Development of a Spin-based Logical Qubit in Silicon

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Abstract

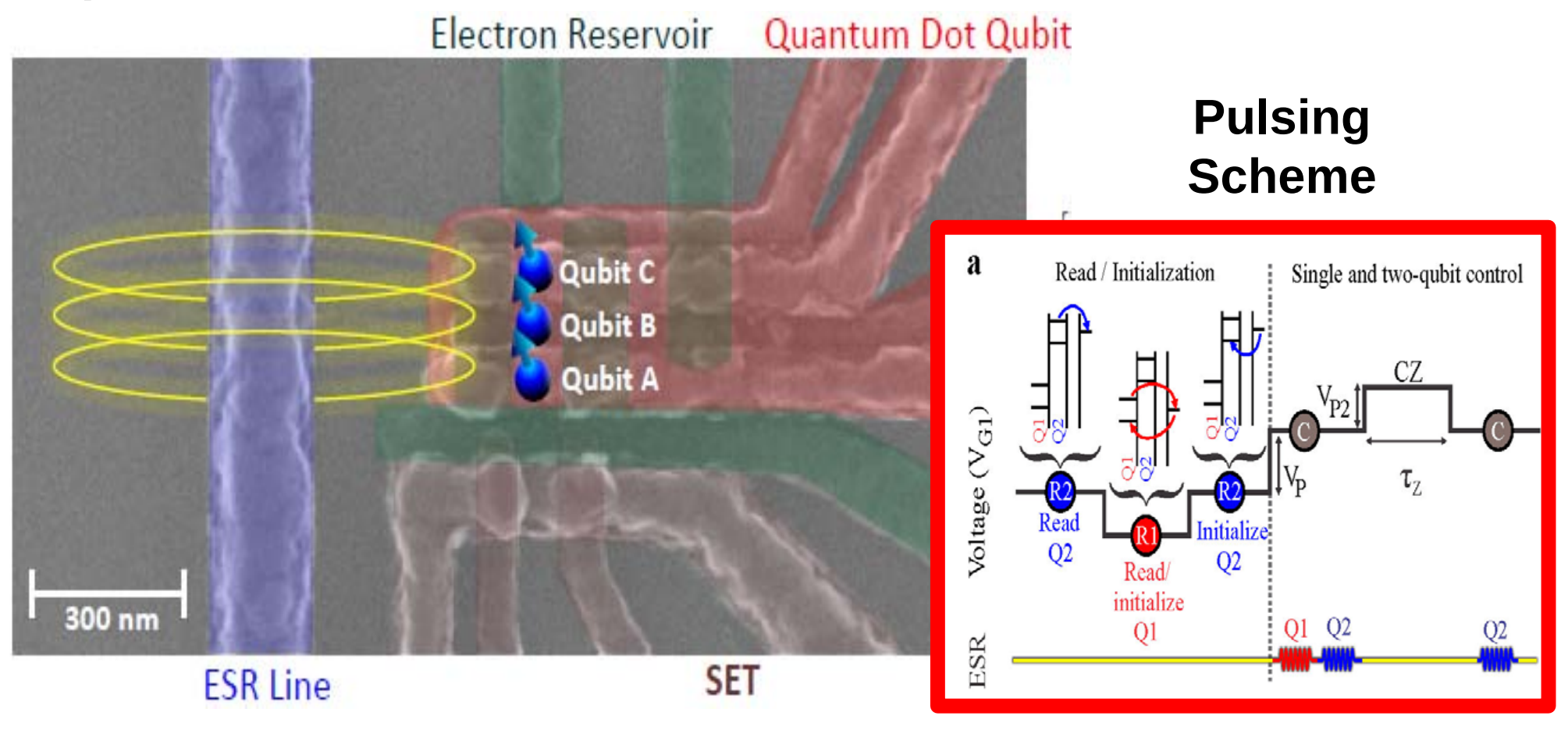
Spin qubits in silicon are excellent candidates for scalable quantum computing (QC) due to their long coherence times (~ seconds) and the enormous investment in silicon integrated circuit technology. This consortium of four universities in Australia and the United States brings together leading university-based research groups in silicon QC, with the aim of developing a spin-based logical qubit. This poster presents key qubit demonstrations and benchmarking experiments by the partners that highlight the strong potential of silicon for QC. The investigators have demonstrated 1-qubit gates using electron spins confined in electrostatically gated quantum dots and donor atoms, and most recently have demonstrated a 2-qubit logic gate using exchange coupled electron spins. They have also demonstrated the high potential of the phosphorus nuclear spin as either a long-lived qubit or as a quantum memory.

2-Qubit Gates in a Scalable Architecture

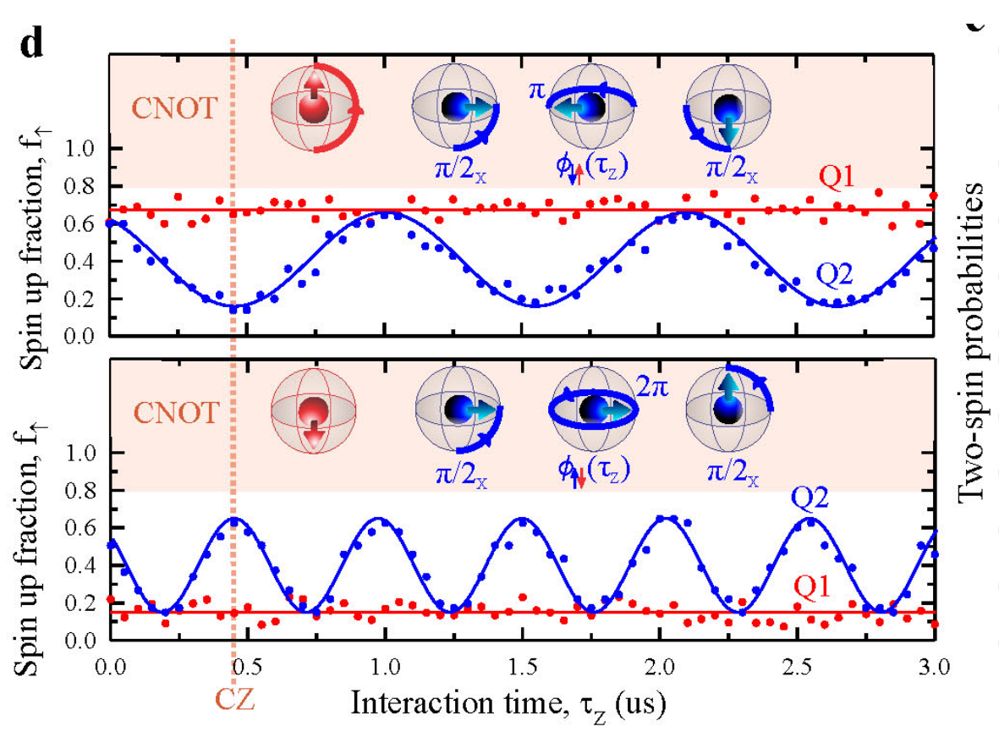
We have demonstrated a 2-qubit gate [1] using single electron spins in **isotopically enriched Si-28** by performing 1- and 2-qubit operations in a quantum dot system using the exchange interaction, as envisaged in the original Loss-DiVincenzo proposal. We realize **CNOT gates via controlled phase (CZ) operations** combined with single-qubit operations. Direct gate-voltage control provides **single-qubit addressability**, together with a switchable exchange interaction. The device layout is easily extendable to larger numbers of qubits.

