Molecular Beam Epitaxy Growth of $Zn_xCd_{1-x}Se/Zn_{x'}Cd_{y'}Mg_{(1-x'-y')}Se$-InP Quantum Cascade Emitters

William O. Charles,[1] Kale J. Franz,[2] Aidong Shen,[1] Qiang Zhang,[1] Claire Gmachl,[2] and Maria C. Tamargo[1]

[1]The City College of New York
[2]Princeton University

Outline

- Introduction
- Designed Electroluminescence (EL) Structure
- Asymmetric Coupled Quantum Well (ACQW) test samples
- II-VI Growth Procedure
- Material and Device Results
- Future Work
- Summary/Conclusion

Introduction

Current technology: InGaAs/InAlAs-InP based QCLs:

- Can be considered mature technology
- Commercial application in gas sensing and free space telecommunication
- Exhibit high performance above 4.5 μm

1.6 W high wall plug efficiency, continuous-wave room temperature quantum cascade laser emitting at 4.6 μm

A. Lyakh,[1,a)] C. Pflügl,[2,b)] L. Diehl,[2] Q. J. Wang,[2] Federico Capasso,[2] X. J. Wang,[3] J. Y. Fan,[3] T. Tanbun-Ek,[3] R. Maulini,[1] A. Tsekoun,[1] R. Go,[1] and C. Kumar N. Patel[1,4,c)]

- High performance below 4 μm is limited by effective CBO

Possible Solutions

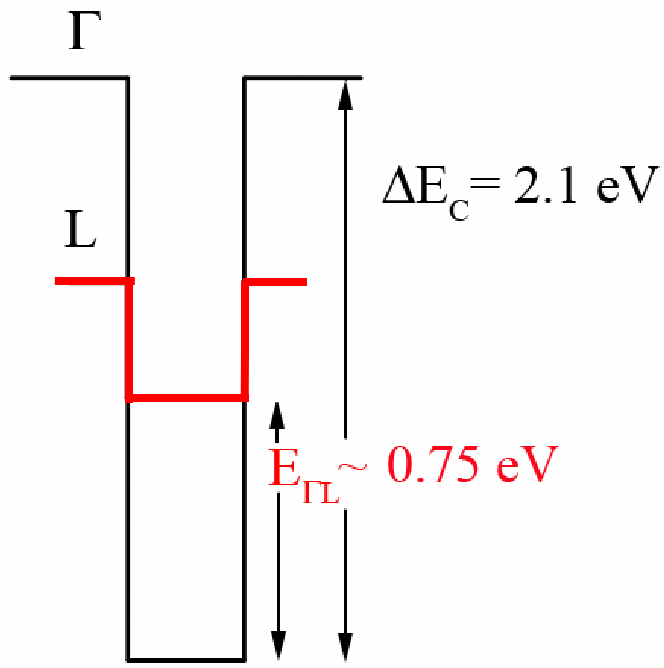
- Strain compensation

Short wavelength ($\lambda \sim 3.4\ \mu m$) quantum cascade laser based on strained compensated InGaAs/AlInAs

Jérôme Faist,[a] Federico Capasso,[b] Deborah L. Sivco, Albert L. Hutchinson, Sung-Nee G. Chu, and Alfred Y. Cho
Bell Laboratories, Lucent Technologies, Murray Hill, New Jersey 07974

- Alternative material systems with larger CBO
  - Antimonides
  - II-VI

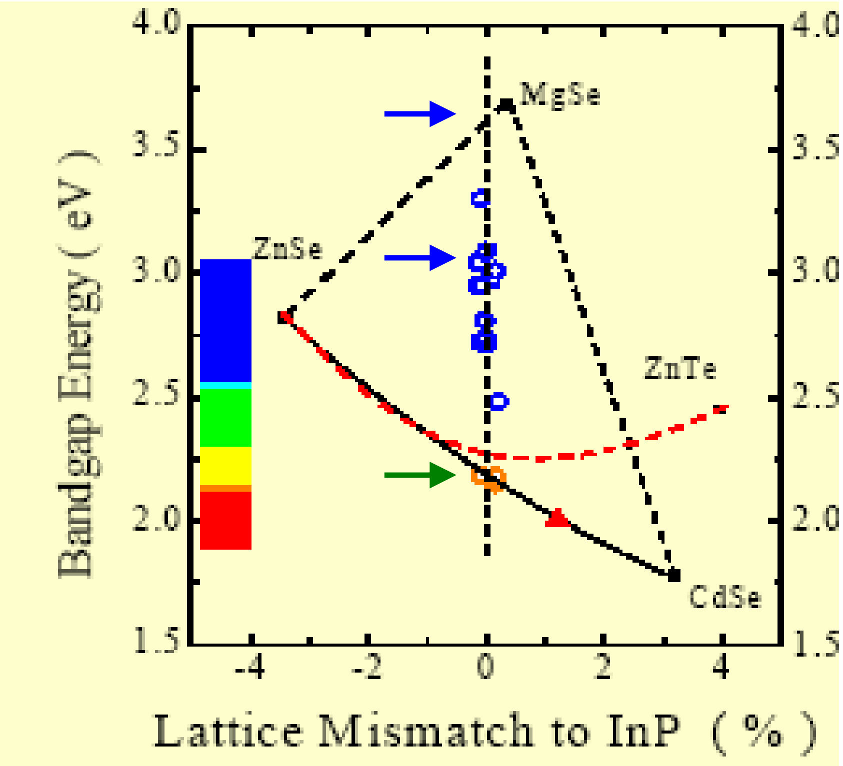
Alternative Material System: Antimonides



AlSb/InAs/AlSb
(InAs or GaSb Substrate)

- CBO = 2.1 eV
- Effective CBO ~ 0.75eV due to intervalley (L-Γ) electron scattering in InAs
- Growth challenges due to the following:
  - lack of common ions
  - As and Sb intermixing at interfaces
  - miscibility gap

