Infrared Physics & Technology 62 (2014) 81–85

Contents lists available at ScienceDirect

Infrared Physics & Technology

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

Improving the performance of a far-infrared quantum-ring-based photodetector utilizing asymmetric multi-barrier resonant tunneling

M. Karimi [a], K. Abedi [b,*], M. Zavvari [c]

[a] Department of Electrical Engineering, Mahabad Branch, Islamic Azad University, Mahabad, Iran
[b] Department of Electrical Engineering, Faculty of Electrical and Computer Engineering, Shahid Beheshti University, G.C. 1983963113, Tehran, Iran
[c] Department of Electrical Engineering, Urmia Branch, Islamic Azad University, Urmia, Iran

HIGHLIGHTS

- Quantum ring inter-subband photodetectors (QRIP) with reduced dark current.
- Asymmetric multi-barrier resonant tunneling (AMBRT) in absorption region layers.
- Higher specific detectivity in the order of $\sim 10^{11}$ cm $\mathrm{Hz}^{1/2}$/W at 100 K.

ARTICLE INFO

Article history:
Received 22 July 2013
Available online 14 November 2013

Keywords:
Quantum ring inter-subband photodetector
Dark current
Resonant tunnelling barrier
Detectivity

ABSTRACT

In this paper, a novel structure for quantum ring inter-subband photodetectors (QRIP) is proposed to reduce its dark current. Some additional layers including asymmetric multi-barrier resonant tunneling (AMBRT) in absorption region layers are exploited to provide near unity tunneling probability for generated photocurrents and completely reject thermally generated electrons. AMBRT structure consists of three asymmetric AlGaAs barriers and two InGaAs wells which are designed for operation wavelength of generated photocurrents by absorption of 20 μm. Simulation results show that AMBRT can considerably reduce the dark current compared to previously proposed resonant tunneling structure about three orders of magnitude. As a consequent, higher specific detectivity for AMBRT-QRIP is obtained in the order of $\sim 10^{11}$ cm $\mathrm{Hz}^{1/2}$/W at 100 K.

1. Introduction

Detection of infrared (IR) radiation can be applied in the areas of night vision, thermal imaging, chemical analysis, nondestructive detection, remote sensing and space applications [1,2]. Different structures have been proposed to work at infrared range including Mercury Cadmium Telluride (MCT) detector, strained layer super lattices, quantum well infrared photodetector (QWIP) and quantum dot (QD) infrared photodetector (QDIP). In recent years, QDIPs have attracted many interests because of their exclusive electro-optical features such as intrinsic sensitivity to the normal incidence, higher operation temperature and long carrier life time which are originated from zero dimension confinement [3–5]. Recently, a new quantum structure which called quantum ring (QR) has been proposed to use within active region of semiconductor detectors resulting in quantum ring inter-subband photodetector (QRIP). QRs are formed through surrounding quantum dots by GaAs-capped layer and annealing it at high temperature to evaporate the center of dots which are uncovered [6]. By continuing the annealing process, the evaporated parts of dots will be dipper and ring shaped structure is formed. Carriers confinement in QRs is stronger than QDs due to small size of QRs and energy levels within rings are closer to conduction band edge which make it suitable for detection of IR and terahertz (THz) lights [6–8]. As the energy levels of a QR are closer to continuum, it is expected to have higher dark currents for a QRIP compared to a QDIP. Dark current is a critical parameter which limits the performance of any photodetector and must be as small as possible to improve specific detectivity, D^*, and attain high temperature operation. Bhattacharya et al. applied resonant tunneling barriers (RT) to reduce QRIP dark current [9]. For such RT based structure significant improvement in detectivity achieved and hence the detector can be utilized in higher operation temperatures. In this paper we first study dark current characteristics of a conventional and RT based QRIP to show how the RT barriers can be used in QRIP to enhance its performance and then propose an asymmetric multi-barrier resonant tunneling (AMBRT) structure for more reduction in its dark current. The responsivity of proposed structure is calculated based on extended models of QDIPs and then the specific detectivity is calculated for AMBRT for different temperatures and the results are compared with other types.

---

* Corresponding author. Tel.: +98 2129904138.
E-mail address: k_abedi@sbu.ac.ir (K. Abedi).

1350-4495/$ - see front matter Crown Copyright © 2013 Published by Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.infrared.2013.11.002

The paper is organized as follows: numerical analysis and simulation results are given and discussed in Section 2 and the paper is concluded in Section 3.

2. Analysis approach and results

2.1. Optical performance

Dark current of a quantum ring photodetector is originated from thermal excitation of electrons which are drifted under applied electric field and reached the contacts at no incident light and can be calculated from [10]:

$$I_D(V) = q \cdot n(V) \cdot v(V) \cdot A \tag{1}$$

where e is electron charge, $v(V)$ is the average electron drift velocity in the barrier material, A is the detector area and $n(V)$ is density of thermally generated electrons calculated from [10]:

$$n(V) = \int N(E) \cdot f(E) \cdot T(E,V) \cdot dE \tag{2}$$

where $f(E)$ is Fermi–Dirac distribution function, $T(E, V)$ is the transmission probability through device calculated by transmission matrix method (TMM) [11,12] and $N(E)$ is the density of states expressed by [10]:

$$N(E) = \sum_i \frac{2N_D}{L_P}\frac{1}{\sqrt{2\pi}\sigma}\exp\left(-\frac{(E-E_i)^2}{2\sigma^2}\right) + \frac{4\pi m^*}{L_p\hbar^2}H(E-E_w) + \frac{8\pi\sqrt{2}}{\hbar^3}m^{*^{3/2}}\sqrt{E-E_c}H(E-E_c) \tag{3}$$

