Indirect carrier leakage in short-wavelength InAs/AlSb quantum cascade lasers

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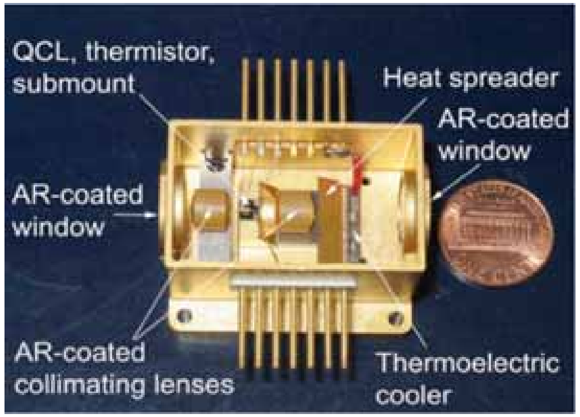
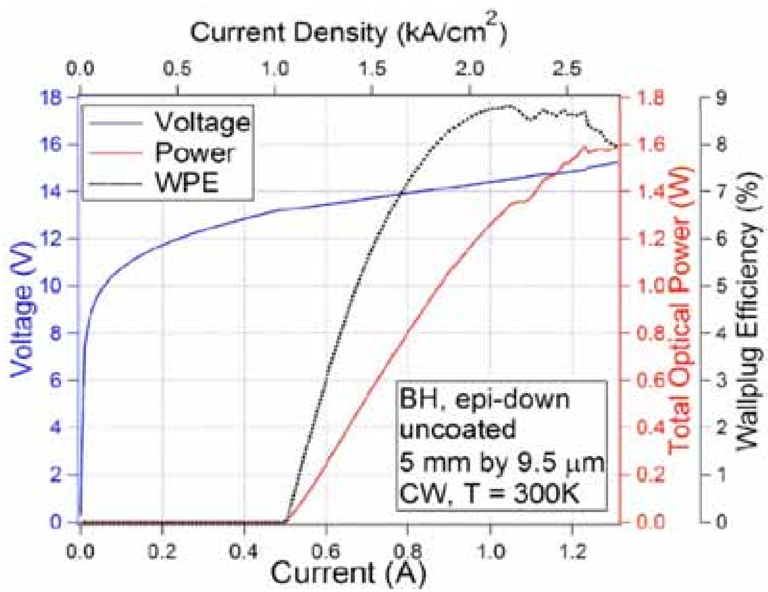
Mid-infrared semiconductor lasers for 2-4μm spectral region

- Applications: gas sensing, free space optical communications, etc.
- Interband QW lasers → limitations for λ>2.5μm due to Auger recombination
- Short-wavelength QCLs (high band offsets needed >400meV to provide lasing at λ<3μm) – no problem of Auger recombination
- Excellent performance of QCLs at λ>4μm (InAlGaAs/InP QCL – 1.6W CW at 300K) → efforts to reduce λ by using new material systems

