Extended Abstracts of the 2001 International Conference on Solid State Devices and Materials, Tokyo, 2001, pp. 664–665

P-2-6

100 K Operated Photovoltaic InAs/GaAs Quantum-Dot Infrared Photodetector with Uniform Dot Density

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I. Introduction

The photovoltaic (PV) responses of ten-stacked InAs/GaAs quantum-dot infrared photodetectors (QDIPs) with different dot distributions are investigated. Higher PV-mode response at 20 K for QDIPs with denser dot density indicates a more pronounced state filling effect and better performance. Also observed is the increase of PV-mode response with increasing temperature form 20 to 100 K. The peak responsivity and detectivity of QDIP are 2.9 mA/W and 4.8×10^6 cm-Hz$^{1/2}$/W at 100 K.

II. Experiments and Results

Samples with the 3 and 2.2 ML InAs coverage are grown on (100) semi-insulating GaAs substrate under As shutter closed condition by solid-source molecular beam epitaxt (MBE) for the investigations of surface morphologies and photoluminescence (PL) measurement [1]. As shown in the atomic-force-microscopy images of Fig. 1, the dot densities for 3 and 2.2 ML InAs coverage are 3.8×10^{10} and 5.8×10^{10} cm^{-3}, respectively. The reduction of dot density of 3 ML InAs coverage is attributed to the coalescence of InAs QDs such that evidently two-group distribution is observed. The temperature-dependent PL intensities for the two samples are shown in Fig. 2. The increase of PL intensities until 90 K is observed indicating the repopulation of electrons in the InAs dots to nearby dots. And for temperature higher than 90 K, the increasing electron energy and nonradiative recombination rate would result in the decrease of PL intensities. The similar trend for the temperature-dependent PL intensities corresponds to the similar dot densities of the two samples.

Under the same growth conditions, two device structures denoted as device A and B with InAs coverage 3 and 2.2 ML are prepared. The device structures are shown in table 1. The fabricated 100×100 μm^2 devices are measured under edge-coupling scheme for spectral responses. The dark I-V characteristics are obtained at various temperatures under cold environment by using HP 4145A. The PV-mode spectral responses at 20 K of devices A and B are shown in Fig. 3. According to the calculated band structure shown in the insert of Fig. 3, the 5 μm peak response is attributed to the first confinement state E_1 to the second confinement state E_2 transition and subsequent tunneling through the GaAs barrier [1]. To explain the phenomenon, temperature-dependent dark currents are fitted with the equation

$$I_D=AT^2\exp(-E_a/kT) \tag{1}$$

where E_a denotes the activation energy which equals ΔE_C-E_f. ΔE_C is the conduction band discontinuity and E_f is the Fermi level. The fitting results under different biases are shown in Fig. 4. The derived zero-bias activation energies of device A and B are 260 and 126 meV, respectively. The higher Fermi level of device B is attributed to the more uniform dot size distribution and the smaller InAs coverage, which results in almost identical electrons stored in each dot and less electrons are needed to occupy the confinement states. Hence, the first confinement state of device B is fully occupied with electrons, which results in the absence of energy relaxation to lower states for photo-excited electrons. With a build-in electrical field induced by potential asymmetry, a pronounced PV-mode response of device B is observed as shown in Fig. 3 [2].

As shown in Fig. 5, the PV-mode response of device B increases with increasing temperature. And for temperature higher than 100 K, the decrease of response is observed. Similar with the trend of temperature-dependent PL intensities, the increasing electron energy and nonradiative recombination rate for temperature higher than 100 K would result in the relaxation of photo-excited electrons transporting the GaAs layer or at the InAs dot region. The peak responsivity and detectivity of QDIP are 2.9 mA/W and 4.8×10^6 cm-Hz$^{1/2}$/W at 100 K, respectively.

III. Conclusion

A more uniform dot size distribution is observed for InAs quantum dots with 2.2 ML grown under As shutter closed condition. The InAs/GaAs QDIP with the same InAs coverage has shown pronounced PV-mode response indicating a strong state filling effect. The similar temperature dependence of PL intensities and PV-mode responses of 2.2 ML InAs coverage samples have assured the attributed mechanisms responsible for the phenomenon.

References

[1] S. Y. Lin et al., Appl. Phys. Lett. **78**, 2784 (2001).
[2] D. Pan et al, Appl. Phys. Lett. **76**, 3301 (2000).

