Comparison of low frequency charge noise in identically patterned Si/SiO_2 and Si/SiGe quantum dots

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Comparison of low frequency charge noise in identically patterned Si/SiO_2 and Si/SiGe quantum dots

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We investigate and compare the charge noise in Si/SiO_2 and Si/SiGe gate defined quantum dots with identically patterned gates by measuring the low frequency $1/f$ current noise through the biased quantum dots in the coulomb blockade regime. The current noise is normalized and used to extract a measurement of the potential energy noise in the system. Additionally, the temperature dependence of this noise is investigated. The measured charge noise in Si/SiO_2 compares favorably with that of the SiGe device as well as previous measurements made on other substrates suggesting Si/SiO_2 is a potential candidate for spin based quantum computing. *Published by AIP Publishing.* [http://dx.doi.org/10.1063/1.4954700]

In recent years, quantum computation has garnered great interest and driven research in several fields with the promise of solving problems that are currently intractable for classical computation. Several schemes have been proposed for the implementation of a quantum computer. Electrons confined in semiconductor based, gate defined, lateral quantum dots are one promising candidate.[1] The semiconductor material has largely been confined to GaAs[2] and more recently, Si/SiGe and Si/SiO_2 heterostructures.[3] Silicon based quantum dots provide several potential advantages over other platforms including a long electron spin coherence lifetime due to a small Overhauser field[4–8] and well developed fabrication techniques and facilities due to its ubiquity in modern semiconductor technology. However, coherence of electrically controlled qubits in silicon, particularly for exchange based qubits, is susceptible to charge noise, which can create fluctuations in both qubit energy levels and orbital motion of electrons.[9–13]

Charge noise in semiconductor quantum dots often exhibits a $1/f$ noise spectrum, which originates from defects and impurities at both heterostructure interfaces and within the semiconductor's bulk.[14,15] This noise has been studied extensively in GaAs for quantum dot and quantum point contact (QPC) systems[14,16–23] and more recently in Si/SiGe.[24] However, such a study has not yet been done for Si/SiO_2 based quantum dots. It has been speculated that Si/SiO_2 may be particularly susceptible to background charge fluctuations relative to other systems, such as Si/SiGe, as the amorphous SiO_2 may give rise a rough interface containing higher defect/impurity density.[9,10]

In this paper, we present several measurements of low frequency charge noise in both Si/SiO_2 and Si/SiGe dot systems using transport measurements. All depletion gates were fabricated using identical electron beam lithography patterns and processes. Based on our experience fabricating and imaging devices, depletion gate location is accurate to within 10 nm of design. Additionally, similar fabrication processes were used whenever possible in order to present the best comparative measurement of the charge noise in these two different types of Si-based materials.

Measurements from four devices are presented in this paper. Two Si/SiO_2 and two Si/SiGe devices were fabricated and measured. One Si/SiO_2 was fabricated on a lightly boron doped silicon wafer grown using the Czochralski (CZ) process and a second on an undoped float-zone (FZ) silicon wafer. Both Si/SiO_2 devices have 20 nm of thermally grown oxide. The Si/SiGe devices were fabricated on the same substrate consisting of a 16 nm silicon well, a 40 nm $Si_{0.7}Ge_{0.3}$ spacer and a 2 nm Si cap. All devices were fabricated by first patterning Ti/Au depletion gates on the substrate. Following this 100 nm of Al_2O_3 was grown using atomic layer deposition to provide an insulating layer. Finally, a 300 nm global top gate was patterned over the device area. Figure 1 shows a schematic cross section view of the Si/SiO_2 devices, as well as a scanning electron microscope (SEM) image of the depletion gate layout used on all devices. The electrical confinement potential is defined by applying appropriate voltages on the depletion gates. Our devices were fabricated with the intention of forming two quantum dots. However, for the purpose of simplifying noise measurements for this experiment, all systems were tuned to form one large single dot instead. The predicted single dot configuration is highlighted by a blue circle in Figure 1. This location was estimated based on the relative strength of depletion gates.

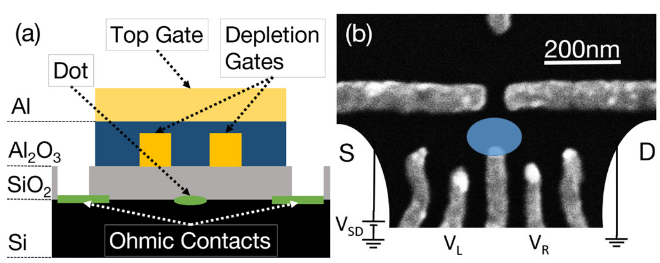

FIG. 1. (a) Schematic cross section of a Si/SiO_2 device. (b) SEM image of a device with the same depletion gate pattern as the devices used. Note the predicted dot location marked with a blue oval. Depletion gates V_L was used to adjust chemical potential of the dot. The location of the source and drain are marked (S and D). For these measurements, a bias, V_{SD}, was applied across the dot.

