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Advancing manufacturing of next-generation light technologies

EPSRC
Engineering and Physical Sciences Research Council

# Mid Infra-red Devices Opportunities and Challenges

Professor Jon Heffernan
University of Sheffield

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# Introduction

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- **Photonics is an underpinning discipline**
- **Huge value across a broad range of industry sectors**
- **Challenge is the integration of many technologies into low-cost, high value manufacturing processes**
- **In this session we focus on Mid Infra-red Photonics as a strongly emerging opportunity and a key capability within the HUB**

## Industry sectors

**Impacting strategic UK industrial sectors by working with partners throughout the value chain.**

Oil and gas | Imaging | Automotive | ICT | Medicine and healthcare | Metrology

Defence and security | Aerospace | Energy | Manufacturing | Telecommunications

## Grand Challenge: Integration

**Developing new low-cost, efficient manufacturing processes to integrate technology platforms and to enable new devices and components including lasers, sensors, new light sources, modulators, transceivers and photonics sub-systems etc.**

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# Today's Presentations

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**MIR Devices (Professor Jon Heffernan, Sheffield)**
- Introduction to laser, LED, detector capabilities in Sheffield

**Silicon Photonics Platforms (Professor Goran Mashanovich, Southampton)**
- Introduction to the Silicon and Germanium based integrated Photonics platforms in Southampton

**Chalcogenide Photonics (Professor Dan Hewak, Southampton)**
- Introduction to MIR fibre and optoelectronic technologies at Southampton

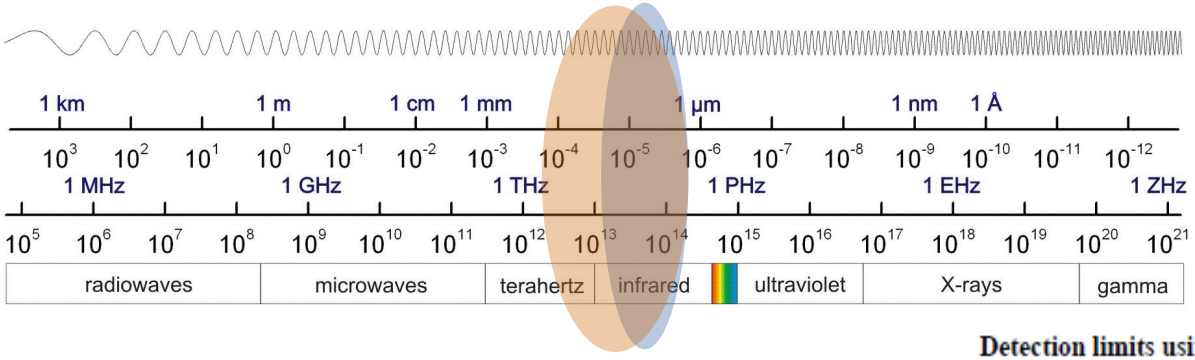
**Optical Coherence Tomography (Professor Steve Matcher, Sheffield)**
- Introduction to OCT technologies and illustration of integration needs and opportunities

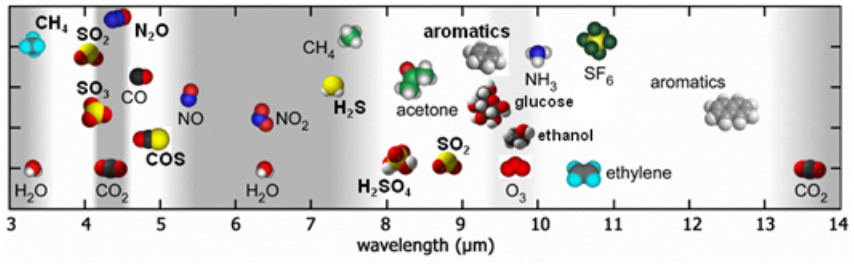
**MIR European Foundry (Iwan Davies, IQE Europe)**
- Introduction to a new European foundry and scale-up opportunities out of Hub work

