Characteristics of a Multicolor InGaAs–GaAs Quantum-Dot Infrared Photodetector

S. Chakrabarti, *Member, IEEE*, X. H. Su, P. Bhattacharya, *Fellow, IEEE*, G. Ariyawansa, and A. G. U. Perera

***Abstract*—A three-color quantum-dot infrared photodetector has been fabricated and characterized. The active absorption region consists of undoped $In_{0.4}Ga_{0.6}As$ quantum dots separated by GaAs barriers. Intersublevel transitions of electrons in the quantum dots results in absorption peaks at ~3.5, 7.5, and 22 μm. The devices were characterized at 80 K and 120 K. The dark current density is 10^{-6} A/cm^2 at 120 K for an applied bias of 1 V. The responsivity and specific detectivity D^* are 0.07 A/W and 4.8×10^{10} cm $\cdot$ Hz$^{1/2}$/W for the 7.5-μm response at 80 K for an applied bias of 3 V.**

***Index Terms*—Dark current, detectivity, InAs–GaAs, infrared detector, quantum dots, responsivity.**

I. Introduction

MULTICOLOR detectors are useful for application in infrared focal plane arrays designed for high-resolution and high-sensitivity imaging [1]. Multiwavelength detection in the same device, based on intersubband transitions in quantum wells [2] and on intersubband transitions from dot-in-well heterostructures [3], have been reported. In the context of infrared detection, quantum dots promise improved performance by virtue of the three-dimensional confinement leading to normal incidence operation, low dark current, large excited state lifetimes, large responsivity and detectivity, and high-temperature operation. Many of these attributes have been realized in the recent past [4]–[9]. There has been no report of multiwavelength detection with quantum-dot infrared photodetectors (QDIPs) based on intersubband transitions within the dots. In this letter, we report the performance characteristics of InGaAs–GaAs QDIPs with peak wavelength responses at ~3.5, 7.5, and 22 μm. In particular, long-wavelength infrared (LWIR) response is important for spectroscopic applications. This is the first time that multiwavelength detection in QDIPs is being reported at temperatures as high as 120 K. The dark current densities are also among the lowest measured in these devices. Unlike most previous work, the QDIPs in this study were grown on Si-doped high conductivity GaAs substrates reducing the optical crosstalk between devices in the LWIR region [10].

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S. Chakrabarti, X. H. Su, and P. Bhattacharya are with the Solid State Electronics Laboratory, Department of Electrical Engineering and Computer Science, University of Michigan, Ann Arbor, MI 48109-2122 USA (e-mail: subho@engin.umich.edu).

G. Ariyawansa and A. G. U. Perera are with the Department of Physics and Astronomy, Georgia State University, Atlanta, GA 30303 USA.

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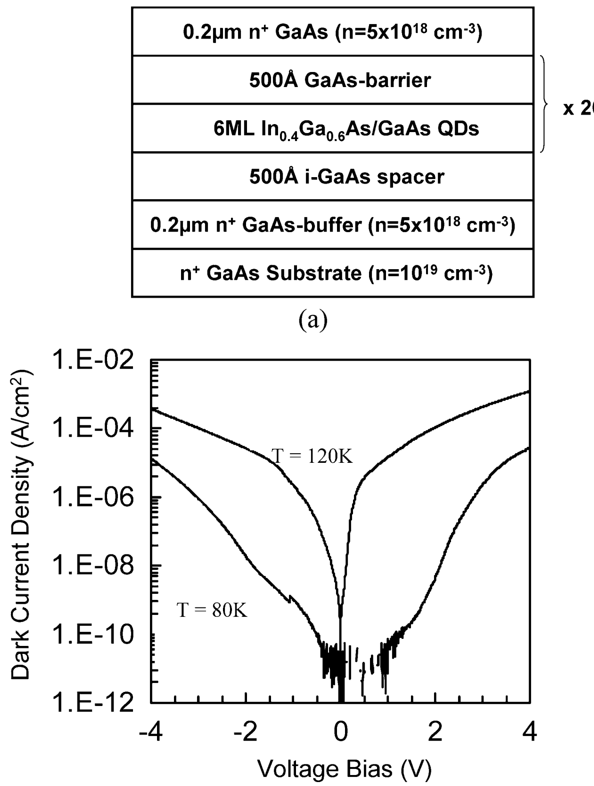

Fig. 1. (a) Schematic of the 20-layer InGaAs–GaAs QDIP heterostructure grown by molecular beam epitaxy. (b) Variation of measured dark current density with bias and ambient temperature.

