The University of Nottingham

# By emitter degradation analysis of high-power diode laser bars

Eric Larkins and Jens W. Tomm

## Outline Part I

# By emitter degradation analysis of high-power diode laser bars

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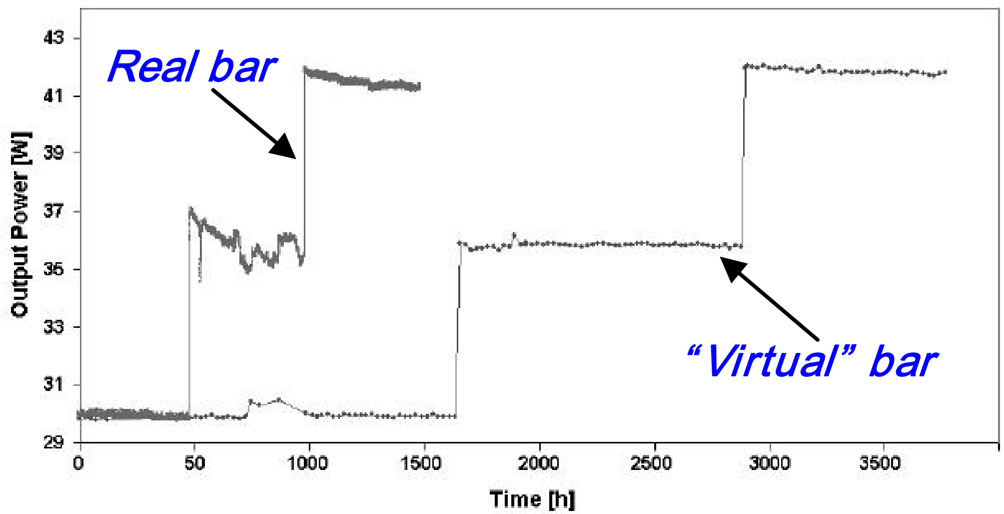
## Outline Part 2



WWW • BRIGHTER • EU

# 1. Introduction

- Compared to single emitter laser chips, it is well known that multi-emitter laser bars degrade faster
  - *Use aging data from real single emitters*
  - *Model a "virtual" bar consisting of 25 of these identical single emitters*
  - *Compare to real aging data of a laser bar of the same batch*




| Device | Time To Failure |
|---|---|
| Single Emitter | ~39,000 hours |
| "Virtual" Bar | ~27,000 hours |
| Real Bar | ~7,900 hours |

*Factor of 3.4 difference*

*Virtual bar model and data courtesy of M. Oudart, Alcatel-Thales III-V Lab*

"Quantum-Well Laser Array Packaging" eds. J.W. Tomm & J. Jimenez, pp. 235-239 (2007)

# 1. Introduction

- The "virtual" bar model neglects packaging-induced strain, current competition and temperature gradients
  - *The "virtual" bar has a lifetime more than 3 times that of the real bar*

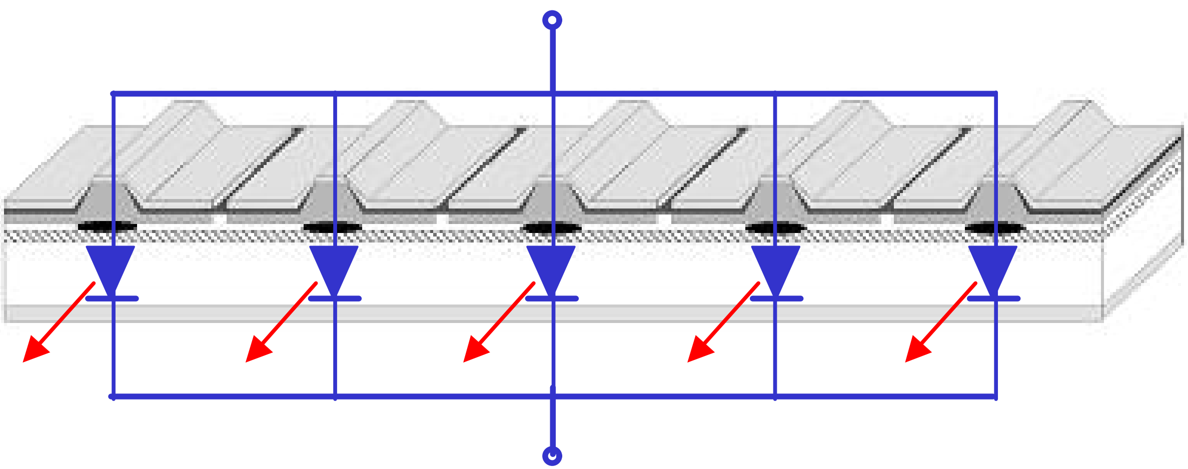
- The more rapid degradation of laser bars as compared to single emitters appears to be related to a combination of:
  - *Increased and inhomogeneous packaging-induced strain*
  - *Current competition between emitters*
  - *Larger and inhomogeneous thermal stress during operation*
  - *Less effective heat-spreading and thermal crosstalk*

- Often little is known about the operating conditions and degradation behaviour of the individual emitters
  - *This can be studied using "By-emitter analysis"*

# 1. Introduction

## What is by-emitter analysis?

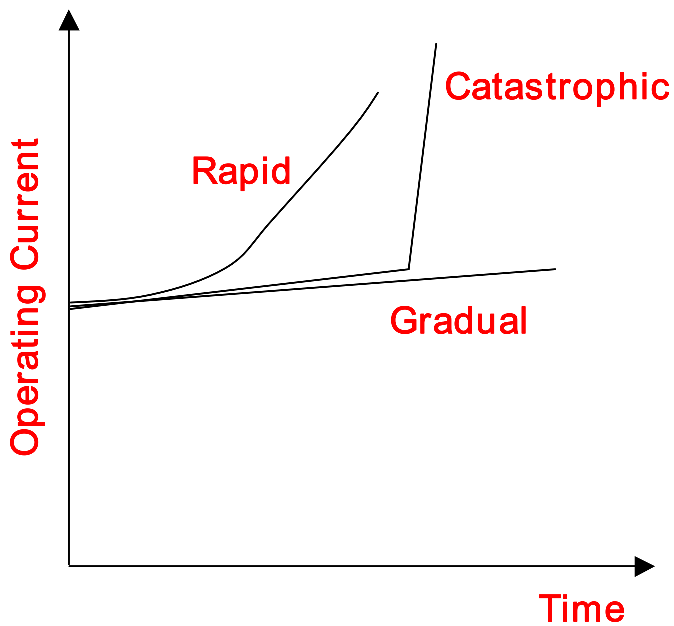
*"By-emitter analysis is a methodology for studying the behaviour and degradation of individual emitters, which are operating in the context of a parallel connected array sharing the same physical substrate and heatsink"*



# 2. Experimental Techniques

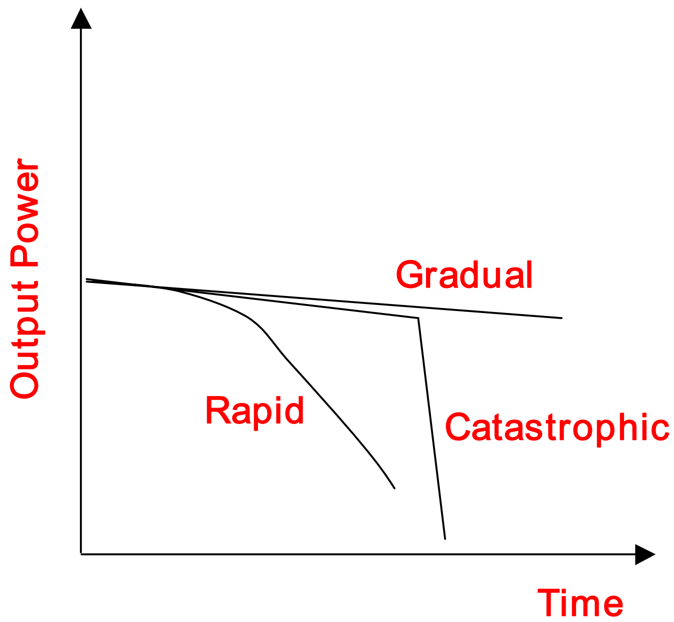
## Conventional Aging Experiments (1)

### 1. Constant Power Mode




*Failure commonly defined as 20% rise in operating current*

### 2. Constant Current Mode

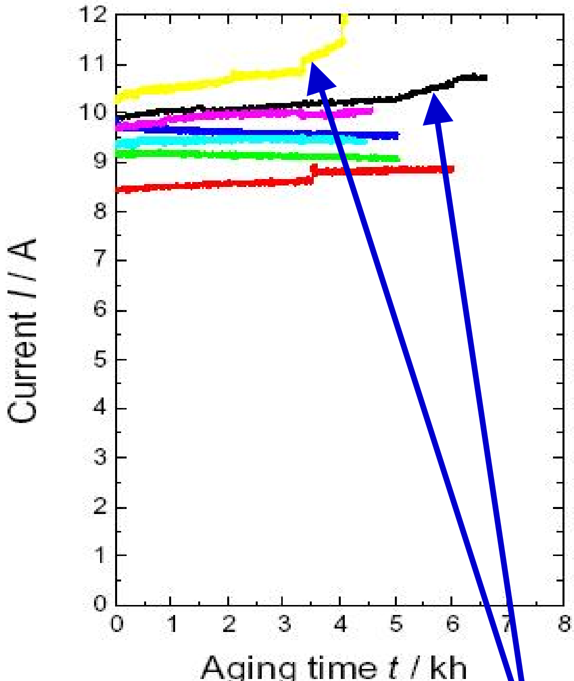



*Failure commonly defined as 20% drop in output power*

# 2. Experimental Techniques

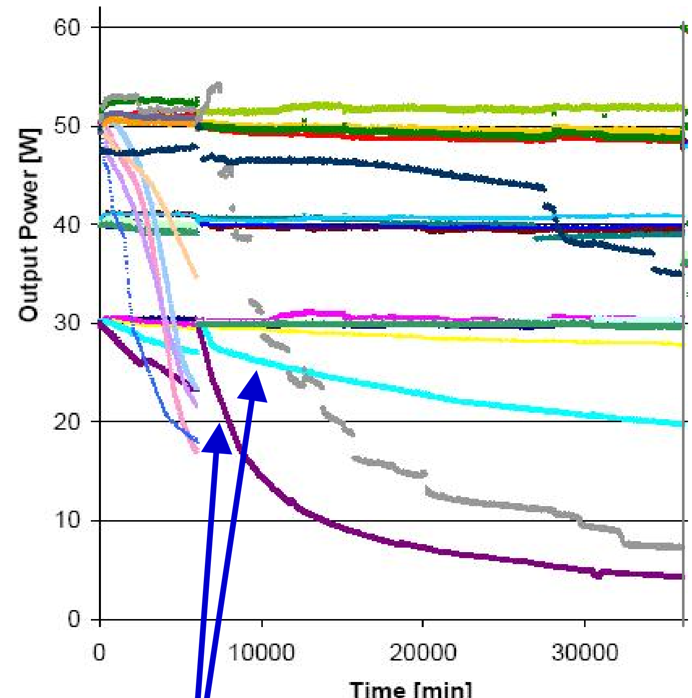
## Conventional Aging Experiments (2)

