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Wavelength-tunable InGaAs-capped quantum-dot infrared photodetectors for multi-color detection

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ABSTRACT

A two-terminal quantum-dot infrared photodetector (QDIP) with stacked 5-period InAs/GaAs and InGaAs-capped InAs/GaAs QD structures is investigated in this paper. The device has exhibited distinct responses at mid-wavelength and long-wavelength infrared regions under positive and negative biases, respectively. Also observed for the device are the equal normal absorption ratios under different voltage biases for the device under either MWIR or LWIR ranges. The device has revealed its potential in the application of voltage-tunable and multi-color detections.

1. Introduction

Quantum-dot infrared photodetectors (QDIPs) have been widely investigated in recent years [1–8]. Compared with conventional quantum-well infrared photodetectors (QWIPs), advantages like high-temperature operation [5,6] and absorption for normally incident light [7,8] have been reported for QDIPs. However, for most of the devices, the detection wavelengths are limited to mid-wavelength infrared range (MWIR, 3–5 μm). To extend the detection wavelengths to the long-wavelength infrared range (LWIR, 8–12 μm), devices like dot-in-well (DWELL) and AlGaAs-capped QDIPs have been proposed [9,10]. In this case, the next issue to be solved for QDIPs would be their capability of multi-color detections. For QWIPs, the most standard approach for two-color detections is the stacked QW structures at two different detection wavelengths separated with an additional contact layer in-between [11]. In this case, a three-terminal device with two separate QWIP devices in one pixel is fabricated. The same approach can also be applied to the fabrication of two-color QDIPs by stacking standard InAs/GaAs and DWELL QDIPs. Voltage-tunable two-color focal-plane arrays (FPAs) have also been demonstrated based on DWELL QDIPs and QWIPs [12,13]. However, the structures of three-terminal devices would complicate read-out integrated circuit (ROIC) design and fabrication procedure of QDIP FPAs.

In this paper, a two-terminal QDIP with stacked 5-period InAs/GaAs and InGaAs-capped InAs/GaAs QD structures is investigated. The device has exhibited distinct responses at MWIR and LWIR regions under positive and negative biases, respectively. At lower applied voltages, the device has exhibited increasing responsivities in both MWIR and LWIR ranges with increasing temperatures. However, at higher applied voltages, monotonically decreasing responsivities are observed for the device with increasing temperatures in both wavelength ranges. To achieve higher operation temperature for this device, increasing QD stack number or the insertion of high-bandgap current blocking layers would be necessary in the future to depress the dark currents.

2. Experiments

The sample discussed in this paper is grown on (1 0 0)-oriented semi-insulated GaAs substrates by using Riber Compact 21 solid source molecular beam epitaxy system. With two n-type doped GaAs as the top and bottom contact layers, a sample with stacked 5-period InAs/GaAs and InGaAs-capped InAs/GaAs QD structures are prepared. The In composition is 15% in the InGaAs capping layers and the InAs coverage are 2.0 and 2.5 mono-layer (ML) for the standard InAs/GaAs and InGaAs-capped QD structures, respectively. The sample structures are shown in Table. 1. Standard photolithography and chemical wet etching are adopted to fabricate the device with $100 \times 100\ \mu m^2$ mesas. To measure the spectral response for the sample under edge-coupling scheme, the device was 45°-polished at one side of the sample. The infrared light source

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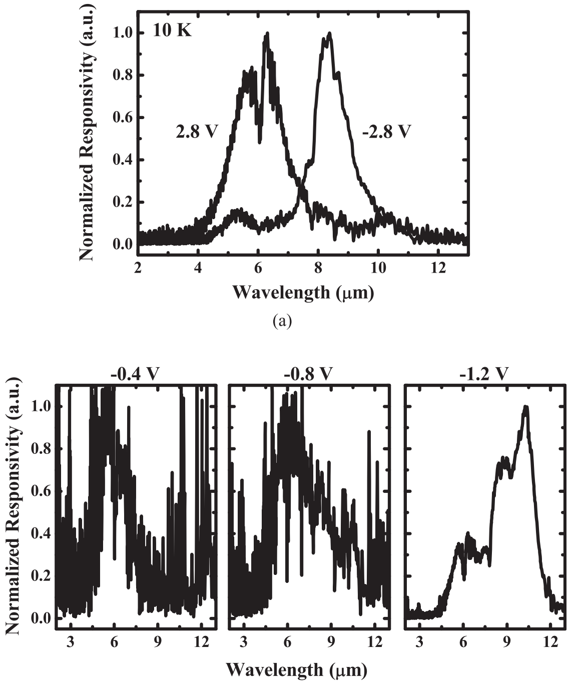
Table 1
The wafer structure of the device.

