Exchange control in a MOS double quantum dot made using a 300 mm wafer process

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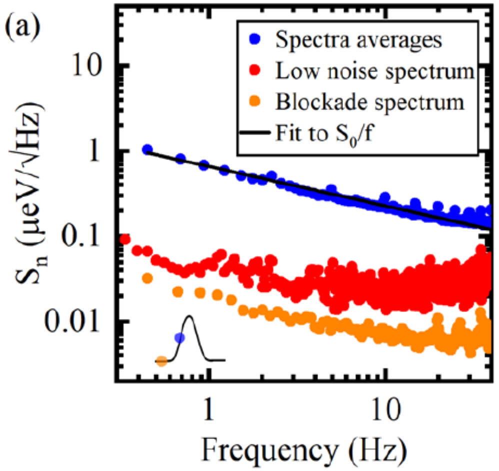
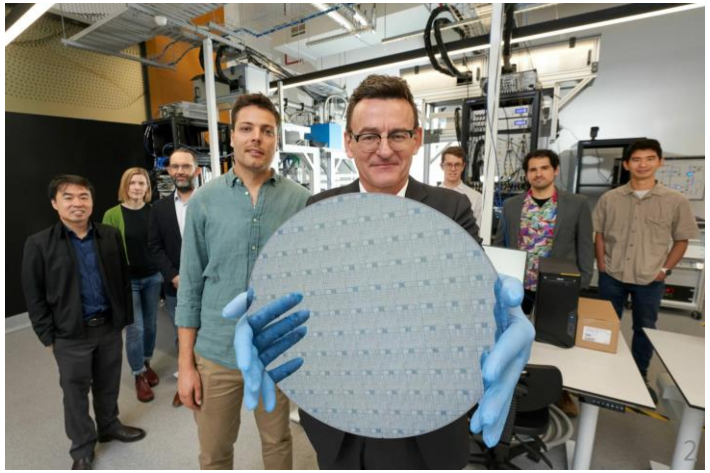
Group Meeting Talk by Rafael, 13.09.2024

Motivation

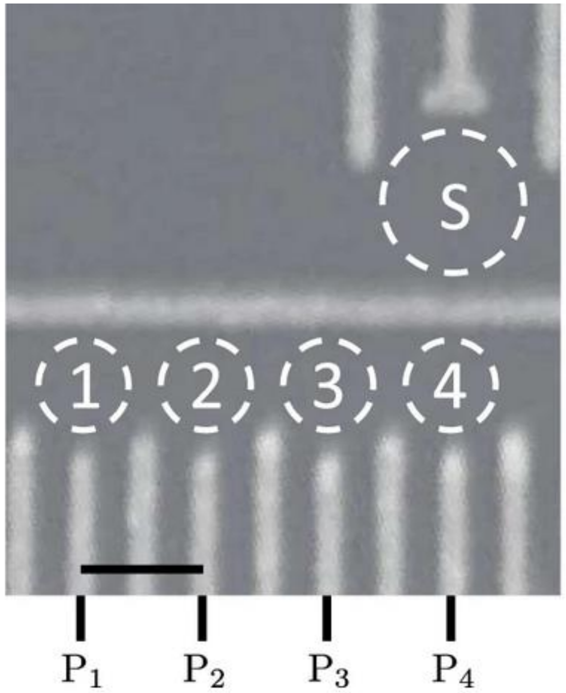
Leveraging the advanced manufacturing capabilities of the semiconductor industry promises to help scale up silicon-based quantum processors by increasing yield, uniformity and integration. Recent studies of quantum dots fabricated on 300 mm wafer metal-oxide-semiconductor (MOS) processes have shown control and readout of individual spin qubits, yet quantum processors require two-qubit interactions to operate. Here, we use a 300 mm wafer MOS process customized for spin qubits and demonstrate coherent control of two electron spins using the spin-spin exchange interaction, forming the basis of an entangling gate such as $\sqrt{\text{SWAP}}$. We observe gate dephasing times of up to $T_2^* \approx 500$ ns and a gate quality factor of 10. We further extend the coherence by up to an order of magnitude using an echo sequence. For readout, we introduce a dispersive readout technique, the radiofrequency electron cascade, that amplifies the signal while retaining the spin-projective nature of dispersive measurements. Our results demonstrate an industrial grade platform for two-qubit operations, alongside integration with dispersive sensing techniques.

