

High-Response i-InAs/n-GaAs Quantum-Dot Infrared Photodetector with No Current Blocking Barrier

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(Received October 10, 2003; accepted November 25, 2003; published March 10, 2004)

We report a high-response normal-incidence infrared photodetector based on the bound-to-continuum transition fabricated on the self-assembled i-InAs/n-GaAs quantum-dot (QD) heterostructure doped in GaAs barrier with no current blocking barrier. The photoresponse characteristics have been confirmed by distinct methods using a SiC global source and a blackbody radiation source. From the blackbody system, the responsivity of 1750 mA/W at a peak wavelength of $\sim 4.7 \mu\text{m}$ (21 K) has been achieved, which is much higher than that reported on the n-InAs/i-GaAs QD-based infrared photodetectors doped in QDs with additional barrier. [DOI: 10.1143/JJAP.43.1218]

KEYWORDS: indium arsenide, quantum dot, infrared photodetector, responsivity, detectivity

1. Introduction

Quantum-dot infrared photodetector (QDIP) and its related heterostructures have been intensively studied in order to realize normal-incidence room-temperature operation overcoming the limitation of quantum well (QW)-based devices.^{1–17)} In spite of the theoretical prediction on QDIPs possessing distinguished infrared (IR) detector performance,^{18–20)} the responsivity (R) and the specific detectivity (D^*) of QDIPs stay at $\sim 10^2$ mA/W and $\sim 10^9$ cm \cdot Hz^{1/2}/W around 100 K in the mid-IR range,^{1–11)} respectively, which are a little inferior to QWIPs. Of current necessity, therefore, is a QDIP device with enhanced performance operating at higher temperatures in longer spectral range near the atmospheric window (8–12 μm). Stiff *et al.* demonstrated characteristics of individual QDIP device operation as high as 150 K in the mid-IR range peaking at $\lambda_p \sim 3.7 \mu\text{m}$ together with a raster-scanned image realized by (13 \times 13) array.¹⁾ Recently, Tang *et al.* reported a QDIP device of photoconductive and photovoltaic mixed mode working up to 250 K in the range of 2–5 μm ,^{2,3)} and Krishna *et al.* presented a two-color detector ($\lambda_p \sim 4.2/7.6 \mu\text{m}$) using InAs/InGaAs dot-in-well (DWELL) structure.⁴⁾ They have adopted modified QDIP structures with a single/double AlGaAs blocking layer or a DWELL structure in which the dark current reduction or better carrier confinement can be expected by the additional potential barrier, as opposed to a drawback of photocurrent sacrifice.

In this letter, we report an achievement of high values of $R \sim 2000$ mA/W and $D^* \geq 10^9$ cm \cdot Hz^{1/2}/W (21 K) at a peak wavelength of $\lambda_p \sim 5.0 \mu\text{m}$ obtained from an i-InAs/n-GaAs QDIP structure doped in GaAs barrier with no current blocking barrier. It shows a quite broad spectral photoresponse over the far-IR wavelength of 3–10 μm operating at temperatures up to around 200 K. In order to confirm the device characteristics, the photoresponse measurements have been done by a couple of distinct methods using a SiC global source dispersed by the far-IR spectrometer and a well-calibrated blackbody radiation source combined with a set of bandpass filters. We present the power dependence of

micro-photoluminescence (μ -PL) spectra as evidence indicating the bound-to-continuum transition in the QDIP operation.

2. Experimental Procedure

The molecular beam epitaxy (MBE) technique was introduced for the growth of QDIP structure, and the self-assembled QD *ensemble* was realized via the Stranski-Krastanow (S-K) growth mode. The n-i-n QDIP device prepared for this study has an active layer stacked by five periods of i-InAs-QD/n-GaAs:Si, and the Si doping in GaAs barrier was adopted for effective IR absorption proven by previous studies.¹²⁾ The growth was conducted at temperatures of 580°C from GaAs buffer to bottom contact layer and of 460°C from the active region to top contact layer. Each layer of InAs QDs with an equivalent thickness of 2.5 monolayers (MLs) was formed on undoped GaAs spacer, and a 3-nm-thick doped layer (1×10^{17} cm⁻³) was positioned at 6 nm above the InAs-QD layer in the 40-nm GaAs spacer for each stack. Taking care of the QD density, the layer thickness and the doping level were designed in order that each dot was occupied by approximately one electron. The thick GaAs overlayer was introduced in the active medium to induce spatially random distribution with broader spectral response. The epitaxial growth and basic properties on the related QD heterostructures are described in detail in previous reports.^{12–15)}