Alternative Materials Systems: II-VI Compounds



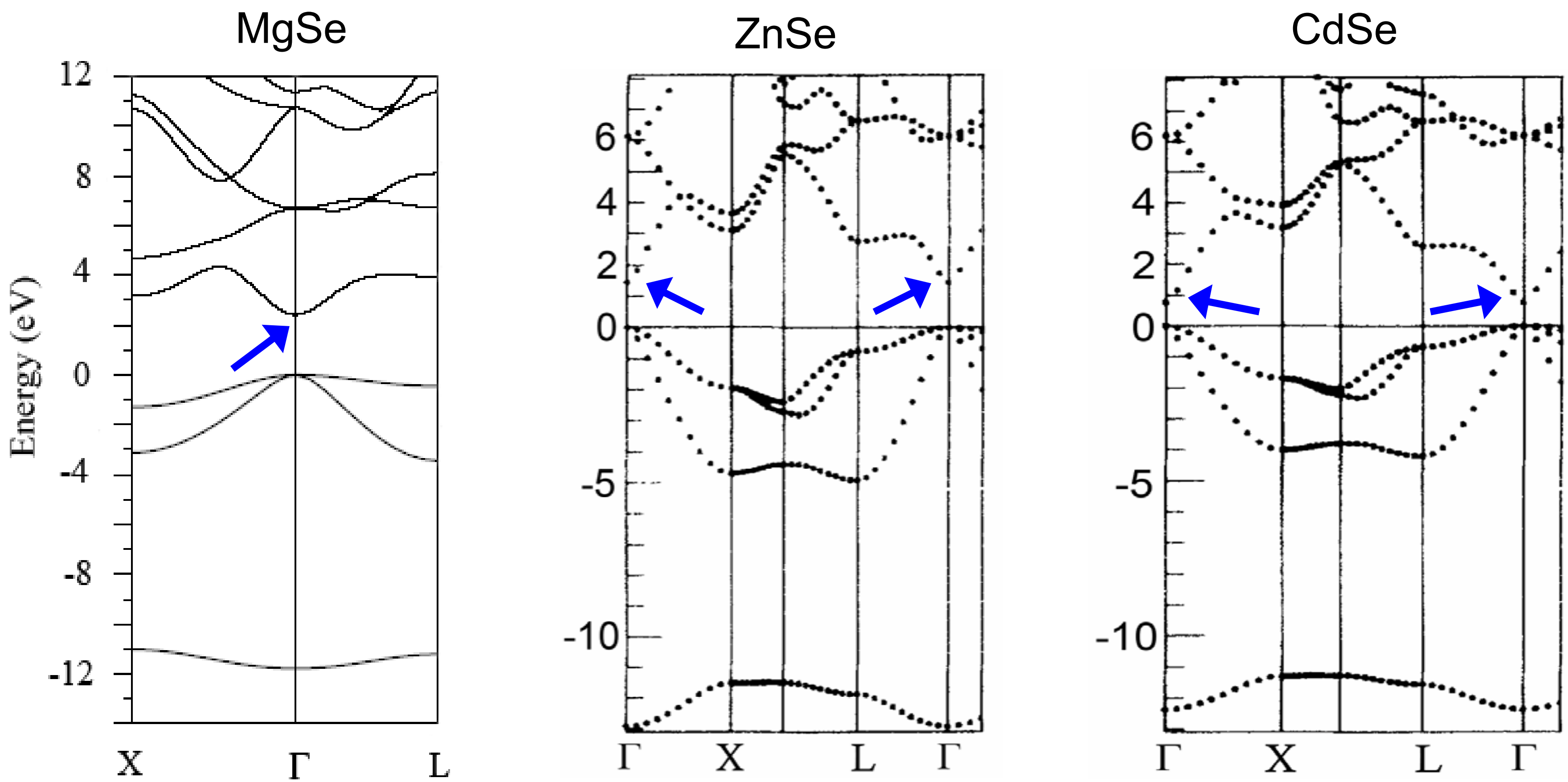
$Zn_xCd_{1-x}Se/Zn_{x'}Cd_{y'}Mg_{(1-x'-y')}Se$-InP

- CBO = 1.12 eV is possible
- Can be grown lattice matched to InP
- $Zn_{0.43}Cd_{0.57}Se/Zn_{0.20}Cd_{0.19}Mg_{0.61}Se$-InP

  has CBO of 0.78 eV which is larger that the effective CBO of InAs/AlSb

  (CBO ~ 0.75 eV)

(Zn,Cd,Mg)Se Band Profiles



S. Duman, S. Bagci, H. M. Tutuncu and G. P. Srivastava PRB 73 205201 (2006)

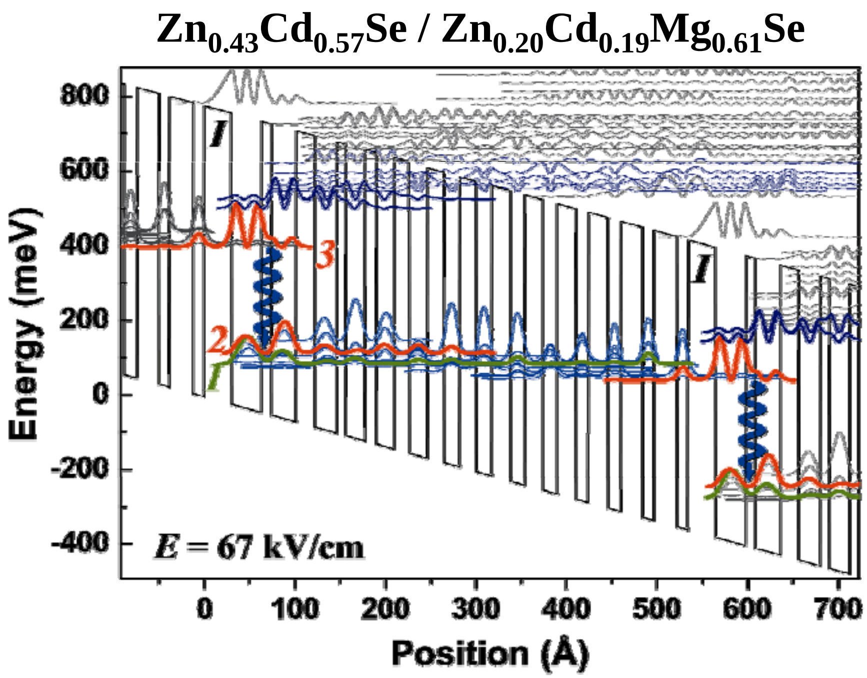
O. Zakharov, A. Rubio, X. Blase, M.L. Cohen, and S.G. Louie, PRB 50 10780 (1994)

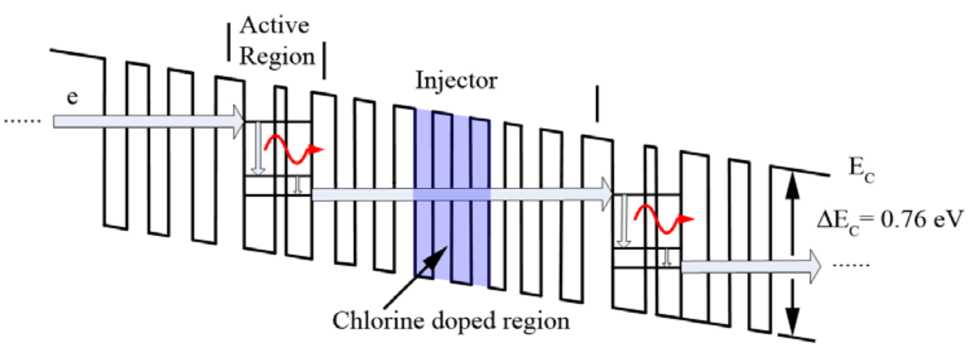
Direct bandgap, No intervalley scattering

Advantages of II-VI Material System

- Can be grown lattice matched to InP
- Is not limited by inter-valley electron scattering
- $Zn_xCd_{1-x}Se/Zn_{x'}Cd_{y'}Mg_{(1-x'-y')}Se$ has larger effective CBO than antimonides
- High performance QCLs within the 3 – 5 μm atmospheric window are possible.

