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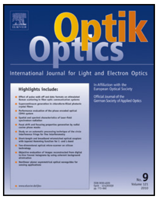

Proposal of a quantum ring intersubband photodetector integrated with avalanche multiplication region for high performance detection of far infrared

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ABSTRACT

In this paper, a novel design of quantum ring infrared photodetector (QRIP) is proposed based on an additional avalanche multiplication region and its performance theoretically is investigated. The device consists of two intrinsic regions including: (i) quantum ring based absorption region which is responsible for absorption longer wavelength radiations and (ii) avalanche multiplication region for multiplying the generated carriers in absorption layer. Since lower electric fields are needed for absorption region to keep the dark current low and higher fields are required for multiplication region, a highly doped charge layer is used to separate absorption and multiplication regions and non-uniformly distribute the electric field. Also to further reduction of dark current, resonant tunneling barriers are embedded in absorption region to provide only a pass for optically excited electrons. Simulation results shows a higher responsivity and specific detectivity about 40 A/W and 2×10^{10} cm Hz$^{1/2}$/W at $\lambda = 20\ \mu$m, respectively.

1. Introduction

The widespread applications of infrared (IR) and terahertz (THz) radiations in the areas of medical diagnostics, security, astronomy, domestic applications, night vision and thermal imaging have attracted much interest in the technologies of transmitting and receiving this range of electromagnetic spectrum [1–3]. In the recent decades some detection technologies have been introduced to work in IR and THz ranges such as mercury cadmium telluride (MCT), type-II strained layer supper-lattice, quantum well infrared photodetector (QWIP), and quantum dot infrared photodetector (QDIP) [4–7]. Among these technologies, detectors based on self-assembled InAs quantum dots (QDs) have widely studied due to their sensitivity to incident normal light, capability to confine carriers in three dimensions and benefiting from mature III–IV technology [8]. Reportedly, in recent years a new form of quantum dots called quantum rings (QR) have been presented to be used in the active region of semiconductor photodetectors resulting in quantum ring infrared photodetector (QRIP) [9]. Quantum rings are developed by adding some steps on the fabrication of quantum dots including Stranski–Krastranov epitaxy of QDs with partial capping layer and subsequent annealing which leads to evaporating of the central part of QD and formation ring shape structure [10]. Since QR is another form of QD, the most properties of them are identical. However, because of small size and ring shape of QRs, the confinement of carriers is stronger and inner energy levels in QR are closer to conduction band edge resulting in lower intersubband energy which makes it suitable for detection of long wavelengths radiations [11,12]. Previously some groups have reported the using of QR in the active region of semiconductor photodetector to monitoring IR and THz lights and proposed some structures such as resonant tunneling barrier to achieve high performance operation [13,14]. In our recent studies, resonant cavity and asymmetric multi barrier resonant tunneling structures have theoretically proposed to improve the performance of quantum ring inter-subband photodetector [15–17].

Because of lower quantum efficiency, the photocurrent of these types of detectors is low which cause a reduced performance [16]. An alternative to increase the generated photocurrent of such detector is to use an avalanche multiplier section in the structure to gain the responsivity. Recently, an intrinsic avalanche multiplication region has been introduced to further enhancement of the

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performance of quantum dot based photodetectors. Krishna et al. coupled intersubband QD detector with a thin, low noise GaAs avalanche layer through a tunnel barrier and observed the SNR enhancement by a factor of 5 [18]. Also, Zavvari et al. integrated a multiplication layer with a quantum dot infrared photodetector to increase generated photocurrent and achieved a higher responsivity of 12 A/W and higher specific detectivity of $6 \times 109\,\mathrm{cm\,Hz^{1/2}/W}$ at 11 μm [19]. Based on these studies, in this paper we use avalanche multiplication for amplification and enhancement the responsivity of a QRIP. To the best of our knowledge, there is no theoretical/experimental report regarding quantum ring avalanche photodetector. The proposed detector is expected to bring the advantages of avalanche photodetector such as higher SNR and combines them with the advantages of quantum ring photodetector such as longer operation wavelength and stronger carrier confinement.

2. Structure design and operation mechanism

The schematic structure of proposed quantum ring avalanche photodetector is shown in Fig. 1. It is evident that the device consists of two separated regions responsible for absorption and multiplication, respectively. The upper intrinsic region of device consists of self assembled InAs quantum rings which are responsible for absorption of long wavelength lights. By intersubband absorption of incident photons in QRs and electron generation in upper states, an electrical current is generated under applied electrical field and moves toward multiplication region which supplies essential gain to amplify the photocurrent and enhance the responsivity. As can be seen from Fig. 1, absorption and multiplication regions are separated from each other through a highly doped charge layer to ensure the non-uniformity of electric field across the structure in such a way that absorption region experiences lower field while multiplication region reaches to stronger field. The charge layer plays a critical role in design of our detector, since lower electric fields are needed for absorption region to keep the dark current low. On the other hand, multiplication region should also have higher fields. In the high field multiplication region, the drifted electrons experience a set of impact ionization events resulting in multiplication and avalanche gain. Since initial injected carrier is electron, lower excess noise and higher operation speed is expected for this device.

