SAND2016-0387PE

MBE Growth of THz & LWIR QCLs

John Reno

THz QCL Example Structure

GaAs LTG (250 C) cap layer		35 A
GaAs	$5x10^{19}$ cm^{-3}	100 A
GaAs	$5x10^{18}$ cm^{-3}	500 A
$Al_{0.15}Ga_{0.85}As$	undoped	33.9 A (12 ML)
GaAs	$1.9x10^{16}$ cm^{-3}	161.0 A (57 ML)
$Al_{0.15}Ga_{0.85}As$	undoped	31.1 A (11 ML)
GaAs	undoped	96.1 A (34 ML)
$Al_{0.15}Ga_{0.85}As$	undoped	48.0 A (17 ML)
GaAs	undoped	53.7 A (19 ML)
$Al_{0.15}Ga_{0.85}As$	undoped	11.3 A (4 ML)
GaAs	undoped	53.7 A (19 ML)
$Al_{0.15}Ga_{0.85}As$	undoped	14.1 A (5 ML)
GaAs	undoped	45.2 A (16 ML)
$Al_{0.15}Ga_{0.85}As$	undoped	11.3 A (4 ML)
GaAs	undoped	48.0 A (17 ML)
$Al_{0.15}Ga_{0.85}As$	undoped	33.9 A (12 ML)
GaAs	$1.9x10^{16}$ cm^{-3}	161.0 A (57 ML)
$Al_{0.15}Ga_{0.85}As$	undoped	31.1 A (11 ML)
GaAs	undoped	96.1 A (34 ML)
$Al_{0.15}Ga_{0.85}As$	undoped	48.0 A (17 ML)
GaAs	$3x10^{18}$ cm^{-3}	0.8 μm
$Al_{0.55}Ga_{0.45}As$	undoped	0.1 μm
S. I. GaAs substrate		

Many Interfaces

Repeat 163 times

Total Active Thickness ~10 μm

Thin Accurate Layers

No Doping

Accurate Doping

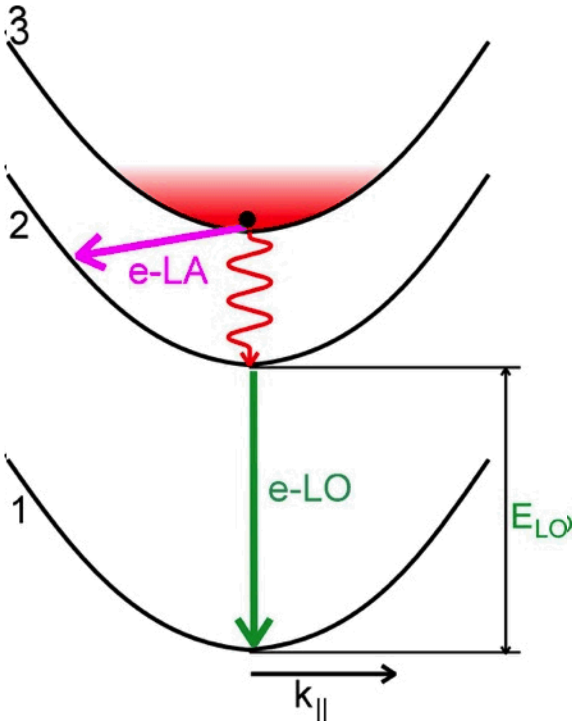
High Al Content

Terahertz intersubband scattering mechanisms

Population inversion:

$$\Delta N = \frac{J}{e}\tau_3\left(1-\frac{\tau_2}{\tau_{32}}\right)$$

must have $\tau_{32} > \tau_2$



$\tau_{21} \approx 0.3$ ps depopulation (e-LO)

$\tau_{32,rad} \sim 10\mu s$ radiative lifetime

$\tau_{e-LA} \sim 100$ ps acoustic-phonon

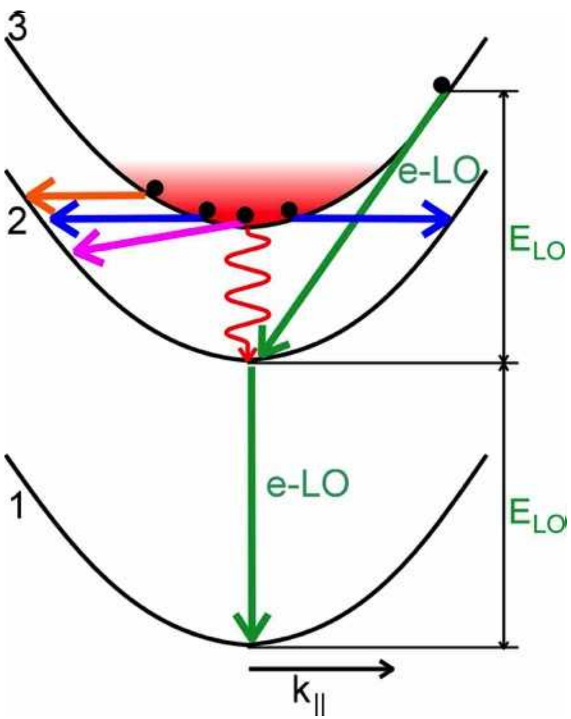
~ Operating Temperature Dependent
=> Growth Does Not Affect, Only Design

Terahertz intersubband scattering mechanisms

Population inversion:

$$\Delta N = \frac{J}{e}\tau_3\left(1-\frac{\tau_2}{\tau_{32}}\right)$$

must have $\tau_{32} > \tau_2$



$\tau_{21} \approx 0.3$ ps depopulation (e-LO)

$\tau_{32,rad} \sim 10\,\mu s$ radiative lifetime

$\tau_{e-LA} \sim 100$ ps acoustic-phonon

$\tau_{e-imp} \sim 7-20$ ps impurity scattering

=> Need VERY Low Background Impurities

Growth Conditions/Techniques

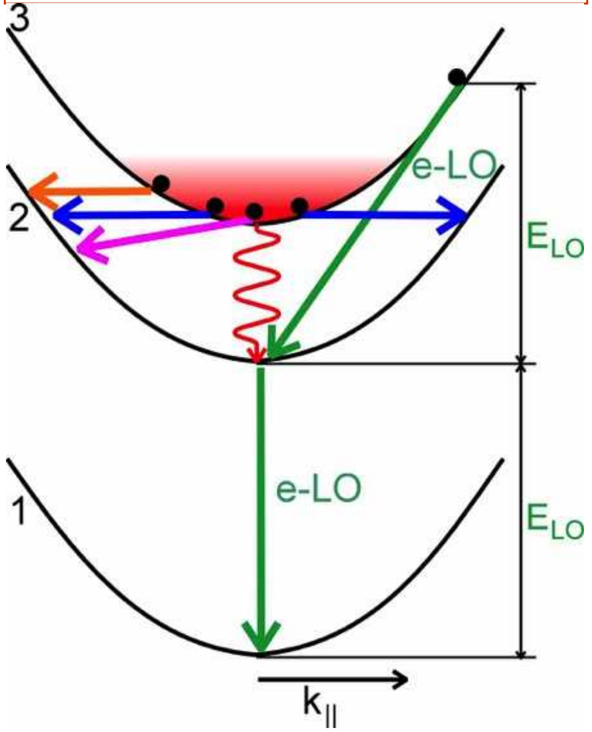
- Issue: Unintentional Background Impurities
- Solutions:
  - Do Not Open System (> a year)
  - Long Slow System Bake Out
  - Outgassing of All Cells & Heaters Prior to Use
  - All Unnecessary Filaments Off