Design of II-VI QC Structure





Simulation Parameters:

$\Delta E_C = 0.78$ V

$\hbar w_{LO} \approx 30$ meV

$m^*_{ZnCdSe} = 0.128$

$m^*_{ZnCdMgSe} = 0.181$

$L_p = 534$ Å

$E_{ph} = 284$ meV (4.4 μm)

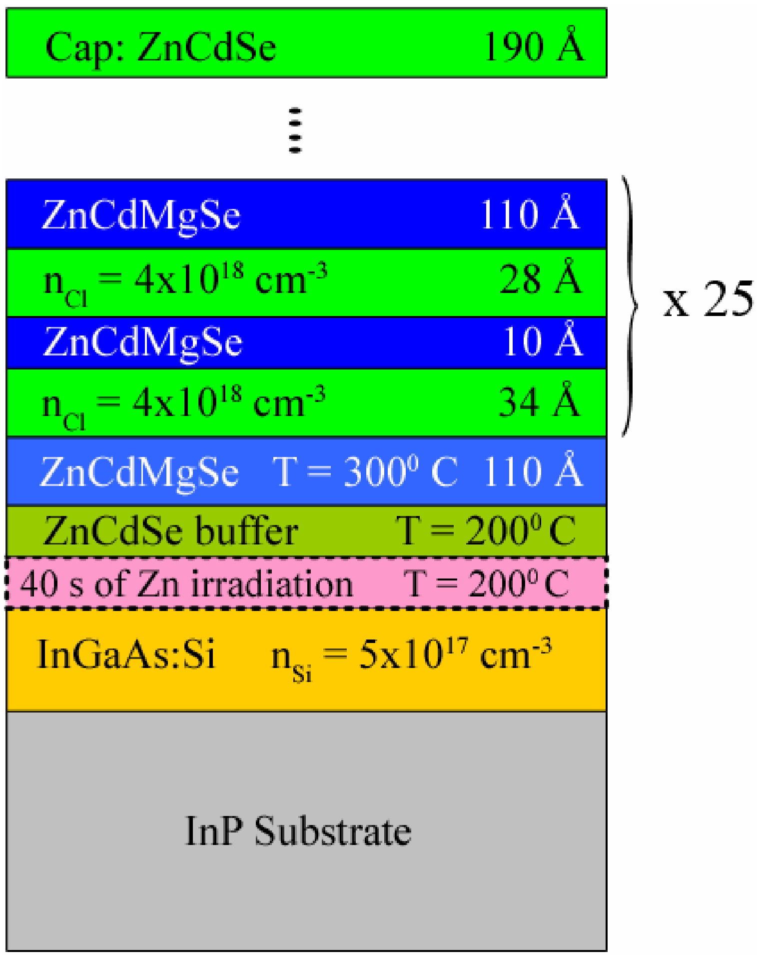
- Active region is composed of 2 asymmetric coupled quantum wells (ACQWs)
- Part of the injector is doped $n \sim 3.0 \times 10^{17}$ cm^{-3}

ACQW Test Sample

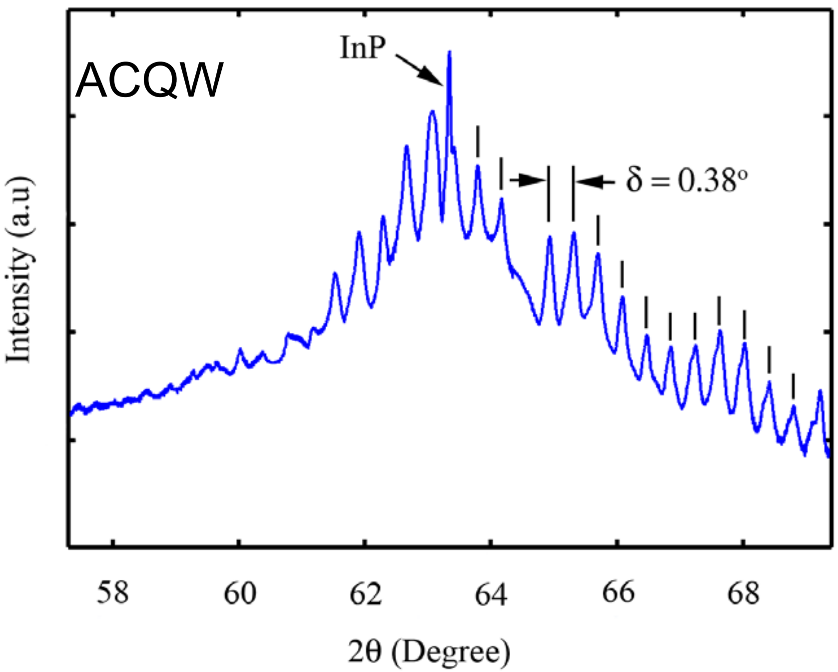
Rationale for ACQW test sample

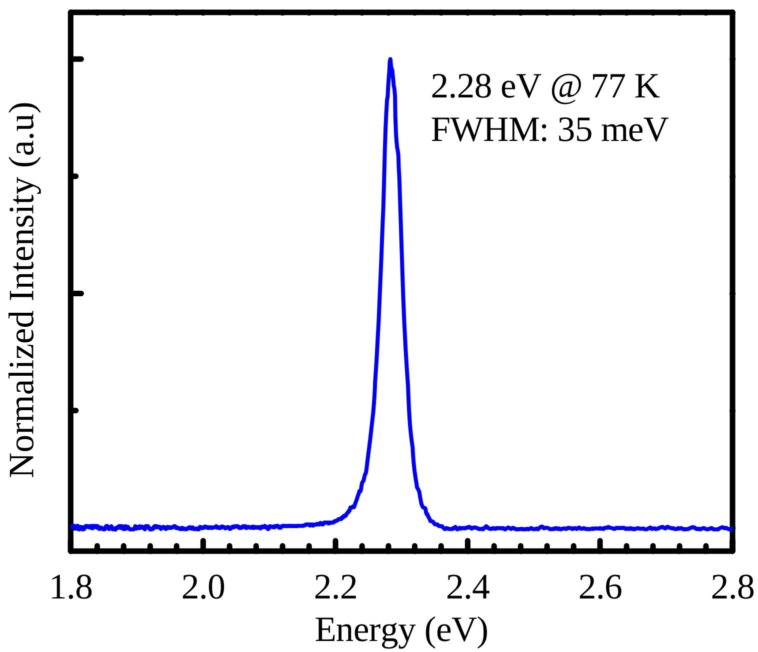
- Determine agreement of active region energy level spacing with simulation
  - Simulation parameters
  - Growth parameters
- Assess material quality and device optical properties before growth of complex EL structure