Because of the same path for dark current generated in the absorption region, it can be also multiplied and strongly deteriorate the operation of detector. Considering the field dependence of dark current, further care must be taken in design of charge layer to hold the electric field low enough. However to achieve better performance and high temperature operation, AlGaAs/InGaAs resonant tunneling barriers are also included in the absorption region to stop thermally excited electrons from current generation. These barriers create a tunneling path with transmission probability of about unity for optically generated electrons and inhibit the thermal distribution of electrons with broad energy from contribution in the output current. More detail about RT barriers can be found in Ref. [20].

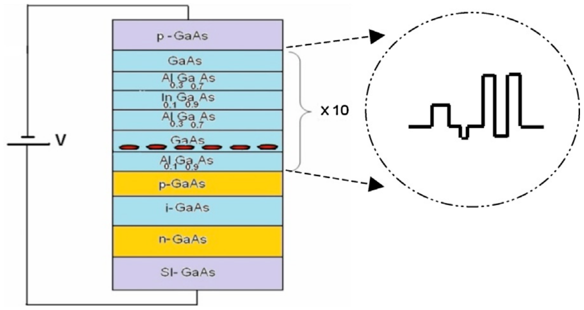

Fig. 1. Schematic of proposed A – QRIP structure with resonant tunneling barriers.

In this paper we use theoretical modeling to show high performance operation of this detector in long and far infrared wavelengths.

3. Theoretical approach

For calculation of intersubband absorption spectra within QR, we need to obtain its conduction band energy states. To do so, we apply effective mass approximation to three-dimension Schrodinger equation and solve it using finite element method which is used to discrete the potential distribution. In our proposed detector, we consider InAs/GaAs material system as it has widely used in fabrication of self assembled QD and QR. 3D Schrödinger equation can be written as [12]:

$$-\frac{\hbar^2}{2m^*}\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}+\frac{\partial^2}{\partial z^2}\right)\varphi(x,y,z)+V(x,y,z)\varphi(x,y,z) = E\varphi(x,y,z) \tag{1}$$

where $\hbar$ is the plank's constant, m^* is electron effective mass, $V(x, y, z)$ is 3D confining potential, φ is electron wave-function and E is energy state of electrons within quantum ring. To obtain precise solution of 3D Schrodinger equation, we consider the modified effective mass of electron in our simulations [21]. The results can be used for calculation of the intersubband absorption spectra through the following equation [22]:

$$a(\hbar\omega)=\frac{\pi q^2}{\varepsilon_0 n_0 c m_0^2 V_{ac}}\cdot\frac{1}{\hbar\omega}\sum\left|\bar{a}\cdot P_{fi}\right|^2 N(\hbar\omega) \tag{2}$$

where q is electron charge, c is speed of light, V_{ac} is effective volume of a QR layer, $\bar{a}$ is incidence light polarization vector, P_{fi} is momentum matrix element and $N(\hbar\omega)$ is density of states within QR which can be calculated from [23]:

$$N(\hbar\omega)=\int_{-\infty}^{\infty}\frac{\hbar\gamma_{fi}/\pi}{(E-E')^2+(\hbar\gamma_{fi})^2}\times\frac{1}{\sqrt{2\pi}\sigma}\exp\left(-\frac{(E_{fi}-E')^2}{(\sqrt{2}\sigma)^2}\right)\times(f_i(E')-f_f(E'))dE' \tag{3}$$

where E_{fi} is transition energy between subbands of f and i. The first term of the above equation refers to a Lorentzian broadening with linewidth of $\hbar\gamma_{fi}$ which is called as homogeneous broadening (HB) and appears due to thermal broadening of energy states and different phonon scattering. In addition, due to self-assembled growth of quantum rings in Stranski–Krastanow (SK) method, shape and size of quantum rings cannot precisely be controlled. This nonuniformity introduces an inhomogeneous broadening (IHB) on absorption spectrum modeled as Gaussian function in Eq. (3) with the line width of σ.

Fig. 2 shows the calculated absorption coefficient as a function of wavelength for two different sizes of QRs. In our study we calculate the absorption only for most probable transition, i.e. from QR ground state to its first excited state. However for the proposed structure, the intersubband absorption is calculated for a transition from ground state to the two-dimensional tunnel state created by RT barriers. As can be seen from figure, absorption spectrum is shifted toward longer wavelength as the size of rings is changed. Changing the ring size leads to decreasing the space between energy levels, and hence photons with longer wavelength can be absorbed. This phenomenon can be useful for designing a tunable QRIP to detect the desired IR and THz window. However, as can