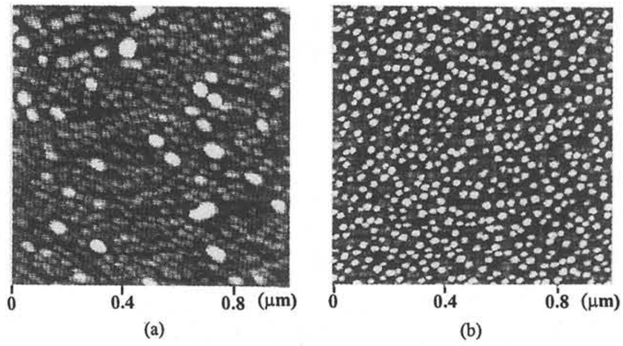

Fig. 1 The 1×1 μm^2 AFM images of InAs quantum dots of (a) 3 and (b) 2.2 ML.

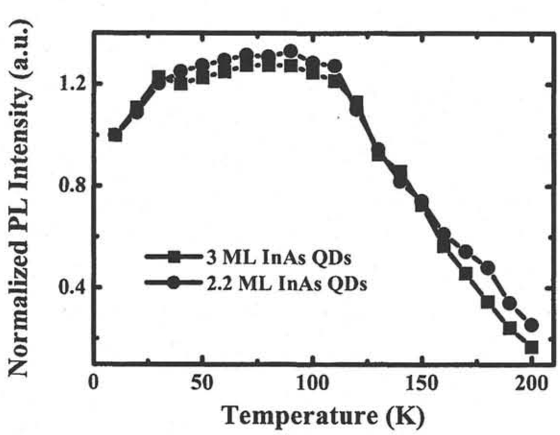

Fig. 2 The normalized PL intensities of 3 and 2.2 ML InAs coverage samples for temperatures from 10 to 200 K.

Sample A	Sample B
500 nm GaAs Top Contact Layer n=1X10^{18} cm^{-3}	
50 nm undoped $Al_{0.1}Ga_{0.9}As$ Blocking Layer	
30 nm undoped GaAs Barrier Layer (10 X)	
3 ML InAs QDs (10 X)	2.2 ML InAs QDs (10 X)
30 nm undoped GaAs Barrier Layer	
50 nm undoped $Al_{0.1}Ga_{0.9}As$ Blocking Layer	
1000 nm GaAs Bottom Contact Layer n=1X10^{18} cm^{-3}	
(100) SI-GaAs Substrate	

The InAs QD region is uniformly doped to 1X10^{18} cm-3

Table 1 The device structures of samples A and B.

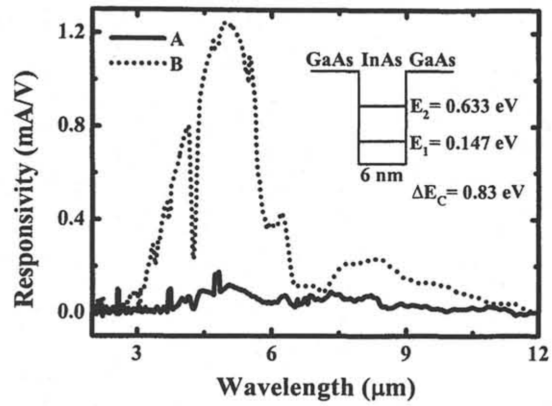

Fig. 3 The spectral responses of devices A and B at 20 K, the insert shows the calculated confinement states of the InAs dot.

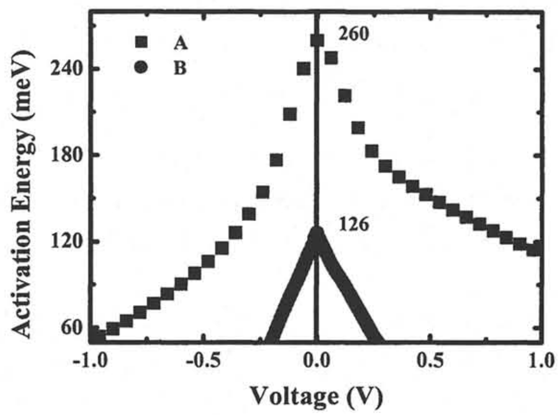

Fig. 4 The activation energies of devices A and B under different biases. The zero-bias activation energies are 260 and 126 meV for devices A and B, respectively.

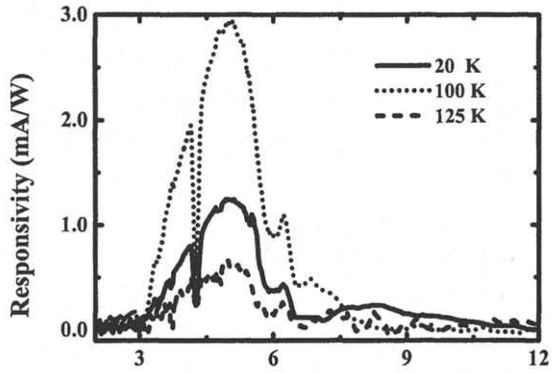

Fig. 5 The spectral responses of device B at 20, 100 and 125 K.