Front. Phys. China (2006) 3: 334−338
DOI 10.1007/s11467-006-0030-z

REVIEW ARTICLE

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Characteristics and developments of quantum-dot infrared photodetectors

Abstract Quantum dots infrared photodetectors (QDIPs) theoretically have several advantages compared with quantum wells infrared photodetectors (QWIPs). In this paper, we discuss the theoretical advantages of QDIPs including the normal incidence response, lower dark current, higher responsivity and detectivity, etc. Recent device fabrication and experiment results in this field are also presented. Based on the analysis of existing problems, some approaches that would improve the capability of the device are pointed out.

Keywords quantum dot infrared photodetector, dark current, photoconductive gain, responsivity, detectivity

PACS numbers 68.65.Hb, 85.60.Gz

1 Introduction

The detection of mid-infrared (MIR) and far-infrared (FIR) radiation is important for device applications involving remote sensing, thermal imaging, night vision and space applications [1]. With the rapid progress in the development of nanotechnology, new types of infrared photodetectors taking advantage of the quantum confinement effect obtained in semiconductor heterostructures have emerged in the past two decades. For example, quantum well infrared photodetectors (QWIPs) in which the photoexcitation of the carriers relies on intersubband absorption in quantum wells have demonstrated great promise for infrared detection and have been widely investigated.

However, QWIPs have their limitations. Due to the transition selection rules, they are not sensitive to normally incident light, and they typically only have a narrow response range in the infrared [2]. In the past several years, a promising new detector type that uses self-assembled quantum dots as active elements of photodetectors, so-called quantum dot infrared photodetector (QDIP) that overcomes several of these problems has been reported [3,4]. In this paper, we discuss the theoretical advantages of QDIPs and the newest experiment results in this area.

2 Anticipated advantages of QDIPs

Generically, QDIPs are similar to QWIPs in the structures and principia [5,6]. As Fig. 1 shows, the electrons are injected from the emitter in the active region with QDs where electrons could be captured by QDs or drift towards the collector. After photoexcitation by IR photon, the emitted electrons drift towards the collector in the electric field provided by the applied bias, and photocurrent was created.

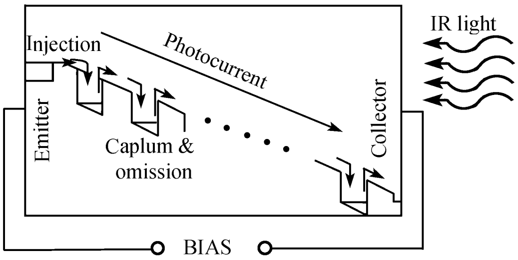

Fig. 1 Schematic of QDIPs principle operation.

In comparison with QWIPs, QDIPs have lower dark cur-

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Received June 13, 2006

rent and higher photoresponse resulting from longer carrier capture and relaxation times. Theory predicts that QDIP performance has several advantages than QWIP as follows.

2.1 Sensitivity for normally incident light

In semiconductor quantum dots, the three-dimensional (3D) confinement leads to very specific features like a δ-like density of states. This δ-like density of states is similar to that observed in atoms and will lead to strong modifications of the optoelectronic properties. The most important characteristic is QDIPs' normal incidence response, which resulted from the 3D confinement of the electrons in the quantum dots because in this case intersubband transitions can be induced by infrared light of any polarization.

2.2 Broader infrared response range

The self-assembled QDs naturally grow with inhomogeneous broadening in the size, composition and strain. More importantly, QDIPs provide a larger response range because the reduced density of states yield a variety of possible transitions which, depending on the occupancy of the QD states, participates in the detection and which effectively leads to a larger homogeneous broadening. For many applications, the wavelength-integrated response would be higher by a factor directly proportional to the bandwidth of the response.

We can change the growth conditions to control the detection range of the detector [7]. For example, the growth temperature can be used to adjust the dots' size or shape, the amount of strained material deposited can be used to control the density of QDs, and the choice of the barrier material, height, and thickness also can be adjusted in conjunction with the QD size to set the detection range.

