A Highly Sensitive Detector for Radiation in the Terahertz Region

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***Abstract*—In this paper, we report progress in the development of a detector for photons in the terahertz region consisting of a lateral quantum dot (QD), defined in a semiconductor heterostructure by mesa patterning and three negatively biased metallic gates, and a single-electron transistor (SET) on top of the mesa and, hence, capacitively coupled to the QD. We study the behavior of the QD as a function of the potential applied to the gates using the SET as a sensitive charge detector and identify the bias region of the device, where it is sensitive to incident terahertz radiation. The QD converts incident photons into charge excitations, which can be detected by the SET, resulting in a signal of the order 10^8 electrons for each absorbed photon. Based on the dark count rate and an estimate of the quantum efficiency, the detector should enable low-power measurements in the terahertz region with noise-equivalent power $\sim 10^{-19}$ W/Hz$^{1/2}$ exceeding the sensitivity of commercially available bolometers by two orders of magnitude.**

***Index Terms*—Quantum dot (QD), single-electron transistor, terahertz detection.**

I. Introduction

WITH RECENT progress in sources of terahertz radiation such as quantum cascade lasers and commercial availability of systems based on time-domain spectroscopy, the terahertz region of the electromagnetic spectrum has become increasingly accessible over the past few years. However, the most commonly used sensitive passive detectors are still based on semiconductor bolometers, which date back to several decades and typically achieve noise-equivalent power (NEP) $\sim 10^{-17}$ W/Hz$^{1/2}$ [1]. If the source of radiation is located at room temperature, the photon-shot noise of the radiation background sets the useful limit for detector sensitivity at the order NEP $\sim 10^{-16}$ W/Hz$^{1/2}$, which is within the range of bolometers. In this situation, novel types of detectors must either be frequency selective or combined with suitable filtering in order to provide any significant advantage over bolometric detection. However, in applications such as satellite-based earth observation, higher sensitivity is of direct benefit, and several new techniques, e.g., cold-electron bolometers [2] and detectors based on semiconductor quantum dots (QDs) [3], [4], have been developed recently. The latter have reached NEP $\sim 10^{-22}$ W/Hz$^{1/2}$, but these detectors are restricted to the laboratory environment as they require high-magnetic fields, dilution refrigerator temperatures, or precise control of the bias conditions.

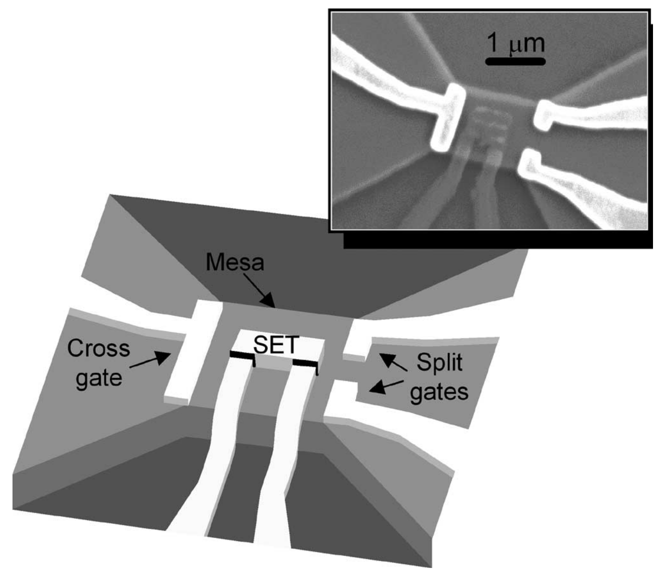

Fig. 1. Diagram and SEM image of the device. In the SEM image, the 2-DEG mesa is visible as a light-gray region and the gates appear white. The leads and island of the SET are visible in the center of the structure.

We report recent measurement results obtained with a quantum-dot-based detector similar to the devices in [5] and [6]. In particular, the behavior of the QD is studied under different operating conditions, and the device response to illumination from a black-body radiator and from a light pipe extending to room temperature is investigated.

