Low-strain InAs/InGaAs/GaAs quantum dots-in-a-well infrared photodetector

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The authors report the design, growth, fabrication, and characterization of a low-strain quantum dots-in-a-well (DWELL) infrared photodetector. This novel DWELL design minimizes the inclusion of the lattice-mismatched indium-containing compounds while maximizing the absorption cross section by enabling larger active region volume. The improved structure uses an $In_{0.15}Ga_{0.85}As/GaAs$ double well structure with $Al_{0.10}Ga_{0.90}As$ as the barrier. Each layer in the active region was optimized for device performance. Detector structures grown using molecular beam epitaxy were processed and characterized. This new design offers high responsivity of 3.9 A/W at a bias of 2.2 V and a detectivity of 3×10^9 Jones at a bias of 2.2 V for a wavelength of 8.9 μm. These detectors offer significant improvement in the responsivity while retaining the long wave infrared spectral properties of the $InAs/In_{0.15}Ga_{0.85}As/GaAs$ DWELL. These detectors if coupled with improved noise characteristics could enable higher temperature operation of DWELL detectors, thus reducing the dependence on cooling equipment. © *2008 American Vacuum Society.* [DOI: 10.1116/1.2835063]

I. INTRODUCTION

Quantum dot infrared detectors (QDIPs) are considered as one of the promising technologies for next generation of detectors in the 3–25 μm region.[1–3] This is due to their lower dark current leading to a higher temperature operation, inherent normal incidence operation, high photoconductive gain due to three-dimensional confinement, and mature growth technology of III-V semiconductors.[3–6] QDIPs have been reported to operate at higher temperatures and room temperature operation has been reported.[7,8] Moreover, the quantum confined Stark effect associated with asymmetrically designed dots-in-a-well (DWELL) detectors results in a bias dependent spectral response, making it suitable for multispectral detection.[9] Variation of the well width results in better control over the intersubband transitions, thereby providing better control over the emission wavelength. Focal plane arrays (FPAs) of sizes up to 640×512 have been demonstrated using the DWELL design highlighting the potential of this technology.[10–14] Additionally two-color response obtained in the single pixel detector has been successfully demonstrated in the FPA.[15–17]

The DWELL detectors used in the above devices use an $InAs/In_{0.15}Ga_{0.85}As/GaAs$ structure where the InAs QDs are embedded in an $In_{0.15}Ga_{0.85}As$ well with GaAs barriers. The transitions in the detection process are the ones from the dot to the well and the dot to the continuum giving rise to a two-color response.[3] The growth of QDs is a self-assembled process owing to the strain in the system due to lattice mismatch. This limits the number of stacks of active region that can be grown in the system before defects set in. Hence, the quantum efficiency (QE) of systems using DWELL structures is low.[18] Several ways have been suggested to improve the QE of DWELL detectors. They include distributed Bragg reflector mirrors to form a resonant cavity, use of a photonic crystal cavity, and an avalanche photodiode in conjunction with the DWELL detector to introduce gain in the system.[19–21] The approach detailed in this paper focuses on maximizing the volume of the active region. This is accomplished by reducing the strain generated during the growth of a single DWELL stack. The strain reduction was achieved by reducing the overall indium content in the system, leading to a lower strain per layer. Here, we report an $InAs/In_{0.15}Ga_{0.85}As/GaAs/Al_{0.10}Ga_{0.90}As$ DWELL detector where the InAs quantum dots are embedded in $In_{0.15}Ga_{0.85}As$ and GaAs wells with the use of $Al_{0.10}Ga_{0.90}As$ barriers. In this structure, the GaAs layer acts as the primary well for the system as opposed to the $In_{0.15}Ga_{0.85}As$ layer in the earlier DWELL detectors.[16] The development of this structure required several cycles of optimization where the dot, well sizes above and below the dot, and the barrier thickness were optimized. This was achieved through a series of characterizations where the parameters above were varied and photoluminescence (PL), atomic force microscopy, and x-ray diffraction studies were used as the benchmarks.