2.3 Lower dark current

Long carrier lifetime has anticipated that the relaxation of electrons is substantially slowed when the inter-level spacing is larger than the phonon energy, or the so-called "phonon bottleneck" effect [8]. If this effect can be fully implemented in a QDIP, the long excited electron lifetime directly leads to a higher responsivity, higher operating temperature, and higher dark current limited detectivity.

The dark current can be given by

$$j_{\mathrm{dark}} = evn_{\mathrm{3D}}$$

where v is the drift velocity, n_{3D} ($\propto \exp(-E_{\mathrm{a}}/K_{\mathrm{b}}T)$) is the electron density in the continuum, where E_{a} is the activation energy, which equals the energy difference between the top of the barrier and the Fermi level in the well or dot.

Similar with QWIP, the main mechanism producing the dark current in the QDIP devices is still the thermionic emission of the electrons confined in the quantum dots [9]. By lowering the doping levels and by using heterojunction barriers for the contacts, the dark current is expected to be lower.

2.4 Higher photoconductive gain

The photoconductive gain g is given by

$$g = \frac{1}{Np_{\mathrm{c}}}$$

where p_{c} is the capture probability of a carrier traversing a quantum dot layer, N is the number of active periods. The normal incident response of the QD array leads to the extra injection of the electrons from the emitter to the collector through the QD array. This operation mechanism provides the photoconductive gain that can significantly exceed.

2.5 Higher responsivity

Peak responsivity is one of the most important performances of QDIPs. The expression is

$$R_{\mathrm{peak}} = \eta g \frac{e\lambda}{hc}$$

where η corresponds to the product of the absorption quantum efficiency and the probability of the photoexcited carriers to escape from the quantum dots, and hc/λ is the energy at the peak wavelength, which multiplies the effective photon irradiance to give an effective irradiance in watts. Because of the improvement of the gain, the infrared responsivity of the QDs system will increase accordingly.

2.6 Higher detectivity

An important figure of merit of the detector is the detectivity D^*, which is given by:

$$D^* = \frac{R\sqrt{A\Delta f}}{I_n}$$

where R is the responsivity of the detector, A is the detector surface, Δf is the measurement bandwidth, and I_n is the generation-recombination noise current, which is given by $I_n^2 = 4eIg\Delta f(1-p_{\mathrm{c}}/2)$. With the increase of R and decrease of I_n, the detectivity of the detector can promise to be higher.

3 Recent performances of QDIPs

There are two possible kinds of device structures for QDIPs: vertical structure and lateral structure [10]. The vertical QDIP [Fig. 2 (a)] collects photocurrent through the vertical transport of carriers between a top and bottom contact while the lateral QDIP [Fig. 2 (b)] collects photocurrent through the transport of carriers across a high-mobility channel between two top contacts.

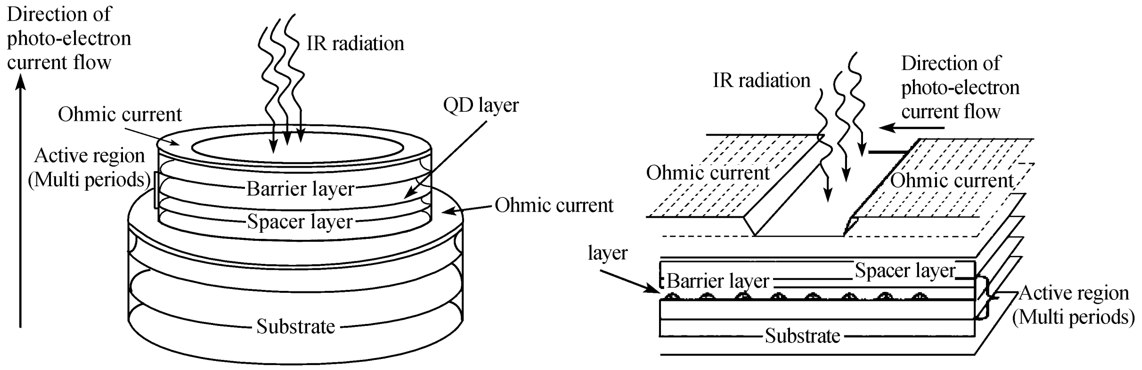

Fig. 2 Schematic diagrams of the two basic quantum-dot detector structures. (**a**) Conventional structure; (**b**) Lateral structure.

