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Electric-field and space-charge distributions in InAs/GaAs quantum-dot infrared photodetectors: ensemble Monte Carlo particle modeling

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Abstract

We proposed a simplified quasi-three-dimensional model for nonequilibrium electron transport in quantum dot infrared photodetectors (QDIPs) based on an ensemble Monte Carlo particle method. Invoking the developed model, we calculated the electric-field and space-charge distributions, in InAs/GaAs and InGaAs/GaAs QDIPs.

Keywords: Quantum dot infrared photodetector; Electric-field distribution; Monte Carlo particle modeling

1. Introduction

Quantum dot infrared photodetectors (QDIPs) [1] utilizing the electron transitions from bound states in QDs into continuum states can exhibit advantages over quantum well infrared photodetectors (QWIPs). The results of theoretical [1–5]) and experimental (see, for example, [6–10]) studies of QDIPs based on different QD structures have been well documented. However, most of fabricated QDIPs are far short of optimum [5,10]. Because of a three-dimensionality of the QDIP structure and nonequilibrium character of the electron transport processes determining their operation, the optimization of QDIPs is a fairly complex problem. In the QDIP analytical models developed and used previously it was assumed that the distribution function of mobile electrons is a Maxwellian one with the effective temperature equal either to the lattice temperature or some value determined by the average electric field. Under this assumption the electron capture rate into all QDs is the same, hence, the space charge stored in QDs is uniformly distributed over the QD structure. However, due to relatively low concentrations of mobile electrons in QDIPs under realistic conditions, the energy distribution of these electrons can be far from a Maxwellian distribution. Moreover, it can be spatially nonuniform due to a nonlocality of the electron heating in a nonuniform electric field.

The role of nonequilibrium and nonlocal effects in QDIPs is not apriori clear. The solution of this problem requires the application of computer modeling of the electron effects in QDIPs. In this communication, we propose a quasi-three dimensional model for electron transport in QDIPs based on an ensemble Monte Carlo (MC) approach which naturally takes into account the effects in question. This model is used to calculate some QDIP characteristics.

2. Device model

We consider QDIPs on the base n-type structures with several two-dimensional QD arrays between the contact layers under infrared illumination. A schematic view of the device structures of a QWIP and a QDIP is shown in Fig. 1.

The model under consideration is a generalized version of that used previously for QWIPs [11]. This model uses an ensemble MC particle method. Our model takes into account the following processes:

(i) escape of bound electrons from QDs (photoexcitation, tunneling, thermoemission);
(ii) injection of mobile electrons from the emitter contact, their collection by another contact;
(iii) electron transport across the structure in the averaged self-consistent electric field;
(iv) capture of mobile electrons by QDs and the effect of their repulsive potential.

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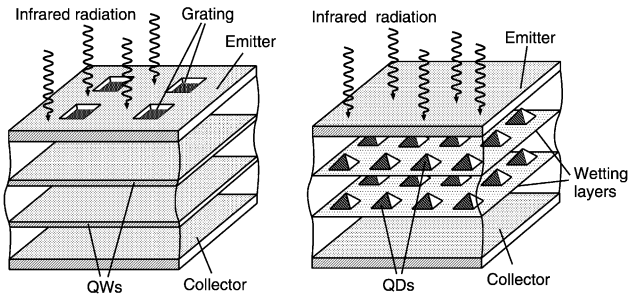

Fig. 1. Schematic view of the QWIP and QDIP structures.

The electron injection from the emitter contact in the QDIPs under consideration is associated with thermionic emission from this contact. This injection is controlled by the space charge of the electrons bound in QDs. The specific of the QDIP structures is that the electron capture by QDs is limited by the self-consistent repulsive potential of QDs. To simplify the model, we assume that the electron dynamics is determined primarily by the average potential formed by charged QDs and donors. The probability of electron passage through the QD array and reflection from this array, as well as the capture probability are determined by the QD density, the average number of electrons occupying QDs of the QD array, and the energy of a mobile electron. It is assumed that only those mobile electrons which have the kinetic energy exceeding the repulsive potential of the charged QD (which is three-dimensional and dependent on the spacing between QDs and their size and charge) can be captured by this QD.

The response of a QDIP to infrared illumination is determined by the rate of the electron photoexcitation from QDs and the rate of the electron capture into QDs. The rate of the electron photoexcitation (per unit area) from the kth QD array ($k = 1, 2, \ldots, K$, where K is the number of the QD arrays) is expressed via the average number of electrons $\langle N_k \rangle$ occupying the QDs of this array as

$$G = \sigma \Sigma_{\rm QD} \langle N_k \rangle I, \tag{1}$$

where σ is the photoexcitation cross-section; $\Sigma_{\rm QD}$ the sheet density of QDs in each QD array; I is the infrared photon flux. The capture rate of the electrons crossing the kth QD array is proportional to the capture probability p_k dependent on the net electron kinetic energy ε and average QD charge $e\langle N_k \rangle$, where e is the electron charge ($e = |e|$). We assume that the electron capture is mainly due to emission of polar optical phonons. Taking into account that the capture of an electron is possible if its energy exceeds the average QD activation energy in the kth QD array ε_k associated with the repulsive potential of the QD charged with electrons [2–5], one can set.