II. Operating Principle and Experiment

The detector (Fig. 1) consists of a GaAs/AlGaAs heterostructure, which is mesa patterned by wet etching so that a narrow channel with a 2-D electron gas (2-DEG) of mobility

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$\mu \sim 10^6$ cm^2/Vs and carrier density $n \sim 2 \times 10^{11}$ cm^{-2} is obtained in the center of the structure. Three metallic gates are fabricated on top of the channel; a single gate extends across the whole width at one end of the channel (cross gate), while at the other end, the two remaining gates, which also act as a dipole antenna concentrating the terahertz radiation at the QD, protrude partially onto the channel (split gates 1 and 2). On top of the center of the structure, an aluminum single-electron transistor (SET) is fabricated, enabling detection of the charge state in the structure underneath [7].

The detector was operated in a top-loading ^{3}He system with a base temperature of approximately 300 mK. The measurement lines connecting to the device were low-pass filtered at room temperature to around 10 kHz. The SET was biased and read out by a purpose-built transimpedance amplifier, and the gate voltages were adjustable between 0 and -10 V, using a total of four 16-bit digital-to-analog converters and one analog-to-digital converter. The electronics was powered by an isolated supply and controlled by a computer via an optical-fiber ring interface.

Terahertz radiation was fed to the device by a 2-mm stainless-steel tube providing a near line-of-sight path from the source to the sample. In some of the experiments, a 5-kΩ resistor sealed inside a metal enclosure at the 1-K stage of the system was used as a black-body emitter. The other experiments were carried out with the tube extending all the way to the room temperature end of the probe, where it was terminated by a silicon window. In all our experiments, infrared and visible wavelengths were blocked by black polyethylene and single-crystal silicon filters at the 1-K stage.

The device is operated by negatively biasing the three gates so that the 2-DEG in the region underneath the gates is depleted and electrons in the center of the channel are separated from the 2-DEG, forming a QD. The potential landscape which determines the transparency of the barriers of the QD to the 2-DEG, and the properties of the QD itself, can be directly controlled by adjusting the gate potentials. The charge induced in the SET island, which is centered directly above the region where the QD is formed, is very sensitive to the charge configuration of the QD so that the formation and charge excitation of the QD can be observed directly.

Incident radiation can couple to the electrons in the QD via a collective excitation known as a Kohn-mode plasma oscillation [8] which decays rapidly into a single-electron excitation, whereby an electron can escape from the QD to the surrounding 2-DEG. This changes the charge-state of the QD, which is easily detected as a change in conductance of the SET. The QD relaxes after some time when an electron receives sufficient thermal energy to cross the barrier from the 2-DEG to the QD.

III. Formation and Manipulation of the QD

The SET island dimensions are on the order of 100 nm, resulting in a charging energy on the order of 250 μeV, and its normal-state resistance is on the order of 20–30 kΩ. As the experiments were carried out at temperatures below 1 K, the SET could be operated in the superconducting state, where the energy gap is determined by the superconducting gap. The highest charge sensitivity is obtained by biasing the SET at the Josephson quasi-particle peak. With constant voltage bias, the SET current exhibits Coulomb oscillations as a function of any of the voltages applied to the three gates (at small negative voltage settings). Fig. 2 shows gray-scale plots of the SET current as a function of the cross-gate voltage and one of the split-gate voltages. The split-gate voltage is varied within one line of the scan: the cross-gate voltage from line to line. The difference between Fig. 2(a) and (b) is due to the direction of the variation of the split-gate voltage, as indicated by the arrows.

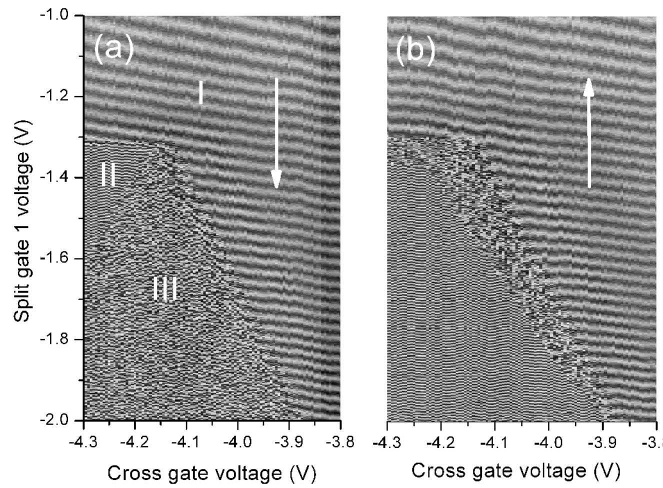

Fig. 2. SET current as a function of one split-gate and cross-gate voltage. The other split gate was held at -1.5 V. (a) and (b) cover the same voltage range but differ in scan direction, resulting in a different appearance of regions II and III, where the QD is formed.

