Quantum Well and Quantum Dot Modeling for Advanced Infrared Detectors and Focal Plane Arrays

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Introduction
QUANTUM WELL INFRARED PHOTODETECTOR (QWIP)  
FOCAL PLANE ARRAY TECHNOLOGY

- Designed artificial infrared material based on highly mature GaAs technology.
- Materials flexibility allows for highly customizable design
  - QWIPs in 4 – 20 µm wavelength range produced routinely.
  - Narrow-band, broad-band, spatially-separated multiband, pixel co-located simultaneous dual-band.
  - Thermal imaging, hyperspectral and multispectral spectrometry, target identification.

CROSS-SECTIONAL  
TRANSMISSION ELECTRON MICROGRAPH

- Intersubband infrared absorption photo-excite carriers
- Carriers are swept away in the Presence of an electric field
Advantages of QWIP Focal Plane Arrays

- Large format, affordable FPA with high fill factor, high uniformity, negligible 1/f noise, and high radiation hardness

Size Comparison of Two Available QWIP Detector Arrays

- JPL 1024 x 1024 Pixel QWIP Focal Plane Array
- 4096 x 4096 Pixel QWIP Detector Array on 6-inch GaAs Wafer

QWIP Stability

- 1/f Noise of QWIP Focal Plane Array

- Mature III-V Material Growth & Processing Technology
  - High Uniformity
  - High Operability
  - High Reliability
  - Mature Manufacturability

- High Yield
  - Low Cost

- Tailorable Wavelength
  - 3 to 16 μm, multi-band and broadband

- Portable IR QWIP Camera Available

- Low Power Dissipation
  - Large RoA

- Low 1/f Noise
  - No 1/f Noise Down to 10 mHz

- No Delamination Due to Temperature Recycling
  - Extremely Stable QWIP-ROIC Interface
  - No Pixel Outages/Array Delaminations After Thousands of Cycles

- Radiation Hard
Temporal Stability Facilitates Systems Design

- **Low 1/f noise.**
  - No 1/f noise down to 30 mHz.

- **Excellent temporal stability**
  - Non-uniformity correction table stored in EPROM.
  - Unchanged since 1998.

- **Multi-hour exposure without constant re-calibration. Capable of long-integration time applications.**

8.5 µm mid-infrared image, obtained with a QWIP focal plane array at primary focus of the Palomar 200-inch Hale telescope.
True Pixel Co-registered, Simultaneously Readable Dualband QWIP FPA

- Dualband pixel architecture
- SEM of metal via connects
- SEM of dualband QWIP array
- 4-inch GaAs wafer with 48 detector dies
- 320x256 pixels Dualband QWIP FPA HYBRID
Dualband QWIP FPA Pathfinder

Features to look for,
The cigarette lighter produce lots of hot CO2 gas. So, flare is broader MWIR due to CO2 emission, where as LWIR (8-9 microns) doesn't have any emission (just the heat).
The hot cigarette lighter flame produce so much MWIR signal, it reflects off from the lens and Jason's face.
The plastic piece Jason is holding is opaque in LWIR, but transparent in MWIR.

Format - 320x256 pixels, dualband & pixel co-registered
Wavebands - 4.4-5.1 & 8-9 µm
NEΔT - 22 & 24 mK for 300K background with f/2 optics
QE - 19% & 15%
Photoconductive gain - 0.5 & 0.3
Detectivity - > 2x10^{11} & 1x10^{11} Jones
Operating temp. - 65 K
Fill factor - > 85%
Current QWIP Development: Implication for QDIP

• JPL is currently in the process of developing 1K x 1K, simultaneous MWIR-LWIR true dual band QWIP FPA
  – Realistic plans for extension to 2K x 2K already in place
  – Leading edge in infrared FPA technology

• The same large-format dual-band FPA technology can be applied to Quantum Dot Infrared Photodetector (QDIP) with no modification, once QDIP exceeds QWIP in single device performance!
From QWIP to QDIP

- The QDIP shares all the positive attributes of QWIP
  - Based on the same mature material systems and processing technology
- The QDIP also has the following advantages over QWIPs
  - Capable of normal incidence absorption, can lead to higher quantum efficiency
  - Capable of higher operating temperature
- QDIP has the potential to out-perform the QWIP, while retaining all of the QWIP advantages.
Why Quantum Dot Infrared Photodetectors?

