AIP | Journal of Applied Physics

The influence of In composition on InGaAs-capped InAs/GaAs quantum-dot infrared photodetectors

Wei-Hsun Lin, Kuang-Ping Chao, Chi-Che Tseng, Shu-Cheng Mai, Shih-Yen Lin, and Meng-Chyi Wu

Citation: Journal of Applied Physics **106**, 054512 (2009); doi: 10.1063/1.3212983
View online: http://dx.doi.org/10.1063/1.3212983
View Table of Contents: http://scitation.aip.org/content/aip/journal/jap/106/5?ver=pdfcov
Published by the AIP Publishing

JOURNAL OF APPLIED PHYSICS **106**, 054512 (2009)

The influence of In composition on InGaAs-capped InAs/GaAs quantum-dot infrared photodetectors

Wei-Hsun Lin,[1] Kuang-Ping Chao,[1] Chi-Che Tseng,[2] Shu-Cheng Mai,[1] Shih-Yen Lin,[3,4,5,a)] and Meng-Chyi Wu[1,2]
[1]*Institute of Electronics Engineering, National Tsing Hua University, Hsinchu 300, Taiwan*
[2]*Institute of Photonics Technologies, National Tsing Hua University, Hsinchu 300, Taiwan*
[3]*Research Center for Applied Sciences, Academia Sinica, Taipei 11529, Taiwan*
[4]*Department of Photonics, National Chiao Tung University, Hsinchu 300, Taiwan*
[5]*Institute of Optoelectronic Sciences, National Taiwan Ocean University, Keelung 20224, Taiwan*

(Received 13 May 2009; accepted 1 August 2009; published online 15 September 2009)

The influence of an additional InGaAs-capped layer on the performance of InAs/GaAs quantum-dot infrared photodetectors (QDIPs) is investigated. For the device with a 15% InGaAs-capped layer, a significant response at 7.9 μm is observed for the QDIP device. The results suggest that with the additional InGaAs-capped layer, the detection wavelengths of the InAs/GaAs QDIPs could be shifted to a longer-wavelength infrared range. A further increase in the In composition will not help to obtain an even longer-wavelength detection, which is attributed to the cancellation of a lower InGaAs state, and InAs-QD bandgap shrinkage resulted from the relaxed compressive strains of the InGaAs layer with a higher In composition.
[doi:10.1063/1.3212983]

I. INTRODUCTION

For the past few decades, lots of efforts have been devoted to the development of quantum-dot infrared photodetectors (QDIPs).[1–4] QDIPs with high responsivities and high operation temperatures have been reported by inserting AlGaAs barrier layers in the device structures to suppress dark currents.[1–3] The effects of QD doping density on the operation voltage and normal-incident absorption of the QDIPs have been also reported.[4] Tang *et al.*[5] demonstrated the thermal images taken by a 256 × 256 grating-less QDIP focal-planar array (FPA) operated at 135 K. However, for most QDIPs, the detection wavelengths are limited to the mid-wavelength infrared (3–5 μm) range. To improve this disadvantage, reports regarding the InAs QDs embedded in InGaAs quantum-well structures (DWELL) have been proposed.[6–9] The fabricated devices have exhibited long-wavelength infrared (LWIR) detection (8–12 μm). Large-format FPAs based on the devices have been also fabricated, which have demonstrated the superior wafer uniformity of the DWELL samples over the QDIP samples.

However, for such devices, an additional InGaAs layer prior to the QD growth is always required to achieve devices with longer detection wavelengths.[10] With the more complicated structures, device parameter optimization such as underlying InGaAs thickness and growth conditions would be required for high device performances and long detection wavelengths. In this report, we investigate the influence of an additional InGaAs-capped layer on the performance of InAs/GaAs QDIPs. As compared to the devices without an InGaAs-capped layer, the QDIPs with an 8 nm $In_{0.1}Ga_{0.9}As$-capped layer exhibit an additional response at 8.4 μm. The phenomenon is attributed to the additional transition mechanism from the QD second excited state to the InGaAs ground state. As the In composition of $In_xGa_{1-x}As$-capped layer increases to 15% in the InGaAs-capped layer, a significant response at 7.9 μm can be observed for the device.

