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Effects of well thickness on the spectral properties of $In_{0.5}Ga_{0.5}As/GaAs/Al_{0.2}Ga_{0.8}As$ quantum dots-in-a-well infrared photodetectors

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We report on the effects of the quantum well (QW) thickness on the spectral response and other characteristics of $In_{0.5}Ga_{0.5}As/GaAs/Al_{0.2}Ga_{0.8}As$ quantum dots-in-a-well infrared photodetectors grown by low-pressure metal-organic chemical vapor deposition. The main device properties are observed to have a strong dependence on the QW parameters. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2927487]

Quantum dot infrared photodetectors (QDIPs) have theoretical advantages over quantum well infrared photodetectors (QWIPs), which make them a potential candidate for high performance photodetectors operating at elevated temperatures.[1,2] However, the growth of self-assembled quantum dots (QDs) is a complicated process and there is a lack of control over the QD band structure and the spectral response of QDIPs. This has motivated experimental studies of the quantum dots-in-a-well (DWELL) structure which offer the advantages of QDIPs while maintaining a degree of spectral tunability inherent of QWIPs.[3]

The DWELL scheme involves embedding the QDs in a quantum well (QW) which in turn is sandwiched between higher bandgap barrier layers. The dot-to-well transition energy is controlled by adjusting the QW thickness. Therefore, spectral tuning can be achieved without altering the QD growth parameters. Spectral tailoring of DWELL detectors has been demonstrated.[4,5] However, the majority of reports on DWELL detectors have been about InGaAs QDs in an InGaAs/GaAs QW with little work covering the InGaAs/GaAs/AlGaAs system.

InGaAs/GaAs/AlGaAs DWELL structures (hereafter referred to as AlGaAs DWELL structures) have advantages that make them worthy of investigation. In particular, the GaAs/AlGaAs QWs are lattice matched, therefore, the GaAs QW layers can be grown arbitrarily thick without the adverse effects of strain. Unstrained GaAs/AlGaAs QWs can have a significantly larger conduction-band offset (CBO) than InGaAs QWs pseudomorphically strained to GaAs for usable indium compositions. Therefore, thicker and deeper QWs can be grown, potentially allowing for a much greater tuning range of the dot-to-well transition energy. In addition, the smaller average value of strain of the AlGaAs DWELL structure can allow a greater number of QD layers to be stacked. This can translate to an enhanced absorption of the incident light due to the larger active region volume and better performance characteristics.

For this work, a series of AlGaAs DWELL structures were grown, fabricated, and characterized to study the dependence of the device spectral response and other performance characteristics on the QW thickness. All device structures, as depicted in Fig. 1, were grown in a low-pressure, horizontal flow metal-organic chemical vapor deposition system (MOCVD) on (001) oriented semi-insulating GaAs substrates. Though there are reports in the literature of QDIPs with 30 DWELL layers in the active region, we have chosen ten DWELL layers for convenience as the aim of this work is to study the effects of the well thickness on the device characteristics. The active region is placed between 1 μm bottom and 300 nm top GaAs contact layers doped with Si atoms to a concentration of about 10^{18} cm^{-3}. Each DWELL layer consists of a 45 nm thick $Al_{0.2}Ga_{0.8}As$ barrier material, a bottom GaAs well layer, $In_{0.5}Ga_{0.5}As$ QDs with a nominal deposition of 5.7 monolayers, and a 7 nm top GaAs QW layer. Three structures were grown, which are identical except for the thickness of the bottom QW layer, which is 1.5, 3, and 5 nm for devices A, B, and C, respectively. The QDs and QWs are grown at 550 °C, whereas the rest of the structure is grown at 650 °C to ensure that a high quality AlGaAs barrier material is deposited. Photoluminescence (PL) measurements were performed by using the 635 nm line of a diode laser. The PL is detected by an InGaAs photodetector after being dispersed through a 0.5 m monochromator. A strong room temperature PL signal was detected from the structures, indicating that high quality defect-free QDs have been grown. The PL spectrum of all structures has a peak varying less than 6 meV, revealing that the QW variations have not impacted upon the QD growth conditions, or the QD ground state energy. Wafers were processed into 250 μm square mesa structures by using contact UV lithography and wet chemical etching. 150 μm diameter circular top and bottom