# Why Mid Infra Red?



**Much of the value in MIR Photonics is in accessing optical activity of environmental substances and materials and low loss transmission in free space**



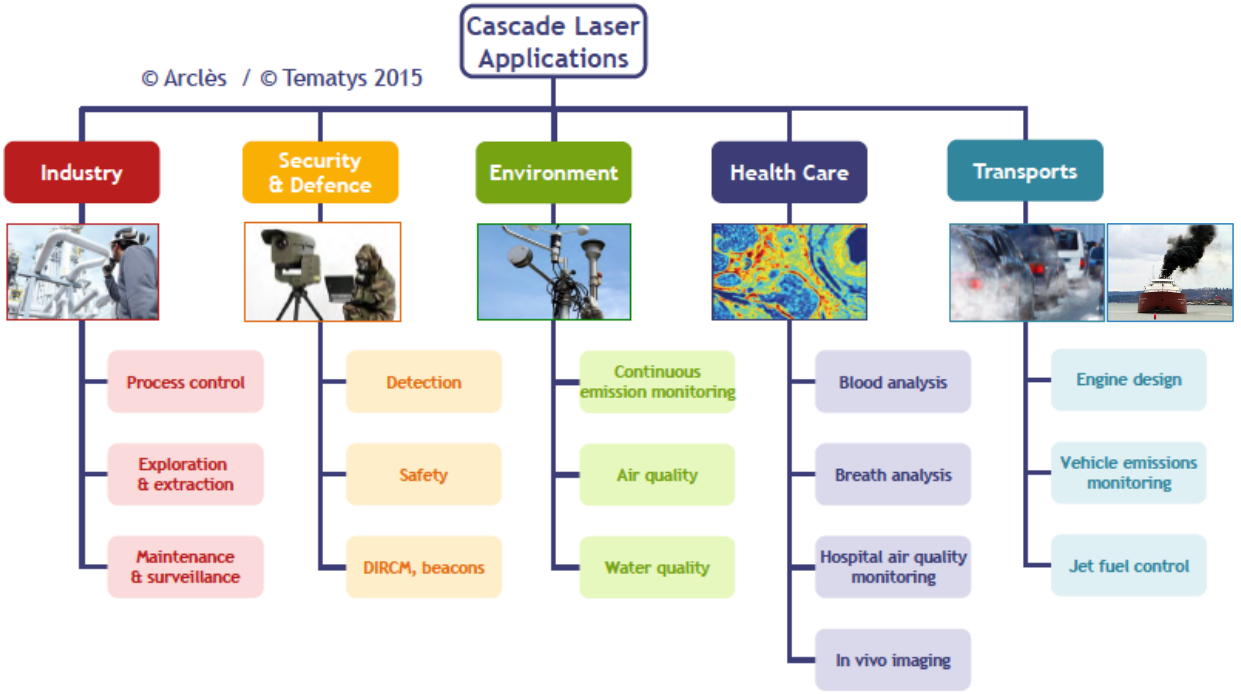

**Detection limits using diode laser spectroscopy**

| Molecule | *ppb* | mid-IR (λ) | *ppb* | Near-IR (λ) |
|---|---|---|---|---|
| H2O | *2.0* | 5.94 µm | *60* | 1.39 µm |
| CO2 | *0.13* | 4.23 µm | *3000* | 1.96 µm |
| CO | *0.75* | 4.6 µm | *500* | 2.33 µm |
| NO | *5.8* | 5.25 µm | *60000* | 1.8 µm |
| CH4 | *1.7* | 3.26 µm | *600* | 1.65 µm |
| HCl | *0.83* | 3.4 µm | *150* | 1.79 µm |
| H2OC | *8.4* | 3.55 µm | *50000* | 1.93 µm |
| NH3 | *0.8* | 10.3 µm | *800* | 1.5 µm |