II. EXPERIMENTS

The samples investigated in this paper were grown on (100)-oriented semi-insulating GaAs substrates by using Riber Compact 21 solid-source molecular beam epitaxy system. One standard InAs/GaAs QDIP and two InGaAs-capped QDIPs with different In compositions were prepared. The device structure parameters are shown in Table I. For all the samples, 600 and 300 nm GaAs layers with $n=2\times10^{18}$ cm^{-3} were grown as the bottom and top contact layers, respectively. The standard QDIP, which is referred to as sample A, consists of ten-period 2.5 ML InAs QDs and 50 nm undoped GaAs barriers. For the InGaAs-capped QDIPs, two samples with ten-period InAs QDs capped by 8 nm InGaAs layers and following 42 nm undoped GaAs barriers were prepared. The two samples with 10% and 15% In compositions in the $In_xGa_{1-x}As$-capped layers are referred as samples B and C, respectively. Standard photolithography

TABLE I. The device structures of samples A–C.

	Samples	A	B	C
	Top Contact	300 nm GaAs $n=2\times10^{18}$ cm^{-3}		
10×	42 nm GaAs	Undoped		
	8 nm $In_xGa_{1-x}As(x=)$	0	10	15
	QD layer	2.5 ML InAs QDs		
	50 nm GaAs	Undoped		
	Bottom contact	600 nm GaAs $n=2\times10^{18}$ cm^{-3}		
	Substrate	350 μm (100) semi-insulating GaAs		

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

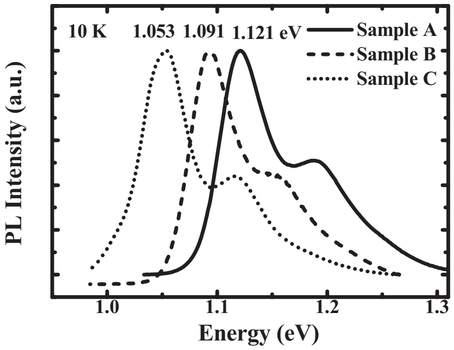
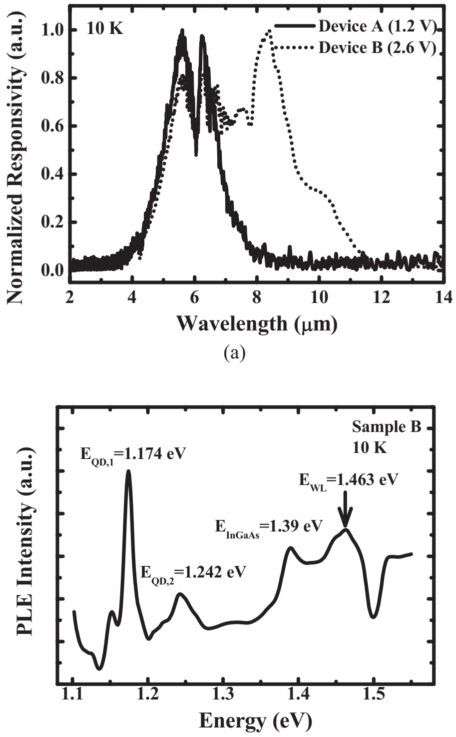


FIG. 1. The normalized 10 K PL spectra of samples A–C.



(a)

(b)

FIG. 2. (a) The normalized 10 K spectral responses of device A biased at 1.2 V and device B biased at 2.6 V, and (b) the 10 K PLE spectrum of sample B.

and wet chemical etching were adopted to fabricate the devices with $100\times100\ \mu m^2$ mesas. Measured under an edge-coupling scheme, the positive and negative biases of the measurements were defined according to the voltages applied to the top contact of the devices. The measurement system for spectral response consisted of a Perkin Elmer Spectrum 100 Fourier transformation infrared spectroscopy coupling with a Janis cryostat and a current preamplifier. The current-voltage (I-V) characteristics were measured by using the Keithley 236 source measure unit.[4]

III. RESULTS AND DISCUSSIONS

The normalized 10 K photoluminescence (PL) spectra of the three samples are shown in Fig. 1. The three samples show a dominant peak at 1.121, 1.091, and 1.053 eV, respectively. A redshift of PL peak wavelength is observed with increasing In composition. Bandgap shrinkage is observed for the InAs QDs with InGaAs-capped layers.[11] It suggests that the compressive strain in the InAs QDs is gradually relaxed with increasing In composition in the capped layer. Also observed are both the transitions from the ground state and first excited state to the valence band for the three samples. The phenomenon is attributed to the state-filling effect of the QD structure, which suggests the consistent and high crystalline quality is obtained for the three samples.

