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High quantum efficiency dots-in-a-well quantum dot infrared photodetectors with AlGaAs confinement enhancing layer

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We demonstrate the high quantum efficiency $InAs/In_{0.15}Ga_{0.85}As$ dots-in-a-well (DWELL) quantum dot infrared photodetectors (QDIPs). A thin $Al_{0.3}Ga_{0.7}As$ layer was inserted on top of the InAs quantum dots (QDs) to enhance the confinement of QD states in the DWELL structure. The better confinement of the electronic states increases the oscillation strength of the infrared absorption. The higher excited state energy also improves the escape probability of the photoelectrons. Compared with the conventional DWELL QDIPs, the quantum efficiency increases more than 20 times and the detectivity is about an order of magnitude higher at 77 K. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2926663]

In the past decade, quantum dot infrared photodetectors (QDIPs) have been widely investigated with different structures and materials because of their potential to become low cost, high temperature operation infrared detectors.[1–8] With the self-assembled In(Ga)As/GaAs quantum dots (QDs), several encouraging results have been demonstrated with operation temperatures higher than 150 K.[5–9] However, with the simple QD structure, the tuning of the detection wavelength is relatively difficult because of the limitation of the self-assembled growth. To overcome this drawback, many efforts have been focused on the dots-in-a-well (DWELL) structure which provides the flexibility to adjust the electronic states with the quantum well.[8–19] The DWELL structure with GaAs wells and AlGaAs barriers has been investigated for different spectral ranges.[18] The QDIPs made with the DWELL structure have an additional advantage of lower dark current because the ground state energy is usually lower. Recently, high quality 640×512 DWELL QDIP imaging focal plane arrays have been demonstrated.[19]

However, the QDIPs made from the DWELL structure usually suffer from poor quantum efficiencies. In DWELL QDIPs, the infrared absorption comes from the transition between the ground state and the excited state in which the electronic wave function extends to the quantum well region. With the inserted InGaAs quantum well, the absorption strength associated with the bound-to-bound transition becomes weaker due to the decreased dipole element. Besides, the photoexcited electrons in the DWELL QDIPs have lower energy relative to the GaAs barrier. So the escape probability for the excited carriers to become free is lower and, as a result, the operation voltage is higher. It has been demonstrated that the quantum efficiency of DWELL QDIPs can be increased by increasing the QD density with Sb surfactants.[11] However, an additional Sb source is required and the QD growth process is more complicated than the conventional devices.

In this study, we designed a modified DWELL structure to enhance both the absorption strength and the escape probability. In this structure, a thin $Al_{0.3}Ga_{0.7}As$ layer was inserted on top of the InAs QD layer. This added layer provides better confinement for the excited state wave function in the QD region and also elevates the excited state energy. The overall quantum efficiency is therefore improved.

Two samples were prepared in this study by a Veeco GEN-II molecular beam epitaxy system on (001) semi-insulating GaAs substrates. One is the confinement enhanced DWELL (CE-DWELL) QDIP while the other is a conventional DWELL QDIP. In each sample, the active region contains ten layers of QDs separated by 53 nm GaAs barrier layers and is sandwiched between two 500 nm n^+GaAs contact layers. For the CE-DWELL structure, 2.2 ML of InAs QDs were deposited on a 2 nm $In_{0.15}Ga_{0.85}As$ layer and then followed by a 2.5 nm $Al_{0.3}Ga_{0.7}As$ confinement layer and a 4.5 nm $In_{0.15}Ga_{0.85}As$. δ-doped Si layers with a concentration of 1×10^{10} cm^{-2} were inserted 2 nm before each QD layer to provide electrons to the QDs. The schematic of the CE-DWELL sample structure is shown in Fig. 1(a). For the conventional DWELL sample, the $Al_{0.3}Ga_{0.7}As$ layer was replaced by an $In_{0.15}Ga_{0.85}As$ layer while other growth parameters were kept to be the same. A surface QD layer with the same growth condition as the embedded QD layers was also deposited for atomic force microscopy (AFM) measurement. Similar QD densities were determined in both samples to be about 2.1×10^{10} cm^{-2}. Given the doping density used, we estimated an average number of carriers in each QD around 0.5.

Due to the strain distribution, the inserted thin $Al_{0.3}Ga_{0.7}As$ layer was expected to aggregate in areas without QDs leaving the tips of the QDs uncovered. Such a property is favored since the structure could provide the barrier that enhances the confinement in the lateral direction but not block the transport of electrons in the vertical direction. In order to confirm this, the structure of the active layer was examined by the cross-sectional transmission electron microscopy (TEM) image shown in Fig. 1(b). It is clearly seen that the AlGaAs layer is flat instead of conforming to the shape of the InAs QDs. The TEM image shows the height of the QD is about 5 nm and the base width is about 26 nm.

