Mirror heating and COD in high-power lasers (Catastrophic Optical Damage)

Jens W. Tomm and Ignacio Esquivias

Outline

1. Introduction
2. Experimental
3. Modeling of facet heating
4. Techniques to decrease facet heating
5. Conclusions

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Outline

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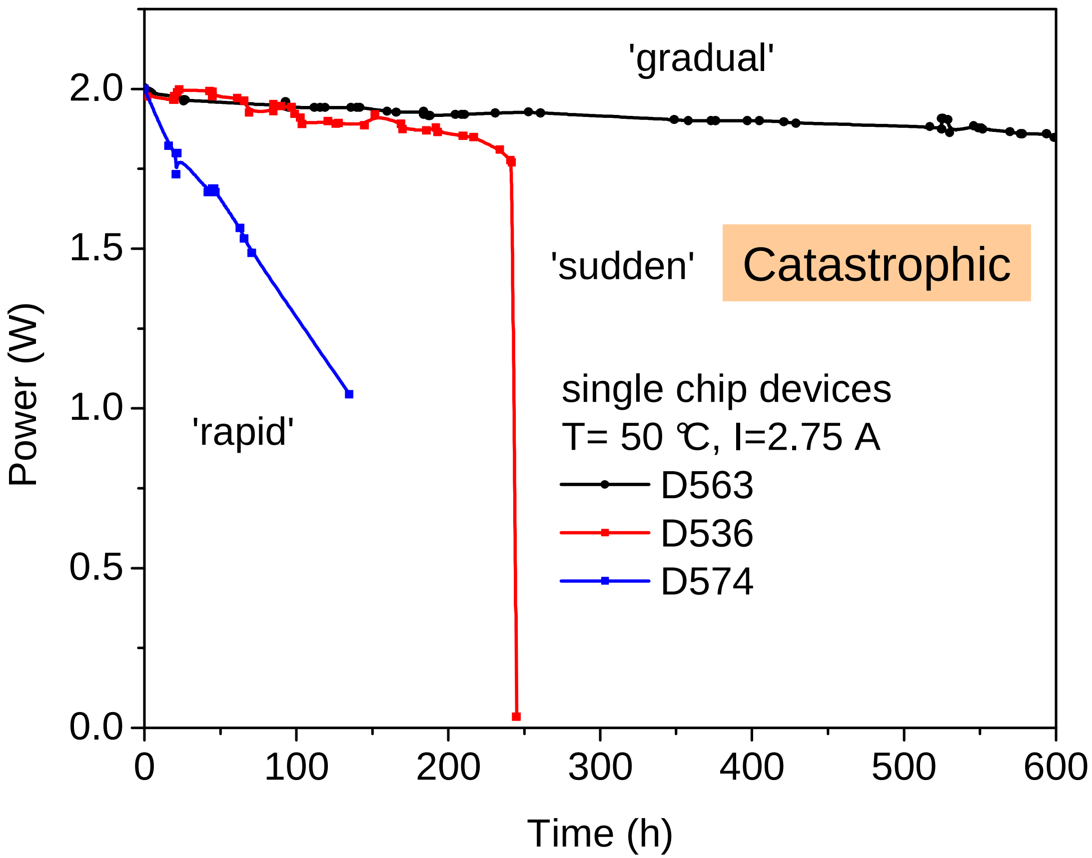
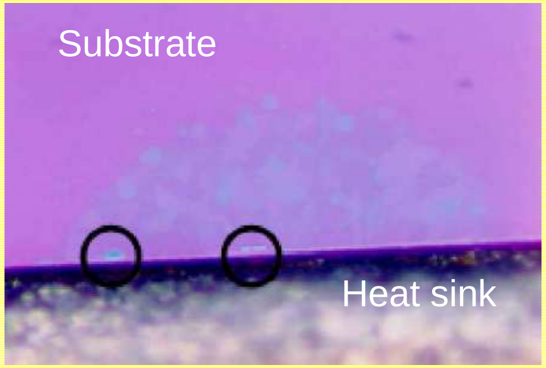
Outline

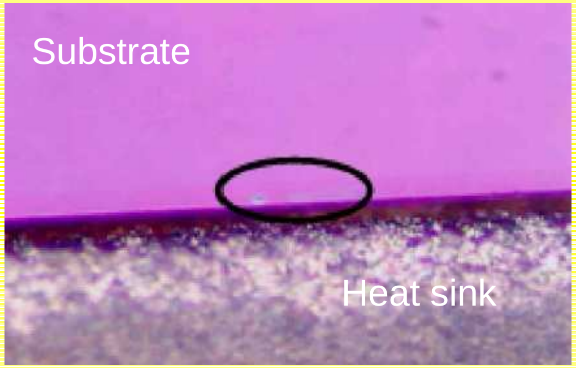
1. Introduction

1.1. Failure modes of high-power diode lasers

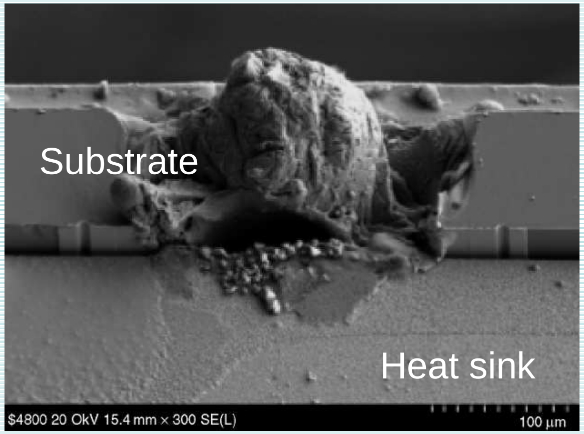


1.2. Catastrophic Optical Damage (COD) and Catastrophic Optical Mirror Damage (COMD)

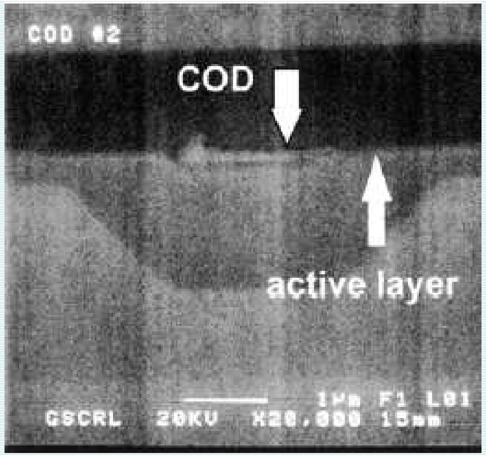




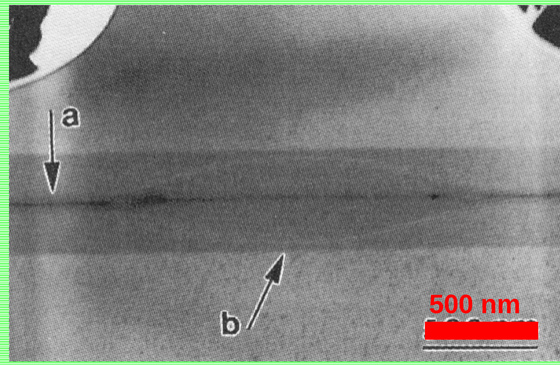
Liu et al. *J. Appl. Phys.* **100**, 013104 (2006).



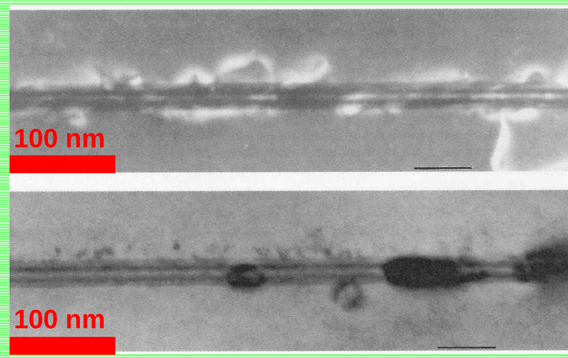
Tomm et al. *Quantum Well Laser Array Packaging* McGraw-Hill, New York (2006).



Ko et al. *Appl. Phys. A* **68**, 467 (1999).



Rechenberg et al. *Inst. Phys. Conf. Ser.***160**, 479 (1997).



Frigeri et al. *Inst. Phys. Conf. Ser.***160**, 483 (1997).

1.3. Physical origins of facet failures (COMD)

Surface – surface recombination velocity, s, sometimes v_s

Infinite space

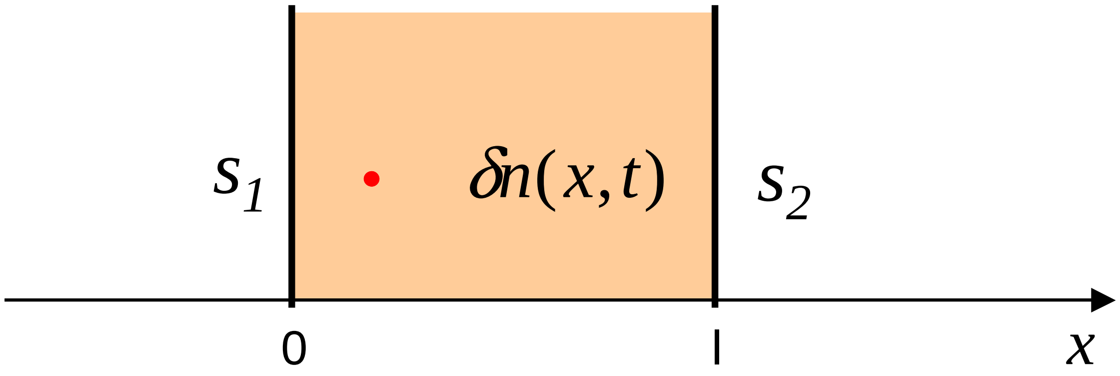
- $\delta n(r,t)$

$$\frac{\partial \delta n}{\partial t} = g - \frac{\delta n}{\tau} + D\frac{\partial^2 \delta n}{\partial r^2} + \mu E \frac{\partial \delta n}{\partial r}$$

0 steady-state — Generation — Recombination — Diffusion — Drift

1.3. Physical origins of facet failures (COMD)

3D→1D



$$\frac{\partial \delta n}{\partial t} = g - \frac{\delta n}{\tau} + D\frac{\partial^2 \delta n}{\partial x^2} + \mu E \frac{\partial \delta n}{\partial x}$$

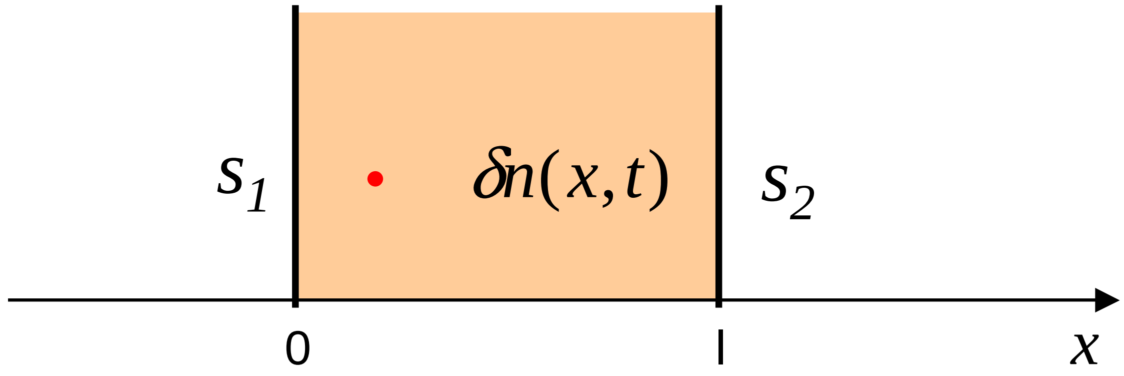
$$-D\left.\frac{\partial \delta n}{\partial x}\right|_{x=0} = s_1 \delta n(0)$$

$$-D\left.\frac{\partial \delta n}{\partial x}\right|_{x=l} = s_2 \delta n(l)$$

Surface recombination
Velocities s_1 and s_2
dim[s] = cm/s

1.3. Physical origins of facet failures (COMD)

3D→1D



$$\frac{\partial \delta n}{\partial t} = g - \frac{\delta n}{\tau} + D\frac{\partial^2 \delta n}{\partial r^2} + \mu E\frac{\partial \delta n}{\partial r}$$

$$j_\perp = -eD\left.\frac{\partial \delta n}{\partial x}\right|_{x=0} = s_1 e\,\delta n(0)$$

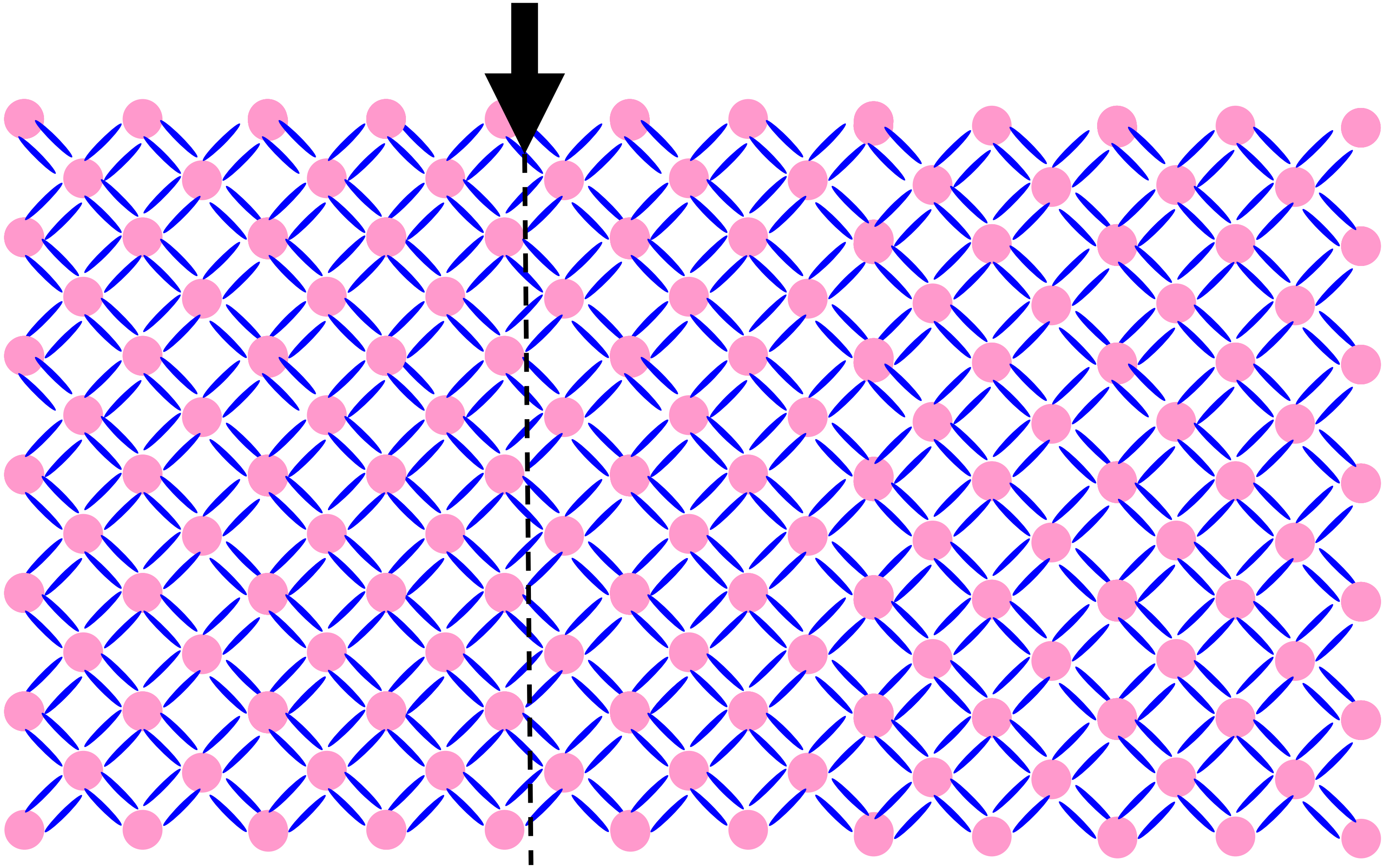
$$j_\perp = -eD\left.\frac{\partial \delta n}{\partial x}\right|_{x=l} = s_2 e\,\delta n(0)$$

Surface recombination

Velocities s_1 and s_2

dim[s] = cm/s

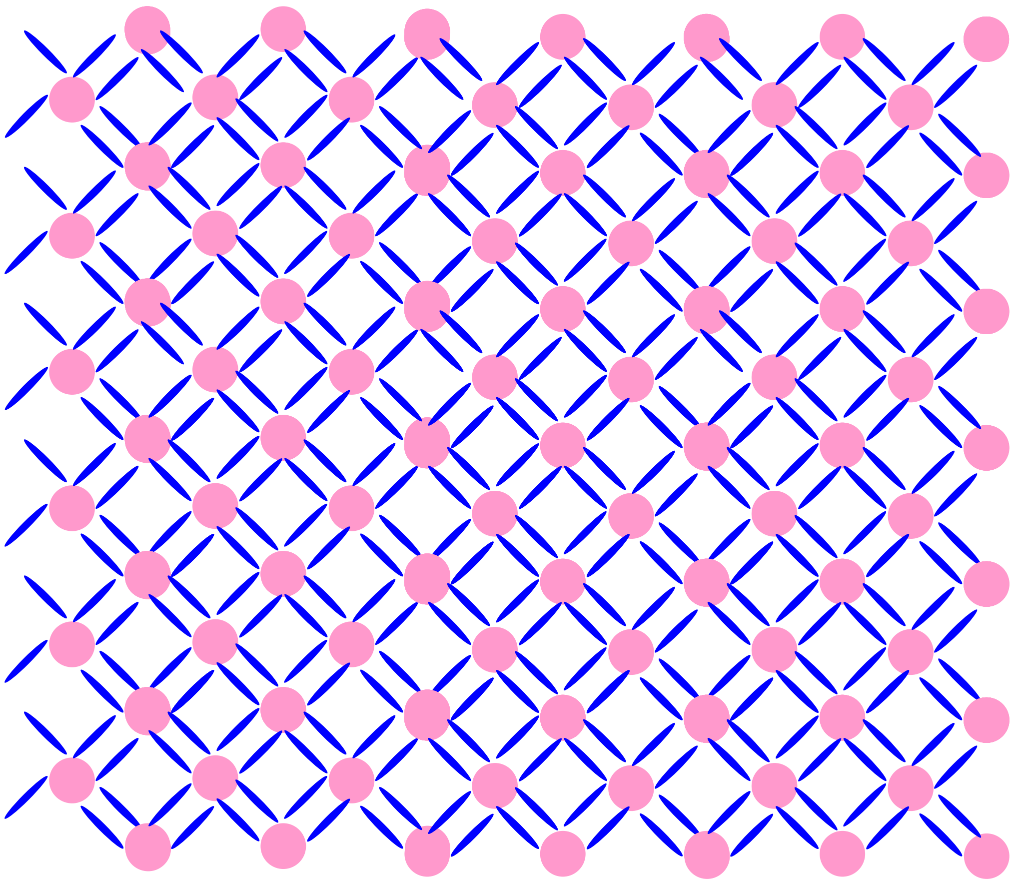
1.3. Physical origins of facet failures (COMD)



1.3. Physical origins of facet failures (COMD)

1. Translation symmetry gets lost

2. Surface reconstruction takes place



1.3. Physical origins of facet failures (COMD)

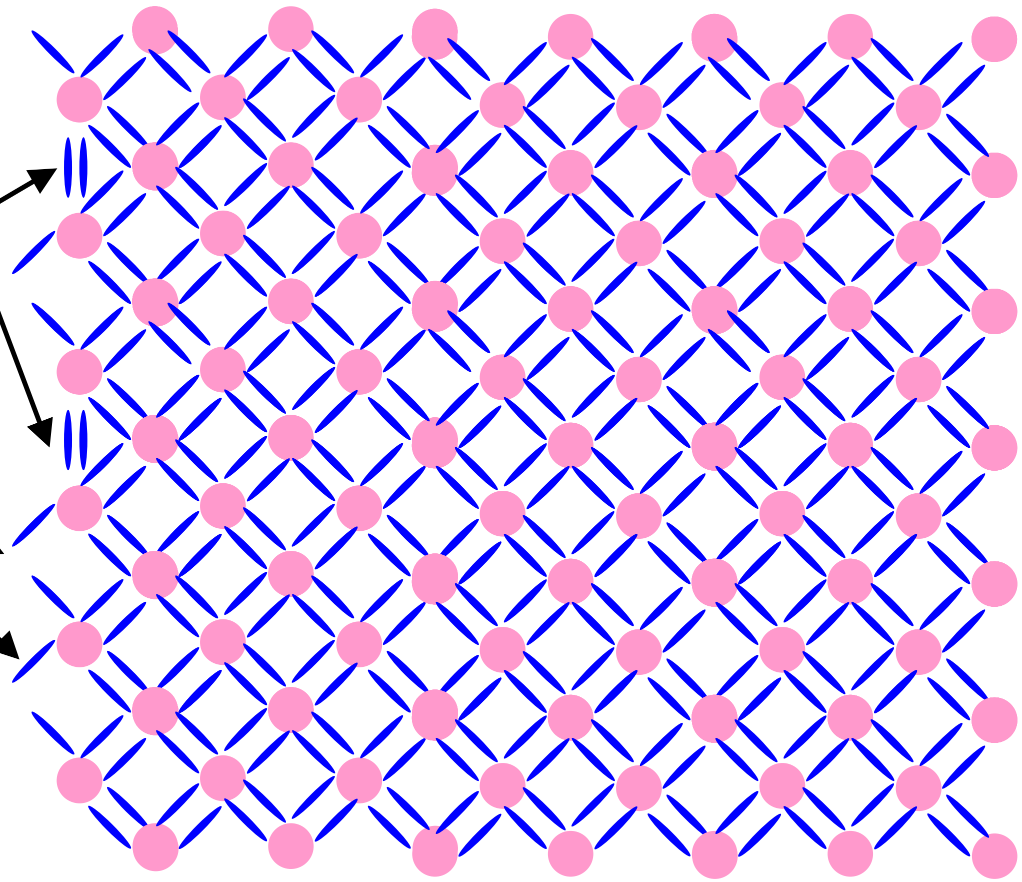
1. Translation symmetry gets lost

2. Surface reconstruction takes place (modification of the bandstructure)

3. Dangling bonds

4. Adosorbates, Oxide

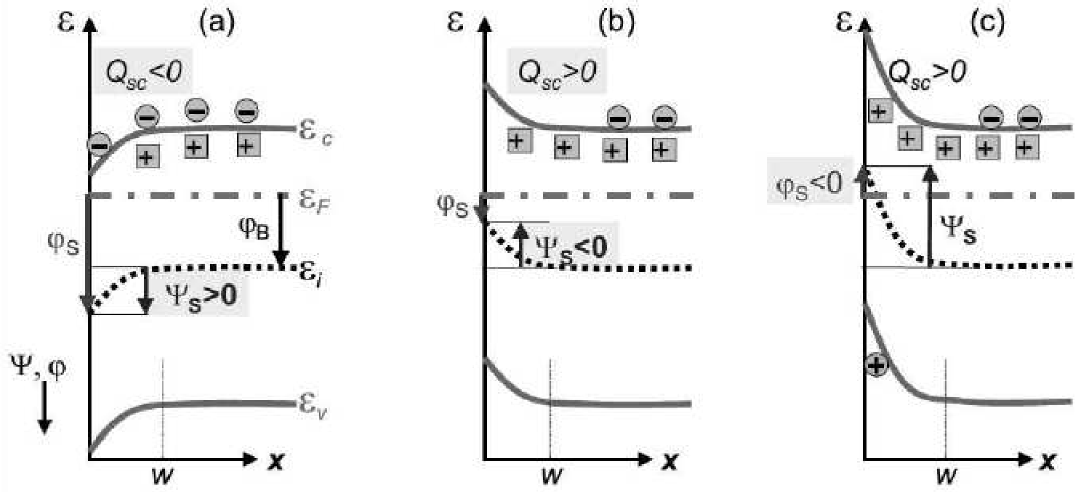
5. Technology
   - Passivation
   - Protection coating
   - Dielectric (AR) coating



1.3. Physical origins of facet failures (COMD)

Consequences:

1. Substantial modification of the band structure at the surface.



Accumulation Depletion Inversion

2. Surface as additional localized recombination channel.

   S , the surface recombination velocity quantifies the efficiency of this mechanism, not its microscopic origin.

