Decomposition of Noise Contributions in QDOGFET Single-Photon Detectors

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ABSTRACT

We report on the noise characteristics 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, studies of the noise and the photoresponse of QDOGFETs have only been performed at sample temperatures of 4K and 77K. Here, we study noise spectra of QDOGFETs for sample temperatures ranging from 11-77K. Observed in the noise spectra are Lorentzian-shaped noise features riding on top of the fundamental 1/*f* noise of the device. We find that the Lorentzian noise features exhibit Arrhenius Law behavior.

INTRODUCTION

The ability to detect and count individual photons of light is of intense interest given today's growing interest in quantum information technologies. Single-photon detectors that can operate at high detection rates and with high detection efficiency are needed to extend the link lengths and data transmission rates of ultrasecure communication systems based on quantum-key distribution (QKD) [1] as well as in future interplanetary and deep-space communication systems [2-4]. Such detectors are also important components in the areas of medical diagnosis and imaging, light detection and ranging (LIDAR) [5], and astronomy. Furthermore, other applications require detectors that are not only sensitive to single photons but that can also resolve the *number* of incident photons that arrive simultaneously. Photon-number-resolving (PNR) detectors are a key enabling technology for linear optics quantum computing [6], impact the security of quantum communications [7], and are crucial measurement tools for studying the quantum nature of light [8-12].

While detectors based on avalanche gain [13, 14] and low-temperature superconducting materials [15, 16] are drawing a tremendous amount of research interest, we are investigating an entirely different method of detection that makes use of self-assembled semiconductor quantum dots (QDs). In these devices, referred to as QDOGFETs (quantum dot optically gated field-effect transistors), QDs are embedded in a specially designed high-electron-mobility transistor (HEMT). The structure consists of alternating layers of GaAs and AlGaAs with a single layer of InGaAs QDs positioned at the GaAs/AlGaAs interface, as shown in Figure 1. A thin layer of material that is doped with Si (denoted as δ-doping) provides excess electrons to the conduction band (CB) forming a two-dimensional electron gas (2DEG) at the GaAs/AlGaAs interface adjacent to the QDs. The detector is fabricated by depositing ohmic contacts, denoted as the source and drain, on the semiconductor structure; by etching a mesa between the contacts; and by depositing a semitransparent platinum (Pt) Schottky barrier gate across the mesa. The active area of the detector is defined by the gated portion of the mesa, which is typically about 4 μm^2 in size and encompasses about 2000 QDs.

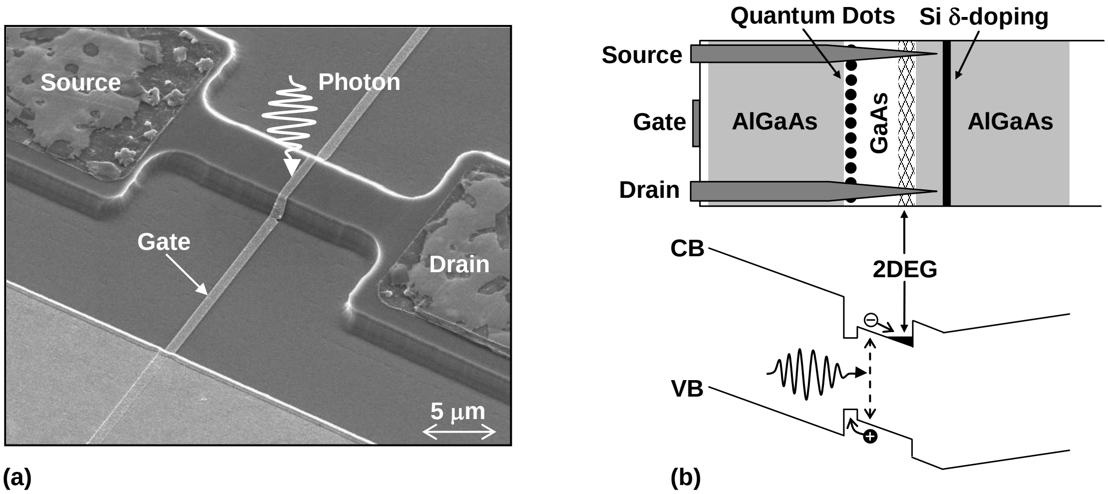

Figure 1. (a) Scanning electron microscope image and (b) schematic diagram of the composition and band structure of the QDOGFET. CB and VB denote the conduction band and valence bands, respectively.

