Enhancing the performance of InAs/InGaAs quantum dots-in-a-well infrared photodetectors

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EPSRC Engineering and Physical Sciences Research Council

EMRSDTC Electro Magnetic Remote Sensing Defence Technology Centre

Outline

- Introduction
- Device design
  - Dots-in-a-well (DWELL) based device design & design considerations
- Spectral Response
  - Tailoring of the two colour behaviour of QDIPs
  - Bias tunability of the spectral photoresponse via the intraband Stark effect
- Performance
  - Effects of doping, number of ML, number of periods
- Ultrafast measurements of carrier lifetimes in QDs

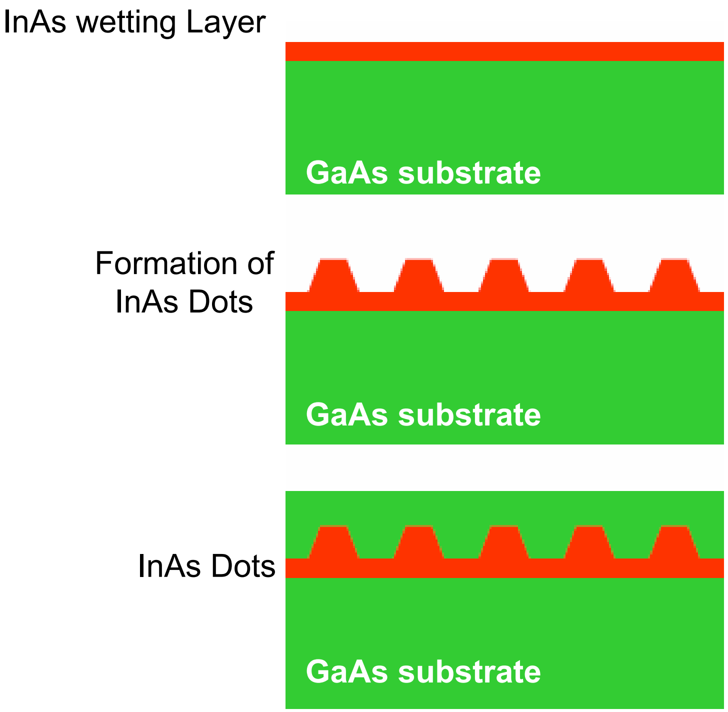
Introduction

Quantum Dot Infrared Photodetectors (QDIPs) have a number of potential advantages:

- 3D confinement – discrete density of states
  - Normal incidence operation
  - Low dark current
  - Longer excited state lifetimes

Introduction - QD growth

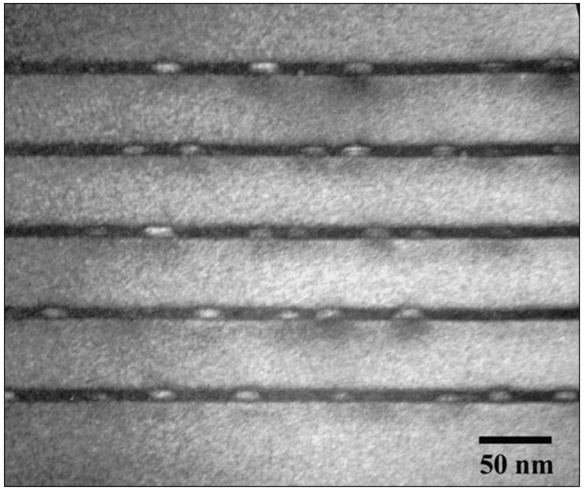
- Stranski-Krastanow growth
  - MBE deposition of a lattice mismatched InAs wetting layer on a GaAs substrate
  - Above critical thickness, strain induced island formation (QD) occurs
  - Quantum dots overgrown by GaAs barrier layer



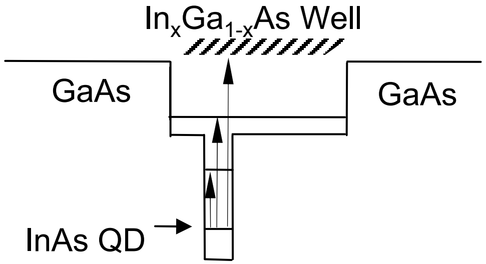
Device design

Dots-in-a-well (DWELL)

- Stranski-Krastanow QD growth
- Active regions consist of **n** periods of InAs dots grown inside an $In_xGa_{1-x}As$ well capped by GaAs barrier layers
- University of Sheffield has previously achieved optimized growth of DWELL QD devices for 1.3μm lasers (I. R. Sellers et al, App.Phys.Lett. **88**, (8) 2006)
- Suitability for detectors previously demonstrated (S. Krishna et al, App.Phys.Lett, 82,(16) 2003)