II. OPTIMIZATION OF STRUCTURE

The samples were grown using a VG Semicon V80H molecular beam epitaxy reactor. The attempts to optimize the growth rate and the amount of material in the quantum dots are listed elsewhere.[22] Initial attempts were made to use a GaAs well along with an InAs QD to form the DWELL structure with $Al_{0.10}Ga_{0.90}As$ as the barrier; however, this was not found to be effective as the structure showed poor

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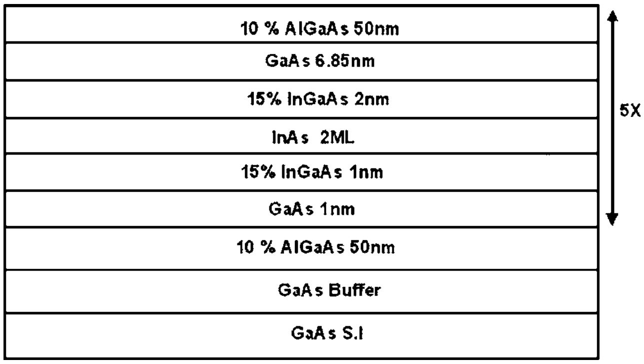

FIG. 1. Baseline structure used for optimizing the DWELL detector. The GaAs layer under the dot and the $In_{0.15}Ga_{0.85}As$ capping layer above the dot were optimized using this structure.

PL intensity. The QD density of the structure was also very low at 10^9 cm^{-2}. Hence, a minimal $In_{0.15}Ga_{0.85}As$ layer was reintroduced between the GaAs well and the dots. The InAs dots were then formed over the $In_{0.15}Ga_{0.85}As$ layer instead of GaAs well. The QD density was increased by two orders of magnitude ($\approx 10^{11}$ cm^{-2}) as a result of this change. Further improvement was achieved through optimizing the amount of material in the QD and doping in the dots.[22]

The GaAs well width under the dot is critical as the dots are essentially formed over the GaAs/$In_{0.15}Ga_{0.85}As$ wells. Since the objective is to minimize the strain, the amount of $In_{0.15}Ga_{0.85}As$ has to be kept at a minimum and the depth of the well below the dot is essentially determined by the GaAs layer. The GaAs shoulder width under the QDs was varied from 10 to 40 Å and the PL from these devices was measured. The structure used to optimize the GaAs well width under the dot is shown in Fig. 1. As seen from the measured PL in Fig. 2, the PL intensity improves as the GaAs thickness is increased.

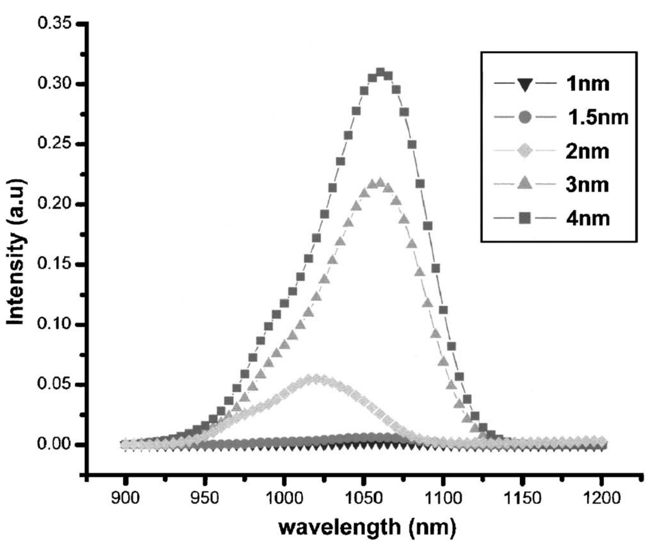

FIG. 2. Photoluminescence intensity from structures with varying GaAs layer thickness under the dot.

