Single-Atom Spin Qubits in Silicon

Our research group collaborates closely with the group of Professor Andrea Morello at UNSW, who now leads the effort in single-P-atom spin qubits in silicon. A part of this collaboration we work with Professor David Jamieson (University of Melbourne) in the development of integrated silicon single-ion detectors, which are used to count the assembly of P-atom devices, one phosphorus atom at a time [9]. The Program makes extensive use of the Australian National Fabrication Facility (ANFF) at UNSW, of which Prof Dzurak is Director.

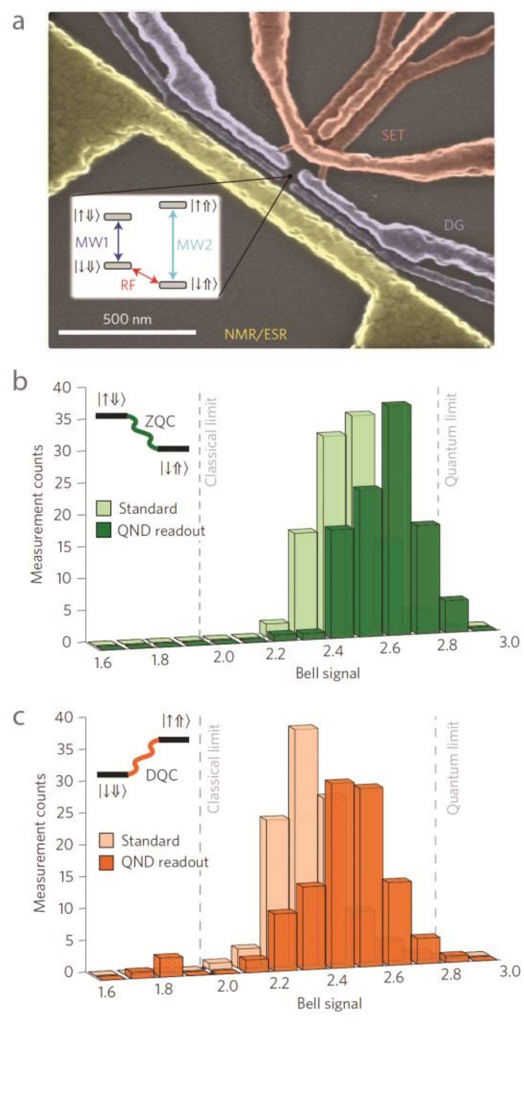
The past five years have seen tremendous progress in the development of spin qubits based upon implanted phosphorus atoms in silicon. In 2012 we published in *Nature* the demonstration of coherent control of a single **electron spin** qubit [1], bound to a deliberately implanted ^{31}P atom. Then in 2013 we demonstrated the control and readout of a qubit based upon the **nuclear spin** of an implanted ^{31}P atom [2]. Both experiments were undertaken in collaboration with Prof Morello and his team.

Both electron and nuclear spin qubits are coherently driven by a local ac magnetic field provided by an on-chip microwave transmission line, delivering pulses in the MHz range for nuclear spin qubit control (via NMR), or the GHz range for electron spin qubit control (via ESR). An integrated single electron transistor (Si-SET) enables single-shot electron spin readout [3].

A key cause of decoherence for spin-based qubits is the presence of nuclear spins in the host crystal. In naturally occurring silicon 4.7% of the nuclei are ^{29}Si with spin $I = ½$, and these cause serious decoherence to the electron spin qubits, severely reducing gate fidelities. To solve this we now fabricate P-atom qubits on silicon wafers with a surface epilayer of almost pure ^{28}Si, with zero nuclear spin, sourced through Prof Itoh at Keio University. P-atom qubits in such ^{28}Si wafers can have control fidelities as high as 99.9% for the electron qubit and 99.99% for the nuclear qubit, measured using Clifford-based randomized benchmarking. Last year we employed Gate Set Tomography, in collaboration with researchers from Sandia National Laboratories (USA), allowing us to identify rotation errors and improve the electron qubit fidelity to 99.94% [8]. These are amongst the highest fidelities for any qubit and provide optimism for the prospects for achieving fault-tolerant QC. Using dynamical decoupling pulse sequences the coherence of the ^{31}P nuclear spin qubit can also be extended to a remarkable T_{2n}^{DD} = 35 s [4].

In 2016 we demonstrated one of the largest violations of Bell's inequality in the solid state using implanted ^{31}P:^{28}Si qubits [5]. Bell states formed from the electron spin qubit and nuclear spin qubit of a single ^{31}P atom were deterministically generated using ESR and NMR pulses, and the Clauser–Horne–Shimony–Holt (CHSH) inequality was determined for both the zero quantum coherence (ZQC) and double quantum coherence (DQC) Bell states. For each Bell state both "standard" electron spin readout, and also QND readout by mapping the electron state on the nucleus, was used – see Figure. Separate experiments on dressed electron spin qubit states in 2016 [6, 7] further demonstrated the flexibility of the donor qubit system.

The devices for these experiments were fabricated by Dr Fay Hudson and Dr Rachpon Kalra, and were measured by Dr Juan-Pablo Dehollain, Dr Stephanie Simmons and Dr Arne Laucht from the group of Prof Morello.



Bell's inequality violation using ^{31}P electron and nuclear spin qubits in ^{28}Si. (a) SEM image of device. **(b,c)** Histograms of Bell signal values obtained for the zero quantum coherence, ZQC **(b)** and double quantum coherence DQC **(c)** Bell states. The data comfortably exceed the classical limit of 2.0, and approach the quantum limit of 2√2. The maximum mean Bell signal of 2.70(9) for the ZQC state using QND readout is amongst the highest in the solid state.

References

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