Short wavelength and strain compensated InGaAs-AlAsSb quantum cascade lasers

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Outline

1. Motivation, design requirements and material systems for $\lambda \approx 3$ - 5 μm QCLs
2. Short wavelength $In_{0.53}Ga_{0.47}As/AlAs_{0.56}Sb_{0.44}$ QCLs lattice matched to InP
3. Strain compensated InGaAs/AlAsSb QCLs
4. Improved performance of strain compensated InGaAs/AlAsSb(AlAs) QCLs

1. Motivation

Gas sensing applications in $\lambda \approx 3$ - 5 μm range

- medicine (breath analysis)
- military (countermeasures)
- exploring of minerals

We concentrate on $\lambda \approx 3.34$ μm for **ethane sensing**

in less explored $\lambda < 4$ μm range for quantum cascade lasers

1. Design requirements and material systems for short wavelength λ ~ 3 – 5 μm QCLs

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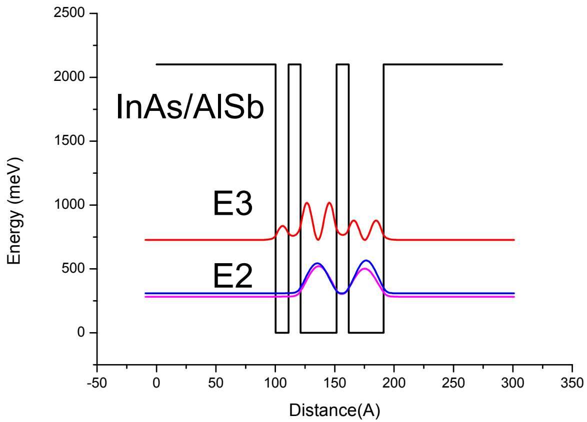
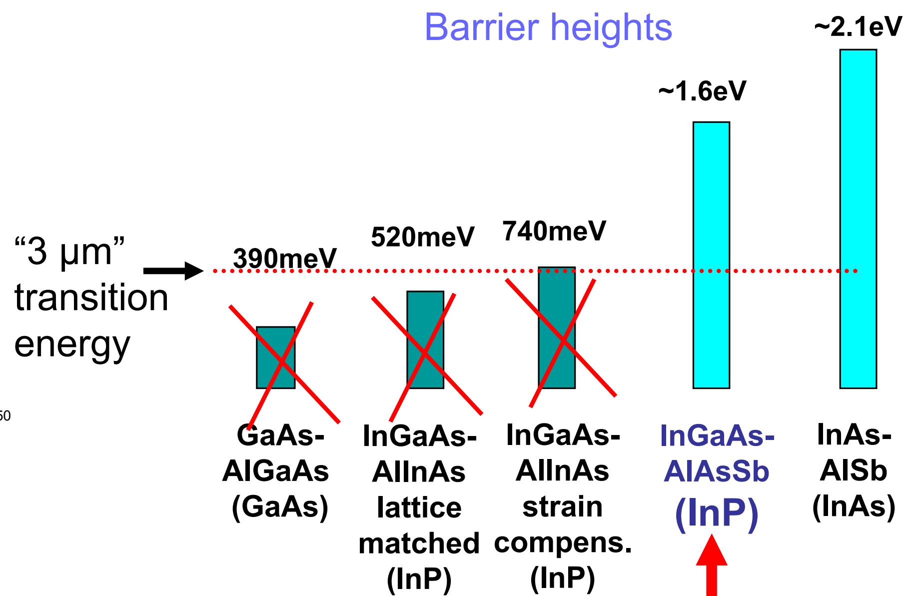
Primary requirement: quantum wells must be deep enough





For λ ≈ 3μm design:

