Low-frequency charge noise in Si/SiGe quantum dots

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Electron spins in silicon have long coherence times [1, 2] and are a promising qubit platform [3, 4]. However, electric field noise in semiconductors poses a challenge for most single- and multi-qubit operations in quantum-dot spin qubits [4, 5, 6]. Here, we investigate the dependence of low-frequency charge noise spectra on temperature and aluminum-oxide gate dielectric thickness in Si/SiGe quantum dots with overlapping gates. We find that charge noise increases with aluminum oxide thickness. We also find strong dot-to-dot variations in the temperature dependence of the noise magnitude and spectrum. These findings suggest that each quantum dot experiences noise caused by a distinct ensemble of two-level systems, each of which has a non-uniform distribution of thermal activation energies. Taken together, our results suggest that charge noise in Si/SiGe quantum dots originates at least in part from a non-uniform distribution of two-level systems near the surface of the semiconductor.

Electron spins in silicon quantum dots are a promising platform for quantum computation [11–13]. Long coherence times enable high fidelity qubit operations required for universal quantum computing. Although silicon qubits largely avoid nuclear spin noise, charge noise in the semiconductor still limits both single- and multi-qubit gate fidelities. Moreover, charge noise levels appear to be similar in different silicon devices and materials [11–16]. Because noise mitigation strategies such as device engineering, dynamical decoupling [17, 18], and dynamically corrected gates [19, 20] rely on a detailed understanding of the noise, a thorough characterization of charge noise is essential.

Here, we characterize the low-frequency charge noise in Si/SiGe quantum dots with overlapping gates [20, 21]. We investigate the dependence of the charge noise spectrum on temperature and Al2O3 gate-oxide thickness. We generally find that the noise increases with the aluminum oxide thickness. Although on average the noise follows a 1/f power-law with a linear temperature dependence, we find strong dot-to-dot variations in the noise spectrum. As we discuss below, we suggest that each quantum dot experiences noise caused by an ensemble of two-level systems (TLSs). Furthermore, we suggest that separate quantum dots experience noise caused by different TLS ensembles, each of which have a different and non-uniform distribution of thermal activation energies. In turn, variations in the TLS ensembles between dots give rise to the dot-to-dot variations in the noise. Specifically, we analyze our measurements in the context of the Dutta-Horn (D-H) model [22] which considers noise generated by an non-uniform distribution of TLSs, and we find good qualitative agreement with our data. In light of these findings, we conclude that charge noise in Si/SiGe quantum dots is caused, at least in part, by a non-uniform distribution of two-level systems near the surface of the semiconductor.

Devices are fabricated on an undoped Si/SiGe heterostructure with an 8 nm thick Si quantum well approximately 50 nm below the surface and a 4 nm Si cap, which forms a thin native SiO2 layer on its surface. Voltages applied to three layers of electrostatically isolated overlapping aluminum gates defined with electron beam lithography accumulate and confine electrons in the Si quantum well forming the quantum dots [Fig. 1(a), (b)] [20, 21].

Prior to quantum-dot fabrication, we deposit Al2O3 on the entire wafer surface via atomic layer deposition. On certain devices, we remove some or all of the Al2O3, allowing us to adjust the thickness of the gate dielectric. Table I shows the parameters of the devices used here. On Device 1, we nominally removed all of the Al2O3 with H3PO4 (Transene Transetch-N), which selectively etches Al2O3 compared with SiO2. We did not attempt to modify the native SiO2 layer. We also note that deposition of aluminum gates directly on an SiO2 surface leads to a thin interfacial layer of AlOx [23].
is therefore likely that a few nm of additional AlO$_x$ exists underneath the aluminum gates on Device 1, and possibly under the gates on all devices. In the following, we will refer to the deposited Al$_2$O$_3$ layer that exists over the device region as the gate-oxide [Fig. 1(b)]. We measured the gate-oxide thicknesses with a combination of white-light optical reflectometry, contact profilometry, and atomic force microscopy. Further fabrication details are given in Methods.

