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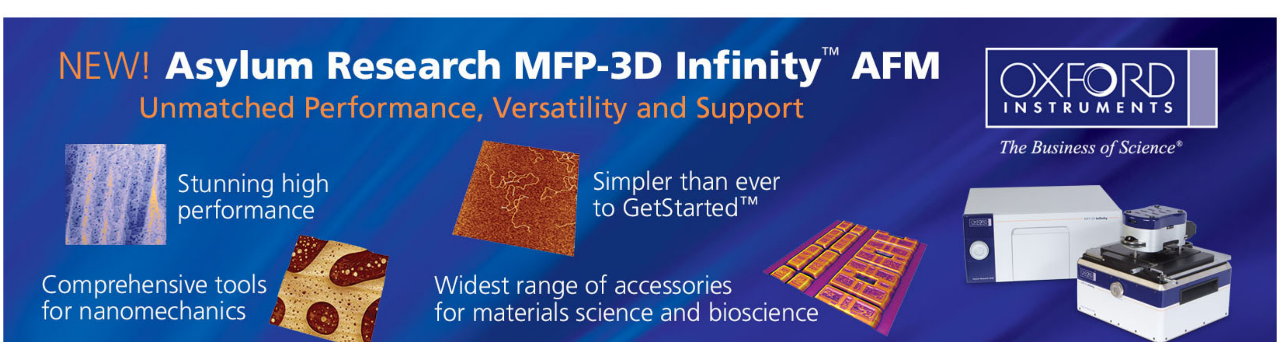

Voltage-tunable two-color quantum-dot infrared photodetectors

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A two-terminal quantum-dot infrared photodetector with stacked five-period InAs/GaAs and InGaAs-capped InAs/GaAs quantum-dot (QD) structures is investigated. The device has exhibited distinct responses at mid-wavelength and long-wavelength infrared regions under positive and negative biases, respectively. The results suggest that the QD confinement states near the anode side are completely filled, such that selective responses at different wavelength ranges would be observed for the stacked structure under different voltage polarities. Also observed are the similar absorption ratios of the device under different incident light polarizations at the two response regions. © *2009 American Institute of Physics*. [doi:10.1063/1.3236543]

Quantum-dot infrared photodetectors (QDIPs) have been widely investigated in recent years.[1–8] Compared with conventional quantum-well infrared photodetectors (QWIPs), advantages such as 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 midwavelength 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 multicolor detections. For QWIPs, the most standard approach for two-color detections is the stacked quantum-well (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. However, the structures of three-terminal devices would complicate read-out integrated circuit (ROIC) design and fabrication procedure of QDIP focal-plane arrays (FPAs).

In this paper, a two-terminal QDIP with stacked five-period InAs/GaAs and InGaAs-capped InAs/GaAs quantum-dot (QD) structures is investigated. The device has exhibited distinct responses at MWIR and LWIR regions under positive and negative biases, respectively. The results suggest that in a biased multistacked QD structures, most of the excited states near the anode side are completely filled with electrons. In this case, most of the photocurrent is from the QD structures near the cathode side of the device. Therefore, with the two stacks of different QD structures, the distinct responses at MWIR and LWIR regions would be observed under different bias polarities. Also observed for the device are the similar absorption ratios under different incident light polarizations at the two response regions, which are advantageous for the fabrication of gratingless QDIP FPAs.

The samples discussed in this paper are grown on (100)-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, three samples with (a) ten-period 2.4 ML InAs/GaAs QD structures, (b) ten-period 8 nm-$In_{0.15}Ga_{0.85}As$-capped 2.0 ML InAs/GaAs QD structures, and (c) stacked five-period InAs/GaAs and InGaAs-capped InAs/GaAs QD structures are prepared, which are referred to as samples A, B, and C, respectively. The sample structures are shown in Table I. The spectral responses of these 100×100 μm^2 devices are measured under an edge-coupling scheme. The measurement system for spectral response consisted of a Perkin Elmer spectrum 100 Fourier transformation infrared spectroscopy with a Janis cryostat and a current preamplifier.[8]

The 10 K spectral responses of devices A and B at ±2.0 V are shown in Fig. 1. As shown in Fig. 1(a), for the responses of device A, identical spectral responses with high responsivities are observed for the device. The results suggest that QDIP samples with high crystal quality are obtained under current growth conditions. Also shown in the figure is the 4–9 μm response with 5.7 μm peak detection wavelength. The results are generally observed for standard InAs/

TABLE I. The wave structures of the samples A, B, and C.

