Enhanced Normal-Incident Absorption of Quantum-Dot Infrared Photodetectors With Smaller Quantum Dots

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Abstract—**Ten-period InAs–GaAs quantum-dot (QD) infrared photodetectors grown under different In adatom supply procedures are investigated. Two In adatom supply procedures of In shutter 1) always opened and 2) periodically opened/closed are adopted in this letter. Larger QD sizes in both height and diameter and more uniform size distribution are observed for samples grown under an In shutter periodically opened/closed condition. The device with QDs grown under the In shutter always opened condition has revealed shorter detection wavelengths and enhanced normal incident absorption. The phenomenon shows that beside the increase of energy difference between confinement states, smaller QD sizes would also enhance the normal incident absorption predicted for the theoretically zero-dimensional QD structures.**

Index Terms—**Quantum dot (QD), quantum-dot infrared photodetector (QDIP).**

I. INTRODUCTION

MUCH effort has been devoted to the development of In(Ga)As–GaAs quantum-dot infrared photodetectors (QDIPs) in the last decade [1]–[6]. Compared with the conventional quantum-well infrared photodetectors (QWIPs), low dark currents and insensitivity to normal incident light are expected for the devices, which make high-temperature operation and grating-less QDIPs possible [7]–[9]. QDIPs and QDIP focal-plane arrays with operation temperatures up to 260 K and 135 K have already been demonstrated, respectively [7], [8]. As for the insensitivity to the normal incident light, it has been reported elsewhere that the intrinsic absorption of QDIPs over normal incident light is ~20% superior to QWIPs [9]. However, device parameters and operation conditions still play an important role for the resultant photocurrent under normal incident light illumination [10]. The results suggest that there are more complicated mechanisms to be investigated in the normal incident absorption of QDIPs. In this letter, the influence of the InAs QD size on device performance of the QDIPs is investigated. Two different growth approaches of 1) standard growth mode without growth interrupt and 2) migration-enhanced (ME) mode with periodical growth interrupts are adopted in this study. The ME growth mode is similar with the ME epitaxy method. The only difference is the always-opened As shutter of the ME mode to keep the As-rich surfaces [11]. Compared with the standard QD growth mode, QDs grown by the ME mode are of larger sizes in both height and diameter. Better QD size uniformity and crystal quality are also obtained for the QDs grown by the ME mode. By using these two growth modes, two QDIP devices are fabricated. Shorter detection wavelengths and enhanced normal incident absorption are observed for the device with QDs grown by the standard mode.

II. EXPERIMENTS

The samples investigated in this letter were grown on (100)-oriented semi-insulating GaAs substrates by Riber Compact 21 solid-source molecular beam epitaxy system. For the measurements of photoluminescence (PL), photoluminescence excitation (PLE), and atomic-force microscopy (AFM), two test samples with bi-QD structures were prepared. One QD structure was embedded in the GaAs barriers for PL/PLE measurements while the other QD structure was grown at the top of the wafer for AFM measurement. Two different growth modes were adopted for the QD structures: 1) standard growth mode without growth interrupts and 2) ME growth mode with periodical open/close procedures of the In shutter. The growth interrupts adopted in the ME mode are to enhance the In adatom migration on the substrate surface. The InAs coverage of the QD structures grown by the two modes were both 2.4 ML determined via *in situ* reflection high energy electron diffraction pattern [12]. In this case, the total period of time for opening the In shutter would be the same for both growth modes. The only difference would be the five times of growth interrupt lasting for 6 s inserted in the QD growth of the ME mode. By using the same growth conditions as the test samples, two device structures were prepared. With 300- and 600-nm n-type GaAs layers doped to 2×10^{18} cm^{-3}

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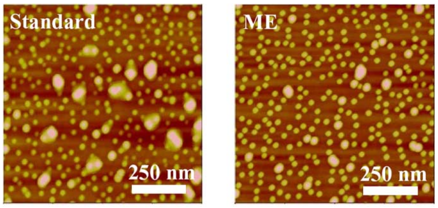


(a) (b)

Fig. 1. AFM images of the samples with the QD structures grown by (a) standard and (b) ME growth modes.