All devices are cooled in a dilution refrigerator with a base temperature of approximately 50 mK and then tuned to the Coulomb blockade regime [Fig 1(c)]. We apply a filtered source-drain bias of less than 1 mV across the device and measure the current $I$ with a SR570 low-noise current preamplifier. Current noise spectra are acquired on a SR760 spectrum analyzer with the plunger gate voltage $V_p$ set on the left, right, and top of a transport peak, where $|dI/dV_p|$ is largest. Figure 2(a) shows the current noise power spectral density measurement. Charge noise is measured by acquiring current noise spectra with the plunger gate $V_p$ set on both sides of a transport peak where $|dI/dV_p|$ is large as shown in the inset. Additional spectra are measured with $V_p$ set within the Coulomb blockade region for a baseline measurement of our experimental setup, and with $V_p$ set on top of the peak where $|dI/dV_p|$ is small as checks to ensure the measurement is sensitive to charge noise. A dashed trendline proportional to $f^{-1}$ is shown.

**Fig. 2** Noise spectrum measurement. **a** Current noise power spectral density measurement. Charge noise is measured by acquiring current noise spectra with the plunger gate $V_p$ set on both sides of a transport peak where $|dI/dV_p|$ is large as shown in the inset. Additional spectra are measured with $V_p$ set within the Coulomb blockade region for a baseline measurement of our experimental setup, and with $V_p$ set on top of the peak where $|dI/dV_p|$ is small as checks to ensure the measurement is sensitive to charge noise. A dashed trendline proportional to $f^{-1}$ is shown. **b** Measured charge noise spectrum showing non-power-law behavior (magenta). The green line is a fit of the spectrum used to obtain the value of $S_e(1$ Hz) and $\gamma(1$ Hz). Dashed lines proportional to $f^0$ and $f^{-2}$ are shown.

We fit the measured $S_e(f)$ to a function of the form $S_e(f) = A f^{-\beta} + B f^{-\gamma f_0}$ from 0.5-9 Hz, where $A$, $\beta$, $\gamma$, and $f_0$ are fit parameters. From this fit we directly extract the charge noise at 1 Hz, $S_e(1$ Hz), and also obtain the frequency exponent at 1 Hz, $\gamma = -\partial \ln S_e/\partial \ln f |_{f=1$ Hz}, by differentiating the fit at 1 Hz. In total, we measured noise spectra on quantum dots on three separate devices with gate-oxide thicknesses of 0 nm, 15 nm, and 46 nm. At the base temperature of our dilution refrigerator, we measured three quantum dots on each device to find $S_e(1$ Hz) to be $0.84 \pm 0.04 \mu eV/\sqrt{Hz}$ on Device 1 (0 nm gate-oxide), $0.94 \pm 0.18 \mu eV/\sqrt{Hz}$ on Device 2 (15 nm gate-oxide), and $1.77 \pm 0.09 \mu eV/\sqrt{Hz}$ on Device 3 (46 nm gate-oxide). A compilation of device parameters and charge noise values is given in Table I. At base temperature, the charge noise generally increases with the gate-oxide thickness. We discuss this observation further below.

In the regime where chemical potential fluctuations dominate the current noise, small current fluctuations $\delta I$ are given by

$$\delta I = \frac{dI}{dV_p} \frac{\delta \epsilon}{\alpha},$$

where $\delta \epsilon$ is a small change in the electrochemical potential and $\alpha$ is the lever arm. We extract $dI/dV_p$ from a fit of the transport peak and use Equation (1) to convert the acquired current noise spectrum $S_I$ to a charge noise spectrum $S_e$ via the relationship

$$S_e = \frac{\alpha^2 S_I}{|dI/dV_p|^2}.$$
Table I: Table of parameters of devices measured at base temperature of our dilution refrigerator. Quantum dots are specified by the plunger gate which they exist beneath as shown in Figure 1(a). For example, QD R1 is formed underneath plunger gate RP1. Values for $S_{1/2}^{1/2}$ (1 Hz) are given for both individual dots and for each device. The reported value of the average $S_{1/2}^{1/2}$ (1 Hz) at each dot is calculated by averaging all measurements taken on that respective dot at base temperature of the dilution refrigerator.

