Operating Temperature Dependence of QDOGFET Single-Photon Detectors

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Abstract: We report on the temperature dependence of the photosensitivity of a quantum dot, optically gated, field-effect transistor (QDOGFET) that uses self-assembled semiconductor quantum dots embedded in a high-electron-mobility transistor to detect individual photons of light. Paramount to the operation of the device is differentiating weak, photo-induced signals from random fluctuations associated with electrical noise. To date, QDOGFETs have only been shown to be single-photon sensitive when cooled to 4 K. Here, we study noise spectra of a QDOGFET for sample temperatures ranging from 7-60 K and discuss how the noise affects the sensitivity of the device when operated at elevated temperatures. We show that the QDOGFET maintains single-photon sensitivity for temperatures up to 35-40 K where increases in operating temperature can be traded for decreases in signal-to-noise ratio.

Introduction

Single-photon detector (SPD) development is crucial to the advancement of quantum information technologies and measurement science. More effective SPDs are needed to improve the security of quantum communication systems based on quantum-key distribution (Hiskett *et al.,* 2006) and to extend the link lengths and data rates of deep-space communications (Mendenhall *et al.,* 2007; *Hemmati et al.,* 2007; *Boroson et al.,* 2004). SPDs are fundamental tools for quantum optics experiments and also impact the areas of observational astronomy, medical diagnosis and imaging, and light detection and ranging (LIDAR) (Priedhorsky *et al.,* 1996). In general, desirable characteristics for SPDs include high detection rates, low dark counts, and high detection efficiency. Some applications require detectors that are not only sensitive to single photons, but that can also count the number of incident photons that arrive simultaneously. Photon-number resolution is critical for the realization of linear optics quantum computing (Knill *et al.,* 2001), impacts the security of quantum communications (Brassard *et al.,* 2000), and is useful for studying the quantum nature of light (Giuseppe *et al.,* 2003; *Waks et al.,* 2004; *Achilles et al.,* 2006; *Waks et al.,* 2006). In addition, for many commercial applications, SPDs must be compact and exhibit modest power and cooling requirement for operation.

In this work, we investigate how the photosensitivity of QDOGFETs (quantum dot optically gated field-effect transistors) depends on operating temperature. In these novel SPDs, quantum dots (QDs) are embedded in a specially designed high-electron-mobility transistor (HEMT) and used as optically addressable floating gates. The QDOGFET structure and principles of operation are illustrated in Fig. 1(a), and are described in further detail by Rowe *et al.* (2006), Gansen *et al.* (2007) and Rowe *et al.* (2008). A photon is detected when it is absorbed in the structure and electrically charges a QD with a photo-generated hole carrier. The charged QD makes itself known by altering the electrical current that flows through the surrounding

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transistor. The photoconductive gain associated with the persistent photoconductivity makes QDOGFETs sensitive enough to detect individual photons of light. Previous reports demonstrate that when cooled to 4 K, QDOGFETs exhibit single-photon sensitivity with high internal quantum efficiency (Rowe *et al.*, 2006) and, moreover, can accurately discriminate between the detection of 0, 1, 2, and 3 photons 83% of the time (Gansen *et al.*, 2007; Rowe *et al.*, 2008). While persistent photoconductivity lasting for hours has been demonstrated for temperatures as high as 145 K (Finley *et al.*, 1998), previous demonstrations of the single-photon sensitivity of QDOGFETs have been limited to operating temperatures of 4 K, where thermally activated noise sources are minimized.

