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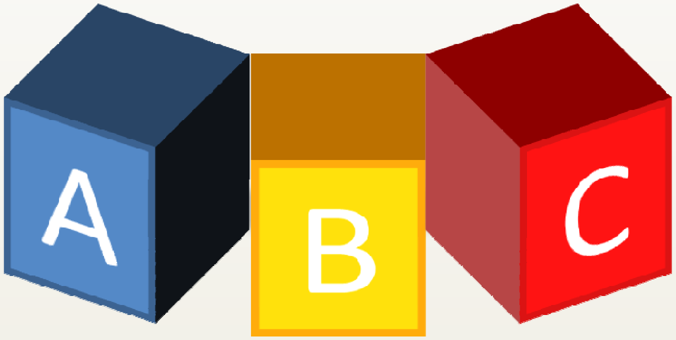
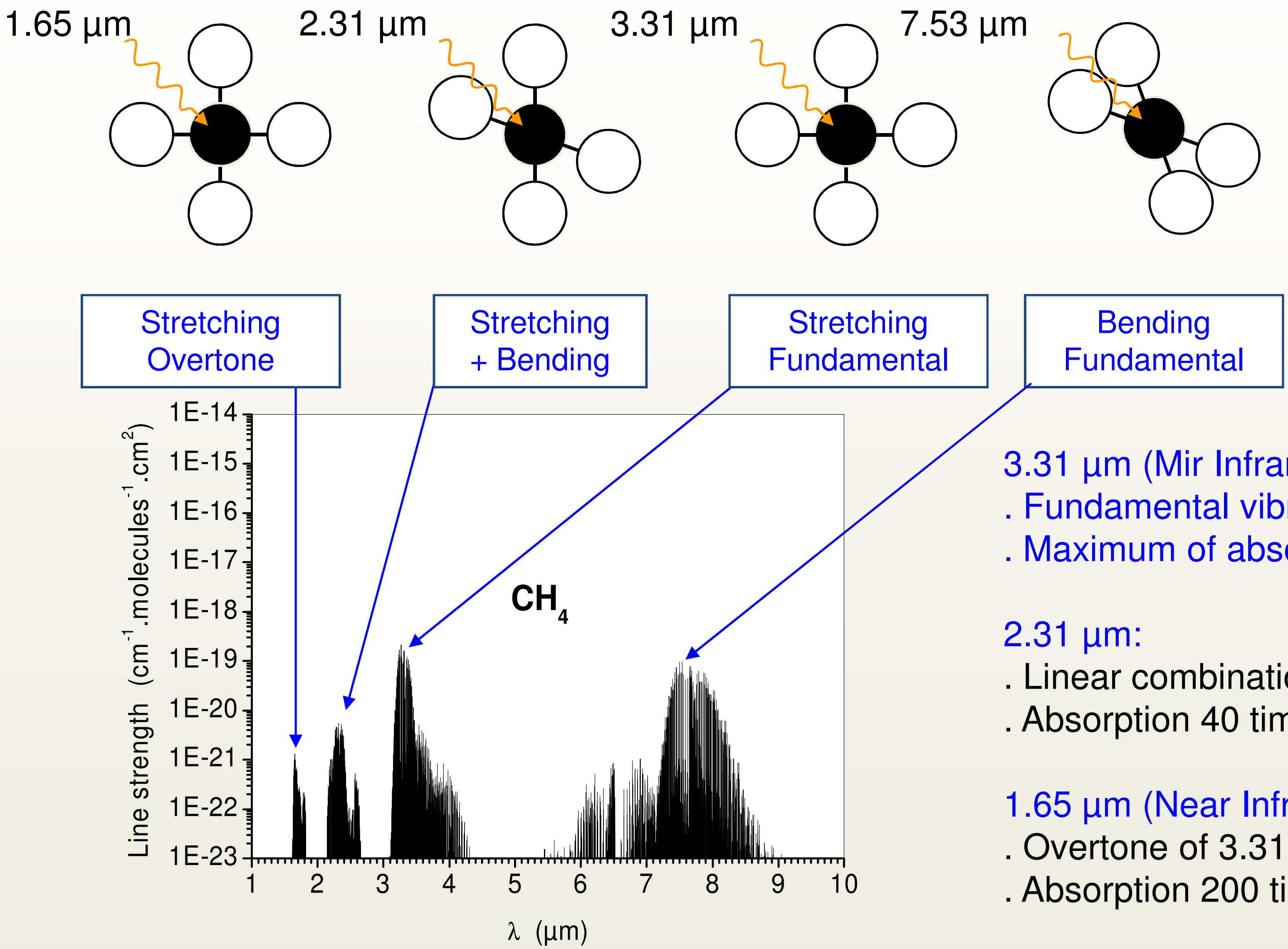
The A,B,C's
of
Mid-Infrared Quantum Well Lasers



