

## Quantum dot infrared photodetectors

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### Abstract

*High detectivity ( $\sim 10^{12} \text{cm}\cdot\text{Hz}^{1/2}\cdot\text{W}^{-1}$  at 10K) InAs/In<sub>0.15</sub>Ga<sub>0.85</sub>As quantum-dots-in-a-well infrared photodetectors with various numbers of monolayers deposited during the Stranski-Krastanow growth procedure are reported. All samples investigated exhibit two-colour behaviour at energies  $\sim 130\text{meV}$  ( $\sim 9\mu\text{m}$ ) and  $\sim 230\text{meV}$  ( $\sim 5\mu\text{m}$ ) associated with bound-to-bound and bound-to-continuum electron transitions, correspondingly. Increasing the number of InAs monolayers from 2.2 to 2.9 results in a blue shift of the long wavelength peak by  $\sim 20\%$ . In addition, significant tunability of the photoresponse spectra with applied bias has been observed and investigated in detail. Finally, a responsivity value of  $R \sim 1\text{A/W}$  at  $-1\text{V}$  and  $5\text{K}$  is reported.*

Keywords: Intersubband transitions, quantum dots, infrared detector, responsivity, detectivity, dark current, multispectral

### Introduction

Recently, intraband quantum dot infrared photodetectors (QDIPs) have attracted considerable attention [1-11] due to their various advantages compared to current HgCdTe and quantum well detector (QWIP) technologies. QDIPs are intrinsically capable of normal incidence detection due to the three dimensional confinement provided by the QDs [1,2], which eliminates the need of diffraction gratings typically used in QWIP devices. QDIPs benefit from long excited carrier lifetimes [2-5], due to greatly suppressed electron-phonon scattering [2], which in turn leads to high photoresponse, high temperature operation and low dark current [3,10,11]. Additionally, several research groups [3,6,7] have shown that the spectral response of a QDIP can be tuned with voltage, making them attractive for use in multi-spectral applications. Finally, absorption via intraband transitions allows

fabrication of the devices using cost-effective III-V material growth and fabrication. QDIPs are suitable for various applications including day and night battlefield multifunction operation, including detection of camouflaged and low signature targets, as well as fulfilling a range of civilian applications such as temperature registration, solid state spectrometry and chemical analysis [3]. This paper reports a detailed mid-infrared study and characterisation of QDIPs incorporating InAs/In<sub>0.15</sub>Ga<sub>0.85</sub>As dots-in-a-well (DWELL QDIP).

### Growth and fabrication of DWELL QDIPs

A set of seven samples with varying numbers of InAs monolayers (MLs),  $N_{\text{ML}}$  and number of electrons per dot,  $N_e$  were grown in the National Centre for III-V technologies at Sheffield University. Samples 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.

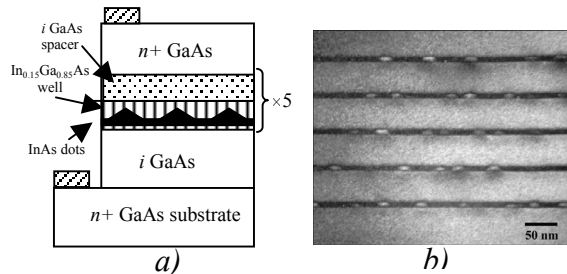


Fig.1 a) Schematic of a DWELL QDIP and b) Cross-sectional TEM of a typical DWELL structure

The device structure, following the growth direction, incorporates a layer of 4000Å  $n+$  Si doped GaAs, an undoped layer containing 5 periods of DWELL absorbing region, 500Å of undoped GaAs and a final 4000Å  $n+$  Si doped GaAs contact layer, similar to that shown in the schematic of Fig.1(a) and the TEM image of Fig.1(b). The DWELL absorbing region consists of  $N_{\text{ML}}$  MLs of InAs placed within an 80Å  $\text{In}_{0.15}\text{Ga}_{0.85}\text{As}$  quantum well, with 10Å of the well below the dots and 70Å above. The active regions are Si  $\delta$ -doped in the GaAs barrier layers, to a concentration of either  $6 \times 10^{10} \text{ cm}^{-2}$  or  $1.2 \times 10^{11} \text{ cm}^{-2}$  corresponding to approximately  $N_e = 1$  or 2 electrons per dot respectively, in order to study the effect of the QD states filling with electrons on the QDIP's performance. In all samples only the QD ground state is occupied, thus the initial state of the electron transitions contributed in the photocurrent is the QD ground state. QDIPs were grown comprising dots with  $N_{\text{ML}} = 2.9, 2.55$  and 2.2MLs InAs for both doping levels of  $N_e = 1$  and 2, making a total of 6 layers in the sequence. A further sample was grown with  $N_{\text{ML}} = 2.55\text{MLs}$  and with  $N_e = 1$  but with the Si  $\delta$ -doping layer grown above the QDs, inside of the 80 Å InGaAs well, to

investigate the effect of the position of the doping.