- High spatial uniformity
  - Reduces need for complex non-uniformity correction circuitry
  - Facilitates large-format FPA fabrication

- Excellent temporal stability
  - Eliminates need for frequent recalibration, simplifies system design

- High quantum efficiency and D*
  - Capable of reaching theoretical ideal photoconductor background limited D* (BLIP limit) for 300K background with f/2 optics

- Increased operating temperature
  - Can achieve the same NEΔT at higher operating temperatures
  - Less demand on cooler, longer system lifetime

- Based on mature wide-band gap III-V semiconductors
  - Excellent manufacturability
  - Faster turn-around, higher availability, lower cost
Quantum Dot Based LWIR FPAs

✓ Build on JPL’s proven track record of delivering infrared FPAs based on quantum effects in III-V photodetectors
  – Large format
  – Excellent uniformity
  – Excellent operability
  – Low 1/f noise
  – Thinned arrays eliminate
    • Optical crosstalk
    • Thermal mismatch with ROIC
    • Pixel delamination

+ Add quantum dots to this current capability
  – Normal incidence absorption
  – Higher temperature operation (lower dark current)
  – Higher responsivity (longer lifetime)
  – Further increase the radiation hardness

= New generation of high performance high operating temperature infrared focal plane arrays
Development of Megapixel MWIR & LWIR QWIP Focal Planes Arrays & 320 x 256 Pixel Dualband QWIP Focal Plane Arrays
OUTLINE

- 1K x 1K MWIR Focal Plane Array
- 1K x 1K LWIR Focal Plane Array
- 320 x 256 Dual-band FPA & Camera
- Summary
1024 x 1024 PIXEL MWIR CAMERA
BROADENED MWIR RESPONSE FOR SPECIFIC DOD APPLICATION

Increased the spectral coverage by utilizing a multi-coupled-quantum-well structure for tracking missiles during boost phase.

Grown on 4-in GaAs wafers.


SPECTRAL RANGE - 4.4 - 5.1 µm
PIXEL PITCH - 19.5 µm
PIXEL ACTIVE AREA - 17.5 x 17.5 µm²
ABSORPTION (peak) Q.E. - 19%
GAIN - 0.3
RESPONSIVITY - 0.27 A/W
OPERATING TEMP. - 80 - 110 K
FRAME RATE - 30 Hz
NON-U (UNCORRECTED) - 5.6%
NON-U (CORRECTED) - 0.05%
OPERABILITY - 99.98%
NEF* - 2 X 10^{-16} W/cm²
OPTICS - f/2.3; 400 mm & f/2; 38 mm
1024x1024 PIXEL MWIR QWIP FPA AND CAMERA DELIVERED TO THIS APPLICATION

Detector pixel with light coupling gratings

1024 x 1024 pixel QWIP focal plane array

1Kx1K MWIR sensor engine

1Kx1K MWIR QWIP camera
1024 x 1024 PIXEL QWIP FPA IMAGERY

- NE\Delta T OF 19 mK WAS ACHIEVED.
DETECTIVITY AND NEF

**Peak D* Vs T for MWR QWIP**
(300 K, f/2.5)

**Noise Equivalent Flux for 1Kx1K MWR QWIP FPA**
(300K, f/2.5)

**IMAGE OF THE EXIT SLIT OF MONOCHROMATOR**

**NORMALIZED SPECTRAL RESPONSE**
NEΔT = 22 mK ( = 19 mK if ADC noise is subtracted)
- Uniformity = 0.03%
- Operability = 99.5%
POINT SPREAD FUNCTION

