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Single Far-Infrared Photon Detection Using an SET

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1. Introduction

Two-dimensional electron gas (2DEG) in a high magnetic field is a strong absorber of electromagnetic waves at cyclotron frequency. Due to this property, extremely sensitive detectors of far-infrared (FIR) can be developed [1]. Reduction of the sensitive 2DEG area together with effect of single electron transistor (SET) amplification [2], allows us to achieve single photon detection in the FIR range [3].

2. Device and Experimental Setup

The SET is fabricated by lithography techniques in the 2DEG of GaAs/AlGaAs heterostructure crystal with sheet carrier density n_s=2.6×10^{15} m^{-2} and mobility μ = 85 m^2/V·sec at 4.2 K. Metal gates are deposited on the top of the crystal as it is shown in Fig. 1. By negatively biasing the gates, laterally defined quantum dot (QD) with diameter about 0.5μm, weakly coupled to two reservoirs, is formed. At low temperature, transport through the QD takes place only when its electrochemical potential is in resonance with the reservoirs. Any small change of the QD potential results in shift of the resonance and can be detected as a switching off the current. To couple the small sensitive area of the QD to the FIR radiation with wavelength about λ=200μm, metal gates are extended on the distance of the order of λ, forming simple dipole antenna structure.

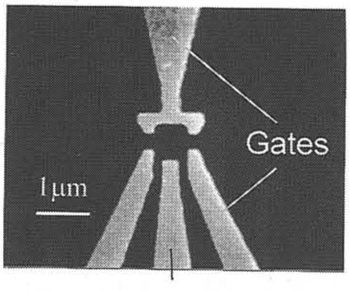

Fig. 1. SEM micrography of the sample.

The sample is situated in mixing chamber of a dilution refrigerator at temperature T≈70mK surrounded by superconducting solenoid. As an emitter of the FIR-radiation, we use long GaAs/AlGaAs Hall-bar device placed in a magnetic field of additional magnet in approximately 1 m far from the mixing chamber. When current is passed through the Hall-bar, an extremely weak radiation at cyclotron frequency is emitted and guided by metal tube to the sample through specially constructed silicon window in the mixing chamber.

3. Detection of Single Photons and Mechanism of Internal Polarization of the QD

When the control gate voltage is fixed at a position of resonant peak in a magnetic field range B=3.4–4.2 T, illumination of the sample by the FIR-radiation causes random telegraph-like noise switches of the conductance through the QD, as it is shown in Fig. 2. The switching rate strongly depends on the current through the emitter. Measurements of the conductance as a function of the control gate voltage show that new peak shifted in negative voltages is formed by the conductance spikes, while the illumination is turned on which is demonstrated in Fig 3. Moreover, at relatively high intensity of the FIR a few short spikes can be detected at the position of doubly shifted peak.

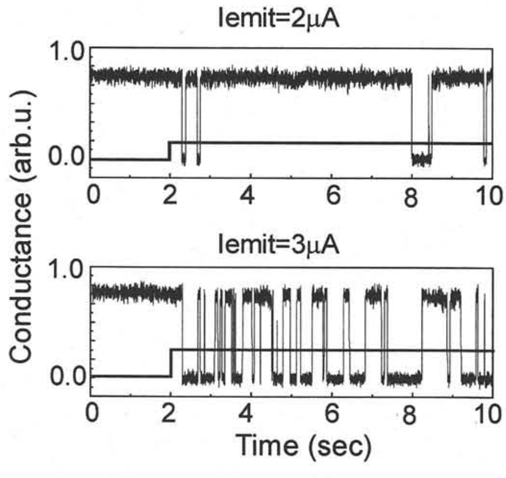

Fig. 2. Time traces of conductance in resonance peak maximum at two levels of the FIR-radiation. Step-like curves plot current through the emitter, which switches on at time t=2sec.