[1] Veldhorst et al ., arXiv:1411.5760; submitted to *Nature.*

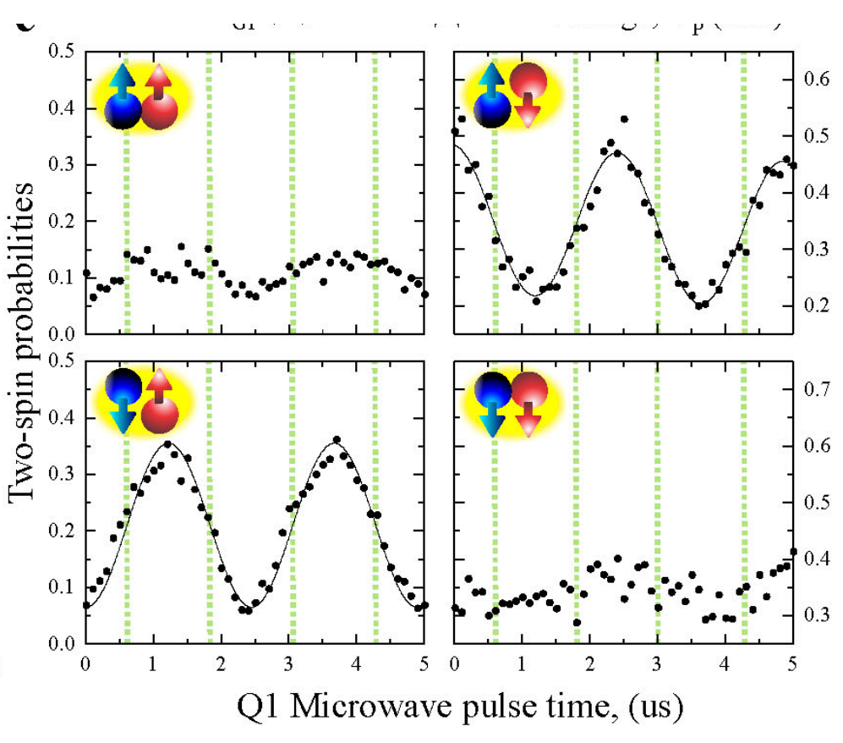
Triple Quantum Dot Device for 2-Qubit Gates



CNOT Gate via CZ



Two-Spin Anti-Correlations

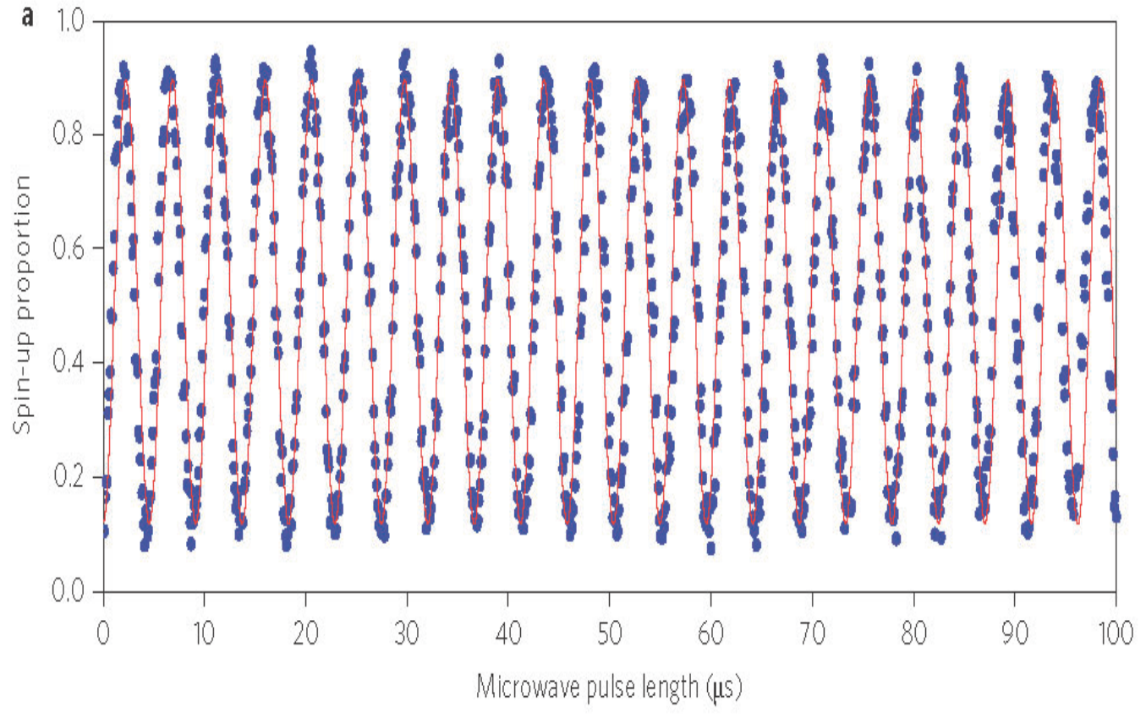


1-Qubit Gates with High Fidelities & Ultra-long Coherence Times

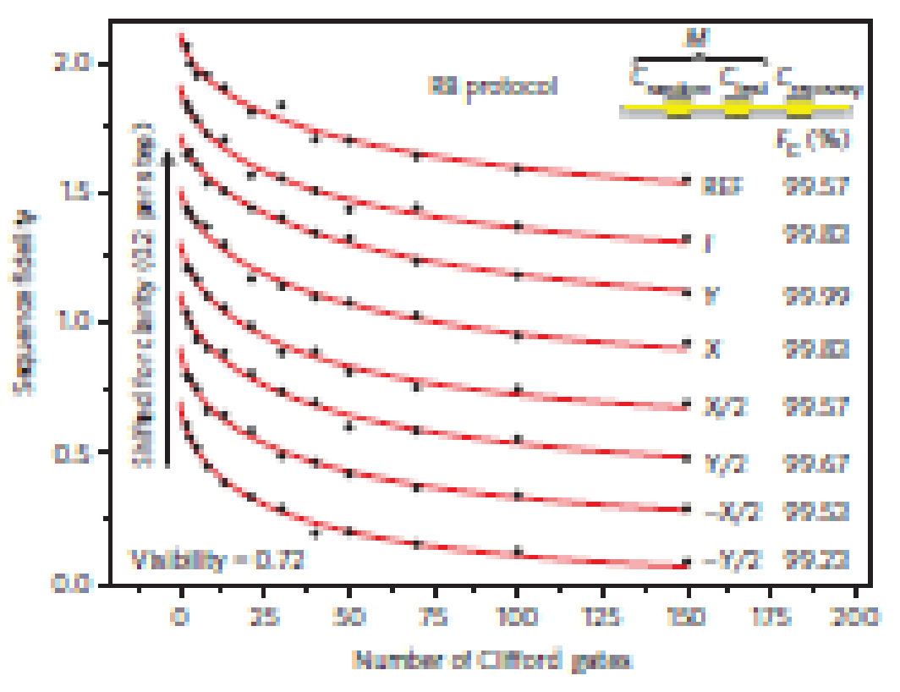
In isotopically-enriched Si-28 both quantum dot and single atom qubits show 1-qubit gate control fidelities $F_C > 99\%$, consistent with fault-tolerant QEC codes. The electron spin qubits have $\boldsymbol{F_C^e > 99.6\%}$ [1-3] and the ^{31}P nuclear spin qubit has $\boldsymbol{F_C^n > 99.99\%}$ [2-3]. Using dynamical decoupling the coherence times can reach $\boldsymbol{T_{2e}^{CPMG} = 0.5}$ **s** for the electron and $\boldsymbol{T_{2n}^{CPMG} = 30}$ **s** for the nuclear spin [2].