II-VI Growth: ACQW Test Sample



High Resolution X-Ray Diffraction Curve and PL for 1st ACQW Test Sample





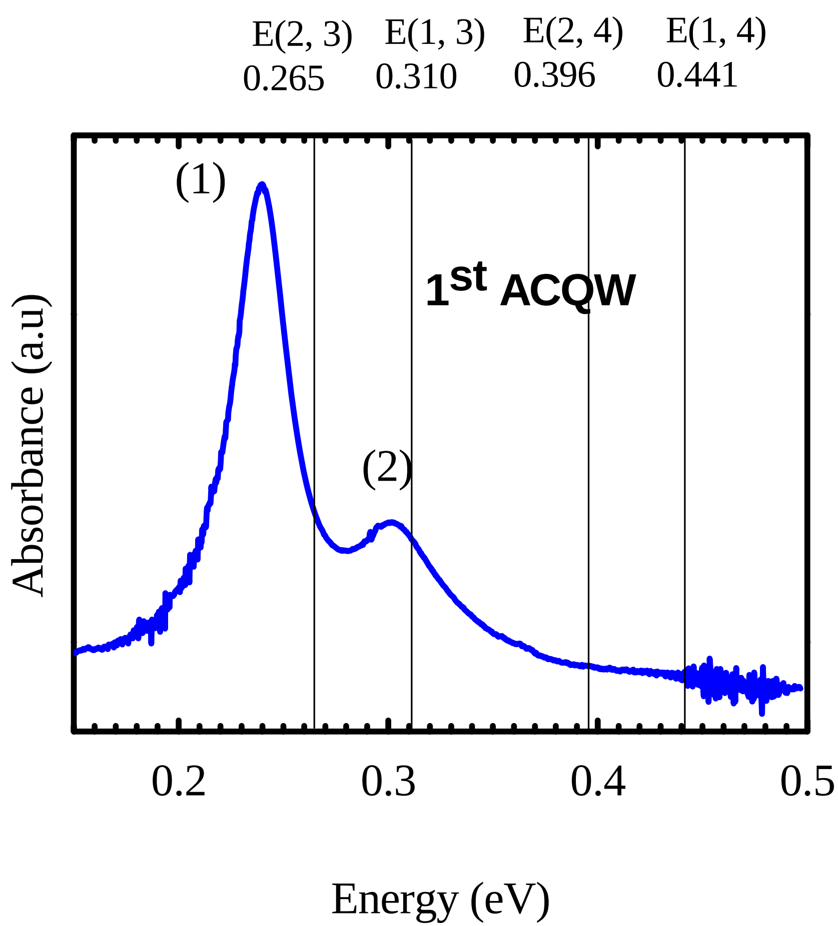
Period thickness: 262 Å

Calculated: 270 Å

Error: +3 %

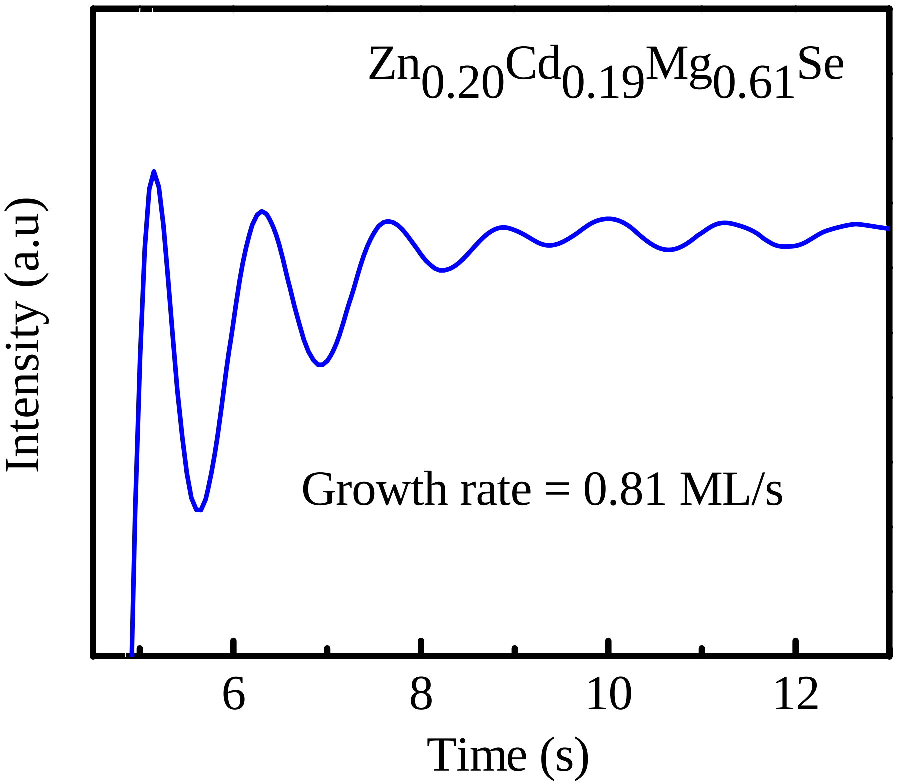
Absence of deep level emission indicates good material quality

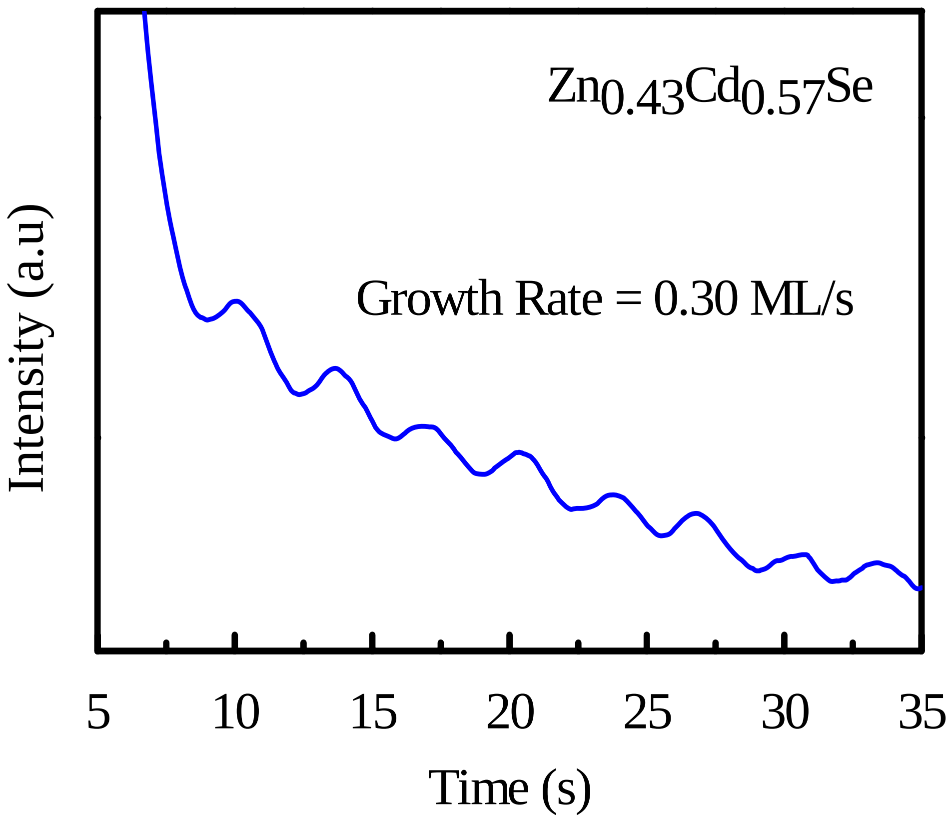
Simulation and FTIR Results for 1st ACQW Test Sample (300 K)



Transition	Simulation (meV)	1st ACQW (meV)
E1 – E4	441	—
E2 – E4	396	—
E1 – E3	310	301
E2 – E3	265 (4.69 μm)	240 (5.18 μm)
E1 – E2	45	61