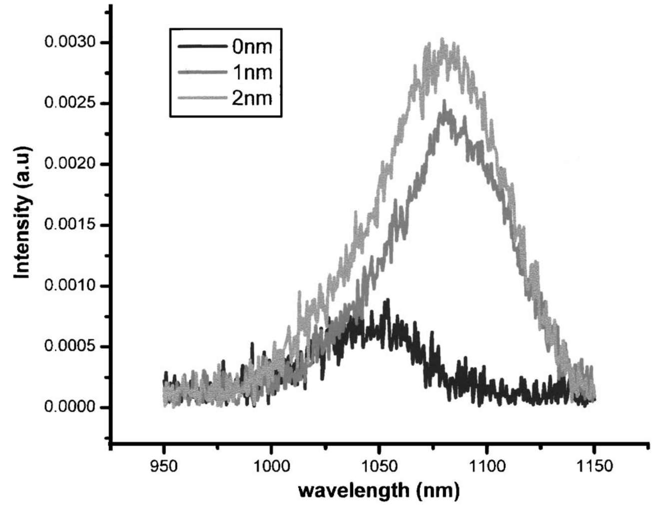

FIG. 3. Photoluminescence intensity from structures as a function of quantum dot capping layer thickness. $In_{0.15}Ga_{0.85}As$ has been used for capping the dots in this study.

The effect of capping the dots with a lower interfacial-strain $In_{0.15}Ga_{0.85}As$ layer was investigated for optimizing the QD optical response. The thickness of $In_{0.15}Ga_{0.85}As$ layer above the dots in Fig. 1 was varied from 0 to 20 Å, and the change in PL observed is shown in Fig. 3. It was observed that the capping of the dots with InGaAs helps us to improve the response from the DWELL structure. While a minor improvement was observed for increasing the capping thickness from 1 to 2 nm, it was determined that the increased number of QD layers that could be grown with the lower strain 1 nm cap would compensate for the slightly decreased functionality. The redshift seen in the PL intensity plots of Figs. 2 and 3 may be due to the wider thicknesses which lead to a smaller quantum confinement. The effect of the thickness of the GaAs layer above the dot has already been investigated and the optimized thickness is used for the detector structures.[16]

III. PROCESSING AND CHARACTERIZATION

Detector structures were then grown with the optimized DWELL design consisting of *n*-doped InAs dots in an $In_{0.15}Ga_{0.85}As$/GaAs well and $Al_{0.10}Ga_{0.90}As$ as the barrier. These layers were then sandwiched between two highly doped *n*-GaAs layers that serve as the contact layers, as shown in Fig. 4. With the reduction in the strain, the number of active region stacks was increased to 30, as opposed to 12 or 15 in InAs/$In_{0.15}Ga_{0.85}As$/GaAs DWELL detectors.[22] Attempts to grow higher order stacks resulted in defects setting in and did not provide good optical response. These were then processed in a class-100 clean room using photolithography, plasma etch, and contact metallization to form individual mesa structures of 410×410 μm^2 with top apertures ranging from 25 to 300 μm in diameter. The contacts were then annealed at a temperature of 380 °C using a rapid thermal annealer to achieve Ohmic contacts.

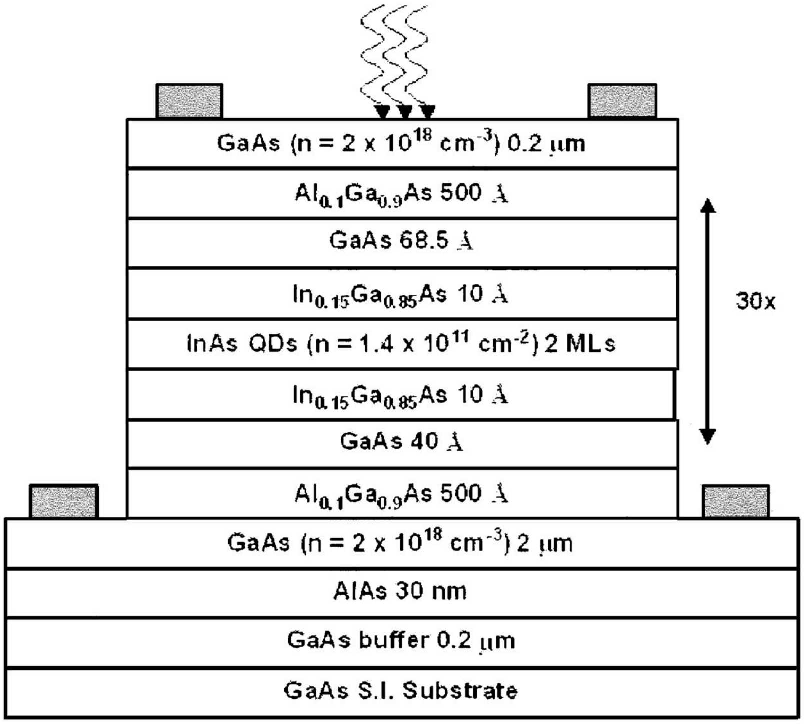

FIG. 4. Schematic of a detector structure grown with $InAs/In_{0.15}Ga_{0.85}As/GaAs/Al_{0.10}Ga_{0.90}As$ structure.