Cross-sectional TEM view of typical DWELL



Conduction Band diagram for active region

Device design

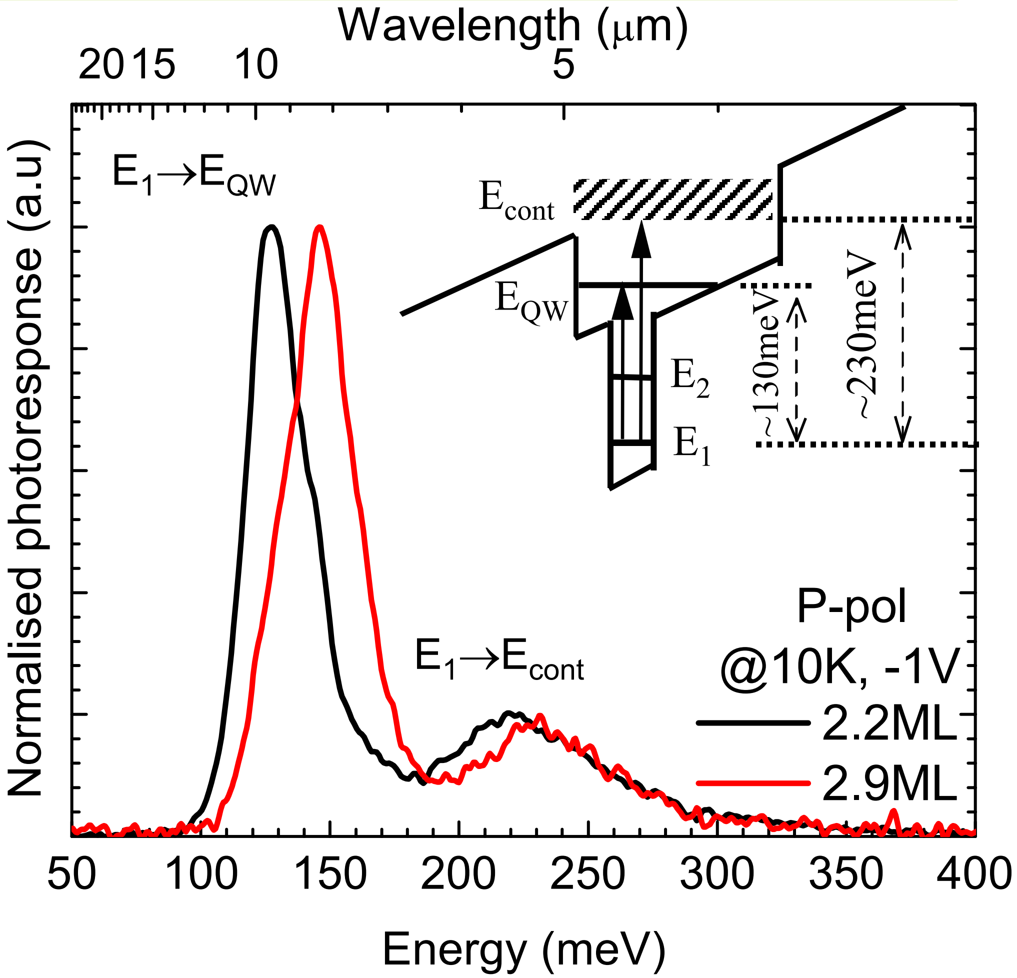
Design considerations-variations

- Dot size (number of deposited InAs monolayers - N_{ML})
- $In_xGa_{1-x}As$ well width
- In composition in $In_xGa_{1-x}As$ well
- Doping
- Number of periods
- Barrier composition

Spectral Photoresponse

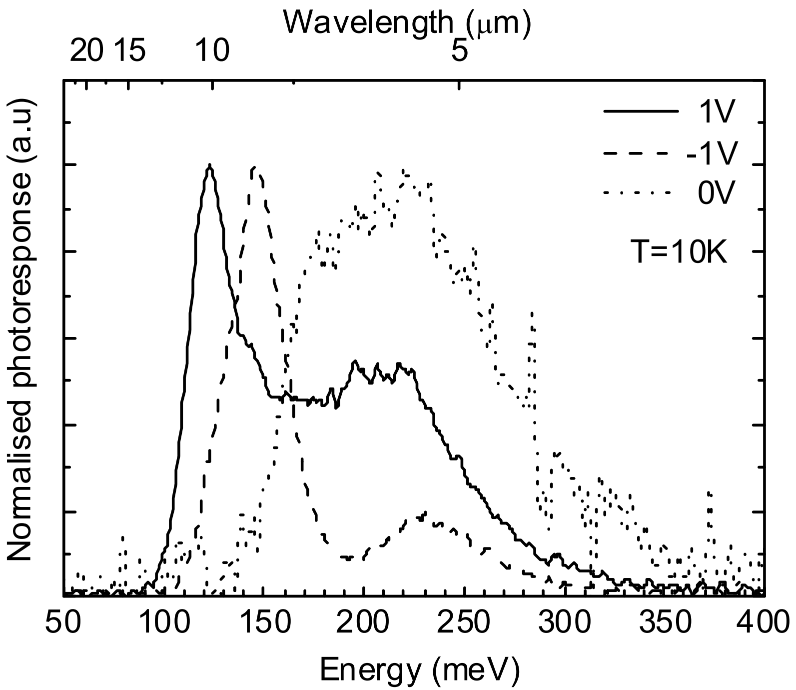
- Typical 2-colour behaviour at ~130-160meV (~9-7µm) and ~230meV (~5 µm)

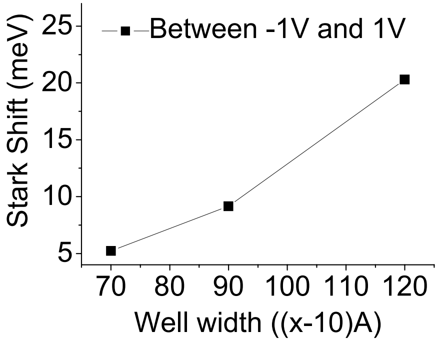
- Pre-growth wavelength tailoring:
  - Dot size dependence (transition energy increases with N_{ML})
  - Also possible to tune the spectral range by varying the QW width

