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Dark current model and characteristics of quantum dot infrared photodetectors

Gang Liu [a,*], Jianqi Zhang [a], Lixiang Wang [b]

[a] School of Physics and Optoelectronic Engineering, XiDian University, Xi'an City, ShaanXi Province 710071, China
[b] College of Computer Science and Technology, Shandong University of Technology, Zibo City, Shandong Province 255049, China

HIGHLIGHTS

- A theoretical dark current model of QDIPs is developed.
- The effect of the nonuniformity in size of dots on dark current is studied.
- The influence of various parameters on dark current is studied.

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ABSTRACT

Dark current of quantum dot photodetectors is one of the most important factors which affects the performance of the device. A theoretical dark current model of QDIPs is developed and presented in this paper. This model takes into account the influence of the distribution of activation energy in nanoscale mechanism due to the nonuniformity in size of quantum dots on dark current. The simulated results are in a good agreement with the experimental data, which shows the validity of the dark current model. Additionally, the influence of design parameters of QDIPs on dark current is also analyzed in the paper.
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1. Introduction

Infrared photodetectors are important for the variety of applications, including medical, earth resources, night vision, targeting and tracking, industry, and energy conservation applications [1–5]. Over the last 20 years, many researchers have paid more and more attention to the studies of quantum dot infrared photodetectors (QDIPs). Because the carriers are confined in 3-dimension, QDIPs are expected to reach higher performance including higher operating temperature, lower dark current and higher photoconductive gain [6,7].

It is well known that dark current is the current that flows in the infrared (IR) detectors even without the incident infrared light [8,9], which determines the signal to noise ratio and the maximum operating temperature of QDIPs [10]. Thus, it is important to minimize the dark current in the device design. A theoretical dark current model of QDIPs may be used to study and analyze the characteristics of the measured dark current, and more importantly, to improve design parameters of the device to reduce their dark current. In 2003, by counting the electrons density in the barrier, Liu developed a dark current model based on carriers drift under applied electrical filed [11]. In his model, activation energy is defined as the difference between the top of the barrier and the Fermi level in the dot. In 2010, Lin et al. studied the physical origin of the activation energy and developed a sequential coupling model to calculate the dark current [12]. In their model, two different mechanisms of the activation energy, nanoscale and microscale mechanism, were developed. Based on the former models and the studies of the carrier velocity, Liu and Zhang [13,14] and Bai et al. [15,16] developed a dark current model of QDIPs. However, the simulated results are smaller than the experimental data. The purpose of this paper is to develop a dark current model of QDIPs by taking into account the effect of the nonuniformity in size of dots on the activation energy. The dark current mechanism and the influence of various parameters on dark current are also studied and analyzed. Moreover, the calculated results are compared to the experimental data. Good agreement between both kinds of data has been obtained which shows the validity of the model.

2. Dark current model

A QDIP device is mainly comprised of active regions, top contact and bottom contact [17]. As Fig. 1(a) shows, the active region,

* Corresponding author.
E-mail address: liug517@126.com (G. Liu).

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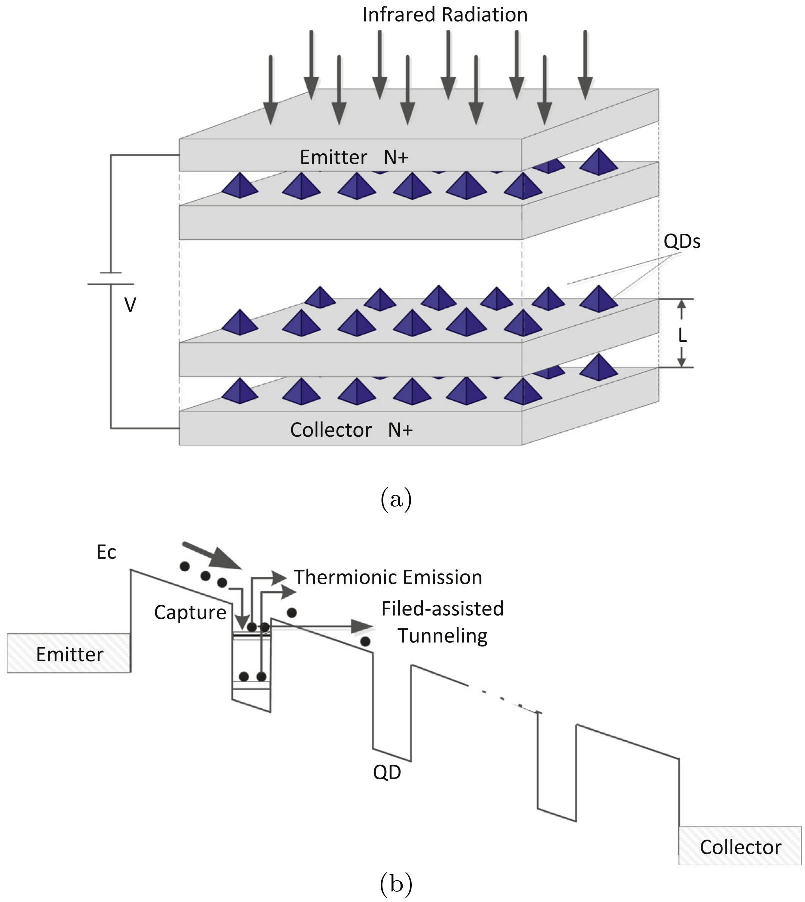