Terahertz intersubband scattering mechanisms

Population inversion:

$$\Delta N = \frac{J}{e}\tau_3\left(1-\frac{\tau_2}{\tau_{32}}\right)$$

must have $\tau_{32} > \tau_2$



$\tau_{21} \approx 0.3$ ps depopulation (e-LO)

$\tau_{32,rad} \sim 10\,\mu s$ radiative lifetime

$\tau_{e-LA} \sim 100$ ps acoustic-phonon

$\tau_{e-imp} \sim 7$ - 20 ps impurity scattering

$\tau_{e-\mathrm{int}} \sim 10$ ps ??? interface roughness

=> Need VERY Smooth Interfaces

Growth Conditions/Techniques

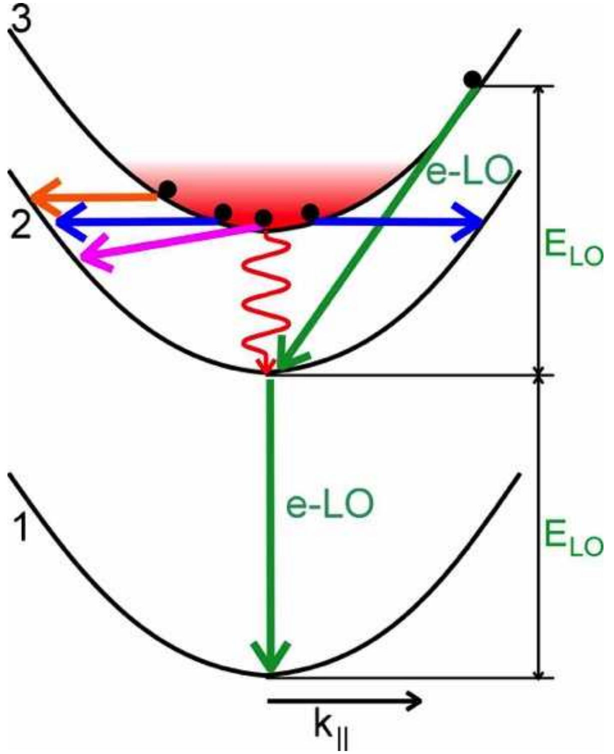
- Issue: Interface Quality
- Problems: High Al Content, Many Thin Layers
- Solutions:
  - Pauses in Lower Contact Layer
  - Growth Temperature 630-635°
  - High Rotation Rates 20-30 rpm
  - High Al Shutter Speed

Terahertz intersubband scattering mechanisms

Population inversion:

$$\Delta N = \frac{J}{e}\tau_3\left(1-\frac{\tau_2}{\tau_{32}}\right)$$

must have $\tau_{32} > \tau_2$



$\tau_{21} \approx 0.3$ ps depopulation (e-LO)

$\tau_{32,rad} \sim 10\,\mu s$ radiative lifetime

$\tau_{e-LA} \sim 100$ ps acoustic-phonon

$\tau_{e-imp} \sim 7$ - 20 ps impurity scattering

$\tau_{e-\mathrm{int}} \sim 10$ ps ??? interface roughness

$\tau_{e-e} \sim 5$ - 50 ps ? electron-electron

=> Need No Additional Doping
=> Need Accurate Doping Control

Growth Conditions/Techniques

- Issue: Doping Accuracy (<5%)
- Solutions:
  - Precalibrate Si Cell at Values Desired
  - Allow Sufficient Time for Stabilization

THz QCL Example Structure

GaAs	LTG (250 C) cap layer		35 A
GaAs		$5x10^{19}$ cm^{-3}	100 A
GaAs		$5x10^{18}$ cm^{-3}	500 A
$Al_{0.15}Ga_{0.85}As$		undoped	33.9 A (12 ML)
GaAs		$1.9x10^{16}$ cm^{-3}	161.0 A (57 ML)
$Al_{0.15}Ga_{0.85}As$		undoped	31.1 A (11 ML)
GaAs		undoped	96.1 A (34 ML)
$Al_{0.15}Ga_{0.85}As$		undoped	48.0 A (17 ML)
GaAs		undoped	53.7 A (19 ML)
$Al_{0.15}Ga_{0.85}As$		undoped	11.3 A (4 ML)
GaAs		undoped	53.7 A (19 ML)
$Al_{0.15}Ga_{0.85}As$		undoped	14.1 A (5 ML)
GaAs		undoped	45.2 A (16 ML)
$Al_{0.15}Ga_{0.85}As$		undoped	11.3 A (4 ML)
GaAs		undoped	48.0 A (17 ML)
$Al_{0.15}Ga_{0.85}As$		undoped	33.9 A (12 ML)
GaAs		$1.9x10^{16}$ cm^{-3}	161.0 A (57 ML)
$Al_{0.15}Ga_{0.85}As$		undoped	31.1 A (11 ML)
GaAs		undoped	96.1 A (34 ML)
$Al_{0.15}Ga_{0.85}As$		undoped	48.0 A (17 ML)
GaAs		$3x10^{18}$ cm^{-3}	0.8 µm
$Al_{0.55}Ga_{0.45}As$		undoped	0.1 µm
S. I. GaAs substrate			