Primary Image

Reflected Image

DIFERENCE IMAGE

22
CROSS SECTION OF 3-D PSF

POINT SPREAD FUNCTION

POINT SPREAD FUNCTION
MTF WITHOUT LENS CORRECTION

MTF of Lens  –  0.2
Pixel Pitch  –  19.5 µm
Nyquist Frequency  –  25.6 Cy/mm

\[
\text{MTF}_{\text{system}} = \text{MTF}_{\text{framegrabber}} \times \text{MTF}_{\text{cabling}} \times \text{MTF}_{\text{focalplane}} \times \text{MTF}_{\text{lens}}
\]

\[
\text{MTF}_{\text{framegrabber}} \times \text{MTF}_{\text{cabling}} \times \text{MTF}_{\text{focalplane}} = 0.5
\]

\[
\text{MTF}_{\text{focalplane}} > 0.5
\]
1024 x 1024 PIXEL LWIR CAMERA
FIGURES OF MERIT

Area = 17.5 x 17.5 µm²
Bias = -1.1 V

Dark/Photo Current (A)

D* (cmHz¹/₂/W)

Background Optics
Bias

300 K
f/2
-1.1 V
CORRECTED IMAGE

Nonuniformity ~ 0.8 %
Operability ~ 99.98%
NEΔT

NEΔT = 16
Window Transmission Assume 95% 
Detector Bias = 1 V, 
Integration time = 29 msec, 
Operating Temperature = 67 K

\[ n_{\text{sys}}^2 = n_{\text{Detector}}^2 + n_{\text{ADC}}^2 + n_{\text{MUX}}^2 \]
\[ 2.4^2 = n_{\text{Detector}}^2 + 0.8^2 + 1.0^2 \]
\[ n_{\text{Detector}} = 2.0 \]
\[ \text{NEDT}_{\text{Detector}} = 13 \text{ mK} \]
MODULATION TRANSFER FUNCTION

MTF Without Lens Correction

- Blue Horizontal MTF
- Red Vertical MTF
- Diffraction Limit at ~ 21 cyc/mm, f/# = 2.3
- Nyquist at ~ 25.6 cyc/mm
- $MTF_{focalplane} > 0.5$
- Frequency above 21 cyc/mm is not justified since it is beyond diffraction limit blurred circle.
PIXEL CO-REGISTERED SIMULTANEOUSLY READING DUALBAND (MWIR & LWIR) QWIP FPA
DUAL-BAND (MWIR & LWIR) DETECTOR

-2V

0V
(Det Com)

Semi Insulating GaAs Si Substrate

MWIR QWIP

LWIR QWIP

Responsivity (arb.u.)

Wavelength (micron)

MWIR

LWIR
DUAL-BAND FPA FABRICATION PROCESS

Grating Etch

Top Metal Deposit

First Mesa Etch

Second Mesa Etch
DUAL-BAND FPA FABRICATION PROCESS

- Isolation Etch
- Deposit Insulation Layer
- Window Opening
- Adhesion Metal Deposit
- Final Metal Deposit
PIXEL CO-LOCATED SIMULTANEOUSLY READABLE
DUALBAND QWIP FPA

Dualband QWIP device structure

SEM of metal via connects

SEM of dualband QWIP array

4-inch wafer with 48 detector dies

Dualband QWIP FPA HYBRID
DUALBAND QWIP – MWIR LOW BACKGROUND

Noise Equivalent Flux for MWIR QWIP
(Low background, 293K, e=5%, f/2.3)

Responsivity vs Wavelength

Detectivity vs Temperature

NEDT vs Temperature
DUALBAND QWIP – LWIR LOW BACKGROUND

RESPONSIVITY

NEF

NEDT

DETECTIVITY
320x256 Pixel Dualband QWIP Camera Delivered to This Application

Dualband sensor engine

320x256 pixel dualband QWIP camera
### 320X256 Pixel Dualband QWIP Specifications

