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Novel Infrared Detectors Based on Semiconductor Quantum Dots

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Abstract

This paper reviews recent progresses in developing self-assembled InAs/GaAs quantum dots based infrared photodetectors, especially, with n-i(QDs)-n configuration.

Introduction

It has been well known that three dimensionally quantum confined nanostructures, so called quantum dots (QDs), promise superior optoelectronic device performances [1]. The main challenge to fabricate practical QD optoelectronic devices is synthesizing *defect-free* and *uniform* QD ensembles with desired optical transition energies. Self-assembled QDs are 3D islands formed spontaneously via epitaxial deposition of few monolayers of semiconductors on lattice-mismatched substrates (e.g., InAs/GaAs) [2-3]. Among various QD synthesis approaches, such as colloidal chemistry, epitaxial self-assembly (Stranski-Krastanov mode), and lithography, epitaxial self-assembly is arguably the most promising approach to synthesize QDs for optoelectronic devices because of its unique combination of great advantages: i) defect free (coherent) crystalline, ii) convenient electrical accessibility, and iii) easy fabrication of QD ensembles. In the past decade, significant progresses have been made in both understanding formation of the InAs/GaAs QDs and controlling their size/shape and uniformity [1]. For the InAs/GaAs QDs, narrow photoluminescence line width of ~25meV can be routinely achieved [4].

The self-assembled InAs/GaAs QDs is an excellent candidate for mid infrared photodetector applications for the following reasons: i) QDs are intrinsically sensitive to normally incident infrared radiation due to its 3D quantum confinement, ii) the material uniformity of InAs/GaAs over large area is expected to be much better than HgCdTe (the leading infrared photodetetctor material), iii) the processing of III-V semiconductor is much more mature than that of HgCdTe, and iv) the photoexcited carriers in QDs have longer life time than that in quantum wells due to suppressed electron-phonon scattering [5-6], which will lead to high photoconductive gain and high operating temperature. Similar to commercially available GaAs/AlGaAs quantum well infrared photodetectors [7], the InAs/GaAs QD infrared photodetectors (QDIPs) are based on intersubband transitions.

Operating mechanism of QDIPs

A schematic of a representative infrared photodetector structure based on InAs/GaAs QDs is shown in Fig. 1. An active InAs QD region consisting of multiple layers of InAs/GaAs QDs is located between highly-doped top and bottom GaAs contact layers.

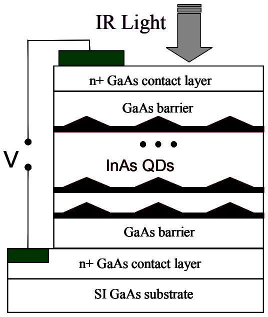

Fig. 1 Schematic of QDIP

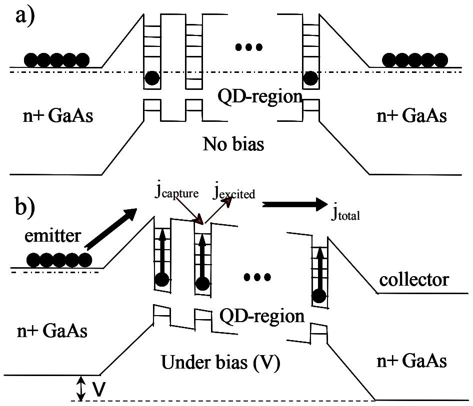

Fig.2 Simplified band diagram of InAs/GaAs QDIPs.

Figure 2 shows a schematic of the greatly simplified band diagram for electrons in the QDIP structure. Panel a) shows the band diagram of the QDIP at zero bias, while panel b) shows the band diagram of the QDIP at bias under infrared radiation. The InAs/GaAs QDs have type I band offset, i.e., electrons and holes are confined in the same low bandgap semiconductor. The incident mid-infrared photons induce intersubband transitions of the InAs/GaAs QDs in the active region, eventually leading to a change in current. Such a change of current upon infrared radiation corresponds to photocurrent.

QDIPs with n-i(QDs)-n configuration

For n-type QDIPs with the vertical electrical contacts shown in the Fig. 1, there are two classes of photodetector configurations: n-i(QDs)-n and n-n(QDs)-n. In the n-n(QDs)-n configuration, the active QD region between top abd bottom contacts is intentionally doped. In the n-i(QDs)-n configuration, that is intentionally undoped, and the electrons in the ground states of the QDs in the active region are transferred and/or injected from contacts. So far, QDIPs with highest detectivity are based on n-i-n configuration. The detectivity (D*) is defined as

$$D^* = \frac{I_s}{I_n}\frac{(A\cdot\Delta f)^{1/2}}{P}$$

where I_s is photocurrent, I_n is noise current, and P is infrared photon power. The device area (A) and band width (Δf) are for normalization. Namely, the detectivity is a normalized signal-to-noise ratio.