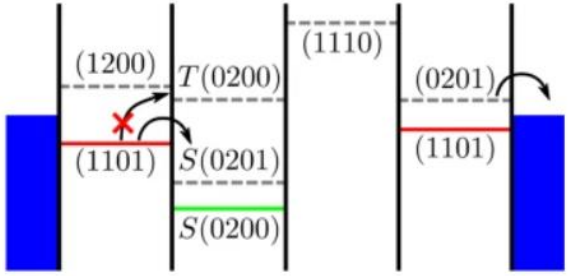


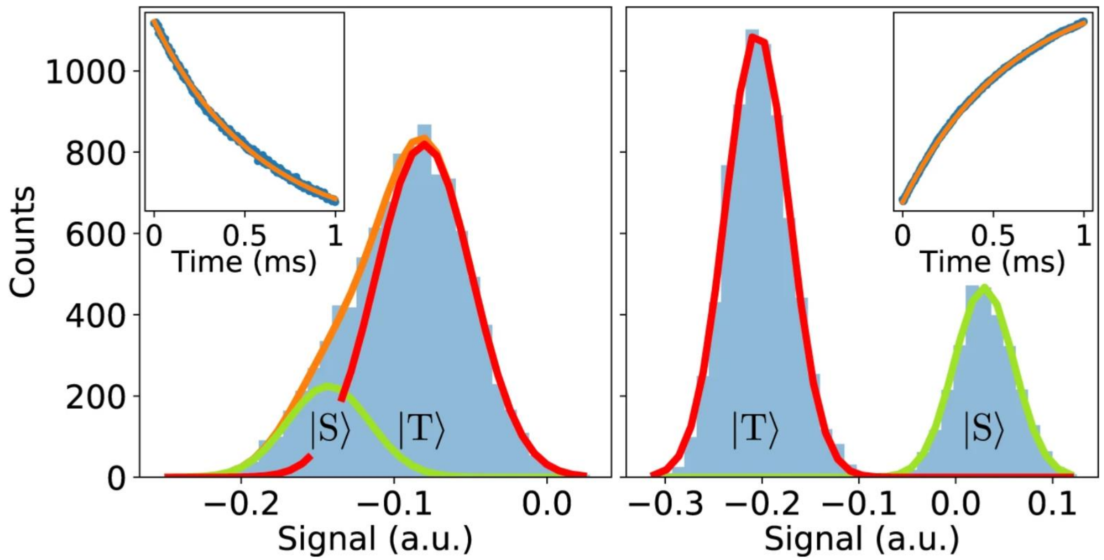


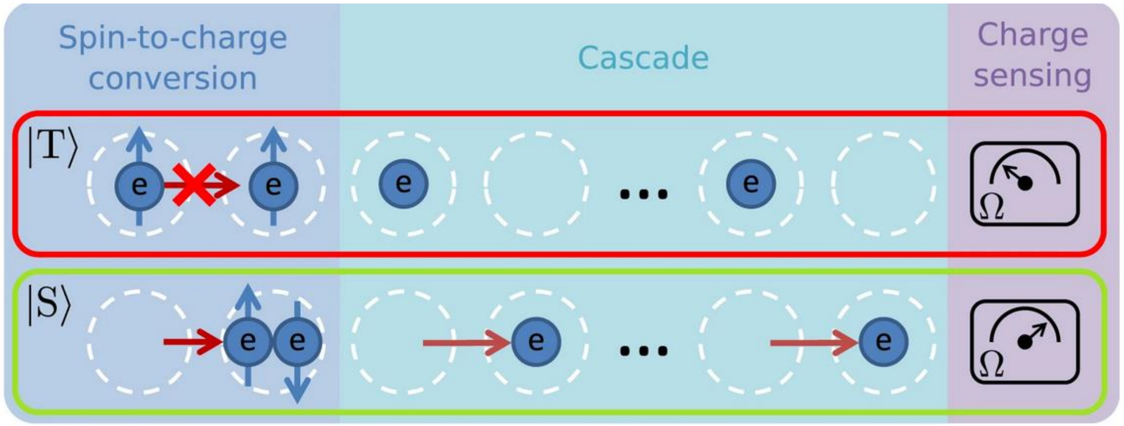
[1] Dumoulin Stuyck et al., *Symposium on VLSI Circuits,* 1-2, (2021)
[2] Elsayed et al. *arXiv:* 2212.06464, (2022)
[3] Diraq, press release

Background: DC-PSB Cascade Readout









Readout SNR:

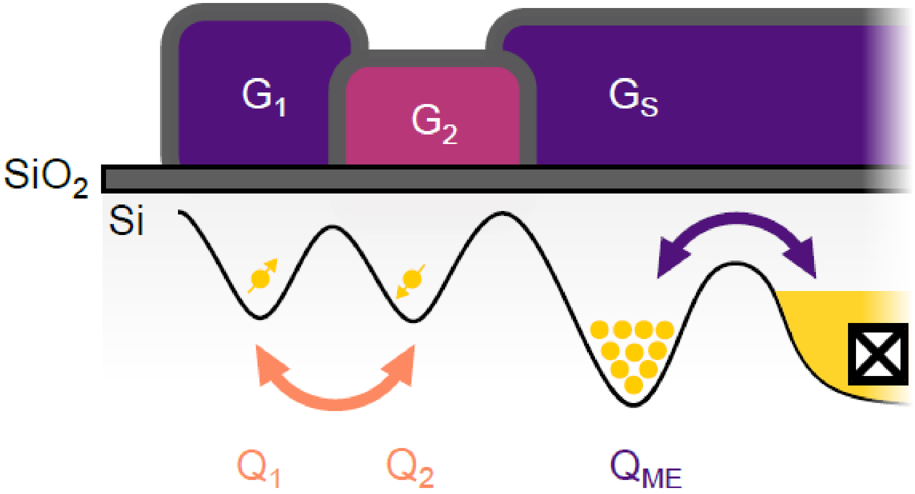
- **Boosted by 3.4 over "classical" PSB at 1 ↔ 2**
- **Due to closer proximity of charge relocation**

Sensor far away from qubit:

- GaAs 4-dot
- PSB at dots 1 ↔ 2
- Cascaded charge relocation
- Strong sensor signal at dot 4

[1] Van Diepen et al., *Nat. Comms*, **12**, 77, (2021) -> Vandersypen Group!

The Device & Setup

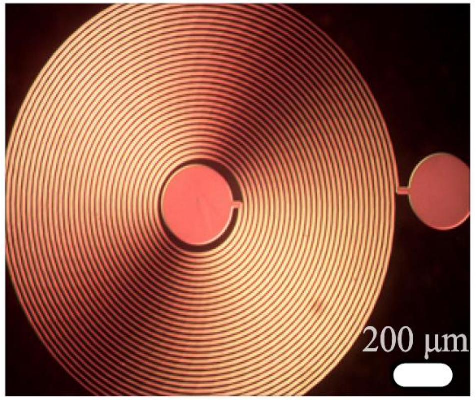


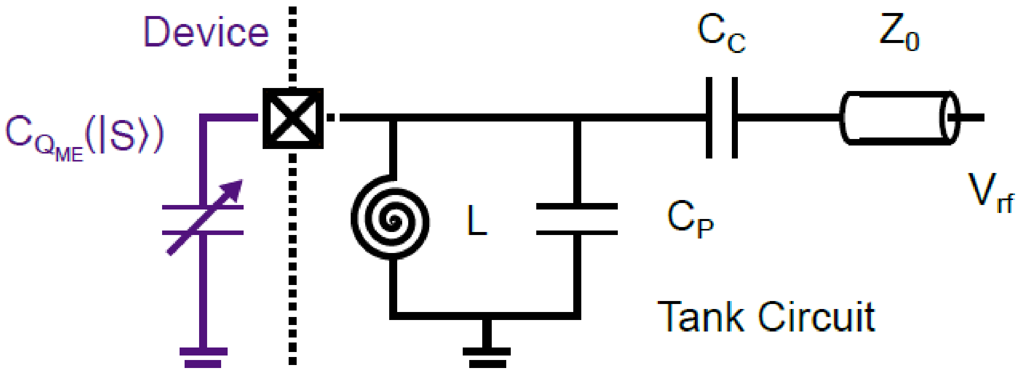
IMEC-device (planar, high-R Si):

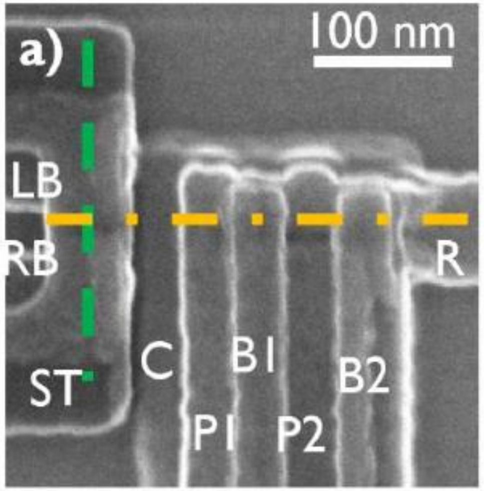
- 30 nm thick poly-Si gates (EBL)
- 8 nm SiO_2 (thermal) + 5 nm (high-T) gate-oxide
- 2 gates but form a triple-dot (“corner-dots” similar in FinFETs?)

