Reliability and Failure Analysis of Optoelectronic Devices

Matteo Meneghini[a], Massimo Vanzi[b], Gaudenzio Meneghesso[a] and Enrico Zanoni[a]

[a]University of Padova, Department of Information Engineering, via Gradenigo 6/B, 35131 Padova, Italy
E-mail: matteo.meneghini@dei.unipd.it
[b]University of Cagliari, Italy

Outline

- Operating principles and structure of LEDs and laser diodes
- Degradation of optoelectronic devices
  - Degradation of the heterostructure of LEDs and laser diodes by means of electro-optical techniques
  - Analysis of the degradation of the properties of ohmic contacts of optoelectronic devices
  - Degradation processes related to Dark Line Defects
  - Degradation of the facets of laser diodes
- Conclusions

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Recombination processes in semiconductors

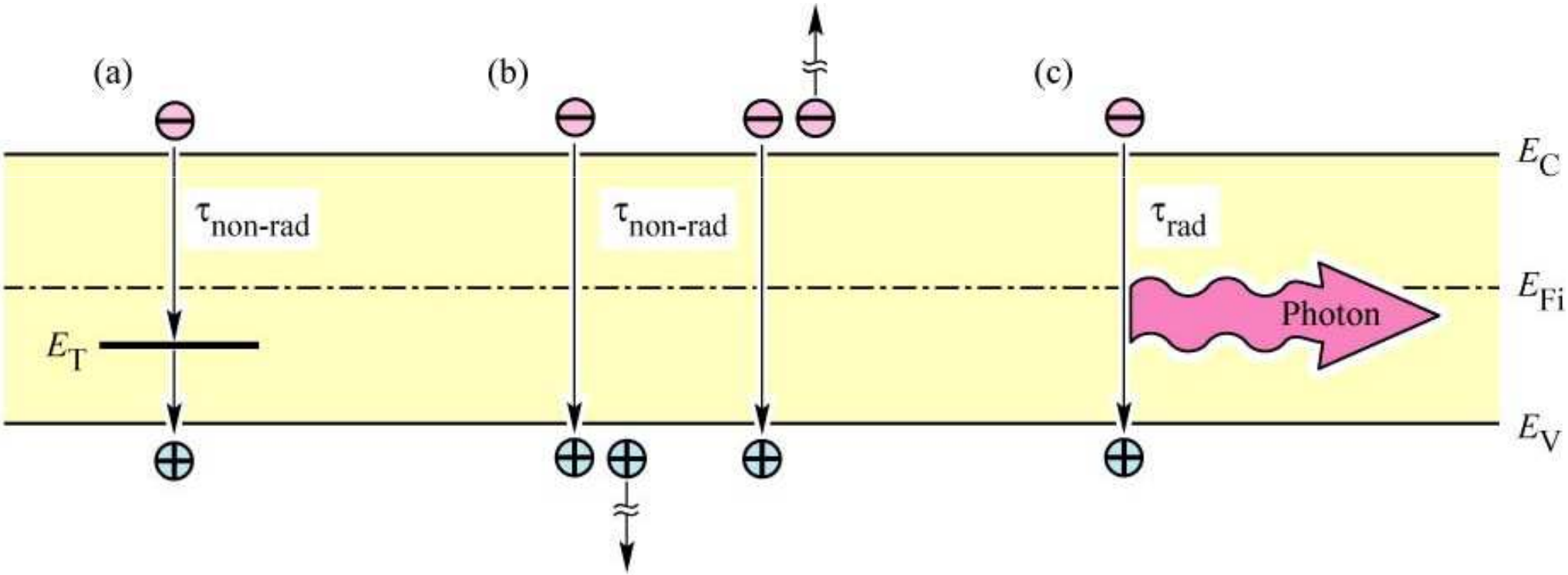


Fig. 2.6. Band diagram illustrating non-radiative recombination: (a) via a deep level, (b) via an Auger process and (c) radiative recombination.

E. F. Schubert
Light-Emitting Diodes (Cambridge Univ. Press)
www.LightEmittingDiodes.org

After EF Schubert, Light Emitting Diodes, 2nd Edition, Cambridge University Press

Surface recombination

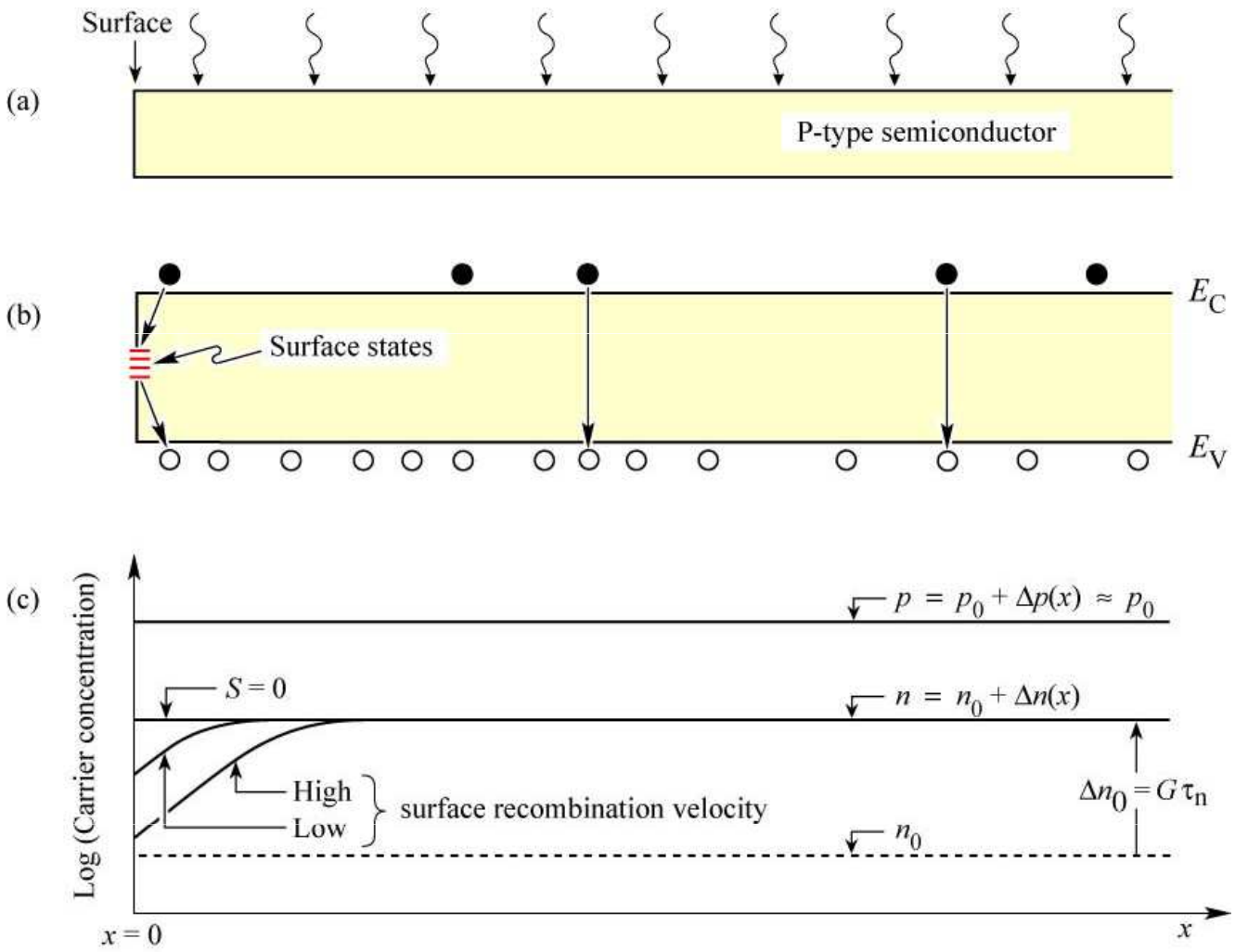
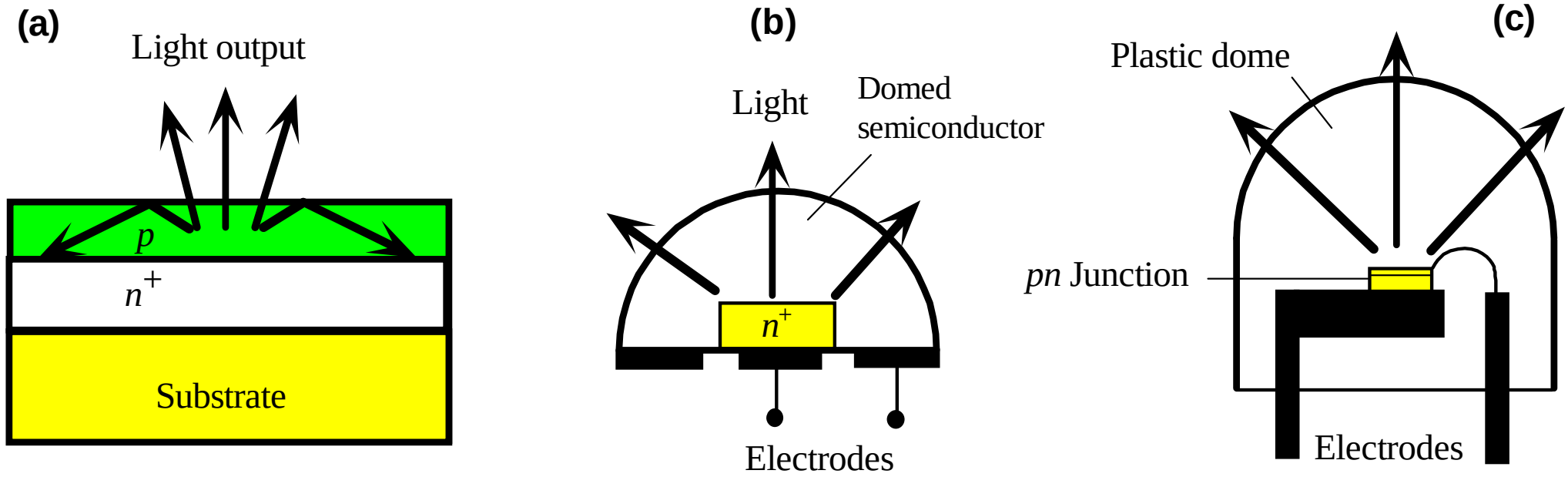


Fig. 2.9. (a) Illuminated p-type semiconductor, (b) band diagram, and (c) minority and majority carrier concentration near the surface assuming uniform carrier generation due to illumination. The excess carrier concentrations are Δn and Δp.

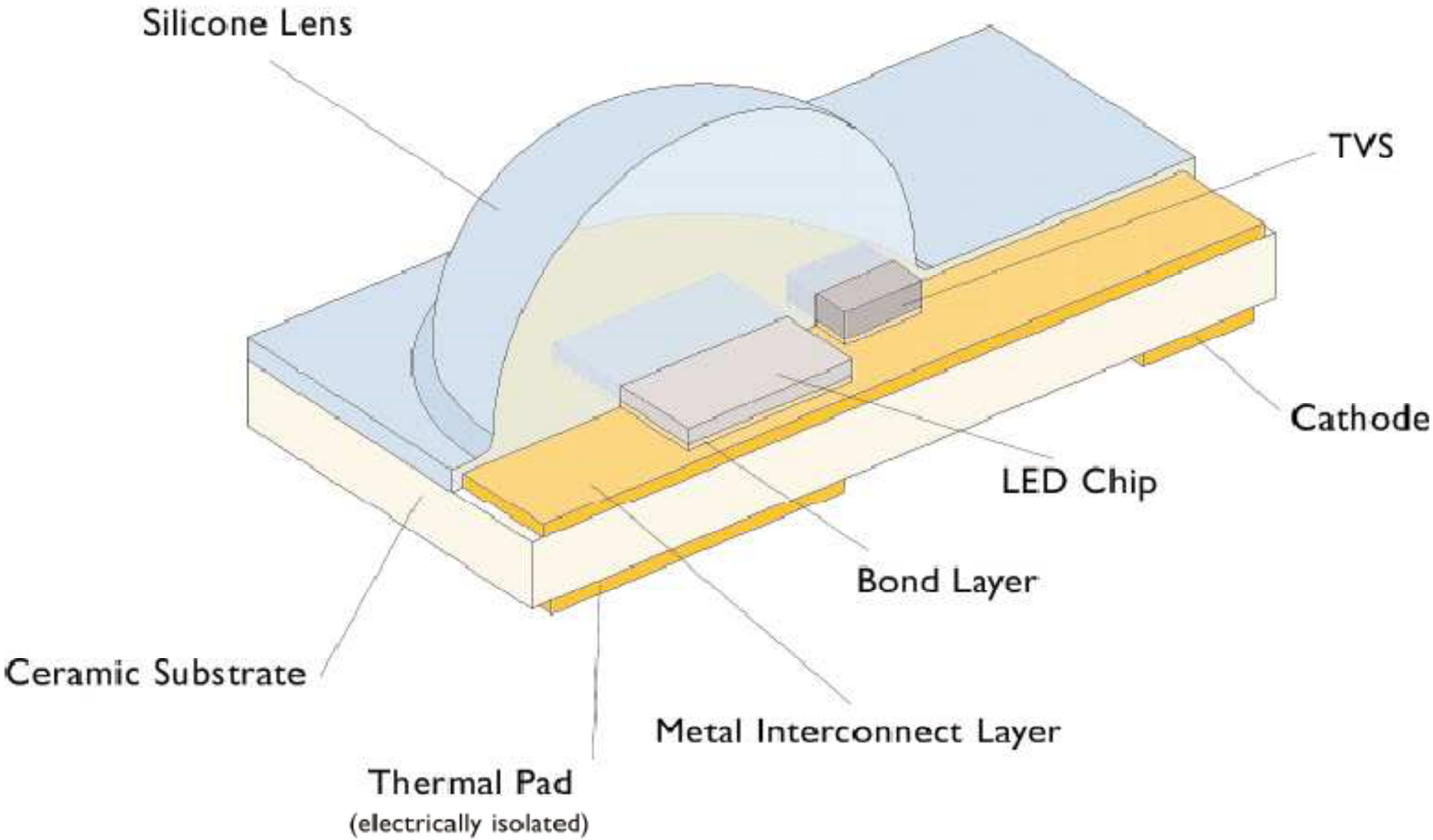
After EF Schubert, Light Emitting Diodes, 2nd Edition, Cambridge University Press

Light Extraction from LEDs



(a) Some light suffers total internal reflection and cannot escape. (b) Internal reflections can be reduced and hence more light can be collected by shaping the semiconductor into a dome so that the angles of incidence at the semiconductor-air surface are smaller than the critical angle. (b) An economic method of allowing more light to escape from the LED is to encapsulate it in a transparent plastic dome.

Structure of a power LED



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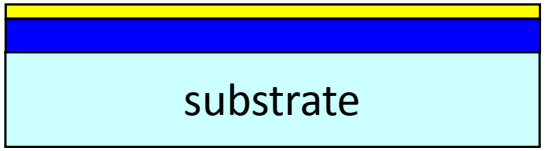
Thin-film LEDs

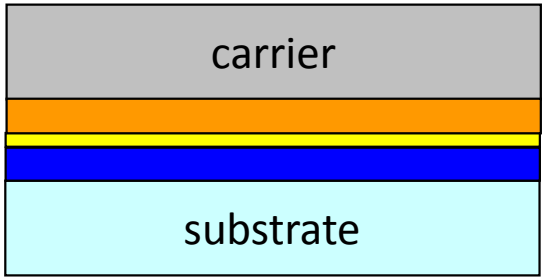
Thin Film technology (ThinGaN) (4 basic steps)

1) High reflectivity p-contact:



epitaxy (≈6 µm)

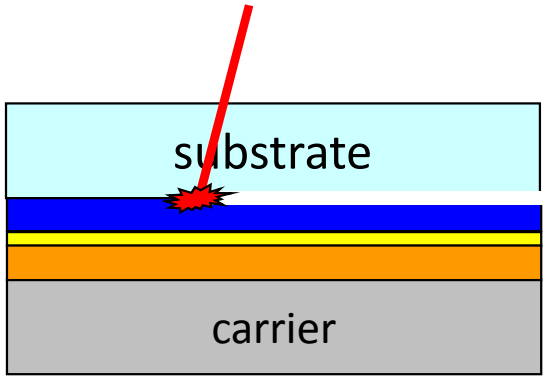
2) Wafer bonding



solder metal

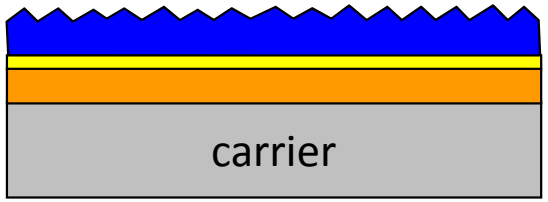
3) Substrate removal

Laser Lift Off (for InGaN on sapphire)



basic process patents owned by OSRAM

4) Surface roughening



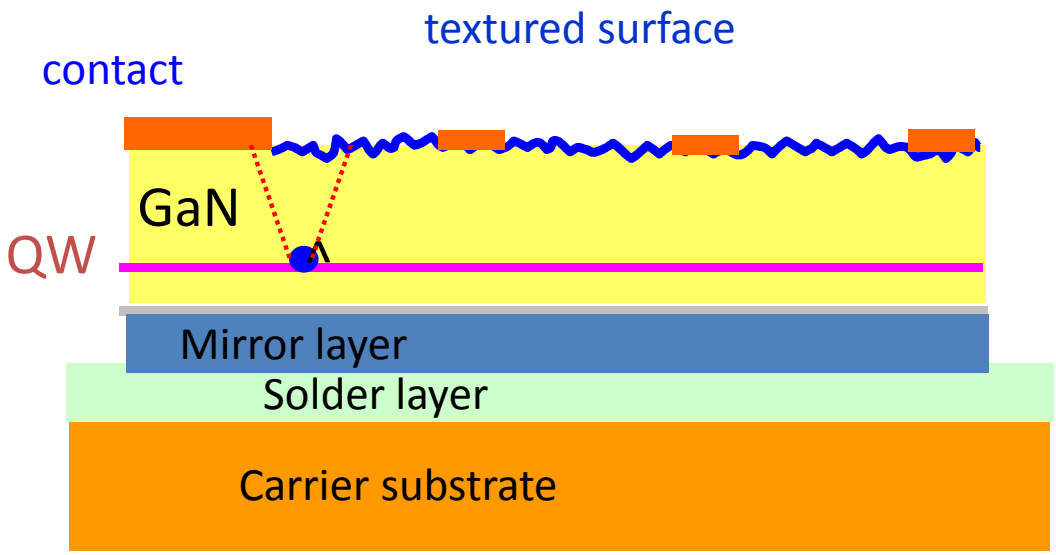
→ increased light extraction

Thin-film LEDs

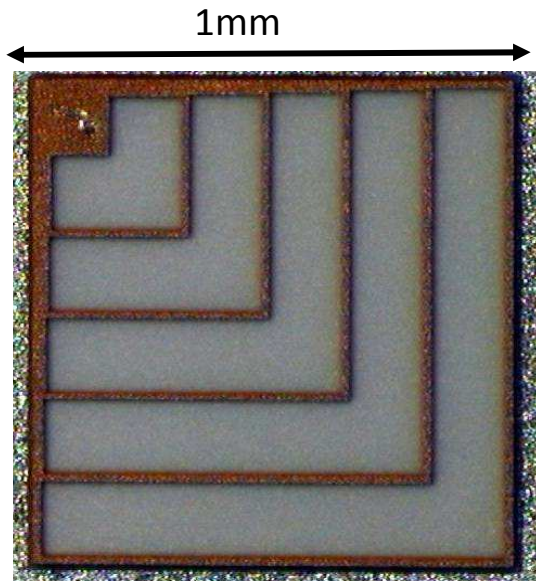
Thinfilm principle:

- prevent absorption in substr. ⇒ highly reflecting mirror
- low internal absorption ⇒ thin epi layers
- prevent waveguiding ⇒ optimize surface roughness

Present actions:



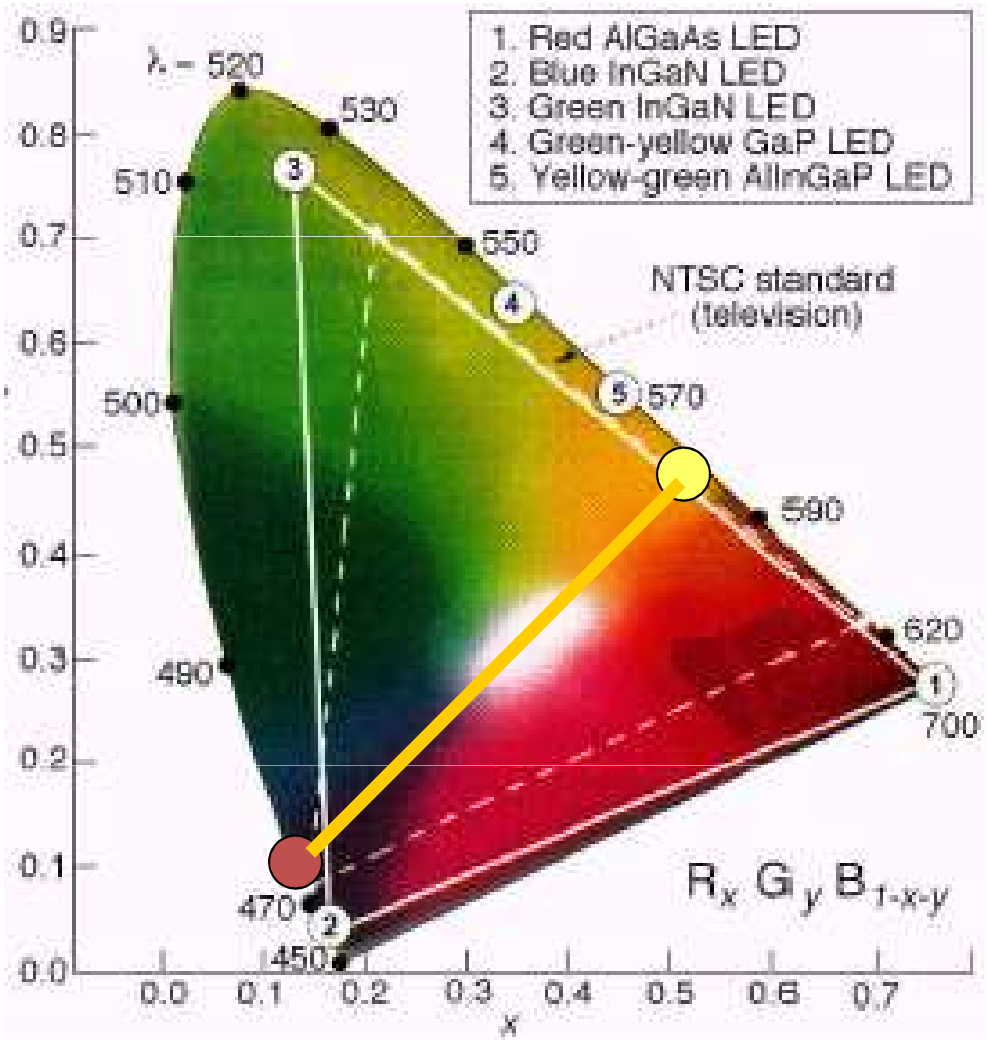
Power thin film LED; scematic side view

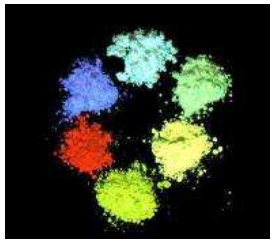


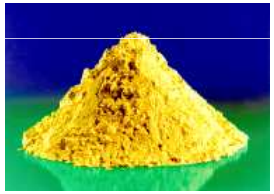
PowerThinGaN top view

Light extraction of 75% is reached

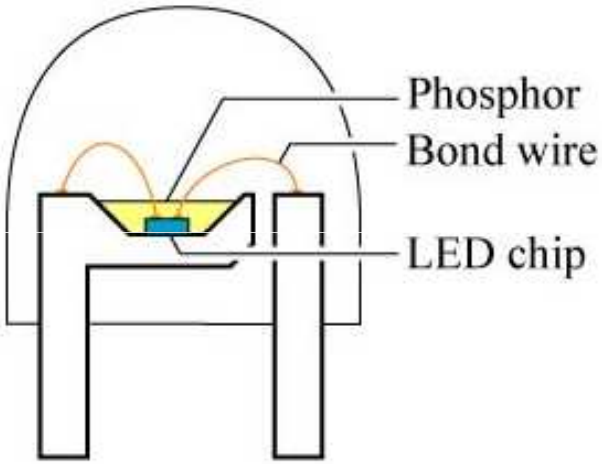
White LEDs

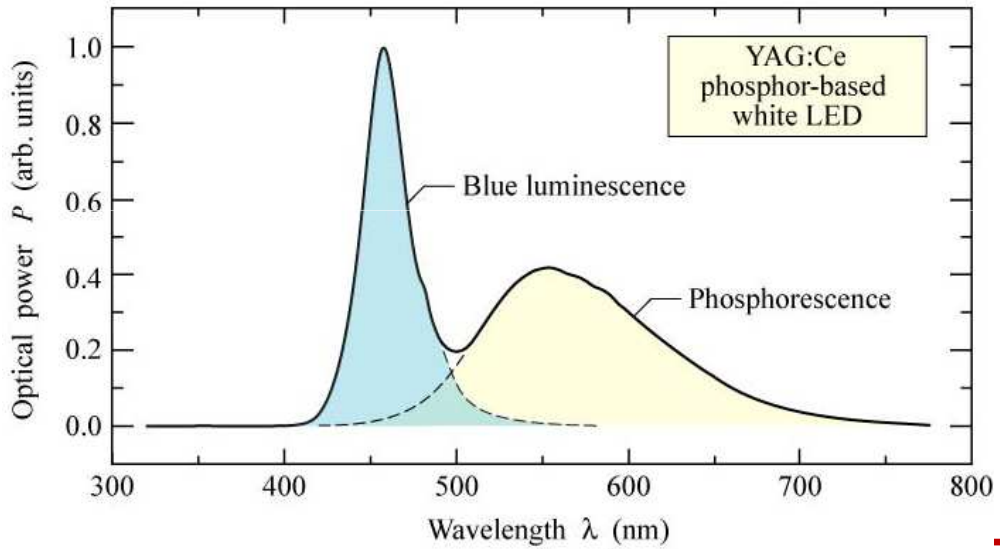






Phosphors

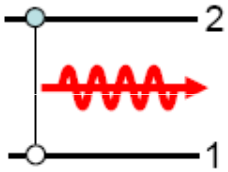




Spontaneous vs Stimulated Emission

Einstein Coefficients

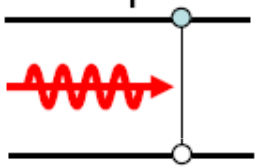
Spontaneous emission:



$$\frac{dn_1}{dt} = A_{21} n_2$$

A_{21} = spontaneous emission coeff.

Absorption:

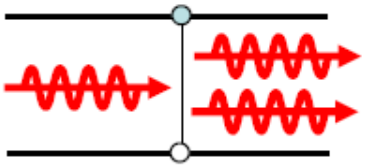


$$\frac{dn_1}{dt} = -B_{12} n_2 I(\omega)$$

B_{12} = absorption coeff.

Occur with single photon and an atomic transition

Stimulated emission:



$$\frac{dn_1}{dt} = B_{21} n_2 I(\omega)$$

B_{12} = stimulated emisssion coeff.

Pre-excited atomic system interacting with photon

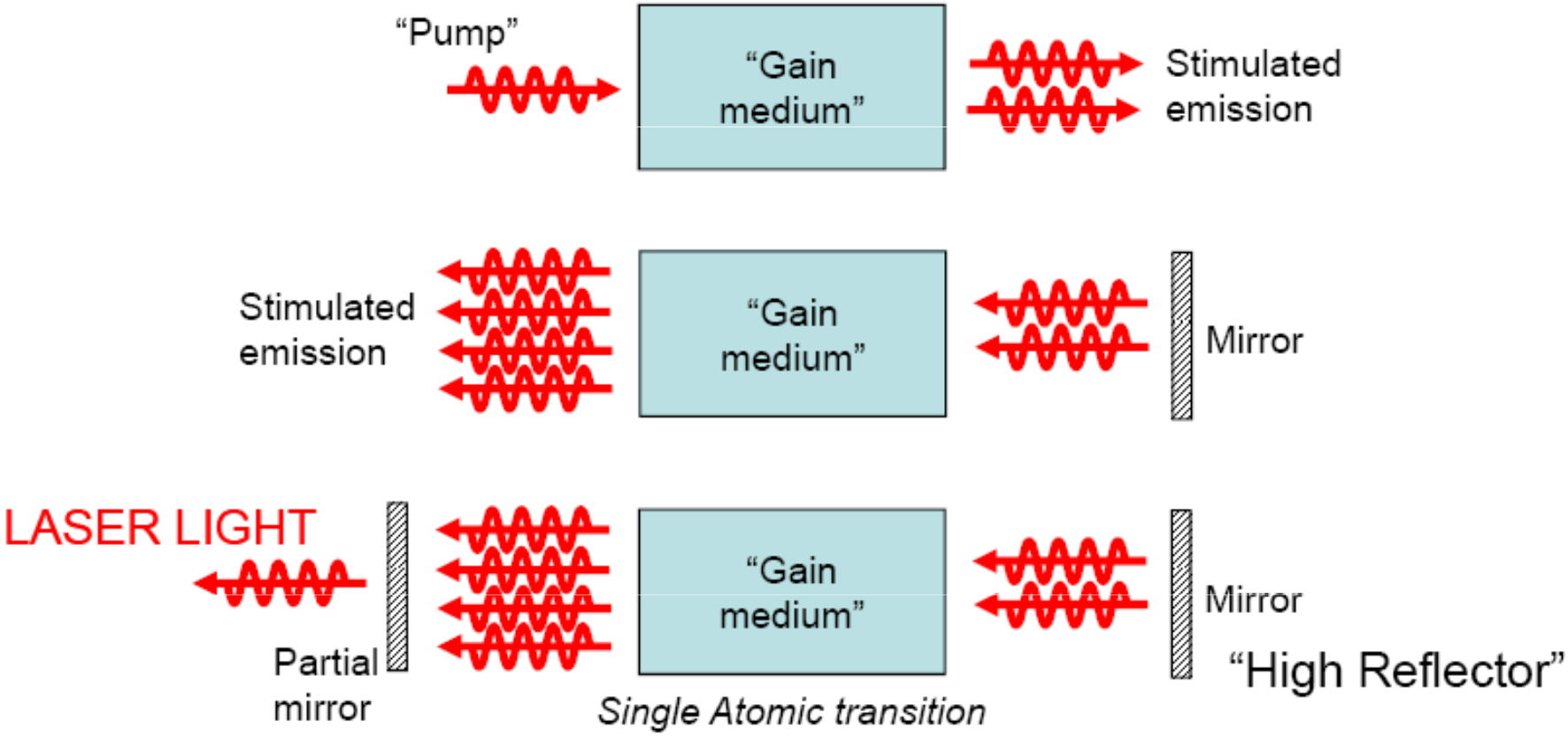
Work by Einstein in 1916

Laser dynamics requires a detailed look at the **rate equations**

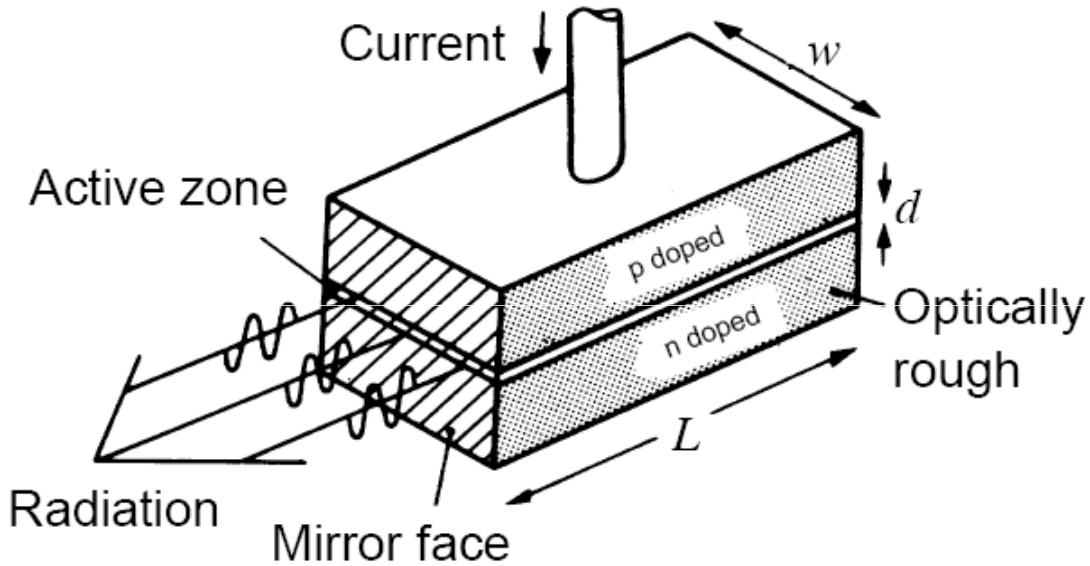
Electron conservation:

$$0 = A_{21} n_2 + B_{21} n_2 I(\omega) - B_{12} n_2 I(\omega)$$

Gain - LASER


"Pump"
"Gain medium"
Stimulated emission
Stimulated emission
"Gain medium"
Mirror
LASER LIGHT
"Gain medium"
Mirror
Partial mirror
"High Reflector"
Single Atomic transition