The confinement effect of the AlGaAs layer was then verified with the photoluminescence (PL) measurement. The

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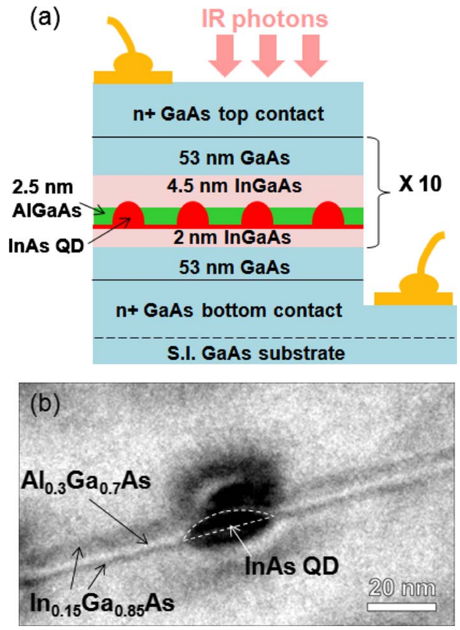

FIG. 1. (Color online) (a) The schematic diagram of the CE-DWELL QDIP. (b) The cross-sectional TEM image of the CE-DWELL structure.

PL spectra were taken with a liquid nitrogen cooled micro-PL system with high excitation density to reveal the higher levels of the QDs. Figure 2 shows the measured spectra of the two samples mentioned above. Four transition peaks which arise from the DWELL states were revealed in the spectra of both samples. Clear leverage of the transition energies was identified in the CE-DWELL sample. The energy difference of the ground state in the two samples is about 62 meV, while the energy difference is 82 meV for the third excited state. The insertion of the AlGaAs layer provides more confinement effect to the higher excited states. The possibility that the observed blueshift might come from the change of dot size and composition due to different capped materials is ruled out because it has been reported that the insertion of an Al contained layer should cause a redshift for the ground state energy due to the suppression of the In segregation.[20] Furthermore, our AFM and TEM results show that the QD shape and size for the two samples are quite similar. So the blueshift of the energy states in our sample should be the result of the better confinement provided by the inserted AlGaAs barrier layer.

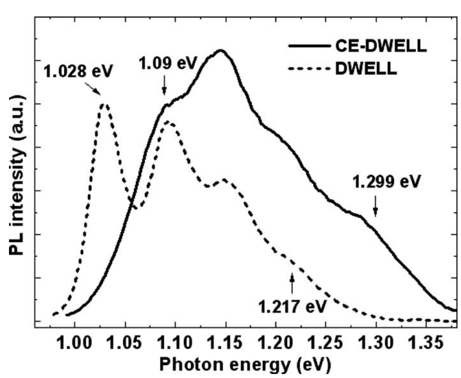

FIG. 2. The high excitation energy PL spectra of the two samples. The solid line is the result for the CE-DWELL sample and the dash line is the spectrum of the DWELL sample. The arrows indicate the ground state and the third excited state transition energies of the two samples.

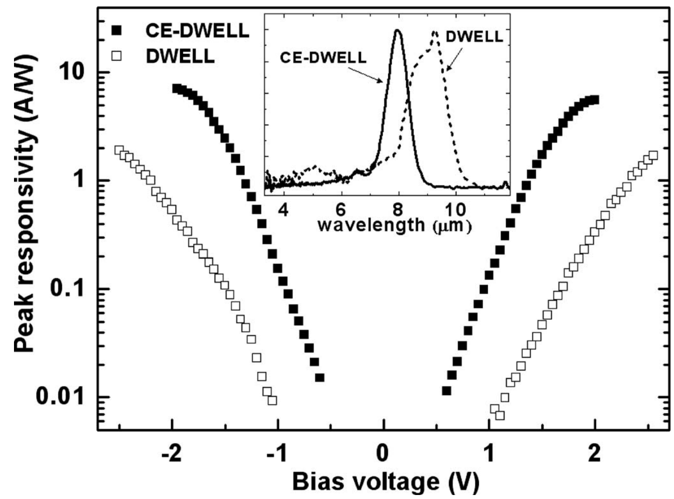

FIG. 3. The voltage dependence of the peak responsivity of the two samples at 77 K. The insert shows the responsivity spectra of the two samples at −1 V and 77 K.

Standard processing techniques were then applied for the device fabrication. $260 \times 370\ \mu m^2$ mesas with AuGe contact rings were formed to allow normal incidence measurement from the mesa top. The device characteristics at different temperatures were measured using a close cycled helium cryostat. In all measurements, the bottom contact is referred as ground. The photocurrent responsivity spectra were measured by Fourier transform infrared spectroscopy and calibrated by a 1000 C blackbody radiation source.