<table>
<thead>
<tr>
<th>Specification</th>
<th>MWIR (4.4–5.1 µm, peak 4.7)</th>
<th>LWIR (8–9.1 µm, peak 8.6)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Spectral Range</strong></td>
<td>- 4.4–5.1 µm</td>
<td>- 8–9.1 µm</td>
</tr>
<tr>
<td><strong>Pixel Pitch</strong></td>
<td>- 40 µm</td>
<td>- 40 µm</td>
</tr>
<tr>
<td><strong>Fill Factor</strong></td>
<td>- 81%</td>
<td>- 86%</td>
</tr>
<tr>
<td><strong>Absorption Q.E.</strong></td>
<td>- 19%</td>
<td>- 15%</td>
</tr>
<tr>
<td><strong>Photoconductive Gain</strong></td>
<td>- 0.2</td>
<td>- 0.3</td>
</tr>
<tr>
<td><strong>Responsivity</strong></td>
<td>- 0.18 A/W</td>
<td>- 0.3 A/W</td>
</tr>
<tr>
<td><strong>Operating Temp.</strong></td>
<td>- 65 K</td>
<td>- 65 K</td>
</tr>
<tr>
<td><strong>Non-U (Uncorrected)</strong></td>
<td>- 5%</td>
<td>- 5%</td>
</tr>
<tr>
<td><strong>Non-U (Corrected)</strong></td>
<td>- 0.3%</td>
<td>- 0.4%</td>
</tr>
<tr>
<td><strong>Operability</strong></td>
<td>- 98%</td>
<td>- 97.5%</td>
</tr>
<tr>
<td><strong>NEF</strong></td>
<td>- 7 X 10^{-16} W/cm²</td>
<td>- 8 X 10^{-16} W/cm²</td>
</tr>
<tr>
<td><strong>FILL FACTOR</strong></td>
<td>- 81%</td>
<td>- 86%</td>
</tr>
<tr>
<td><strong>OPERATING TEMP.</strong></td>
<td>- 65 K</td>
<td>- 65 K</td>
</tr>
<tr>
<td><strong>NON-U (UNCORRECTED)</strong></td>
<td>- 5%</td>
<td>- 5%</td>
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<td>- 0.3%</td>
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<td>- 8 X 10^{-16} W/cm²</td>
</tr>
<tr>
<td><strong>FRAME RATE</strong></td>
<td>- 30 Hz</td>
<td>- f/2.3; 400 mm &amp; f/2 24 mm</td>
</tr>
</tbody>
</table>

**OPTICS**

- f/2.3; 400 mm & f/2 24 mm
**DUALBAND QWIP MOVIE**

**Features to look for,**
The cigarette lighter produce lots of hot CO2 gas. So, flare is broader MWIR due to CO2 emission, where as LWIR (8-9 microns) doesn't have any emission (just the heat). The hot cigarette lighter flame produce so much MWIR signal, it reflects off from the lens and Jason's face. The plastic piece Jason is holding is opaque in LWIR, but transparent in MWIR.

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**Format**
- 320x256 pixels, dualband & pixel co-registered

**Wavebands**
- 4.4-5.1 & 8-9 μm

**NEDT**
- 22 & 24 mK for 300K background with f/2 optics

**QE**
- 19% & 15%

**Photoconductive gain**
- 0.2 & 0.3

**Detectivity**
- > 2x10^{11} & 1x10^{11} Jones

**Operating temp.**
- 65 K

**Fill factor**
- > 81%
Mine Detection

- Mine Detection is a current issue that LWIR can answer
- QWIPs are a technology of choice.
1024 x 1024
Two-Color QWIP ROIC:
ISC0501
### 1024 x 1024 Pixels Dualband ROIC Specification