Top Contact	300 nm GaAs $n = 2 \times 10^{18}$ cm^{-3}
5×	
42 nm GaAs	Undoped
8 nm $In_xGa_{1-x}AS$(x=)	15
InAs QDs (ML)	2.0 ML InAs QDs
50 nmGaAs	Undoped
5×	
InAs QDs (ML)	2.5 ML InAs QDs
50 nmGaAs	Undoped
Bottom contact	600 nm GaAs = 2×10^{18} cm^{-3}
Substrate	350 μm (1 0 0) semi-Insulating GaAs

was normally incident to the polished surface of the sample. The positive and negative biases of the measurement are defined to the voltages applied to the top contact of the device. The measurement system of the spectral response consists of the Perkin Elmer spectrum 100 Fourier transform infrared system (FTIR) coupling with a Janis cryostat and a current pre-amplifier [15].

3. Results and discussions

The normalized spectral responses of the device under ±2.8 V are shown in the Fig. 1a. As shown in this figure, two distinguished responses are observed at MWIR and LWIR ranges under positive and negative biases, respectively. According to the previous publication regarding the InGaAs-capped QDIPs, the response at the LWIR range is attributed to the contribution of the InGaAs-capped QDs and the MWIR response from the InAs QDs [15]. To further investigate the response switching between MWIR and LWIR ranges, the normalized 10 K spectral responses of the device at −0.4, −0.8 and −1.2 V are shown in Fig. 1b. As shown in the figure, both responses at MWIR and LWIR ranges are observed at low applied voltages. The dominant response is at MWIR range. With increasing negative applied voltages, LWIR responses would gradually become dominant. The results would be the 8.4 μm response of this device at −2.8 V as shown in Fig. 1a. The results suggest that most of the photocurrent would come from the QD structures near the cathode side. Therefore, when the device is operated under different voltage parities, responses at different wavelengths would be observed for the stacked structure. Also shown in Fig. 1b is the 10.4 μm response at LWIR range instead of the 8.4 μm response at lower negative applied voltages. The phenomenon is attributed to the strong Stark effect the device experienced under high applied voltages providing the asymmetric InGaAs-capped QD structures [15].

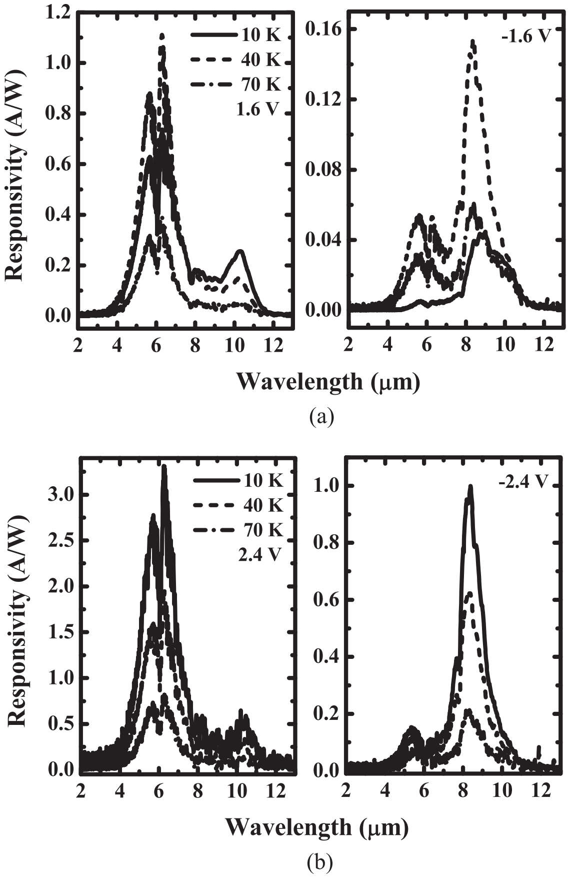


(a)

(b)

Fig. 1. (a) The normalized 10 K spectral responses of the device at ±2.8 V and (b) the normalized 10 K spectral responses of the device at −0.4, −0.8 and −1.2 V, respectively.

The spectral responses of the device measured under different temperatures 10, 40 and 70 K at ±1.6 V are shown in Fig. 2a. As shown in the figure, both the MWIR and LWIR responses would increase with increasing measurement temperature up to 40 K. And with further increasing the temperature, responsivity drops are observed for the device, which is attributed to the increase of electron–phonon scatterings at the higher operation temperature range. However, when the device is operated under ±2.4 V at the same temperature range as shown in Fig. 2b, monotonically decreasing responsivities would be observed for this device. The phenomenon suggests that the capturing process for photo-excited electrons back to the QDs is not pronounced, which may be resulted from the high electron momentum provided by the high external electric field. In this case, increasing electron–phonon scatterings with increasing measurement temperatures would result in the



(a)

(b)

Fig. 2. The spectral response of the device with 10, 40 and 70 K under positive (a) ±1.6 and (b) +2.4 V.

monotonically decreasing responsivities. At lower applied voltages, the dominant photocurrents would be the tunneling currents resulted from the photo-excited electrons in the InAs QDs. In this case, with increasing temperatures, the decreasing probability of the photo-excited electrons captured by QDs would result in increasing responsivities [14]. The results have also indicated that to take advantage of this effect to enhance the operation temperature, the increase of the QD stack number would be necessary to enlarge the operation voltage range, in which tunneling photocurrents dominate.

