Detection wavelength and device performance tuning of InAs QDIPs with thin AlGaAs layers

S.Y. Wang [a,*], H.S. Ling [b], M.C. Lo [b], C.P. Lee [b]

[a] Institute of Astronomy and Astrophysics, Academia Sinica, P.O. Box 23-141, Taipei 106, Taiwan
[b] Department of Electronic Engineering, National Chiao Tung University, 1001 Ta Hsueh Road, HsinChu 300, Taiwan

ARTICLE INFO

ABSTRACT

QDIPs with thin inserted AlGaAs layers adjacent to the QDs were investigated for the tailoring of detection wavelength and device performance. Simple InAs/GaAs QDIPs and DWELL QDIPs with different insertion layer structure were studied. The thin AlGaAs layer is shown to effectively modify the electron wavefunction and associated confined state energies which lead to the change of the detection wavelength and the polarization dependent quantum efficiency. Furthermore, the dark current and conductive gain also change with different device structures. The insertion of AlGaAs layers provides an additional freedom of tuning the electronics states involved in the infrared detection and also enables the improvement of the absorption and device performance.

1. Introduction

The three dimensional confinement of the quantum dot (QD) structure provides the possibility to suppress the electron phonon interaction and relax the selection rule of intersubband transition in the quantum well (QW) structures. Thus, quantum dot infrared photodetectors (QDIPs) are of great potential to overcome the drawbacks of the commercialized QWIPs and become low cost, high temperature operation infrared detectors [1–10]. From the early stage of the QDIPs study, it is well known that the performance of QDIPs is quite limited with the simple InAs/GaAs QD structure. In the past, high band gap material layers and tunneling barriers have been introduced in QDIPs to enhance the performance by the reduction of the dark current [1–4]. Moreover, QDIPs with operation temperature higher than 200 K and even room temperature has been demonstrated with different device structures [3–5]. Besides, QDs within QWs to form the dots-in-a-well (DWELL) structure has also been proposed to provide the flexibility to adjust the electronic states and the detection wavelength with the QW [6–9]. Furthermore, DWELL QDIPs have an additional advantage of lower dark current due to the lower ground state energy. Recently, high quality 640×512 DWELL QDIP imaging focal plane arrays have been demonstrated [9].

On the other hand, QDIPs with thin AlGaAs layer deposited on top of the InAs QDs were demonstrated to suppress the dark current and enhance the device performance [1,2]. Recently, we also demonstrated high quantum efficiency QDIPs with the insertion of thin high bandgap barriers on top of QDs in the DWELL structure [10]. In QDs, due to the smaller size and the intermixing with the barriers, the wavefunctions of the excited states extend further out of the QDs [11]. The modification of the barrier structure can dramatically change the device performance even though the thickness is thin. This approach provides additional parameters for the tuning of the performance of QDIPs. In this paper, detailed studies on the QDIPs with thin AlGaAs layers were conducted. QDIPs with different AlGaAs parameters were analyzed to compare the response spectrum and device performance.

2. Basic characteristics of the samples

Two sets of samples were prepared for this study: InAs/GaAs QDIPs with thin AlGaAs layers and InAs/InGaAs/GaAs DWELL QDIPs with thin AlGaAs layers. The samples were grown by Veeco Gen II MBE machine on (1 0 0) GaAs semi-insulating substrates. Within each sample, ten periods of InAs QDs were used in the active region with modulated doping layers 2 nm away from each QD layer to provide a doping density $\sim$1e-/dot. The typical size of the quantum dot is about 60 Å in height and 220 Å in radius. The QD density is around 2×10^{10} cm^{-2}. Each barrier thickness between two QD layers is kept at 50 nm. In each sample, the active region was sandwiched by 5000 Å n-type contact layers. All samples were examined with atomic force microscopy to confirm the dot morphology and density with the additional QD layer deposited

* Corresponding author. Tel.: +886 2 33652200x823; fax: +886 2 23677849.
  E-mail address: sywang@asiaa.sinica.edu.tw (S.Y. Wang).

on the wafer surface. Low temperature (20 K) micro-photolumi-nescence (μ-PL) was used to probe the electronics states of the samples especially the excited states. Standard processing tech-niques were applied to define the mesas and to generate ohmic contacts. AuGe contact ring is fabricated on the mesa top to allow the normal incident measurement.