<table>
<thead>
<tr>
<th>ROIC Parameter</th>
<th>Specification Requirement</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Array Configuration</td>
<td>1024 x 1024</td>
<td>Large-format</td>
</tr>
<tr>
<td>Pixel Size</td>
<td>30µm x 30µm</td>
<td></td>
</tr>
<tr>
<td>Spectral Range</td>
<td>MWIR: 4.3-5.1um (Color A)</td>
<td>Drives well capacity requirements</td>
</tr>
<tr>
<td></td>
<td>LWIR: 8-9um (Color B)</td>
<td></td>
</tr>
<tr>
<td>Input Polarity</td>
<td>Hole Collection</td>
<td>GaAs/AlGaAs QWIP detector</td>
</tr>
<tr>
<td>Input Configuration</td>
<td>Direct Injection (DI)</td>
<td>P-Channel Inputs</td>
</tr>
<tr>
<td>Input Clock Rise and Fall</td>
<td>CLK: 10ns rise/fall</td>
<td>10% to 90%</td>
</tr>
<tr>
<td></td>
<td>FSYNC, DATA: 10ns rise/fall</td>
<td></td>
</tr>
<tr>
<td>Number of Outputs</td>
<td>8 Analog per color</td>
<td>Additional 1 reference output/Color Analog at 10MHz (8/Color+1Ref/Color=18 outputs total)</td>
</tr>
<tr>
<td>Output Modes</td>
<td>4, and 8 Analog per color</td>
<td>Common Output Mode for each color</td>
</tr>
<tr>
<td>Windowing</td>
<td>Row Only Windowing</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Minimum Window of 1 Rows</td>
<td></td>
</tr>
<tr>
<td>Frame Rate (1024 x 1024)</td>
<td>60Hz (8 outputs per color)</td>
<td>ITR, IWR, Additional 1 reference output/color</td>
</tr>
<tr>
<td>Total Well Capacity</td>
<td>≥ 17 x 10^6 carriers</td>
<td>Unit Cell Layout Limited, Goal of 20 x 10^6 carriers</td>
</tr>
<tr>
<td>Well Capacity Ratio</td>
<td>4:1 (LWIR:MWIR)</td>
<td>± 10%, Repartition can be accomplished with 1-3 layer mask change</td>
</tr>
<tr>
<td>Noise</td>
<td>≤ 420 e_rms^ at 3.4x10^6 e-</td>
<td>MWIR (Color A)</td>
</tr>
<tr>
<td></td>
<td>≤ 1250 e_rms^ at 13.6x10^6 e-</td>
<td>LWIR (Color B)</td>
</tr>
<tr>
<td>Power</td>
<td>≤ 600mW</td>
<td>8 Output Mode with No Output reference, Goal of ≤ 400mW</td>
</tr>
</tbody>
</table>
SUMMARY

- Demonstrated 1024x1024 pixel MWIR & LWIR focal plane arrays.
- Demonstrated 320x256 pixel MWIR/LWIR pixel collocated focal plane array.
- Increased QE from 19% to 36%. We will incorporate high QE material with dualband QWIPs.
Long-Wavelength Infrared (LWIR) Quantum Dot Infrared Photodetector (QDIP) Focal Plane Array
Motivation for Quantum Dot Based LWIR FPAs

✔ Build on the advantages of QWIP FPAs
  – Large format
  – Excellent uniformity
  – Excellent operability
  – Low 1/f noise
  – Thinned arrays eliminate
    • Optical crosstalk
    • Thermal mismatch with ROIC
    • Pixel delamination

+ Add quantum dot capabilities
  – Normal incidence absorption
  – Higher temperature operation (lower dark current)
  – Higher responsivity (longer lifetime)
  – Further increase the radiation hardness

= New generation of high performance high operating temperature infrared focal plane arrays
Outline

