

On the Performance of Quantum Dot Infrared Photodetectors Based on a Dots-in-a-Well Structure

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Abstract

We report on InAs/In_xGa_{1-x}As/GaAs quantum-dots-in-a-well infrared photodetectors (DWELL QDIPs) exhibiting two-colour behaviour, associated with bound-to-bound and bound-to-continuum intraband electron transitions. We have found these devices to exhibit a good performance with responsivities of >1A/W in the 7-11 μ m atmospheric window and detectivities of >10⁹cmHz^{1/2}W⁻¹ at 77K. Furthermore by increasing the number of the quantum dot layers in active region whilst improving the control over the growth of the InAs dots, we have achieved a responsivity of ~10A/W and detectivity of ~10¹⁰ cmHz^{1/2}W⁻¹ at 77K for $\lambda \approx 7.5\mu\text{m}$. In addition, as the first step towards creation of the focal plane arrays, we have introduced Al_{0.1}Ga_{0.9}As barriers in DWELL QDIP structure, which efficiently block the dark current, however providing comparable high detectivities at the same time.

Recently, intraband quantum dot infrared photodetectors (QDIPs) have attracted considerable attention due to the potentially beneficial characteristics which arise from the three-dimensional confinement provided by the quantum dots (QDs). These include the intrinsic capability of normal incidence detection [1,2], and longer excited state carrier lifetimes due to greatly suppressed electron-phonon scattering[3-6]. The latter property in turn has been suggested as the reason for the high photoresponse observed for QD based devices [4]. It has also been predicted that QDIPs should have reduced dark currents relative to quantum well infrared photodetectors (QWIPs) which is also a result of the three-dimensional confinement provided by the QDs [7,8]. Recent reports demonstrate that QDIP performance is beginning to approach that of the more mature QWIP technology [8-11], and

detectivities of ~10⁹-10¹¹cmHz^{1/2}W⁻¹ at 77K have been reported for various designs of QDIPs operating in the 7-11 μ m window [2,9,12,13]. Additionally, it has been shown that the spectral response of a QDIP can vary from single to potentially three colour behaviour, which may also be voltage dependent [14-18].

In the present work we report on the performance of two-colour QDIPs incorporating InAs/In_xGa_{1-x}As dots-in-a-well (DWELL), associated with bound-to-bound and bound-to-continuum electron transitions at energies ~130meV ($\lambda \sim 9\mu\text{m}$) and ~230meV ($\lambda \sim 5\mu\text{m}$) respectively. The DWELL structure has the advantage of a well defined transition from the bound state in the dot to a state within the quantum well (QW). The DWELL design is also beneficial as it is possible to tailor the transition energy by changing the DWELL design. We have previously reported on the

tailoring of spectral characteristics of DWELL QDIPs by using different number of monolayers of InAs ($N_{ML}=2.2, 2.55$ and 2.9) deposited during the growth [19]. In present study we were able to increase significantly the responsivity and corresponding detectivity of DWELL QDIPs by doubling the number of QD layers in the active region of the detector. Moreover, by growing the InAs QDs in AlGaAs matrix we have reduced the dark current by few order of magnitude, but keeping the detectivity values $\sim 10^{10}$ $\text{cmHz}^{1/2}\text{W}^{-1}$. This is very promising approach for designing of focal plane arrays, where the heat dissipation is an issue.

Three DWELL structures were grown by molecular beam epitaxy (MBE) upon semi-insulating GaAs substrates. GaAs barrier layers were grown at 580°C at a rate of 0.7ML/s , whereas the $\text{In}_{0.15}\text{Ga}_{0.85}\text{As}$ well and the InAs quantum dots were grown at 510°C at a rate of 0.1ML/s . The growth method is the same as previously used for optimised growth of similar DWELL QD devices, resulting in high quality structures with very low defect densities [20, 21]. The first structure (sample A) incorporates a bottom contact layer of 4000\AA $n+$ Si doped GaAs, an undoped layer containing 5 periods of DWELL ($N_{ML}=2.55$, 80\AA $\text{In}_{0.15}\text{Ga}_{0.85}\text{As}$) absorbing region, separated by 500\AA of undoped GaAs and a final 4000\AA $n+$ Si doped GaAs contact layer. The second structure (sample B) incorporated 10 periods of the same DWELL design as sample A but the active region was Si δ -doped in the GaAs barrier layers, to a concentration of $6 \times 10^{10}\text{cm}^{-2}$ corresponding to approximately 1 electron per dot. The third structure (sample C) consisted of a 5 period DWELL absorbing region (doped to 1 electron per dot) with 2.55ML of InAs dots placed within an 80\AA $\text{In}_{0.05}\text{Ga}_{0.95}\text{As}$ quantum well separated by $\text{Al}_{0.1}\text{Ga}_{0.9}\text{As}$ barrier layers. The indium composition in this structure was reduced to obtain the same band-offset as the devices

separated by GaAs barrier layers.

