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Self quenched quantum dot avalanche photodetector for mid-infrared single photon detection

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HIGHLIGHTS

- A single photon detector (SPD) for mid IR wavelength is proposed and its performance is studied.
- The structure is designed for self-quenching operation.
- Dark count rate and detection efficiency of the proposed SPD is calculated at different temperatures.
- Dynamic operation of detector is studied by calculation of self-quenching and self-recovering times.

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ABSTRACT

In this paper a single photon detector with operating wavelength of 6 μm is proposed and its performance characteristics are studied. Intersubband absorption of single photons in quantum dot layers leads to creation of photoelectrons which are injected to multiplication region and under above breakdown condition a large output pulse is generated. The detector is designed for self quenching operation in which an additional layer called transient carrier buffer (TCB) is used for trapping of backward avalanche generated holes at the interface of TCB and charge layer. The accumulated holes impose an additional charge in such a way that the voltage across the multiplication region drops and the output is quenched. A model is developed to analyze the performance of detector and results of simulation predict detection efficiency about 12% at $T = 150$ K. Also the quenching and recovering performance of detector is studied and results show that both higher temperatures and higher bias improve dynamics of detector. However higher temperatures result in higher dark count rate.

1. Introduction

Detection of mid and long infrared lights is highly desired because of its wide applications in astronomy, medicine, imaging systems and free space optical communication [1,2]. On the other hands, studies of semiconductor quantum dots are very important from both a theoretical and technological perspective since they may lead to the fabrication of novel devices ranging from nano-transistors to semiconductor lasers and detectors [3–5]. Quantum dot infrared photodetectors (QDIP) are promising technology for detection of mid and long IR wavelengths with some advantages over other structures such as quantum well infrared photodetectors or low band gap detectors [6–8]. Some of these advantages arises from 3D confinement of carriers in quantum dots (QD) which leads to lower dark current and higher photoconductive gain [9,10]. However for the case that incoming signal is weak, the detector must be capable of single photon detection. In recent years Geiger mode operation of single photon detectors (SPD) have been reported in near IR wavelengths [11,12]. Extending the operation wavelength of a conventional SPD to mid and long IR can be attained by a detector which benefits the avalanche multiplication of a QDIP photocurrent.

Previously we proposed an avalanche quantum dot infrared photodetector (AQDIP) which can be used for detection of mid and long IR wavelengths [13] and a SPD working at mid-IR wavelength is proposed for the first time based on this structure [14]. For this SPD some additional layers are included in the structure of AQDIP for self-quenching and self-recovering operation. In this paper we study the optical performance of proposed AQDIP–SPD and the effect of additional layers on its dynamics. A theoretical approach is described to calculate detection efficiency and dark count rate (DCR) of detector as two important parameters of a SPD. In order to study the dynamics of device, we use the continuity equations to obtain a model of temporal behavior of multiplication region electric field and detector output current.

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The paper is organized as follows. In Section 2 device operation is described and Section 3 includes the optical performance and dynamics of SPD. The paper is concluded in Section 4.

2. Physics of operation

Schematic of the structure of proposed QD–SPD is shown in Fig. 1(a). As depicted in figure, the device has a separated absorption grading charge multiplication structure with an additional layer which is inserted between charge and absorption regions. The absorption region consists of 10 stacks of InAs/GaAs QD layers by which the incident mid and long IR wavelengths can be absorbed via intersubband transitions between electronic subbands. However because of low density of incident photons in counting mode and then lower photocurrents, thermally generated dark current might be in higher orders and considerably reduce the performance of device. Resonant tunneling (RT) barriers are included in absorption region to keep the dark current low enough for higher performance operation of detector. In this case only the energies in resonance with tunnel state of RT barriers are allowed to pass and other energies are stopped from contribution in current generation. The generated photocurrent is then a result of drifting the optically generated electrons from intersubband transition between QD states and tunnel state. By proper design of RT barriers the dark current can be reduced about 2–3 orders of magnitude [15]. Absorption region (QD layers and RT barriers) is designed such that the device shows peak absorption for $\lambda = 6\ \mu m$ incident photons. The peak wavelength can be tuned by design of RT barriers and QD size. On the other hands, for further reduction in dark current at operation bias, the electric field of absorption region should be keep at lowest possible values. A thin highly doped charge layer is used for nonuniform distribution of electric field across the device. Therefore at a certain bias, such nonuniform electric field sets the electric field of multiplication region at the highest order to reach breakdown while it keeps the field of absorption region low.