At cross-gate voltages below -4.1 V, a boundary is reached as the split-gate voltage is reduced below -1.3 V [Fig. 2(a)]. At this point, the periodicity of the Coulomb oscillation with respect to the split gate in region I is reduced by a factor of about 4.6 in region II. As the split-gate voltage is further reduced, a second diagonal boundary is crossed, at which the periodicity seems to disappear (region III). Closer inspection of the data reveals, however, that in fact, Coulomb oscillations are still underlying this part of the plot but are obscured by a series of discrete shifts in gate voltage. The plot in Fig. 2(b) shows that when the scan direction is reversed, the boundary of the nonperiodic region has changed. Furthermore, when the scan direction is changed by 90°, i.e., the roles of split gate and cross gate are reversed, the nonperiodic region is adjacent to the boundary given by the split-gate-one voltage reaching -1.3 V, i.e., regions II and III roughly swap places (not shown).

We attribute this difference in the plots, with respect to the scan direction to a nonadiabatic behavior of the QD, when it is manipulated by varying the gate potentials. It is important to note that the applied voltage is not an absolute measure of barrier height and that the voltage scale for a particular gate can change upon temperature cycling of the sample. The behavior of the QD is illustrated in Fig. 3: The QD is formed at the boundary between regions I and II, resulting in an increase in the effective capacitance between the gates and the SET island [5]. This was confirmed in previous measurements, where the conductance of the mesa was measured as a function of gate

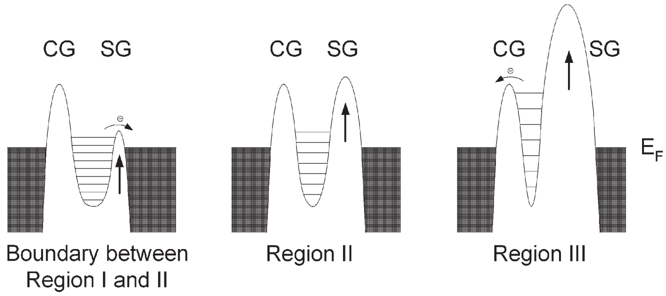

Fig. 3. Energy diagram of the QD for a scan in which the split-gate potential is decreased resulting in a metastable state of the QD in region III, where electrons tunnel through the cross-gate barrier.

potentials [6]. As the split-gate voltage is reduced further, toward region III in Fig. 2(a), the potential barrier due to this gate increases. At the same time, the QD is squeezed so that the chemical potential is increased, and at the boundary to region III, the barrier formed by the cross gate becomes transparent to tunneling of electrons from the QD to the 2-DEG. As this process is not correlated to the speed of the scan, discrete changes in charge appear randomly in this part of the graph. The same process takes place when the scan direction is changed by 90°, with the roles of the split gate and the cross gate reversed. When the scan direction is reversed (split-gate voltage starting from the most negative value), it is important to notice that in each line of the scan the split-gate potential prior to data acquisition had to be ramped to this value. Hence, the QD starts off partially depleted at the beginning of each line of the scan. As the split gate is made less negative during the scan, initially, no change in QD charge occurs and periodicity is observed. However, at some point, the chemical potential of the QD will be reduced below the Fermi level of the 2-DEG and tunneling into the QD becomes possible, probably through the cross-gate barrier, resulting again in a region with nonperiodic appearance.

IV. Terahertz Detection

In order to demonstrate operation of the detector at 300 mK, initially the 5-kΩ resistor at the 1-K stage was used as a source of radiation. By applying a voltage to the resistor, dissipating up to 10 mW, its temperature was increased above 1 K. Even though it is difficult to estimate the number of photons emitted, the resistor functions as a simple and useful source of terahertz radiation.