The normalized 10 K spectral responses of device A biased at 1.2 V and device B biased at 2.6 V are shown in Fig. 2(a). Besides the peaks at ~6 μm, an additional response at 8.4 μm is observed for device B. According to our previous report, the dominant transition mechanism in the InAs/GaAs QDIPs is from the QD first excited state ($E_{QD,1}$) to the wetting-layer state (E_{WL}) transition.[12] It is possible that the additional 8.4 μm response resulted from the QD excited states to the quantum-well (QW) ground state of the InGaAs-capped layer. To further investigate the attribution, the 10 K photoluminescence excitation (PLE) spectrum of sample B is shown in Fig. 2(b). As shown in this figure, besides the QD first excited state $E_{QD,1}$, QD second excited state $E_{QD,2}$, and the WL state E_{WL}, an additional peak corresponding to the QW ground state in the InGaAs layer E_{InGaAs} is observed at 1.39 eV. The energy difference between the QD second excited state $E_{QD,2}$ and E_{InGaAs} is 0.148 eV (8.37 μm), which is consistent with the observation of the additional response peak at 8.4 μm for device B. The results suggest that with the additional InGaAs-capped layer, besides the original $E_{QD,1}$-E_{WL} transition, an additional $E_{QD,2}$-E_{InGaAs} transition can be observed for device B.

The normalized 10 K spectra of devices B and C biased at 2.6 V are shown in Fig. 3. The significant response at around 7.9 μm is observed for device C. From the previous description, the main transition mechanism of the InGaAs-capped QDIP should be resulted from the $E_{QD,2}$-E_{InGaAs} transition. Therefore, with increasing the In composition in the capped layer, the InGaAs state with a lower energy is expected. In that case, longer detection wavelengths should be also observed for device C. However, an even shorter detection wavelength is observed for the device. It is attributed to the compressive-strain relaxation of the InAs QDs at the presence of the InGaAs-capped layers. For device C with a higher In composition in the capped layer, the compressive

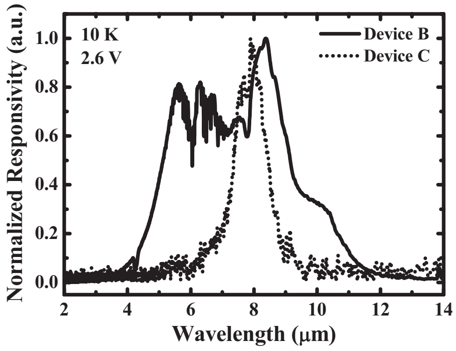


FIG. 3. The normalized 10 K spectral responses of devices B and C biased at 2.6 V.

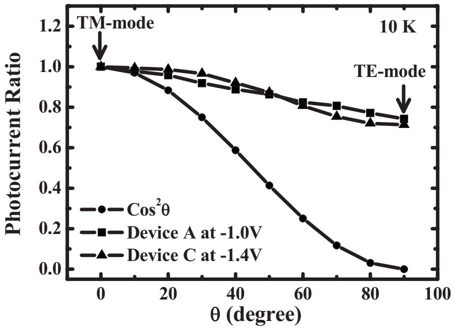


FIG. 4. The photocurrent ratios of devices A and C biased at −1.0 and −1.4 V under different incident-light polarizations.

strain in the QDs would be relaxed to a larger extent such that a larger bandgap shrinkage of the InAs QDs would be observed. The phenomenon is also observed in the PL spectra of the three samples, as shown in Fig. 1. In this case, although a lower E_{InGaAs} state is observed due to the higher In compositions, the QD bandgap shrinkage would also result in the lower QD confinement states such that a shorter detection wavelength is observed for device C. The results suggest that for InGaAs-capped QDIPs, there is a trade off between E_{InGaAs} state lowering, and bandgap shrinkage resulted from the relaxed strains to achieve the long detection wavelengths at >8 μm.

