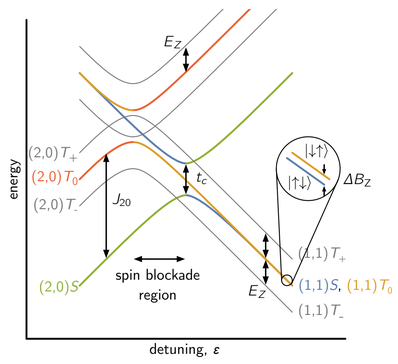
2. Singlet-triplet (ST) qubit

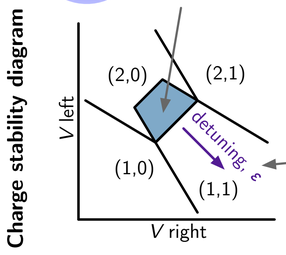
Double quantum dot (QD)

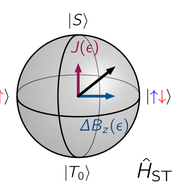


Pauli spin blockade (PSB)







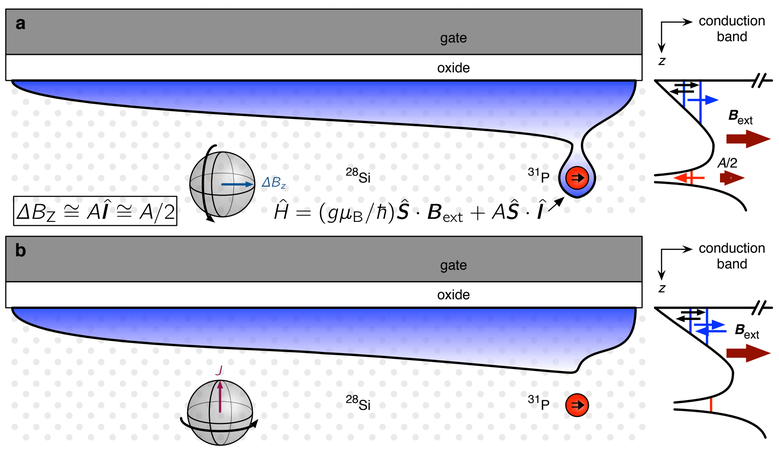


Bloch sphere control

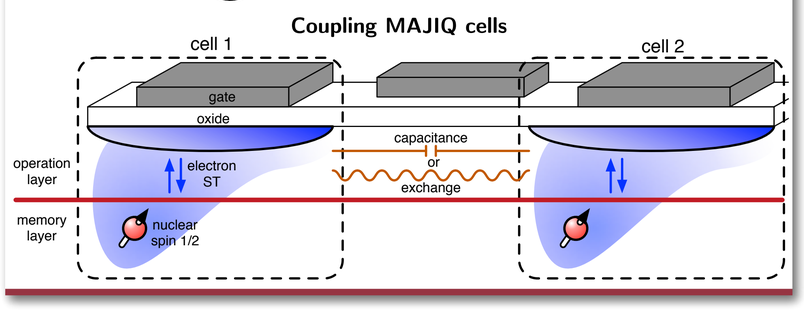
$$\hat{H}_{ST} = -J(\epsilon)\frac{\hat{\sigma}_z}{2} - \Delta B_z(\epsilon)\frac{\hat{\sigma}_x}{2}$$

3. Our "MAJIQ" qubit

MAJIQ: MOS (M) hyperfine (A) exchange (J) nuclear spin (I) qubit (Q)

