Failure Mechanisms in Semiconductor Lasers

2 decades of

Failure Analysis and Failure Physics

by

Massimo Vanzi

University of Cagliari

Toulouse, 12/05/2006

Outline:

- Failure Analysis of lasers: a puzzling question
- Paleophotonics examples
- The early ’80s: the era of Burn Out, COD and DLD
- The late 80’s: InP/InGaAsP structures. The ESD epics
- The ‘90s: laser pumps for fiber amplification. Sudden failures and REDR
- The 2Ks: external tunable devices. Is the chip the major issue?
- The evolution of an electrical/optical model for laser degradations
- Conclusions ***?***

ISTFA '95, 21st International Symposium for Testing and Failure Analysis, 6-10 November, 1995, Santa Clara, California

The Rules of the Rue Morgue

M. Vanzi
University of Cagliari, Cagliari, Italy

TEN YEARS AGO

"What caused the shift of the optical thresold of a laser diode, or what place a polysilicon whisker choose when it led the Iddq of your gate array to increase are puzzling questions"

(Massimo Vanzi, ISTFA95)

but

"What song the Syrens sang, or what name Achilles assumed when he hid himself among women, although puzzling questions, are NOT beyond all conjecture."

(Sir Thomas Browne, Urn Burial)
quoted by E.A.Poe at the beginning of
The Murders in the Rue Morgue

ANY FAILURE ANALYST with some practical experience remembers those analyses that challenged his own professional reputation. They are those cases where the novelty of the device or the puzzle of the symptoms put the analysis out of any known possibility of solution. They are what we call *advanced failure analyses*.

Toulouse, 12/05/2006

Analyzing a failed laser diode in ’80s:

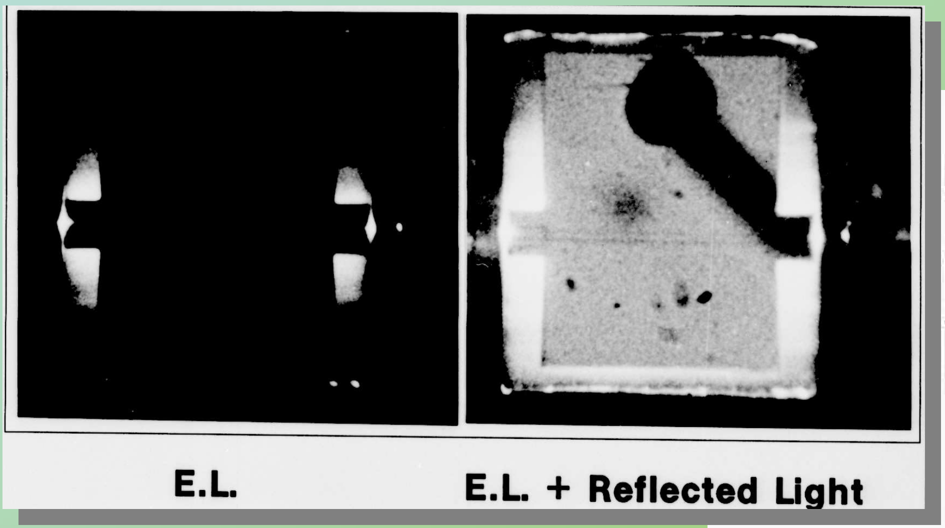
1) Find the head and the tail of the dog
2) The total set of informations: it does no more light
3) Your instruments: hammer, saw, drill, an optical microscope (maybe IR) and the not yet widespread SEM. An electrical curve tracer.

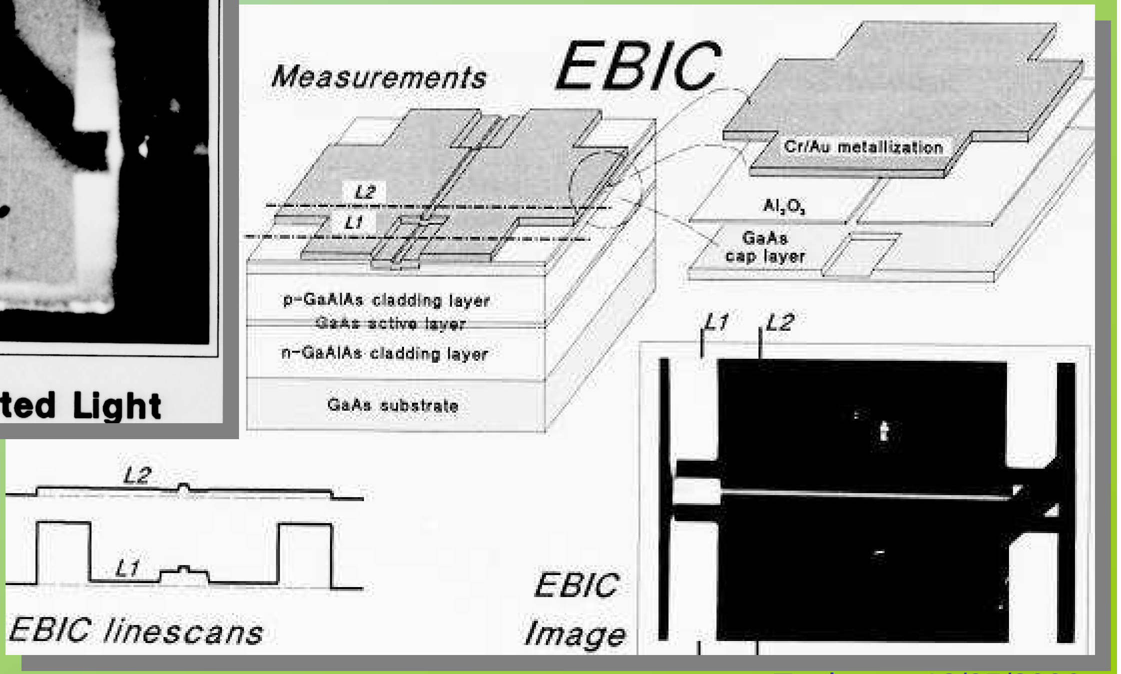
In that period, Technology and Reliability ran a furious race,
with the latter continuously trying to discover the new *failure mechanisms* intrinsic to the new devices,
to invent suitable *techniques* to detect them,
to model their *kinetics*,
to find any precursor able to early point out any risk occurrence.

