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High-detectivity, normal-incidence, mid-infrared ($\lambda \sim 4\,\mu$m) InAs/GaAs quantum-dot detector operating at 150 K

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Normal-incidence InAs/GaAs quantum-dot detectors have been grown, fabricated, and characterized for mid-infrared detection in the temperature range from 78 to 150 K. Due to the presence of an $Al_{0.3}Ga_{0.7}As$ current blocking layer in the heterostructure, the dark current is very low, and at $T = 100$ K, $I_{dark} = 1.7$ pA for $V_{bias} = 0.1$ V. The peak of the spectral response curve is at $\lambda \sim 4\,\mu$m, with $\Delta\lambda/\lambda = 0.3$ and $V_{bias} = 0.1$ V. At $T = 100$ K, for $V_{bias} = 0.3$ V, the peak detectivity, D^*, is 3×10^9 cm Hz$^{1/2}$/W, and the peak responsivity, R_p, is 2 mA/W with a photoconductive gain of $g = 18$. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1385584]

Over the past few years, quantum-dot infrared photodetectors have been widely investigated[1–4] for mid-infrared applications such as space based infrared imaging, thermography for electrical and mechanical fault detection, Fourier transform infrared spectroscopy (FTIR), and environmental and chemical process monitoring. Two of the major advantages quantum-dot infrared photodetectors (QDIPs) offer over quantum well infrared photodetectors are: (i) normal-incidence operation due to the absence of any polarization selection rules in quantum dots, and (ii) high-temperature operation due to the favorable carrier dynamics in quantum dots.[5] The normal-incidence operation eliminates the need for fabricating complicated gratings and optocouplers on top of the detectors, and the high-temperature operation offers the highly desirable possibility of using cost effective Peltier and air-cooled systems. Moreover, since the quantum dots are based on the mature GaAs-based technology, they do not suffer from the large interface instabilities or etch-pit and void defect densities that plague the mercury cadmium telluride detectors.[6]

High quality, defect-free quantum dots have been grown by self-organized epitaxy and have been incorporated into many electronic and optoelectronic devices. Recently, we[2,7] and several other groups[8–10] have demonstrated normal-incidence far-infrared detection in the range of 5–17 μm, using intersubband transitions in self-organized quantum dots. However, the large dark current in these devices limits their operation to less than 80 K. This increased dark current could be attributed to the long intersubband relaxation time in the quantum dots. Due to the increased lifetime of the excited states, a significant fraction of the carriers populate the excited states of the dots. Since the thermal activation barrier for the excited state is significantly lower than for the ground state, there is a large thermionic contribution to the dark current. It is important to note, however, that this increased intersubband relaxation time also leads to efficient detection since the photogenerated carriers stay for a longer time in the excited states, increasing the probability of their contribution to the photocurrent. Additionally, quantum-dot detectors are expected to demonstrate good performance at elevated temperatures due to the increase of intersubband relaxation times with increasing temperature.[11] Wang *et al.*[12] have recently demonstrated reduced dark current in quantum-dot detectors by covering the InAs quantum dots with a 30 Å $Al_{0.2}Ga_{0.8}As$ layer, measuring a D^* value of 2.5×10^9 cm Hz$^{1/2}$/W at $T = 77$ K using a 45° polished facet. In this letter, we demonstrate a normal-incidence InAs/GaAs quantum-dot detector with extremely low dark current ($I_{dark} = 1.65$ pA, $V_{bias} = 0.1$ V, $T = 100$ K), very high detectivity ($D^* = 3 \times 10^9$ cm Hz$^{1/2}$/W, $T = 100$ K), and reasonable performance for a temperature as high as 150 K, all of which are important milestones in the development of normal-incidence vertical QDIPs.

The quantum-dot detectors were grown on (100) semi-insulating GaAs substrates using a solid source Varian Gen-II molecular beam epitaxy system with an uncracked As_4 source. The heterostructure and device schematic of the detectors are shown in Fig. 1(a). A 0.5 μm GaAs($n = 2 \times 10^{18}$ cm^{-3}) bottom contact was first grown at 620 °C, followed by a 250 Å undoped GaAs layer. The substrate temperature was lowered to 500 °C, and 2.2 ML of InAs dots were grown. The dot formation process was monitored by observing the transition in the reflection high energy electron diffraction pattern from a streaky to a spotty pattern, which occurred at ~1.7 ML. Silicon was used to directly dope the dots with an electron concentration of $0.5–1 \times 10^{18}$ cm^{-3} in order to provide carriers for absorption. A 15 s pause was introduced to enable the dot formation process. A 250 Å undoped GaAs barrier was then grown, and the barrier and dot layers were repeated ten times. Then the substrate temperature was ramped to 620 °C for the growth of a current blocking 400 Å $Al_{0.3}Ga_{0.7}As$ layer and a 0.1 μm GaAs($n = 2 \times 10^{18}$ cm^{-3}) contact layer.