Structure of a laser diode

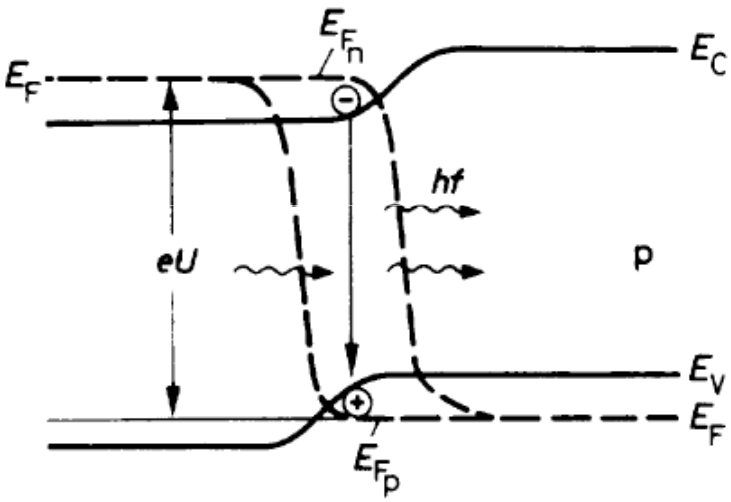


Basic structure of a laser diode

Optical resonator realized with the Fabry–Perot condition

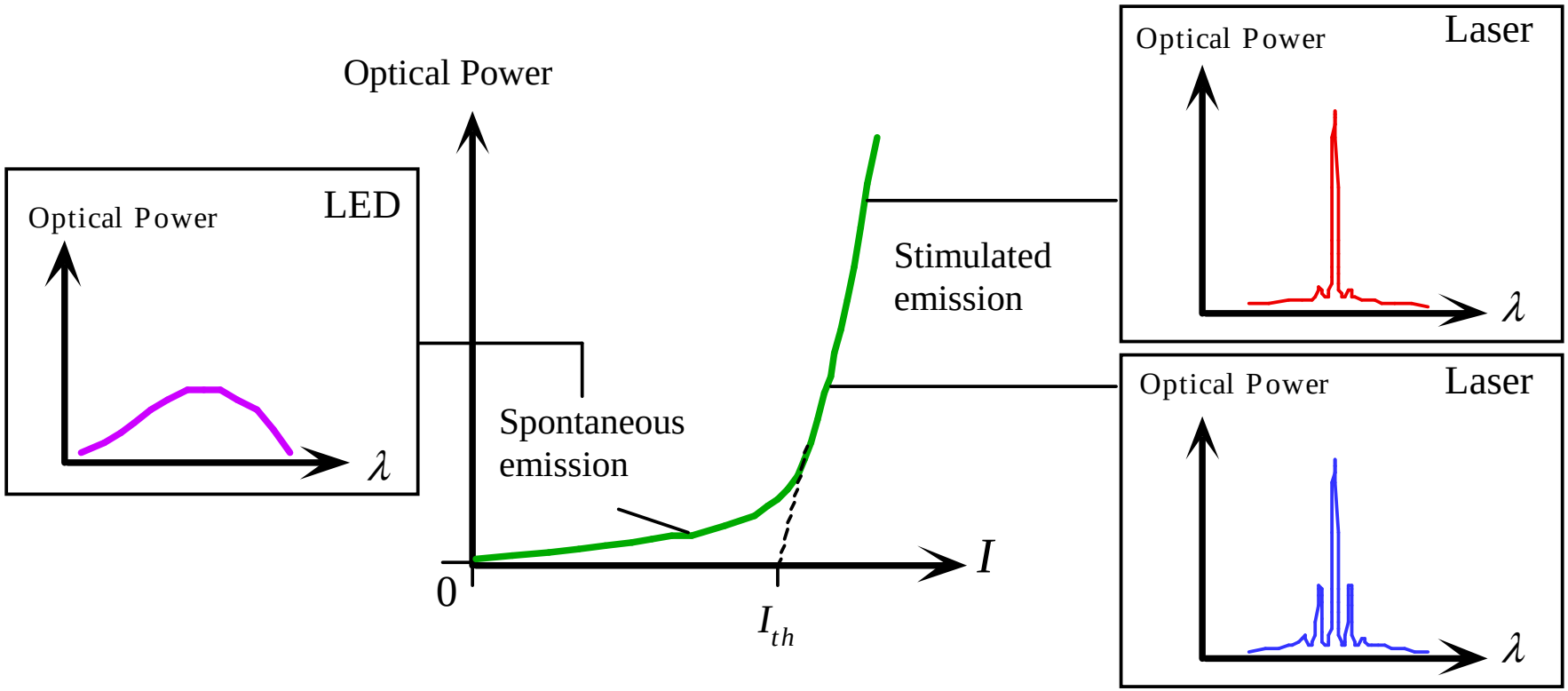
$$m\lambda = 2nL$$

(m integer number, λ wavelength, n refraction index, L resonator length)



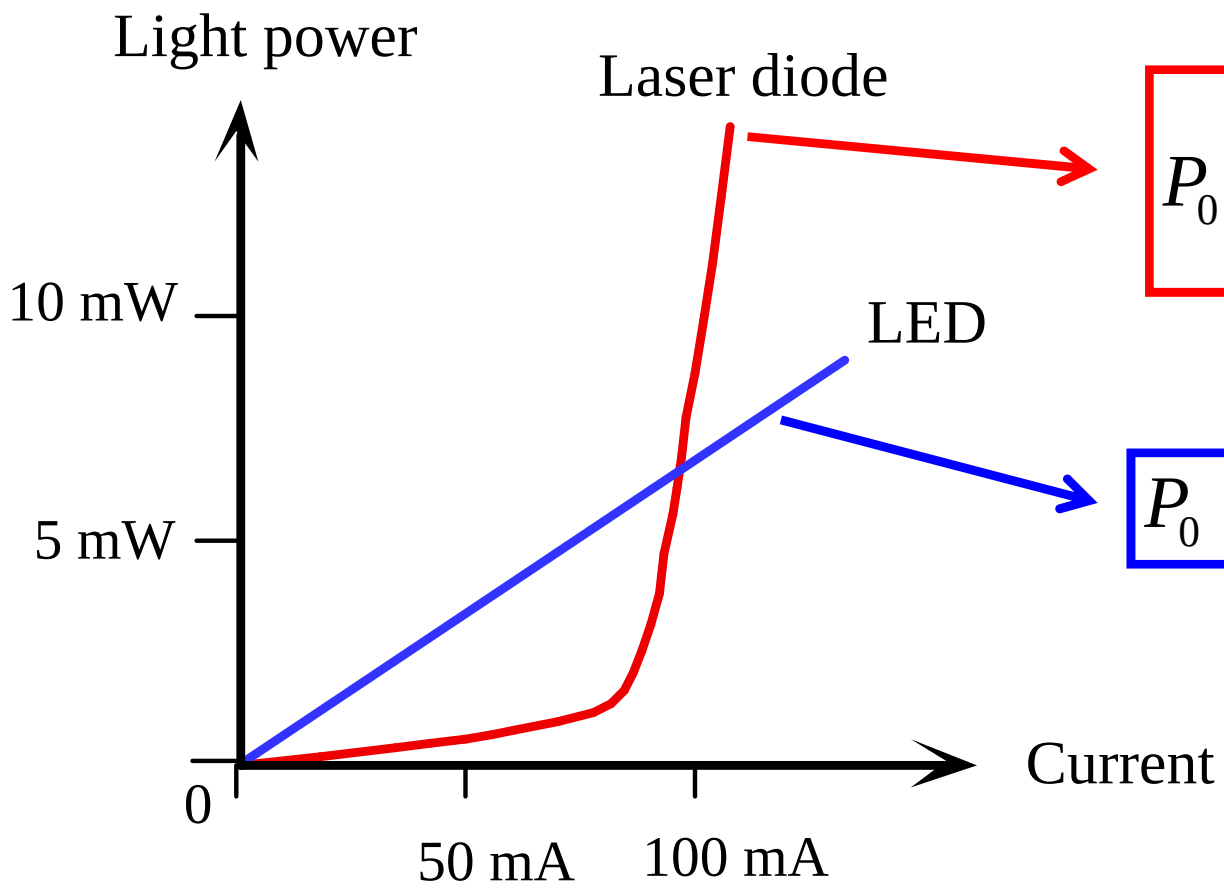
Population inversion at the p–n junction as the lasing condition (*i. e.* stimulated emission larger than optical absorption)

Optical characteristics of Laser Diodes



Typical output optical power vs. diode current (*I*) characteristics and the corresponding output spectrum of a laser diode.

LEDs vs Laser Diodes

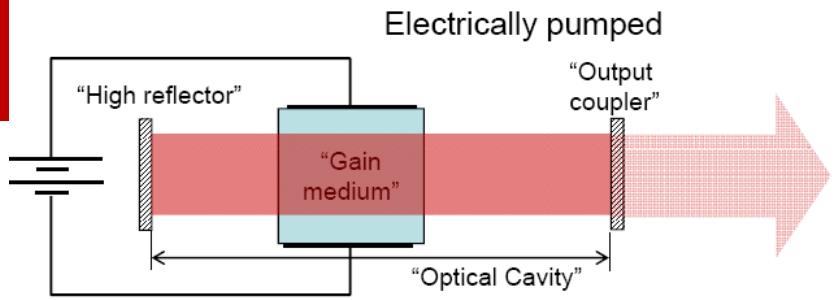


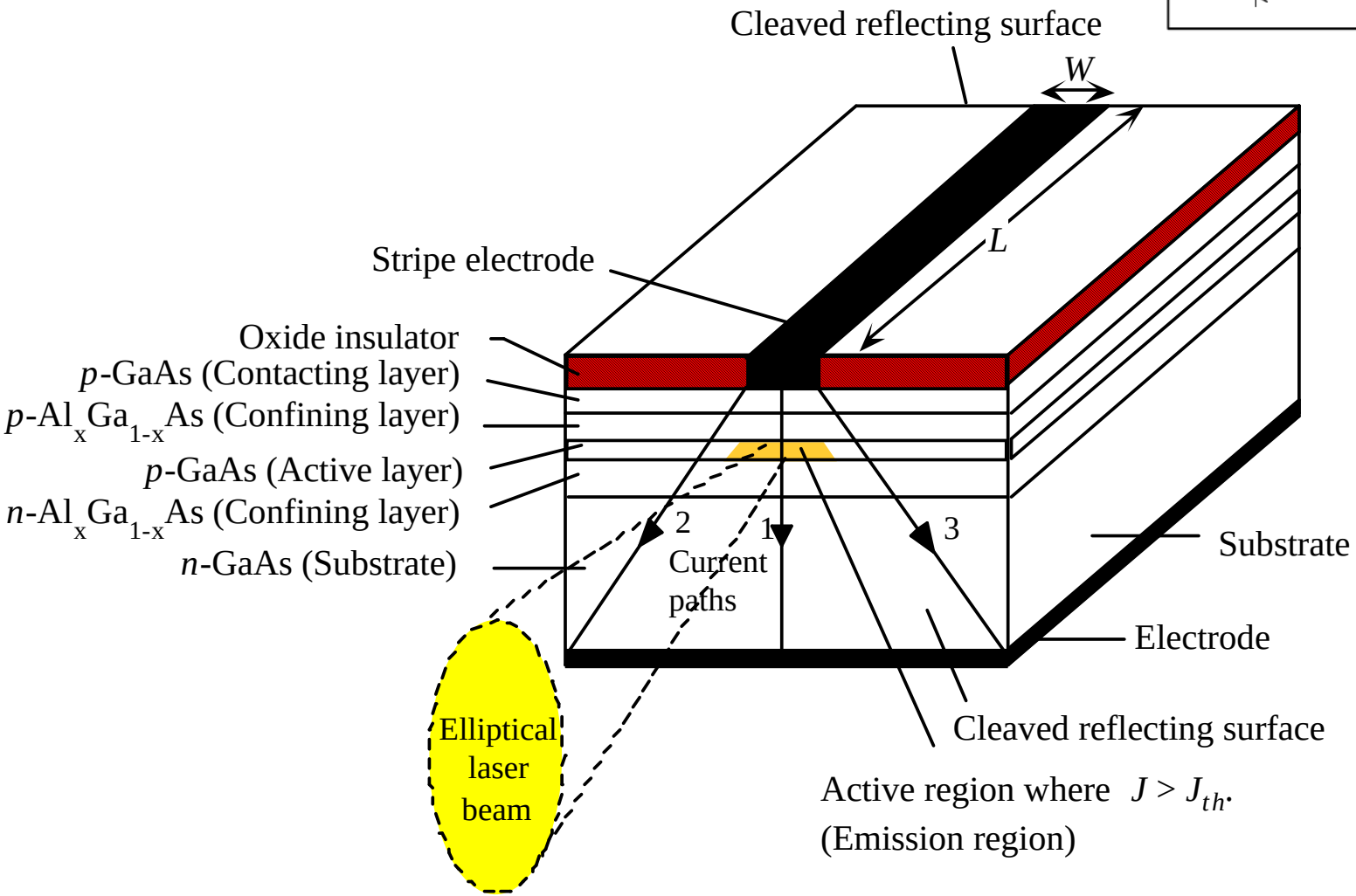
$$P_0 = \frac{hc^2 \tau_{ph} W (1-R)}{2qn\lambda}(J - J_{th})$$

$$P_0 \propto J$$

Typical optical power output vs. forward current for a LED and a laser diode.

Structure of a laser diode





Schematic illustration of the the structure of a double heterojunction stripe contact laser diode

Structure of a laser diode

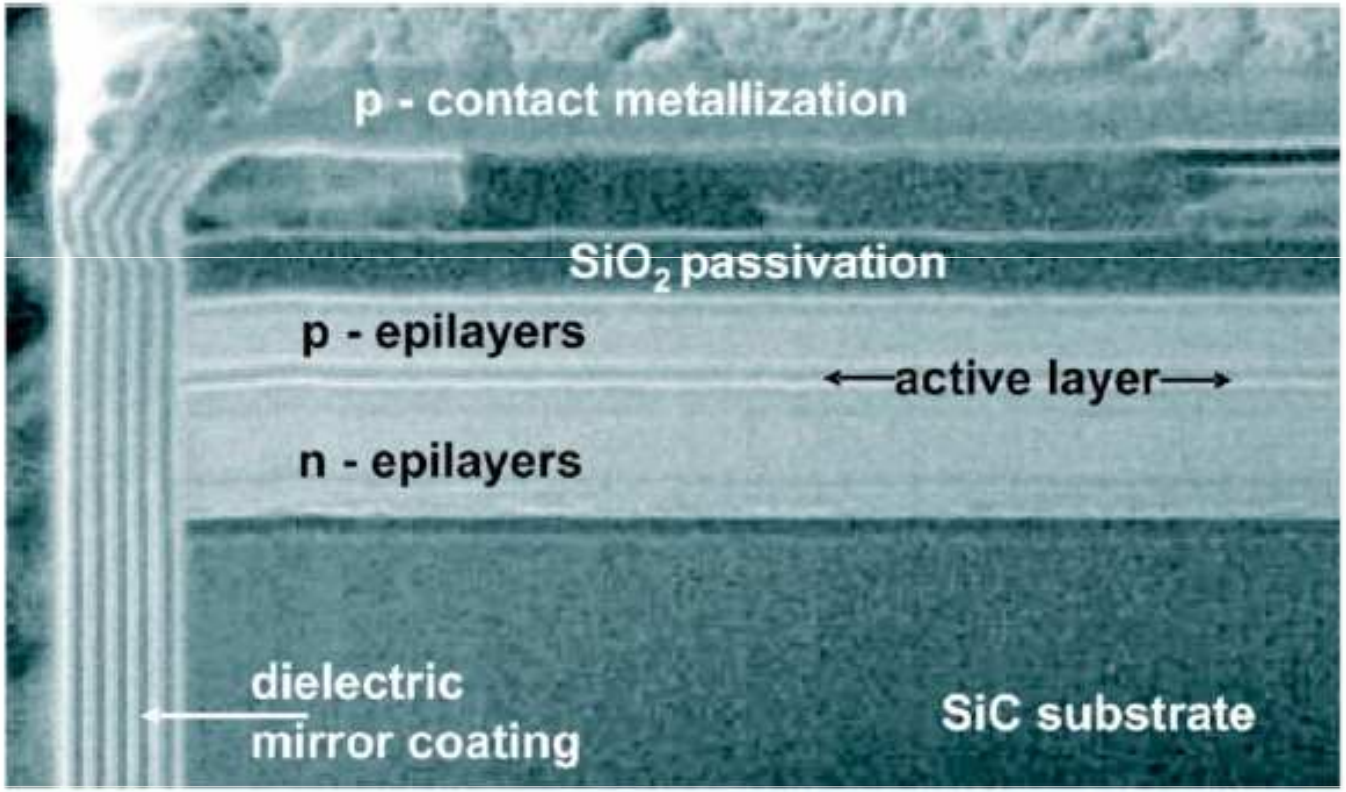


FIG. 1. SEM image showing the side view of a laser diode with mirror coatings. The cut through the laser diode was done by a focused ion beam.

Degradation of optoelectronic devices

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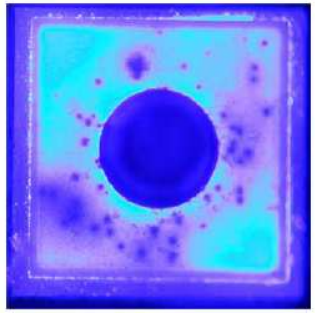
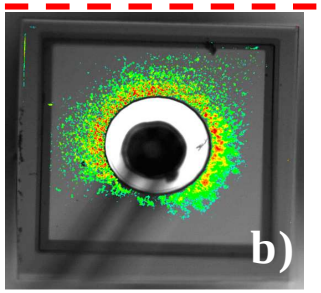
Critical factors for LED degradation

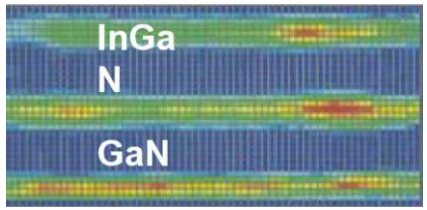


Degradation of the phosphorous layer



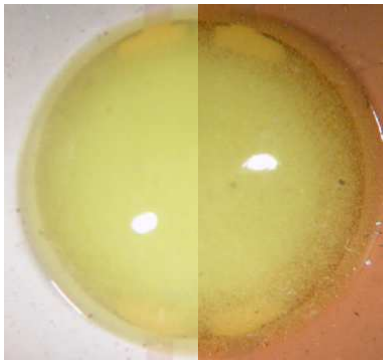
Degradation of ohmic contacts (Mg-related)

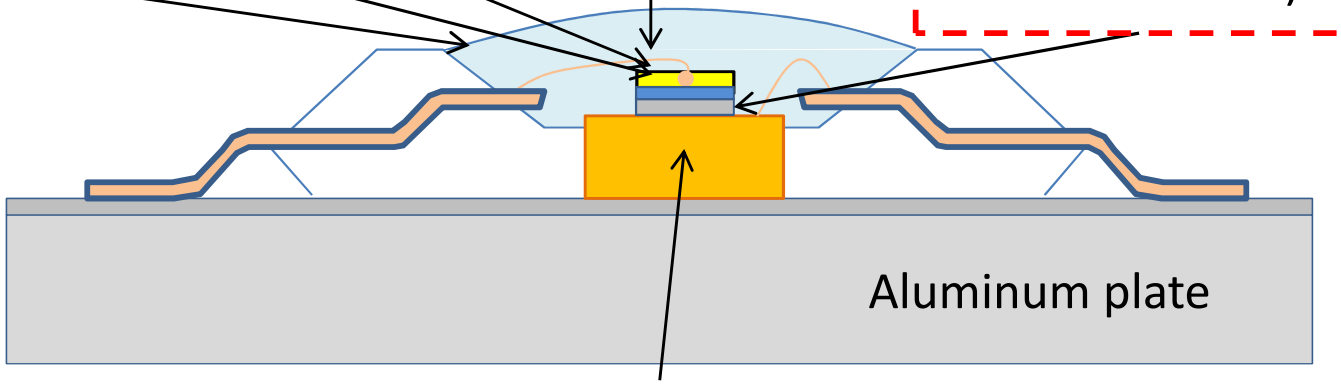
Detachment of the bonding wire



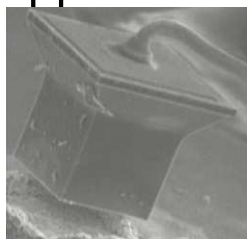
Defects in the active layer (non-rad rec., impurity diffusion, In-related effects)

Browning of the lens and package material

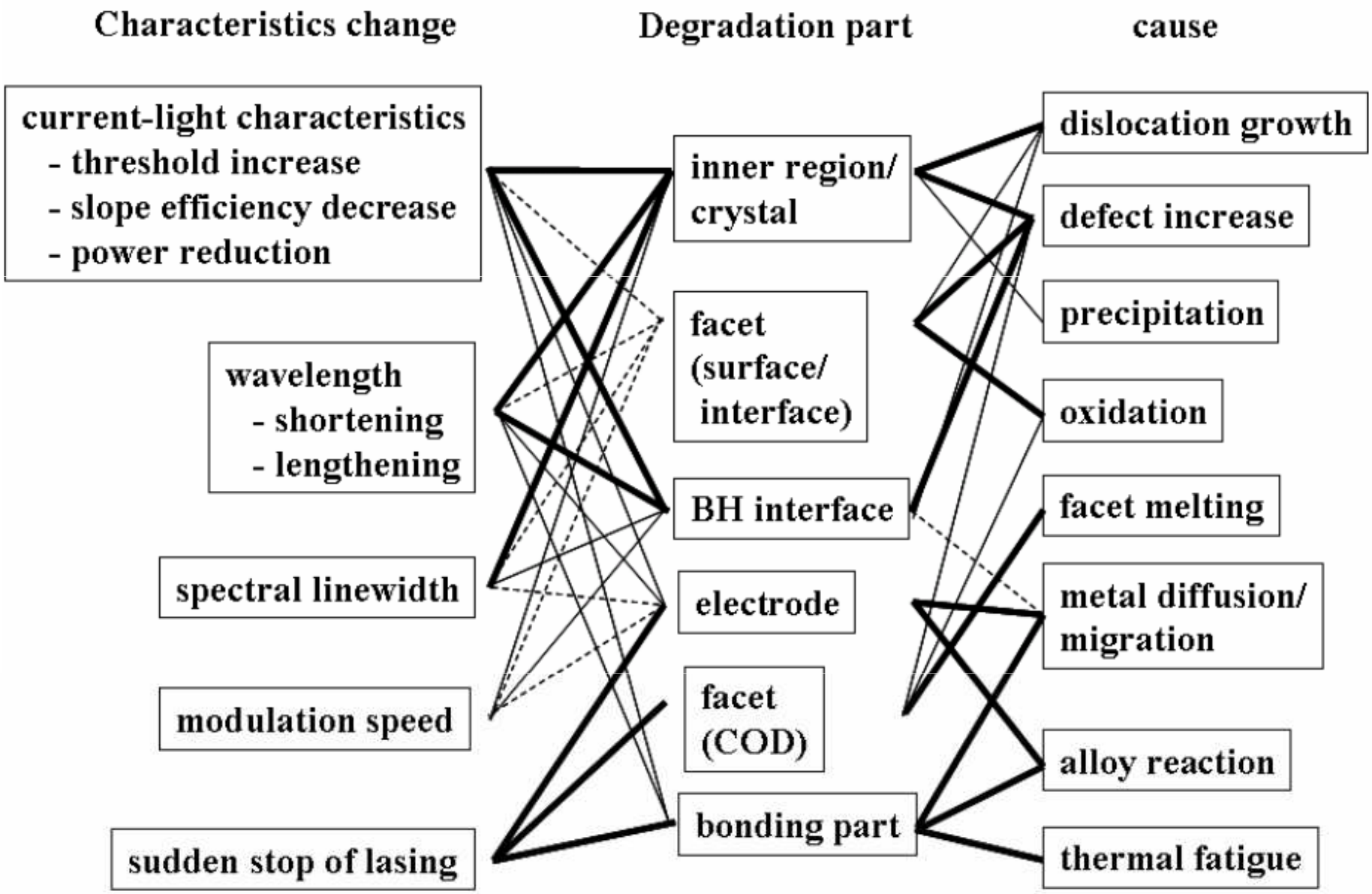




Detachment from the copper frame



Critical factors for laser diode degradation

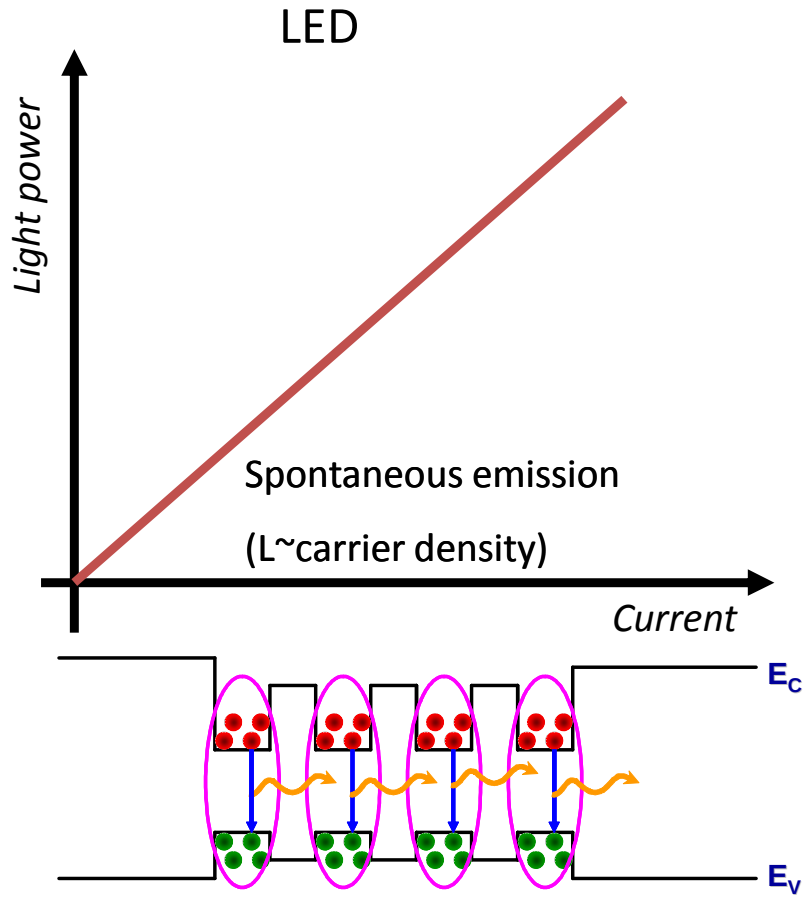


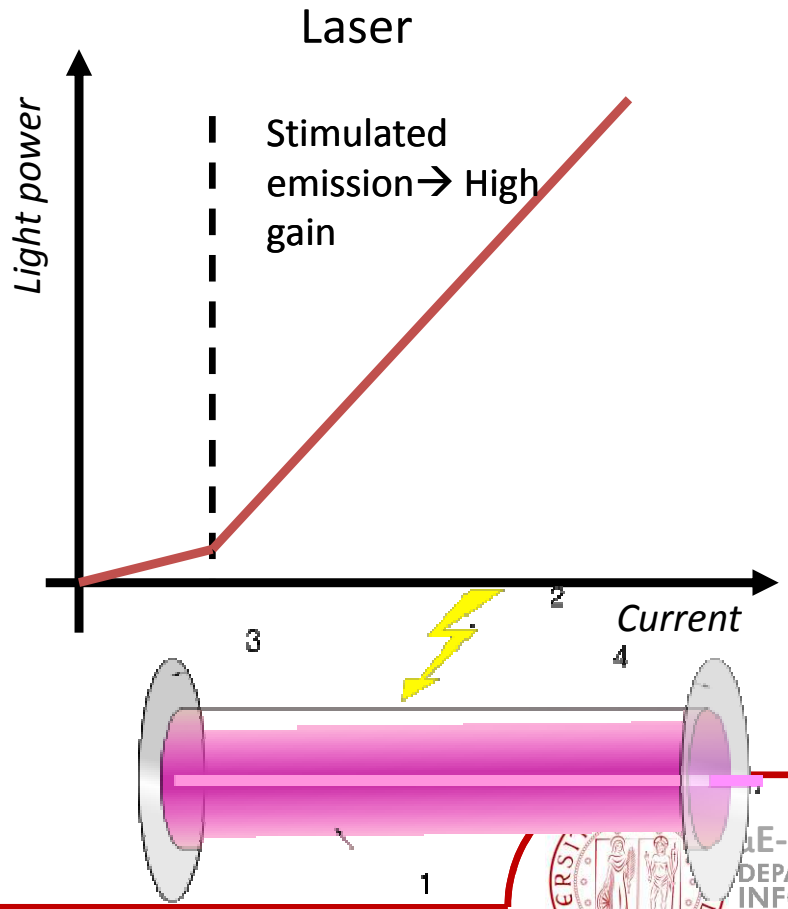
After M. Fukuda, ESREF 2007

Optical Characteristics of LEDs and Laser Diodes

Optoelectronic devices:

- **High densities of injected carriers**
- **LEDs → Light output power is nearly proportional to injected current**
- **Laser Diodes → Above threshold optical power has a linear dependence on injected current**

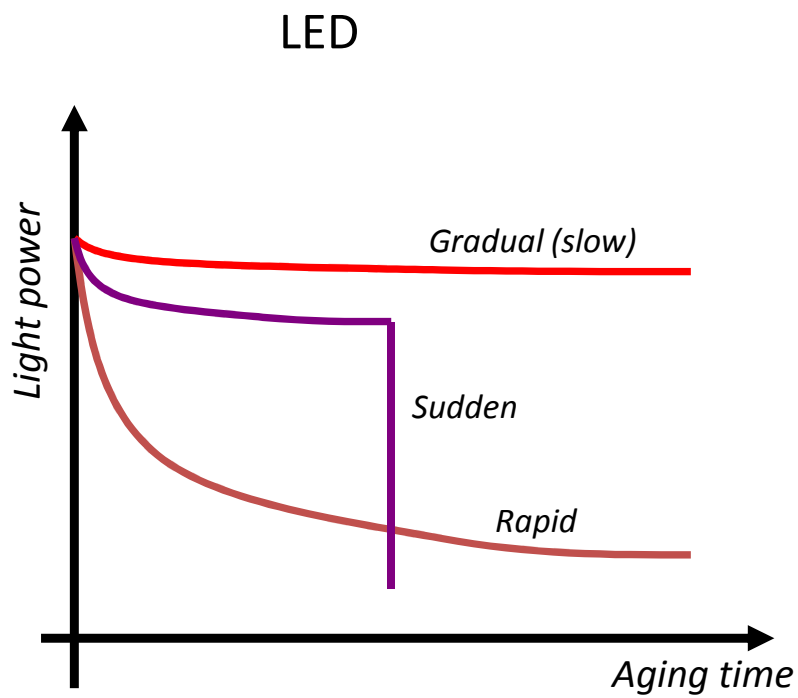


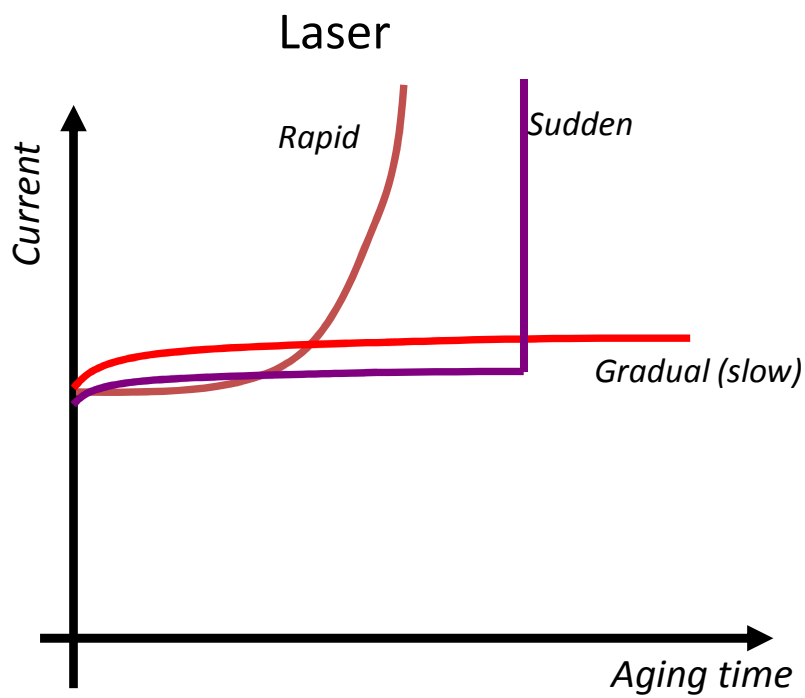


Stress conditions for LEDs and Laser Diodes

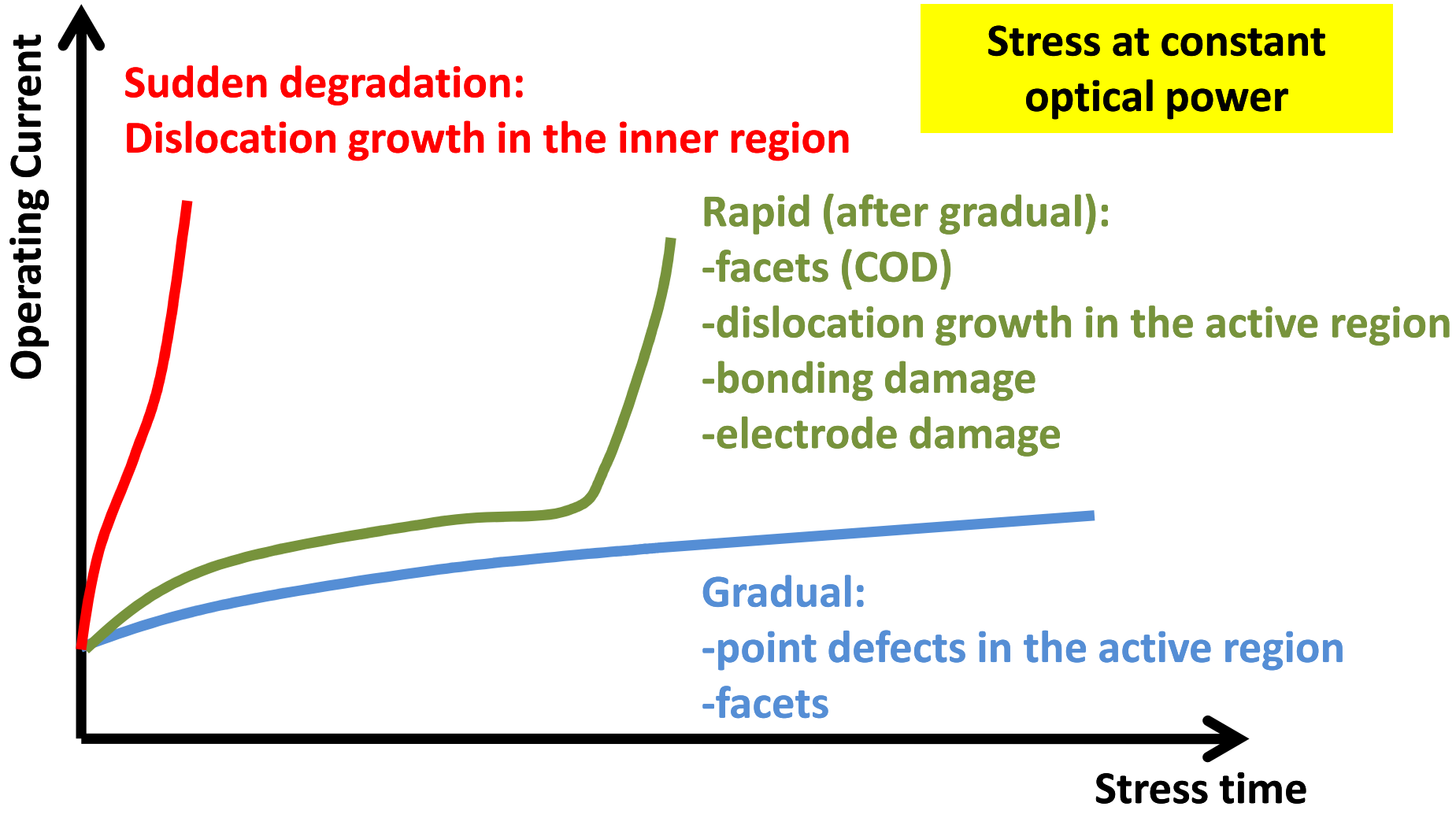
Driving methodology

- LED → Constant current driving (dimming) → Degradation parameter: Optical power
- Laser → Constant Optical Power driving (eg disk writing) → Degradation parameter: operating current