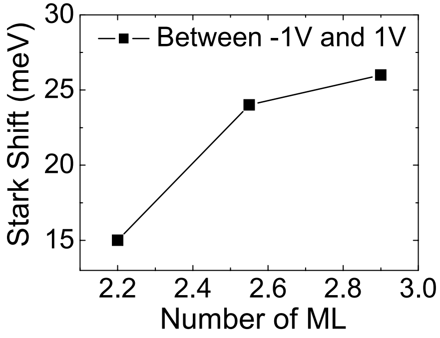


Spectral behaviour

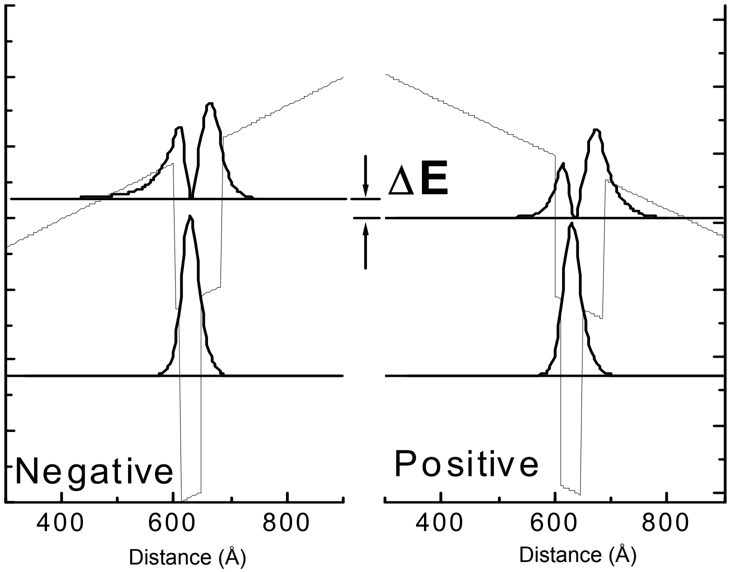
- The $E_1 \rightarrow E_{QW}$ transition is not observed at zero bias due to low probability of carriers tunnelling from QW state
- Photocurrent spectrum at +1V is red-shifted with respect to that at -1V, indicating an asymmetric dependence on applied bias due to off-centre position of the QD layer in the well
- Furthermore, the $E_1 \rightarrow E_{QW}$ transition is bias tuneable due to the intraband Stark effect

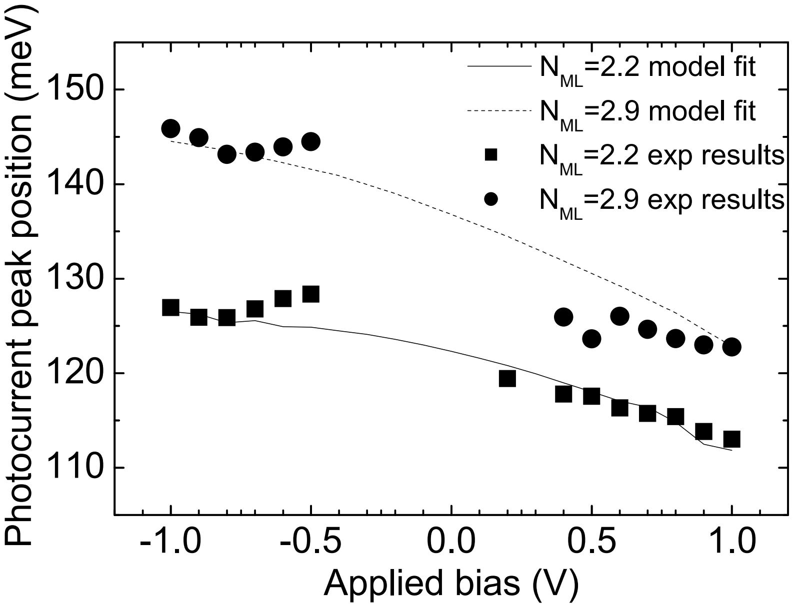






Spectral behaviour- Well within a well approximation for DWELL

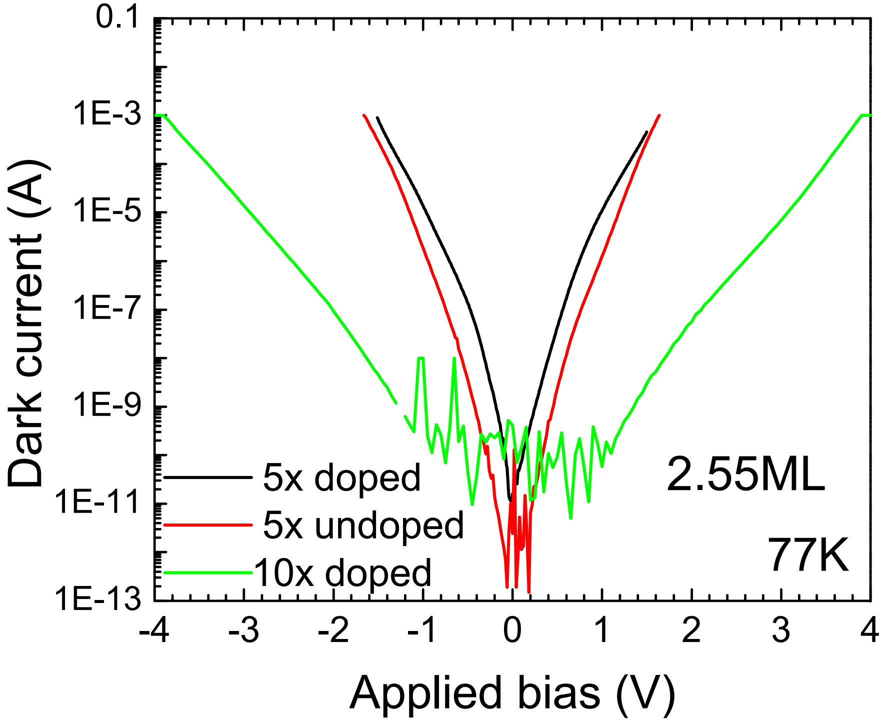


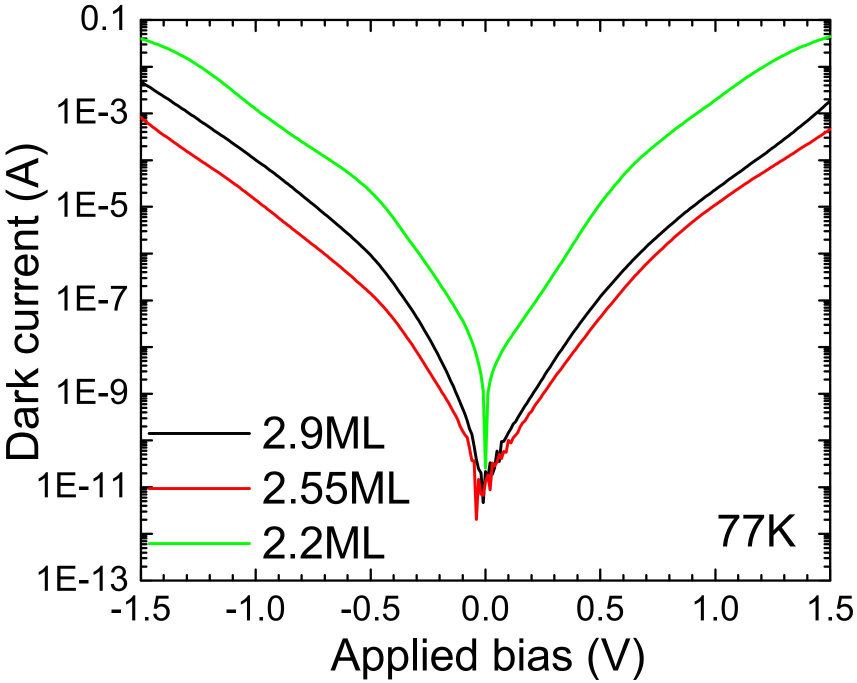


- Intuitively expect larger dots – less asymmetry - smaller shift
  - **Opposite observed experimentally**
- However if the well-within a well simulation assumes increasing asymmetry with dot size the experimental data are fitted
- No definite information on size shape or compositional gradient of dots
- The agreement of this model with experimental data indicates that the ***electron wavefunction becomes more localised at the base of dot for increasing number of ML***