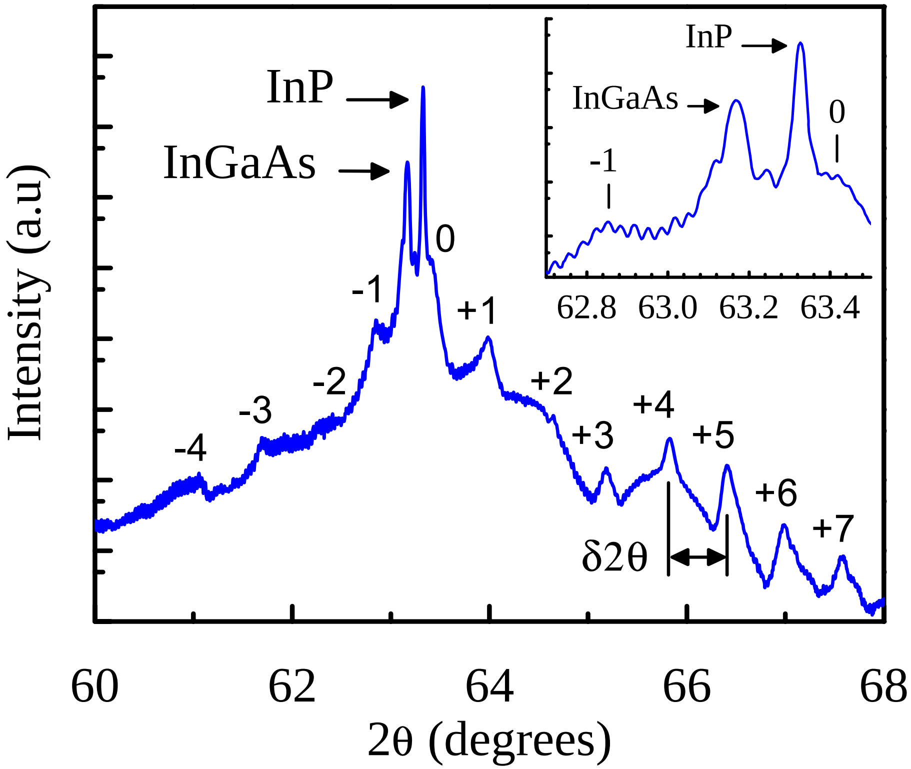
Growth Recalibration: RHEED Oscillations

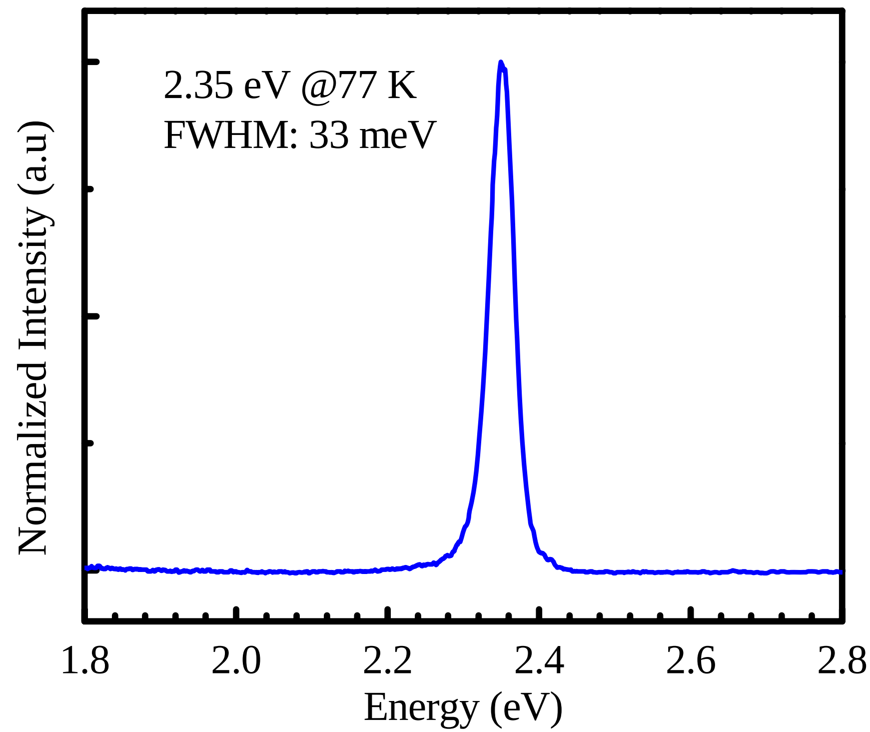




- This is the first report of RHEED oscillations in these materials
- Confirms layer-by-layer MBE growth