Prior to photocurrent (PC) measurements the wafers were processed into 400 and 200  $\mu\text{m}$  diameter mesas using standard photolithography and wet chemical etching techniques. Annular top contacts to allow optical access were deposited by evaporation.

## Results

The PC measurements were carried out using a vacuum Bruker IFS-66v/s Fourier-transform infrared spectrometer with a broad-band mid-infrared light source. It was found that there was no difference in the photocurrent spectral dependence between samples having different  $N_e$  but similar  $N_{\text{ML}}$  as expected. Results from layers having  $N_e = 1$  will be presented here unless otherwise specified.

Figure 2 shows typical low temperature (10K) photoresponse spectra of the DWELL QDIPs. We observed two absorption peaks centred at  $\sim 130 \text{ meV}$  ( $\sim 9\mu\text{m}$ ) and  $\sim 230 \text{ meV}$  ( $\sim 5\mu\text{m}$ ), due to electron transitions from the InAs quantum dot ground state  $E_1$  to the  $\text{In}_{0.15}\text{Ga}_{0.85}\text{As}$  quantum well state,  $E_{\text{QW}}$  and GaAs continuum states,  $E_{\text{cont}}$  respectively as shown in the inset of Fig.2. By varying  $N_{\text{ML}}$  from 2.2ML to 2.55ML to 2.9ML we have controllably altered the size of the QDs, achieving a significant shift ( $\sim 20\%$ ) of  $E_1 \rightarrow E_{\text{QW}}$  peak (Fig.2). This provides us with an additional freedom during the design stage of the DWELL QDIP since we can also tune the spectral ranges by changing the quantum well width.

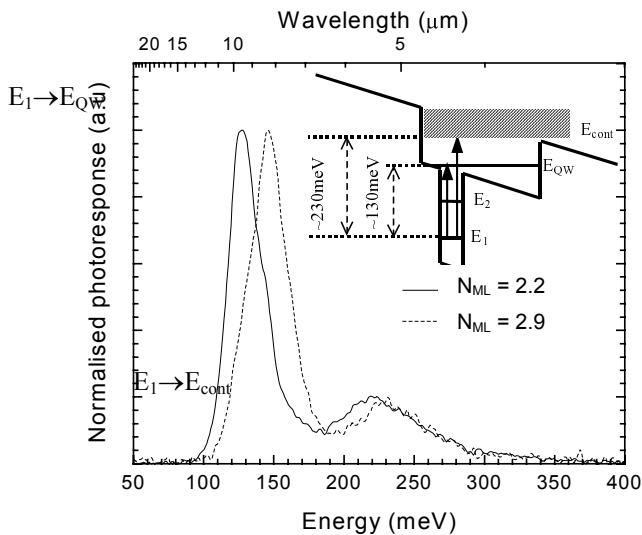


Fig.2 Normalised low temperature photoresponse for InAs QD samples with  $N_{ML} = 2.2$  and  $2.9$  at  $-1$  V. The inset shows a schematic of the DWELL band structure and the possible electron transitions involved.

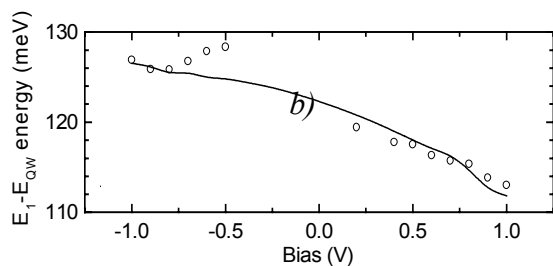
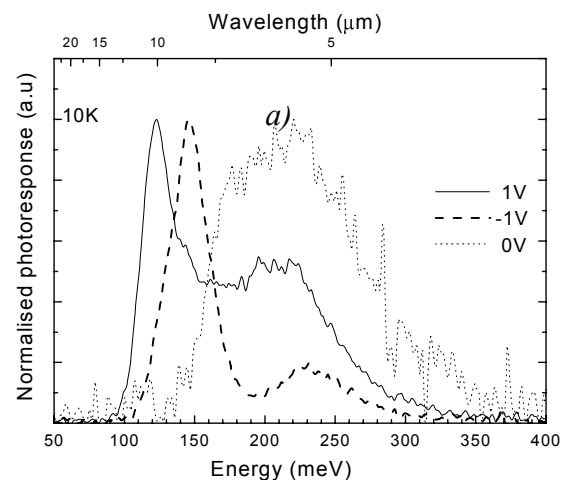


Fig.3 a) Typical normalised photoresponse for a QDIP at 5K containing dots with  $N_{ML} = 2.2$  at a bias of 0V (dotted line), +1V (solid line) and  $-1$  V (dashed line). b) Bound-to-bound transition energy dependence on applied bias: experiment (dots) and fit (line).

