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Investigation of p-type multicolour-broadband quantum dot infrared photodetector

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ABSTRACT

The feasibility of quantum dot infrared photodetector (QDIP) for the detection of multiple infrared transitions over a broad spectral range is investigated. In contrast to the usual n-type QDIPs, this design utilizes the transitions between the valence subband states for the multicolour broadband functioning. The hole energy levels and corresponding wavefunctions are computed using the strain dependent multiband k.p approach and subsequently used to evaluate the optical matrix elements for intraband transitions. The theoretical formulation is applied to determine the dark current, spectral responsivity and detectivity of the QDIP. The calculated dark current shows good agreement with the experimental data. In addition, we identify the role of strain in determining the responsivity spectra and in shifting the peak response wavelength. We hope that this study would be useful for the further development of QDIPs based on intervalence subband transitions.

1. Introduction

In recent years, multiband IR photodetectors have attracted enormous interest due to their numerous exciting applications, such as advanced IR imaging systems, enhanced target discrimination and identification [1], medical diagnostics, astronomy, [2], land mine detection and navigational aids. In addition, multiband IR detectors can significantly enhance the overall performance of the device as

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compared to the single band detector technology [3]. The progress in the multi-band and hyper-spectral IR technology will enable to monitor the global warming or climate change, possibility of sensing of auroras and space backgrounds [4], and prospects to determine the absolute temperature difference between the missile targets.

Motivated by these considerations several approaches have been examined to develop the multi-colour broadband IR photodetectors, such as multicolour detectors based on mercury–cadmium telluride (MCT) [5–7] and quantum well infrared photodetectors (QWIPs) [8]. QWIPs are fabricated using well- matured III-V material systems. QWIP technology offers many advantages like ease of fabrication with high repeatability, high yield, low cost, good uniformity and narrow absorption region that can be tuned with the size and material compositions [9]. However, QWIPs suffer from various drawbacks including inability to detect normal incidence radiation, low quantum efficiency and detectivity and high dark current which restrict its operation to low temperatures [10]. Alternatively, MCT detectors provide high quantum efficiency and high temperature operation, but have high cost, lower yield and spectral nonuniformity particularly in the long wavelength range [11]. Type II superlattices structures (SLS) based on InAs/GaInSb material system have been extensively studied to see their prospects as an alternate material system for the multi-colour IR detection technology [12]. While these technologies have shown comparable performance with the MCT technology, unmatured growth technique, substrate preparation and surface passivation problems for InAs/GaInSb-based devices, require further research in order to fully develop the optimal solution to these problems.

In attempts to realize the high temperature operation with broad spectral response, several researchers have demonstrated the broadband response in bulk p-type GaAs heterostructure, which utilizes transitions amongst the various types of hole states such as heavy hole (hh), light hole (lh) and split-off hole (SO) to offer the broadband response [13]. However, fast dephasing process of the carriers in bulk semiconductors limits the performance of these detectors.

Besides all these efforts, quantum dot infrared photo detectors (QDIPs) utilizing self-assembled QDs have emerged as the promising candidate to provide the multi-colour and broad infrared spectral response simultaneously [14]. The broader response is due to the QDs having several discrete states and QDs growth mechanisms which naturally lead to a variation in the dot size resulting in the inhomogeneous broadening [15]. QDIPs are sensitive to the normal incidence radiation and expected to display lower dark currents as compared to the QWIPs [16]. In addition, QDs based devices exhibit external radiation hardness [17], which make QDIP's suitable for use in radiation environments such as in space applications. Unfortunately, QDIP's currently suffer from lower quantum efficiency as compared with QWIPs and MCTs. This problem may be alleviated by use of multilayer structure [18] or resonant cavity [19,20]. To date, most of the demonstrations of QDIP's were achieved with n type III-V heterostructure [21–24].These QDIPs are based on the intersubband transitions of electrons within the conduction band of the QDs. In contrast to the n-type QDIPs, p type QDIPs has received little attention. However, recently, researchers have begun to shown an increased interest in p-type QDIP's [25,26] because of some promising features shown by them, such as elevated quantum efficiency [27] less dark current and much broader response in comparison with the n-type QDIP's.

The objective of this work is to investigate a multilayer p-type QDIP structure, which can offer multicolour detection over a broad spectral range. The multiple band Luttinger Hamiltonian is numerically solved by creating the Hamiltonian matrix in Hilbert space of Hermit Gaussian functions for describing the complex valance band structure of QDs. The energy eigenvalues and wavefunctions obtained in this manner are employed to determine the intraband optical matrix elements and subsequently the spectral responsivity, dark current and detectivity have been calculated. The details of the theoretical formulation are presented in Section 2, while the results are discussed in Section 3. Important conclusions have been mentioned in Section 4.

2. Theoretical approach

The operation of p-type QDIP is based on the transition involving the several discrete energy states within the valence band of quantum dots. The energies and the wave functions of these states are determined by the k.p method [28] represented by the Luttinger–Kohn Hamiltonian in an