Exploiting a Single-Crystal Environment to Minimize the Charge Noise on Qubits in Silicon

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Quantum computing algorithms, run on silicon hardware using electron spin qubits, are controlled by magnetic and/or electric fields.[1–3] As a result, magnetic noise and charge noise are two intrinsic mechanisms that ultimately limit the gate fidelities. The magnetic noise can be decreased with silicon isotopic purification methods to remove $^{29}$Si (with $I = 1/2$) atoms, thereby resulting in a nuclear spin-free environment, with $^{28}$Si concentrations as low as 60 ppm.[4–7] Charge noise, however, is more difficult to control since its origins are not fully understood and seems to be specific to the qubit-hosting material platform. The pervasive nature of charge noise has several implications for quantum computing implementations in silicon. First, it limits the gate fidelities of single spin qubits by coupling to the electron g-factor[8] and to the electric drive pulse in the presence of a micro-magnet.[6,7] Second, charge noise hinders spin-cavity coupling through the charge degree of freedom,[9–11] posing a challenge for designing efficient long-range interconnects between qubits. Finally, for two-qubit gates where the coupling between two electron spin qubits is achieved via the exchange interaction with strength $J$.13,12–18

For silicon gate-defined quantum dots, the dominant source of charge noise is known to originate from within the oxide dielectric that separates the quantum wells from the electrostatic gates, and/or near the interface between the semiconductor and the dielectric.[20–24] More specifically, Si-MOS qubits are exposed to an amorphous Si/SiO$_2$ interface while SiGe devices have Si/SiGe heterointerfaces in very close proximity to the quantum well with an additional Si/Al$_2$O$_3$ interface nearby.[20–23] Ongoing efforts in device fabrication are aimed at improving the quality of these interfaces. Improving interface quality, however, provides a challenging optimization problem with the charge noise magnitude depending on many parameters including wafer type,[23] lithographic gate design,[24] interfacial disorder,[25] and oxide thickness.[23] In this work, we show that the effect of these surface or interface defects, that give rise to charge noise, can be significantly reduced by fabricating crystalline qubits that are remote from surfaces and interfaces. We perform a comprehensive charge noise analysis of crystalline donor atoms in silicon, where the qubits, charge sensor, and control gates are defined using atomically precise phosphorus doping. The only interface in this platform is between silicon and its native oxide, which can be separated from the active plane of the qubits by tens to hundreds of nanometers of epitaxially grown Si[26] (see Figure 1a).
In nanoelectronic devices, the power spectral density of charge noise $S_0$ has a frequency dependence of $S_0(f) = S_0 \cdot f^{\alpha}$, where $S_0$ is the power spectral density at 1 Hz and the spectral exponent $\alpha$ is typically ≈1 with reported values between 0.5 and 2.\[6–8,20–24,27–31\] The power-law nature of charge noise can be explained by an ensemble of thermally activated two-level fluctuators (TLFs) where each TLF switches between two metastable states.\[34,35\] The level of charge noise in a device is typically quantified by the $S_0$ value obtained via charge sensor measurements using Coulomb blockade.\[7,20–24,28,31,36\] Alternatively, the $S_0$ value can be measured via a superconducting cavity coupled to a double quantum dot, where the microwave signal transmitted through the resonator is sensitive to the charge environment of the double quantum dot.\[36,37\] Reported values of the 1 Hz noise level $S_0$ in silicon using these two techniques range from 0.11 to 12 $\mu$eV$^2$ Hz$^{-1}$.\[7,22–24,27–31,36\] (see Table 1).