Low-temperature photoluminescence measurements were performed on the as-grown wafer and the ground state

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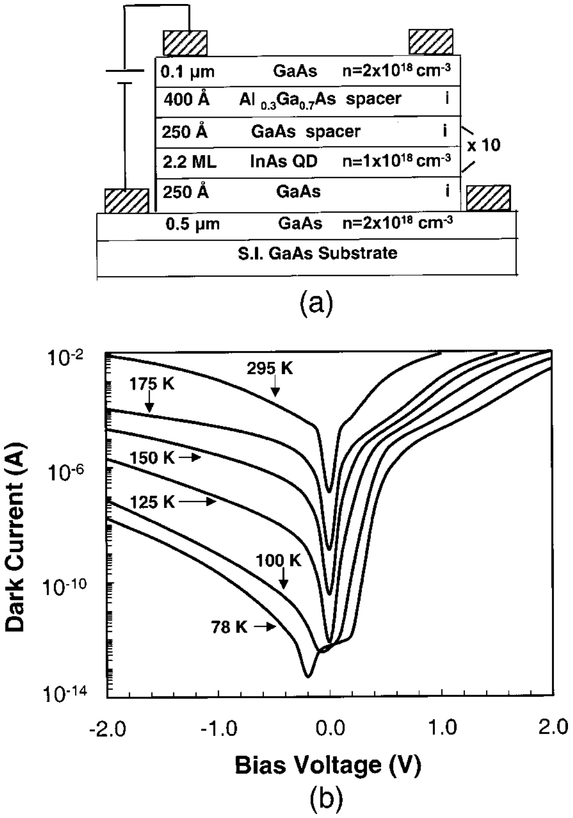

FIG. 1. (a) The heterostructure and device schematic of a vertical *n-i-n* InAs/GaAs quantum-dot detector with a current blocking $Al_{0.3}Ga_{0.7}As$ layer. The metal contacts are ring shaped; (b) dark current measured for the quantum-dot detector at different temperatures.

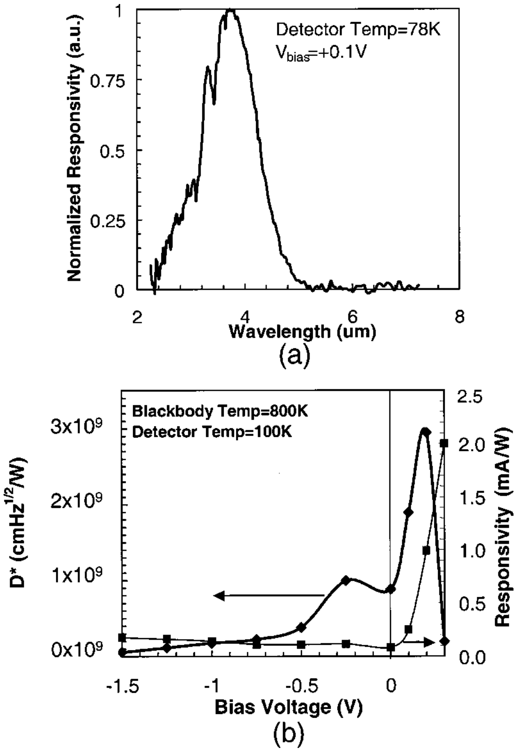

FIG. 2. (a) Spectral response of the detector at $T = 78$ K for $V_{\mathrm{bias}} = 0.1$ V due to bound-to-continuum transitions in the dot; (b) peak detectivity and responsivity of the vertical QDIPs at 100 K.

interband transition was observed at 1.17 eV at $T = 17$ K. Vertical quantum-dot detectors with ring contacts were fabricated using standard photolithography and wet etching techniques. Ni/Ge/Au/Ti/Au contacts were evaporated, and the sample was annealed at 400 °C for 1 min. Dark current measurements were performed at different temperatures using a HP 4145B semiconductor parameter analyzer. The dark current at various temperatures is shown in Fig. 1(b). The dark current for this quantum-dot detector is extremely low ($I_{\mathrm{dark}} = 1.7$ pA, $V_{\mathrm{bias}} = 0.1$ V, $T = 100$ K) compared to the dark current in a similar quantum well structure ($I_{\mathrm{dark}} = 10\ \mu$A, $V_{\mathrm{bias}} = 0.1$ V, $T = 60$ K) containing three periods of doped 80 Å $In_{0.15}Ga_{0.85}As$/500 Å GaAs quantum wells ($n = 1 \times 10^{17}\ \mathrm{cm}^{-3}$) and two additional undoped 500 Å GaAs spacer layers between the quantum wells and the contact layers.[13] There is also a distinct asymmetry in the dark current curves, and this arises from the asymmetrically placed $Al_{0.3}Ga_{0.7}As$ barrier.