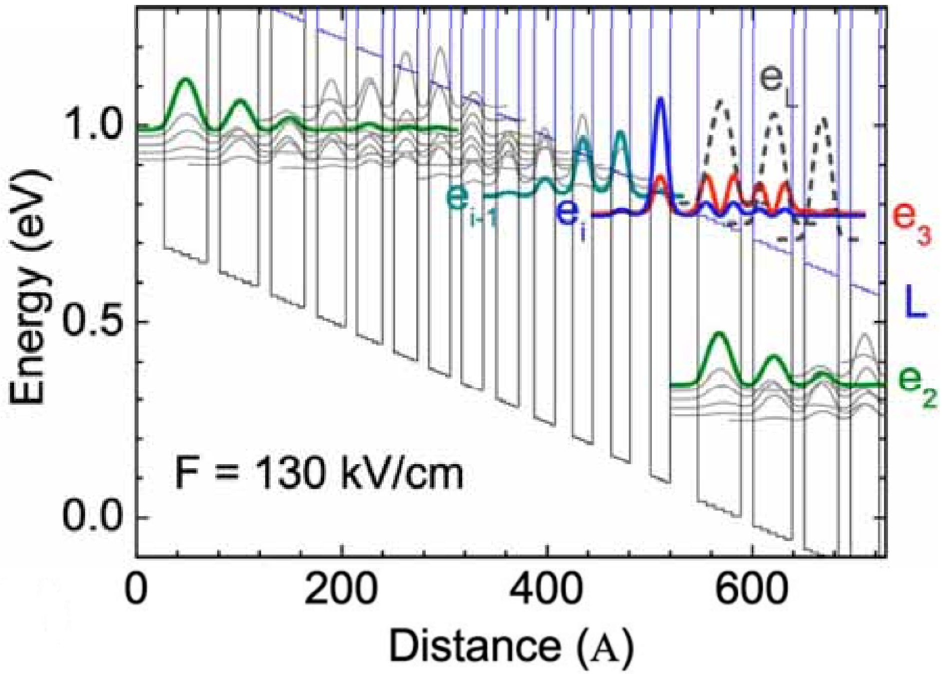


A. Lyakh et al, Appl. Phys. Lett. **92**, 111110 (2008).



Short-wavelength QCLs

J. Devenson et al, Appl. Phys. Lett. **91**, 251102 (2007)

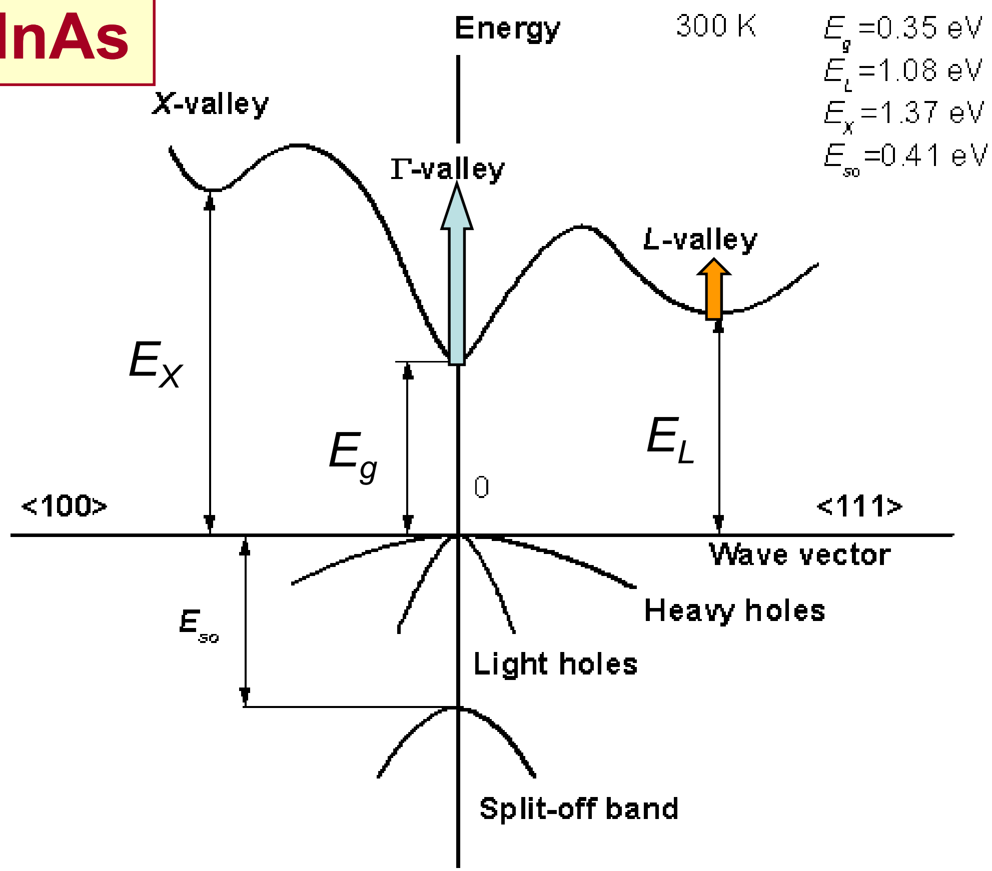


Conduction band diagram of InAs/AlSb 2.9µm QCL
Solid curves - the moduli squared of the relevant electron wave functions.
Dotted lines - e_L levels associated with the *L* valley calculated using Γ-*L* separation value of 0.73 eV.