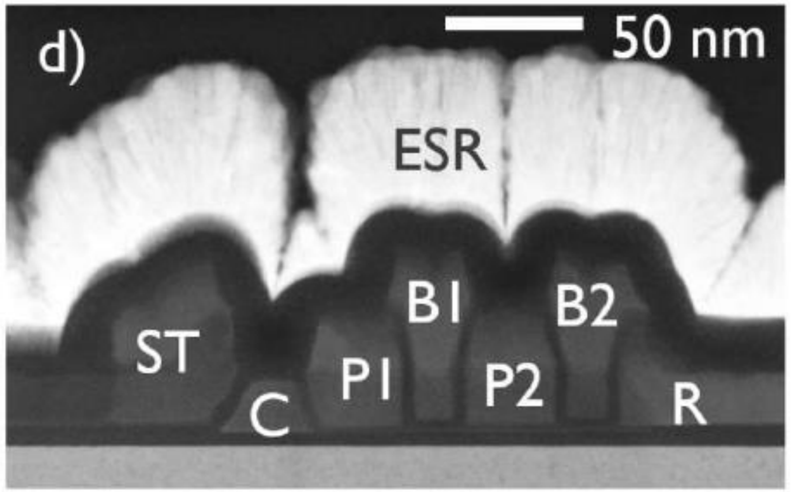
Reflectometry setup:

- Superconducting spiral inductor in parallel with **ohmic contact**
- Sensitive to reservoir transitions of large dot Q_{ME}



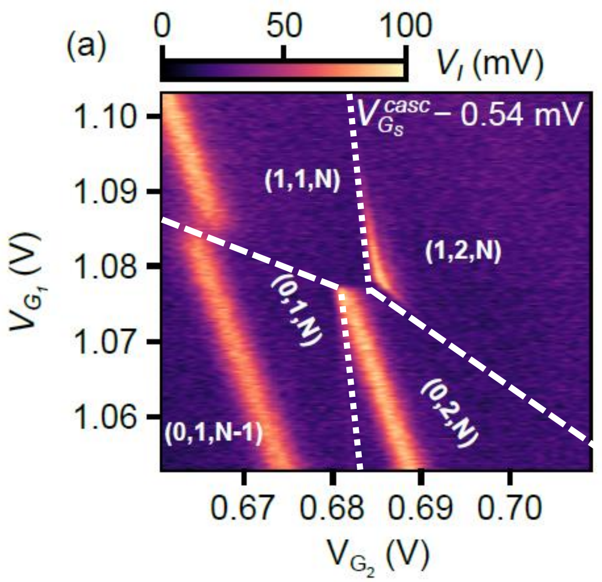


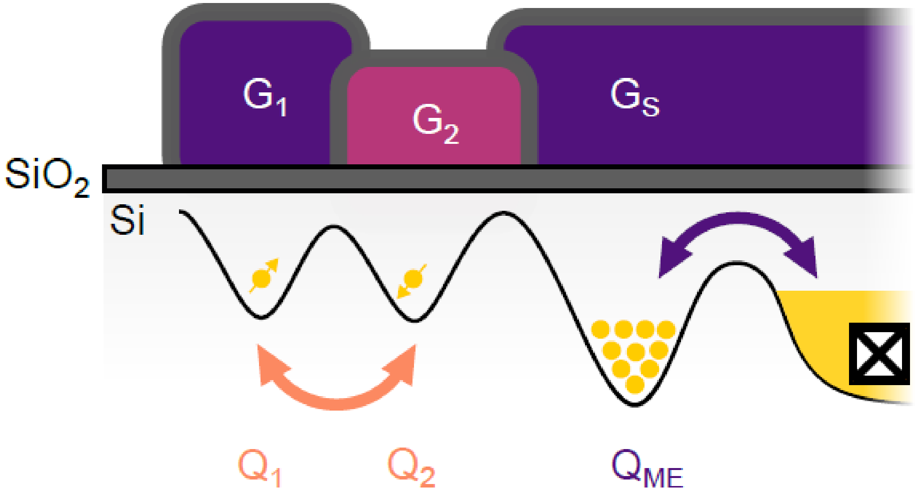




[1] Dumoulin Stuyck et al., *Symposium on VLSI Circuits,* 1-2, (2021)
[2] Ahmed et al., *Phys. Rev. Appl,* **10**, 014018, (2018)

Making Sense of the Stability Map (an Attempt)