3. InAs/GaAs QDIPs with thin AlGaAs layers

Simple InAs/GaAs QDIPs is known to show high dark current generated from the leakage path through the spacing between QDs. In our early work, with 25 Å of $Al_{0.2}Ga_{0.8}As$ current blocking layers on top of the QDs, the leakage path is effectively blocked and the dark current is thus largely reduced by several orders of magnitude [1]. Due to the strong confinement in the InAs/GaAs QD structure, the insertion of the AlGaAs current blocking layer hardly changes the ground state energy but slightly elevates the excited state energy. The detection wavelength is thus slightly shorter. Furthermore, the normal incident absorption is also en-hanced due to the better confinement along the QDs plane.

Interesting behavior of wavelength tuning was observed when an additional 1 nm $Al_{0.2}Ga_{0.8}As$ layer was inserted several nm be-low the QDs in the InAs/GaAs QDIPs with current blocking layers. A series of samples were prepared with the different separation be-tween the added $Al_{0.2}Ga_{0.8}As$ layer and the QD layer and compared with the control sample without the 1 nm $Al_{0.2}Ga_{0.8}As$ layers. Fig. 1 shows the schematics of the samples. The distances x from the QD layers to the 1 nm $Al_{0.2}Ga_{0.8}As$ layers are 5, 7 and 11 nm for the three samples, respectively. Fig. 2 shows the photoresponse spec-tra of the samples including the control sample. A broad detection peak is shown in the simple InAs/GaAs structure as also reported by other groups [6]. The broad response peak in the control sample separated into two peaks with the insertion of the AlGaAs layers. Clearly, the peak at 6 μm is almost fixed regardless the insertion of the AlGaAs layer while the peak with slightly higher energy shifts toward the shorter wavelength as the AlGaAs layer is closer to the QDs. Also, the signal of the higher energy peak is weaker with the decrease of the distance x. The insertion of the AlGaAs layer breaks the degeneracy of the two transitions which have sim-ilar energies. The excited state of the transition with higher state energy is probably pushed out of the confinement and the oscilla-tion strength for the transition becomes weaker and weaker as the transition energy is lifted. From the PL and response spectra, the transitions shown in the response correspond to the wetting layer states. The inserted AlGaAs layers are adjacent to the QD wetting layers and effectively alter the wavefunctions of the states.

For the sample with 5 nm separation, only a narrow peak at 6 μm is shown in the response spectrum. The quantum efficiency (QE) is thus enhanced by a factor of five compared with the control sample. On the other hand, with the extremely thin AlGaAs layers,
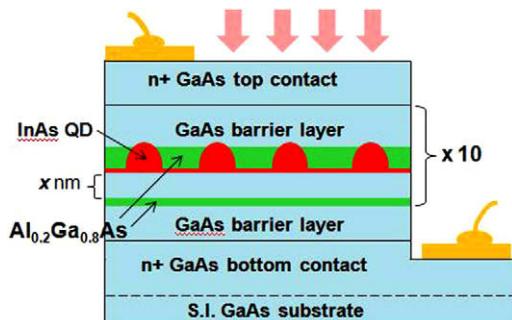