For the purpose of quantum computation, not only does the charge noise have to be considered at 1 Hz, but also at the whole frequency bandwidth corresponding to the operation times of the quantum circuitry. Therefore, a practical measure of charge noise is an integral over the total measurement bandwidth and can be expressed as:\[16\]

$$\sigma_{\epsilon} = \sqrt{\int_{f_{\text{low}}}^{f_{\text{high}}} S_{\epsilon}(f) df}$$

(1)

where $f_{\text{low}}$ and $f_{\text{high}}$ are, respectively, the lowest and highest frequencies that couple to the qubits during the measurement. The $\sigma_{\epsilon}$ values are typically measured using a double quantum dot system, where the fluctuations in the detuning energy $\epsilon$ between the two dots result in observable dephasing of coherent exchange oscillations.\[13,15,17,39–44\] Due to the 1/f nature of charge noise, the integrated charge noise $\sigma_{\epsilon}$ is dominated by the low-frequency noise components. Therefore, it is desirable to keep the total measurement time $T_M$ as short as possible because it is $T_M$ that determines the low-frequency limit of the noise bandwidth $f_{\text{low}} = 1/T_M$. While the exchange-based two-qubit gate time is typically shorter than 1 $\mu$s,\[13,15\] the duty-cycle (duration between two experiment runs) might be much longer (=few ms) due to readout and initialization steps.\[3,13,14\] Additionally, each duty-cycle needs to be repeated hundreds or thousands of times in order to build statistical significance for a single data point. As a result, the total measurement time $T_M$ used to completely map, for example, a full Rabi oscillation is typically on the order of seconds to hours.\[3,17,44\] Unfortunately, the $T_M$ times for the integrated charge noise measurements reported in the literature are not standardized, which prevents a direct comparison of $\sigma_{\epsilon}$ values across different research groups and between different material platforms.\[3,19,36,40–45\] Within this work, we present $\sigma_{\epsilon}$ as a function of $T_M$, which provides a practical measure of the magnitude of the charge noise, that takes into account the bandwidth of the noise measurements to allow a straightforward comparison between different material systems.

We characterize the charge noise in a crystalline two-qubit Si:P device with an integrated single electron transistor (SET) sensor. We compare three different approaches for analyzing charge noise across various frequency ranges: 1) the noise around 1 Hz is measured via SET current spectroscopy,\[7,20,22,23,27–31,46\] 2) the sub-millihertz regime is investigated by tracking a SET peak as a function of time where we monitor the shift in electrochemical potential of the SET,\[21,24,36\] and 3) by measuring the pure dephasing time $T_\chi$ of two-electron-spin coherent oscillations as a function of total measurement time.\[3,19,39–45\] In methods (1) and (2), the SET serves directly as a noise sensor, while in method (3), the SET is used to read-out the qubits that are subjected to charge noise. The device was fabricated in natural silicon and patterned using scanning tunneling microscope (STM) hydrogen lithography where a hydrogen mask is selectively desorbed from the silicon surface allowing for incorporation of phosphorus atoms.\[20\] The device consists of two donor dots, the SET island with source and drain leads, as well as four control gates (left, middle, right, and SET gate) (see the overview in Figure 1a). The STM image in Figure 1b shows a close-up of the top of the SET and the two donor dots after dosing with phosphine gas. From observed charging energies and spin relaxation times, we conclude that the left (L) and right (R) donor dots consist of 3 P and 2 P atoms, respectively (see S1, Supporting Information, for more details). After STM lithography, the P atoms are incorporated into the silicon crystal lattice and subsequently encapsulated with ≈40 nm of epilayered grown silicon in ultrahigh vacuum (UHV).\[28\] After removal from the UHV system, a native oxide forms at the surface. Finally, aluminium vias are used to create ohmic contacts to the buried Si:P leads ≈2 $\mu$m away from the central region of the device.

