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Transition mechanism of InAs/GaAs quantum-dot infrared photodetectors with different InAs coverages

Chi-Che Tseng
Institute of Photonics Technologies, National Tsing Hua University, Hsinchu 300, Taiwan

Tung-Hsun Chung, Shu-Cheng Mai, Kuang-Ping Chao, and Wei-Hsun Lin
Institute of Electronics Engineering, National Tsing Hua University, Hsinchu 300, Taiwan

Shih-Yen Lin[a]
Research Center for Applied Sciences, Academia Sinica, Nankang, Taipei 11529, Taiwan,
Department of Photonics, National Chiao-Tung University, Hsinchu 300, Taiwan,
and Institute of Optoelectronic Sciences, National Taiwan Ocean University, Keelung 20224, Taiwan

Meng-Chyi Wu
Institute of Photonics Technologies, National Tsing Hua University, Hsinchu 300, Taiwan
and Institute of Electronics Engineering, National Tsing Hua University, Hsinchu 300, Taiwan

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In this article, the authors investigate the influences of different InAs coverages on the photoluminescence excitation (PLE) spectra and spectral responses of InAs/GaAs quantum-dot infrared photodetectors (QDIPs). An increase in InAs coverage would lead to an increase in energy separation between heavy-hole state and light-hole state in the wetting layer (WL) region in the QD PLE spectra. The results suggest that most of the strain resulted from the InAs/GaAs lattice mismatch may be accumulated in the WL instead of the QD region. Also observed are the similar energy separations of energy levels responsible for the intraband absorption in the PLE spectra of the QDIPs such that similar detection wavelengths are observed for the devices. © *2010 American Vacuum Society.* [DOI: 10.1116/1.3368607]

I. INTRODUCTION

The growth of self-assembled (InGa)As quantum dots (QDs) on GaAs substrates for practical applications and fundamental research have been widely investigated in recent years.[1–3] The influence of strain accumulation on energy levels has also been investigated.[4] For practical applications, long-wavelength laser diodes based on QD structures[5] and quantum-dot infrared photodetectors (QDIPs) have been developed.[1,2,6] The performance of the devices suggests that strain reduction in QDs plays a key role in obtaining good optical characteristics of the QDIP structure. Beside the energy levels in QD structures, the energy level that resulted from the two-dimensional wetting layer (WL) is also frequently observed in related reports.[7,8] The heavy-hole (HH) and light-hole (LH) splittings that resulted from the strain accumulation have been reported elsewhere.[9,10] Theoretical calculation has been proposed to derive the wetting layer thickness according to the HH-LH energy splitting.[10] However, until now, there is no report regarding the influence of strain in QD structures on the performance of practical devices such as QDIPs.

In this article, the photoluminescence excitation (PLE) spectra and spectral response of InAs/GaAs QDIPs with different coverages are investigated. Increasing the energy separation between HH state and LH state in the WL region is observed in the PLE spectra with increasing InAs coverage of the QD structures. The results imply that most of the strain that resulted to the InAs/GaAs lattice mismatch may be accumulated in the WL instead of the QD region. Further investigation is still required to confirm this conclusion. The multilongitudinal optical (multi-LO) phonon peaks observed in the PLE spectra are similar to the phonon energies of the InAs bulk material, which further confirms the attribution. A model is also proposed for the transition mechanisms responsible for the peaks observed in the PLE spectra. The similar energy separations of energy levels responsible for the intraband absorption for QDIPs with different InAs coverages indicate in part why most QDIPs could only operate in the midwavelength infrared range (MWIR) (3–5 μm).

II. EXPERIMENT

The QDIP samples investigated here were grown on (100)-oriented semi-insulating GaAs substrates in a Riber Compact 21 solid-source molecular beam epitaxy system. Sandwiched between 0.3 and 0.6 μm thick GaAs contact layers with $n=1\times10^{18}$ cm^{-3}, ten-period InAs/GaAs QDs with 1.5, 2.0, 2.5, and 3.0 ML (monolayer) InAs coverages and 30 nm GaAs barriers are prepared. The sample structures are shown in Table I. The PL and PLE spectra of the QDIP samples were measured at 10 K by using a Jobin Yvon's NanoLog3 system with a tungsten-halogen lamp as the light source. For the measurements of spectral responses, the QDIP samples were fabricated into 100×100 μm^2 devices using standard photolithographic techniques, contact metal evaporation, and wet chemical etching. The measurement

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[a] Electronic mail: shihyen@gate.sinica.edu.tw

TABLE I. Sample structure of the QDIPs with different InAs coverages.