On the basis of these designs, people presented and fabricated some new ideas to control the response range and improve the performances of devices.

3.1 QDIPs with AlGaAs current blocking layer

Several groups have reported some results on QDIPs with AlGaAs barriers [11, 12]. Wang *et al.* have demonstrated an active region structure which introduced a thin AlGaAs current blocking layer as shown in Fig. 3.

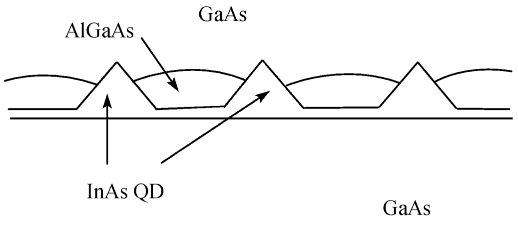

Fig. 3 Schematic diagram of the AlGaAs current blocking layer.

They believed that the excellent transport property of GaAs can induce large dark current such as the dark current and thus the spacing between dots can provide an unperturbed path to the carriers. The insertion of 3 nm $Al_{0.25}Ga_{0.75}$ As is supposed to degrade the transport property of carriers. By controlling the thickness of the AlGaAs layer, the dark current can be lowered for over 1 000 times while the high responsivity and gain are still obtained.

3.2 QDIPs with undoped quantum dots

Most of the studies on QDIPs have dealt with n-doped quantum dots between two contact layers. A group has studied n-type InAs QDIPs with undoped InAs multiple QD regions [13]. Their experimental results indicate that InAs/GaAs QDIPs with an undoped active region show smaller dark current than those with a doped active region.

In this case, they expect the photoresponse to exhibit a strong dependence as a function of the applied bias as well as a lower responsivity as compared to n-doped structures. Using AlGaAs blocking barriers, a detectivity ~10^{10}cm·Hz$^{1/2}$/W at 77 K with a photoresponse peak at 6.2 μm and a −0.7 V bias was reported. Especially, the dark current density is dramatically decreased (from 1 A/cm^2 to 10^{-6} A/cm^2 at 77 K) compared to that of the doped QD structure.

3.3 DWELL (dots-in-a-well) structure

Hirakawa *et al.* [14] have designed and fabricated a dots-in-a-well structure that utilizes photoionization of self-assembled InAs QDs and lateral transport of photoexcited carriers in the modulation-doped AlGaAs/GaAs two-dimensional channels. Figure 4 shows its schematic conduction band profile. In this report, they investigated the lifetime of photoexcited carriers and found that the lifetime depends exponentially on the distance between the hetero-interface channel and the QD layer. They observed extremely large photoconductive gains (~ 10^{5-6}) when the lifetime of the order of 0.1 – 1 ms even at $T = 77$ K.

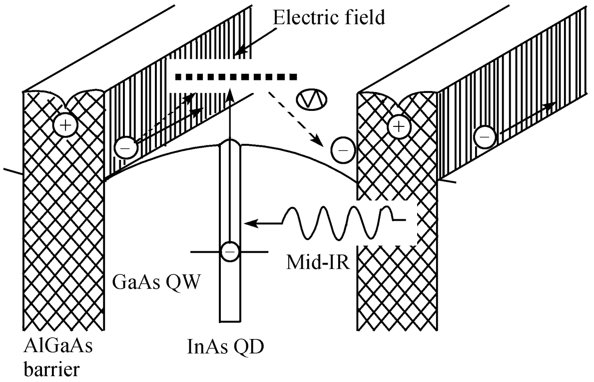

Fig. 4 Schematic conduction band profile of lateral quantum dot infrared photodetector structure.