E3-E2 ~420 meV

Upper laser level (E3) energy ~ **700 meV**

focus of our research with well established InP technology

1. Wavelength: how low can we go in InGaAs/AlAsSb system?

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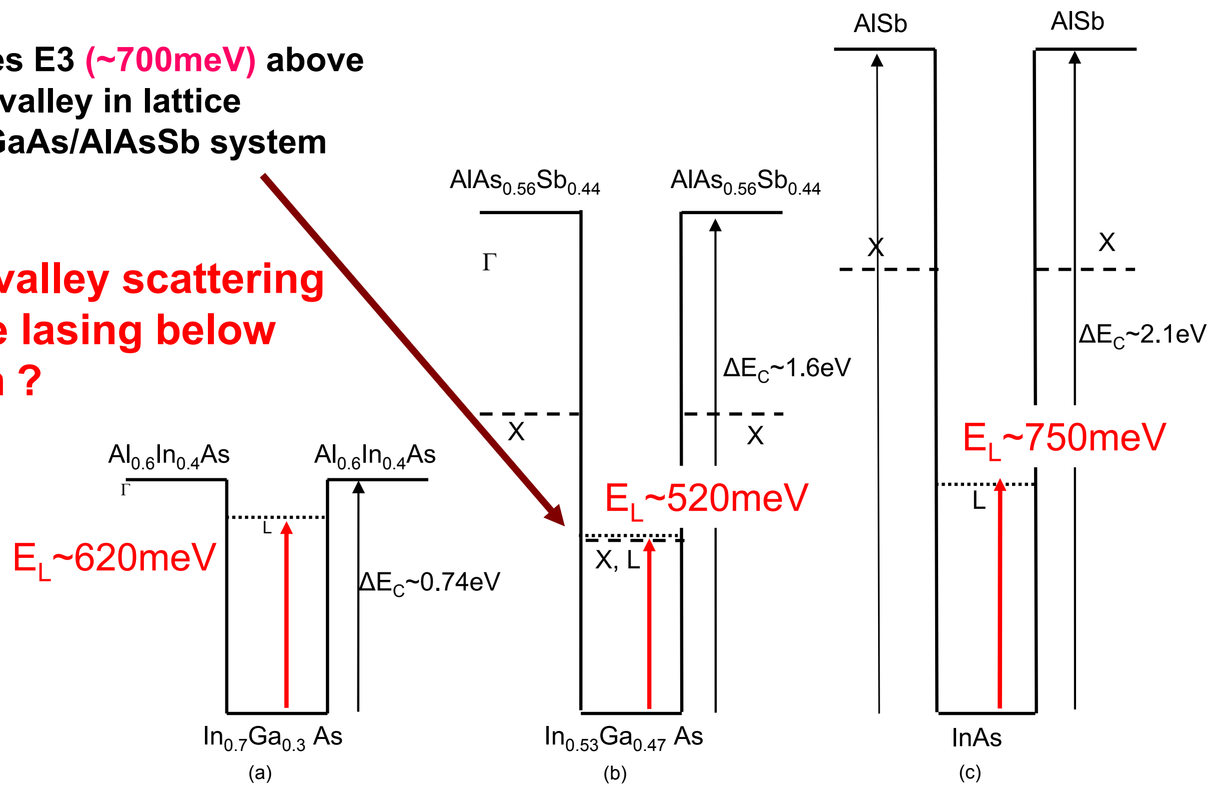
λ=3μm places E3 (~700meV) above the satellite valley in lattice matched InGaAs/AlAsSb system

Will intervalley scattering "stop" the lasing below λ ~ 3.7 μm ?



InGaAs/AlInAs/InP (strain compens.)