Figure 1. Single-crystal two-qubit device. a) A cross-sectional representation of a phosphorus-donor device in crystalline silicon. The actual STM image of the device is shown in the central image, where bright regions correspond to bare silicon that allows for incorporation of P donors. The device consists of two donor dots, four control gates (left, middle, right, and the SET gate), and the single electron transistor (SET) charge sensor, tunnel coupled to the source and drain leads. A protective layer of epitaxial Si (≈40 nm) separates the device from the surface. b) Close-up STM image shows the top part of the SET and positions of two donor dots, L (3P) and R (2P), separated by ≈12 nm. In this architecture, the SET acts as a charge sensor as well as an electron reservoir.
In this work, using different experimental methods we independently obtain both parameters, \( S_0 \) and \( \sigma_e \), and show theoretically predicted consistency between those two measures. For comparison with different material platforms we argue that it is important to quote the value of \( \sigma_e \) together with the corresponding measurement time, \( T_m \).

| Reference | Material | Method | \( S_0 [\mu eV^2 Hz^{-1}] \sqrt{S_0 [\mu eV Hz^{-0.1}]} \) | \( \alpha \) | \( f(\epsilon) \) relation used | \( T_m \) | \( \sigma_e [\mu eV] \) |
|-----------|----------|--------|-----------------|-----|------------------|-----|--------|
| This work | Si:P | SET tracking | 0.0088 ± 0.0004 | 0.094 ± 0.002 | 1.63 ± 0.01 | \( f(\epsilon) = \frac{\epsilon}{2} + \frac{\epsilon^2}{4} + t_0^2 \) | 1 h | 2.2(2) |
| He et al.(|5|) | Si:P | \( \alpha \)-based | 14.4 ± 6.1 | 3.8 ± 0.8 | 1.76 | \( f(\epsilon) = J_0 \exp\left(\frac{\epsilon}{E_0}\right) \) | 1 h | 4 |
| Mi et al.| Si/SiGe | Cavity | 0.11 | 0.33 | 1.4 | \( f(\epsilon) = J_0 \exp\left(\frac{\epsilon}{E_0}\right) \) | 1 s | 16 |
| Struck et al.| Si/SiGe | SET spectr. | 0.22 | 0.47 | | | 1 s | 0.74(2) |
| Connors et al.| Si/SiGe | SET spectr. | 0.71 ± 0.07 | 0.84 ± 0.04 | 1 ± 0.4 | | | |
| Freeman et al.| Si/SiGe | SET spectr. | 4 ± 0.92 | 2 ± 0.23 | | | | |
| Thorgrim. et al.| Si/SiGe | Hybrid qubit | | | | | | |
| Shi et al.| Si/SiGe | Charge qubit | | | | | | |
| Wu et al.| Si/SiGe | \( \alpha \)-based | | | | | | |
| Watson et al.| Si/SiGe | \( \alpha \)-based | | | | | | |
| Freeman et al.| Si/SiO\(_2\)| SET spectr. | 0.24 ± 0.10 | 0.49 ± 0.10 | | | | |
| Rudolph et al.| Si/SiO\(_2\)| SET tracking | 1 ± 1.2 | 1 ± 0.6 | 1.07 ± 0.13 | | | |
| Petit et al.| Si/SiO\(_2\)| SET spectr. | 4 | 2 | | | | |
| Kim et al.| Si/SiO\(_2\)| SET spectr. | 11.56 | 3.4 | | | | |
| Jock et al.| Si/SiO\(_2\)| \( \alpha \)-based\(2\) | | | | | | |
| Fogarty et al.| Si/SiO\(_2\)| \( \alpha \)-based | | | | | | |
| H.-Collard et al.| Si/SiO\(_2\)| \( \alpha \)-based | | | | | | |
| Petit et al.| Si/SiO\(_2\)| \( \alpha \)-based | | | | | | |

\( ^{\text{a}} \)Value calculated using the noise spectrum (Equation (1)). \( ^{\text{b}} \)A transition is observed between \( \alpha = 1 \) and \( \alpha = 2 \); \( ^{\text{c}} \)Device implanted with P donors; \( ^{\text{d}} \)Spin-orbit qubit; \( ^{\text{e}} \)Singlet-triplet qubit formed between Si-MOS quantum dot and a P donor.