Early 80's. The AlGaAs/GaAs laser era.

A failed laser is:

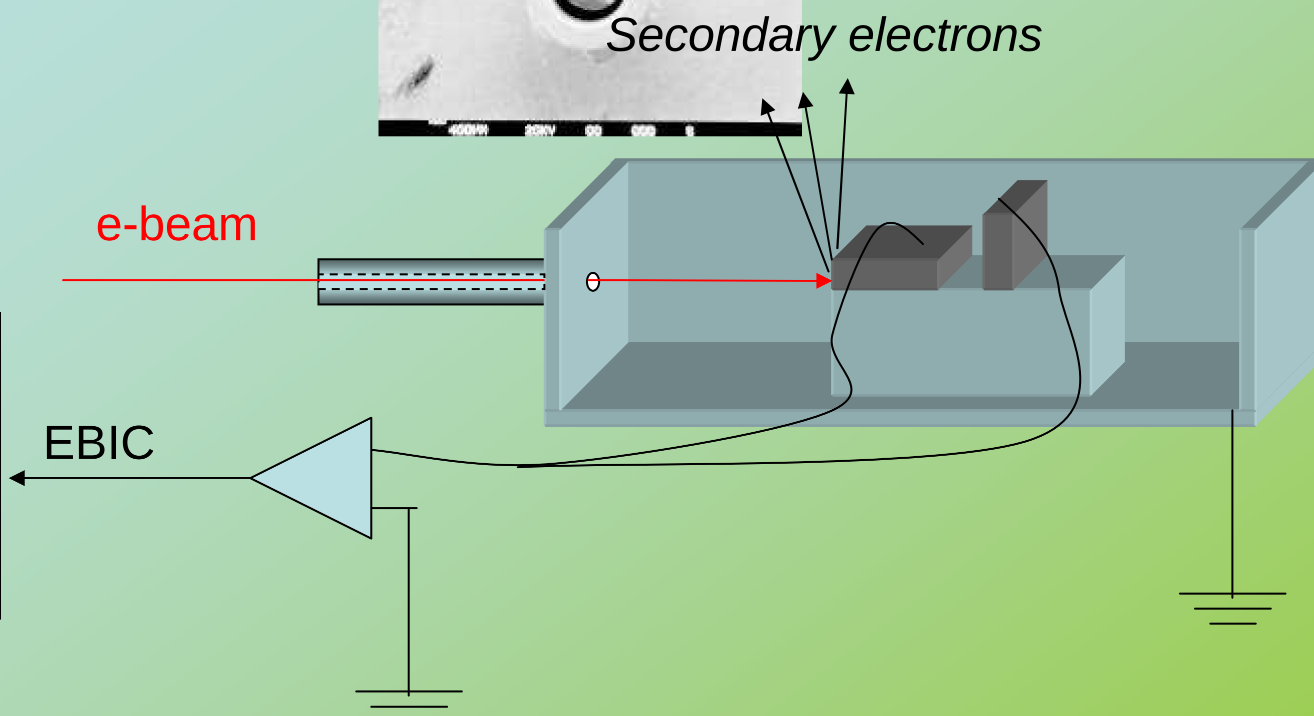
• an optical emitter whose output power decreased below tolerances
• an electrical diode shorted, open or leaky. Quite rarely OK.
• a microscopic object, whose observation requires IR for optical microscopy, and whose active region is smaller or comparable with the optical resolution.
• an interesting specimen for EBIC, provided its detailed structure is known and a reference is available.

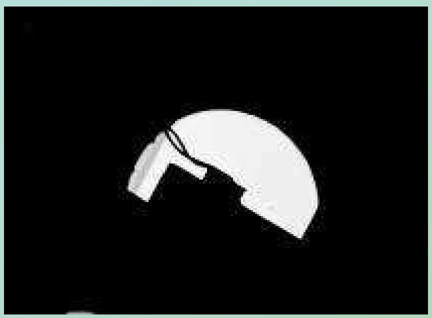


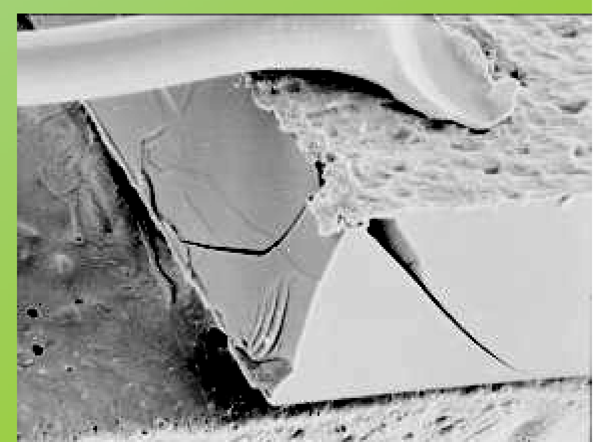


1982: paleophotonics/1

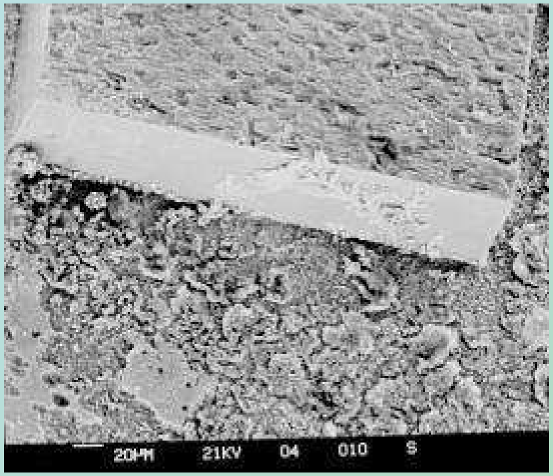
- A primitive soldering process
- The faithful EBIC response