Degradation of Laser Diodes



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Gradual degradation of the Active Region
-
Generation of defects

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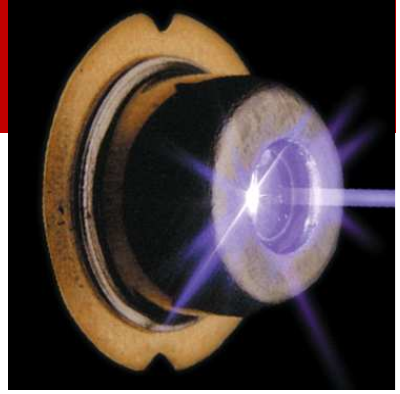
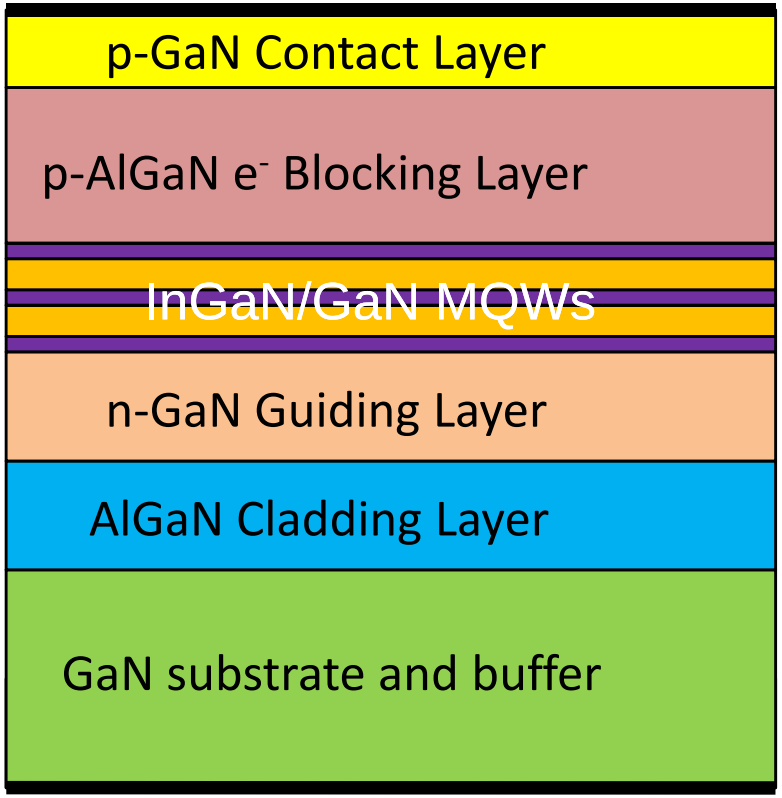
A case study: degradation of the active region of Blu-Ray LDs





Devices characteristics:

- Vertical structure devices (on GaN)
- Emission wavelength = 405 nm
- Slope efficiency = 1.6 W/A
- Threshold current density = 3.2 kA/cm^2 (29 mA)

Stress fixtures:

- Devices mounted on Peltier fixtures
- Junction-to-case thermal resistance ~ 52 K/W
- Maximum self-heating during stress → 15 ℃

Adopted stress conditions:

Fixed parameter	Varying parameter
Fixed current (70 mA dc)	Temperature in the range 30-70 °C
Fixed T_c (180 °C)	No bias
Fixed T_c (70 °C)	Current in the range 200 µA-80 mA dc

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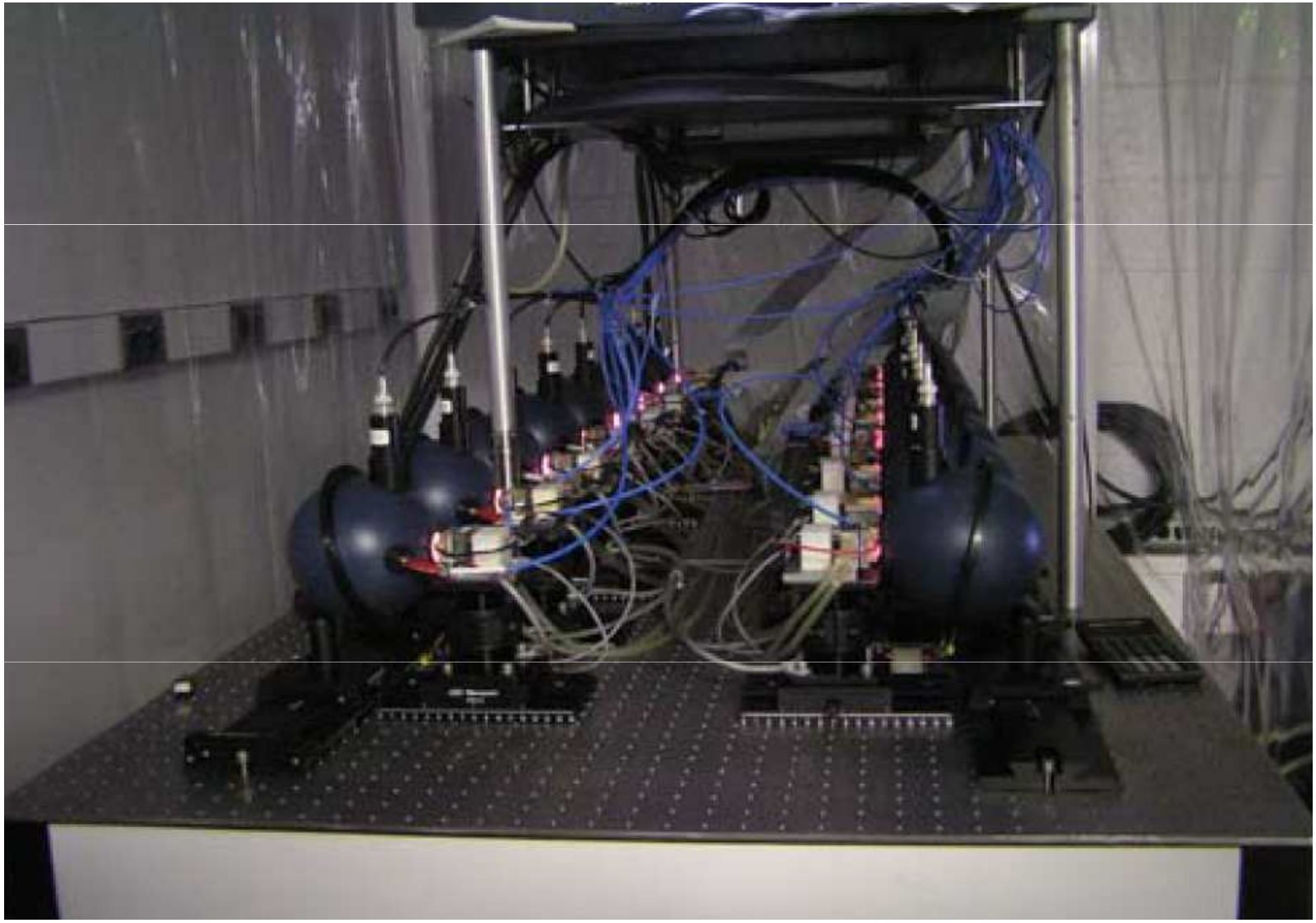
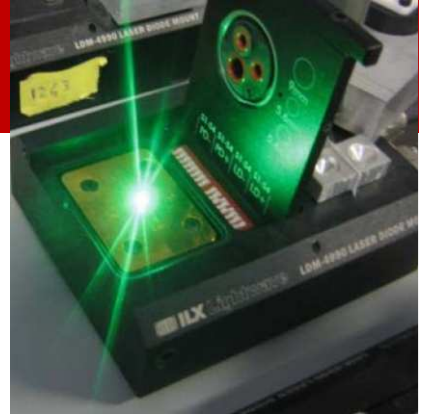
A typical stress setup



Thermal characterization – Calibration phase

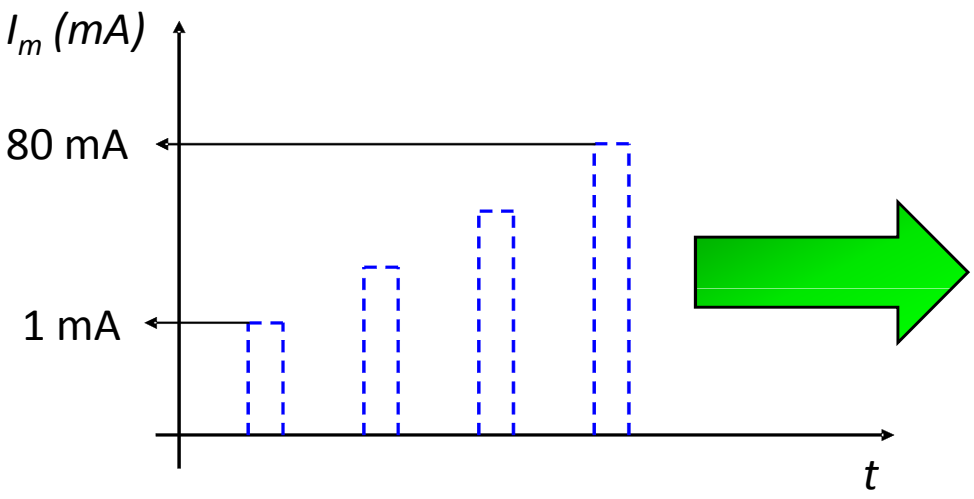


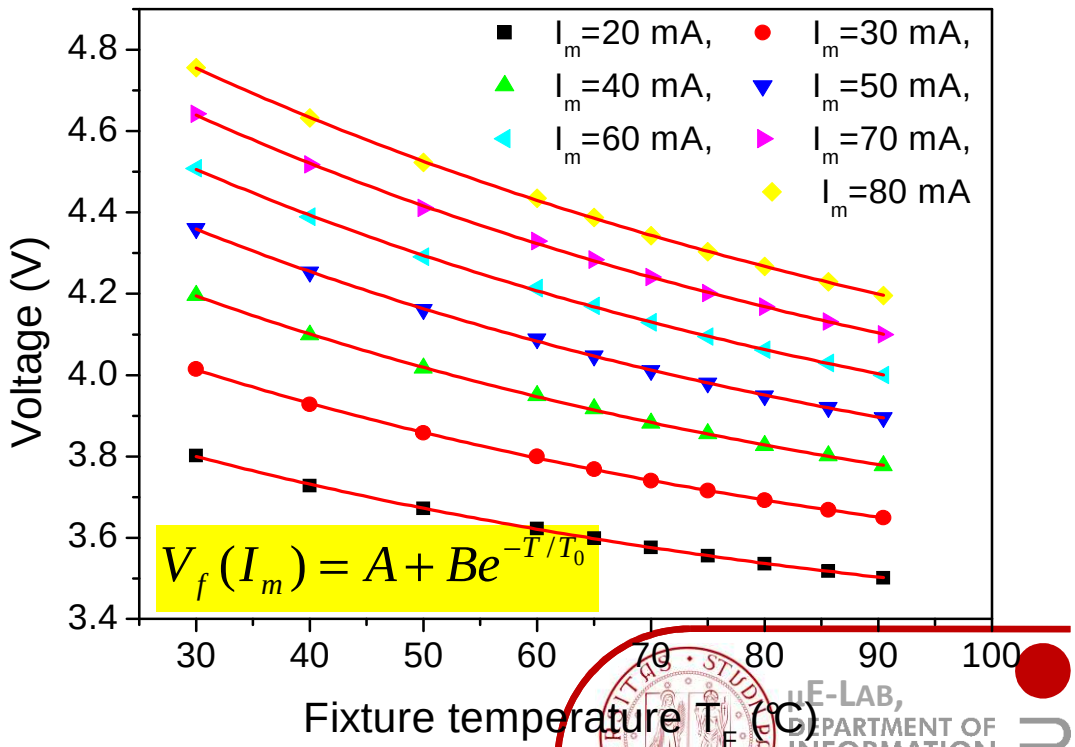
Goal → To evaluate junction temperature during operation

Method → Xi and Schubert, Appl. Phys. Lett., 85, 2163, 2004.

Calibration phase

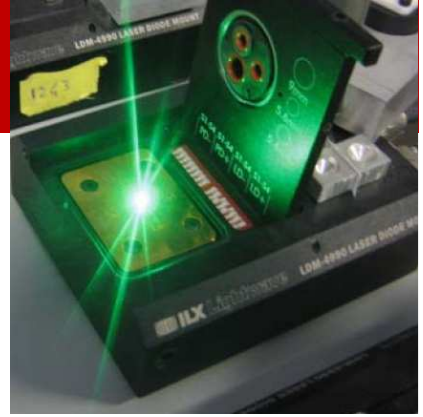
- Samples on a Peltier-fixture (30<T<90°C)
- Short current pulses → Voltage measurements





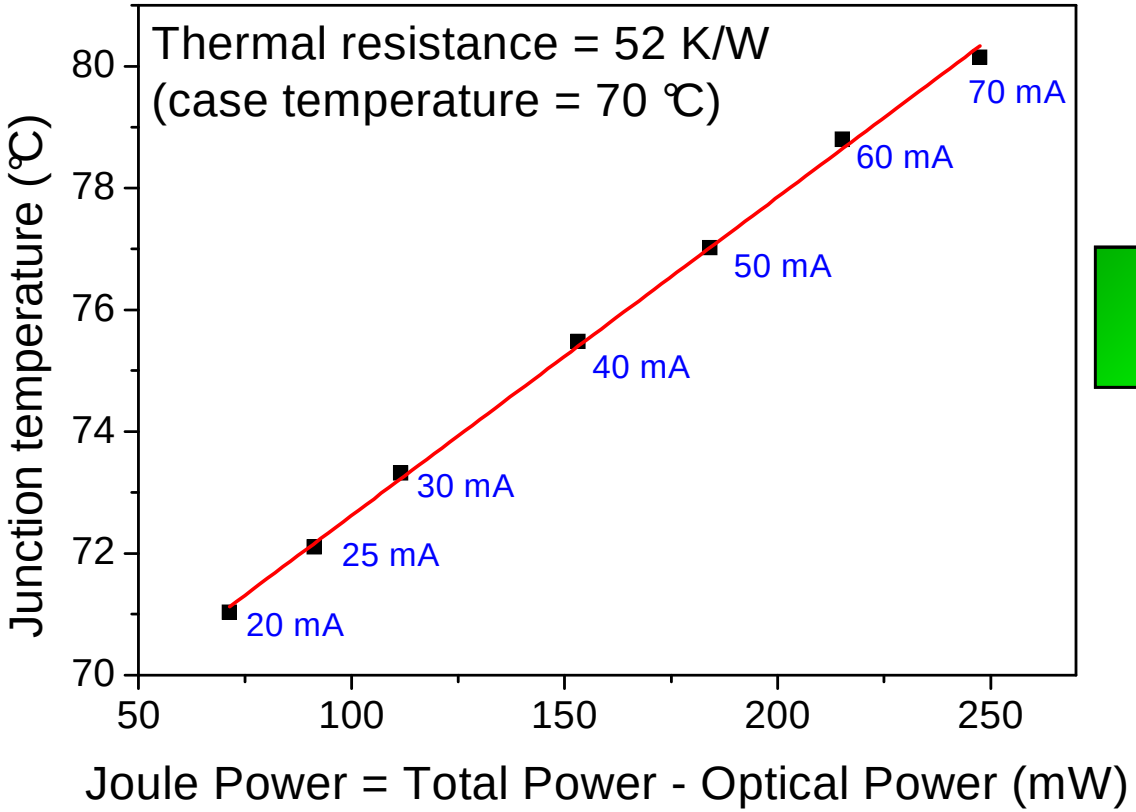
Extrapolation of A, B and T_0 for the calculation of R_{th}

Thermal characterization – R_{th} extrapolation



Junction temperature evaluation

- Fixed temperature (70℃)
- Fixed current (I_m)
- Voltage measurement after self heating transient →Junction temperature evaluation



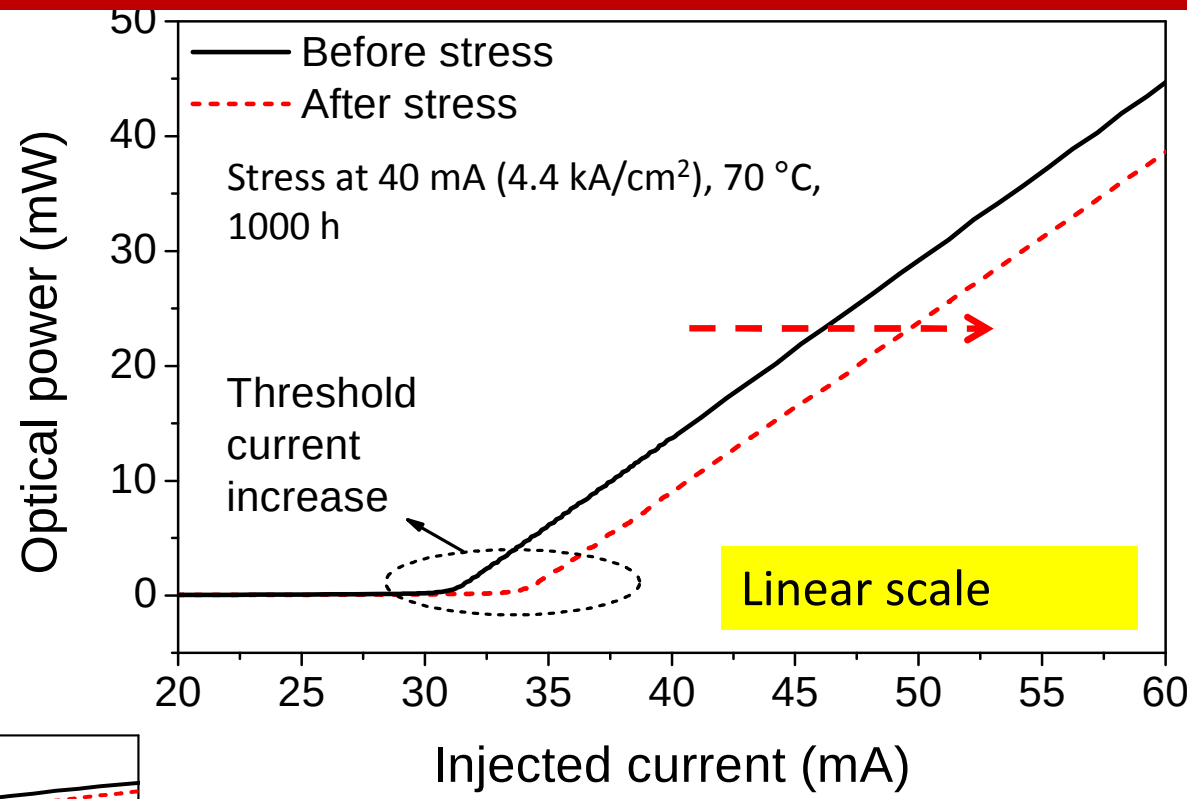
- R_{th} = 52 K/W
- During stress at 70 mA, T_F=70 °C, T_j~80 °C (within recommended limits)

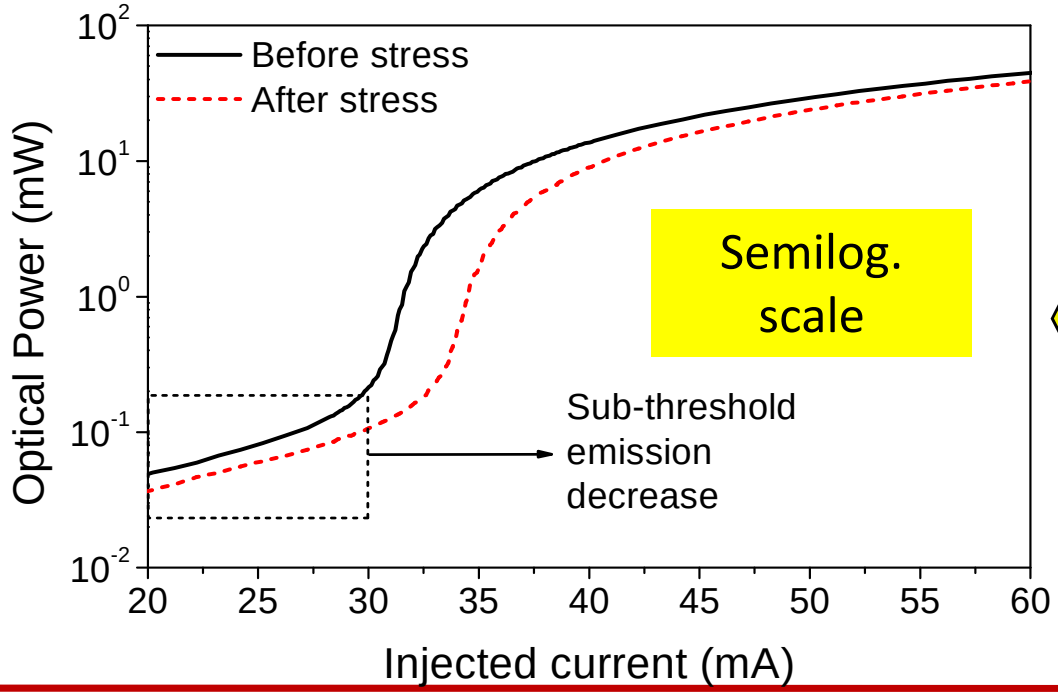
L-I Characteristics before/after stress

- L-I curves measured before and after stress at 40 mA, 70 ℃

<u>After stress:</u>

- Increased I_{th}
- Same slope efficiency





- Stress induces also the decrease of sub-threshold emission (see semilog. plot)

Stress at 40 mA (4.4 kA/cm²), 70 °C, 1000 h

I_{th} increase vs OP_{sub} decrease

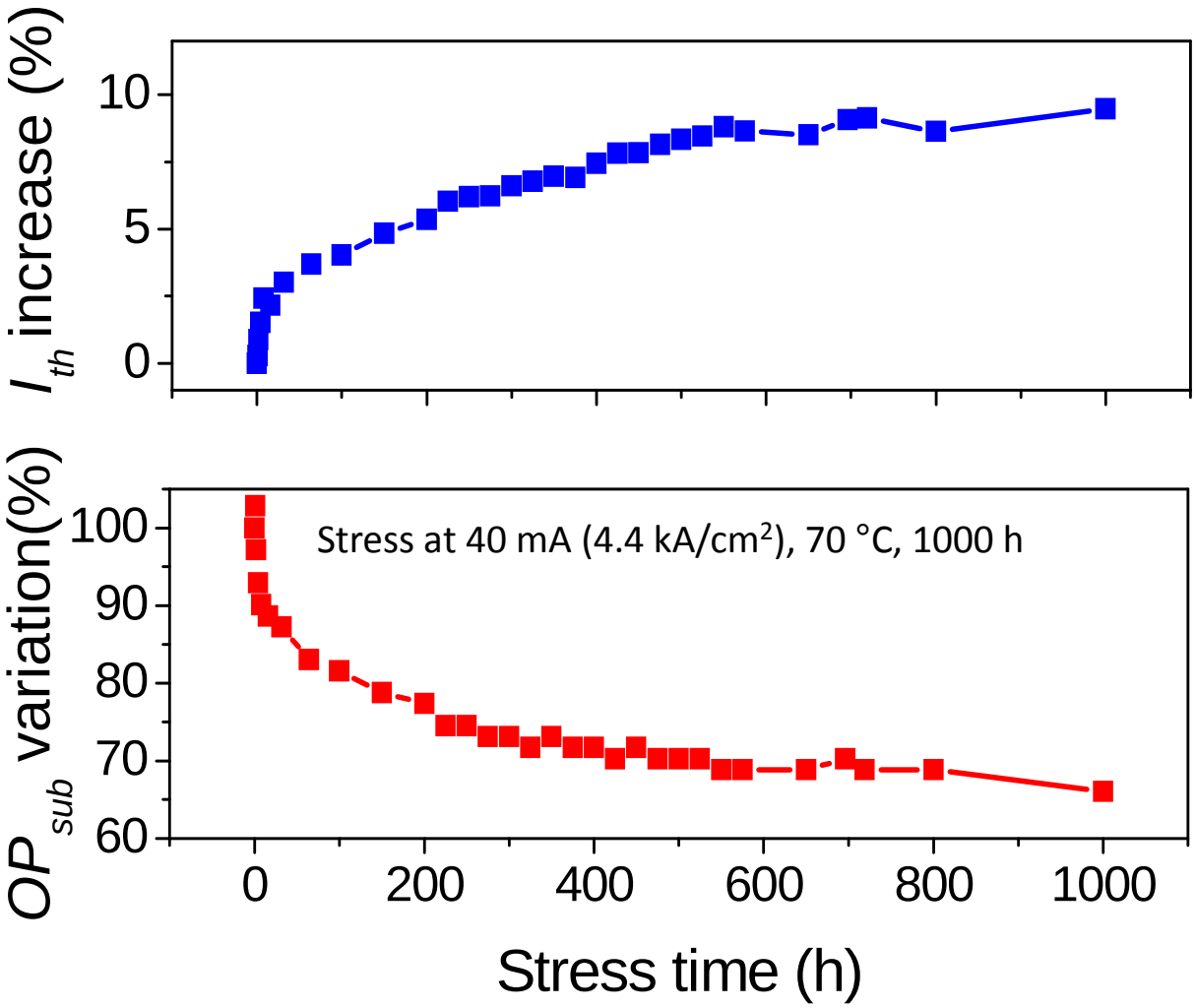
Comparison between:

Threshold current increase

$$\Delta I_{th} = \frac{I_{th}(t)}{I_{th}(0)} - 1$$

Sub-threshold OP decrease (at 28 mA)

$$\Delta OP_{sub} = 1 - \frac{OP_{sub}(t)}{OP_{sub}(0)}$$



The two parameters vary with the same kinetic → Correlation

Correlation between I_{th} increase and OP_{sub} decrease

Carriers recombination lifetime τ is determined by the balance between the non-radiative (A) and radiative (B) recombination

$$\frac{1}{\tau} = A + BN$$

I_{th} is proportional to the ratio between threshold carrier density (n_{th}) and the carriers recombination lifetime τ

$$I_{th} \propto \frac{n_{th}}{\tau} = n_{th}(A + Bn_{th})$$

Since:

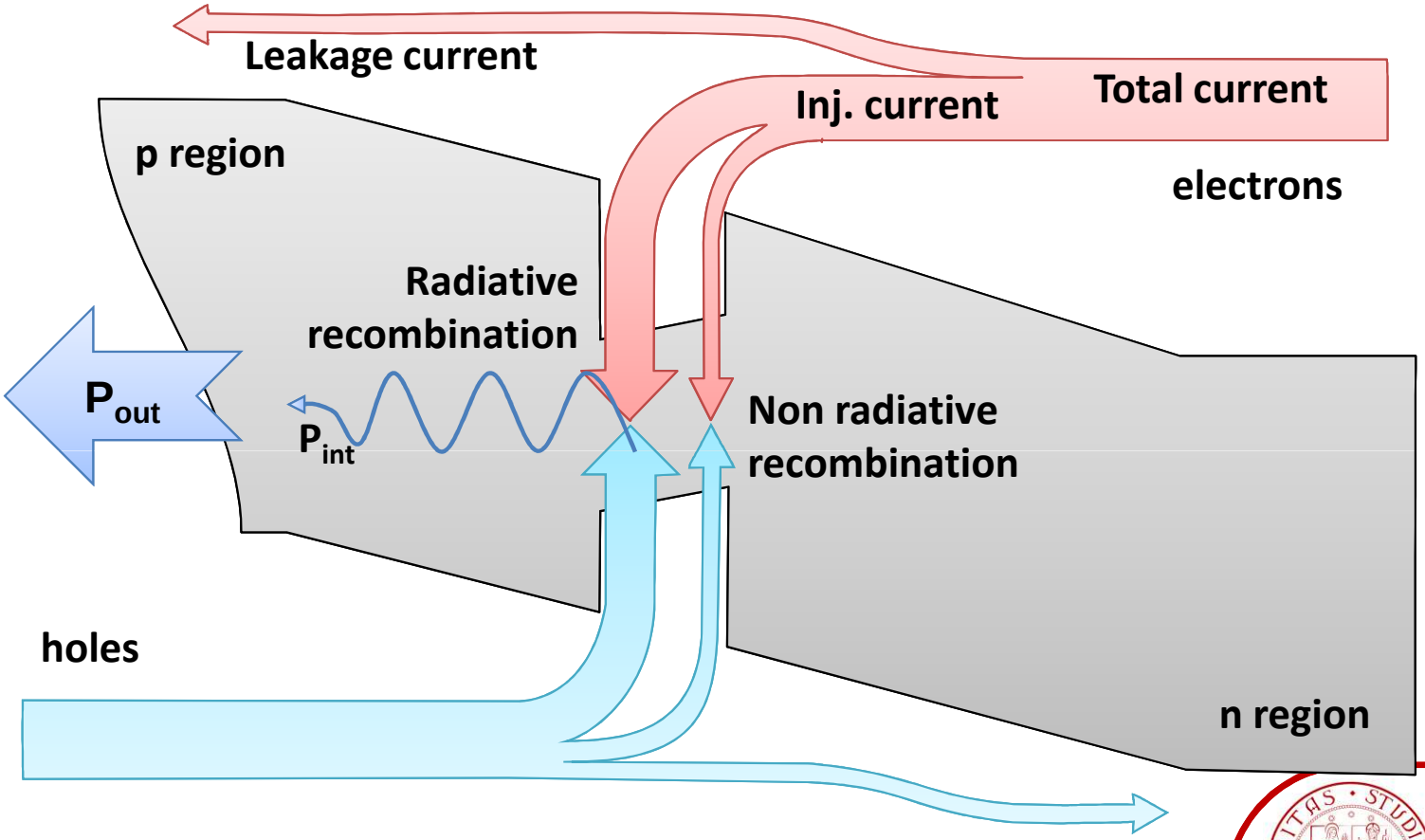
- Both OP_{sub} and I_{th} depend on the balance between radiative and non-radiative recombination events (τ)
- The variations of these two parameters have similar kinetics
- Coefficient *A* is related to the defectiveness of the active layer (increasing during stress, Tomiya 2004)

I_{th} and OP_{sub} variation can be attributed to the increase of the non-radiative recombination rate *A*

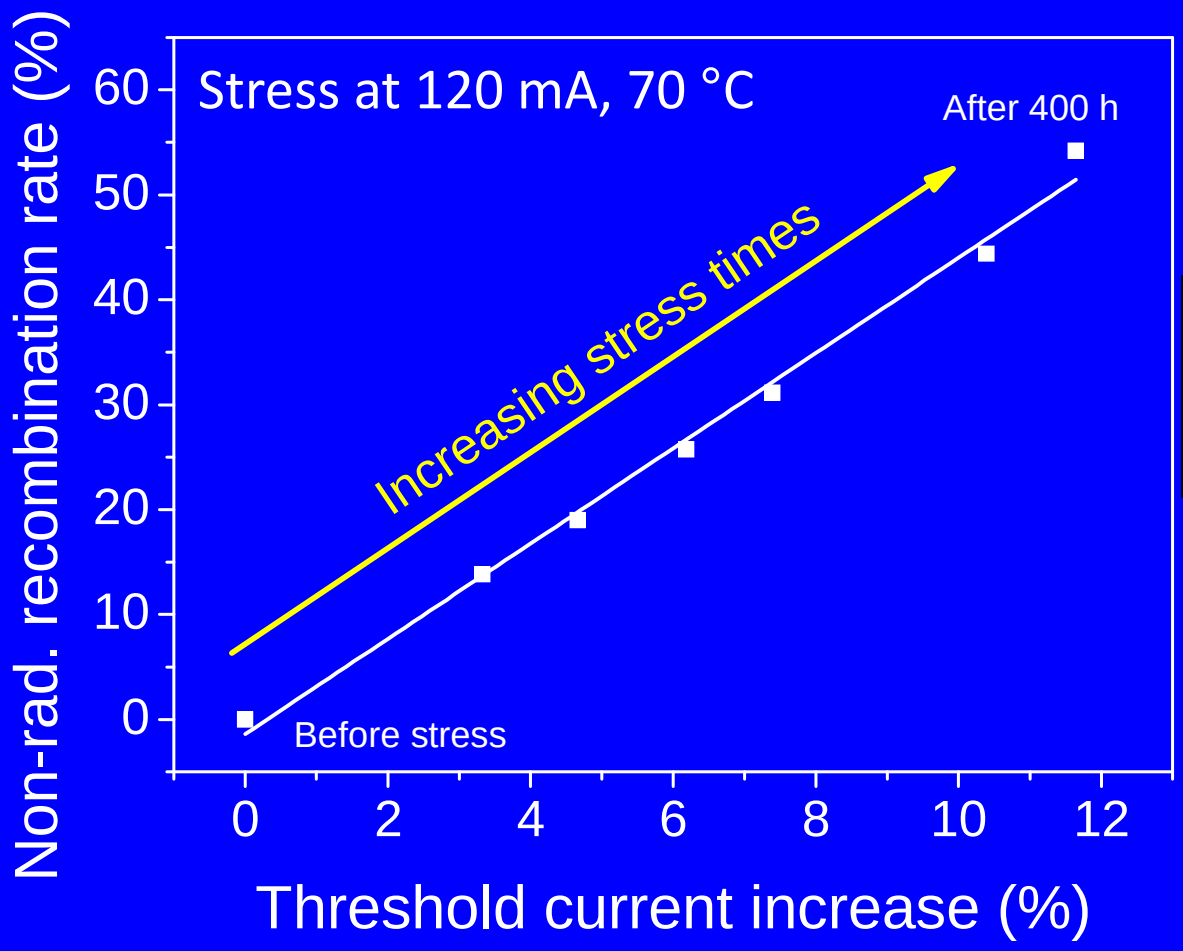
Measurement details: τ_{nr} extrapolation

Purpose: Extrapolate non-radiative lifetime during ageing

Method: Proposed by Van Opdorp in 1981
Based on subthreshold Optical measurement



τ_{nr} during stress time



Linear correlation between the increase in I_{th} and A

$$I_{th} \propto n_{th}(A + Bn_{th})$$

Previous reports (Tomiya2004, Marona2006) → The decrease in τ_{nr} can be correlated to the increase of the concentration of defects in the active region of the devices

→ Which is the driving force for degradation?