Performance - Dark current

- Previously achieved low dark current (Id) for DWELL samples
  - **Optimised 2.55ML, used henceforth**

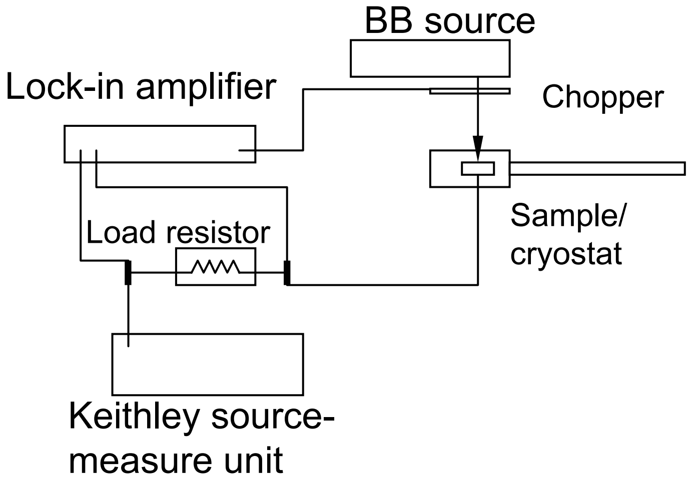


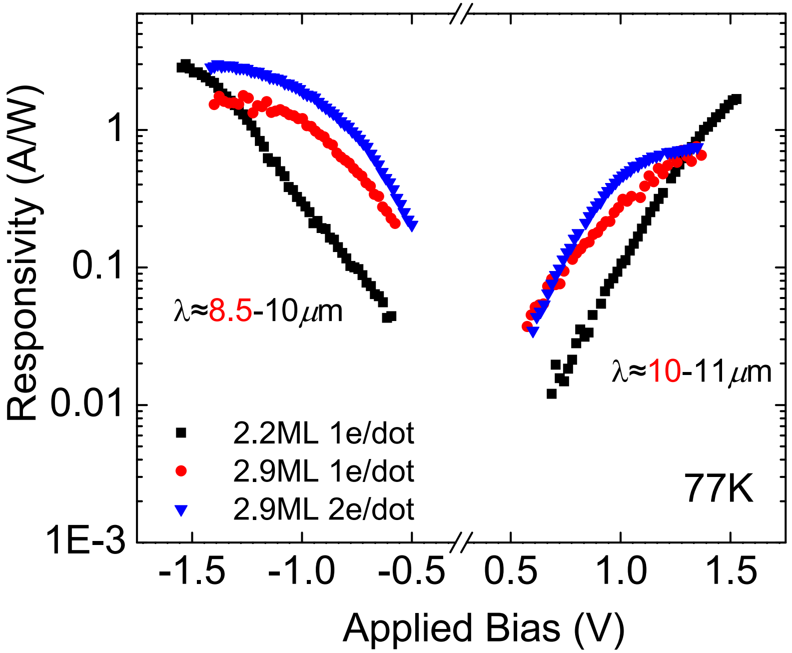


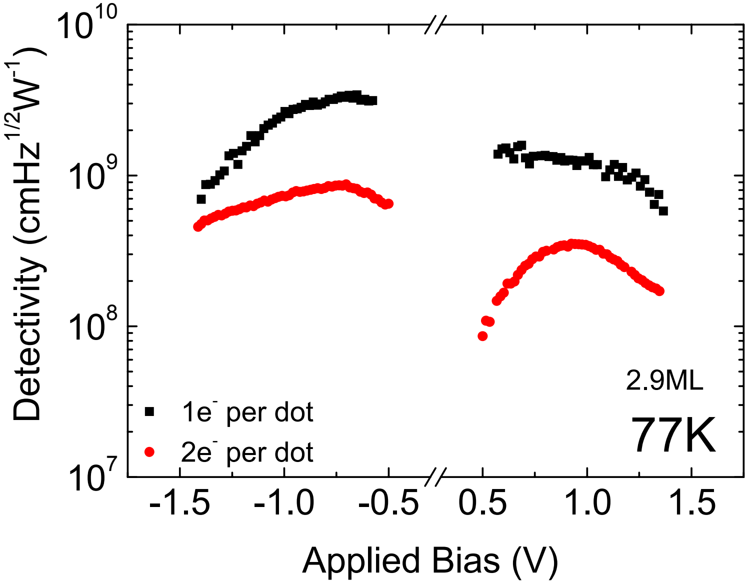
- Achieved a further significant reduction of Id for double number of periods (10) and improved growth
- Undoped DWELL QDIP also reduced dark current

Performance - Responsivity

~1A/W @ ~±1V @77K for DWELL detectors in the wavelength range of 8.5-10µm for negative bias and 10-11µm for positive.