- InAs/AlSb exhibits highest conduction band Γ -Γ offset of 2.1eV.
- Largest separation between direct and indirect minima of conduction band (Γ-L separation is 0.72-0.76eV in InAs).
- Modelling → Γ-L electron leakage from the upper laser levels may influence the laser performance.
- Use high hydrostatic pressure to investigate presence and importance of carrier leakage into L-valley

Effect of high-pressure on conduction band of InAs

InAs



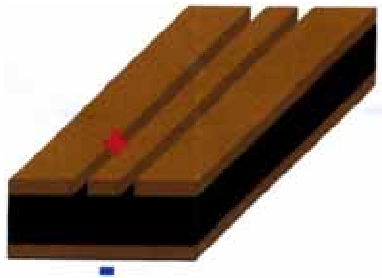
Use hydrostatic pressure to manipulate band structure at constant T:

- dE_{Γ}/dp = 10.2 meV/kbar
- dE_L/dp = 3.2 meV/kbar
- $d(E_L - E_{\Gamma})/dp$ = - 7 meV/kbar

This provides a possibility to investigate the importance of carrier leakage into *L*-valley using high pressure

Experiment

Samples



MBE grown

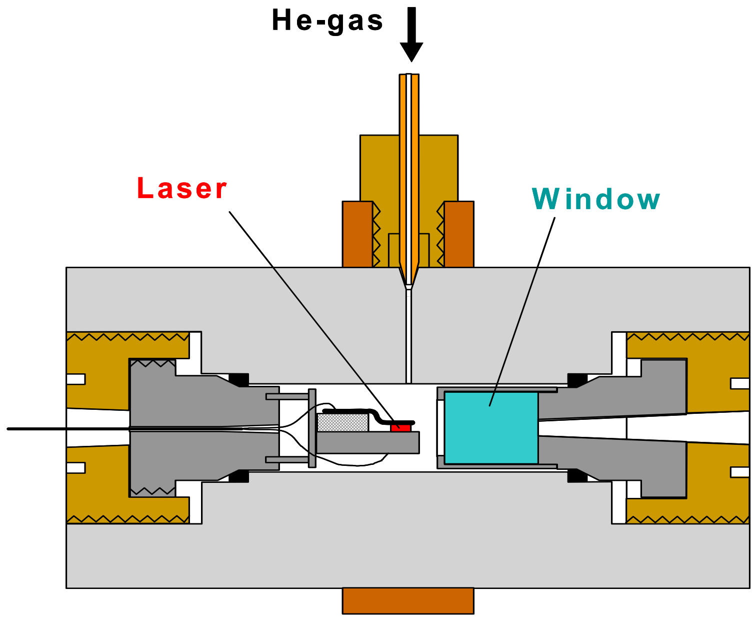
InAs/AlSb QCLs on (100) InAs substrate

λ~2.9µm and 3.3µm at RT

Ridge lasers (12 and 17 µm wide)