[2] Veldhorst et al ., *Nature Nanotechnology* 9, 981 (2014).
[3] Muhonen et al ., *Nature Nanotechnology* 9, 986 (2014).
[4] Muhonen et al ., *J. Phys. Condens. Matt.* (2015).

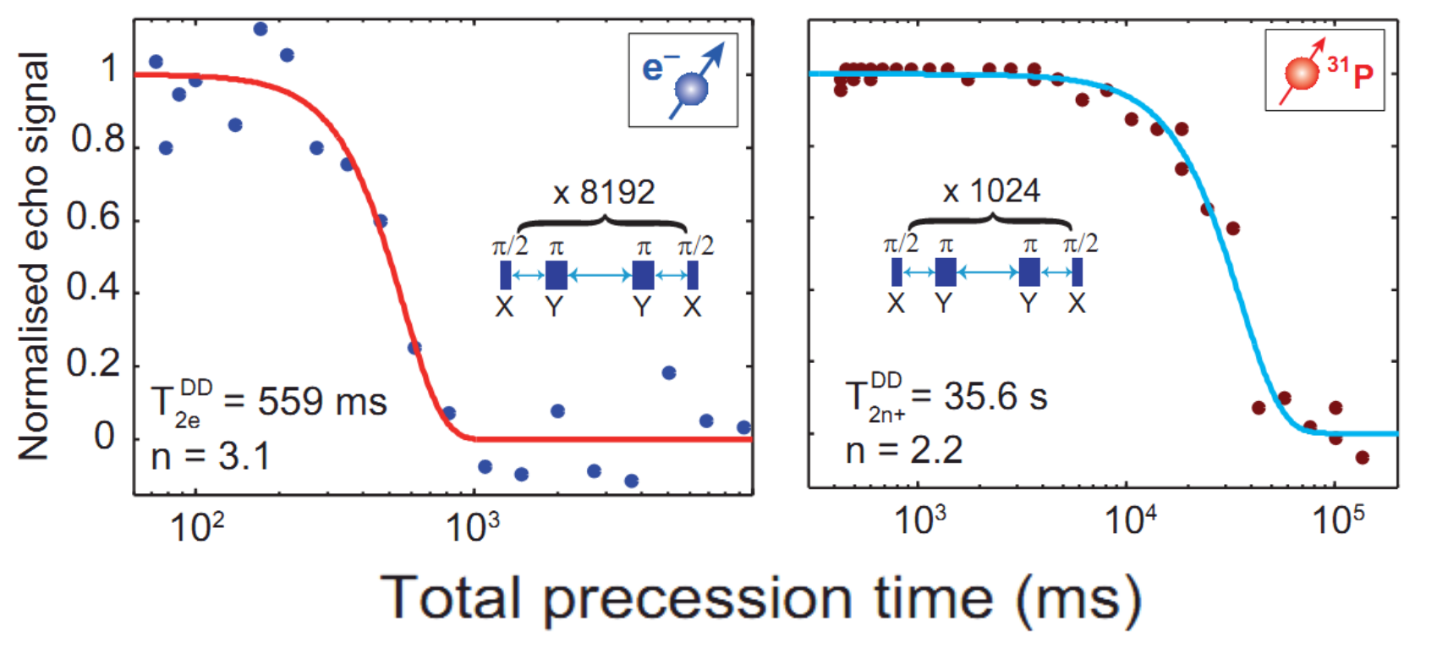
Electron Spin Qubit



Electron Spin Qubit



Electron Spin Qubit
Nuclear Spin Qubit

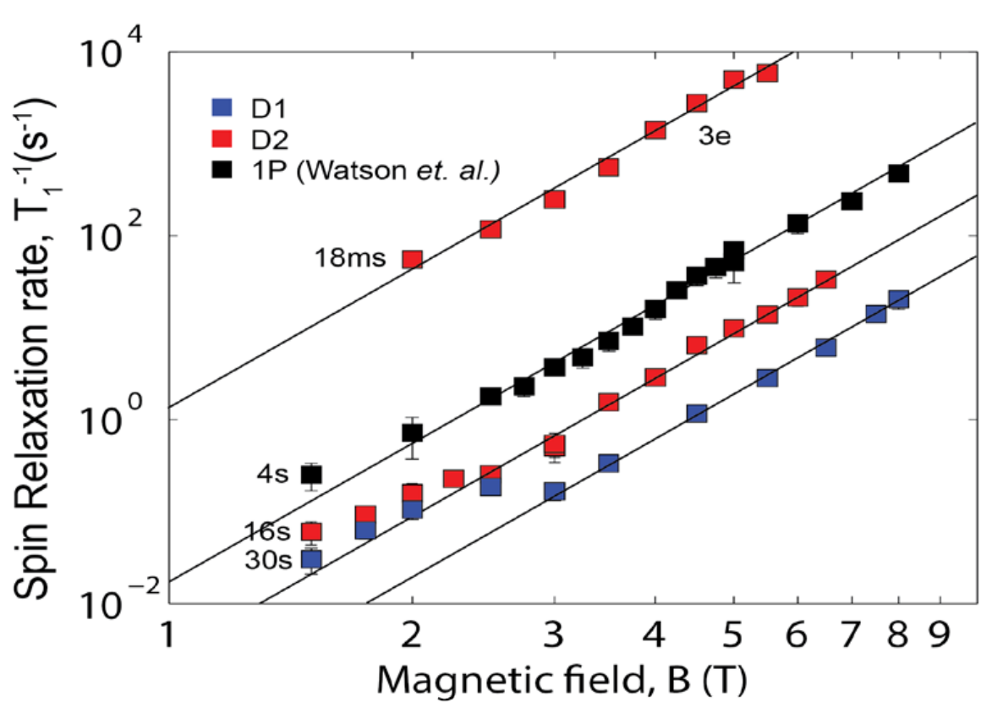


High-fidelity Qubit Readout & Long Spin Lifetimes

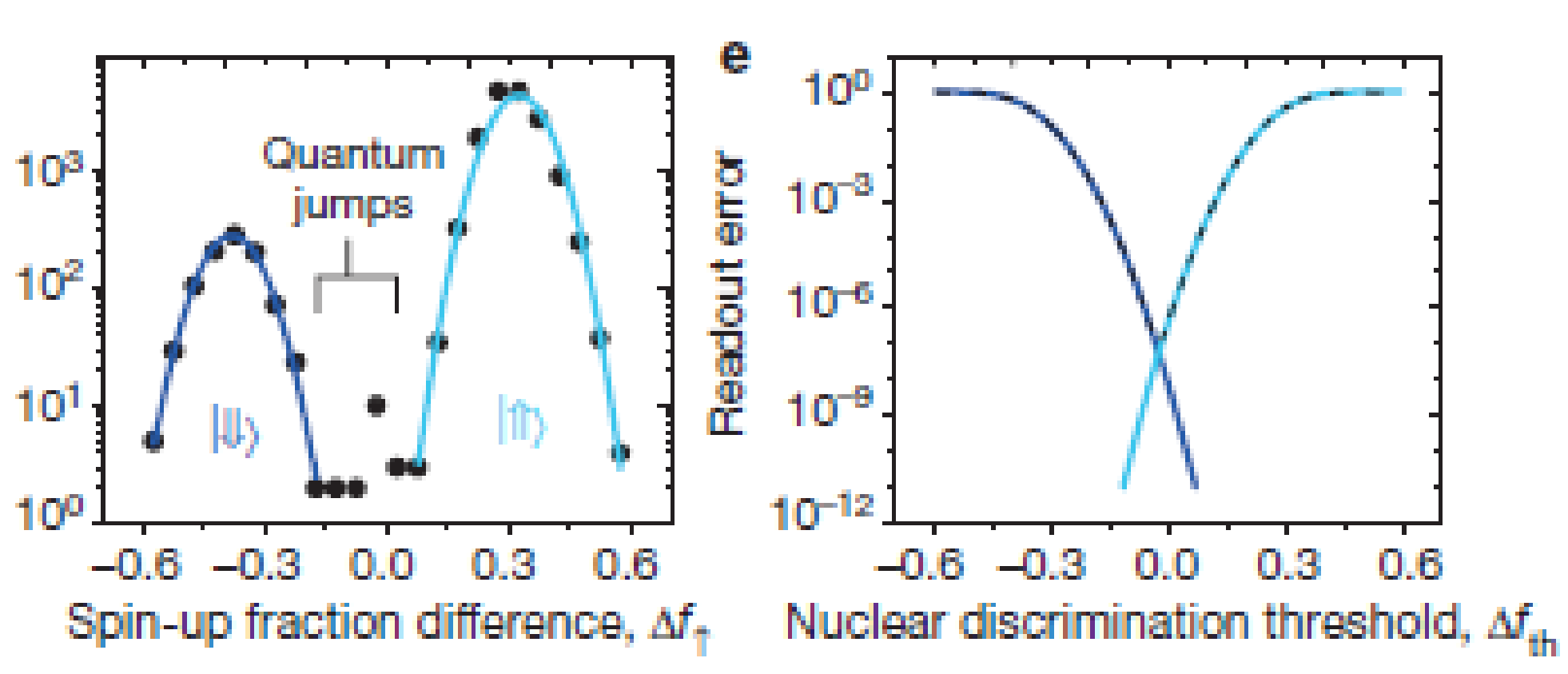
Electron spin readout in both quantum dots and single atom qubits employs spin-dependent tunneling and either SET [5] or QPC [6] charge sensing. We have measured electron spin readout fidelities of $\boldsymbol{F_M^e = 97\%}$ [3], and electron qubit lifetimes of $\boldsymbol{T_{1e} = 30}$ **seconds** [7]. Nuclear spin (^{31}P) qubits have fidelities $\boldsymbol{F_M^n > 99.99\%}$ [3,8]], due to their very long lifetimes $\boldsymbol{T_{1n}}$ **~ minutes** [3,8].

[5] Morello et al ., *Nature* 467, 687 (2010).
[6] Prance et al., *Phys. Rev. Lett.* 108, 046808 (2012).
[7] Büch et al., *Nature Comms.* 4, 2017 (2013). [8] Pla et al ., *Nature* 496, 334 (2013)