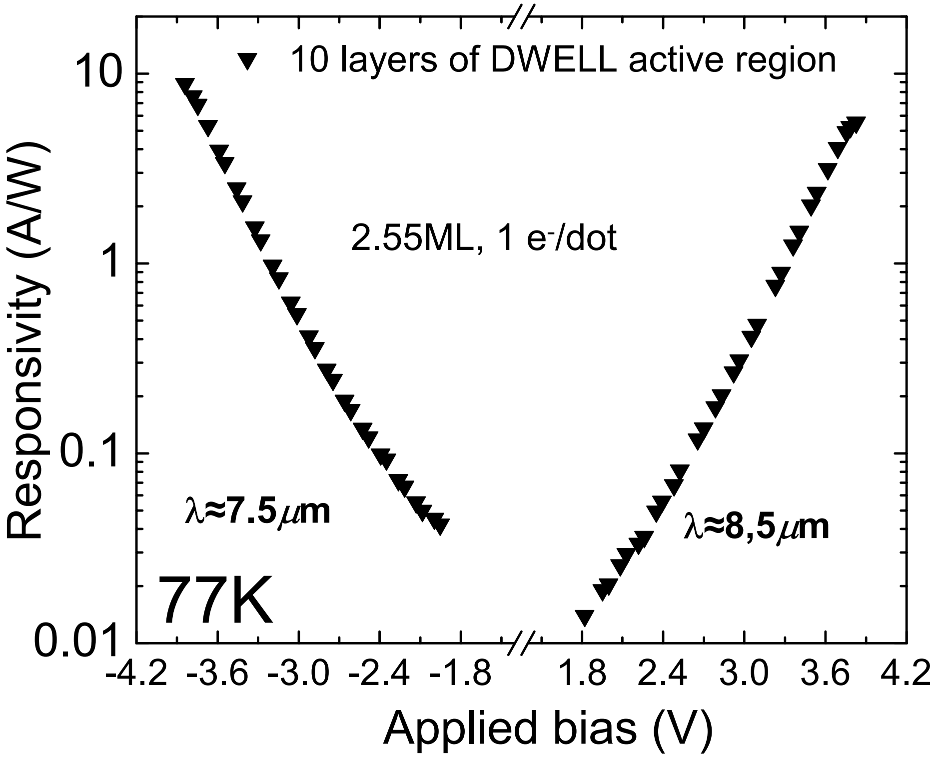




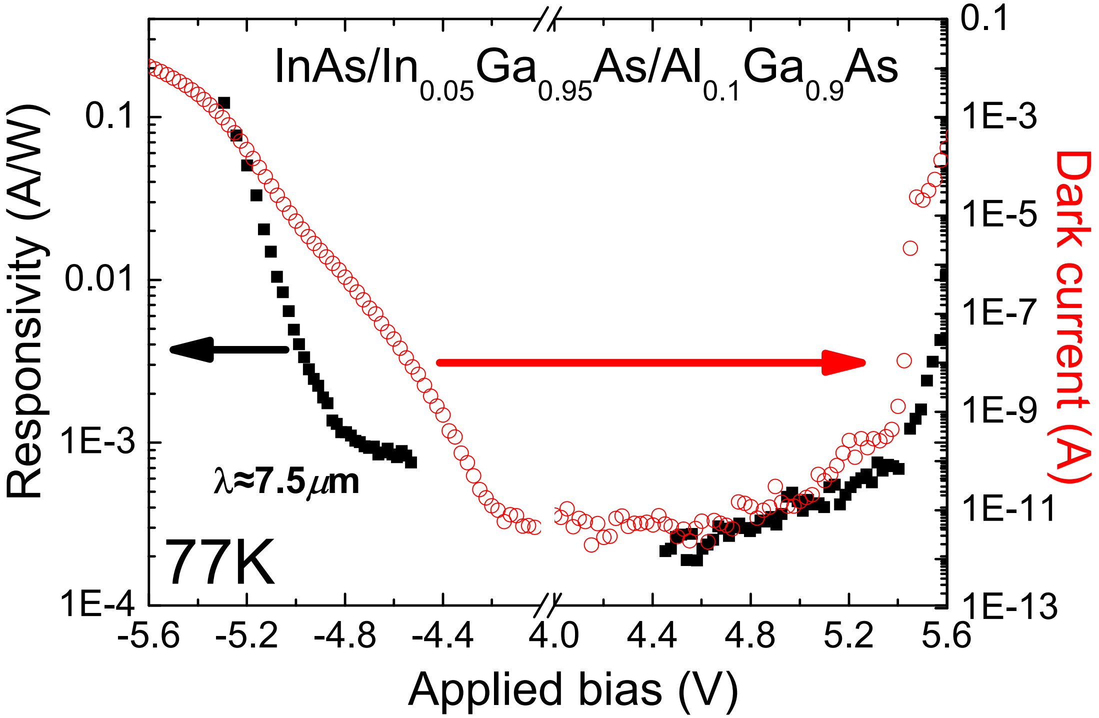


Performance - Responsivity

- Achieved a responsivity of **~1A/W at ~7-8μm** for 5 layer DWELLs at 77K
- Enhanced performance with very high responsivity **~10A/W at 7-8μm** for double (10) number of periods of active region (larger absorbing region and improved growth)

