Physical Model and Characteristics of Quantum Dot Infrared Photodetectors

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Quantum dot infrared photodetectors (QDIPs) utilizing bound-to-continuum electron transitions (or bound-to-bound transitions followed by electron tunneling) were proposed and analyzed theoretically by one of the authors [1]. The fabrication of QDIPs based on InAs/GaAs, InGaAs/GaAs, and GaAs/InGaP heterostructures and the results of their experimental study were reported recently by several research teams (see, for example, Refs. [2,3,4,5]. The fabricated QDIPs exhibited characteristics worse than expected.

To answer the questions why QDIPs are still inferior to QWIPs and can QDIPs surpass QWIPs, we developed an analytical and numerical device models of QDIPs and used these models for a theoretical analysis of the QDIP characteristics. A schematic view of the QDIP structure is shown in Fig. 1. The models take into account the main physical factors determining the operation of QDIPs:

(1) the space charge of electrons captured in QDs and donors, and the effect of this charge on the spatial distribution of the self-consistent electric field;

(2) the activation character of the electron capture due to a repulsive potential of charged QDs and the limitation of the QD filling imposed by the Pauli principle;

(3) the features of thermionic electron emission from QDs and thermionic electron injection from the emitter contact;

(4) the existence of "punctures" in between QDs and the fluctuations of the QD size and the density of QDs in each layer;

(5) the heating of mobile electrons by the electric field.

We calculated the dark current and the responsivity of QDIPs as functions of their structural parameters, the applied voltage, and the temperature. Some examples of the obtained characteristics for a InAs/GaAs QDIP with ten QD layers, interlayer distance of 100 nm, and QD lateral size a_{QD} = 15 nm at temperature T = 40 K are shown in Figs. 2 and 3. The calculated characteristics are in excellent agreement with those of realistic QDIPs studied experimentally[5], as can be seen from Figs. 2a and 3a. The revealed relations between the QDIP operation characteristics and structural parameters explain relatively high dark currents and low responsivities observed in experiments. Our results explain experimental observations of a rather sharp dark current-voltage and responsivity-voltage characteristics of QDIPs as well as nontrivial dependences of the dark current and responsivity on the density of QDs in the QD layers and the doping level of the active region. The obtained results highlight the ways toward a significant improvement of the QDIP performance.

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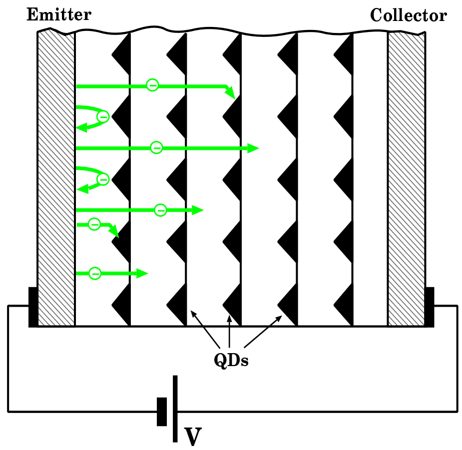

Figure 1: Schematic view of the QDIP structure. Arrows indicate electron trajectories.

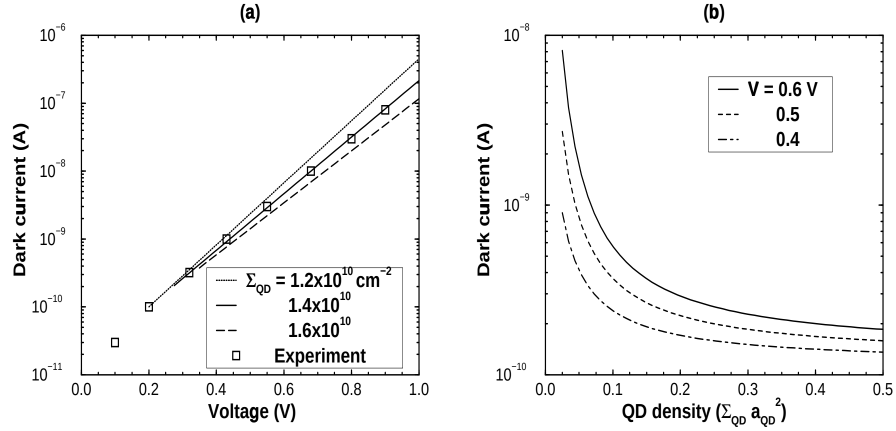

Figure 2: Calculated and experimental dark current versus voltage and QD density.

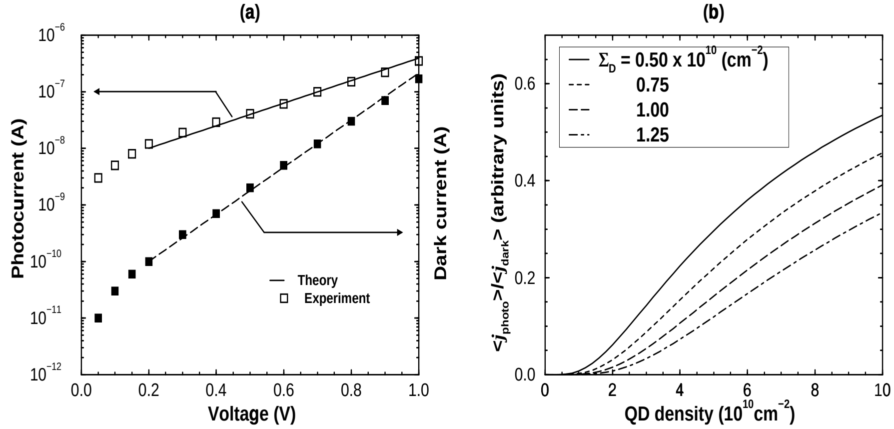

Figure 3: Comparison of photocurrent and dark current.