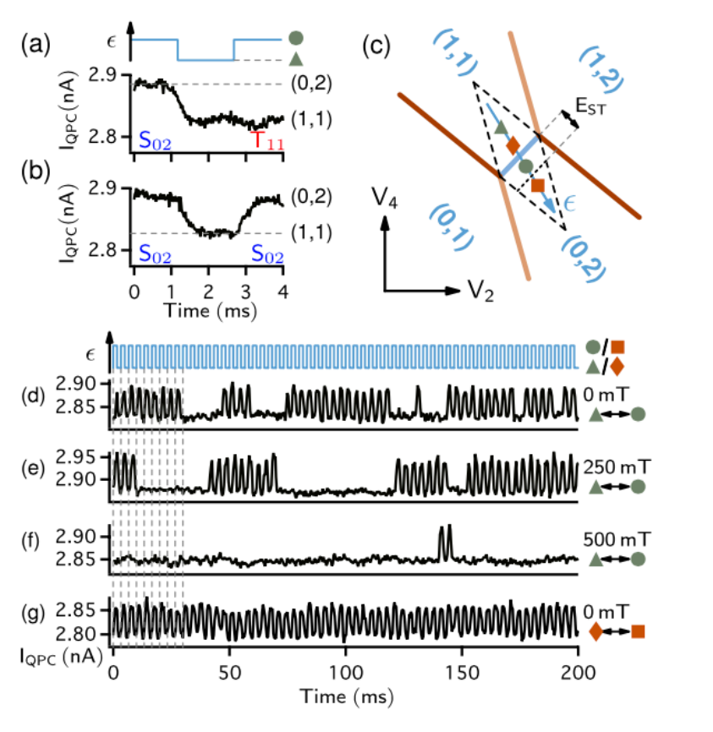
Electron Spin Lifetimes



Nuclear Spin Readout Fidelity Analysis



Electron Spin Readout

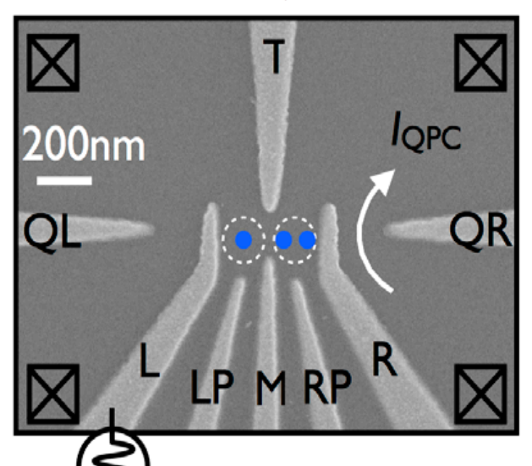


High-speed Logic Gates

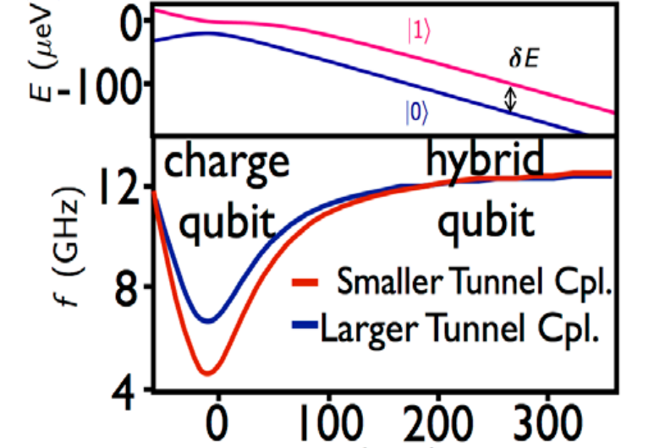
High-speed, high-fidelity qubits can be operated in Si quantum dots using either dc gate voltage pulses [9] or resonant ac gate voltage pulses [10]. Recently, we have demonstrated coupling between four quantum dots [11], and shown how tuning the internal degrees of freedom in double dot qubits can increase significantly the measured coherence time [12].

[9] Kim et al., *Nature* 511, 70 (2014).
[10] Kim et al., submitted, arXiv:1502.03156.
[11] Kim et al., unpublished.
[12] Thorgrimsson et al., unpublished.