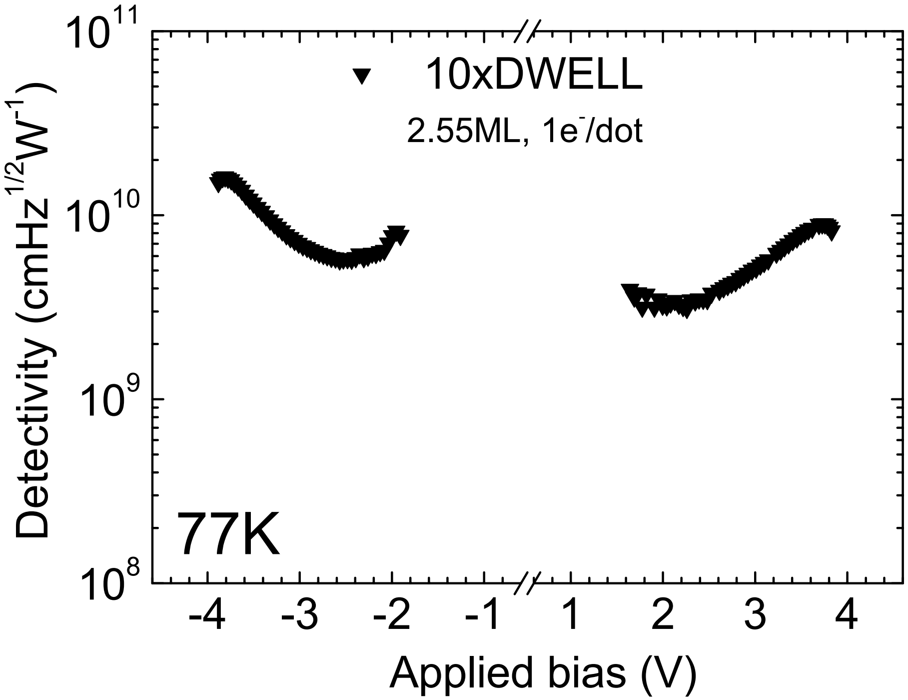


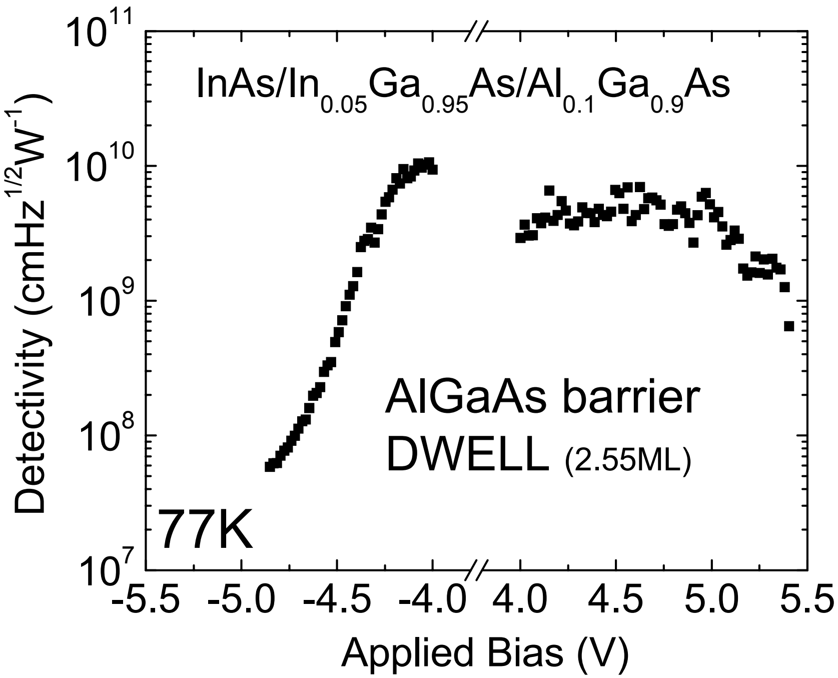
Performance - AlGaAs barriers



- Lower responsivity than GaAs matrix DWELLs (~2 orders of magnitude)
- Dark current decreased dramatically (higher barrier than GaAs - more confinement)

Performance - Detectivity

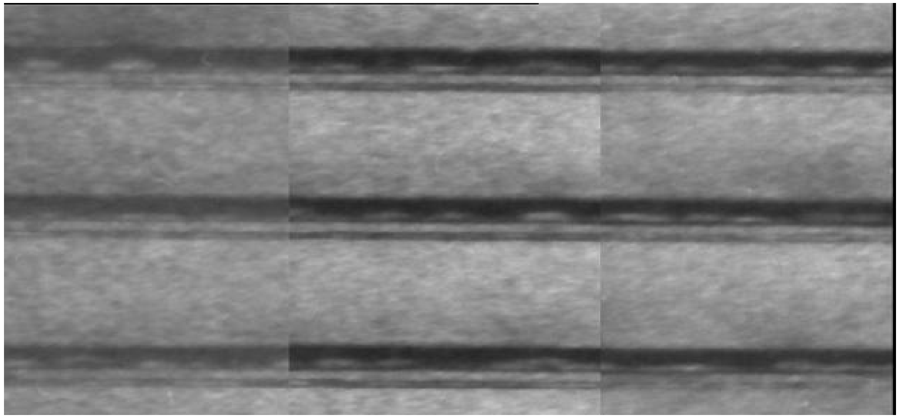




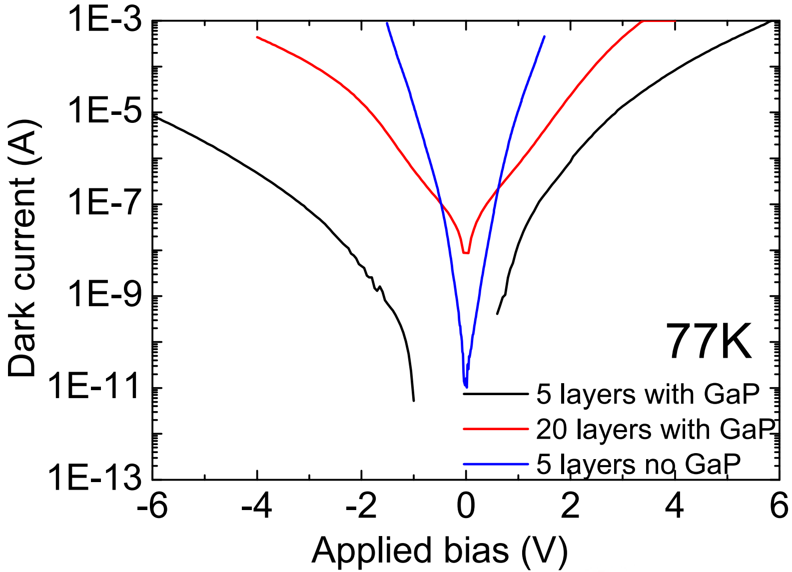
- 10 layer DWELL with D **~10^{10}cmHz$^{1/2}$W^{-1}**
- AlGaAs barrier 5 layer DWELL with D of **10^{10}cmHz$^{1/2}$W^{-1}**
- **Comparable to the highest detectivity values for QDIPs in the literature**

DWELL QDIPs with GaP

- DWELL QDIPs with GaP strain compensation layers



Motivation: *the growth of many (>20 layers of DWELL) to overcome the limitation of a small absorbing region in QD structures*