Fig. 1. (a) Schematic view of the QDIPs structure, (b) the device heterostructure schematic under dark conditions.

sandwiched between top and bottom contacts, is a multiple two-dimensional array of QDs separated by barriers. The top and bottom contacts are used as the emitter and collector, respectively. The incident infrared light is absorbed in the active regions, which results in electrons intraband transitions, in other words, subband–subband or subband-continuum transitions. Electrons injected from the emitter may be captured by QDs or drift toward the collector under the applied electrical field. The dark current is the current that flows arising from sources other than incident infrared light excitation mechanisms. As shown in Fig. 1(b), the free carriers associated with dark current mainly come from thermal emission and filed assisted tunneling. The dark current density can be estimated as [15]

$$\langle j_D \rangle = 2e\left(\frac{2\pi m^* K_B T}{h^2}\right)^{3/2} \exp\left(\frac{-E_a}{K_B T}\right)\mu F\left(1+\left(\frac{\mu F}{v_s}\right)^2\right)^{-1/2} \quad (1)$$

where e is the electron charge, m^* the barrier effective mass of electron, K_B the Boltzmann constant, h the Planck constant, E_a the activation energy depending on the total electron transport, F the applied electrical field, μ the mobility and v_s the saturation velocity of electron. In Eq. (1), the expression $2(2\pi m^* K_B T/h^2)^{3/2}\exp(-E_a/K_B T)$ and $\mu F(1+(\mu F/v_s)^2)^{-1/2}$ indicate the three-dimensional electron density in the barrier and the drift velocity under the applied electrical filed, respectively.

It has been proved that two different models of the activation energy, scilicet, micro- and nanoscale models, are coexist in QDIPs [21]. The total activation energy can be expressed as a function of the two different models

$$E_a = E_{0,m}\exp(-F/F_0) + E_{0,n} - \alpha F \quad (2)$$

where $E_{0,m}$ and $E_{0,n}$ are the activation energy under microscale and nanoscale electron transport mechanism at zero bias ($F = 0$ kV/cm), respectively. F is the applied electrical field. It is obviously that Eq. (2) can be divided into two parts, $E_{0,m}\exp(-F/F_0)$ and $E_{0,n} - \alpha F$, which are functions of the applied electrical field, and related to the activation energy under microscale and nanoscale transport mechanism, respectively. The activation energy under microscale is defined as the difference between the Fermi level and the top of the conduction band of the barrier, which is related to thermal emission [18]. The activation energy under nanoscale is defined as the ionization energy of the QD [19], which is related to tunneling mechanism. F_0 and α are fitting parameters and used to represent the change rate of E_a under the micro- and nanoscale, respectively. According to the mechanism of activation energy under nanoscale mechanism, the value of $E_{0,n}$ is related to the size of the QDs. Because of the presence of the fluctuations in size of QDs, a Gaussian distribution can be used to reflect the spread of activation energy in nanoscale of QDs

$$D(E_n) = \frac{1}{\sqrt{2\pi}\sigma_E}\exp\left(-\frac{(E_n - \langle E_{0,n}\rangle)^2}{2\sigma_E^2}\right) \quad (3)$$

where the Gaussian linewidth σ_E describes the spread of activation energy levels in nanoscale due to the fluctuations in size of QDs.

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