Measurement results: Correlation of I_{th} and τ_{nr}

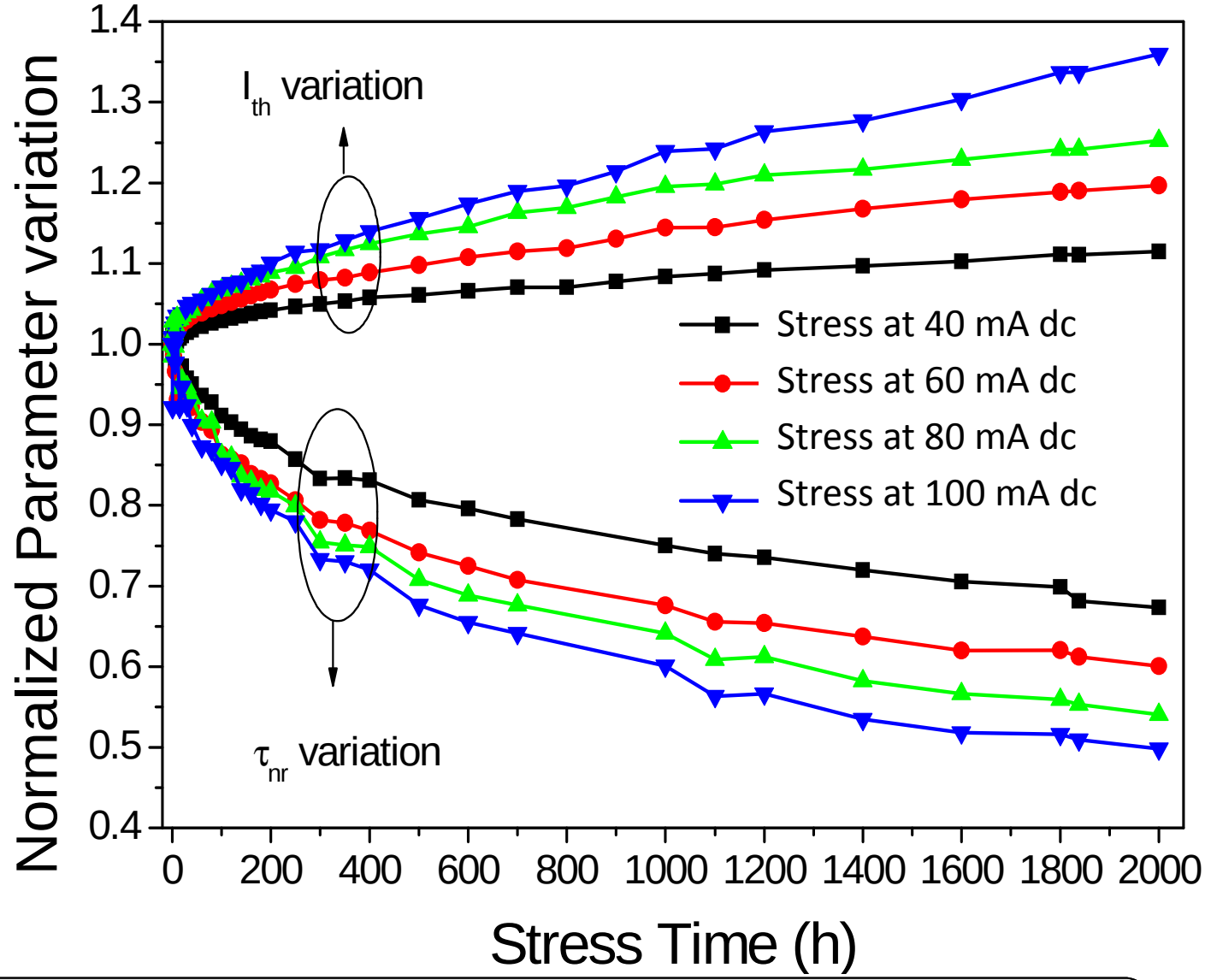
Constant current ageing,
Fixed temperature = 70°C

Comparison between:

I_{th} increase

τ_{nr} decrease

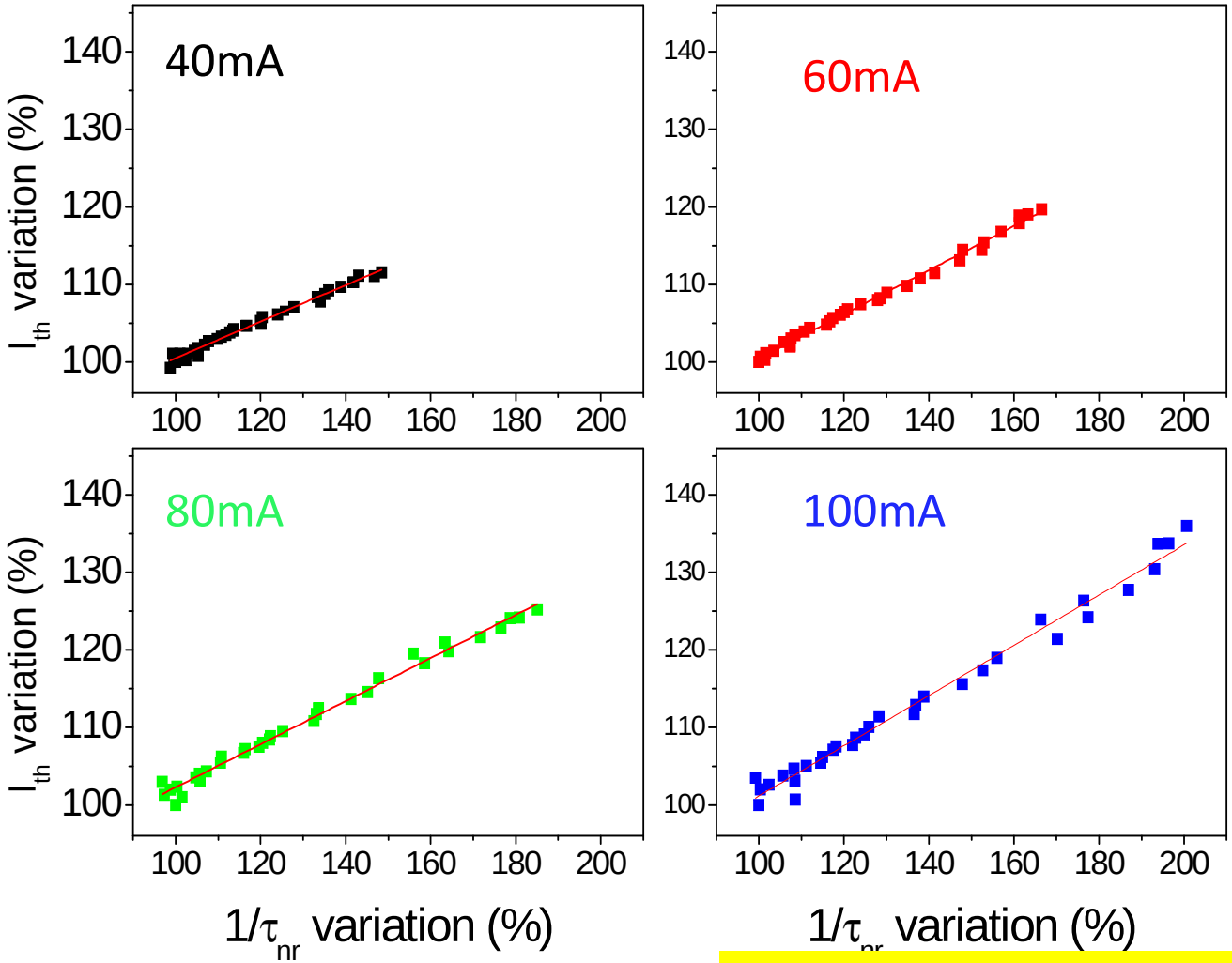
Parameters vary according to the **square root of time**



I_{th} and τ_{nr} are correlated during device degradation
Which is the effects of different chaning ageing current?

Measurement results: Effects of ageing current

Plot of I_{th} increase as a function of $1/\tau_{nr}$



The correlation is confirmed

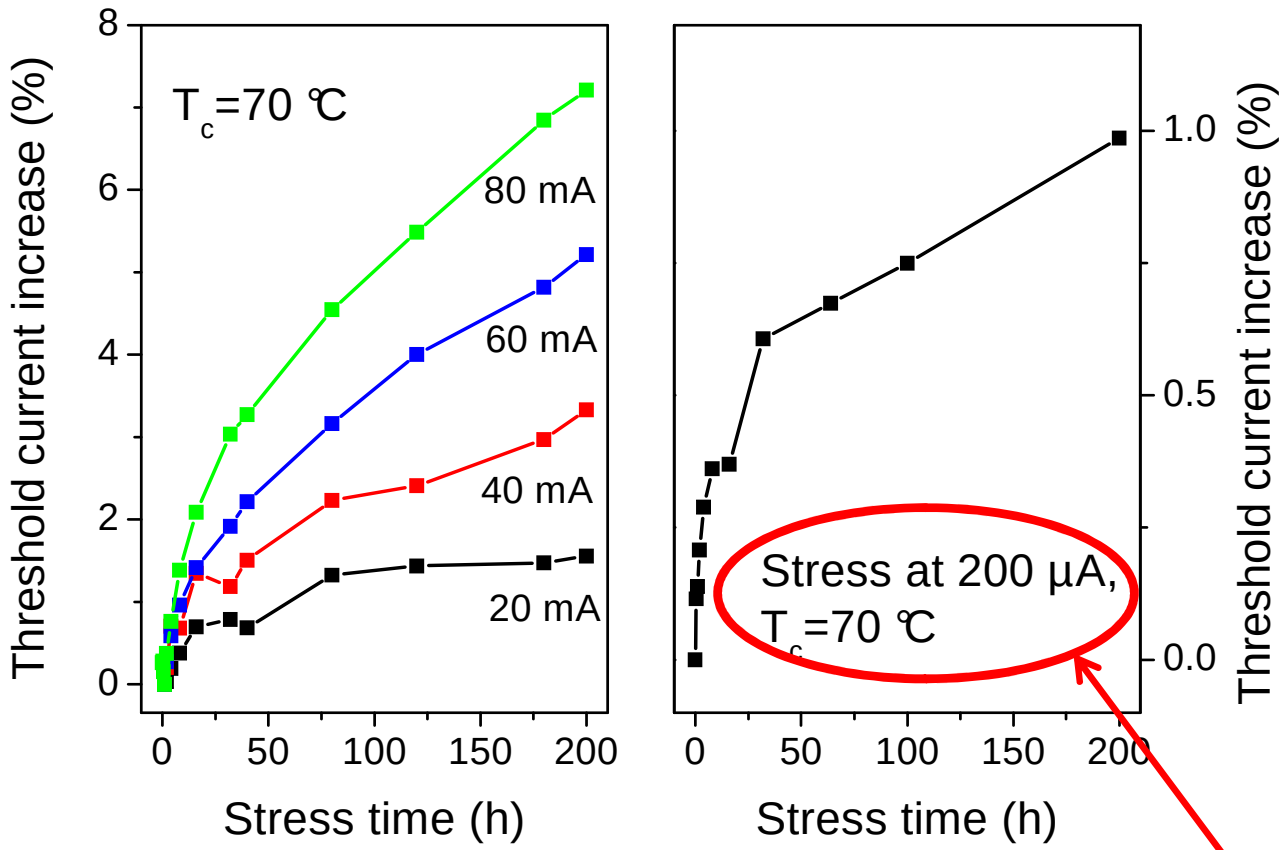
Compatible with trasparency condition

$$I_{th} = qV\left[(1/\tau_{nr})n_{th} + Bn_{th}^2\right]$$

The two mechanisms have the same dependence on the driving currents

Trivellin et al, ESREF 2009

Effect of stress current on the degradation kinetics



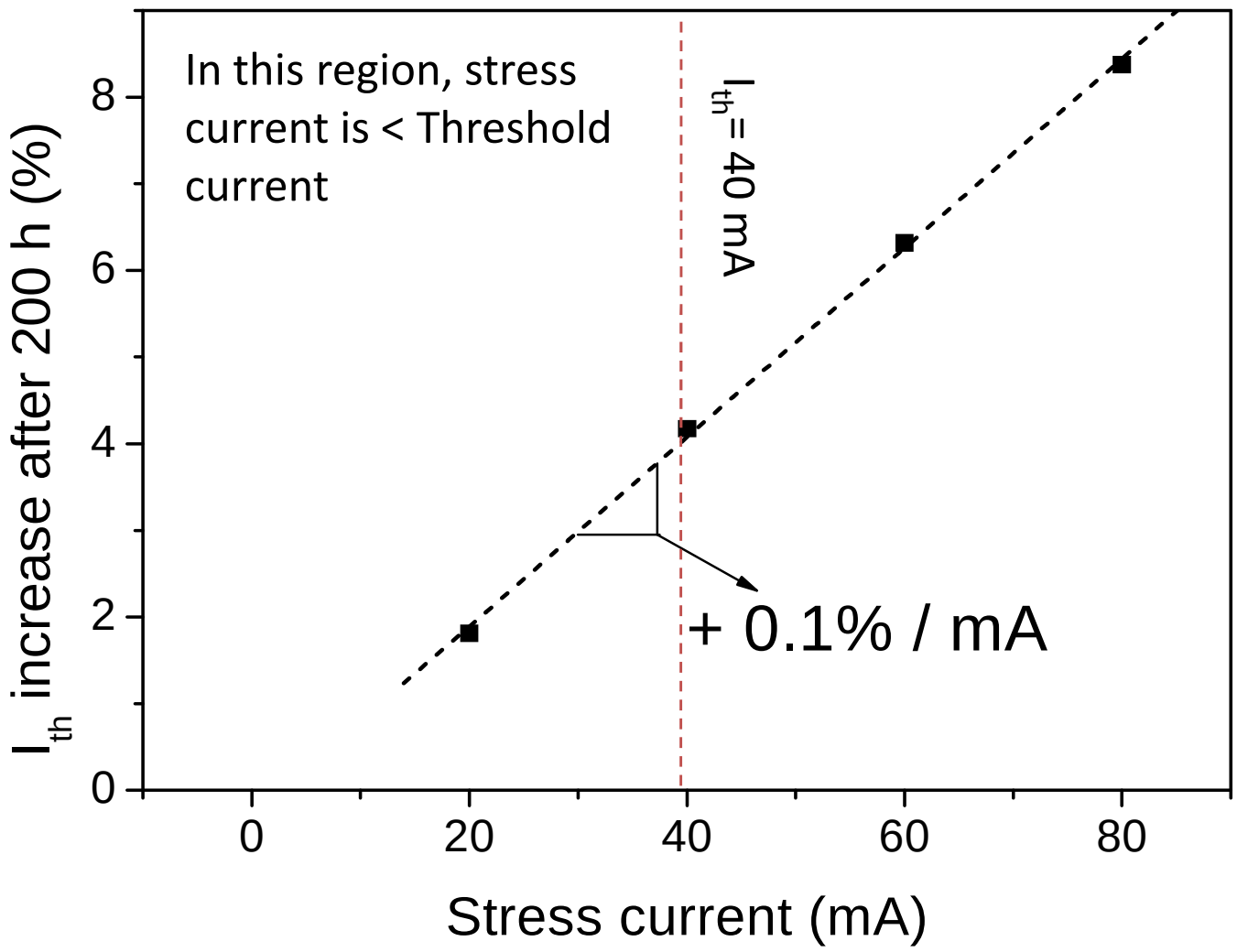
Stress conditions:

- Case temperature=70 °C
- Stress current=200µA-80 mA
- Maximum junction temperature = 82 °C

Increasing stress current determines faster degradation

- Degradation kinetics are strongly determined by the stress current level
- At 70 °C → Threshold current is 40 mA
- Degradation occurs also below lasing threshold (and at 200 µA!), i.e. without strong optical field and self-heating→ Role of current?

Degradation Rate vs Stress Current

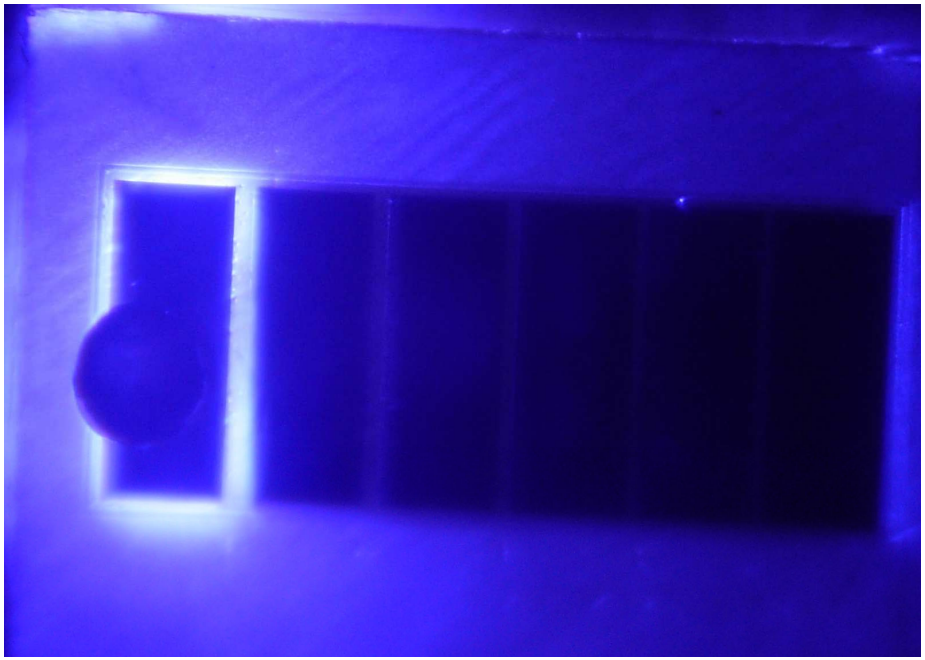


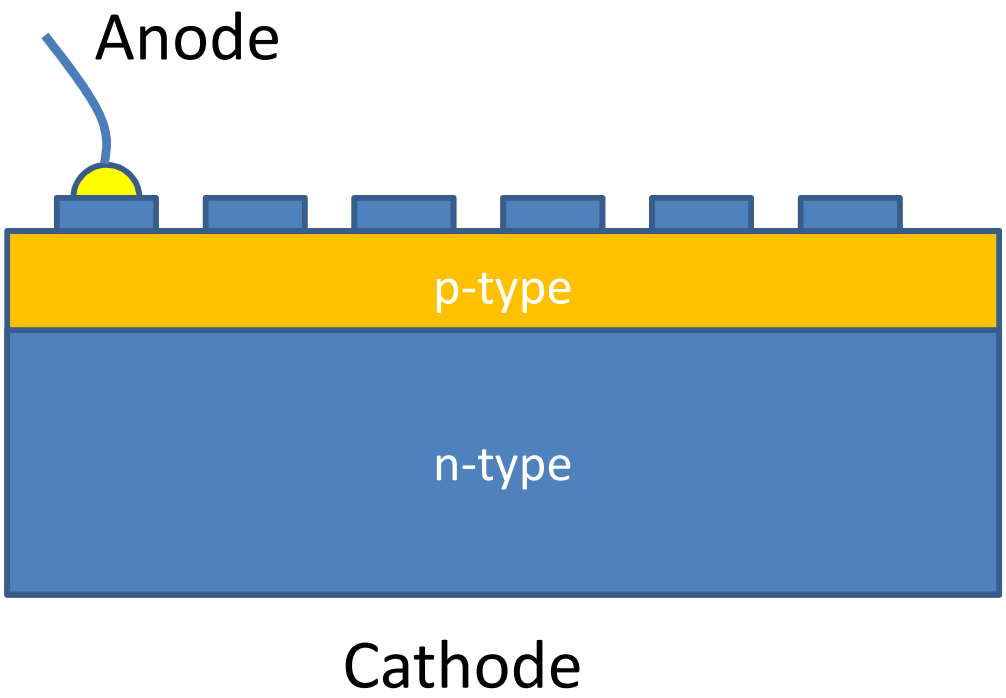
At the stress temperature (70 °C), threshold current is 40 mA

Degradation rate = I_{th} increase after 200 h of stress

- Degradation occurs also below threshold
- Degradation rate is strongly determined by stress current level

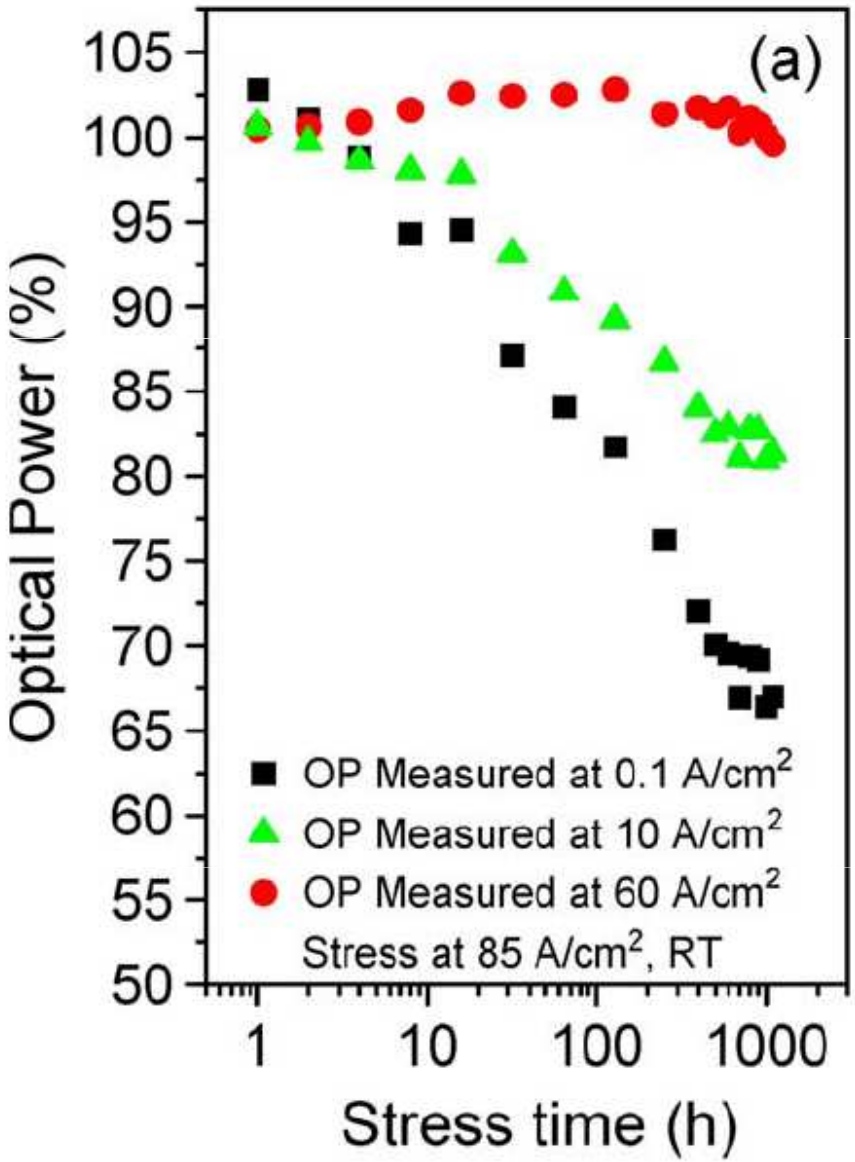
Study of the degradation of the active region by C-V measurements

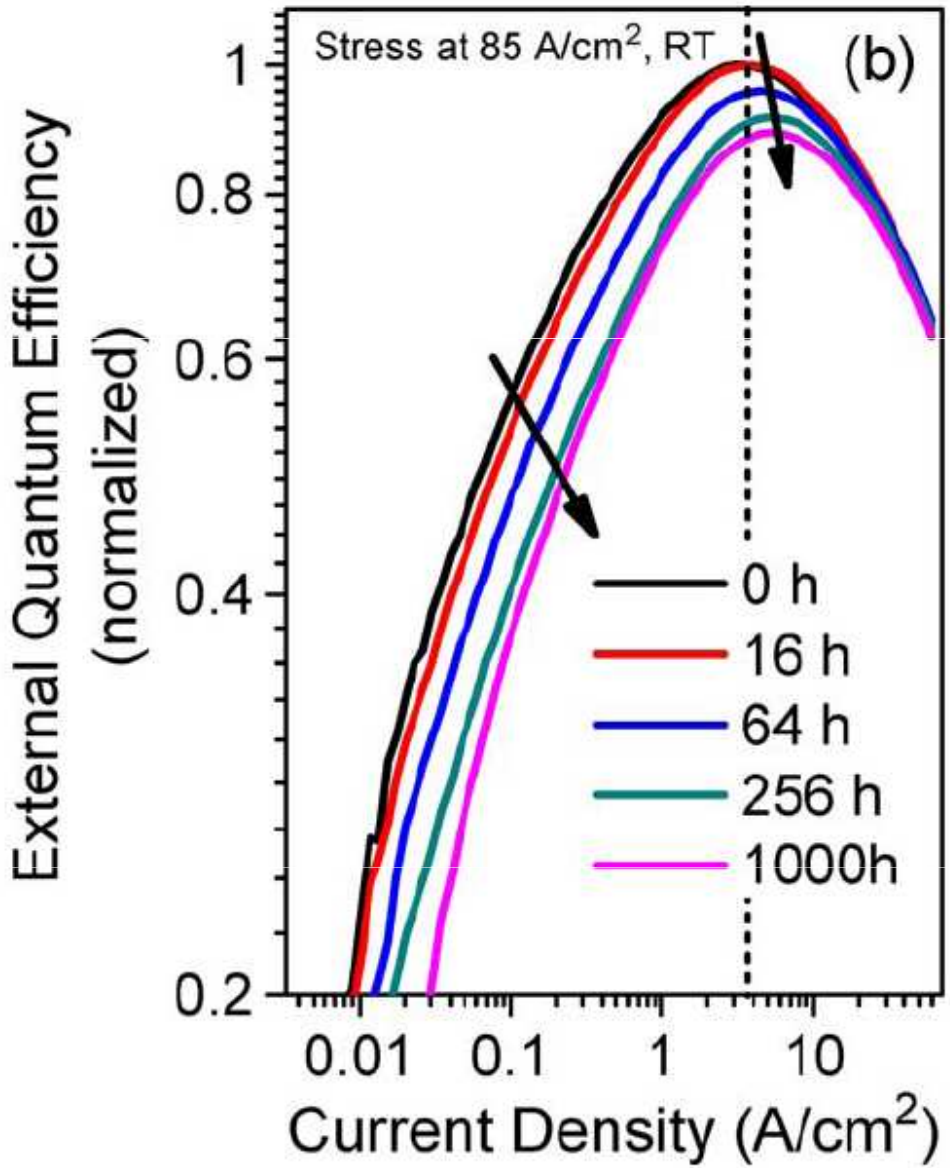




The area for the C-V measurements is close to 500 x 75 μm^2

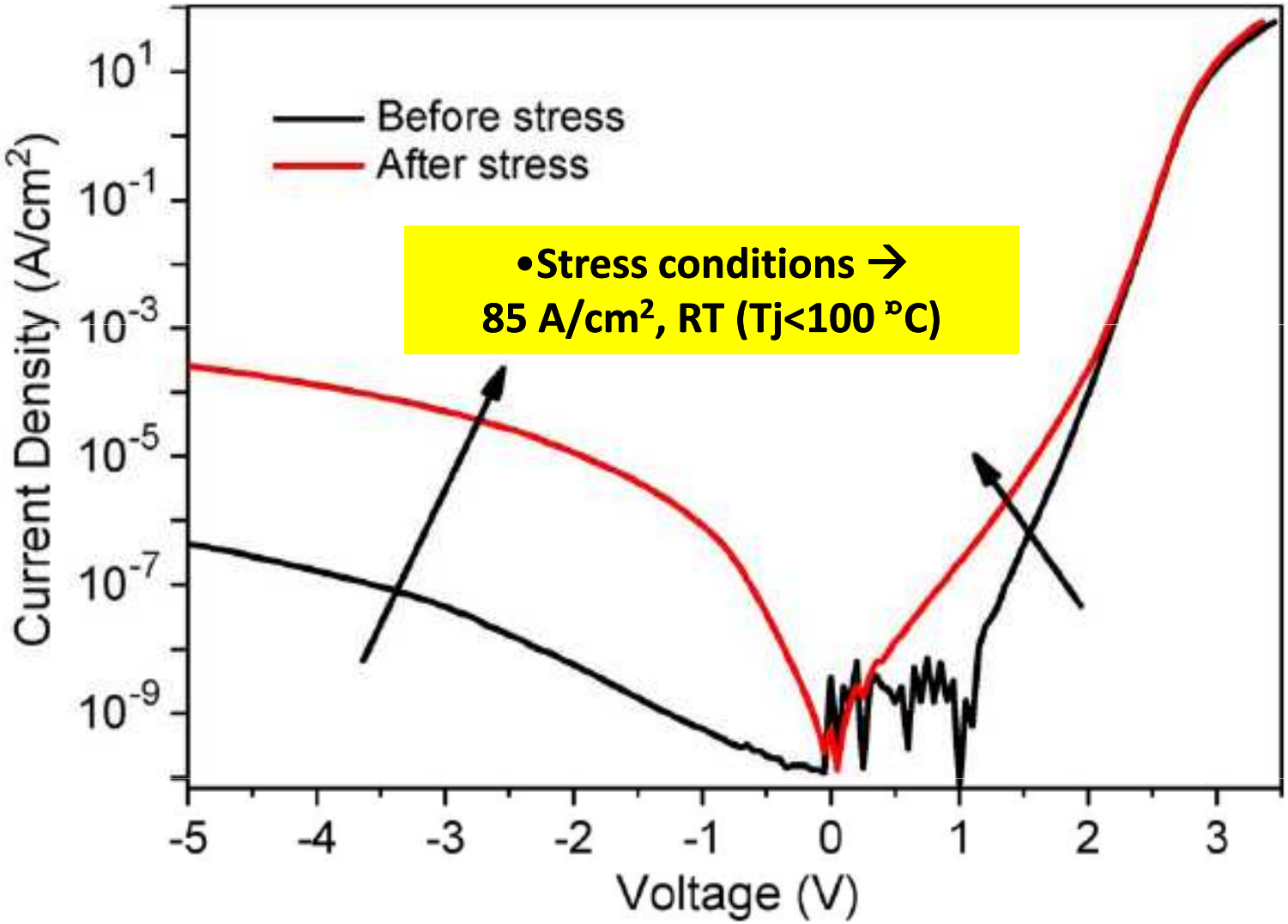
Constant current stress – Output power during stress





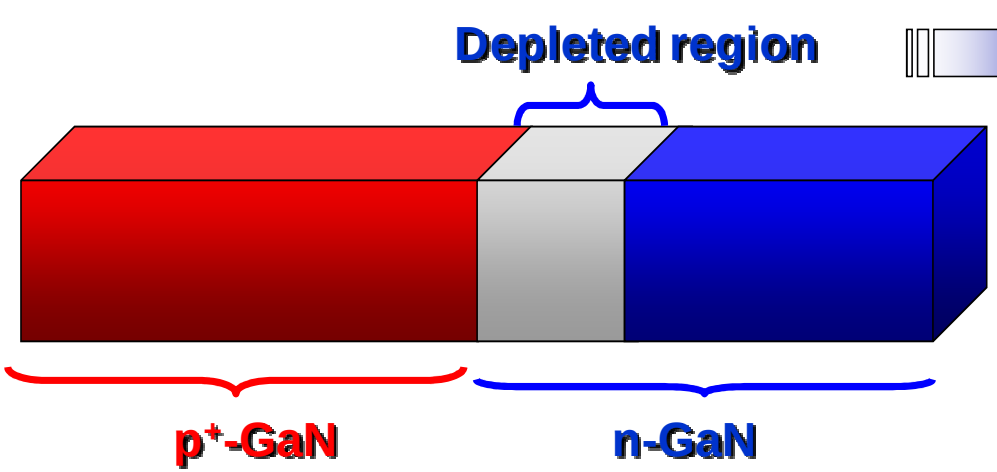
•Stress conditions →
85 A/cm², RT (Tj<100°C)

Current ageing – Current – Voltage Characteristics



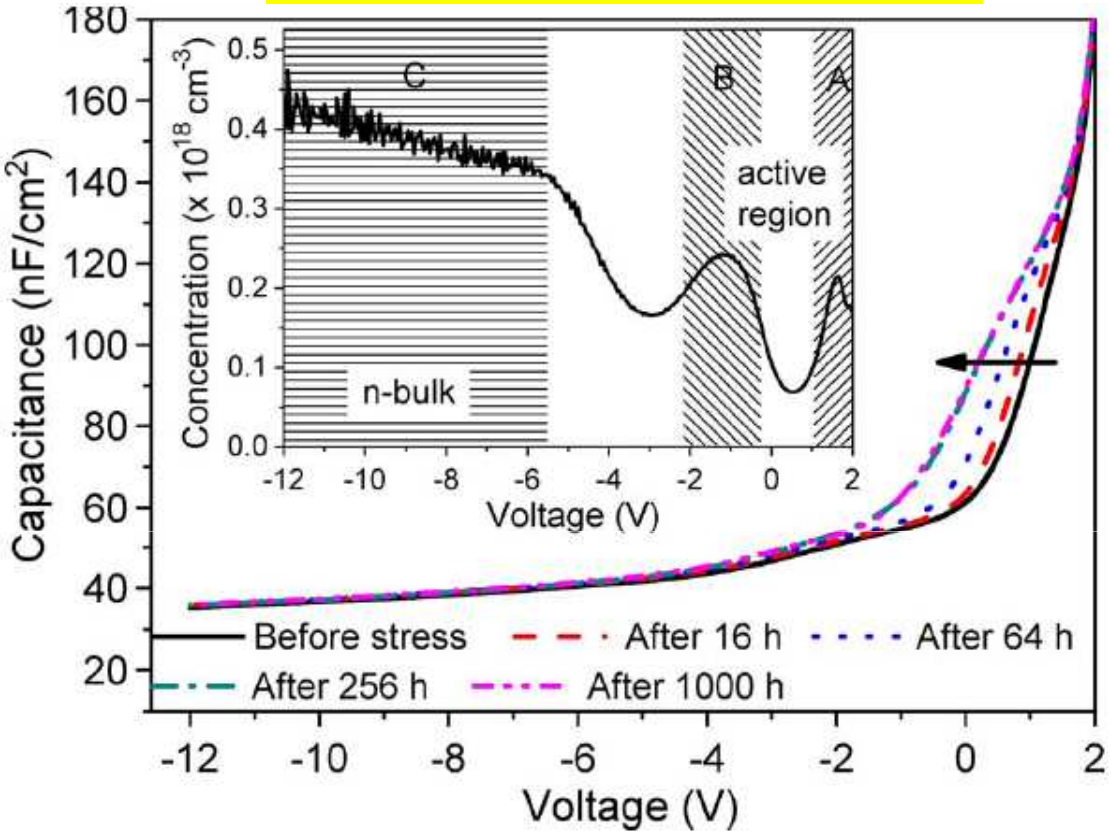
•Stress induces significant modifications in the electrical characteristics of the devices (increase in reverse and generation-recombination components)