Fig. 1. The schematics of the device structure of the InAs/GaAs QDIPs with thin AlGaAs layers.
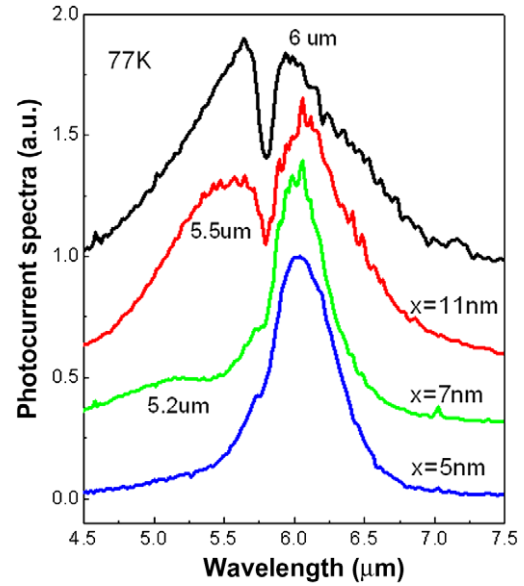

Fig. 2. The response spectrum of the InAs/GaAs samples. From the top to the bottom are the spectra for the sample without AlGaAs, and sample with 11, 7 and 5 nm separation from the QD layers to the 1 nm $Al_{0.2}Ga_{0.8}As$ layers.

the current gain is only slightly decreased. The performance is thus enhanced. At 77 K, the peak detectivity is about 4.1×10^{10} cm $Hz^{0.5}$/W for this sample. Such improvement shows the location of the thin layers can provide the flexibility of selecting the transi-tions within QDs.

4. DWELL QDIPs with thin AlGaAs layers

With DWELL structure, due to the lower bandgap of InGaAs, the quantum state energies are lower and the confinement is weaker compared with the InAs/GaAs QD structure. Therefore, unlike the case in the simple InAs/GaAs structure, the thin AlGaAs layers deposited on top of the QDs can modify the excited states as well as the ground states in DWELL structure. This implies more impacts on the device performance are expected with the insertion of Al-GaAs layer. To explore the possible effects, three samples were pre-pared to study the changes of the electronics states with the AlGaAs layers in DWELL QDIPs. Sample A is a conventional DWELL QDIPs with 9 nm $In_{0.15}Ga_{0.85}As$ quantum well. The QDs layer is inserted on 2 nm of $In_{0.15}Ga_{0.85}As$. In sample B, 2.5 nm of $In_{0.15}Ga_{0.85}As$ layer on top of QDs in sample A is replaced by $Al_{0.3}Ga_{0.7}As$ of the same thickness. In sample C, the 2 nm $In_{0.15}Ga_{0.85}As$ under the QDs in sample B is further replaced with GaAs layer i.e. the QDs are formed on GaAs. The confinement of the QD states of the samples gradually increases from sample A to sample C due to the higher barrier sur-rounding the QDs. This is confirmed by the μ-PL spectra as shown in Fig. 3. The ground state energy increases from 1.028 eV of sample A to 1.116 eV of sample C.

Meanwhile, the energy separation between the energy states also increases. The detection wavelength is blueshifted as the con-finement enhances. Fig. 4 shows the photocurrent spectra of the samples. The detection peak shifted from 9 μm to 7.3 μm from sample A to sample C. Furthermore, multiple peaks were shown in sample C instead of the single peak as in other samples. The 5.5 μm peak is similar to the transition peak from the ground state to the wetting layer state shown in InAs/GaAs QDIPs. On the other hand, the peak at 7.5 and 8.2 μm is similar to the bound to bound transitions in samples A and B. In sample C, the QDs are not totally embedded in the QW as in the other samples. The states associated with the wetting layer are more confined with the GaAs and
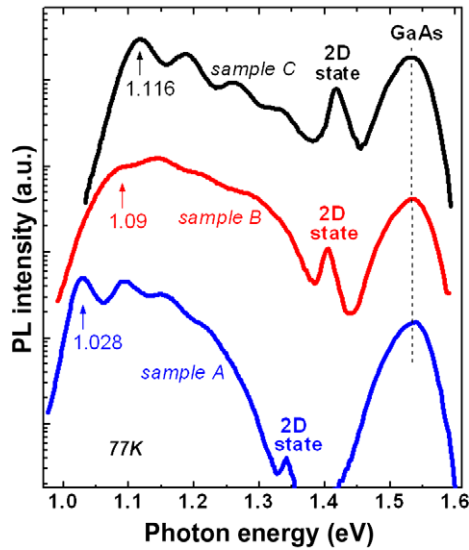
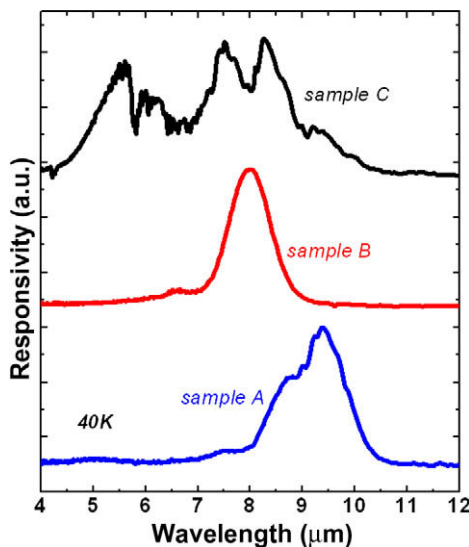**Fig. 3.** The high excitation power μ-PL spectra of the three DWELL QDIPs.