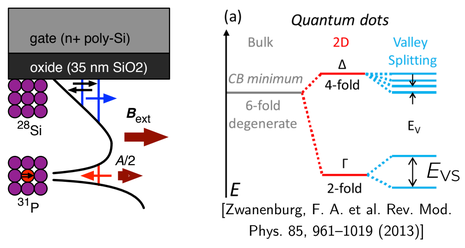


Coupling MAJIQ cells



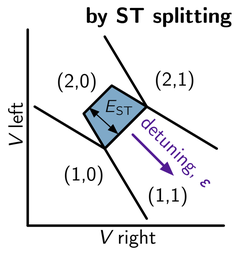
4. Valley splitting engineering

Valley splitting in MOS

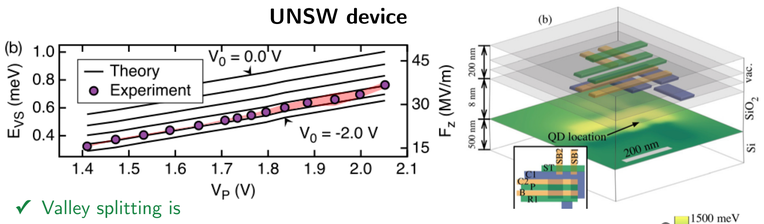


[Zwanenburg, F. A. et al. Rev. Mod. Phys. 85, 961–1019 (2013)]

Spin blockade window is limited by ST splitting E_{ST}

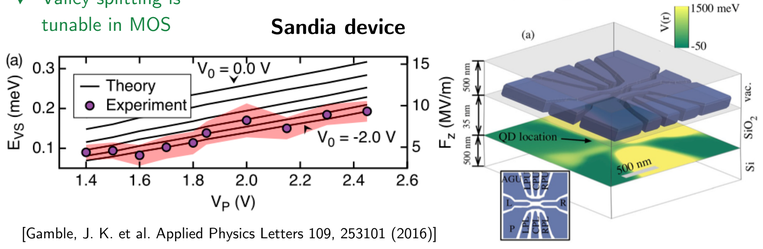


UNSW device



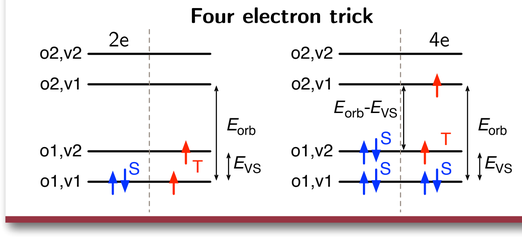
✓ Valley splitting is tunable in MOS

Sandia device



[Gamble, J. K. et al. Applied Physics Letters 109, 253101 (2016)]

Four electron trick

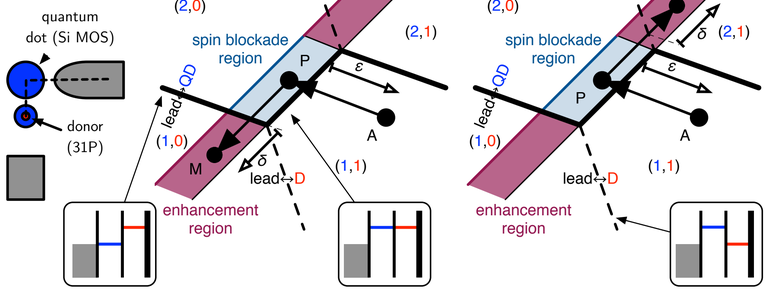


× QD-D systems can still have small VS because of donor constrainsts

- Circumvent small ST splitting
- Change QD size to adjust tunnel coupling to donors/ other QDs

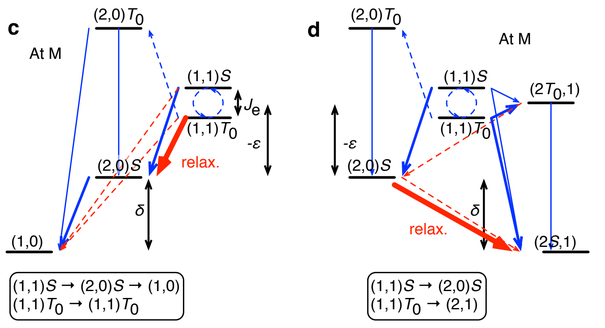
5. Enhanced latching readout (ELR)

