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Detectivity dependence of quantum dot infrared photodetectors on temperature

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HIGHLIGHTS

- A detectivity model of QDIP is derived by the equilibrium equation under the dark condition.
- The complexity of the change of the average electrons number in a quantum dot is analyzed in details.
- The influence of the detectivity on the temperature is discussed.

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ABSTRACT

The detectivity of Quantum dot infrared photodetectors (QDIPs) has always attracted a lot attention as a very important performance parameter. In the paper, based on the theoretical model for the detectivity with the consideration of the common influence of the microscale electron transport, the nanoscale electron transport and the self-consistent potential distribution of the electrons, the dependence of the detectivity of the QDIP on temperature is discussed by analyzing the influence of the temperature on the average electrons number in a quantum dot. Specifically, the average electrons number in a quantum dot shows different change trends (from the increase to decrease) with the increase of the temperature, but the detectivity presents the single decrease trend with the temperature, which can provide the designers with the theoretical guidance for the performance optimization of the QDIP devices.

1. Introduction

The detectivity is a very important performance parameters of QDIPs (quantum dot infrared photodetectors), and it embodies the detecting ability of the photodetectors. The bigger its value is, it means, the better the performance of the photodetectors is. And thus what related with the detectivity of the QDIP is always the hot topic problems concerned by researchers to obtain more high performance of the photodetectors [1–3]. Based on the device model of the QDIP proposed by Ryzhii [4,5], Rogalski and his coworker propose the physical model of the QDIP with the consideration of the continuous potential distribution of electrons and the electrons emission (including thermal emission and field-assisted tunneling emission) in 2009 [6]. In this model, the average electrons number in a quantum dot is estimated by the balance relationship of the current under the dark condition, and on the basis of this estimation value, the performance parameters such as responsivity and the detectivity are further simulated and calculated as functions of the electric field density and the temperature. In 2010, Mahmoud and his co-workers have rebuilt the device model by taking the effect of donor charges on the spatial distribution of the electric potential in the QDIP active region [7]. In this model, the average electron number in a quantum dot is quantized by the new current balance relationship, at the same time, the detectivity is recalculated and optimized by the analyzing the influence of the electric field density, temperature, and some structure parameters. In 2012, by the similar method, the detectivity model of the QDIPs is further improved with the consideration of the influence of the electrons transport including the microscale and nanoscale electron transport [8,9]. From the build process of these models, it can be found that the average electrons number in a quantum dot, which can be determined by the current balance relationship under dark condition, is the key parameter of the build process of these models, and it play an important role in the calculations of the detectivity. Hence, the influence of the average electron number in a quantum dot should be involved in the study of the detectivity. In this paper, it is with the consideration of the different changes of the average electrons number in a quantum dot with the increase of the temperature that the dependence of the detectivity of the QDIP on the temperature is mainly discussed and analyzed, which does not appear in previous literature. It can seen from our obtained results that the average electron number in a quantum dot shows the complex change tends (from the

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increase to decrease) with the increase of the temperature, whereas the detectivity presents a decrease trend with the increase of the temperature. These relationships between the complexity of the different change of the average electrons number in a quantum dot and the simplicity of the change of the detectivity are analyzed, and the corresponding reasons for the change tend of the detectivity with the increase of the temperature are discussed in details, which can provide the device designers with the reliable theoretical support for the detector optimization.

2. Model

QDIP devices detect an infrared light by electrons translation between the subband and the subband or the subband and the continuum in quantum dots, and mainly consist of the barrier layers and repetitive quantum dots layers [10]. As shown in Fig. 1, the QDIP consists of the top contact, a stack of quantum dots layers and bottom contact, where the top and bottom contacts are usually used as the emitter and collector, respectively, the stack of quantum dots layers sandwiched between the emitter and the collector is separated by the barrier layers. Each quantum dots layer is mainly composed of many periodically distributed identical quantum dots, and the lateral size of quantum dots is supposed as large enough, so each quantum dot has a large number of bound states to accept more electrons. However, the transverse size of quantum dots is smaller than the distance between the quantum dots layers to provide with the single energy level related to the quantization in the direction. Based on these assumptions, the detectivity model of the QDIP is derived with the consideration of the influence of the total electron transports (including the microscale electron transport and the nanoscale electron transport) and the continuous distribution of the electric potential in active region.