# Applications



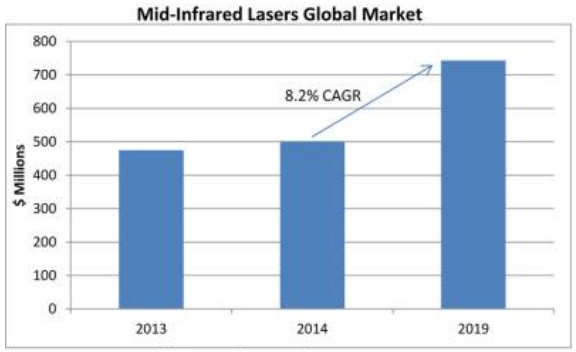
Diverse application space with technological, societal and regulatory drivers for innovation



# Market Opportunities

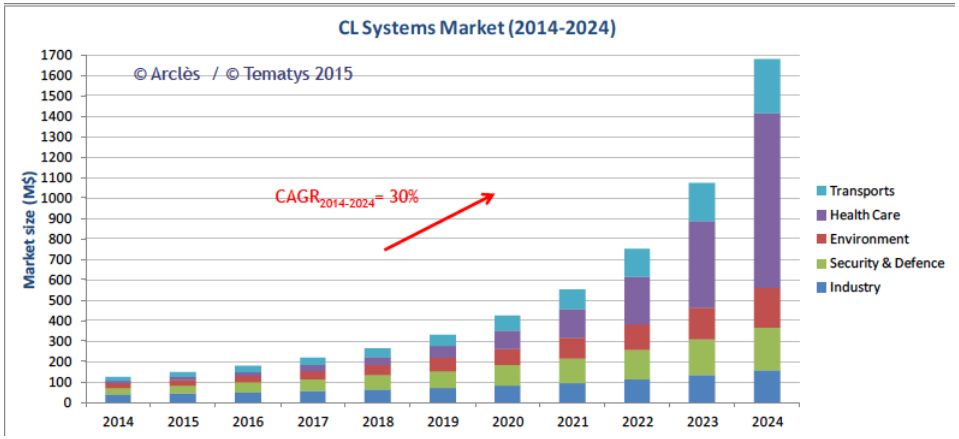


- **Significant growth in Mid-IR laser markets as new technology innovations have emerged and manufacturability of technology such as QCLs has become established. CAGR 8%**




Source: BCC Research (PHO016A), November 2014

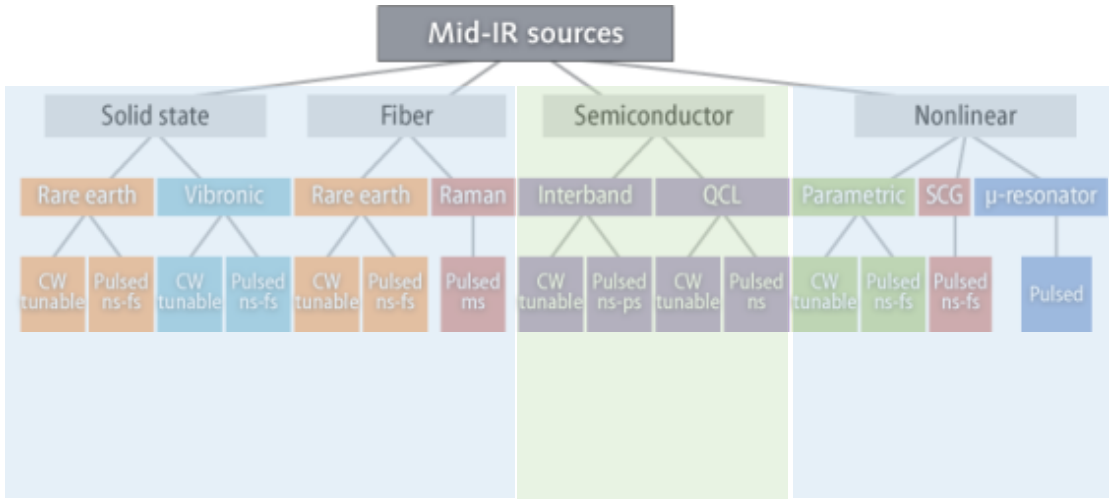
- **Larger applications markets in sensing, monitoring, countermeasures and healthcare, CAGR 30%**