Some values for *S* at GaAs-surfaces

Sample	Dopant (cm^{-3})	D (cm^2/sec) τ_R, ns	Surface preparation	Surface orientation	s (*cm / sec*)
n-GaAs	Te $6x10^{16}$	13	Br:Methanol	(100)	$5\pm1x10^5$
n-GaAs	10^{17}	13	Br:Methanol	(111B)	$3\pm1x10^5$
n-GaAs	10^{17}	13	NaOC1	(111A)	$3\pm1x10^5$
p-GaAs	Cd $7x10^{17}$	6.8	Br:Methanol	(111B)	$4\pm1x10^5$
p-GaAs	Cd $7x10^{17}$	6.8	NaOC1	(111A)	$4\pm1x10^5$
p-GaAs (oxide)	$1.7x10^{17}$ 200 nm	11.0	oxide	3° off (100)	$7\pm1x10^5$
p-GaAs (without oxide)	$1.7x10^{17}$	11.0	Br:Methanol	3° off (100)	$7\pm1x10^5$
n-GaAs (without oxide)	$2x10^{18}$	7.0	Br:Methanol	(100)	$3\pm1x10^5$
n-GaAs	$2x10^{18}$	7.0	HF:HC1:H_2O_2	(100)	$3\pm1x10^5$
n-GaAs (oxide)	$2x10^{18}$ 50 nm	7.0 400 ps	oxide	(100)	$2\pm1x10^6$
p-GaAs	Zn $1x10^{19}$	6.5	Br:Methanol	3° off (100)	$3\pm1x10^6$
GaAs:Cr	10^{16}-10^{17}	10 150 ps	Br:Methanol	2° off (100)	$2\pm1x10^5$

K. Jarasiunas private information

S acts as an additional heat source at the surface

1.4. The thermal runaway model of COMD

Temperature at the facet is determined by

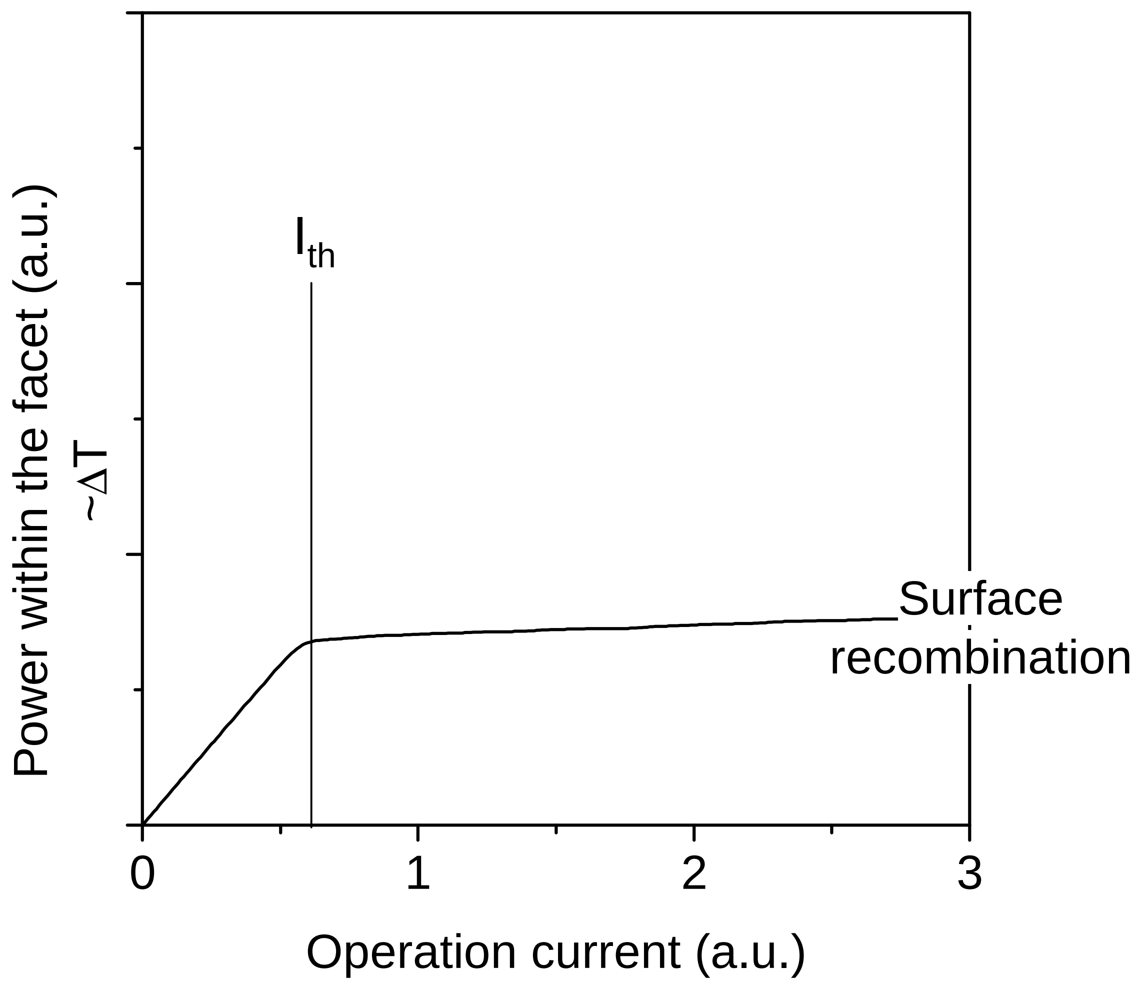
- surface recombination rate $\sim s_0 * \delta n$
- gradual aging (increased $s_1 > s_0$) $\sim s_1 * \delta n$
- re-absorbed power $\sim P$
- current $\sim I$
- bulk-temperature $\sim U*I - P$

All these mechanisms make T increasing.

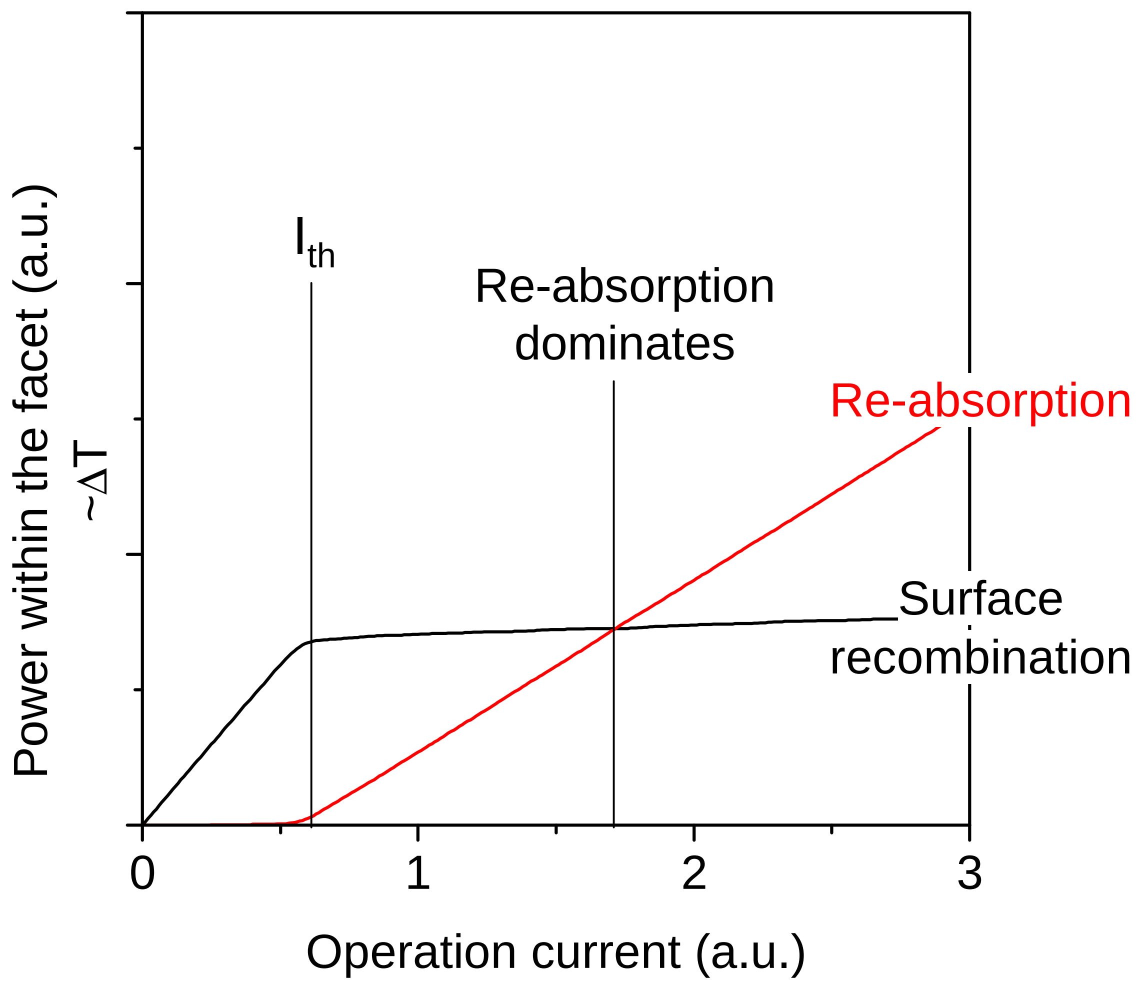
Problems:

- We do not know the weight factors
- No means to separate them from each other.

1.4. The thermal runaway model of COMD Scheme



1.4. The thermal runaway model of COMD Scheme



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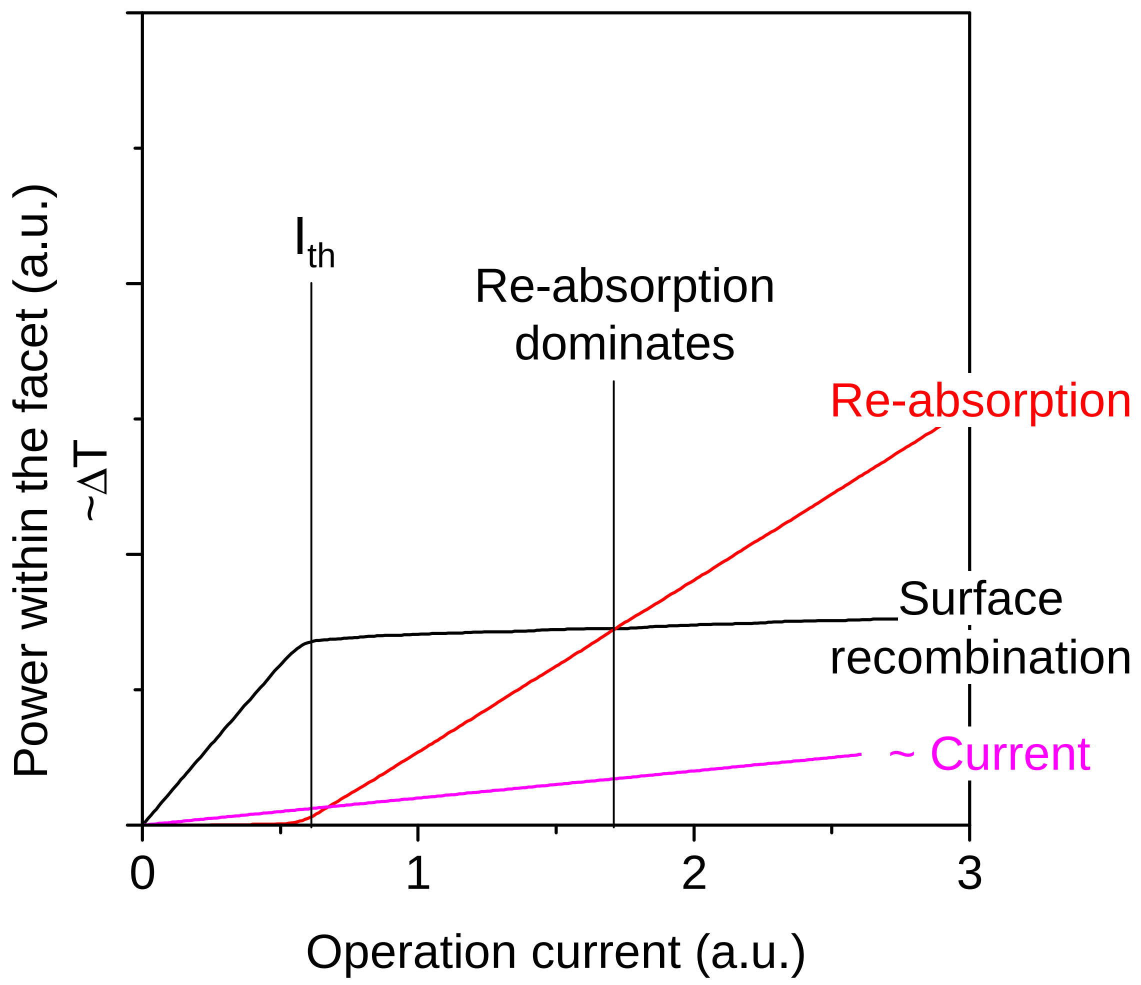
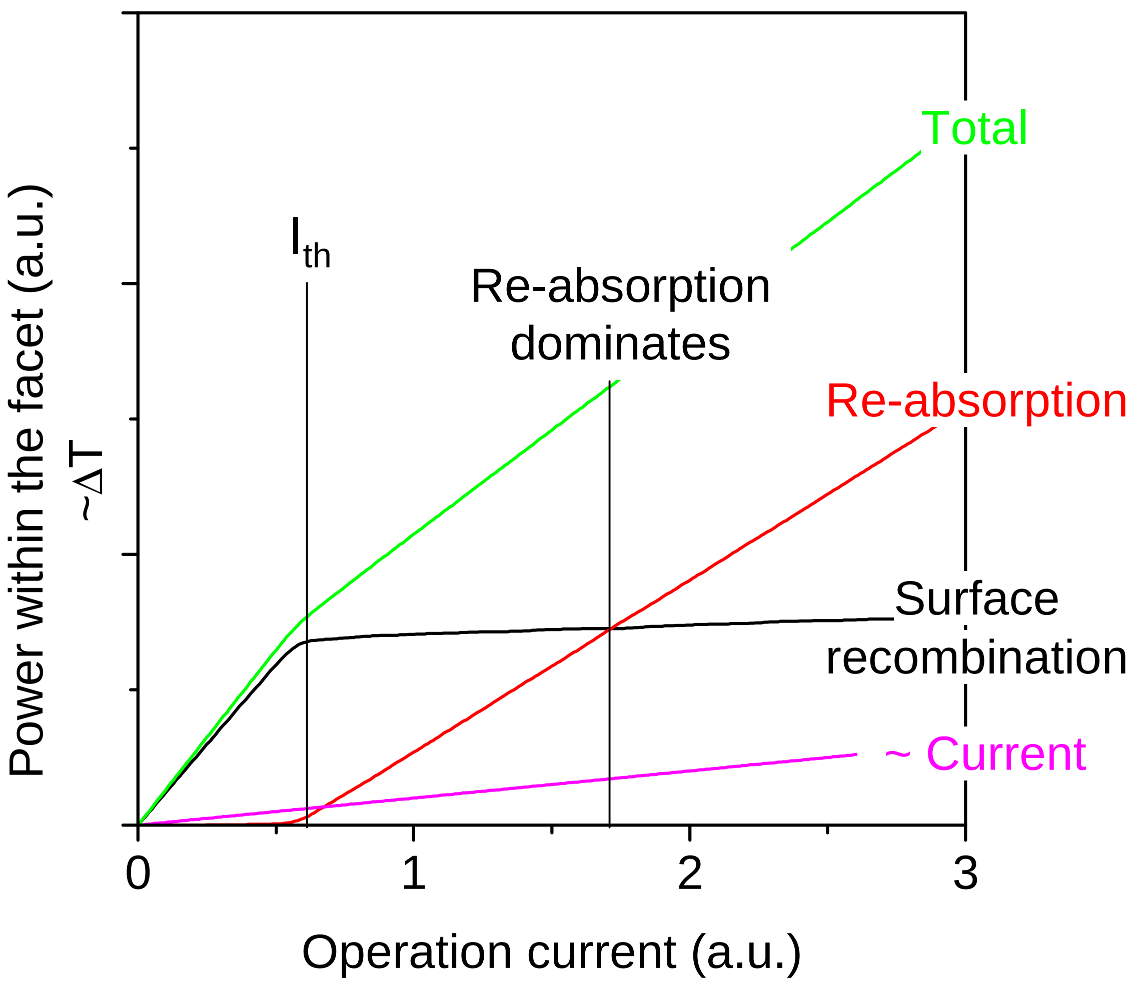
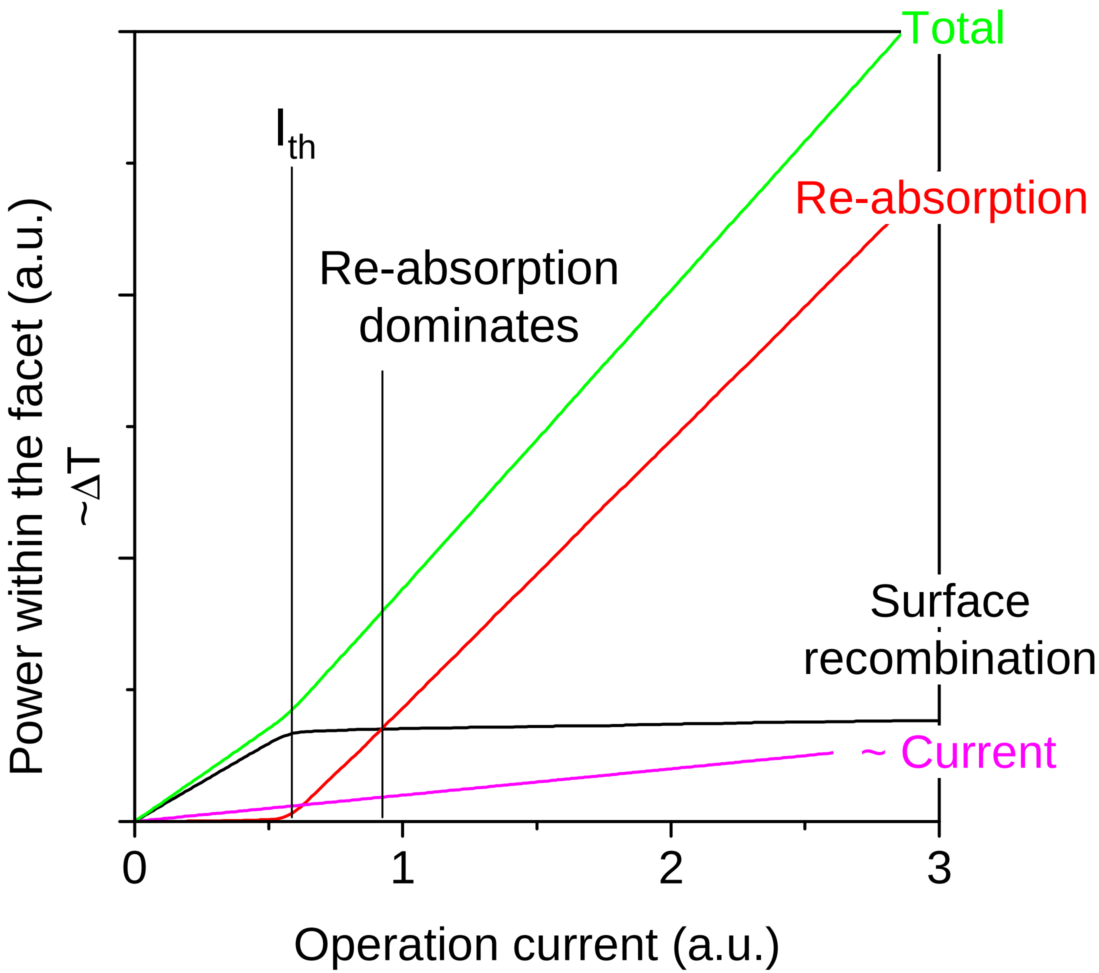


1.4. The thermal runaway model of COMD
Scheme



but …

1.4. The thermal runaway model of COMD Scheme



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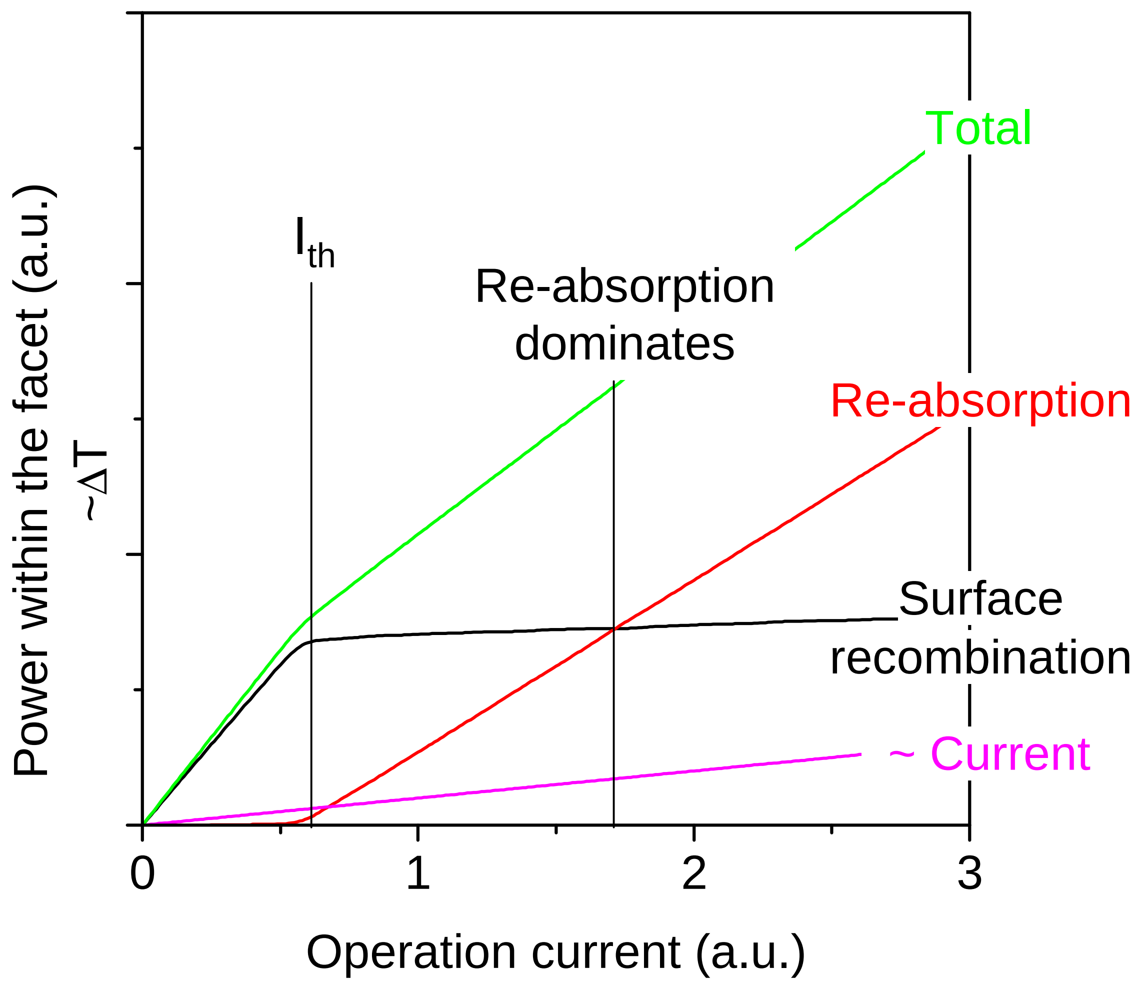

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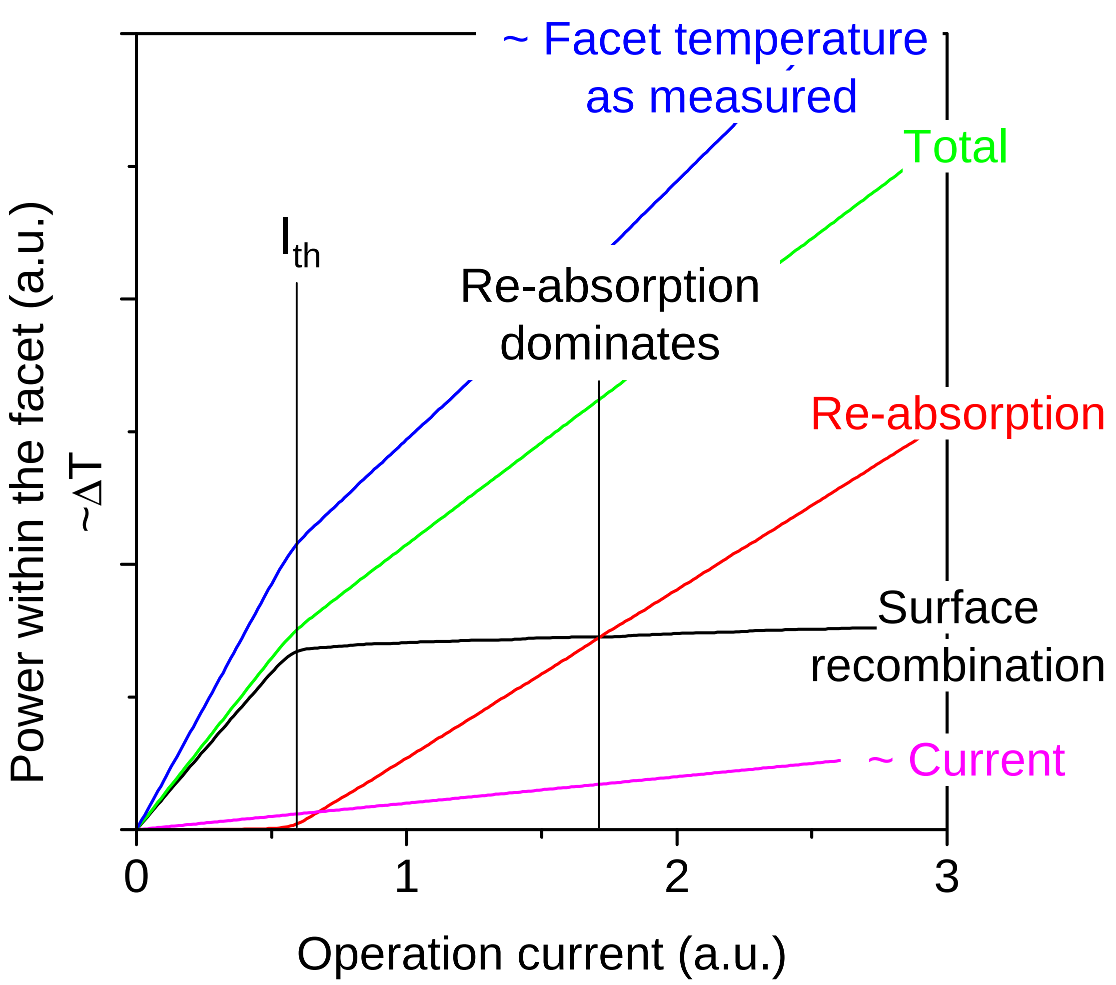
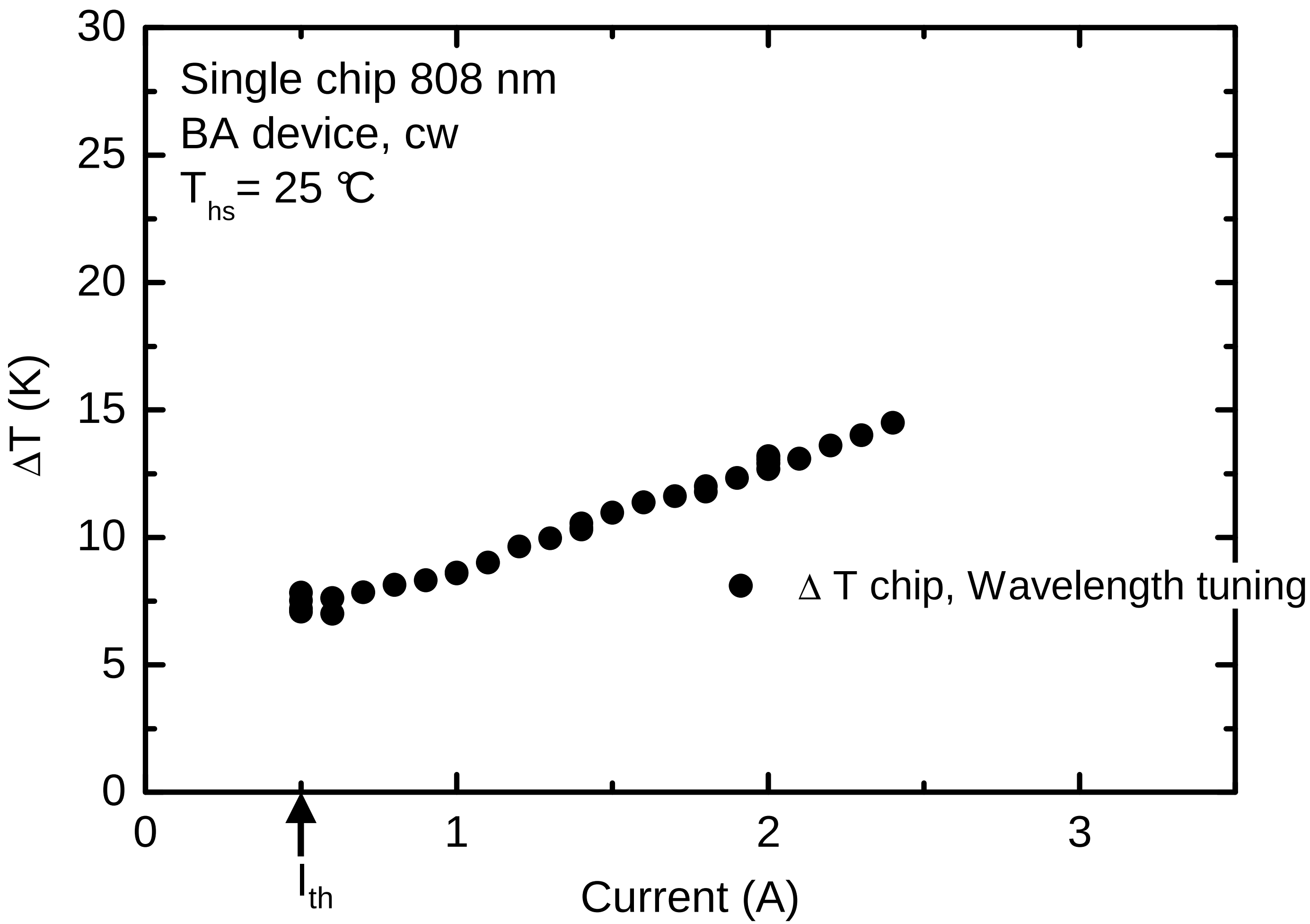