| Device | Gate-Oxide (nm) | QD | $\alpha$ (eV/V) | $S_{1/2}^{1/2}$ (1 Hz) (μeV/$\sqrt{Hz}$) |
|--------|-----------------|----|---------------|-----------------------------------|
|        |                 | QD Avg |               | Device Avg                        |
| 1      | 0               | R1   | 0.088         | 0.77 ± 0.072                      |
|        |                 | L1   | 0.109         | 0.94 ± 0.072                      |
|        |                 | L2   | 0.050         | 0.87 ± 0.072                      |
| 2      | 15              | R1   | 0.073         | 0.93 ± 0.18                       |
|        |                 | L1   | 0.080         | 1.17 ± 0.18                       |
|        |                 | L2   | 0.098         | 1.77 ± 0.09                       |
| 3      | 46              | R1   | 0.148         | 1.22 ± 0.18                       |
|        |                 | R2   | 0.036         | 1.87 ± 0.09                       |
|        |                 | L1   | 0.038         | 1.59 ± 0.09                       |

The model of Dutta and Horn [22] extends the McWhorter model to account for a non-uniform distribution of TLSs. The D-H model has successfully described $1/f$ noise in a large variety of solid state systems [22, 40–42]. Under the assumption that the width of the distribution of activation energies is larger than $k_BT$, one can expand the result of Equation (2) in powers of $T$ to obtain

$$S_{\epsilon}(f, T) = \frac{k_B T}{2\pi f} D(\tilde{E}),$$

where $\tilde{E} = -k_BT \ln (2\pi f \tau_0)$. Equation (5) shows that if $D(E)$ is not constant, then $S_{\epsilon}(f, T)$ will not vary linearly with temperature. Additionally, if $\gamma \neq 1$, then Equation (5) suggests $D(\tilde{E})$ must not be constant. Moreover, by defining $\gamma = -\partial \ln S_{\epsilon}/\partial \ln f$, one can use Equation (5) to obtain the following relation between the noise power $S_{\epsilon}(f, T)$ and the frequency exponent $\gamma(f, T)$.
\[ \gamma(f, T) = 1 - \frac{1}{\ln(2 \pi f \tau_0)} \left[ \frac{\partial \ln S_\gamma(f, T)}{\partial \ln T} - 1 \right]. \] (6)

Equations 5 and 6 are the basis of the D-H model. Equation 5 relates the temperature dependence of the noise to the density of the TLSs. Equation 6 relates the temperature dependence of the frequency exponent to that of the noise magnitude. Note that Equation 6 implies that deviations from \( \gamma = 1 \) imply a non-uniform distribution of TLSs and a non-linear temperature dependence of \( S_\gamma(f, T) \) as discussed above. Figure 4 shows representative plots of our measurements of \( S_\gamma(1 \text{ Hz}, T) \) and \( \gamma(1 \text{ Hz}, T) \). All data sets show deviations from both \( \gamma = 1 \) and linear temperature dependence of \( S_\gamma(1 \text{ Hz}, T) \).

According to the D-H model, these data suggest a non-uniform distribution of activation energies \( D(E) \). We show that our data is in qualitative agreement with the D-H model in several ways. First, using the measurements of \( \gamma(1 \text{ Hz}, T) \), we integrate Equation 6 to generate a prediction for \( S_\gamma(1 \text{ Hz}, T) \) (see Methods). We generally observe good qualitative agreement with our measurements of \( S_\gamma(1 \text{ Hz}, T) \) using this approach, although some of the sharp features are not perfectly captured [Fig. 4(a)-(c)]. Second, to generate a predicted form of \( \gamma(1 \text{ Hz}, T) \) from our measured noise power spectral density, we smooth the data using a moving 50-point average. We then take the logarithmic derivative of the smoothed line to extract a prediction for \( \gamma(1 \text{ Hz}, T) \) based on Equation 6. Again, our predictions based on the D-H model show reasonable qualitative agreement with the data [Fig. 4(d)-(f)]. In all cases, we fixed the maximum attempt frequency \( \omega_0 = 1/\tau_0 \) at 5 s\(^{-1}\) to maximize the fit quality across all data sets. The required value of \( \omega_0 \), which controls the size of deviations from \( \gamma = 1 \) and linear temperature dependence in the D-H model, is puzzling because \( 1/f \) noise has been observed at higher frequencies in Si/SiGe quantum dots [4,15]. One possible explanation is that the assumptions of the D-H model are not entirely satisfied in our experiment. For example, the
presence of sharp features in the activation energy distribution, as suggested by individual Lorentzian features in the measured spectra, may cause strong deviations from $\gamma = 1$. However, we note that predictions of the D-H model depend logarithmically on $\omega_0$, so our results only weakly depend on its precise value.