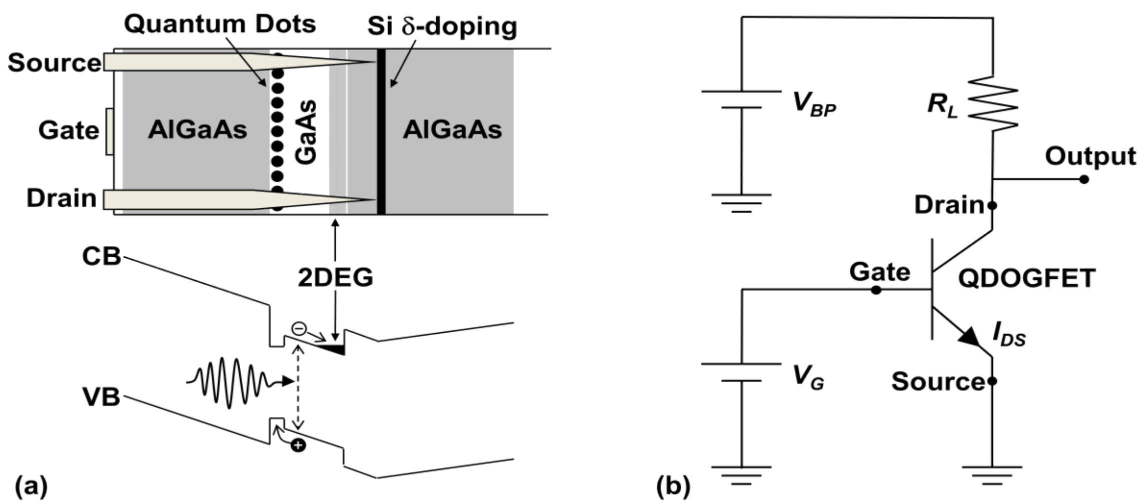

Figure 1. (a) Schematic diagram of the composition and band structure of the QDOGFET single-photon detector. CB and VB denote the conduction band and valence band, respectively, and 2DEG denotes the two-dimensional electron gas. (b) Detection circuitry used to characterize the electrical noise and photoresponse of the QDOGFET.

Here we present the results of a systematic study, where we measured the noise spectra of a QDOGFET for different sample temperatures and use a mathematical framework that was recently developed to determine how the sensitivity of the detector will vary with temperature. We show that for temperatures between 7 – 60 K, the QDOGFET exhibits a high degree of $1/f$ noise [*i.e.* the power spectral density (PSD) of the noise is inversely proportional to frequency] for a frequency range of at least 100 kHz and that the noise increases as a function of temperature. Following the mathematical formalism developed in previous work (Rowe *et al.*, 2010), we use the noise data to map the signal-to-noise ratio (SNR) of the detector's single-photon response as a function of temperature and measurement frequency. Our analysis indicates that QDOGFETs can operate over a broad range of temperatures, where increases in the operating temperature can be traded for decreased sensitivity. We show that the QDOGFET can detect photons with a SNR greater than 3:1 at a measurement frequency of 50 kHz for temperatures up to 35-40 K.

This work highlights a potential advantage QDOGFETs have over a number of the top performing SPDs that are currently being developed. Many of today's detectors that have set the standard for detection rate, photon-number resolution, and detection efficiency operate at temperatures well below 10 K. For instance, superconducting transition-edge sensors (TESs) (Miller *et al.,* 2003; Lita *et al.,* 2008; Calkins *et al.,* 2011) provide excellent photon-number resolution and detection efficiency at visible and infrared wavelengths; however, they operate at ~100 mK. In addition, superconducting nanowire single-photon detectors (SNSPDs) (Lolli *et al.,* 2012; Gol'tsman *et al.,* 2001; Baek *et al.,* 2009; Shibata *et al.,* 2010; Baek *et al.,* 2011; Dorenbos *et al.,* 2011; Il'in *et al.,* 2012; Hadfield *et al.,* 2005) and photon-number-resolving arrays (Divochiy *et al.,* 2008) are known for their picosecond response times (Hadfield *et al.,* 2005), but are typically cooled to 3-4 K. Alternatively, visible-light photon counters (VLPCs) (Waks *et al.,* 2003; Waks *et al.,* 2006) that utilize avalanche multiplication operate at 7 K. QDOGFETs are novel alternatives to these detector technologies and may be employed for applications where cooling to below 10 K is not feasible or where tolerance to temperature fluctuations is required.

QDOGFET Detection System

Fig. 1(b) shows a schematic of the detection circuitry used to operate the QDOGFET. The QDOGFET and load resistor (R_L) were mounted on the same temperature tunable cold stage of a liquid helium cryostat and biased with a DC voltage supply, V_B. A thin-film resistor that exhibited a resistance of approximately 100 kΩ at room temperature was used as the load in the circuit. The $GaAs/Al_{0.2}Ga_{0.8}As$ QDOGFET exhibited an active region that was approximately 2 μm x 2 μm and contained InGaAs quantum dots. The QDOGFET was reversed biased with a DC gate voltage, V_G, that produced maximum transconductance, as desired for photodetection. When illuminated, photo-induced changes in the transistor current, I_{ds}, were read out as voltage changes at the circuit output.

