Single-shot readout with the radio-frequency single-electron transistor in the presence of charge noise


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The radio-frequency single-electron transistor (rf-SET) possesses key requirements necessary for reading out a solid state quantum computer. This work explores the use of the rf-SET as a single-shot readout device in the presence of $1/f$ and telegraph charge noise. For a typical spectrum of $1/f$ noise we find that high fidelity, single-shot measurements are possible for signals $\Delta q > 0.01e$. For the case of telegraph noise, we present a cross-correlation measurement technique that uses two rf-SETs to suppress the effect of random switching events on readout. We demonstrate this technique by monitoring the charge state of a metal double dot system on microsecond time scales. Such a scheme will be advantageous in achieving high readout fidelity in a solid-state quantum computer. © 2005 American Institute of Physics. [DOI: 10.1063/1.1897423]

Electrical circuits that exploit entangled quantum states have the potential to revolutionize information processing. One of the key requirements for the realization of such technology is the ability to perform reliable initial state preparation and readout of quantum bits (qubits) with both high fidelity and efficiency. This formidable challenge amounts to the detection of single charge, flux, or spin states on time scales shorter than the qubit mixing time using detectors that operate with sensitivities near the quantum limit. The radio frequency single electron transistor (rf-SET) is a readout device that possesses such requirements, exhibiting high sensitivity, switchable back action and a quantum measurement efficiency that approaches unity.

As pioneered by Schoelkopf et al., the rf-SET consists of an SET electrometer embedded in an impedance matching network to enable fast operation. SETs are sensitive to charge since current flow through the device depends critically on the electrostatic potential of the center “island.” Here we discuss “single-shot” measurements in which the rf-SET is used to detect a charge state in a single pass, without repeating the preparation of that state. Although single-shot measurements are the most efficient mode of readout (and desirable for quantum error correction), they are challenging in the case of fast operation since bandwidth-narrowing techniques commonly used to reduce noise also limit the response time.

The purpose of the present work is to address how single-shot measurements are affected by charge noise. In our setup we distinguish between two types of charge noise: $1/f$ noise arising from many fluctuating charge traps that are weakly coupled to the SET and telegraph noise due to single traps that are strongly coupled to the SET. We find that the effect of $1/f$ noise on readout fidelity is negligible in our setup for measurement times shorter than $t_{\text{meas}} \approx 10 \mu$s. However telegraph noise, characterized by discontinuous switching of charge between metastable trap configurations can affect readout fidelity since switching may occur on time scales commensurate with the measurement time.

To investigate the effects of telegraph noise on readout fidelity we have built an Al/Al$_2$O$_3$ readout simulation device, where the charge state of two coupled metal dots is measured with a twin rf-SET detector. We present single-shot measurements of this nanoscale device taken simultaneously with two rf-SETs. These results demonstrate the feasibility of using rf-SETs to perform readout in a single shot, via the use of a cross-correlation technique to greatly suppress the effect of charge noise. Such measurement schemes may be important if rf-SETs are to achieve high fidelity readout, in the presence of charge noise.

Turning now to the details of our experiment, Fig. 1 shows an electron micrograph (a) and schematic (b) of our device, including gates A1, A2, G1, G2, and the double-dot structure (single tunnel barrier) capacitively coupled to the two rf-SETs either side. Simultaneous independent operation

![Electron micrograph of the twin rf-SET and double-dot device.](image)