InGaAs/AlAsSb/InP

InAs/AlSb

2. Short wavelength InGaAs/AlAsSb QCLs lattice matched to InP

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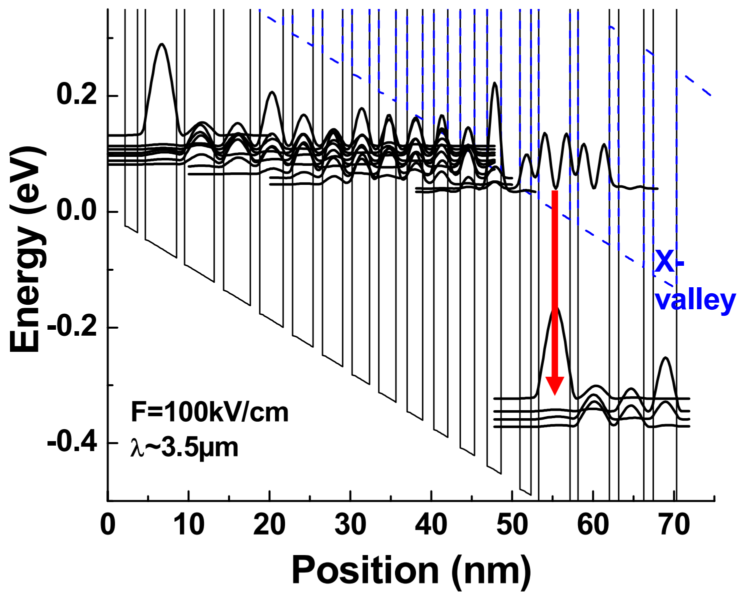
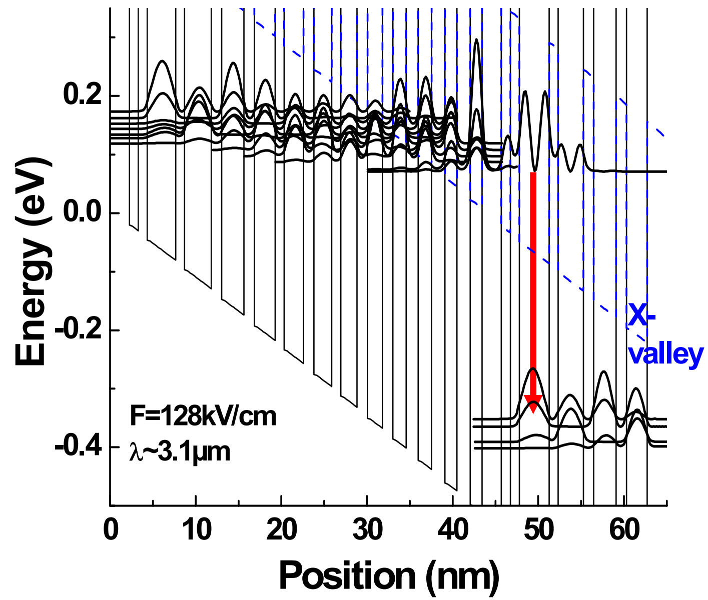
Band profiles

M3255,
λ ~ 3.5 μm laser



M3253,
λ ~ 3.05 μm laser



Upper laser levels are calculated to be higher by ~ 30 and ~ 120 meV than the minimum of the satellite valley in $In_{0.53}Ga_{0.47}As$ lattice matched to InP

2. Short wavelength InGaAs/AlAsSb QCLs lattice matched to InP

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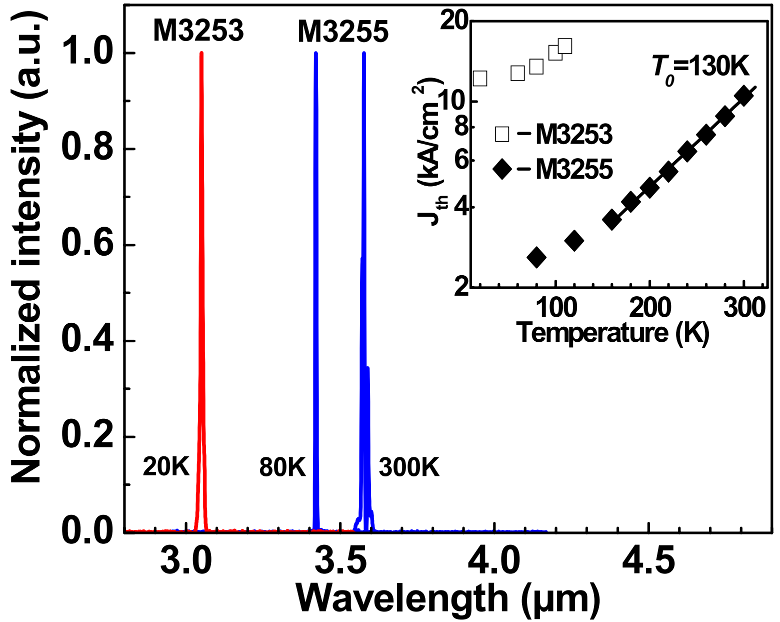
Ridge size:
25µm x 1.5mm
no HR coating



λ~3.05 µm is the shortest wavelength for InGaAs/AlAsSb/InP QCLs

(Revin et al. APL , 90, 021108 (2007))