We measured the electrical noise in the output voltage by amplifying the signal and sending it to a spectrum analyzer. Measured in this way, the total noise can be separated into three major contributions: the QDOGFET noise, the thermal noise associated with the load resistance, and the noise produced by the amplifier. The PSD (in units of V^2/Hz) of the measured noise can be expressed in terms of the circuit parameters as

$$N_V = G^2 (R_Q \parallel R_L)^2 (N_Q + N_L) + G^2 N_{VA}, \qquad [1]$$

where G is the voltage gain of the amplifier; R_Q is the total resistance of the QDOGFET (*i.e.* the combined resistance of the transistor channel and contacts); N_Q is the PSD (A^2/Hz) of the of the QDOGFET noise; N_{VA} is the PSD (V^2/Hz) of the of the amplifier's input noise; and N_L is the thermal noise of the load resistor. When $V_B = 0$, the QDOGFET essentially behaves as a resistor and contributes thermal noise of magnitude $N_Q = 4k_BT/R_Q$; however, when a bias voltage is applied, the QDOGFET's noise contributions are modified.

Because we are interested in how the noise in QDOGFETs ultimately limits their sensitivity, we performed a systematic set of measurements that allowed us to remove the noise contributions of the amplifier and load resistor and determine the noise, N_Q, fundamental to the QDOGFET. At each fixed sample temperature, we measured N_V with V_B = 2 V and the noise spectra for V_B = 0, where only thermal noise contributes to N_Q. Because G, R_L, and R_Q all vary with temperature, we measured these parameters as well. To determine the noise contributions from the load and amplifier (second and third terms in Eq. [1]), we calculated the thermal noise associated with the QDOGFET using the experimentally determined resistance, R_Q, and then subtracted it from the data collected with V_B = 0. Once N_L and N_{VA} were known, we used them in conjunction with Eq [1] to determine N_Q with the bias applied. This procedure was repeated for selected temperatures between 7 K and 60 K.

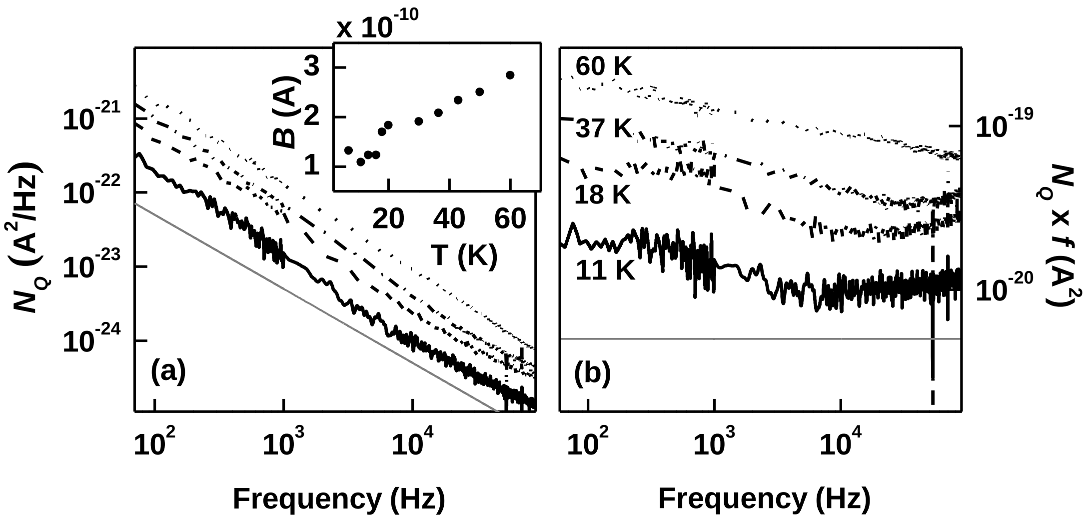

Figure 2. (a) PSD of the QDOGFET noise for select operating temperatures: 11 K (solid black), 18 K (dash), 37 K (dash-dot), 60 K (dot). (b) N_Q multiplied by frequency. The straight lines represent pure 1/*f* dependence and are shown for comparison. (Inset) The amplitude coefficient, *B*, of the 1/*f* noise as a function of temperature.