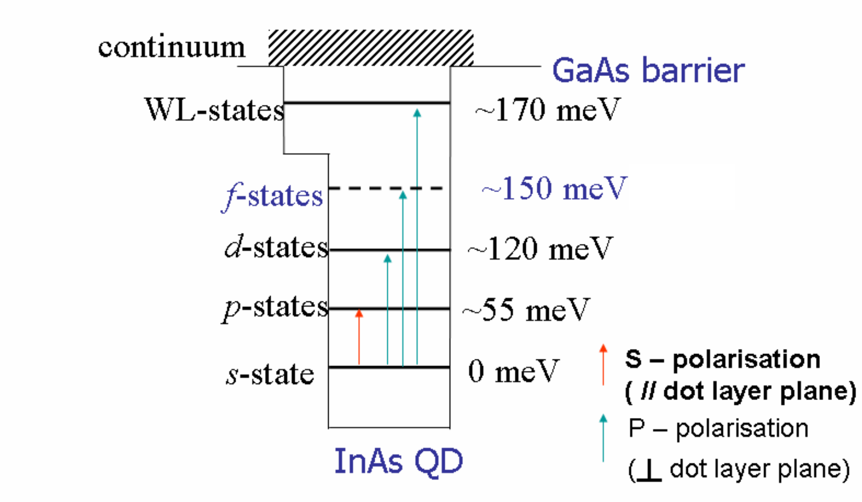
Strain balancing works:

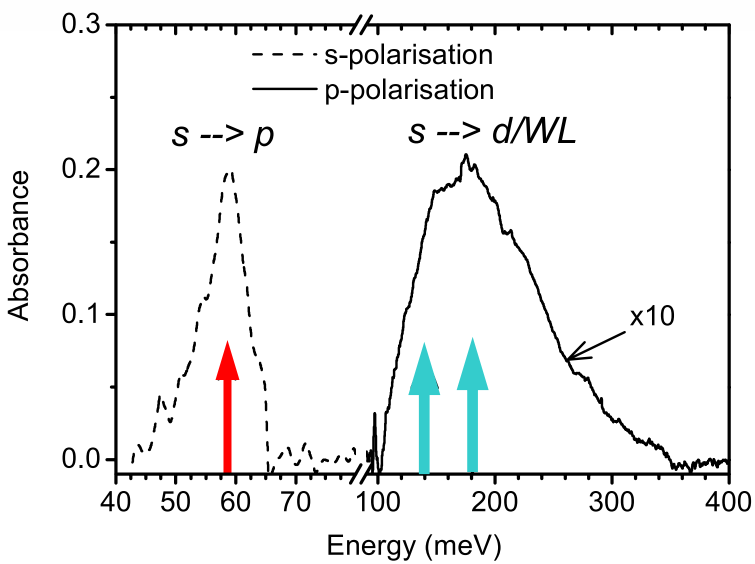
- 5 layer with GaP significantly better than 5 layer without
- Also GaP provides current blocking barrier

Carrier lifetimes in QDs

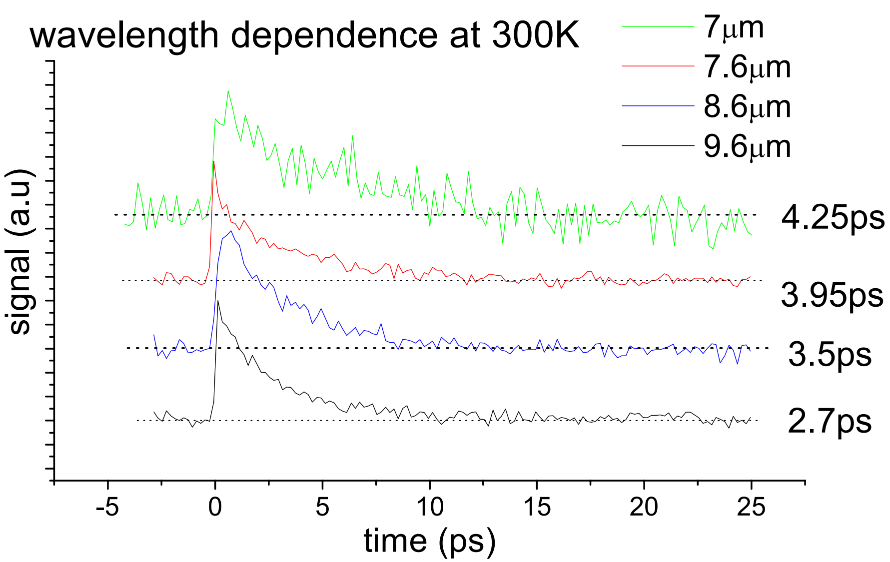
- Theoretical predictions of longer carrier lifetimes in QD devices than QW based devices
- Attributed to various mechanisms (multiphonon scattering, polaronic effects)
- Ultrafast spectroscopy of QD structures using mid-IR intraband pump-probe set up to measure & investigate carrier relaxation processes

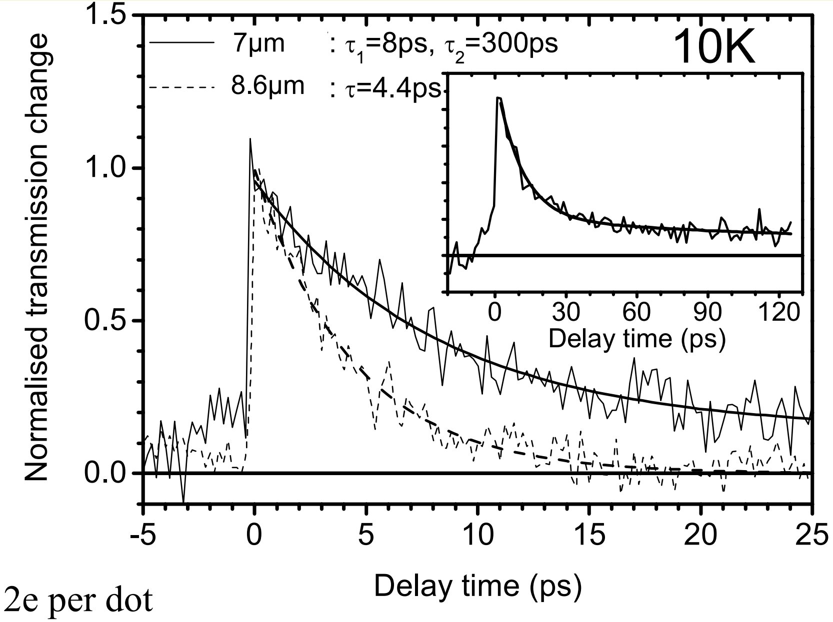
(E. A. Zibik et al., *Phys. Rev. B* **70**, 161305(R) 2004)





