Optics Communications 282 (2009) 3499–3508

Contents lists available at ScienceDirect

Optics Communications

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

Ultra-high detectivity room temperature THZ-IR photodetector based on resonant tunneling spherical centered defect quantum dot (RT-SCDQD)

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ARTICLE INFO

Article history:
Received 16 September 2008
Received in revised form 19 May 2009
Accepted 27 May 2009

Keywords:
Resonant tunneling
Spherical defect
Quantum dot
Terahertz-infrared photodetector
Detectivity
Room temperature

ABSTRACT

In this paper, a novel structure for THZ-IR photodetector based on resonant tunneling spherical centered defect quantum dot (RT-SCDQD) operating at room temperature is proposed. The proposed structure includes a quantum dot with centered defect following a resonant tunneling double barrier. It is shown that inserting a centered defect leads to considerable enhancement in absorption coefficient at long wavelength in small dot size (1.05×10^6–$7.33 \times 10^6\ \mathrm{m}^{-1}$ at 83 μm). This effect guarantees large responsivity of the proposed system for THZ-IR photodetector. In this proposal, intersublevel transitions in related states positioned at mid energies of large conduction-band-offset materials (GaN/AlGaN) are used to depress the thermal effect in dark current. Adding the resonant tunneling double barrier to the quantum dot resolves the basic problem of collecting electrons from deep excited state without applying large bias voltage. Also, employing the RT double barrier reduces the ground state dark current term. Reduction of the dark current and increasing the responsivity yields ultra-high detectivity, 5×10^{16} and $2.25 \times 10^9\ \mathrm{cm\ Hz^{1/2}/W}$ at 83 μm, at 83 and 300 K, respectively. Analysis of the proposed structure is done analytically.

1. Introduction

Long-wavelength infrared (especially mid and far) photodetectors have been considered for imaging in military and medical applications and have critical roles in night vision and intravascular applications. One of the important features of these devices is the ability of detectors in operating at room temperature. Unfortunately, there haven't been any suitable proposals for room temperature operation while holding the other characteristics acceptable up to now. For this reason, in this paper we try to describe a novel structure for operating at room temperature as well as other high-level characteristics. In the following, we review some interesting published ideas for this purpose and discuss about advantages and disadvantages of them.

Intersubband absorption in zero-dimensional quantum dot structures has advantages in optical applications compared with two-dimensional quantum-well structures. This is due to their sharp delta-like density of states, the reduced intersubband relaxation times and hence lower detector noises in these nanostructures [1,2]. Intersubband absorption of GaAS-based quantum dot structures has been extensively investigated in recent years. For example, infrared absorption has been reported for charged InGaAs quantum dots for wavelengths higher than 20 μm, and for doped InAs dots in the range of 10–20 μm, respectively. Mid-infrared photoconductivity at around 3 μm has also been studied for delta-doped InAs/AlGaAs quantum dots for subbands to continuum transitions [1,2].

Long-wavelength infrared detection is one of the major applications of self-assembly grown semiconductor quantum dots [3]. Most of the long-wavelength infrared detectors are generally limited to the peak position wavelength range of 4–9 μm [4,5]. A study of the intersubband absorption in InAs/GaAs quantum dots has been done in [4]. The long-wavelength infrared intersubband absorption in $In_{0.3}Ga_{0.7}As/GaAs$ multiple quantum dots is reported in [3]. The peak position wavelength varies in range $\lambda \sim 8.6$–13 μm with variation of monolayer numbers (between 10 and 60). While these QDs have been demonstrated successfully in mid-infrared wavelength photodetectors, the promise of new applications at longer wavelengths in the far-infrared (30–300 μm) or terahertz (1–10 THz) regions of the spectrum is providing motivation to extend their operating wavelength [6].