Many Interfaces

Repeat 163 times

Total Active Thickness ~10 µm

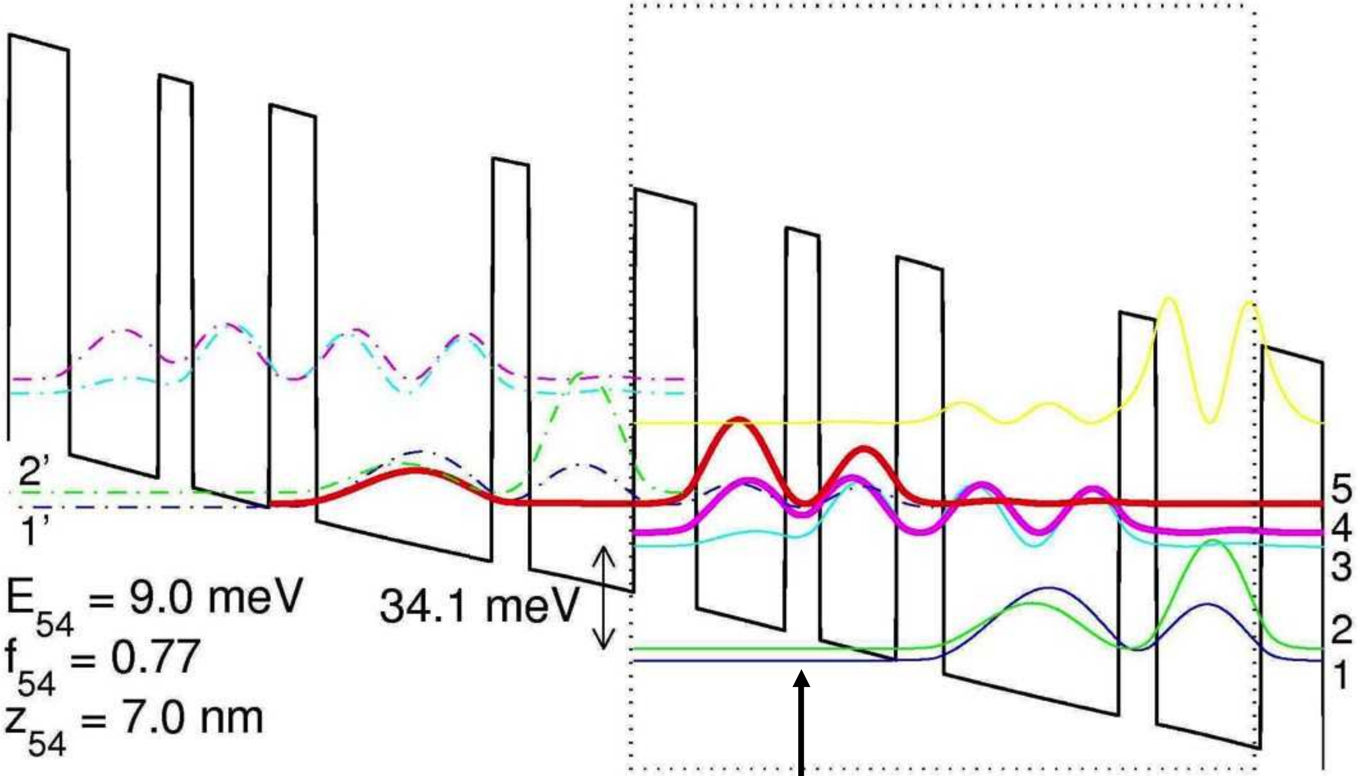
High Al Content

Thin Accurate Layers

No Doping

Accurate Doping

Significance of Layer Thickness



11 ML (3.1 nm) Determines $\hbar\omega$

Changed by 2 ML shifted wavelength from 100μm to 141μm

Growth Conditions/Techniques

- Issue: Thickness Consistancy/Stability (<1%)
- Problems: Many Thin Layers
  Long Growth Time (~16 hrs)
- Solutions:
  - Allow Sufficient Time for Cells to Stabilize
  - Determine Cell Stability (0.3-5% /µm)
  - Ramp Cell Ga Cell During Growth (0.1-0.2° /hr)
  - PID Values Carefully Tuned

Growth Conditions/Techniques

- Issue: Thickness Accuracy (<1%)
- Problems: Thin Layers, Shutter Transients
- Solutions:
  - Ga & Al RHEED Oscillations Daily
    - Numerous measurements taken to 4 sig figs
    - Average
  - Measure Period by X-ray
  - Determine Correction Factor (~1%)

Growth Conditions/Techniques

- Issue: Al Concentration Accuracy ($<0.2\%$)
- Solutions:
  - Ga & Al RHEED Oscillations Daily
    - Numerous measurements taken to 4 sig figs
    - Average
  - Calculate Concentration
    - Adjust Cell Temp if Concentration Not ± 0.0005 of Target

Growth Conditions/Techniques

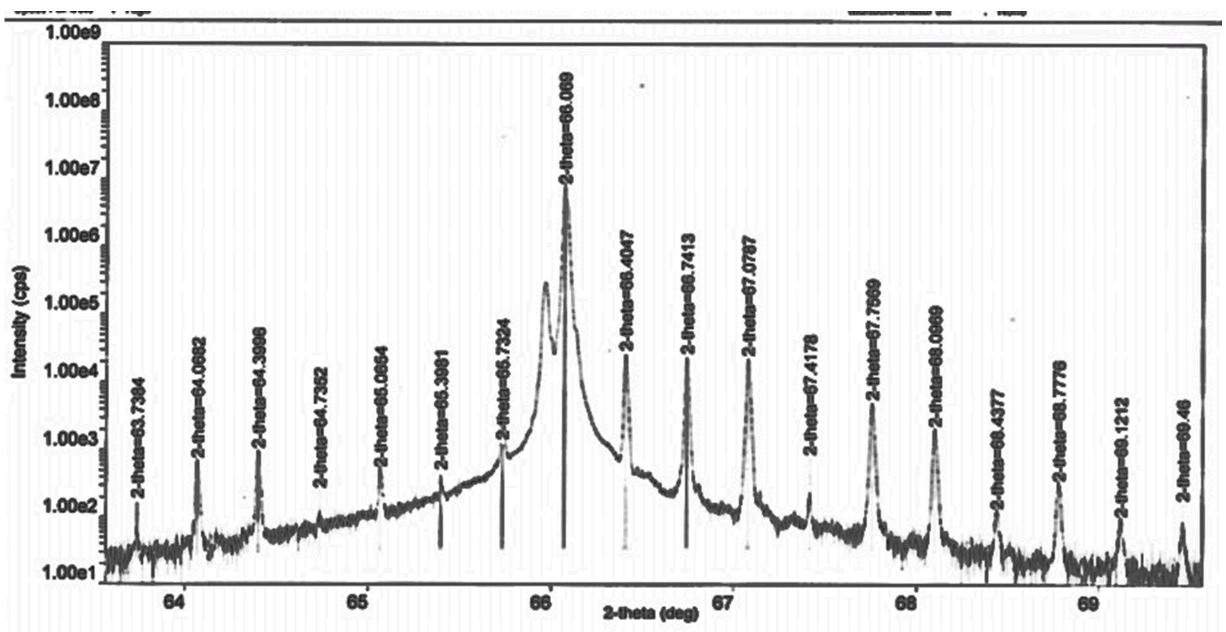
- Issue: Thickness & Composition Accuracy
- Problems: RHEED Oscillations Are NOT Accurate
- Solutions:
  - Determine RHEED Correction Factor for Every Cell
    - Use RHEED to measure growth rate
    - Grow sequentially on same day 2 MQWs
      - GaAs/AlGaAs AlAs/AlGaAs
  - Measure Periods by X-ray
  - Determine Correction Factors (~0.1%)