Therefore, the measured data reflect the true characteristics of a single device.

II. Device Fabrication

The InGaAs–GaAs QDIP heterostructures were grown by molecular beam epitaxy on (001)-oriented Si-doped n^+ ($n = 10^{19}$ cm^{-3}) GaAs substrates. The device heterostructure is schematically shown in Fig. 1(a). The GaAs layers were grown at 610 °C and the $In_{0.4}Ga_{0.6}As$ quantum dots were grown at 500 °C. The undoped self-organized quantum dots were formed by the deposition of six monolayers of InGaAs. *In situ* reflection high energy electron diffraction was used to monitor the formation of the quantum dots and, in particular, observe the transition from the two-dimensional wetting layer (after five monolayers) to three-dimensional islands. The individual quantum dots are pyramidal in shape, with a base of ~25 nm and height of 6 nm, as evidenced from high-resolution transmission electron microscopy studies [5]. On account of the progressive change in the strain distribution, larger dots are formed at the top of the heterostructure, compared to those at the bottom of the stack [11] with an associated dot density of 4×10^{10} cm^{-2}. As shown in Fig. 1(a), the active region of the device consists of 20 dot layers separated by 500 Å GaAs barrier layers. A standard, three-step photolithography, wet-etching, and contact metallization process was employed to fabricate the vertical n-i-n mesa-shaped QDIPs. The first step is the deposition of Ni–Ge–Au–Ti–Au by electron beam evaporation to form the top ring contact. The mesa-shaped device is defined by wet etching, with the top contact as the mask. The same multilayered metals are evaporated to form the bottom ring contact. The active area of the detector exposed to infrared radiation is determined by the inner radius of the top ring contact (300 μm) and is approximately 2.83×10^5 μm^2.

The dark current–voltage characteristics of the QDIPs were measured with an HP 4145 Semiconductor Parameter Analyzer. Measurements were made for both bias polarities, where positive bias denotes a positive polarity of the top contact. The measured dark current densities at 80 K and 120 K are shown in Fig. 1(b). The slight asymmetry in the data for opposite bias polarities is believed to arise from the asymmetry in the shape of the quantum dots. The measured dark currents (e.g., $J_{\rm dark} = 10^{-8}$ A/cm^2 at 80 K for -2 V) are the lowest values for QDIPs, and significantly lower than comparable QWIPs [2].

III. Results and Discussion

The devices were mounted on suitable chip carriers and wire bonded and the calibrated spectral response and calibrated responsivity, under normal incidence, were measured with a globar broad-band source and Perkin–Elmer S2000 Fourier transform infrared spectrometer. The spectral response of the QDIP and a composite bolometer with a known sensitivity are concurrently measured with the same combination of optical elements. The resulting three-color response is shown in Fig. 2(a). In order to understand the origin of the three peaks, centered at 3.5, 7.5, and 22 μm, reference is made to the electronic states of the InGaAs quantum dots calculated with a eight-band **k.p.** formulation [12], as shown in Fig. 2(b), in which the wetting layer is included as a two-dimensional electron gas. The long-wavelength peak centered at 22 μm is due to transition of photoexcited electrons from the ground state to the first excited states ($\Delta E \sim 50 - 60$ meV) in the quantum dots. The transition with a peak at 7.5 μm (155 meV) is thought to be due to transitions from the dot ground state to the GaAs barrier states or the wetting layer states. The former is more likely, as evidenced by the sharp long wavelength cutoff of the transition in Fig. 2(a). The broad response with peak at 3.5 μm is due to bound-to-continuum transitions from the dot ground states to dot levels in the continuum. Shown in the inset of Fig. 2(a) are the optimized spectral response at 3.5 and 7.5 μm, measured at 80 K. At bias values of ≤ -0.5 V, the 3.5-μm response is dominant, while for biases of $\geq$2 V, the 7.5-μm response is dominant. Both responses can be simultaneously obtained in the bias range of -0.5 to 2 V. The peaks at 7.5 and 22 μm, resulting from transitions between quasi-bound states, are