### 1. Constant Power Mode




*Increases in current signify degradation*

### 2. Constant Current Mode

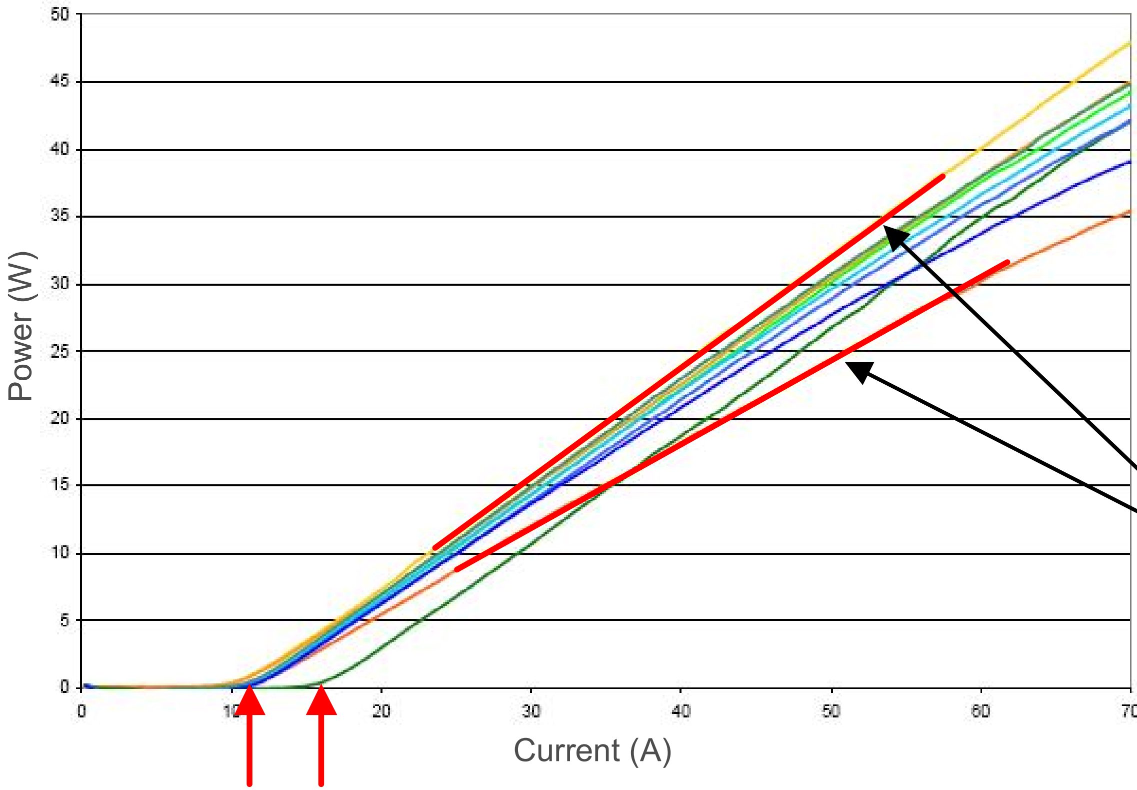



*Decreases in power signify degradation*

# 2. Experimental Techniques

## Conventional Aging Experiments (3)

<u>**P-I Characterisation**</u> *(typically performed before and after each aging test)*




***Important figures of merit for the <u>full bar</u> can be determined:***

***1) Threshold current***

***2) Slope efficiency***

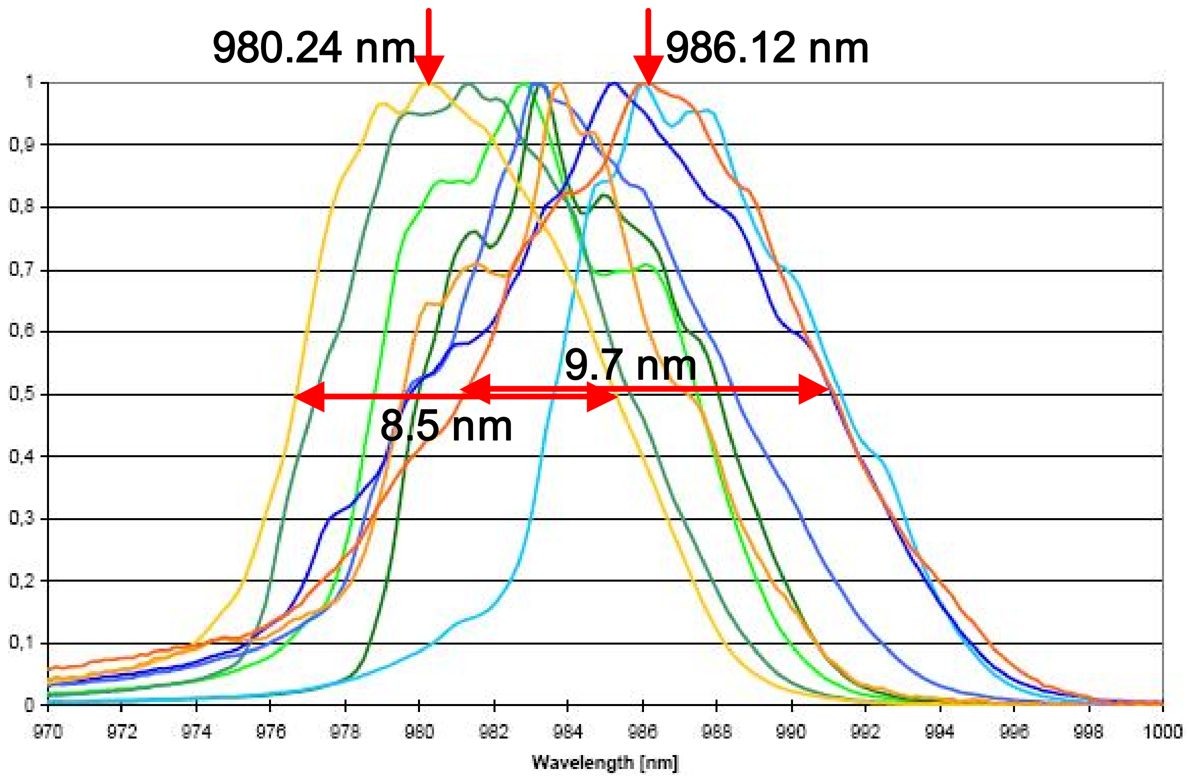
***Varying efficiencies for different bars*** ***(0.62W/A & 0.78 W/A in examples shown)***

***Threshold currents for different bars*** ***(11A & 16A in examples shown)***

# 2. Experimental Techniques

## Conventional Aging Experiments (4)

**Spectral Characterisation** *(typically performed before and after each aging test)*




*Important figures of merit for the full bar can be determined:*

*1) Peak wavelength*

*2) Spectral width*

*Clear differences in peak wavelengths and spectral widths can be seen for different bars*

# 2. Experimental Techniques

## Quantities Measureable at the By-Emitter Level

– Many quantities relating to an individual emitter within a laser bar can be measured *in-situ*

- ***Power***
- ***Emission spectrum***
- ***Near-field pattern***
- ***Bandgap***
- ***Defect level***

– However, it is NOT possible to determine the current of each individual emitter (parallel connected array)

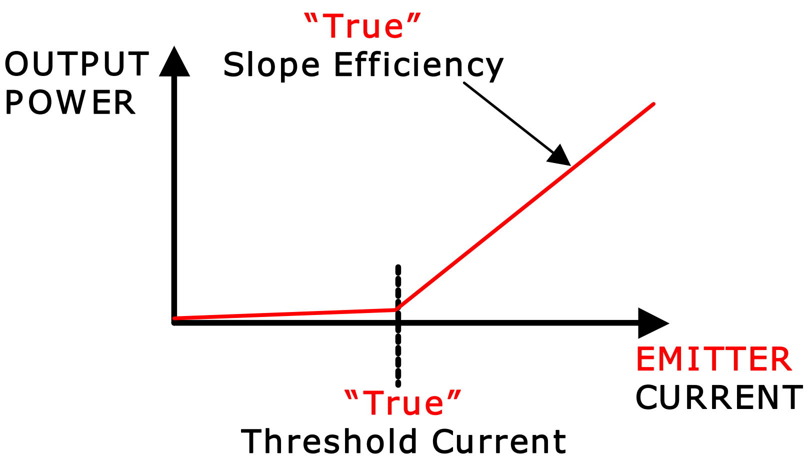
– The *true* threshold currents and slope efficiencies of individual emitters can therefore NOT be determined