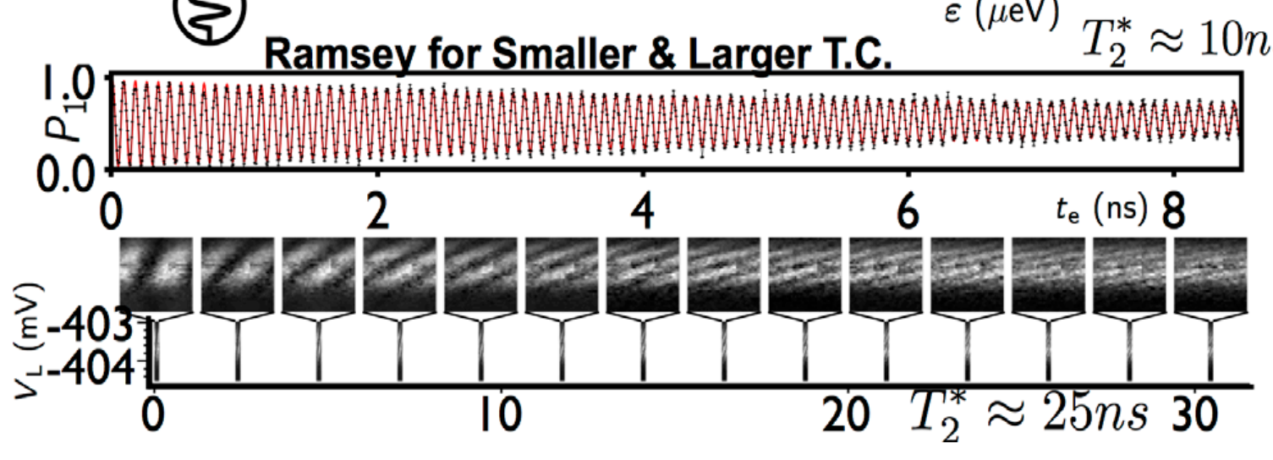
Si/SiGe DQD device



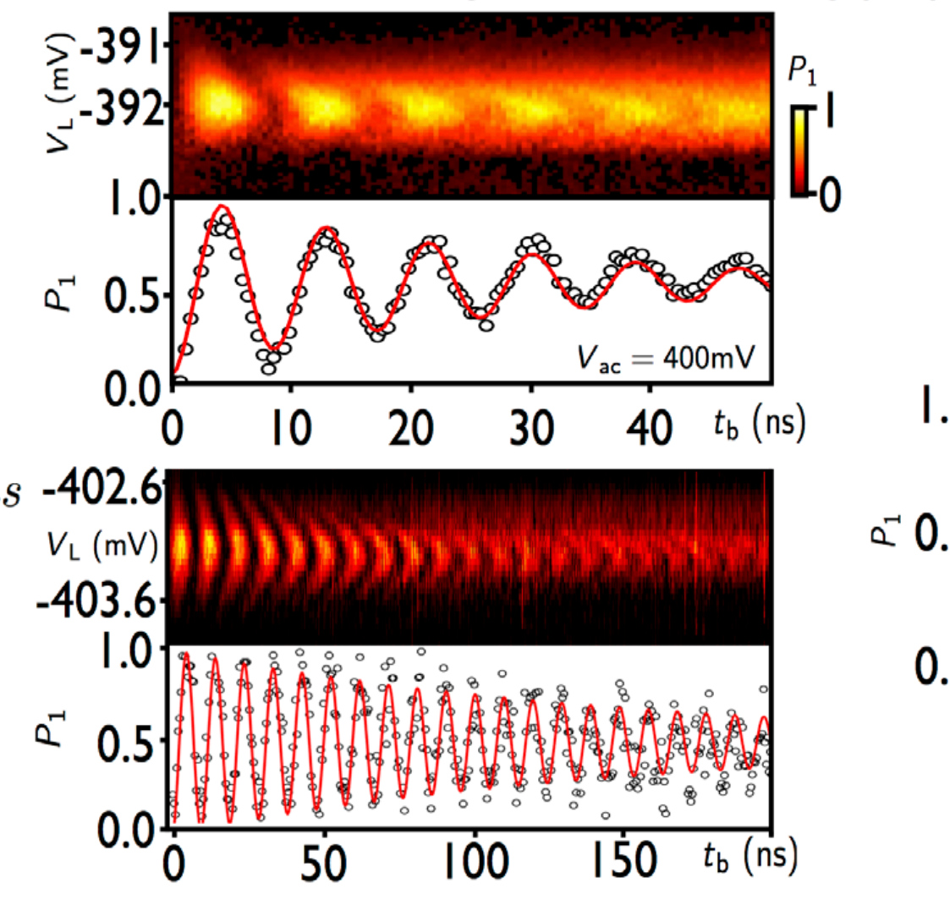
Spectroscopy



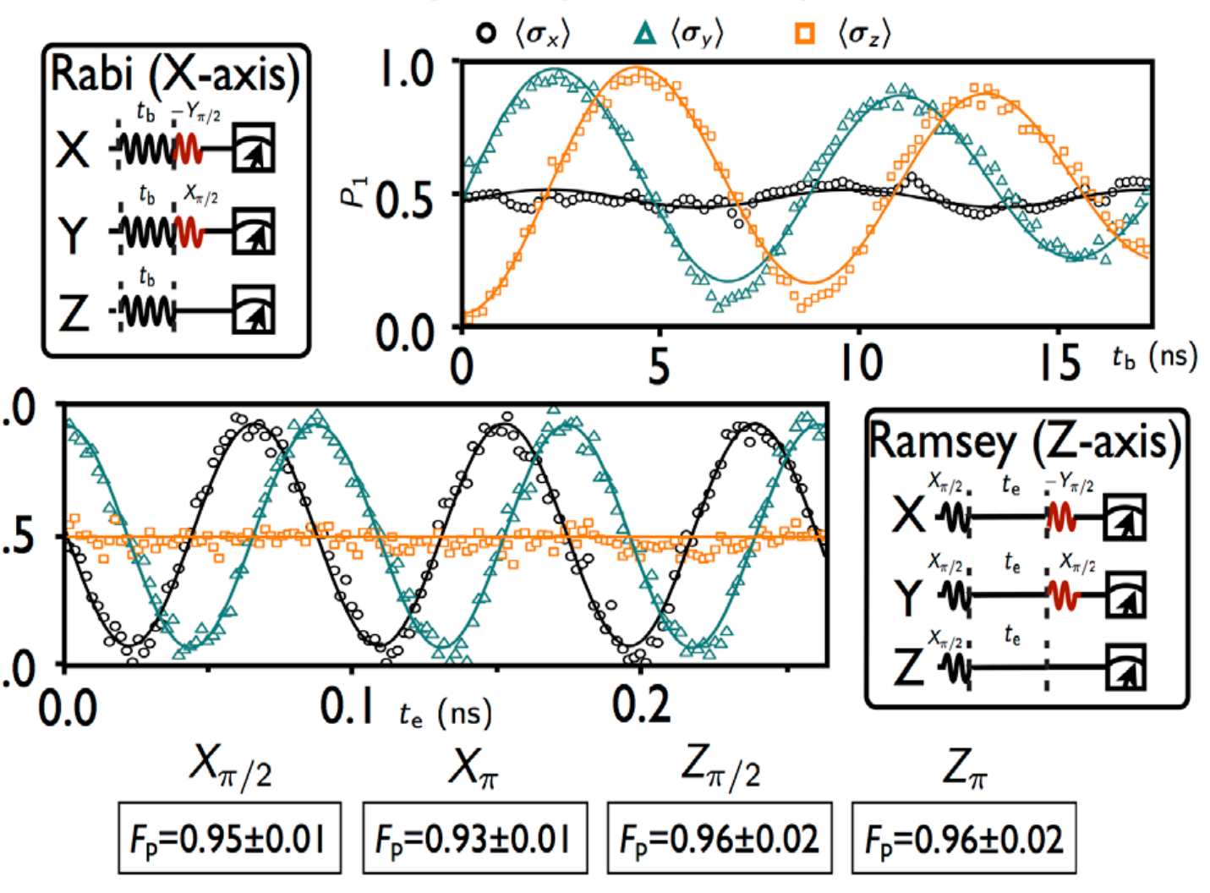