Heterostructure degradation → C-V measurements



Information about charge distribution

- **Stress conditions → 85 A/cm², RT (Tj<90°C)**

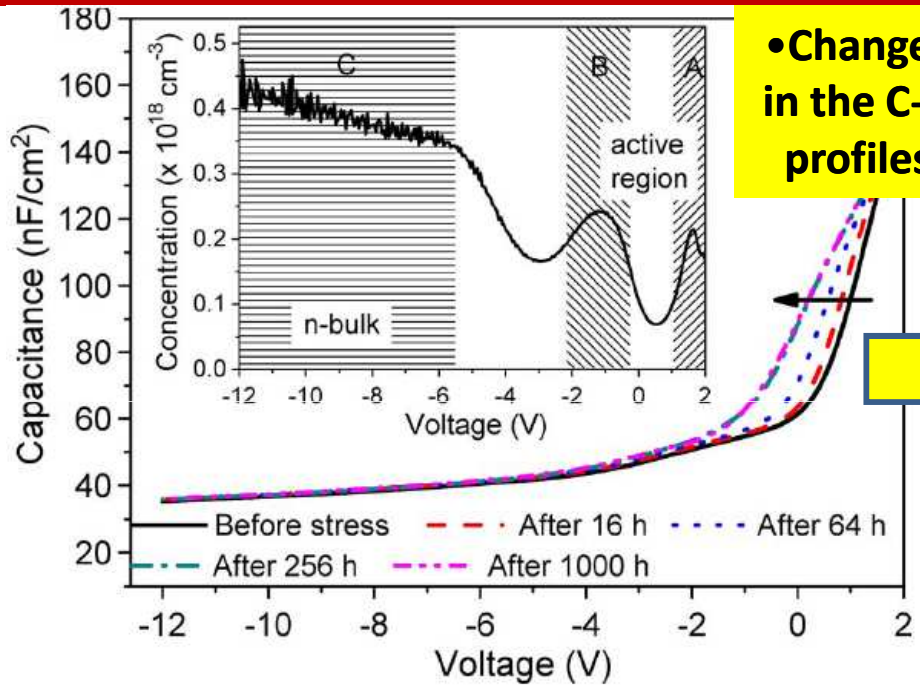


Apparent charge distribution

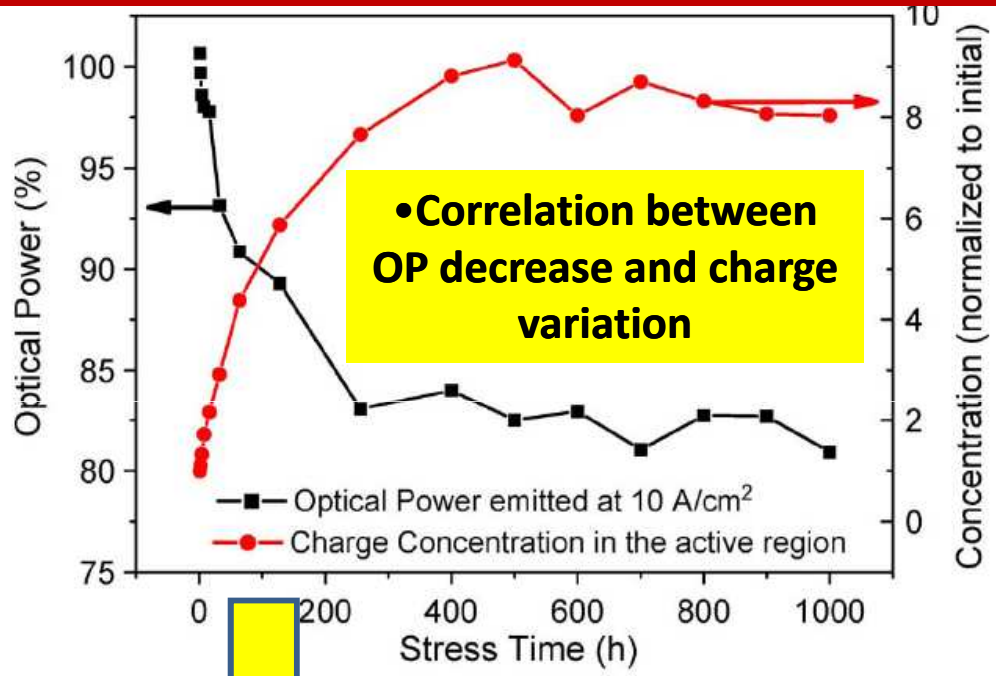
- **Detection of changes of the charge profile induced by stress**

- A. Castaldini, IWN 2004
- Phys. Stat. Sol. (c) 2, 2862 (2005)
- J. Appl. Phys. 99, 053104 (2006)

Correlation between OP loss and C-V data

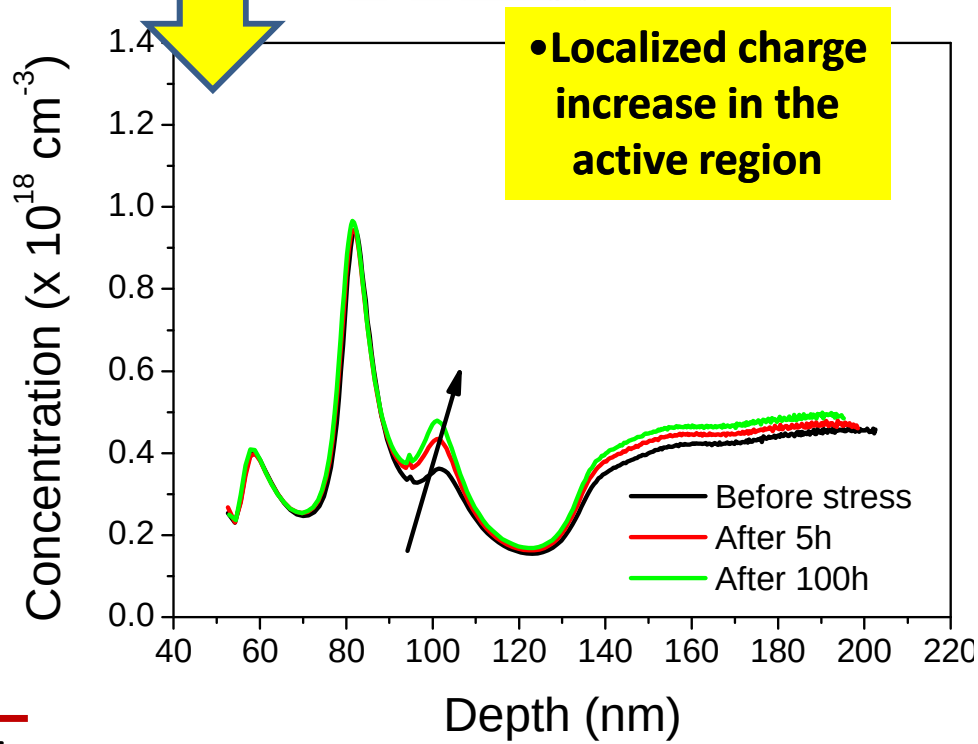


•Changes in the C-V profiles



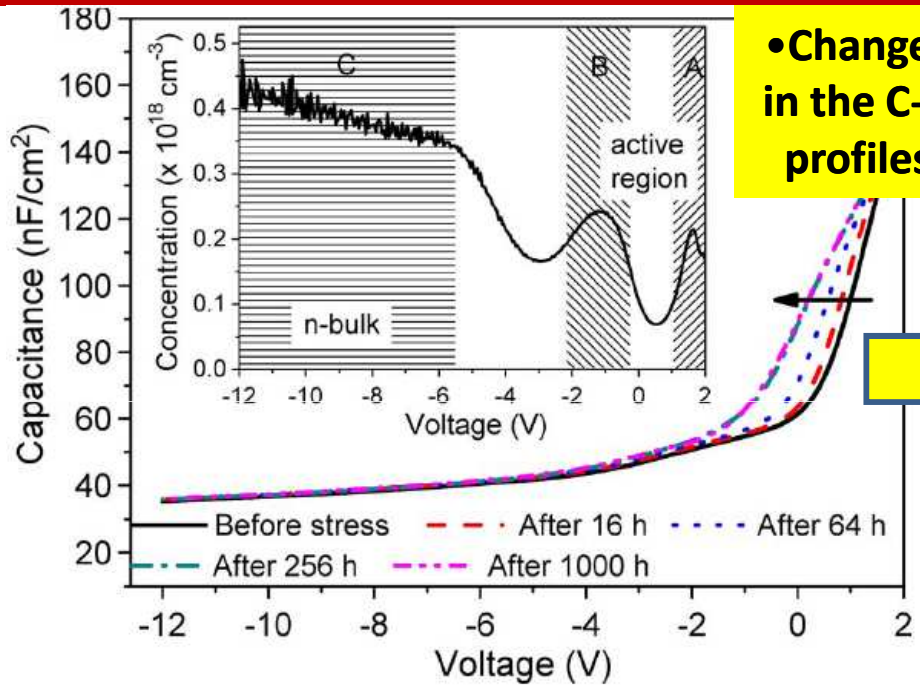
•Correlation between OP decrease and charge variation

1. **Stress induced a significant increase in the C-V curve (concentrated in the active region)**
2. **Strong correlation between OP decrease and charge variation**
3. **DLTS analysis indicated that stress induces the increase of a DL peak (detected DLs have Ea in the range 250-900 meV)**

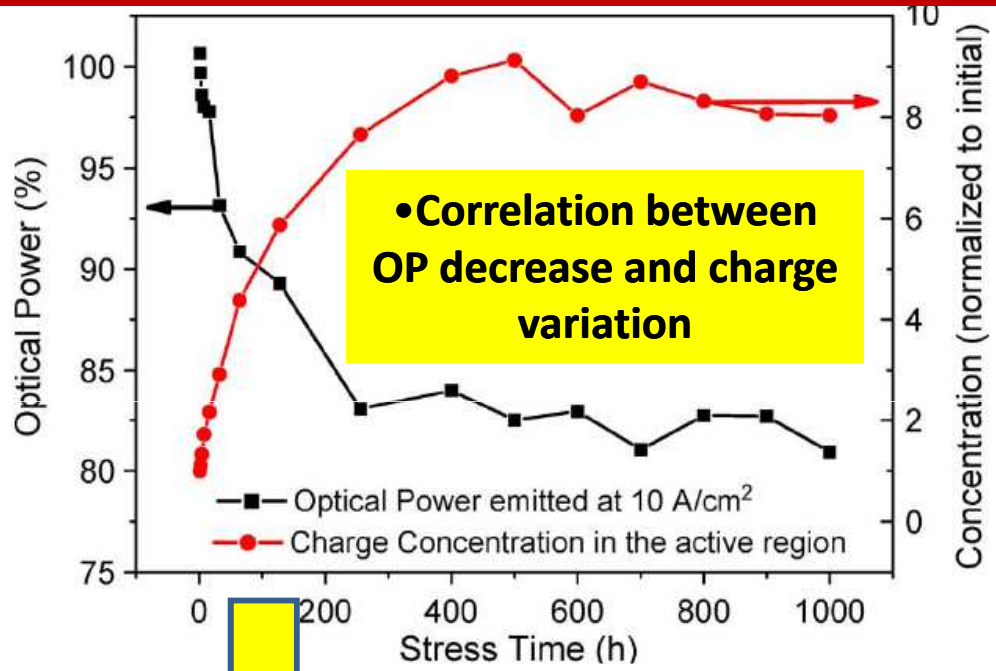


•Localized charge increase in the active region

Correlation between OP loss and C-V data



•Changes in the C-V profiles



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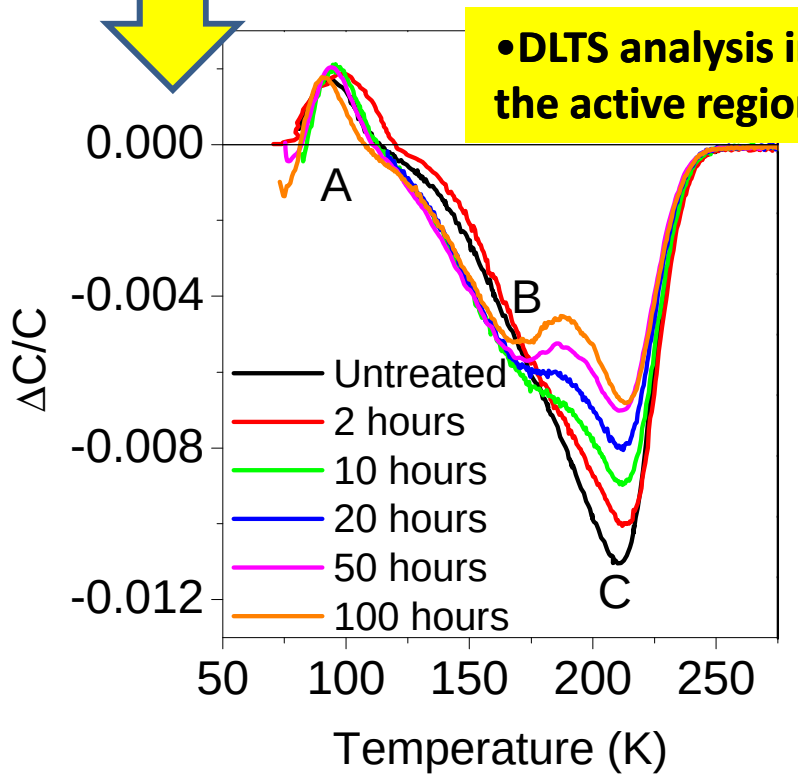
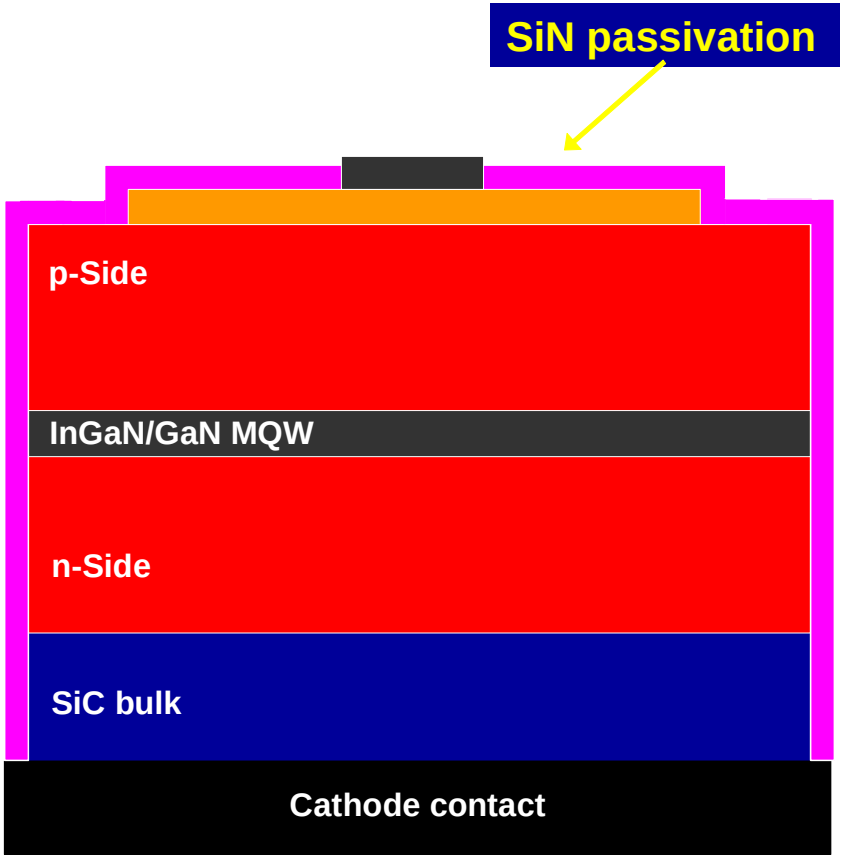


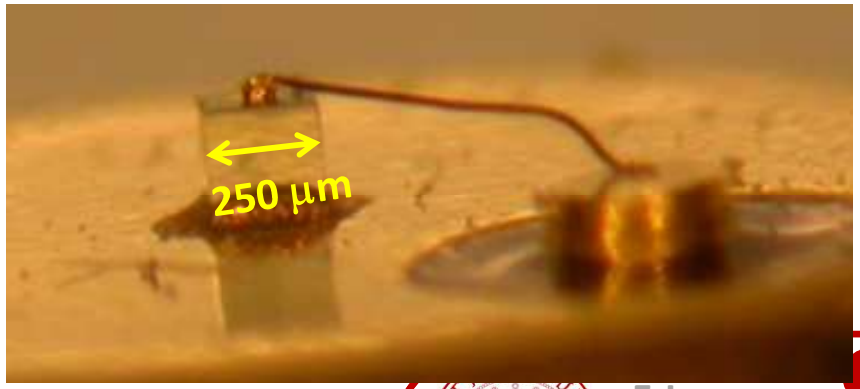
•DLTS analysis in the active region

Gradual degradation
-
Degradation of the contacts

A case study: degradation of the ohmic contacts of LEDs

- **Devices with vertical structure grown on SiC**
- **Bare LED chips mounted on TO18 package**
- **LEDs covered with SiN passivation to reduce surface leakage and encapsulate the devices**
- **LEDs submitted to stress at high temperatures (180<T<250 ℃)**





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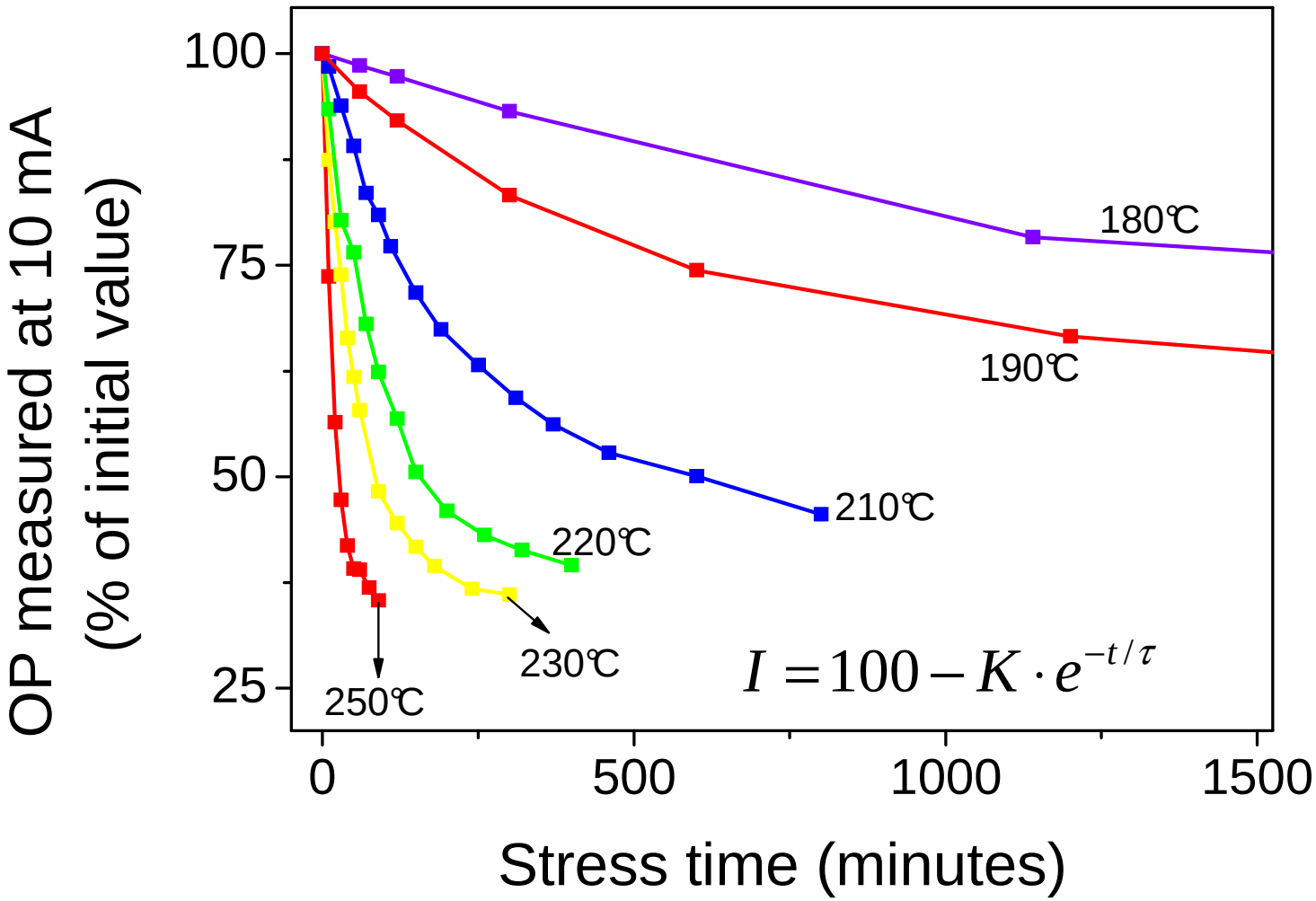
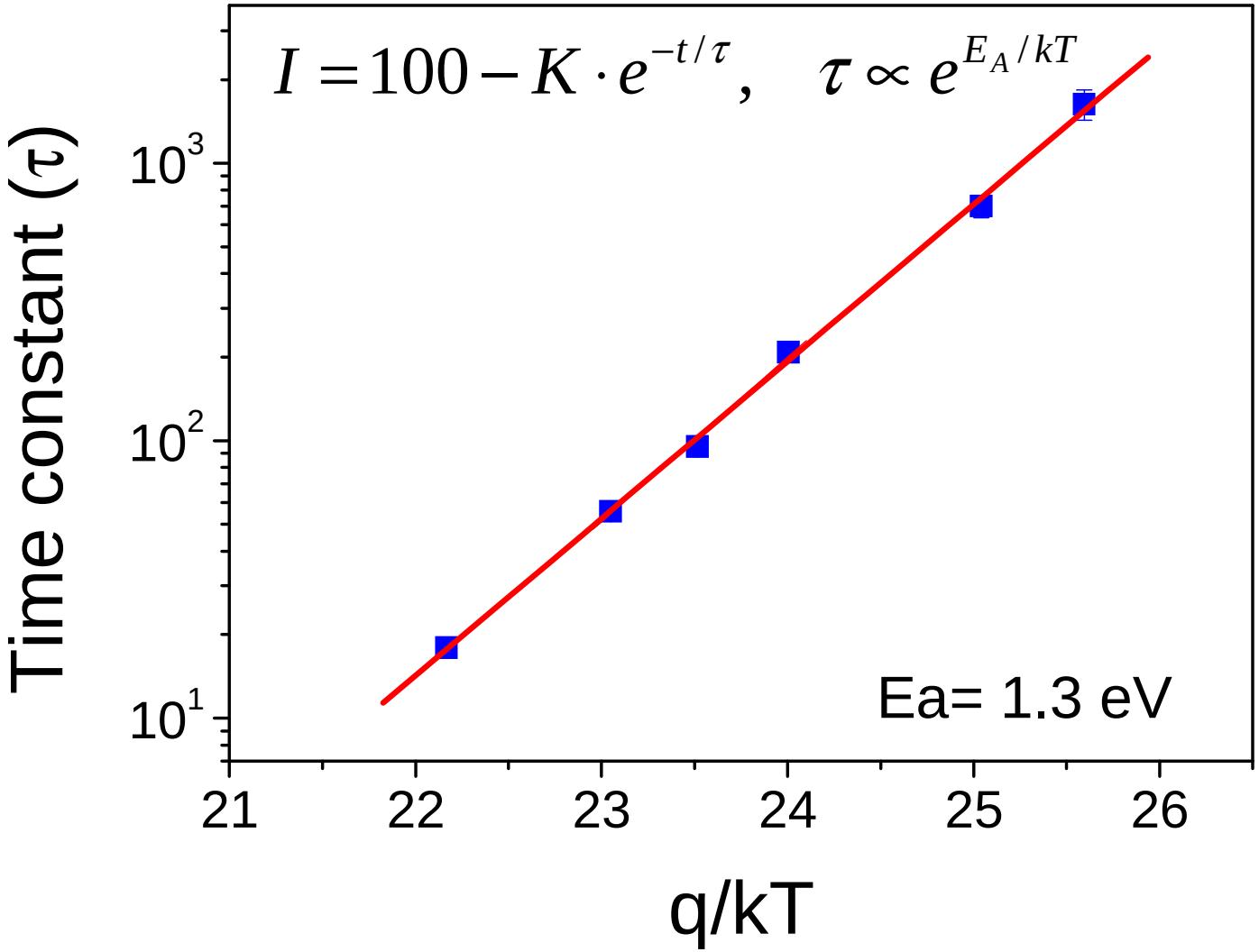
Stress of bare LED chips – OP during stress



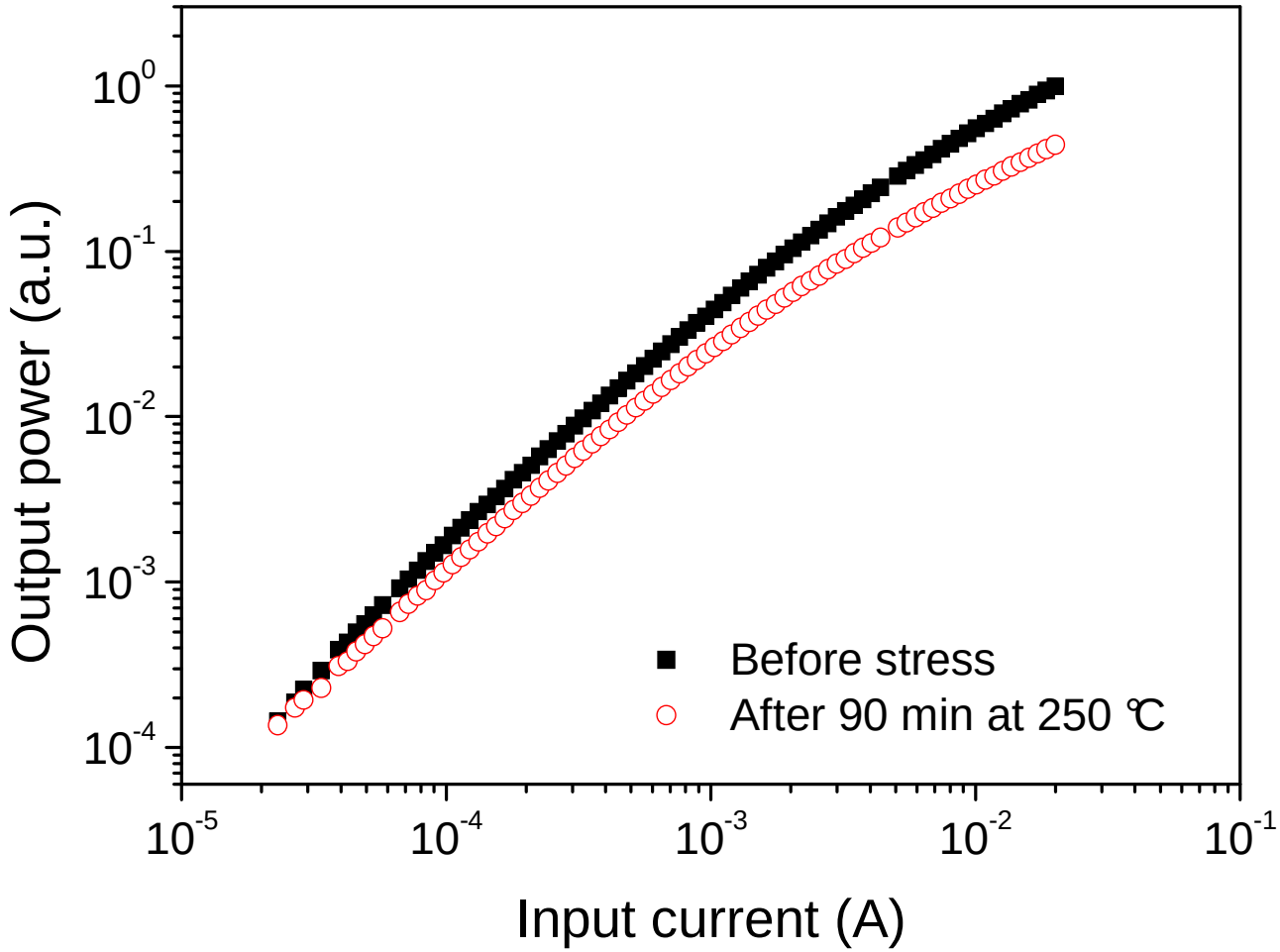
Increasing stress temperature determines stronger degradation

Stress of bare LED chips – Activation energy



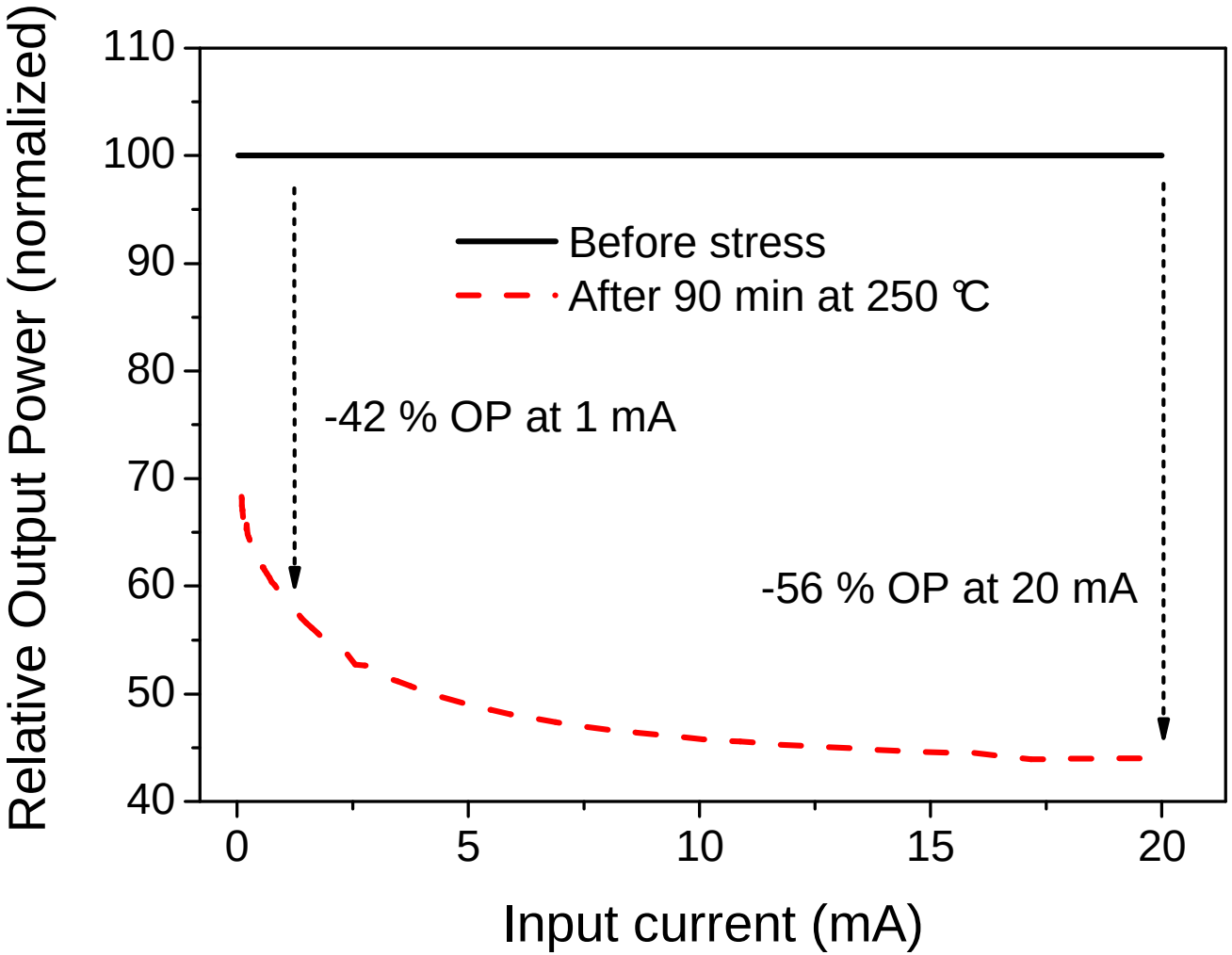
OP degradation is thermally activated (Ea=1.3 eV)