The principles of operation of the QDOGFET are shown in the context of the band diagram of the structure in Figure 1(b). The device is designed to efficiently detect photons absorbed in the GaAs layer separating the 2DEG and the QDs. Key to detecting photons with this structure is that the conductivity of the 2DEG depends strongly on the electric field produced by the gate. When a photon is absorbed in the GaAs absorption layer, it excites an electron from the valence band (VB) to the CB leaving behind an empty state, or hole. With a reverse bias applied to the gate, the hole is swept by the internal electric field toward the QD layer, where it is trapped by a dot, while the excited electron is swept in the opposite direction, where it joins the 2DEG. Confined to a QD, the positively charged hole screens the internal field produced by the gate contact, subsequently changing the amount of current flowing in the 2DEG, as dictated by the transconductance, g_m, of the transistor. This change persists for as long as the hole is trapped in the dot. In the small-signal limit, the increase in the channel current (I_{ds}) caused by the trapping of N photogenerated holes in the QD layer is given by

$$\Delta I_{ds} = g_m \frac{eW}{\varepsilon' A} N, \quad [1]$$

where e is the elementary charge, W is the distance between the Pt gate and the QD layer, ε' is the electric permittivity, and A is the active area. Over time, the charging of the QDs caused by the capture of even a single photo-generated hole results in a large change in the cumulative charge transferred in the 2DEG. The *photoconductive gain* [17] associated with this process provides the detector with single-photon sensitivity. Moreover, because ΔI_{ds} is proportional to N, the channel response provides a direct measure of the number of detected photons.

Previously, we demonstrated that the QDOGFET can discriminate between the detection of 0, 1, 2, and 3 photons with 83% fidelity [18]; however, these studies represent only the first steps to developing practical PNR detectors and address only part of the potential functionality of these nanostructures. For instance, these initial measurements were performed at an operating temperature of 4 K. For practical applications, much higher operating temperatures are desired.

Paramount to detecting individual photons of light is differentiating weak, photo-induced signals from random fluctuations associated with electrical noise (*i.e.* the random fluctuation in the transistor current). In recent work [19], we investigate the spectral content of the noise from cooled QDOGFETs at two fixed temperatures (4 K and 77 K) and presented a mathematical framework for single-photon detectors based on photoconductive gain. In this work, we showed that the performance of such detectors can be determined through purely electrical measurements of their noise spectra.

Here, we extend our previous investigations of the noise in QDOGFETs by studying how the noise of these devices varies with temperature. The noise in GaAs/AlGaAs two-dimensional electron systems has been studied extensively [e.g. Ref 20 and references therein] due to its impact on the performance of many semiconductor devices, such as HEMTs and Hall-bar structures. In these previous reports, noise spectra characterized by Lorentzian-shaped noise superimposed on a $1/f$ background has been reported and various noise mechanisms discussed. The features observed in the noise spectra have been shown to depend strongly on the dimensions of the structure, the sample temperature, and applied gate fields. In regard to QDOGFET detectors, it is important to identify the noise mechanism in order to engineer better performing devices and to determine the performance trade-offs involved with operating the devices at temperatures higher than 4 K. In this work, we present noise spectra of QDOGFETS for sample temperatures ranging from 11-77 K. We show the existence of Lorentzian noise features riding on top of the fundamental 1/*f* noise of the transistor current. We create Arrhenius plots for the Lorentzian features and show that they are characteristic of thermally activated noise sources.

METHODS

We performed our noise studies with the QDOGFET connected to biasing amplification circuitry appropriate for operating it as a single-photon detector. The device was housed in a liquid helium cryostat on a temperature tunable stage. The output of the QDOGFET was amplified by a two-stage amplifier. The first stage of the amplifier was placed in close proximity to the QDOGFET and was cooled to the same temperature as the sample. The second amplifier stage was positioned outside of the cryostat and was held at room temperature. Under dark conditions (i.e. no laser light illumination), the amplified signal was measured using real-time spectrum analyzer. At each sample temperature, the amplification and noise spectra of the amplifiers were obtained. This allowed us to subtract the amplifier noise from the total noise present in the system, leaving only the noise spectrum characteristics of the biased QDOGFET.

Figure 2(a) shows a sample of our measurements, where the power spectral density, *N*(*f*), of the noise exhibited by the QDOGFET channel current is shown for a sample temperature of 13.5 K with an external gate bias of 0 V.

