A Highly Sensitive Terahertz Photon Detector Based on a Semiconductor Quantum Dot

Peter Kleinschmidt, Stephen P. Giblin, Alexander Tzalenchuk, Leonid Kulik and Vladimir Antonov

Abstract— **We have developed a detector for photons in the terahertz region consisting of a lateral semiconductor quantum-dot (QD), defined in the two-dimensional electron gas (2-DEG) of a mesa-patterned heterostructure using three metallic gates, and a metallic single-electron transistor (SET) fabricated on top of the mesa. The SET is capacitively coupled to the QD. THz photons can be absorbed by the QD resulting in excitations associated with a change in charge-state of the QD, which can be detected directly as a change in the conductance of the SET. We characterize the detector by using radiation from a black-body emitter at the 1 K stage of our apparatus. Operation of the detector at a temperature of 300 mK is demonstrated and the noise equivalent power (NEP) is estimated to be of the order of $10^{-19}\,\mathrm{W}/\sqrt{\mathrm{Hz}}$ based on a dark count rate of 0.1/s and a quantum efficiency of the order of 0.1 %.**

I. Introduction

At THz frequencies, the thermal background of sources at room temperature limits the useful range of sensitivity for passive detectors to NEP~10^{-16} W/√Hz [1], accessible with semiconductor bolometers. In the absence of such a background, detectors with higher sensitivity are desirable. This situation may arise where the source is at a lower temperature, or if the characteristic of the source differs from that of a black body and the background can be eliminated by narrow-bandwidth filtering.

Detectors based on semiconductor QDs have achieved unprecedented sensitivity of the order of $NEP = 10^{-22}\,\mathrm{W}/\sqrt{\mathrm{Hz}}$ [2]. However, these detectors require temperatures below 100 mK and high magnetic fields (~ 4 Tesla), restricting applications to the laboratory environment.

The detector we have developed operates at 300 mK and without magnetic field, and has the potential to function at temperatures accessible with ^{4}He systems (~ 1 K).

This work was supported by the UK Department of Trade and Industry Pathfinder Programme, project ESQ01T3, and by the European Commission IP Teraeye.

P. Kleinschmidt, S. P. Giblin and A. Tzalenchuk are with the National Physical Laboratory, Hampton Road, Teddington, Middlesex, TW11 0LW, UK

L. Kulik is with the Institute of Solid State Physics, Russian Academy of Sciences, Chernogolovka, 142432 Russia.

V. Antonov is with the Physics Department of Royal Holloway, University of London, Egham, Surrey, TW20 0EX, UK

II. Detection Principle

The detector consists of a semiconductor QD coupled to a single electron transistor. The QD is formed in the two-dimensional electron gas of a mesa-patterned GaAs/AlGaAs heterostructure with a mobility of 10^6 $cm^2V^{-1}s^{-1}$ and a carrier density of 2×10^{11} cm^{-2}. Metallic gates on top of both ends of the mesa are negatively biased with respect to the 2-DEG, so that the 2-DEG underneath is depleted and the area in the centre of the mesa is pinched off, resulting in a QD containing of the order of 2000 electrons. The detector investigated here uses three gates, one of which (CG) extends across the whole width of one end of the mesa (cross gate), while the other two gates (SG1 and SG2) protrude partially on the other end of the mesa, forming a split gate.

The aluminium SET is fabricated on top of the structure, so that the SET island is located directly above the QD and capacitive coupling between island and QD is maximized. Due to the difficulty in fabrication, the charging energy of the SET is only of the order of 250 μV. However, since the device is operated at 300 mK, the SET is superconducting and the energy gap is extended to 4Δ ~ 700 μV, where Δ is the superconducting gap of aluminium. Inside the gap region of a superconducting SET an additional current peak appears due to the Josephson quasiparticle cycle. The SET is biased at this peak, where it is most sensitive to charge induced on the island.

The gate voltages are adjusted such that the mesa is pinched off and the QD is formed, but the potential barriers due to the depleted areas underneath the gates are low enough to allow excitation by incident radiation. In this regime, an incident THz photon can be absorbed by the QD, and the absorbed energy is sufficient for an electron in the QD to cross the potential barrier to the surrounding 2-DEG, leaving the QD in a different charge state. This is detected by the SET as a step change in conductance.

III. Characterization of the Quantum Dot

The quantum-dot is characterized by measuring the SET conductance as a function of the voltages applied to the three gates. At negative gate voltages above a device dependent threshold, Coulomb oscillations in the conductance of the SET are observed for all three gates (region A). This can be seen in the two-dimensional plot of figure 1, which shows the SET conductance as a function of the cross gate voltage (V_{CG}) and the voltage of one of the gates of the split gate pair (V_{SG1}), with the remaining gate (SG2) held at a constant voltage. The

scan direction within one line of this plot is from right to left, and from top to bottom between lines. In the region where the voltage V_{SG1} is below –1.35 V and V_{CG} below a threshold varying from –4.1 V to –3.9 V, depending on V_{SG1}, the characteristic changes (region B). This region shows periodicity in the cross gate voltage, albeit with a smaller period, but the dependence on V_{SG1} appears to be irregular and may not be resolved. In the narrow, triangular region adjacent to the boundary at V_{SG1} = –1.35 V, no periodicity is observed (region C). The observed change in periodicity is due to pinch-off of the mesa, which is associated with a change in the effective capacitance between the gates and the SET island.

