



UNIVERSITY OF LEEDS

This is a repository copy of *Theory and design of (111) oriented Si/SiGe quantum cascade lasers*.

White Rose Research Online URL for this paper:
<http://eprints.whiterose.ac.uk/110097/>

Version: Published Version

Conference or Workshop Item:

Valavanis, A orcid.org/0000-0001-5565-0463, Lever, LJM, Evans, CA et al. (2 more authors) Theory and design of (111) oriented Si/SiGe quantum cascade lasers. In: Photon 08, 26-29 Aug 2008, Edinburgh, UK. (Unpublished)

Reuse

Unless indicated otherwise, fulltext items are protected by copyright with all rights reserved. The copyright exception in section 29 of the Copyright, Designs and Patents Act 1988 allows the making of a single copy solely for the purpose of non-commercial research or private study within the limits of fair dealing. The publisher or other rights-holder may allow further reproduction and re-use of this version - refer to the White Rose Research Online record for this item. Where records identify the publisher as the copyright holder, users can verify any specific terms of use on the publisher's website.

Takedown

If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing eprints@whiterose.ac.uk including the URL of the record and the reason for the withdrawal request.



eprints@whiterose.ac.uk
<https://eprints.whiterose.ac.uk/>



Theory and design of (111) oriented Si/SiGe quantum cascade lasers

A. Valavanis*, L. Lever, C. A. Evans, Z. Ikonić and R. W. Kelsall

* a.valavanis05@leeds.ac.uk



- Conduction band structure
- QCL design
- Transport calculations
- Waveguide modelling and gain

