High-performance InAs/GaAs quantum-dot infrared photodetectors with a single-sided $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ blocking layer

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Ten-stacked InAs/GaAs quantum-dot infrared photodetectors with single $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ blocking layers at either side of the stacked dots are investigated. With peak responsivity 214 mA/W and specific detectivity $1.17 \times 10^{10} \text{ cm Hz}^{1/2}/\text{W}$ at $6 \mu\text{m}$, quantum-dot infrared photodetectors with single-sided blocking layers are superior in responsivity with compatible detectivity as compared to those without blocking layers. Enhancement of the photoelectron avalanche process and the absence of negative differential conductance are observed. The devices exhibit two different infrared absorption regions at $2\text{--}6$ and $6\text{--}10 \mu\text{m}$, which indicates a wide detection window of the device.

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The quantum-dot infrared photodetector (QDIP) has attracted much attention in recent years.^{1–3} Due to its long carrier capture and relaxation times,⁴ and that it is intrinsically sensitive to normal incidence photoexcitation, QDIPs are expected to have high responsivity, polarization independence, and, in some theoretical work, low dark current.⁵ Our previous work has shown that a high-performance InAs/GaAs QDIP can be fabricated with peak responsivity 170 mA/V and detectivity $1.07 \times 10^{10} \text{ cm Hz}^{1/2}/\text{W}$ at $6 \mu\text{m}$.⁶ In this letter, to improve the performance of the QDIP, a single $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ blocking layer is grown at either side of the quantum-dot (QD) structure. Higher responsivity and compatible detectivity are achieved with this structure.

The samples are grown on (100) semi-insulating GaAs substrates by VG 80H solid-source molecular-beam epitaxy at 510°C . The device structure is listed in Table I. Sandwiched between $0.5 \mu\text{m}$ top and $1 \mu\text{m}$ bottom GaAs contact layers with Si doped to $1 \times 10^{18} \text{ cm}^{-3}$, ten periods of a 3 ML InAs QD and a 30 nm GaAs barrier are grown, where the 3 ML InAs quantum-dot layer is grown in the Stranski–Krastanov growth mode and uniformly doped to $1 \times 10^{18} \text{ cm}^{-3}$ under arsenic shutter closed condition. The In cell temperature is 834°C . To suppress the dark current of the device, an extra $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ blocking layer is grown at either side of the QD structure, where the sample with the blocking layer near the substrate side is referred to as sample A and that near the front surface as sample B. After a two-step process, the $100 \times 100 \mu\text{m}^2$ device is fabricated. The responsivity of the device is measured under an edge-coupling scheme with closed-cycle cryogenics and Perkin–Elmer S2000 Fourier transform infrared spectroscopy. The absolute value of the spectral responsivity is calibrated with a standard blackbody radiation source operated at 1080 K . By carefully shielding the device from the background infrared radiation, dark I – V curves are measured with a HP4145A semiconductor parameter analyzer.

As shown in Fig. 1(a), the asymmetrical spectral responses under positive and negative biases are observed for the two samples, where the response of sample A is dramatically higher under negative bias and sample B under positive bias. The positive bias means the positive voltage is applied

on the top GaAs contact layer. As shown in Fig. 1(b), the highest peak detectivity of sample A at $6 \mu\text{m}$ occurs at -2.4 V with $D^* = 1.17 \times 10^{10} \text{ cm Hz}^{1/2}/\text{W}$ and responsivity $R = 214 \text{ mA/W}$, whereas for sample B it occurs at 1.7 V with $D^* = 4.15 \times 10^9 \text{ cm Hz}^{1/2}/\text{W}$ and $R = 1181 \text{ mA/W}$. Compared to that without a blocking layer at 1.1 V with $D^* = 1.07 \times 10^9 \text{ cm Hz}^{1/2}/\text{W}$ and $R = 170 \text{ mA/W}$ at $6 \mu\text{m}$,⁶ the devices under discussion are superior in responsivity with compatible detectivity. The mechanism responsible for high responsivity is the enhancement of the photoelectron avalanche process,^{7,8} which is made possible due to the increase of operation voltage with the effective depression of dark current because of the blocking layer. With most of the voltage drop occurring across the blocking layer, the local high-field domain-induced negative differential conductance at the QD structure is not observed in these two devices.^{9,10} And still, compared with their TM-mode responses, the TE-mode response is found to be 37% and 50% for sample A at -1 V and sample B at 1 V , respectively. The background-limited performance reaches 175 K , such that a 175 K spectral response can be obtained for these two devices, which is superior to that without the blocking layer, i.e., 125 K .