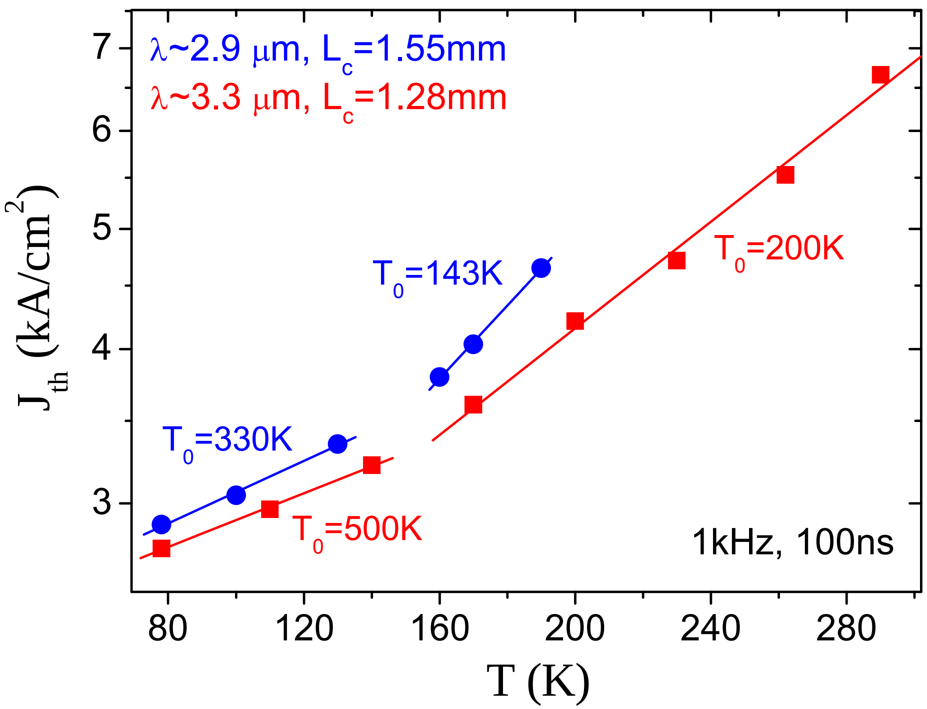
L_{cavity}=1.1-2.05 mm

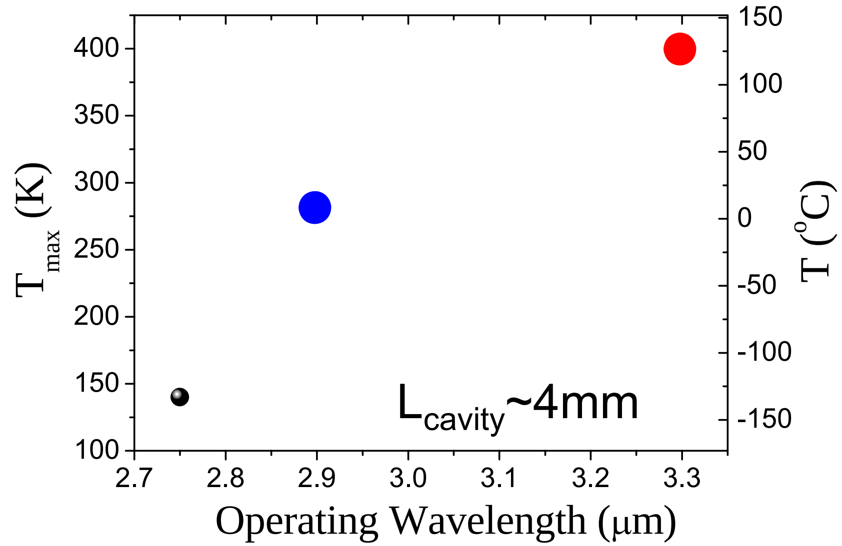
High-pressure cell



- **Pressures up to 10kbar**
- **Temperatures down to 80K**

Temperature dependence of I_{th}





J. Devenson et al, APL **91**, 251102 (2007)

- Lower J_{th}, higher T_0 and maximum operating temperature, T_{max}, for longer wavelength devices
- Temperature sensitive loss process is more important at shorter wavelengths
- This is consistent with indirect Γ-*L* carrier leakage since the shorter wavelength devices have a smaller Γ-*L* separation