1.4. The thermal runaway model of COMD Experiment



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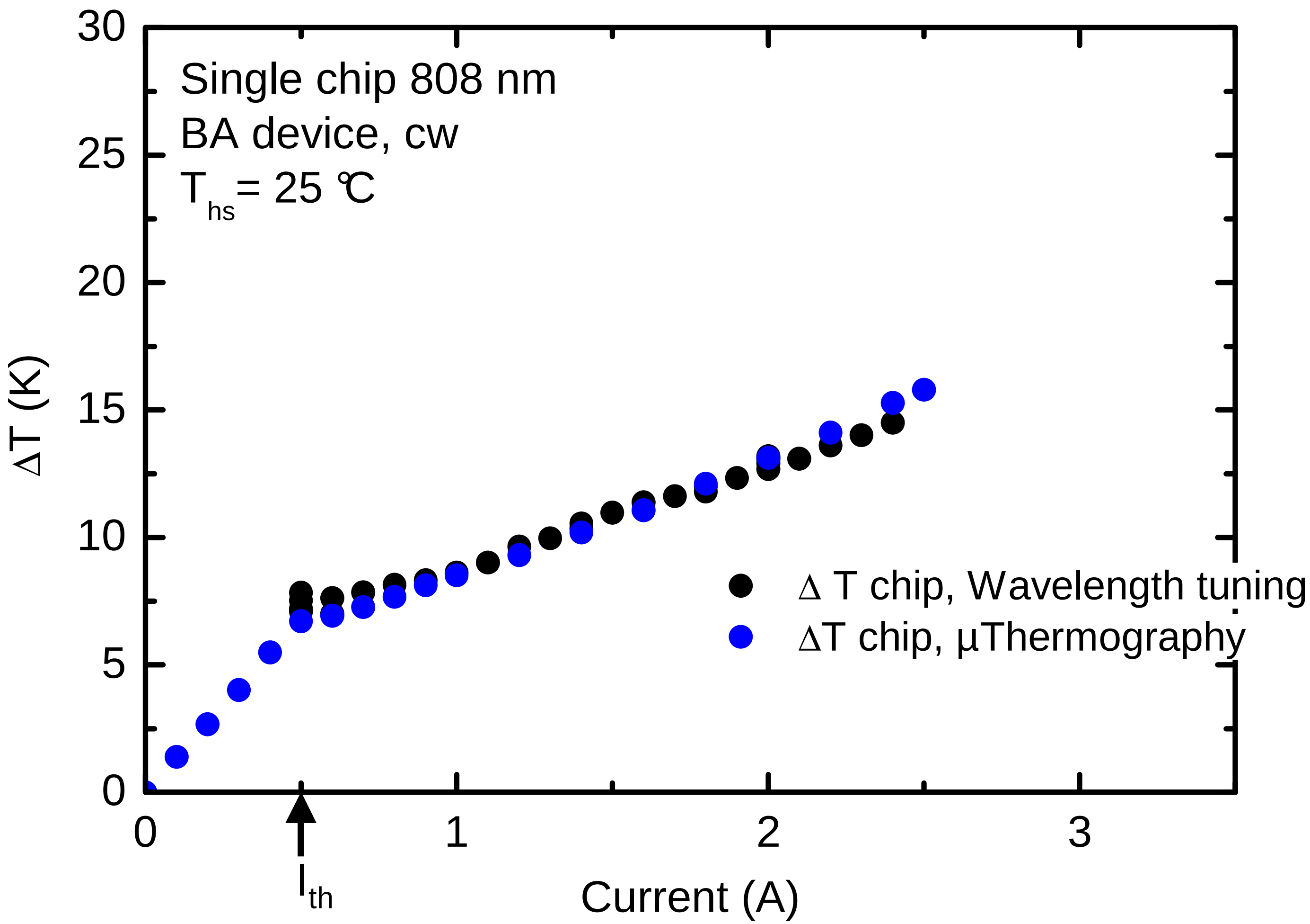

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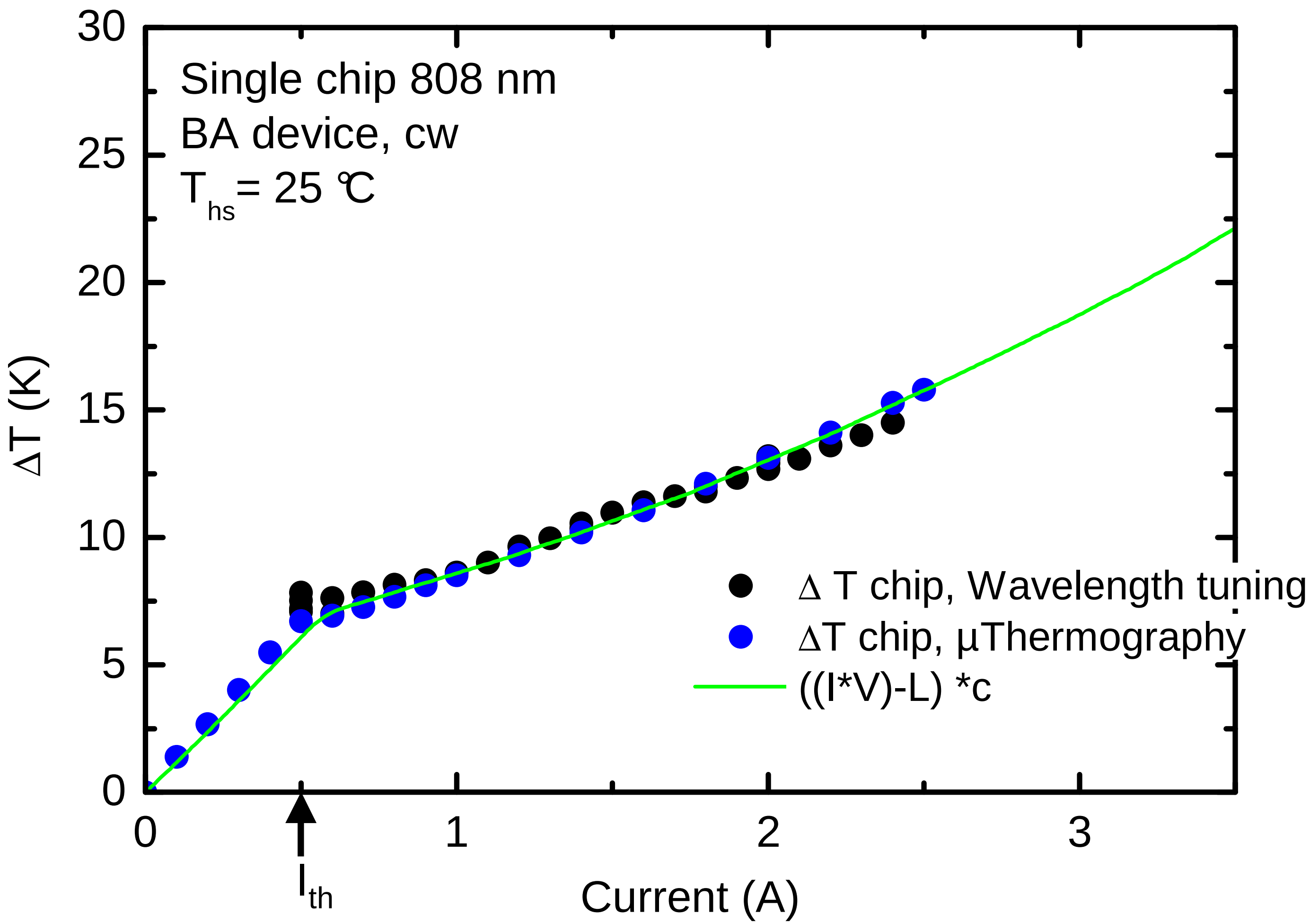

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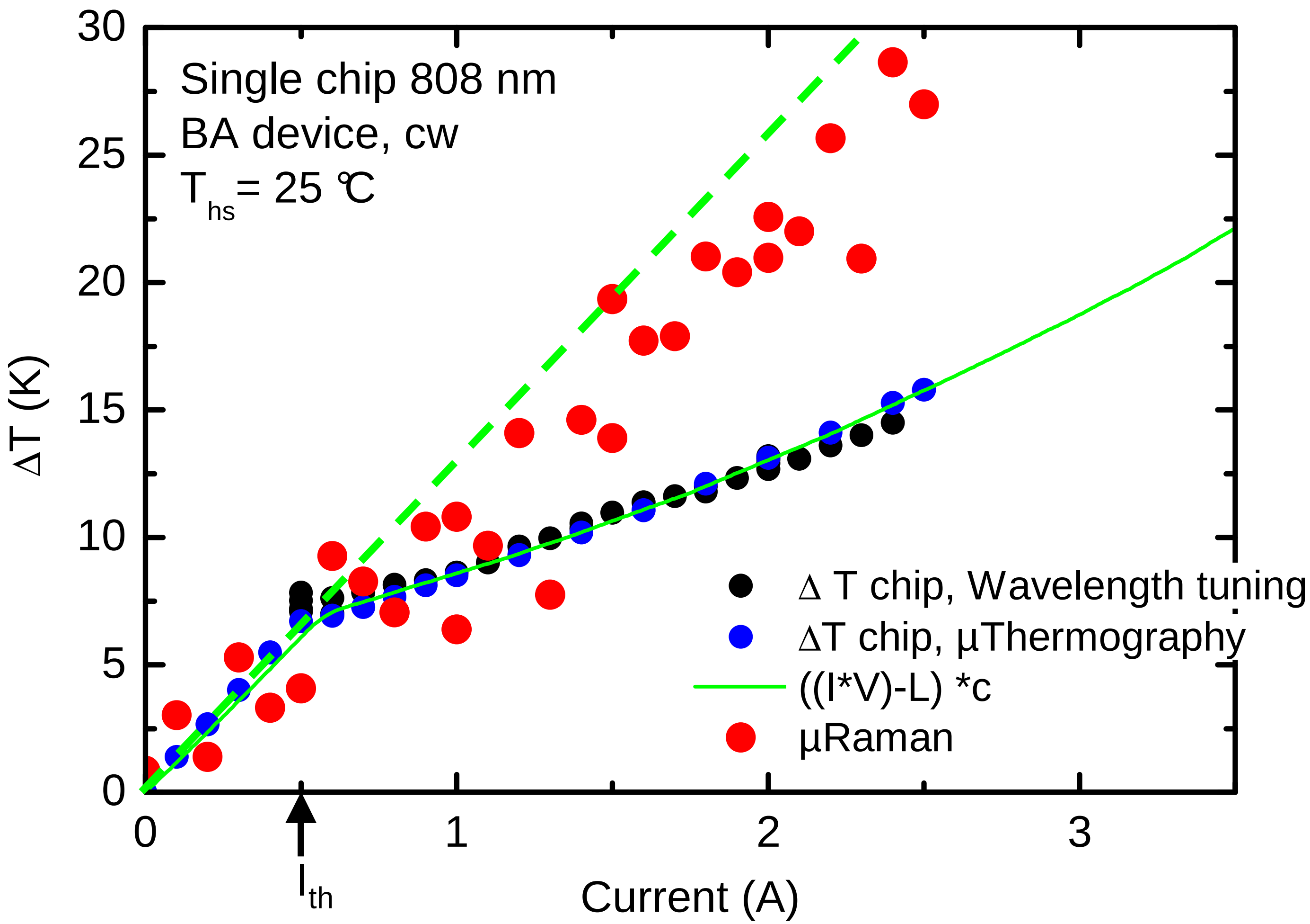
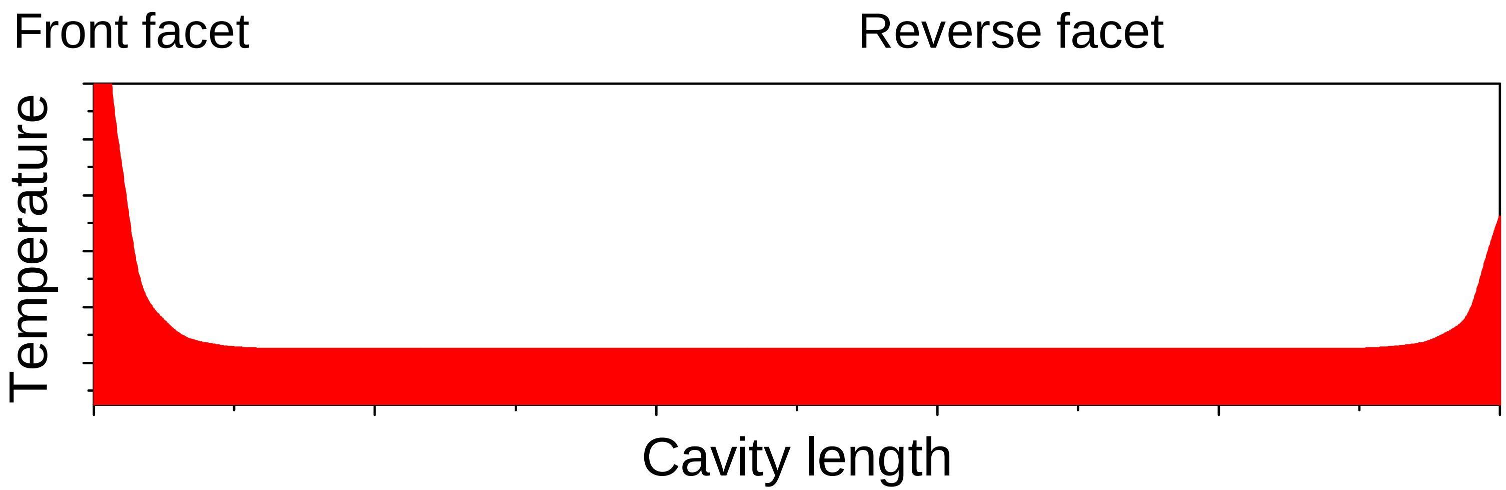


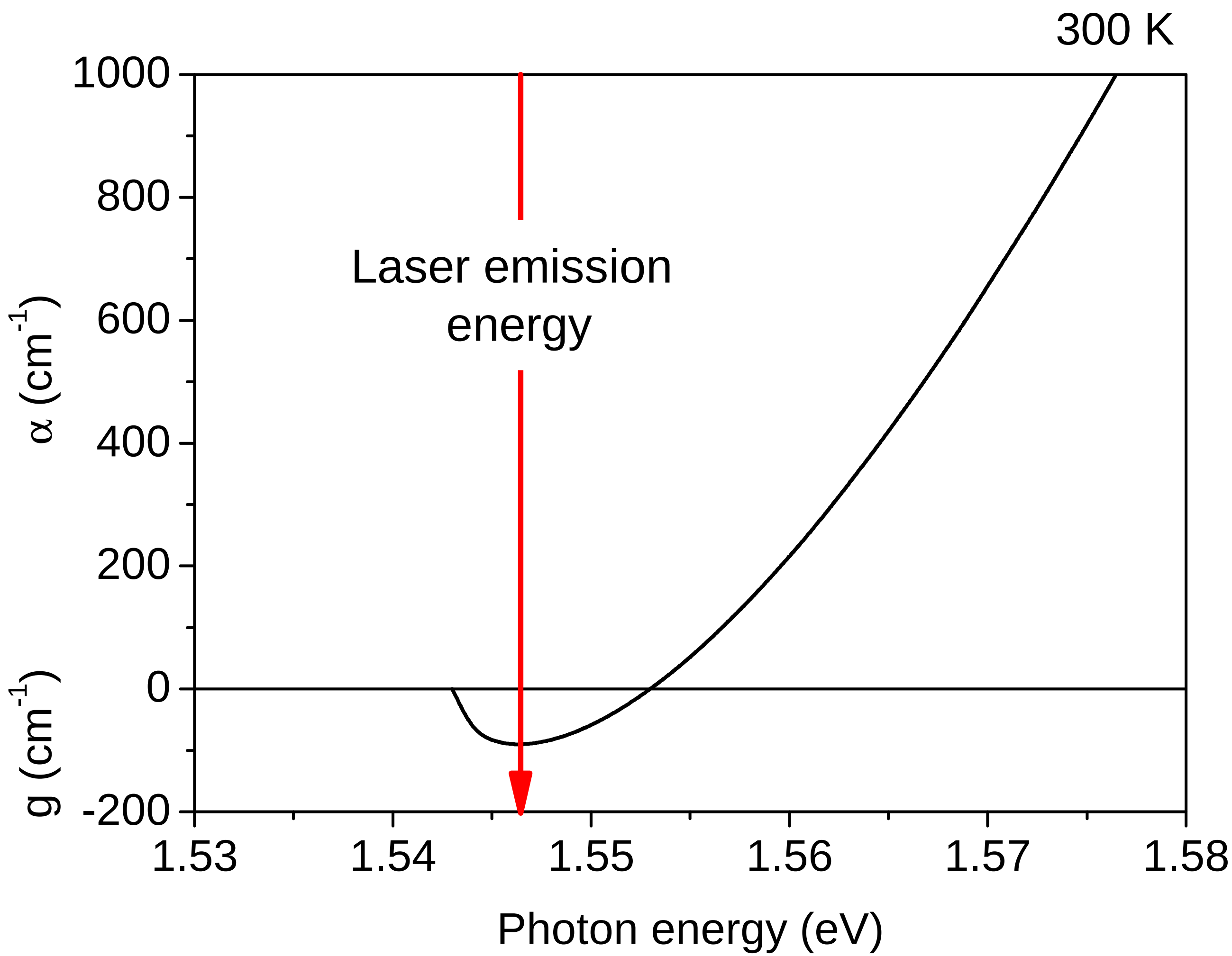
1.4. The thermal runaway model of COMD



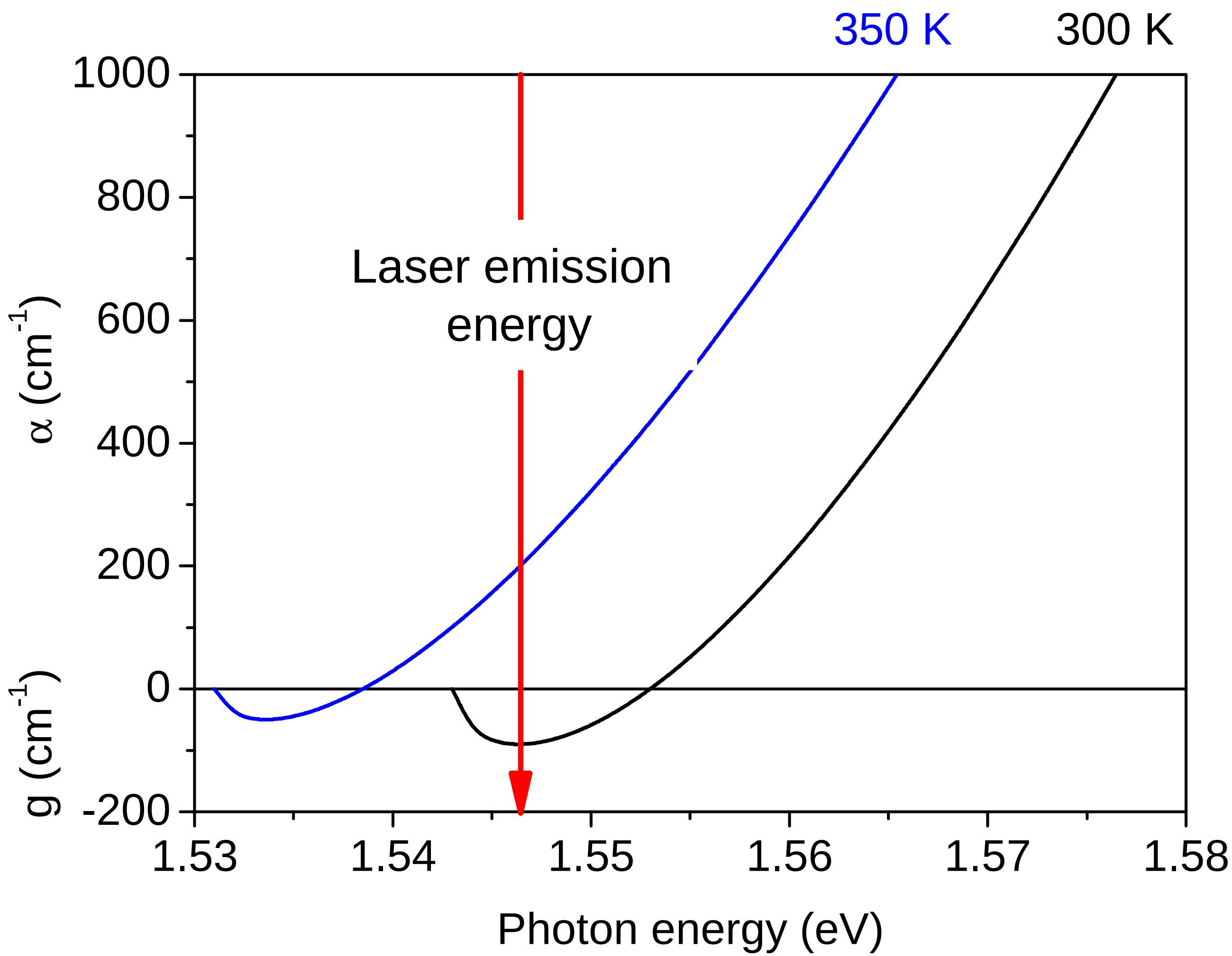
What happens with a semiconductor (QW) if the temperature increases?