As what said above, when the QDIP device is irradiated by the infrared light, electrons transition will take place from the subband to the subband or from the subband to the continuum in quantum dots, and it will directly lead to the changes of the conductivity. It is via the quantization of the change of the conductivity that the detection of infrared light is accomplished in the QDIP. Hence, according to the photoconductive detection mechanism of the QDIP, with a thermal noise ignored, the detectivity of QDIP can be determined as [11]:

$$D^* = \frac{R_i\sqrt{A_d\Delta f}}{I_n} \tag{1}$$

where R_i is the current responsivity of the QDIP, A_d is the area of the QDIP, Δf is the width of the frequency, which is supposed as 1, I_n the noise current of the photodetector.

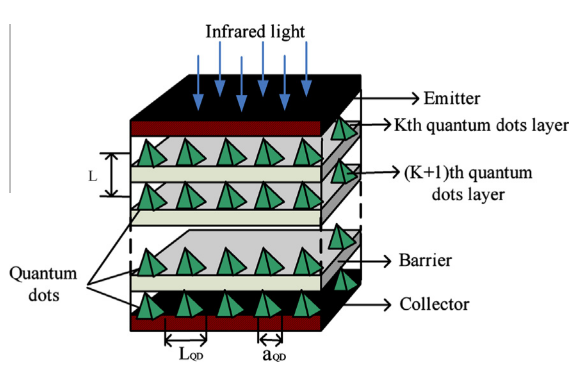

Fig. 1. Schematic view of the QDIP structure, where the triangular pyramids represent quantum dots.

In the QDIP, the noise is mainly from the generation–recombination (G–R) process of carriers, hence, according to the physical mechanism of G–R noise, the noise current of the QDIP can be shown as [12]:

$$I_n = \sqrt{4eg_nI_{dark}} \tag{2}$$

where e is the charge of an electron, I_{dark} the dark current, g_n the noise gain of photodetectors, which approximately equals photoconductive gain g_p in the QDIP.

Substituting Eq. (2) into Eq. (1), we can obtain the expression of the detectivity, which can be given as:

$$D^* = \frac{R_i\sqrt{A}}{\sqrt{4qI_{dark}g_n}} \tag{3}$$

The dark current of the QDIP can be calculated by the product of the dark current density and the area of the photodetector. Moreover, the dark current density can be calculated by counting the mobile carrier density in the barriers [11–13] in QDIPs, which is shown as:

$$\langle j_{dark}\rangle = 2ev\left(\frac{m_bkT}{2\pi\hbar^2}\right)^{3/2}\exp\left(-\frac{E_a}{kT}\right) \tag{4}$$

where e is the electron charge, v the drift velocity of electrons, m_b the effective mass of electron, k the Boltzmann constant, T the temperature, $\hbar$ the reduced Planck constant, E_a the active energy, which depends on the whole electrons transports including the microscale electron transport and the nanoscale electron transport, and it can be given as [14]:

$$E_a = E_{0,micro}\exp(-E/E_0) + E_{0,nano} - \beta E \tag{5}$$

where E is the electric field density, $E_{0,micro}$ and $E_{0,nano}$ respectively represent the activation energy under the microscale and the nanoscale transport at zero bias($E = 0$ kV/cm), E_0 and β describe the change rate of the activation energy under the microscale and the nanoscale electron transport mechanism with the electric field, respectively.

As well known to us, the current responsivity of the QDIPs, which is defined as the current of the detector per a unit of incident power, can be calculated by the ratio of the detector photocurrent to the incident photo flux power, and it can be written as follows

$$R_i = \frac{J_{photo}}{\Phi_s hv} = \frac{e\Phi_s\eta g_p}{\Phi_s hv} \tag{6}$$

where Φ_s is the incident photo flux density on a detector, which is supposed as 8×10^{17} photons/cm^{2}s [6], v the frequency of an incident infrared light, g_p the photoconductivity gain, and η the quantum efficiency, which is related to the average electron number in a quantum dot in the QDIP, and it can be shown as [6]:

$$\eta = \delta\langle N\rangle K\sum\nolimits_{QD} \tag{7}$$

where δ is the electron capture cross section coefficient, and it is adjusted to meet experimental comparison in our simulation, $\langle N\rangle$ the average electrons number in a quantum dot, K the total number of quantum dots layer in the QDIP, Σ_{QD} the quantum dot density in a quantum dot layer.

Substituting Eq. (7) into Eq. (6), we can obtain the expression of the responsivity, which can be shown as:

$$R_i = \frac{\delta eg_p\langle N\rangle\sum_{QD}K}{hv} \tag{8}$$

Substituting Eqs. (4), (5), (8) into Eq. (3), we can ultimately obtain the detectivity which can be written as: