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Physical model for the dark current of quantum dot infrared photodetectors

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ABSTRACT

Dark current has attracted much attention in recent years due to its great influence on the performance of the QDIP. In this paper, a model for the dark current is proposed with the consideration of the influence of the nanoscale electron transport on the dark current based on the dark current model proposed by H.C. Liu. The model permits calculating the dark current as a function of the electric field, and it can further estimate the photocurrent, the current responsivity and the detectivity via the current equilibrium equation under the dark condition. The results obtained show a good agreement with the experimental results and manifest the validity of the proposed model.

1. Introduction

With the expansion of detection fields, there may be more and more demands for the quantum dot infrared photodetector(QDIP) with a high performance in the future. Since the dark current can bring about the degradation on performance of the QDIP, it has caused an extensive concern to pursue the high performance QDIP devices [1–5]. According to the operating principle of the QDIP devices, the dark current should essentially depend on the electron transport process in the QDIP devices. Based on this fact, H.C. Liu proposed the dark current model [6,7] by counting the mobile carrier density in the barrier, and supposed that the dark current was only dependent on the contribution of the microscale electron transport. However, in fact, the nanoscale electron transport, which exists in the total electron transport process of QDIP devices [8–10], also has a very great impact on dark current, hence the influence of the nanoscale electron transport on the dark current should be considered in the dark current calculation. In the paper, we propose a model for the dark current, which is based on the dark current model proposed by H.C. Liu. This model improves the calculation of the activation energy, which is the characteristic parameter of the electron transport, in the previous dark current model with the consideration of the influence of the nanoscale electron transport on the dark current. As a result, the model including the common influence of the microscale and the nanoscale electron transport on the dark current makes the dark current calculation more accurate than that of the primal dark current model proposed by H.C. Liu. Furthermore, the model can also be used to estimate other performance parameters of QDIP devices. Specifically, by accounting for the current equilibrium equation between the new dark current and rates of electrons (including the capture rate and emission rate) under the dark condition, we investigate the main performance of QDIP such as the photocurrent, the responsivity and the detectivity to prove the correctness and feasibility of the model. The obtained results not only shows a good agreement with the experimental results, but also can provide the photodetector designers with the theoretical support and the experimental guidance in the pursuit of the high performance of the QDIP devices.

2. Dark current model

In general, the QDIP device is mainly composed of barrier layers of excited regions and repetitive quantum dot composite layers [11] , and its layer structure is shown in Fig. 1. The top and the bottom contacts with heavily doped are used as the emitter and the collector, respectively. The quantum dot layers sandwiched between the emitter and collector are separated by barrier layers. In this paper, each quantum dot layer consists of many periodically distributed identical quantum dots with the density Σ_{QD}, and the sheet density of doping donors is equal to Σ_D. It is supposed that the lateral size of quantum dots a_{QD} is so large that each quantum dot has a large number of bound states to accept more electrons. In addition, compared with the distance between the quantum dot layers L, the transverse size of quantum dots is very small, thus quantum dots can provide with a single energy level related to the quantization in the direction. L_{QD},

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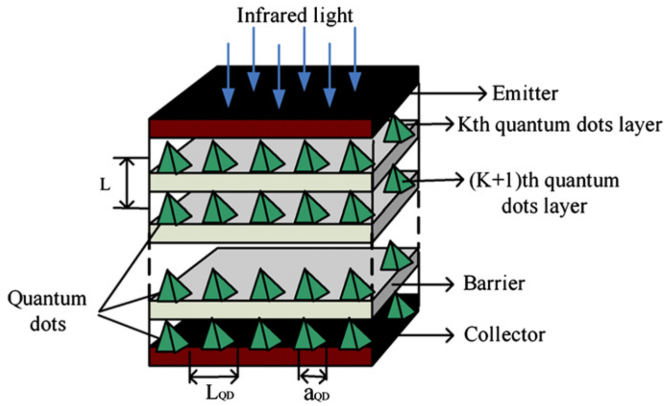

Fig. 1. Schematic view of the QDIP structure, where the triangular pyramids represent quantum dots.

which represents the lateral distance between the quantum dots, equals $\sqrt{\sum_{QD}}$. $\langle N_k \rangle$ is the average number of electrons in a quantum dot belonging to the kth quantum dot layer, where k can be chosen within 1-K(K is the total number of quantum dots layer in our model).

Based on these assumptions, the dark current density [6,7] can be estimated as:

$$\langle j_{dark} \rangle = evn_{3D} \tag{1}$$

where e is the electron charge, v the drift velocity of electrons in the barrier and n_{3D} the three-dimensional density of electrons. With the diffusion contribution neglected, the three-dimensional electron density [6,7] can be estimated by:

$$n_{3D} = 2\left(\frac{mkT}{2\pi\hbar^2}\right)^{3/2} \exp\left(-\frac{E_a}{kT}\right) \tag{2}$$

where m is the electron effective mass, k and $\hbar$ the Boltzman and normalized Planck constants, respectively, T the temperature, and E_a is the activation energy, and equals the energy separation between the Fermi level and the top of conduction band edge.