High Resolution X-Ray Diffraction Curve and PL for 2nd ACQW Test Sample



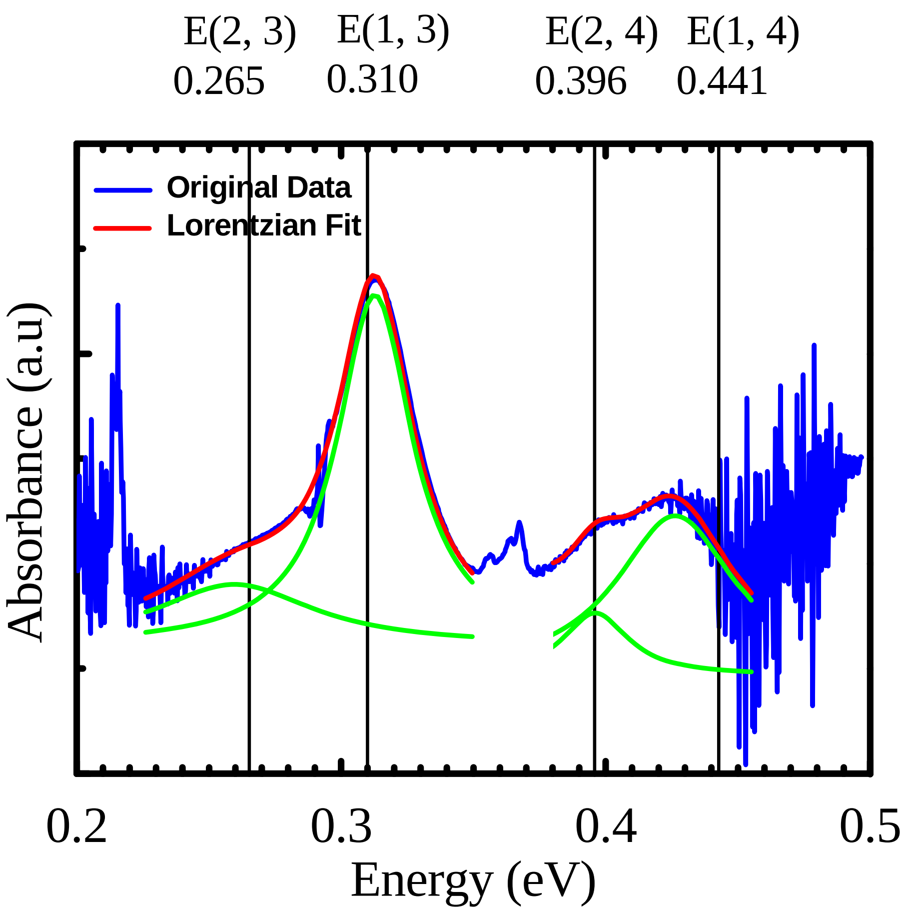


Period thickness: 262 Å

Calculated: 270 Å; Error: +3 %

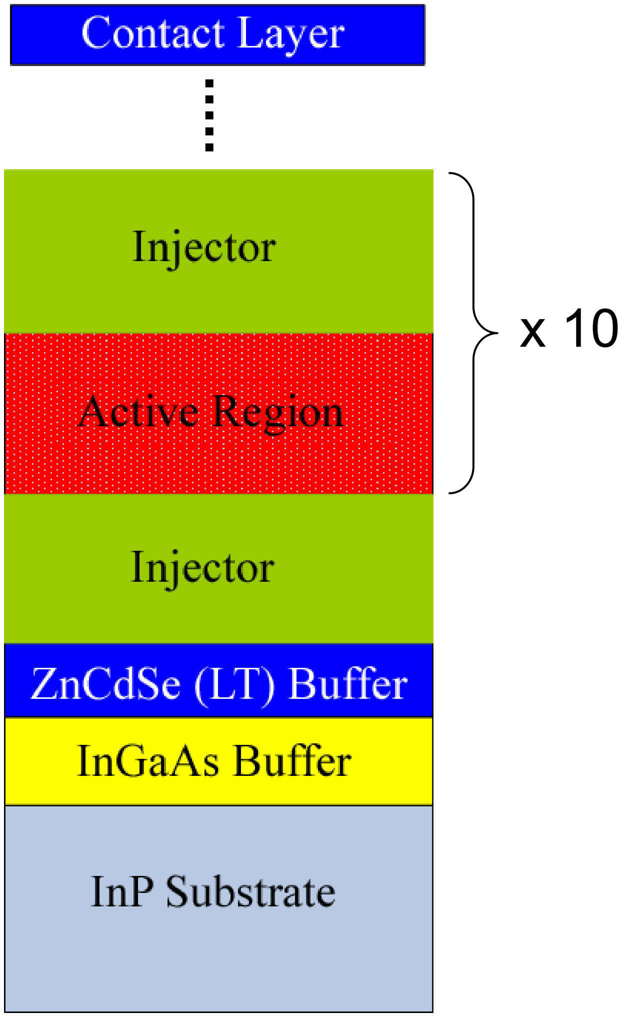
The relatively narrow linewidth is indicative of good interface quality and thickness control

Simulation and FTIR Results for 2nd ACQW Test Sample (300 K)



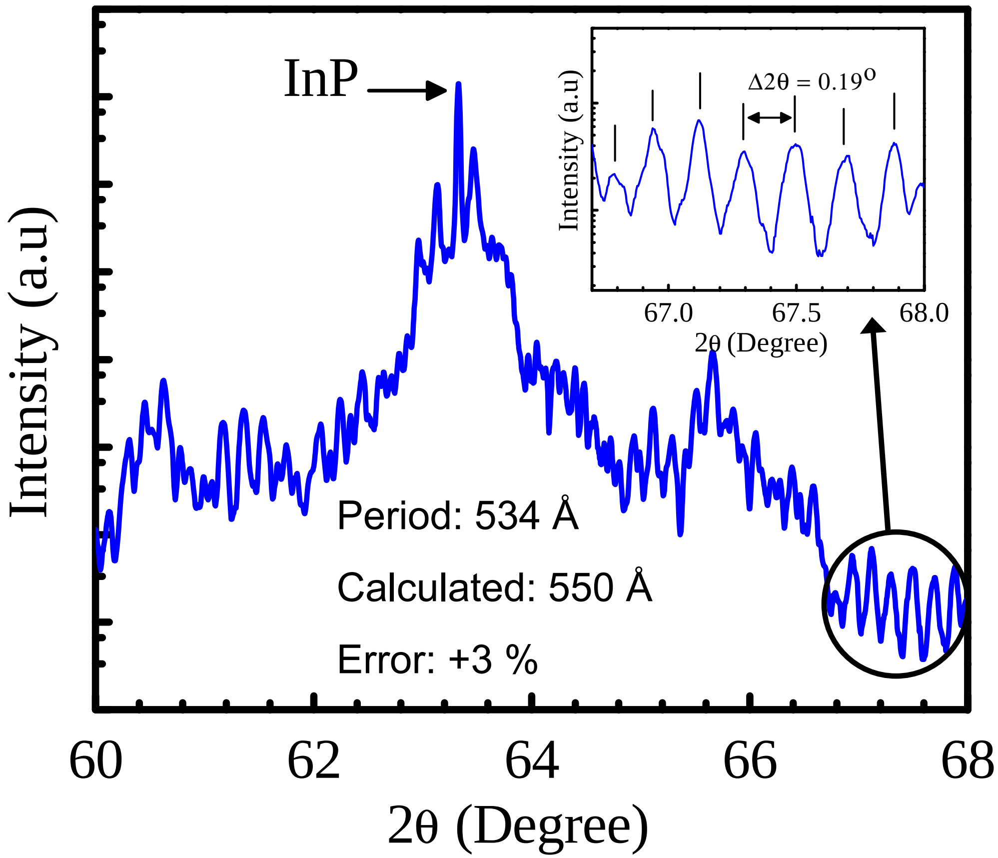
Transition	Simulation (meV)	1st ACQW (meV)	2nd ACQW (meV)
E1 – E4	441	—	427
E2 – E4	396	—	397
E1 – E3	310	301	313
E2 – E3	265 (4.69 μm)	240 (5.18 μm)	261 (4.76 μm)
E1 – E2	45	61	52

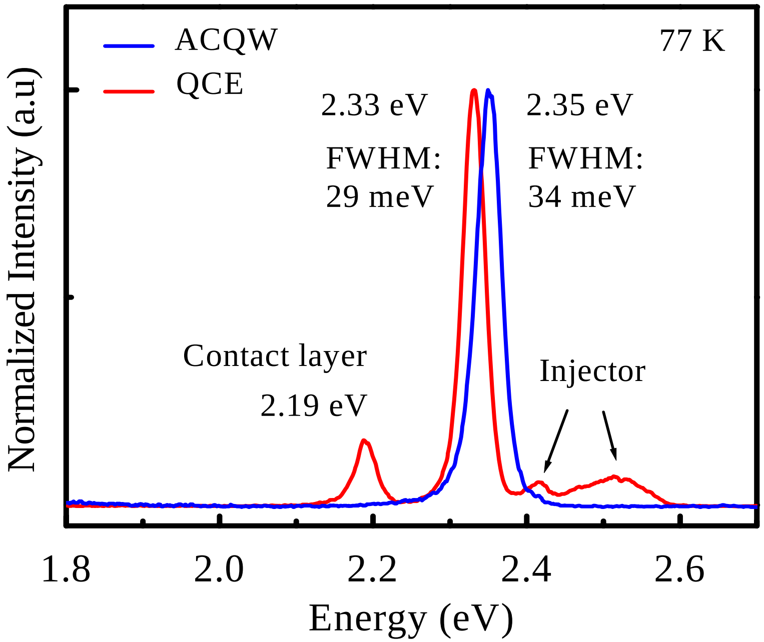
QC Electroluminescence Structure



- EL structure was grown using optimized well/barrier growth rates
- Spacer was replaced with Injector
- Contact layer:
  - 2000 Å thick ZnCdSe:Cl
  - $n_{Cl} = 4 \times 10^{18}$ cm^{-3}