The highest sensitivity to this radiation is found when the detector is operated in region III near the boundary to region I. An absorbed photon causes an electronic excitation over the cross-gate barrier. In the time trace in the inset of Fig. 4, this can be seen as a sequence of switching of the SET conductance. The top trace was taken with the emitter switched off, showing only one switching event due to background-charge fluctuations. In the lower trace, the emitter is switched on, and the incident radiation causes switching at a rate beyond the time resolution of the experimental setup. The switching events in this trace correspond to electronic excitations due to photon absorption and subsequent relaxation. Time traces such as in Fig. 4 can be analyzed by counting the number of switching events, but

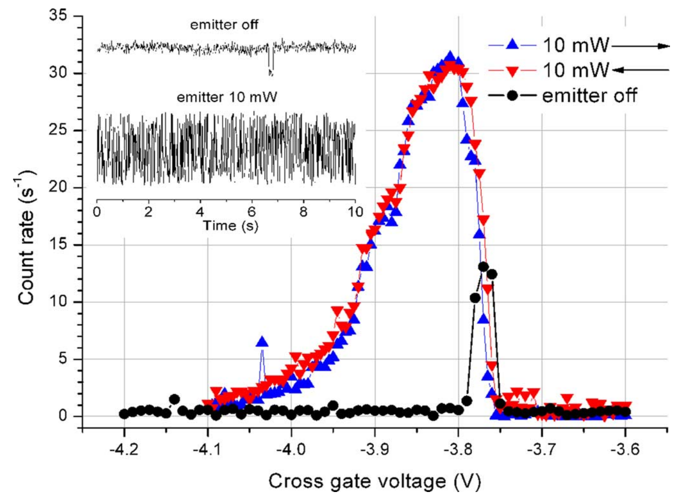

Fig. 4. Photon count rate as a function of the cross-gate voltage. Circles are without illumination, triangles are with 10-mW dissipation in emitter, with increasing (decreasing) cross-gate voltage for triangles upwards (downwards). $V_{\mathrm{SG1}} = V_{\mathrm{SG2}} = -1.4$ V. Inset: Time trace of SET conductance with emitter off (upper trace) and emitter dissipating 10 mW (lower trace). $V_{\mathrm{CG}} = -3.85$ V, and $V_{\mathrm{SG1}} = V_{\mathrm{SG2}} = -1.4$ V.

quantitative analysis is limited to count rates below about 30 per second due to the speed of the SET readout.

The count rate of time traces, with the cross-gate voltage as a parameter, is shown in Fig. 4. Without illumination, there is a small peak in the count rate at this boundary where the cross-gate barrier is low enough for thermal excitations to cause switching events in the QD. The count rate rapidly drops off as the cross-gate voltage is further decreased such that these events are strongly suppressed. When the device is illuminated by radiation from the black-body emitter, the count rate increases drastically at cross-gate voltages within 200 mV from the boundary of region III. In Fig. 4, this is shown for both increasing and decreasing cross-gate voltage, with no significant difference between these two data sets. It might be expected that a similar region of high sensitivity should also be found near the boundary between regions I and II, where excitations across the split-gate potential barrier should be possible. However, our measurements did not show comparable sensitivity in this region, probably because the pinch-off due to the potential barrier of the split gate, which occurs at a point where only a small constriction in the 2-DEG exists between the split gates, is much more sudden than in the case of the cross gate.

The NEP of a single-photon detector at a photon frequency ν is determined by the dark switching rate N and the quantum efficiency η (which is the fraction of photons detected per number of photons incident on the detector) so that NEP $=(2N)^{1/2}h\nu/\eta$ [1]. The dark switching rate N in the quantum-dot-type detector is given by the switching events caused by background-charge fluctuations at the bias point with the highest count rate under illumination; in our case, $N \sim 1/10$ s. The quantum efficiency of the detector, which depends on the coupling of the radiation into the antenna and the coupling between antenna and QD, neither of which was optimized in the device used here, is estimated as $\eta \sim 0.1\%$ [4]. This results in NEP $\sim 10^{-19}$ W/Hz$^{1/2}$ at a frequency of 0.5 THz. The dark