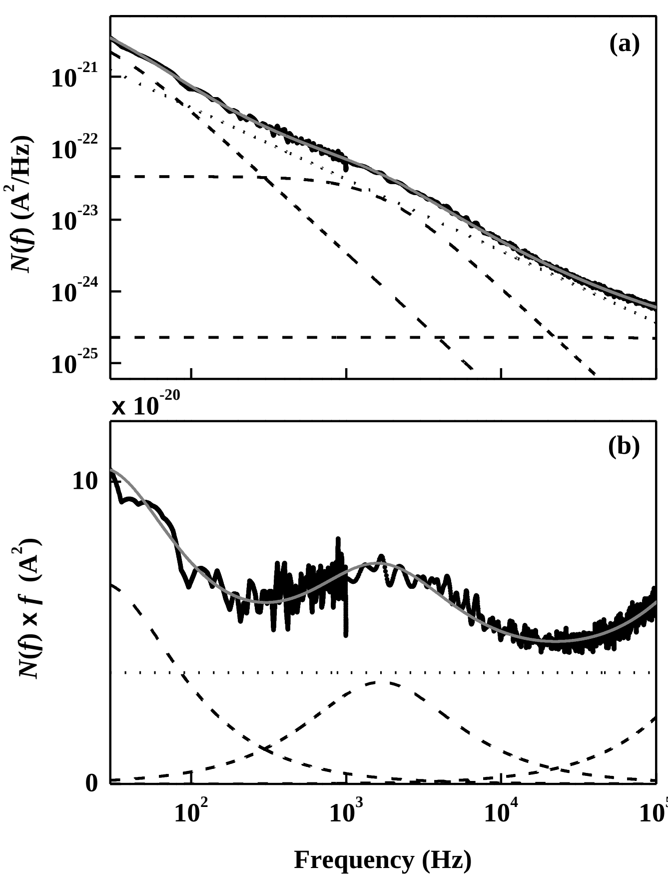

Figure 2. (a) Power spectral density, *N*(*f*), of the noise in the QDOGFET current for a sample temperature of 13.5 K and a gate bias of 0 V. (b) *N*(*f*) multiplied by the frequency. The solid gray line in each panel is a multiparameter fit to the data based on the functional form shown in Equation [2]. The Lorentzian and 1/*f* contributions are represented as dashed and dotted lines, respectively.

Also shown in the figure, is the result of a multiparameter fit to the data, where the functional form of the noise spectral density is given by

$$N(f) = \frac{A}{f} + \frac{B}{\left(f/f_B\right)^2 + 1} + \frac{C}{\left(f/f_C\right)^2 + 1} + \frac{D}{\left(f/f_D\right)^2 + 1} \quad [2]$$

Here, the first term represents the 1/*f* noise, while the three subsequent terms represent Lorentzian contributions with independent amplitudes and characteristic frequencies (f_i), where $i=B$, C, or D. The individual contributions of these four terms are represented by dotted and dashed lines in Figure 2. The data exhibits, to a high degree, a 1/*f* dependence; however, some subtle “knees” in the data characteristic of Lorentzian contributions are present. These Lorentzian features are more easily viewed in Figure 2(b), where *N*(*f*) is multiplied by the frequency. In this representation, the 1/*f* contribution results in a constant offset while each Lorentzian component produces a peak in the data, centered at its characteristic frequency. Portions of three Lorentzian features are observed in the data – one at a very low frequency, one at ~1.7 kHz, and one a frequency higher than 100 kHz.

RESULTS

Noise spectra obtained for a series of sample temperatures can be seen in Figure 3. In the figure, black and gray arrows are used to highlight the temperature dependence of two independent Lorentzian peaks. Notice that these features systematically move to higher frequencies with increasing temperature. This tendency is consistent with the behavior of thermally activated noise mechanisms.