According to traditional quantum-size-effect idea, operating in intersubband-long-IR wavelengths requires large size of quantum structure which leads to low sheet density of quantum dots in each layer in optoelectronic devises. On the other hand, the absorption peak weakens when the resonant frequency is shifted to lower energies (long wavelengths). The maximum reported value for

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0030-4018/$ - see front matter © 2009 Published by Elsevier B.V.
doi:10.1016/j.optcom.2009.05.064

absorption coefficient is about $1.7 \times 10^4\ cm^{-1}$ at 45 μm resonant wavelength [7]. It is obvious that these problems degrade device performance [8]. So it will be interesting to obtain long wavelength transition resonances without increasing the size of the quantum structure and increasing the absorption peak in lower energies [9]. We will show that it is possible to increase the absorption coefficient of the proposed structure with introducing a defect to center of quantum dot, without increasing the dot size.

The next motivation of this work is to explore the possibility of extending the detection wavelength of QDIP to terahertz wavelengths. Improving the performance of QDIP depends fundamentally on minimizing the leakage (dark) current which plagues all light detectors. Three major factors contribute to the existence of the dark current. The first factor is the sequential tunneling between quantum wells through the barrier layers. The tunneling actually has to be mediated by a 'third party', such as a phonon or an electron. Thus, it is fairly independent of temperature and is thought to be dominant below 30 K. This term is negligible especially in the quantum dot structures due to the phonon bottleneck effect. The second factor is thermally assisted tunneling or field induced emission, which involves thermal excitation within the well followed by tunneling into the continuum. The final contribution is called thermionic emission and is related to direct excitation to the continuum band. It is found that both of the sequential tunneling and the thermionic emission contributions to the dark current increase as the wavelength of the detector extends from the mid- to the far-infrared [6,10].

The first reports about mid-infrared photoconductivity with InAs quantum dots were published in 1997 [1,11] and far-infrared photoconductivity (17 μm) in self-organized InAs quantum dots was reported in 1998 [12]. The photoresponse remained however very noisy due to the high temperature of the measurement (90 K) and could not be observed for a bias larger than 0.5 V. A short wavelength InGaAs photodetector with InGaP barriers is investigated by Kim et al. [13]. The photoconductivity was measured at normal incidence where at the peak wavelength of 5.5 μm, the responsivity and detectivity were 130 mA/W and $4.74 \times 10^7\ cm\ Hz^{1/2}/W$ at 77 K, respectively. This figure of merit remains however more than two orders of magnitude lower than GaAs/AlGaAs QWIPs operating at the same wavelength. The reported InAs/GaAs QDIP in [14] has a peak at 10 μm, operates at normal incidence and a peak detectivity of $7 \times 10^9\ cm\ Hz^{1/2}/W$ is achieved at 30 K. This value remains much weaker than the achieved value with state of the art quantum-well infrared photodetectors. The detectivities of 6×10^8 and $5 \times 10^8\ cm\ Hz^{1/2}/W$ are obtained at room temperature and 80 K, respectively, at 9 μm for far-infrared self-assembled InAs quantum dot photodetector [15].

Several groups have been reported experimental results for QDIPs with AlGaAs barriers. Liu et al. have embedded 50 layers of InAs quantum dots with $Al_{0.33}Ga_{0.65}As$ barriers. The reported results have shown that the AlGaAs barriers induce blue shift. At 80 K, a responsivity of 0.1 A/W has observed at 5 μm and bias voltages of ∼3 V [16]. Another approach consists on using an $Al_{0.3}Ga_{0.7}As$ current blocking barrier between the contacts and the active region where detectivity values, $D^* \sim 3 \times 10^9\ cm\ Hz^{1/2}/W$ at 100 K, were measured for a peaked photoresponse around 3.75 μm [17,18]. Using AlGaAs blocking barriers, a detectivity of $D^* \sim 10^{10}\ cm\ Hz^{1/2}/W$ at 77 K with a photoresponse peak at 6.2 μm and a 0.7 V bias is reported with responsivity of 14 mA/W [19]. The same authors have reported an InAs QDIP that utilize $In_{0.15}Ga_{0.85}As$ strain-relief cap layers [20]. This device exhibits normal-incidence photoresponse peaks at 8.3 or 8.8 μm for negative or positive bias, respectively. At 77 K and −0.2 V bias, the responsivity is 22 mA/W and the peak detectivity is $3.2 \times 10^9\ cm\ Hz^{1/2}/W$. The highest responsivities have been achieved using lateral quantum dot infrared photodetectors where the carrier transport is shifted to a neighboring channel with high electron mobility. Lee et al. have reported a responsivity of 4.7 A/W at low temperature (10 K) for a 9 V applied bias for the first time [21].