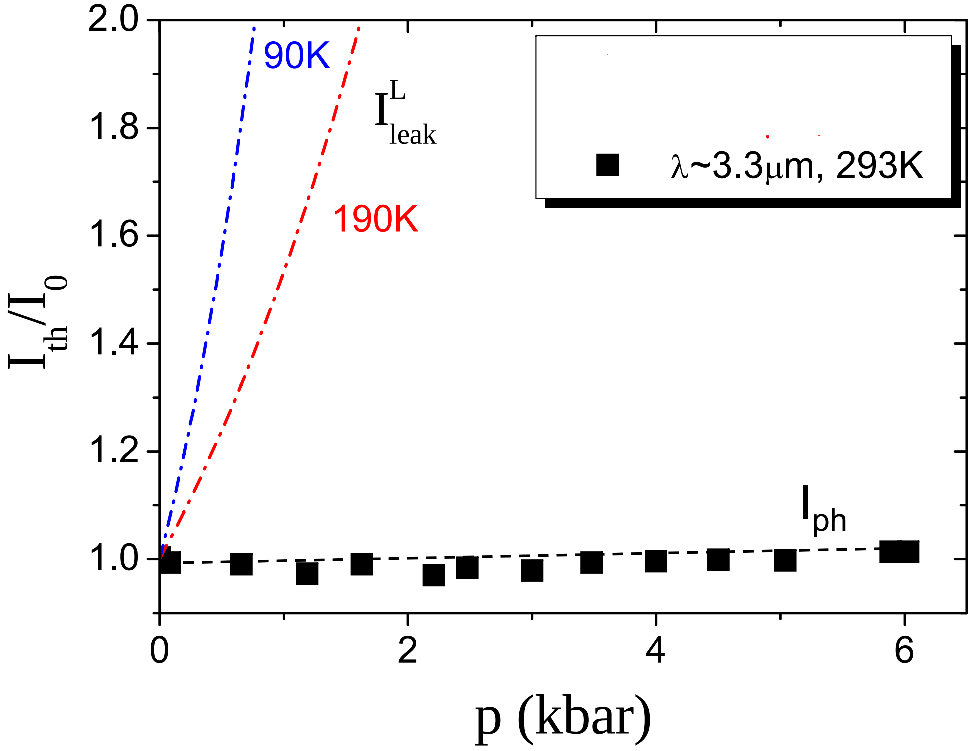
Carrier leakage as function of T and p

$$I_{leak}^{L}(T) = I_{0leak}\exp\left(-\frac{E_a}{kT}\right)$$

$$I_{leak}^{L}(p) \propto \exp\left(-\frac{dE_a}{dp}\frac{p}{kT}\right) \propto \exp\left(-\frac{dE_L - dE_\Gamma}{dp}\frac{p}{kT}\right)$$

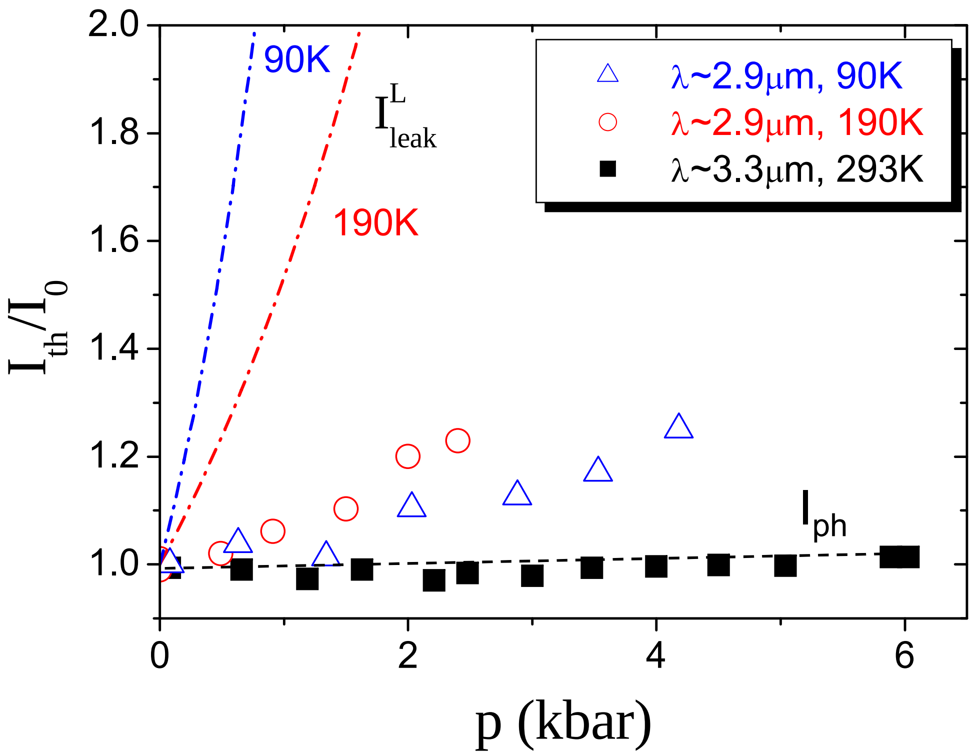
Indirect carrier leakage has approx. exponential pressure dependence with $dE_L - dE_\Gamma \approx -7$meV/kbar