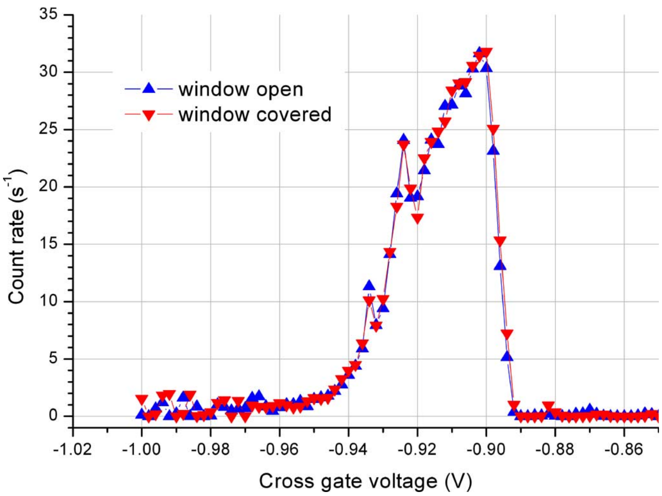

Fig. 5. Photon count rate as a function of the cross-gate voltage with a stainless-steel tube to room temperature and window at the top of tube open/covered (triangles upwards/downwards). $V_{\rm SG1} = V_{\rm SG2} = -1.6$ V.

count rate could effectively be reduced if one can discriminate between background-charge fluctuations and charge excitations due to photon absorption. This would be achievable by operating the SET in a charge-locked loop, resulting in an output signal proportional to the charge.

Higher order excitations have been observed in QD-type detectors [3], but these are not time-resolved in our setup. By improving the readout of the signal from the SET using a cold amplifier (eliminating cable capacitances) or operating the SET in a tank circuit (RF-SET) [9], these would be accessible, greatly improving the speed and the dynamic range of our detector.

The second set of photosensitive measurements was focused on detecting terahertz radiation from room temperature. For this purpose, the stainless-steel tube was extended to the top of the probe, with three filters inserted at the 1-K stage of the cryostat. In the subsequent measurements, the same device was used, but the sample had undergone a temperature cycle and this resulted in a different cross-gate capacitance, changing the periodicity and boundary with respect to the voltage applied to this gate. However, taking the different capacitance into account, it was easy to bias the device at the same point as previously and to measure the photon count as a function of the cross-gate voltage. The result is shown in Fig. 5 and is quite similar to the previous graph with the emitter at full power where the readout limits the count rate. Hence, it appears that radiation from the warmer parts of the system saturates the detection system. As an additional feature, there are two peaks at voltages of about -0.925 and -0.935 V, which are not present in the previous plot where only a slight enhancement of the count rate is visible at the corresponding points. The main purpose of this paper was to be able to detect radiation originating from a thermal source outside the cryostat, but as the detector was saturated with background radiation, we observed no contrast between the measurements with an open window at the top of the probe and with the window covered with black polyethylene. An ac technique using a chopper was also attempted but did not provide an improvement to the detection scheme. Ultimately, the background from the warmer parts of the system needs to be reduced below the saturation limit of the detector by adding more filter stages or using cooled optics for this experiment to succeed.

V. Conclusion

We have demonstrated operation of a photon detector at terahertz frequencies with simplified system requirements as compared to previous QD-type detectors. Detection at a device temperature of 300 mK has been achieved, at a level exceeding most sensitive detectors operating in similar conditions. The QD has a range of sensitivity of about 200 mV so that by adjusting the gate voltages, the spacing of the energy levels in the QD could be controlled. In combination with a linearized charge readout, this could enable frequency tuneability of the detector. Radiation from the warm parts of the apparatus presently prevents detection from an ambient source. This could be eliminated by using cooled components for the coupling of radiation into the detector. In addition, narrowband filtering or an ac technique could be used to reduce the thermal background and the dynamic range could be increased, enabling detection from an ambient source.

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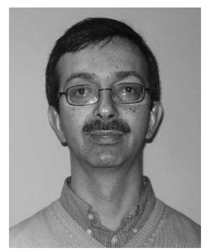

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