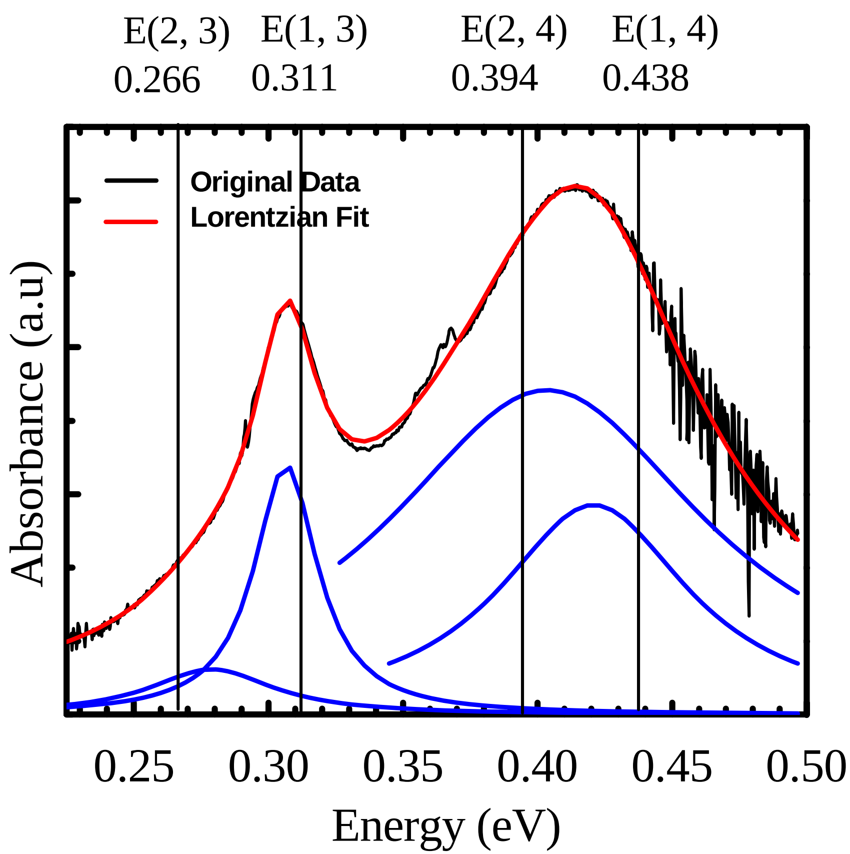
High Resolution X-Ray Diffraction Curve and PL for EL Sample





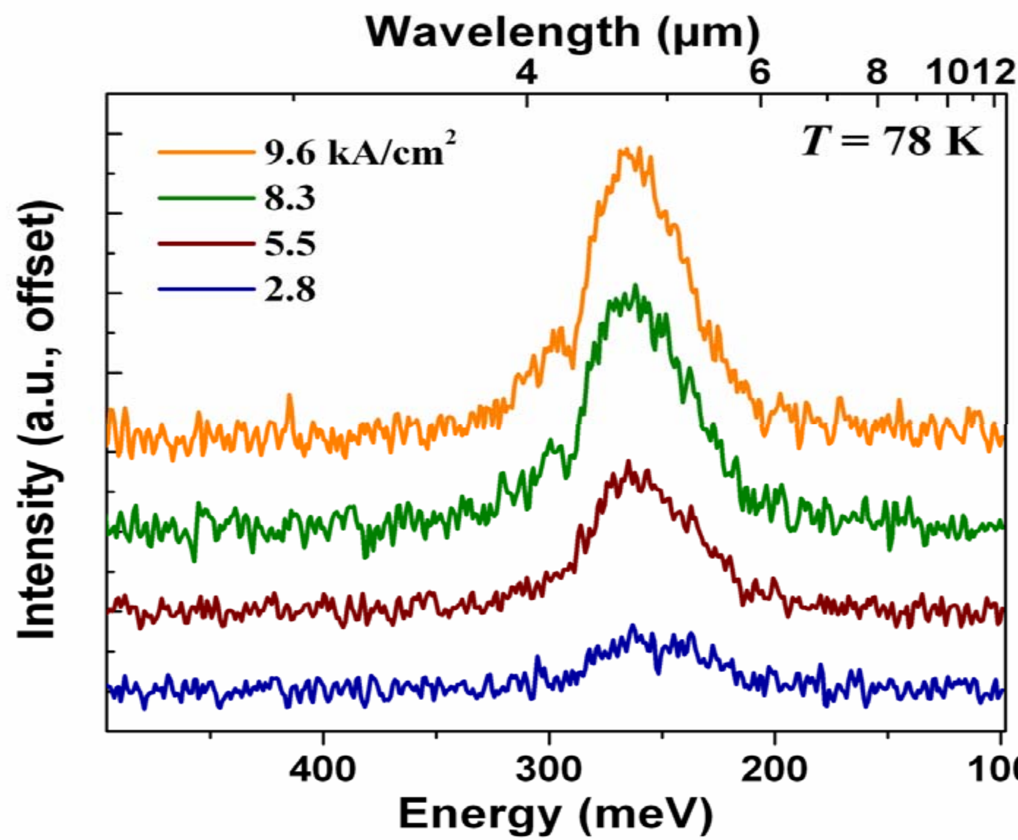
- Absence of deep level emission indicates good material
- Narrow emission suggest good thickness control and interface quality

Simulation and FTIR Results for Optimized EL Sample (300K, unbiased)



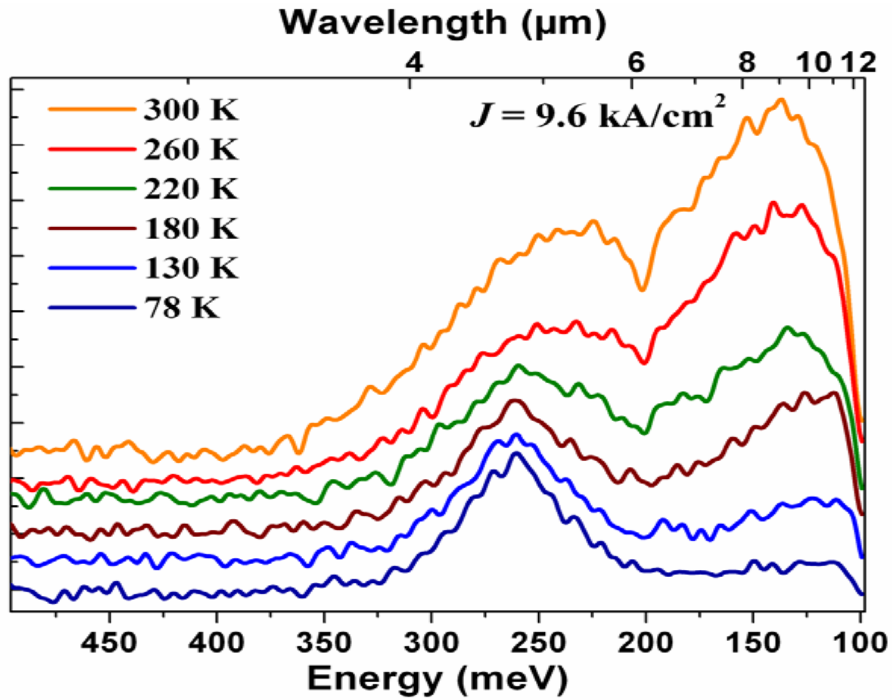
Transition	Simulation (meV)	2nd ACQW (meV)	QC Emitter (meV)
E1 – E4	438	425	421
E2 – E4	394	400	403
E1 – E3	311	313	307
E2 – E3	266 (4.67 µm)	268 (4.63 µm)	278 (4.47 µm)
E1 – E2	45	45	29