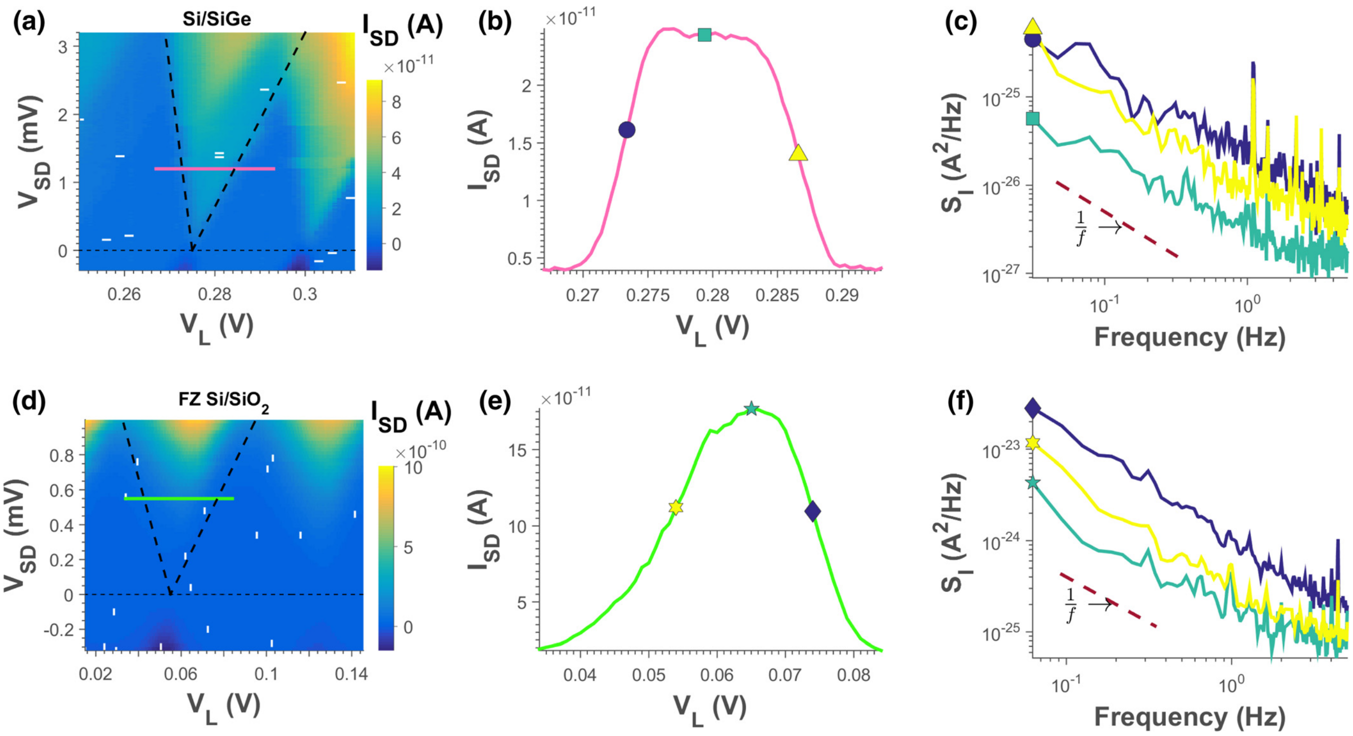

FIG. 2. (a) and (d), Coulomb diamond for the Si/SiGe (FZ Si/SiO$_2$) device, DC through the dot, I_{SD} is plotted versus the bias voltage, V_{SD} and the tuning gate voltage, V_L. The pink (green) line marks the location of the current trace shown in (b) and (e). (b) and (e), I_{SD} current trace across the marked current peak in the Si/SiGe (FZ Si/SiO$_2$) dot. (c) and (f) Current noise spectra taken along the current trace. The spectra are color coded to match the markers in (b) and (e) at the value of V_L where they were taken. Note how the magnitude of the spectra is correlated with $\frac{\partial I_{SD}}{\partial V_L}$. Several of the large peaks above 1 Hz are permanent features due to the pulse tube cooler operating in the refrigerator during measurement.

All devices were measured in dilution refrigerators cooled to a base temperature of approximately 60 mK. DC data in the coulomb blockade regime were obtained by applying a source drain bias on the order of millivolts. The resulting current was measured after passing through a SR570 low noise current amplifier. Noise spectra were obtained using a SR785 spectrum analyzer.