Yves Rouillard, Guilhem Boissier and Grégoire Narcy

IES Laboratory
Université Montpellier 2
France

Absorption spectroscopy: The case of methane



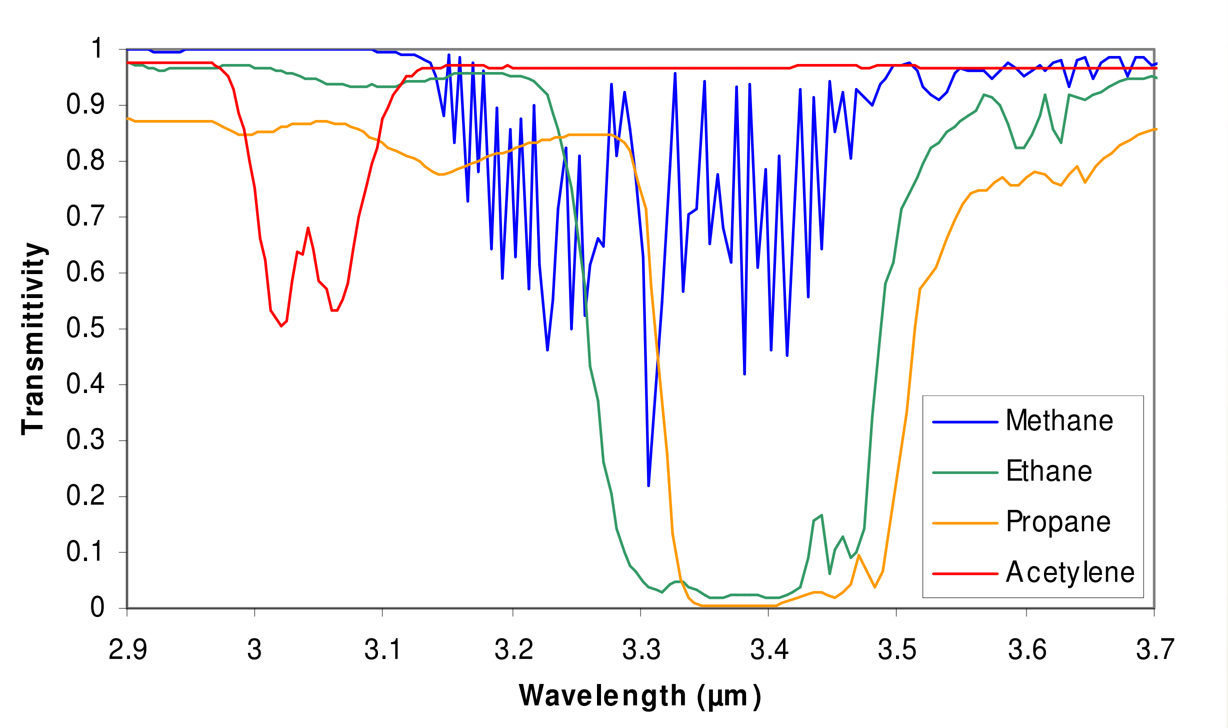
(Hitran database)

3.31 µm (Mir Infrared):
. Fundamental vibration
. Maximum of absorption

2.31 µm:
. Linear combination of vibrations
. Absorption 40 times weaker

1.65 µm (Near Infrared):
. Overtone of 3.31 µm vibrations
. Absorption 200 times weaker

Some interesting ranges for other hydrocarbons



(Chemistry WebBook, NIST)

Methane:
Peak at 3.31 µm

Ethane:
Half maxima at 3.28 µm
and 3.49 µm

Propane:
Half maxima at 3.31 µm
and 3.51 µm

Acetylene:
2 peaks at 3.03 and 3.06 µm

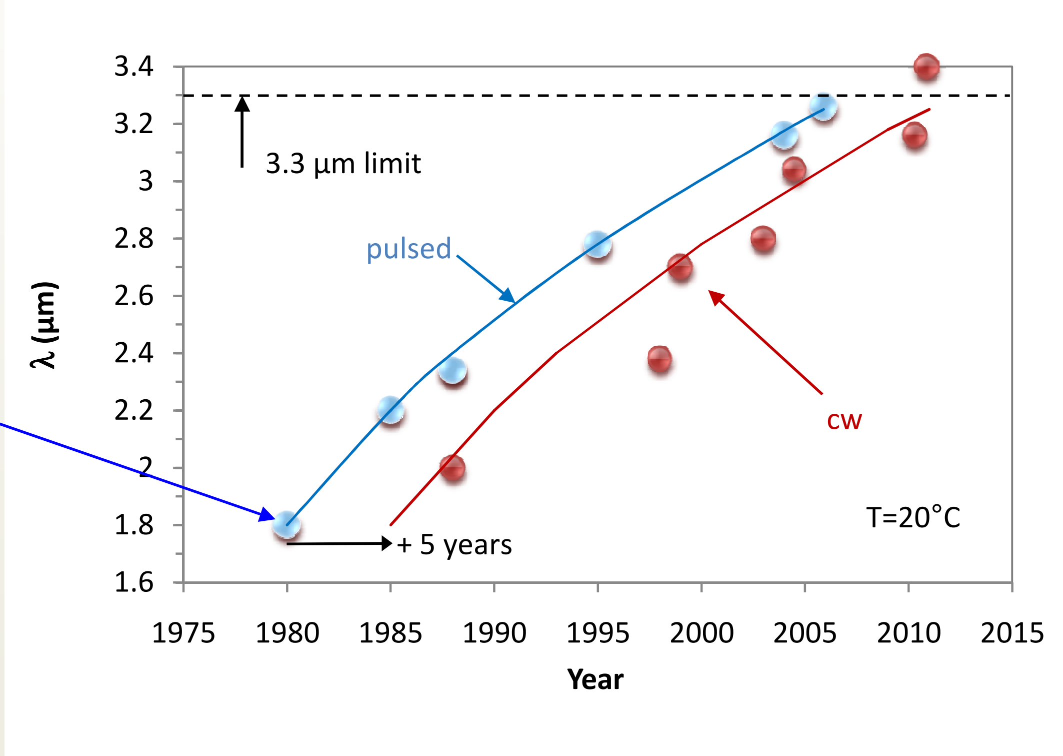
The 3.0-3.1 µm range is interesting for Acetylene sensing

The 3.3-3.4 µm range is interesting for natural gas sensing

A History of GaInAsSb/AlGa(In)AsSb Laser diodes

1980: DH laser at 1.8 µm in pulsed mode at 20°C (NTT, S. Kobayashi)
1988: DH laser at 2.0 µm in cw mode at 20°C (Ioffe, A. Baranov)
1988: DH laser at 2.34 µm in cw mode at 20°C (Lebedev, A. Bochkarev)
2004: QW laser at 3.04 µm in cw mode at 20°C (Univ. Munich, C. Lin)
2005: QW laser at 3.26 µm in pulsed mode at 20°C (Univ. Munich, M. Grau)
2010: QW laser at 3.40 µm in cw mode at 20°C (S. Univ. New York, T. Hosoda)