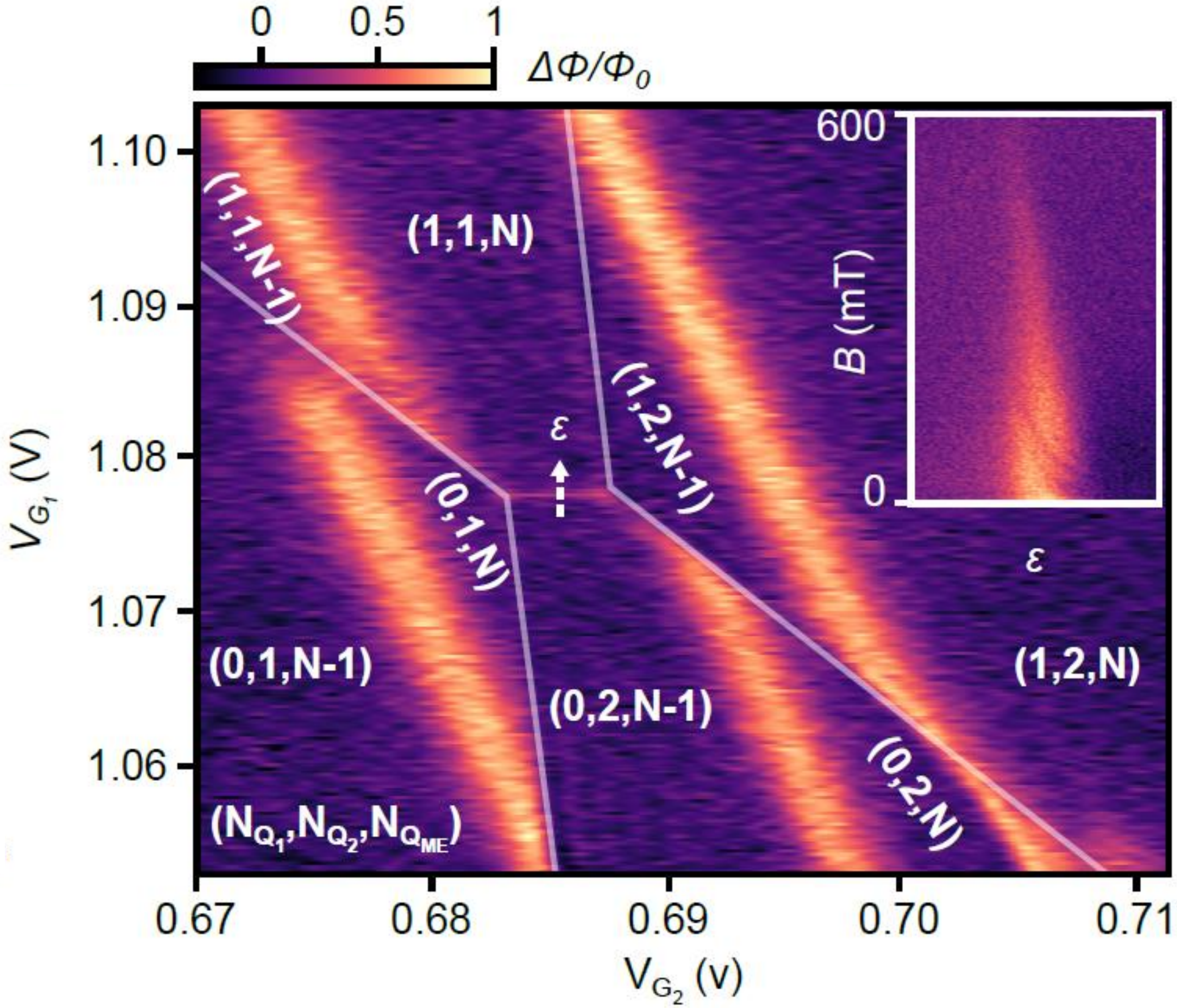


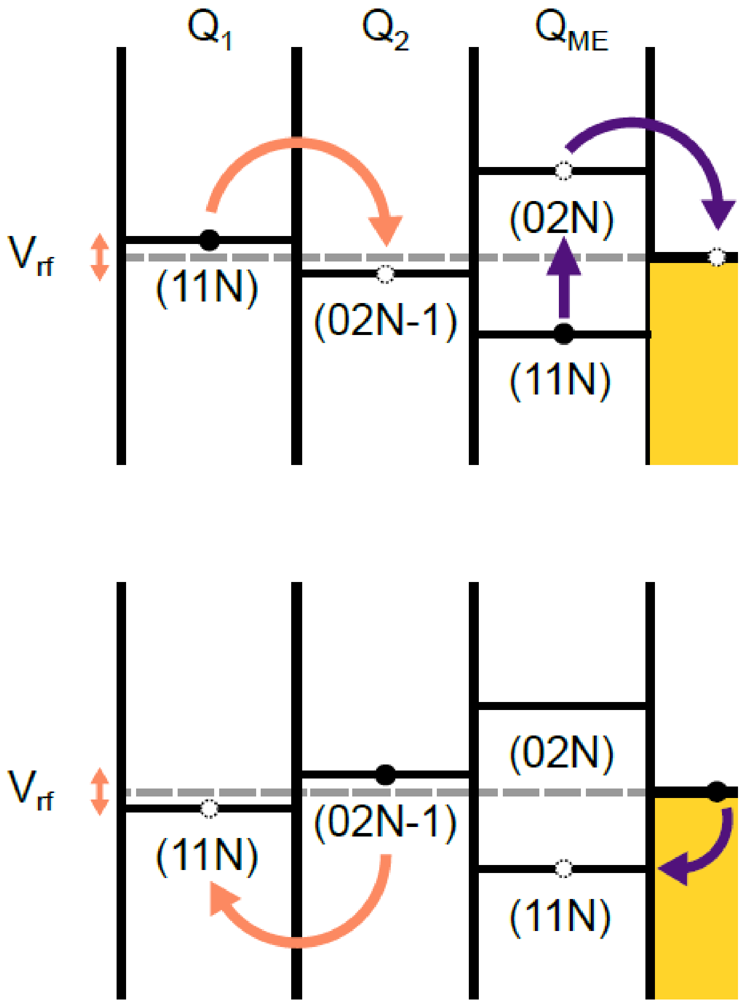


Observe jumps in sensor transition:

- "2" slopes -> Q_1 & Q_2
- Charge configuration of Q_1 & Q_2 known (not shown explicitly)
- Vary G_s voltage
- **Faint feature at interdot transition (1,1,N) ↔ (0,2,N-1)**
- **"Electron Cascade" because it is a 2^{nd} order-process**

The Cascade





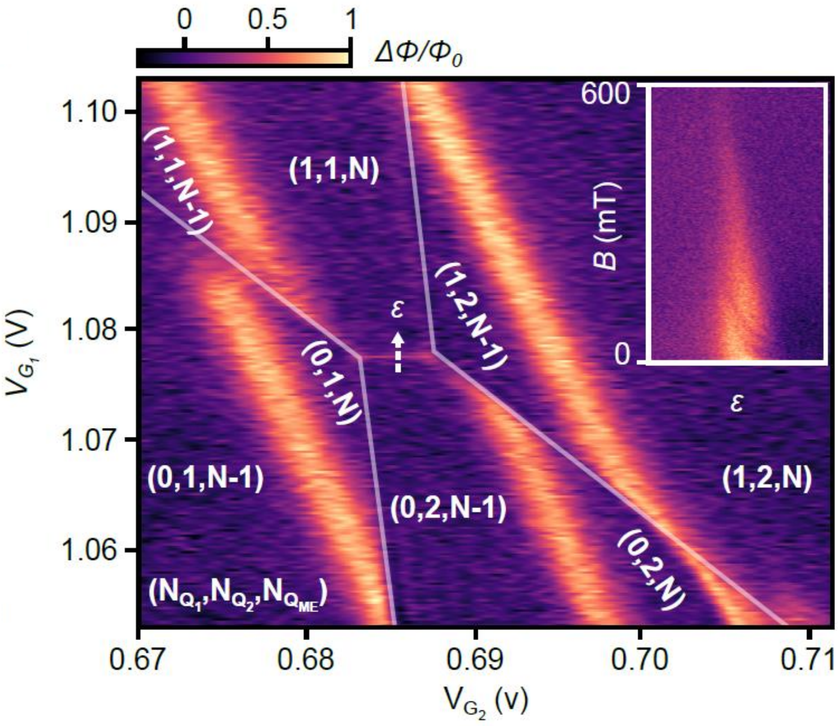
RF excitation of tank capacitively "drags" the level of Q_2 across the interdot transition in a cycle

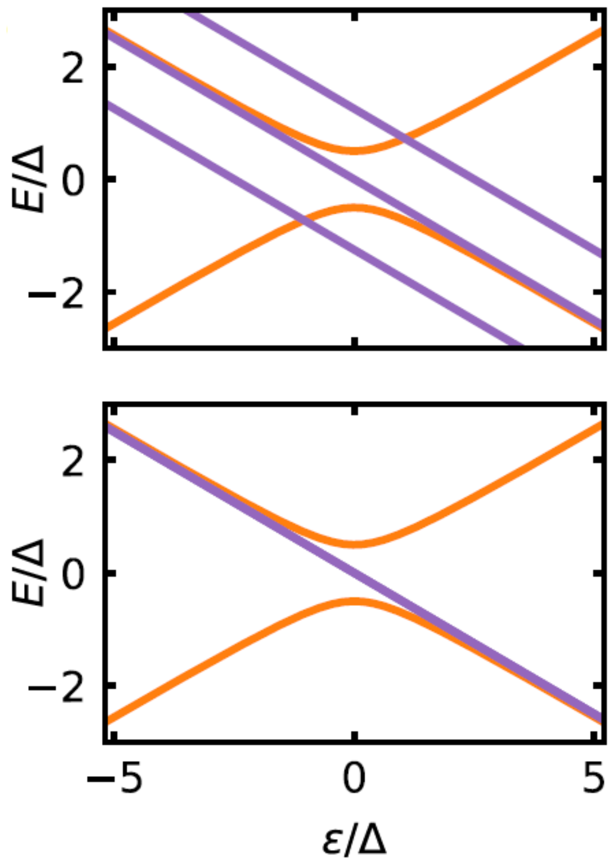
-> Larger dispersive shift than through in-situ dispersive charge readout!