Under breakdown condition where the avalanche gain is very high, any generated photo-electron in QD layers which is injected to multiplication region, can trigger an avalanche and lead to a high detectable output current. However since the generated carriers travel in opposite sides, the generated current is multiplied in a feedback process and reach higher orders which can damage the detector. Hence after the detection, avalanche should be quenched by reducing the voltage across the multiplication region. Different mechanisms have been proposed for quenching of a SPD [16]. In free running mode, the detector is biased above breakdown and after detection, the voltage of multiplication region is reduced to below breakdown by passive or active circuits and consequently avalanche is quenched [17]. In gated mode operation detector is biased below breakdown and short period pulses are applied to elevate its voltage to above breakdown. Falling of the pulse leads to reduction in avalanche gain and hence quenching the output [18].

In our proposed device a carrier transient buffer (TCB) layer is used to create a valance band discontinuity by which the backward holes are trapped. The accumulated holes impose an additional charge in the interface of TCB and charge layer which leads to reduction of electric field in multiplication region and hence the avalanche is quenched. Such mechanism is called self-quenching where no external circuit is used for quenching of detector [19]. After quenching, the electric field of multiplication region should be restored to its above breakdown level which enables it to detect another incident photon. This process needs to deplete all accumulated holes from interface of charge and TCB layer which can be done either by thermionic emission or tunneling current. Detail of quenching and recovering can be seen in Fig. 1(b) which shows the valance band interface of TCB and charge layers.

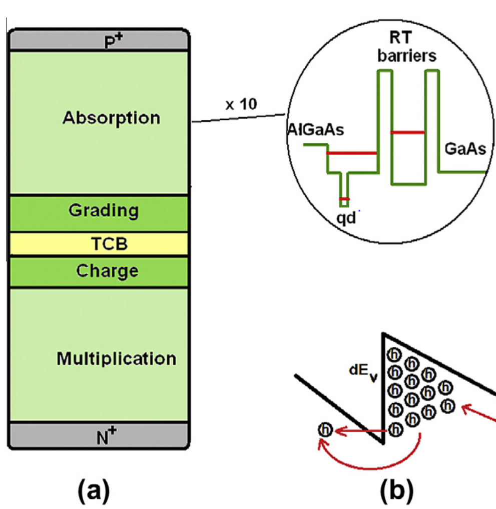

Fig. 1. (a) Schematic of layers of AQDIP–SPD. (Inset shows one stack of absorption region including RT barriers.) (b) Accumulation and extracting of incoming holes from multiplication region in the valance band discontinuity of charge and TCB layers.

3. Theoretical model and simulation approach

3.1. Optical performance

Detection efficiency of a SPD can be obtained from [20]:

$$\eta_{\text{det}} = \eta \cdot P_{br} \tag{1}$$

where η is quantum efficiency of absorption region and P_{br} is breakdown probability of multiplication region. Quantum efficiency (QE) of a QD layer can be calculated by [21]:

$$\eta = \Gamma \cdot (1 - \exp(-\alpha(\hbar\omega) \cdot l_{eff})) \tag{2}$$

where Γ is escape factor related to recombination mechanisms of electrons in QDs and is a bias and temperature dependent factor. As the temperature rises up, this factor decreases and leads to reduction in responsivity of QD absorption layers [22]. l_{eff} is effective absorption length and α is intersubband absorption coefficient calculated by the procedure of [23]. The breakdown probability, P_{br}, can be calculated for multiplication region using models developed before [24].

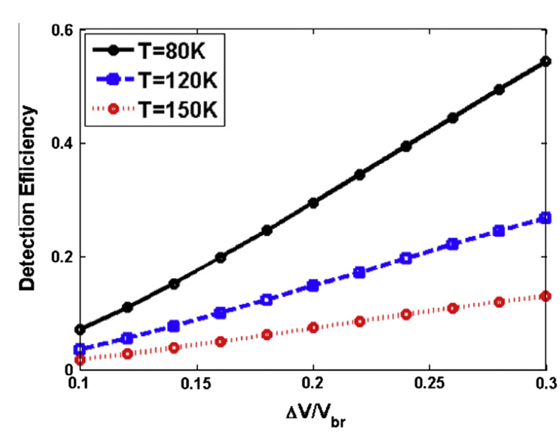

Fig. 2. Calculated detection efficiency of AQDIP–SPD vs. normalized overbias for different temperatures.