Soichi Kobayashi

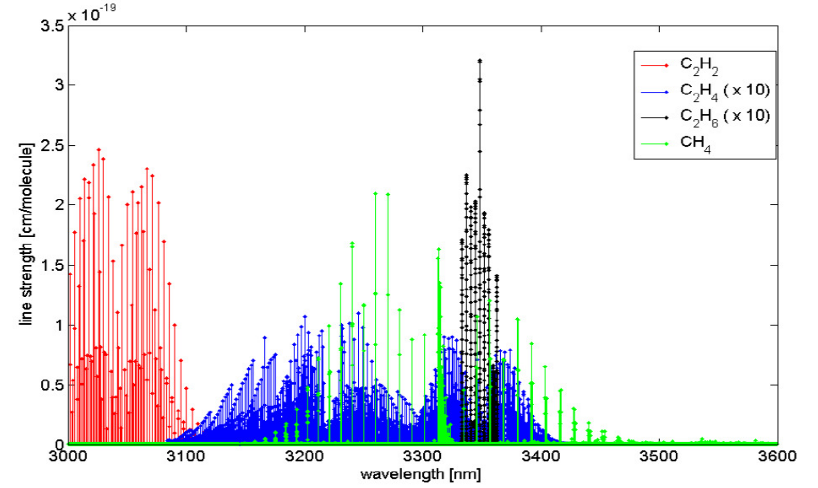


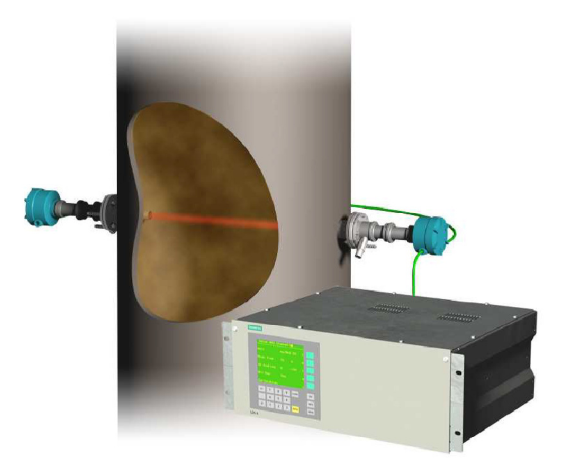
The history of mid-infrared laser diodes can be summarized as a race toward long wavelengths

Mid Infrared lasers: Spectroscopic applications

QW DFB at 3.06 µm:
For measuring C_2H_2 in C_2H_4 (polyethylene plants, 40% of plastics)

S. Belahsene et al.
Phot. Tech. Lett. 22-15, 1084 (2010)
U. Montpellier + Nanoplus





Siemens Laser Analytics - LDS 6

QW DFB at 3.37 µm:
Useful for measuring CH_4 and C_2H_6 (portable detectors able to discriminate between naturally occuring methane and natural gas)

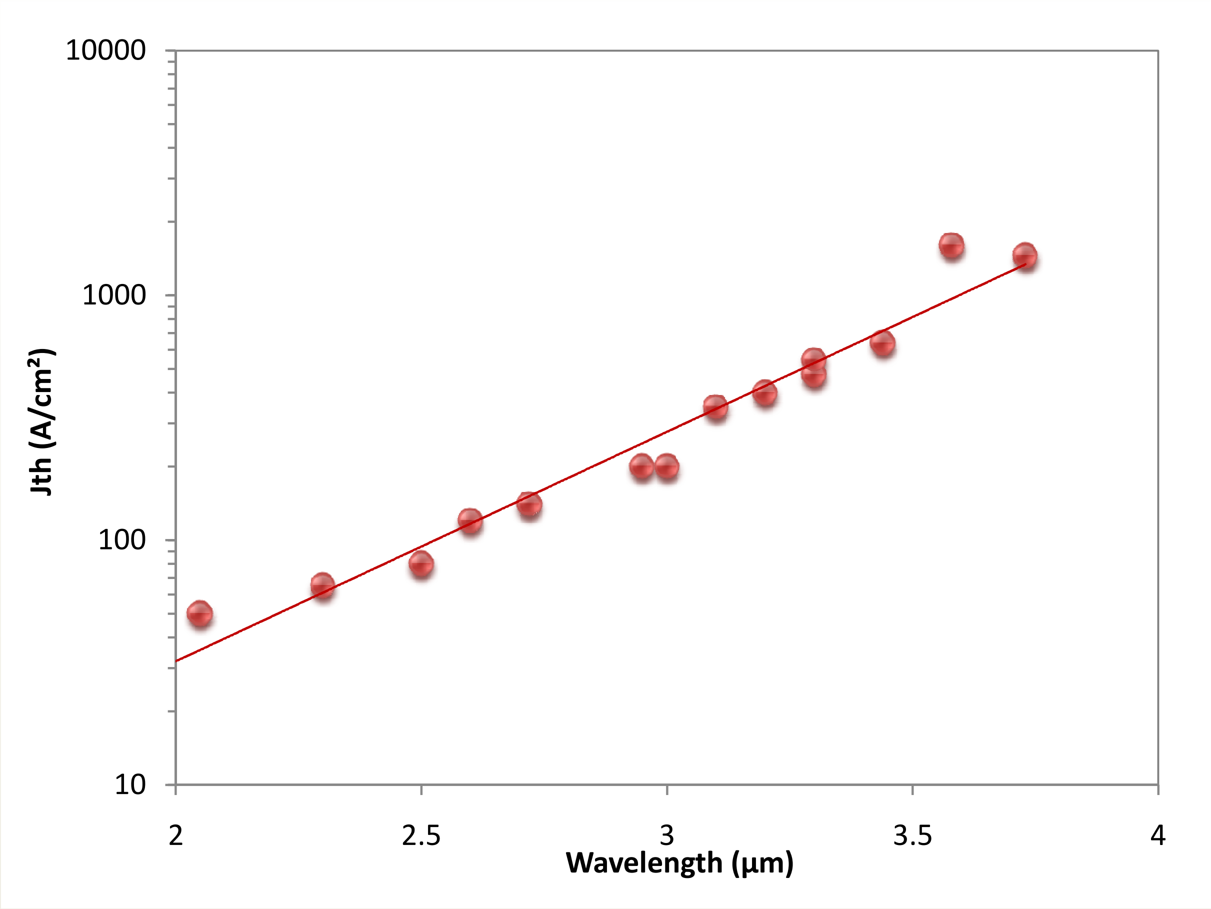
L. Naehle et al.
Electron. Lett. 22, 47-1 (2011)
U. Montpellier + Nanoplus

GMI – DPIR
(device at 3.37 µm was a prototype)

Requirement for a portable detector: $P_{elec} < 1$ W

With a DFB at 3.37 µm at 10°C :
P_{el}= 0.15 A x 1.6 V + 0.1 W (µ-Peltier)
= 0.34 W

Record Threshold Current Densities (J_{th})



Results by:

Turner 1998 (50 A/cm² at 2.05 µm)

Vizbaras 2011 (120 A/cm² at 2.6 µm)