In past five years, we have extensively studied the QD infrared photodetectors based on intersubband transitions of the InAs/GaAs QDs. Surprisingly, Chen and Baklenov et al found that QDIPs with n-i(QDs)-n configuration show desired higher detectivity and lower dark current than that with n-n(QDs)-n configuration [8][9]. In order to enhance detectivity and to reduce dark current, we also introduced the concept of current blocking layer in QDIP structures (see Fig. 3) [8][9]. The AlGaAs layers placed beside

QD layers in the active region act as current blocking layers. These AlGaAs blocking layers significantly reduce dark current and noise current with less decrease in photocurrent, and enhances detectivity by a factor of about six [10].

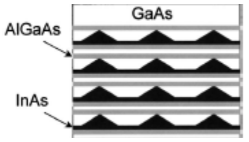

Fig. 3 InAs/GaAs QDs embedded between AlGaAs current blocking layers.

The photoresponse wavelength of the photodetector is another important operating parameter for infrared applications. The binary InAs/GaAs QDs based QDIPs typically exhibits a photoresponse wavelength around 7μm. In order to push the photoresponse wavelength of QDIPs into 8-14 μm atmosphere window, Kim and Chen et al first demonstrated QDIP structures with photoresponse wavelength at ~9μm, which consists of 5 layers of InGaAs capped InAs QDs (see Fig. 4) [11][12]. The InGaAs capping layers modify the band offset and strain status of the InAs QDs, thus tailoring the photoresponse wavelength of the QDIP.

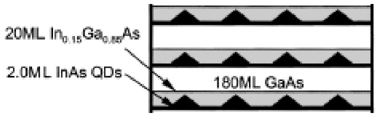

Fig. 4 InGaAs capped InAs/GaAs QDs

Multi-color infrared photodetectors are highly desirable for various applications, such as discriminations of absolute temperature and unique signatures of object in scenes. They can greatly simplify infrared imaging systems, and reduce system size, weight and cost. Chen and Kim et al reported the first voltage-controlled tunable middle- and long-wavelength 2-color QDIP, the active region of which contains two types of InAs QDs with different size/shape [13][14]. The relative photoresponse in this dual-wavelength structure is tunable up to two orders of magnitude with bias (see Fig. 5). With the InGaAs capped InAs QDs, we also achieved a very narrow FWHM (full-width-at-half-maximum) of the QD photoresponse, 6.0 meV ($\Delta\lambda/\lambda$=4.6%, λ=9.7 μm) [15].

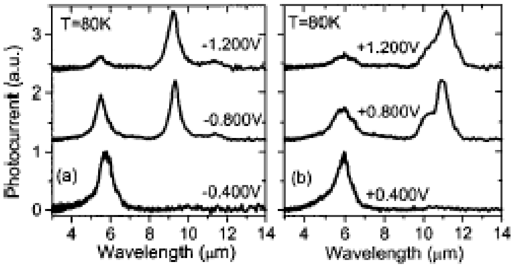

Fig. 5 Bias-controlled tunable 2-color infrared photoresponse of InAs/GaAs QDIP [13]

All these above-mentioned n-i(QDs)-n QDIPs consist of 5 layers of QDs in the active region. Based on the 9μm QDIP structures (see Fig. 4), Kim et al demonstrated, at 77K and at 9.3 μm, a very high QDIP detectivity of $3x10^{11}$ Jones [16], at least comparable to the highest D* of the quantum well infrared photodetectors [7]. For this n-i(QDs)-n QDIP, an increase of QD layer number from 5 layers to 10 layers dramatically enhanced the detectivity.

Many other groups have demonstrated normal-incidence QDIPs based on InAs QDs. Nearly all of them have n-n(QDs)-n configuration [17-26].

Summary

In past several years, significant progresses have been made in developing the self-assembled InAs/GaAs QDs based photodetectors in the mid-infrared atmosphere window (3-14 μm). These significant progresses indicate a realistic hope that QDIPs can be exploited for mid-infrared imaging application.

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