Ramsey for Smaller & Larger T.C.



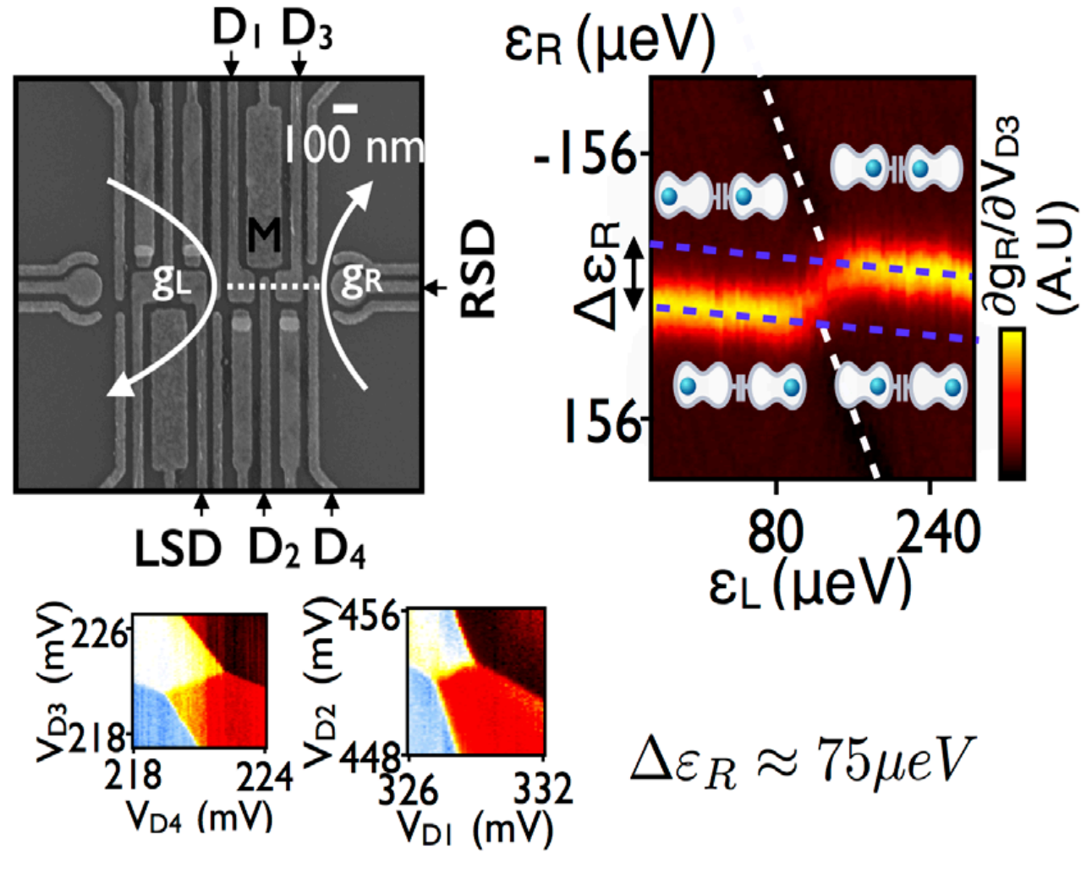
Rabi for Smaller and Larger Tunnel Coupling (T.C)



