Infrared Physics & Technology 54 (2011) 224–227

Contents lists available at ScienceDirect

Infrared Physics & Technology

journal homepage: www.elsevier.com/locate/infrared

Temperature dependence of quantum efficiency in Quantum Dot Infrared Photodetectors

S.Y. Wang [a,*], H.S. Ling [a], C.P. Lee [b]

[a] Institute of Astronomy and Astrophysics, Academia Sinica, P.O. Box 23-141, No. 1, Roosevelt Rd, Sec. 4, Taipei 10617, Taiwan, ROC
[b] Department of Electronic Engineering, National Chiao Tung University, 1001 University Road, Hsinchu 300, Taiwan, ROC

ARTICLE INFO

Article history:
Available online 25 December 2010

Keywords:
Quantum dot
Intersubband
Infrared detector

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.

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 photoresponse 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 (1 0 0) 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 2×10^{10} cm^{-2}. For sample A, each barrier consists of 47 nm GaAs

* Corresponding author. Tel.: +886 2 23665338; fax: +886 2 23677849.
E-mail address: sywang@asiaa.sinica.edu.tw (S.Y. Wang).

1350-4495/$ - see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.infrared.2010.12.018

and 3 nm $Al_{0.2}Ga_{0.8}As$ layers [1]. For sample B, the InAs QDs were deposited on 4 nm of $In_{0.15}Ga_{0.85}As$ layer and then capped with 2 nm $Al_{0.25}Ga_{0.75}As$ and 3 nm $In_{0.15}Ga_{0.85}As$ 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 2×10^{10} cm^{-2} in each QD layer. In sample B, the doping level is about 4×10^{10} 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 μm (∼205 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 μm (∼150 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.

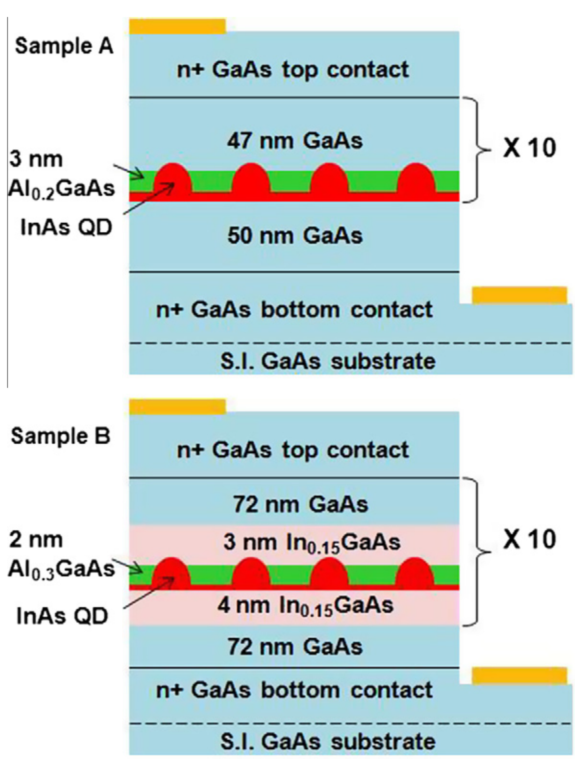

Fig. 1. The schematics of the device structure of sample A and sample B.

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 1×10^{-13} $A/Hz^{1/2}$ 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 ±0.75 V and ±1.2 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