- More free carriers get generated (conductivity increases)
- Band edge shrinks (absorption increases)
- Degradation gets increased
- …

Example: Re-absorption of laser light at the heated facets



Example: Re-absorption of laser light at the heated facets



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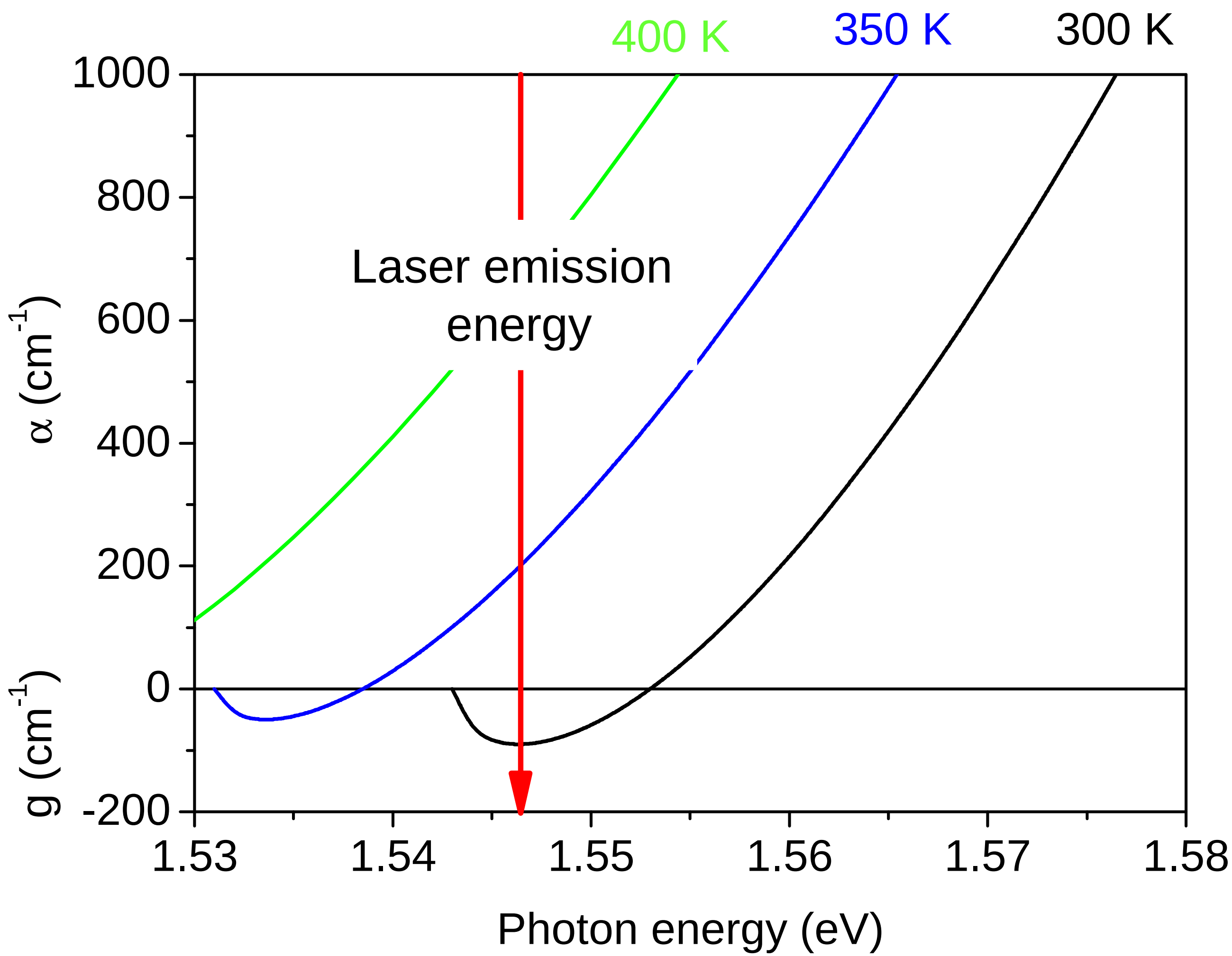
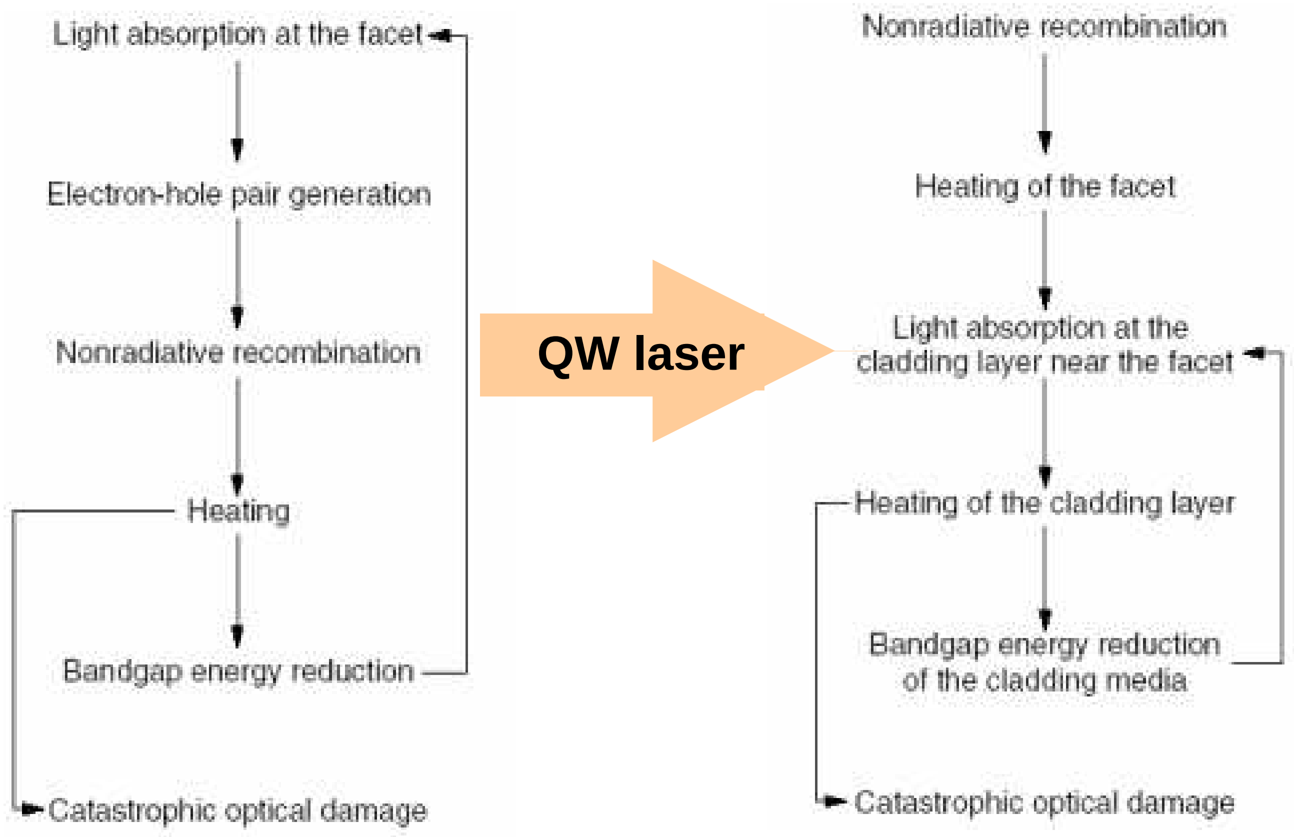


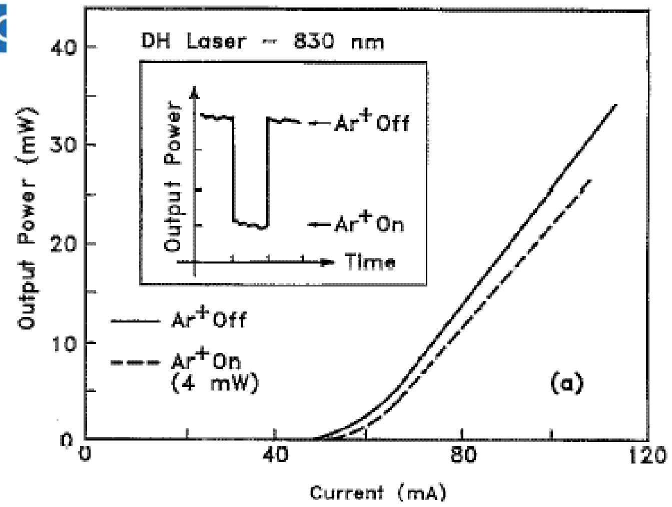
COMD scenario: Thermal runaway

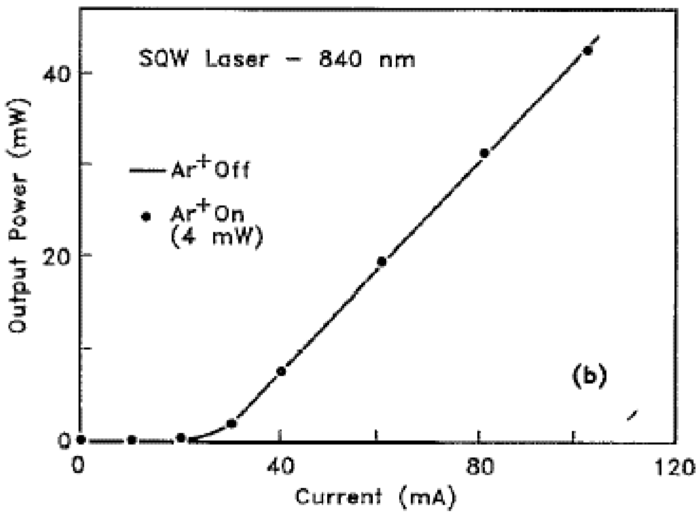


Henry et al. J. Appl. Phys. **50**, 3721 (1979)

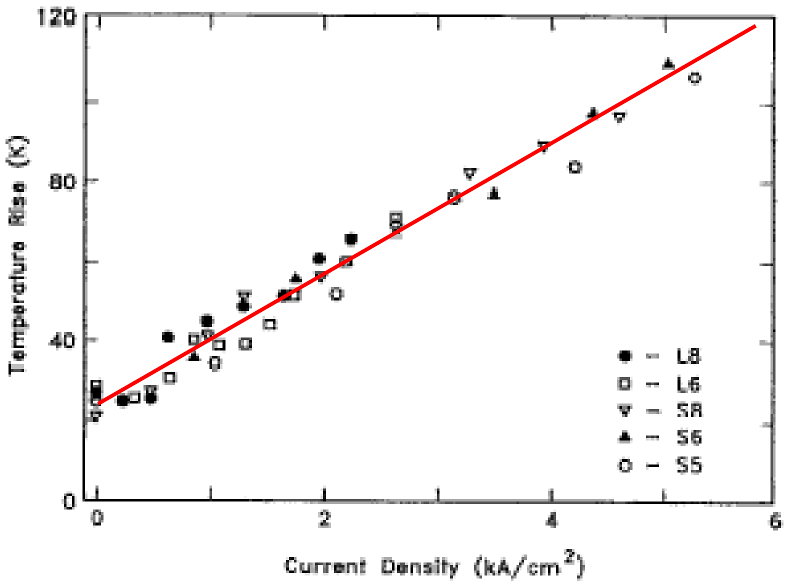
Chen and Tien, J. Appl. Phys. **74**, 2167 (1993)

COMD mechanism in QW-devices





Tang et al.
Appl. Phys. Lett.
60, 1043 (1992)



Evidence for current-density-induced heating of AlGaAs single-quantum-well laser facets

Tang et al. Appl. Phys. Lett. **59**, 1005 (1991).

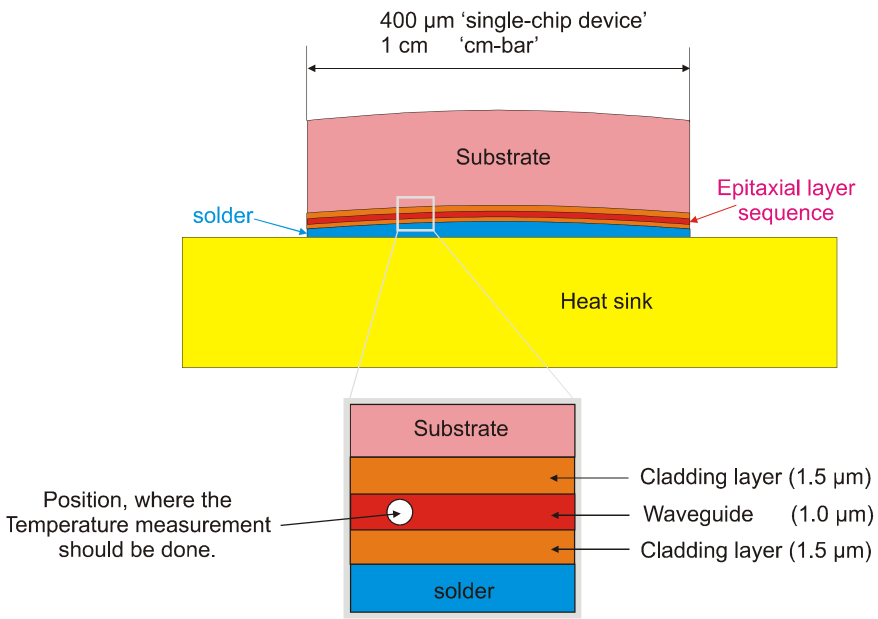
Scenarios are based on consideration of intrinsic properties.

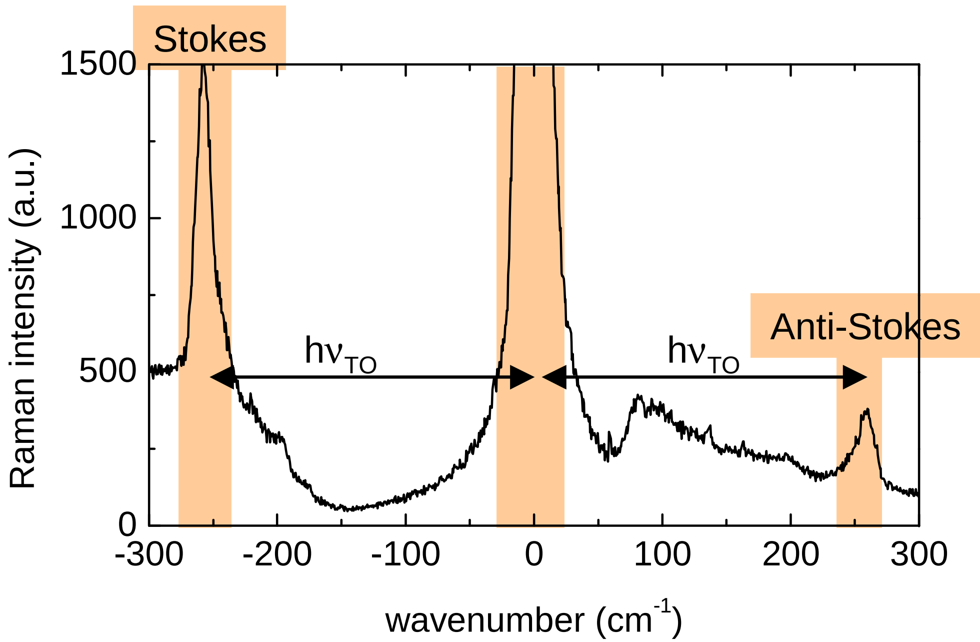
but …

2. Experimental

2.1. Available techniques for in-situ analysis of COMD

2.1.1 Micro Raman Spectroscopy





$$\frac{I_{St}}{I_{a-ST}} = const\left(\frac{\nu_l - \nu_{ph}}{\nu_l + \nu_{ph}}\right)^4 \exp\left(\frac{hc\nu_{ph}}{kT}\right)$$

T	temperature	ν_{ph}	frequency of phonons
I_{St}	Stokes intensity	h	Planck´s constant
$I_{a\text{-}St}$	anti-Stokes intensity	c	velocity of light
ν_l	frequency of excitation light	k	Boltzmann constant

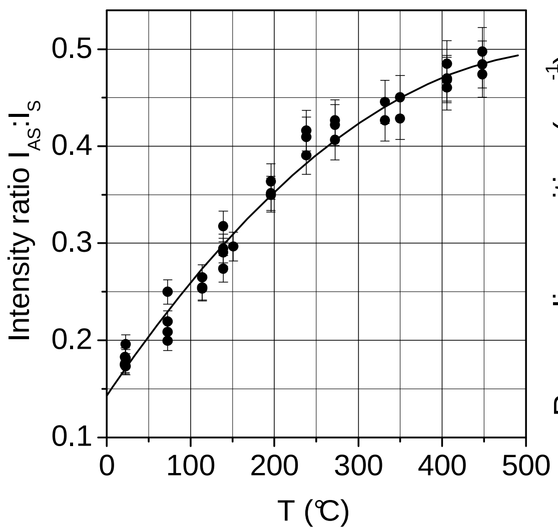
2.1.1 Micro Raman Spectroscopy

Methodology: Calibration of the temperature measurement

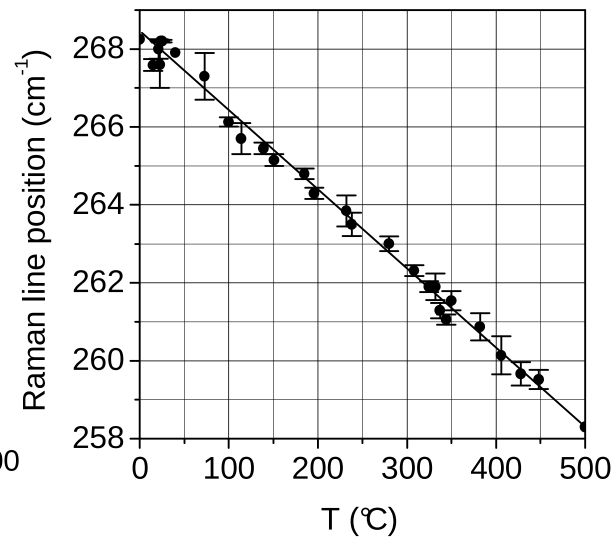
Two completely independent approaches
based on the same spectra:

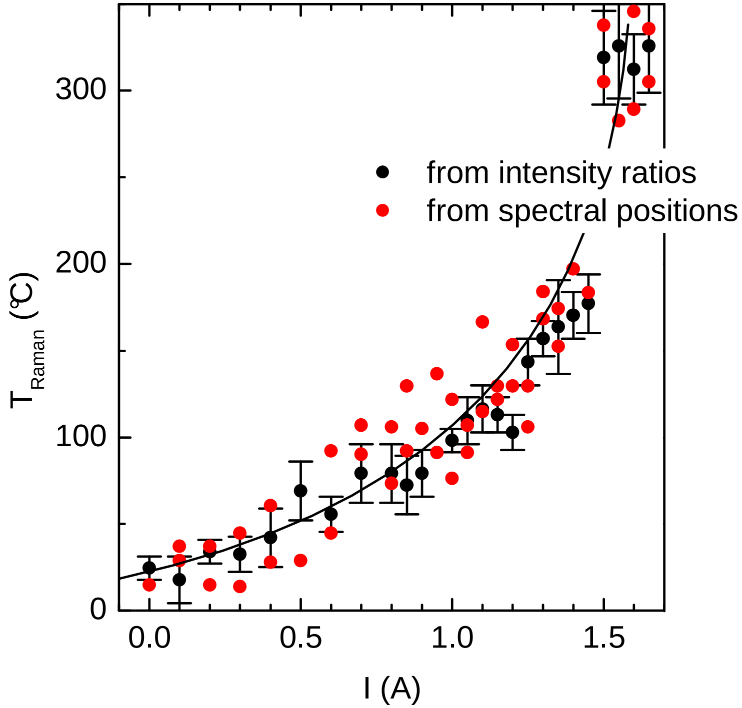
Example:

1. Intensity ratio



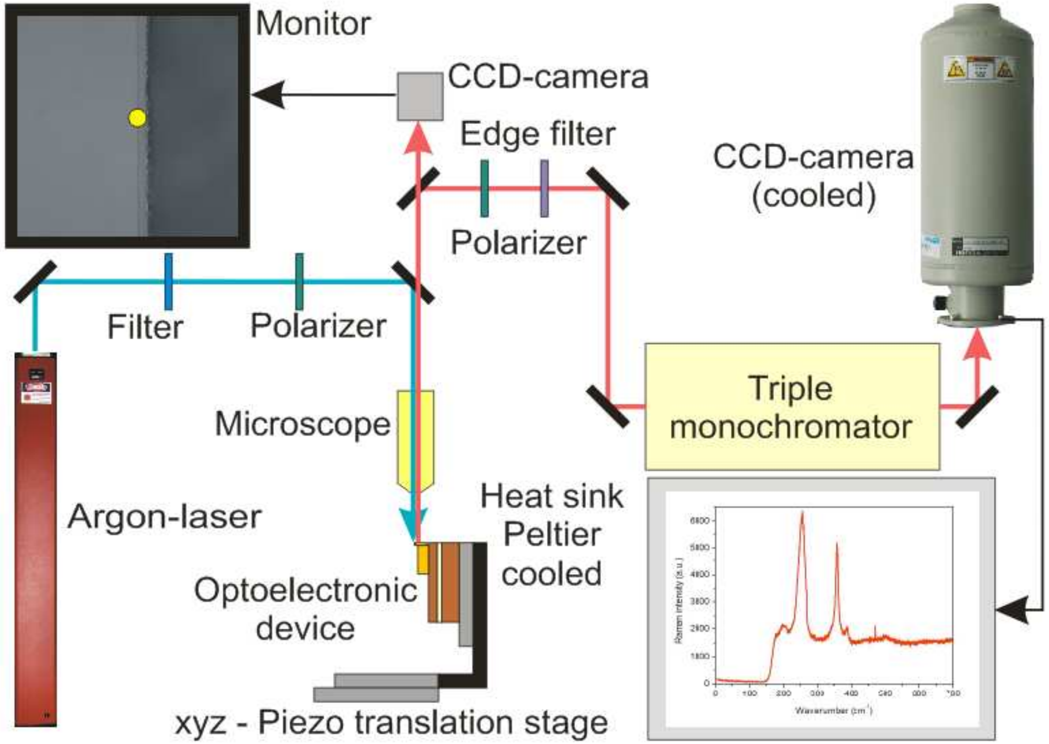
2. Line position

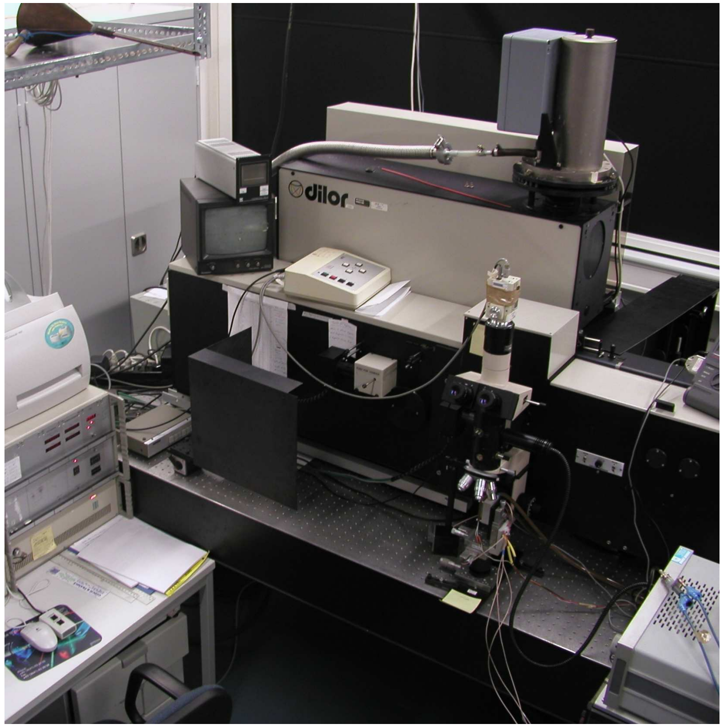




2.1.1 Micro Raman Spectroscopy

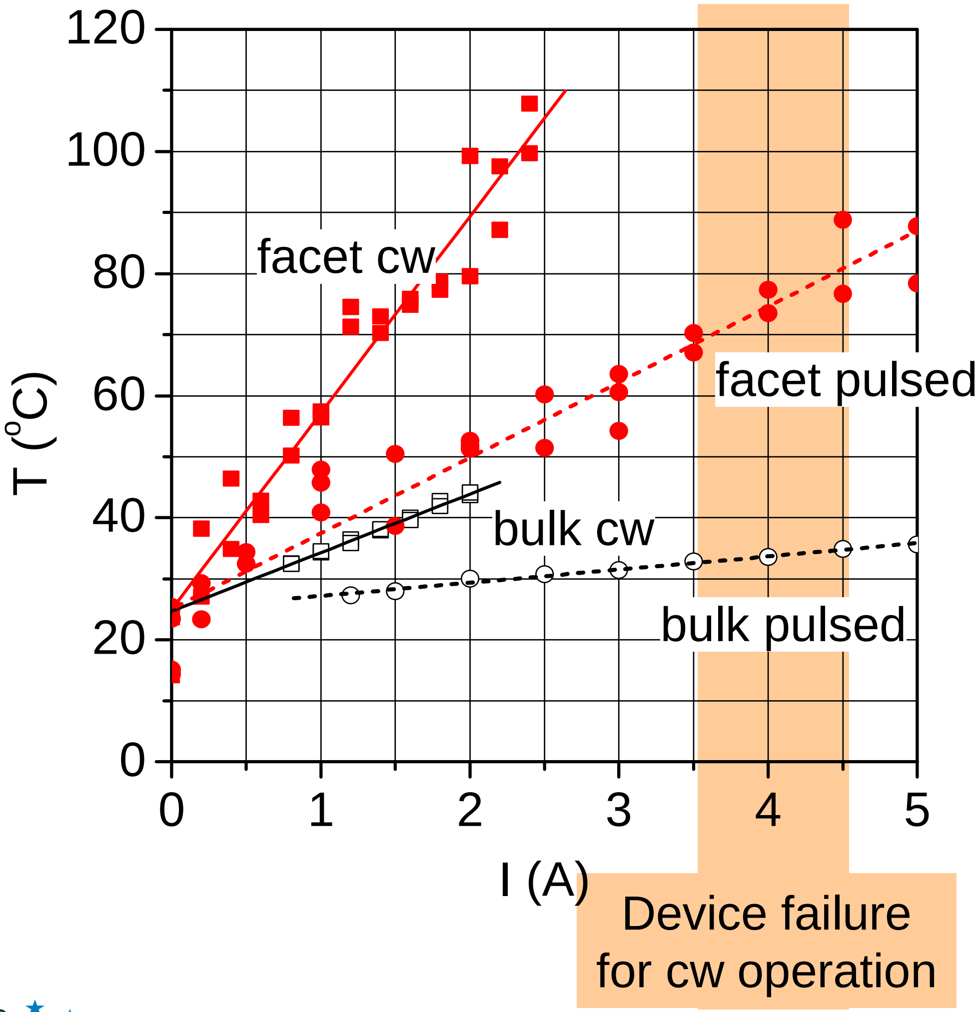
µ-Raman-Spectrometer DILOR-xy





2.1.1 Micro Raman Spectroscopy

Example:



Standard AlGaAs
2 W single emitter

repetition rate	20 kHz
pulse width	8 µs
duty cycle	16%

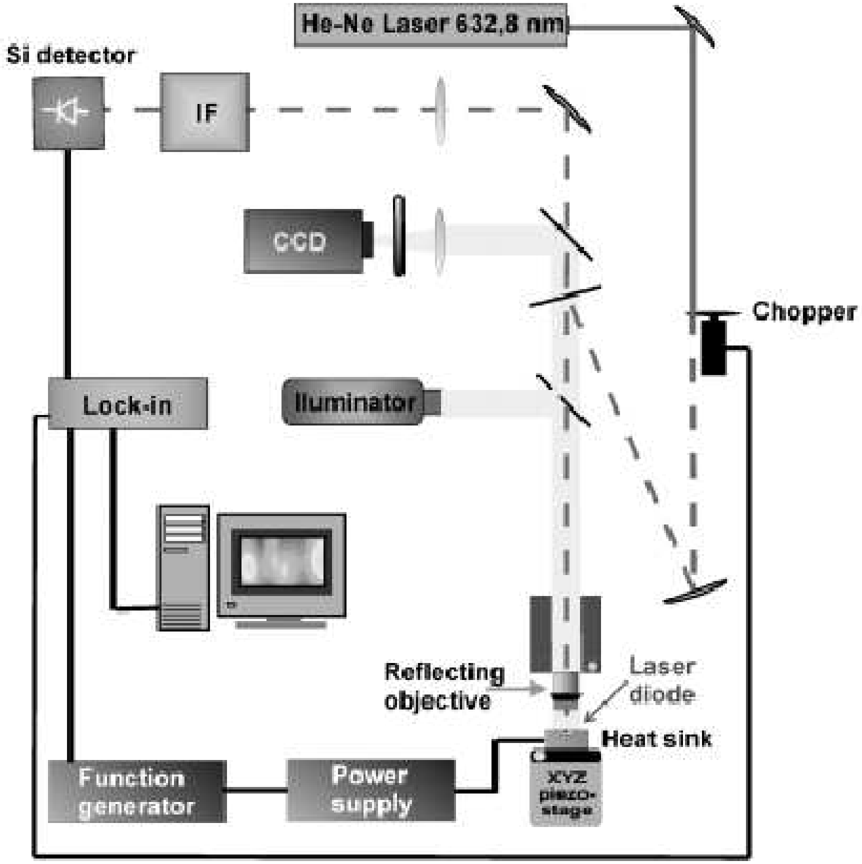
bulk	cw	9.6 K/A
	pulsed	2.2 K/A
facet	cw	32.2 K/A
	pulsed	12.4 K/A

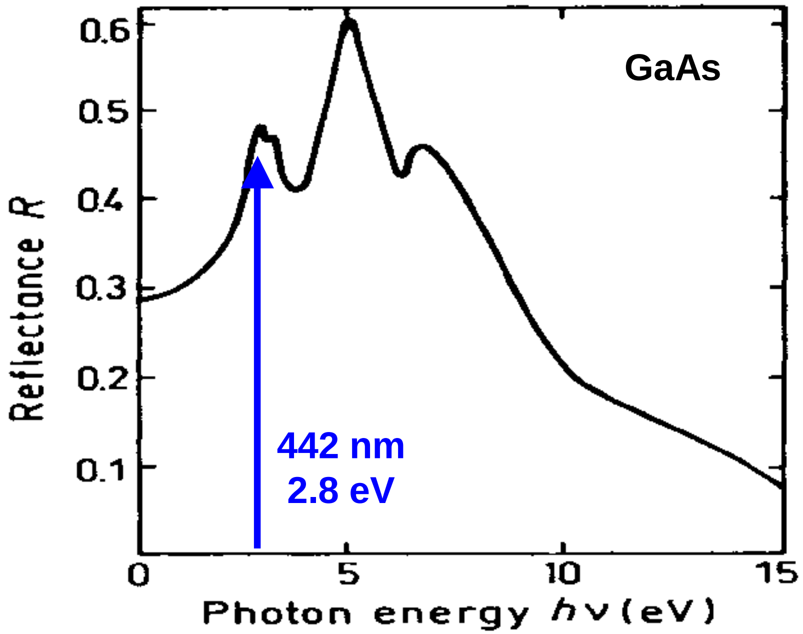
red data obtained by µRaman
open symbols from wavelength shift

WWW • BRIGHTER • EU

2.1.2 Thermoreflectance

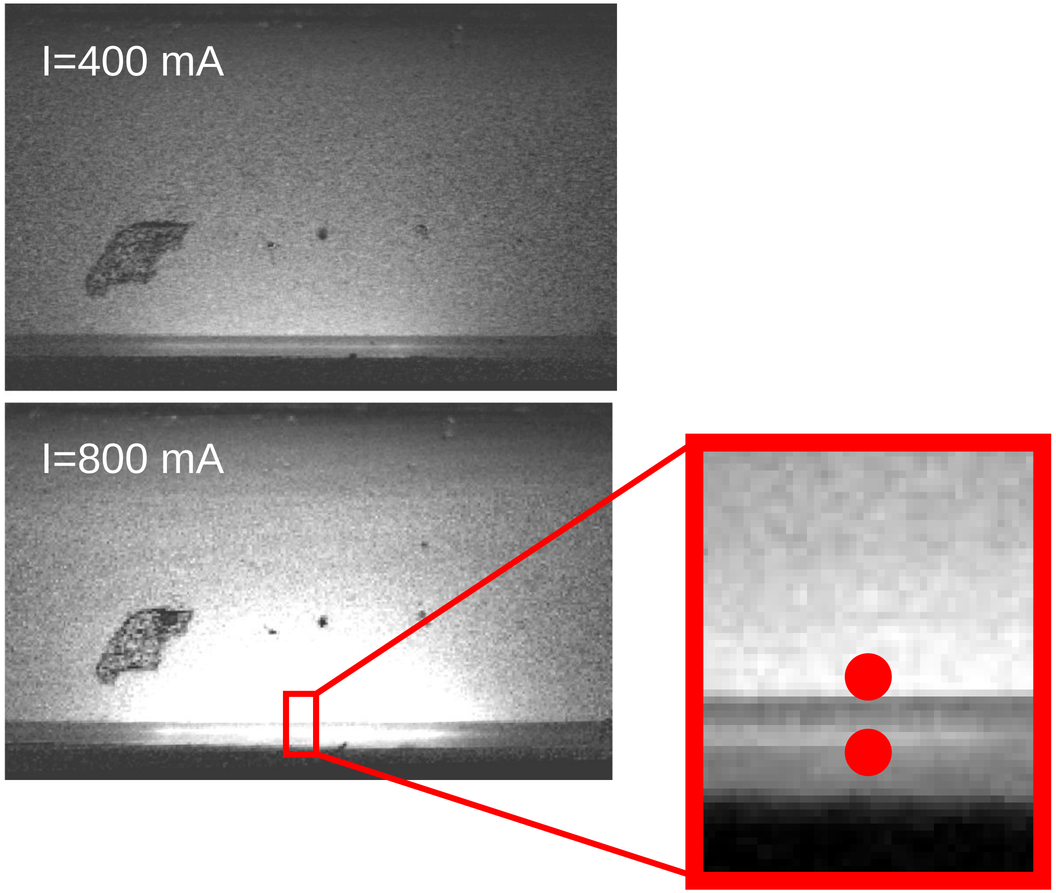
P. W. Epperlein, G. L. Bona, and P. Roentgen, Appl. Phys. Lett. 60, pp. 680-682, 1992.

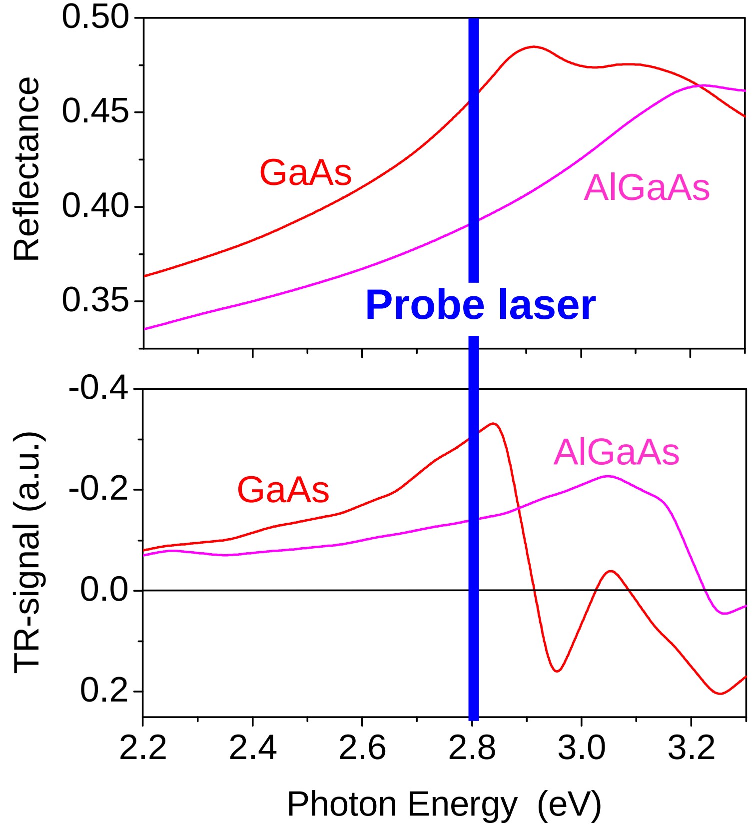




Wawer et al. phys. stat. sol. (a) **202**, 1227, (2005).

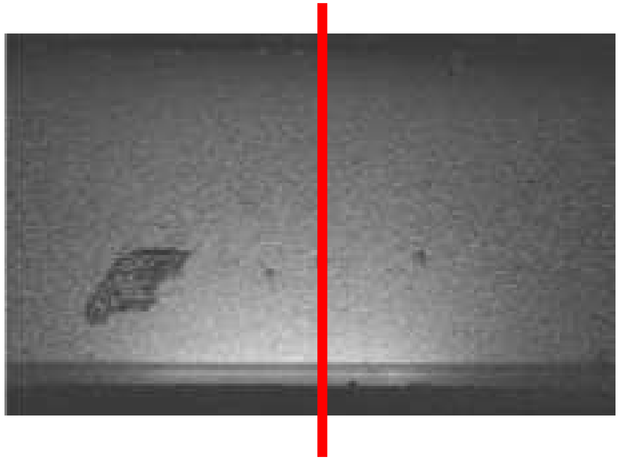
Thermoreflectance maps from front facets of broad-area lasers

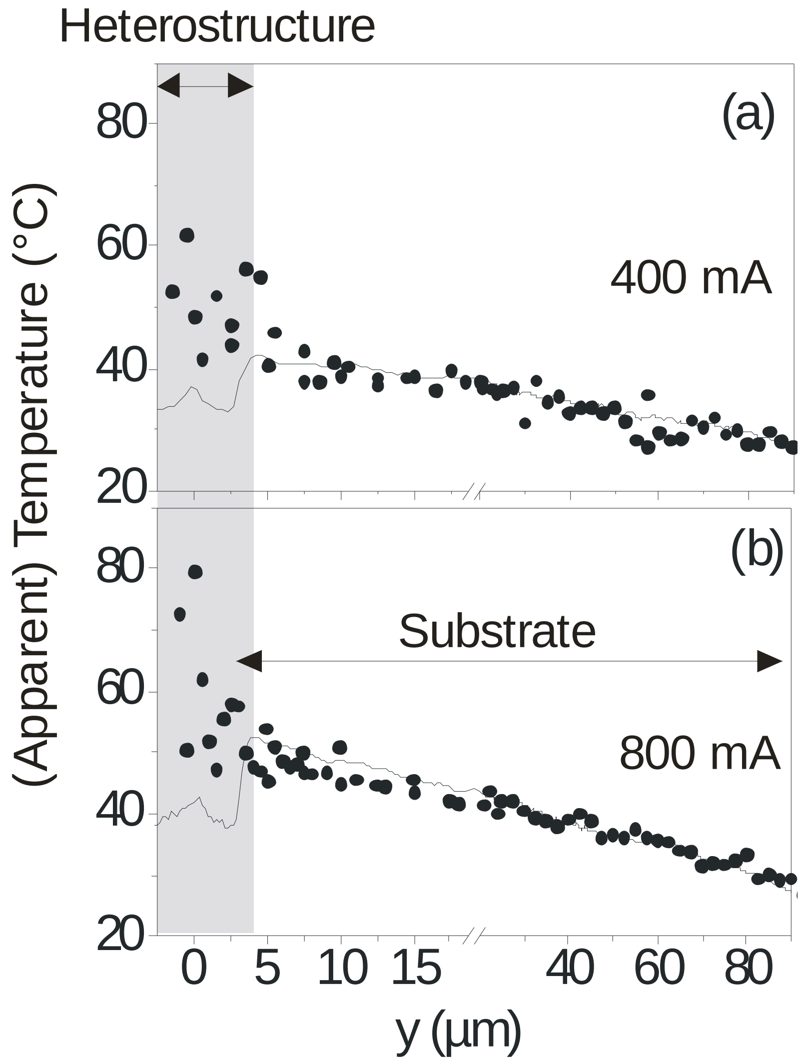




Ochalski et al. Appl. Phys. Lett. 89, 071104, 1-3 (2006).

Comparison between Thermoreflectance and micro-Raman-scans





Dots: Raman
~200 s per data point
Line: Thermoreflectance
1s per data point

Surface sensitive temperature test methods:

- micro-Raman
- Reflectance-methods

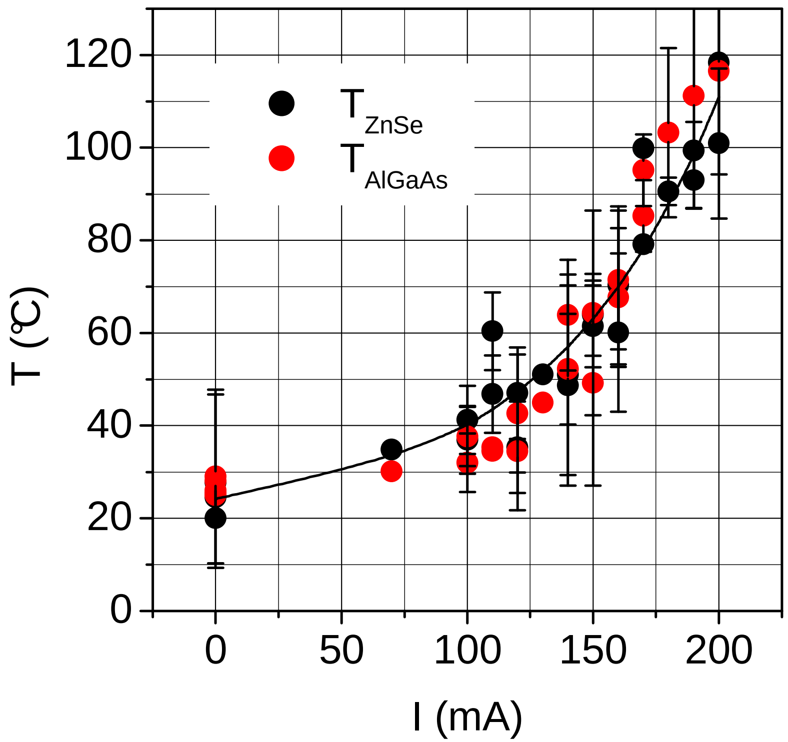
both are also sensitive

- surface alterations (TR even to mirror!)
- to stresses

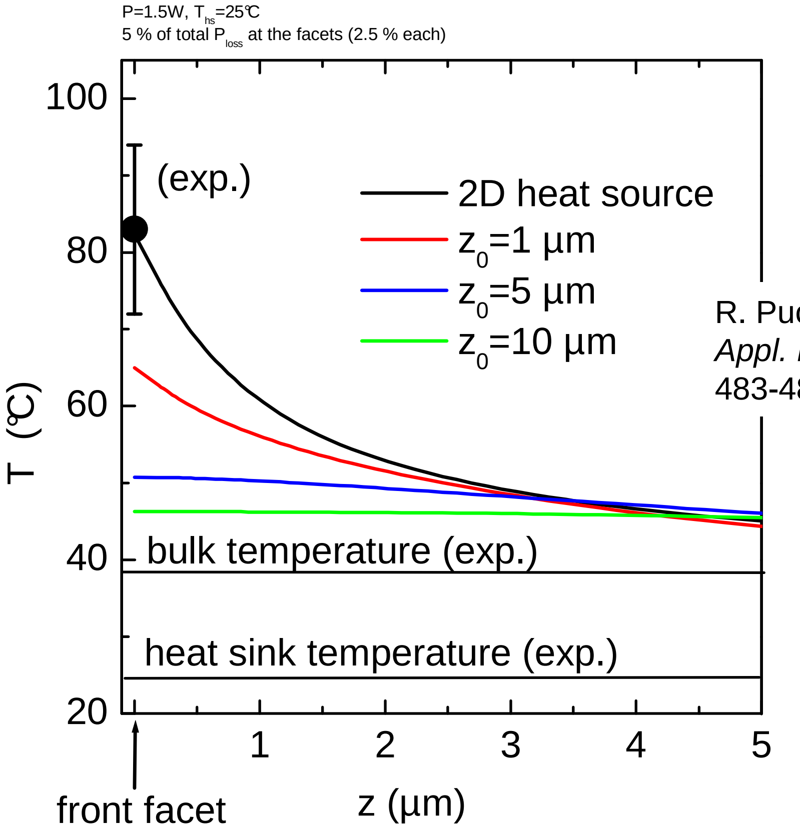
Alternative analytical methods:

Photoluminescence (Barrier)
Cathodoluminescence
Real time observation of the near-field
EL
L-I-V
Destructive Analysis
PLM
CL
TEM, X-ray

2.2. Experimental results: Surface temperature measurement

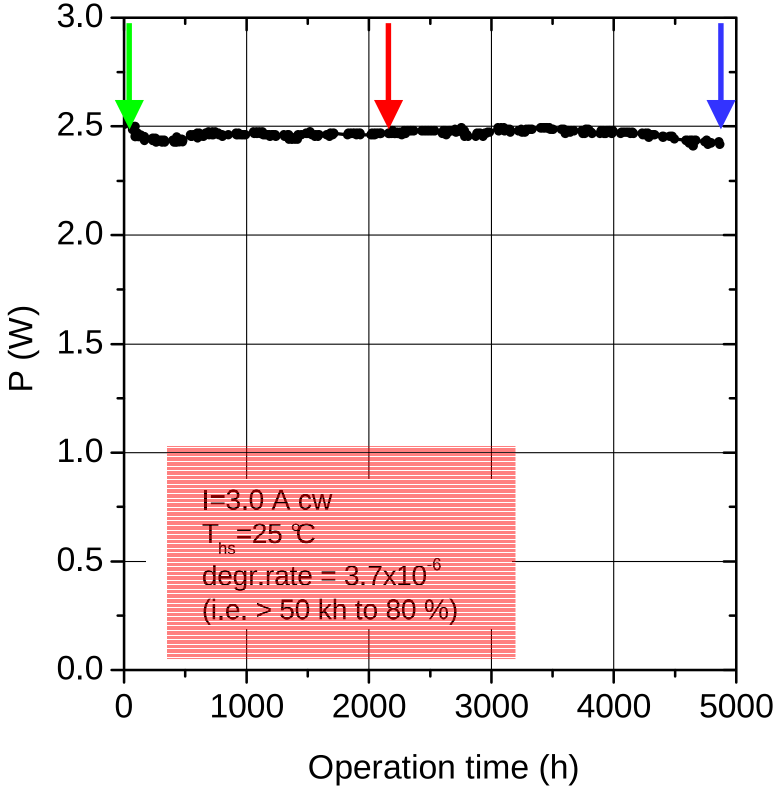


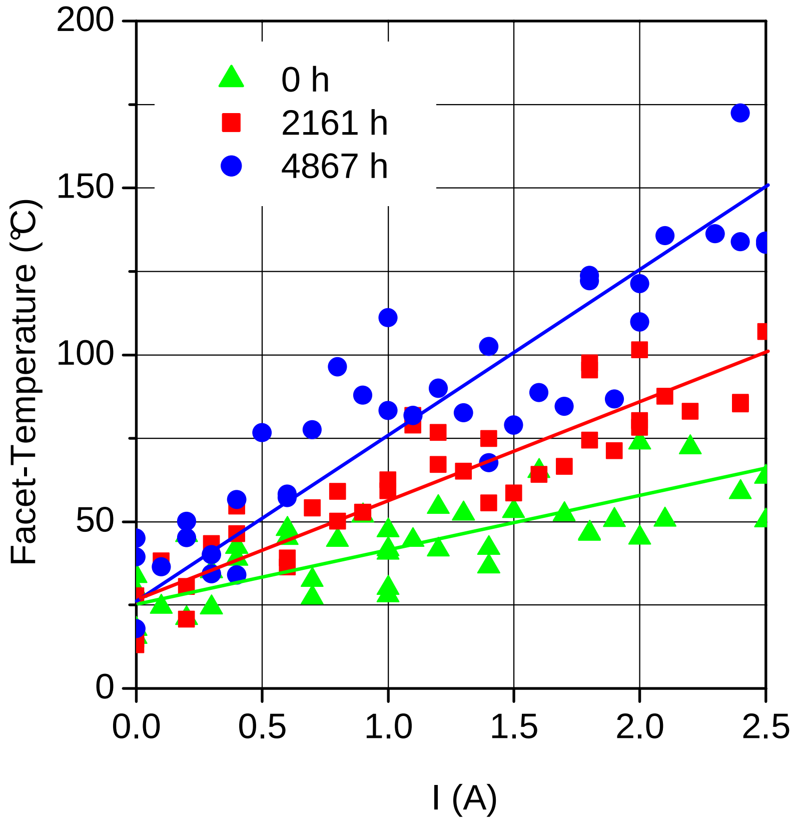
RW-laser G. Erbert FBH-Berlin



R. Puchert et al *Appl. Phys. A* **66**, 483-486 (1998).

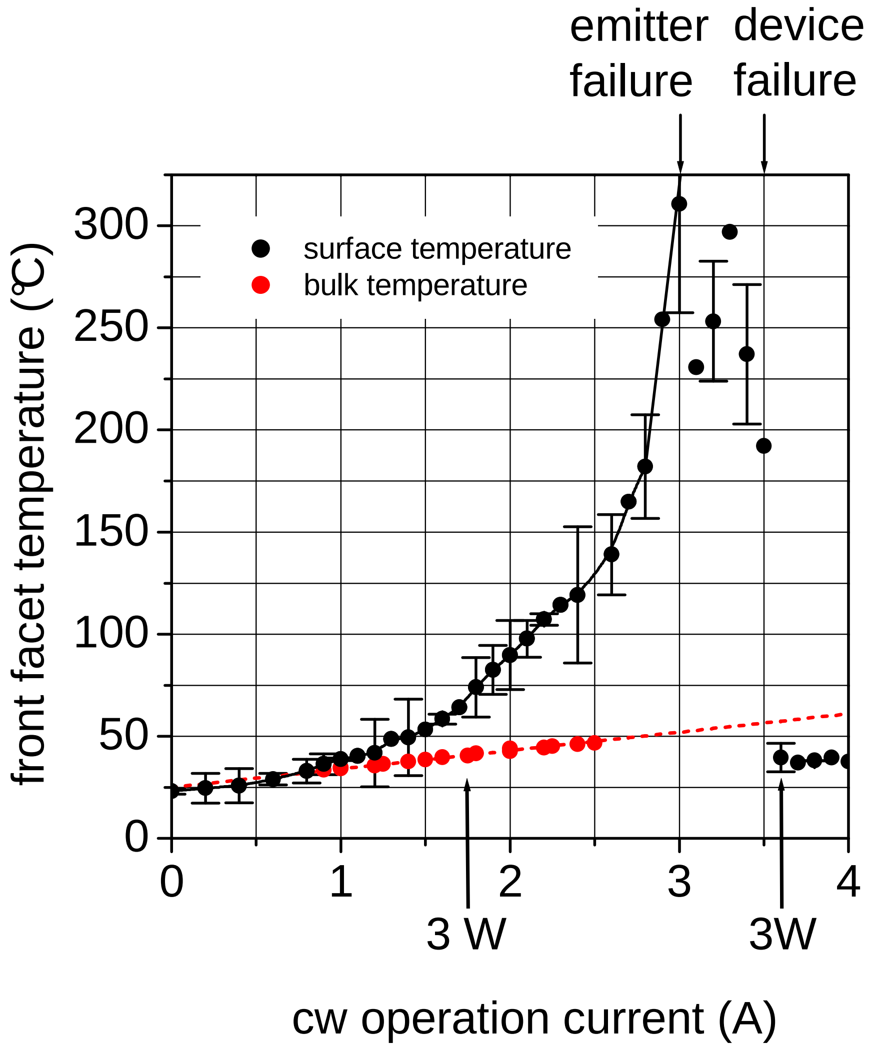
2.2. Experimental results: Surface temperature measurement vs. operation time