# 2. Experimental Techniques

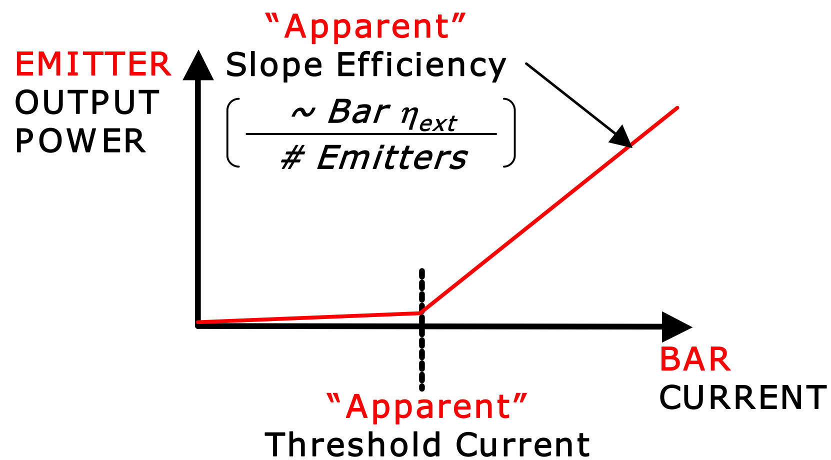
## *"Apparent"* Threshold Current & *"Apparent"* Efficiency

– However, to compare the performance of individual emitters two "apparent" quantities can be defined

- ***"Apparent" threshold current***
- ***"Apparent" slope efficiency***




Single emitter laser

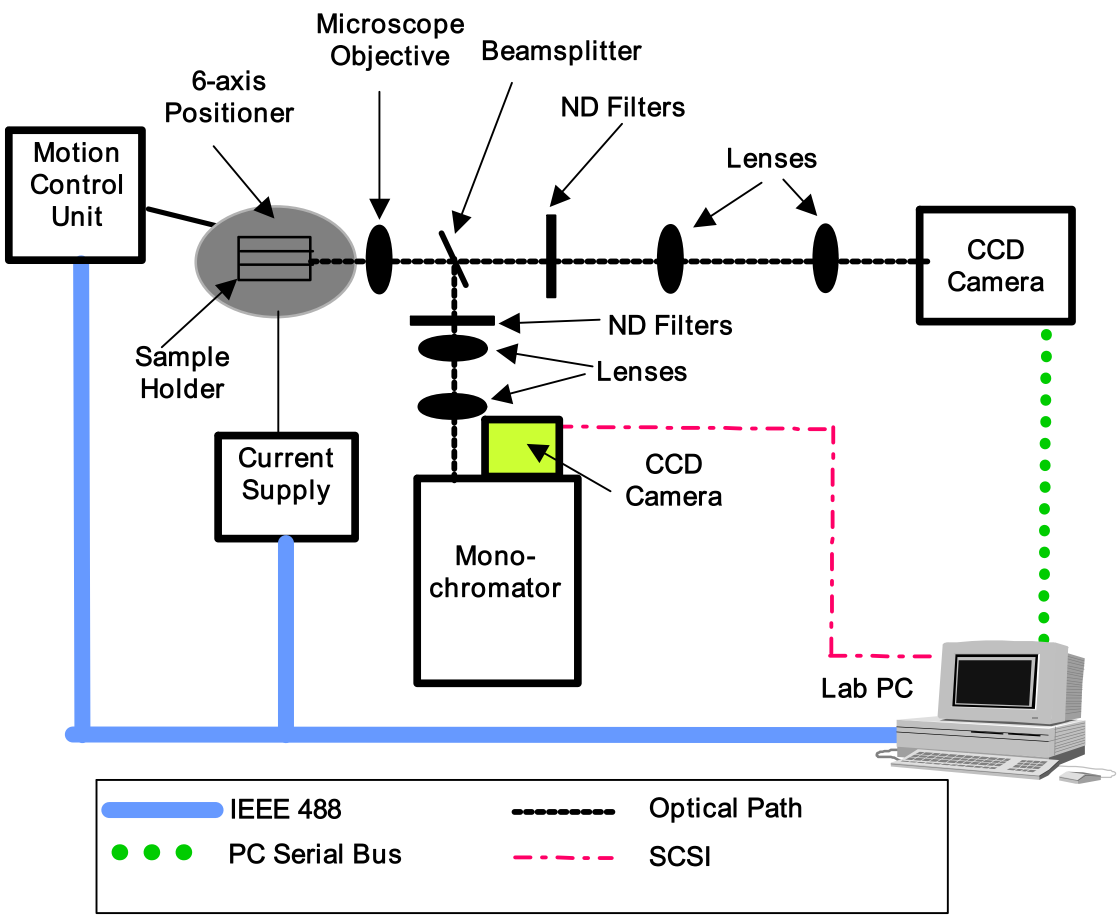



Isolated emitter in laser bar

# 2. Experimental Techniques

## Measuring Emitter Beam Parameters (1)

(Power, emission spectrum, near-field pattern)



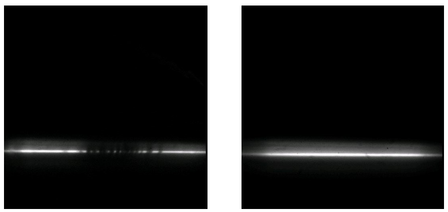

***Simultaneous measurement of individual emitter near-field images and EL spectra***

# 2. Experimental Techniques

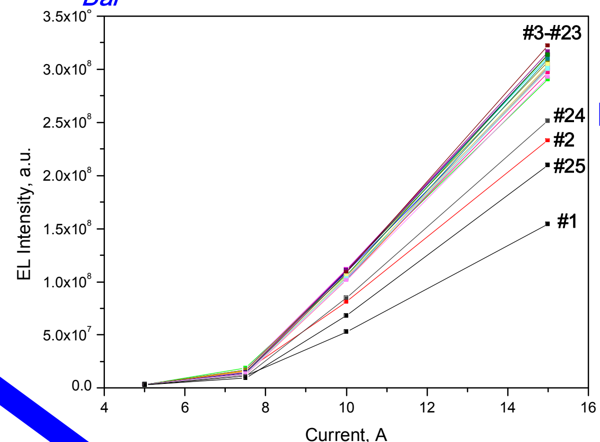
## Measuring Emitter Beam Parameters (2)

(Power, emission spectrum, near-field pattern)

***Near-field pattern images of individual emitters***



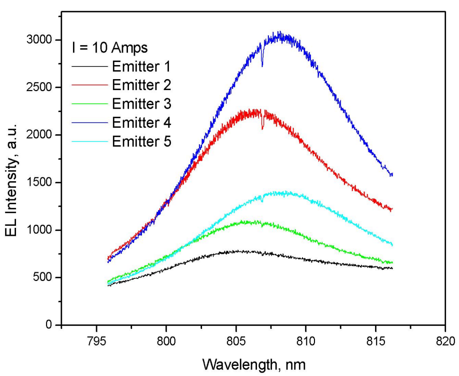
***P-I$_{Bar}$ curves for individual emitters***




Apparent threshold currents & apparent efficiencies for individual emitters

- defects
- self-heating

***EL Spectra of individual emitters***

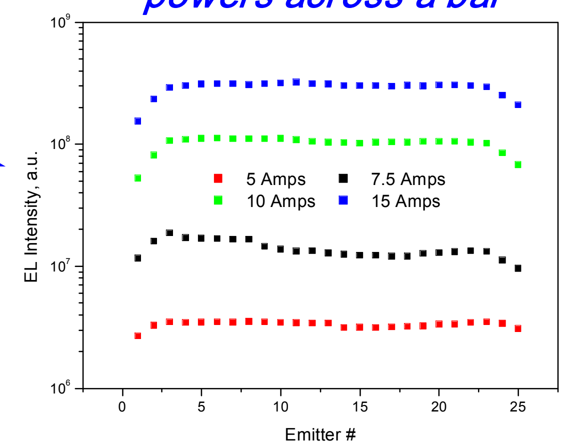



λ-shift as a function of bias current for individual emitters

*- band filling (blue shift)*

*- self-heating (red shift)*

***Relative emitter powers across a bar***

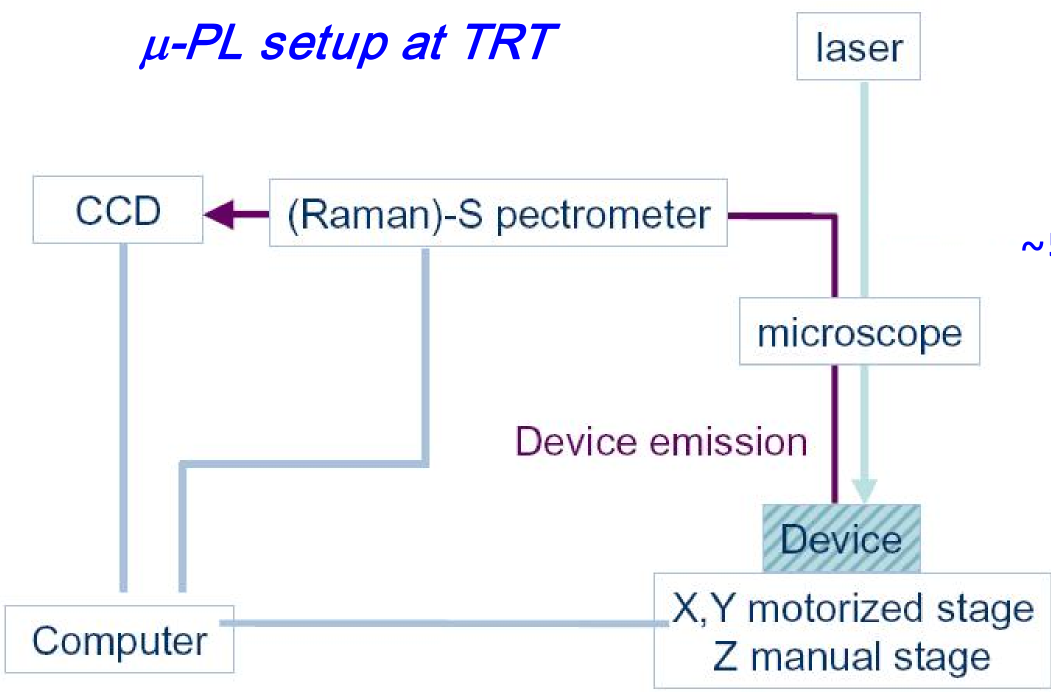


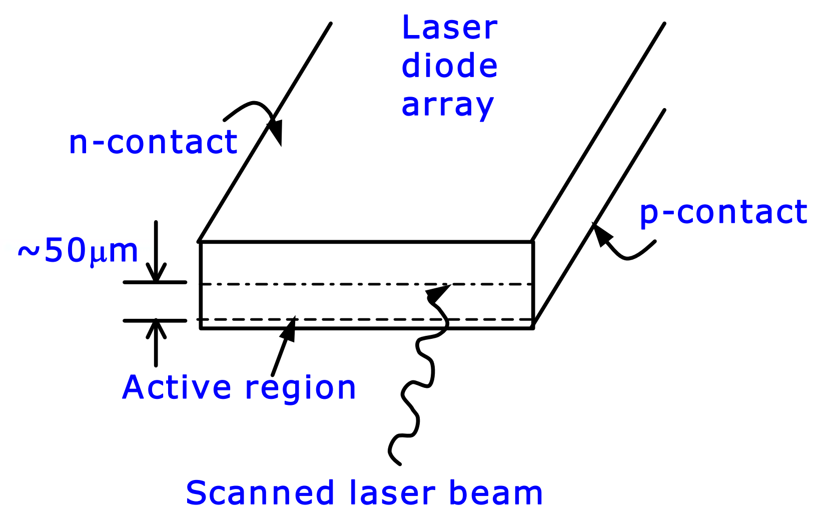
# 2. Experimental Techniques

## Measuring Packaging-Induced Strain (1)

– Micro-Photoluminescence Spectroscopy (μ-PL)