Figure 3 shows the responsivity spectrum and the responsivity curves at different biases of the two samples at 77 K. The responsivity peak for the CE-DWELL sample is around 8 μm which is shorter than the peak for the DEWLL sample (9.2 μm) as expected from the PL measurement. Assuming 70% of the bandgap difference is in the conduction band, the infrared response is identified to be from the transition between the ground state to the third excited state in both samples. This bound to bound transition is consistent with the relatively narrow bandwidth $(\Delta\lambda/\lambda_p)$ of the spectrum. Comparing the responsivity curve of the two samples, a clear increase of the responsivity in the CE-DWELL sample is shown over the whole bias region. At −1.2 V and 77 K, the responsivity for the CE-DWELL sample is 0.536 A/W while it is only 0.023 A/W for the conventional sample.

To further probe the origin of the increase of responsivity, the device gain was calculated through the noise measurement assuming the *G-R* noise dominates.[21] Due to the limit of the measurement system, noise current smaller than 1×10^{-13} A/Hz$^{0.5}$ could not be correctly measured in lower bias range. Both the current gain and the calculated quantum efficiency are shown in Fig. 4 for comparison. The difference in responsivity is primarily attributed to the difference of quantum efficiency. Compared with the quantum efficiency of the DWELL sample, the quantum efficiency of the CE-DWELL sample is much higher over the measured bias range and increases faster with the applied voltage. The highest quantum efficiency in CE-DWELL is around 2% at −1 V, which is clearly superior to that in DWELL (0.08% at −1.3 V). It is noticed that the response spectral width is wider in the DWELL sample and the comparison of the peak quantum efficiency might not be fair. Nevertheless, the inte-

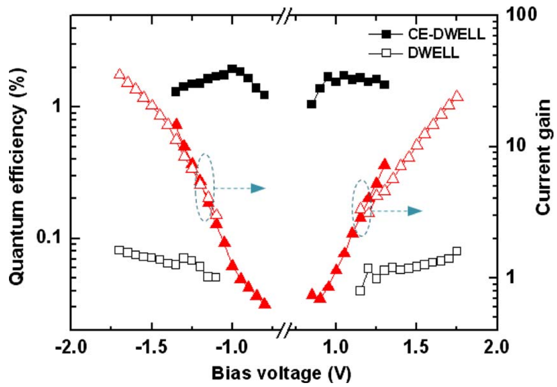

FIG. 4. (Color online) The current gain (triangles) and quantum efficiency (squares) of the two samples at different voltages at 77 K.

grated quantum efficiency of the CE-DWELL sample is still superior to the DWELL sample by a factor of 16. The inserted AlGaAs layer confines the QD's excited-state wave function to be more localized, so the absorption strength of the ground state electrons is enhanced due to the better wave function coupling. In addition, the excited-state energy in the CE-DWELL sample is about 60 meV higher than that in the DWELL sample (see Fig. 2). The escape probability is thus higher and as a result the operation voltage is lower for the CE-DWELL sample. On the other hand, the two samples have essentially similar current gain in the bias region of −1.3–1.25 V. So the carrier transport property is preserved in the CE-DWELL structure even though the wide bandgap AlGaAs layer was added. This is consistent with our expectation since the AlGaAs layer mainly covers the QD edges and leaves the upper portion of the QDs uncovered, thereby serving as the path for the flow of the photocarriers.

The higher ground state energy of the CE-DWELL sample could generate higher dark current and it has been observed in the measurement. The dark current density was 3.82×10^{-4} A/cm^{-2} at −1 V at 77 K for the CE-DWELL sample but it was only 3.3×10^{-5} A/cm^{-2} for the DWELL sample under the same condition. However, the increase of the quantum efficiency overcomes the increased dark current. As a result, the overall performance of CE-DWELL QDIPs is far more superior to that of the conventional ones. At 77 K, the highest detectivity measured for the CE-DWELL detector is 1×10^{10} cm Hz$^{0.5}$/W (at −0.9 V), which is ten times higher than that in the DWELL detector (1×10^{9} cm Hz$^{0.5}$/W at −1.2 V).

In summary, we designed a modified DWELL structure for QDIPs. A thin AlGaAs layer was inserted on top of InAs QDs as a confinement enhancing layer. This enhanced confinement effect greatly enhanced both the absorption quantum efficiency and the escape probability. At the same time, the transport property of carriers was almost not affected. At 77 K, the maximal quantum efficiency was increased by about 25 times and the peak detectivity was increased by about ten times with a lower bias voltage. Our results demonstrate that the confinement enhanced structure is a very promising approach toward the realization of high performance QDIPs.

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