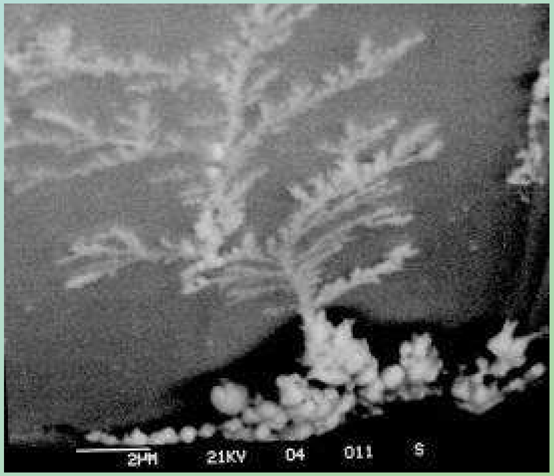






paleophotonics/2





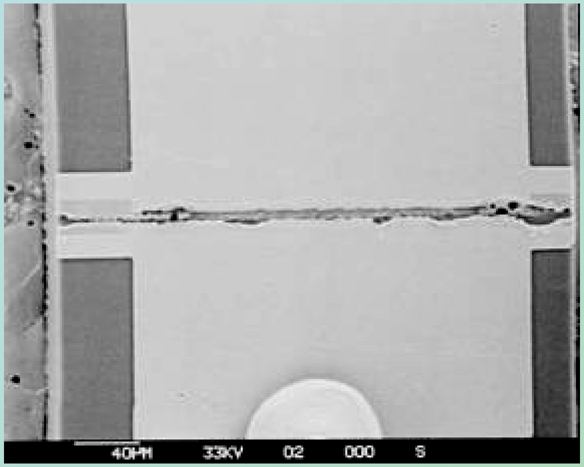
EBIC again: the discovery of a parasitic diode. Mechanism: corrosion

In both cases the die attach was the origin of the problem:
bad material, bad deposition/soldering process.

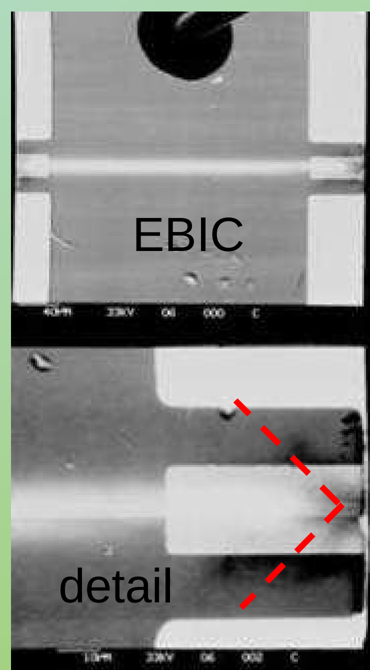
In both cases, also, the photonic degradation was nearly negligible:
some slight increase of the required current (leakage)

EBIC started to play the role of a suitable technique for investigating LDs

The golden age of Burn-Out: it explained everything, and always EOS (Electrical Over Stress) was indicted for the crime.