$$p_k \propto p_0 \sqrt{\varepsilon} n_k(\varepsilon) \Theta(\varepsilon - \varepsilon_k) \Theta(\varepsilon_0 + \varepsilon_k - \varepsilon) \Theta(N_m - \langle N_k \rangle). \tag{2}$$

Here $p_0 \propto a_{\rm QD}^2 \Sigma_{\rm QD}$ is the probability of the capture of an electron crossing an uncharged QD array, $n_k(\varepsilon)$ is the energy distribution function of unbound Γ-electrons at the kth QD array, i.e. at the coordinate $z = kL$, L is the spacing between the QD arrays, $\varepsilon_k = e^2\langle N_k \rangle / C_{\rm QD}$, where $C_{\rm QD}$ is the QD capacitance, $a_{\rm QD}$ is the QD lateral size (so that $\pi a_{\rm QD}^2$ is the QD area), ε_0 is the polar optical phonon energy, N_m is the maximum number of electrons which can be accepted by the QD, and $\Theta(x)$ is the unity step function. Formula (2) reflects the assumption that primarily those electrons which have the net electron kinetic energy ε in the range $\varepsilon_k \le \varepsilon \le \varepsilon_0 + \varepsilon_k$ can be captured. The last factor in Eq. (2) is due to the Pauli principle.

The electron injection from the contact and the electron propagation across the QD structure is determined by the self-consistent electric field found from Poisson equation in which the space charge is associated with the charged QDs, mobile electrons (photoexcited and injected), and donors. The distribution function of the electrons at the contacts, i.e. at $z = 0$ and W (where $W = (K + 1)L$ is the QD structure thickness) set to be semi-Maxwellian with the lattice temperature T. Such distributions are realized by an MC procedure. The electrons with $p_z < 0$ at $z = 0$ and with $p_z > 0$ at $z = W$ can freely leave the QD structure. The propagation of the $\Gamma-$, $L-$ and $X-$ electrons is considered in the framework of an ensemble MC particle technique in which the electron interactions with phonons, impurities, and charged QDs are treated as the scattering processes. For definiteness we study QDIPs with InAs QDs buried in a GaAs lightly doped (undoped) matrix sandwiched between heavily doped GaAs contact regions.

The three-dimensional spatial distribution of the electric potential $\varphi = \varphi(x, y, z)$ in the QDIP active region can be presented in the form:

$$\Delta\varphi = \frac{4\pi e}{æ} \sum_{i,j,k} [\langle N_k \rangle \rho(x - x_i, y - y_j) \delta(z - z_k) - \rho_{\rm D}]. \tag{3}$$

Here, $\Delta = \partial^2/\partial x^2 + \partial^2/\partial y^2 + \partial^2/\partial x^2$ is the three-dimensional Laplace operator; $æ$, the dielectric constant; $\rho(x, y)$, and $\delta(z)$ are the QD form-factors in lateral (in the QD array plane) and transverse (growth) directions, respectively, $x_i = L_{\rm QD}(i + 1/2)$ and $y_j = L_{\rm QD}(j + 1/2)$ are the in-plane QD coordinates ($i, j = 0, \pm 1, \pm 2, \ldots$ are the in-plane indexes of QDs), $L_{\rm QD} = \Sigma_{\rm QD}^{-1/2}$ is the lateral period of the QD structure, and $\rho_{\rm D}$ is the donor concentration, which is assumed to be uniform across the QDIP active region. For the sake of definiteness, we assume that transverse size of QDs, $l_{\rm QD}$, is much smaller than their lateral size and the spacing in the transverse direction ($l_{\rm QD} \ll a_{\rm QD}, L$).

In QDIPs with fairly low QD densities (like most of fabricated QDIPs), the capacitance of a QD having a flattened (disk-like) shape equals to $C_{\rm QD} = (2æa_{\rm QD}/\pi^{3/2})$. If the QD density increases, the spacing between QDs and their capacitance becomes small. In this case, the QD activation energy tends to zero. Such a situation corresponds to the transition from a QDIP to a QWIP. In the model under consideration, we assume that the most important features

of the mobile electrons motion in the QDIP active region are associated with the action of the electric field averaged in the lateral directions. This field equals $\langle E\rangle = -\mathrm{d}\langle\varphi\rangle/\mathrm{d}z$, where $\langle\varphi\rangle$ is the potential averaged in the lateral directions. Thus, the electron dynamics between the events of scattering with phonons, impurities, and charged QDs are determined by the averaged (in the lateral directions) electric field and the equations of the electron motion are

$$\frac{\mathrm{d}p_x}{\mathrm{d}t} = \frac{\mathrm{d}p_y}{\mathrm{d}t} = 0, \qquad \frac{\mathrm{d}p_z}{\mathrm{d}t} = -e\langle E\rangle. \tag{4}$$

Simultaneously, the electric field lateral nonuniformities associated with the QD charges are taken into account in the expression for the electron capture probability (see Eq. (2) and they can also be considered as an additional scattering mechanism of mobile electrons. As follows from Eq. (3), the averaged potential obeys the following equation:

$$\frac{d^2\langle\varphi\rangle}{\mathrm{d}x^2} = \frac{4\pi e}{\varpi}[\Sigma_{\mathrm{QD}}\langle N_k\rangle\delta(z - z_k) - \rho_{\mathrm{D}}] \tag{5}$$

with the boundary conditions $\langle\varphi\rangle|_{z=0} = 0$ and $\langle\varphi\rangle|_{z=W} = V$, where V is the applied bias voltage.