# MIR Devices



**Active areas of Research in Southampton**




**Active areas of Research in Sheffield**

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# III-V Semiconductor Capabilities in the Hub

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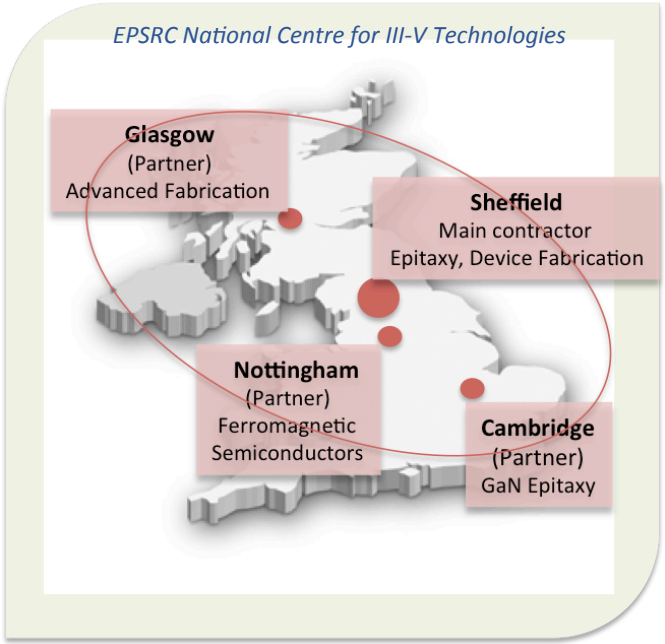
**Longstanding experience in the growth of III-V semiconductors in University of Sheffield**
**Material supply to the Hub through the EPSRC National Centre for III-V Technologies (since 1979)**





*Extensive Epitaxy and device processing capability including:*

- *9 MBE and MOVPE reactors*
- *High spec device fabrication cleanrooms*
- *Full suite of materials and device characterization*
- *Working with many companies as well as academia*
- *ISO9001 certified*

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# Sheffield Epitaxy

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All major III-V materials and devices supplied covering spectral range from UV to THz

## Epitaxy

- Arsenides (MBE and MOVPE)
- Phosphides (MBE and MOVPE)
- Antimonides (MBE)
- Dilute Nitrides (MBE)
- Nitrides (MOVPE, MBE)
- Novel materials (Bismides, ferromagnetics…)
- Quantum Dots and Nanowires
- 2D materials and Van der Waals epitaxy (MBE)

## DEVICES

- Edge Emitting Lasers
- VCSELs
- VECSELs, SESAMs
- Quantum Cascade Lasers
- LEDs, SLEDs
- Multijunction Solar Cells
- Detectors (including SPADs)
- Modulators
- Single Photon emitters
- Photonic crystal devices
- Microcavities
- RTDs
- FETs, HEMTs and power electronics
- Nanostructures
- Magnetic heterostructures

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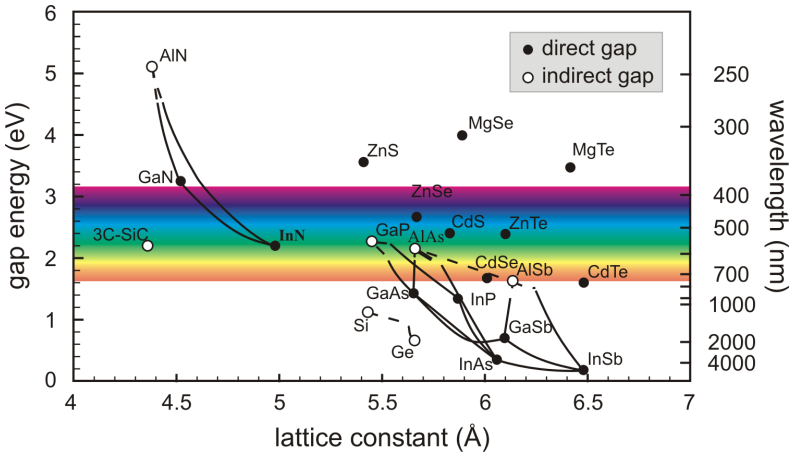
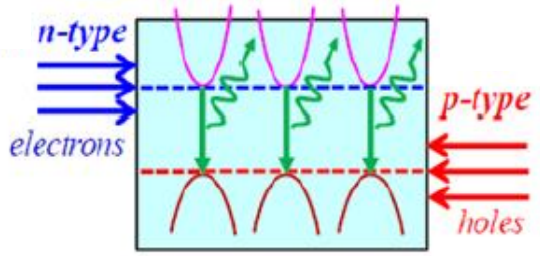
# MIR Devices