• Initial Device Development

• Focal Plane Array Development

• Improved quantum efficiency devices

• Summary
Initial Device Development
Quantum Dot Infrared Photodetectors (QDIPs)

- InAs quantum dots (QDs) embedded in GaAs matrix
- Quantum dots act as infrared absorbers
- Dot size and doping adjusted for optimum response
- Multiple stacks of QD layers grown to boost quantum efficiency
- Photoconductor
  - Unipolar device, n⁺ contacts.
Quantum Dot Growth

- Grown in JPL’s Veeco Gen III Molecular Beam Epitaxy (MBE) machine (4 inch capable)

- Quantum dots formed by a self-assembly process
  - Deposition of semiconductor on lattice-mismatched substrate

- InAs and InGaAs dots on GaAs substrates
Dot-in-the-Well (DWELL) QDIP

- Embed InAs dots in InGaAs quantum wells
- Motivation: Precise control of quantum well width enables easier wavelength tuning
Wavelength Tuning in DWELL QDIP

- Experimentally measured spectral responsivity of DWELL QDIP
- Continuous spectral tunability via well width variation

![Graph showing normalized responsivity vs wavelength (µm) with ability to tailor for MWIR to LWIR.]
Normal and 45° Incidence Response

• Much stronger normal incidence response as compared to quantum well infrared photodetectors (QWIPs)
• 45° incidence yields even stronger response
• Consistent with theoretical modeling results
Observation of strong 45° incidence response led to implementation of reflection grating
Normal incidence response now significantly enhanced by grating

Grating Enhancement
Internal Quantum Efficiency

- QDIPs typically have low QE. Prior published reports of QDIP QE in literature with QE at 0.1%.

- Internal QE of 0.67% was obtained for the initial DWELL-QDIP device through noise measurement.

- Subsequent material improvement yielded QE= 2.8% through FTIR absorption measurement.
Quantum Efficiency and Gain

• Conventional QDIPs have low QE and high gain
  – $g=823$, $\eta=0.02\%$, Appl. Phys. Lett. 84, 2166 (2004)
  – $g\sim1000$, $\eta\sim0.1\%$, Nanotech. 16, 219 (2005)
  – High gain due to polaron-relaxation related long carrier lifetime

• Dot-in-the-well QDIPs have smaller gain
  – Carriers trapped by quantum wells

• DWELL QDIPs have higher QE
  – Higher electron concentration near dots
  – More rapid refilling of QD ground state
  – Possibly leading to higher QE

• Can engineer trade-off between QE and gain
  – Note BLIP $D^*$ depends on absorption QE, independent of gain
QE and Gain Trade-Off in DWELL QDIP

- DW24-1 has a shallower quantum well: $g=2.4$, QE=1.2% (77K)
- DW20-3 has a deeper quantum well: $g=0.4$, QE=2.8% (77K)
Quantum Dot Infrared Focal Plane Array Development
Focal Plane Array

- Originally proposed a small 32x32 test array
- Detector: 30-stack InAs Q-dots embedded in InGaAs/GaAs quantum wells; doping=2 e per dot; single device QE=2.8%
- Integrated reflection grating structure
- 640x512; 25 µm pixel pitch (23 µm pixel width)
- ROIC:
  - direct injection, well capacity 11 million electrons
Infrared Imaging

- 640x512 image taken at 60 K using f/2 optics
- Non-uniformity <0.2% (corrected); >99% operability; NEDT = 40 mK
FPA Performance - Imaging

- 640x512 image taken at 60K using f/2 optics
FPA Uniformity

Average of 64 Frames

- Uncorrected nonuniformity < 6.7%
- Corrected nonuniformity < 0.2%
- Operability > 99%

Blackbody T = 20°C
FPA Figures of Merit

- Wavelength: 9 µm
- Array Size: 640x512
- Pixel Pitch: 25 µm
- Quantum Efficiency: 5%
- Detectivity: $2 \times 10^{10}$ Jones
- NEΔT: 40 mK
Improved Quantum Efficiency
Quantum Dot Infrared Photodetectors
Improved QE Device with Enhanced Normal Incidence Absorption