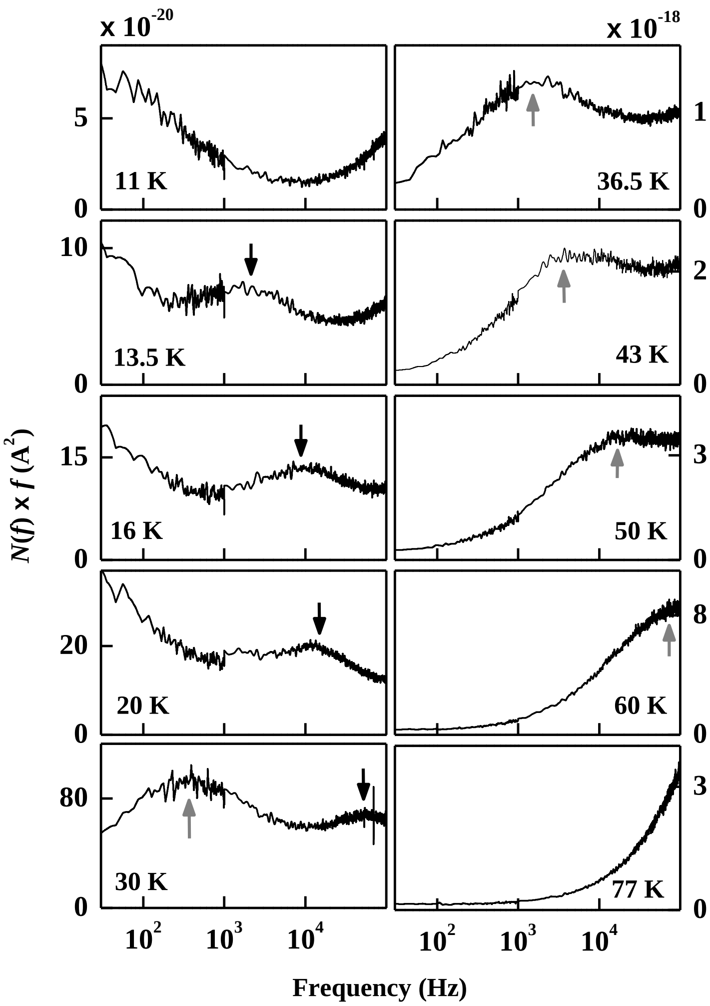

Figure 3. Noise spectra at selected temperatures for a gate bias of 0 V. Black and gray arrows highlight the temperature dependence of two independent Lorentzian noise features.

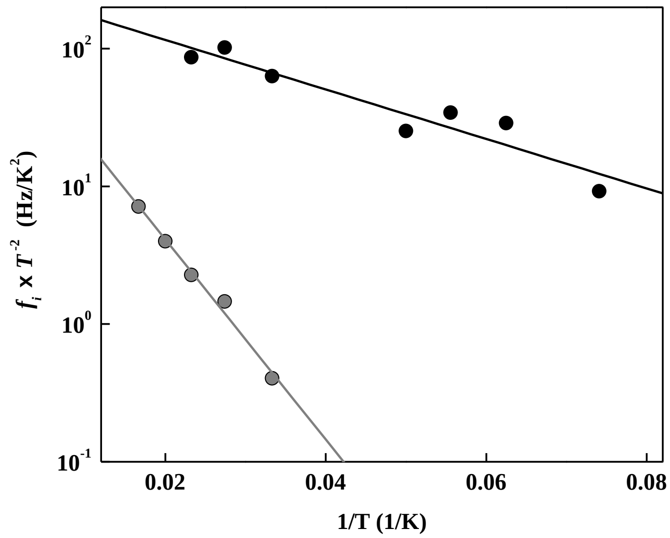

Figure 4. Arrhenius plot of Lorentzian noise features. The gray and black data points correspond to the features highlighted in Figure 3 by gray and black arrows, respectively. The lines are the results of fits to the data using Equation [3] where $f_o \sim T^2$.

CONCLUSIONS

We have performed a systematic study of the noise exhibited by QDOGETs as a function of operating temperature. In this work, we discussed the properties of noise spectra for sample temperatures ranging from 11-77 K. The data exhibit Lorentzian noise features riding on top of the fundamental 1/*f* noise. We created Arrhenius plots for the Lorentzian features and showed that they behave in accordance with Arrhenius Law for thermally activated noise sources.

The results of this work will be used to deduce the operational limitations of QDOGFET detectors and to engineer better performing devices. Previous studies of two-dimensional-electron systems point to a variety of different sources that can contribute noise. Further analysis of the data presented in this work will help ascertain which mechanisms contribute for our specific device makeup and geometry. Persistent photoconductivity in HEMTs has been observed at temperatures as high as 150 K [25]. Consequently, it should be the noise characteristics that ultimately limit the operating temperature of QDOGFET detectors. Among the top performing PNR detectors are those based on low-temperature superconducting materials [15, 16]. The stringent cooling requirements of these detectors are highly undesirable for practical applications. As a result, this work may demonstrate an advantage of QDOGFETs over competing technologies.

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