(001) conduction band

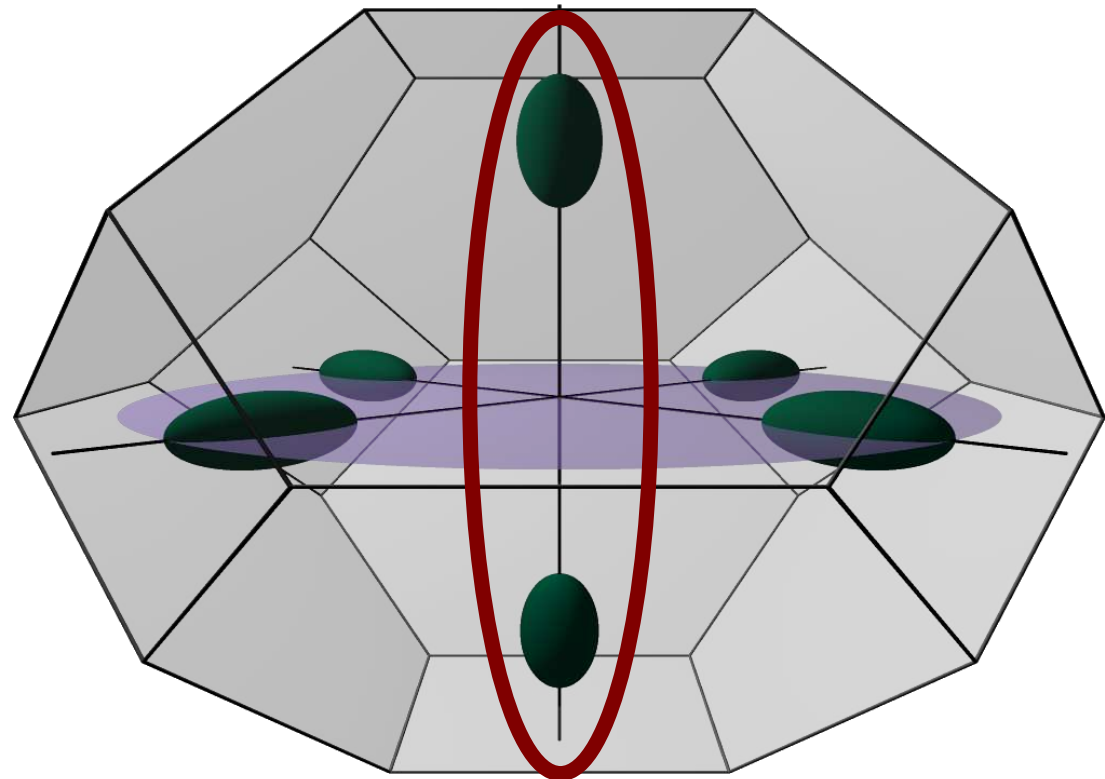


UNIVERSITY OF LEEDS

Bulk Si/SiGe band edge in 6 valleys (for Ge < 85%)

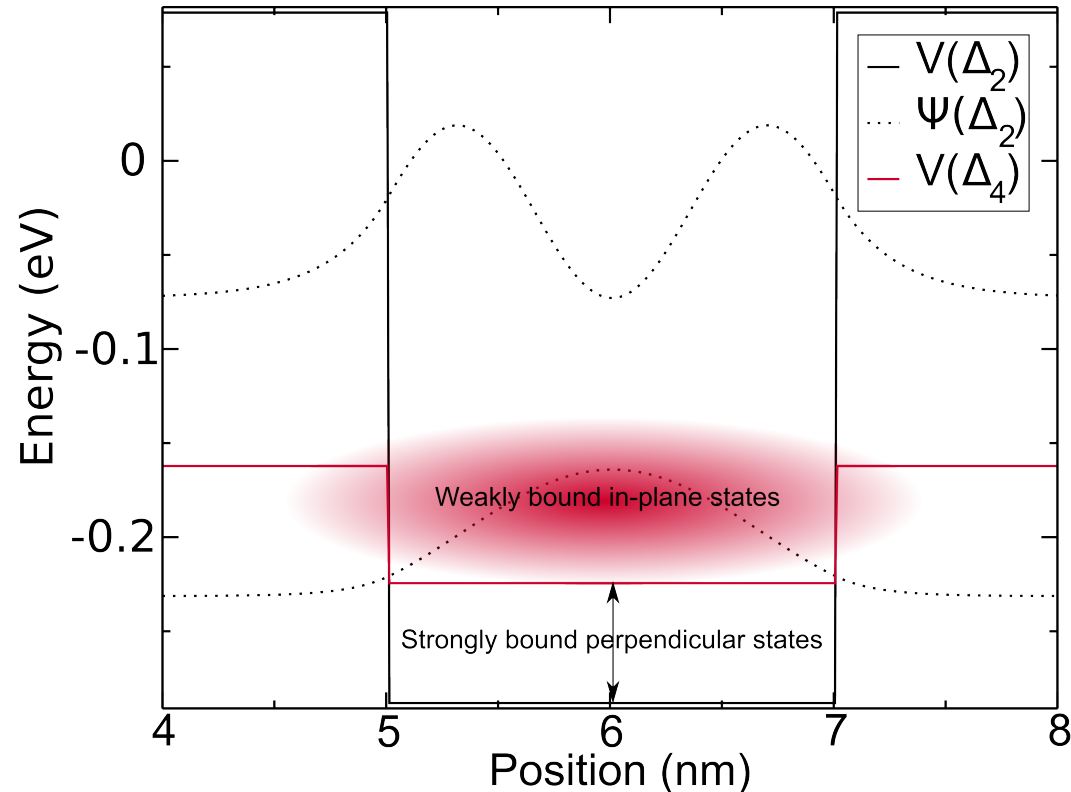
QCL design complicated due to:

- Strain → **different energies for valley sets (perpendicular & in-plane)**
- Anisotropy → **different effective masses for valley sets**
- Perp. effective mass $\approx 0.92 m_e$ → **small oscillator strength**



Usable (001) band offset limited [2]:

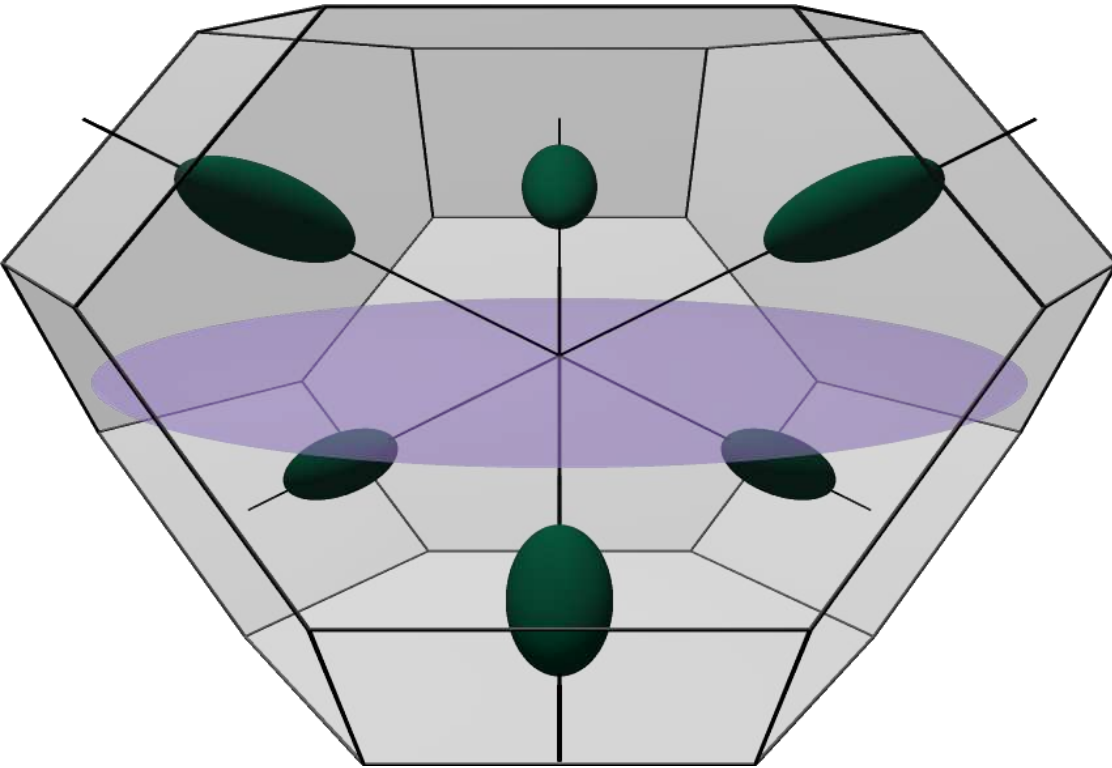
- Deep quantum wells for perp. valleys. ($\Delta V \approx 400$ meV)
→ **Strongly bound states**
- **But**, shallow wells for in-plane valleys overlap
→ **Strong optical absorption**
→ **Leakage currents**
- QCL design limited to energies below in-plane valleys