2. Short wavelength InGaAs/AlAsSb QCLs lattice matched to InP

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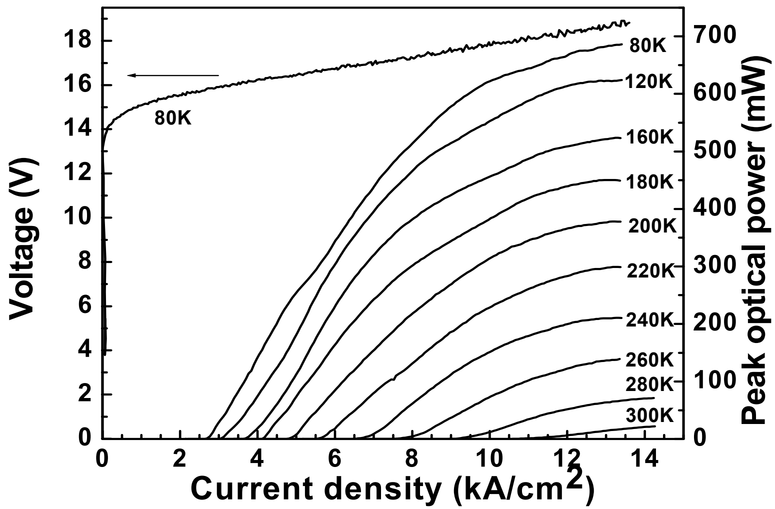
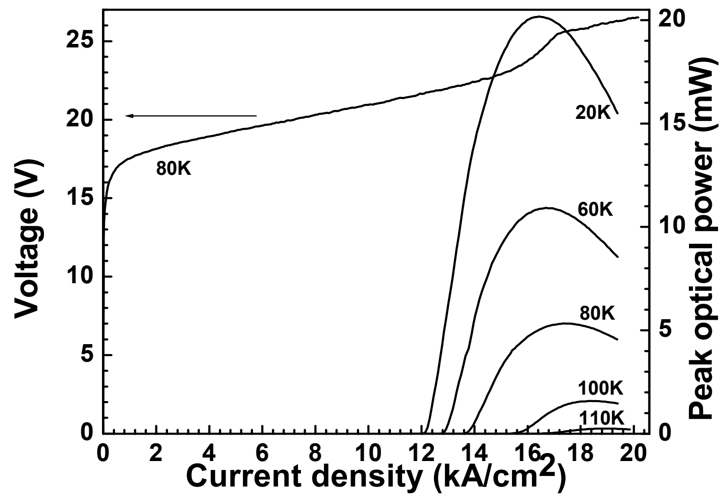
room temperature, λ ~ 3.6 µm laser



only low-temperature, λ ~ 3.05 µm



There is possibly strong influence from intervalley scattering but it does not stop the lasing!

3. Strain compensated InGaAs/AlAsSb QCLs on InP

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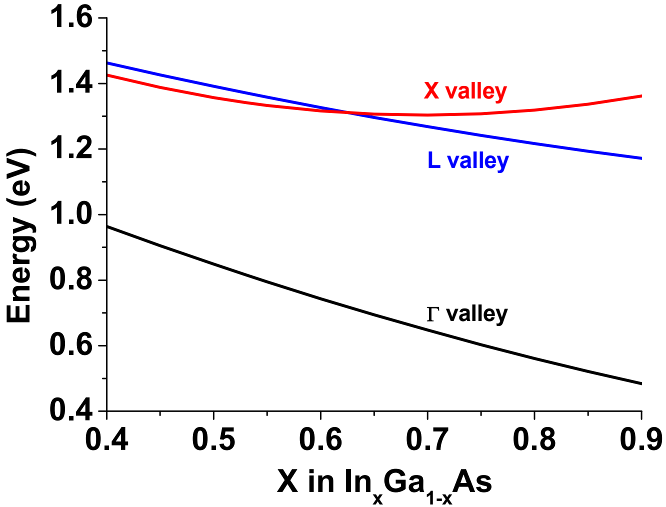
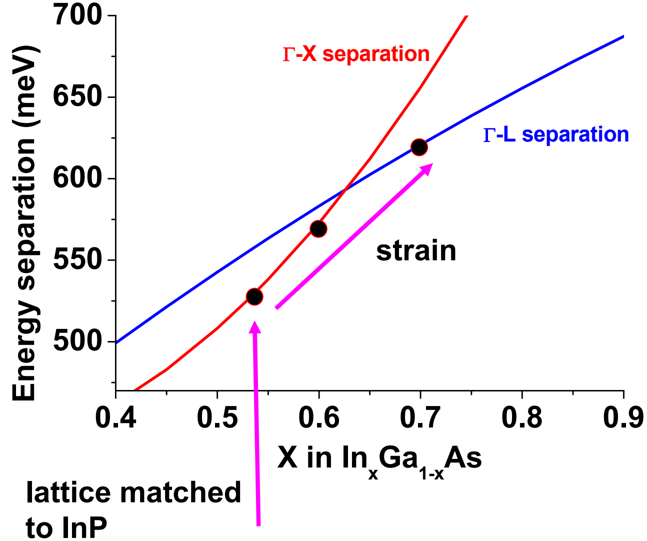
How to reduce the intervalley scattering?