*μ-PL setup at TRT*




*Courtesy of TRT, Paris, France*

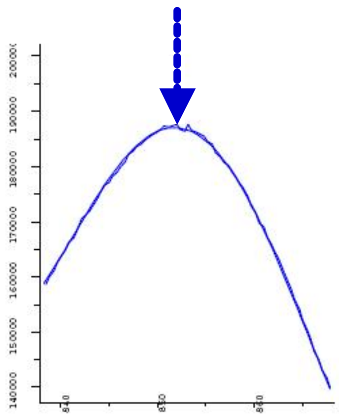
# 2. Experimental Techniques

## Measuring Packaging-Induced Strain (2)

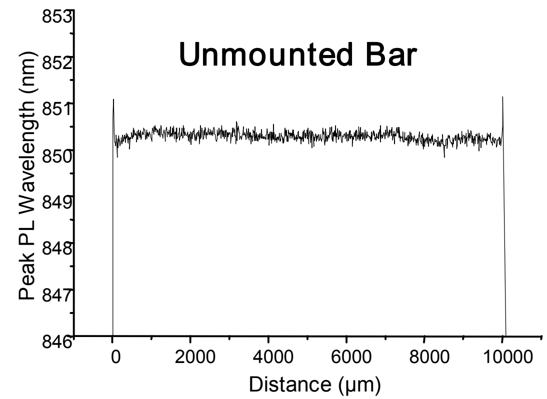
– Micro-Photoluminescence Spectroscopy (μ-PL)

PL spectrum measured at the centre of the substrate every 10μm along the bar

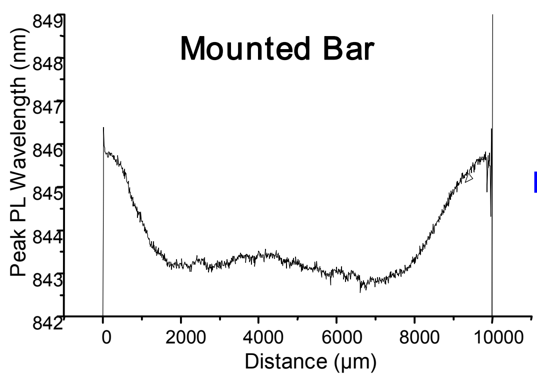
Peak PL wavelength found by fitting each spectrum



Record position of PL Peak along bar




PL shift caused by packaging-induced strain



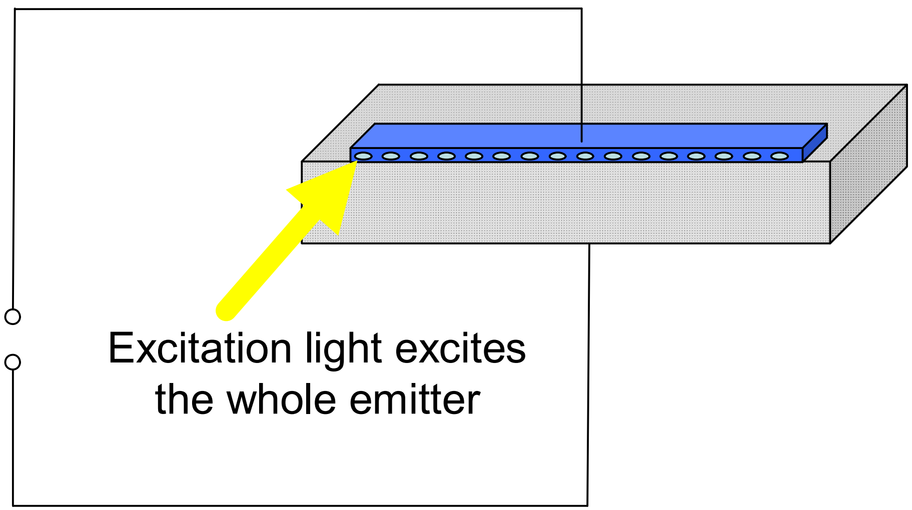

By knowing the geometry of the bar, a peak PL value (a measure of packaging-induced strain) can be assigned to each emitter

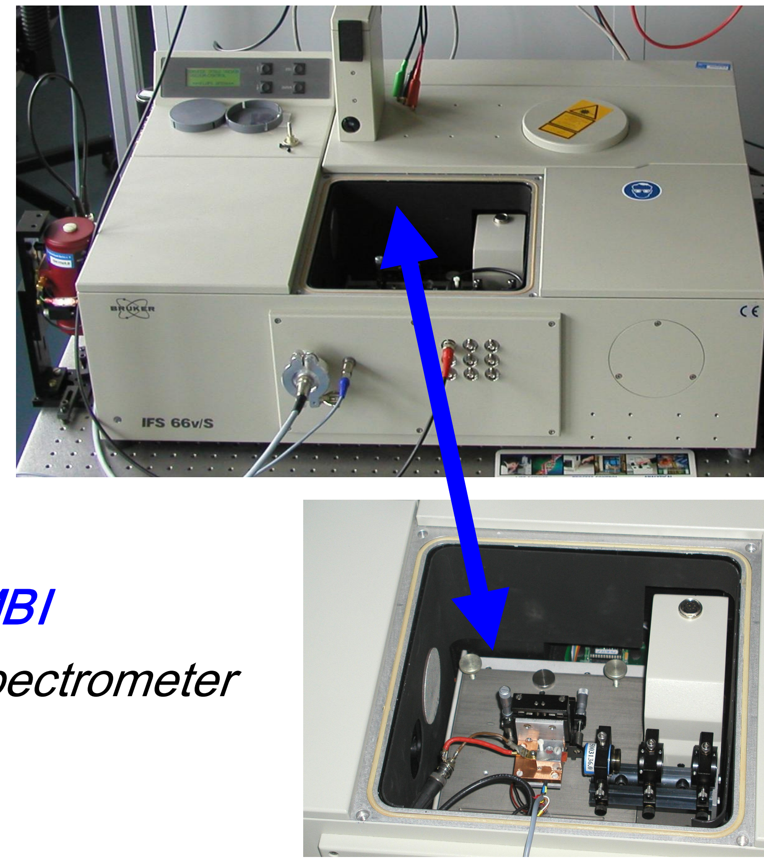
*Courtesy of TRT, Paris, France*

# 2. Experimental Techniques

## Measuring Strain and Defects (1)

– Photocurrent Spectroscopy (PCS)




***Spatially-resolved PC measurement at MBI***

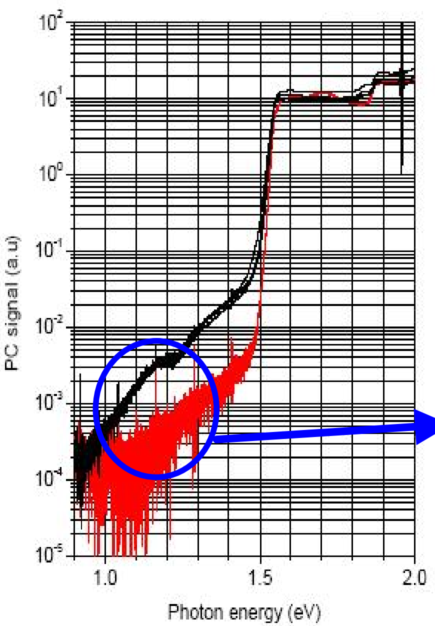
*System based upon a Fourier-Transform spectrometer*

# 2. Experimental Techniques

## Measuring Strain and Defects (2)

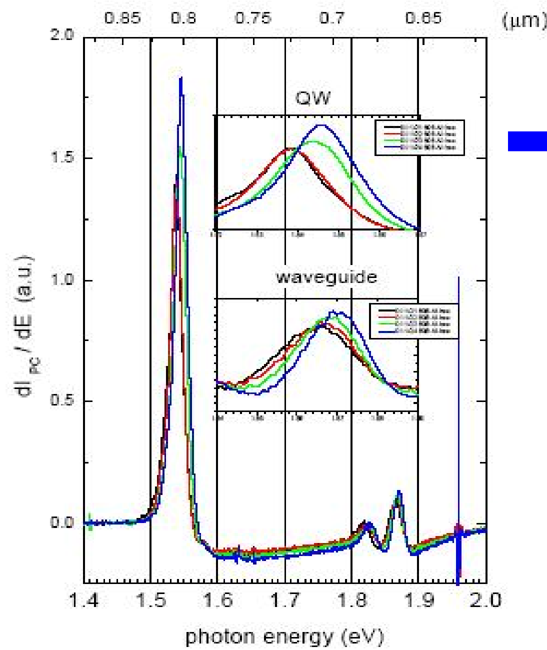
– Photocurrent Spectroscopy (PCS)