To characterize the charge noise, we first use SET current spectroscopy measurements in which we study fluctuations in the SET current that arise from electrical noise coupling to the gate voltage in the frequency regime 600 \( \mu Hz – 8 \) Hz. We follow the analysis methods outlined in refs. \([21,22,29–31]\). In Figure 2a,b, we measure the SET current \( I \) and transconductance \( \partial I / \partial V_{\text{SET}} \) as a function of the SET gate voltage \( V_{\text{SET}} \). The effects of charge noise are most pronounced at the sides of the Coulomb peak, where the current \( I \) is most sensitive to voltage fluctuations. We observe that the current noise power spectral density \( S_I \) measured at the top of the Coulomb peak (light blue in Figure 2c) is smaller than at the side of the Coulomb peak (dark blue in Figure 2c), confirming that the measurement is indeed sensitive to charge noise. On the side of the Coulomb peak, we observe a characteristic charge noise power-law frequency dependence \( \propto 1/f^{\alpha} \) with \( \alpha = 1.59 ± 0.06 \). Above 0.3 Hz, we observe a deviation from the power-law behaviour, which suggests the presence of one or more TLFs switching between two metastable states at the rate of \( >0.3 \) Hz, within the frequency range typically associated with defects at the Si and native oxide interface as previously reported in the Si:P system\([30]\) (see S2, Supporting Information).
Three different methods to quantify charge noise. a–c) SET current spectroscopy. d,e) SET peak-tracking. f,g) Dephasing of exchange-based coherent oscillations. a) Current through the SET, $I$, measured as a function of the SET gate voltage $V_{\text{SET}}$ reveals the shape of the SET Coulomb peak. b) The absolute value of transconductance $\partial I / \partial V_{\text{SET}}$ as a function of $V_{\text{SET}}$. The highest sensitivity to voltage fluctuations is achieved when $V_{\text{SET}}$ is tuned to the side of the SET Coulomb peak. c) Current spectrum $S_I$, measured on the side of the SET Coulomb peak and on the top of the SET Coulomb peak. Below 0.3 Hz, the spectrum $S_I$ on the side of the SET Coulomb peak is fitted using a power-law function $S_I(f) \propto f^{-\alpha}$ with $\alpha = 1.59 \pm 0.06$. d) In the SET peak-tracking experiment, the shape of the SET Coulomb peak is fitted with a hyperbolic secant function, allowing us to determine the center of the peak with respect to the SET gate voltage $V_{\text{SET}}$. e) The SET current trace is repeatedly taken over 22 h, which allows us to extract the peak position for each line-scan (red line). f) Exchange-driven coherent oscillations. The gray line shows the normalised probability of measuring the $|\uparrow \downarrow\rangle$ spin state after the detuning pulse. This data set was taken over the total time of 8 h. The yellow line shows the fitted Gaussian decay envelope, with $T^*_2$ (8 h) $= 194 \pm 10$ ns. g) Dephasing time $T^*_2$ with error bars (gray shaded region) and corresponding charge noise $\sigma_e$ (circle markers with error bars) as a function of total measurement time, $T_M$. The decrease of $T^*_2$ (increase of $\sigma_e$) over time is caused by the additional low-frequency charge noise that couples to the system. The fit to the integrated noise $\sigma_e$ (yellow line) suggests a power-law noise spectrum $S(f) = S_0 f^\alpha$ with $\alpha = 1.61 \pm 0.02$. The second type of noise measurement is the SET peak-tracking experiment.[21,24] Here, we measure the charge noise across the 50 μHz to 1 mHz frequency range by monitoring the position of the Coulomb peak in voltage space as a function of time. In this experiment, we repeatedly scan over an SET peak using the SET gate. Each trace is then fitted with a hyperbolic secant function (Figure 2d), which allows us to extract the position of the SET peak center for each line-scan (Figure 2e). The small (40 μV) source–drain bias applied during this measurement results in a relatively narrow peak allowing us to monitor small changes in peak position that arise from charge noise. We find the spectrum of electrochemical potential fluctuations to follow a power-law function $S_V \propto f^{-\alpha}$ with $\alpha = 1.64 \pm 0.05$. In the third method of charge noise characterization, we quantify the direct impact of charge noise on two exchange-coupled qubits. Here, the low-frequency boundary of the charge noise bandwidth is $f_{\text{low}}$ which we vary from 35 to 280 μHz, and is determined by the total measurement time $T_M$ as $f_{\text{low}} = 1/T_M$. Consequently, we characterize charge noise in this frequency range by studying the relation between $T_M$ and the pure dephasing time $T^*_2$ of two exchange-coupled electron spins.[39] To determine $T^*_2$, we perform exchange oscillations by detuning the electrons to a region where the exchange interaction $J$ is larger than the local magnetic field difference between the two donor dots, $\Delta E_Z$, and the dephasing is dominated by charge noise rather than magnetic noise.[2,15] In our system, $\Delta E_Z$ is set by the difference in hyperfine couplings on both qubits and was determined to be $\Delta E_Z/h = 5 \pm 3$ MHz ($h$ is Planck’s constant), while $J$ is in the range of ⟨50–100⟩ MHz (see S3, Supporting Information, for more details). The pulse sequence starts with loading a random electron spin on the left qubit while a spin down is deterministically initialized on the right qubit. Such an initialization protocol results in a mixture of $|\uparrow \downarrow\rangle$ and $|\downarrow \downarrow\rangle$ states[15,47] (see S4, Supporting Information). During the exchange pulse, the $|\downarrow \downarrow\rangle$ state remains unchanged while the population of $|\uparrow \downarrow\rangle$ oscillates as shown in Figure 2f.[15] The $T^*$ value can be extracted by fitting a Gaussian decay envelope to the coherent oscillation data, while the oscillation frequency directly corresponds to $\Delta E_Z = f - J$. Next, we measure $T^*_2$ as a function of the total measurement time $T_M$.[6,7,39,40] Acquisition of a single set of coherent exchange oscillations was set to 1 h, giving $T^*_2$ (1 h) $= 335 \pm 46$ ns. We then repeat the measurement and average the resulting $|\downarrow \downarrow\rangle$ probabilities from two consecutive experimental runs, so that the fitted decay function corresponds to the measurement time of 2 h, and we obtain...
\( T_{1} (2 \text{ h}) = 279 \pm 27 \text{ ns} \). By repeating this process, we are able to plot \( T_{1} \) as a function of the total measurement time \( T_{M} \) that is varied from 1 to 8 h (see Figure 2g, square markers). We observe a decrease in \( T_{1} \) as the measurement time is increased. This arises as more lower frequency noise components couple to the detuning noise with increasing \( T_{M} \). The corresponding values of detuning fluctuations \( \sigma_{r} \) can be calculated using \( \sigma_{r} = \frac{\hbar}{\sqrt{2\pi T_{1}^{2}}} \mid_\epsilon = \epsilon_{m} \) (2)