Since the electron transport is characterized by the activation energy, from the E_a in Eq. (2), it can be seen that in the model only the influence of the microscale electron transport on the dark current is considered, but actually, the nanoscale electron transport [9,10] also has a great effect on the dark current. Therefore, in our model, the former activation energy in the dark current calculation is improved with the consideration of the influence of the nanoscale electron transport on the dark current. Since the common influence of both electron transports(the nanoscale transport and the microscale transport) on the dark current can be perfectly demonstrated by the sequential coupling model [12], and thus, by introducing the sequential coupling model, we can quantify the influence of the nanoscale electron transport on the activation energy in the dark current calculation.

Just as shown in Fig. 2, the sequential coupling model including the microscale and the nanoscale electron transport supposes that the total electron transport should undergo the three processes in a sequential way [12]:(1) thermal emitting over the effective potential barrier presenting the built-in band profiles (being the microscale electron transport), (2) being captured by the quantum dot, (3)escaping from the quantum dot (as the nanoscale electron transport). The activation energies of the process (1) and (3) are respectively presented as: $E_{a,micro}$ and $E_{a,nano}$, and thus the contribution of the total electron transport, which is characterized by the activation energy E_a, can be estimated as:

$$E_a = E_{a,micro} + E_{a,nano} \tag{3}$$

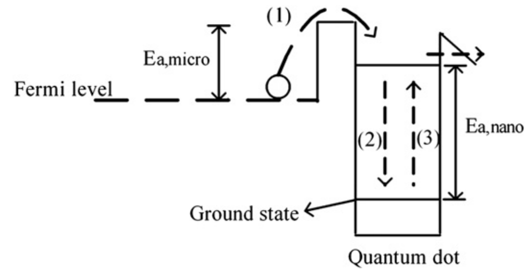

Fig. 2. Sequential coupling model of electrons transport in QDIP.

where $E_{a,micro}$ is the activation energy corresponding to the microscale electron transport [12–14], which is the transport behavior of electrons over the effective potential barrier in microscale(corresponding to electrons emission in process (1)), and the value of $E_{a,micro}$ equals the energy separation between the Fermi level and the top of conduction band edge. $E_{a,nano}$ is the activation energy under the nanoscale electron transport [8,9,12] model, which supposes that the total electron transport process only includes the behavior of electron escaping from the quantum dot in the nanoscale environment in the direct vicinity of the quantum dots, this escaping is related to tunneling. $E_{a,nano}$ is defined as the ionization energy of the quantum dots. According to the experimental results [12], $E_{a,micro}$ and $E_{a,nano}$ can be, respectively, obtained as:

$$E_{a,micro} = E_{0,micro}\exp(-E/E_0) \tag{4}$$

$$E_{a,nano} = E_{0,nano} - \beta E \tag{5}$$

where E is the applied electric field intensity across the device, $E_{0,micro}$ and $E_{0,nano}$, respectively, represent the activation energies under the microscale and the nanoscale model at zero bias (E=0 kV/cm), E_0 and β are the fitting parameters, which describe the change rate of the activation energy under the microscale and the nanoscale electron transport model with the electric field, respectively. The parameter E_0 indicates the dependence of the thermal emission over the effective potential barrier on the bias voltage [13,14]. β originates from the correspondence between the electron escaping from the quantum dot (related to tunneling mechanism) and the bias voltage [9,10]. In addition, the negative signs in Eq. (4) and (5) illustrate that the change trend of the activation energy is contrary to that of the electric field.

Substituting Eq. (3) into Eq. (2), then we get the new dark current density, which is shown in Eq. (6).

$$\langle j_{dark} \rangle = 2ev\left(\frac{m_b k_B T}{2\pi\hbar^2}\right)^{3/2} \exp\left(-\frac{E_{a,micro}+E_{a,nano}}{kT}\right) \tag{6}$$

Based on the above analysis, the dark current model puts emphasis on the common influence of the two transports (the microscale transport and the nanoscale transport) on the activation energy. In nature, the microscale transport model mainly takes into account the thermal emission of electrons over the effective potential barrier, and the nanoscale model puts emphasis on the contribution of electrons from the thermionic emission and the field-assisted tunneling in the process of escaping from the quantum dot. Hence, by considering the detailed current balanced relation, which shows the equivalent in the rate of capture into and of emission from the quantum dots under dark conditions [15,16], we can obtain the other expression of the dark current in Eq. (7).

$$\frac{\langle j_{dark} \rangle}{e\sum_{QD}} P_c = G_k + G_t \tag{7}$$