Calculations are based on Vurgaftman et al, JAP. **89**, (2001)

The use of higher indium composition should help in increasing the "effective" (free from intervalley scattering) depth of InGaAs QWs

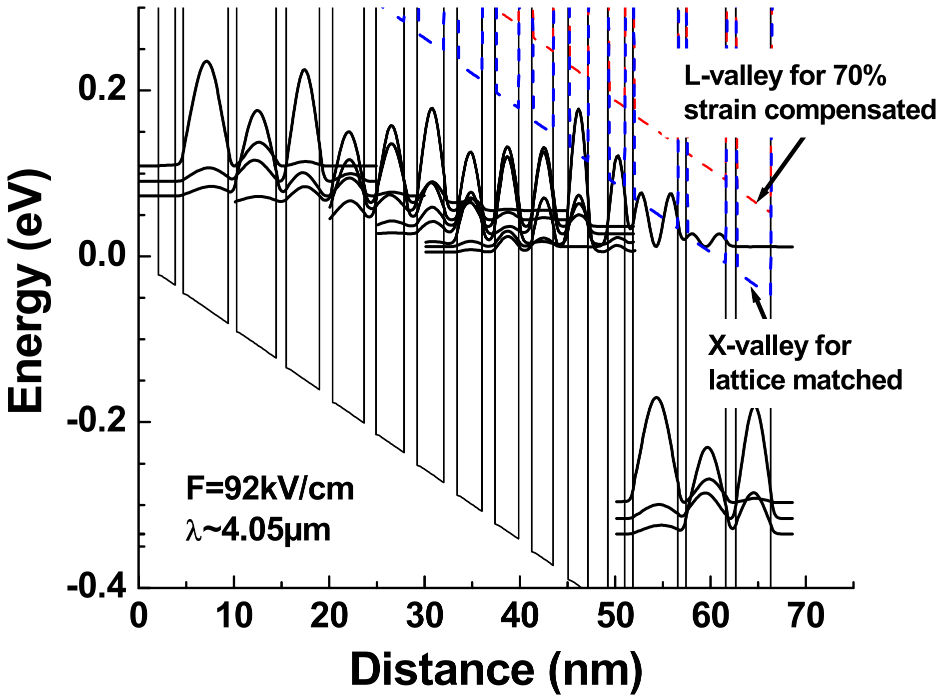
3. Strain compensated InGaAs/AlAsSb QCLs on InP

Identical design:

$In_{0.53}Ga_{0.47}As/AlAs_{0.56}Sb_{0.44}$ - M3254 (reference)

$In_{0.6}Ga_{0.4}As/AlAs_{0.67}Sb_{0.33}$ - M3259 (strain compensated)

$In_{0.7}Ga_{0.3}As/AlAs_{0.78}Sb_{0.22}$ - M3257 (strain compensated)



3. Strain compensated InGaAs/AlAsSb test superlattices

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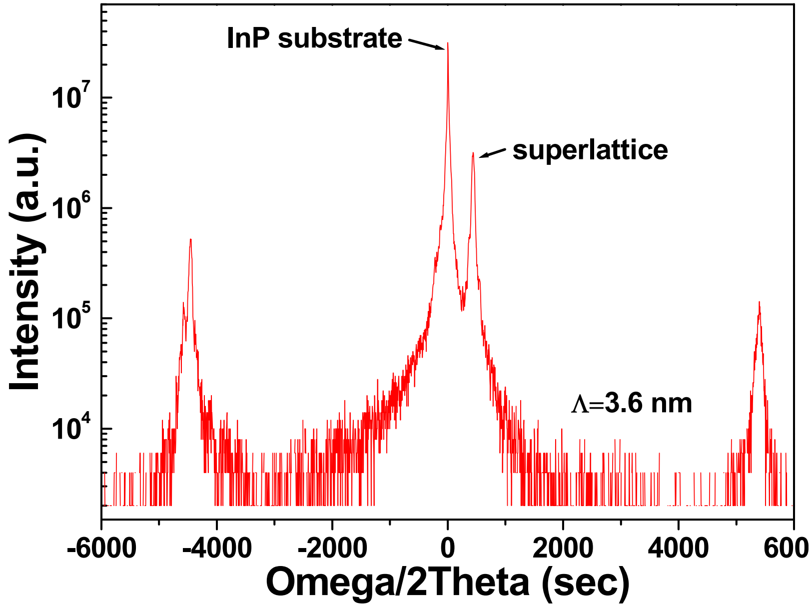
Sb fraction has to be adjusted to give the best compensation of the strain