Single Band THz QCL Growth Accuracy

250C →	GaAs	LTG (250C) cap layer	35 A
	GaAs	5×10^{19} cm^{-3}	100 A
	GaAs	5×10^{18} cm^{-3}	500 A
	$Al_{0.30}Ga_{0.70}As$	undoped	27 A
	GaAs	undoped	60 A
	GaAs	6.30×10^{16} cm^{-3}	48 A
	GaAs	undoped	60 A
	$Al_{0.30}Ga_{0.70}As$	undoped	34 A
Repeat 313 times ↕	GaAs	undoped	84 A
	$Al_{0.30}Ga_{0.70}As$	undoped	27 A
	GaAs	undoped	60 A
	GaAs	6.30×10^{16} cm^{-3}	48 A
	GaAs	undoped	60 A
	$Al_{0.30}Ga_{0.70}As$	undoped	34 A
	GaAs	5×10^{18} cm^{-3}	0.1 um
	$Al_{0.55}Ga_{0.45}As$	undoped	0.4 um

Structure

X-ray



Note Evenly Spaced Peaks

Period

X-ray: 312.7Å

Request: 313.0Å

=> 0.09% Low

Two Band THz QCL Growth Accuracy

250°C ⟶	GaAs	LTG (250°C) cap layer	35 A
	GaAs	5×10^{19} cm^{-3}	100 A
	GaAs	5×10^{18} cm^{-3}	
	$Al_{0.15}Ga_{0.85}As$	undoped	
	GaAs	3.3×10^{16} cm^{-3}	
	$Al_{0.15}Ga_{0.85}As$	undoped	
	GaAs	undoped	
	$Al_{0.15}Ga_{0.85}As$	undoped	
Repeat 88 times	Substack B		
Repeat 85 times	Substack A (		
	GaAs	5×10^{18} cm^{-3}	
	$Al_{0.55}Ga_{0.45}As$	undoped	
	n+ or undoped GaAs		

Structure

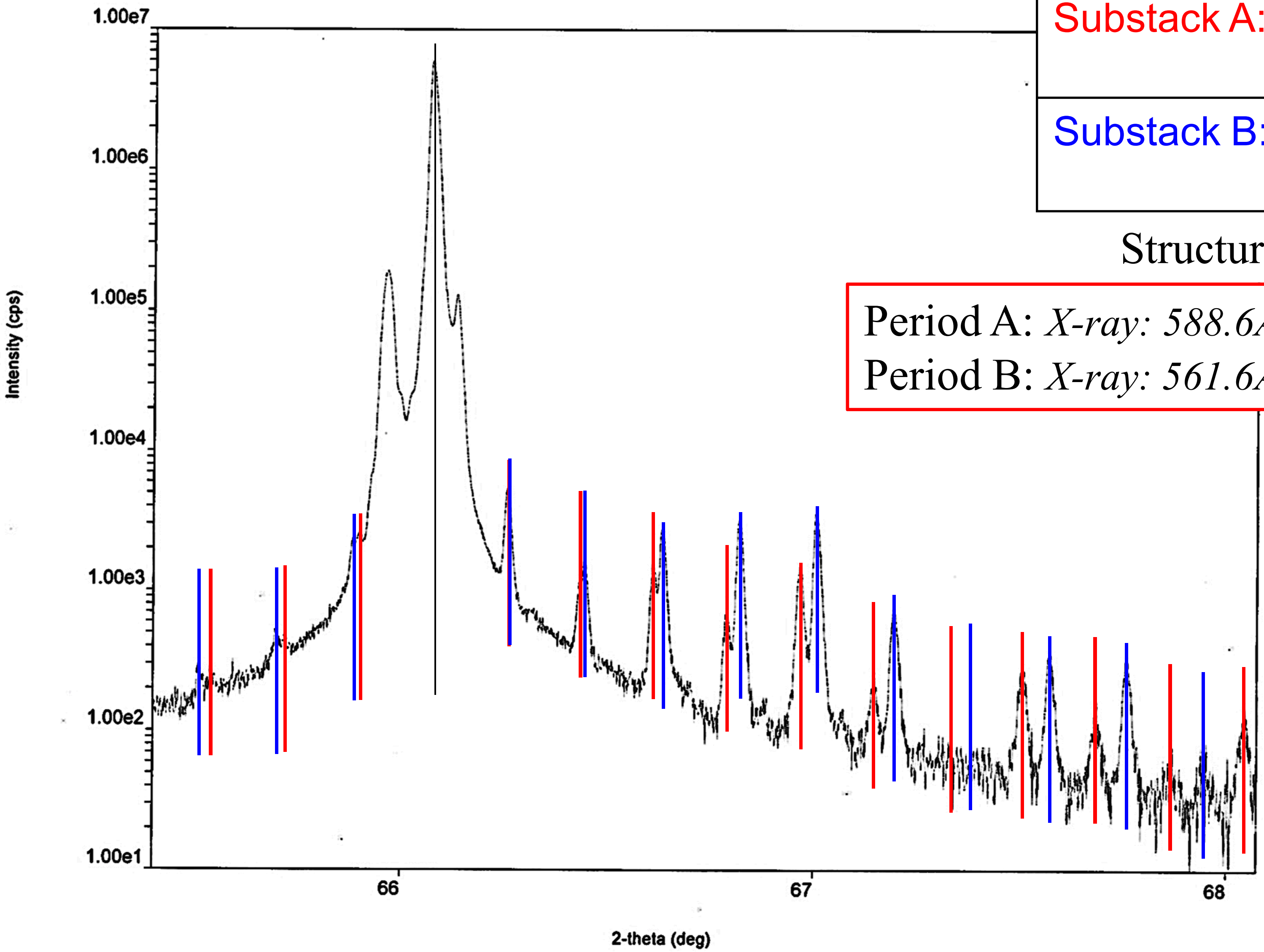
Substack A: (FL172C-M12, 2.8-4.2 THz)