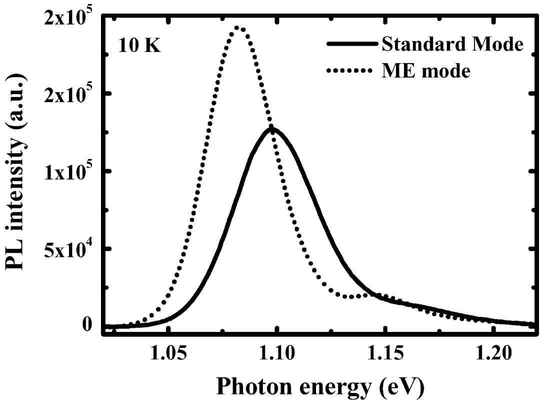


Fig. 2. The 10 K PL spectra of the test samples grown by these two growth modes.

as the top and bottom contact layers, respectively, the ten-period 2.4-ML InAs/30-nm GaAs QD structures were grown as the active region. With the QD structures grown by standard and ME growth modes, the samples are referred to as samples A and B, respectively. After mesa formation and metal evaporation, $100 \times 100\ \mu\mathrm{m}^2$ devices were fabricated for measurements. The device measurement is carried out under an edge-coupling scheme. The measurement system for spectral response consisted of a Fourier transformation infrared spectroscopy coupling with a Janis CCS-150 cryostat and a current preamplifier [10]. The PL and PLE spectra were measured by using a Jobin Yvon's NanoLog3 system coupled with a Janis CCS-150 cryostat.

III. RESULTS AND DISCUSSION

The AFM images of the QD test samples grown by standard and ME modes are shown in Fig. 1. The dot densities for the two test samples extracted from the AFM images are 3.16 and $3.31 \times 10^{10}\ \mathrm{cm}^{-2}$, respectively. The slightly lower dot density for the sample grown by standard growth mode is resulted from the QD coalescence such that more severe two-group size distribution is observed for the sample. Insufficient In adatom migration on the substrate surface should be responsible for this phenomenon. Therefore, a more uniform QD size distribution would be observed for the sample grown by ME growth mode. The dot heights/diameters of the two samples extracted from the AFM images are 6/39.3 and 8.8/43.1 nm, respectively. The results suggest that with sufficient migration for the In adatoms, larger QDs with better size uniformity would be obtained.

The 10 K PL spectra of the two test samples are shown in Fig. 2. This figure reveals that the PL peaks at 1.097 and 1.082 eV are observed for the two test samples grown by standard and ME growth modes. The lower PL peak energy for the ME-grown sample is attributed to its larger InAs QD size such that a lower ground state is obtained for the sample. Also, the two samples show a full-width at half-maximum (FWHM) of 39.5 and 32.2 meV of the PL spectra. Considering the PL peak of each individual QD to be δ-function like, the observed PL spectrum would be a summation of all the luminescence from each QD. The FWHM value of the PL spectrum would represent the uniformity of the QD structures. In this case, the observation of a narrower FWHM for the ME-grown sample is consistent with the results obtained from the AFM image that better QD size uniformity is obtained for the sample. Also observed in the figure is the higher PL intensity and an additional PL peak at $\sim$1.15 eV for the sample grown under ME mode. The observation of PL peaks with higher energies is resulted from the state-filling effect of the QD structure [13]. The observed higher PL intensity and significant PL peak resulted from the QD excited state reveal the better quality of the sample grown under ME mode. Therefore, as compared to the QDs grown by standard growth mode, ME-grown QDs are of larger sizes in both height and diameter and better size uniformity and of better crystal quality.