Figure 4 shows the predictions for $S_c(1 \text{ Hz}, T)$ and $\gamma(1 \text{ Hz}, T)$ made by the D-H model for three representative cases with varying quality of agreement between measurements and predictions. Given the generally good qualitative agreement between our data and the D-H predictions, we suggest that the charge noise results from a non-uniform distribution of TLSs. We note that the observation of Lorentzian features in the noise spectra corroborate this view [Fig 2(b)]. Comparisons between our data and the D-H model for all devices measured are shown in Methods and Extended Data Figure 1.

We obtain further insight into the nature of the noise source by measuring the temporal correlation of the charge noise on two neighboring quantum dots. First, we tune dots L1 and R1 on Device 2 to the Coulomb blockade regime. We set both plunger gates to the sides of their respective transport peaks, and we acquire a time series of current fluctuations on each dot simultaneously for 3200 seconds and repeat this procedure 20 times (see Methods). We calculate correlation coefficients of the current fluctuations between dots for each 3200-second time series and average the result across the 20 repetitions and find a correlation coefficient $\rho(\delta I_{L1}, \delta I_{R1}) = -0.006 \pm 0.032$, which indicates that the noise at each dot is independent and local. Together with our earlier results, it seems plausible that charge noise is caused by a small number of TLSs in close proximity to each quantum dot.

Our data suggest several possible explanations for the charge noise. One explanation is that the aluminum oxide itself contains the TLSs. In this case we would expect that reducing the oxide thickness would reduce the overall noise. It is also possible that the TLSs exist in the semiconductor near its surface or at the SiO$_2$/AlO$_x$ interface, and decreasing the aluminum oxide thickness improves screening effects from the metallic gates. If the individual TLSs consist of dipole charge traps [13-16], however, the metal gates will only screen dipoles oriented parallel to the surface. Image charges associated with dipoles oriented perpendicular to the surface would increase their contribution to the noise. For randomly oriented dipoles, one would not expect a significant change in the noise as the distance to the metal gates decreases. Thus, we suggest that the charge noise is caused at least in part by TLSs in the aluminum oxide, or dipole TLSs oriented parallel to the wafer surface and located either in the semiconductor near its surface or at the SiO$_2$/AlO$_x$ interface. However, it seems more likely that interface TLSs would be oriented parallel to the wafer surface than TLSs in the bulk of the semiconductor. In all of these cases, we emphasize that reducing the AlO$_x$ thickness is expected to reduce the noise, as suggested by this and previous work [17].

In summary, we find that the presence of an aluminum oxide gate dielectric layer tends to increase charge noise in Si/SiGe quantum dots. We observe that most quantum dots on a given device suffer from similar levels of noise, though there often exist significant dot-to-dot variations in the temperature dependence of the noise across dots in the same device. In the context of the Dutta-Horn model, our findings suggest that a non-uniform distribution of TLSs is responsible for the charge noise. Based on our results, it seems plausible that a small number of TLSs near the surface of the semiconductor or in the gate-oxide cause the charge noise. Our data underscore the importance of controlling defect densities in the gate-stack on top of silicon quantum dots. Our results also emphasize the importance of fully characterizing the charge noise of individual quantum dots to determine optimal spin qubit dynamical decoupling protocols. Furthermore, we suggest the use of as little aluminum oxide as possible in the active region of Si/SiGe spin qubits as an effective means to reduce charge noise.