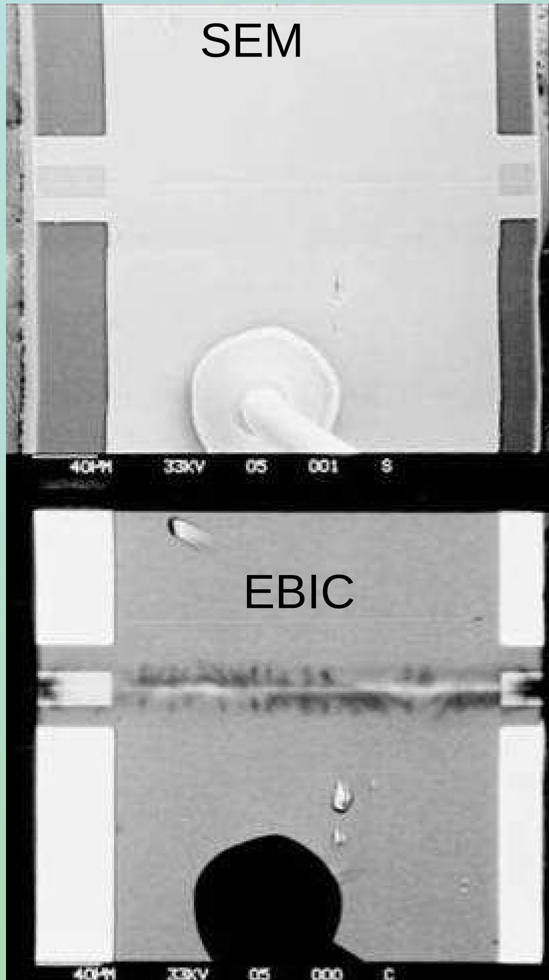
…and even it seemed not so wrong,

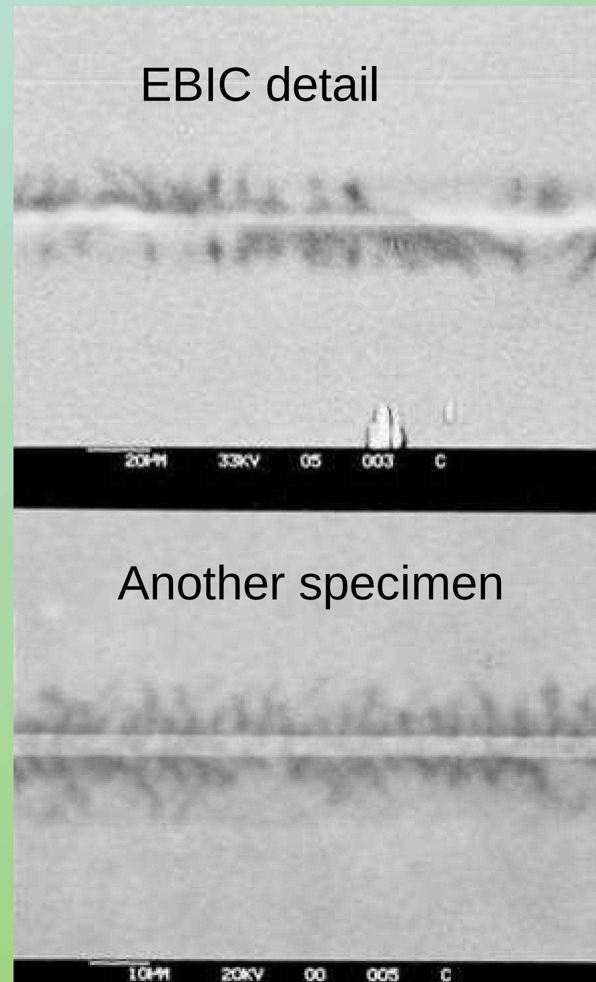


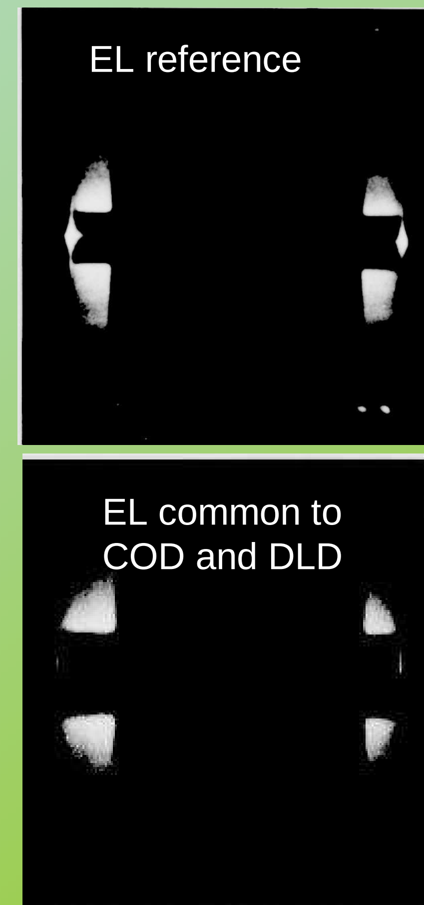
until EBIC started to reveal lattice-oriented dark stripes at the “burned” mirrors

A “ghost” was evoked:
the mysterious COD (Catastrophic Optical Damage) whose only known feature was to affect the laser mirrors.

Just in time to discover dark lines also inside some optically degraded lasers

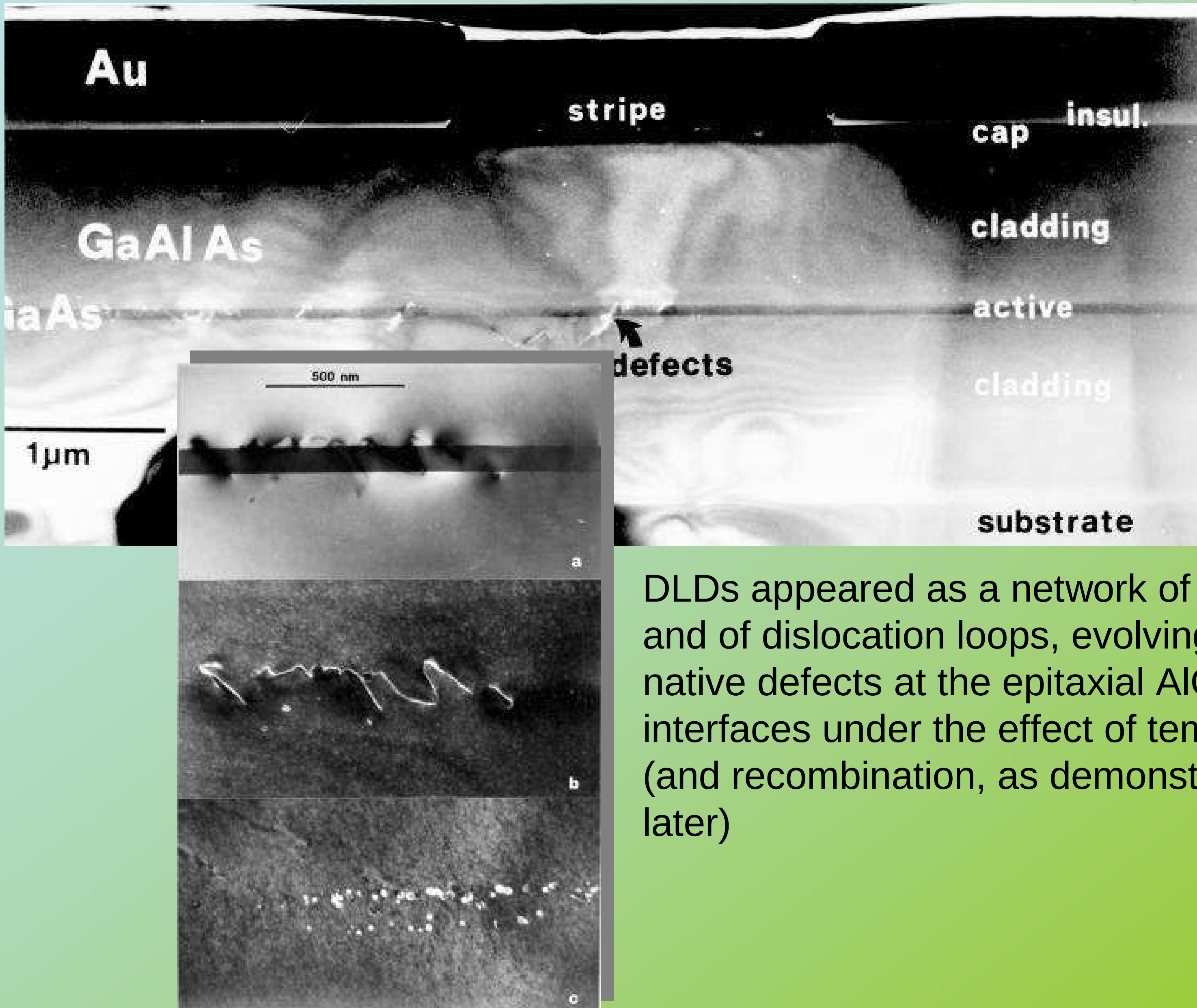






…and to create another "pseudo-mechanism" : the DLD (Dark Line Defects), a tautology for the failure mode. NOT a failure mechanism.