Pressure dependence of I_{th}



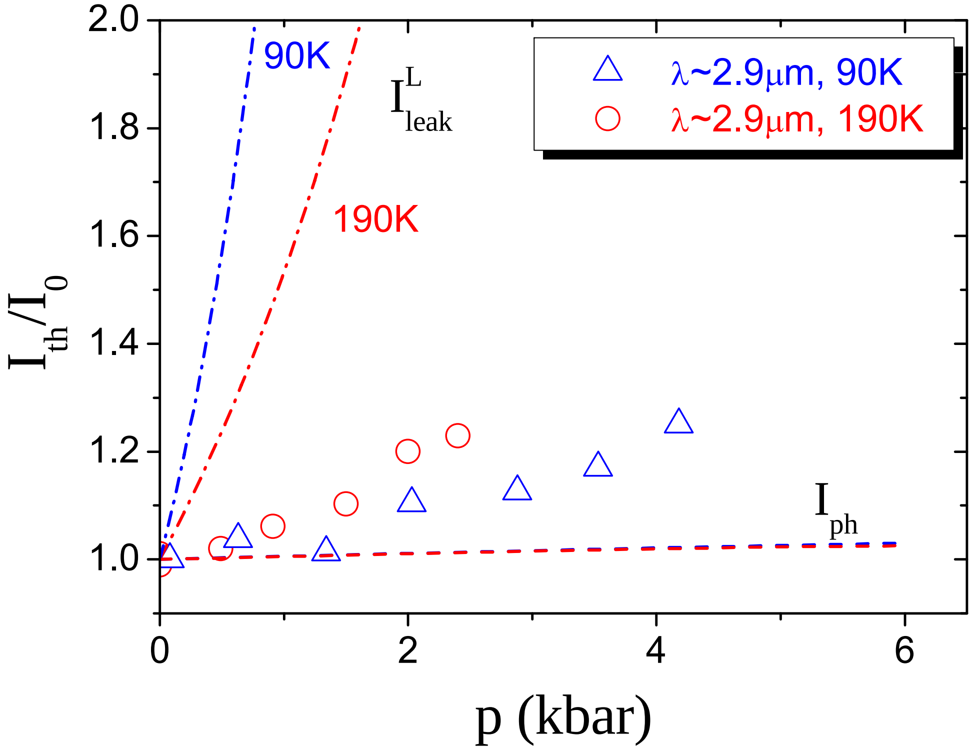
- I_{th} of 3.3μm QCL at 293K is almost pressure independent even at RT indicating that I^L_{leak} is negligible in this device even at RT
- I_{th}~I_{ph} - current due to intersubband carrier relaxation via LO phonon scattering with very weak pressure dependence

Pressure dependence of I_{th}



- I_{th} of 3.3μm QCL at 293K is almost pressure independent even at RT indicating that I^L_{leak} is negligible in this device even at RT
- I_{th}~I_{ph} - current due to intersubband carrier relaxation via LO phonon scattering with very weak pressure dependence
- In contrast, I_{th} in 2.9μm QCL increases considerably with increasing pressure
- Laser operation stops at 2.4kbar at 190K and at 4.2kbar at 90K