The detectors were mounted on a leadless chip carrier and inserted into an Oxford Instruments cryostat. The spectral response was obtained using a FTIR spectrometer. The normalized responsivity spectrum ($\lambda_{\mathrm{peak}} = 3.8\ \mu$m, $\Delta\lambda/\lambda = 0.3$) obtained at $T = 78$ K for $V_{\mathrm{bias}} = 0.1$ V is shown in Fig. 2(a). The extremely low bias voltage is compatible with the standard readout circuits used in focal plane arrays. The broad nature of the response ($\Delta\lambda/\lambda > 0.2$) suggests that the transition could be due to a bound-to-continuum transition, as proposed by Pan, Towe, and Kennerly.[3] We find that the peak wavelength of the response spectrum is dependent on the composition and height of the $Al_{0.3}Ga_{0.7}As$ barrier layer. Thus, the barrier could be used not only to decrease the dark current, but also to tune the position of the spectral response peak. This is especially useful for two-color imaging applications where, in the same epitaxial sample, quantum-dot layers with the barrier could be used for mid-wavelength detection and quantum-dot layers without the barrier could be used for long-wavelength detection.

Photocurrent measurements were performed for temperatures in the range of 78 to 150 K using a calibrated 800 K blackbody source and f3 optics. Radiation from the blackbody was normally incident on the detector. A germanium filter ($\lambda_c \sim 1.8\ \mu$m) was used to verify that the response was not due to interband transitions. The photocurrent was amplified using a Keithley 428 current amplifier, and an Ono-Sokki CF-360Z fast Fourier transform analyzer was used to obtain the frequency spectrum of the response. The detector signal was obtained by averaging the response over a 50 Hz bandwidth centered around the chopper frequency, and the detector noise was obtained by averaging over a similar bandwidth in a signal-free part of the spectrum away from the chopper frequency. After subtracting the amplifier noise and accounting for the overlap of the blackbody spectrum with the spectral response of the detector (obtained from the FTIR measurement), the responsivities and detectivities were calculated. Figure 2(b) shows the peak responsivity and the peak detectivity as a function of bias at $T = 100$ K. Even though the measured $D^* = 3 \times 10^9\ \mathrm{cm\,Hz^{1/2}/W}$ at $T = 100$ K is an extremely high value for normal-incidence vertical quantum-dot detectors, the responsivity is still relatively low ($R_p = 2$ mA/W). This is because the added AlGaAs layer degrades the transport property of the carriers and decreases the photocurrent. Figure 3(a) shows the temperature dependence

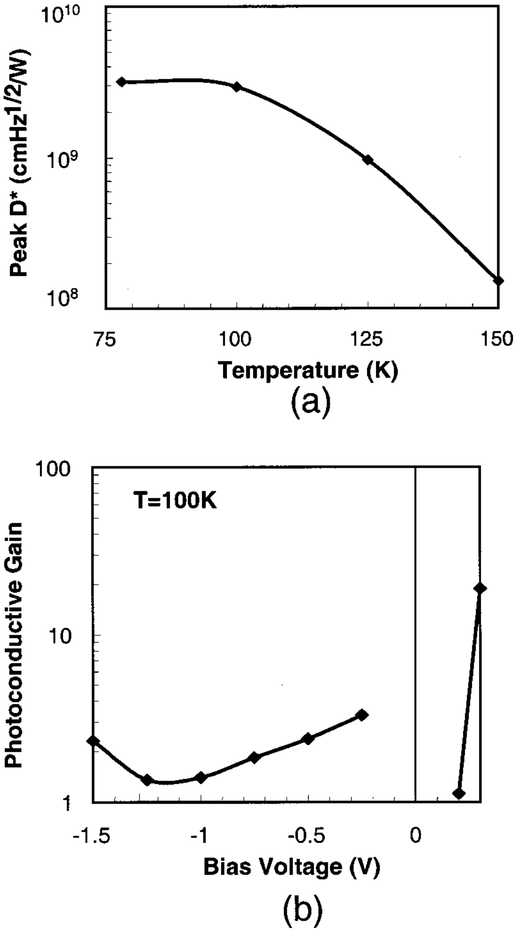

FIG. 3. (a) Temperature dependence of the peak detectivity and (b) photoconductive gain as a function of bias at $T = 100$ K. The values close to zero are ignored due to the large error in obtaining the noise current.

of the peak detectivity. The operating temperature of 150 K is a substantial advancement in the performance of normal-incidence vertical QDIPs.

Photoconductive gain was also measured in these detectors. Figure 3(b) shows the photoconductive gain as a function of bias at $T = 100$ K. Note that the photoconductive gain near zero bias has been omitted since the values are artificially high due to the extremely low dark current. The reduced gain in the reverse bias could be due to the decrease in the mobility of the carriers caused by the presence of the AlGaAs barrier. The sharp increase in the gain under forward bias conditions suggests that the main contribution to the gain could be from impact ionization.

In conclusion, we report a mid-infrared InAs/GaAs quantum-dot detector containing a current blocking $Al_{0.3}Ga_{0.7}As$ layer with a λ_{peak} of 4 μm, a peak responsivity of 2 mA/W, and a very high peak detectivity of 3×10^9 cm Hz$^{1/2}$/W at $T = 100$ K. The device exhibits very low dark current and operates until 150 K, improving the high-temperature performance of normal-incidence vertical quantum-dot infrared photodetectors. We have also measured a photoconductive gain of $g = 18$ for $V_{bias} = 0.3$ V in these detectors.

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