where \( \epsilon_{m} \) is the detuning energy at which \( T_{1} \) is measured. To obtain the value of \( \frac{\partial J}{\partial \epsilon} \mid_\epsilon = \epsilon_{m} \), we measure \( J \) as a function of \( \epsilon \) as detailed in S3, Supporting Information. Using Equation (2), we then calculate \( \sigma_{r}(T_{M}) \), which is shown in Figure 2g with circle markers. The yellow line is a fit to the \( \sigma_{r}(T_{M}) \) data using Equation (1) for the integrated noise with a frequency dependence of \( S_{\epsilon} \propto 1/\epsilon^{\alpha} \). From the fit, we obtain the spectral exponent of \( \alpha = 1.61 \pm 0.02 \), consistent with the noise spectrum measured using the previous two methods. The high frequency boundary of the integral was approximated by \( f_{\text{high}} = 1/T_{\text{rep}} \) where \( T_{\text{rep}} = 1 \text{ ms} \) is the duty-cycle of the experimental pulsing sequence. It is interesting to note that the product of \( T_{1} \) and \( \frac{\partial J}{\partial \epsilon} \) is constant for all detunings, as we show in S5, Supporting Information. As a consequence, the \( \sigma_{r}(T_{M}) \) value for a given \( T_{M} \) is independent of the detuning \( \epsilon \).