Bias dependent spectral response was measured for a pixel using a Nicolet 870 Fourier transform infrared spectrometer. The spectral response from two of the devices at a bias of 3.2 V is shown in Fig. 5. Sample A has a GaAs well width of 4 nm under the dot and $In_{0.15}Ga_{0.85}As$ cap of 1 nm above the well, whereas sample B has a GaAs well width of 3 nm under the dot and no $In_{0.15}Ga_{0.85}As$ cap above the well. The response from these devices shows a peak at around 10 μm which is in the long wave infrared range, and the spectral characteristics are comparable to that of the standard DWELL (Ref. 22) detector.

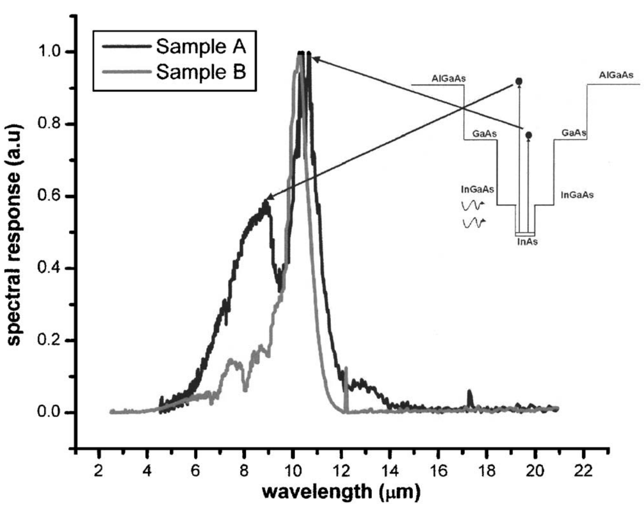

FIG. 5. Normalized spectral response observed from detectors with an $InAs/In_{0.15}Ga_{0.85}As/GaAs/Al_{0.10}Ga_{0.90}As$ structure at a bias voltage of 3.2 V. The energy band diagram of the system is also shown.

For characterizing the responsivity, the samples were cooled down to liquid nitrogen temperature (77 K) and were irradiated using a calibrated blackbody at 700 K. The photocurrent was amplified using a SRS 570 low noise amplifier and then measured using a SRS760 fast Fourier transform spectrum analyzer. The peak responsivity was then computed using the expression

$$R_i = \frac{I_0}{\int_{\lambda_1}^{\lambda_2} \frac{R(\lambda)}{R(\lambda_c)} L_e(\lambda,T) A_s A_d \frac{tF_F}{r^2} d\lambda}, \qquad (1)$$

where I_0, L_c, A_s, and A_d are the photocurrent, the blackbody spectral excitance, area of the source, and area of the detector, and r, t, and F_F are the distance between the source and the detector, the transmission of the window, and geometrical form factor, respectively. The detectivity D^* was then computed as

$$D^* = \frac{\sqrt{A_d \Delta f}}{i_n} R_p, \qquad (2)$$

where A_d is the detector area, Δf is the noise equivalent bandwidth, i_n is the noise current, and R_p is the responsivity of the detector. The plots of variation of responsivity and detectivity with the applied bias for samples A and B are shown in Figs. 6 and 7. It can be seen that the responsivity of sample A is much higher than that of sample B for most of the voltage range which may be attributed to the $In_{0.15}Ga_{0.85}As$ cap present in sample A. The $In_{0.15}Ga_{0.85}As$ cap helps us to improve the responsivity of the system without affecting the spectral characteristics of emission. The new design shows significant improvements in quantum ef-

