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The transition mechanisms of a ten-period InAs/GaAs quantum-dot infrared photodetector

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This study explores the growth and effects of a ten-period InAs/GaAs quantum-dot infrared photodetector (QDIP). With a uniform quantum-dot (QD) size distribution and a QD density of 2.8×10^{10} cm^{-2}, this 10 K photoluminescence spectrum shows a peak energy at 1.07 eV and a narrow full width at half maximum of 31.7 meV. The QDIP exhibits an asymmetric response under different voltage polarities and a high responsivity of 1.7 A/W at −1.1 V. Another noticeable observation in the spectral response of the device is the 6 μm peak detection wavelength with a high spectral broadening $\Delta\lambda/\lambda$ of 0.67. By analyses of the photoluminescence excitation spectrum and the temperature dependence of spectral response, the wide spectral response of the QDIP is attributed to the summation of transitions between QD excited states and the wetting layer states, instead of transitions between QD ground state and higher excited states. © *2008 American Vacuum Society.* [DOI: 10.1116/1.2990784]

I. INTRODUCTION

Self-assembled InAs/GaAs quantum-dot infrared photodetectors (QDIPs) with high responsivity, normal incident absorption, and wide detection wavelengths in the midinfrared range have been successfully demonstrated by several reports.[1–5] Compared with conventional quantum-well infrared photodetectors, QDIPs provide the advantages of long carrier capture and relaxation times,[6] no polarization selection rule for normal incidence light and high-temperature operation. Although lots of effort has been devoted to the structure design and spectral response of QDIPs,[7–9] detailed discussion on the transition mechanisms of the devices is still unavailable. In this article, ten-period InAs/GaAs QDIPs are investigated for this purpose. With a uniform QD size distribution, the QDIPs exhibit a high responsivity with high spectral broadening $\Delta\lambda/\lambda$ of 0.67 at the peak detection wavelength of 6 μm. From the observations of photoluminescence excitation (PLE) spectra, the wide spectral response is attributed to the summation of transitions between the QD excited states and the wetting layer (WL) states, instead of the transitions between QD ground state and higher excited states.

II. EXPERIMENTAL

The samples discussed in this article were grown on (100)-oriented semi-insulating GaAs substrates by solid-source molecular-beam epitaxy. For the measurements of atomic-force microscopy (AFM) and PL/PLE, one QD sample with two InAs quantum-dot structures were grown with (a) a 2.4 ML QD layer grown in the 60 nm GaAs matrix, which is sandwiched between two additional 30 nm AlAs carrier confinement layers to measure PL and PLE spectra, and (b) the other uncapped QD layer grown under the same conditions to observe the surface morphology by AFM. For the QDIP sample, the active region consists of ten-period quantum-dot structures with 2.4 ML InAs coverage and 30 nm GaAs barriers sandwiched between 0.3- and 0.6-μm-thick GaAs contact layers with $n = 1 \times 10^{18}$ cm^{-3}. The InAs QD structures in the QDIP sample are undoped. The ten-stacked QDIP sample was fabricated into 100×100 μm^2 devices using standard photolithographic techniques, contact metal evaporation, and wet chemical etching. The measurement system for spectral response consists of Spectral 100 Fourier transformation infrared spectroscopy coupling with a cryostat and a current preamplifier.[8,9]

III. RESULTS AND DISCUSSIONS

Figure 1(a) shows the AFM image with a scan field of 1×1 μm^2. Statistical analysis yields a uniform QD distribution with a dot density of 2.8×10^{10} cm^{-2}, an average dot diameter of 54 nm, and a dot height of 6 nm. The results suggest that the QD growth condition is optimized. Figure 1(b) shows the 10 K PL and PLE spectra of the QD sample. This 10 K PL spectrum shows a peak energy at 1.07 eV and a full width at half maximum (FWHM) of 31.7 meV. The