As shown in Fig. 2, under low biases, two different peaks with wavelengths ranging from 2 to 6 and 6 to $10 \mu\text{m}$ are observed, corresponding to the first confinement state E_1 to second confinement state E_2 transition and subsequent tunneling through the GaAs energy barrier and E_2 to continuum transitions, respectively.⁶ With increasing negative bias for sample A and positive bias for sample B, the inten-

TABLE I. Device structure of samples A and B.

		Sample A	(Sample B)
		Thickness (nm)	Doping density (cm^{-3})
10×[	n^+ GaAs	500	1×10^{18}
	$\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$	—(50)	—(Undoped)
	GaAs	30	Undoped
	InAs	3 ML	1×10^{18}
	$\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$	50 (—)	Undoped (—)
	n^+ GaAs	1000	1×10^{18}
(100) Si–GaAs substrate

FIG. 1. (a) Spectral responsivities under four different biases and (b) voltage-dependent specific detectivities of samples A and B measured at 25 K.

sity of the 6–10 μm peak would decrease at first. And, for voltage lower than -0.3 V for sample A and higher than 0.1 V for sample B, the peak would reappear and grow with increasing bias. To obtain more insight on the electron distribution of the structures, temperature-varying dark currents are analyzed assuming $I_D = A^* T^2 \exp(-E_a/kT)$, where A^* is the Richardson constant, T is the temperature, and E_a is activation energy which equals to $(\Delta E_C - E_F)$. ΔE_C is the conduction-band discontinuity and E_F is the Fermi level. The derived activation energies under different biases are shown in Fig. 3. It is shown that the zero-bias activation energies are 810 meV for sample A and 515 meV for sample B. The lower activation energy of sample B is due to the enhancement of the thermal-assisted impurity tunneling current resulting from strain-induced dislocations in the front blocking layer, which effectively lower the energy barrier height.

FIG. 2. Integration of responsivity curves of samples A and B in the 2–6 and 6–10- μm -wavelength range, where the photocurrent minimum occurs at -0.3 V for sample A and 0.1 V for sample B.

FIG. 3. Activation energies of samples A and B under different biases derived from their dark I - V curves.

Zero-bias band diagrams, according to the fitting result, are shown in Fig. 4. The actual Fermi level of the ten-stacked InAs/GaAs QD structure is, in fact, higher than the calculated result for the GaAs/InAs/GaAs heterostructure. Consequently, as shown in Fig. 4, the electron occupancy of the second energy state E_2 would increase near the top contact for sample A and bottom contact for sample B, which would result in the photovoltaic response of the 6–10 μm peak. With increasing negative bias for sample A and positive bias for sample B, the electrons in the E_2 state would be gradually depleted, which results in the decrease of the 6–10- μm -peak response. And, with further increasing the applied voltage, electrons injected from the contact layer would increase the electron occupancy of the E_2 state near the bottom (top) contact for sample A (B), which results in the increase of the 6–10- μm -peak response.

In conclusion, ten-stacked InAs/GaAs quantum-dot infrared photodetectors with single $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ blocking layers at either side are superior in responsivity with compatible detectivity as compared to those without blocking layers. Two different infrared absorptions at 2–6 and 6–10 μm are

FIG. 4. Zero-bias band diagrams of (a) sample A and (b) sample B.

observed, which indicates the wide detection window of the device.

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