To acquire low frequency noise data from our systems, we first tuned to a region where the device behaves as a single dot in the Coulomb blockade regime. Subsequently, all data were taken modifying only the bias voltage across the dot, V_{SD}, or the voltage on gate V_L, used to adjust the chemical potential of the dot's energy levels, ϵ. The lever arm α of the gate V_L, which relates $V_L\alpha = \epsilon$, and charging energies were extracted from Coulomb Diamond measurements where current, I_{SD}, is measured through the dot relative to V_{SD} and V_L, a sample trace can be seen in Figure 2.[25] These values are reported in Table I.

Low frequency current noise spectra up to 5 Hz, constrained by the bandwidth of our current amplifier, were recorded with a fixed bias as a function of V_L across several peaks in I_{SD}. The spectra and corresponding DC across a single peak are shown in Figure 2 for both substrates. Note the $1/f$ frequency dependence of the data. The predicted shot noise of our device at the maximum DC measured, ∼200 pA, is 6×10^{-29} A^2/Hz, well below the observed noise floor in both systems. Figures 2 and 3 demonstrate that the noise level is largest on the sides of the current peak and exhibits a local minimum near the maximum value of current. As seen previously, we confirm that the noise level is strongly correlated with trans-conductance $dI/d\epsilon$ and exhibits a local minimum at the peak of the current profile.[17] Given that the maximum current through the dot is set by tunneling rates to the source and drain, Γ_S, and Γ_D, respectively, and is observed to be relatively constant over a single current peak, we approximate the noise due to fluctuations in Γ_S, Γ_D, and ϵ as uncorrelated. Then, to first order, small current fluctuations in time about a fixed point (ϵ_0, Γ_{S0}, Γ_{D0}) are given by

$$\delta I(t) = \frac{\partial I}{\partial \epsilon}\delta\epsilon(t) + \frac{\partial I}{\partial \Gamma_S}\delta\Gamma_S(t) + \frac{\partial I}{\partial \Gamma_D}\delta\Gamma_D(t). \quad (1)$$

TABLE I. Summary of device measurements. The $\Delta\epsilon$ value is reported at 1 Hz for every device as well as the lever arm α and the charging energy E_C.

Sample	$\Delta\epsilon$ (μeV/$\sqrt{\text{Hz}}$)	α (eV/V)	E_C (meV)
CZ Si/SiO$_2$ BE5	1.70 ± .43	0.03	1.3
FZ Si/SiO$_2$ AF5	0.49 ± .10	0.01	0.7
Si/SiGe AB3	2.0 ± .23	0.02	1.7
Si/SiGe AC2	2.1 ± .24	0.09	2.5

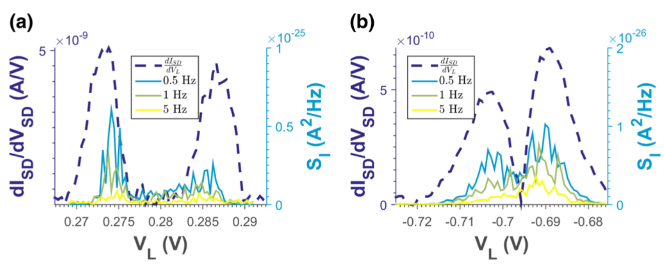

FIG. 3. Current noise, S_I, as a function of V_L at 0.5 Hz, 1 Hz, and 5 Hz plotted versus transconductance dI/dV_L for SiGe (a) and CZ Si/SiO$_2$ (b).

As has been previously observed, the strong correlation of noise with transconductance indicates that the majority of noise is due to fluctuations in ϵ as opposed to tunneling.[17,23] In order to isolate the noise in ϵ for comparison with other systems, we subtract the spectra measured at maximum I_{SD}, defining $V_L = V_0$ at this location. Since $dI_{SD}(\epsilon)/dV_L$ is 0 at this point, and hence $dI_{SD}/d\epsilon$ as well, the spectra $S_I(V_0, f)$ represents the noise contribution due to fluctuations in tunneling rates as well as any other uncorrelated background noise in our system. Then

$$\Delta I_\epsilon(V_L, f) = \sqrt{S_I(V_L, f) - S_I(V_0, f)}, \tag{2}$$

where ΔI_ϵ is current noise due to fluctuations of ϵ only. Finally, since the magnitude of potential fluctuation is small, we can use the relation $\Delta I_\epsilon \alpha = |dI_{SD}/dV_L| \Delta\epsilon$ to convert the current noise into potential noise.[17] In order to produce a single spectrum for the charge noise in each device, we averaged several points around the peak value of $|dI_{SD}/dV_L|$, where our sensitivity is best. The resulting spectra are consistent with a $1/f$ model, and several example spectra are plotted in Figure 4. In order to examine the variability of noise, $\Delta\epsilon$ was measured at a minimum of two Coulomb peaks in each device, and the extracted values were found to be consistent within error. Values for $\Delta\epsilon$ at 1 Hz are reported in Table I; these final values were obtained by averaging all measurements on each device. The lowest observed noise was in the FZ Si/SiO_2, $0.49 \pm .10\,\mu eV/\sqrt{Hz}$ at 1 Hz.