The QD formation was confirmed by a cross-sectional image of the transmission electron microscope (TEM) as shown in the inset of Fig. 1, and the dot density of $\sim 5 \times 10^{10}$ cm⁻² was identified from the atomic force microscopy (AFM) profile of an uncapped QD structure.¹²⁾ Circular-ring and square shaped electrodes were formed on top and bottom n⁺-GaAs layers, respectively, by using the standard photolithography and the wet-chemical etching procedures, and the diameter of the illumination opening for individual device was 450 μm ($A = 1.6 \times 10^5 \mu\text{m}^2$). A couple of distinct measurements were independently performed at the normal-incidence configuration. One is the continuous-spectrum method using a broadband global source dispersed by the far-IR spectrometer with a pair of gratings of 60 and 120 grooves/mm and calibrated by a HgCdTe detector. The

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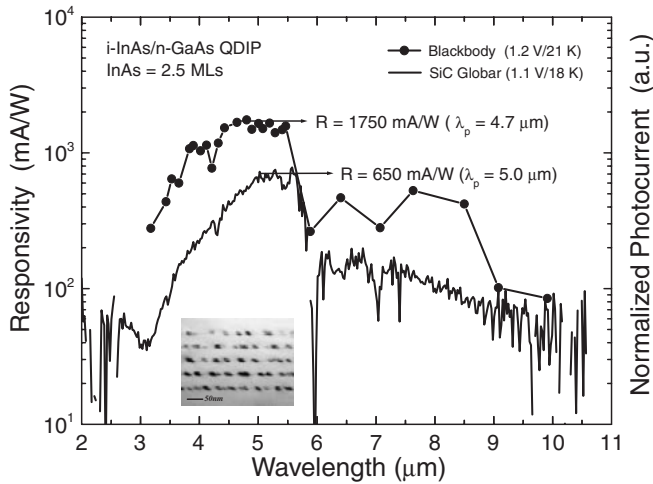


Fig. 1. The responsivity data (1.2 V/21 K, solid circles) by blackbody source and the normalized photocurrent spectrum (1.1 V/18 K, solid line) which directly corresponds to the responsivity by globar source. Both curves show similar IR detection behavior over the spectral range of 3–10 μm within the filter bandwidth of ~0.2 μm.

other is the point-by-point measurement by a combination of a well-calibrated commercial blackbody radiation source (IR-564, Infrared System Development Corp.) and a set of bandpass filters (OCLI). The filter set used in this experiment consists of 43 filters with a narrow bandwidth of ~0.2 μm in the range of 3–14 μm. A typical visible-to-near-IR monochromator system with a He–Ne (632.8 nm) laser and a liquid-nitrogen cooled Ge photodetector was used in the μ-PL measurements.