GaAs	undoped	95 A (33.5 ML)
$Al_{0.15}Ga_{0.85}As$	undoped	17 A (6 ML)
GaAs	undoped	78 A (27.5 ML)
$Al_{0.15}Ga_{0.85}As$	undoped	37 A (13 ML)
GaAs	1.25×10^{16} cm^{-3}	184 A (65 ML)
$Al_{0.15}Ga_{0.85}As$	undoped	27 A (9.5 ML)
GaAs	undoped	105 A (37 ML)
$Al_{0.15}Ga_{0.85}As$	undoped	45 A (16 ML)
Total:	**3.9×10^{15} cm^{-3} average**	**588 A (207.5 ML)**

Substack B: (FL175M-M3, 2.0-2.75 THz)

GaAs	undoped	82 A (29 ML)
$Al_{0.15}Ga_{0.85}As$	undoped	31 A (11 ML)
GaAs	undoped	68 A (24 ML)
$Al_{0.15}Ga_{0.85}As$	undoped	42 A (15 ML)
GaAs	3.3×10^{16} cm^{-3}	161 A (57 ML)
$Al_{0.15}Ga_{0.85}As$	undoped	37 A (13 ML)
GaAs	undoped	93 A (33 ML)
$Al_{0.15}Ga_{0.85}As$	undoped	51 A (18 ML)
Total:	**9.4×10^{15} cm^{-3} average**	**565 A (200 ML)**

Two Band THz QCL Growth Accuracy



Substack A: 2.8-4.2 THZ period=588Å	
Substack B: 2.0-2.75 THz period=565Å	

Structure Summary

Period A: *X-ray: 588.6Å, Request: 588.0Å*
Period B: *X-ray: 561.6Å, Request: 565.0Å*

Three Band THz QCL Growth Accuracy

250∘C →	GaAs	LTG (250∘C) cap layer	35 A
	GaAs	5×10^{19} cm^{-3}	100 A
	GaAs	5×10^{18} cm^{-3}	500 A
	GaAs	undoped	88 A (31 MI
	$Al_{0.15}Ga_{0.85}As$	undoped	48 A (17 MI
	GaAs	undoped	59 A (21 MI
	GaAs	1.2×10^{17} cm^{-3} 2.4e17	48 A (17 MI
	GaAs	undoped	59 A (21 MI
	$Al_{0.15}Ga_{0.85}As$	undoped	57 A (20 MI
Repeat 62 times	Substack C (OWI210H-M4)		
Repeat 66 times	Substack B (OWI218G-M6)		
Repeat 68 times	Substack A (FL172C-M12)		
	GaAs	5×10^{18} cm^{-3}	0.1 um
	$Al_{0.55}Ga_{0.45}As$	undoped	0.4 um
n+ or undoped GaAs substrate			

Structure

Substack A: (FL172C-M12, 2.8-4.2 THz)

GaAs	undoped	95 A (33.5 ML)
$Al_{0.15}Ga_{0.85}As$	undoped	17 A (6 ML)
GaAs	undoped	78 A (27.5 ML)
$Al_{0.15}Ga_{0.85}As$	undoped	37 A (13 ML)
GaAs	1.4×10^{16} cm^{-3}	184 A (65 ML)
$Al_{0.15}Ga_{0.85}As$	undoped	27 A (9.5 ML)
GaAs	undoped	105 A (37 ML)
$Al_{0.15}Ga_{0.85}As$	undoped	45 A (16 ML)
Total:	**4.4×10^{15} cm^{-3} average**	**588 A (207.5 ML)**

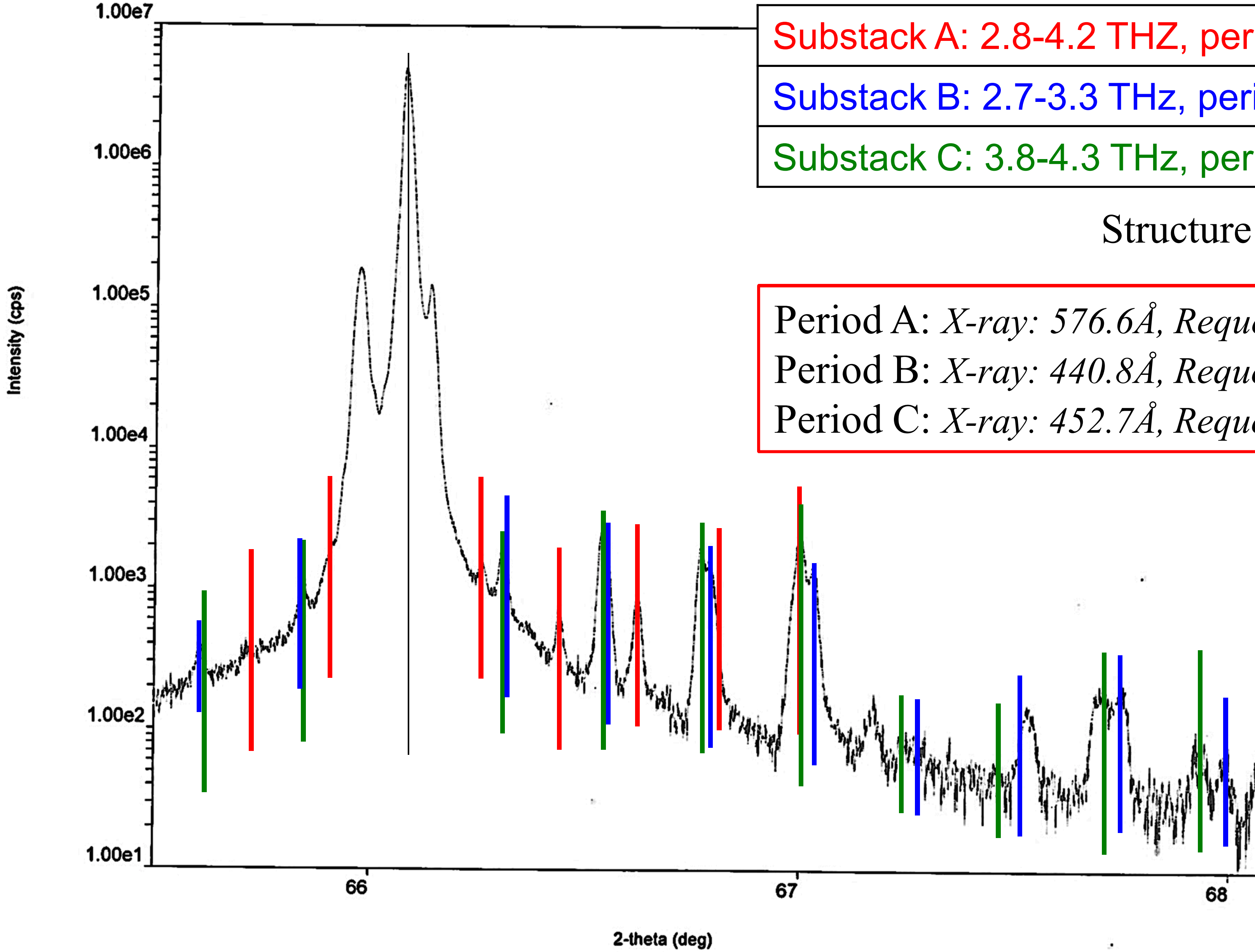
Substack B: (OWI218G-M6, 2.7-3.3 THz)