3. Results and conclusions

The developed model was used for the calculation of the electric field and charge distributions as well as the QDIP responsivity. It was assumed that the QDIP structural parameters are as follows: the spacing between QD arrays in the growth direction $L = 30$ nm, number of the QD arrays $K = 10$, $a_{\mathrm{QD}} = 15$ nm, $N_m = 6$, $p_0 = 0.5$, and $\sigma = 2\times10^{-15}$ cm^2.

The QD density (in each QD array) and the concentration of donors (distributed uniformly over the QD structure) were chosen to be in the ranges $\Sigma_{\mathrm{QD}} = (4\text{–}8)\times10^{10}$ cm^{-2} and $\rho_{\mathrm{D}} = (0\text{–}8/3)\times10^{16}$ cm^{-3}, respectively. This corresponds to the number of donors per a QD from zero to two. Some results are shown in Figs. 2 and 3.

Fig. 2 shows the spatial distributions of the electric field averaged in lateral directions for $\rho_{\mathrm{D}} = 1.66\times10^{16}$ cm^{-3} at different voltages V, i.e. for different $E = V/(K+1)L$. The calculated spatial distributions of bound electrons (average occupancy of the QD arrays with different indices) at different voltages were used to find how the total number of bound electrons $N = \sum_{k=1}^{K}\langle N_k\rangle/K$ per unit area of a QDIP varies with changing voltage. This dependence shown in Fig. 3 is akin to that obtained previously from simplified analytical models.

In conclusion:

1. A simplified quasi-three-dimensional model based on ensemble MC particle technique for nonequilibrium electron transport in QDIPs has been developed. The transfer from exact potential and electric field distributions described by Eq. (3) to averaged distributions given by Eq. (5) is the main simplification of our model. Actually, the same assumptions are made in analytical and numerical models of devices in which a significant portion of the space charge is stored on impurities which scatter and trap mobile electrons. The substitution of the real potential by some effective potential is used in other applications of the ensemble MC particle method [12].
2. The spatial potential and electric field distributions, the spatial distributions of bound electrons, and the responsivity–voltage characteristics have been calculated.
3. The obtained preliminary results show that
   - the model can be used for evaluation of nonequilibrium electron transport in QDIPs and estimation of their characteristics
   - strongly nonequilibrium electron transport phenomena in QDIPs can significantly complicate the QDIP operation.

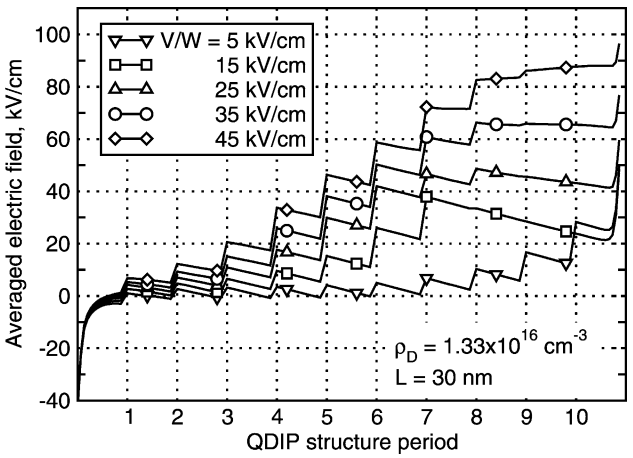

Fig. 2. Spatial distributions of the electric field averaged in lateral directions ($\rho_{\mathrm{D}} = 1.33\times10^{16}$ cm^{-3}).

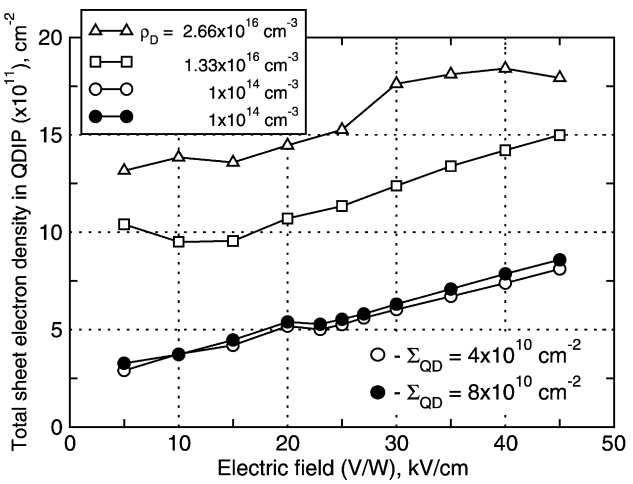

Fig. 3. Total sheet electron density versus applied voltage.

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