3. Results and Discussion

The responsivity data (1.2 V/21 K, solid circles) by the blackbody source are compared in Fig. 1 with a photocurrent spectrum (1.1 V/18 K, solid line) by the globar source normalized to the spectral photon flux, which directly corresponds to the responsivity. Both curves show similar IR response behavior over the spectral range of 3–10 μm peaking around 4.5–5.5 μm, and are consistent with each other within the filter bandwidth of ~0.2 μm. The peak values of R and equivalent D^* are 1750/650 mA/W and $1.2 \times 10^9/3.2 \times 10^8 \text{ cm}\cdot\text{Hz}^{1/2}/\text{W}$ for the blackbody/globar source, respectively. (For reference, $R/D^* = 2 \text{ mA/W}/2.9 \times 10^9 \text{ cm}\cdot\text{Hz}^{1/2}/\text{W}$ ($T = 100 \text{ K}$, $\lambda_p = 3.7 \mu\text{m}$), $155 \text{ mA/W}/2.3 \times 10^9 \text{ cm}\cdot\text{Hz}^{1/2}/\text{W}$ ($T = 36 \text{ K}$, $\lambda_p = 2.8 \mu\text{m}$), and $730 \text{ mA/W}/1.5 \times 10^9 \text{ cm}\cdot\text{Hz}^{1/2}/\text{W}$ ($T = 60 \text{ K}$, $\lambda_p = 4.2 \mu\text{m}$) for Stiff *et al.*,¹⁾ Tang *et al.*,^{2,3)} and Krishna *et al.*,⁴⁾ respectively.) The value of R obtained in this study is much higher than the previously reported data as enumerated just above, and the D^* value is fairly high taking consideration of no current blocking barrier. The high R -value indicates that the present i-InAs/n-GaAs QDIP structure doped in GaAs barrier is very effective for IR absorption.

Figure 2 presents the dependences of D^* on temperature (open circles) and bias voltage (open squares) for the globar system together with the corresponding data (solid circle/square, 1.2 V/21 K) for the blackbody system. The two curves monotonically decrease with both increasing temperature (bottom scale) and decreasing bias voltage (top scale), and survive up to 190 K and down to 0.8 V. The misfit

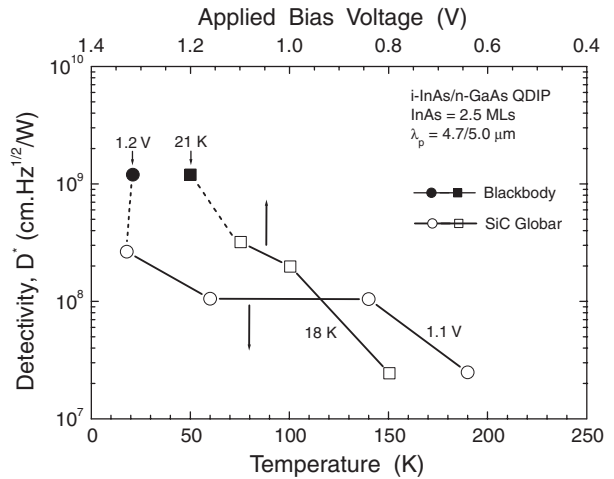


Fig. 2. Temperature (open circles) and bias voltage (open squares) dependences of D^* by the globar system, and the corresponding value (solid circle/square) by the blackbody system. The two curves monotonically decrease with both increasing temperature (bottom scale) and decreasing bias voltage (top scale), and survive up to 190 K and down to 0.8 V.

between two D^* -values for blackbody/globar sources is partially due to the difference in the noise frequency range. In determining the D^* 's, we have used the current noise density measured at high frequency (60 pA/Hz^{1/2} at 6 kHz) and low frequency (80 pA/Hz^{1/2} at 200 Hz) for blackbody and globar sources, respectively, because of the different experimental setup. Therefore, the D^* value raised by 4/3 can be expected if we apply the high-frequency noise density to D^* for globar source. We think that the remaining misfit in D^* 's may be possibly attributed to the spectrometer system including a HgCdTe detector used for the photon flux calibration of globar source. This indicates that the choice of the dynamic frequency range for signal recovery and the photon flux calibration in the far-IR spectrometer system using globar source have to be carefully done in the manipulation of D^* . Table I is a comparative summary of normal-incidence characteristics on the QDIP device measured by the blackbody radiation source and the SiC globar source.

Finally, in order to verify that the photoresponse of QDIP originates from the bound-to-continuum transition, we have investigated the μ-PL spectra (77 K) for various measurement conditions and QDIP samples. Figure 3 exhibits two sets of μ-PL spectra taken (a) at three different excitation-

Table I. The comparative summary of the normal-incidence device characteristics of an i-InAs/n-GaAs QDIP structure measured by the blackbody radiation and the SiC globar sources.