Top contact	300 nm GaAs $n = 2\times 10^{18}$ cm^{-3}			
30 nm GaAs (ten times)	Undoped			
InAs QDs (ML) (ten times)	1.5	2.0	2.5	3.0
30 nm GaAs	Undoped			
Bottom contact	600 nm GaAs $n = 2\times 10^{18}$ cm^{-3}			
Substrate	350 μm (100) semi-insulating GaAs			

system for spectral response consists of a Spectral 100 Fourier transformation infrared spectrometer with a cryostat and a current preamplifier.[11]

III. RESULTS AND DISCUSSION

Normalized 10 K PL spectra of the QDIP samples with different InAs coverages are shown in Fig. 1. The decrease in PL peak energy at 1.135, 1.116, 1.108, and 1.092 eV is observed with increasing InAs coverage. For the sample with a 1.5 ML InAs coverage, the luminescence at 1.24 eV is attributed to higher order excited state of 1.5 ML InAs QDs. Since relatively weaker QD luminescence intensity is observed for the sample, the luminescence of the *n*-type GaAs contact layer is observed. To further investigate the PL peak shift with different InAs coverages, there are two major mechanisms proposed for the energy level transitions in the QD structures. One mechanism is related to the height of QDs, where the lower energy levels are expected for taller QDs. The other mechanism is related to strain accumulation in the QD structures, where a band gap broadening is expected with larger compressive strain accumulation. The larger redshift of PL peak wavelength with a higher InAs coverage for the QDIP samples is attributed to the former mechanism. The results may also indicate that strain accumulation does not play a significant role in the QD structures with increasing InAs coverage. If the strain does accumulate in the QD structures with increasing InAs coverage, the influence of both mechanisms may cancel out each other such that the monotonically decrease in PL peak energy could not be observed.

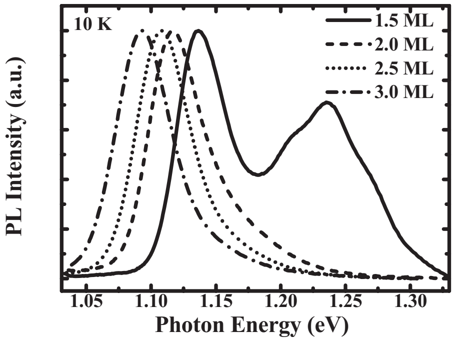

FIG. 1. Normalized 10 K spectra of the QDIP samples with different InAs coverages.

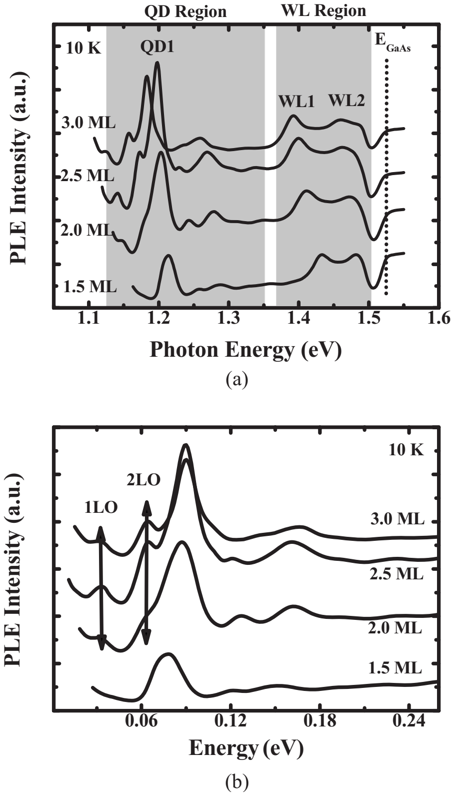

FIG. 2. (a) 10 K PLE spectra with the PL peak energy as the detection energy and (b) shifted PLE spectra by setting the detection energies as zero of the QDIP samples.