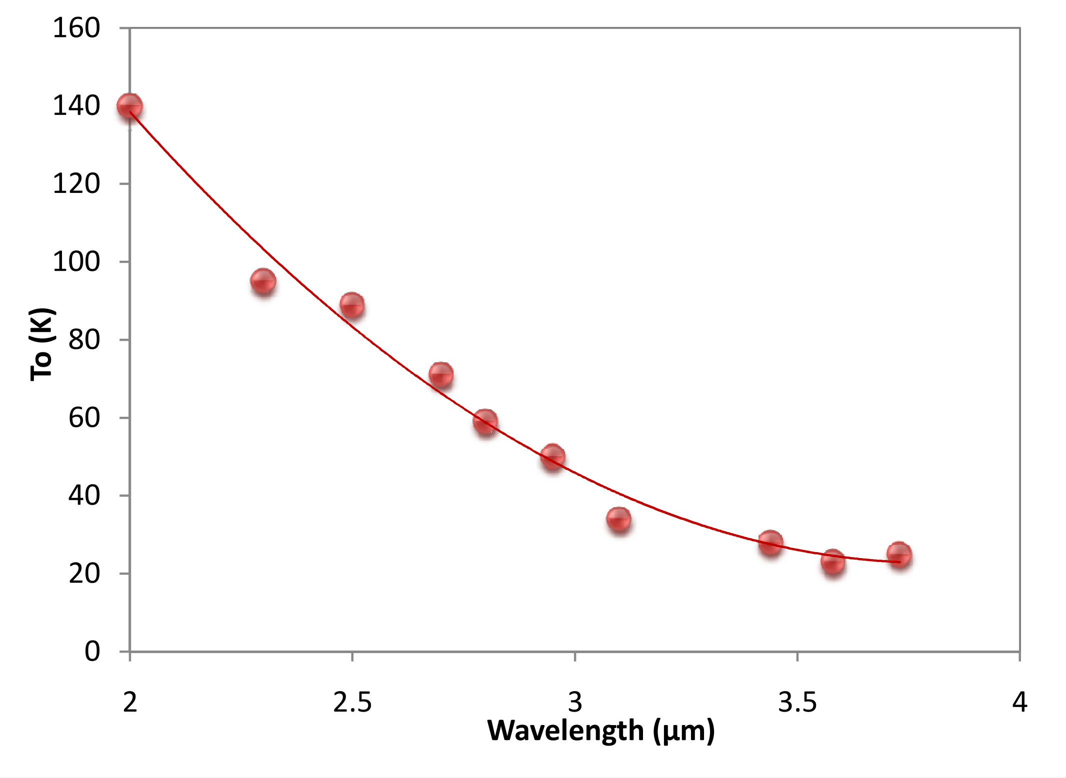
Belenky 2011 (545 A/cm² at 3.3 µm)

Vizbaras 2012 (1450 A/cm² at 3.7 µm)

…and many others…

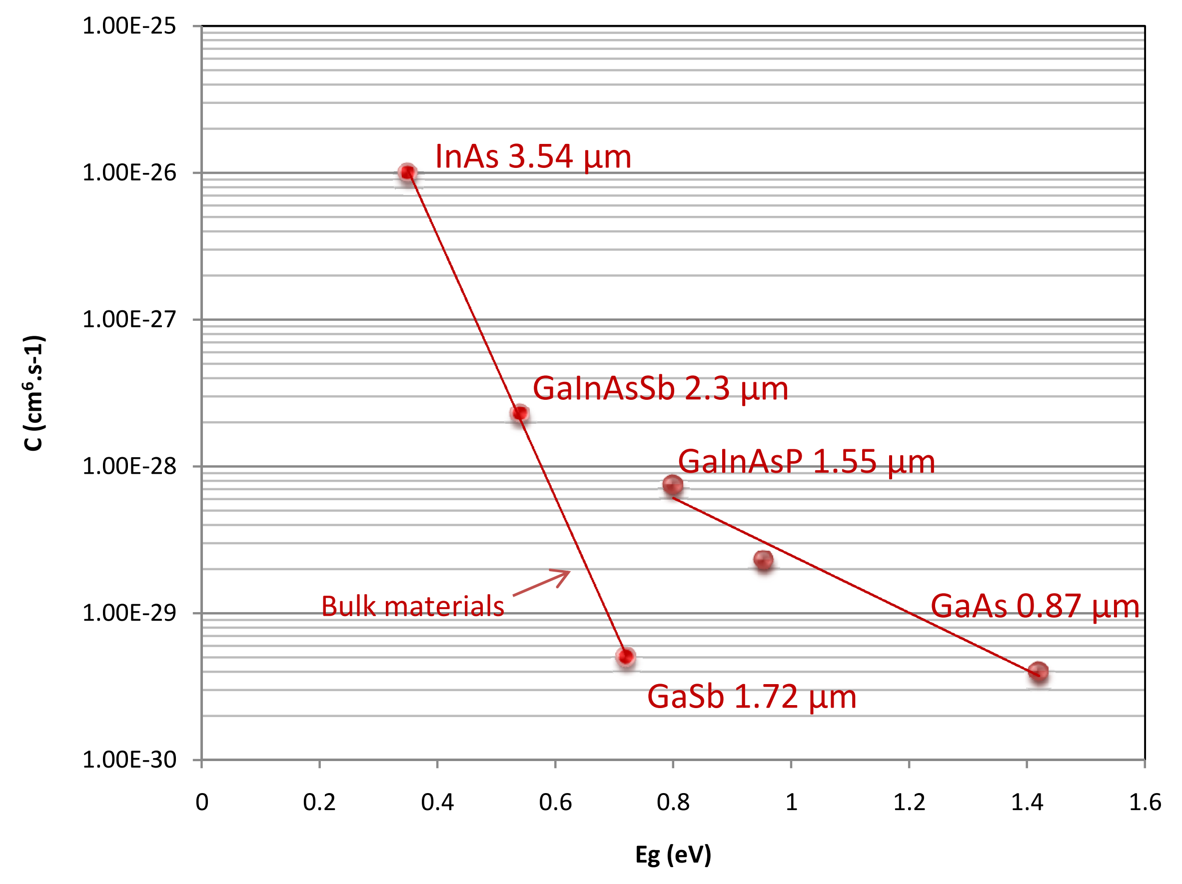
From 2.05 µm to 3.7 µm, J_{th} is multiplied by 30 !

Best Characteristic Temperatures (T_0)



At 2.3 µm, T_0 equals 95 K but plummets to 25 K at 3.3 µm !