(111) conduction band



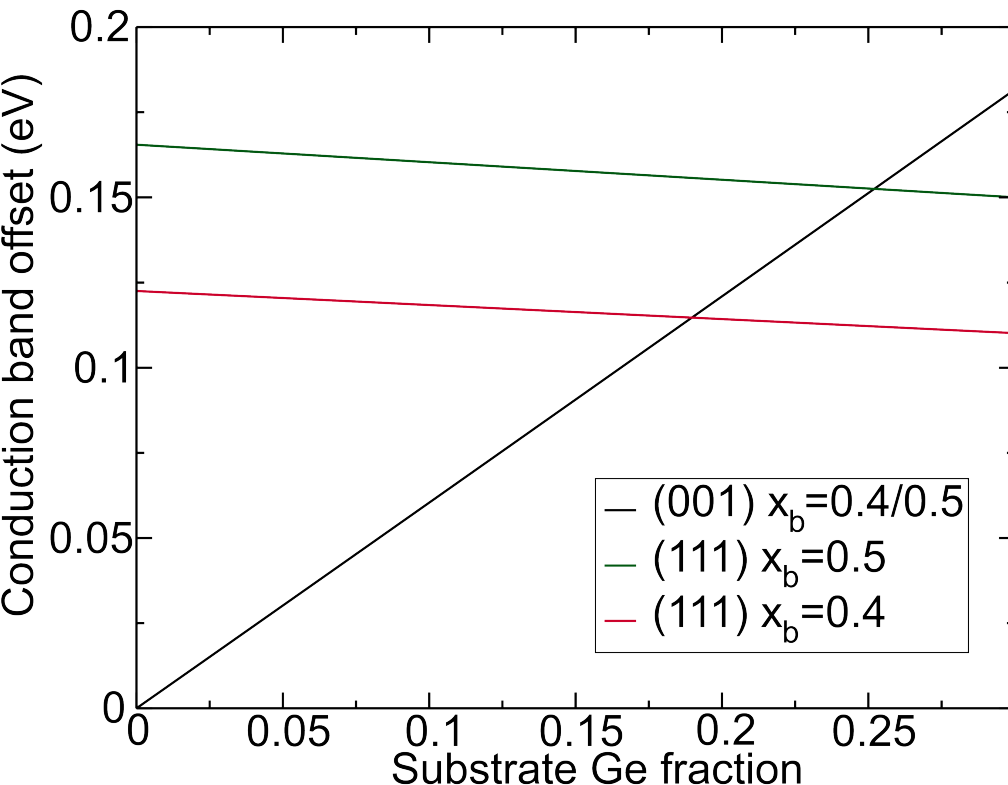
UNIVERSITY OF LEEDS



Many problems solved by moving to (111) orientation:

- Identical valley cross-sections
 - **All valleys at same energy**
 - **All effective masses identical**
- Smaller quantisation effective mass $\approx 0.26 m_e$ [1]
 - **larger oscillator strength**

[1] S. Smirnov & H. Kosina, Solid-State Electron. **48**, 1325 (2004)