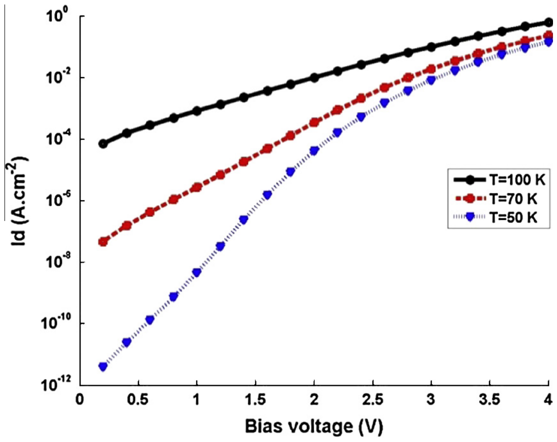

Fig. 1. Dark current of QRIP versus bias voltage for different temperatures.

where L_p is the absorption length, N_D is the density of quantum dot surface, E_i is the energy levels within QR and $H(E)$ is the step function. Energy levels within QR can be obtained from eight band $k \cdot p$ calculations for InAs QRs of 25, 10 and 2 nm sizes as outer radius, inner radius and height, respectively which are confined in GaAs matrix. $k \cdot p$ calculations for QRs are similar to that of QDs and we follow the procedure of [13,14]. The first term in Eq. (3) is quantum ring density of states, the second term describes the wetting layer density of states which E_w is wetting layer energy and the last term corresponds to density of states in the bulk barrier material with conduction bandage energy of E_C.

In a QR structure, due to low spacing between energy levels, electrons within ring can be excited easily by thermal energy and hence it is expected to higher dark currents. Fig. 1 shows the calculated dark current for a conventional QRIP as a function of bias voltage for different temperatures. According to figure the dark current increases with applied bias as a result of increase in drift velocity. On the other hand, for higher temperatures, dark current reaches to higher orders which limit the operation temperature of QRIP. The reason arises from the fact that for higher temperatures, the distribution of electrons in higher energies increases and there are more electrons to contribute in current generation. Results show that the dark current is in the order of 10^{-4}, 10^{-7} and 10^{-11} A/cm^2 for 50, 70 and 100 K at 0.4 V, respectively. These values of dark current make mandatory incorporation of high cost cryogenic cooling systems. To avoid using expensive cooling systems and improve specific detectivity, a QRIP with low dark current is desired and any technique for suppressing the dark current can enhance the performance of device at higher temperatures. Previously RT barriers have proposed as an efficient way to lower the dark current of a QRIP [9]. Such structure blocks all of thermally excited electrons and provides a pass for photoexcited carriers. Tunneling probability for electrons with energies identical to resonance energy of barriers is about unity, whereas it decreases rapidly when the electrons energy moves away from resonance energy.

Fig. 2(a) depicts the band structure of a RT barrier and Fig. 2(b) shows its calculated tunneling probability. As can be seen, tunneling probability is unity for electrons with energy of 0.062 eV (corresponding to inter-subband transition energy of 20 μm) and is zero for other energies. Calculated dark current for the RT–QRIP is shown in Fig. 3. It is evident that using RT barrier lowers the dark current of conventional QRIP about two orders of magnitude.

For more reduction in dark current, we propose asymmetric multi-barrier resonant tunneling structure. Heterostructure schematic of one stack of AMBRT-QRIP absorption region is shown in Fig. 4(a). Fig. 4(b) shows the band structure of AMBRT which consists of a third additional barrier in its structure. Using this barrier would lead to make a resonant tunnel state with more narrow

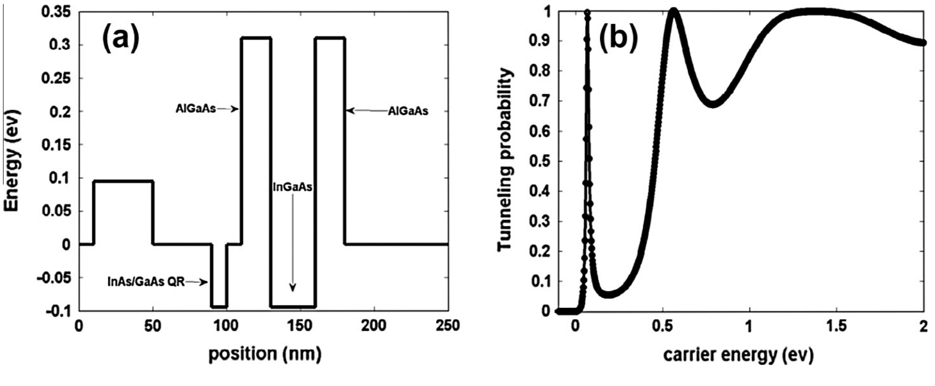

Fig. 2. (a) Band structure of RT-QRIP and (b) tunneling probability of RT barriers for 20 μm wavelength.