



Temperature dependence of quantum efficiency in Quantum Dot Infrared Photodetectors

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ABSTRACT

The behavior of quantum efficiency in QDIPs was studied in details with simple InAs/GaAs QDs and DWELL QDs structures. Despite of the large difference of the excited state energy between the two samples, the QE shows similar trends with temperature and bias voltage. The voltage to reach the QE plateau decreases with temperature and the maximum QE decreases with temperature. Considering the repulsive potential from the charge inside the QDs, the effective barrier height and thickness for the photoexcited carrier is much reduced and the QE variation with voltage follows the calculated tunneling probability. Furthermore, the multi-phonon interaction which leads to the relaxation of the excited carrier is shown to be important to the decrease of QE with temperature. The enhanced relaxation rate decreases the maximum QE value at higher temperature.

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1. Introduction

The three dimensional confinement of the quantum dot (QD) structure provides the possibility to suppress the electron phonon interaction and relax the selection rule of intersubband transition in the quantum well (QW) structures. Thus, Quantum Dot Infrared Photodetectors (QDIPs) are of great potential to overcome the drawbacks of the commercialized QWIPs and become lower cost, high temperature operation infrared detectors [1–10]. From the early stage of the QDIPs study, it is well known that the performance of QDIPs is quite limited with the simple InAs/GaAs QD structure. In the past, high band gap material layers and tunneling barriers have been introduced in QDIPs to enhance the performance by the reduction of the dark current [1–4]. Moreover, QDIPs with operation temperature higher than 200 K and even room temperature has been demonstrated with different device structures [3–5]. Besides, QDs within QWs to form the dots-in-a-well (DWELL) structure has also been proposed to provide the flexibility to adjust the electronic states and the detection wavelength with the QW [6–10]. High quality 640×512 DWELL QDIP imaging focal plane arrays have been demonstrated [9].

Compared with QWIPs, QDIPs show more complicated photoreponse characteristics respected to the bias and temperature. In our previous study, it was shown that the responsivity, current gain and thus the quantum efficiency (QE) varies dramatically with voltages and temperatures [11]. The responsivity of QDIPs

increases with the device temperature for two orders of magnitude. Such temperature dependence is originated mainly from the increase of the current gain due to the increase of repulsive Coulomb potential from increase of charge in QDs. Accordingly, the quantum efficiency of QDIPs decreases with temperature and varies with voltage. However, only limited numbers of studies on the modeling and theoretical simulation of QDIPs were published so far [5,12,13] and the results were not able to fully explain the characteristics of QE measured. Since QE is the most important parameter to the device performance under the normal operation conditions, it is essential to understand the behavior of QE in QDIPs. Thus, in this paper; detailed studies on the behavior of the quantum efficiency in QDIPs were conducted. QE data from QDIPs with two different structures were analyzed and compared with the proposed mechanism responsible for the QE variation.

2. Basic characteristics of the samples

Two QDIPs with different structures were prepared for this study: InAs/GaAs QDIPs with thin AlGaAs current blocking layers (sample A) and InAs/InGaAs/GaAs confinement enhanced DWELL QDIPs (sample B). The two structures were selected so that the excited state energies of the intersubband transition in the two samples can be largely different. Both samples were grown by Veeco Gen II MBE machine on (100) GaAs semi-insulating substrates. Within each sample, 10 periods of InAs QDs were used as the active region. The typical size of the quantum dot is about 60 Å in height and 220 Å in radius and the QD density is around $2 \times 10^{10} \text{ cm}^{-2}$. For sample A, each barrier consists of 47 nm GaAs

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and 3 nm $\text{Al}_{0.2}\text{Ga}_{0.8}\text{As}$ layers [1]. For sample B, the InAs QDs were deposited on 4 nm of $\text{In}_{0.15}\text{Ga}_{0.85}\text{As}$ layer and then capped with 2 nm $\text{Al}_{0.25}\text{Ga}_{0.75}\text{As}$ and 3 nm $\text{In}_{0.15}\text{Ga}_{0.85}\text{As}$ layers sequentially to form the DWELL structure [10]. Fig 1 shows the schematics of the device structures. In each sample, the active region was sandwiched by 5000 Å n-type contact layers. In sample A, the Si doping level is about $2 \times 10^{10} \text{ cm}^{-2}$ in each QD layer. In sample B, the doping level is about $4 \times 10^{10} \text{ cm}^{-2}$. Both samples were examined with atomic force microscopy to confirm the dot morphology and density with the additional QD layer deposited on the wafer surface. 77 K photoluminescence (PL) and photoluminescence excitation (PLE) spectrum were taken to probe the energy of electronics states of both samples. Standard processing techniques were applied to define the mesas and to generate ohmic contacts. AuGe contact ring is fabricated on the mesa top to allow the normal incident measurement.