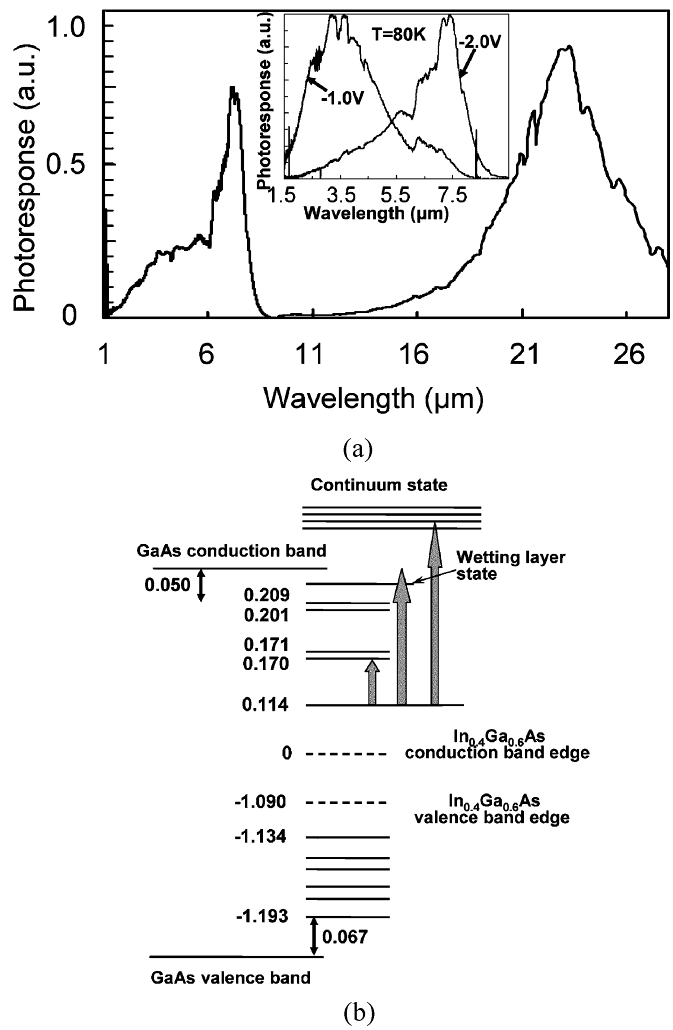

Fig. 2. (a) Spectral response of the 20-layer InGaAs–GaAs quantum-dot infrared detector. The inset shows the normalized two-color response at 80 K. (b) Calculated electronic states in a $In_{0.4}Ga_{0.6}As$ quantum dot of base and height equal to 25 and 8 nm, respectively, using an eight-band k.p. formulation.

narrower $(\Delta\lambda/\lambda \sim 0.2)$ than the one at 3.5 μm resulting from bound-to-continuum transitions $(\Delta\lambda/\lambda \sim 0.79)$. The 22-$\mu$m transition is observed distinctly at very low temperatures (up to 20 K) where most of the electrons are in the ground state and the first excited states are relatively empty. With increase of temperature, the excited states become more populated and the rate of transitions decreases. The peak responsivity for the 7.5-μm photoresponse is plotted in Fig. 3(a) as a function of bias for $T = 80$ K. It is seen that the responsivities are adequately high for application in focal plane arrays.