Stress of bare LED chips – L-I curves



- **Optical power decrease was more prominent at high measuring current levels**

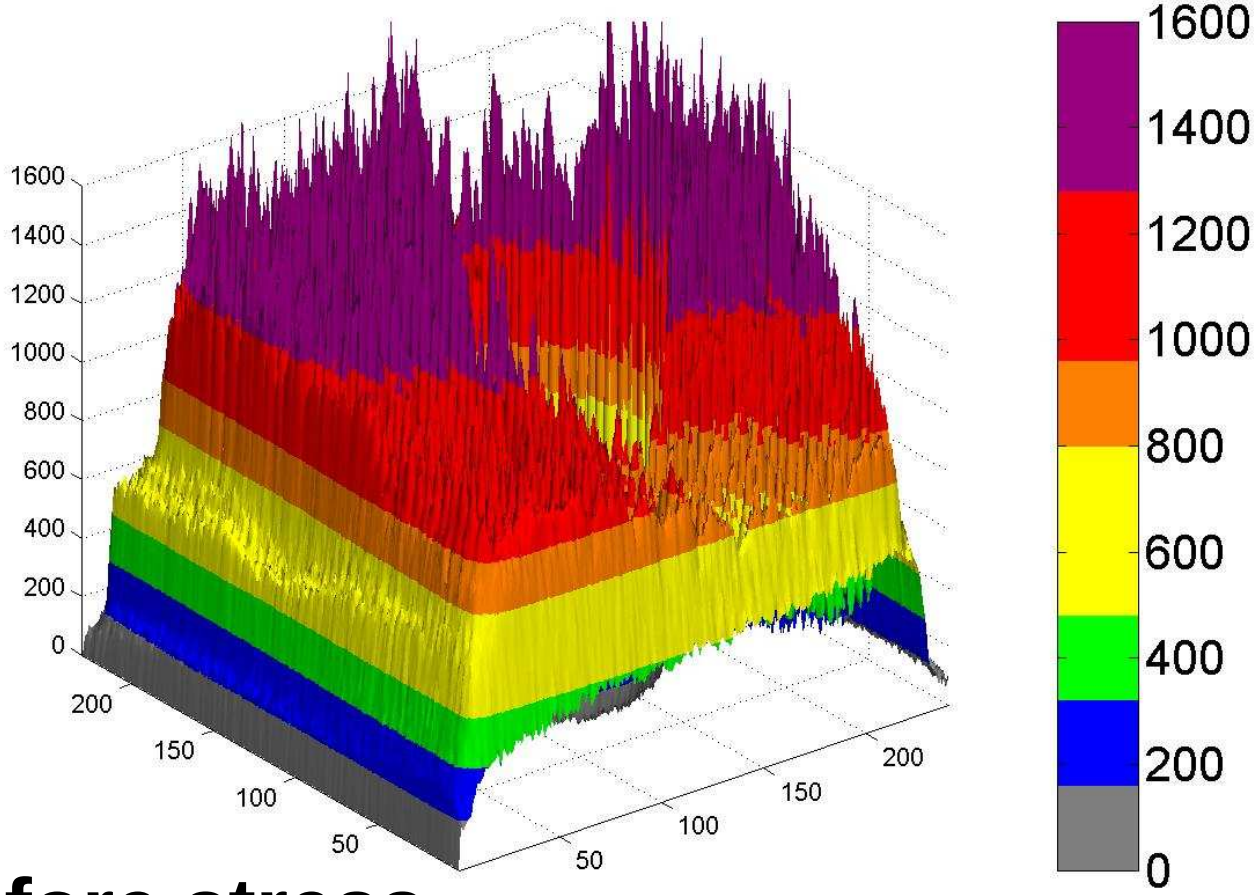
Stress of bare LED chips – Normalized L-I curves



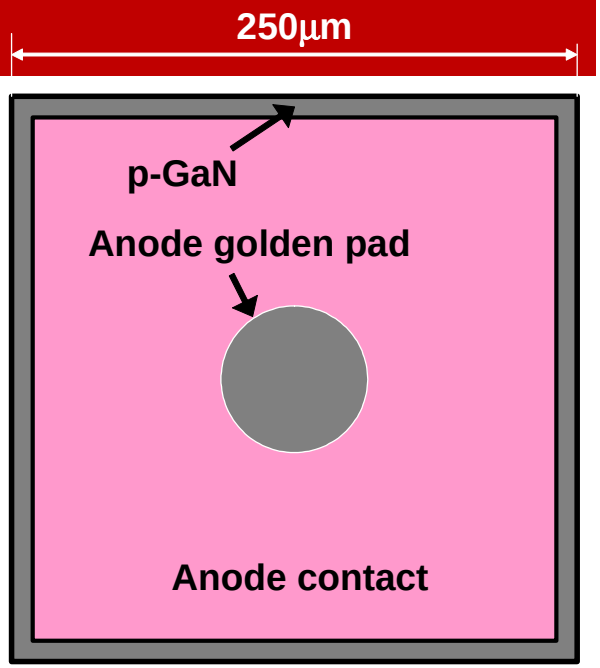
- **Optical power decrease was more prominent at high measuring current levels**

Stress of bare LED chips – EMMI

M. Meneghini et al., IEEE TED 53 (12), 2981-2987 (2006)



Before stress

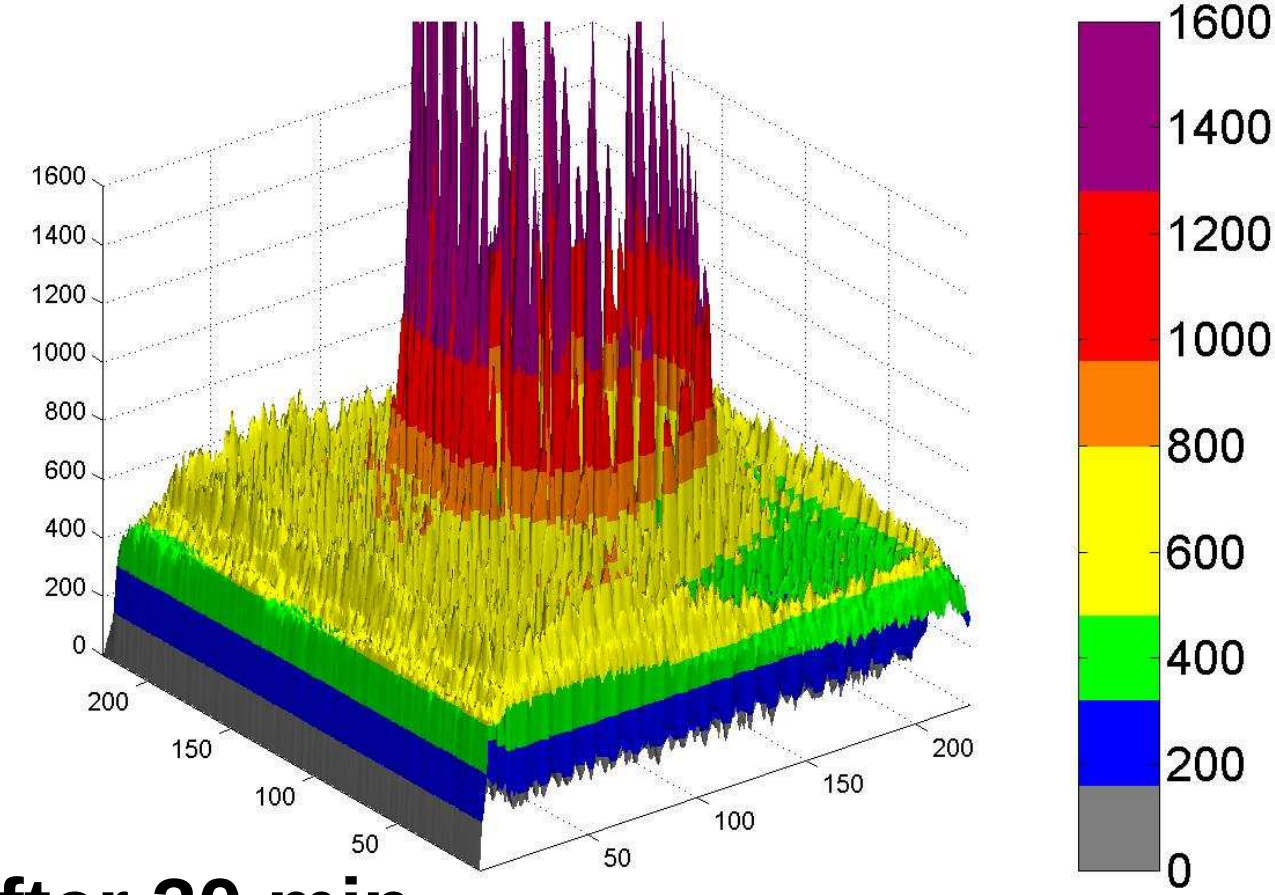


- **Stress at 250 ℃**
- **I=10 mA**

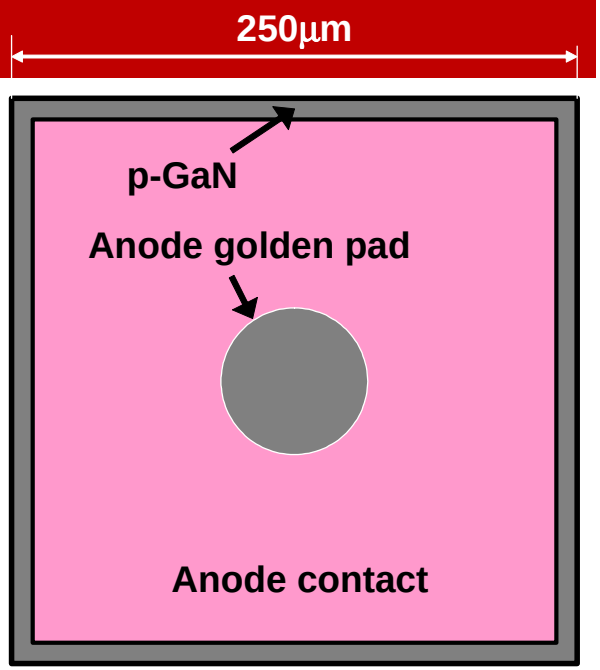
Before stress: uniform pattern

Stress of bare LED chips – EMMI

M. Meneghini et al., IEEE TED 53 (12), 2981-2987 (2006)



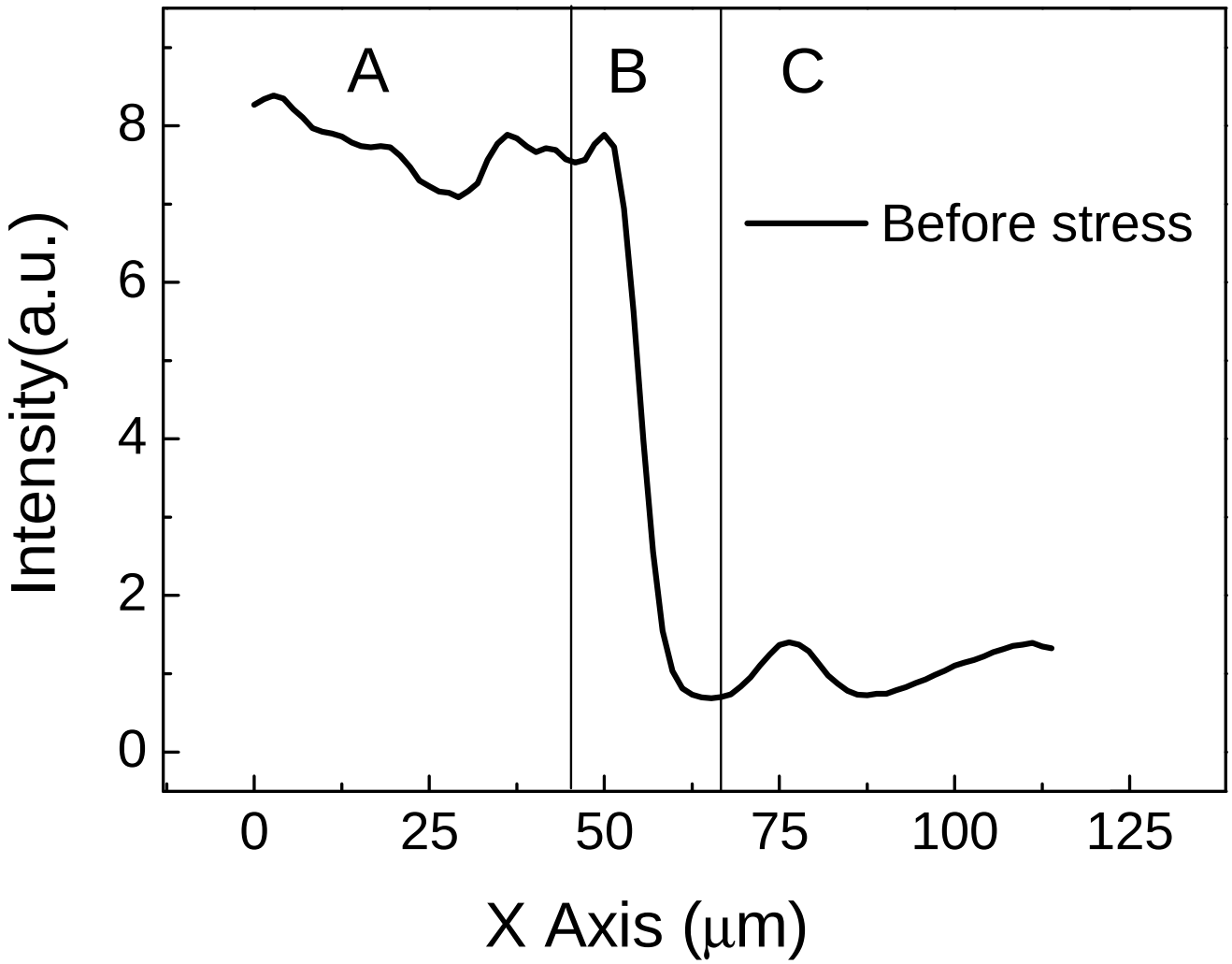
After 30 min

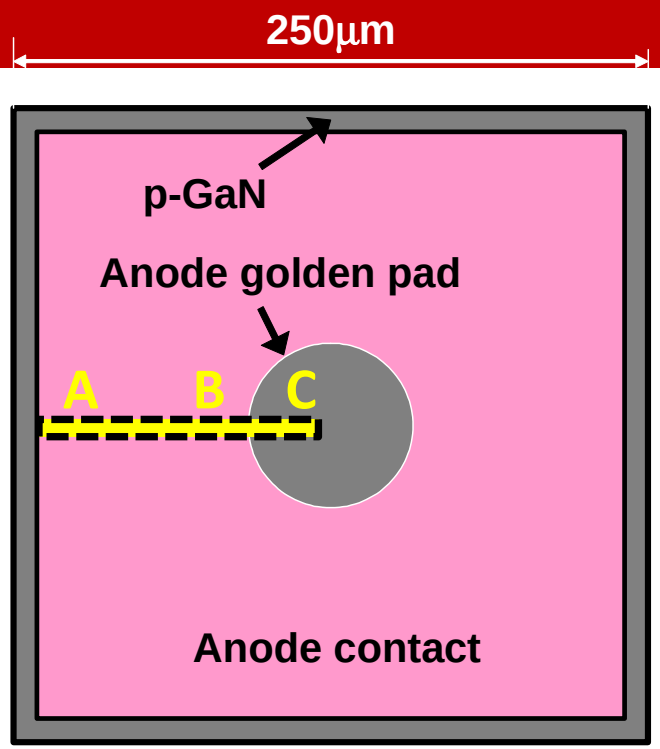


- **Stress at 250 ℃**
- **I=10 mA**

Before stress: uniform pattern

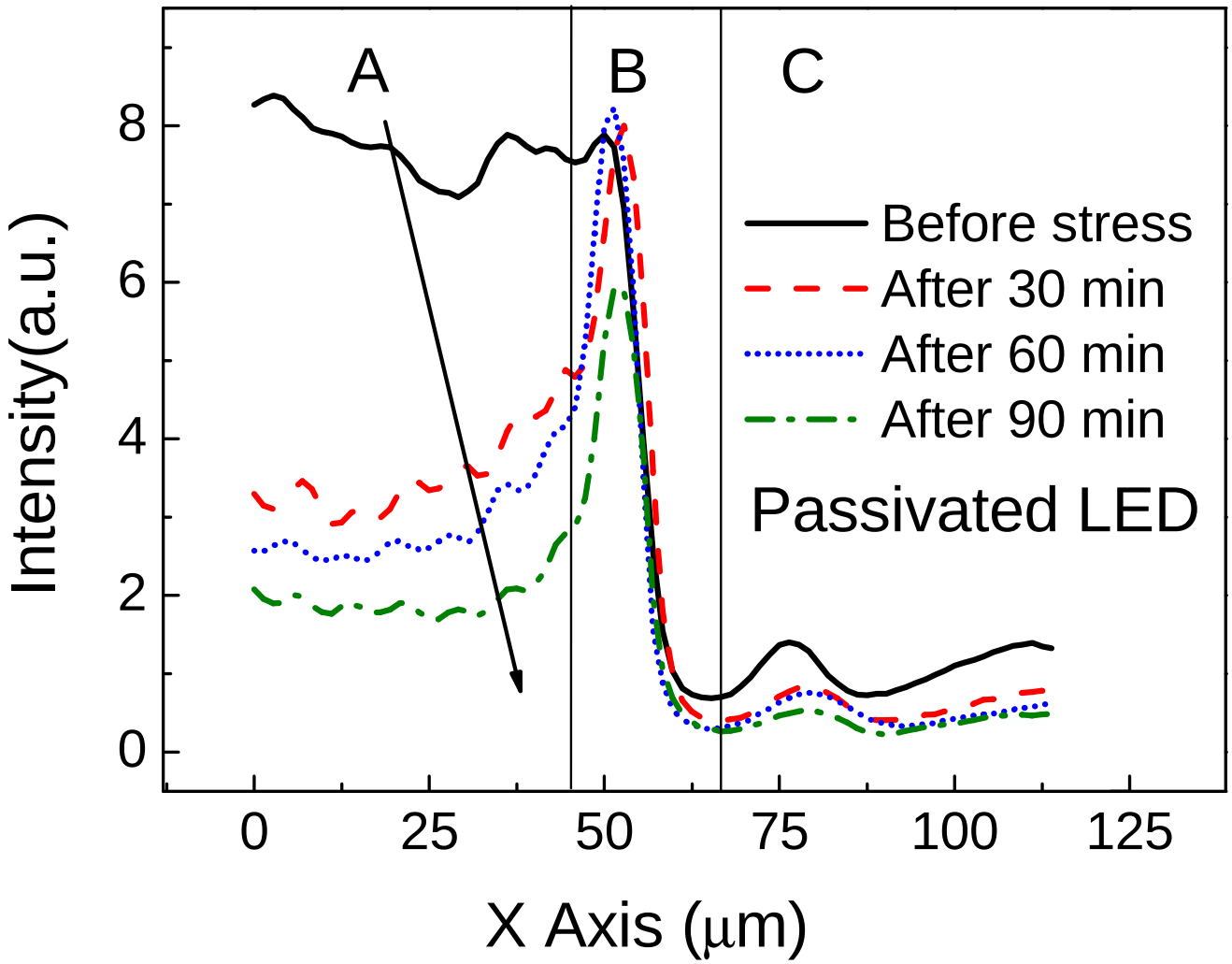
Stress of bare LED chips – EMMI

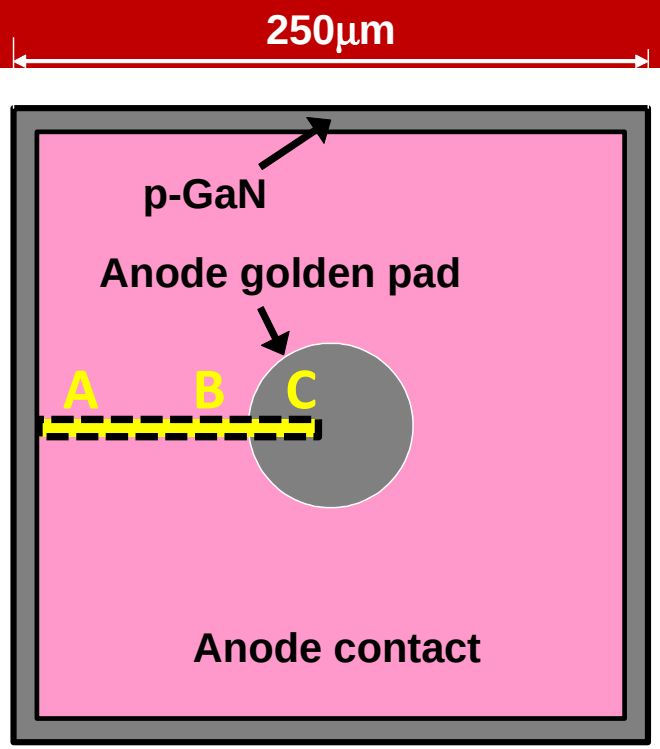




Before stress → Uniform emission profile in regions A and B

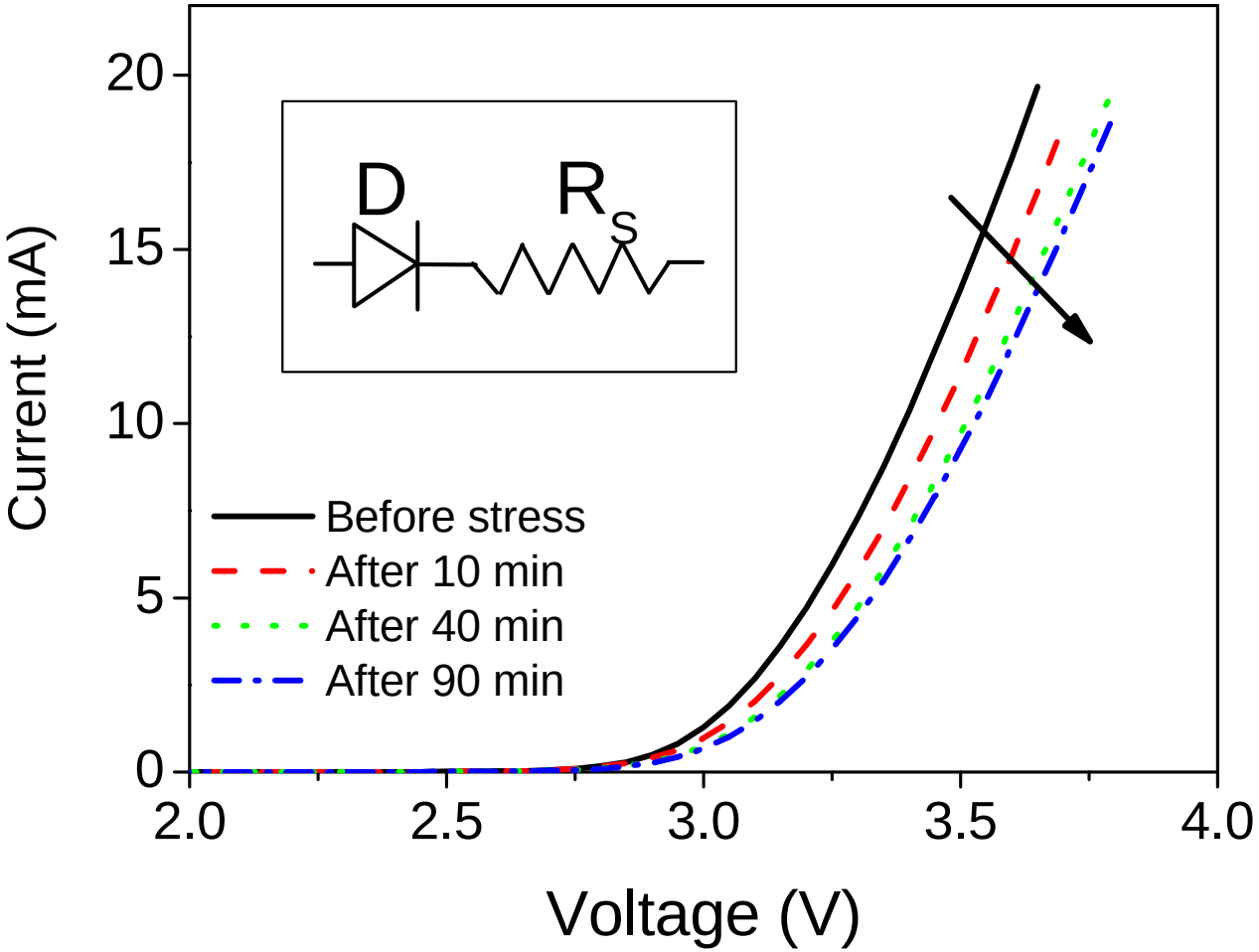
Stress of bare LED chips – EMMI





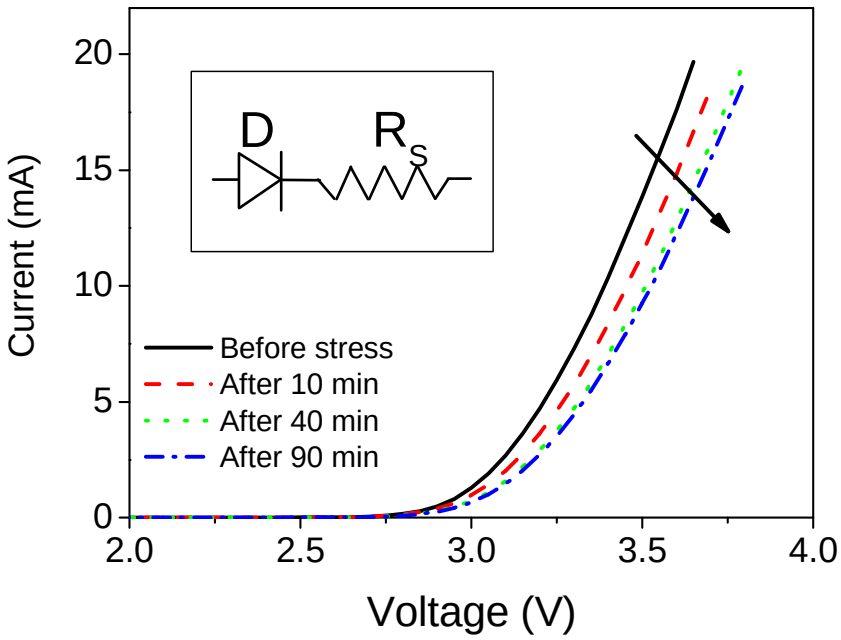
After stress → Strong decrease of the light emission in region A (far from the central pad)

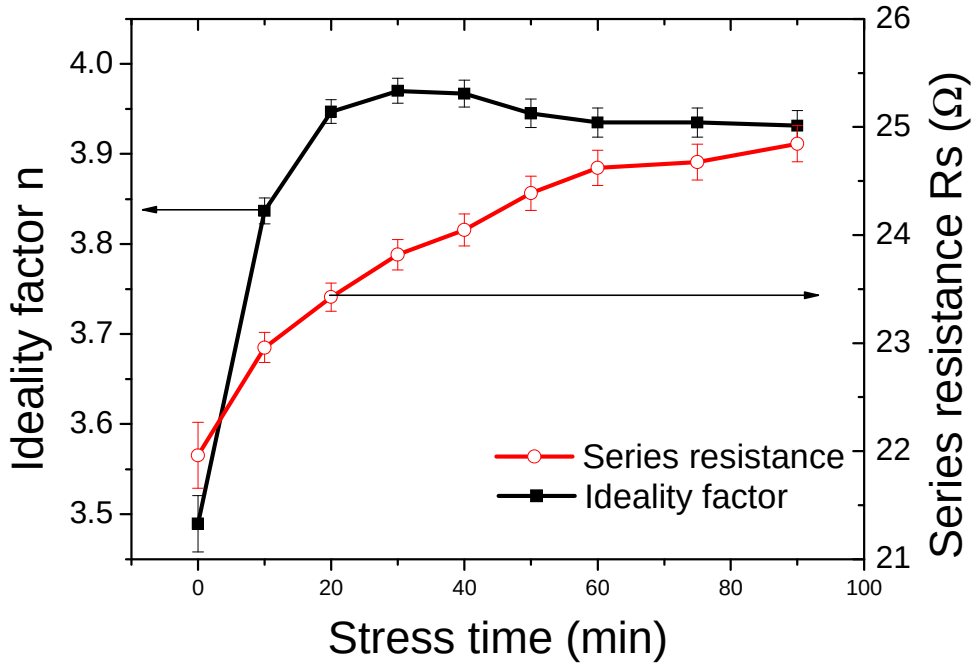
Stress of bare LED chips – I-V curves



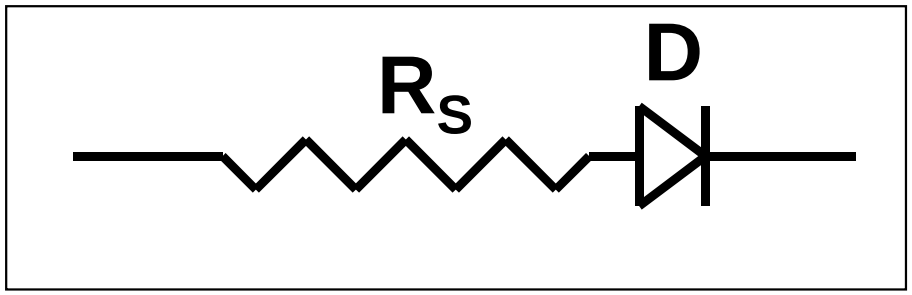
High temperature treatment determines the shift of the I-V curves towards higher voltages

Stress of bare LED chips – Fitting of the I-V curves





$$I \propto I_0 e^{\frac{q(V-RI)}{nkt}}$$

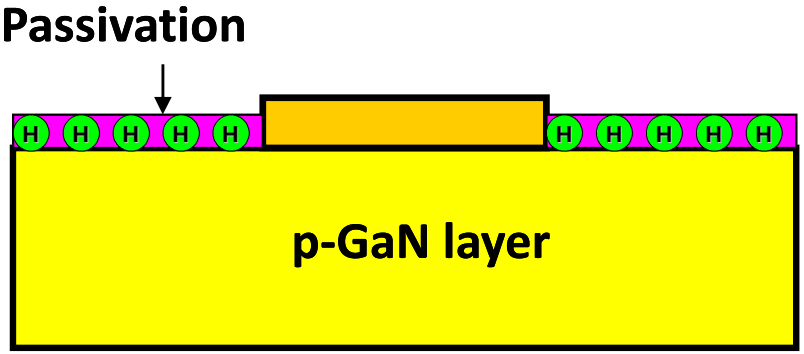


•Rs Increase → Increased resistivity of p-GaN and contacts

•n increase → Degradation of the properties of the ohmic contacts

Stress of bare LED chips – Role of Passivation

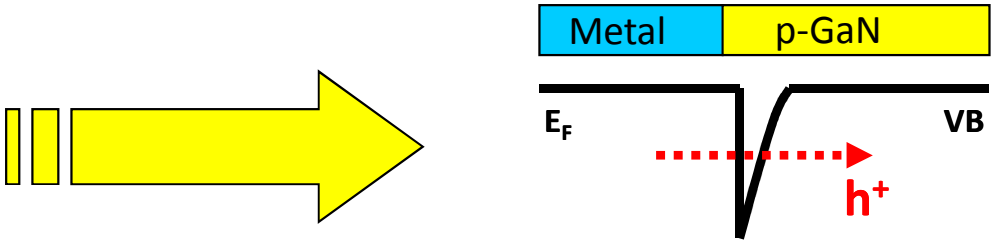
- PECVD introduces H in the passivation layer and/or at the interface with p-GaN



- Generation of Mg-H complexes → Lowering of effective acceptor concentration

Analysis on TLMs → Information on the effects of stress on M/S system

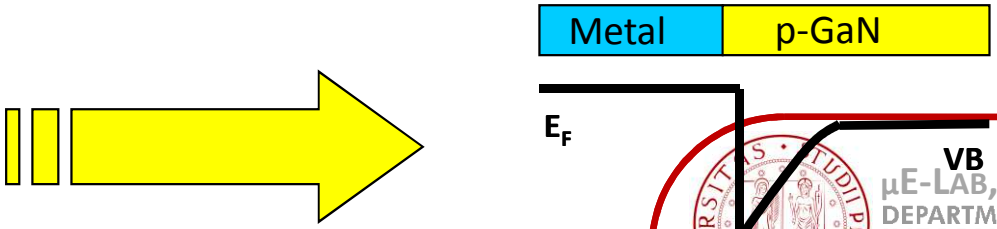
Ohmic contacts on p-type GaN → Tunnel junctions (very high acceptor concentration)



Stress lowers active dopant concentration at p-side

→ Schottky barrier broadening

→Rectifying behavior



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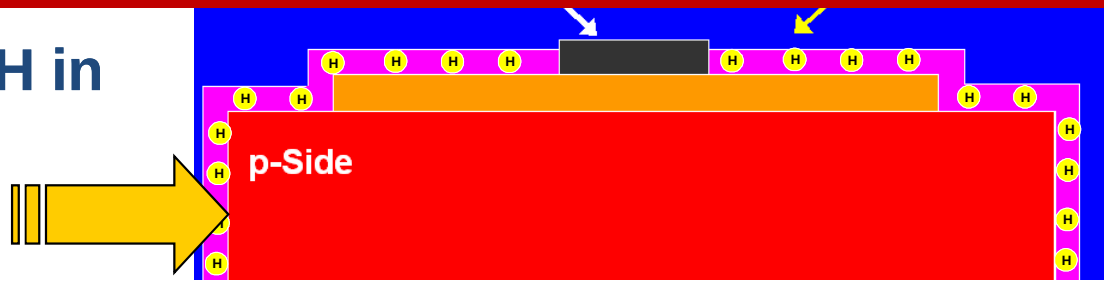
Stress of bare LED chips – Role of Passivation

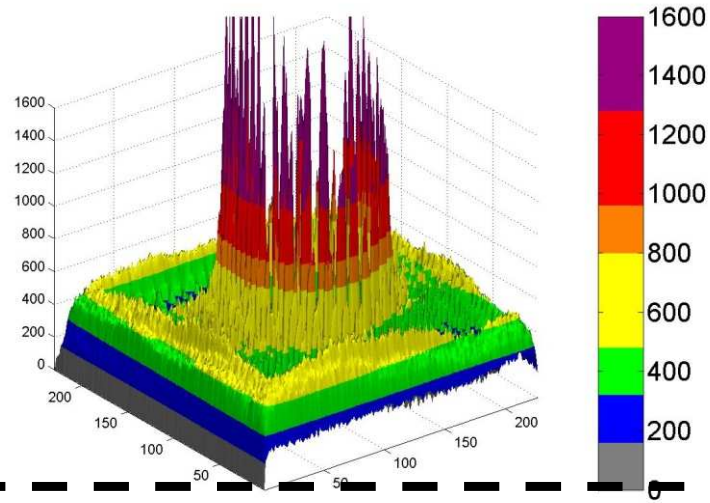
- **Passivation deposition introduces H in the passivation layer and/or at the interface with p-GaN (SiH_4 as precursor)**