Searching for the culprit in degradation of performances



The Auger recombination coefficient C is multiplied by 44 from 2.3 µm to 3.54 µm in bulk materials

Auger is the most likely culprit !

Why does Auger increase at long wavelength (small E_g)?

. Auger coefficient depends on an activation energy, E_a:

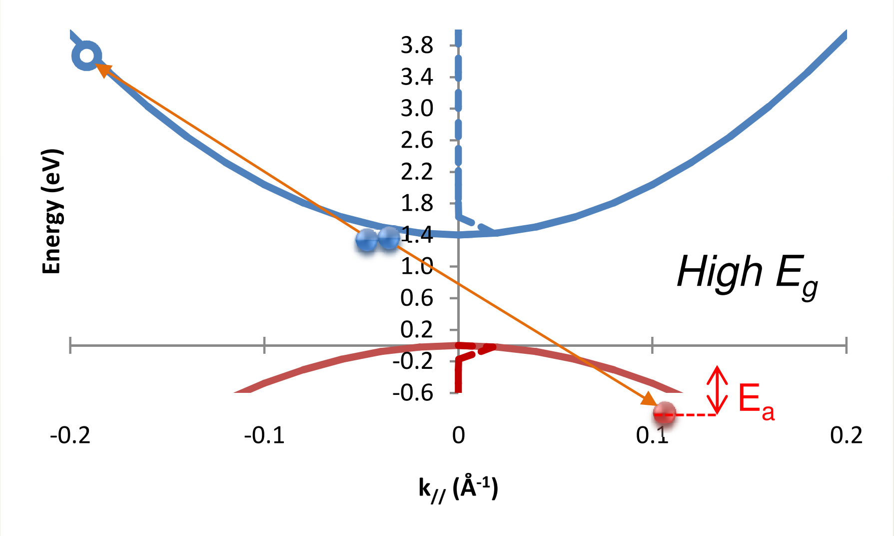
$$C = C_0 \cdot \exp\left(\frac{E_a}{kT}\right)$$

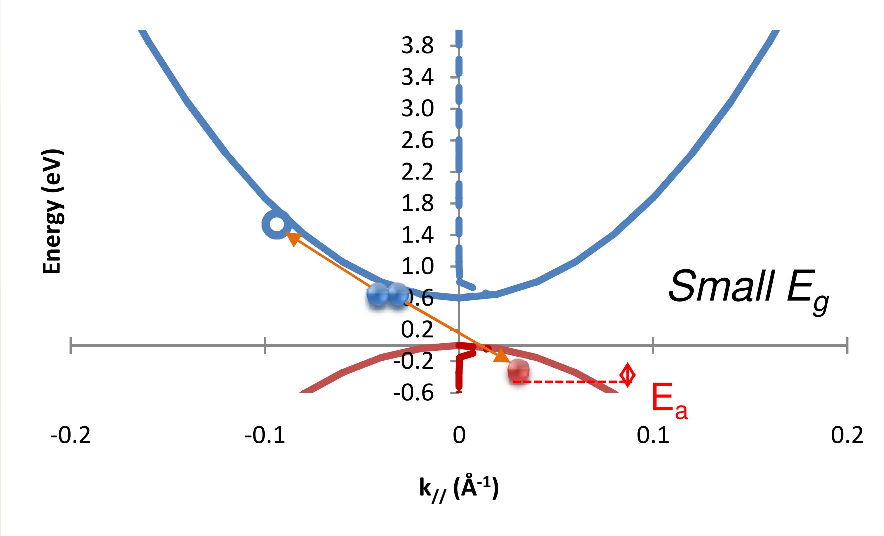
. The activation energy E_a is proportional to the bangap energy E_g:

$$E_a^{CHCC} = \left(\frac{m_c}{m_c + m_{hh}}\right) \cdot E_g \qquad E_a^{CHLH} = \left(\frac{m_{lh}}{2 \cdot m_{hh} + m_c - m_{lh}}\right) \cdot E_g$$

$$E_a^{CHSH} = \left(\frac{m_{so}}{2 \cdot m_{hh} + m_c - m_{so}}\right) \cdot \left(E_g - \Delta_{so}\right) \text{ if } E_g \geq \Delta_{so}$$

. In the CHCC process, E_a is the minimal possible kinetic energy of the hole involved in the process:





Small E_g => Small E_a

What is the value of the activation energy ?

. Calculated values for lasers at 2.6 µm made from GaInAsSb:

lattice matched GaInAsSb (such as in a heterostructure laser) : $E_a^{CHCC} = \left(\dfrac{m_c}{m_c + m_{hh}} \right) \cdot E_g = 0.040\,\text{eV}$

$E_g = 0.47$ eV, $m_c = 0.025\ m_0$, $m_{hh} = 0.270\ m_0$

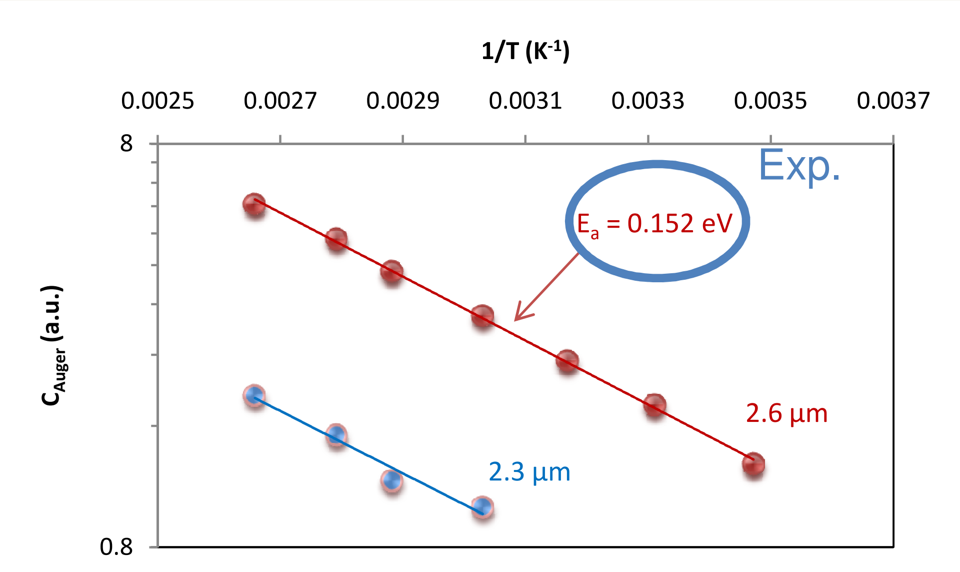
+1.5 % strained GaInAsSb (such as in a QW laser) : $E_a^{CHCC} = \boxed{0.170\,\text{eV}}$ Calc. CHCC

$m_{hh} = 0.044\ m_0$

$\text{Rq} : E_a^{CHLH} = 0.725\,\text{eV} \qquad E_a^{CHSH} = \text{ruled out because } E_g \le \Delta_{so}$

Strain increases the activation energy and allows the operation of QW lasers in the mid-infrared

. Experimental values for QW lasers at 2.3 µm and 2.6 µm made from GaInAsSb:



D. Garbuzov et al.
Appl. Phys. Lett. 74, 2990 (1999)

CHCC is the most likely process in QW lasers emitting in the mid-infrared

How does Auger impact the threshold current ?