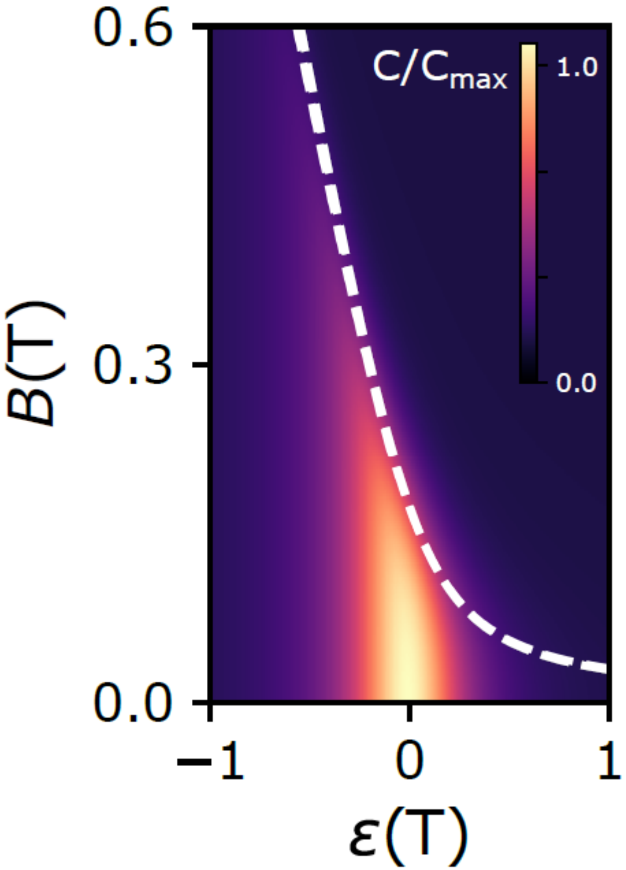
-> SNR amplification: $A = 1 + \frac{1-\alpha_{\mathrm{r,ME}}}{\alpha_{\mathrm{r,2}}-\alpha_{\mathrm{r,1}}} > 1$

Non-demolition RO!

Detecting PSB (the Quantum Motion-way…)

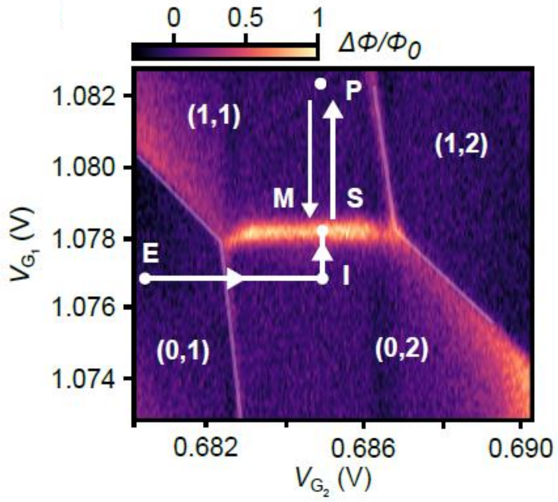


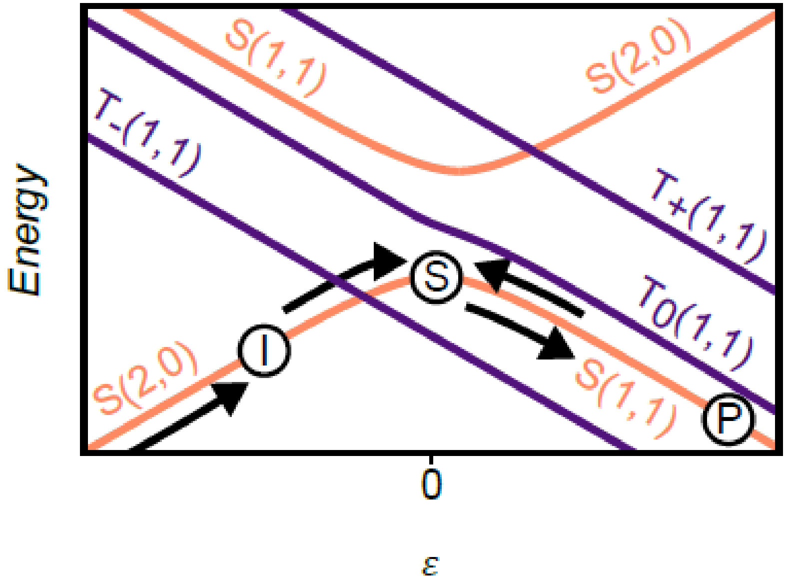


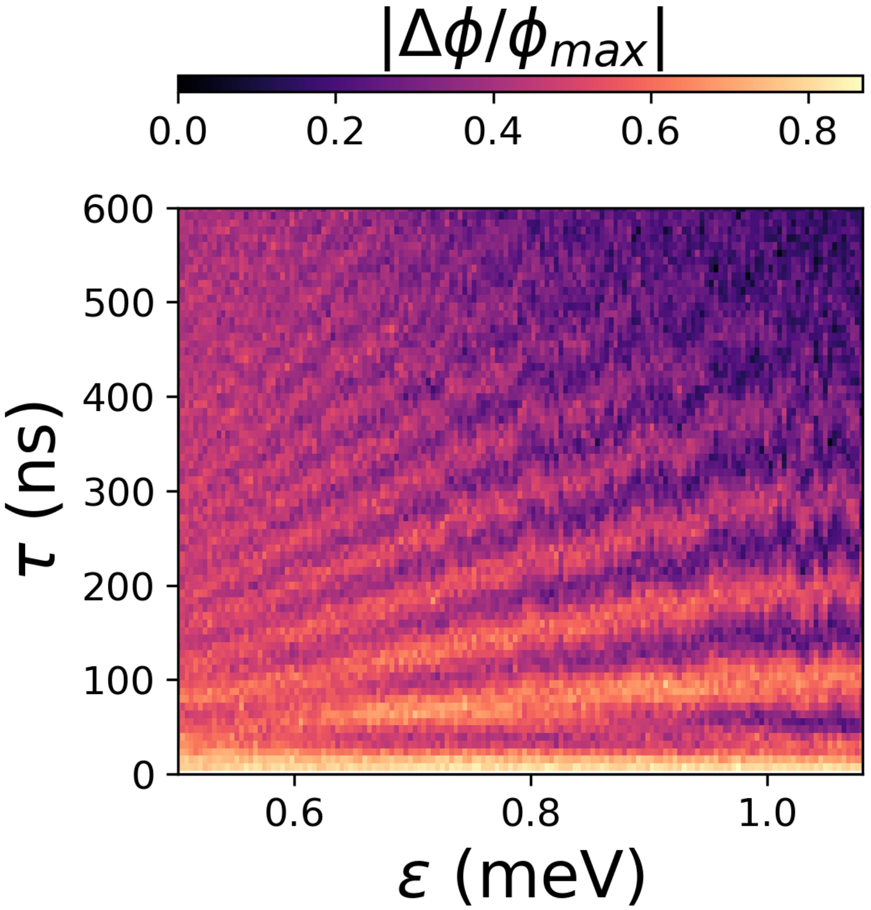


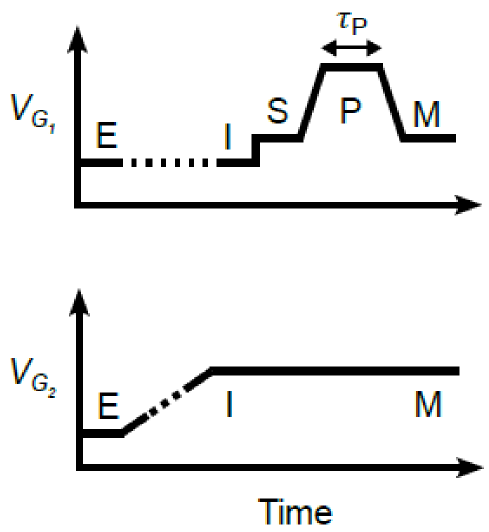
Model yields $t_c = 2.4\ GHz\ \ T_e = 50\ mK$

Singlet-Triplet Oscillations









Pulse scheme:

- Load singlet in (0,2)
- Separate electrons to (1,1)
- Time-evolution at finite detuning
- Adiabatic ramp to readout point