X-rays diffraction has been used to assess
- quality,
- thickness and
- remaining strain

in the strain compensated InGaAs/AlAsSb test superlattices with periods similar as in the injectors

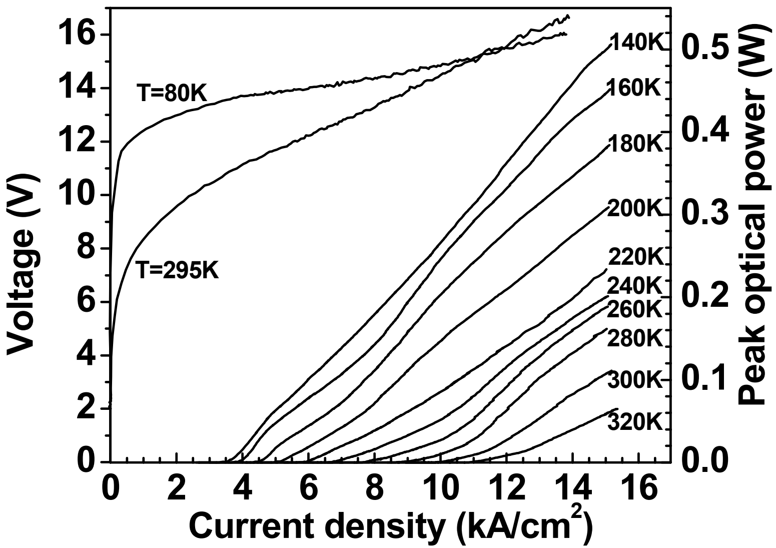
100 periods

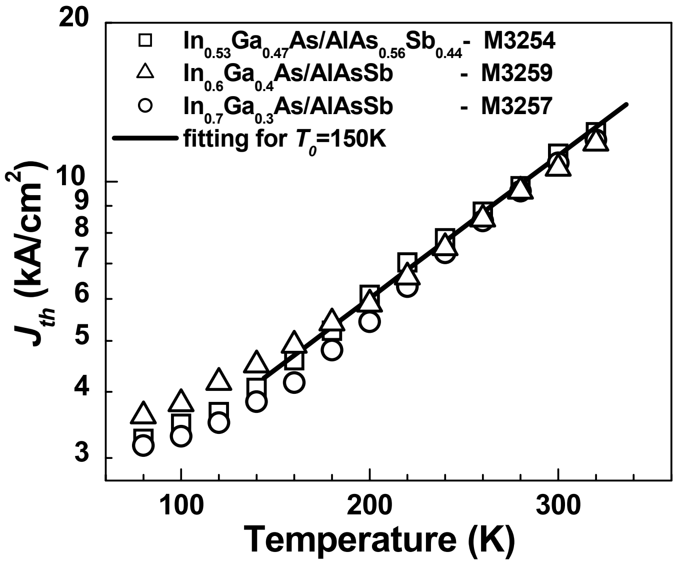
$In_{0.67}Ga_{0.33}As$ - 22 Å (~ 8 MLs)

$AlAs_{0.76}Sb_{0.24}$ (?) - 13 Å (~ 4 MLs)

3. Feasibility of strain compensated InGaAs/AlAsSb QCLs on InP

λ~4-4.3μm $In_{0.7}Ga_{0.3}As/AlAs_{0.78}Sb_{0.22}$





No degradation for strain compensated QCLs with the performance similar to the lattice matched QCLs

(Revin et al. APL , 90, 151105 (2007))