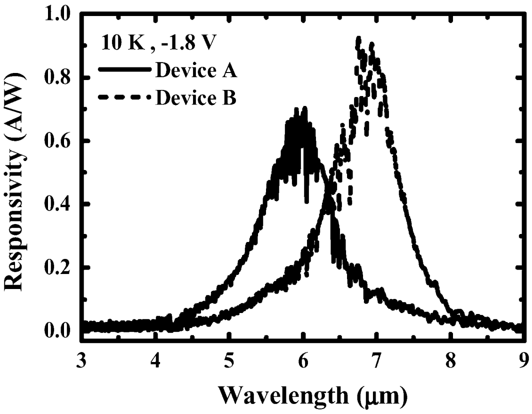
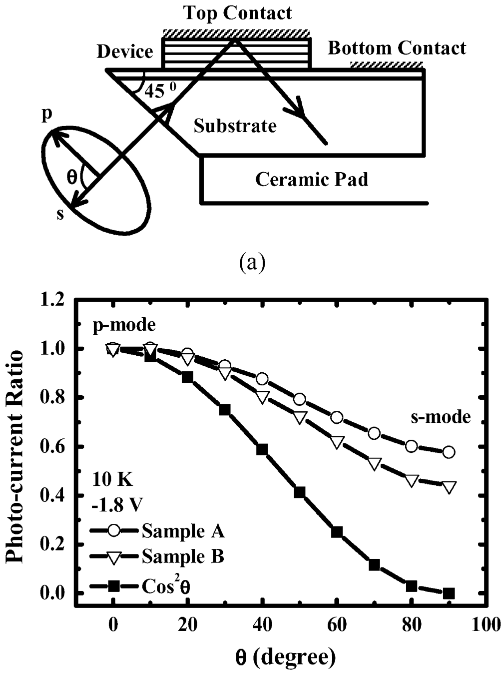


Fig. 3. The 10 K spectral responses of Devices A and B at -1.8 V.

To investigate the influence of QD size on the performance of QDIPs, Devices A and B grown by standard and ME growth modes were prepared. The 10 K spectral responses of Devices A and B operated at -1.8 V are shown in Fig. 3. Both devices exhibit a high responsivity and a broad detection window, which are consistent with the frequently observed QDIP performance [9], [10]. Also observed in the figure is the shorter detection wavelength of Device A (6 μm) compared with Device B (7 μm). The results suggest that the sample with smaller QD sizes would show shorter detection wavelengths, which is attributed to the enhanced energy difference between the confinement states of the QD structures.

Another interesting phenomenon to be investigated is the influence of QD size on the normal incident absorption of the QDIPs. The measurement configuration for the polarization-dependent responsivity for the QDIPs is shown in Fig. 4(a). Infrared light with different polarizations was irradiated into the device via the 45°-polished surface, where the light with s-mode polarization is the normal incident light. The



(b)

Fig. 4. (a) The 10 K spectral responses of Devices A and B at −1.8 V and (b) the 10 K PLE spectra of the test samples grown by standard and MEE growth modes.

photocurrent ratios obtained via photocurrents measured under different polarized lights divided by the photocurrent under p-mode light at applied voltage −1.8 V of Devices A and B are shown in Fig. 4(b). Devices A and B exhibit ratios of 0.58 and 0.44 under s-mode light irradiation. Considering the similar device structures of the two devices, the QD structures with different growth modes should be responsible for the reduced normal incident absorption of Device B. The results suggest that QDIPs with smaller QD sizes would have the enhanced normal incident absorption as in the case of Device B grown by ME mode. It is demonstrated that with minor reduction in the QD sizes, the normal incident absorption predicted for the theoretical zero-dimensional QDs would be greatly depressed.

IV. CONCLUSION

The influence of the InAs QD size on the device performance of the InAs–GaAs QDIPs is investigated. Compared with the standard QD growth mode, QDs grown by ME mode are of larger sizes in both height and diameter. Better QD size uniformity is also obtained for the QDs grown by ME mode. QDIPs grown by the two growth modes are also fabricated in this letter. Longer detection wavelengths and reduced normal incident absorption are observed for the device with QDs grown by ME mode. The results suggest that beside the increase of energy difference between confinement states, the enhanced normal incident absorption can also be observed for QDs with smaller sizes. This demonstrates that with minor increase in the QD sizes, the normal incident absorption predicted for the theoretical zero-dimensional QDs would be greatly depressed.

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