The other unique characteristic of QDIPs is their insensitivity for incident-light polarizations. The photocurrent ratios of devices A and C biased at −1.0 and −1.4 V under different incident-light polarizations are shown in Fig. 4. To perform this measurement, a polarizer was placed between the infrared light source and the detector.[4] Incident-light polarization changing from transverse-magnetic to transverse-electric (TE) modes are denoted as from 0° to 90° in Fig. 4. In this case, the TE-mode incident light is referred as the normal-incident light. Similar normal-incident absorptions of ~70% are observed for devices A and C. The results reveal that with the additional InGaAs-capped layer, the detection wavelengths could be pushed to the LWIR range, and the unique characteristic of normal-incident absorption of QDIPs could still be maintained. The phenomenon is advantageous for the development of QDIPs operated in the LWIR range by using the InGaAs-capped QD structures.

IV. CONCLUSIONS

In conclusion, we have demonstrated the influence of an additional InGaAs-capped layer on the performance of InAs/GaAs QDIPs. As compared to the device without the InGaAs-capped layer, an additional response at 8.4 μm can be observed for the device with an 8 nm $\mathrm{In_{0.1}Ga_{0.9}As}$-capped layer. With increasing the In composition up to 15% in the InGaAs-capped layer, a significant response at 7.9 μm is observed for the device. The results reveal that a further increase in In composition will not help to obtain an even longer-wavelength detection. The phenomenon is attributed to the cancellation of the lower InGaAs state, and InAs-QD bandgap shrinkage resulted from the relaxed compressive strains of the InGaAs layer with a higher In composition. Similar normal-incident absorptions observed for the devices are advantageous for the QDIPs in the LWIR range by using the InGaAs-capped QD structures.

ACKNOWLEDGMENTS

This work was supported in part by the National Science Council of Taiwan under Grant No. NSC 98-2221-E-001-001.

[1] S. Y. Lin, Y. R. Tsai, and S. C. Lee, Appl. Phys. Lett. **78**, 2784 (2001).
[2] S. Chakrabarti, A. D. Stiff-Roberts, P. Bhattacharya, S. Gunapala, S. Bandara, S. B. Rafol, and S. W. Kennerly, IEEE Photonics Technol. Lett. **16**, 1361 (2004).
[3] S. F. Tang, S. Y. Lin, and S. C. Lee, Appl. Phys. Lett. **78**, 2428 (2001).
[4] S. T. Chou, M. C. Wu, S. Y. Lin, and J. Y. Chi, Appl. Phys. Lett. **88**, 173511 (2006).
[5] S. F. Tang, C. D. Chiang, P. K. Weng, Y. T. Gau, J. J. Ruo, S. T. Yang, C. C. Shih, S. Y. Lin, and S. C. Lee, IEEE Photonics Technol. Lett. **18**, 986 (2006).
[6] S. D. Gunapala, S. V. Bandara, C. J. Hill, D. Z. Ting, J. K. Liu, S. B. Rafol, E. R. Blazejewski, J. M. Mumolo, S. A. Keo, S. Krishna, Y. C. Chang, and C. A. Shott, Proc. SPIE **6206**, 62060J (2006).
[7] S. Krishna, D. Forman, S. Annamalai, P. Dowd, P. Varangis, T. Tumolillo, A. Gray, J. Zilko, K. Sun, M. Liu, J. Campbell, and D. Carothers, Appl. Phys. Lett. **86**, 193501 (2005).
[8] G. Ariyawansa, A. G. Unil Perera, G. S. Raghavan, G. von Winckel, A. Stintz, and S. Krishna, IEEE Photonics Technol. Lett. **17**, 1064 (2005).
[9] L. Höglund, P. O. Holtz, H. Pettersson, C. Asplund, Q. Wang, H. Malm, S. Almqvist, E. Petrini, and J. Y. Andersson, Appl. Phys. Lett. **93**, 203512 (2008).
[10] S. Raghavan, D. Forman, P. Hill, N. R. Weisse-Bernstein, G. von Winckel, P. Rotella, S. Krishna, S. W. Kennerly, and J. W. Little, J. Appl. Phys. **96**, 1036 (2004).
[11] K. Nishi, H. Saito, S. Sugou, and J. S. Lee, Appl. Phys. Lett. **74**, 1111 (1999).
[12] C. C. Tseng, S. T. Chou, S. Y. Lin, C. N. Chen, W. H. Lin, Y. H. Chen, T. H. Chung, and M. C. Wu, J. Vac. Sci. Technol. B **26**, 1831 (2008).