Towards passive terahertz imaging using a semiconductor quantum dot sensor

L. Kulik[1], V. Antonov[2], S. Giblin[3], P. Kleinschmidt[3], and A. Tzalenchuk[3]

[1] Institute of Solid State Physics, RAS, Chernogolovka, 142432 Russia
[2] Physics Department, Royal Holloway, University of London, Egham, Surrey TW20 0EX
[3]National Physical Laboratory, Hampton Road, Teddington, Middlesex TW11 0LW

Abstract— **Passive terahertz imaging of high spectral sensitivity can be performed using a low temperature sensor coupled to an optical system delivering radiation from room temperature. We study this system in application to security screening and material analysis. Different types of low temperature sensors based on GaAs/AlGaAs quantum dots have been designed and characterised. The most sensitive sensor, which is able to detect individual terahertz photons, consists of a quantum dot coupled to a metallic single electron transistor. This sensor requires state of the art nanofabrication. A more robust but less sensitive sensor with relaxed nanofabrication demands, the point contact, is also being developed. The spectral sensitivity of the system is determined by the excitation spectrum of the quantum dot and spectral characteristics of the antenna. We designed a sensor to make an assessment of the combination of traditional log-periodic and near field antennae coupled to the quantum dot, and to compare performance of the sensors with single electron transistor and point contact.**

Index Terms—**Quantum dots, Single Electron Transistor, Terahertz Imaging**

I. Introduction

Terahertz radiation attracted a lot of attention in the last decade as the source of information for Biomedicine and Homeland Security. In contrast to X-rays, Terahertz radiation is not ionizing, hence a greatly reduced health risk. Compared to other inspection and imaging techniques it offers increased image contrast for differentiation between various soft materials and the possibility of chemical identification. Although imaging applications that employ Terahertz waves have been under consideration for many years, at present there is no system that can be fully implemented in practical situations. Main reasons for this are the very high cost of system components, fairly low brightness of incoherent far-infrared sources and relatively poor sensitivity of bolometric detectors. The most successful developments in this area are Time Domain Spectroscopy [1] and heterodyne microwave systems [2]. We study an alternative approach, passive imaging based on low temperature spectrally sensitive detectors [3]. A passive THz imager consists of an optical system forming an image of the object held at room temperature and bringing radiation to a low temperature detector, a system of filters, which squeeze the bandwidth of radiation to particular spectral lines and low-temperature spectral detectors based on Quantum Dots (QD). Advantages of our system over others are in its passive nature, remote operation and high spectral sensitivity.

Previously we have developed a detector, based on a QD sensor coupled to a Single Electron Transistor (SET), which offered ultimate sensitivity [3]. In this report we present a new design of QD spectral sensors for the Passive Terahertz Imager. The detector with the QD coupled to the point contact is less sensitive but it has relaxed nanofabrication requirements and operation conditions.

II. Operation principle and design of the sensor

The layout of the QD sensor is shown in Fig.1. The QD of about 1.3 μm in size is formed in a GaAs/AlGaAs

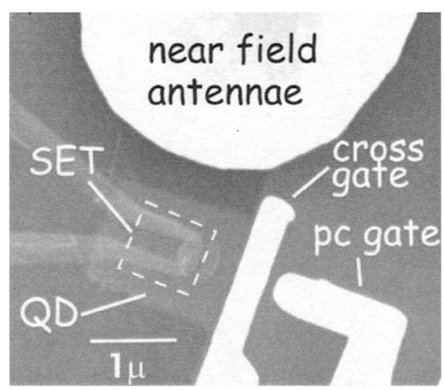

Fig. 1. SEM picture of the THz sensor. QD is formed mesa pattern and biased cross gate. Single Electron Transistor is set at the top of the QD to detect potential of the QD. The point contact is defined by cross and pc gate. Conductance of the point contact is affected by the charge state of the QD.

heterostructure, first by mesa etching and then by applying negative bias to a metal gate. The QD is situated some 100 nm below the surface and is weakly coupled to the two-dimensional electron gas (2DEG) of the heterostructure.

Mobility and concentration of the plain 2DEG are 8×10^5 cm^2/Vs and 2.4×10^{11} cm^{-2} respectively. Operation of the sensor is based on detection of a change of QD potential upon absorption of a THz photon. The THz photons induce plasma oscillations in the QD, which decay with excitation of an electron out of the QD. The QD acts as a photon-electron transducer. The next stage of the device is designed to pick up and amplify this effect.

An aluminum SET formed on top of the QD is essentially an ultra-sensitive electrometer capable of detecting a minute change in electric field. The SET responds to a small change in the electric potential by a large change in conductance, which can be measured by room-temperature electronics. When capacitively coupled to the QD, it allows detection of fractional changes in the number of electrons on it. Fabrication of SET devices is rather demanding, but also the operation temperature of the device is limited by the SET, realistically to below 1 K.

Time traces of the SET current are shown in Fig. 2. SET current drops once an electron is excited out of the QD, followed by recovery to the original value when an electron tunnels back to the QD. These events are seen in the figure as spikes of the SET current exceeding the noise level. Thus absorption of the photons by the QD can be recorded.

The same type of measurement, but having lower sensitivity, can be performed by using a point contact (PC) in the 2DEG in place of the SET. The PC is formed by applying negative potentials to a cross-gate and a pc-gate. The potential of the QD, which is determined by the number of electrons on it, is superimposed onto the static gate potentials. The size and hence the conductance of the PC is determined by the combined potential.

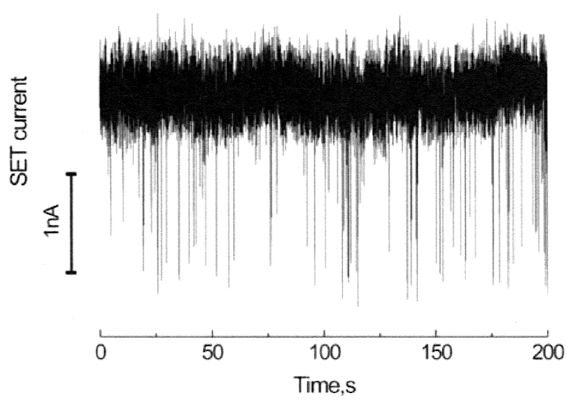

Fig. 2 Time traces of SET current measured at T=100mK. Spikes exceeding noise level reflects excitation and relaxation of the electrons out of the QD.

In this instance (fig. 1) we fabricated both the SET and the PC on one chip coupled to the same QD. This will enable us to perform correlated measurements and to compare the performance of the two readout devices.

The whole structure is placed in the focal point of a broadband, 0.2-2 THz, self-complementary log-periodic antenna.

The excitation spectrum of the QD has a resonance related to plasma oscillation. The half width of the resonance amounts to 2% of the frequency [4]. Further improvement of the spectral resolution can be achieved by using a near-field antenna. We placed the antenna next to the QD, see Fig.1. It has the shape of a rectangle with curved ends and spans 50 μm (~λ/2). The antenna plays a double role in our device. It singles out a narrow spectral range from the broadband radiation and concentrates the electric field to the position of the QD. Our modeling of this design gives the estimated amplification of the electric field at the center of the QD by a factor of 500.

III. Conclusion

We have designed and fabricated a QD sensor with two types of readout element: a single electron transistor and a point contact. The sensor is placed in a focal point of the broad band, 0.2-2 THz, self-complementary log-periodic antenna. An additional near-field antenna is placed next to the QD to select particular spectral lines of incoming radiation and concentrate the electric field in the vicinity of the QD. Correlated measurements of both readout elements, aiming to compare their efficiency, are underway.

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

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