GaAs	undoped	85 A (30 ML)
$Al_{0.15}Ga_{0.85}As$	undoped	34 A (12 ML)
GaAs	undoped	85 A (30 ML)
$Al_{0.15}Ga_{0.85}As$	undoped	21 A (7.5 ML)
delta-dope	3×10^{10} cm^{-2}	
$Al_{0.15}Ga_{0.85}As$	undoped	21 A (7.5 ML)
GaAs	undoped	164 A (58 ML)
$Al_{0.15}Ga_{0.85}As$	undoped	48 A (17 ML)
Total:	**6.6×10^{15} cm^{-3} average**	**458 A (162 ML)**

Substack C: (OWI210H-M4, 3.8-4.3 THz)

GaAs	undoped	85 A (30 ML)
$Al_{0.15}Ga_{0.85}As$	undoped	37 A (13 ML)
GaAs	undoped	88 A (31 ML)
$Al_{0.15}Ga_{0.85}As$	undoped	48 A (17 ML)
GaAs	undoped	59 A (21 ML)
GaAs	2.4×10^{17} cm^{-3}	48 A (17 ML)
GaAs	undoped	59 A (21 ML)
$Al_{0.15}Ga_{0.85}As$	undoped	57 A (20 ML)
Total:	**2.4×10^{16} cm^{-3} average**	**481 A (170 ML)**

Two Band THz QCL Growth Accuracy



Substack A: 2.8-4.2 THZ, period=588Å

Substack B: 2.7-3.3 THz, period=458Å

Substack C: 3.8-4.3 THz, period=481Å

Structure Summary

Period A: *X-ray: 576.6Å, Request: 588Å*

Period B: *X-ray: 440.8Å, Request: 458Å*

Period C: *X-ray: 452.7Å, Request: 481Å*

LWIR Example Structure

MOCVD Grown Clads

MOCVD	InP	7.0×10^{18} cm^{-3}	8500 A
	InP	2.0×10^{16} cm^{-3}	40000 A
Repeat 76 times (λ=9.4 μm) Total 33,364 Å 3.34 μm	$In_{0.52}Al_{0.48}As$	undoped	40 A
	$In_{0.53}Ga_{0.47}As$	undoped	19 A
	$In_{0.52}Al_{0.48}As$	undoped	8 A
	$In_{0.53}Ga_{0.47}As$	undoped	56 A
	$In_{0.52}Al_{0.48}As$	undoped	10 A
	$In_{0.53}Ga_{0.47}As$	undoped	51 A
	$In_{0.52}Al_{0.48}As$	undoped	11 A
	$In_{0.53}Ga_{0.47}As$	undoped	42 A
	$In_{0.52}Al_{0.48}As$	undoped	13 A
	$In_{0.53}Ga_{0.47}As$	undoped	32 A
	$In_{0.52}Al_{0.48}As$	undoped	15 A
	$In_{0.53}Ga_{0.47}As$	undoped	32 A
	$In_{0.52}Al_{0.48}As$	undoped	20 A
	$In_{0.53}Ga_{0.47}As$	2.13×10^{17} cm^{-3}	31 A
	$In_{0.52}Al_{0.48}As$	2.13×10^{17} cm^{-3}	29 A
	$In_{0.53}Ga_{0.47}As$	undoped	30 A
n-InP substrate, $(1\text{-}2) \times 10^{17}$ cm^{-3}			

Thin Layers

Lattice Matched Alloys

InP Substrates

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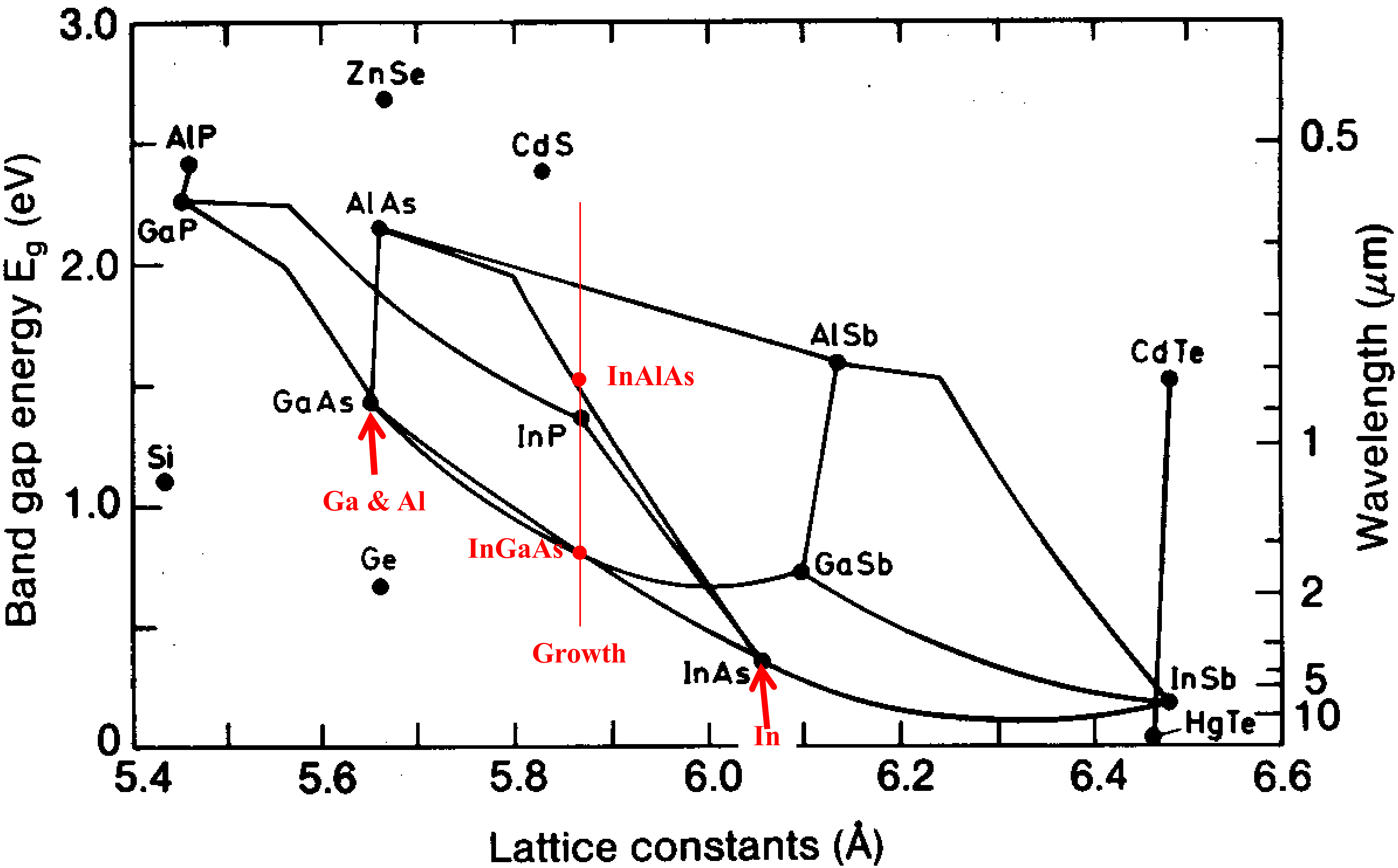