3. Strain compensated InGaAs/AlAsSb QCLs on InP

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Details of the design and performance

Wafer number	M3254	M3259	M3257
Indium concentration in InGaAs quantum wells (%)	53	60	70
Position of the lowest satellite valley in InGaAs quantum wells (meV)	+520	+570	+620
Energy between upper laser level and the lowest satellite valley in InGaAs quantum wells (meV)	80	115	160
Calculated wavelength (μm)	4.15	4.1	4.05
Wavelength of the laser emission for T = 80 / 300 K (μm)	4.1/4.4	4.1/4.4	4/4.3
FWHM of EL peak for T = 80 / 300 K (meV)	40/73	44/68	42/72
Average J_{th} for T = 80 / 300 K (kA/cm^{2})	3.4/11.3	3.6/10.6	3.2/10.9
Maximum pulsed optical power at J ~ 15kA/cm^2 for T = 80 / 300 K (W)	0.8/0.15	1.2/0.2	0.7/0.12
Characteristic temperature T_0 (K)	155	165	150

4. Strain compensated InGaAs/AlAsSb QCLs with AlAs barriers

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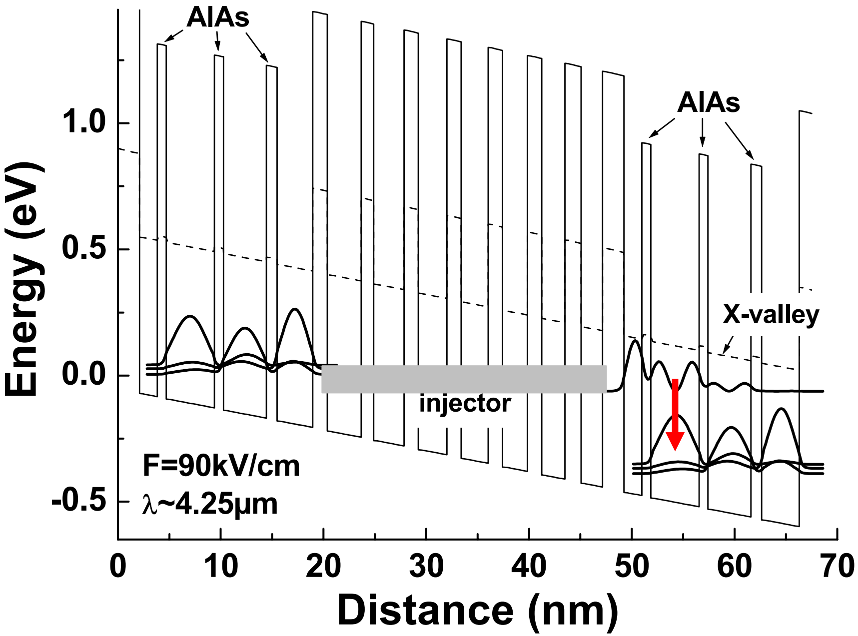
Further improvement of QCL performance

Identical design:

$In_{0.6}Ga_{0.4}As/AlAsSb(AlAs)$ - M3260 (wafer A)

$In_{0.6}Ga_{0.4}As/AlAsSb$ - M3259 (wafer B)

AlAs barriers in the active region (~3 MLs) should help to reduce interdiffusion of Sb at InGaAs/AlAsSb interfaces in the active regions



4. Strain compensated InGaAs/AlAsSb QCLs with AlAs barriers

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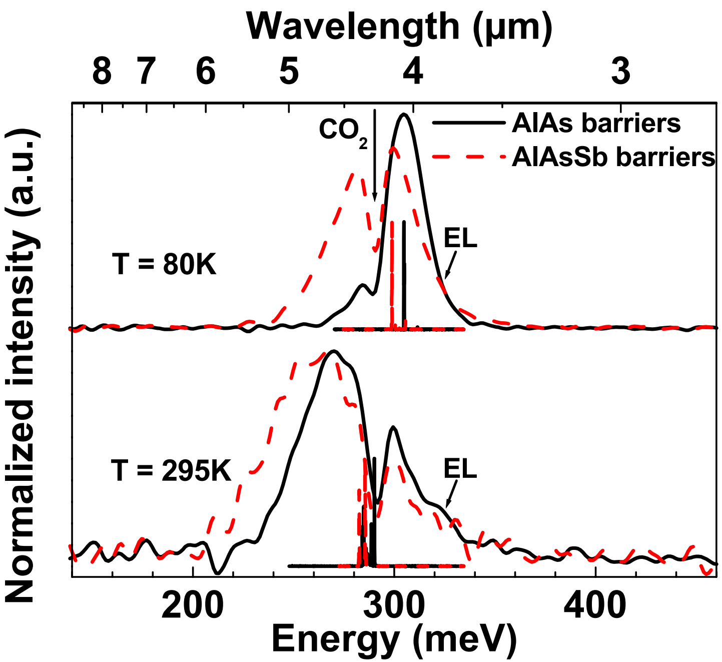
For QCLs with AlAs barriers