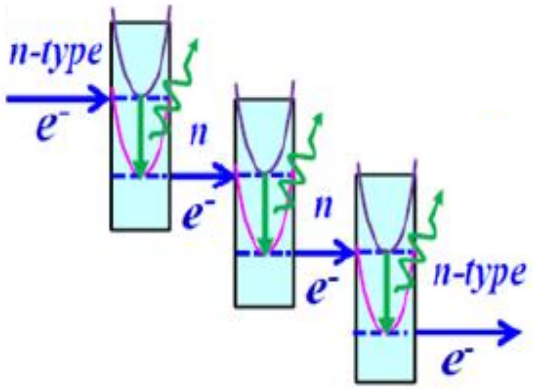

Conventional interband emitters such as lasers and LEDs (and detectors in reverse)

## Challenging materials for such devices

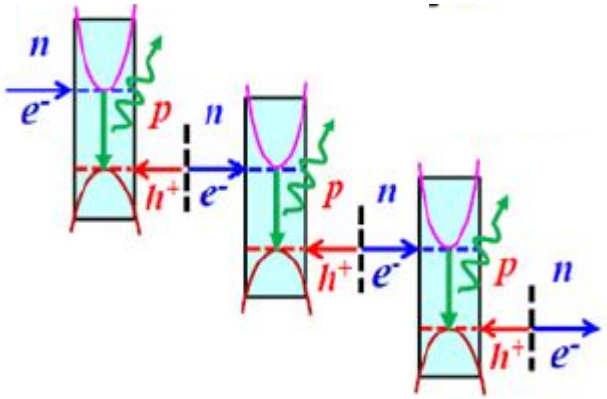
- Limited and expensive substrates
- High intrinsic carrier concentrations
- Auger recombination
- Difficulty with lattice matching of alloys and with mixed group-V materials

# Solution: Cascade Structures






Intersubband Cascade structures



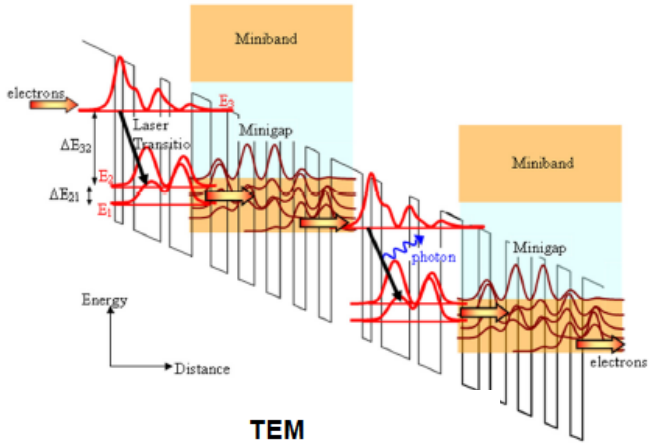

Type II Interband Cascade structures

# Quantum Cascade Lasers

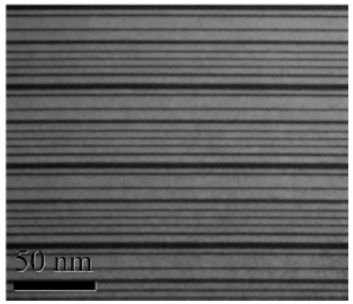


+ Emission determined by quantum confined energy levels in Quantum wells =>
  Not dependent on bandgaps (not exactly true)
+ Emission from ~3micron to THz region (with appropriate design)
+ Broad gain profile allowing for large tuning range and very narrow linewidths in single devices