3.0
2.0
1.0
0
Band gap energy E_g (eV)
0.5
1
2
5
10
Wavelength (μm)
5.4
5.6
5.8
6.0
6.2
6.4
6.6
Lattice constants (Å)
ZnSe
AlP
CdS
GaP
AlAs
AlSb
CdTe
InAlAs
GaAs
InP
Si
Ga & Al
InGaAs
Ge
GaSb
Growth
InAs
InSb
HgTe
In

Growth Conditions/Techniques

- Issue: In Growth Rate
- Problems: RHEED Oscillations Are NOT Accurate
- Solutions:
  - Rough In RHEED Correction
    - Grow ~50% InGaAs on GaAs
    - X-ray to Determine Composition
      - Peak Broad due to Dislocation
    - Use Composition to Determine Actual In Rate
    - Determine Rough In Concentration

Growth Conditions/Techniques

- Issue: Lattice Match
- Solutions:
  - Using Corrected Ga(Al) & In RHEED
    - Grow InGa(Al)As on InP with Best Guess Composition
  - Measure Mismatch by X-ray
  - Determine Better Composition Guess
  - Repeat

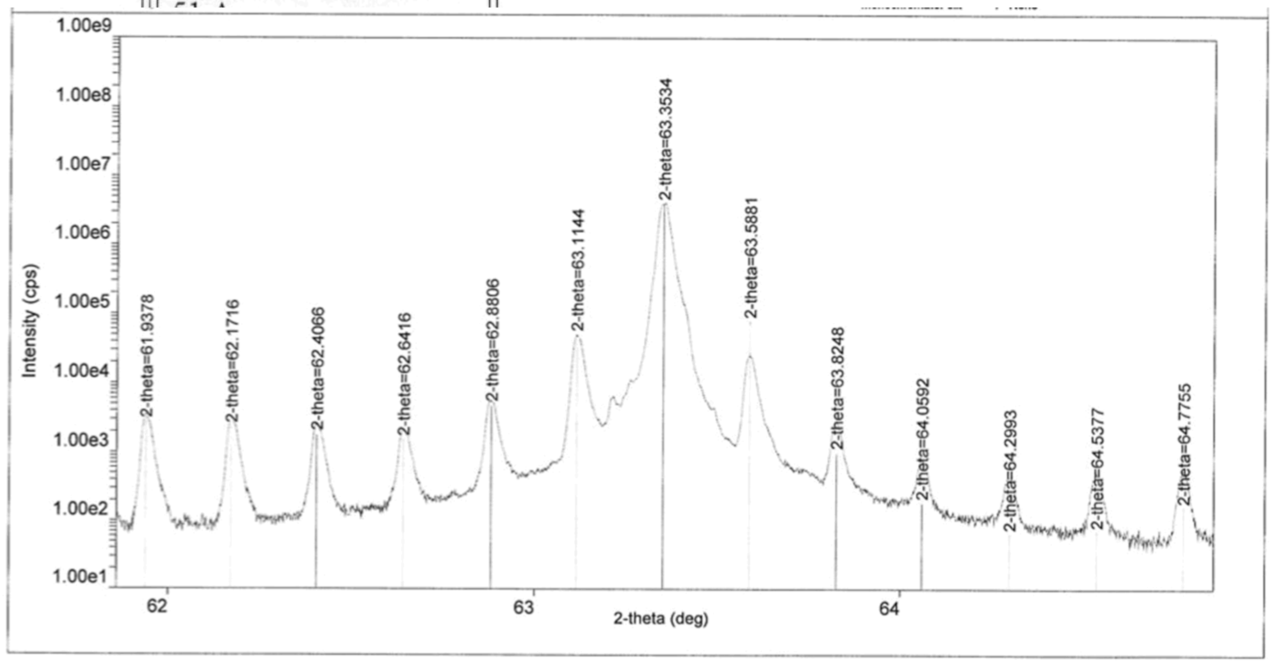
Growth Conditions/Techniques

- Issue: Layer Thickness Accuracy
- Problems: RHEED Oscillations Are NOT Accurate
- Solutions:
  - Using RHEED Correction Factor for Ga, Al, & In Cells
    - Set to Lattice Matched Compositions
    - Grow sequentially on same day TWO InGaAs/InAlAs MQWs with Different InGaAs Thicknesess
  - Measure Periods by X-ray
  - Determine Alloy Growth Rate Corrections

Single Band LWIR QCL Growth Accuracy

Repeat 76 times (λ=9.4 µm)	$In_{0.52}Al_{0.48}As$	undoped	40 A
	$In_{0.53}Ga_{0.47}As$	undoped	19 A
	$In_{0.52}Al_{0.48}As$	undoped	8 A
	$In_{0.53}Ga_{0.47}As$	undoped	56 A
Total 33364Å 3.34 µm	$In_{0.52}Al_{0.48}As$	undoped	10 A
	$In_{0.53}Ga_{0.47}As$	undoped	
	$In_{0.52}Al_{0.48}As$	undoped	
	$In_{0.53}Ga_{0.47}As$	undoped	
	$In_{0.52}Al_{0.48}As$	undoped	
	$In_{0.53}Ga_{0.47}As$	undoped	
	$In_{0.52}Al_{0.48}As$	undoped	
	$In_{0.53}Ga_{0.47}As$	undoped	
	$In_{0.52}Al_{0.48}As$	undoped	
	$In_{0.53}Ga_{0.47}As$	2.13×10^{17} cm^{-3}	
	$In_{0.52}Al_{0.48}As$	2.13×10^{17} cm^{-3}	
	$In_{0.53}Ga_{0.47}As$	undoped	
	n-InP substrate, (1-2)		