Devices were fabricated into mesas using standard wet chemical etching. Spectral measurements were carried out using a vacuum Bruker IFS-66v/s Fourier-transform infrared spectrometer with a broad-band mid-infrared light source, and dark current was measured by using a standard Keithley source-measure unit.

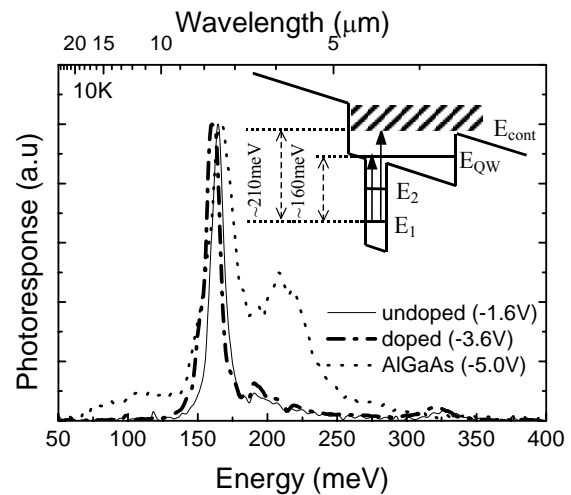


Fig.1: Spectral response of DWELL QDIPs A: 5 undoped active regions, B: 10 doped active regions and C: 5 active regions and AlGaAs barriers. Inset: Schematic of DWELL conduction band with optical transitions shown by arrows.

Fig.1 shows the 10K photoresponse spectra of three DWELL QDIP samples for the value of maximum applied biases. In all samples only the QD ground state is occupied, thus the initial state of the intraband transitions is the QD electron ground state. A schematic conduction band diagram with the described transitions is shown in the inset of Fig.1. A larger photocurrent signal ($\sim 5x$) was measured for p-polarised incident radiation, coupled into the sample via the substrate polished to 45° , relative to s-polarised radiation. This is expected as the $E_1 \rightarrow E_{QW}$ transition arises due to confinement in the growth direction. For each sample we observe two photocurrent peaks centred at ~ 160 meV ($\lambda \sim 7.5\mu\text{m}$) and ~ 210 meV ($\lambda \sim 6\mu\text{m}$), which we attribute to electron transitions from the

InAs QD ground state E_1 to the $\text{In}_{0.15}\text{Ga}_{0.85}\text{As}$ QW state E_{QW} and GaAs continuum states E_{cont} , respectively, the latter being very clear for the sample C but in the form of a high energy shoulder for the other two. The magnitude of the $E_1 \rightarrow E_{\text{QW}}$ and $E_1 \rightarrow E_{\text{cont}}$ peaks increases with applied bias. However, the intensity of the bound-to-bound ($E_1 \rightarrow E_{\text{QW}}$) photoresponse increases more rapidly and becomes dominant with bias.

Fig. 2 shows the typical dark current characteristics for 400 μm mesa etched devices for each of the three structures. We have observed an excellent homogeneity of the dark current response over a number of devices for each DWELL design. Smaller devices in diameter (200 μm) have exhibited identical current densities, which signify that the dark current mechanism is from the bulk of the structure rather than leakage resulting from the etching process. The dark current results primarily from the thermal excitation of trapped carriers in the QD [7, 8].

We observe a good dark current behaviour of the undoped sample A of $1\mu\text{A}@-1\text{V}$ and 77K. For the 10 layer doped DWELL, the dark current is further reduced, as the electric field is applied over an area approximately double the size. Also, in the case of the 5 layer sample there is an increased probability of direct leakage paths from one contact to the other, without the carriers going through the dot structure. A dramatic decrease is observed for sample C, which incorporates 5 periods of DWELL absorbing regions separated by $\text{Al}_{0.1}\text{Ga}_{0.9}\text{As}$ barrier layers. This is because of the higher offset of the AlGaAs barrier relative to the QD ground state, providing improved confinement, whilst sustaining the QW state in approximately the same position, due to reduced In composition ($x=5\%$) in the well.