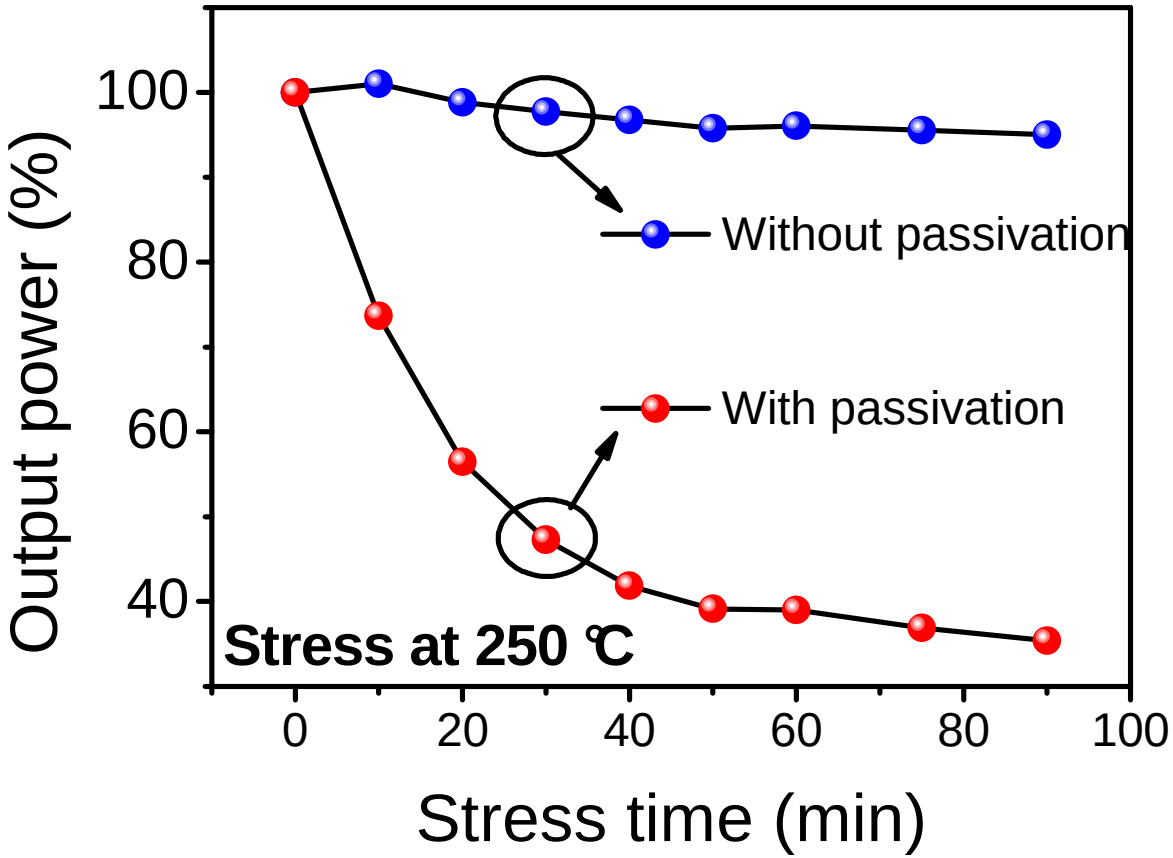
- **Heating at 250 °C allows this hydrogen to interact with LEDs surface**
  - **S. M. Myers, J. Appl. Phys., 89, 6, 3195, 2001**
  - **C. H. Seager, J. Appl. Phys., 92, 12, 7246, 2002**

- **Generation of Mg-H complexes and/or degradation of ohmic contacts (worsening of transport properties)**

- ***Golden pad obstructs hydrogen diffusion towards p-GaN***
- ***Degradation takes place mainly out of the pad region***
- ***Emission is concentrated under the pad***



Stress of bare LED chips – Role of Passivation



- **Degradation is strongly related to the presence of the SiN-PECVD passivation layer**
- **During PECVD process, SiH_4 and NH_3 are used as precursors (passivation contains hydrogen)**

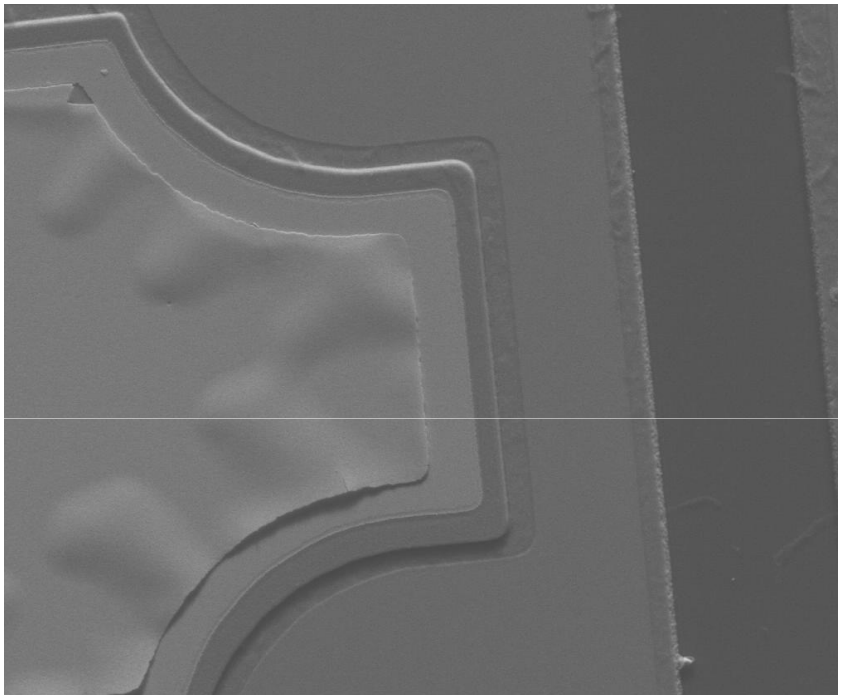
Degradation of the contacts of power LEDs

Aim: characterization of the degradation of the metal/semiconductor contacts

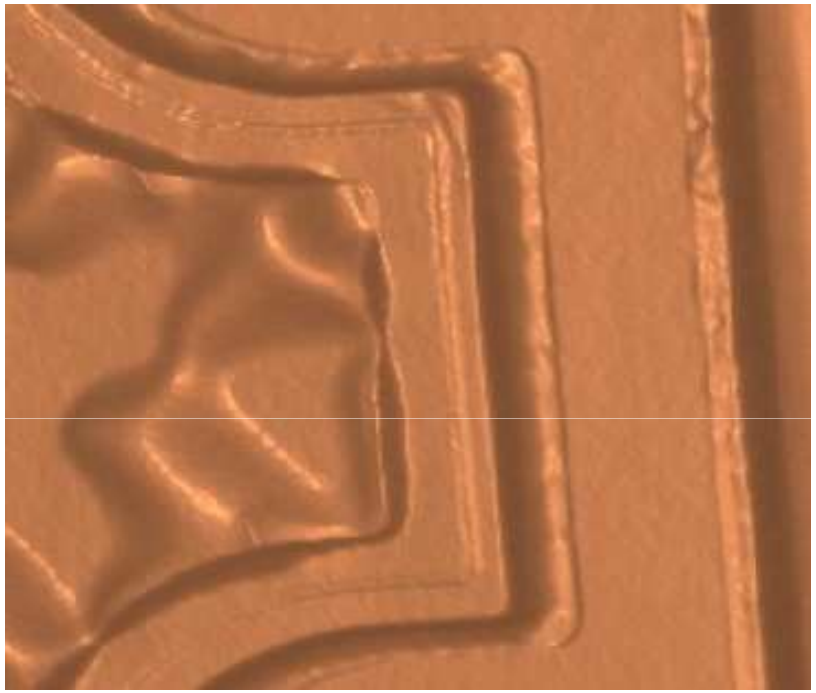
Techniques:

- Scanning Electron Microscopy (SEM)
- Energy dispersive X-ray Spectrometry (EDS)

Back-scattered image



3D reconstruction



Poor adhesion of the metal layer → Related to R_s increase?

Degradation of the ohmic contacts of LEDs

- **Bare InGaN LED chips have been submitted to thermal storage (180<T<250°C)**
- **OP degradation has a nearly exponential decay, and is correlated to emission crowding**
- **Thermally activated process, Ea=1.3 eV**
- **OP decay is related to the degradation of the electrical properties of the LEDs → Increased Rs, worsening of the properties of the ohmic contacts, determining emission crowding**
- **Degradation is related to the presence of PECVD-SiN passivation → Role of hydrogen in devices degradation**
- **Sputtering has been proposed as an alternative for passivation**

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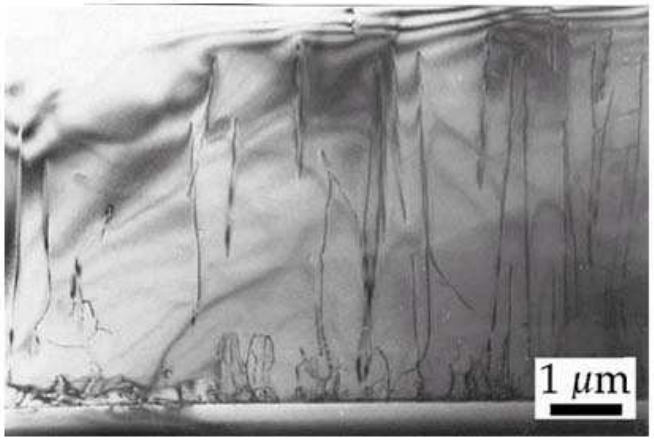
Rapid degradation of the active region
-
Dark Line Defects

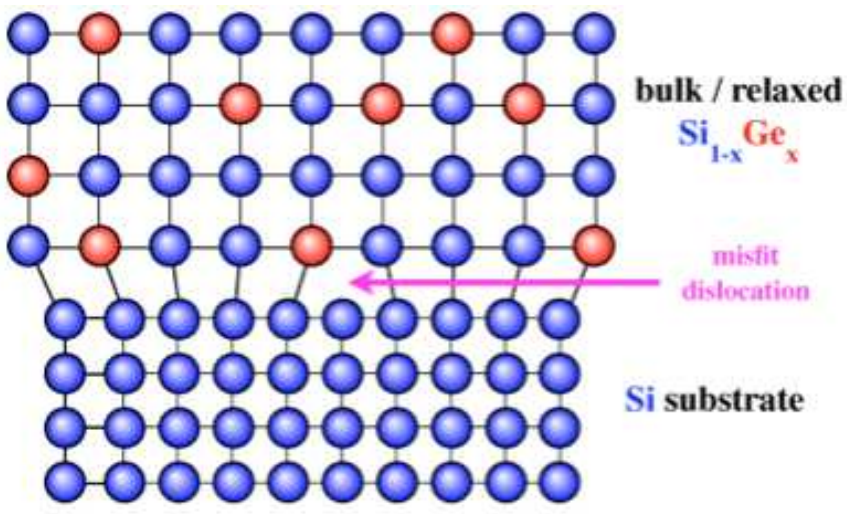
Dark line defects

- The structure of the DLDs has been the object of many studies. Transmission Electron Microscopy (TEM) analyses of DLDs present them as dense three-dimensional networks of dislocation loops and dipoles
- These clusters of crystal defects develop around a threading or a misfit dislocation crossing the active layer, and are primarily found at the QW and the neighbouring cladding layers

- Threading dislocations can be present in the heterostructure as a consequence of the crystal growth process. Most of the threading dislocations emerge from the substrate and thread through the epitaxial multilayer structure



- Misfit dislocations arise from internal stresses associated with the differences between the latti parameters of the layers forming the multilayer structure. They can also be introduced by handling and mounting processes

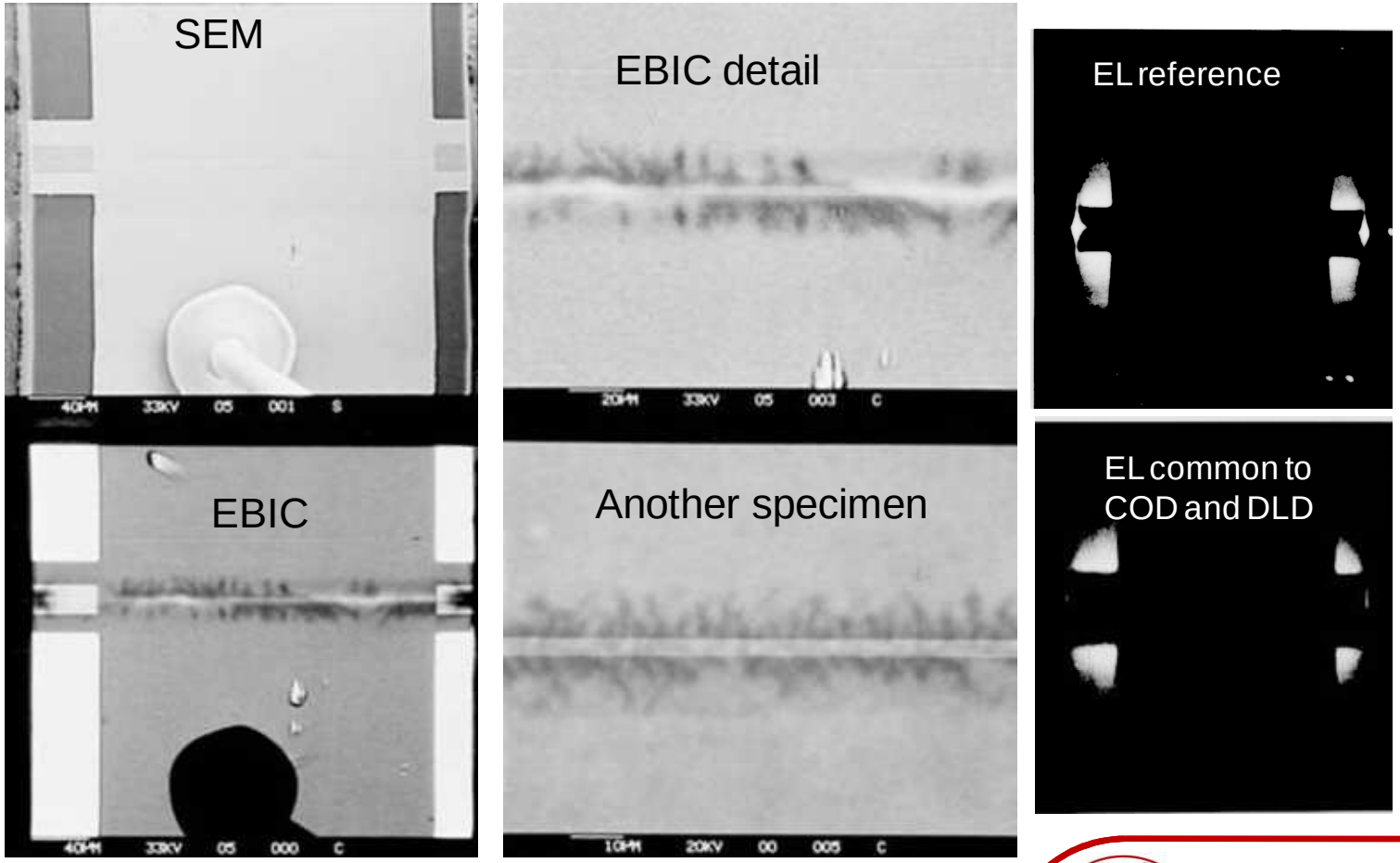


Dark line defects

- DLDs appear as region of very low or even dark luminescence efficiency
- DLDs can appear as oriented dark structures in CL and EL images

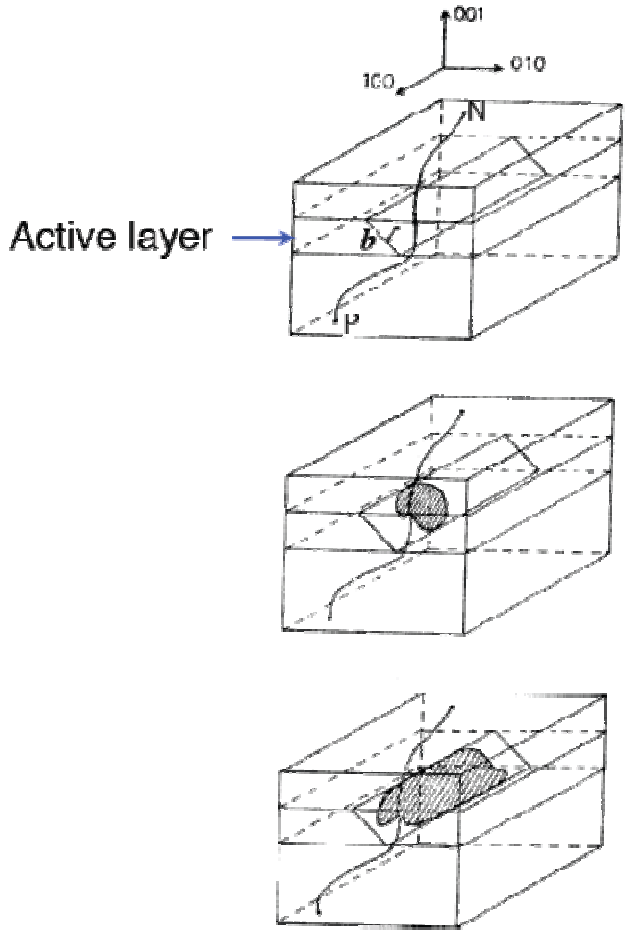
- They are located in the active region and are constrained to the waveguide region

- EBIC images also show a dark constrast, which reveals a high charge-trapping efficiency in those region



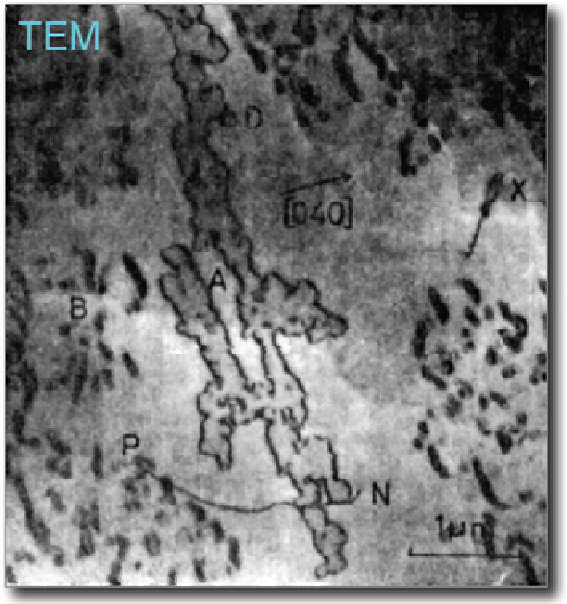
Dark line defects

- When studied by TEM DLDs appear as clusters of dislocations loops and dipoles
- The dislocation motion leading to the formation of DLDs proceeds by Recombination-enhanced dislocation climb/glide
- Consists of an increase in the dislocation length mediated by either the absorption or emission of point defects

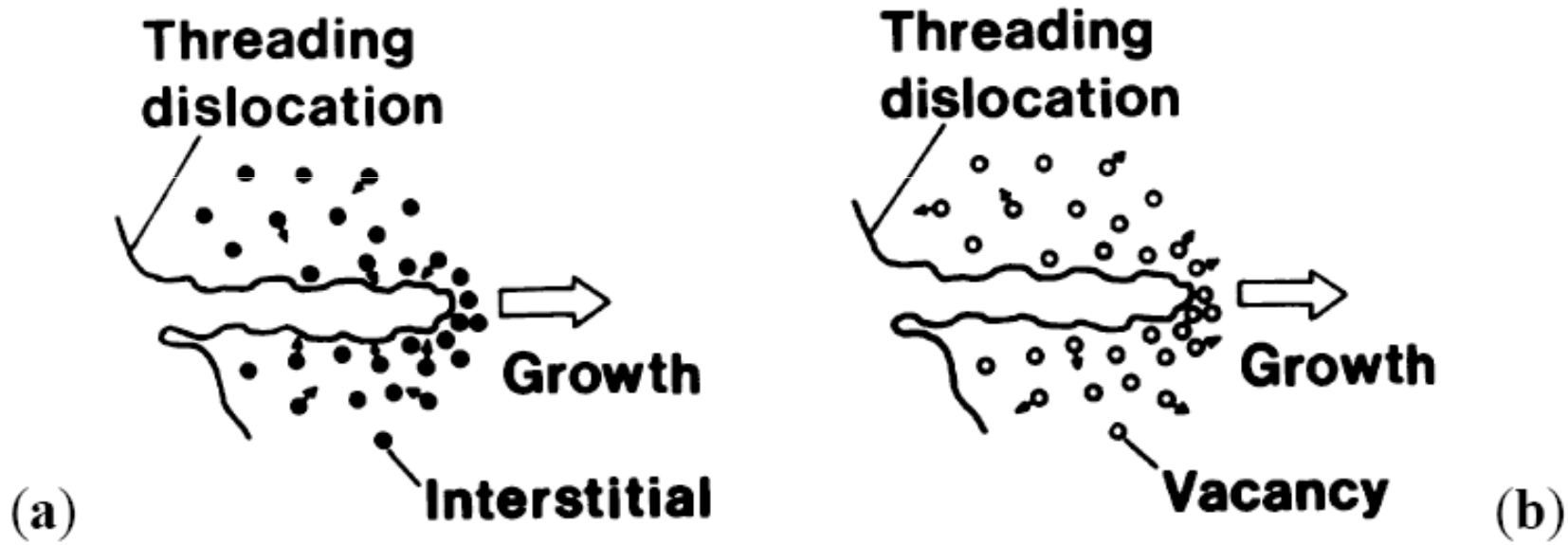


Scheme of the growth of a dislocation network in the active layer of the laser device. (a) Initially, the dislocation **PN** with the Burgers vector ***b*** crosses the layer; (b) climb into the active zone; (c) further climb confined to the active zone causes elongation along the [100] direction.

[Hutchinson, Dobson 1975]

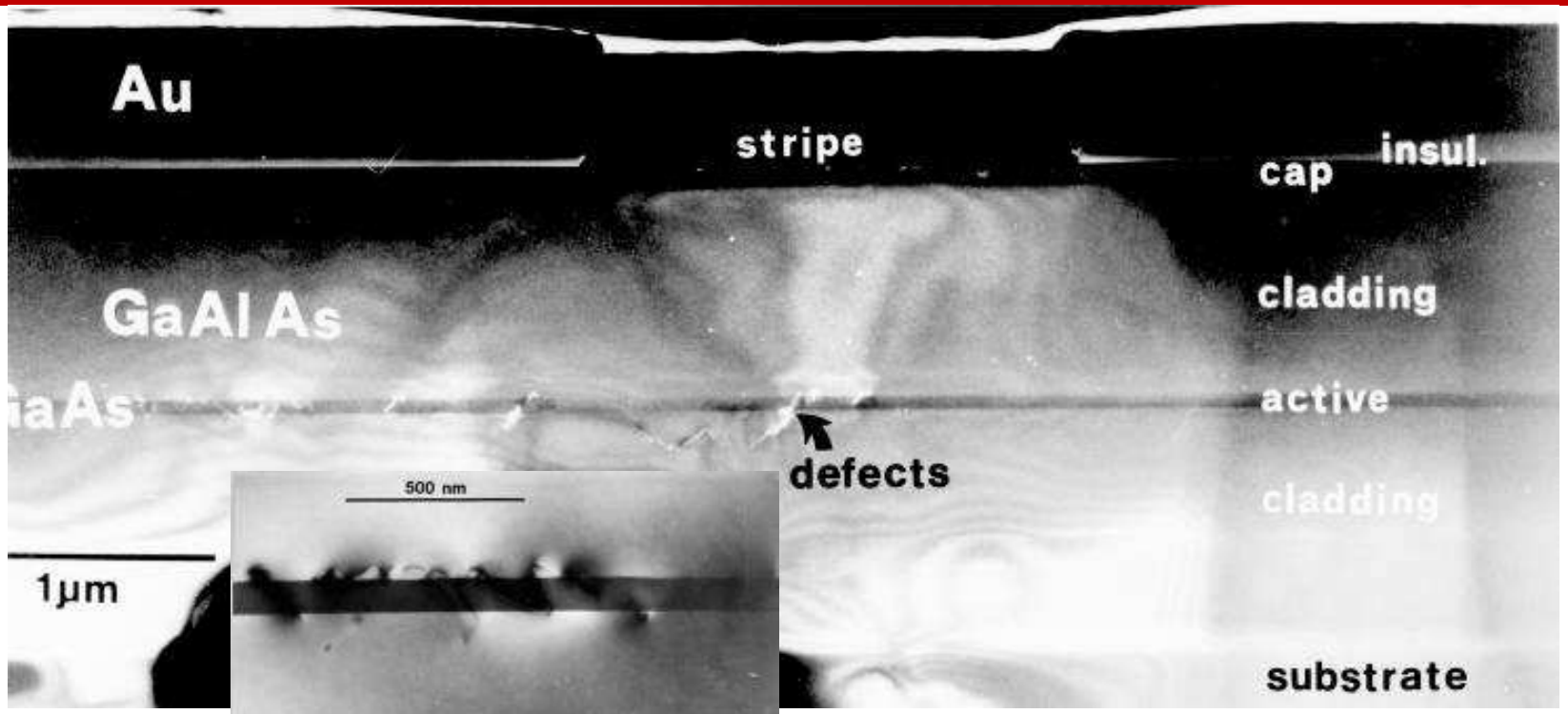


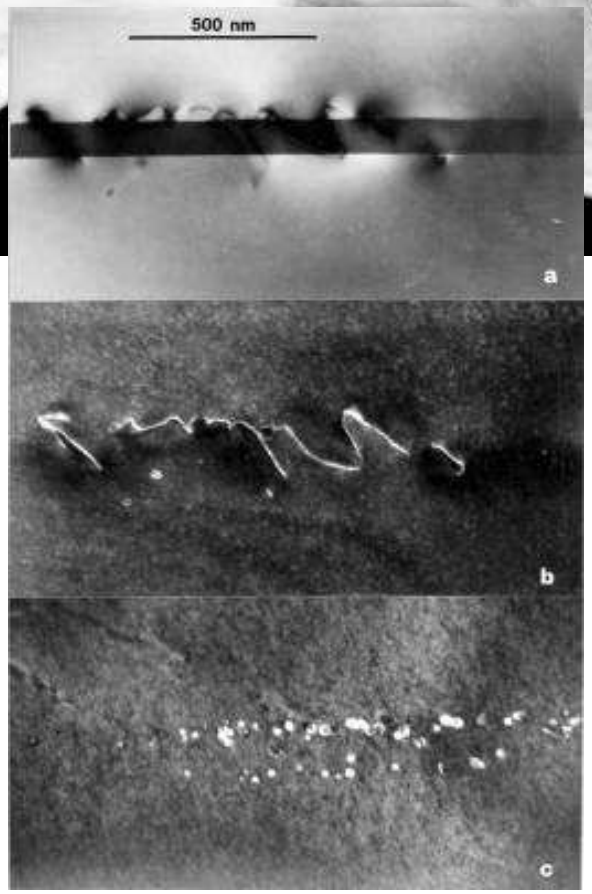
Dislocation climb in the active layer



Two models proposed for the extension of ⟨100⟩-oriented dark-line defects in degraded optoelectronic devices via dislocation climb. (*a*) Model related to absorption of interstitials, (*b*) emission of vacancies.

Dark line defects





DLDs appear as a network of dislocations and of dislocation loops, evolving from native defects at the epitaxial AlGaAs/GaAs interfaces under the effect of temperature (and recombination, as demonstrated years later)

Dark line defects

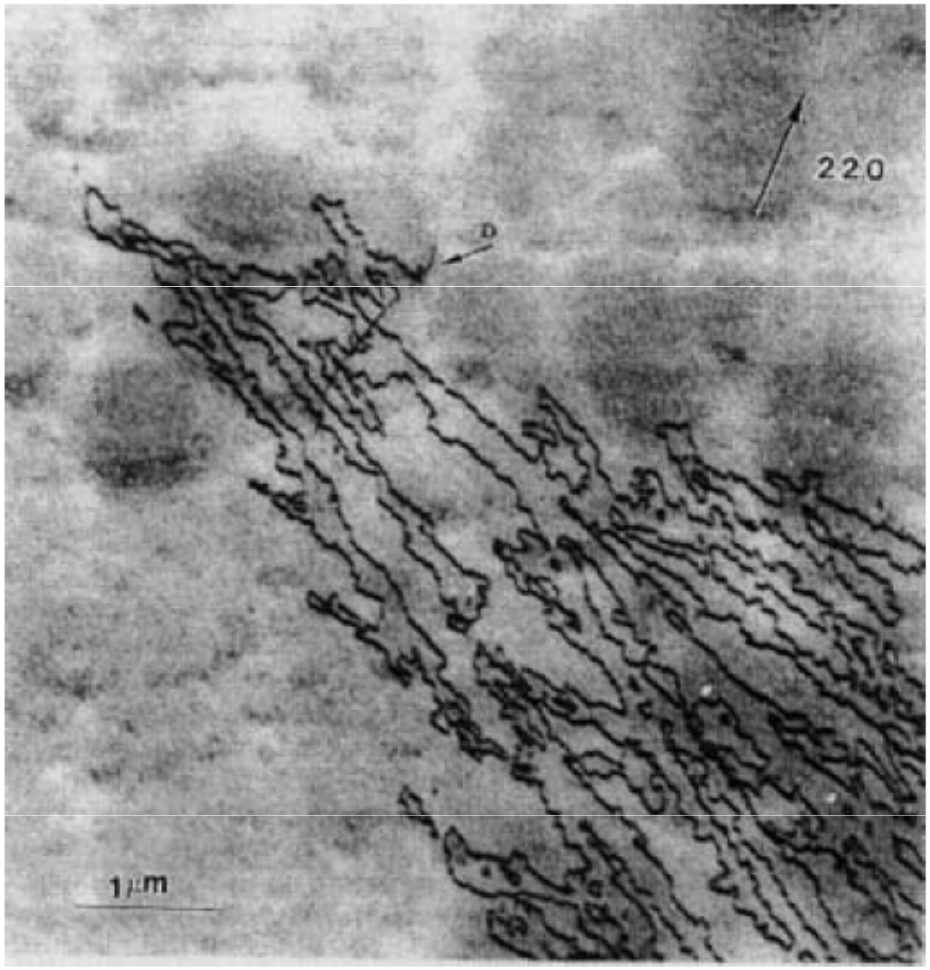
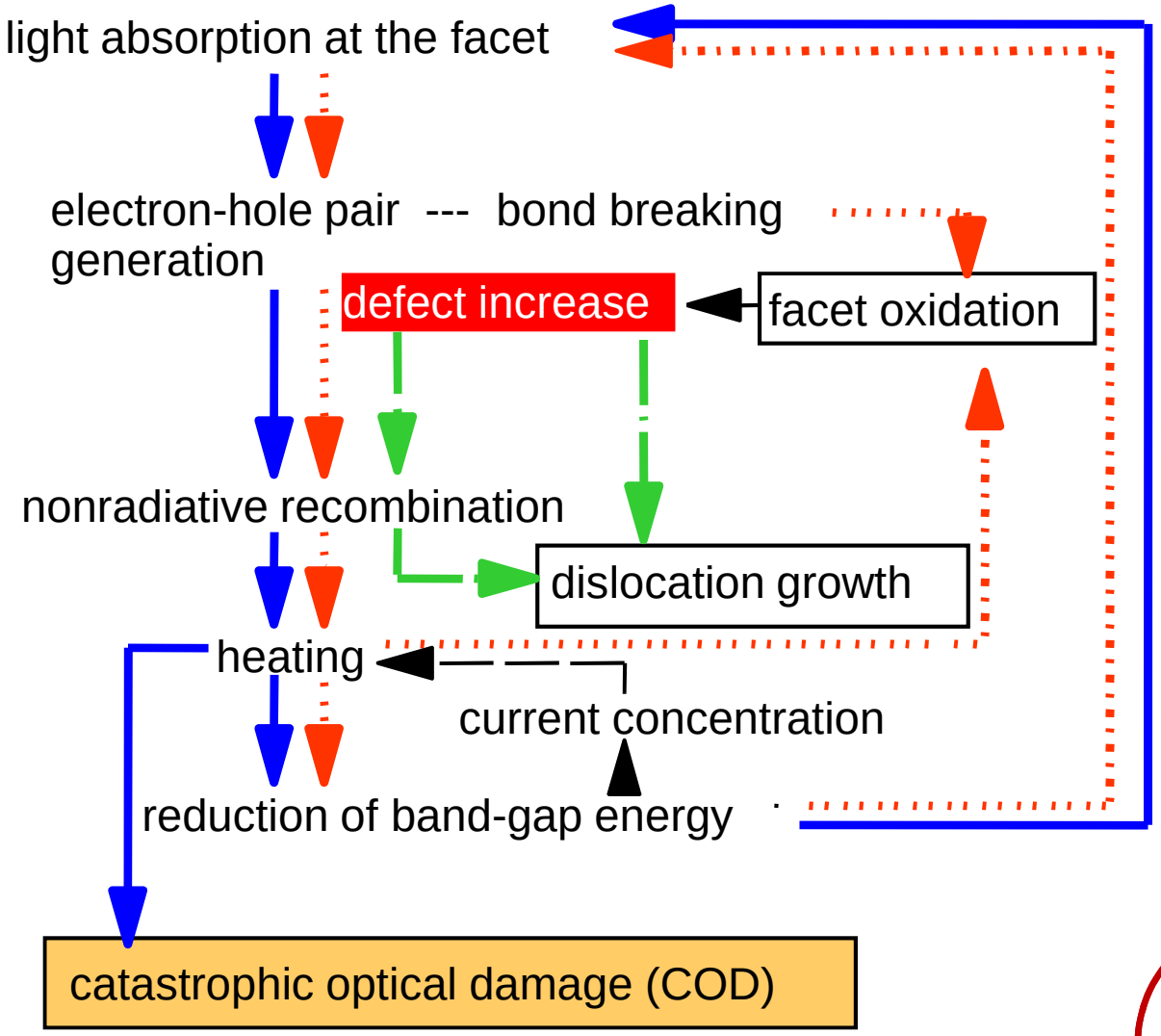


Fig. 3. Dislocation microloops and dislocation network in an AlGaAs/GaAs laser. The microloops are indicated by arrows.