Structure



Period

X-ray: 438.6Å

Request: 439Å

=> 0.09% Low

Note: Evenly Spaced Peaks

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Five Band LWIR QCL

MOCVD	InP	7.0×10^{18} cm^{-3}	8500 A
	InP	2.0×10^{16} cm^{-3}	4
Repeat 12 times	@ 448 A = 5376 A	Substack E	
Repeat 9 times	@		
Repeat 6 times	@		
Repeat 5 times	@		
Repeat 10 times	@		
Repeat 5 times	@		
Repeat 6 times	@		
Repeat 9 times	@		
Repeat 12 times	@		

Substack A: (λ=7.3 µm)

$In_{0.52}Al_{0.48}As$	undoped	40 A
$In_{0.53}Ga_{0.47}As$	undoped	15 A
$In_{0.52}Al_{0.48}As$	undoped	10 A
$In_{0.53}Ga_{0.47}As$	undoped	48 A
	undoped	12 A
	undoped	47 A
	undoped	13 A
	undoped	42 A
	undoped	15 A
	undoped	32 A
	undoped	17 A
	undoped	30 A
	undoped	18 A
	undoped	28 A
	undoped	23 A
	2.53×10^{17} cm^{-3}	26 A
	2.53×10^{17} cm^{-3}	34 A
	undoped	24 A

Substack B: (λ=8.5 µm)

$In_{0.52}Al_{0.48}As$	undoped	40 A
$In_{0.53}Ga_{0.47}As$	undoped	18 A
$In_{0.52}Al_{0.48}As$	undoped	8 A
$a_{0.47}As$	undoped	53 A
$_{0.48}As$	undoped	10 A
$a_{0.47}As$	undoped	48 A
$_{0.48}As$	undoped	11 A
$a_{0.47}As$	undoped	43 A
$_{0.48}As$	undoped	14 A
$a_{0.47}As$	undoped	36 A
$_{0.48}As$	undoped	17 A
$a_{0.47}As$	undoped	33 A
$_{0.48}As$	undoped	24 A
$a_{0.47}As$	2.54×10^{17} cm^{-3}	31 A
$_{0.48}As$	2.54×10^{17} cm^{-3}	34 A
$a_{0.47}As$	undoped	29 A

Substack D: (λ=10.4 µm)

$In_{0.52}Al_{0.48}As$	undoped	38 A
$In_{0.53}Ga_{0.47}As$	undoped	21 A
$In_{0.52}Al_{0.48}As$	undoped	7 A
$In_{0.53}Ga_{0.47}As$	undoped	59 A
$In_{0.52}Al_{0.48}As$	undoped	8 A
$In_{0.53}Ga_{0.47}As$	undoped	53 A
$In_{0.52}Al_{0.48}As$	undoped	9 A
$In_{0.53}Ga_{0.47}As$	undoped	42 A
$In_{0.52}Al_{0.48}As$	undoped	12 A
$In_{0.53}Ga_{0.47}As$	undoped	38 A
$In_{0.52}Al_{0.48}As$	undoped	13 A
$In_{0.53}Ga_{0.47}As$	undoped	37 A
$In_{0.52}Al_{0.48}As$	undoped	17 A
$In_{0.53}Ga_{0.47}As$	2.21×10^{17} cm^{-3}	34 A
$In_{0.52}Al_{0.48}As$	2.21×10^{17} cm^{-3}	24 A
$In_{0.53}Ga_{0.47}As$	undoped	32 A

ck C: (λ=9.4 µm)

$_{0.48}As$	undoped	40 A
$a_{0.47}As$	undoped	19 A
$_{0.48}As$	undoped	8 A
$a_{0.47}As$	undoped	56 A
$_{0.48}As$	undoped	10 A
$a_{0.47}As$	undoped	51 A
$_{0.48}As$	undoped	11 A
$a_{0.47}As$	undoped	42 A
$_{0.48}As$	undoped	13 A
$a_{0.47}As$	undoped	32 A
$_{0.48}As$	undoped	15 A
$a_{0.47}As$	undoped	32 A
$_{0.48}As$	undoped	20 A
$a_{0.47}As$	2.13×10^{17} cm^{-3}	31 A
$_{0.48}As$	2.13×10^{17} cm^{-3}	29 A
$a_{0.47}As$	undoped	30 A

Substack E (λ=11.5 µm):

$In_{0.52}Al_{0.48}As$	undoped	38 A
$In_{0.53}Ga_{0.47}As$	undoped	21 A
$In_{0.52}Al_{0.48}As$	undoped	5 A
$In_{0.53}Ga_{0.47}As$	undoped	60 A
$In_{0.52}Al_{0.48}As$	undoped	6 A
$In_{0.53}Ga_{0.47}As$	undoped	55 A
$In_{0.52}Al_{0.48}As$	undoped	7 A
$In_{0.53}Ga_{0.47}As$	undoped	45 A
$In_{0.52}Al_{0.48}As$	undoped	10 A
$In_{0.53}Ga_{0.47}As$	undoped	39 A
$In_{0.52}Al_{0.48}As$	undoped	11 A
$In_{0.53}Ga_{0.47}As$	undoped	38 A
$In_{0.52}Al_{0.48}As$	undoped	17 A
$In_{0.53}Ga_{0.47}As$	2.21×10^{17} cm^{-3}	37 A
$In_{0.52}Al_{0.48}As$	2.21×10^{17} cm^{-3}	24 A
$In_{0.53}Ga_{0.47}As$	undoped	35 A

Should Be Fun!

QCL Growth Summary

- MBE growth conditions must be tuned for the specific device structure.
- RHEED is a reproducible technique and can be corrected to also be quite accurate.
- X-ray diffraction is a powerful technique and can be used to enable MBE growth with high precision.
- Growth and doping calibrations need to be done as close to the actual device growth conditions as possible.

- One, two, and three band THz QCLs have been grown with good match between design and X-ray.
- One band LWIR QCLs have been grown lattice-matched with good match between design and X-ray.