To further investigate the optical characteristics of the QDIP samples, the 10 K PLE spectra with the PL peak energy as the detection energy are shown in Fig. 2(a). It has been reported elsewhere that the PLE peak wavelength of QDs will change with different detection energies.[3,12] Therefore, although not shown here, the PLE peaks of QD1 changing under different detection energies are related to the absorptions in the QD structures while the peaks of WL1 and WL2 with unchanged location resulted from the QW-like InAs WLs, as shown in Fig. 2(a). The GaAs band-gap-edge absorption is also observed in the spectra, which is labeled as E_{GaAs}. By setting the detection energies as zero, the shifted PLE spectra of the QDIP samples are shown in Fig. 2(b). An inspection of Fig. 2(b) reveals that the peaks with the same energy separation of 32 meV are observed in the spectra for the samples with different InAs coverages. The peaks are attributed to the involvement of 1LO and 2LO phonons in the QD ground-state luminescence. Considering the LO photon energy of bulk InAs as 28 meV, similar phonon energies of the samples indicate that strain accumulation in the QDs does not increase with increasing the InAs coverage. The results are consistent with the previous assumption observed from the PL spectra.

To explain the transition mechanisms of the QD PLE spectra, a simplified band structure and the different transition mechanisms in PL/PLE spectra of the QDIP samples are shown in Fig. 3. Assuming that most of the compressive strain resulted from the InAs/GaAs lattice mismatch is accumulated at the WL, HH-LH splitting can be observed in the valence band of WL. For the InAs QDs, since no pronounced strain accumulation is observed in the investigated InAs coverage range of 1.5–3.0 ML, HH-LH degeneracy should still

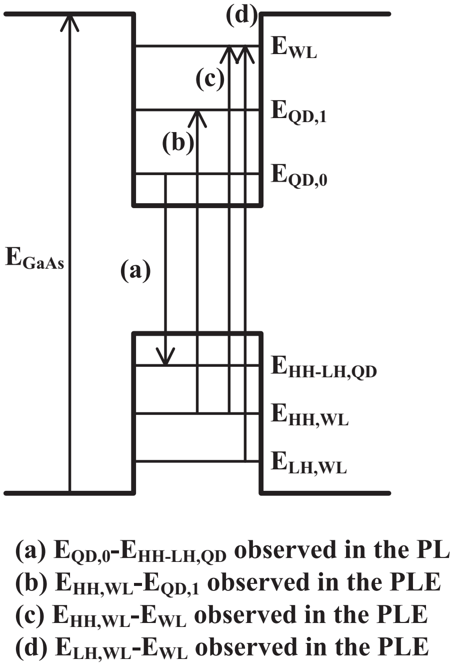

FIG. 3. Simplified band structures and the different transition mechanisms in PL/PLE spectra of the QDIP samples.

be observed. In this case, three states $E_{\text{HH-LH,QD}}$, $E_{\text{HH,WL}}$, and $E_{\text{LH,WL}}$, which correspond to the QD ground state, WL HH state, and WL LH state, respectively, are obtained in the valence band. In the conduction band, the three states $E_{\text{QD},0}$, $E_{\text{QD},1}$, and E_{WL} correspond to QD ground state, QD first excited state, and the WL state, respectively, as depicted in this figure. In addition, the optical recombination process of (a) $E_{\text{QD},0}-E_{\text{HH-LH,QD}}$ would result in the PL peaks observed in Fig. 1. For the absorption processes, there are three allowed transitions of (b) $E_{\text{HH,WL}}-E_{\text{QD},1}$, (c) $E_{\text{HH,WL}}-E_{\text{WL}}$, and (d) $E_{\text{LH,WL}}-E_{\text{WL}}$ in the structure. For absorption (b), although the wave functions of the two states are of different parities, the transition should still be allowed. The reasons are (a) the initial state $E_{\text{HH,WL}}$ is at the WL region and the destination state $E_{\text{QD},1}$ is at the QD region and (b) QD and WL structures are adjacent to each other. In this case, the wave function overlapping is not negligible such that the absorption process (b) would still be observed.