Single-reservoir system

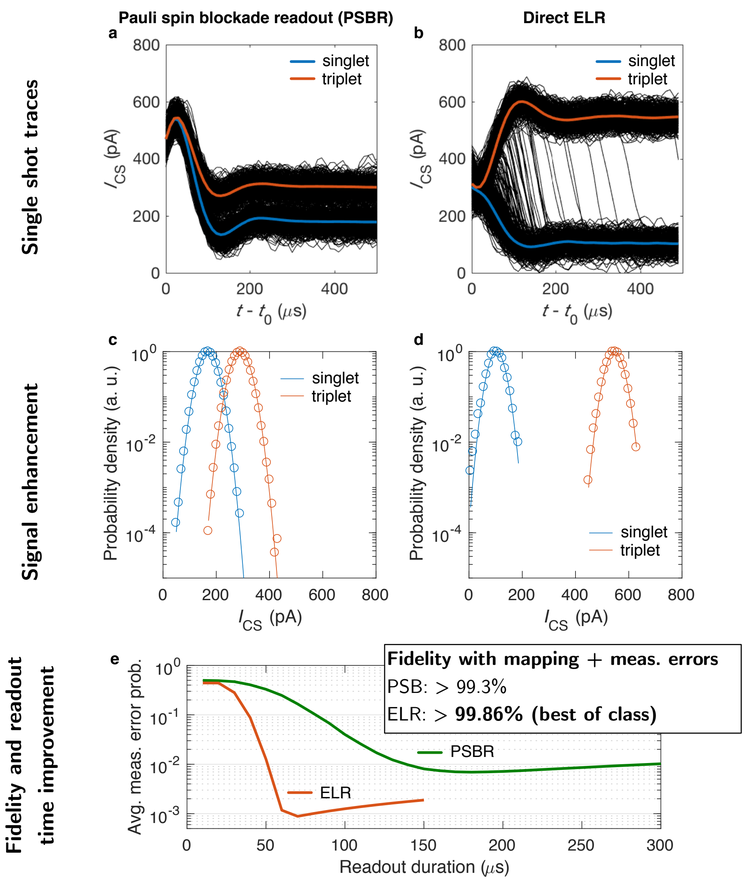


Mechanisms

✓ Reverse ELR enhances the lifetime by changing the relaxation mechanism

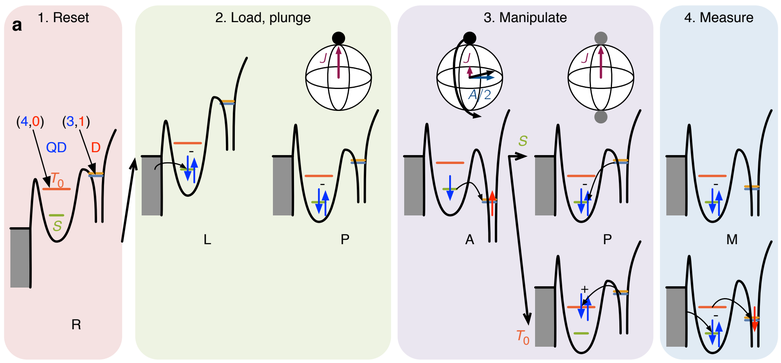


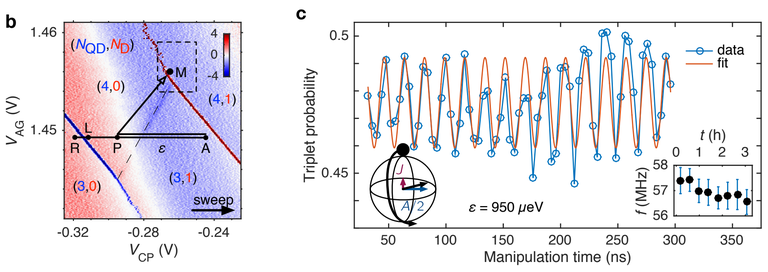
6. Comparison of ELR and spin blockade



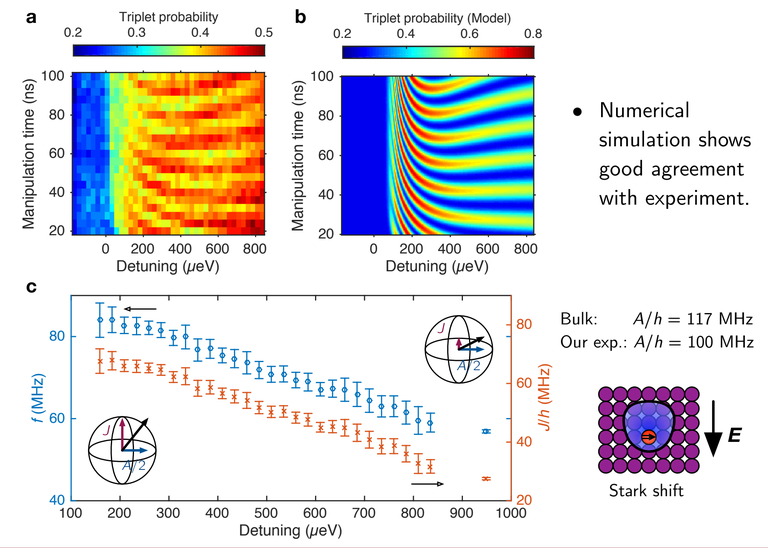
7. Hyperfine-driven ST rotations

Rapid separation of a singlet state triggers S to T_0 rotations driven by the interaction with the nuclear spin



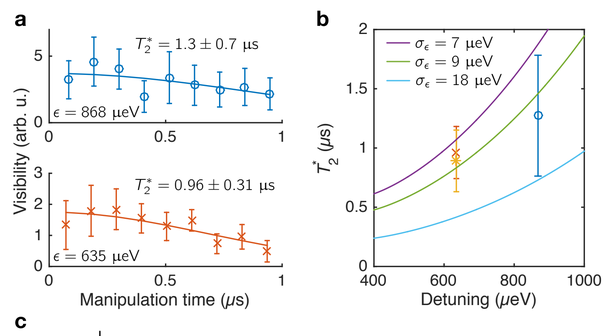


Characterize exchange and hyperfine interactions



- Numerical simulation shows good agreement with experiment.

8. Coherence time



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Reference	Petersson *et al.* \cite{petersson2010}	Shi *et al.* \cite{shi2013}	Eng *et al.* \cite{eng2015}	This work
Material	GaAs/AlGaAs	Si/SiGe	Si/SiGe	Si (MOS)
$2\sigma_\epsilon$ (μeV)	7.4	10	9.2	18
$k_B T_e$ (μeV)	6.9	12	6.9 – 8.6	18

- First measure of **charge noise** in the MOS system
- Noise (std. dev. σ_ϵ) is found to be similar to other "clean" heterosystems when accounting for temperature
- New exp. by Rudolph *et al.* [6] has lower $2\sigma_\epsilon = 7.0$ μeV

[i] Petersson, K. D., Petta, J. R., Lu, H. & Gossard, A. C. Phys. Rev. Lett. 105, 246804 (2010).
[ii] Shi, Z. et al. Phys. Rev. B 88, 075416 (2013).
[iii] Eng, K. et al. Science Advances 1, e1500214 (2015).

Conclusions & Perspectives

- ✓ First coherent **donor-quantum dot** system.