- Replaced InGaAs/GaAs with superior GaAs/AlGaAs quantum wells
- Less overall strain; more quantum dot stacks
- Improved doping profile in quantum well/dot region

Original

High QE Device

- 30 periods
- > 60 periods
Improved QE Device Performance

- Highest QE measured in QDIPs
  - DW 19-1, 40 QD stacks; DW19-2, DW19-3, 60 QD stacks
- First set of quantum dots in GaAs/AlGaAs wells are far from optimized but are yielding best D* among our DWELL devices
QDIP Exhibits High Normal Incidence

- Highest normal incidence response we have seen in an intersubband IR detector
- Expect further normal incidence response enhancement through integration of an optical reflection grating
Rapid Progress

- Significant improvements in D* and QE
  - D* normalized to 10 µm for ease of comparison
Summary

• QDIP Device Development
  – demonstrated high normal and 45° incidence responsivity
  – demonstrated utility of using an integrated reflection grating

• Highest quantum efficiency (QE) obtained in a quantum dot infrared photodetector (QDIP)
  – Demonstrated 16% absorption QE
  – Demonstrated the possibility of achieving improved QE over QWIP

• Demonstrated that QDIP FPA retains the uniformity advantages of QWIP FPA
  – Large-format (640x512) QDIP based FPA
  – High operability (>99%)
  – Low non-uniformity (< 0.2% corrected)
  – Low NEΔT (40 mK@ 60K)
Quantum Well and Quantum Dot Modeling
Motivation and Approach

• Experimentally measured photoresponse of an InAs/InGaAs/GaAs dot-in-the-well (DWELL) structure shows normal incidence response can be a sizeable fraction of the 45° incidence response.

• Experimentally measured photoresponse of an AlGaAs/GaAs/AlGaAs QWIP structure shows sizeable backgroud absorption at long wavelengths (>10 \( \mu \) m)

• Explore this physical phenomenon by theoretical investigation (14-band model + impurity) for possible explanations.
The fundamental transition (ground to $p_x$ or $p_y$ like states) yields no appreciable photocurrent.

- Very strong normal incidence absorption.
- But upper state is deeply bound

Observed photocurrent is attributed to transitions from the $s$-like ground state to states in the $p_z$- or $d$- like and higher states.

- Predominantly $z$-polarization absorption. (QWIP-like; can activate with grating)
- Also has weaker $x,y$-polarization (normal incidence) absorption.
Normal and 45° Incidence Response in Dot-in-the Well Structure

- 45° incidence yields stronger response
- Relative to the 45° response, the normal incidence response is much stronger than in QWIPs
- Similar behavior seen in QDIPs
Observation and Possible Explanations

- Relatively strong normal incidence response observed experimentally

- Simple effective mass model predicts no normal incidence oscillator strength for transitions from s-like ground state to $p_z$ like states.

- Possible Explanations:
  - Band structure effects (due to mixing with other bands)
  - Impurity scattering Effects
    - Dopant hydrogenic wave function radius can be comparable to size of quantum dot
  - Transition to higher states

- Investigate theoretically
Theoretical Analysis

- Energy and wave functions computed using a stabilized transfer matrix technique by dividing the system into many slices along growth direction.
- Envelope function approximation with energy-dependent effective mass is used.
- Effective-mass Hamiltonian in k-space:
  \[
  \left(\frac{k_x^2 + k_y^2}{m_t(E)} + \frac{\partial^2}{m_l(E) - E}\right)F(k) + \sum_k [V(k,k') + V_{\text{imp}}(k,k')]F(k') = 0
  \]
  is solved via plane-wave expansion in each slice.
- 14-band k·p effects included perturbatively in optical matrix elements calculation.

- Dopant effects incorporated as screened Coulomb potential.