PC spectrum measured for each emitter

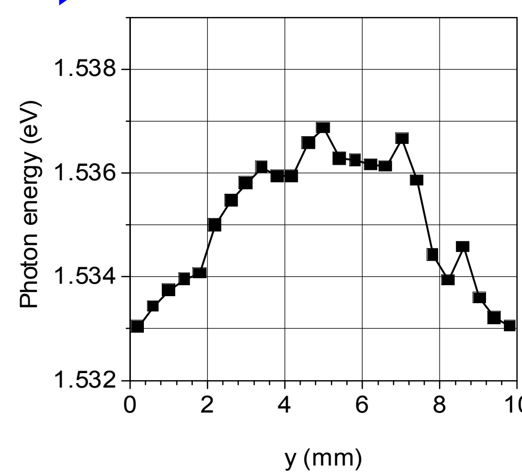



Peak magnitude of the PC defect band used as a relative measure of the defect concentration

Derivative of PC spectrum gives QW and waveguide transition energies



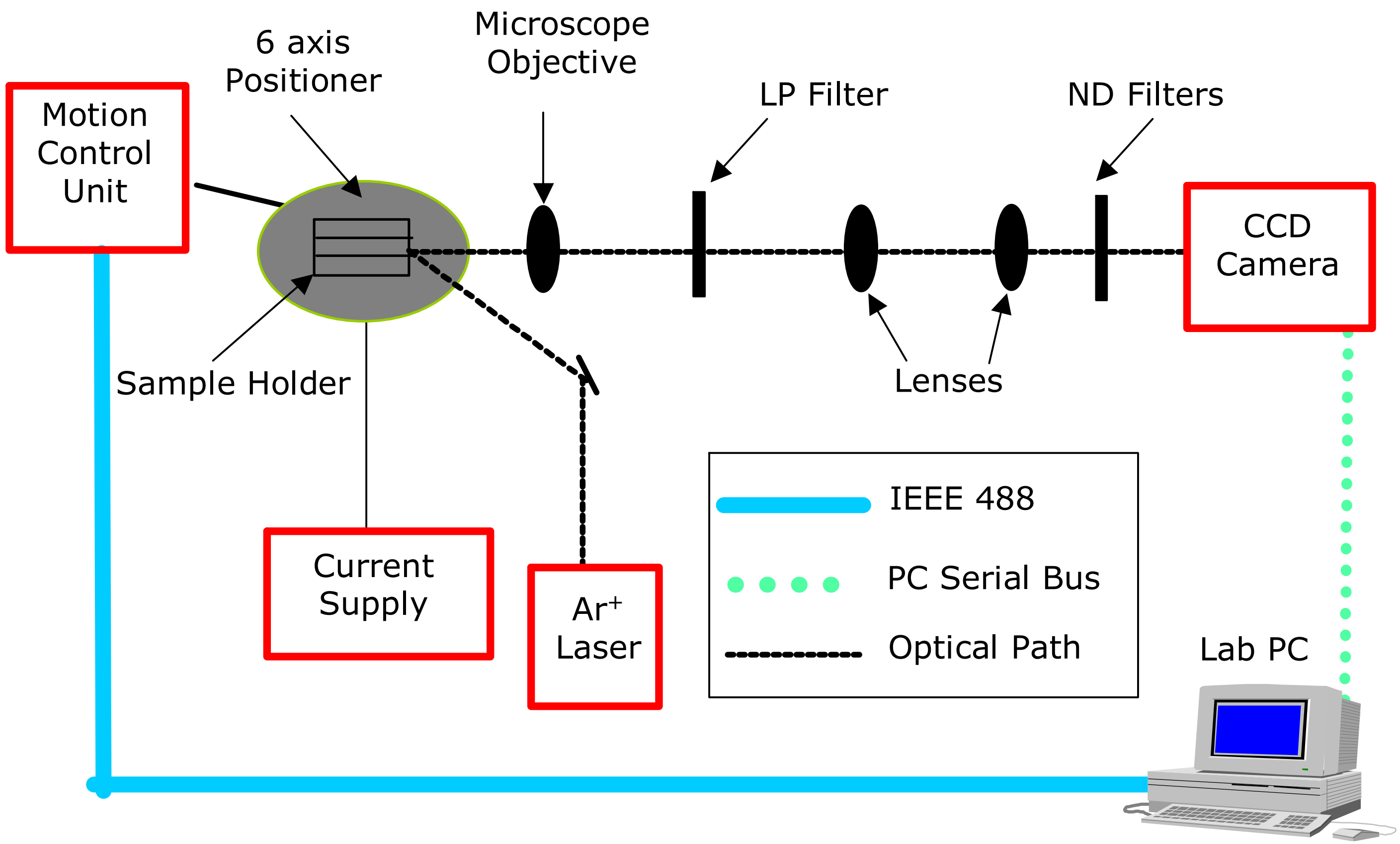

Spectral position of the QW transition plotted for each emitter across the bar



# 2. Experimental Techniques

## Defect Imaging (1)

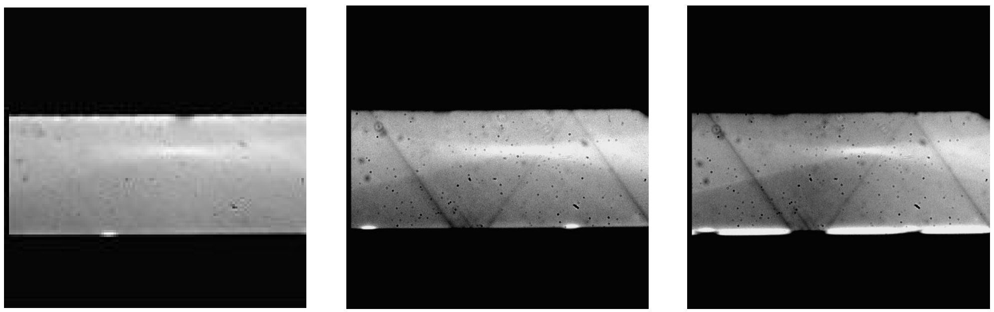
– Photo- and Electroluminescence Microscopy (PLM/ELM)



# 2. Experimental Techniques

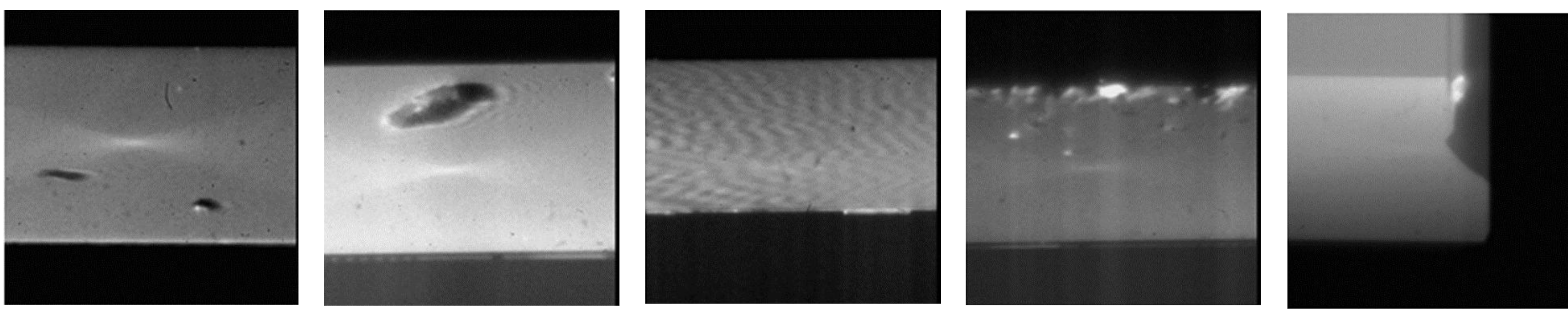
## Defect Imaging (2)

– Photo- and Electroluminescence Microscopy (PLM/ELM)



Dark line defects (DLDs) observed in PLM images

Reduced luminescence seen in ELM images where DLD intersects active region



PLM can also reveal other defects, facet contamination and damage to a bar

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# 2. Experimental Techniques

## Summary of By-Emitter Techniques (1)

| Technique: | Quantities measured: | Sensitive to: |
|---|---|---|
| Micro-Photoluminescence | $E_g$ (substrate) | Packaging-induced strain |
| Photocurrent Spectroscopy | $E_g$ (quantum well) | Packaging-induced strain |
| Laser Beam Induced Current | Sub-bandgap absorption | Defects, Shifts in absorption edge |
| Photoluminescence Microscopy | Defects | Non-radiative recombination centres |
| Electroluminescence Microscopy | Defects, Relative emitter power, $I_{th\_app}$, $\eta_{ext\_app}$ | Non-radiative recombination centres<br>Temperature, $\Delta E_g$, Scattering loss, $\eta_{int}$ |
| Near-field spectra | Defects<br>$\Delta\lambda/\Delta I$ | Non-radiative recombination centres<br>Temperature, Quasi-Fermi level sep. |

# 2. Experimental Techniques

## Summary of By-Emitter Techniques (2)

**μ-PL:** Scan of 1cm bar with spectra every 10μm takes ~ 20 minutes

**PCS:** Individual emitter spectrum takes ~ 10 minutes

*⇒ 2-3 hours required to measure full bar*

**LBIC:** Subset of PCS with 2 λ's (above & below bandgap) ~ 20 mins.

**Near-field images & EL spectra:**

*Typically measured at 10 bias currents*

*For a 20 emitter bar, total measurement time ~ 1 hour*

*However, setup time per bar is also ~ 30 minutes*

*Note: In a detailed study, measurements may be repeated 3-4 times*

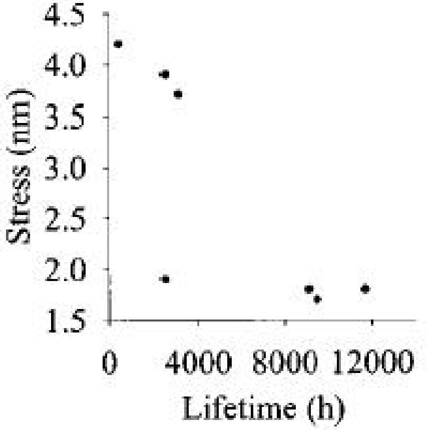
*(e.g. before burn-in, after burn-in, after 1st aging step, after 2nd aging step)*