Splitting of S and T_0: $h\Omega = \sqrt{J(\varepsilon)^2 + \Delta E_Z^2}$

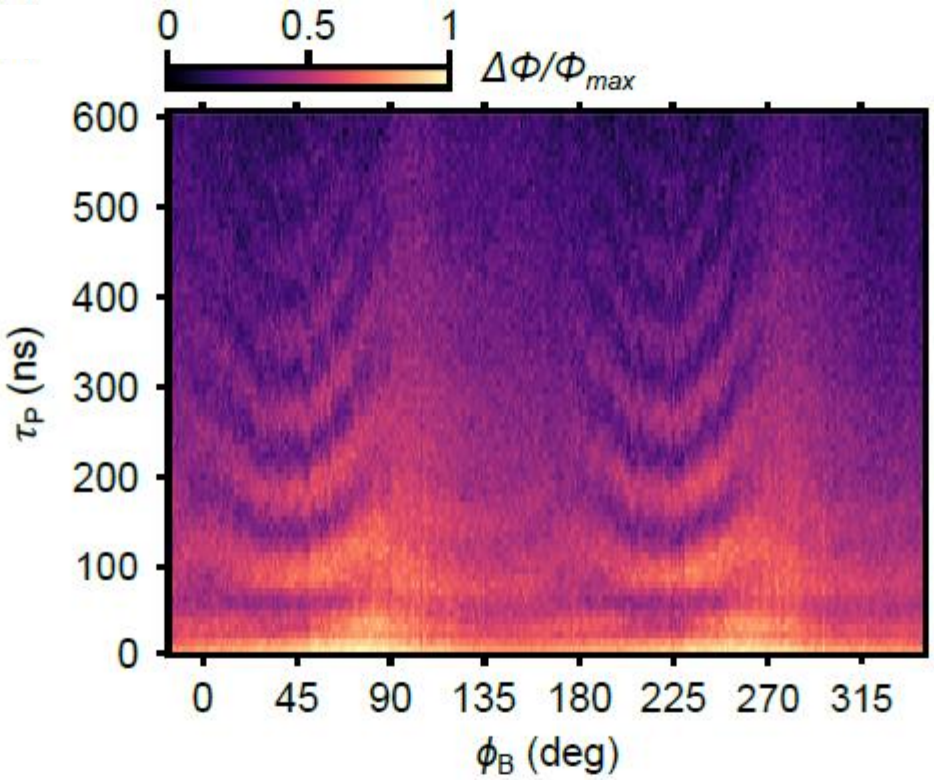
Spin detuning $\Delta E_Z = \Delta g \mu_B B + g \mu_B \Delta B_{HF}$

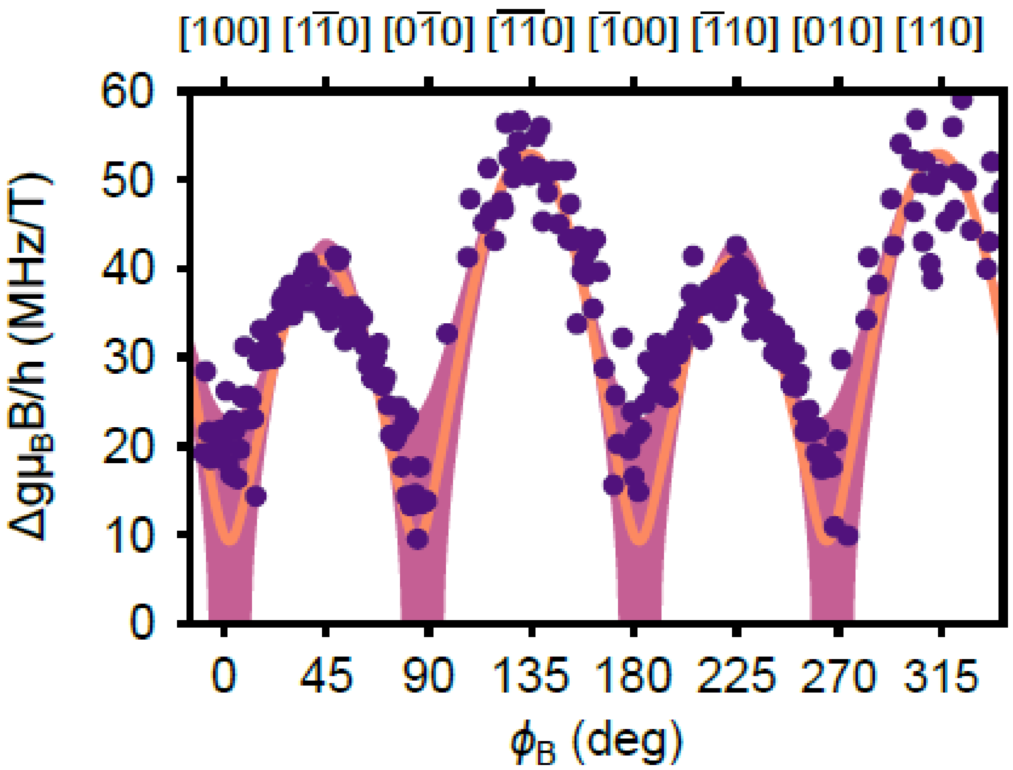
Applied field: 250 mT
vs. Holes in planar Si:[1] 5 mT
vs. Holes in planar Ge/SiGe:[2] 0.5 mT

Hyperfine energy: 3.4 neV

[1] Liles et al., *Nat. Comms*, **15**, 7690 (2024)
[2] Jirovec et al., *Nat. Mater*, **20**, 1106-1112, (2021)

Spin-Orbit Interaction





$\Delta E_Z = \Delta g \mu_B B + g \mu_B \Delta B_{HF}$

Variations of Δg with in-plane field angle:

- Change in S-T oscillation frequency
- Model based on Rashba and Dresselhaus SOI:

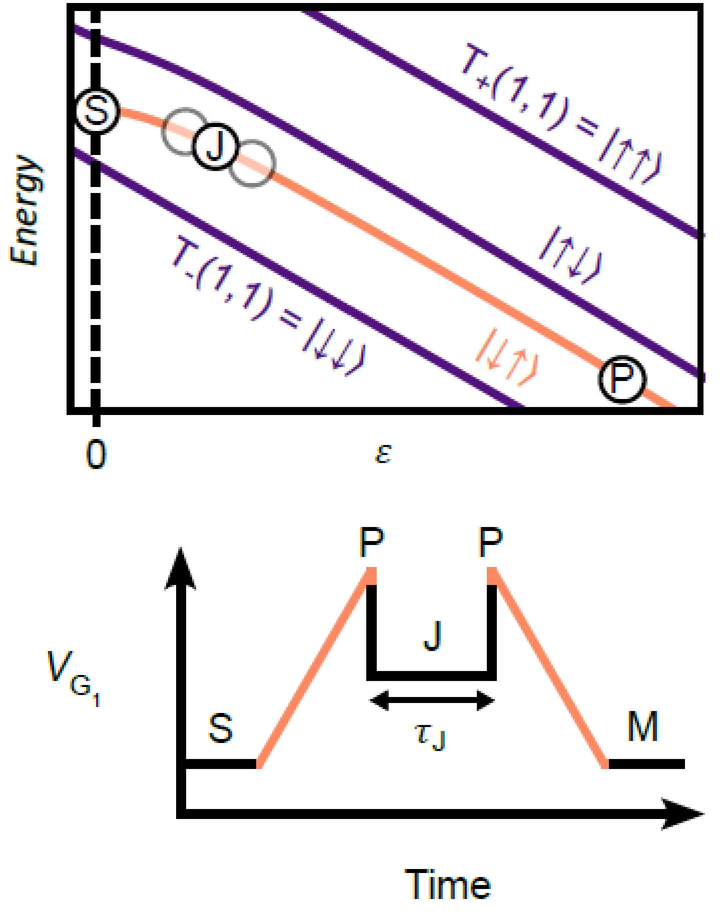
$$\Delta E_z/h = \sqrt{(|B|\,|\Delta\alpha - \Delta\beta\sin(2\phi_B)|)^2 + (g\mu_B\sigma_{\mathrm{HF}}/h)^2}$$