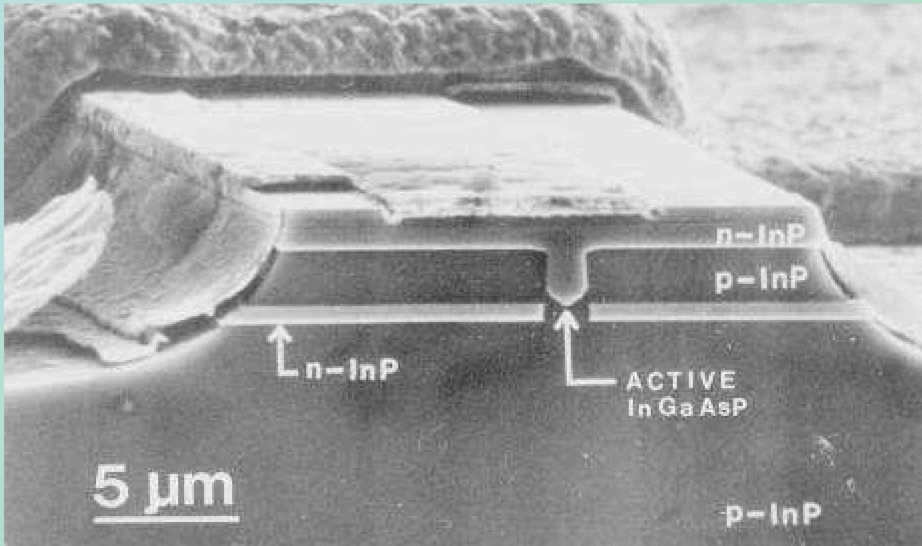
It was time to look inside the die. The Cross- Sectional TEM (with no FIB…)

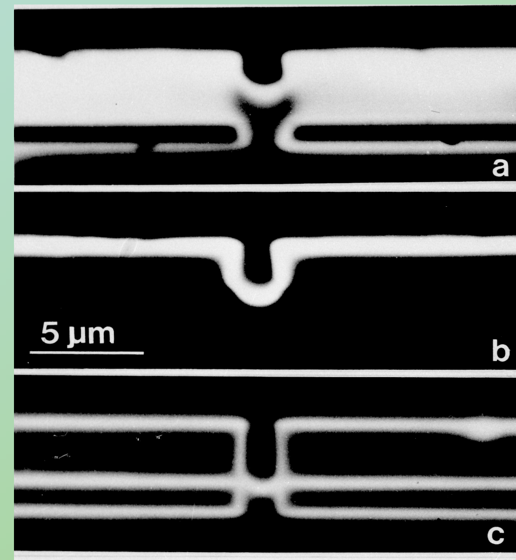


DLDs appeared as a network of dislocations and of dislocation loops, evolving from native defects at the epitaxial AlGaAs/GaAs interfaces under the effect of temperature (and recombination, as demonstrated years later)

Late ’80s: The InP/InGaAsP Buried Crescent structure

InP/InGaAsP BC laser facet
after dielectric removal and stain





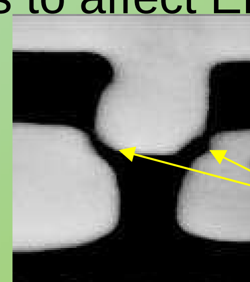
np diode

?

pn diode

EBIC on untreated facets

1988: EBIC proves suitable also for direct inspection of laser facets
Surface conduction seems to affect EBIC mapping even on good devices…