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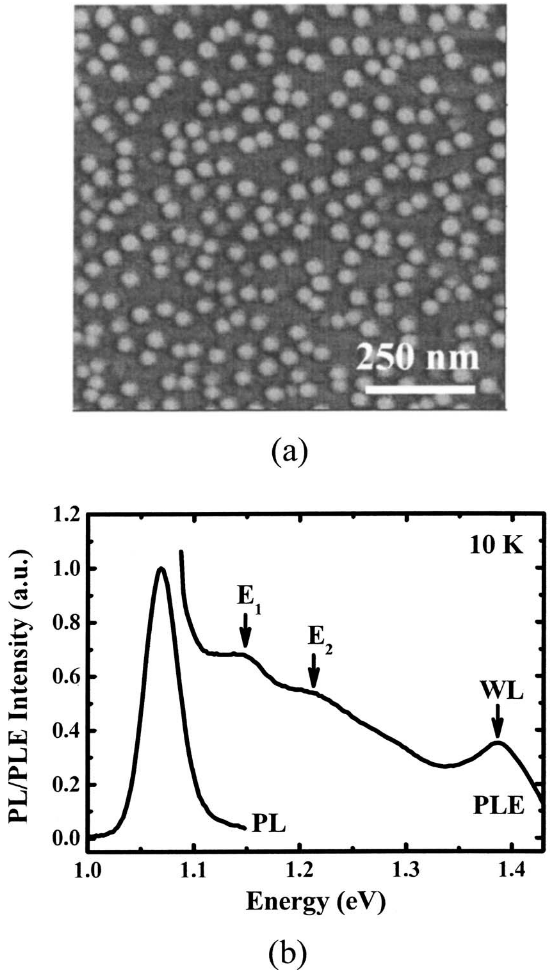

FIG. 1. (a) AFM image with a scan field of $1\times1\ \mu m^2$ and (b) 10 K PL and PLE spectra of the QD sample.

narrow FWHM value suggests that the QD sample has a uniform QD size distribution embedded in the GaAs barrier layers, which is consistent with the observation from the AFM image, as shown in Fig. 1(a). With the PL peak energy as the detection energy, the 10 K PLE spectrum of the QD structure exhibits two excited states E_1 and E_2 located at 1.07 and 1.21 eV, respectively. The additional peak locates at 1.39 eV, which corresponds to luminescence from the wetting layer.

Figure 2 shows the 10 K spectral response of the ten-period QDIP biased at ±1.1 V. A high responsivity up to 1.7 A/W can be observed for the QDIP biased at -1.1 V. The asymmetric response under different voltage polarities is attributed to the asymmetric QD growth procedure. Prior to the QD formation, a thin 1.7–1.8 ML InAs WL would be formed by the Stranski–Krastanov growth mode. In this case, the photocurrents of the QDIP under negative biases would encounter the InAs WL instead of the GaAs barriers, which would make the photocurrents tunnel easily through the barrier. Therefore, a much higher responsivity under negative biases would be expected to be observed. Another noticeable observation in the spectral response of the device is the high

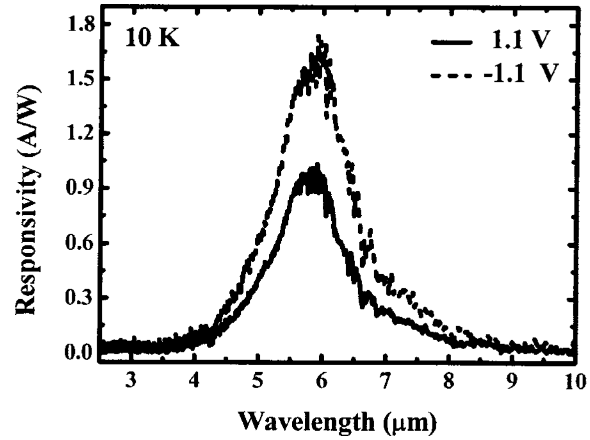

FIG. 2. 10 K spectral response of the ten-period QDIP biased at ±1.1 V.