We now combine all three noise measurements, taken using different methods over the different frequency regimes. For each method, we express the results as the charge noise power spectral density \( S_{\epsilon} \) (units of eV\(^2\) Hz\(^{-1}\)). From the SET transport measurements, \( S_{\epsilon} \) is calculated using

\[
S_{\epsilon} = \frac{a_{1}^{2} S_{1}}{(\partial I / \partial V_{\text{SET}})}
\]

where \( S_{1} \) is the current noise spectrum taken on the side of the SET peak and \( a_{1} = 0.056 \pm 0.005 \text{ eV V}^{-1} \) is the lever arm of the control gate to the SET (see S6, Supporting Information, for calculation of \( a_{1} \)). Next, from the peak-tracking experiment, we convert the electrochemical potential fluctuations \( S_{v} \) into \( S_{\epsilon} \) with

\[
S_{\epsilon} = a_{1}^{2} S_{v}
\]

Finally, the integrated noise \( \sigma_{r} \) measured via two-spin dephasing as a function of the low-frequency boundary \( f_{\text{low}} = 1/T_{M} \) allows us to calculate the corresponding noise spectrum using

\[
S_{\epsilon}(f_{\text{low}}) = -\frac{1}{2} \frac{\partial (\sigma_{r})}{\partial f_{\text{low}}}
\]

The combination of these three measurements allows us to collectively obtain \( S_{\epsilon}(f) \) over four decades of frequency, as shown in Figure 3a. Such a broad frequency range allows us to extract the noise spectrum with a high accuracy, as has previously been achieved by Yoneda et al.,[8] who combined two different qubit measurements to obtain a charge noise spectrum over 7 frequency decades. In our results, we find good agreement across both qubit and charge sensor measurements and fit a total noise spectrum of \( S_{\epsilon}(f) = S_{0} f^{\alpha} \), where \( \alpha = 1.63 \pm 0.01 \) and \( S_{0} = 0.0088 \pm 0.0004 \text{ eV}^{2} \text{ Hz}^{-1} \) over the frequency range 35 \text{ MHz} to 0.3 \text{ Hz}. The noise spectrum is consistent in terms of \( S_{0} \) and \( \alpha \) across all three experiments, regardless of whether we use the SET or the qubits to probe the noise. This would indicate that a simple SET current spectroscopy measurement during device pre-screening may be sufficient to estimate the charge noise levels affecting the qubits. This observation, whilst significant, would need to be verified by performing a similar analysis on future devices. We note that the observed value of \( \alpha = 1.63 \pm 0.01 \) falls between \( \alpha = 1 \) expected for an ensemble of TLFs and \( \alpha = 2 \) expected for a single TLF above its switching frequency.[13] This is in agreement with the previous reports of \( 1 < \alpha < 2 \) and suggests that the noise is dominated by a small number of TLFs with a non-uniform distribution of activation energies and/or uneven spatial distribution on the length-scales of the device.[23]
Table 1 summarizes charge noise results published for different silicon platforms from epitaxial Si/SiGe system to amorphous Si/SiO₂ devices. This table allows us to compare the charge noise magnitude measured in the single-crystal device with the state-of-the-art silicon gate-defined quantum dot devices. We find that the $S_0$ parameter obtained in this work is more than one order of magnitude lower than previously reported values. Earlier Si:P results[38] have shown that the dominating source of charge noise arises from the native Si/SiO₂ interface despite it being many tens of nanometers (≈40 nm in this case) away. This separation from the interface is in contrast to Si-MOS where the qubits are formed directly at the interface with the oxide.[23] Charge fluctuations at the remote native oxide interface in our buried Si:P devices would be expected to have a lesser impact on $S_0$ as confirmed with our findings. The qubits in the Si/SiGe platform are also separated by tens of nanometers from the oxide, similarly to Si:P system. However, the Si/SiGe system has a heterointerface nearby[20,22] and previous reports have indicated that the presence of the Al₂O₃ gate oxide introduces significant charge noise.[22,23] We note that in a recent study of a similar donor-based sample, but grown under different conditions, we observed $\sigma_e = 16–100 \mu$eV[15] and a 1 Hz noise value of $S_0 = 14.4 ± 6.1 \mu$eV² Hz⁻¹. By minimizing the pressure during the silicon growth, we have reduced the number of impurities that might inadvertently incorporate in the silicon layer that encapsulates our device.[48,49] Since impurities are known to act as TLFs, this would result in lowering of the charge noise. In this sample, with $S_0 = 0.0088 ± 0.0004 \mu$eV² Hz⁻¹, we observe a 1600-fold decrease in the power spectral density of the charge noise.

