LETTER

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High-fidelity readout and control of a nuclear spin qubit in silicon

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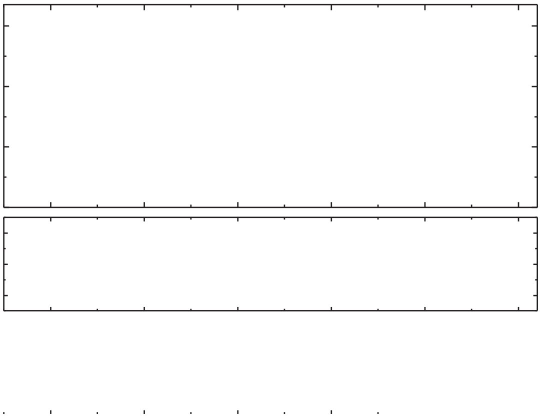
Detection of nuclear spin precession is critical for a wide range of scientific techniques that have applications in diverse fields including analytical chemistry, materials science, medicine and biology. Fundamentally, it is possible because of the extreme isolation of nuclear spins from their environment. This isolation also makes single nuclear spins desirable for quantum-information processing, as shown by pioneering studies on nitrogen-vacancy centres in diamond[1–4]. The nuclear spin of a ^{31}P donor in silicon is very promising as a quantum bit[5]: bulk measurements indicate that it has excellent coherence times[6,7] and silicon is the dominant material in the microelectronics industry. Here we demonstrate electrical detection and coherent manipulation of a single ^{31}P nuclear spin qubit with sufficiently high fideliti TJ 0 -1.126 TD [(vid)14(ual)-378(qub)13(its)14(„th)11(e)-386(bui)13(ldi)14(ng)-378(blo)14(cks



depending on the state of the nuclear spin: $n_{e1} < c_e B_0$ .. A/2 for nuclear spin $|\Downarrow\rangle$ and $n_{e2} < c_e B_0$ 1 A/2 for nuclear spin $|\Uparrow\rangle$. In a single-atom experiment, if we assume that the ESR measurement duration is much shorter than the nuclear spin flip time, then we expect only one active ESR frequency at any instant. Detecting ESR at the frequency n_{e1} therefore indicates that the nuclear spin is in state $|\Downarrow\rangle$, whereas detection at n_{e2} implies the nuclear spin is $|\Uparrow\rangle$.

Having identified the two resonance frequencies through an ESR experiment (see Fig. 1d and also ref. 10), we performed repeated measurements of the nuclear spin state (Fig. 2a) by toggling the microwave frequency n_{ESR} between n_{e1} and n_{e2}, obtaining the electron-spin-up fraction $f_\uparrow$ at each point (see Supplementary Information). If the quantity $Df_\uparrow$ 5 $f_\uparrow(n_{e2})$ 2 $f_\uparrow(n_{e1})$ is positive, we assign the nuclear state $|\Uparrow\rangle$, and vice versa. A histogram of $Df_\uparrow$ (Fig. 2d) shows two well-separated Gaussian peaks, corresponding to the two possible nuclear orientations, with widths determined by the signal-to-noise ratio (SNR) of the measurements (Supplementary Information). The nuclear spin readout error (Fig. 2e) is obtained by fitting the two peaks and integrating each Gaussian beyond a discrimination threshold Df_{th}. At the optimal ti value of Df_{th} 5 2 0.025, the SNR-limited readout error is $2\ 3\ 10^{2\ 7}$.

We observe that the nuclear spin state remains unchanged for several minutes before exhibiting a •quantum jump• to the opposite state.[2] It is also evident (Fig. 2b) that the nuclear spin is predominantly oriented in the $|\Uparrow\rangle$ state, which we attribute to an electron…nuclear spin flip-flop process, in which the energy difference $E_{\uparrow\Downarrow}$ 2 $E_{\downarrow\Uparrow}$ (that is, between states $|\uparrow\Downarrow\rangle$ and $|\downarrow\Uparrow\rangle$) is released to the phonon bath.[18–26] Because $E_{\uparrow\Downarrow}$ 2 $E_{\downarrow\Uparrow}$? k_BT in our experiment, this process acts only in the direction $|\uparrow\Downarrow\rangle$ R $|\downarrow\Uparrow\rangle$ (that is, only spontaneous emission of phonons occurs), and it cannot be responsible for the observed nuclear spin jumps from $|\Uparrow\rangle$ to $|\Downarrow\rangle$. We have verified that the $|\Uparrow\rangle$ R $|\Downarrow\rangle$ transition originates from the readout process, where the donor undergoes repeated ionization and neutralization events. These events result in a

n_{n0} 5 $c_n B_0$. Figure 3b shows the magnetic-field dependence of the three NMR frequencies, which agree with the expected values assuming the bulk ^{31}P gyromagnetic ratio c_n 5 17.23 MHz T$^{2\ 1}$ (ref. 23). Furthermore, we extract g 5 1.9987(6) (see Supplementary Information), which is within about 0.01% of the bulk value for Si:P, whereas the hyperfine splitting A 5 114.30(1) MHz is Stark shifted[5] from the bulk value of 117.53 MHz (ref. 24). The observation of a Stark shift of A is important, as it has been proposed[5] as a mechanism to address individual ^{31}P nuclear spin qubits while applying a global microwave field.

We now analyse the fidelity of our solid-state qubit. Single-shot nuclear spin readout can be performed with extremely high fidelity, owing to the quantum non-demolition (QND)[11] nature of the measurement. The physical phenomena responsible for the observed quantum jumps of the nuclear spin originate from the measurement through the electron spin, and can be viewed as a deviation from QND ideality (see Supplementary Information). For the nuclear $|\Uparrow\rangle$ state, this results in a lifetime of $T_{\Uparrow}$ 5 1,500(360) s (obtained from extended data of the measurement in Fig. 2a). For the nuclear $|\Downarrow\rangle$ state, the cross-relaxation process, which is caused by phonons modulating the hyperfine coupling, yields $T_{\Downarrow}$ 5 65(15) s (Fig. 2a). These lifetimes must be contrasted with the nuclear-spin measurement time, T_{meas}, which has been optimized here to maximize the nuclear-spin readout fidelity (see Supplementary Information). Combining the optimal measurement time (T_{meas} 5 104 ms) with the observed nuclear-spin lifetimes yields the QND fidelities: $F_{QND}(|\Uparrow\rangle)$ 5 exp(2 $T_{meas}/T_{\Uparrow}$) 5 0.99993(2); and $F_{QND}(|\Downarrow\rangle)$ 5 exp(2 $T_{meas}/T_{\Downarrow}$) 5 0.9984(4). We have therefore obtained readout fidelities between 99.8% and 99.99%, the highest reported so far for any solid-state qubit, and comparable with the fidelities observed for qubits in vacuum-based ion-trap systems[13]