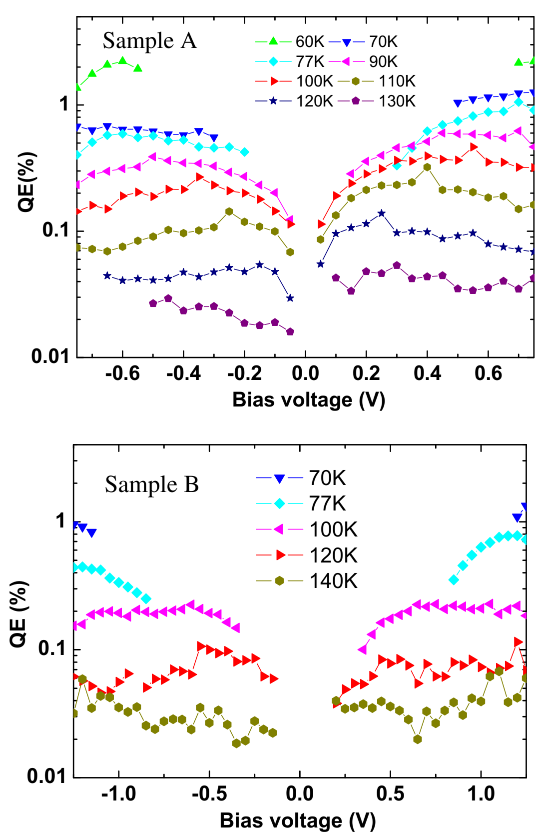

Fig. 2. The quantum efficiency of sample A and sample B at different voltages and temperatures.

to allow the high tunneling probability of the photoelectrons. However, it is not the case for most experimental results of QDIPs. Usually, the barrier thickness is thicker than 50 nm in QDIPs. The measured QE falls in the order of 1% which is quite close to the measured absorptance of 30 layers of QDs (2.8%) [9]. This implies the high escape probability of excited carriers. Although some theoretical models have been published to simulate the characteristics of QDIPs [12,13], the analysis of QE is limited and no attempt was made to compare the calculated QE with the experimental data. Some discussion was made by Lim et al. in Ref. [5], but it is not detailed enough to explain the data we measured.

On the other hand, we have studied the charge inside QDs through the analysis of the temperature dependence of current gain [11]. The charge in QDs is shown to generate repulsive field which decreases the capture probability of the free carriers through the QDs. The number of charge in QDs increases with temperature and bias voltage as a result of higher dark current. A small change of average charge number in QD (less than one electron in average) can generate dramatic difference of the electric field around the QD. The typical charging energy into a QD can be approximated with

$$E \sim \frac{e^2\langle N\rangle}{C} \quad \text{with } C = 2\varepsilon^* a_{QD}/\pi\sqrt{\pi} \tag{1}$$

where $\langle N\rangle$ is the average charge number in the QDs, C is the capacitor of the QD and a_{QD} is area of the QD. In our device, the charging energy in QD for one electron is about 167 meV which is essential to help the escape probability of the excited carriers. Taking the QD charge into account, the tunneling probability of the excited carrier is calculated by the WKB approximation.

$$T(F) = \exp\left(-\frac{4}{3}\cdot\frac{2m^*}{\hbar^2}\cdot\frac{(E_{ex}-E_{GaAs})^{3/2}}{eF}\right) \quad \text{with } F = \frac{e\langle N\rangle}{4\pi\varepsilon a^2} + \frac{V}{L} \tag{2}$$

where E_{ex} is the excited state energy, E_{GaAs} is the energy of GaAs conduction band edge. F is the total electric field on the barrier generated by the charge in QDs and by the applied voltage V within the thickness of the active region L. The QD height is about 6 nm and the distance needed to lower the barrier to the level of the excited state energy is about 25 nm. For simplicity, the electric field generated by QD charge is approximated by the field at distance a around 15 nm from the quantum dot to get the average field on the barrier. The total field is dominated by the QD charge field which is a function of voltage and temperature. With the average charge number calculated from the current gain, the tunneling probability was calculated and scaled to the measured QE. Fig. 3 shows the calculated result with the measured data for both samples A and B at four different temperatures. The trend of QE basically followed the calculated tunneling probability. The tunneling probability deviated more from the measured QE at higher biases and higher temperature. This is probably because the chance of impact ionization is getting higher under such conditions and the measured gain is not fully reliable. Due the strong electric field, the deeply bounded states are elevated and the effective barrier height and thickness are much reduced. The excited carrier can thus easily escape the QDs and contribute to the photocurrent. Although the barrier difference is about 100 meV in the two samples, the slightly more charge in sample B can overcome the barrier and thus the two sample show similar QE characteristics.