High energy shift and narrower EL peaks
- InGaAs QWs are clear from Sb and have better profile
- better interface quality (?)



Laser and electroluminescence spectra

4. Strain compensated InGaAs/AlAsSb QCLs with AlAs barriers

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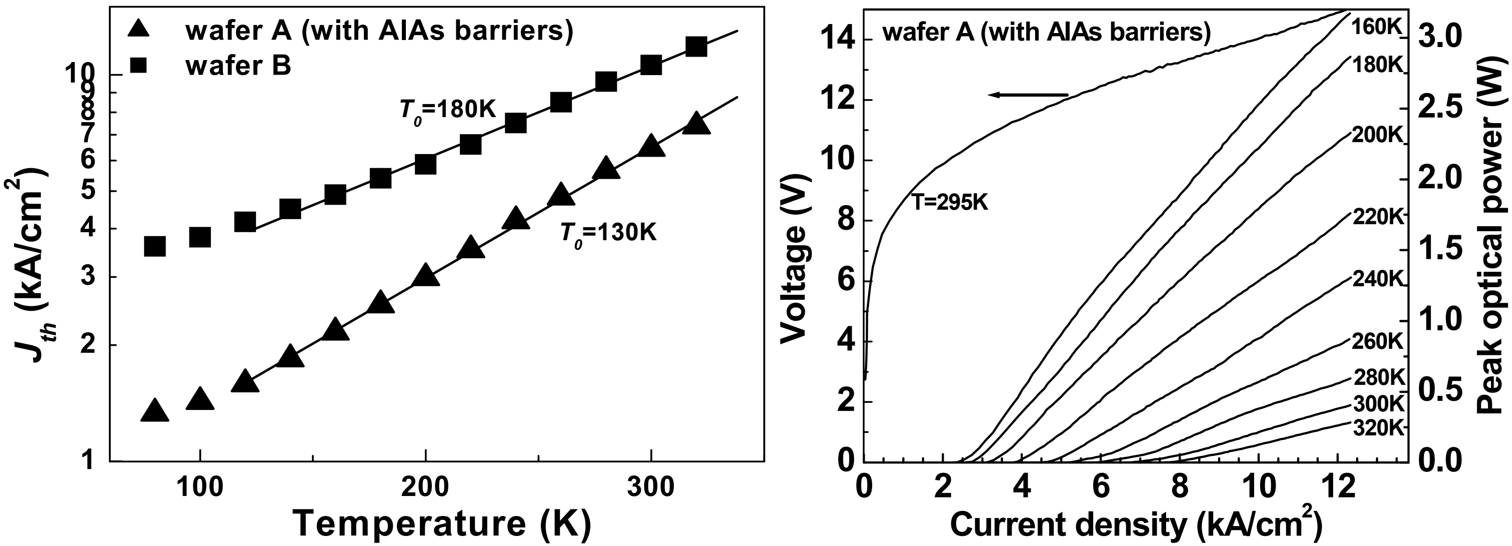

Improved performance for the QCLs with AlAs barriers :

- **lower threshold - by factor more than 2,**
- **higher optical power - 0.5 W at 300K compared with 0.15 W for wafer B**

(Revin et al. APL , 91, 051123 (2007))

Conclusions

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1. First $In_{0.53}Ga_{0.47}As/AlAs_{0.56}Sb_{0.44}$ QCLs lattice matched to InP working down to 3.05 μm
2. First strain compensated InGaAs/AlAsSb QCLs
3. Improved performance of InGaAs/AlAsSb QCLs with AlAs barriers in the active regions
4. Expected room temperature operation for the strain compensated QCLs down to λ ~ 3.2 - 3.3 μm

Acknowledgements: dti POISE