Absorptions (b), (c), and (d) correspond to the three PLE peaks of QD1, WL1, and WL2, respectively, as shown in Fig. 2(a). In this case, the energy difference between absorptions (c) and (d) would be equal to the HH-LH splitting in the WL. Therefore, as shown in Fig. 2(a), the increase in HH-LH splitting 48, 62, 63, and 69 meV with increasing the InAs coverage is observed for the QDIP samples. It implies that an increase in InAs coverage would lead to pronounced compressive strain accumulation in the WL region. Combined with the previous assumptions, it could be concluded that with increasing the InAs coverage, most of the compressive strains resulted from the InAs/GaAs lattice mismatch will be accumulated in the WL instead of the QD region. This phenomenon would result in the increase in HH-LH splitting in the WL, similar phonon energy with the bulk InAs material in the QDs, and the redshift of PL peak wavelength with increasing InAs coverage, as discussed above. To confirm this conclusion, more detailed investigation is still required in the future.

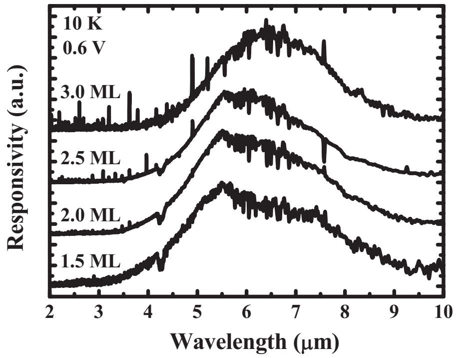

FIG. 4. 10 K spectral responses of the four QDIP samples biased at 0.6 V.

The 10 K spectral responses of the four samples biased at 0.6 V are shown in Fig. 4. As shown in this figure, similar responses in the range of 3–9 μm with peak detection wavelengths of ~6 μm are observed for the four samples. The broad detection wavelengths are frequently observed for the InAs/GaAs QDIPs. The phenomenon indicates that although the QDIPs used different InAs coverages, the energy difference between the confinement states responsible for the intraband transitions is almost the same for the four samples. Going back to the 10 K PLE spectra shown in Fig. 2(a), another interesting phenomenon observed in the spectra is the similar energy differences of 0.22, 0.21, 0.2, and 0.2 eV between PLE peaks of QD1 and WL1 for the samples with 1.5, 2.0, 2.5, and 3.0 ML InAs coverages. The values are quite close to the peak responses of the devices at ~6 μm (0.21 eV). As described in the previous paragraph, the energy difference between PLE peaks of QD1 and WL1 would correspond to the energy difference in $E_{\text{QD},1}-E_{\text{WL}}$. In this case, it is reasonable to conclude that for the InAs/GaAs QDIPs, $E_{\text{QD},1}-E_{\text{WL}}$ transitions are responsible for the observed spectral responses. Since most of the strain would be accumulated in the WL instead of the QD region, energy level lowering with increasing dot height will be observed with increasing InAs coverage. The broadening of the HH-LH splitting would compensate the lowering of the QD energy levels such that similar energy differences are observed for the QDIP samples with different InAs coverages. In this case, similar detection wavelengths are observed for QDIPs with different InAs coverages. The results explain in part why most QDIPs would only operate in the MWIR range (3–5 μm).

IV. CONCLUSIONS

In conclusion, we have demonstrated the effects of coverage on the PL/PLE and spectral responses of InAs/GaAs QDIPs. An increase in InAs coverage would lead to an increase in HH-LH splitting in the WL, similar phonon energy with the bulk InAs material in the QDs, and a redshift of PL peak wavelength. Most of the compressive strains are thus accumulated in the WL instead of the QD region. A correlation between the PLE spectra and the spectral responses of the devices is also established. The transition between the QD first excited state and the WL state is responsible for the responses of the InAs/GaAs QDIPs. The similar detection wavelengths of the devices suggest that if longer detection wavelengths are expected to be achieved for QDIPs, it is necessary to insert an addition energy level between the QD first excited state and the WL state.

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