Fig. 4. The response spectra of the three DWELL QDIPs at 40 K and −1 V.

riers because of the elevated excited state energy. The excited state energy associated with the transition in samples with confinement enhance layers (samples B and C) is about 80 meV higher than that of the conventional DWELL sample (sample A).

The thin AlGaAs layer deposited on the QDs mostly covers the region without QDs and the sidewalls of the QDs. The confinement effect provided thus is more on the QDs plane (x–y plane) rather than in the growth direction (z direction). To examine such effect, the polarization dependent photo-response of our devices was measured using the 45° edge coupling scheme. In Fig. 5, the normalized responsivity versus the polarization angle for the three samples was shown along with the InAs/GaAs sample mentioned in the previous section and the conventional AlGaAs/GaAs QWIP sample. 90° polarization angle means the electric field of the polarized radiation is parallel to the epilayers (TE mode). 0° means the polarization is perpendicular to the 90° and is mixed with TM and TE mode. The TE response depends not only on the confinement along x–y plane but also on the confinement in z direction. Sample B clearly shows the best performance of the TE radiation due to the better confinement in x–y plane but relatively weaker confinement in z direction. The stronger confinement in z direction in sample D slightly reduced the TE response but it is still better than that of sample A due to the enhanced confinement along x–y plane. However, compared with InAs/GaAs samples, the normal incident response is still better in the DWELL sample due to the weaker confinement in z direction.

The inserted AlGaAs layer not only changes the absorption but also alters the dark current and carrier transportation. As mentioned, the ground state energy is higher when the confinement is stronger. However, the higher ground state energy induces higher dark current. For example, the dark currents at 77 K and 1 V are 1.16×10^{-8} A, 3.26×10^{-7} A and 6.62×10^{-6} A, respectively, for samples A, B and C. The dark current increases for about 500 times with the energy change of the ground states of $\sim$60 meV. In principle, the dark current should increase for more than four orders of magnitude if we consider pure thermal excitation ($\sim$exp($\Delta E/$kT)). However, due to the higher barrier of the AlGaAs layers, the increase of the dark current is much less than expected. This reduces the drawback of the higher ground state energy. Besides, the conductive gain of the devices also depends on the device structure. In DWELL structure, the QWs effectively capture the carriers and reduced the current gain. As the InGaAs layer is replaced with the AlGaAs barriers, the transit time through the quantum well is shorter and the current gain is enhanced. Although it might be expected that the inserted AlGaAs layer could deteriorate the carrier transport, the barrier is thin enough to maintain the reason-
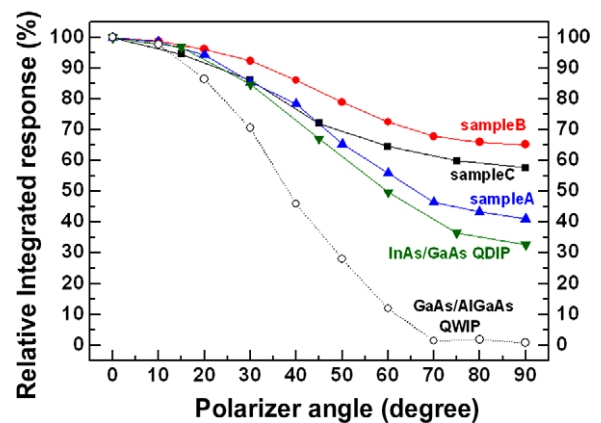
AlGaAs barriers. The oscillation strength for the transition to the wetting layer state is thus enhanced and therefore, the 5.5 μm peak becomes obvious. The asymmetric structure of sample C also induces the splitting of the single detection peak in other two samples and generated the bias tunable detection. Two detection peaks were shown at 7.5 and 8.2 μm. These two peaks around 8 μm under the negative biases shift to 10 μm under the positive biases.