Recently, Chu et al. have demonstrated an 11 A/W responsivity associated with a resonant photoresponse around 186 MeV (6.65 μm) using an InGaAs channel layer [22]. A Ge quantum dot photodetector has been demonstrated using a MOS tunneling structure [23] where the responsivities of the presented photodetector with five-period Ge quantum dot are 130, 0.16 and 0.08 mA/W at wavelengths of 820 nm, 1300 nm and 1550 nm, respectively. The device with 20-period Ge quantum dot exhibits the responsivity of 600 mA/W at 850 nm and the reported room temperature dark current density is $0.06\ mA/cm^2$. An optimized growth of multiple (40–70) layers of self-organized InAs quantum dots separated by GaAs barrier layers (in order to enhance the absorption of quantum dot infrared photodetectors) is investigated in [24]. In devices with 70 quantum dot layers, at relatively large operating biases (smaller than 1.0 V), the dark current density and the peak responsivity are $10^{-5} A/cm^2$ and ∼0.1–0.3 A/W measured for temperature ranges from 150 K to 175 K, respectively. The peak detectivity varies in the range of 6×10^9–$10^{11}\ cm\ Hz^{1/2}/W$ for temperature range of 100–200 K.

A resonant tunneling quantum dot infrared photodetector has investigated theoretically and experimentally in [25]. In this device, the transport of dark current and photocurrent are separated by the incorporation of a double barrier resonant tunneling heterostructure for each quantum dot layer. The proposed device uses $In_{0.4}Ga_{0.6}As$–GaAs quantum dots and has implemented by molecular beam epitaxy. The introduced system was designed to operate at room temperature and 6 μm. Also the measured data exhibit a strong photoresponse peak at 17 μm. The dark current in the tunneling based devices are almost two orders of magnitude smaller than those in conventional devices. Measured dark current values are $1.6 \times 10^{-8}\ A/cm^2$ at 80 K and $1.55\ A/cm^2$ at 300 K for 1 V applied bias. Measured values of peak responsivity and specific detectivity are 0.063 A/W and $2.4 \times 10^{10}\ cm\ Hz^{1/2}/W$, respectively, under a bias of 2 V, at 80 K for the 6 μm response. For the 17 μm response, the measured values of peak responsivity and detectivity at 300 K are 0.032 A/W and $8.6 \times 10^6\ cm\ Hz^{1/2}/W$ under 1 V bias, respectively.

In conventional bound–continuum terahertz photodetectors, the electron energy level will be closer to the top of the quantum well. In fact, the energy of the incoming photons may be in the order of the thermal broadening of the electron distribution. Therefore all the mentioned contributions to the dark current are expected to increase [6,10].

Intersubband transitions in GaN-based hetrostructures have been the topic of extensive researches for their advantages. Broad wavelength range and high-temperature operation are available in these structures [26]. In this letter, we propose a GaN-based resonant tunneling spherical centered defect quantum dot (RT-SCDQD) to increase the responsivity, decrease the dark current and enhance the detectivity in THZ range. It will be shown that the responsivity increases due to increasing the absorption coefficient in SCDQD structure. Since the deep intersubband transitions which are achievable in wide conduction-band-offset material (GaN/AlGaN), increase the activation energy, so the second and third terms of the dark current are predicted to decrease. In order to collect the electrons from deep excited level, a double barrier structure is proposed which resonances with this level. This structure cancels the escape of ground state electrons through the tunneling, leading to ultra-small ground state dark current.

The organization of this paper is as follows: in Section 2, mathematical background for modeling the proposed structure is presented. Simulation results and discussion are presented in Section 3. Finally, the paper ends with a brief conclusion.