- The technique applies to quantum wells and quantum dots (or any 2D periodic nanostructures).
Quantum Well
Band Structure Effect on Oscillator Strengths

- GaAs/Al$_{0.26}$Ga$_{0.74}$As quantum well
  - 54 Å wide GaAs well

- Band structure effect predicts > 0.2% $x$ to $z$ oscillator strengths ratio at $k_x = 0.02$

- In general agreement with results reported in the literature
Ground State Energy with Impurity

- With dopant, ground state energy vs. z-position (z=0 at edge, z=27 at well center)

- Green line is the ground state energy without dopants

- Single dopant simulation

- Different cell sizes used to simulate different doping concentration
Quantum Well Energy Levels with Dopant

- A single dopant is placed in a supercell with 100 Å lateral dimensions
  - Dopant located at 6 Å from cell of the 54 Å wide GaAs well

- Dopant potential binding energy ~ few meV

- Supercell zone folding effects seen in energy levels
Dopant Effects on Oscillator Strengths

- Incorporation of dopant potential can increase the normal incidence oscillator strength
- More realistic simulations can be done using larger supercells with multiple randomly placed dopants
Dopant Effects on Oscillator Strengths

- Simulation geometry
  - Supercell with 300 Å lateral dimensions
  - 10 randomly placed dopants in QW region of supercell

- Oscillator strength computed with the lowest 5 energy levels filled

- Only z oscillator strength when there is no dopant potential

- Dopants induce normal incidence oscillator strengths.
Absorption Coefficient

- 40 impurities and 8 impurities
- Low energy: intrasubband;
- xy dominant
Quantum Dot
Simulation Geometry

InAs quantum dot embedded in GaAs

- **Truncated pyramid (lens-shaped) QD on wetting layer**
  - Base width 265 Å
  - Dot height 25 Å
  - Wetting layer thickness 5 Å
  - Lens shaped dot

- **Incorporate dopant potential**
  - Single dopant
  - Vary lateral position
  - Vary vertical position
Charge densities of low-lying states in lens-shaped QD

s-like

p_x/p_y like

d-like

p_z like
Quantum Dot with Dopant Impurity
Energy Levels

- Single dopant in a supercell
- Dopant position
  - Vary lateral (x) position
  - Vertical position fixed at 5 Å above top of wetting layer
- Energy level of QD with no dopant indicated by:
  - Green dashed line: even in x
  - Blue dotted line: odd in x
- Degeneracy removed by off center dopants
Effect of Dopant Potential on Oscillator Strengths

- Examine transitions from s-like ground state to 2\textsuperscript{nd} set of excited states (d-manifold)

- No x oscillator strength without dopant potential

- With well-placed dopant, x oscillator strength can exceed z oscillator strength
Quantum Dot with Dopant Impurity Energy Levels

- Single dopant in a supercell
- Dopant position
  - Vary vertical (z) position
  - Lateral position fixed at 40 Å off center
- Energy level of QD with no dopant indicated by dashed lines
- Degeneracy removed by off center dopants
Effect of Dopant Potential on Oscillator Strengths

- Examine transitions from s-like ground state to 2\(^{nd}\) set of excited states (d-manifold)

- Varying vertical position of dopant

- No x oscillator strength without dopant potential

- With well-placed dopant, x oscillator strength can exceed z oscillator strength
Effect of Dopant Potential on Oscillator Strengths

- Single dopant within the quantum dot
  - X: 40Å off center
  - Z: 5 Å above top of wetting layer

- No impurity oscillator strengths plotted as drop lines
  - X and y symmetric

- At transition energies above that of the fundamental (s-p) transition, dopant potential in general increases normal incidence oscillator strength at the expense of z oscillator strength
Summary

• Observed relatively strong normal incidence photoresponse in low-aspect ratio quantum dot devices

• Theoretical investigations indicate scattering due to dopant impurity potential could contribute to normal incidence response