# 3. Strain Threshold

- Defects and packaging-induced strain affect degradation & lifetime
- Larger compressive stress

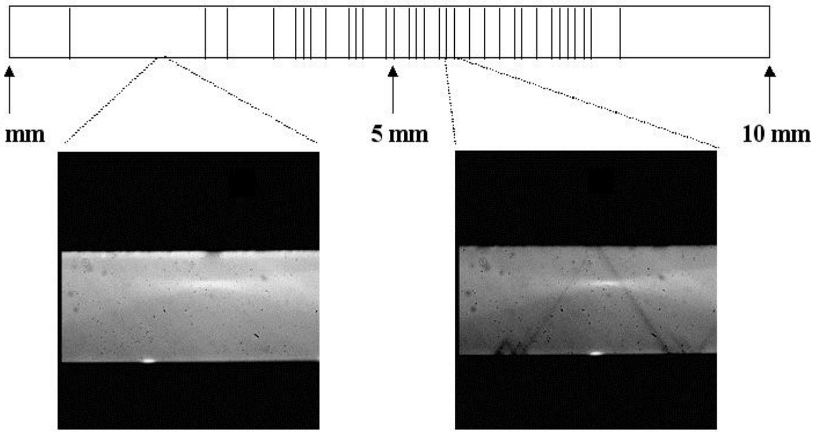
  ⇒ *Shorter device lifetime*

  Martin *et al.*, APL **75**, 2521 (1999)




- V-shaped facet defects observed in degraded laser bars
- Higher defect density in highly-compressively strained regions

  Andrianov *et al.*, JAP **87**, 3227 (2000)



# 3. Strain Threshold

## Objective:

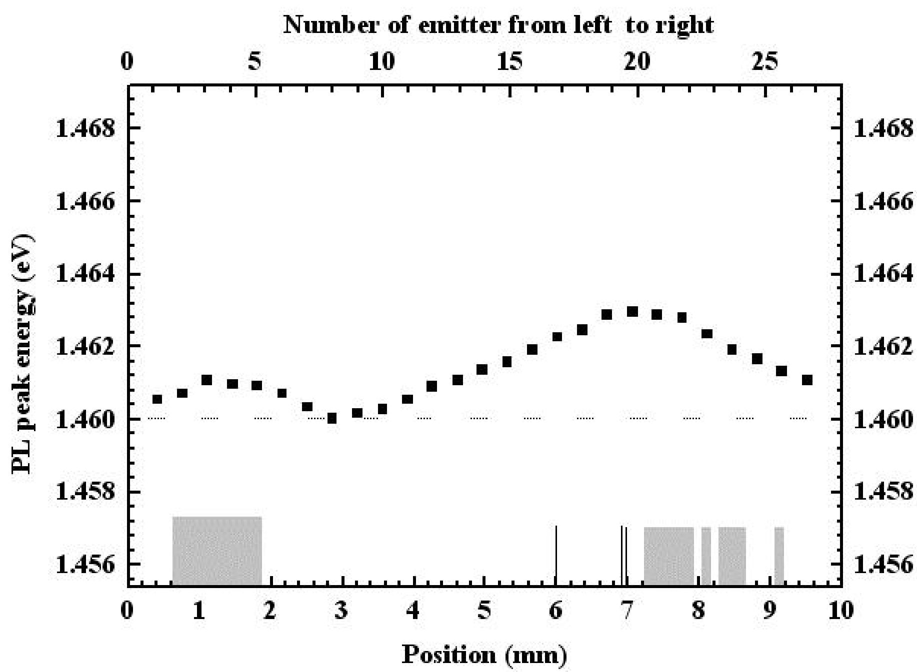
- Study correlations between local strain & individual emitter degradation
  - *Micro-Photoluminescence*
  - *Photoluminescence Microscopy*
  - *Electroluminescence Microscopy*
  - *Photocurrent Spectroscopy*

- References

  - R. Xia *et al.*, Synthetic Metals **127**, 255 (2002)
  - R. Xia *et al.*, Photon. Technol. Lett. **14**, 893 (2002)
  - R. Xia, PhD Thesis, University of Nottingham (2002)

# 3. Strain Threshold

- Local strain for each emitter determined by μ-PL
- Defects imaged by PLM and ELM




= strain free condition

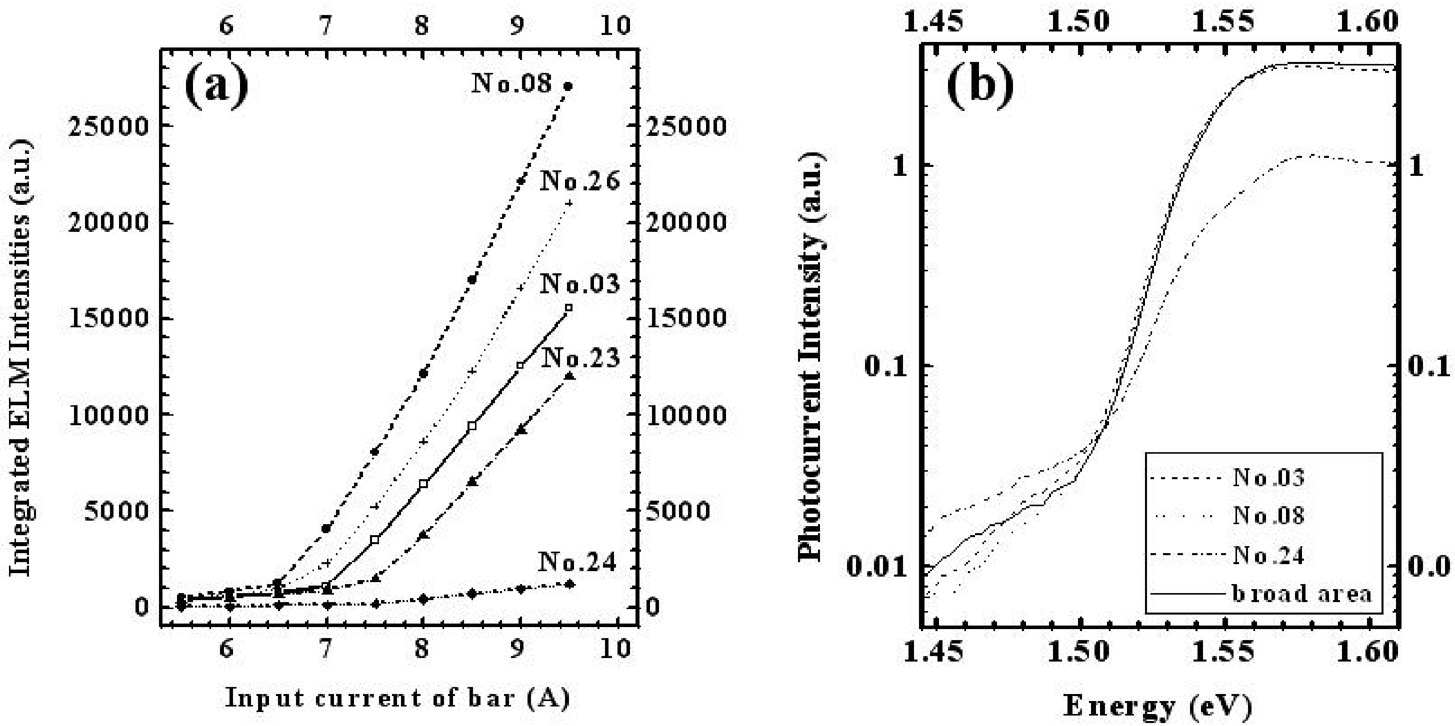
= defect observed

= region with several defects

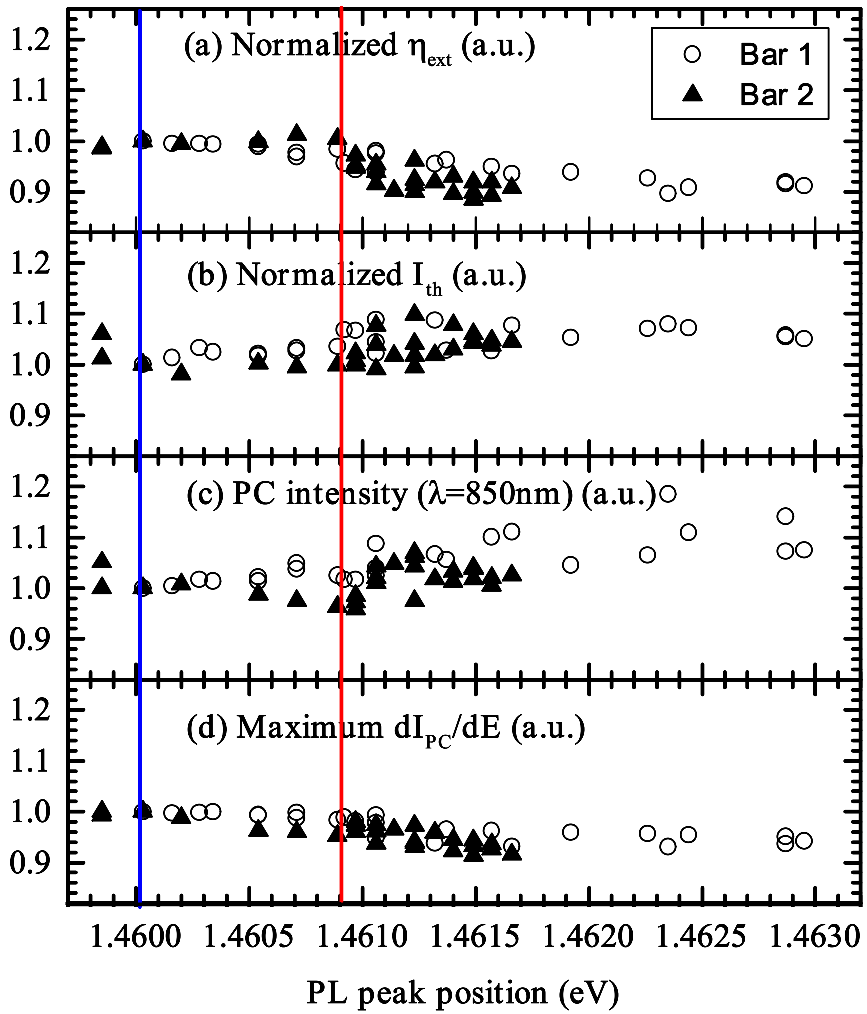
***Increased number of defects observed in emitters with a higher level of packaging-induced strain***