Rapid degradation of the active region
-
Facet Degradation

Facet degradation

While the lifetime of low power laser diodes is limited by gradual degradation, the maximum optical power of high power laser diodes is mostly limited by the catastrophic optical mirror damage (COMD). This failure consists in the destruction of the mirror facets



Courtesy of Prof. M. Fukuda

Facet degradation

The key parameters controlling the COMD are:

- the Surface Recombination Velocity (SRV);
- the density of defects at the facet;
- the facet treatment and coating, which partially determine the previous parameters;
- the temperature dependence of the band gap of materials forming the active region;
- the optical power and the current injection;
- the thermal conductivities of the different layers forming the laser structure

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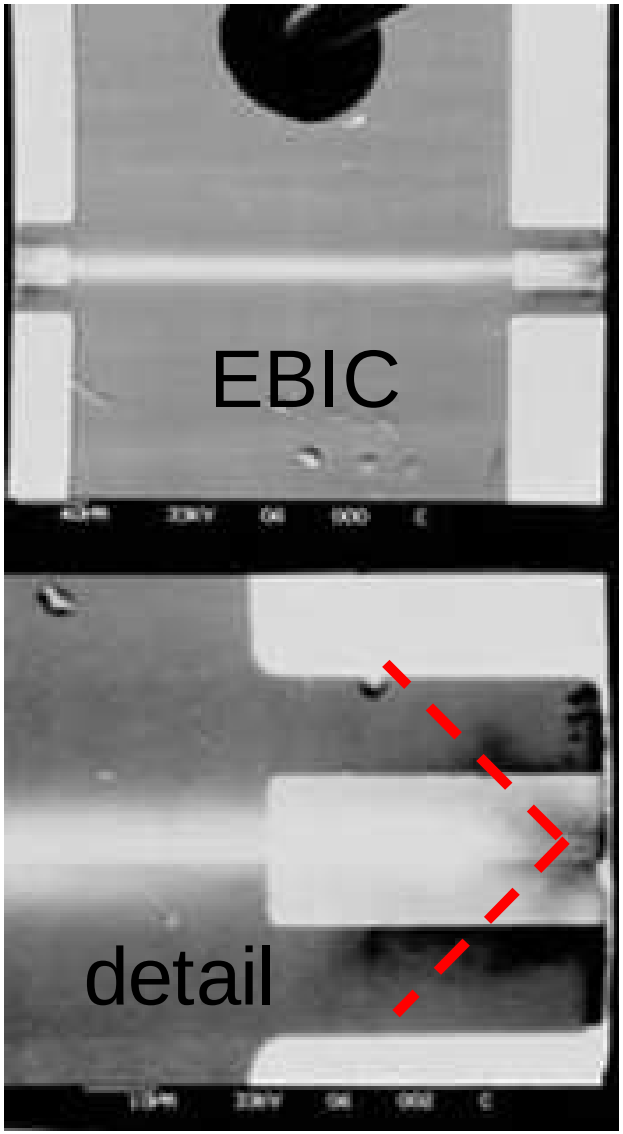
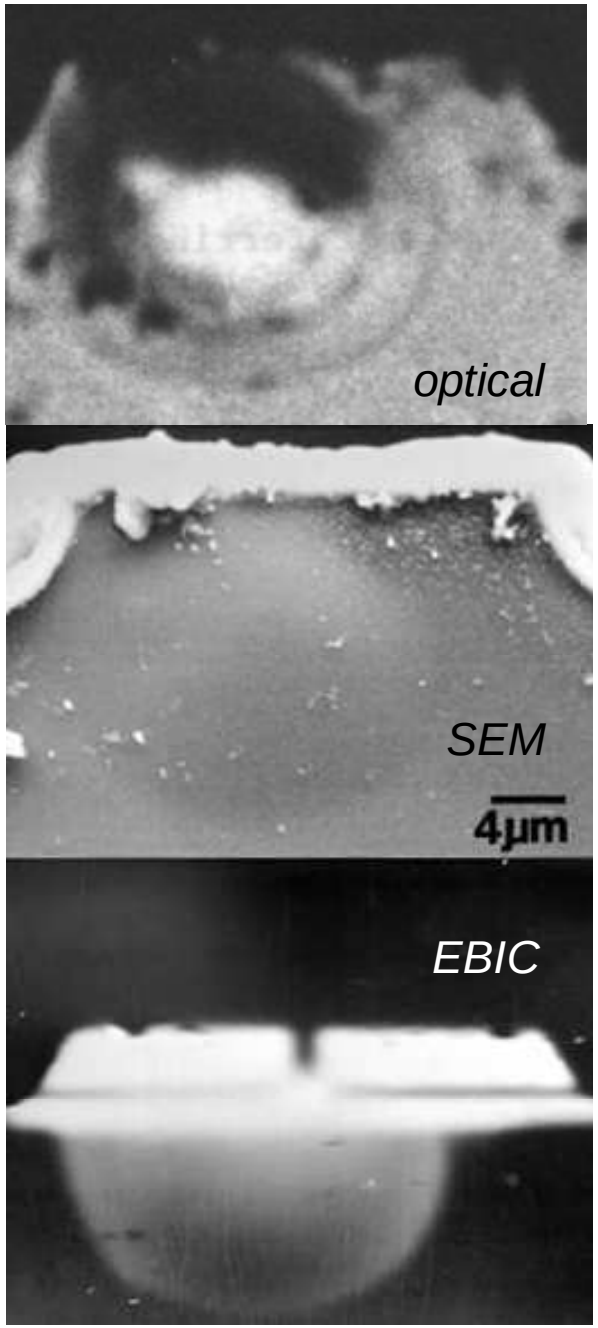
Facet degradation

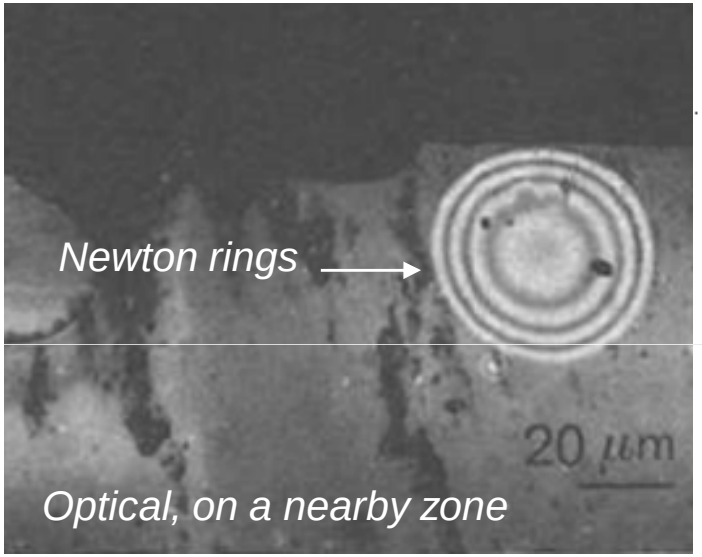


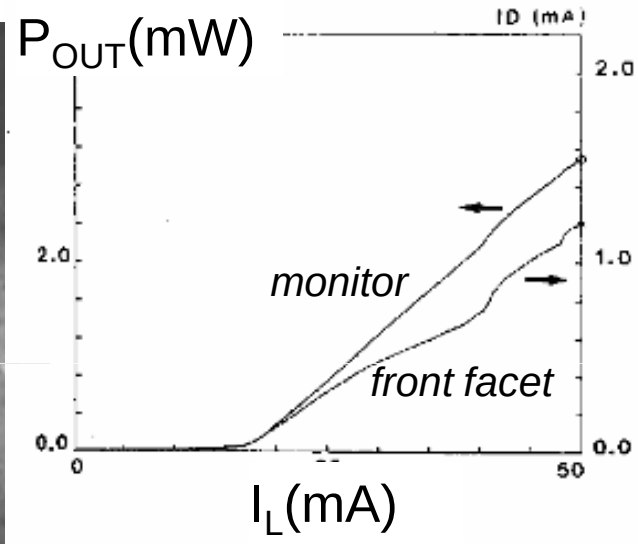
EBIC reveals lattice-oriented dark stripes at the “burned” mirrors

COD (Catastrophic Optical Damage) affects the laser mirrors

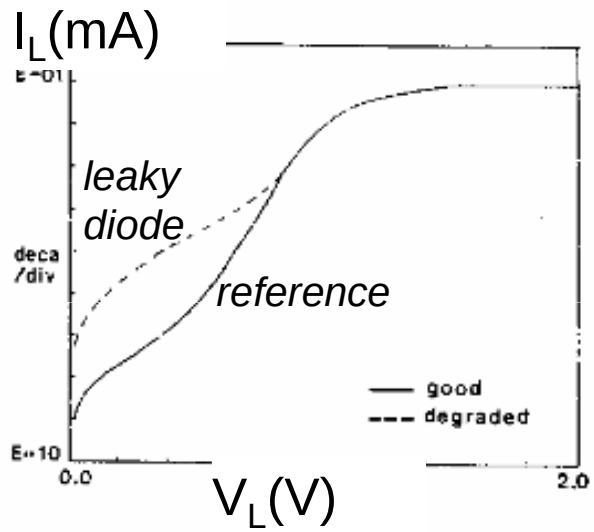
Facet degradation







Degradation after THB tests.
Mechanism: detachment of the mirror coating



Facet degradation

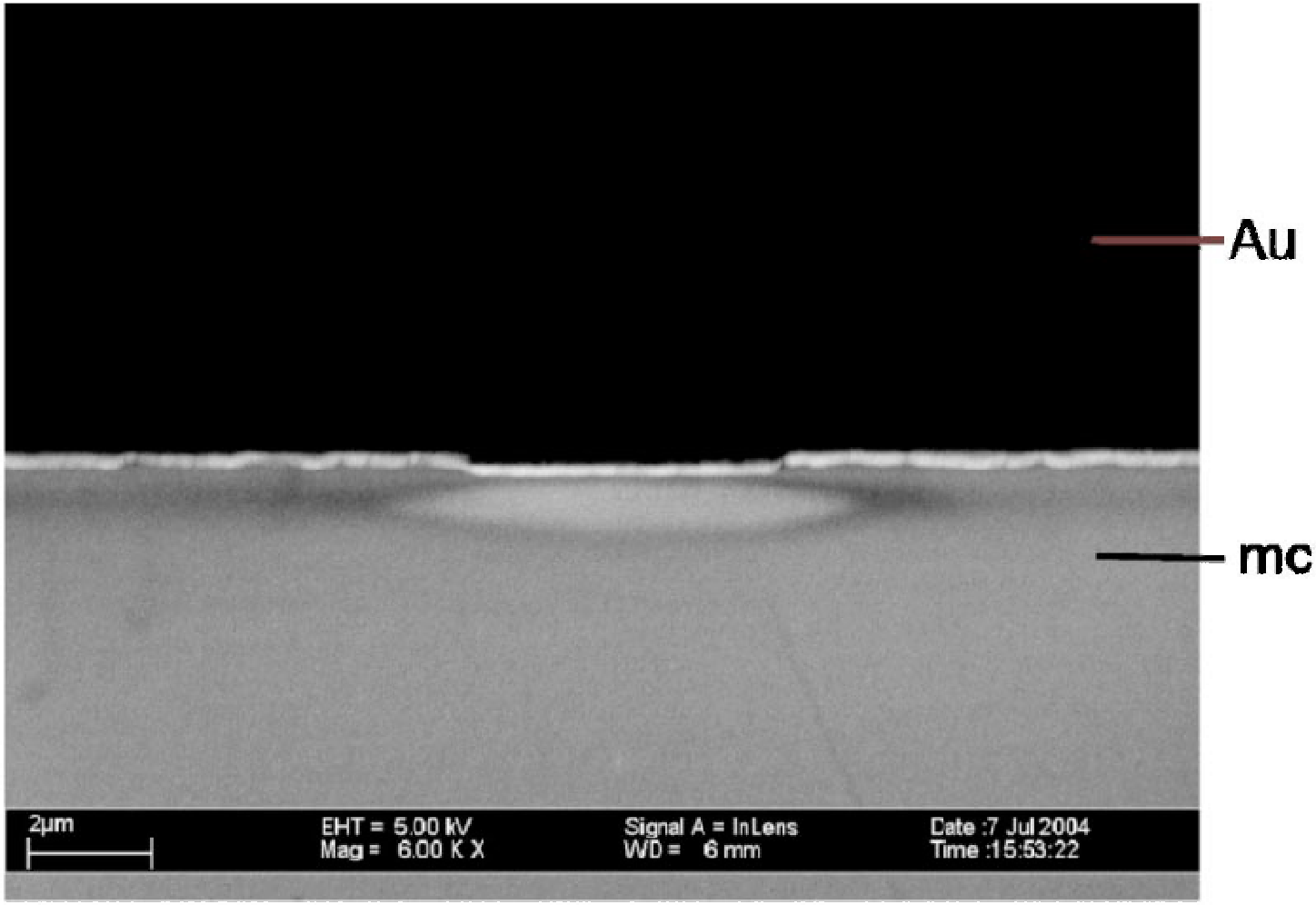


FIG. 5. Scanning electron microscope picture of the facet of a laser diode operated at high currents after the appearance of a COD. The label mc points at the mirror coating.

Facet degradation

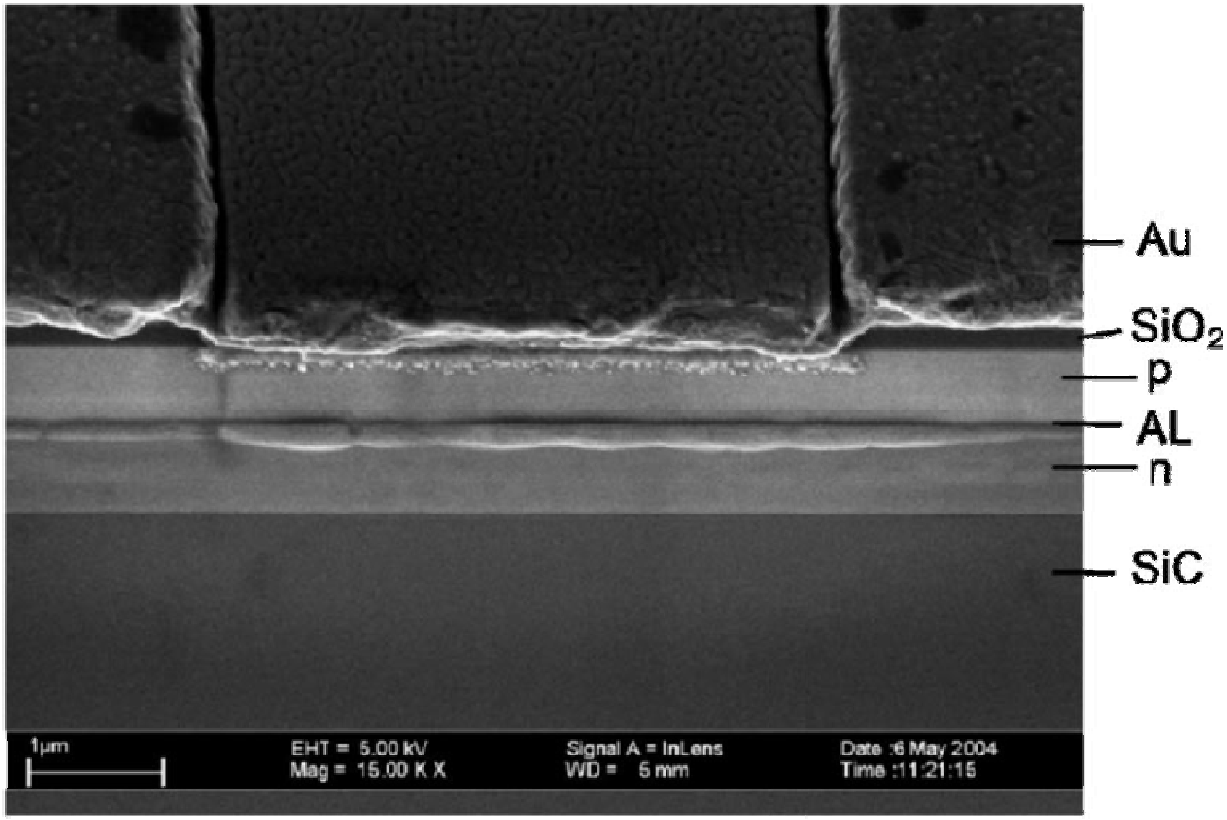


FIG. 8. SEM image of the facet of a laser diode, which was operated in air with water vapor. The label p points at the p-layers, AL at the active layers, and n at the n-layers.

Photoinduced oxidation of the facet. The water molecules near the facet can be cracked to H+ and OH− and to further radicals by photolysis and trigger the oxidation

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Catastrophic Degradation

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ESD-related failure

Damages caused by ESD

LED can be damaged by ESD so badly that they fail totally. This means, that they emit neithe light nor are electrically conductive. If the LED is damaged, but still electrically conductive, it i considered disturbance.

Total failure

An LED, which is completely failed by ESD, does not only remain completely dark, but is als no longer electrically conductive any longer. Therefore also any further LED in series connection do not light, even if they are undamaged. This is immediately visible after the damage.

- Immediately visible
- Several LED in one electrical row dark

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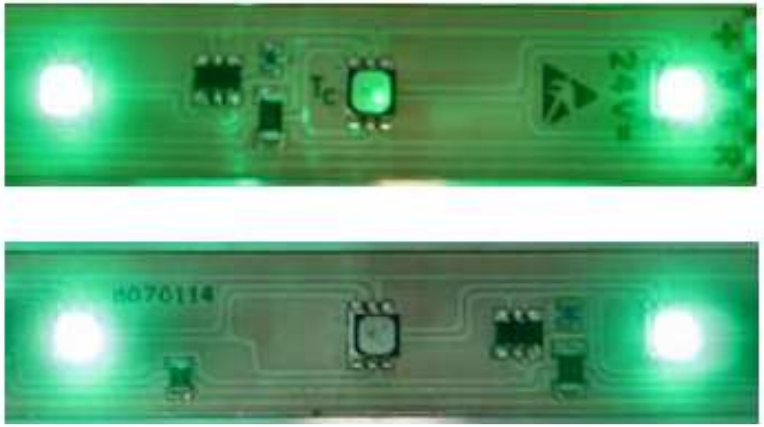
ESD-related failure

Disturbance

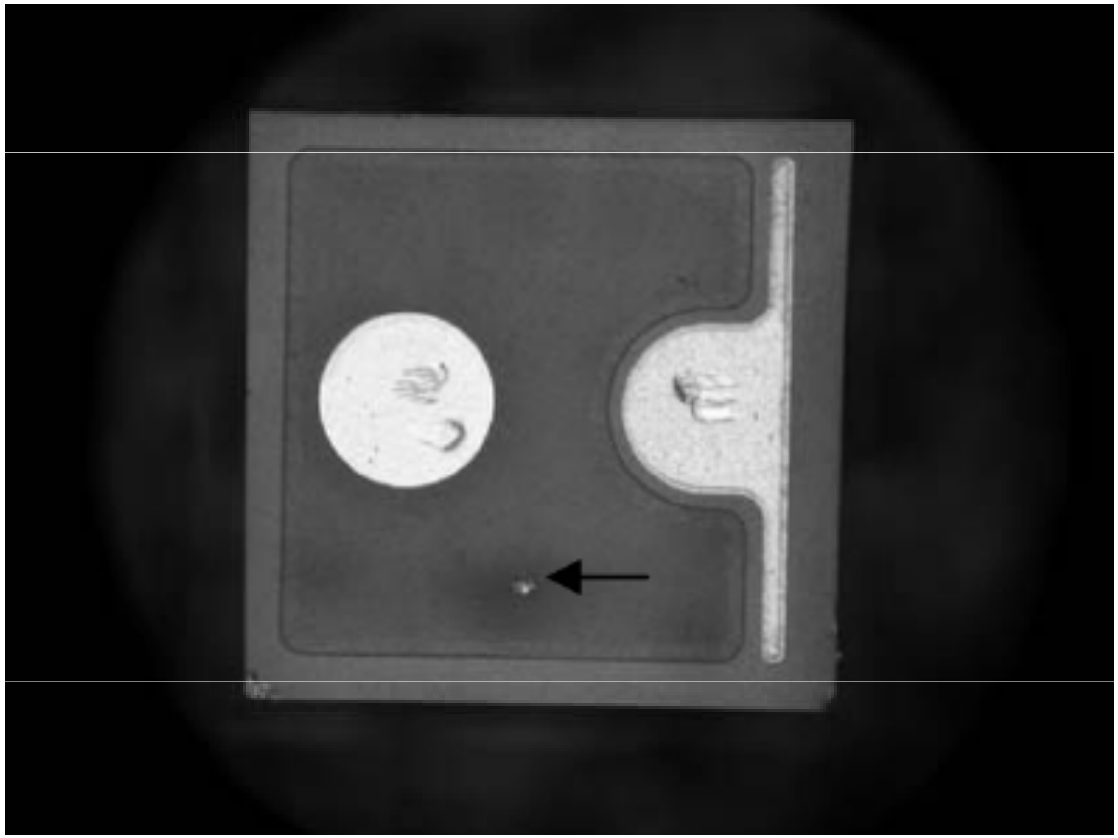
In contrast to total failure, LED can be damaged in a way that initially still light, however rapidly become dim. Since the damaged components remain electrically conductive, the remaining module continues to light normally.



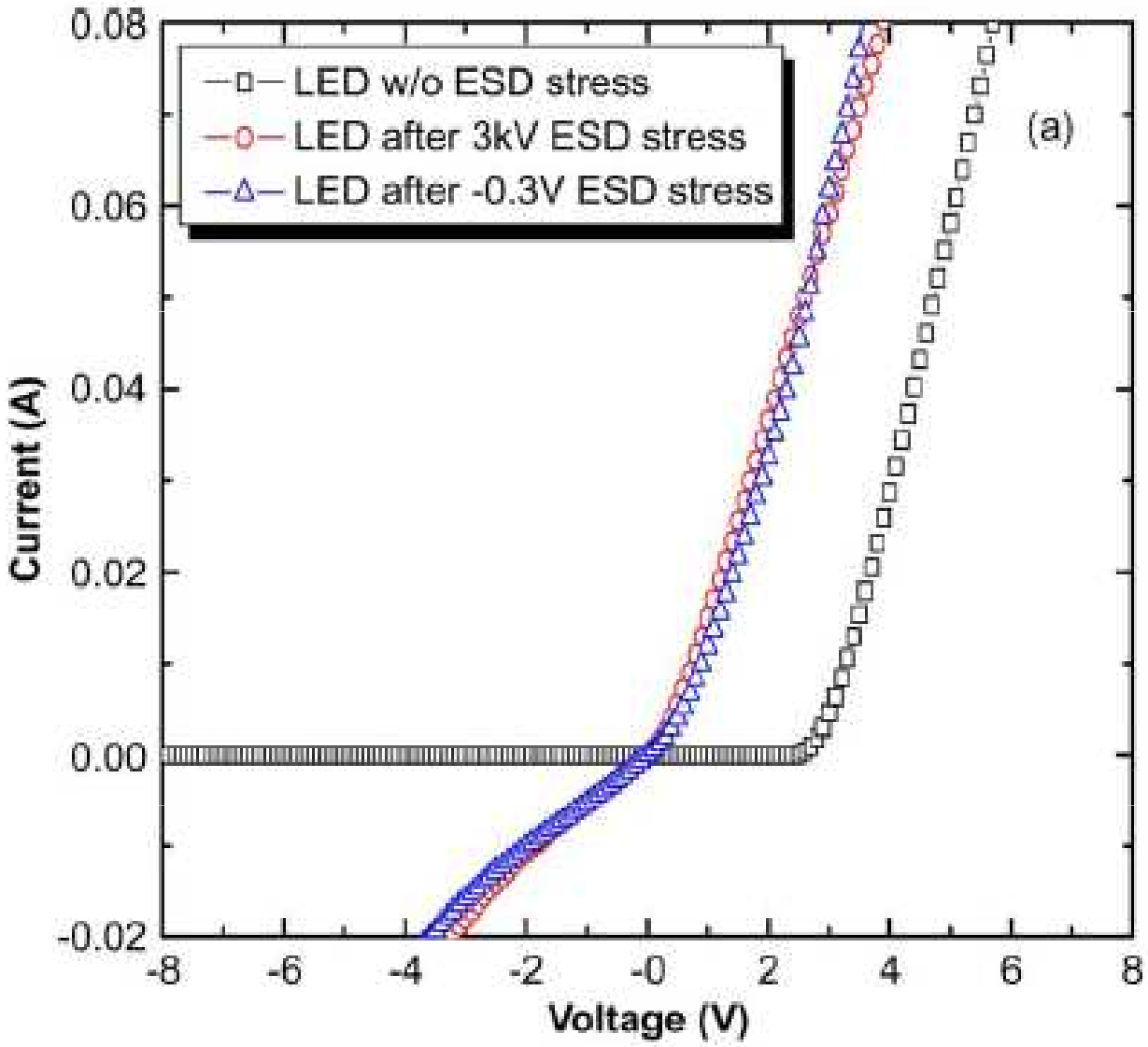
- Damaged LED can initially light
- Becomes dim quickly

Most damages become visible after a short period of operation. We recommend therefore a function test of approx. 1 hour, in particular for installations with difficult access.

ESD-related failure

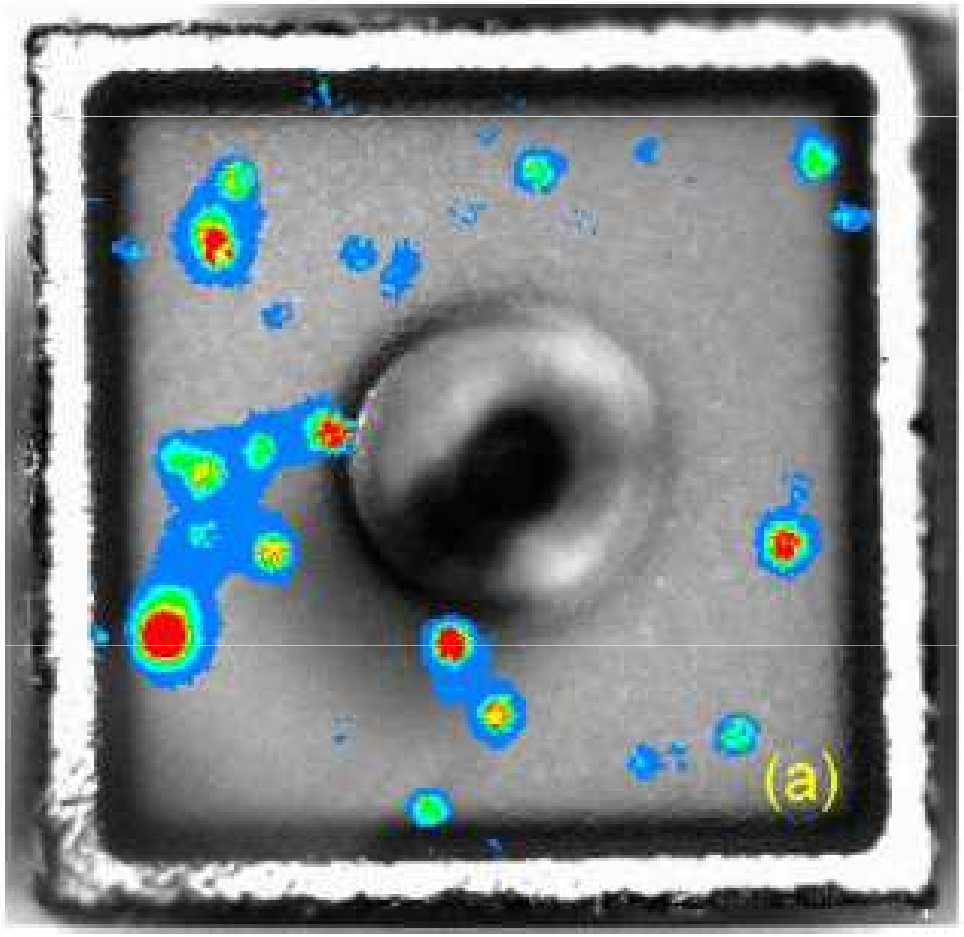


ESD-related failure

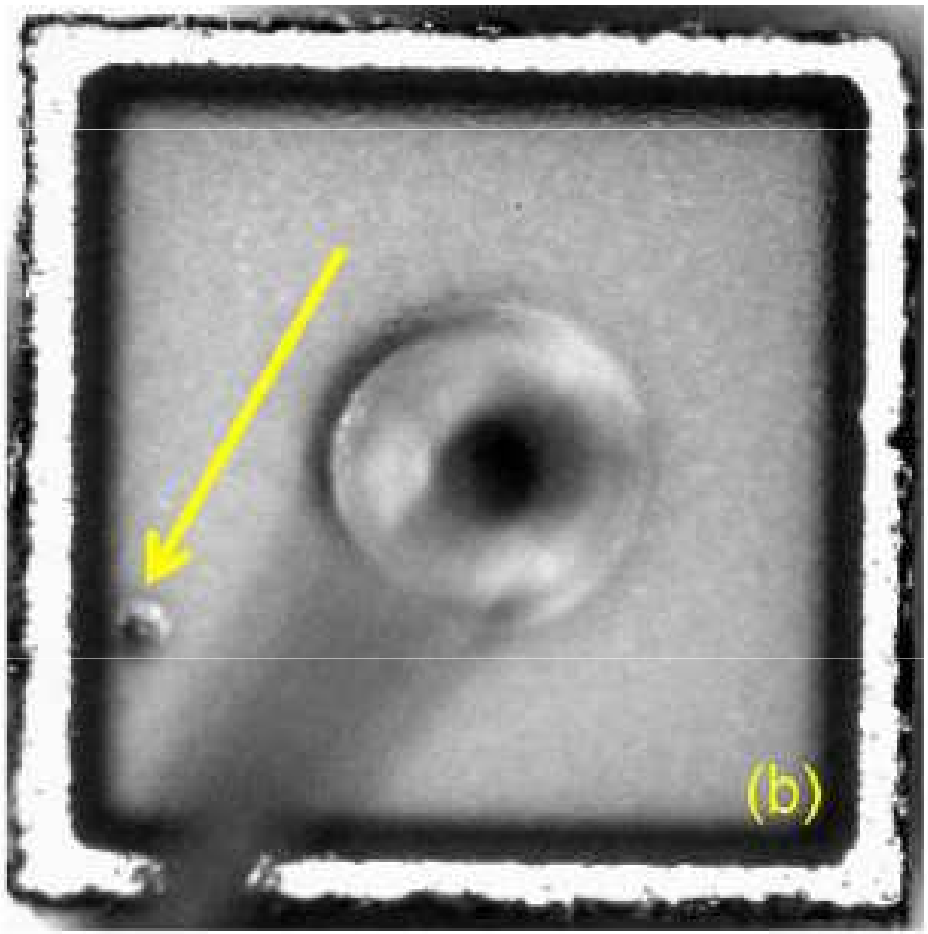


ESD-related failure

Reverse-bias EL distribution (before any ESD stress)

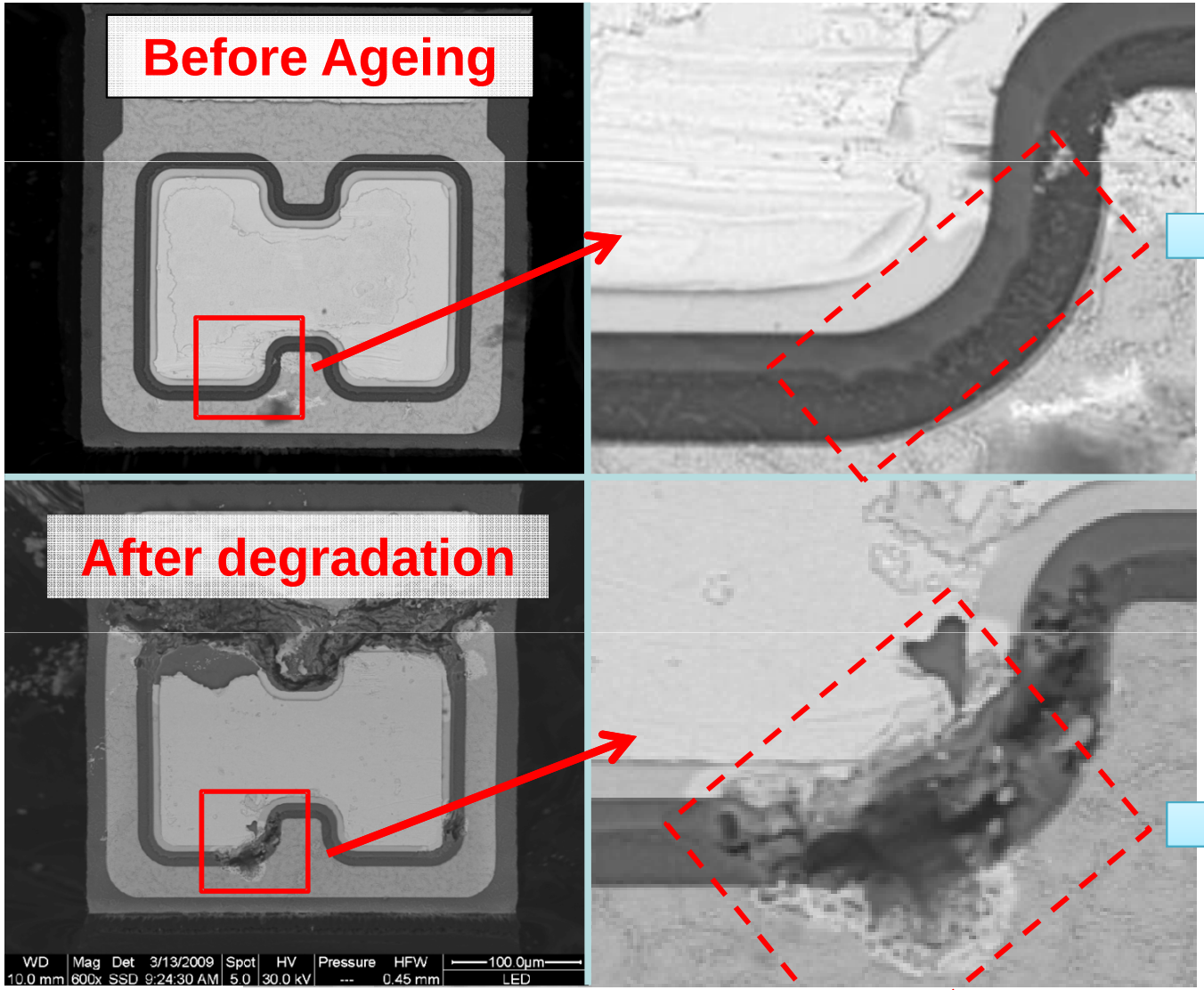


Micrograph after ESD failure (failed region is indicated by an arrow)



Sudden failure related to EOS

Failure analysis by means of SEM images



Poor definition of the mesa borders

Spike

Catastrophic Failure

Conclusions

With this presentation we have given an introduction on the operating principles and degradation mechanisms of LEDs and laser diodes

Based on a number of case studies, we have presented guidelines for the investigation of:

- The degradation of the heterostructure of LEDs and laser diodes by means of electro-optical techniques
- The analysis of the degradation of the properties of ohmic contacts of optoelectronic devices
- Degradation processes related to Dark Line Defects
- The degradation of the facets of laser diodes