Results of Noise Measurements and Analysis

The PSD of the QDOGFET noise is plotted in Fig. 2(a) at four different operating temperatures. The noise spectra exhibit a high degree of 1/*f* character and grow in magnitude as the temperature is increased. In Fig. 2(b), we plot $N_Q \times f$ to accentuate the features of the spectra that deviate from pure 1/*f* noise. When displayed in this way, 1/*f* noise appears as a constant background, and any gradients in the data indicate additional contributions. To evaluate more quantitatively how the underlying 1/*f* noise increases with temperature, we fit the PSD measured at each temperature with a function that adds a single Lorentzian peak (with characteristic frequency f_L) to the 1/*f* contribution

$$N_Q(f) = \frac{L^2}{\left(f / f_L \right)^2 + 1} + \frac{B^2}{f} . \quad [2]$$

The temperature dependence of the amplitude coefficient, *B*, is plotted in the inset to Fig. 2(a). It increases from approximately 0.1 nA at lower temperatures to 0.3 nA at 60 K.

To determine how the increased noise observed at higher temperatures impacts the photosensitivity of the QDOGFET, we must also investigate how the photoresponse of the device changes with temperature. As illustrated in Fig. 1(a), the detector responds to light when a hole carrier excited by a photon in the absorption layer of the device is trapped by a QD. The charged QD screens the gate field, producing a change in the channel current, ΔI_{ds}, that persists for as long as the hole carrier is trapped in the dot. The detection circuitry shown in Fig. 1(b) converts this current change into a persistent change in the output voltage.

Noise in the output voltage can obscure week photo-induced steps; however, an effective way to reduce the impact of electrical noise when the arrival time of the photons is known is to apply an *average difference filter* (ADF) to the signal. An ADF integrates the signal over equal time intervals before and after the arrival of the light pulse and then takes the difference of the two integrated values. The un-normalized transfer function of an ADF filter is given by

$$W(f) = \frac{2}{i\pi f} \sin^2(\pi f \tau / 2) . \quad [3]$$

where τ is the total averaging time.

Recently, a mathematical framework was developed to predict the SNR of SPDs based on photoconductive gain when an ADF is employed (Rowe *et al.*, 2010). Within this framework, the filtered signal produced by a pulse of light is given by

$$S = \Delta D \tau / 2, \quad [4]$$

where $\Delta D = \Delta I_{ds} R_L$ is the amplitude of the photo-induced change in the output voltage. The change in the channel current caused by a photon depends on the parameters of the QDOGFET and surrounding circuitry and is given by $\Delta I_{ds} = g_m (eW)/(\varepsilon' A)$. In this expression e is the elementary charge, W is the epitaxial layer thickness, ε' is the electric permittivity of the material, A is the transistor active area, and $g_m \equiv \Delta I_{ds} / \Delta V_g$ is the transconductance of the QDOGFET in series with the load resistor. ΔD can subsequently be expressed as

$$\Delta D = \frac{g_m e W R_L}{\varepsilon' A} , \quad [5]$$

where the system transconductance is related to the fundamental transconductance of the QDOGFET, g_m^o, in the absence of a load resistance by $g_m = g_m^o[R_Q/(R_L + R_Q)]^2$.

Plotted in Fig. 3(a) is ΔD predicted by Eq. [5] using experimentally determined g_m and R_L values (plotted in the inset) and parameters appropriate for the geometry and composition of the QDOGFET. The material permittivity is taken to obey the weak temperature dependence reported by Strzalkowski *et al.* (1976). A notable characteristic of the photoresponse predicted by the model is that ΔD is relatively constant with temperature even though R_L and g_m have strong temperature dependences. The resistance R_L is approximately 100 kΩ at 60 K, but almost doubles as the temperature approaches 7 K. Since ΔD is proportional to R_L, this effect, in and of itself, should cause ΔD to increase as the operating temperature is decreased. However, ΔD is also proportional to g_m, which degrades as R_L increases. The competing dependences of g_m and R_L on temperature roughly cancel, resulting in little temperature dependence predicted for the total signal.