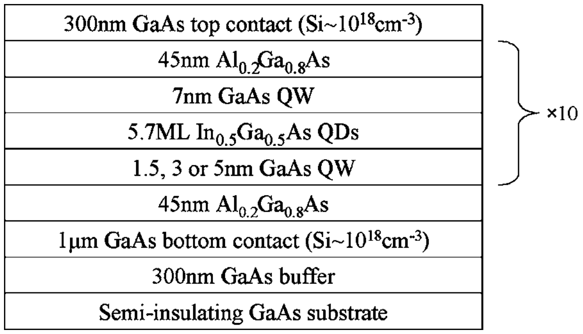

FIG. 1. Diagram of the DWELL structures grown by MOCVD.

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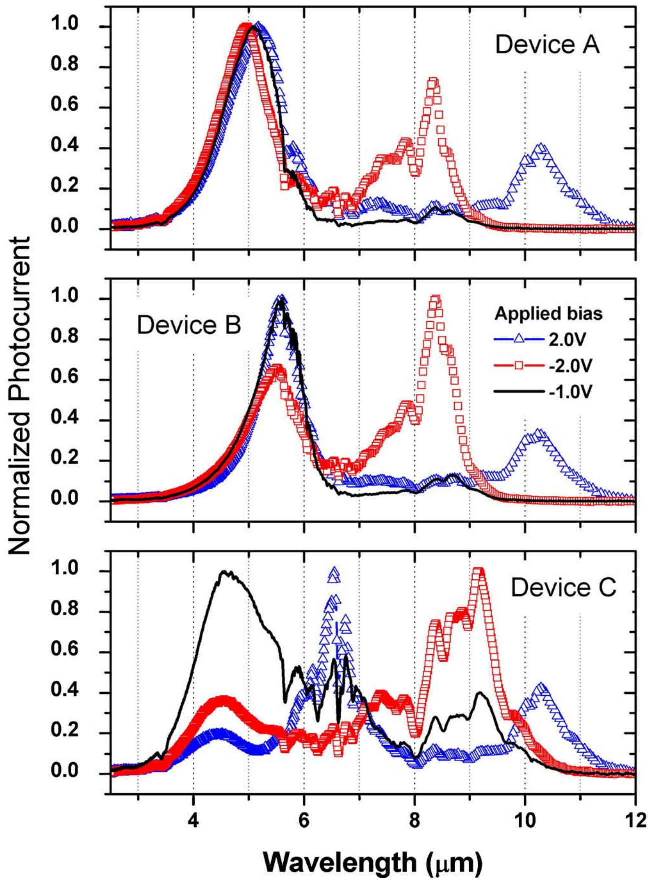

FIG. 2. (Color online) 77 K normal incidence spectral response of all devices for various applied biases.

Ohmic metal contacts were formed by the thermal evaporation of Ge/Au with a subsequent 380 °C alloying for 60 s. Devices were wire bonded into DIP packages and mounted into a liquid nitrogen cooled Dewar ready for characterization.

Figure 2 displays the normal incidence 77 K spectral response of all devices for various applied biases, which is obtained with a Nicolet Impact 400 Fourier transform infrared spectrometer and a SRS 570 low-noise current preamplifier.

As discussed in our previous work,[6] for the growth parameters that optimize the optical quality of $In_{0.5}Ga_{0.5}As$ QDs grown on GaAs,[7] the electrons are not strongly confined to the QDs. In the growth direction, there is only one quantized state and all QD excited states are due to quantization changes in the x-y directions. Strong absorption of x-y polarized light typically occurs at about 20 μm and does not contribute to the photocurrent.