Carrier lifetimes in QDs





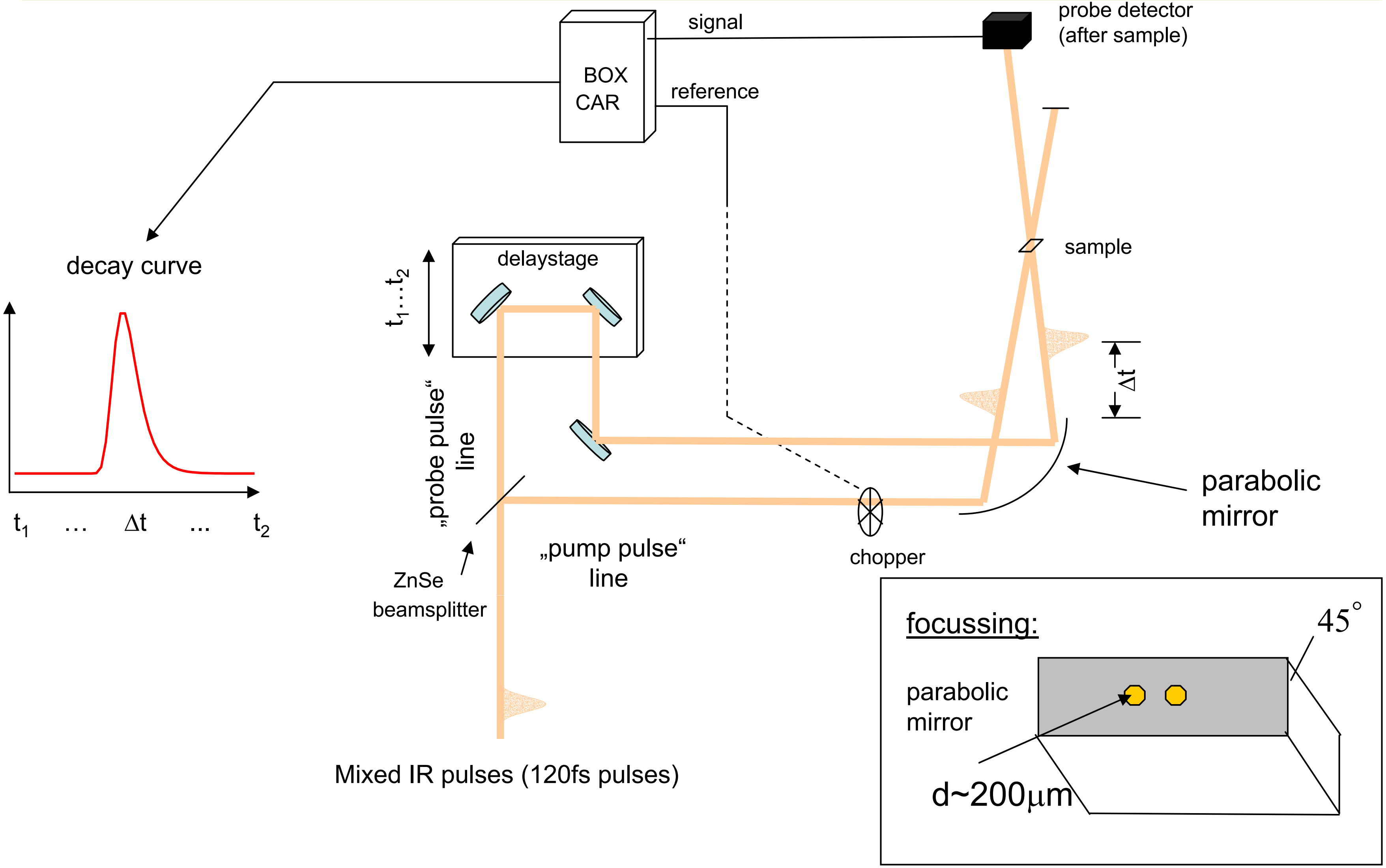
InAs/GaAs QDs with 2e per dot

- Long decay observed at low temperatures if excitation to the wetting layer/barrier states
  - electron capture and thermal re-emission (RT) or tunnelling (10K) from adjacent QDs
- Wavelength dependence of the short decay time excitation into different states
  - different scattering processes - *under investigation*
- Currently measuring lifetimes in DWELL structures to investigate excited state lifetimes

Summary

- Pre-growth wavelength tailoring of the two colour operation of DWELL QDIPs and Dark current control via
  - Control over the number of ML's & variation of the well width
- Post-growth applied bias voltage tuneable wavelength response due to intraband Stark effect
- High performance with increased number of absorbing active regions (10x) with responsivity of **~10A/W** and detectivities of **~10^{10}cmHz$^{1/2}$W^{-1}@77K for ~7-8µm**
- AlGaAs barriers 5 layer DWELL with detectivities of **~10^{10}cmHz$^{1/2}$W^{-1} @77K for ~7-8µm**
- Introduction of GaP strain compensation layers to DWELL QDIPs allowing the growth of 20 layers of active region
- **Demonstration of measured excited carrier lifetimes, (~8ps) longer than QWIPs (~1ps)**

Appendix Pump-Probe technique



Appendix – Theoretical work (University of Leeds)

- Realistic model of DWELLs developed by P. Harrison, D. Indjin, N. Vukmirovic
- Energy levels and wavefunctions found using 8 band strain dependent *k•p* model
- Preliminary calculations support evidence of Intraband stark shift dependence on N_{ML} similar to simple well within a well model – whilst indicating the localisation towards the base of the dot

k•p model (truncated cone dots)

h=8nm, D=15nm (2.2): 111 - 126meV
h=8nm, D=22.5nm (2.9): 125 -144meV

well within a well model

N_{ML} = 2.2 : 112 - 127meV

N_{ML} = 2.9 : 123 - 145meV