Process Tomography & Fidelity



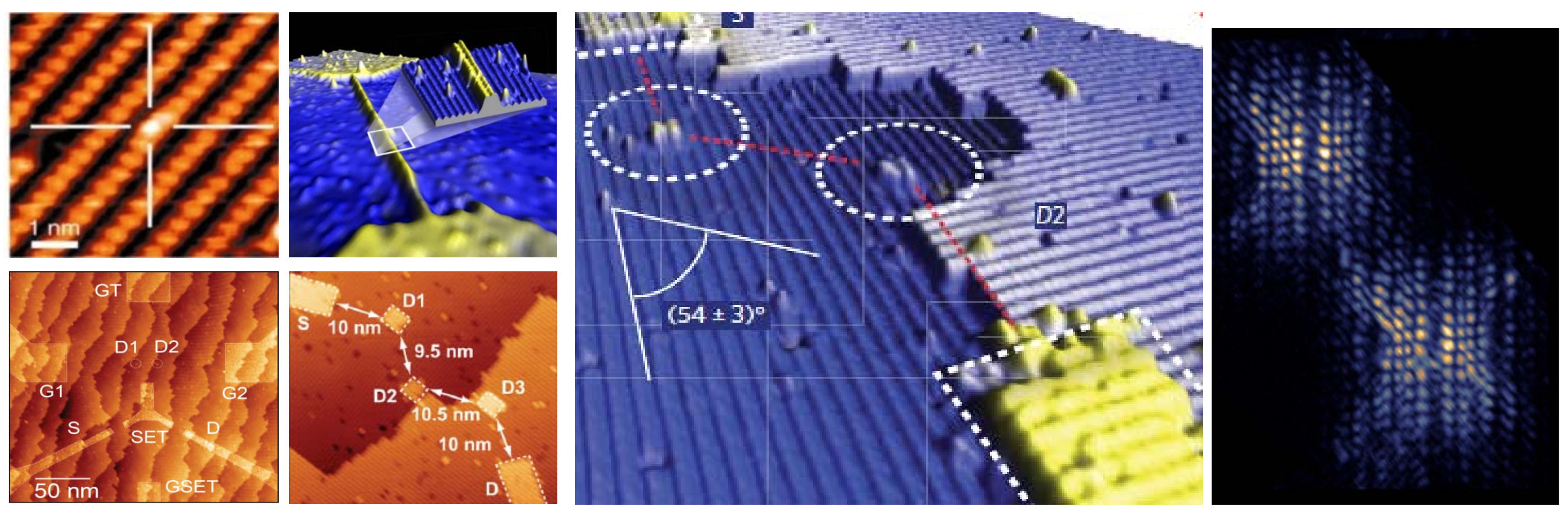
Capacitive Coupling of two DQDs

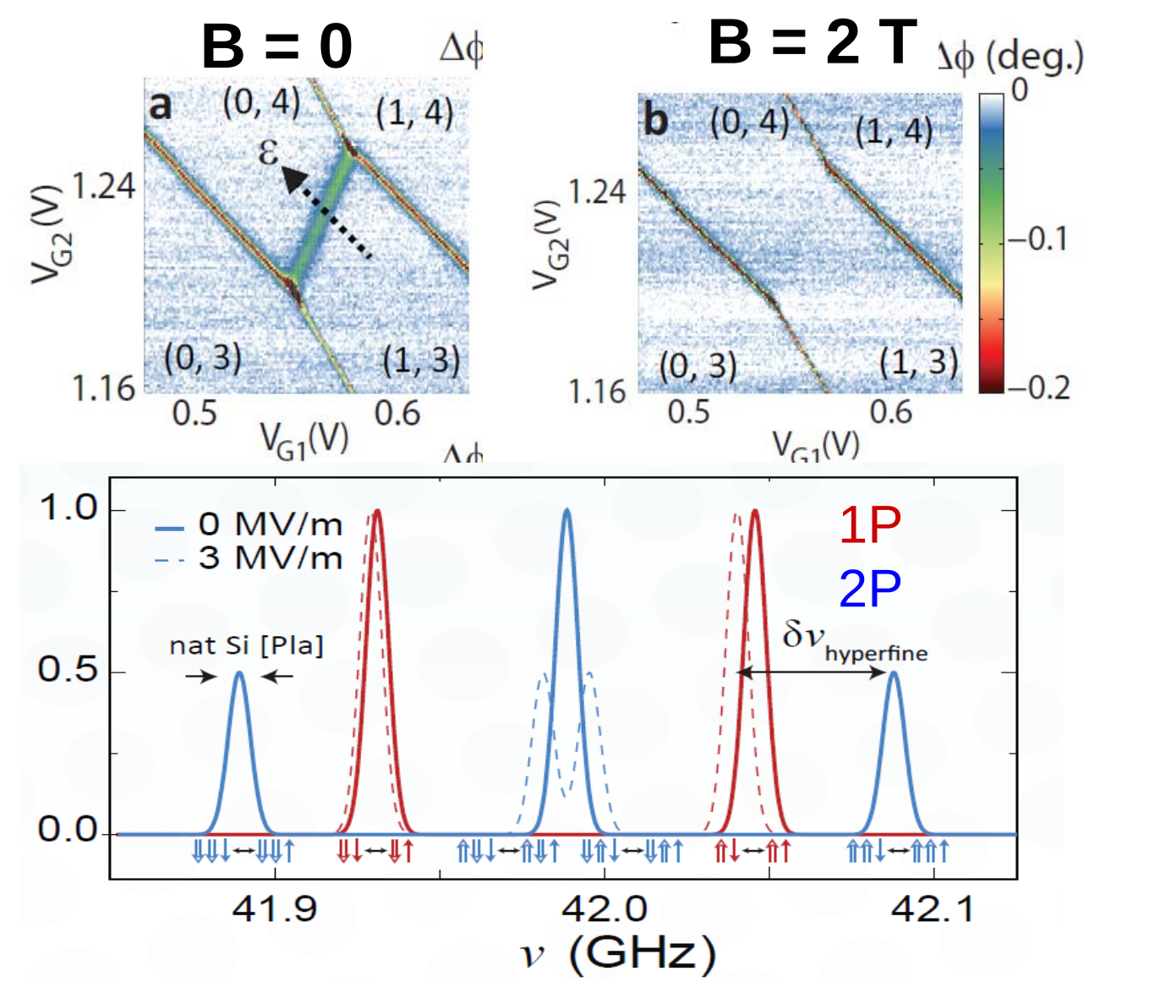


Donor Qubits in a Scalable Architecture

Atomic precision engineering of donor qubits with electron spin $\boldsymbol{F_M = 99.6\%}$, $\boldsymbol{T_{1e} = 30}$ **seconds** and error rates ~10^{-5}. Precision donor positioning [13-14] allows understanding the exact environment [15] of many qubit systems [16] and a route to scale to a surface code architecture [23]. Dispersive read-out allows optimisation of exchange coupling [16] and scalable architectures with low gate densities [17].

[13] Fuchsle et al ., *Nature Nanotechnology* 7, 242 (2012). *Ibid* 5, 502 (2010).
[14] Weber et al ., *Science* 335, 64 (2012).
[15] Salfi et al., *Nature Materials* 13, 605 (2014).
[16] Weber et al ., *Nature Nanotechnology* 9, 430 (2014); *Nano Letters* 14, 1830 (2014).
[17] House et al., unpublished.