In another report [15], the QDIPs in which InAs self-organized quantum dots embedded in AlAs/GaAs superlattice matrix were realized. For – 1.5 V bias, a peak responsivity of 2.5 A/W was obtained at $T = 78$ K. At room temperature, the dark current density of this device is only 3.2×10^{-4} A/cm^2 for –2.0 V bias.

3.4 QDIPs with new material system

The most widely studied QDIPs are made of self-assembled In (Ga) As dots on GaAs substrates. Recently several groups have investigated photodetectors with other materials such as the Ge/Si QD system [16]. In IR responsivity property, the QDIPs they fabricated have a very broad and tunable spectrum of $1.6 - 20$ μm under applied biases. This is very useful for applying the devices in thermal image detection. For detectivity, the maximum single wavelength detectivity of their devices is about 2.1×10^{10} cm·Hz$^{1/2}$/W under 0.2 V for 6 μm wavelength at 30 K. They also demonstrated The I - V characteristics which show that the dark current is reduced by the thick Si blocking layers.

Other than the Ge/Si system, InAs/InAlAs multi-layer quantum dots had also been used in the active region of infrared detectors with quite well performance [17].

3.5 QDIPs with high operating temperature

HgCdTe detectors and QWIPs need to operate in very low temperatures, while QDIPs have the potential application in room temperature. Chakrabarti *et al.* [18] reported a detector structure with 0.34 A/W peak responsivity, which can work at 150−175 K. Jiang *et al.* [19] designed multi-layer quantum dot detectors whose response range is 6.7–11.5 μm, and its operating temperature was 260 K. Kim *et al.* [20] reported InAs/GaAs room temperature QDIP, which indicated an exciting prospect. Figure 5 shows the absorption spectrum of this structure at 300 K.

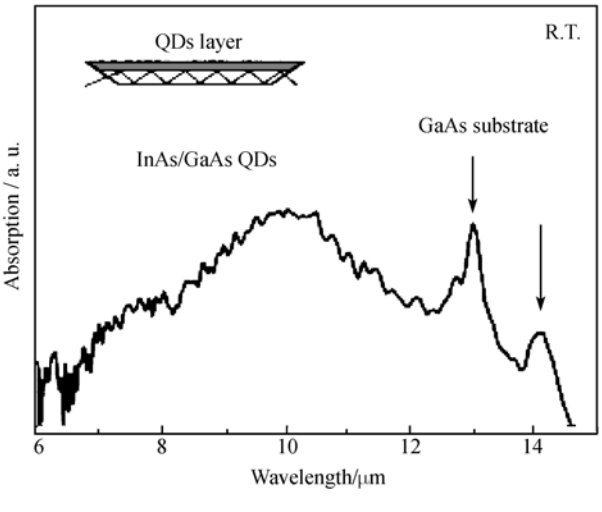

Fig. 5 FTIR absorption spectrum at 300 K for InAs QD arrays embedded in GaAs.

The high responsivity was achieved using lateral quantum dot infrared photodetectors where the carrier transport is shifted to a neighboring channel with high electron mobility [21, 22]. Lee *et al.* first reported a responsivity of 4.7 A/W at a low temperature (10 K) for a 9V applied bias [12]. Recently, Chu *et al.* demonstrated an 11 A/W responsivity associated with a resonant photoresponse around 6.65 μm using an InGaAs channel layer. Le *et al.* fabricated the LWIR dots-in-a-well structure achieving 12.4 A/W at –2.4 V bias [22]. From what was mentioned above, we can see that the lateral quantum dot photodetectors exhibit very high responsivity values. However, the drawback of this structure is the lower compatibility of its architecture for focal plane arrays.