Threshold current density:

$$J_{th}=\frac{q\cdot N_w\cdot L_w}{\eta_i}\cdot\left(AN_{th}+BN_{th}{}^2+CN_{th}{}^3\right)$$

. N_w: number of quantum wells (typically, 2)
. L_w: thickness of quantum well (≈ 10 nm)
. η_i: internal quantum efficiency (≈ 75 % at 2.3 µm)
. A: monomolecular recombination coefficient (≈ 1.10^{8} s^{-1} at 2.3 µm)
. B: radiative recombination coefficient (≈ 4.10^{-10} $cm^3.s^{-1}$ at 2.3 µm)
. C: Auger recombination coefficient (≈ 2.10^{-28} $cm^6.s^{-1}$ at 2.3 µm)

Threshold carrier density:

$$N_{th}=N_{tr}\cdot\exp\left(\frac{\alpha_i+\alpha_m}{g_0}\right)$$

Transparency carrier density:

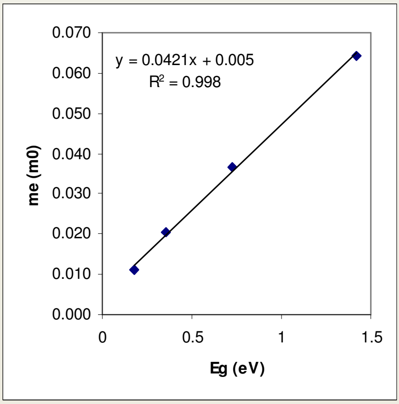
$$e^{-\frac{N_{tr}}{N_c}}+e^{-\frac{N_{tr}}{N_v}}=1$$

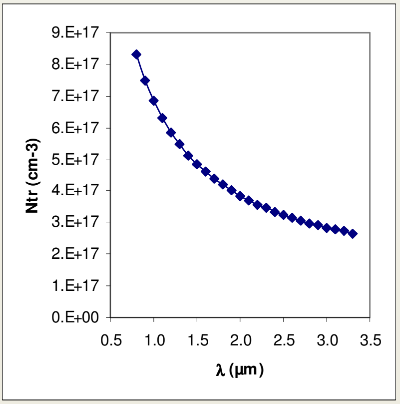
Effective carrier density:

$$N_c=\frac{m_c\cdot kT}{\pi\hbar^2\cdot L_w},N_v=\frac{m_{hh}\cdot kT}{\pi\hbar^2\cdot L_w}$$

. N_{tr}: transparency carrier density (≈ 3.10^{17} cm^{-3} at 2.3 µm)
. α_i: internal loss (≈ 5 cm^{-1} at 2.3 µm)
. α_m: mirror loss (≈ 12 cm^{-1} for a 1 mm-long diode)
. g_o: (≈ 30 cm^{-1})

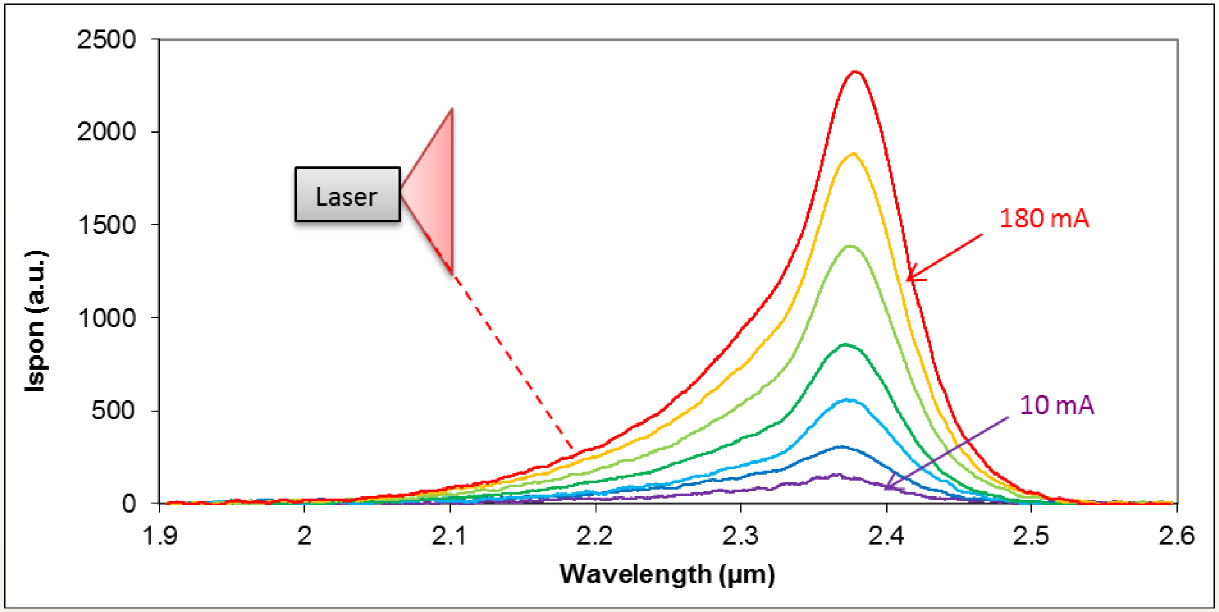
The threshold current density depends on 10 parameters !