$$\Delta\alpha = 6.2^{+1.6}_{-1.5}\ \mathrm{MHz/T} \quad \Delta\beta = 45^{+5}_{-7}\ \mathrm{MHz/T}$$

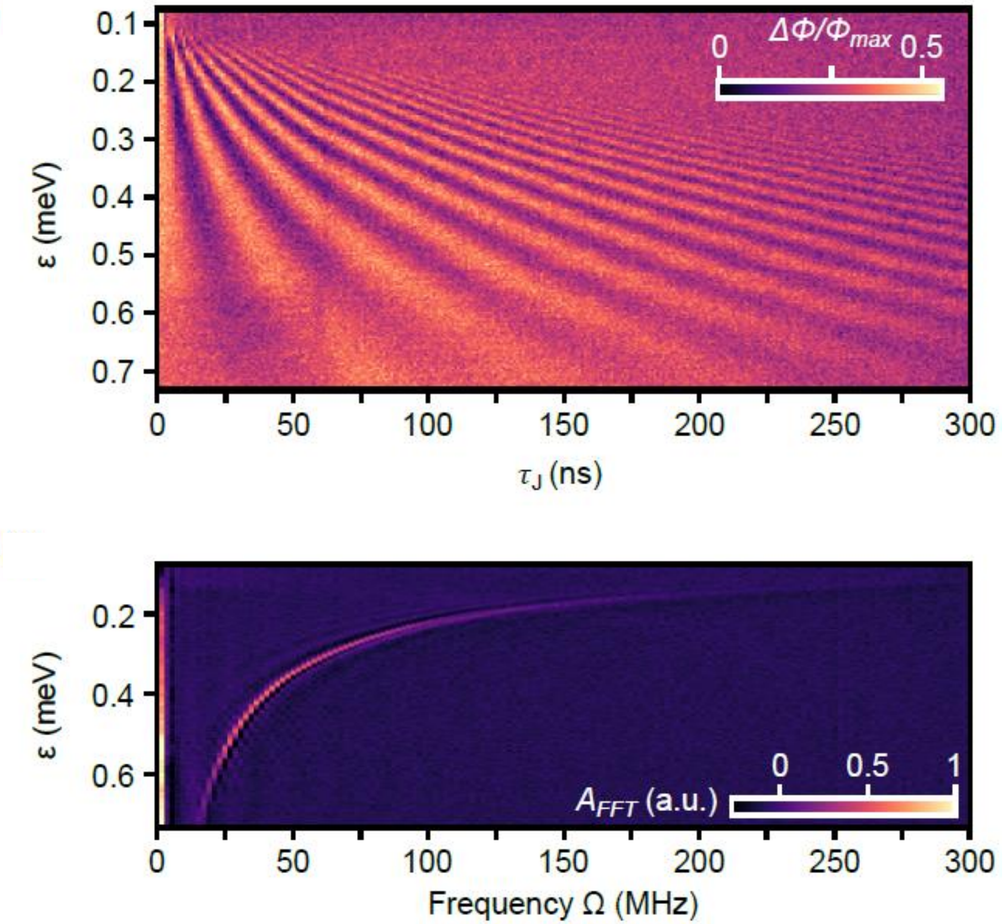
For comparison, easily achievable for holes in FinFETs and GeSi NWs:

$$\Delta g = 1 \leftrightarrow 14\ GHz/T$$

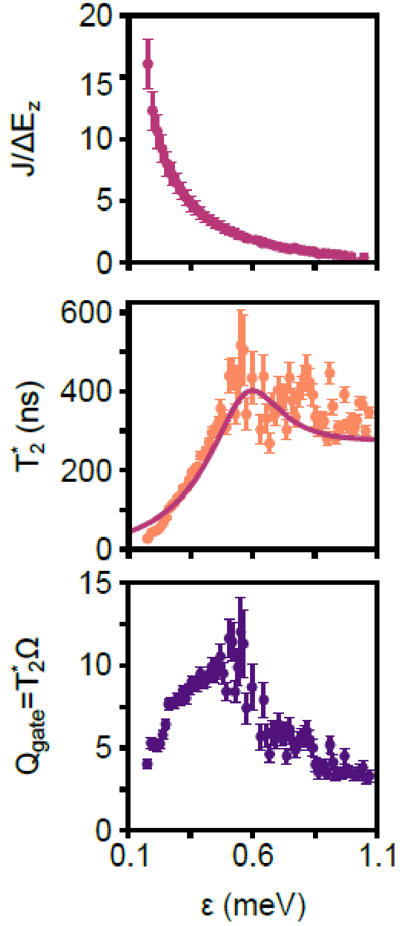
Exchange Control & Coherence



Exchange-oscillations of $|\uparrow\downarrow\rangle \leftrightarrow |\downarrow\uparrow\rangle$
Coherence called T_2^*
Spin-noise limited at larger detuning
Entangling gate! (Fidelity ≤ 98%)



$$\frac{1}{T_{2*}} = \frac{1}{\sqrt{2}\hbar}\sqrt{\left(\frac{J}{h\Omega}\frac{dJ}{d\varepsilon}\delta\varepsilon_{\mathrm{rms}}\right)^2 + \left(\frac{\Delta E_z}{h\Omega}\delta\Delta E_{z,\mathrm{rms}}\right)^2}$$



$$\delta\varepsilon_{rms} = 5.4 \pm 0.1\ \mu\text{eV}$$

$$\delta E_{Z,rms} = 3.4\ neV$$

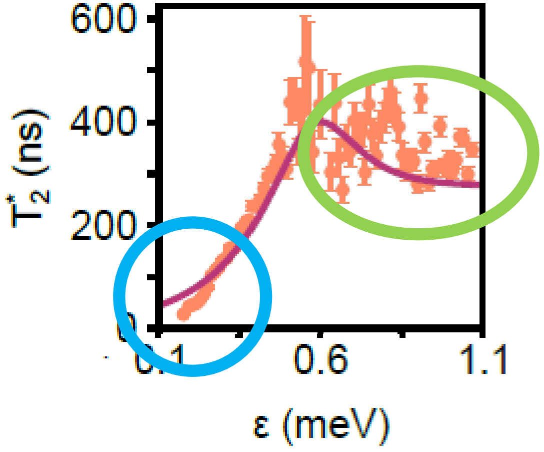
Really that low Charge/Detuning Noise ???