**FIG. 1.** (a) Electron micrograph of the twin rf-SET and double-dot device. The rf-SETs detect the charge state of the two metal dots which are coupled by a tunnel junction (center of image); (b) is a schematic showing the two rf-SETs and the double-dot with associated gates and capacitances.
of two rf-SETs is made possible using the technique of wave-length division multiplexing in conjunction with a single cryogenic amplifier. Details of our setup, including a demonstration of simultaneous operation can be found in Ref. 12. Figure 2(a) shows the simultaneous response of both rf-SETs in the time domain to a 100 kHz square wave signal of amplitude $\sim 0.1e$ applied to gate A2. The voltage on the vertical axis is the output signal from our demodulation circuit and proportional to the amount of reflected rf power. The capacitances between the gates and the SET islands were in the range of $1 - 10\, \text{aF}$ and the device resistances were 43.4 $\text{k}\Omega$ (SET1) and 30.4 $\text{k}\Omega$ (SET2). Independent control of the dc source-drain bias across each SET permits both devices to be simultaneously operated in the superconducting state at the double Josephson quasiparticle resonance, where near quantum-limited readout efficiency is approached. Figure 2(b) (taken from Ref. 12) shows the frequency spectrum of both rf-SETs in response to an amplitude modulation (AM) gate signal ($\sim 0.1e$) at 2.5 MHz. The frequency-domain sensitivity ($\delta q$) of both devices was characterized by measuring the signal to noise ratio of an AM sideband in a given resolution bandwidth $B$. For the case of simultaneous operation, the minimum detectable signal was $\delta q = 7.5\, \text{me}/\sqrt{\text{Hz}}$ for SET1 and $\delta q = 4.4\, \text{me}/\sqrt{\text{Hz}}$ for SET2. We note that determining the minimum detectable charge $\Delta q = \delta q \times \sqrt{B}$ from these sensitivity measurements assumes that the noise is white throughout the measurement time. While this is true at higher frequencies (where thermal noise from the rf amplifier and shot noise associated with the SET current dominate), longer measurement times will include unequally weighted or “colored” noise sources, typical of a $1/f$ spectrum.

In our setup the $1/f$ noise spectrum meets the white noise floor at 100 kHz as shown in the inset to Fig. 2(b). Consequently, measurements made on time scales shorter than 10 $\mu$s are not affected by $1/f$ noise. However, in the case of very small signals ($\Delta q/0.01e$) the measurement time required for high fidelity readout increases drastically due to $1/f$ noise since the noise increases with $t_{\text{meas}}$ but signal only with $V(t)_{\text{meas}}$. This limitation defines a lower limit of $\Delta q \sim 0.01e$ on the size of the charge signal that can be read out efficiently in a single shot measurement.

In order to explore the interplay between charge noise and readout fidelity experimentally, we have performed single-shot time-domain measurements of various signal amplitudes. The data in Fig. 3 was obtained by applying a square wave signal (rise time $\sim 10\, \text{ns}$) to gate G2 (see Fig. 1) and measuring the output voltage of our demodulation circuit as a function of time. The trace in Fig. 3(a) shows the result of 256 averages of a $\Delta q = 0.01e$ step. Figure 3(b) shows single-shot traces of a $\Delta q = 0.05e$ and $0.2e$ gate signal in a measurement window of $t_{\text{meas}} = 0.6\, \mu$s. The slope of the transition between the two levels is finite since the bandwidth of the resonant circuit ($\sim 100\, \text{ns}$) acts as a low pass filter. Figures 3(c)–3(e) show the corresponding signal histograms and fitted Gaussian probability distribution functions (PDFs) for the time-domain data. The overlap of the PDFs corresponds to the probability of missing one readout signal level for the other.

Although $1/f$ noise is negligible in the time considered here, we find additional noise sources that reduce the measured time-domain sensitivity (which is equal to the full width at half maximum of the PDF for a signal to noise ratio of 1), in comparison to measurements made in the frequency domain, where signals are strongly averaged [as in Fig. 2(b)]. This difference in sensitivity can be explained by taking into account the additional noise introduced by the oscilloscope, demodulation circuitry and the effect of the finite rf-SET bandwidth ($\sim 10\, \text{MHz}$) in comparison to the measurement time $t_{\text{meas}} = 0.6\, \mu$s. Our single-shot time-domain sensitivity ($\delta q = 5.3 \times 10^{-5}e/\sqrt{\text{Hz}}$) differs by close to a factor of 10 in comparison to our frequency-domain measurements ($\delta q = 4.4 \times 10^{-6}e/\sqrt{\text{Hz}}$ which are averaged) and highlights the need for a low-noise measurement setup in addition to a near quantum-limited detector. In this regard we note that the time-domain sensitivity is a more appropriate parameter characterizing the time required to perform a single-shot measurement.