The major advantage of the insertion of AlGaAs layer is the enhancement of QE. As mentioned, due to the weaker confinement of InGaAs QWs, the QE is generally weaker in DWELL structure compared with InAs/GaAs QD structure. The AlGaAs layer enhances the confinement of the QD states and improves the QE. The peak QE at 77 K is 0.08% and 2% for samples A and B, respectively. With the additional AlGaAs layers, QE is enhanced for more than one order of magnitude. For sample C, though the response spectrum is much wider, the peak QE (0.24% at 77 K) is still three times higher than that of sample A. The enhancement of QE is not only from the increase of the oscillation strength of the transitions but also from the higher escape probability of the excited car-

Fig. 5. The normalized responsivity versus the polarization angle for the three DWELL samples. The curves of InAs/GaAs QDIP and AlGaAs/GaAs QWIP were also included for comparison.

able current gain. Thus, the current gain for sample C is higher than the other samples and sample A is the one with lowest current gain due to the thick InGaAs QW. Combined with the higher QE, the responsivity for the sample with AlGaAs layers is more than ten times higher than that of the conventional DWELL structure. For example, the responsivity at 77 K and 1 V for the three samples are 5.2, 134, 169 mA/W, respectively. Therefore, higher detectivity is expected for samples of AlGaAs barriers. The peak detectivity at 77 K for sample B is 1.0×10^{10} cmHz$^{0.5}$/W. For comparison, the peak detectvitiy at 77 K is 1.0×10^{9} cmHz$^{0.5}$/W for sample A and 1.2×10^{9} cmHz$^{0.5}$/W for sample C. Although the detection band is much wider for sample C, the peak detectivity is still similar to that of sample A.

In principle, the change of Al content in AlGaAs layers can increase or decrease the confinement states energies accordingly. However, the epitaxial process of the QDs makes the issue more complicated. A series of single layer confinement enhanced DWELL structure was prepared with different Al content in the AlGaAs layer ranging from 0% to 30%. Fig. 6 shows the PL spectra of the samples as well as the PL spectrum of the conventional DWELL structure. Surprisingly, opposite trend of the ground state energy shift was clearly shown in the figure. The sample with the weakest confinement (i.e. the sample with GaAs layer) generates the highest ground state energy. The intermixing effect during the epitaxial process dominates the behavior. As published, strong intermixing of the Ga atoms with InAs QD was observed when the InAs QDs is covered by the GaAs layers [12]. With the increase of the Ga content in the QD, the ground state energy is thus enhanced. When the Al content increases, the intermixing effect decreases and the ground state energy is thus lower. When the Al content is around 20%, the decrease of intermixing effect and the increase of the confinement are balanced. No obvious ground state energy shift was observed when the Al content is higher than 20%.