- ✓ **Fast**, **compact**, **all-electrically** driven ST qubit in MOS.
- ✓ Built-in access to **nuclear spin** could enable high fidelity qubit memory or nuclear spin computer.
- ✓ **Charge noise** in MOS **on par** with other systems.
- ✓ Valley splitting is **tunable** in MOS
- ✓ **4-electron trick** enables engineering of QD electronic properties
- ✓ **Enhanced latching readout**, > **99.86%** single shot readout fidelity. Bigger **signal**, enhanced **lifetime**, **dipole-independent** readout.

References

[1] Singh, M. et al. Applied Physics Letters 108, 062101 (2016).
[2] Tracy, L. A. et al. Applied Physics Letters 108, 063101 (2016).
[3] Gamble, J. K., Harvey-Collard, P. et al. Valley splitting of single-electron Si MOS quantum dots. Applied Physics Letters 109, 253101 (2016).
[4] Harvey-Collard, P. et al. High-fidelity single-shot readout for a spin qubit via an enhanced latching mechanism. ArXiv e-prints (2017). 1703.02651.
[5] Harvey-Collard, P. et al. Coherent coupling between a quantum dot and a donor in silicon. ArXiv e-prints (2015). 1512.01606.
[6] Rudolph, M., Harvey-Collard, P. et al. Coupling MOS quantum dot and phosphorous donor qubit systems. In 2016 IEEE International Electron Devices Meeting (IEDM), 34.1.1–34.1.4 (2016).

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Exceptional service in the national interest

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