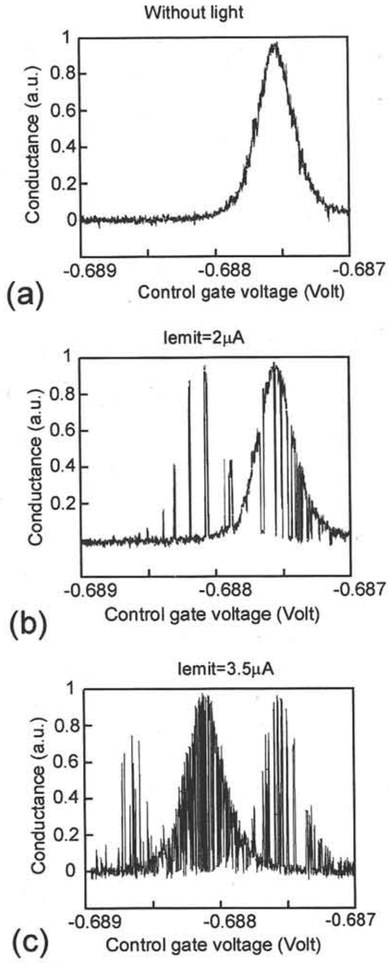

Fig. 3. Conductance peak as a function of control gate voltages: (a) without illumination, (b) at low photon flux, and (c) at relatively high photon flux.

We ascribe each switch of the conductance to excitation of the QD by single FIR-photon, which can be explained through a picture of internal polarization of the QD. In the high magnetic fields, energy spectrum of electrons is split into Landau levels. Fig. 4 schematically shows electron energy diagram of the QD for the magnetic field at which the first Landau level (LL1) is completely occupied, while the second one (LL2) is partially occupied (here we neglect spin splitting as it is much weaker in GaAs). Resonantly absorbed photon at nearly cyclotron frequency excites electron-hole pair as seen in the Fig. 4. Then, the electron and the hole rapidly release access energies through interaction with lattice and go, respectively, towards the center and perimeter of the QD. In other words, single photon absorption results in polarization of the QD because of transfer of one electron from the perimeter to the center of the dot. This drops the QD electrochemical potential and can be observed as switching off the resonant current. When the photon flux is high, multiple excitation becomes probable but our measurements show that the lifetime rapidly decreases with the number of simultaneously excited electrons.

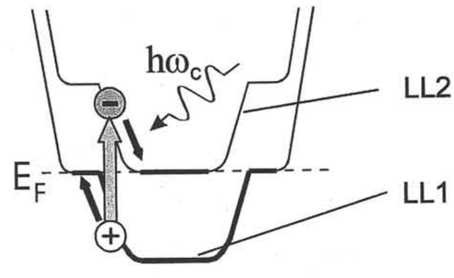

Fig. 4. Schematic representation of the excitation mechanism for the QD. By resonant photon absorption, electron-hole pair is excited. Then, the electron eventually goes to the center, while the hole to the perimeter of the QD.

4. Discussion

In the current experiments, we succeeded in detection of single photons for the wavelength range from 170μm to 220μm. This range can be drastically extended by either controllable change of carrier concentration or implementation of high frequency circuit (to detect shorter conductance switches). Lifetime of the excited states is varied from 1 msec (in low frequency measurements where 1 msec is an instrumental time constant) to 20 minutes, reaching the maximal value when the last electron remains on the LL2, and then rapidly drops. We should point out that the long lifetime is not an obstacle for measuring high photon flux because in such a case, one can measure switches in the position of the second or the third excited states, where the lifetime is drastically shorter. In these experiments, dark switching rate is so small that NEP recalculated for detector of power with similar sensitivity is equivalent to 10^{-22} W/Hz$^{1/2}$, which is about six order superior to the best available FIR detectors in this range. Temperature dependency investigation shows that the single photon detection regime can be possible up to 0.4K when the lifetime is of the order of seconds for the present device and hopefullwill be extended in future experiments by changing the sample geometry.

References

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