It is to be noted that the QDIPs described here have $In_{0.4}Ga_{0.6}As$–GaAs quantum dots, without any associated wells, as the absorption material. The polarization dependence of the absorbance of similar quantum-dot detectors has been measured and reported by us [13]. The QDIPs have a higher sensitivity for normal incidence (transverse-electric (TE) polarized light). This is because the intersubband transition matrix element is very strong for in-plane (TE) polarized light due to the high biaxial strain field and the dot shape. Also, as mentioned earlier, the device heterostructures were grown on n$^+$ Si-doped substrates. Therefore, multiple reflections in the

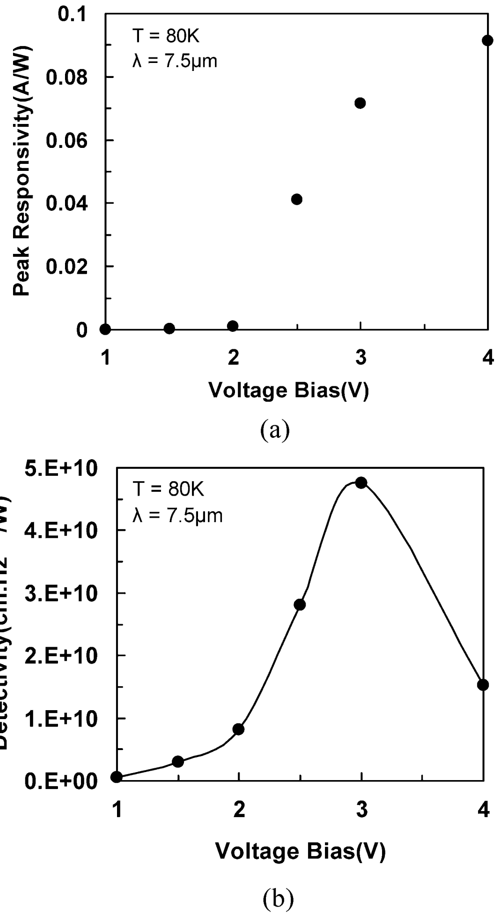

Fig. 3. Measured (a) peak responsivity, and (b) peak detectivity as a function of applied bias for the 7.5-μm response at $T = 80$ K.

substrate and eventual absorption by the test device of LWIR radiation incident on the chip, outside the active area of the device, is minimized or eliminated [10]. Hence, the responsivity values quoted here reflect the characteristics of a single device. On the other hand, we have observed that the responsivity and D^* values of QDIPs grown on semi-insulating GaAs substrates is enhanced by a factor of three to five, if the area outside the device under test is not appropriately shielded from the incident radiation.

The specific detectivity (D^*), which is a measure of the signal-to-noise ratio of the device, was obtained from the measured peak responsivity and noise density spectra at different temperatures and applied biases. The noise spectra were measured with a dual-channel fast Fourier transform signal analyzer and a low noise preamplifier. A thick copper plate was used as a radiation block to provide the dark conditions for the measurements. The measured values of D^* for 7.5-μm response at 80 K are plotted in Fig. 3(b) as a function of bias. The value of D^* reaches a maximum of 4.8×10^{10} cm $\cdot$ Hz$^{1/2}$/W at 3 V and decreases thereafter, due to the monotonic increase of the dark current with bias. These values of D^* are among the highest measured for QDIPs in the LWIR range and are attributed to the extremely low dark currents measured in these devices. At 4.6 K, the specific detectivities of the peaks at 3.5, 7.5, and 22 μm are 8.8×10^9, 5.4×10^{10}, and 3.3×10^{10} cm $\cdot$ Hz$^{1/2}$/W, respectively, for a 1.5-V bias.

IV. Conclusion

We report a three-color QDIP based on absorption transitions in $In_{0.4}Ga_{0.6}As$ quantum dots. Peak responses are observed at 3.5, 7.5, and 22 μm and these can be related to calculated energy spacings between bound–bound and bound–continuum states in the dots and associated wetting layer and barrier states. For the response at 7.5 μm, the peak responsivity and specific detectivity D^* are 0.07 A/W and 4.8×10^{10} cm $\cdot$ Hz$^{1/2}$/W at 80 K for a bias of 3 V.

References

[1] S. D. Gunapala and S. V. Bandara, "Quantum well IR photodetector focal plane arrays," in *Semiconductor and Semimetals*. New York: Academic, 2000, vol. 62.