- (001) energy range limited by strain splitting between valley sets

→ **Large substrate Ge content desirable**

- But ~10% Ge needed for mechanical stability

→ **Usable energy range ~ 50 meV**

- No strain splitting between valleys in (111) orientation

→ **Band offset increases with barrier Ge fraction**

→ **50% Ge barriers give 150 meV band offset**

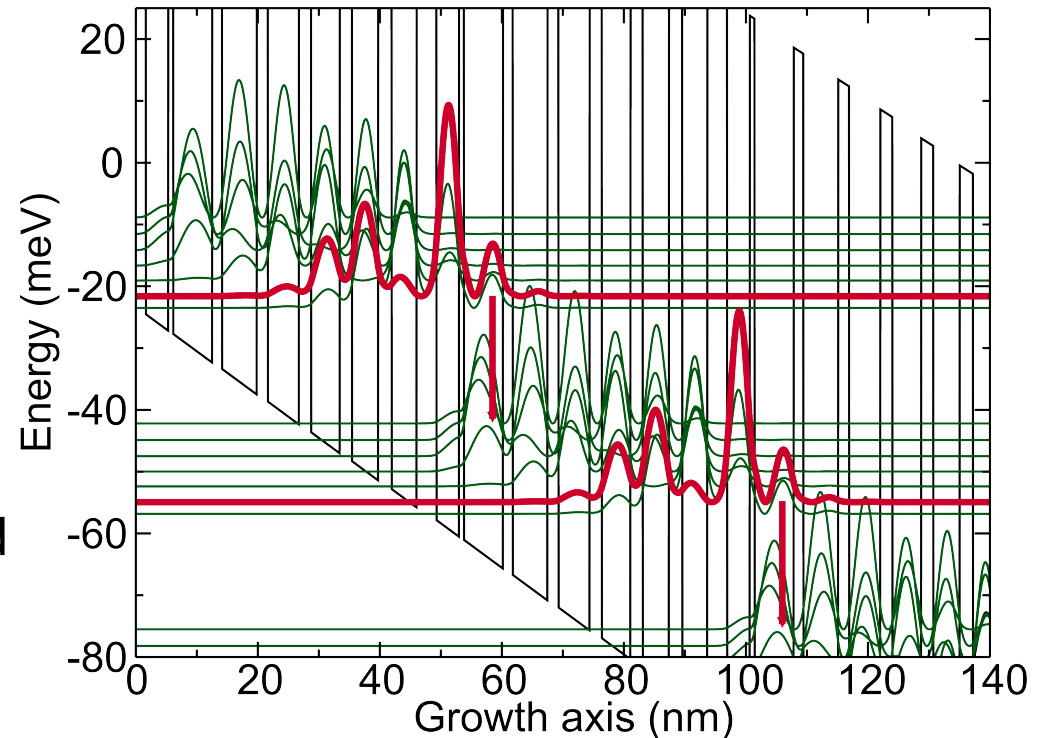


Bound to continuum QCL design

UNIVERSITY OF LEEDS

5.2 THz, seven well design

- Optical transition between **bound state** and **continuum states**
- Si wells/ $\text{Si}_{0.6}\text{Ge}_{0.4}$ barriers
- n-type doping of $5 \times 10^{16} \text{ cm}^{-3}$ throughout (modulation doping may be poor)
- Designed for 7.4 kV/cm applied electric field
- 10% Ge virtual substrate for strain balance



Scattering rates used to determine populations:

- Time independent perturbation model of scattering
- Self-consistent solution of rate equations gives populations

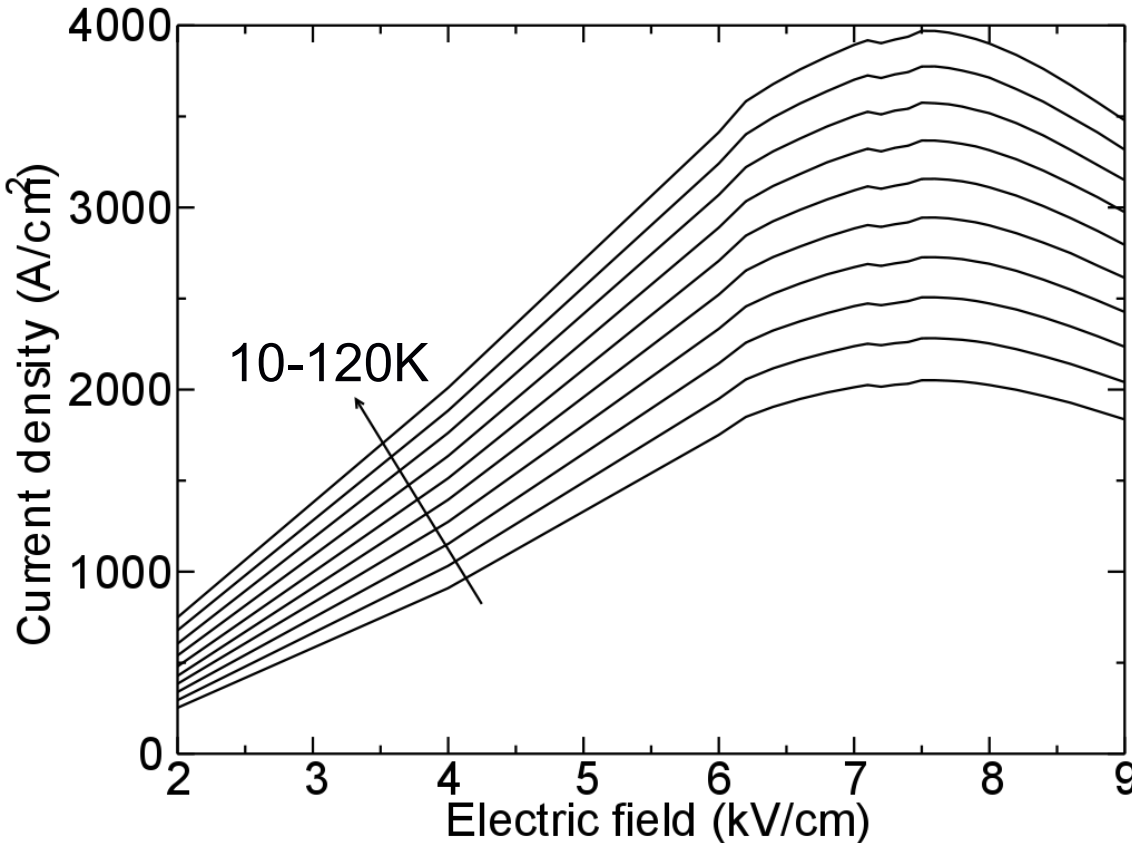
Population inversion achieved:

- Fast Coulombic scattering depopulates miniband
- Long upper laser level lifetime:
 - Si wells minimise alloy disorder scattering
 - Low Ge barriers reduce interface roughness
 - Optical transition (20 meV) below phonon energy (43 meV)

Current density



UNIVERSITY OF LEEDS



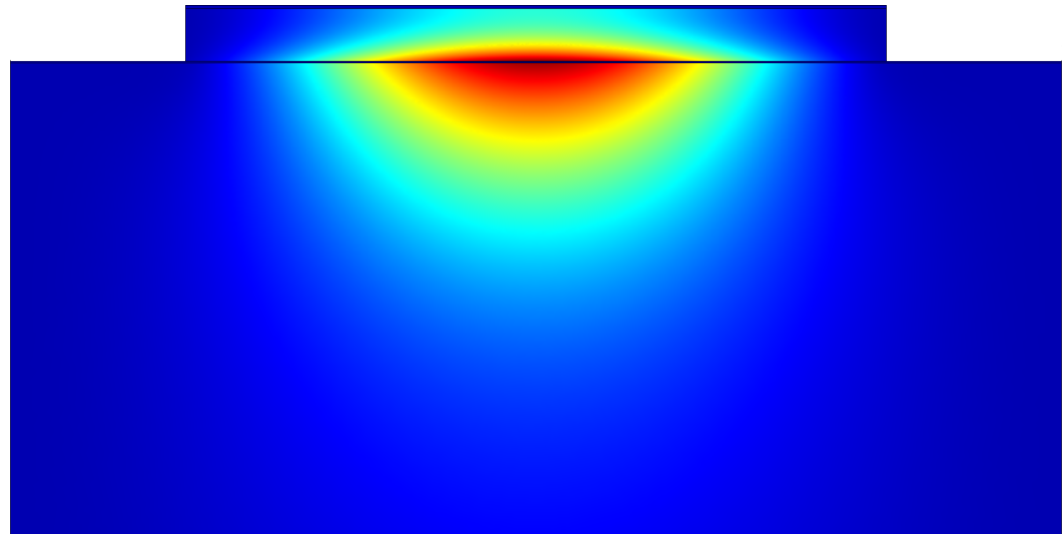
- Current density peaks at design field due to band alignment
- Low temperature peak of 2 kA/cm^2
- Current increases with temperature due to faster scattering

2D finite element modelling of modal overlap:

Surface plasmon waveguide:

- Poor confinement, $\Gamma=17\%$
- Low waveguide losses $a_w=10 \text{ cm}^{-1}$
- High threshold gain:

$$g_{\text{TH}} = \frac{a_w + a_m}{\Gamma} = 68 \text{ cm}^{-1}$$



Double-metal waveguide:

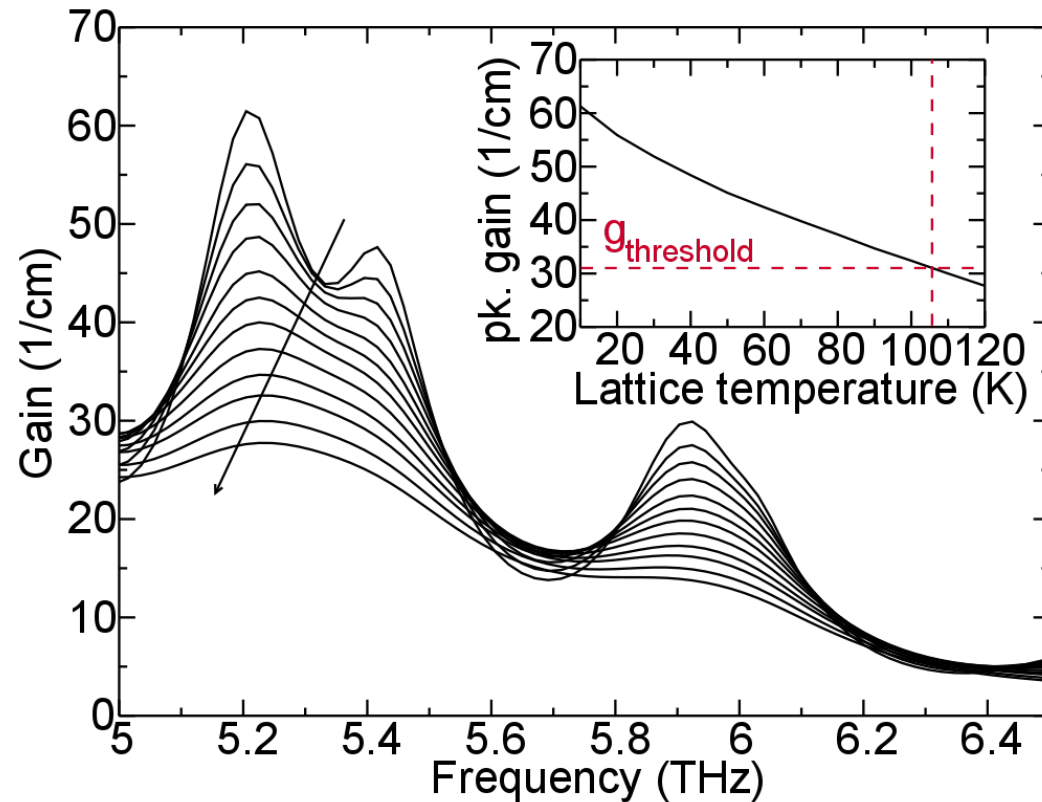
- $\Gamma=100\%$
- Threshold gain of 31 cm^{-1}

Gain spectrum



UNIVERSITY OF LEEDS

- Calculated at 7.4 kV/cm applied electric field
- Peak at 5.2 THz
- Other peaks due to transitions to lower energy subbands
- Gain decreases with temperature due to
 - Linewidth broadening
 - Reduced population inversion
- Gain exceeds losses up to 105 K



(111) oriented Si/SiGe is a good candidate for THz QCLs

- Low effective mass: $m_q = 0.26 m_e$
- Large usable band offset: $\Delta V \sim 150 \text{ meV}$

Net gain predicted for bound-to-continuum laser

- 5.2 THz emission
- Double metal waveguide has gain threshold of 31 cm^{-1}
- Gain predicted up to 105 K

Acknowledgments



UNIVERSITY OF LEEDS

This work is supported by

- EPSRC doctoral training allowance funding
- DTI-MNT contract 491: “Fast THz Cameras”

EPSRC

Engineering and Physical Sciences
Research Council

dti