# 3. Strain Threshold

- ELM measurements reveal varying thresholds and efficiencies
- PC measurements reveal different levels of sub-bandgap absorption



# 3. Strain Threshold




Packaging-induced strain shifts the GaAs μ-PL peak by ~16 MPa/nm*

Blue line represents strain free level

Emitters with stress > 8.4 MPa (red line) show:

a) a reduced (apparent) $\eta_{ext}$
b) a larger (apparent) $I_{th}$
c) a larger sub-bandgap photocurrent
d) a reduced absorption edge slope

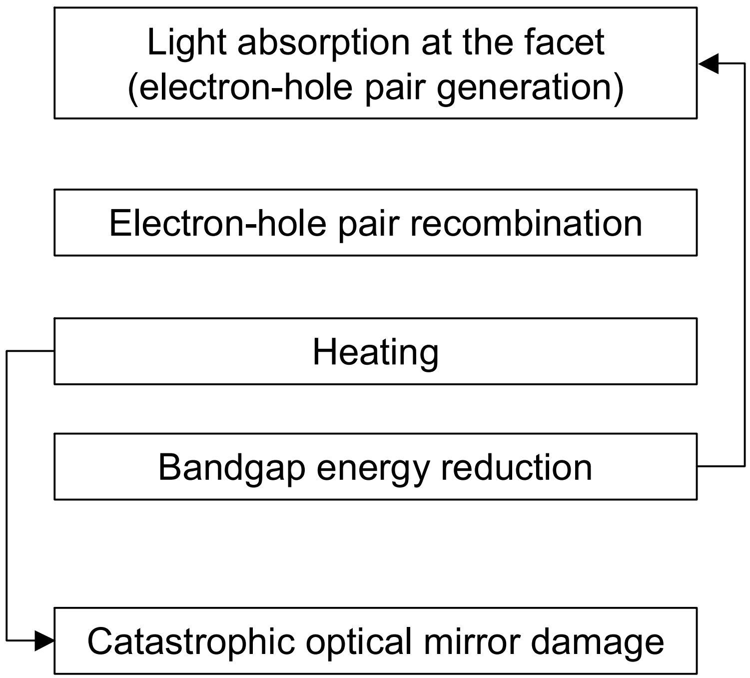
➢ ***Strain threshold for degradation!***

* M. L. Biermann, *et al.*, J. Appl. Phys. **96**, 4056-65 (2004)

# 4. Thermal Runaway

*"Thermal runaway refers to a situation where an increase in the temperature changes the operating conditions in a way that causes a further increase in the temperature leading to a destructive result"*

*Models for thermal runaway leading to COD*




*The situation is more complex in laser arrays!*

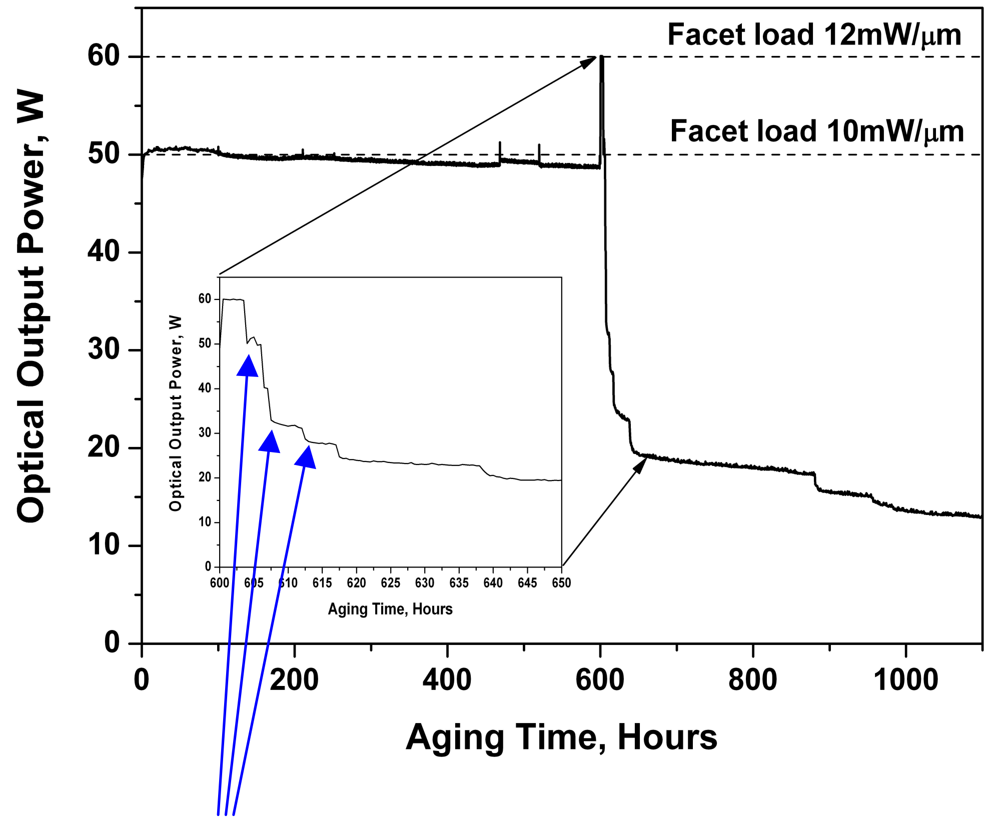
*Interaction between emitters must be considered:*

- current competition
- thermal cross-talk
- mechanical strain

Henry *et al.*, JAP 50, 3721 (1979)

# 4. Thermal Runaway

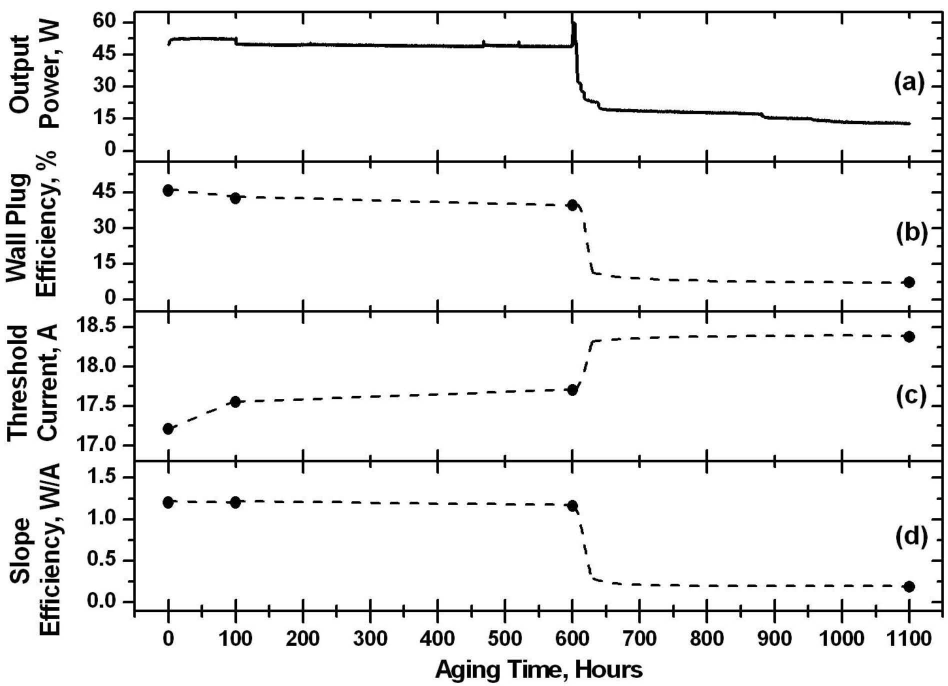
- Aging Step 1
  - 600 hours
  - I = 60A
  - Facet load = 10mW/μm
  - 1.4% drop in output power
- By-emitter measurements then performed
- Aging Step 2
  - I = 75A
  - Facet load = 12mW/μm
  - Catastrophic degradation observed in <10 hours




*Sudden drops in the output power each represent failure or one or more emitters*

# 4. Thermal Runaway

- As the bar degrades over time, the following are also observed:
  - *Decrease in wall plug efficiency*
  - *Increase in threshold current*
  - *Decrease in slope efficiency*