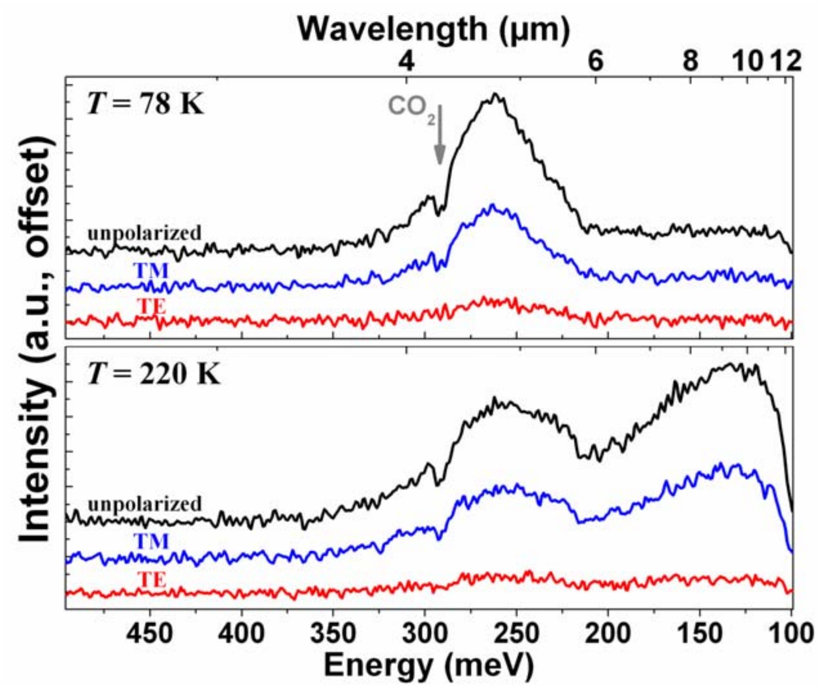
Electroluminescence spectra for QC emitter



- QC emitter with Pt/Au metal contacts
- Emission was observed at 4.8 μm

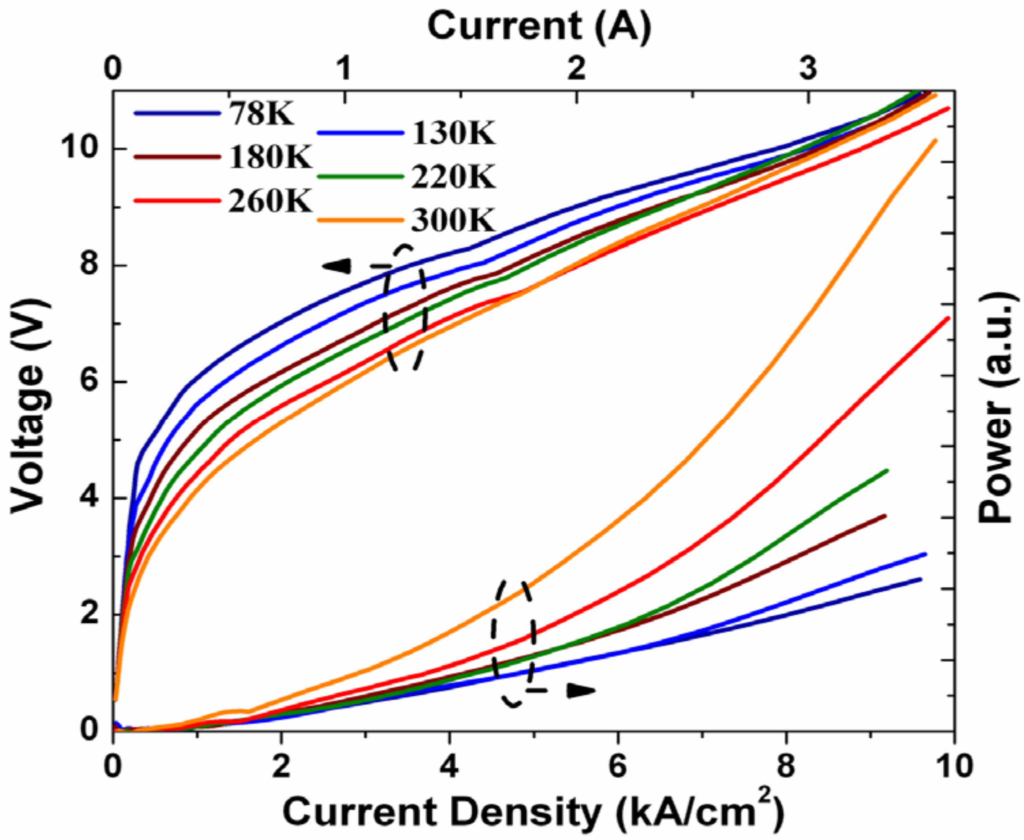
Electroluminescence spectra for QC emitter





- Second peak emerged at ~ 9.4 μm with increasing device temperature
- Polarization analysis indicates that both emission peaks are due to ISB transitions

I-V Curve for QC emitter



- Turn on voltage range from ~ 3.5 to 7 V

Current and Future Work

Optimizing the device results

- New QC structures were grown and will be investigated for emission
  - 2-well ACQW design with more repeats and a cladding
  - superlattice active region design
  - In-situ contact deposition is being explored

Demonstration of electroluminescence below 4 μm

- With current materials compositions (CBO ~ 0.78 eV)
- Using strain compensated structures
- ZnMgSe and metastable MgSe barriers

Summary/Conclusions

- EL structure was designed for emission at 4.5 μm (300 K)
- ACQW test samples were grown to investigate:
  - Energy level spacing in active region
  - Accuracy of simulation parameters
  - Assess material quality and device optical properties
- HR-XRD and PL results indicate that the layer thickness control and well/barrier interfaces are quite good
- FTIR analysis of the QC structure indicate an active region energy level distribution that is in good agreement with simulation results.
- Electroluminescence was observed at 4.8 μm (300 K). This is the first report of electroluminescence in a non III-V QC device.
- These results demonstrate that these II-VI materials are very promising for short wavelength QCLs.