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METHODS

A. Device

All devices were fabricated on an undoped Si/SiGe heterostructure and Al$_2$O$_3$ was deposited on the entire surface via atomic layer deposition. The Al$_2$O$_3$ in the active region of Device 1 was etched completely via Transene Transetch-N. The Al$_2$O$_3$ in the active region of Device 3 was partially etched using buffered oxide etch such that 46 nm of gate-oxide remained. A forming gas anneal step was performed on Device 2 immediately following aluminum oxide deposition. We measured Al$_2$O$_3$ thicknesses in both the unetched and etched (if the device was etched) regions of each device using white-light optical reflectometry. On Devices 1 and 3, we cross-checked these measurements by measuring the height of the etch boundary via contact profilometry and atomic force microscopy, respectively. Once the Al$_2$O$_3$ gate-oxide was deposited or removed, three layers of overlapping aluminum gates were defined on all devices via a combination of photolithography and electron beam lithography steps. Aluminum was deposited via thermal evaporation on Devices 1 and 2, and electron beam evaporation on Device 3.

B. Dutta-Horn Model

Extended Data Figure 1 shows measurements of $S_e(1 \text{ Hz}, T)$ and $\gamma(1 \text{ Hz}, T)$ on all quantum dots, as well as the predictions made by Equation 6 of the Dutta-Horn model. Measured values of $S_e(1 \text{ Hz})$ and $\gamma(1 \text{ Hz})$ are obtained from a fit of the measured spectra to a function of the form $A/\Gamma + B/\Gamma^2 + 1$ from 0.5-9 Hz.

Dutta-Horn predictions for $S_e(1 \text{ Hz}, T)$ are made from the measured values of $\gamma(1 \text{ Hz}, T)$ via integrating Equation 6. In most cases, D-H predictions of $S_e(1 \text{ Hz}, T)$ capture the broad features in the data.

We make predictions for $\gamma(1 \text{ Hz}, T)$ using the measured values of $S_e(1 \text{ Hz}, T)$ with Equation 6. We smooth $S_e(1 \text{ Hz}, T)$ by taking a moving 50-point average, and then we take the logarithmic derivative of the smoothed line. Most temperature sweeps are done in 2-5 mK steps, so a 50-point average results in a smoothing of points across a range of approximately 250 mK, possibly explaining why the predictions made by the D-H model often miss narrow features in the data.

C. Temporal Correlation Measurement

In order to measure the temporal correlation of the charge noise, we tune gate voltages on Device 2 such that quantum dots L1 and R1 are formed approximately 100 nm apart underneath plunger gates LP1 and RP1, respectively. Because the dots are separated by a screening gate there is negligible interdot tunneling. We separately bias each dot and adjust their respective tunnel barriers such that the peak current is a few hundred pA. We set each plunger gate voltage to the side of a transport peak. We then simultaneously acquire 3200-second time series of the current fluctuations through each device at a sampling rate of 1 kHz, and we repeat this until a total of 20 time series have been acquired from each dot. Our data acquisition card has spurious peaks at multiples of
0.33 Hz and multiples 0.5 Hz. Thus, we digitally apply a low-pass filter by first calculating the FFT of each time series, multiplying each of the resulting spectra by a transfer function of the form \( f(\omega) = \frac{1}{1 + i\omega/\omega_C} \) and then taking the inverse Fourier transform of the filtered spectra. Here, \( \omega_C/2\pi = 0.3 \) Hz is the cutoff frequency of the low-pass filter. We determine the correlation coefficient

\[
\rho(A, B) = \frac{\text{cov}(A, B)}{\sigma_A \sigma_B}
\]

for each of the 20 pairs of simultaneously acquired time series and average correlation coefficients across all pairs to get an average correlation coefficient of \( \rho(\delta I_{L1}, \delta I_{R1}) = -0.006 \pm 0.032 \).
Extended Data Fig. 1 Measured $S_\varepsilon(1\, \text{Hz}, T)$ and $\gamma(1\, \text{Hz}, T)$ of all quantum dots measured, and their corresponding Dutta-Horn predictions. a-d Device 1 quantum dot R1. e-h Device 1 quantum dot L1. i-l Device 1 quantum dot L2. m-p Device 2 quantum dot R1. q-t Device 2 quantum dot L1. u-x Device 3 quantum dot R1.