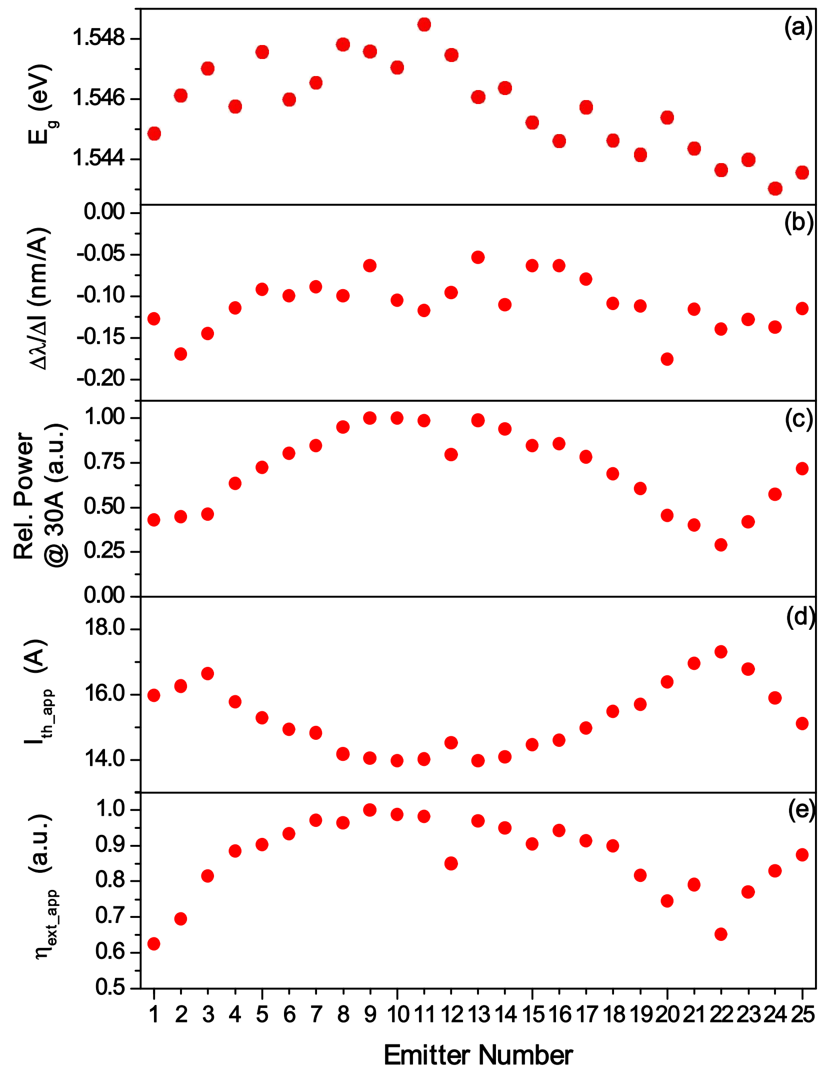



***Remember:***

***These measurements are of the bar as a single entity***

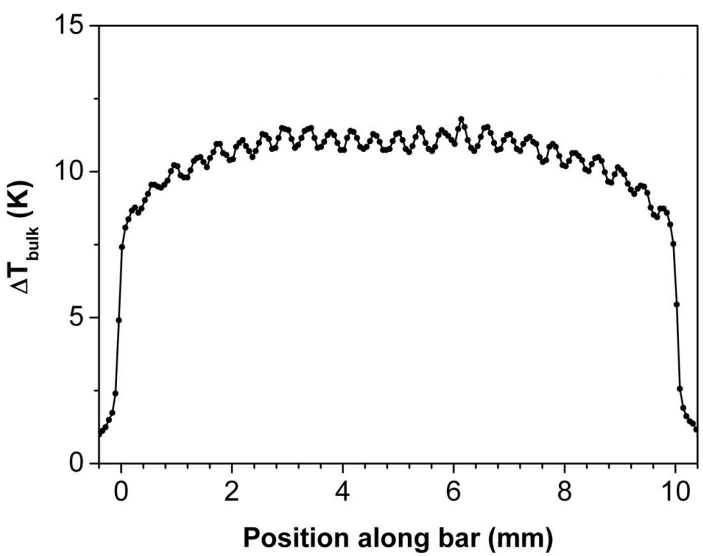
# 4. Thermal Runaway

- Lower bandgap for edge emitters
  - *Causes small variations in emitter turn-on voltages*
  - *Also causes more significant variations in emitter operating currents*
- λ-shift determined below threshold
  - *Larger negative λ-shift in edge emitters as current increases*
  - *Suggests current is increasing faster in the edge emitters*
- Edge emitters have less power (up to 60%) than those in centre
  - *Consistent with higher $I_{th\_app}$ and lower $\eta_{app}$ observed in the edge emitters*
  - *Again supports the idea that the edge emitters are hotter*



# 4. Thermal Runaway

- By-emitter results suggest that the current is increasing faster in the edge emitters and these edge emitters are hotter
  - ➢ *However, can a temperature distribution with a minimum at the bar centre and hotter at the edges really be correct?*
- Bulk & facet temperature measurements made on new & aged devices

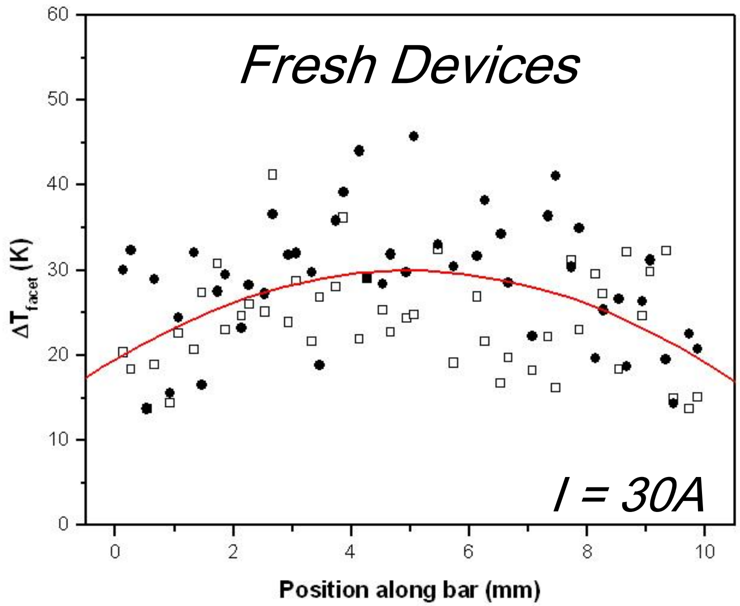


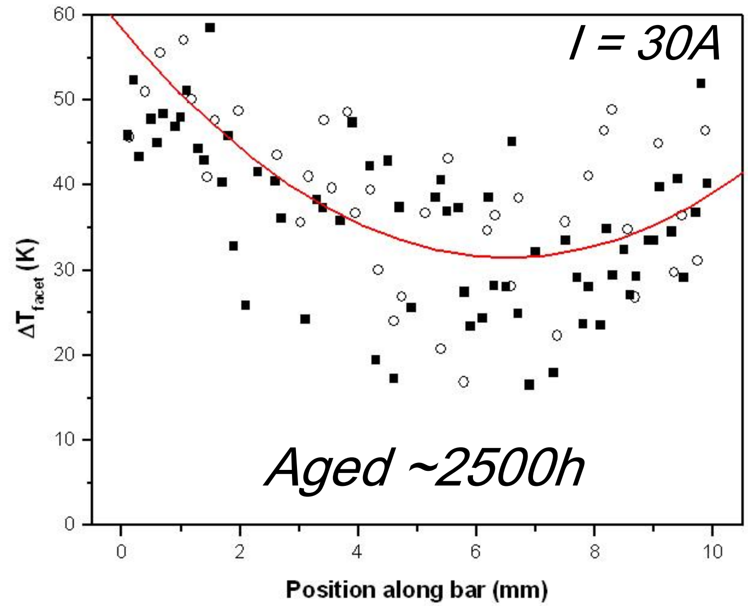

*Typical bulk temperature profile of a high-power laser bar*

*Similar profiles are observed for <u>both new and aged devices</u>*

# 4. Thermal Runaway

- Raman facet temperature measurements reveal an interesting trend




- A temperature distribution that is hottest in the centre is only true of the bulk temperature and the facet temperature of <u>new</u> devices
  - ➢ ***Facet temperature distributions can be inverted in <u>aged</u> devices***

# 4. Thermal Runaway

- Possible causes of higher facet temperatures
  - *More defects in edge emitters*
  - *Larger currents in edge emitters*
  - *Higher surface currents at the bar edges*

$\Rightarrow$ *More non-radiative recombination*

$\Rightarrow$ *Increased emitter currents & temperatures*

$\Rightarrow$ *Positive feedback for defect generation/propagation*

$\Rightarrow$ *Thermal runaway of the emitter current*

$\Rightarrow$ *Onset of even more rapid degradation*

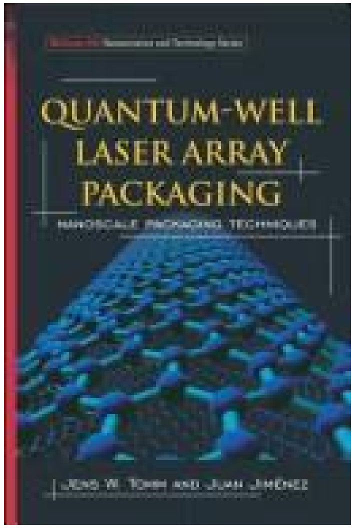
- References:


  - S. Bull *et al.*, J. Mat. Sci: Mat. Electron. (2008), DOI:10.1007/s10854-008-9577-5
  - S. Bull *et al.*, J. Appl. Phys. **98**, 063101 (2005)
  - S. Bull, PhD Thesis, University of Nottingham (2004)

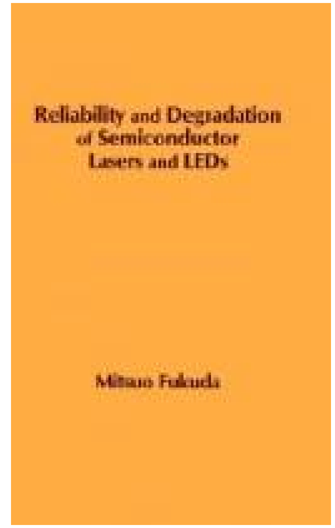
# 5. Summary

- The by-emitter method uses a wide range of complementary techniques
- **Two successful examples presented:**
  - *Observation of a strain threshold for increased degradation*
  - *Observation of the thermal runaway mechanism*
- Results demonstrated that a better understanding of bar degradation mechanisms can be gained by analysing individual emitters
- **And, in Part 2:**
  - *Strain measurement & detection of defects will be considered in more detail*
  - *Examples of not only defects caused by packaging-induced strain, but also of strain caused by defects*

# Suggested follow-up reading:




Jens W. Tomm and
Juan Jiménez, eds.,
**Quantum-Well Laser Array Packaging,**
McGraw-Hill, 2006
(ISBN 0071460322)




M. Fukuda,
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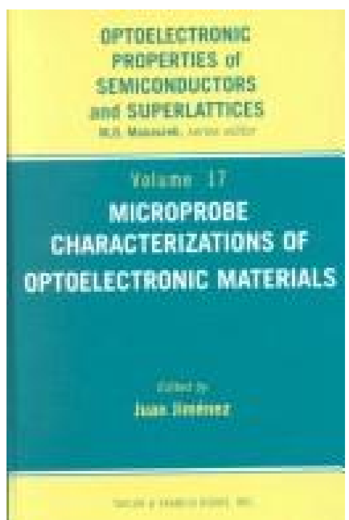


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