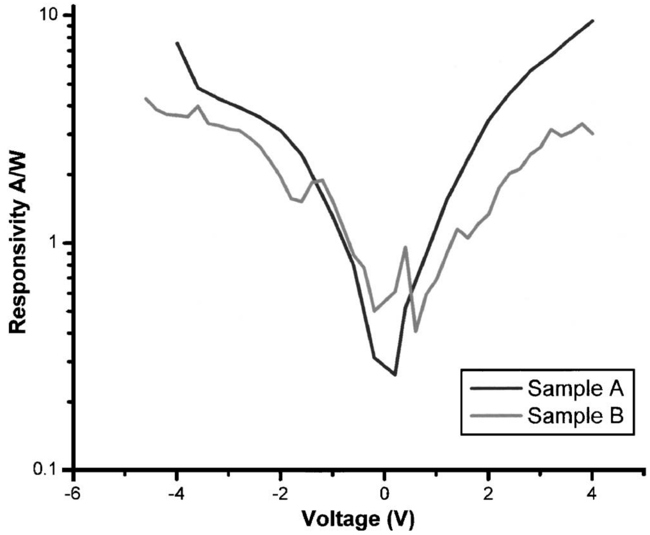

FIG. 6. Responsivity of the devices as a function of the applied bias at 77 K.

ficiency over the $InAs/In_{0.15}Ga_{0.85}As/GaAs$ DWELL structures, the details of which are discussed elsewhere.[23] For calculating the QE, the photoconductive gain of the system is computed and the QE is found out as $\eta = hcR_i/gq\lambda_p$, where λ_p is the peak emission wavelength and g is the photoconductive gain. QEs of 13.5% and 15.6% have been measured for 8.35 and 6.5 μm, respectively.[23] A high QE of 6% has already been measured in InGaAs/GaAs DWELL detectors, and a QE of 35% has been measured in InP based QDIPs.[7,10]

IV. CONCLUSION

In conclusion, we report a novel low-strain DWELL design with an $InAs/In_{0.15}Ga_{0.85}As/GaAs/Al_{0.10}Ga_{0.90}As$ active region. The low-strain active region enabled a two times increase in the overall volume of photon absorbing material, when compared to the standard $InAs/In_{0.15}Ga_{0.85}As/GaAs$ DWELL detector. Optimizations were performed on each layer in the active region to improve response from the detector. It was observed that an $In_{0.15}Ga_{0.85}As$ capping layer above the quantum dots helps us to improve the responsivity of the system, without altering the spectral characteristics. Through the reduction of strain, a higher number of stacks of active region were grown in the detector structure. An improvement in the responsivity of the system has been observed. A peak responsivity of 3.9 A/W at 2.2 V bias and a peak detectivity of 3×10^9 Jones at a bias of 2.2 V for a wavelength of 8.9 μm were observed. Similar values have been observed in DWELL structures only by the use of resonant cavities.[19] We believe that by improving the noise characteristics of this structure, it would be possible to operate this device at much higher temperatures than in the conventional DWELLs. Further work would involve examining the changes in noise characteristics of the system due to the change in the device structure.

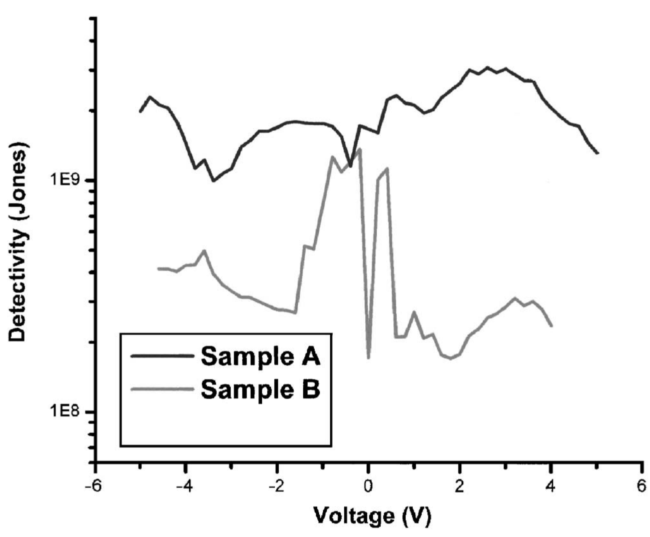

FIG. 7. Detectivity of the devices as a function of the applied bias at 77 K.

ACKNOWLEDGMENT

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