	Sample	A	B	C
	Top contact		300 nm GaAs $n=2\times10^{18}$ cm^{-3}	
5×	42 nm GaAs		undoped	
	8 nm $In_XGa_{1-X}As$(X=)	0	0.15	0.15
	InAs QDs (ML)	2.5	2.0	2.0
5×	42 nm GaAs		undoped	
	8 nm $In_XGa_{1-X}As$(X=)	0	0.15	0
	InAs QDs (ML)	2.5	2.0	2.5
	50 nm GaAs		undoped	
	Bottom contact		600 nm GaAs $n=2\times10^{18}$ cm^{-3}	
	Substrate		350 μm (100) Semi-insulating GaAs	

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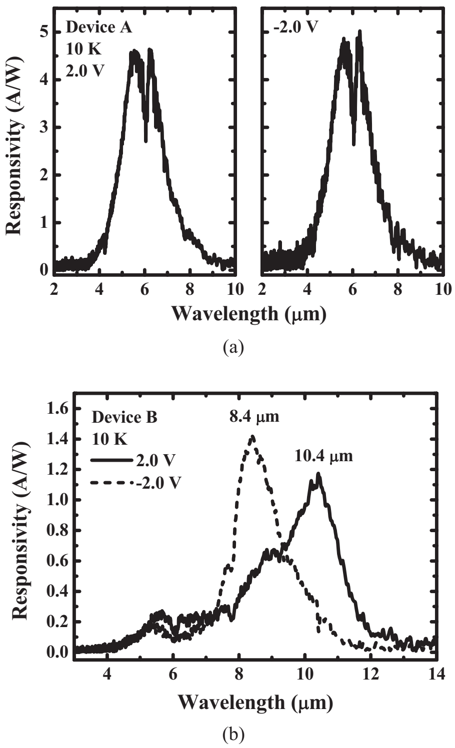

FIG. 1. The 10 K spectral responses of devices (a) A and (b) B at ±2.0 V.

GaAs QDIPs. The 10 K spectral responses of device B at ±2.0 V are shown in Fig. 1(b). As shown in the figure, LWIR responses at 10.4 and 8.4 μm are observed for device B at 2.0 and −2.0 V, respectively. With the InGaAs capping layer, an additional InGaAs QW ground state (E_{InGaAs}) would appear in the structure. The energy position of the state is lower than the original InAs wetting-layer state (E_{WL}). Therefore, the LWIR responses of device B are attributed to the energy difference reduction between the QD excited states and the destination state for intraband absorptions.[12] The detection wavelength variation in device B under different voltage polarities is attributed to the Stark effect of the asymmetric QD structures.[12]

The normalized 10 K spectral response of device C at ±2.6 V are shown in Fig. 2(a). As shown in the figure, MWIR responses resulted from the InAs/GaAs QD structures would dominate under positive biases, while LWIR responses at the InGaAs-capped QD structures are dominant at negative biases. The two distinct responses of device C at MWIR and LWIR ranges have demonstrated the capability of the two-terminal device for two-color detections under different voltage polarities. To further investigate the response switching between MWIR and LWIR ranges, the 10 K spectral responses of device C at −0.4, −0.8, and −1.2 V are shown in Fig. 2(b). As shown in the figure, both responses at MWIR and LWIR ranges are observed at low applied voltages. With increasing negative applied voltages, LWIR responses would gradually become dominant. The results would be the 8.4 μm response of device C at −2.6 V as shown in Fig. 2(a). Similar phenomenon is also observed for the device under positive biases. Also shown in Fig. 2(b) is the 10.4 μm response at LWIR range instead of the 8.4 μm response at lower negative applied voltages. This is because under relatively low electrical fields applied to the

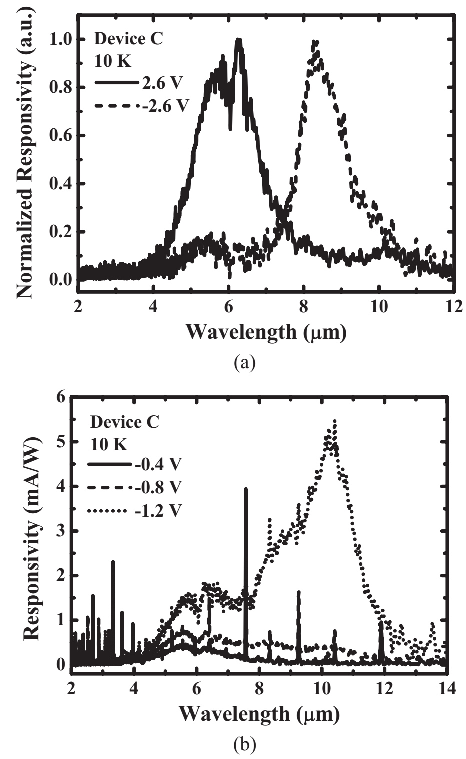

FIG. 2. (a) The normalized 10 K spectral responses of device C at ±2.6 V and (b) the 10 K spectral responses of device C at −0.4, −0.8, and −1.2 V.

asymmetric QD structures, the Stark effect would become less significant.