However, the device performance can be different even though the states are almost the same. Two samples with Al$_{0.3}$Ga$_{0.7}$As and Al$_{0.2}$Ga$_{0.8}$As confinement enhancing layers were compared. In the two samples, the thickness of the In$_{0.15}$Ga$_{0.85}$As QW above the Al-GaAs layer was reduced to 28 Å to improve the current gain. Fig. 7 shows the responsivity spectra of the two samples at 77 K and 1 V. The two samples show almost identical spectral response with a peak at 7.3 μm due to the similar quantum state energies as mentioned above. The peak response position is shorter than that of
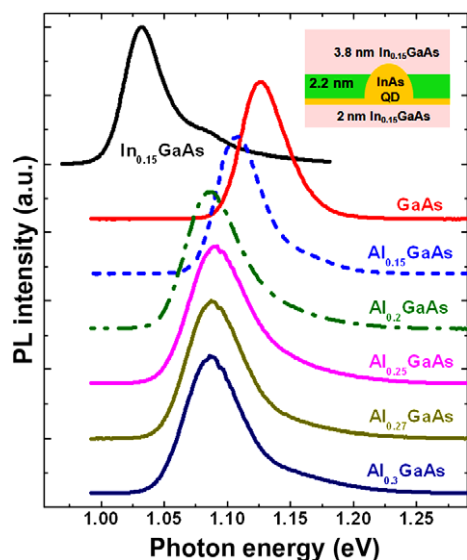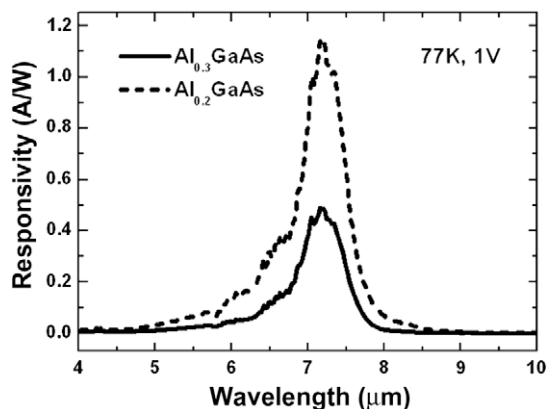

Fig. 7. The responsivity spectra of the samples with Al$_{0.2}$Ga$_{0.8}$As and Al$_{0.3}$Ga$_{0.7}$As layers.

sample B because of the thinner QW. It is clear that lower barrier of Al$_{0.2}$Ga$_{0.8}$As layers does improve the responsivity due to the better conductive gain. However, in the Al$_{0.3}$Ga$_{0.7}$As sample, the suppression of the intermixing effect gives a smaller effective QD size and more concentrated electron wavefunction. The QE is thus higher for the sample with Al$_{0.3}$Ga$_{0.7}$As layers. Combined with the lower dark current, at 77 K, the peak detectivity of the sample with Al$_{0.3}$Ga$_{0.7}$As layers is 4.8×10^{10} cmHz$^{0.5}$/W, which is about two times higher than the peak detectivity of the sample with Al$_{0.2}$Ga$_{0.8}$As layers.

5. Summary

QDIPs with thin inserted AlGaAs layers close to the QDs were investigated for the tailoring of detection wavelength and device performance. Simple InAs/GaAs QDIPs and DWELL QDIPs with different insertion layer structure were studied. The thin AlGaAs layers can modify the electron wavefunctions and change the detection wavelength and bandwidth of QDIPs. With the AlGaAs layer on top of the QD in DWELL structure, the performance could be greatly enhanced and provide the possibility for multicolor detection. Furthermore, the AlGaAs layer provides more confinement mainly on x–y plane and induces higher TE absorption. The insertion of the AlGaAs layer in DWELL QDIPs modifies all parameters of QDIPs. With different requirements for different applications, different AlGaAs layers with different QW structure could provide the flexibility to fit the requirements.

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**Fig. 6.** The PL spectra of the samples with different Al content in the AlGaAs layer. The PL spectrum of the conventional DWELL structure is also included.