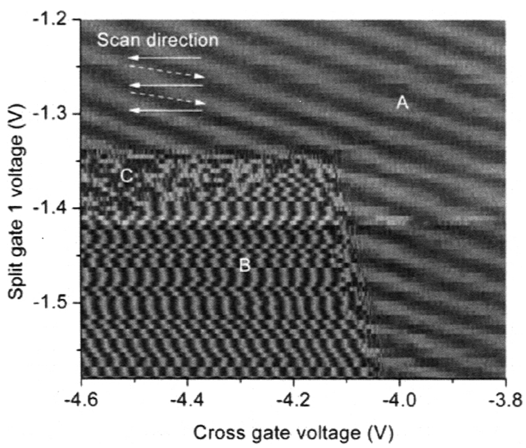

Fig. 1. SET conductance as a function of the voltages of the cross gate and one half of the split gate. V_{SG2} = –1.5 V, bias voltage 0.5 mV, T = 320 mK.

This behaviour is consistent with the results reported in [3], where the conductance through the mesa was also measured. In region B, the QD is completely isolated. However, as the cross gate voltage decreases further, the depletion area underneath this gate increases so that the confinement area of the QD is decreased. As a result, the levels in the QD are moved towards higher energies. Eventually tunneling through the other barrier becomes possible. The appearance in region C is due to a sequence of step changes which we attribute to a sequence of these tunneling events.

IV. Photon Detection

The detector is expected to be sensitive to incident THz radiation in region B and C, close to the boundary to region A, where the QD is isolated, but THz excitation is sufficient for electrons to escape.

The sensitive region of the detector was determined by illumination from a black-body emitter at the 1 K stage of our apparatus. The emitter was heated to an elevated temperature, estimated to be in the range of 10 K to 100 K. Unwanted radiation in the visible and infrared region was eliminated by silicon and black polyethylene filters.

Figure 2 shows SET conductance traces over identical voltage ranges with and without illumination. Illumination results in switching between different levels of conductance, caused by charge excitation of the QD. The SET conductance is an *e*-periodic function of the island charge. In addition, a low rate of switching events is observed at all voltage settings, even without illumination. This complicates the analysis of the data and prevents identifying the energy levels involved.

The sensitive region of the detector extends along the boundary between region B and A inside region B. Photosensitivity was also expected at the boundary between region C and A, but at this boundary, the photo response is very small. This is likely to be due to the particular shape of the potential landscape underneath the split gate, where the reduction of the potential first leads to the formation of a channel so that pinch-off only occurs when a large area underneath the gates is already depleted. Based on the dark-count rate and an estimate for the quantum efficiency, the noise-equivalent power can be calculated. The dark-count rate is of the order N = 0.1/s and the quantum efficiency is likely to be similar to that estimated by Astafiev et al. [4] for a similar structure and geometry as η = 0.1 %. At ν = 500 GHz, this results in $NEP = \sqrt{2N}h\nu/\eta \approx 10^{-19}\ \mathrm{W}/\sqrt{\mathrm{Hz}}$.

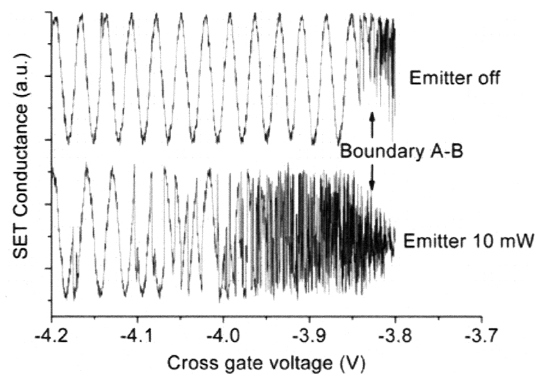

Fig. 2. Photoresponse at boundary A-B. $V_{SG1} = V_{SG2}$ = –1.34 V, bias voltage 0.5 mV, T = 300 mK.

V. Conclusion

A highly sensitive detector for THz radiation based on a quantum-dot device has been developed and characterized. The principle of operation of the detector at 300 mK has been demonstrated using a black-body emitter. Further development using linearized charge-readout is envisaged. Also, a higher operating temperature is desirable, as is characterization of the frequency response using a tunable source. Furthermore, the possibility of coupling radiation from outside the cryogenic system to the detector is being investigated.

References

[1] P. L. Richards, "Bolometers for infrared and millimeter waves", *J. App. Phys.*, vol. 76, pp. 1-24, July 1994.

[2] S. Komiyama, O. Astafiev, V. Antonov, T. Kutsuwa, and H. Hirai, "A single-photon detector in the far-infrared range", *Nature*, vol. 403, pp. 405-407, Jan. 2000.

[3] H. Hashiba, V. Antonov, L. Kulik, S. Komiyama, and C. Stanley, "Highly sensitive detector for submillimeter wavelength range", *Appl. Phys. Lett.*, vol. 85, pp. 6036-6038, Dec. 2004.

[4] O. Astafiev, S. Komiyama, T. Kutsuwa, V. Antonov, Y. Kawaguchi, and K. Hirakawa, "Single-photon detector in the microwave range", *Appl. Phys. Lett.*, vol. 80, pp. 4250-4252, June 2002.