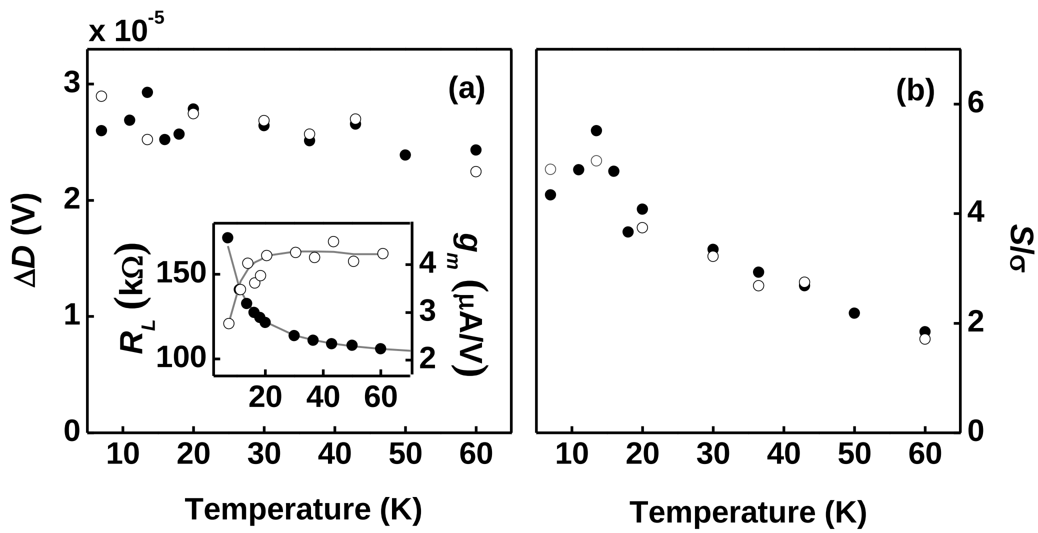

Figure 3. (a) The single-photon response, ΔD, measured optically (open circles) and predicted using Eq. [5] and parameters characteristic of the QDOGFET and circuitry (solid circles). (b) The SNR determined by optical measurements (open circles) and predicted by Eq. [7] using the experimentally measured noise spectra when an ADF with τ = 20 μs is used (solid circles). (Inset) The load resistance (solid circles) and transconductance (open circles) of the detection system as a function of temperature. The solid line curves are included as guides to the eye.

Once the photoresponse and the noise spectrum of the detection system are known, we can use the mathematical framework outlined by Rowe *et al.* (2010) to predict the SNR of the system's response to single photons. The ADF (Eq. [3]) filters the signal such that only noise frequencies close to the measurement frequency, $f_m = 1/\tau$, substantially influence the sensitivity of the measurement. Noise will produce fluctuations in the filtered signals, S, produced by single photons with standard deviation

$$\sigma = \left[\int_0^\infty W^2(f) N_V(f) df \right]^{1/2} . \quad [6]$$

Consequently, for a particular measurement frequency, the detection system will respond to photons with SNR given by the ratio of Eq. [4] to Eq. [6],

$$\frac{S}{\sigma} = \frac{g_m e W R_L}{2\varepsilon' A f_m} \left[\int_0^\infty W^2(f) N_V(f) df \right]^{-1/2} . \quad [7]$$

The SNR predicted by Eq. [7], given the measured noise spectra, are plotted as a function of operating temperature in Fig. 3(b) for a measurement frequency of f_m = 50 kHz. At the lowest temperatures studied, a SNR of approximately 5:1 is predicted. The ratio decreases to 2:1 at 60 K due to increased noise. In previous work (Rowe *et al.*, 2010), a SNR of 3:1 was chosen to be the benchmark for single-photon sensitivity. Using this benchmark, the data indicate that the detection system will maintain single-photon sensitivity up to operating temperatures of 35-40 K.

Experimental Verification

To check that the mathematical model properly predicts the behavior of the detection system shown in Fig. 1(b), we performed optical measurements with the system at a number of different operating temperatures. To test our predictions, we illuminated the device with a train of 4000 pulses of light from a diode laser that were properly tuned to be absorbed in the GaAs absorption layer of the QDOGFET. The light pulses were 15 ns in duration and were attenuated such that on average approximately one photon was detected per pulse. The detection system's bias conditions were the same as those used in the noise measurements. With a constant reverse bias applied to the QDOGFET, the system operates in continuous mode, where the QDs discharge randomly. By operating the device in this way, we avoided the additional noise contributions associated with electrically discharging the dots after each pulse of light (Rowe *et al.*, 2010).