Quantitative estimations of carrier leakage



- Dashed lines show calculated $I_{ph}(p)$ for 2.9μm QCL at 90K and 190K
(similar calculations for GaAs/AlGaAs QCL - S. R. Jin et al, APL **89**, 221105, 2006)

- Estimate fractional contribution of leakage by assuming that:

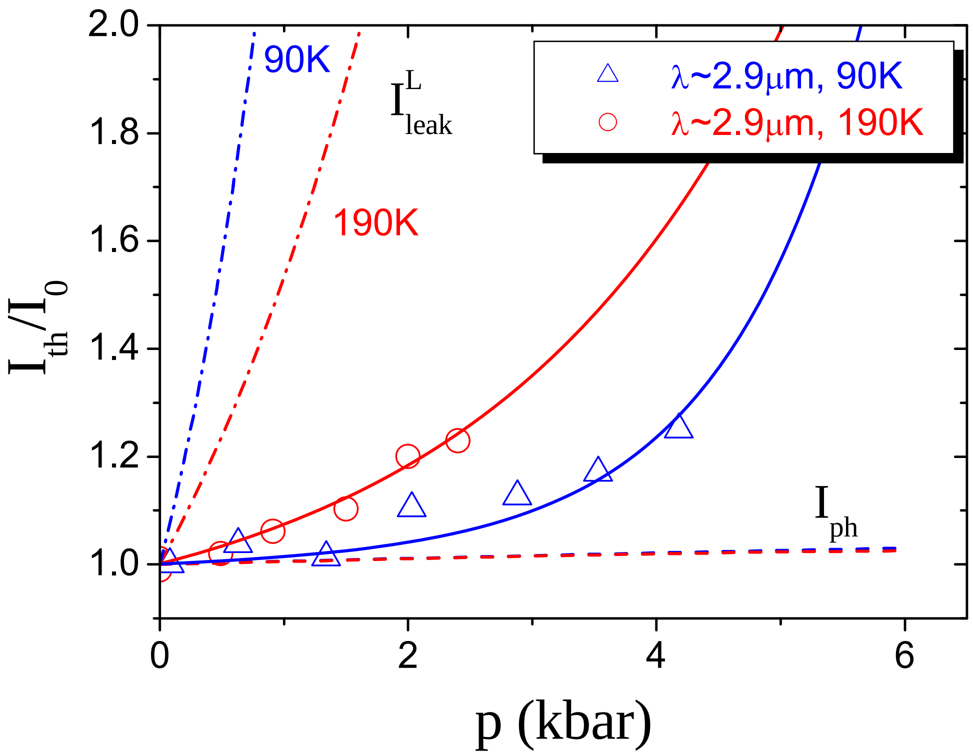
$$I_{th} = I_{ph} + I^L_{leak}$$

or

$$\frac{I_{th}}{I_0} = (1-x)\cdot\frac{I_{ph}}{I_{ph0}} + x\cdot\frac{I^L_{leak}}{I^L_{leak0}}$$

