Wavelength-Tunable InGaAs-Capped Quantum-Dot Infrared Photodetectors

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***Abstract*—Quantum-dot infrared photodetectors (QDIPs) with InGaAs capping layers are investigated. Compared with the standard QDIP with 2.5-mono-layer (ML) InAs QDs, the detection wavelength is shifted from 6 to 7.9 μm for an 8-nm InGaAs-capped QDIP. By decreasing the QD coverage from 2.5 to 2.0 ML, an even longer detection wavelength 10.4 μm is observed, which is attributed to the higher energy levels of the QD excited states resulted from the smaller QDs. By further increasing the capping layer thickness to 12 nm, longer detection wavelengths with broad response 10–18 μm is observed for the InGaAs-capped QDIP.**

***Index Terms*—Quantum-dot infrared photodetectors (QDIPs).**

I. INTRODUCTION

COMPARED with conventional quantum-well infrared photodetectors (QWIPs), advantages of quantum-dot infrared photodetectors (QDIPs) like high-temperature operation and normal incident absorption have been widely investigated [1]–[5]. However, for most of the QDIPs, the detection wavelengths are limited in the midwavelength infrared (MWIR, 3–5 μm) range. To improve this disadvantage, reports regarding to the InAs QDs embedded in InGaAs quantum-well structures (DWELL) have been proposed [6]–[9]. The devices have exhibited the long-wavelength infrared [(LWIR) 8–12 μm] detection. However, for such devices, an additional InGaAs layer prior to the QD growth is always required to achieve the devices operated at longer detection wavelengths [10]. With the more complicated structures, device parameter optimization such as underlying InGaAs thickness and growth conditions would be required. Therefore, a simpler QDIP structure with tunable detection wavelengths from MWIR to LWIR ranges would be advantageous for the application of multicolor detection.

In this letter, ten-period QDIPs with InGaAs capping layers are investigated. Compared with the detection wavelength 6 μm of the standard QDIP with 2.5-mono-layer (ML) InAs QDs, the insertion of the additional 8-nm $\mathrm{In_{0.15}Ga_{0.85}As}$ layer of a InGaAs-capped QDIP would result in a detection wavelength shift to 7.9 μm. The results suggest that the dominant transition mechanism in the InGaAs-capped QDIPs is from the QD excited state to the InGaAs QW ground state. By decreasing the QD coverage from 2.5 to 2.0 ML, a longer detection wavelength 10.4 μm is observed. The phenomenon is attributed to the higher QD excited states resulted from reduced QD sizes such that a reduced energy difference between the QD excited state and the InGaAs QW ground state is obtained. By further increasing the capping layer thickness to 12 nm, even longer detection wavelengths ranging from 10 to 18 μm are observed for the InGaAs-capped QDIP.

II. EXPERIMENTS

The samples investigated in this letter are grown on (100)-oriented semi-insulated GaAs substrates using a Riber Compact 21 solid source molecular beam epitaxy (MBE) system. For all the samples, 600- and 300-nm GaAs layer with n-type doping $2\times10^{18}\mathrm{cm}^{-3}$ are grown as bottom and top contact layers. Four samples with ten-period (a) 2.5-ML InAs QDs/50-nm GaAs, (b) 8-nm $\mathrm{In_{0.15}Ga_{0.85}As}$/2.5-ML InAs QDs/42-nm GaAs, (c) 8-nm $\mathrm{In_{0.15}Ga_{0.85}As}$/2.0-ML InAs QDs/42-nm GaAs, and (d) 12-nm $\mathrm{In_{0.15}Ga_{0.85}As}$ /2.0-ML InAs QDs/38-nm GaAs are prepared, which are denoted as Samples A, B, C, and D, respectively. Standard photolithography and chemical wet etching are adopted to fabricate devices with 100×100 $\mu\mathrm{m}^2$ mesas. An edge-coupling scheme is adopted for the spectral response measurements of all the devices. The measurement system for the spectral response consists of a Perkin Elmer Spectrum 100 Fourier Transformation infrared spectroscopy coupling with a Janis cryostat and a current preamplifier [4].

III. RESULTS AND DISCUSSION

Normalized 10 K spectral responses of devices A and B operated at 2.0 V are shown in Fig. 1(a). As show in the figure, peak responses of 6 and 7.9 μm are observed for Samples A and B, respectively. Significant detection wavelength red shift to the LWIR range is observed for Device B with an additional InGaAs capping layer. Also shown in the figure is the narrower response full-width at half-maximum (FWHM) of Device B. To explain the phenomenon, the 10 K spectral responses of Device B at 0.6, 1.0, and 1.4 V are shown in Fig. 1(b). As shown in the figure, the peak responses of the device would shift from MWIR to LWIR range with increasing applied voltages. The results suggest that there are two transition mechanisms involved in the spectral response measurements of Device B. At low applied voltages,

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Manuscript received September 11, 2009; revised November 19, 2009; accepted November 20, 2009. First published January 08, 2010; current version published January 27, 2010. This work was supported in part by the National Science Council, Taiwan under Grant NSC 98-2221-E-001-001.