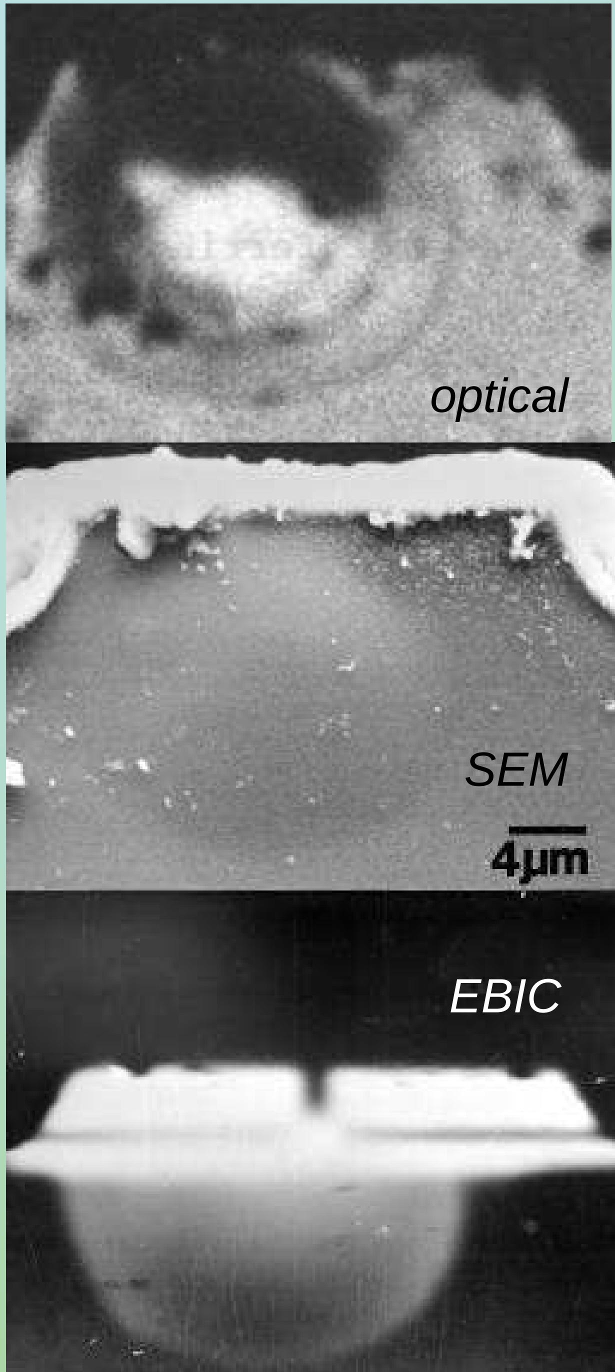


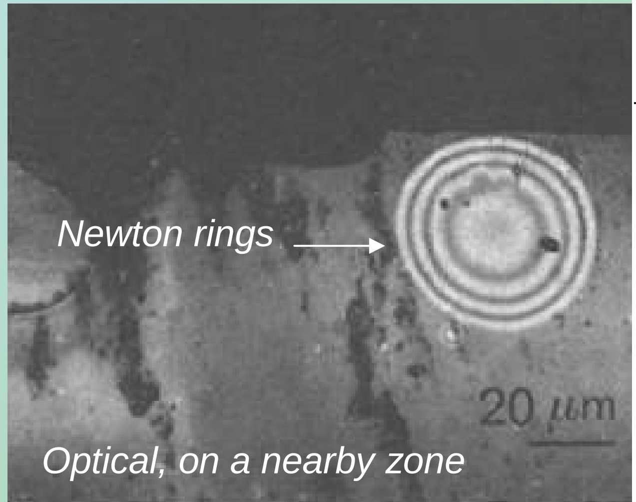
EBIC “whiskers” running along the p-InP epitaxial surface of the Buried Crescent structure

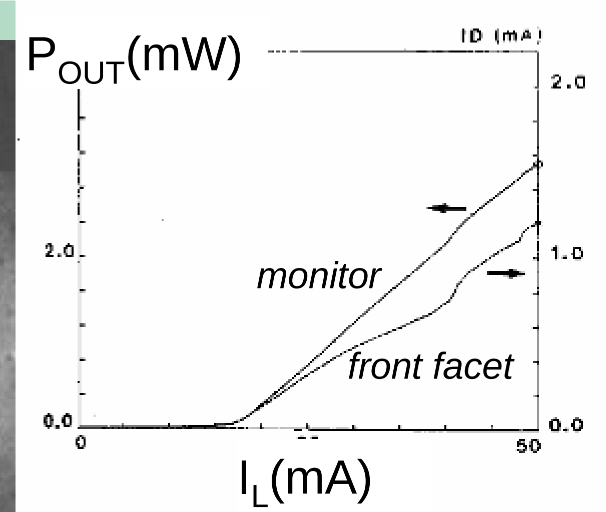
regular

anomalous

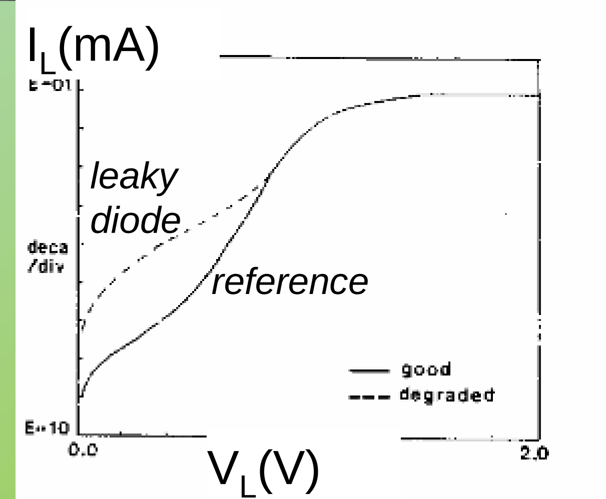
… as well as lattice defects.







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

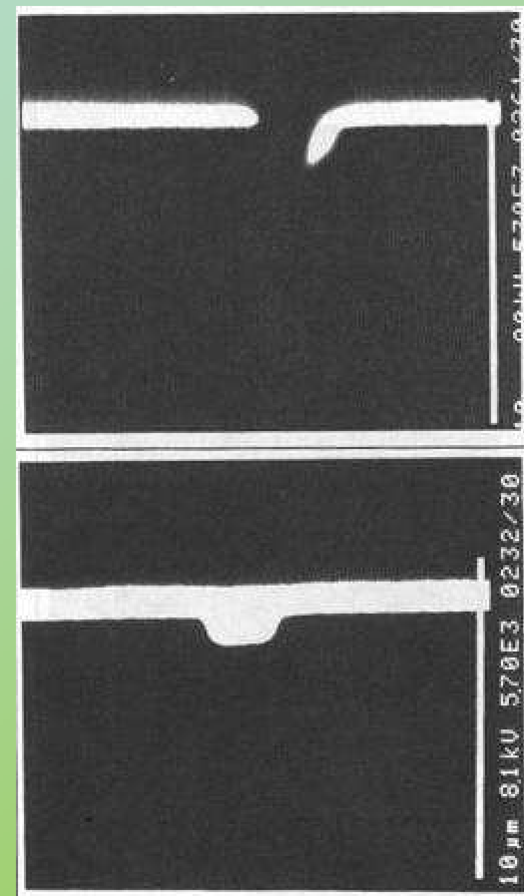


A beautiful way for revealing anomalous surface states, responsible for detectable electrical effects (leakage)

The ESD epics

Under ESD tests the laser diodes fail. The usual failure mode is a short circuit, and EBIC shows junction perforation at least at one of the facets.