Spectral peaks are only expected to be dependent on the QW thickness if they are due to transitions between QD and QW states. Devices A, B, and C display such peaks. The 6.8 μm (0.183 eV) peak of device C is attributed to a transition between the QD ground state and the first excited state of the combined QD/QW. This dot-to-well peak blueshifts to 5.6 μm (0.222 eV) and 5.14 μm (0.242 eV) for devices B and A, respectively, due to the increased confinement energy of the thinner QWs.

The peak of device C at 4.5 μm (0.276 eV) is attributed to transitions between the QD ground state and the conduction band edge of the AlGaAs barrier layers. Dot-to-continuum peaks are not observed in the other devices due to their much smaller absorption coefficients compared to the dot-to-well absorption coefficients. It is assumed that at low bias voltages, the energy of the dot-to-continuum peak (0.276 eV) is the energy difference between the QD ground state and the barrier band edge. Therefore, the confinement energy of the QD ground state relative to the GaAs band edge is 0.276 eV, subtract the GaAs/AlGaAs CBO (0.167 eV), which is 0.109 eV. A simplified conduction-band diagram depicting the energies of the DWELL structures is shown in Fig. 3. The QW variations are not expected to affect the QD ground state energy since the wave function is mostly confined to the QD region. This is confirmed by the 77 K PL measurements with all structures having a PL peak within 6 meV at 1.21 eV. Therefore, the QD ground state energy of all structures relative to the GaAs conduction band edge is about 0.109 eV.

The large difference in the dot-to-well transition energy of 59 meV from devices A to C, which is 35% of the GaAs/AlGaAs CBO, is only possible because the ground state energy of the QDs is only about 0.109 eV from the GaAs conduction band edge. This results in a first excited state wave function that delocalizes from the QD. Therefore, the energy of the first excited state of the combined QD/QW is sensitive to the QW width and is significantly larger than the QW ground state energy for all structures. The ground state energy of a 8.5, 10, and a 12 nm $GaAs/Al_{0.2}Ga_{0.8}As$ QW is calculated to be 35, 28, and 23 meV, representing devices A, B, and C, respectively. These energies are 98, 85, and 51 meV less than the energy of the dot-to-well peaks of devices A, B, and C, respectively.

The longer wavelength peaks seen in all devices at about 8.5 and 10 μm for negative and positive applied bias, respectively, originate from transitions between the QD ground state and the QW ground state. The voltage dependence of these spectral peaks is attributed to the quantum confined stark effect (QCSE). This view is supported by the bias dependence of the peaks, with the 10 μm peaks shifting to longer wavelengths with an increasing positive bias and the 8.5 μm peak shifting to shorter wavelengths with an increasing negative bias. The QCSE of QWIP structures has been thoroughly investigated.[8,9] In general, for symmetric QW structures, the stark shift is small. However, large shifts have been observed for asymmetric structures such as stepped

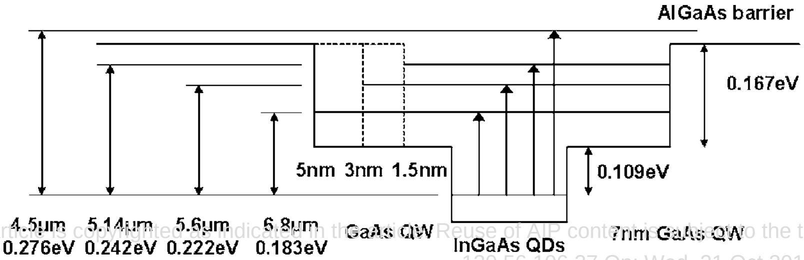

FIG. 3. Simplified conduction-band diagram of the AlGaAs DWELL structure, displaying the different energy levels of devices *A*, *B*, and *C*.