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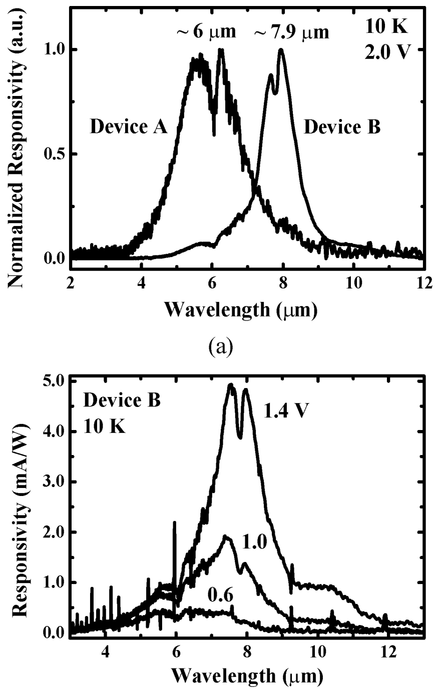
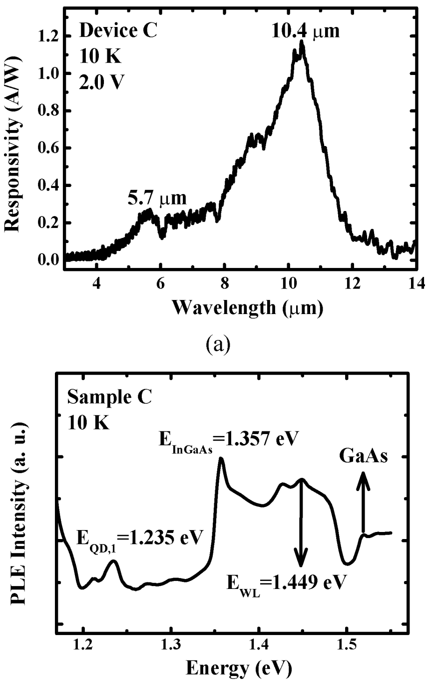
Digital Object Identifier 10.1109/LPT.2009.2037727



(a)

(b)

Fig. 1. (a) Normalized 10 K spectral responses of Devices A and B at 2.0 V and (b) the 10 K spectral responses of Device B at 0.6, 1.0, and 1.4 V, respectively.



(a)

(b)

Fig. 3. (a) The 10 K spectral response of Device C at 2.0 V and (b) the 10 K PLE spectrum of Sample C with its PL peak energy 1.151 eV as the detection wavelength.

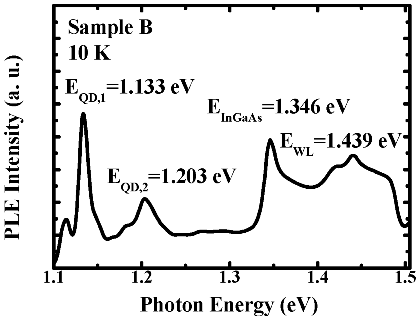


Fig. 2. The 10 K PLE spectrum of Sample B with its PL peak energy 1.054 eV as the detection wavelength.

dominant transition is the one at the MWIR range while the LWIR response would dominate at higher applied voltages.

To further investigate the transition mechanisms of Device B, the 10 K photoluminescence excitation (PLE) spectrum of Sample B is shown in Fig. 2 with its PL peak energy 1.054 eV as the detection wavelength. Four peaks are observed in the spectrum, which are the first excited state of the QDs $E_{\mathrm{QD},1}$, the second excited state of the QDs $E_{\mathrm{QD},2}$, the QW ground state in the InGaAs layer E_{InGaAs}, and the wetting layer state E_{WL} [11]. As shown in the figure, the energy differences of $E_{\mathrm{QD},2} - E_{\mathrm{WL}}$ and $E_{\mathrm{QD},2} - E_{\mathrm{InGaAs}}$ are 0.236 and 0.143 eV (5.25 and 8.67 μm), respectively. The values are close to the observed dominant response peaks 6 and 7.9 μm at low and higher applied voltages, as shown in Fig. 1(b). The results suggest that the LWIR response of Device B is resulted from the transition between $E_{\mathrm{QD},2}$ and E_{InGaAs} states [11]. With increasing applied voltage over Device B, the dominant transition would change from $E_{\mathrm{QD},2} - E_{\mathrm{WL}}$ to $E_{\mathrm{QD},2} - E_{\mathrm{InGaAs}}$, which is attributed to the lower energy of the E_{InGaAs} state compared with the E_{WL} state such that the tunneling probability of the photo-excited electrons at the E_{InGaAs} state is lower at low applied voltages.