In addition to the tunneling probability, the carrier distribution and carrier relaxation process are also important to the QE [5]. Under higher temperature, the probability for the ground states to be populated decreases but the excited states are more likely to be occupied. The probability to have an electron in ground state

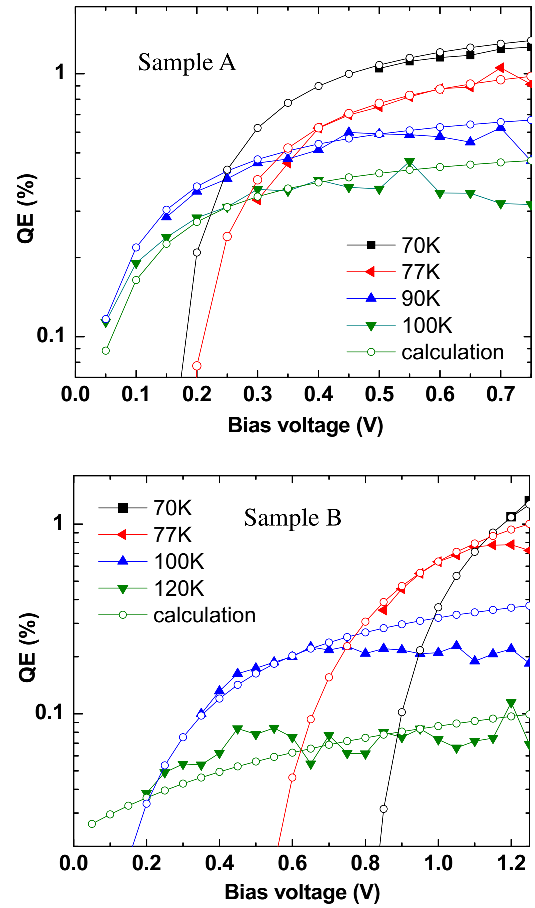

Fig. 3. The quantum efficiency and calculated tunneling probability at four different temperatures for both samples. The lines with solid symbols are the quantum efficiency and the lines with open symbols are the calculated values.

(P_g) and a empty excited state (P_e) can be calculated with the Fermi distribution.

$$P_g \cdot (1-P_e) \propto \frac{1}{1+e^{(E_g-E_f)/kT}}\cdot\left(1-\frac{1}{1+e^{(E_{ex}-E_f)/kT}}\right) \tag{3}$$

With the assumption that the Fermi energy falls in between the ground state energy and excited state energy, the change of the probability in Eq. (3) is quite small to be within a factor of 1.5 from 40 K to 160 K. It is not the major cause for the decrease of QE. On the other hand, the carrier relaxation time can be much faster with the increase of temperature due to the multi-phonon process. Considering the temperature dependent part only, the relaxation time for each type of multi-phonon interaction is inversely proportional to products of the number of phonons which follows the Boson distribution [14]:

$$\frac{1}{\tau} \propto \prod_{\varpi_i} \frac{1}{(e^{\hbar\omega_i}/kT - 1)} \tag{4}$$

where τ is the relaxation time for certain type of multi-phonon process and $\hbar\omega_i$ is the energy for the phonons involved. In order to effectively relax the carriers to the lower states, the involvement of optical phonon is needed. To compare this effect with the decrease of QE, the product in Eq. (4) of one LO and one LA phonon interaction and one LO and two LA phonons interaction in calculated. The calculated product is then multiplied with the carrier distribution factor in Eq. (3) and compared with the maximum QE in Fig 4. From 60 K to 160 K, the QE drops for about two orders of magnitude. The calculated carrier distribution and phonon

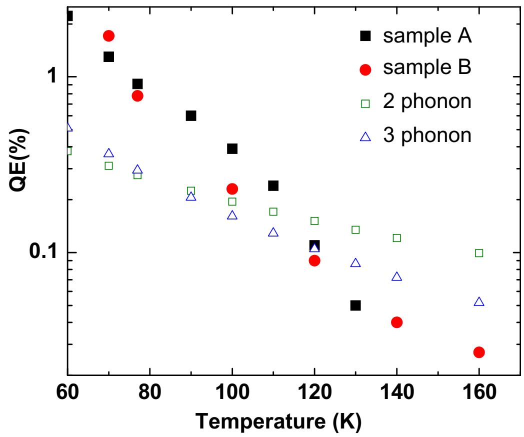

Fig. 4. The maximum QE value for sample A and sample B at different temperature (solid symbols) and the calculated product of Eqs. (3) and (4) for 2 phonon (open square) and 3 phonon (open triangle) interaction.

relaxation time shows similar trend of decrease with temperature. However, the suggested change is only one order of magnitude which is much less than the measured result. This indicates other effects might also be crucial to the QE of QDIPs. It has been suggested that the intraband Auger interaction can help to extract the carrier out of QDs [15]. Such effect requires two electrons at excited states and one empty lower state. It is a preferred process at higher temperature. As there is no strong temperature dependence of Auger coefficient in the temperature range we interested in, our result excludes the intraband Auger interaction to be the major mechanism for the extraction of excited carriers in QDIPs.