[2] C. J. Chen, K. K. Choi, W. H. Chang, and D. C. Tsui, "Two-color corrugated quantum-well infrared photodetector for remote temperature sensing," *Appl. Phys. Lett.*, vol. 72, pp. 7–9, 1998.

[3] S. Krishna, S. Raghavan, G. von Winckel, A. Stintz, G. Ariyawansa, S. G. Matsik, and A. G. U. Perera, "Three-color ($\lambda_{p1} \sim 3.8$ μm, $\lambda_{p2} \sim 8.5$ μm, and $\lambda_{p3} \sim 23.2$ μm) InAs/InGaAs quantum-dot-in-a-well detector," *Appl. Phys. Lett.*, vol. 83, pp. 2745–2747, 2003.

[4] S. Raghavan, P. Rotella, A. Stintz, B. Fuchs, S. Krishna, C. Morath, D. A. Cardimona, and S. W. Kennerly, "High-responsivity, normal-incidence long-wave infrared ($\lambda \sim 7.2$ μm) InAs/In0.15Ga0.85As dots-in-a-well detector," *Appl. Phys. Lett.*, vol. 81, pp. 1369–1372, 2002.

[5] L. Jiang, S. S. Li, N. T. Yeh, J. I. Chie, C. E. Ross, and K. S. Jones, "$In_{0.4}Ga_{0.6}As$/GaAs quantum dot infrared photodetector with operating temperature upto 260 K," *Appl. Phys. Lett.*, vol. 82, pp. 1986–1988, 2003.

[6] B. Kochmann, A. D. Stiff-Roberts, S. Chakrabarti, J. D. Phillips, S. Krishna, J. Singh, and P. Bhattacharya, "Absorption, carrier lifetime and gain in InAs/GaAs quantum dot infrared photodetectors," *IEEE J. Quantum Electron.*, vol. 39, no. 3, pp. 459–467, Mar. 2003.

[7] E. T. Kim, A. Madhukar, Z. Ye, and J. C. Campbell, "High detectivity InAs quantum dot infrared photodetector," *Appl. Phys. Lett.*, vol. 84, pp. 3277–3279, 2004.

[8] S. Chakrabarti, A. D. Stiff-Roberts, P. Bhattacharya, S. D. Gunapala, S. Bandara, S. B. Rafol, and S. W. Kennerly, "High temperature operation of InAs-GaAs quantum dot infrared photodetectors with large responsivity and detectivity," *IEEE Photon. Technol. Lett.*, vol. 16, no. 5, pp. 1361–1363, May 2004.

[9] S. Chakrabarti, A. D. Stiff-Roberts, P. Bhattacharya, and S. W. Kennerly, "High responsivity AlAs/InAs/GaAs superlattice quantum dot infrared detector," *Electron. Lett.*, vol. 40, pp. 197–198, 2004.

[10] W. G. Spitzer and J. M. Whelman, "Infrared absorption and electron effective mass in n-type Gallium Arsenide," *Phy. Rev.*, vol. 114, pp. 59–63, 1959.

[11] S. Chakrabarti, A. D. Stiff-Roberts, P. Bhattacharya, and S. W. Kennerly, "Heterostructures for achieving large responsivity in InAs/GaAs quantum dot infrared photodetectors," *J. Vac. Sci. Technol. B*, vol. 22, pp. 1499–1502, 2004.

[12] H. Jiang and J. Singh, "Strain distribution and electronic spectra of InAs/GaAs self-assembled dots: an 8-band study," *Phy. Rev. B*, vol. 56, pp. 4496–4701, 1998.

[13] S. Chakrabarti, P. Bhattacharya, A. D. Stiff-Roberts, Y. Y. Lin, J. Singh, Y. Lei, and N. Browning, "Intersubband absorption in annealed InAs/GaAs quantum dots: a case for polarization-sensitive infrared detection," *J. Phys. D, Appl. Phys.*, vol. 36, pp. 1794–1797, Jul. 2003.