A quantity proportional to the radiative current density

Spontaneous emission observed from the tilted facet of a laser emitting at 2.38 µm below threshold:



Spontaneous emission rate: $r_{spon}(\lambda) = K \cdot I_{spon}(\lambda) \cdot \lambda$

Integrated spontaneous emission rate:

$$\begin{aligned} R_{spon} &= \int_0^{+\infty} r_{spon}(\lambda) \cdot d\lambda \\ &= B \cdot N^2 \end{aligned}$$

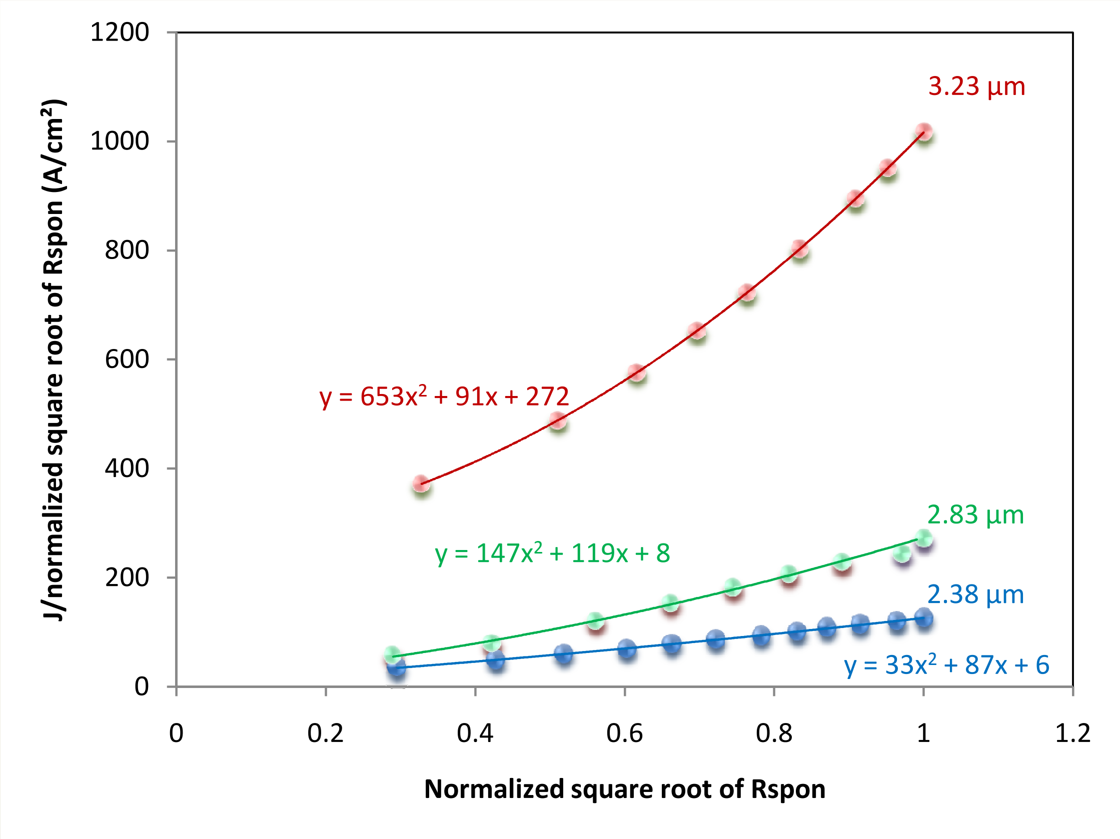
The integrated spontaneous emission rate R_{spon} is proportional to $J_{rad} = q\, N_w\, L_w\, BN^2$!

In search of the A, B, C coefficients

We have: $\sqrt{R_{spon}} = k \cdot N$

$$J = k' \cdot \left(AN + BN^2 + CN^3 \right)$$

Therefore: $\dfrac{J}{\sqrt{R_{spon}}} = k'' \cdot \dfrac{AN + BN^2 + CN^3}{N} = k'' \cdot \left(A + BN + CN^2 \right)$



Let's normalize $\sqrt{R_{spon}}$

so that $\sqrt{R_{spon}}$ = 1 at threshold

Plotting $\frac{J}{\sqrt{R_{spon}}}$ as a function of $\sqrt{R_{spon}}$ is equivalent to plotting $A + BN + CN^2$ as a function of N

On this plot, a laser dominated by,

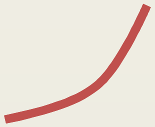
. monomolecular recombination will be shown as a flat line

y = A

. radiative recombination, as a slope

y = BN

. Auger recombination, as a power function



y = CN²

Determining the proportion of Auger at threshold

There are many things to be learned from the parabolas:

. For example, the proportion of the Auger recombination current at threshold:

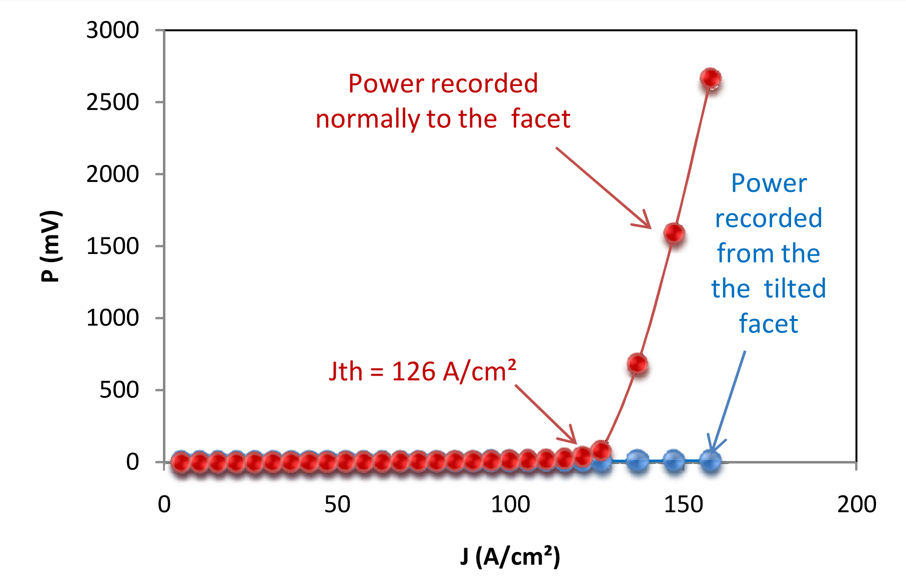
Lambda (µm)	Parabola (A/cm²)	Jth (A/cm²)	JAuger(A/cm²)	JRad (A/cm²)	JMono (A/cm²)	Proportion of Auger
2.38	$y = 33x^2 + 87x + 6$	126	33	87	6	26%
2.83	$y = 147x^2 + 119x + 8$	275	147	119	8	54%
3.23	$y = 653x^2 + 91x + 272$	1017	653	91	272	64%

. And more than that, the value of the A, B & C coefficients !