In the above treatment we have neglected the effects associated with telegraph noise originating from charge traps that are strongly coupled to the SET. These large discontinuous jumps have the potential to compromise readout in two ways: (1) high frequency switching events that occur during the measurement time greatly increase the time required to...
achieve high readout fidelity and (2) slower fluctuations can produce readout errors if they occur in the time interval between calibration and readout. In this context calibration is the process of mapping the basis states of the qubit to characteristic output signal levels of the SET. This calibration process is essential and places additional constraints on the requirement for detector stability.

In an effort to study the effect of telegraph noise on readout we have used the twin rf-SET to measure the charge state of a double dot system. In this experiment, electrons are adiabatically transferred between two aluminum metal dots using an electric field established by the adjacent electrodes (A1 and A2) shown in Fig. 1. This charge motion is simultaneously detected by two rf-SETs located either side of the double dot. Gates G1 and G2 (see Fig. 1) are used to keep the rf-SETs biased to charge sensitive regions by nulling the direct effect of the A gates on the SETs. For the architecture used here the induced charge signals on the SET islands due to charge transfer in the double dot is of order 0.1e.\textsuperscript{16} Cross correlation of signals from the two rf-SET permits suppression of spurious charge noise that originates from fluctuating charge traps in the surrounding material system. Although we have previously applied correlated measurements to suppress the effect of telegraph noise occurring on the time scale of minutes in dc-SETs,\textsuperscript{16} the present work demonstrates our ability to detect the motion of single electrons on submicrosecond time scales and distinguish, in real time, transfer signals from background charge noise. In further contrast to our previous work,\textsuperscript{16} the rf measurement techniques demonstrated here facilitate the study of high frequency charge noise and its influence on readout fidelity for time scales commensurate with solid-state quantum computing.

Figure 4(a) shows the simultaneous response of both rf-SETs to electron motion between the two dots. The characteristic sawtooth behavior arises from the polarization of the metal dots by the electric field [from gates A1 and A2, see Fig. 4(c)], followed by a tunnel event when the field overcomes the charging energy of the double dot system. The signals are in antiphase as one SET senses the departure of an electron and the other its arrival. Using a multichannel digital oscilloscope it is possible to multiply the derivatives of the signals and thereby perform a real-time cross correlation. Sharp peaks are produced in the correlation whenever a tunnel event occurs, as shown in Fig. 4(b).

Figure 4(d) shows the result of a single-shot measurement of the charge state of the double dot system. In this instance telegraph noise affected the output of SET2 but not SET1 as indicated by the shaded region of the figure. By comparing the signals from both SETs we are able to register that an effective readout error has occurred. We believe that such detection schemes may be of importance in maintaining high readout fidelity, in the presence of charge noise.

Charge noise is unavoidable in the solid state. In systems where the rf-SET is used to perform readout, charge noise serves to reduce readout fidelity and limits the minimum charge signal detectable in a single-shot measurement. We note that these constraints are an important consideration for the feasibility and design of readout architectures for both quantum computers and classical nanoscale devices. For architectures that have capacitive coupling to the readout detector similar to our nanoscale device [such that \( \Delta q > 0.01 \) see Fig. 1(b)] the influence of \( 1/f \) noise is negligible, provided readout can be performed on time scales <10 \( \mu s \). Note that even for this case however, the presence of telegraph noise presents a challenge to high-fidelity readout. The cross-correlated single-shot measurements of a nanoscale device presented here, serve to illustrate that this challenge can be overcome by correlating signals from two rf-SETs. In conclusion we have investigated the rf-SET as an efficient and sensitive readout device capable of detecting the motion of single electrons on submicrosecond time scales, even in the presence of both \( 1/f \) and telegraph charge noise.

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