In Fig. 3(a), we compare ΔD determined from the optical measurements to the signal calculated using Eq. [5] and the experimentally measured g_m and R_L. We determined ΔD from our optical measurements by using the ADF to determine the change in the output voltage produced by each pulse of light and then dividing the average change by the average number of photons detected per pulse, λ. The statistical method used to determine λ is described by Rowe *et al.* (2010). Overall, there is excellent agreement between the optical results and those predicted by our model.

To show that our model effectively predicts the sensitivity of the detection system, in Fig. 3(b) we compare S/σ determined from our optical measurements to the values predicted using the noise spectra. For the optical measurements, the standard deviation, σ, of the system's response to a photon was determined by applying the ADF 4000 distinct times to the output signal acquired in the absence of light [as described by Rowe *et al.* (2010)] and by removing contributions associated with the external amplifier. Again, there is very good agreement between the optically determined values and those predicted by the model.

Conclusions

We have investigated the effects of operating temperature on the photosensitivity of QDOGFETs. We measured the noise spectra of a QDOGFET as a function of temperature, and detailed how the noise impacts the device's photosensitivity using a mathematical framework that was recently developed for detectors that employ photoconductive gain. We subsequently checked the validity of the model by performing optical measurements. Our study shows that QDOGFETs function as SPDs at temperatures above 4 K where increased operating temperature can be traded for decreased SNR. The QDOGFET system maintained single-photon sensitivity (based on a 3:1 SNR benchmark) for temperatures up to 35-40 K for a measurement frequency of 50 kHz.

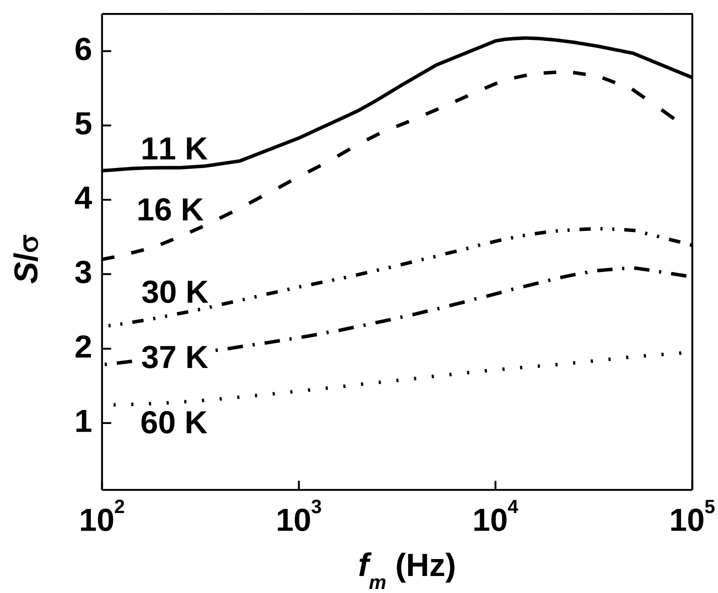

Figure 4. The SNR predicted by Eq. [7] as a function of the measurement frequency, $f_m = 1/\tau$, for a fixed load resistance of R_L = 100 kΩ.

The mathematical model used in this work provides a convenient way of determining the photosensitivity of a QDOGFET detection system once the transconductance and noise spectrum are known without the need to set up on optical measurement. Consequently, devices can be characterized quickly by performing a few simple electrical measurements. The model can be used to test yield (*i.e.* predict what fraction of the QDOGFETs produced are capable of detecting single photons) and to determine how changing the experimental parameters affects the sensitivity of the detection system. For instance, in Fig. 4 we show how the SNR varies with measurement frequency and operating temperature for a fixed load resistance, R_L = 100 kΩ. If the noise was strictly $1/f$ in nature, σ given in Eq [6] would be proportional to τ, and as a result, S/σ would be independent of f_m (Rowe *et al.*, 2010). In this case, the detector would operate at arbitrarily fast detection rates without losing sensitivity. The variations in the S/σ curves with f_m are caused by the non-1/f contributions to the noise (Fig. 2). Specifically, it is the Lorentzian contributions observed at low frequencies in the noise spectra that result in reduced SNR at those frequencies.

The SNR calculations shown in Fig. 4 were performed with R_L = 100 kΩ because this load resistance has provided good results in the past (Gansen *et al.*, 2007); however, improved performance may be possible by modifying the load resistance. System optimization will be the subject of future work.

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