spectral broadening $\Delta\lambda/\lambda$ of 0.67 at peak wavelength of 6 μm. The phenomenon has been previously attributed to the multitransition mechanisms.[8,9]

To further investigate the transition mechanisms of the device, Fig. 3 shows the normalized 10 K spectral response at 1.0 V and the PLE spectrum with the energy coordinate shifted by $(E_{WL}-E)$. The spectral-response range of the device is between the two peaks $(E_{WL}-E_1)$ and $(E_{WL}-E_2)$. This implies that the spectral response is the result of the summation of transitions between the excited states and the WL state. Other evidence supporting this inference is the increase in spectral response with increasing temperature.

Figure 4 shows the spectral response of the QDIP biased at 1.0 V under 10 and 77 K. As shown in this figure, a significant increase in spectral response at 77 K can be observed for the device. A previous report has shown that the increase in photocurrent with increasing temperature resulted from the decrease in electron-capture probability by QDs.[10] However, assuming the absorption of the QDIPs to be the transitions between confinement states in the QD structures, the temperature dependence of the electron-capture probability should not be significant, considering the large energy difference between the GaAs band edge and the QD excited

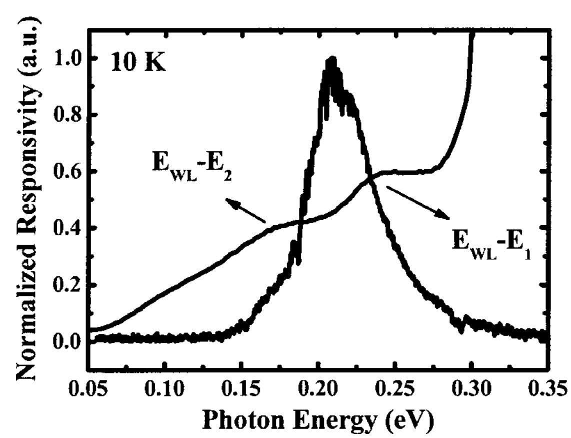

FIG. 3. The normalized 10 K spectral response at 1.0 V and the PLE spectrum with the energy coordinate shifted by $(E_{WL}-E)$.

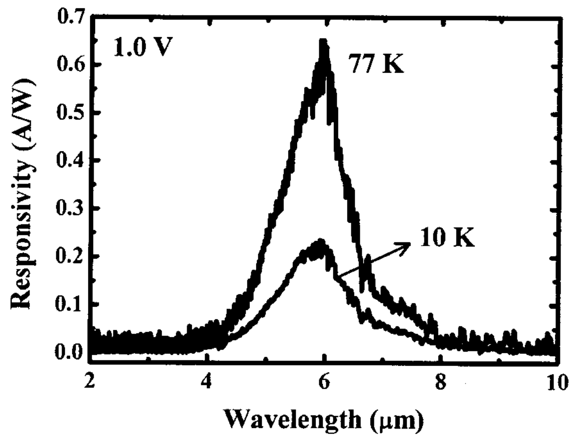

FIG. 4. The spectral response of the ten-period QDIP biased at 1.0 V under 10 and 77 K.

states. Therefore, the spectral response is attributed to the summation of transitions between the excited states and the WL state, which is occupied by all the photoexcited electrons at the WL states. The influence of operation temperature on the electron-capture probability would be very significant considering the reduced energy difference between GaAs band edge and the WL state.

IV. CONCLUSIONS

In summary, we have demonstrated the growth of a ten-pair InAs/GaAs QDIP with a uniform QD size distribution. The device shows a peak detection wavelength at 6 μm with a high responsivity of 1.7 A/W and a high spectral broadening $\Delta\lambda/\lambda$ of 0.67 at 6 μm peak wavelength. By observations of the 10 K PLE spectrum, the wide spectral response of the device is attributed to the summation of transitions between the QD excited states and the WL state, instead of the transitions between the QD ground state and higher excited states. This observation of increasing responsivity with increasing temperature would also support the inference.

ACKNOWLEDGMENTS

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