x – fraction of I_{th} due to leakage at p=0

Pressure dependence of I_{th}

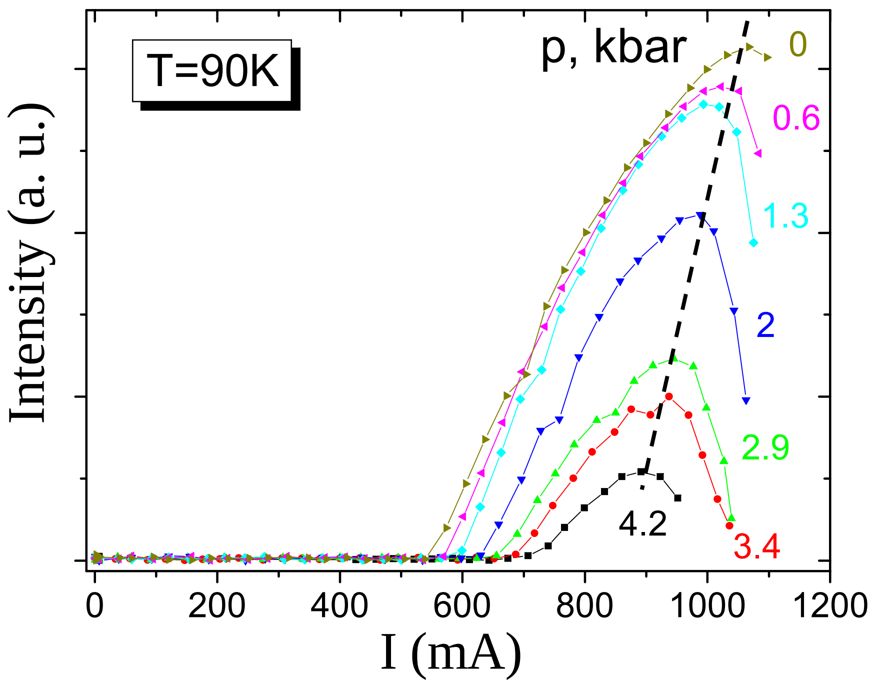


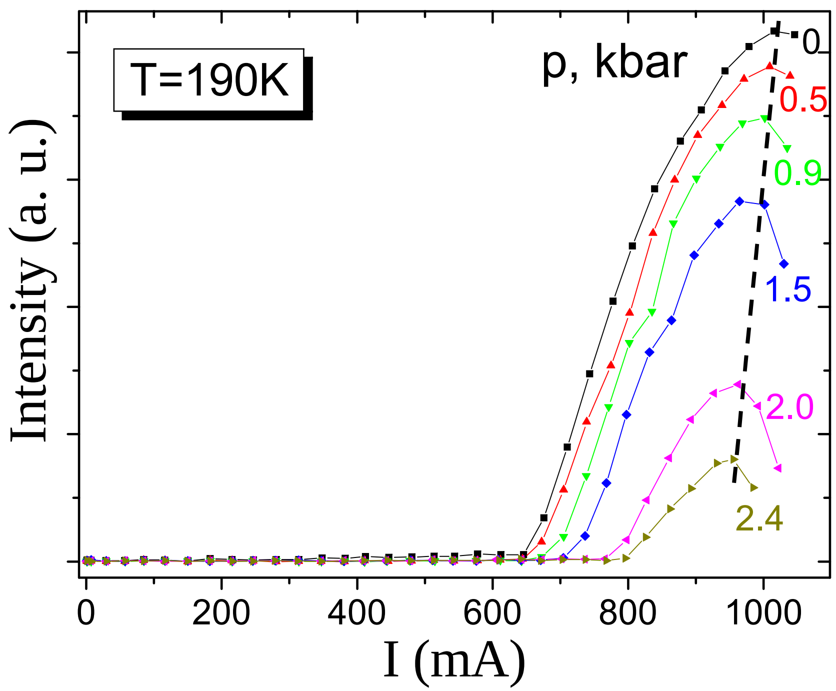
- x = 0.006 (0.6%) at 90K
- x = 0.13 (13%) at 190K
- By applying pressure we increase leakage current up to 29% of I_{th} at 190K and 20% of I_{th} at 90K

$$\frac{I_{th}}{I_0} = (1-x)\cdot\frac{I_{ph}}{I_{ph0}} + x\cdot\frac{I^L_{leak}}{I^L_{leak0}}$$

x – fraction of I_{th} due to leakage at p=0

Pressure dependence of L-Is: 2.9μm QCL





- Maximum available current, I_{max}, decreases with increasing pressure
- This is explained by the reduction of population of the upper level of lasing transition due to leakage into the L-valleys
- Such behaviour is not observed in the 3.3μm QCLs

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photonics

Conclusions

- The impact of Γ-L scattering on the temperature performance of short wavelength InAs/AlSb QCLs was investigated using high hydrostatic pressure.

- The results show evidence of that this loss mechanism is important in ~2.9 μm lasers (~20% of I_{th} at maximum T), but much less pronounced in ~3.3 μm devices, enabling their superior temperature performance.

- We suggest that increased leakage into the L-minima is the reason for the even lower maximum operating temperature (140 K) of lasers emitting near 2.75 μm.