Temperature dependence of $\Delta\epsilon$ was measured over several different temperatures between 60 mK and 500 mK in one of the SiGe devices as well as the CZ Si/SiO_2 device. The standard $1/f$ noise model assumes an even spatial distribution of electron traps and activation energies. This model gives rise not only to a $1/f$ frequency dependence, but also to a temperature dependence of the following form:[17,23]

$$S \propto \frac{kT}{f}. \tag{3}$$

Temperature dependence of measured potential fluctuations across a single Coulomb peak is plotted in Figure 5 for the CZ Si/SiO_2 and a SiGe device. Temperature dependence is observed in both the Si/SiGe and the Si/SiO_2 systems. The measured temperature dependence is consistent with a linear model, although more detailed measurements could reveal nonlinearities. There are several practical considerations that

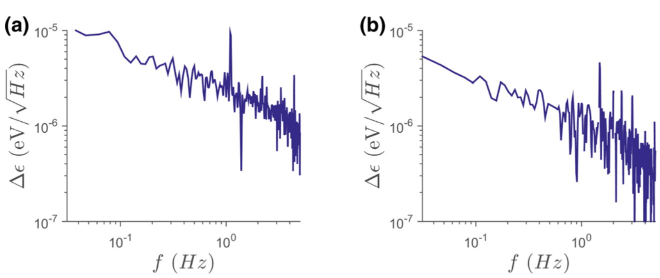

FIG. 4. Potential energy fluctuations calculated by averaging several points near the maximum value of transconductance for SiGe (a) and CZ SiO_2 (b).

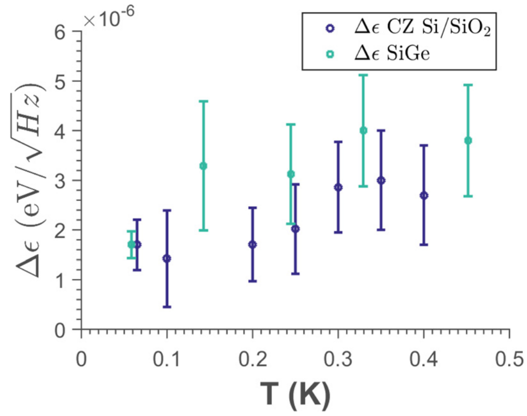

FIG. 5. Temperature dependence of measure potential energy noise at 1 Hz across a single Coulomb peak for the CZ Si/SiO_2 device and a Si/SiGe device.

could explain a departure from the expected linear dependence. In particular, the effective electron temperature is likely higher than the measured base temperature of the device. This should create a region of nonlinearity in the measured $1/f$ noise versus temperature at low temperatures as the electron temperature does not depend linearly on the measured lattice (refrigerator) temperature. Alternatively, it has been suggested that for a regime in which several states contribute to the total current through the device relaxation of conduction electrons within the device may enhance $1/f$ noise by transferring energy to nearby impurities.[15,17] If such a processes contributed substantially to potential fluctuations, temperature dependence could depart from the expected form. However, we find this unlikely as measurements taken at several bias voltages between 5 mV and 1.5 mV did not show any clear signs of bias dependence.

We fabricated several identically patterned Si/SiO_2 and Si/SiGe quantum dot systems and measured low frequency charge noise in order to make a direct comparison between substrates. Noise was measured using transport data through single quantum dots operating in the coulomb blockade regime. Noise measurements at separate current peaks on the same device were found to be similar. Temperature dependence of both systems was also examined and observed to be consistent with standard $1/f$ noise models. The measured charge noise in both Si-based materials was found to be roughly the same order of magnitude. Therefore, the measured noise from our Si/SiO_2 devices compares favorably with our measurements of Si/SiGe as well as with previous measurements of low frequency noise in GaAs systems,[26] demonstrating that the low frequency charge noise in Si/SiO_2 quantum dot systems is low enough to support spin qubits for quantum information processing. This finding is somewhat surprising since it has been observed that charge impurities in Si/SiO_2 devices tend to have a strong effect on dot locations and tunneling rates from device to device. It is possible that the majority of charge impurities is much deeper in energy and contributes little to charge noise. In fact, we have observed that, once cooled, dot formation on Si/SiO_2 devices remains stable, suggesting that the impurities affecting dot formation might have large activation energies and may be treated as fixed charges.

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