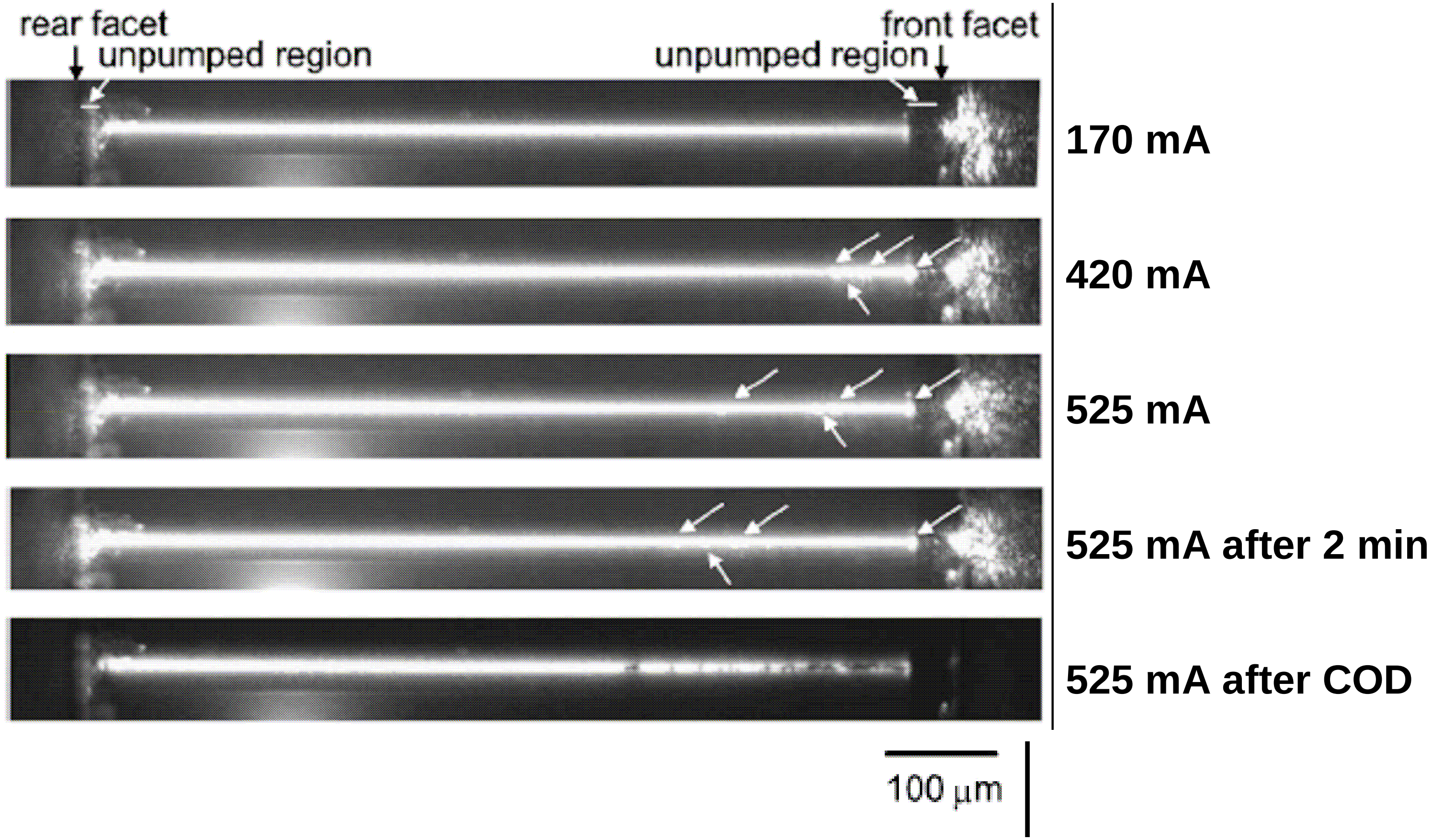
COMD-level lowers during aging …

2.2. Experimental results: Direct monitoring of COMD



J. W. Tomm et. al
Appl. Phys. A **70**, 377-381 (2000).

2.2. Experimental results: Direct monitoring of COMD

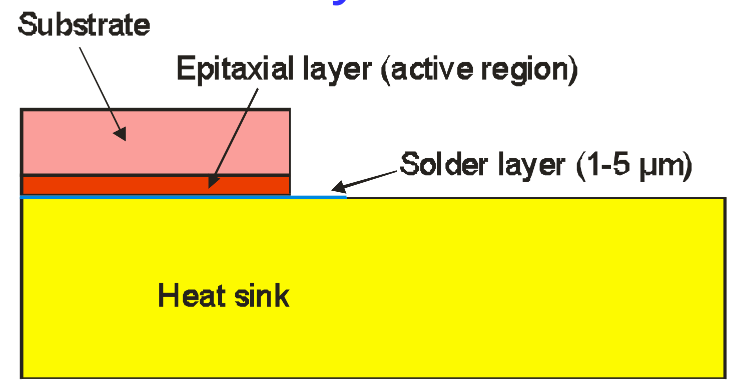


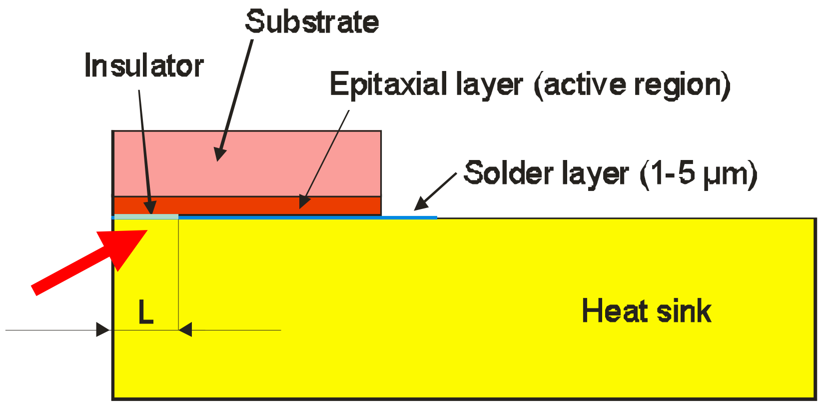
Al-free RW-laser (w=3.5 µm) 980 nm, P_{COD}=7.6 MW/cm^2

K. H. Park et. al Appl. Phys. Lett., 73, 2567-9 (1998).

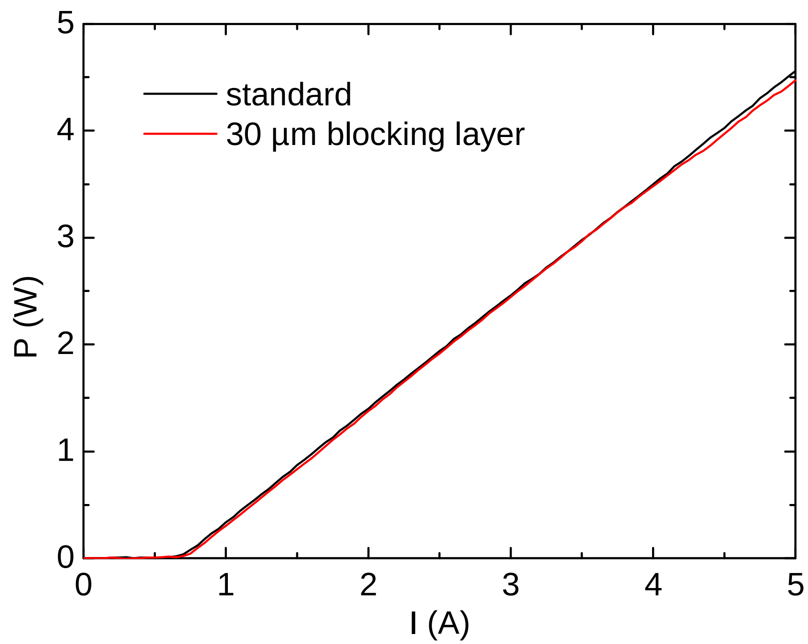
2.2. Experimental results: How to lower facet heating?

Approach: Current blocking layer





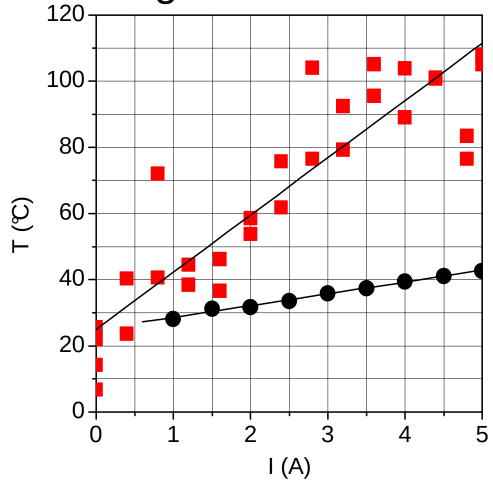
Device properties
7 nm $In_{0.12}Ga_{0.88}As$ QW, λ=940 nm
800 nm $Ga_{0.8}Al_{0.2}As$-waveguide
200 µm wide stripes, L=2 mm,
mounted p-side down



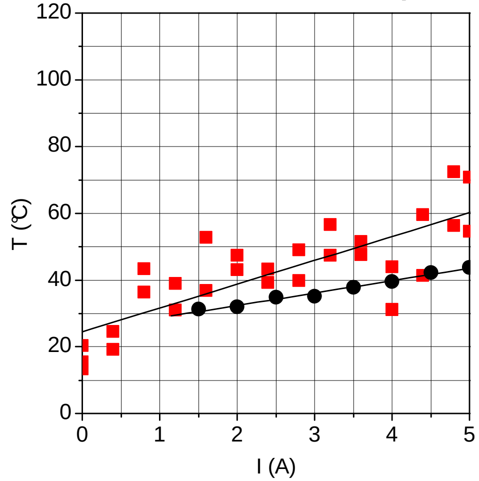
F. Rinner et. al *J. Appl. Phys.* **93**, 1354-1362, (2003).

Approach: Current blocking layer

'regular device'



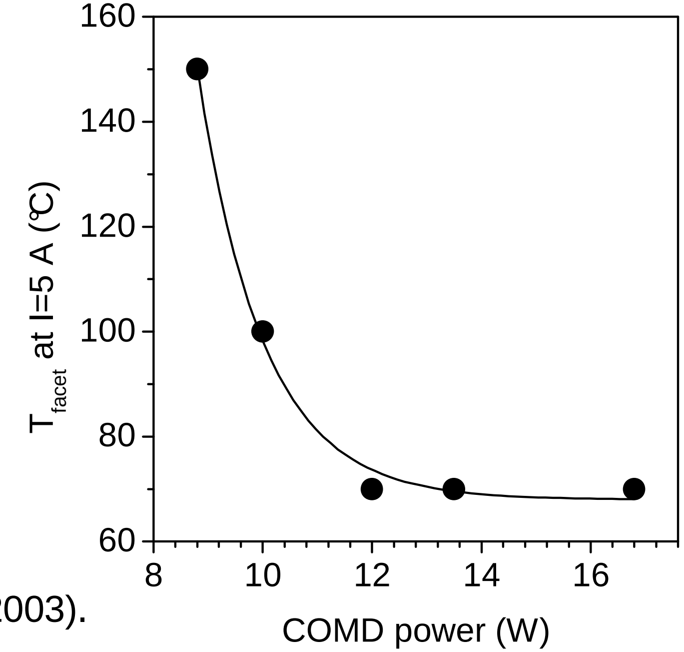
device with a 30 µm current blocking layer



Reduction of the facet over-heating by a factor of 3-4.

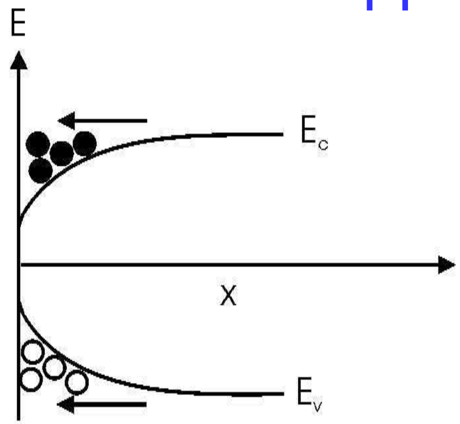
For this type of QW device the facet heating <= 5 A is **not** caused by the optical load.

	blocking layer length (µm)	facet temperature rise (K/A)	averaged waveguide temperature rise (K/A)	facet overheating (K/A)
A	0	(17.3±1.5)	(3.6±0.1)	(13.7±1.6)
B	0	(16.2±1.5)	(4.0±0.2)	(12.2±1.7)
C	30	(7.1±1.3)	(3.7±0.2)	(3.4±1.5)
D	30	(7.9±1.7)	(4.3±0.2)	(3.6±1.9)

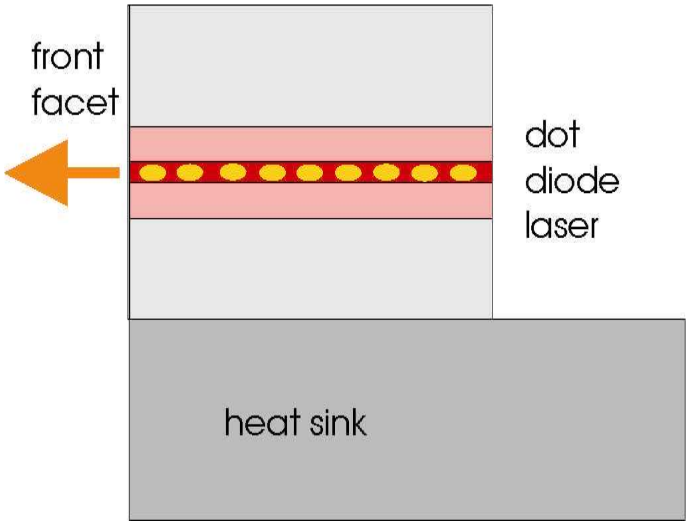


F. Rinner et. al *J. Appl. Phys.* **93**, 1354-1362, (2003).

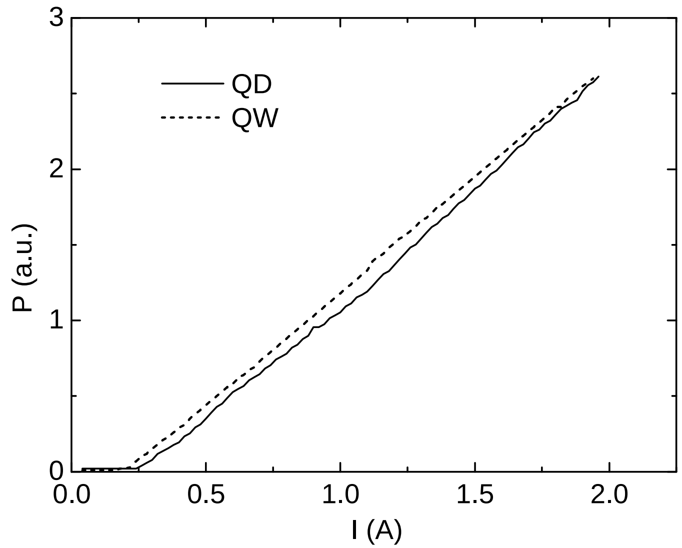
Approach: Quantum-dot lasers



Device properties*
3 layers of InAs/GaAs QDs or $In_{0.2}Ga_{0.8}As$ QW,
λ=1100 nm
300 nm GaAs-waveguide
50 µm wide stripes, L=1 mm, mounted p-side up

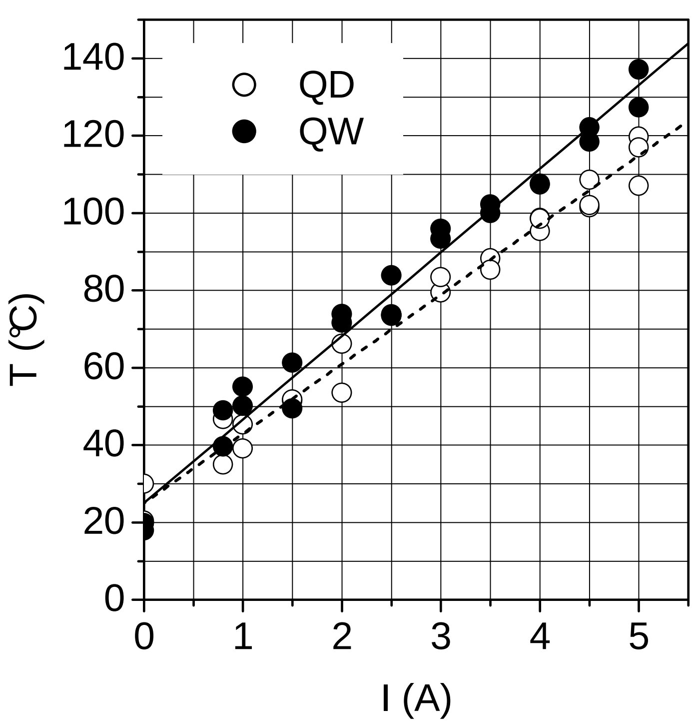


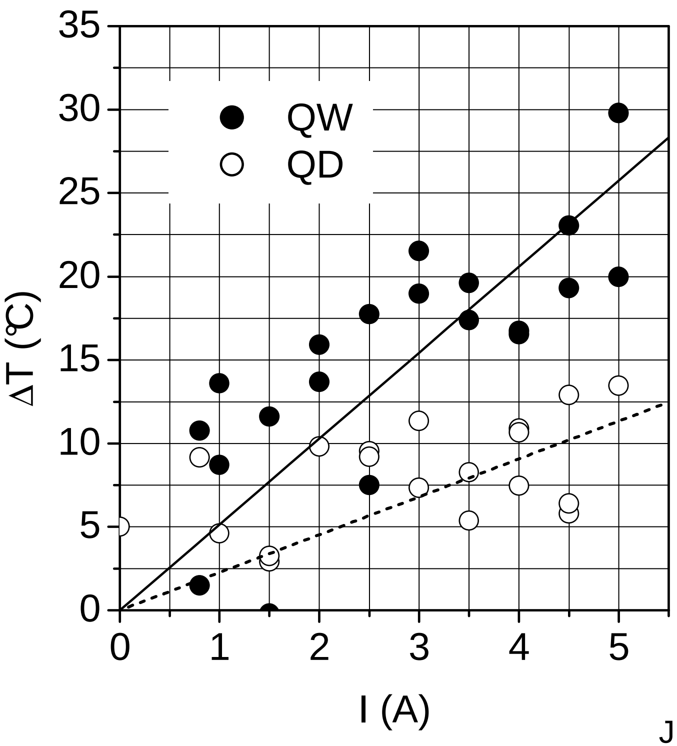
*Ch. Ribbat and R. Sellin "High power quantum dot lasers" in M. Grundmann (Ed.) *Nano-Optoelectronics Concepts, Physics and Devices*, Springer, Heidelberg, pp. 353-370, 2002.



Approach: Quantum-dot lasers

devices mounted p-side up
pulsed operation (5 µs pulses, 28 kHz rep. rate, 14% duty cycle)





Reduction of the facet overheating by a factor of more than 2

J. W. Tomm et al.
SPIE Proc. **4993** (2003).

Outline (II)

3. Modeling of Facet Heating and COMD

3.1Introduction

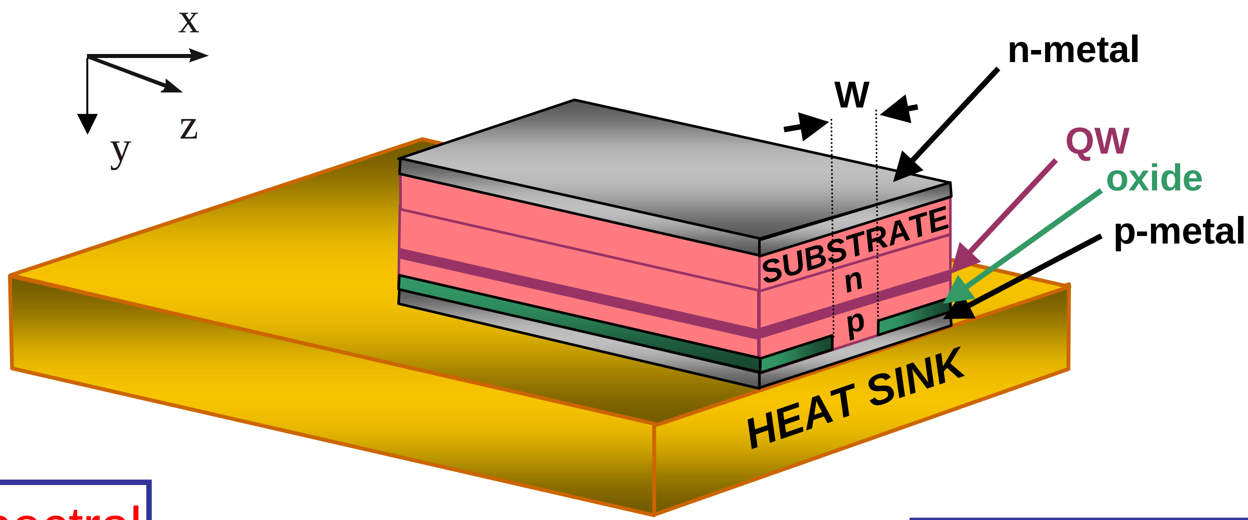
Goals of modeling

- Better understanding of physical processes
- Qualitative guidelines to improve reliability and COMD level
- Optimum: Quantitative recommendations to optimize laser design and develop strategies for improving performance

Main difficulties of modeling facet heating

- Those of modeling laser diodes:
  - ✓ 3D device
  - ✓ Complex optical/electrical/thermal interaction
  - ✓ Spectral/ temporal issues
  - ✓ Unknown and non-uniform internal parameters
- Plus... those of facet heating:
  - ✓ Surface physics/chemistry
  - ✓ Unknown basic mechanisms

Models of Facet Heating: options



Temporal / Spectral
- CW / Dynamic
- Single-frequency

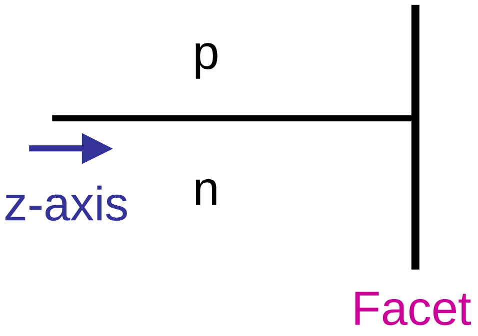
Laser Model
- Selfconsistent or not

Electrical Models
- Monopolar/ Bipolar
- 3D / 2D / 1D
- Definition of surface recombination

Thermal Models
- 3D / 2D/ 1D
- Definition of bulk and facet heat sources

3.2 Description of Facet Heating Models
Electrical Models (I)

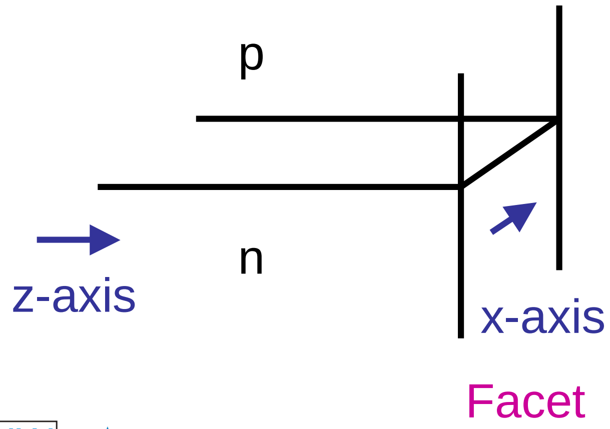
1D (z), Longitudinal direction: [Henry 79], [Nakwaski 90], [Yoo 92], [Chen 93], [Schatz 94], [Menzel 98], [Romo 03]



$$\frac{dn}{dt} = \frac{J}{ed_{act}} + D\frac{d^2n}{dz^2} - \frac{n}{\tau_n} - A(n - n_{tr})N_{ph}$$

$$D\frac{\partial n}{\partial z}\bigg|_{z=Facet} = -s_0 n$$

2D (x-z), Longitudinal and lateral directions: [Lee 93]



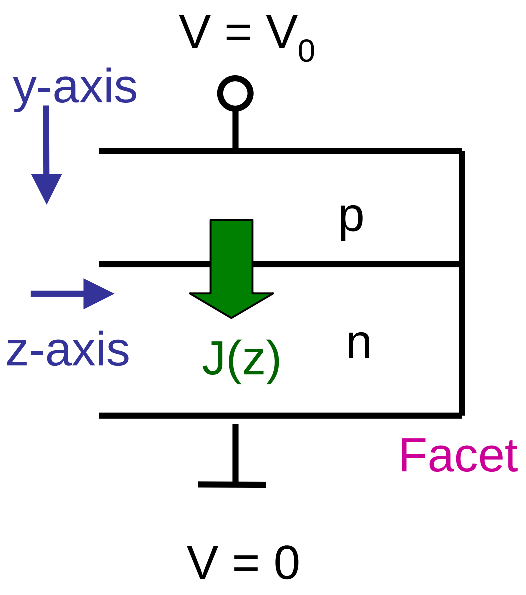
$$\frac{dn}{dt} = \frac{J}{ed_{act}} + D\frac{d^2n}{dz^2} + D\frac{d^2n}{dx^2} - \frac{n}{\tau_n} - A(n - n_{tr})N_{ph}$$

Main drawback

J is longitudinally uniform (or assumed)

Electrical Models (II)

2D (y-z), Long. and vertical directions: [Romero 99], Laser Simulator HAROLD 3.0



- Poisson equation
- Continuity equations for holes and electrons
- QW balance for holes and electrons
- Boundary conditions:

$$\nabla\phi\Big|_{normal} = \frac{Q_{SURF}}{\varepsilon} \qquad j_n\vec{n} = R^{SURF} \qquad j_p\vec{n} = -R^{SURF}$$

$$R^{SURF} = \frac{\left(n_s p_s - n_i^2\right)}{s_{op}^{-1}\left(n_s + n_{T_s}\right) + s_{on}^{-1}\left(p_s + p_{T_s}\right)} = f\left(N_t, E_t, \sigma_t\right)$$

Main drawback: Only valid for Broad Area Lasers

3D (x-y-z): Not yet reported

Thermal Models (I)

Heat Flow Equation: $$\vec{\nabla}\left(\kappa\vec{\nabla}T\right) = -w\left(x, y, z\right)$$

κ: thermal conductivity
w (x, y, z): local heat sources

1D (z), Longitudinal direction: [Henry 79], [Yoo 92], [Menzel 98]

2D (x-z), Long. and lateral directions: [Lee 93]

2D (y-z), Long. and vertical directions: [Romero 99], Laser Simulator HAROLD 3.0

3D (x-y-z): [Nakwaski 90], [Chen 93], [Schatz 94], [Romo 03]