Infrared Source	Blackbody Radiation	SiC Globar
Spectrometer System	Bandpass Filters ($\Delta\lambda \sim 0.2 \mu\text{m}$)	Gratings (60/120 gr/mm)
Operation Voltage (V)	1.2	1.1
Measurement Temperature (K)	21	18
Peak Wavelength (mm)	4.7	5.0
Peak Responsivity (mA/W)	1750	650
Noise Current Density (pA/Hz ^{1/2})	60 (at 6 kHz)	80 (at 200 Hz)
Peak Detectivity (cm·Hz ^{1/2} /W)	1.2×10^9	3.2×10^8

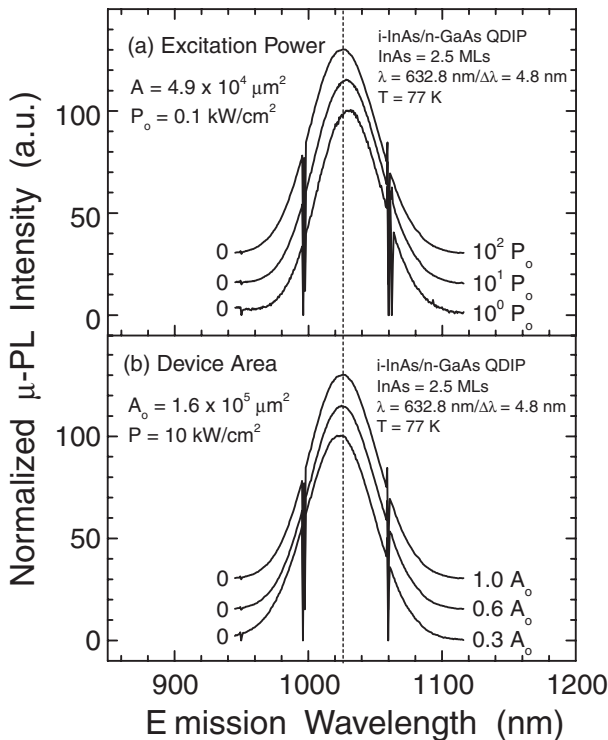


Fig. 3. Two sets of μ -PL spectra (77 K) taken (a) at three different excitation-power densities and (b) from three kinds of devices with different area. All the spectra clearly show almost no changes in peak energies and spectral shapes.

power densities of 0.1–10 kW/cm² and (b) from three kinds of devices with different areas of 0.5–1.6 × 10⁵ μm² simultaneously fabricated on an identical wafer. All the spectra clearly show almost no changes in peak energies and spectral shapes, which suggest that there exists no excited state in QDs. It indicates that the photoresponse data presented in this study may be possibly due to the bound-to-continuum transition of QD *ensemble*.

4. Summary and Conclusions

In summary, we reported an achievement of highly effective normal-incidence mid-IR QDIP with $R = 1750$ mA/W and $D^* = 1.2 \times 10^9$ cm·Hz^{1/2}/W at $\lambda_p \cong 4.7$ μm (21 K) in the i-InAs/n-GaAs QD heterostructure doped in GaAs barrier with no current blocking barrier. We confirmed that the mid-IR absorption originated from the bound-to-continuum transition of QD *ensemble* through the power dependence of μ -PL spectra. The value of R was

much higher than that reported on n-InAs/i-GaAs QDIP structures with additional barrier. We suggested that the mid-IR response of i-InAs-QD/n-GaAs QDIP device doped in GaAs barrier was very efficient in comparison with n-InAs-QD/i-GaAs structures doped in QDs.

Acknowledgments

This work was supported in part by MOIC (Contract No. IMT2000-B4-1), and mainly carried out at the National Research Laboratory on Quantum Dot Technology at KRISS designated by MOST (Contract No. M1-0104-00-0127). One of the authors (SKN) acknowledges the partial support provided by KOSEF through the Quantum-Functional Semiconductor Research Center at Dongguk University in 2003.

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