It is important to note that previous measurements of charge noise in different silicon platforms have focused either on SET current spectroscopy to obtain values for $S_0$[7,22,23,27,28,31] or on exchange-based dephasing to extract the fluctuations in detuning between two quantum dots, $\sigma_{\varepsilon}$.[3,19,40–44] This work experimentally links these two measures, $S_0$ and $\sigma_{\varepsilon}$, in our devices by showing that the measured $\sigma_{\varepsilon}$ is in agreement with the power-law frequency spectrum $S_0$ integrated over the noise bandwidth (Equation (1)). We show that $\sigma_{\varepsilon}$ is dominated by the charge noise at low-frequencies, the cut-off of which is determined by the total measurement time as $f_{\text{low}} = 1/T_M$. The $\sigma_{\varepsilon}$ values can be obtained by measuring the $T_1$ time of coherent oscillations (Equation (2)), with values reported in the literature ranging from 2 to 21$\mu$eV.[3,19,40–44] Unfortunately, the comparison between these results is challenging because $T_M$ for the coherent-oscillation measurements is neither standardized nor often provided, as shown in Table 1. For instance, Jock et al.[40] report a relatively low value of $\sigma_{\varepsilon} = 2 ± 0.6 \mu$eV. However, without providing the $T_M$ for this measurement, it makes a direct comparison of charge noise magnitude impossible. Our results highlight that the value of $\sigma_{\varepsilon}$ is not well-defined or useful as a metric when presented as a stand-alone measure. We enable a straightforward comparison between different silicon platforms by providing $\sigma_{\varepsilon}$ as a function of $T_M$, which represents a practical measure of the overall noise magnitude. In particular, for $T_M = 1$ h, we obtain $\sigma_{\varepsilon} = 2.4 ± 0.2 \mu$eV, which is in excellent agreement with the value of $\sigma_{\varepsilon} = 2.2 \mu$eV calculated using the charge noise spectrum (Equation (1)). We note that in reference,[36] the value of $\sigma_{\varepsilon}$ was not extracted using coherent oscillations as in other $\sigma_{\varepsilon}$ values in Table 1, but measured via a cavity coupled to the double dot system.

In that work, the histograms of the cavity signal were in agreement with the measured charge noise spectrum, giving a value of $\sigma_{\varepsilon} = 0.74 \mu$eV calculated for $T_M = 1$ s. Following the same steps, for $T_M = 1$ s, we calculate $\sigma_{\varepsilon} = 0.17 \mu$eV in our sample.