- Very challenging epitaxy (thousands of layers)
- Short and long wavelength regimes are still difficult with low temperature operation




TEM



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# Sheffield a pioneer in Quantum Cascade Lasers

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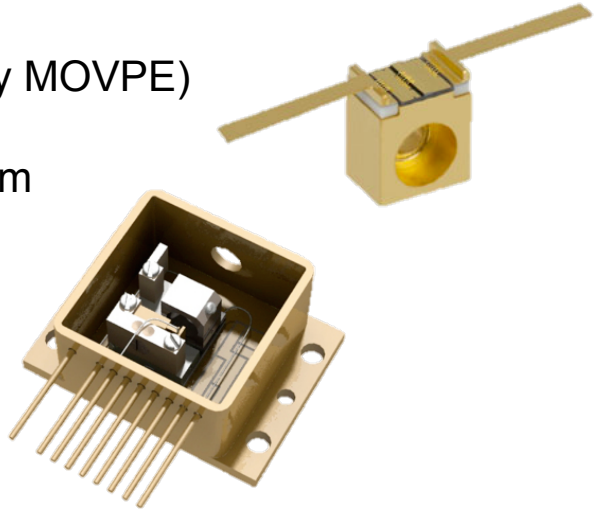
## Broad experience and capabilities for QCLs in Sheffield

- QCLs by MBE and MOVPE (first group in world to demonstrate by MOVPE)
- GaAs/AlGaAs system, InGaAs/InP system, InGaAs/InGaSb system
- Wavelengths from 3.1micron to 12micron
- Watt-class outputs
- DFB structures for single mode narrow linewidth
- Our lasers have been incorporated in a variety of systems including into commercial systems for gas and environmental sensing



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# Quantum Cascade Lasers

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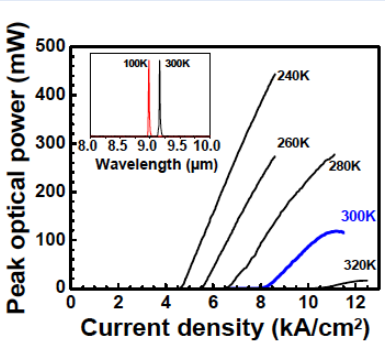
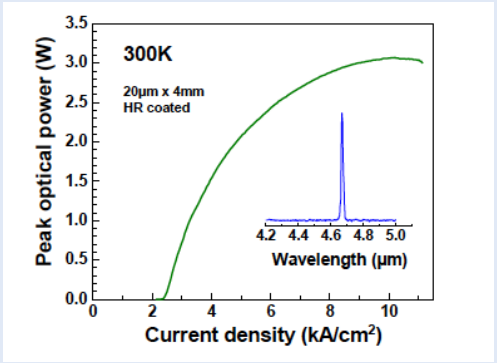
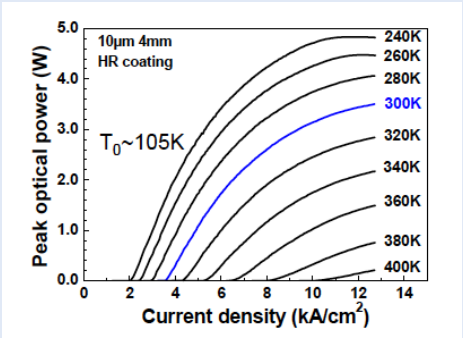
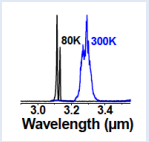