4. Summary

The characteristic of QE in QDIPs was investigated with different QDIP structures. The trend of QE was shown to be insensitive to the QDIP structure and the escape energy from the excited state. Instead, the charge inside QDs generates significant electric field and dominates the characteristics of QE under different voltage and temperature. Considering the electric field from the QD charge, the QE follows the same trend as the tunneling probability of the excited carriers. This means the QDIPs with bound excited states is a preferred structure to provide higher QE due to the higher oscillation strength and similar carrier escape probability. Furthermore, the enhanced multi-phonon relaxation of the excited carrier at higher temperature decreases the maximum QE at higher temperature. However, the calculated decrease is smaller than the measured result. Further investigation for the mechanism responsible for the decrease of peak QE is needed to fully explain the experimental result.

References

[1] S.Y. Wang, S.D. Lin, H.W. Wu, C.P. Lee, Appl. Phys. Lett. 78 (2001) 1023–1025.
[2] Z. Chen, O. Baklenov, E.T. Kim, I. Mukhametzhanov, J. Tie, A. Madhukar, Z. Ye, C. Campbell, J. Appl. Phys. 89 (2001) 4558–4563.
[3] S. Chakrabarti, A.D. Stiff-Roberts, P. Bhattacharya, S. Gunapala, S. Bandara, S.B. Rafol, S.W. Kennerly, IEEE Photon. Technol. Lett. 16 (2004) 1361–1363.
[4] P. Bhattacharya, X.H. Su, S. Chakrabarti, G. Ariyawansa, A.G.U. Perera, Appl. Phys. Lett. 86 (2005) 191106.
[5] H. Lim, W. Zhang, S. Tsao, T. Sills, J. Szafraniec, K. Mi, B. Movaghar, M. Razeghi, Phys. Rev. B 72 (2005) 0855332.
[6] E.T. Kim, A. Madhukar, Z. Ye, J.C. Campbell, Appl. Phys. Lett. 84 (2004) 3277–3279.
[7] S. Krishna, Infrared Phys. Technol. 47 (2005) 153–163.
[8] G. Ariyawansa, A.G. Unil Perera, G.S. Raghavan, G. von Winckel, A. Stintz, S. Krishna, IEEE Photon. Technol. Lett. 17 (2005) 1064–1066.
[9] S.D. Gunapala, S.V. Bandara, C.J. Hill, D.Z. Ting, J.K. Liu, S.B. Rafol, E.R. Blazejewski, J.M. Mumolo, S.A. Keo, S. Krishna, Y.C. Chang, C.A. Shott, IEEE J. Quantum Electron. 43 (2007) 230–237.
[10] H.S. Ling, S.Y. Wang, C.P. Lee, M.C. Lo, Appl. Phys. Lett. 92 (2008) 193506.
[11] S.Y. Wang, M.C. Lo, H.Y. Hsiao, H.S. Ling, C.P. Lee, Infrared Phys. Technol. 50 (2007) 166–170.
[12] V. Ryzhii, I. Khmyrova, M. Ryzhii, V. Mitin, Semicond. Sci. Technol. 19 (2004) 8–16.
[13] P. Martinuk, A. Rogalski, Bull. Pol. Acad.: Technol. 57 (2009) 103–116.
[14] T. Inoshita, H. Sakaki, Phys. Rev. B 46 (1992) 7260–7263.
[15] T. Gebhard, D. Alvarenga, P.L. Souza, P.S.S. Guimaraes, K. Unterrainer, M.P. Pires, G.S. Vieira, J.M. Villas-Boras, Appl. Phys. Lett. 93 (2008) 052103.