To explain the operation mechanisms of device C, the band diagrams of the device under positive and negative biases are shown in Fig. 3. According to the photoluminescence excitation (PLE) spectrum published elsewhere,[12] the highest energy level E_{WL} is at least 60 meV lower than the GaAs conduction band edge. Considering the Fermi levels at the contact layers are only about 5 meV below the GaAs conduction band edge, the confinement states E_{WL}, E_{InGaAs}, and QD states (E_{QD}) are well below the GaAs conduction band edge. The states are also depicted in the figure. As shown in the figure, when the device is under positive biases, the confinement states in the first few layers near the anode side would be fully occupied with electrons. In this case, less

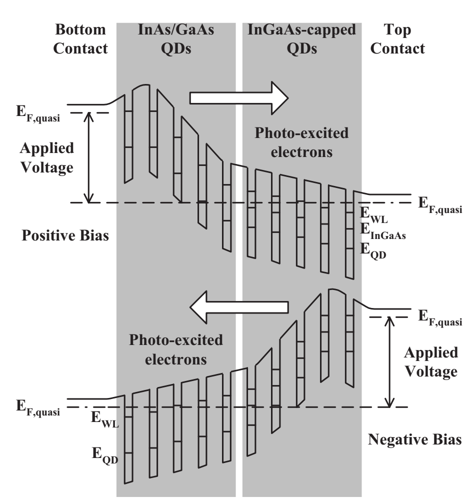

FIG. 3. The schematic band diagrams of device C under positive and negative biases.

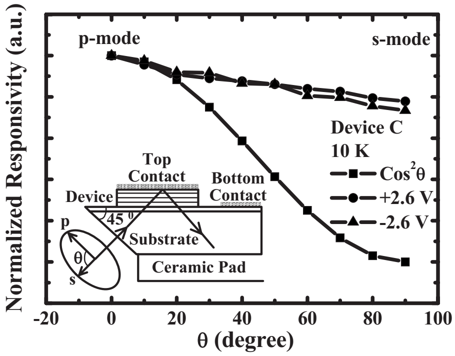

FIG. 4. The normalized responsivities of device C under different incident IR light polarizations at ±2.6 V. The insert shows the measurement configuration. The theoretical $\cos^2 \theta$ curve for QW structures derived under the dipole-transition approximation is also shown as a reference.

photocurrent from the intraband transitions of the QD structures near the anode side would be observed. Most of the photocurrent would come from the QD structures near the cathode side. In the case of device C, the QD structure near the cathode side is of standard InAs/GaAs QDs. The dominate responses of device C under positive biases shown in Fig. 2(a) would be similar with device A. When device C is negatively biased, most of the photocurrent would come from the InGaAs-capped QD structure. The dominate responses would be similar with device B under negative biases. Therefore, LWIR response at 8.4 μm would be observed for device C under negative biases. The simple stacked structures of standard QD and InGaAs-capped QD structures as device C have demonstrated distinct responses at MWIR and LWIR ranges under different bias polarities. The results are very advantageous for the development of two-color detections for QDIPs without a third electrical terminal.

Besides the demonstration of two-color detections by using the stacked structures as device C, the other important issue is the maintenance of the advantages like normal incident absorption for QDIPs. The normalized responsivities of device C under different incident light polarizations at ±2.6 V are shown in Fig. 4. The measurement configuration is shown in the insert of Fig. 4. The theoretical $\cos^2 \theta$ curve for QW structures derived under the dipole-transition approximation is also shown as a reference. As shown in the figure, when device C is under *s*-mode IR light irradiation, the responsivities are still of 74%–77% the values under *p*-mode IR light irradiation under either positive or negative biases. 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.

In conclusion, a two-terminal QDIP with stacked five-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. The operation mechanisms of the two-color detections for the stacked structure are explained in this paper. The high response ratios for the device under *s*-mode IR light irradiation at both response ranges suggest that gratingless two-color QDIP FPAs could be achieved via this structure. Since only two electrical terminals are required for such a device, the structure would simplify the ROIC design and the fabrication procedure for FPAs.

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