GaAs/AlGaAs QCLs at 9μm band by MOVPE

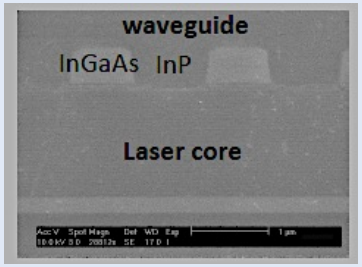



InGaAs/InAlAs/InP QCLs at 5μm band by MOVPE

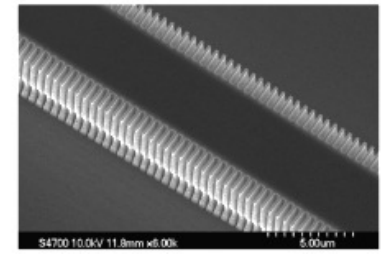


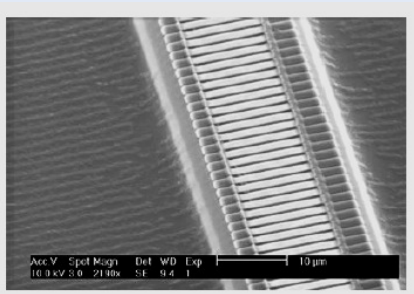

InGaAs/AlAsSb QCLs at 3.3μm by MBE with MOVPE overgrowth

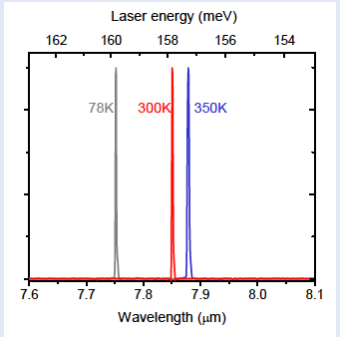



3rd Order buried grating



1st Order lateral grating






DFB laser Operation

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# New Directions and Manufacturability



**Remaining key challenges and opportunities at device level include:**

- Mass manufacture of QCLs is still to be achieved. Partially market limited but very challenging epitaxy
- Further progress in wall-plug efficiency, high power, low threshold, tunable and mode-locked lasers still required
- More work on thermal management and packaging technologies required

# New Directions within the HUB



**Hub will address major new device innovation and significant advances in applications-driven integration for manufacturing**

- We will be developing improved QCLs
- We will be developing Interband Cascade lasers for improved device performance and manufacturability
- We will develop Sb-based MOVPE for manufacturing of short wavelength QCL and ICLs
- LEDs and detectors also based on these approaches are possible

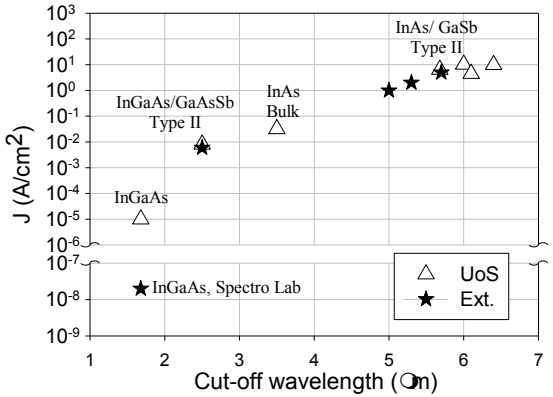
# Beyond Sources



## Other III-V Technologies available within the HUB

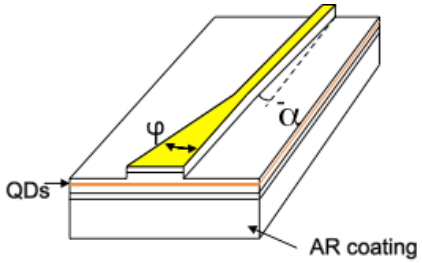
### Detectors

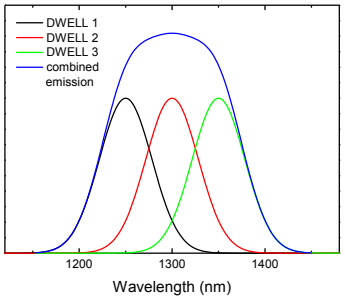
- Critical component in high sensitivity applications. MIR is particularly challenging
- High quality Epitaxy
- Broad materials coverage for full wavelength range
- Detector design and innovation