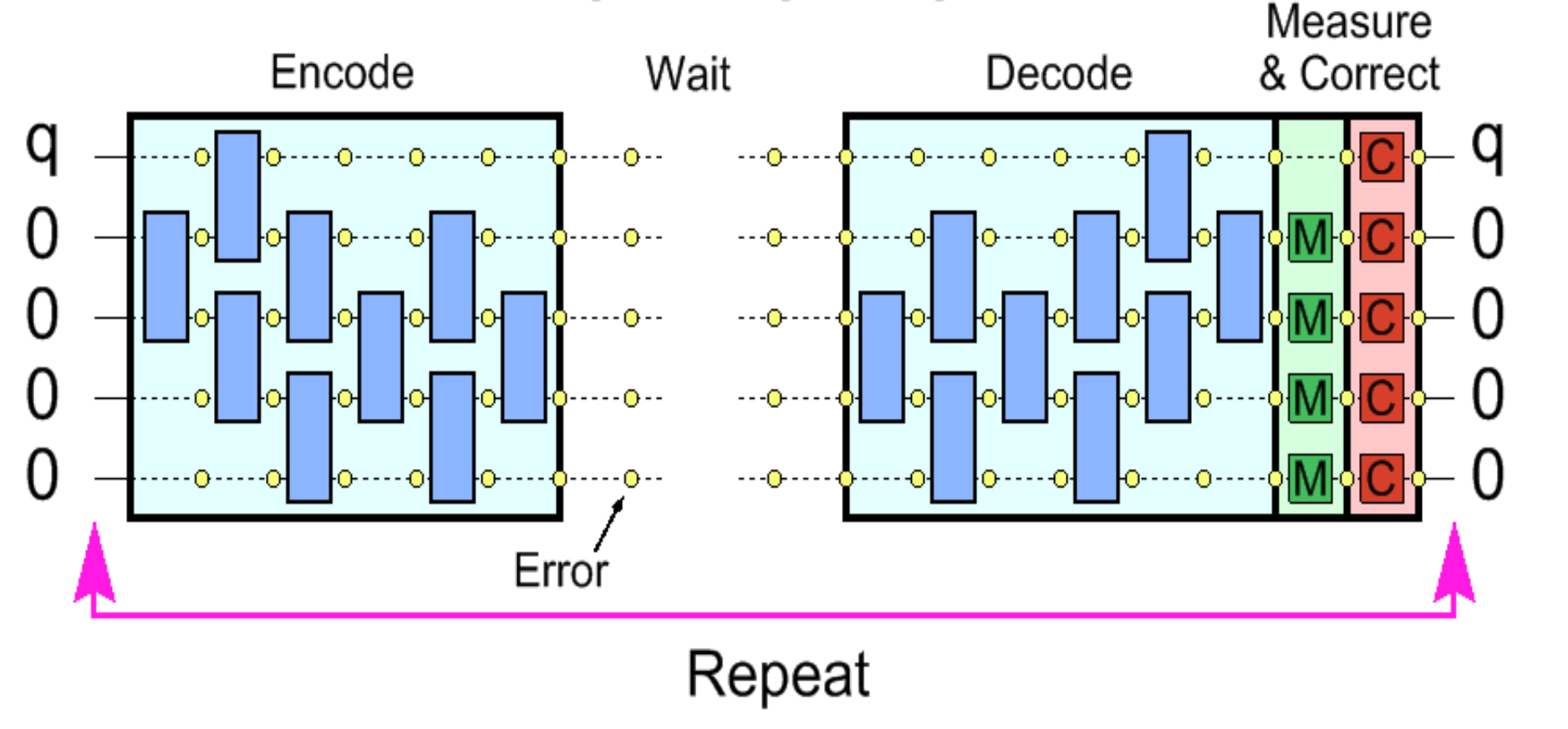


Quantum Error Correction Theory

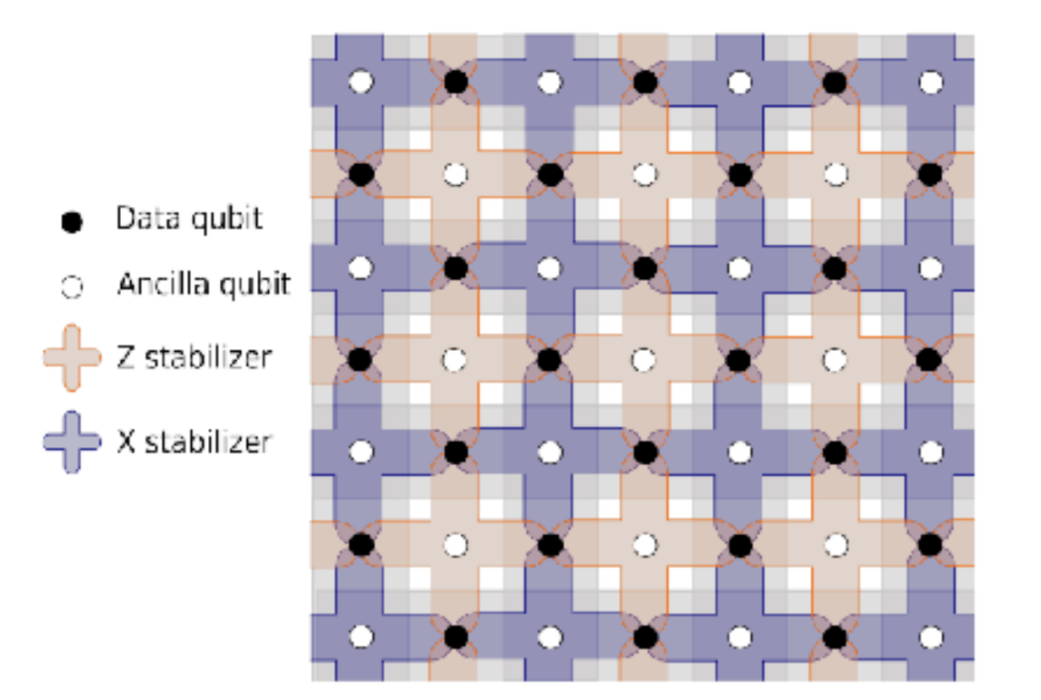
The theory teams at Melbourne and Maryland are leaders in the areas of solid-state theory and device modelling, spin-qubit architectures [18], robust qubit control [19-20], and QEC for spin qubits, having played a key role in the development of surface code QEC [21-22]. Most recently we have developed a detailed architecture for single atom qubits [23] that is capable implementing surface code QEC.

[18] Hollenberg et al., *Phys. Rev. B* 74, 045311 (2006). [19] Wang et al., *Nature Comms.* 3 , 997 (2012).
[20] Kestner et al., *Phys. Rev. Lett.* 110, 140502 (2013).
[21] Wang, Fowler and Hollenberg, *Phys. Rev. A* 83, 020302(R) (2011).
[22] Fowler, Whiteside, and Hollenberg, *Phys. Rev. Lett.* 108, 180501 (2012).
[23] Hill et al., unpublished.

Storing a single logical qubit



Surface Code Theory & Implementation



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