Coherent magnetic and electrical control of a single spin-7/2 donor atom in Silicon


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The computational power of a quantum processor depends upon the dimensionality \( d \) of its Hilbert space. For an \( n \)-qubit processor, this is simply \( d = 2^n \). However, it is also possible to use naturally occurring systems where \( d \) is intrinsically large. For example, the nuclear spin of a \(^{123}\text{Sb} \) atom has \( d = 8 \) owing to its large spin \( I = 7/2 \). When implanted in silicon it acts a substitutional group-V donor which binds an extra electron, yielding \( d = 16 \), or the equivalent of four qubits, within just one atom. The quadrupole interaction in heavy group-V donors offers a natural way to control nuclear spins using electric fields, which are easier to confine in a nanoscale device, as opposed to magnetic fields. Past work by Asaad et al. [1] showed that the nucleus of a single \(^{123}\text{Sb} \) atom can be integrated in a nanoelectronic device and be used to encode quantum information through Nuclear Electric Resonance.

Here we demonstrate coherent quantum control over the entire 16-dimensional Hilbert space of an implanted \(^{123}\text{Sb} \) donor atom in a silicon chip, using both magnetic and electric fields. The resonant electric and magnetic excitation, at radiofrequency (for the nucleus) and microwave (for the electron) is delivered by a single on-chip microwave antenna. We characterize the quadrupole interaction and investigate the performance and noise sources for both magnetic and electric coherent control. Using Gate Set Tomography, we extract one-qubit gate fidelities on the ionized nucleus \( > 99.8\% \) for both electric and magnetic drive. We find state-dependent Ramsey coherence times of the 7 NMR transitions ranging from \( T_2^* = 18 \) ms (for the 5/2 \( \rightarrow \) 7/2 transition) to \( T_2^* = 56 \) ms (for the 1/2 \( \rightarrow \) -1/2 transition). We ascribe the difference in dephasing rates to a spin state-dependent sensitivity to electric field noise.

These results pave the way to the exploitation of high-spin donor nuclei such as \(^{123}\text{Sb} \) to encode error-correctable logical qubits [2], provide advantages in quantum sensing [3] and allow all-electrical spin control in nanoscale semiconductor devices.