### SLEDs

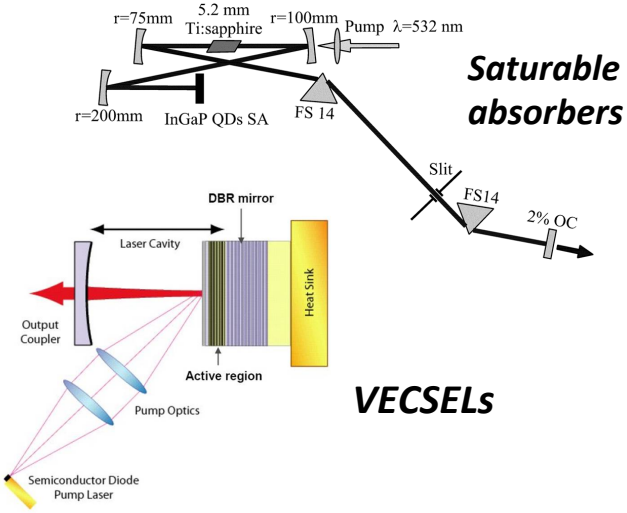
- Broad spectral emission
- Less critical epitaxy than lasers
- Limited power applications




### Solid-state Hybrids

- Semiconductor component in solid-state laser systems
- Variety of challenges at MIR




***Saturable absorbers***

***VECSELs***

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# MIR-Sensing Platform

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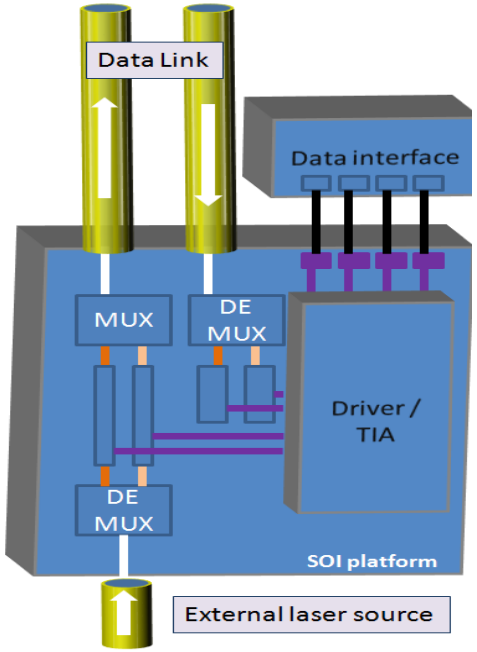
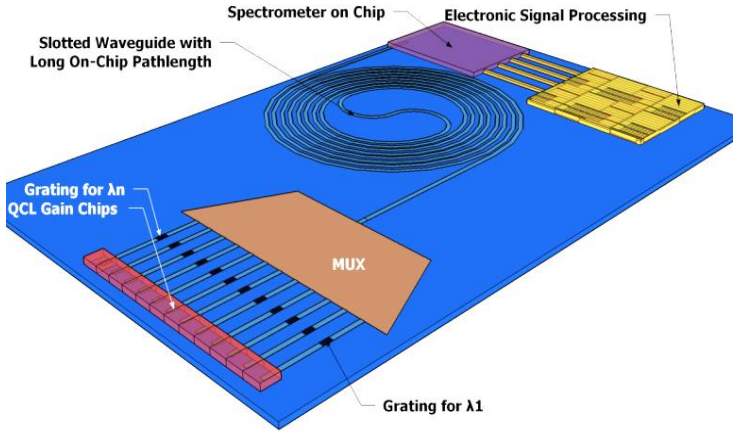
## Hub will address major new device innovation and significant advances in applications-driven integration for manufacturing




Silicon Photonics platform (NIR)




MIR sensing platform

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# Conclusion



**World class III-V Semiconductor Epitaxy and device fabrication facilities available through the Hub:**

- **Innovation in semiconductor devices in the Mid-infra red**
- **Developing integrated applications-led platforms**
- **Working with industry and academic partners to develop high value manufacturing processes**

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# Thank you for your attention