4 Problems and improvement direction

Despite QDIPs having intrinsic potential advantages and being widely studied, the present devices have not fully demonstrated the potential advantages that have been predicted theoretically. There are at least several aspects should be attached more importance to and be improved.

4.1 Studying of the doping control

In order to populate dots with electrons, doping is an essential step in QDIPs. But a problem emerges that if the doping is directly done in the same layer as the dots, the random distribution could lead to a significant potential fluctuation On the other hand, if the doping is done in the barriers (modulation doping), the random distribution of the ionized dopants could lead to leakage current path. Therefore, the situation where the doping process should be done needs deep consideration.

Furthermore, the doping density is important for the QDs formation. When the doping level is low, Si or Be atoms can relax the strain in the neighboring atoms and act as nucleation centers for the formation of QDs. This is favorable for getting uniform QDs. However, when the doping level is high, it will decrease the uniformity of QDs. On the other hand, the high density of doping may lead to high dark current which is harmful to the application.

4.2 Controlling the QDs size and density

We know that so far most self-assembled quantum dots grown for QDIPs are wide in the in-plane direction (15—25 nm) and narrow in the growth direction (3—8 nm). The confinement in the growth direction is therefore very strong, while the in-plane confinement is comparatively weak, resulting in several levels in the dots. This is believed to be one of the most important reasons why normal incident response in QDs array is weak.

Therefore, if strong and dominant normal incidence absorption is expected, we should make the dots smaller so that there is only one bound state in the dots or the second state is very close to the top of the barrier. If a broader response spectrum is desired, there should be two or more states in the dots. One example is shown in Fig. 6, which was reported by Wang *et al.* [23]. They fabricated a type of three-color detector by changing the quantum dots grown temperature. For good characters of detectors, a high dot density is also expected in order to improve the absorption quantum efficiency. This efficiency is essential to obtain high responsivity and detectivity.

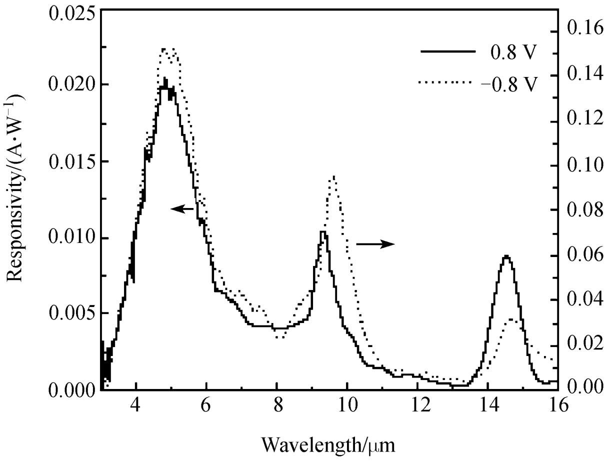

Fig. 6 The normalized responsivity spectrum of the multicolor detector QD material.

4.3 Studying of the wetting layer and spacer layer

In Stranski-Krastanow (S-K) growth mode, multi-layers of QDs are required in order to acquire satisfying dot densities and achieve sufficient photocurrent. But strain accumulation generated by such stacking is a large concern as it can lead to the formation of misfit dislocations that could degrade device performance. For QDIPs, comparatively wide spacers are required to reduce the tunneling and thermally assisted tunneling dark current components [24]. Therefore, controlling the spacer layers between different QD layers is very important.

Before the appearance of inland structures, a wetting layer will grow on the substrate firstly. To some extent, the wetting layer is similar to QW in structure and it may be one of the possible tunnels of exited carriers. But in most reports, the role of the wetting layer was neglected. This is one of the study areas that need to be extended.

5 Summary

In theory, quantum dots infrared photodetectors ideally have several advantages over quantum wells infrared photodetectors. We discuss the key issues related to QDIPs including the normal incidence response, lower dark current, higher responsivity and detectivity, etc. The recent device design and experiment results in this area are demonstrated and analyzed. On the basis of these contents we point out some of the approaches that may improve the capability of the device.

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