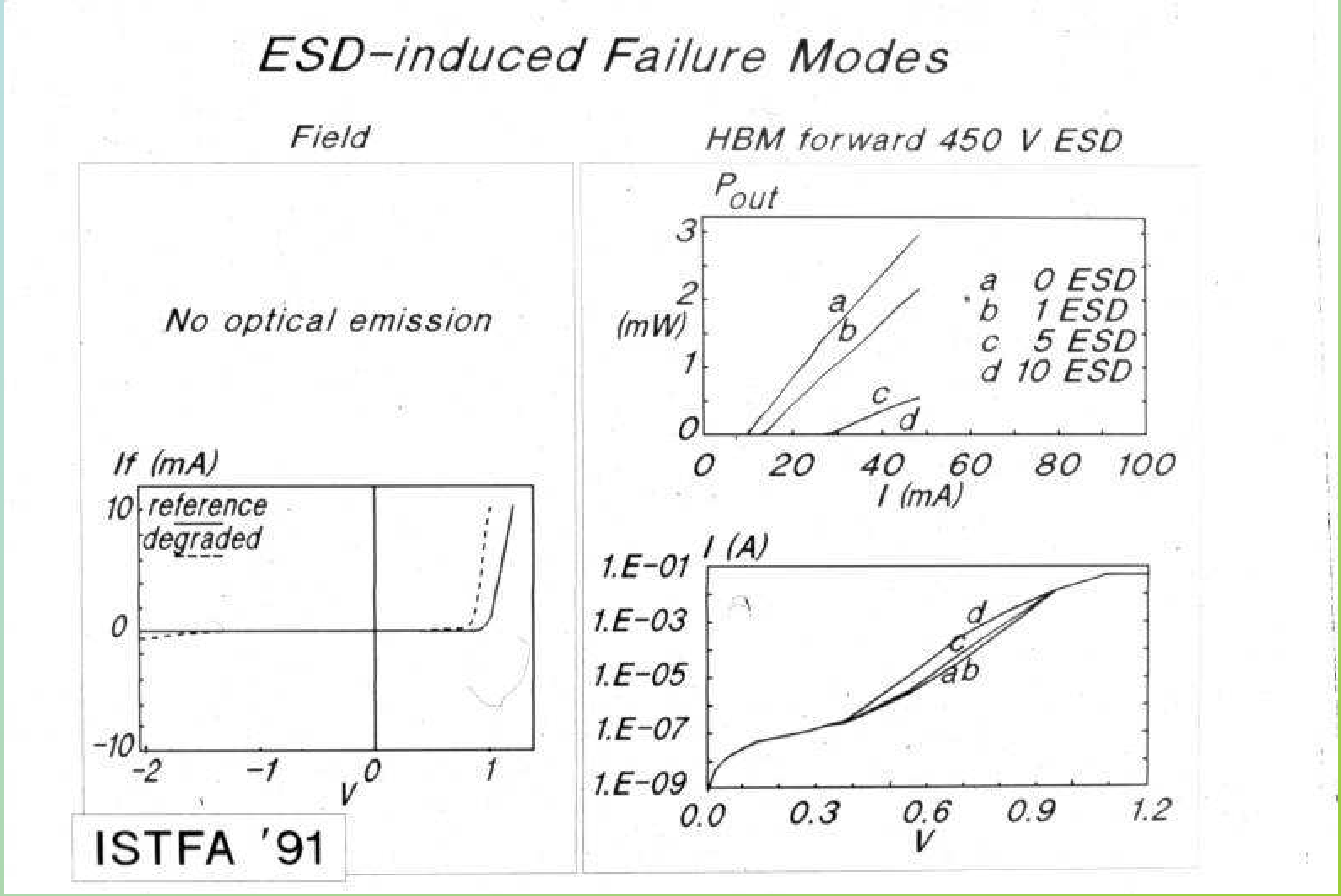
failed



reference

(from A.Urbieta, G.Zanon,IBM France, proc. ESREF 90)

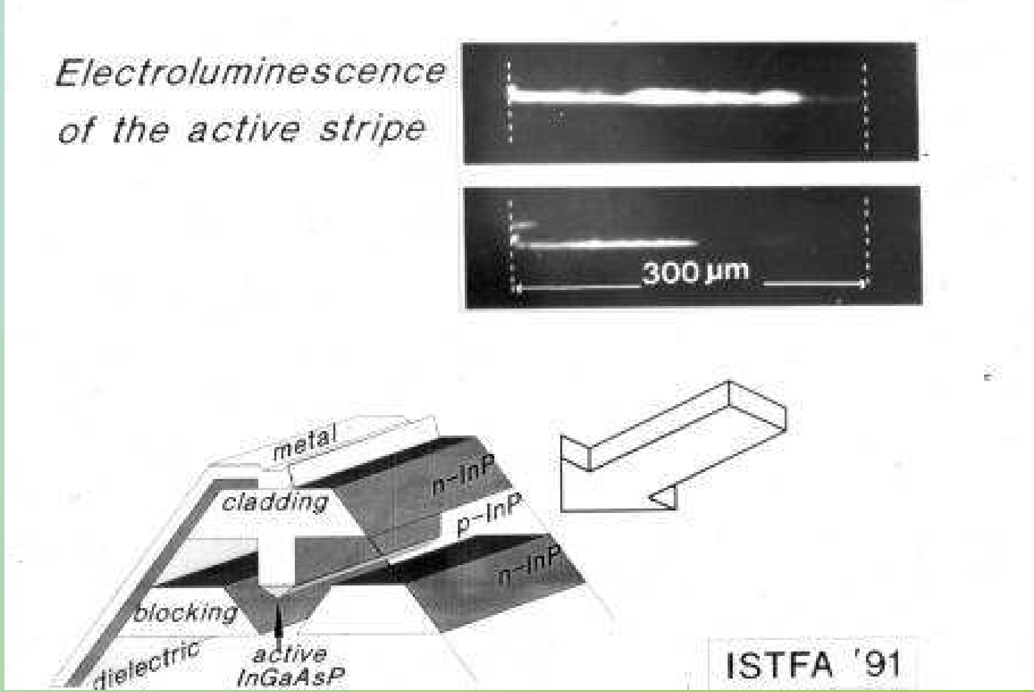
1991: the unusual behavior of InP/InGaAsP devices