J_{th} depends on 10 parameters,
Let's use J_{tr} instead…

$$J_{tr} = \frac{q \cdot N_w \cdot L_w}{\eta_i} \cdot \left(AN_{tr} + BN_{tr}^{2} + CN_{tr}^{3}\right)$$

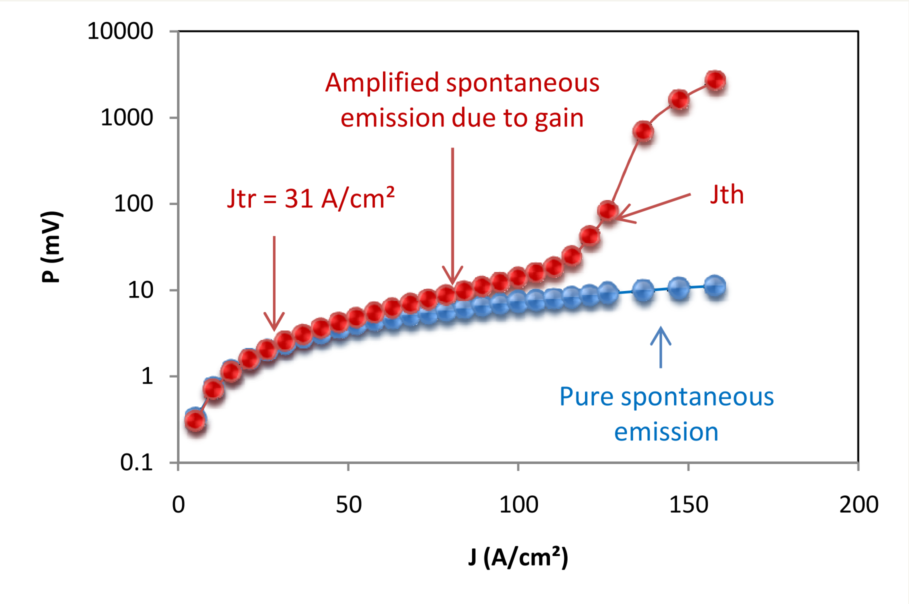
…because the transparency carrier density N_{tr} depends only on the electron and hole masses



Power recorded normally to the facet

Power recorded from the the tilted facet

Jth = 126 A/cm²



Amplified spontaneous emission due to gain

Jtr = 31 A/cm²

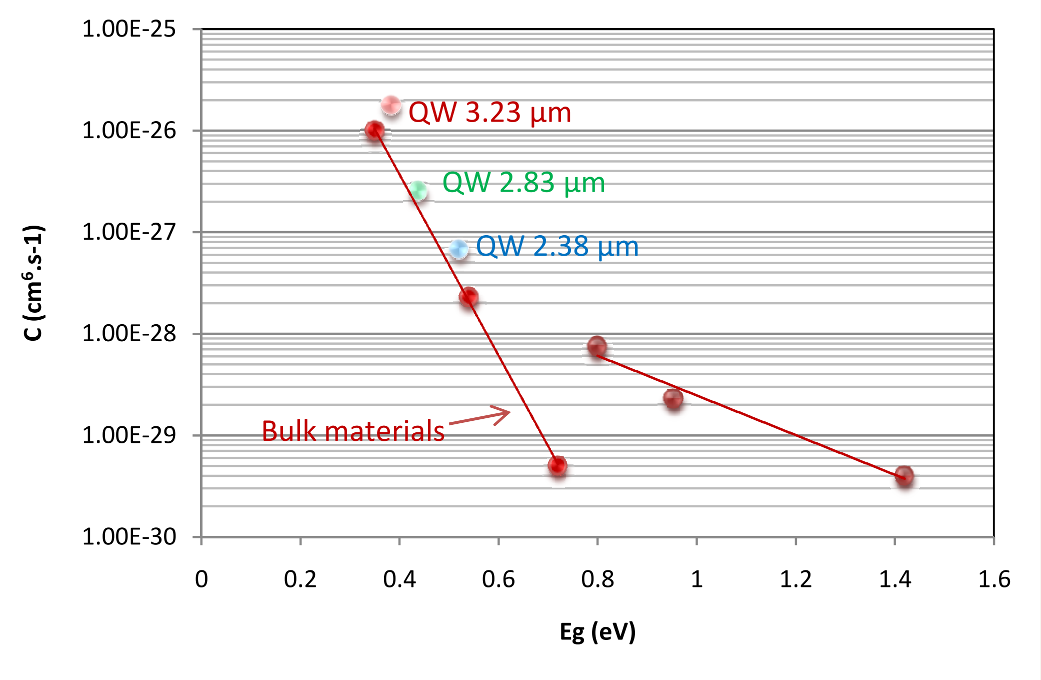
Jth

Pure spontaneous emission

Determining the A, B, C coefficients

After calculating N_{tr}, we can determine A, B, C:

Lambda (µm)	Jtr (A/cm^2)	JAuger(A/cm^2)	JRad (A/cm^2)	JMono (A/cm^2)	Ntr (cm-3)	A (s-1)	B (cm3.s-1)	C (cm6.s-1)
2.38	31	5	24	3	3.3E+17	4.5E+07	1.1E-09	6.8E-28
2.83	52	19	29	4	2.9E+17	4.7E+07	1.2E-09	2.5E-27
3.23	356	153	35	168	2.7E+17	1.4E+09	1.1E-09	1.8E-26



From 2.4 to 3.2 µm, the Auger coefficient is multiplied by 25 in QW lasers

Conclusion

We have developped a method based on
recording the spontaneous emission from the tilted facet of a laser

We determined the A, B, C coefficients of mid-infrared quantum well lasers
from our experiments:

. At 2.4 µm, the Auger coefficient C equals 6.5E-28 cm^{6}.s^{-1}
. At 2.8 µm, C = 2.5E-27 cm^{6}.s^{-1}
. At 3.2 µm, C = 1.8E-26 cm^{6}.s^{-1}

This exponential rise explains
the increase of the threshold currents of mid-infrared quantum wells

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