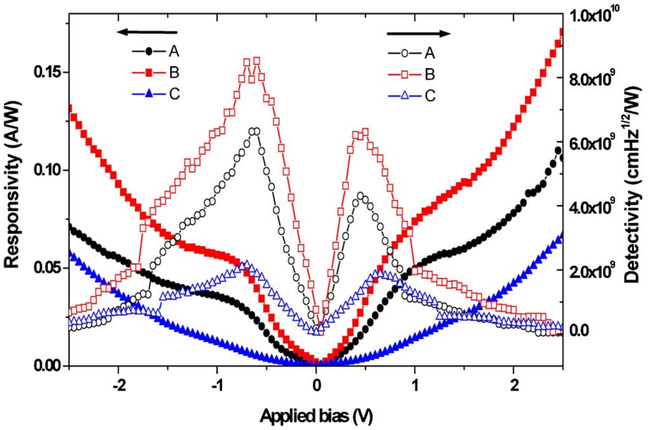

FIG. 4. (Color online) 77 K normal incidence peak responsivity and detectivity of all devices as a function of applied bias.

wells. More recently, there have been experimental and theoretical reports of a large stark shift in DWELL QDIP devices.[10] Since the wavelengths redshift for positive biases and only have a small dependence on the thickness of the bottom QW layer, it is likely that the excited state wave functions causing these long wavelength peaks are more confined to the top QW region.

In addition to the spectral response, the device responsivity and detectivity is also strongly dependent on the QW thickness. Normal incidence peak responsivity and detectivity measurements were performed by using the method described in Ref. 11 and by taking the spectral peak as the dot-to-well transition for all devices. The equipment used included a calibrated 800 °C blackbody radiation source chopped at 140 Hz, a SRS SR570 low noise current preamplifier, and a SRS SR760 fast Fourier transform spectrum analyzer. As shown in Fig. 4, devices A and B have a significantly larger responsivity than device C for the dot-to-well peaks. At the biases that give the maximum detectivity, the responsivity of devices A, B, and C are 23, 40, and 6.8 mA/W, respectively. This indicates that the dot-to-well absorption coefficients of devices A and B are significantly larger than the dot-to-well and dot-to-continuum absorption coefficients of device C. The well thickness can also influence the responsivity by its effect on the escape probability of an electron excited to a well state. From the spectral response and responsivity data, this effect appears to be less significant. Device *B* has a larger responsivity than device A, even though the QD/QW excited state of the former is bound more strongly. Also, the dot-to-continuum peak of device C is seen to increase rapidly with an increasing positive bias, whereas it diminishes for negative biases, suggesting that the voltage dependence on the wave function has a larger influence on the photocurrent for this particular peak. The responsivity dependence on the QW width is most likely due to the influence of the QW on the excited state wave functions and, in turn, the transition operator acting on the ground state and excited states. Also, the spectral response of devices A and B do not contain any clear peaks in the continuum, indicating that the absorption coefficients of any dot-to-continuum transitions for these devices must be much smaller than those of the dot-to-well transitions.

Due to the increased responsivity of device B, it has the largest peak detectivity of 8.5×10^9 cm Hz$^{1/2}$/W as compared to 6.3×10^9 and 2.1×10^9 cm Hz$^{1/2}$/W for devices A and C, respectively.

In summary, a series of $\mathrm{In_{0.5}Ga_{0.5}As/GaAs/Al_{0.2}Ga_{0.8}As}$ DWELL Infrared detectors with varying QW thickness have been grown, fabricated, and characterized. Strong dot-to-well transitions have been observed with a spectral response that has a significant dependence on the QW thickness. We have demonstrated that the AlGaAs DWELL structure enables the spectral response to be tailored over a wide energy range while maintaining optimized QD growth conditions. In addition, by varying the QW width, we have shown that an enhanced responsivity and detectivity could be obtained for an optimized well width of 10 nm. An improvement of the detectivity is expected by optimizing the doping profile of further structures and increasing the number of QD layers.

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