Although LWIR responses are already observed for Device B, devices with even longer detection wavelengths are still required. In this case, an efficient approach to decrease the energy difference between the QD excited state and the InGaAs QW ground state is to push the QD excited state to higher energy levels. To achieve this goal, smaller QDs are required. Therefore, Sample C with lower InAs coverage 2.0 ML is prepared. The 10 K spectral response of Device C at 2.0 V is shown in Fig. 3(a). As shown in the figure, a peak response at 10.4 μm with responsivity of 1.17 A/W at 2.0 V is observed, while a much weaker peak is observed at 5.7 μm. The high responsivity of the device at 10.4 μm suggests optimized growth conditions are adopted for the InGaAs-capped structures. Without an additionhal InGaAs layer grown prior QD growth, the device has exhibited a long detection wavelength up to 10.4 μm. The 10 K PLE spectrum of Sample C is shown in Fig. 3(b) with its PL peak energy 1.151 eV as the detection wavelength. As shown in the figure, similar peak positions are observed for the energy levels E_{InGaAs} and E_{WL} of Samples B and C, which suggest that the E_{InGaAs} and E_{WL} states would not change significantly with the QD coverage. On the other hand, the QD first excited state has been raised up to 1.235 eV. In this case, the dominant transitions responsible for Device C should be $E_{\mathrm{QD},1} - E_{\mathrm{InGaAs}}$ and $E_{\mathrm{QD},1} - E_{\mathrm{WL}}$ transitions. The energy differences for the two transitions are 0.122 and 0.214 (10.16 and 5.79 μm), respectively. As shown in Fig. 3(a), both transitions are observed

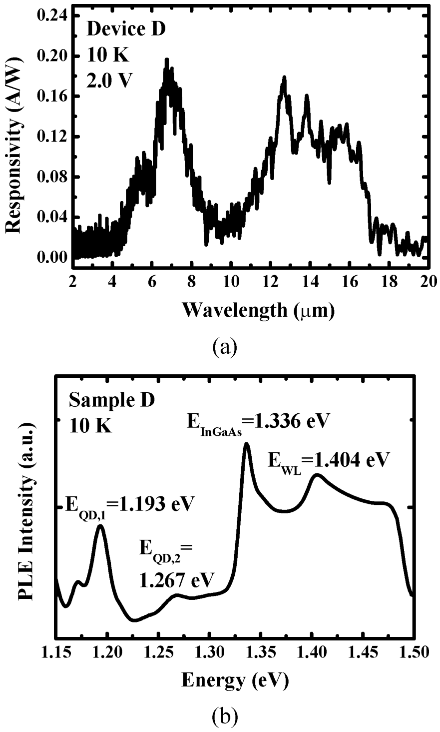


Fig. 4. (a) The 10 K spectral response of Device D at 2.0 V and (b) the 10 K PLE spectrum of Sample D with its PL peak energy 1.114 eV as the detection wavelength.

while the dominant one at 2.0 V is the $E_{\mathrm{QD},1} - E_{\mathrm{InGaAs}}$ transition, which is similar to the behaviors of Device B at high applied voltages.

To push the detection wavelengths beyond 10.4 μm, one effective approach is to grow a thicker InGaAs capping layer such that a lower E_{InGaAs} state would be obtained. The 10 K spectral response of Device D at 2.0 V is shown in Fig. 4(a). As shown in the figure, two major responses are observed with one at 7 μm and the other with broad detection wavelengths between 10–18 μm. The 10 K PLE spectrum of Sample D is shown in Fig. 4(b) with its PL peak energy 1.114 eV as the detection wavelength. As shown in the figure, the energy differences of $E_{\mathrm{QD},2} - E_{\mathrm{InGaAs}}$ and $E_{\mathrm{QD},2} - E_{\mathrm{WL}}$ are 0.069 and 0.137 eV (18 and 9.1 μm), respectively. Therefore, the broad response between 10 and 18 μm of Device D should be attributed to the summation of $E_{\mathrm{QD},2} - E_{\mathrm{InGaAs}}$ and $E_{\mathrm{QD},2} - E_{\mathrm{WL}}$ transitions. As for the peak at 7 μm, one possible mechanism responsible for the response is the summation of transitions between $E_{\mathrm{QD},1}$ to E_{InGaAs} or E_{WL}. As shown in Fig. 4(b), the energy differences are 0.143 and 0.211 eV (8.7 and 5.9 μm), respectively. However, since no similar responses are observed for Devices B and C, further investigations are required to confirm the attribution.

IV. CONCLUSION

Tunable detection wavelengths from MWIR to LWIR ranges of InGaAs-capped QDIPs have been achieved. To achieve LWIR responses, two different approaches of (a) uprising the QD excited state by reducing the QD sizes and (b) lowering the InGaAs state by increasing the capping layer thickness are both proved to be effective. The detection wavelengths of InGaAs-capped QDIPs could be easily tuned from 6 to 10 μm or even longer wavelength. The high responsivities of the devices have also demonstrated that the simpler InGaAs-capped QD structures can be easily prepared without severe strain accumulation. The results are advantageous for the development of multicolor QDIP FPAs at both MWIR and LWIR ranges.

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