"Tricks" to consider the heat sink
Mathematical methods

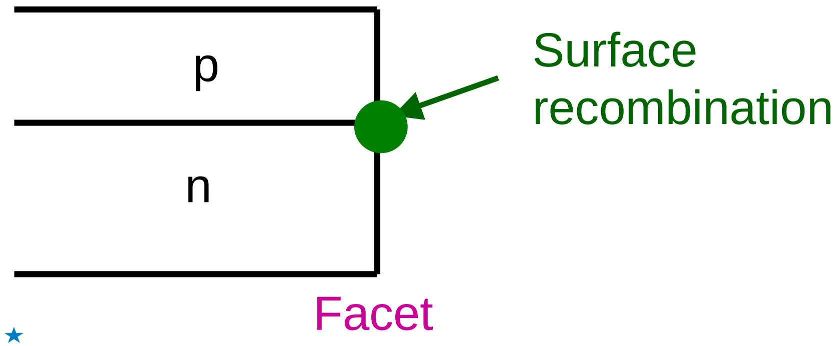
Thermal Models (II)

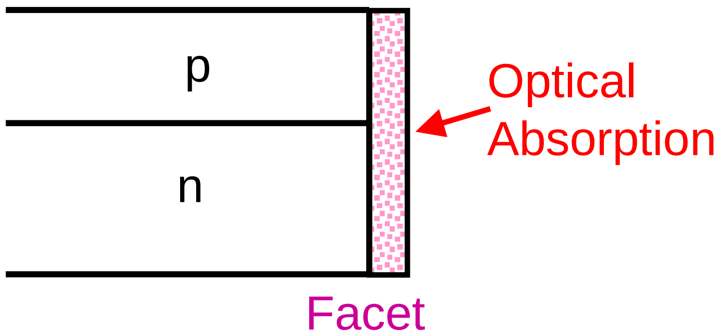
Local Bulk Heat sources

- Joule ∝ $|J|^2 \cdot \rho$
- SRH ∝ n
- Auger ∝ n^3 (or $n \cdot p^2 + p \cdot n^2$)
- Free carrier absorption ∝ $(n \cdot \alpha_{fcn} + p \cdot \alpha_{fcp}) \cdot N_{ph}$ (x, y, z)
- Excess power: uniform, needed for thermodynamical balance

Facet Heat sources

- Surface recombination ∝ n and s_0 (or surface trap density)
- Optical absorption ∝ P_{out} and $N_{ph}(x, y)$





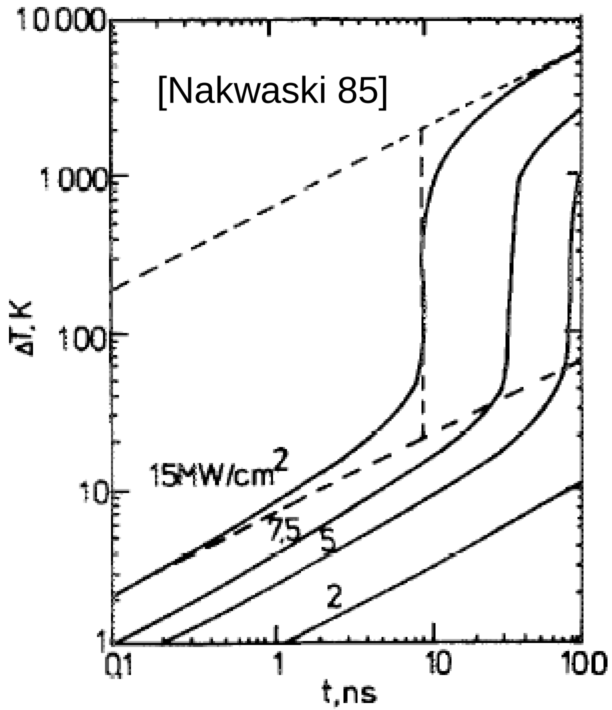
Laser model

Dynamic models: [Nakwaski 85&90], [Menzel 98]

- **Time dependent solution**
- **Direct information on Thermal run-away**

CW models: [Henry 79], [Yoo 92], [Chen 93], [Lee 93], [Schatz 94], [Romero 99],[Romo 03], Laser Simulator HAROLD 3.0

- **Thermal run-away can be inferred from lack of convergence of electrical/thermal equations**



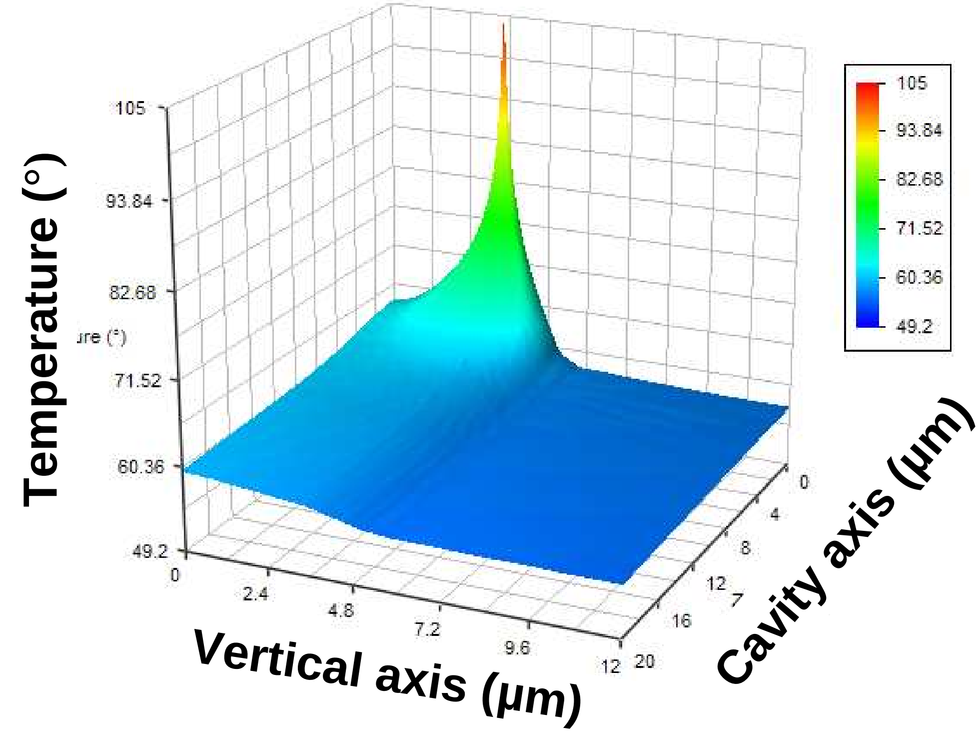
Non-Selfconsistent: [Henry 79], [Nakwaski 90], [Yoo 92], [Chen 93], [Lee 93], [Schatz 94],

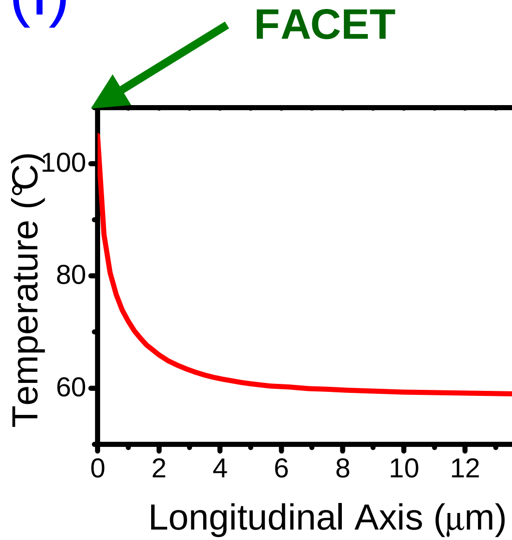
- **Solves only a region close to the facet**

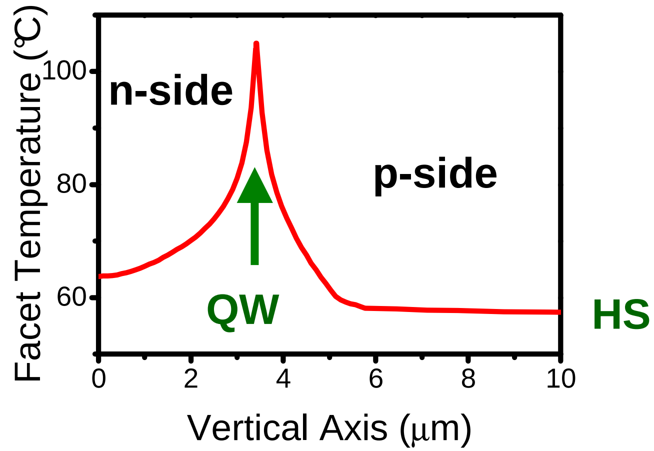
Selfconsistent: [Menzel 98], [Romero 99],[Romo 03], Laser Simulator HAROLD 3.0

- **Solution of the complete cavity**

3.3 Some modeling results
Temperature profiles (I)







Temperature profile depends on thermal conductivity

$$\Delta T(z) = \Delta T(0)\exp\left(-\frac{z}{L_{th}}\right)$$

L_{th} Thermal diffusion length

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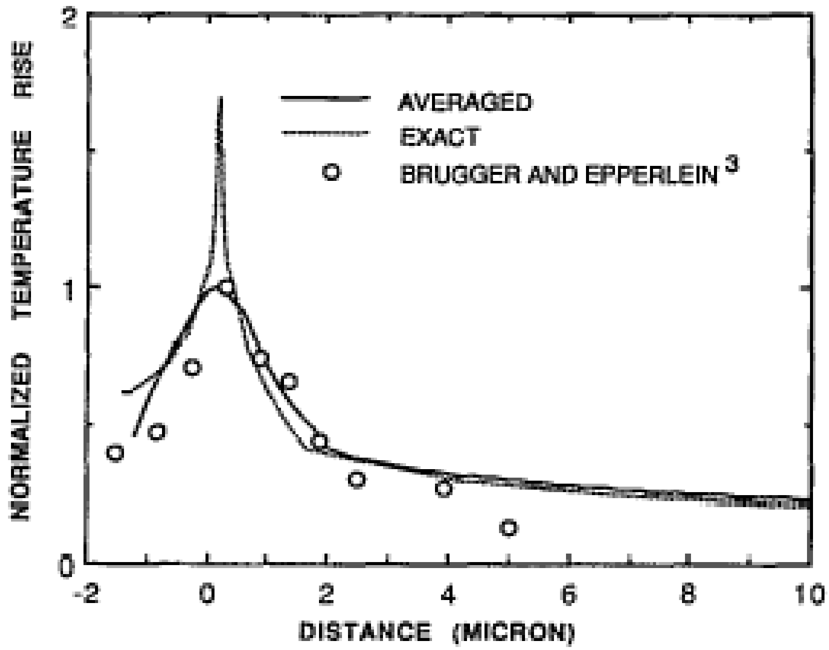
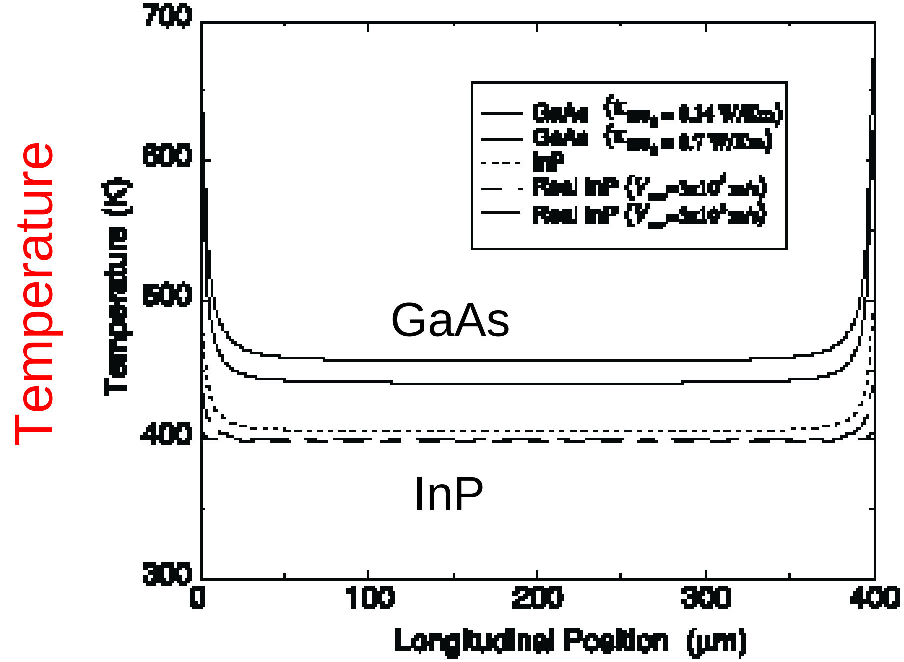
Temperature profiles (II)

[Chen 93] **GaAs/AlGaAs laser**



Along the facet (y-axis)

[Romo 03]

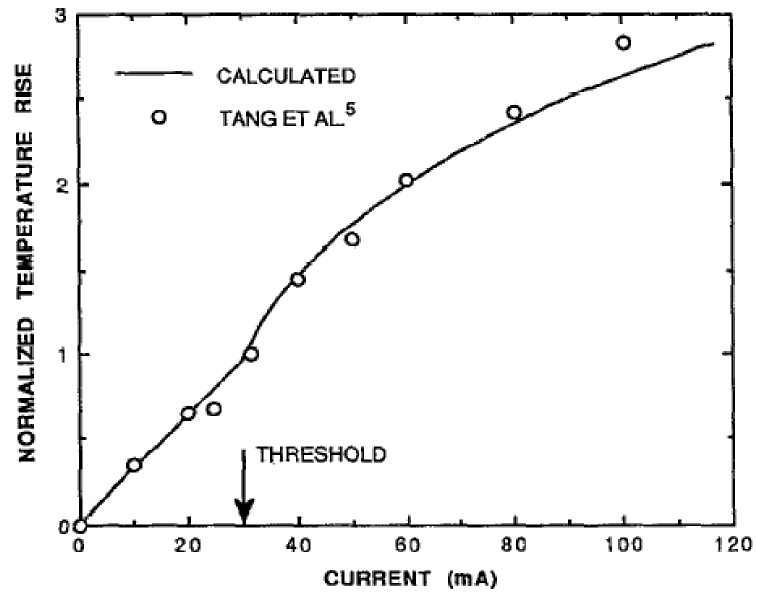


Along the cavity (z-axis)

Typical thermal diff. length ~ 1-3 µm

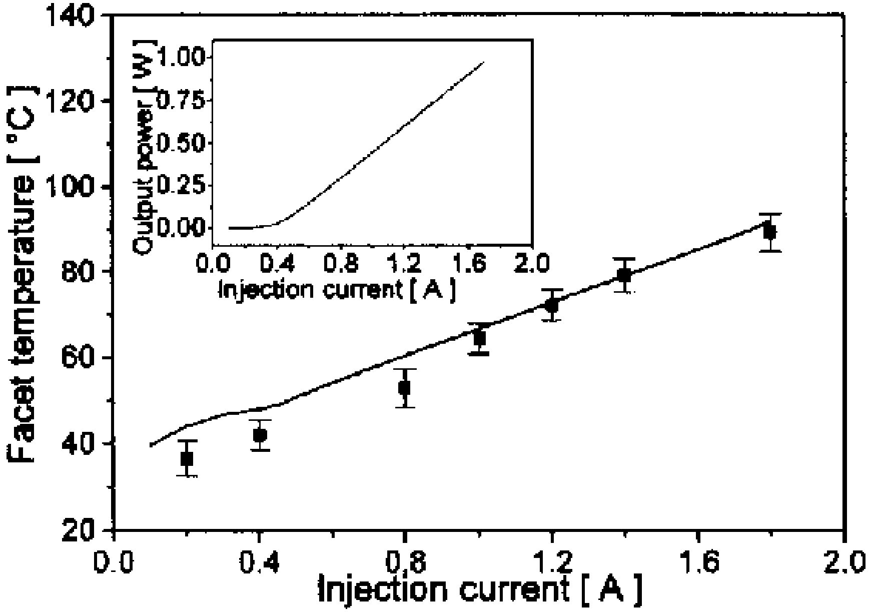
Facet Temperature vs Power/Current (I)

[Chen 93] **GaAs/AlGaAs laser**



[Menzel 98b] **AlGaAs laser**

Facet Temperature



Current

Current

Facet heating by surface recombination

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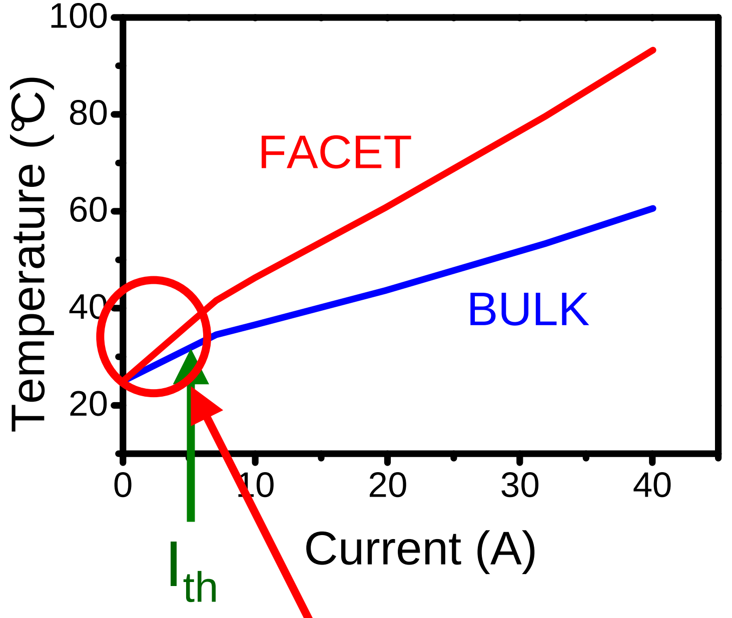
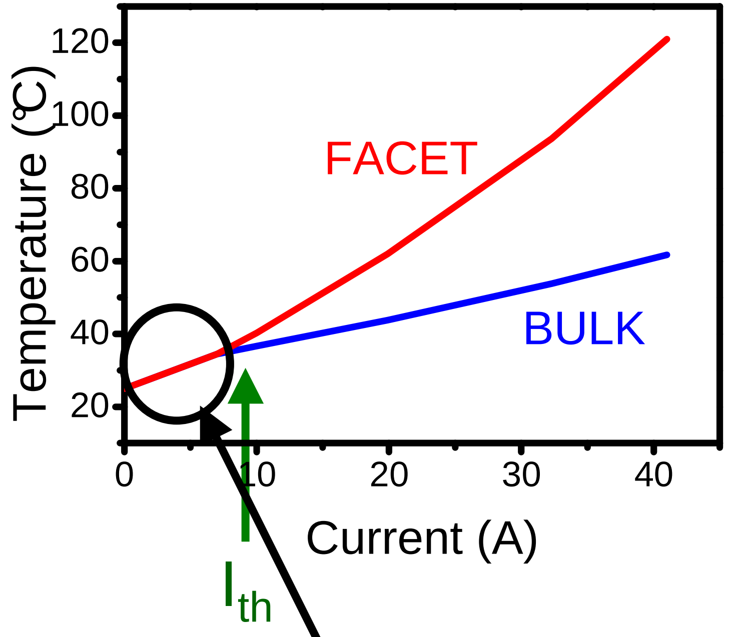
Facet Temperature vs Power/Current (II)





[Batko 98]

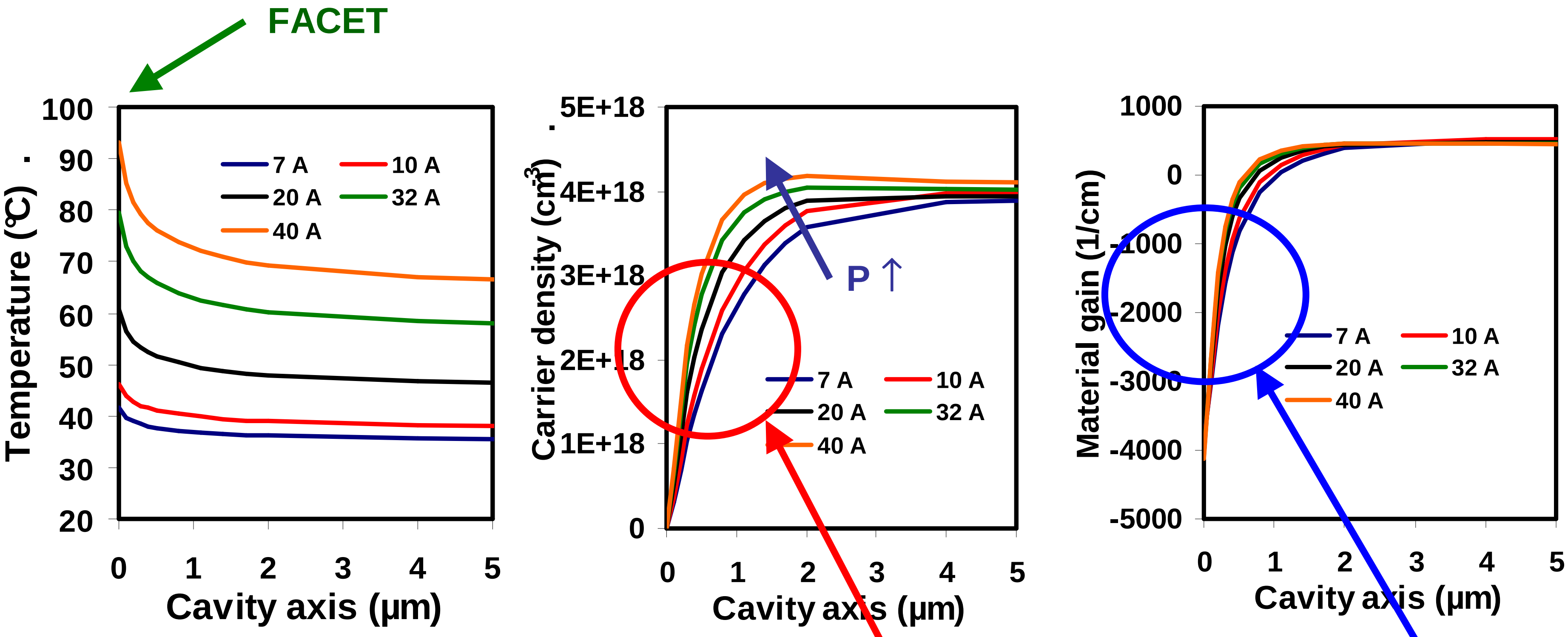
808 nm AlGaAs laser bar

Facet heating below threshold

NO Facet heating below threshold

Internal parameters

Surface recombination



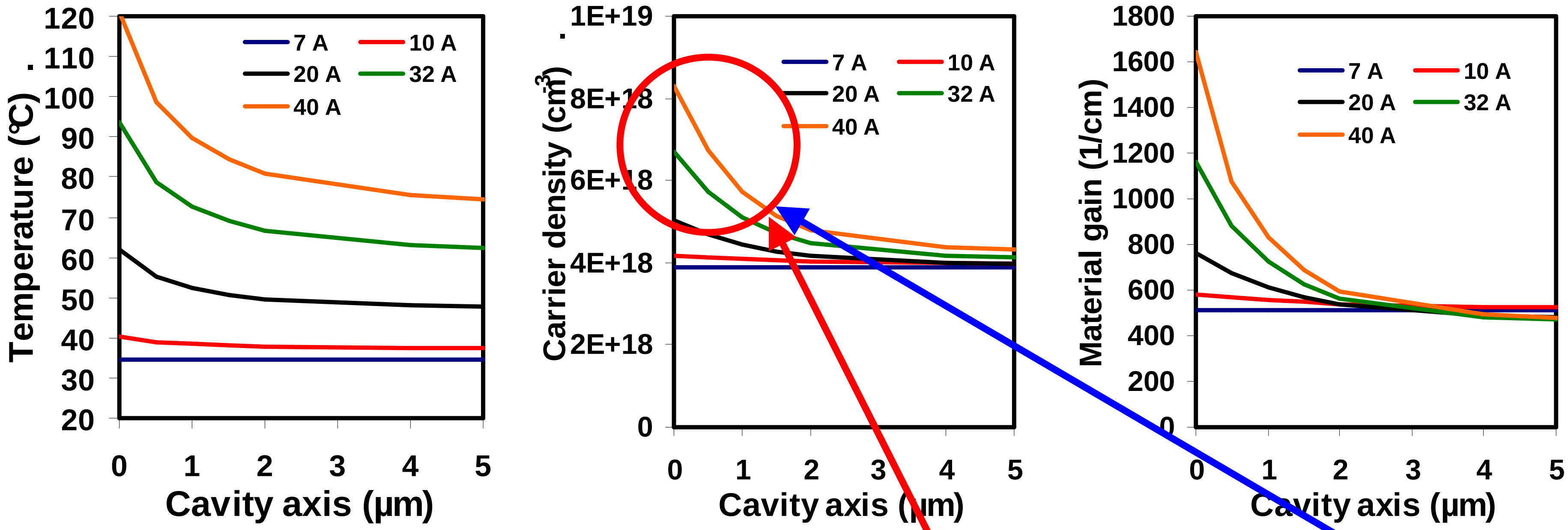
[Batko 98] **808 nm AlGaAs laser bar**

CARRIER DEPLETION

OPTICAL ABSORPTION

Internal parameters

Facet optical absorption



808 nm AlGaAs laser bar

[Batko 98]