To further investigate the influence of measurement temperatures on the responsivities of the device under different applied voltages, the 10, 40 and 70 K responsivities of the device under different applied voltages are shown in Fig. 3. As shown in the figure, different dependences of the responsivities over the measurement temperatures at different applied voltage ranges are observed. At low applied voltages, increasing responsivities with increasing temperatures are observed, which is attributed to the decrease of QD capture probabilities over photo-excited electrons with increasing temperatures. However, at high applied voltages, monotonically decreasing responsivities with increasing temperatures are observed. One possible mechanism responsible for this phenomenon is the less pronounced influence of the recapturing process for the electrons back to the QDs resulted from the high external applied voltages. In this case, with increasing temperatures, the dominant mechanism would the increasing electron–phonon scatterings instead of the decreasing QD capturing probabilities. As for the medium applied voltages such as ±1.6 V as shown in Fig. 2a, a increase followed by a decrease of responsivities is observed, which is attributed to the competition of the two mechanisms of decreasing capture probabilities and increasing electron–phonon scattering with increasing temperatures.

The last issue to be discussed is the normal incident absorption of the device at the MWIR and LWIR ranges. To perform this measurement, a polarizer was placed between the infrared light source and the detector. The polarizer would change from 0 to 90° corresponding to p- and s- mode incident lights for spectral response measurements. The definition of the incident light polarization is shown in Fig. 4a. The normalized responsivities of the device under different incident light polarizations at ±2.8 V are shown in Fig. 4b. As shown in the figure, 77% normal incident absorption ratios are observed for the device under ±2.8 V. The results suggest that either for the standard InAs/GaAs QDs or the InGaAs-capped QDs, the normal incident absorption expected for QDIPs is still observed. According to this result, this device is advantageous for the fabrication of grating-less QDIP devices.

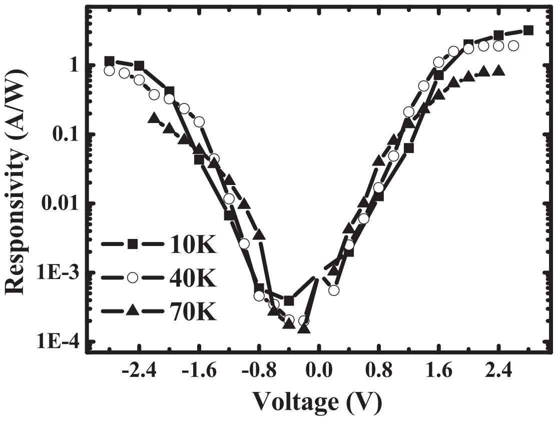
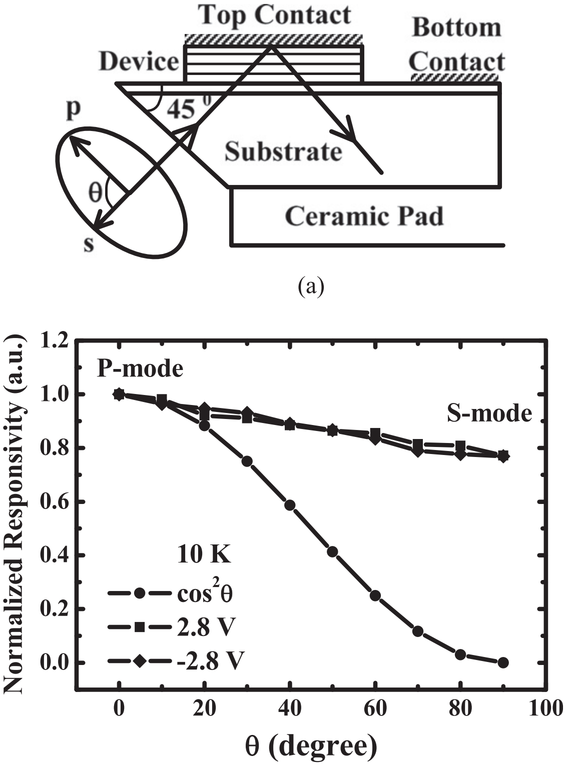


Fig. 3. The 10, 40 and 70 K responsivilities of the device at different applied voltages.



(a)

(b)

Fig. 4. (a) The definition of incident light polarization and (b) The normalized responsivities of the device under different incident IR light polarizations at ±2.8 V. The theoretical $\cos^2\theta$ curve for QW structures derived under the dipole-transition approximation is also shown as a reference.

4. Conclusions

In the conclusion, a two-terminal QDIP with stacked 5-period InAs/GaAs and InGaAs-capped InAs/GaAs QD structures is investigated. The device has exhibited distinct responses at MWIR and LWIR regions under positive and negative biases, respectively. At lower applied voltages, the device has exhibited increasing responsivities in both MWIR and LWIR ranges with increasing temperatures. However, at higher applied voltages, monotonically decreasing responsivities are observed for the device with increasing temperatures in both wavelength ranges. Also observed for the device are the equal normal absorption ratios for the device under either MWIR or LWIR ranges, which suggest that the special characteristic of insensitivity to incident light polarizations exist for either InAs QDs or InGaAs-capped QDs.

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