The intersubband transition responsible for the photocurrent was deduced from the PL, PLE and the responsivity spectra of the two samples, assuming a 2:1 energy ratio in the electron and hole states. In sample A, the PL ground state transition energy is about 1.13 eV with a responsivity peak of $6 \mu\text{m}$ ($\sim 205 \text{ meV}$). Combining the PLE peaks around 1.19 and 1.42 eV, the transition observed is from the ground state to the wetting layer state corresponding to the 1.42 eV PLE peak. For sample B, the ground state PL energy is about 1.07 eV due to the insertion of InGaAs QW. The PLE spectrum shows two peaks at 1.23 and 1.29 eV for the QD states and the other peak at 1.43 eV for the QW state. The infrared responsivity peak at $8.3 \mu\text{m}$ ($\sim 150 \text{ meV}$) is thus from the QD ground state to the QD excited state with 1.28 eV PLE peak. The energy differences from the excited state to the GaAs band edge are about 55 meV and 150 meV for sample A and sample B respectively. Large difference about 100 meV between the two samples is achieved as we expected.

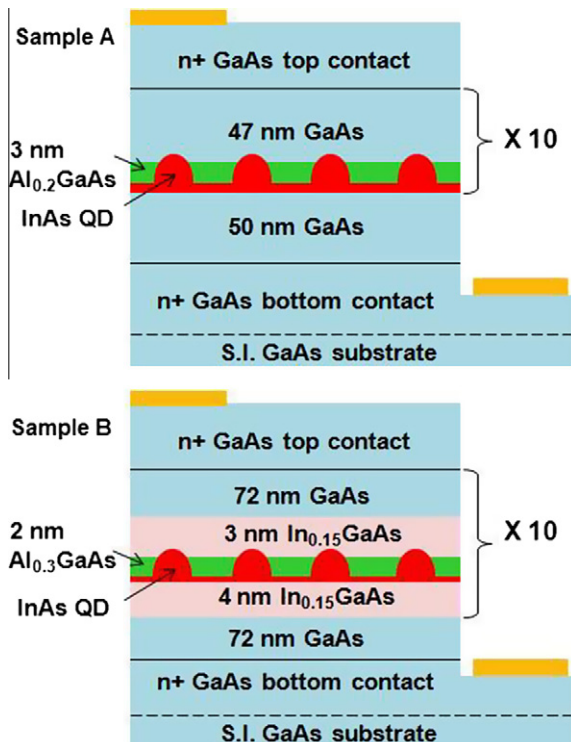


Fig. 1. The schematics of the device structure of sample A and sample B.

3. Result and discussion

In order to investigate the temperature dependence of QE, we measured the current gain and separated the quantum efficiency from the responsivity. Both noise current and responsivity of the devices were measured at different temperatures and biases. The white noise part of the noise spectrum is dominated by the carrier generation and recombination process in QDIPs and used to calculate the current gain and then the QE.

Due to the limit of the measurement system, noise current smaller than $1 \times 10^{-13} \text{ A/Hz}^{1/2}$ cannot be correctly measured. Thus, the QE at low biases with lower temperatures is not available. Also, the QE values at higher biases are not correct due to the possible impact ionization process which leads to the overestimate of current gain. As a result, the QE at different temperature shown in Fig. 2 is limited to $\pm 0.75 \text{ V}$ and $\pm 1.2 \text{ V}$ for sample A and sample B respectively. For voltages higher than these two values, the kinetic energy for passing through a barrier is higher than the activation energy of the dark current. Although the available range of QE is limited, it is clearly shown that the characteristics of QE of the two samples is quite similar. The large difference in the excited state energy seems not to be crucial to the QE. In both samples, the voltage needed to reach the QE plateau decreases with temperature and the maximum QE decreases with temperature. For example, the QE reaches the plateau value 0.4% at 0.25 V and 100 K, but it takes 0.4 V to reach plateau value 0.8% at 77 K in sample A. Similarly, QE in sample B reaches the plateau value 0.8% at 1 V and 77 K and the voltage decreases to 0.5 V at 100 K for the QE value around 0.2%.

In order to generate photocurrent, the excited carriers need to escape from the bounded state in the QD. For deeply bounded excited state, thinner barrier under high electric field is required

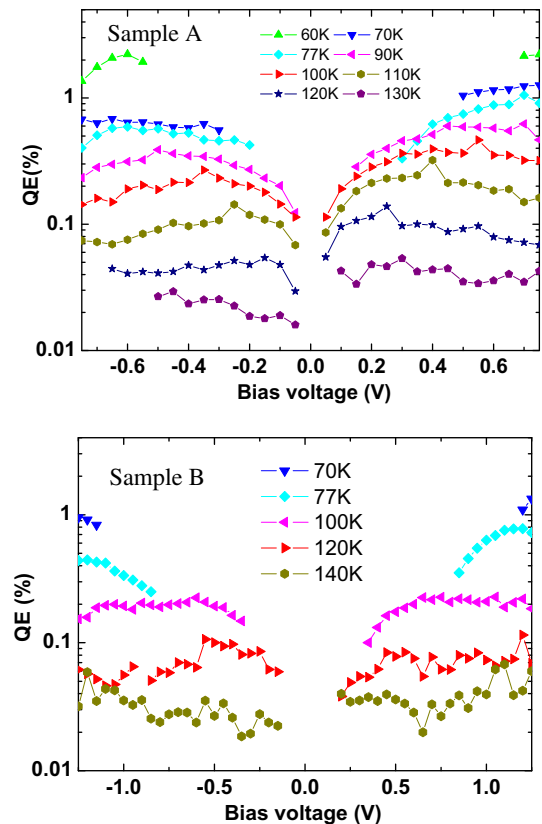


Fig. 2. The quantum efficiency of sample A and sample B at different voltages and temperatures.

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