CARRIER ACCUMULATION

ADDITIONAL HEATING by Auger rec. and FCA

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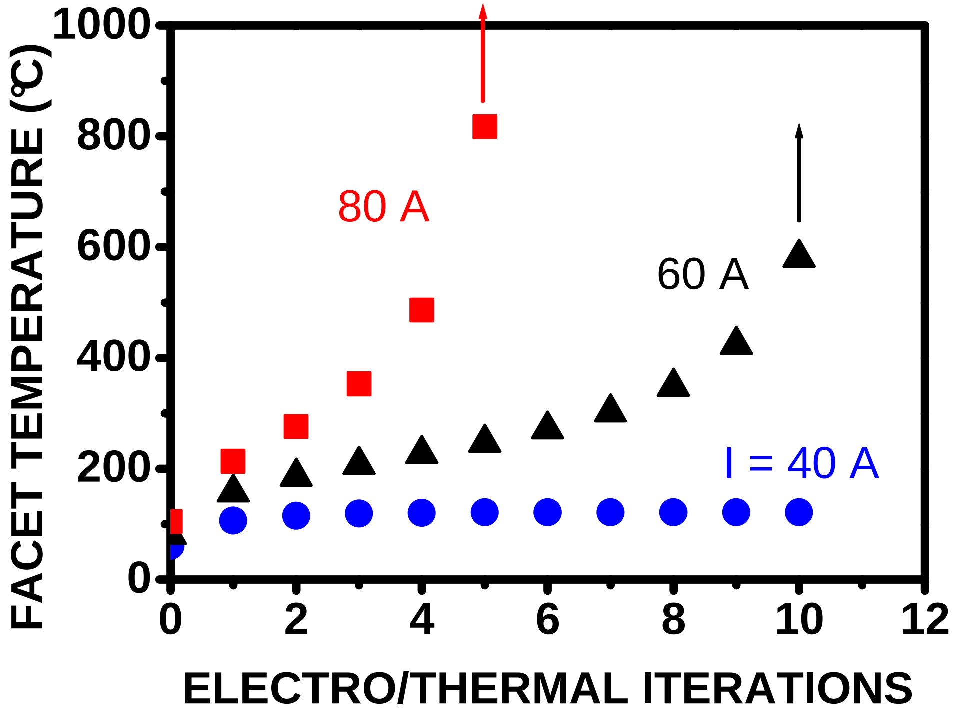
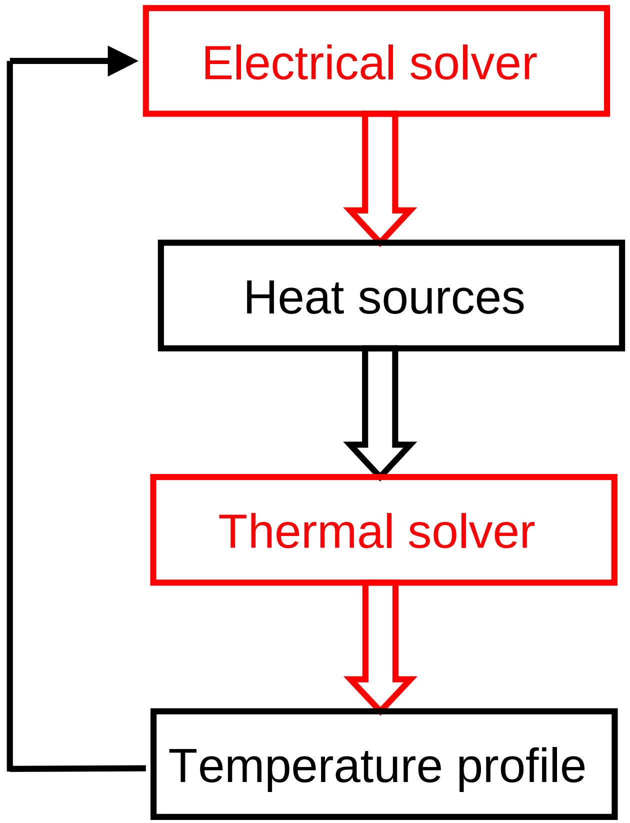
Thermal run-away by facet optical absorption

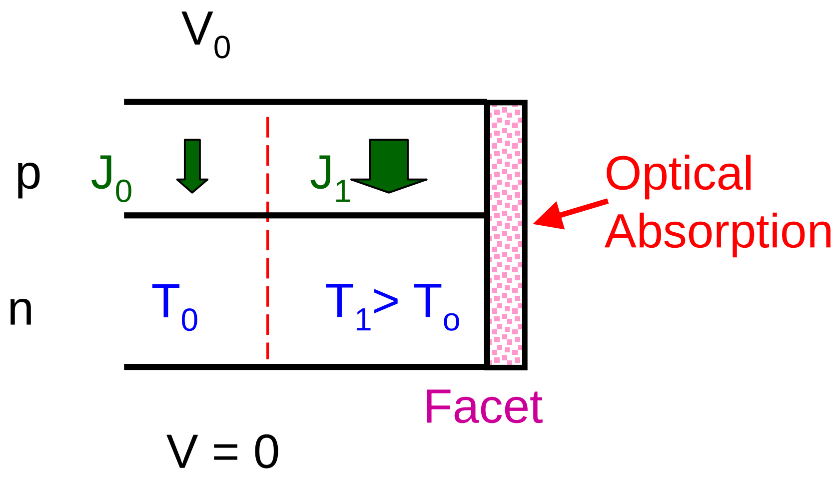


[Batko 98] **808 nm AlGaAs laser bar**

Iterative procedure



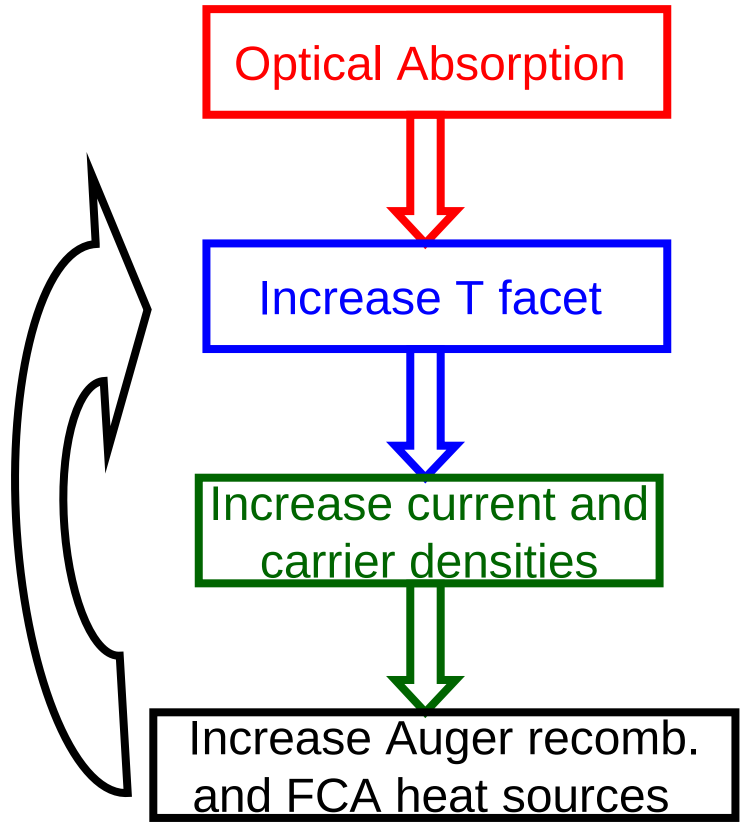
Thermal run-away by facet optical absorption



$$J = J_0 \exp\left(\frac{eV}{mkT}\right)$$

$$J_0 \propto \exp\left(-\frac{E_g}{kT}\right)$$

[Romero 00]



Final remarks in modeling of facet heating (I)

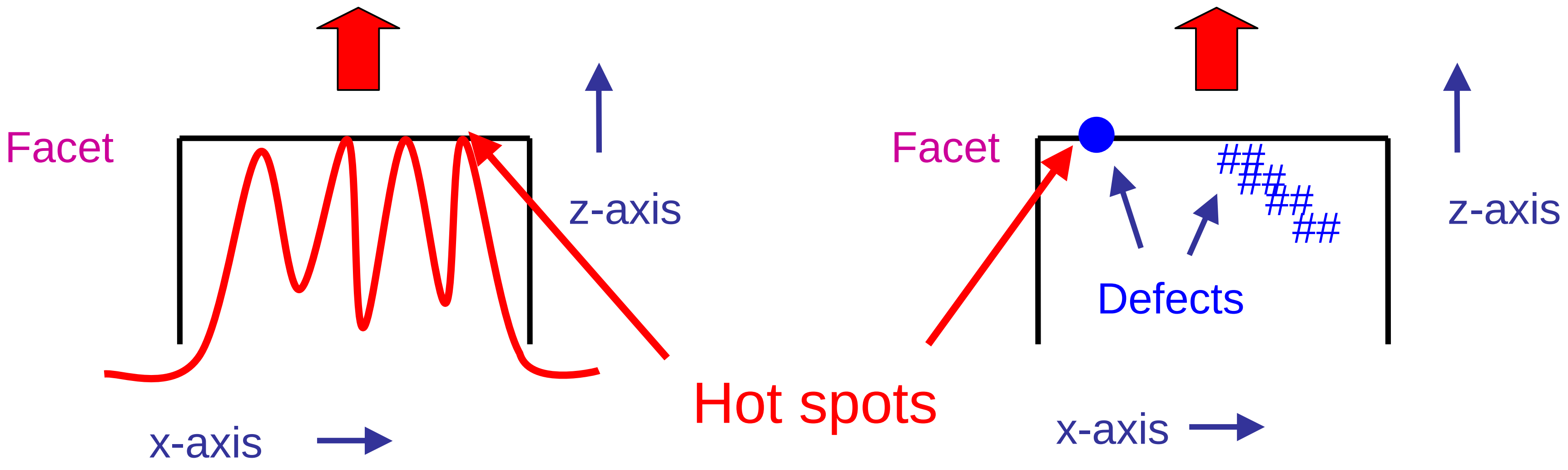
Question: Would it be better to simulate facet heating with 3D/spectral/dynamic/electro/optical/thermal model (microscopic and multibody) ?

Maybe YES, but probably NOT

Final remarks in modeling of facet heating (II)

Question: Are all relevant issues included in present facet heating models ?

Clearly NOT



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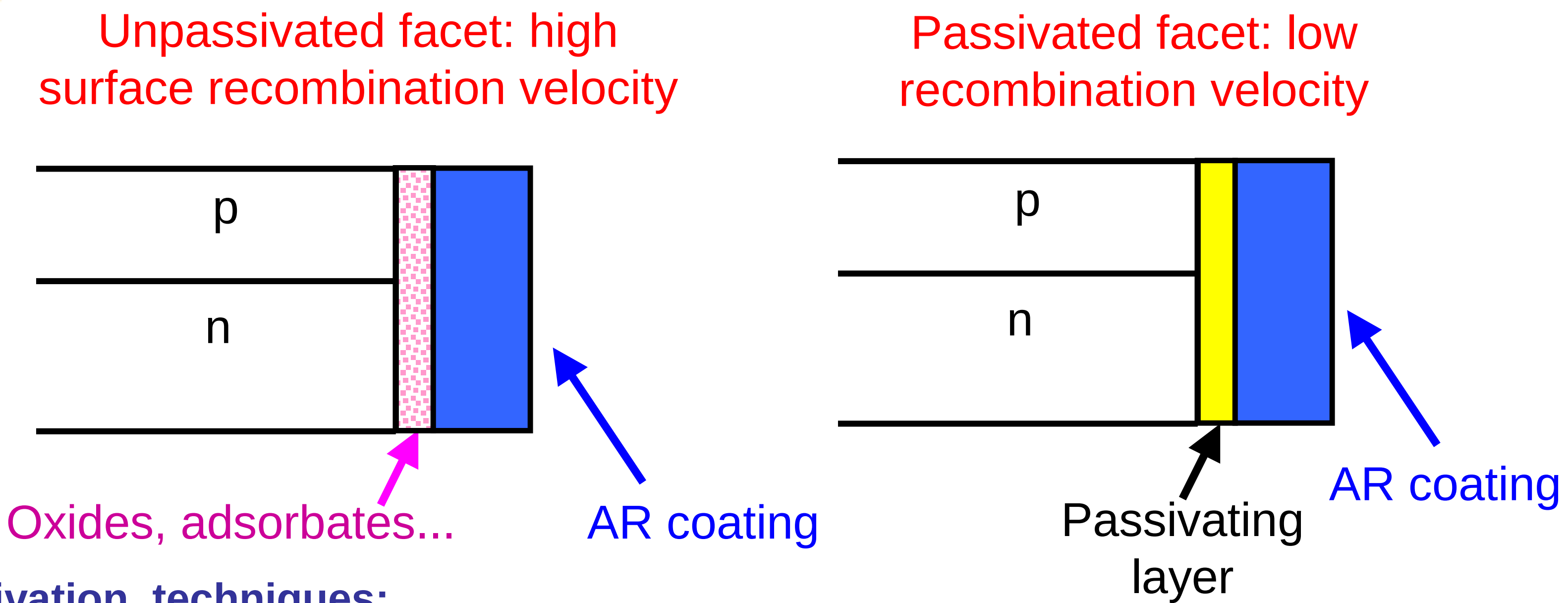
Outline (II)

4. Techniques to decrease facet heating and COMD

- ✓ Non-Injecting-Mirrors (NIMs), or current blocking layers
- ✓ Quantum Dot lasers
- ✓ Facet passivation
- ✓ Non-Absorbing-Mirrors (NAMs)
- ✓ Low optical confinement structures

4.1 Facet Passivation

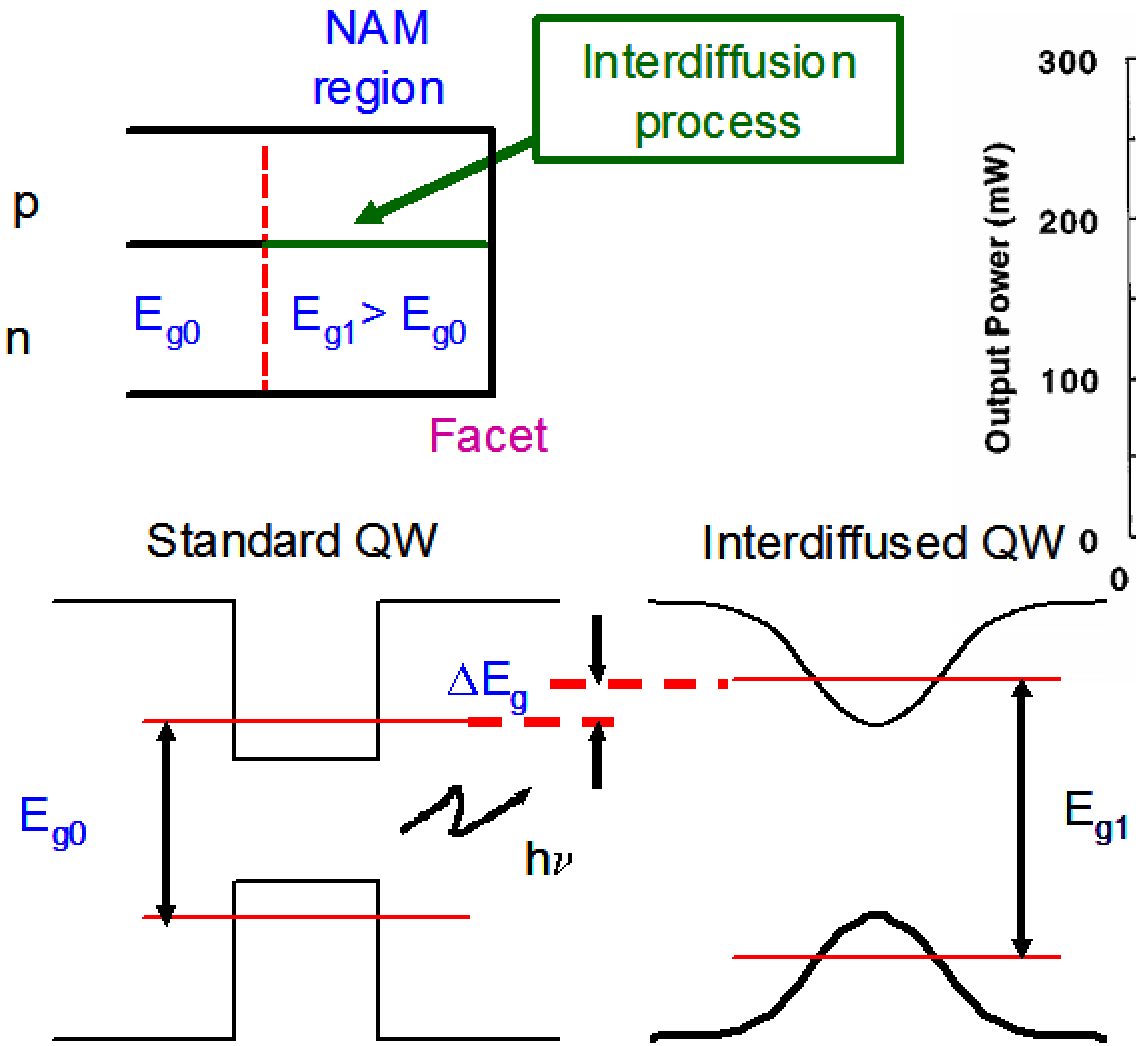


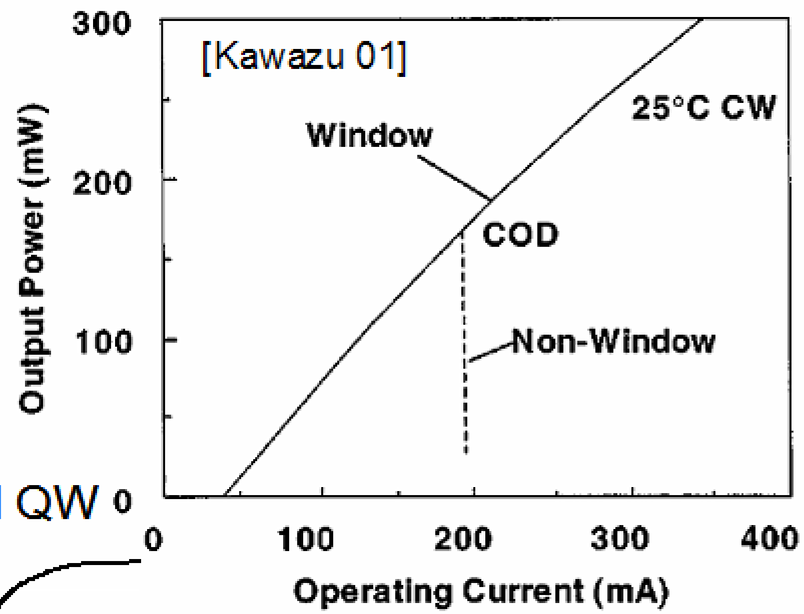
Passivation techniques:

- ✓ **E2 process [Gasser 92]: UHV cleaving + in situ a-Si (or Ge, Sb) deposition**
- ✓ **Sulphation, $(NH_4)S_x$ treatment + coating**
- ✓ **Hydrogenation or Nitridation + coating**
- ✓ **Deposition of ZnSe, Si_3N_4, Ga_2O_3 or ...**

Technological receipt: patent or industrial secret !!!

4.2 Non-Absorbing-Mirrors (I)

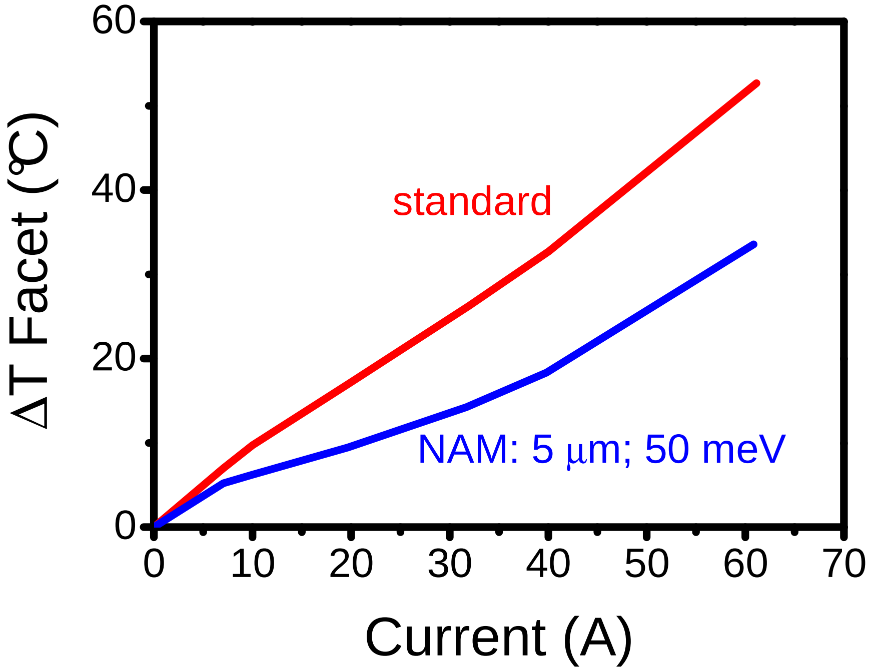


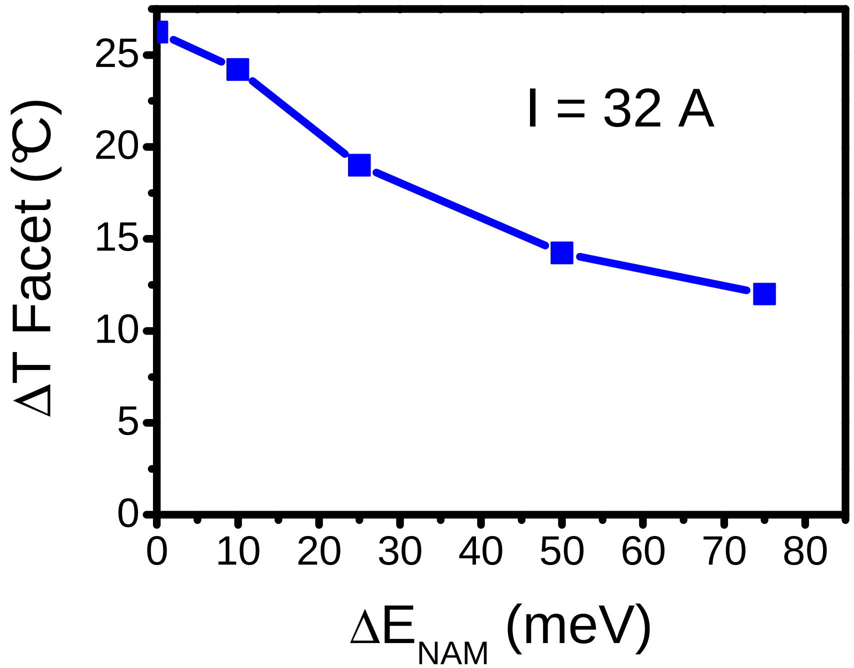


780 nm AlGaAs laser

Laser photons are not re-absorbed at the facets

Non-Absorbing-Mirrors (II)

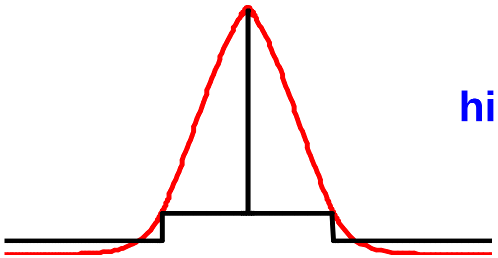




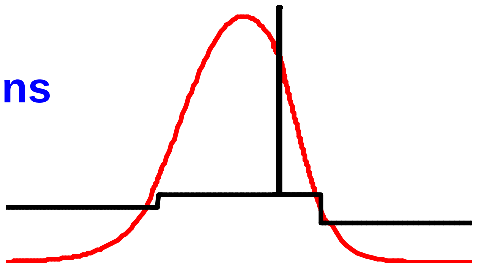
Facet heat source: surface recombination

[Batko 98] **808 nm AlGaAs laser bar**

4.3 Low optical confinement waveguides



high d/Γ designs



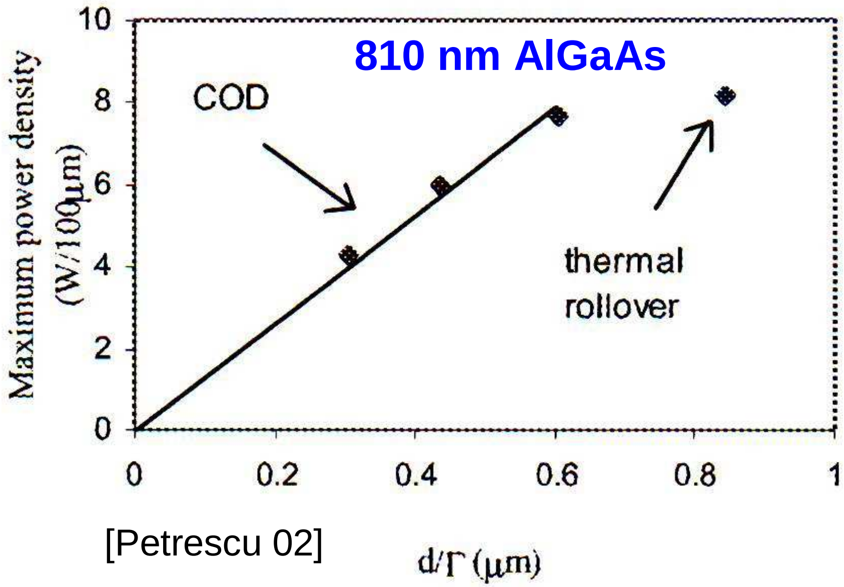
Large Optical Cavity

Asymmetric Structures

$$P_{\max,\,cw} = \frac{d}{\Gamma} W \frac{(1-R)}{(1+R)} \overline{P}_{COMD}$$

[Botez 99]

$\overline{P}_{COMD} =$ Internal power density at COMD (W/cm^2)



[Petrescu 02]

5. Conclusions (I)

- ✓ Front facet heating represents an important issue for COMD and long term reliability
- ✓ Mechanisms:
  1. Surface recombination appears as an additional heat source at facets.
  2. Surface recombination is the **starting point** of facet heating.
  3. Above threshold, re-absorption of laser light increases surface recombination rate and facet temperature.
  4. Further mechanisms, e.g. absorption at interfacial layers, surface currents...
- ✓ There are techniques allowing the monitoring of:
  - Facet temperatures (µRaman, Thermoreflectance)
  - Evolution towards COMD

5. Conclusions (II)

- ✓ COMD scenario: thermal runaway model
- ✓ Modeling tools can help to understand the underlying physics
- ✓ Modeling tools, validated by experimental results, can provide guidelines to improve devices
- ✓ There are options to make devices more robust against COMD:
  - Current blocking layers (NIMs)
  - QD-gain media
  - Surface passivation
  - Non-Absorbing Mirrors (window)
  - Low optical confinement designs

✓ There is still a lot to learn about facet heating and COMD !!!!

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