Our findings confirm that where charge noise is a significant factor in the two-qubit gate fidelity, it is important to optimise $T_M$. From our charge noise spectrum measured here, we can plot the theoretically modeled infidelity (one minus fidelity) of the two-qubit $\sqrt{\text{SWAP}}$ operation as a function of total measurement time $T_M$ (Figure 3b). The two-qubit gate fidelity is obtained by comparing the ideal $\sqrt{\text{SWAP}}$ process matrix to the one calculated based on the time evolution of the two-electron spin Hamiltonian and with $\sigma_{\varepsilon}$ determining the standard deviation of the detuning noise distribution (see S7, Supporting Information). In the current work, the duty-cycle of a two-qubit experiment was $1$ ms, limited by the tunnelling times between qubits and the SET detector that determine readout and initialization times. However, it has been demonstrated that tunnel times can be atomically engineered to enable fast (1.5 $\mu$s) single-shot readout.[50] Future work will focus on integrating our two-qubit experiments with these rapid readout techniques to allow for a short duty-cycle on order of $<10$ $\mu$s and, consequently, improvement of two-qubit operations. In particular, with the current noise characteristics, we estimate that the reduction of $T_M$ down to 0.65 s would correspond to charge noise levels sufficiently low ($\sigma_{\varepsilon} = 0.13 \mu$eV) to achieve two-qubit $\sqrt{\text{SWAP}}$ gates with 99.99% fidelity. Similarly, $T_M$ of 4.2 s yields $\sigma_{\varepsilon} = 0.24 \mu$eV and $\sqrt{\text{SWAP}}$ fidelity of 99.98%. Alternatively, the low-frequency charge noise can be reduced using feedback-controlled classical circuitry that implements real-time Hamiltonian estimation, which has been shown to be effective for $f ≥ 10$ Hz.[32,51] Thus, the gate fidelities can be improved even further with active feedback.

In summary, we have characterized the charge noise of single-crystal atom qubits in silicon. Using three different methods, we measured noise spectra that follow the same power-law dependence over more than four decades in frequency. We showed that the dephasing of exchange-based coherent oscillations corresponds to the integrated noise over the measurement frequency range, which agrees with the noise spectrum independently obtained via SET current spectroscopy and SET peak tracking measurements. In order to benchmark the noise measurement in different quantum device platforms, we employ an objective and practical measure, the value of $\sigma_{\varepsilon}$ as a function of measurement time $T_M$. Based on the relation between $T_M$ and the integrated noise $\sigma_{\varepsilon}$, we estimate that the two-qubit $\sqrt{\text{SWAP}}$ operations with ≥99.99% fidelity can be achieved with atomic engineering of fast (≈$\mu$s) SET-to-qubit tunnel rates. Additionally, we present an overall low noise level of $S_0 = 0.0088 ± 0.0004 \mu$eV² Hz⁻¹ in this single-crystal device where the qubits are spatially separated from the native oxide and without any heterointerfaces nearby.

Supporting Information
Supporting Information is available from the Wiley Online Library or from the author.
Acknowledgements

The research was supported by the Australian Research Council Centre of Excellence for Quantum Computation and Communication Technology (project number CE170100012), the US Army Research Office under contract number W911NF-17-1-0202, and Silicon Quantum Computing Pty Ltd. M.Y.S. acknowledges an Australian Research Council Laureate Fellowship. This work was performed in part at the NSW node of the Australian National Fabrication Facility.

Note: The layout of Table 1 was modified slightly on October 6, 2020, after initial publication online.

Conflict of Interest

M.Y.S. is a director of the company Silicon Quantum Computing Pty Ltd.

Author contributions

L.K., D.K., S.K.G., and Y.H. fabricated the device. L.K. and B.T. performed the measurements. L.K., S.K.G., Y.H., D.K, B.T., and J.G.K. analyzed the data. D.K. and S.K.G. performed the numerical simulations. The manuscript was written by L.K., S.K.G., J.K., and M.Y.S. with input from all other authors. M.Y.S. conceived and supervised the project.

Keywords

atomic electronics, charge noise, quantum computing, qubits, single-crystal silicon

Received: May 16, 2020
Revised: July 22, 2020
Published online: August 23, 2020

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