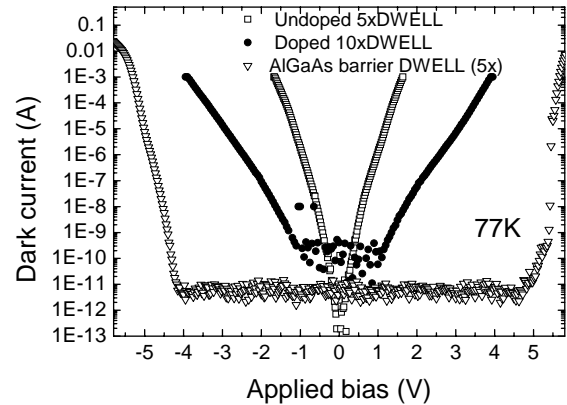


Fig.2: Dark current characteristics for samples A: 5 undoped active regions, B: 10 doped active regions and C: 5 active regions and AlGaAs barriers

Peak responsivity (R_p) measurements were made using a calibrated black body source with a temperature of 1005K and a modulation frequency of 160Hz, with the detector mounted inside a cryostat with KRS5 windows. Fig.3 show the peak responsivities for the samples A (undoped) and B (doped; ten layers), along with their corresponding detectivities, which have been calculated by taking into account the dark current densities and the peak responsivities [11, 22, 23]. A peak responsivity of $\sim 1\text{A/W}@-1\text{V}$ and 77K is observed for the undoped sample A at $\lambda \approx 7.5\mu\text{m}$, with detectivity in the order of $10^9\text{cmHz}^{1/2}\text{W}^{-1}$. An improved performance is observed for sample B with R_p in the order of several A/W, reaching a maximum of 10A/W at -4V at 77K and $\lambda \approx 7.6\mu\text{m}$. We believe that this increase in R_p is more due to larger absorbing region provided by the 10 layer structure rather than the doping concentration. As the dark current of this device is reduced as well, the resulting detectivity is in the order of $10^{10}\text{cmHz}^{1/2}\text{W}^{-1}$.

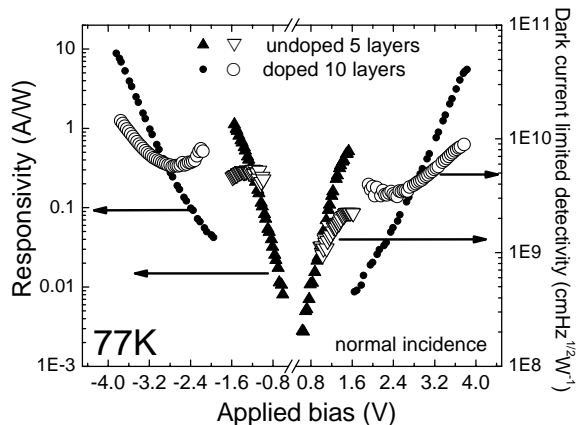


Fig.3: Peak responsivities (filled symbols) and corresponding detectivities (open symbols) for samples A (undoped 5x) and B (doped 10x).

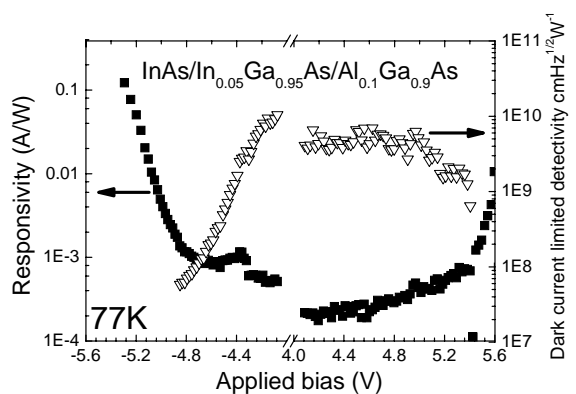


Fig.4: Peak responsivity and the corresponding detectivity for sample C with $Al_{0.1}Ga_{0.9}As$ barrier layers at 77K and $7.4\mu m$

The performance of sample C can be seen in Fig. 4. When the AlGaAs barriers are incorporated, the QW state becomes more confined as a result of the higher energy barrier of the AlGaAs and hence the tunnelling probability of the carriers from the InGaAs well states is reduced along with the thermal excitation probability. This results in a smaller photocurrent and hence lower value of peak responsivity, in the order of 10mA/W for the same temperature and wavelength range as the previous two samples. However the reduction of the thermally excited dark current is more dominant than the decrease of the peak responsivity, resulting in detectivity in the range of $10^{10} cmHz^{1/2}W^{-1}$, which is similar to that of a ten layer structure.

In conclusion, we reported on the good performance of two colour dot-in-a-well DWELL quantum dot infrared

photodetectors, with designs that varied in number of periods doping concentration and choice of barrier layer. We have found these detectors to exhibit detectivities in the order of $10^9-10^{10} cmHz^{1/2}W^{-1}$ at temperatures of 77K in the wavelength range of 7-8 μm .

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