The bias dependence of the photoresponse for the sample  $N_{ML} = 2.2$  ML is presented

in Fig.3a. At zero bias only the photocurrent peak due to electron transitions from the QD ground state to the continuum states is observed. The absorption  $E_1 \rightarrow E_{QW}$  does not contribute to the photocurrent at zero and low negative or positive biases because of low electron escape probability from the quantum well state. The magnitude of the  $E_1 \rightarrow E_{QW}$  and  $E_1 \rightarrow E_{cont}$  peaks increase with bias magnitude. However, the intensity of the bound-to-bound ( $E_1 \rightarrow E_{QW}$ ) photoresponse increases more rapidly and becomes dominant at biases of  $\pm 1$  V.

In addition, the  $E_1 \rightarrow E_{QW}$  peak is tuneable with applied bias due to the intraband Stark effect. The photocurrent spectrum at +1V is red-shifted with respect to that at -1V, thus indicating an asymmetric dependence on the applied bias due to the off-centre position of the QD layer in the well as shown in the inset of Fig.2. The bias dependence of the bound-to-bound transition energy is shown in Fig.3b. We used a well-within-a-well model to fit our experimental data. In this model the QD ground state wavefunction in the vertical (growth) direction was approximated using a narrow  $In_{0.15}Ga_{0.85}As$  quantum well. This is a satisfactory assumption since the quantum dot normally has much smaller size in the growth direction (the direction of the applied bias in our case) and therefore the position of the dot ground state will be mainly affected by changing the confining potential in this direction. Our calculations (solid line) are in good agreement with the experimental data (open dots), when the narrow InGaAs quantum well (approximating the dot) is chosen  $\sim 3.6$  nm wide and with an In content of  $\sim 35\%$ .

Fig.4 shows typical IV characteristics at 77K for QDIP 200 $\mu$ m diameter mesas with  $N_{ML} = 2.2, 2.55$  and  $2.9$  MLs and  $N_e = 1$ . It can be seen that there is a minimum in the dark current characteristic when  $N_{ML} = 2.55$ , we believe this minimum comes about from two mechanisms which counteract one another. It is believed that as the dots get

larger and deeper, the confinement of the carriers improves, which leads to a concurrent reduction in thermionic emission. However, increasing  $N_{ML}$  also introduces strain into the DWELLS resulting in structural defects, thus creating parallel leakage paths down the sides of the dots. It was also found that the doping positioned inside the quantum well, on top of the dots, increases the dark current. An increase in doping results in an increase of the dark current as expected.

This work is the first to determine the optimum position of the Si  $\delta$ -dopant and value of  $N_{ML}$  for DWELL QDIPs to obtain lowest dark current operation.

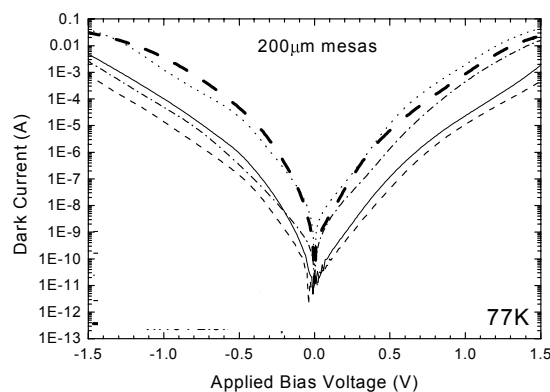


Fig.4 Dark current characteristics for DWELL QDIPs at 77K with  $N_{ML} = 2.9$  (solid), 2.55 with doping below (dash) and above the dot (dash dot) and 2.2ML (dot) with  $N_e = 1$ , and  $N_{ML} = 2.9$  with  $N_e = 2$  (dash thick)

Preliminary measurements of the peak responsivity were performed using a calibrated black body source. We found that the peak responsivity gradually increases with bias reaching the value of  $\sim 1A/W$  at  $-1V$  for the peak corresponding to bound-to-bound transitions for  $N_{ML} = 2.55$  and  $N_e = 1$  DWELL QDIP operating at temperature of 10K. Operation of the QDIPs at higher temperatures up to 70K has been demonstrated. Using the responsivity data and the bias dependence of the dark current, the dark current limited peak detectivity was calculated. In contrast to the responsivity measurements the maximal

detectivity value of  $\sim 10^{12} \text{cm}\cdot\text{Hz}^{1/2}\cdot\text{W}^{-1}$  at 10K was obtained at lower bias of  $-0.8V$ . To our knowledge this is the highest detectivity and one of the highest responsivity values reported so far for QDIPs in the  $9\mu\text{m}$  spectral range.

## Summary

The current results demonstrate both the suitability of DWELL QDIPs for controllable, multi-spectral mid-infrared detectors with large peak responsivity ( $\sim 1A/W$  at 10K) and large detectivity ( $\sim 10^{12} \text{cm}\cdot\text{Hz}^{1/2}\cdot\text{W}^{-1}$  at 10K) whilst also providing detailed information regarding the conduction band structure of the DWELLS.

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