This work:
Planar Si electron in IMEC-device

$\delta E_{Z,rms} = 3.4\ neV$

$\delta \varepsilon_{rms} = 5.4 \pm 0.1\ \mu\text{eV}$

Fit gone wrong?

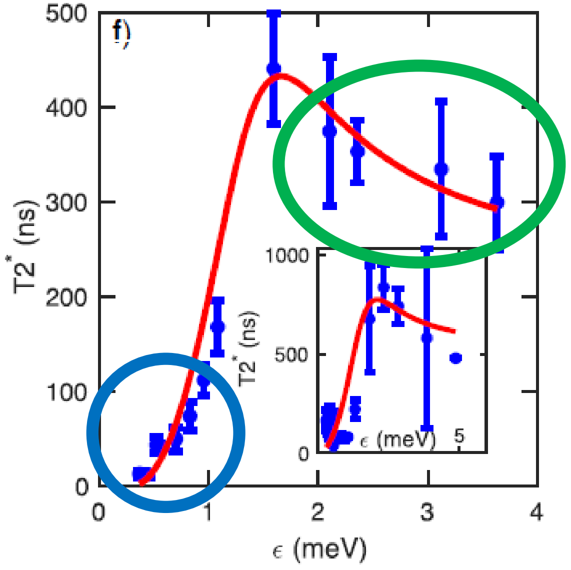


Measurement time = 79 h: definitely not single-shot

Liles et al., *Nat. Comms*, **15**, 7690 (2024):
Planar Si hole in Diraq-device

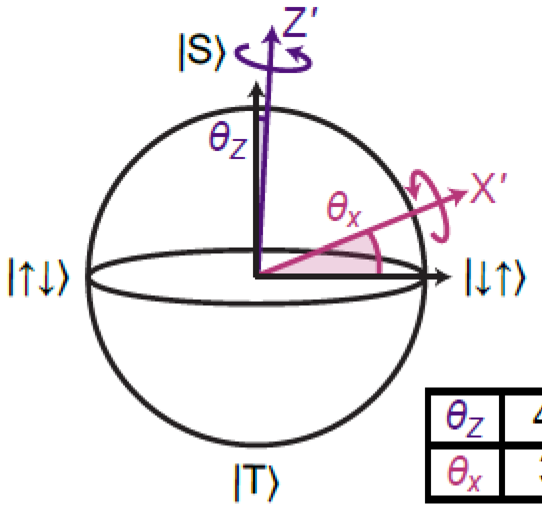
$\Delta E_Z = 4\text{neV}$

$\delta \epsilon = 30 \mu\text{eV}$

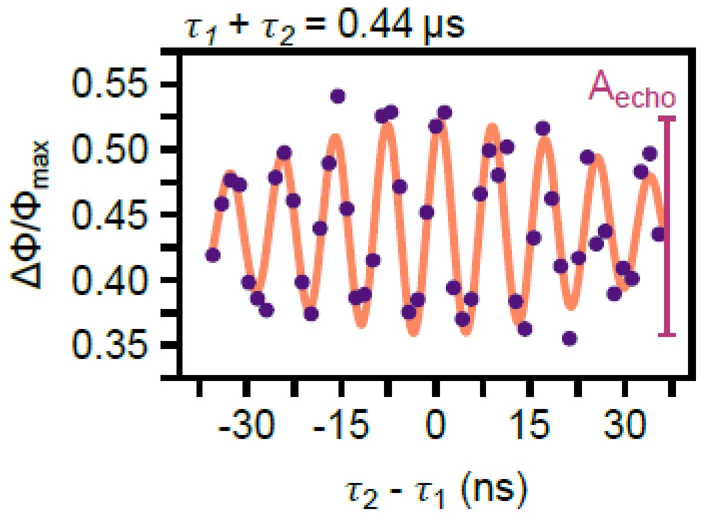


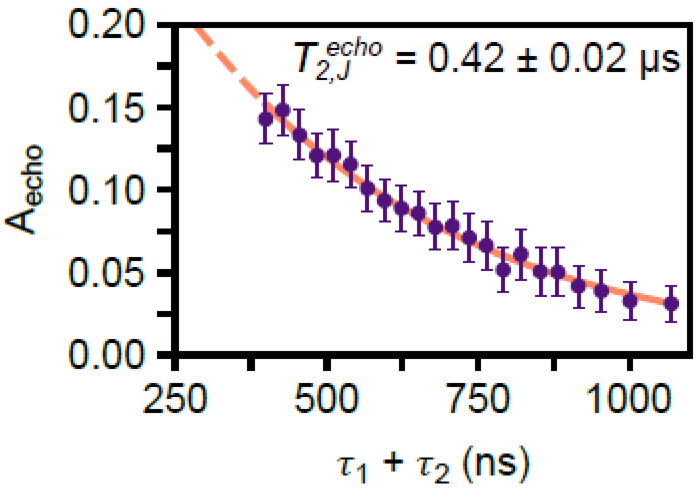
$$\frac{1}{T_2*} = \frac{1}{\sqrt{2}\hbar}\sqrt{\left(\frac{J}{h\Omega}\frac{dJ}{d\varepsilon}\delta\varepsilon_{\mathrm{rms}}\right)^2 + \left(\frac{\Delta E_z}{h\Omega}\delta\Delta E_{z,\mathrm{rms}}\right)^2}$$

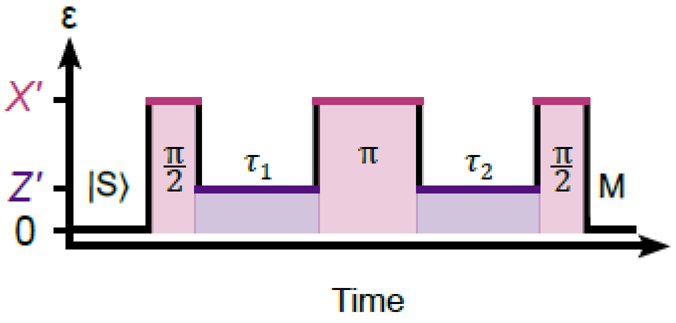
Echo Sequence

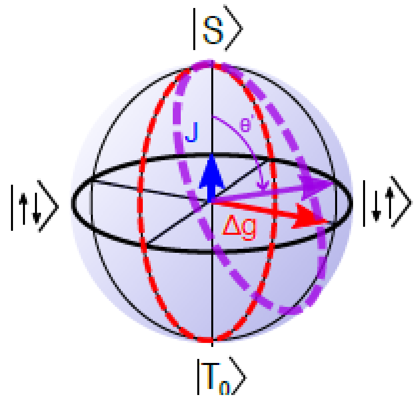


θ_Z	4.5(6)°
θ_x	34(4)°









Two-axis control imperfect due to limited control of $^{J}/_{\Delta E_Z}$

- Calibrating pulse lengths difficult
- Decay of echo amplitude yields: $T_2^{Echo} = 420\ ns$ (vs 1.2 us in [1])

[1] Liles et al., *Nat. Comms*, **15**, 7690 (2024)

Conclusions

RF-Electron Cascade Readout:

- Cool experiment, but only works for very specific tuning of dots
- Expands on single-lead dispersive charge sensor
- No single shot or readout fidelity reported

Singlet-Triplet qubit:

- Industrial device fabricated on 300 mm process
- Competitive coherence times and noise levels
- Not enough tunability (need more gates)
- Possibly longer range electron cascade experiments in the future…

Thanks for your attention ☺