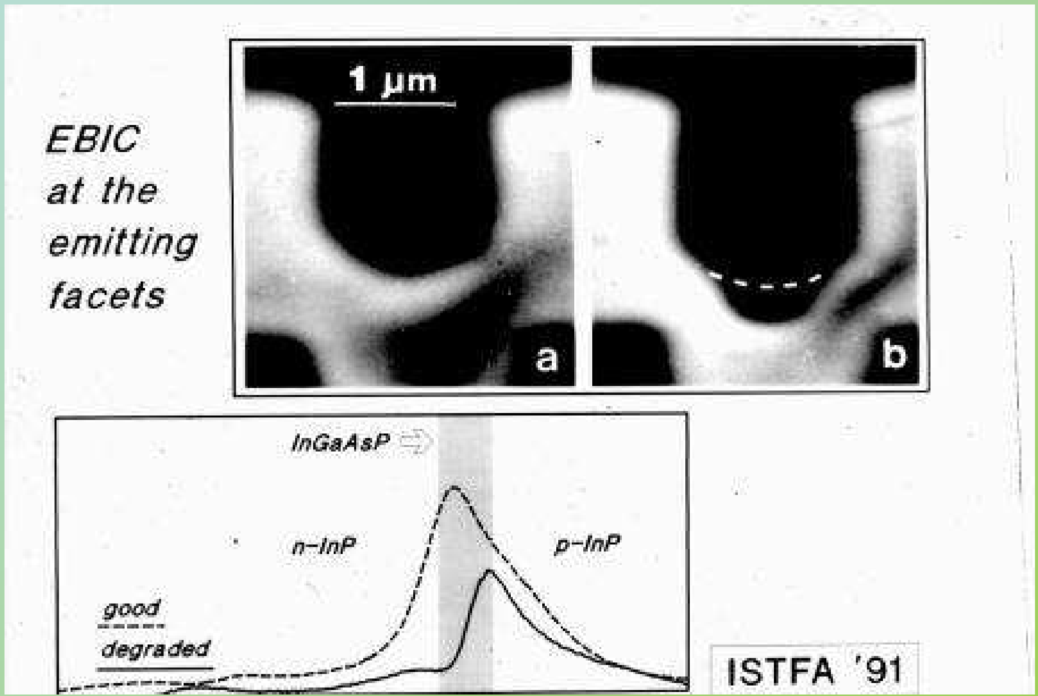


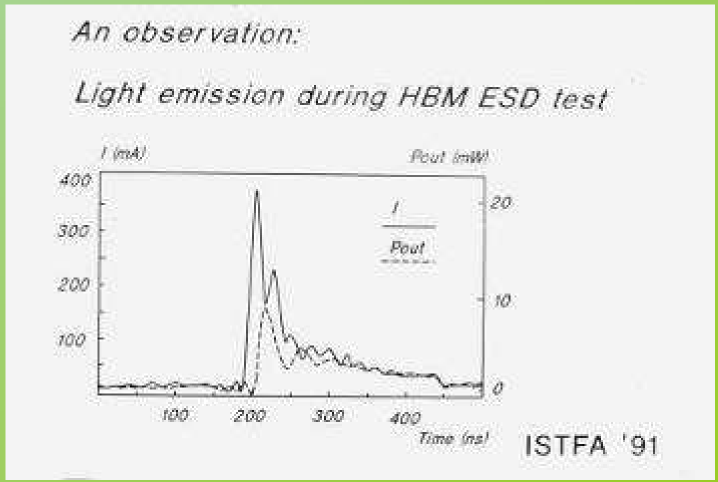
The latest "praeternatural" interpretation: *loss of confinement (!)*

Back to earth: one of the most difficult Failure Analyses

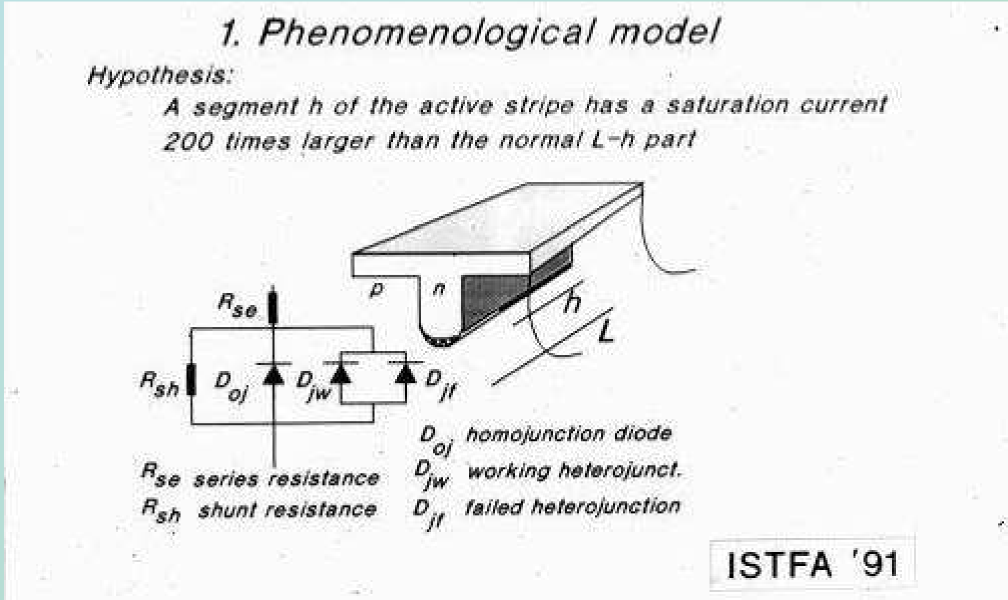
The set of observations:
a real puzzle



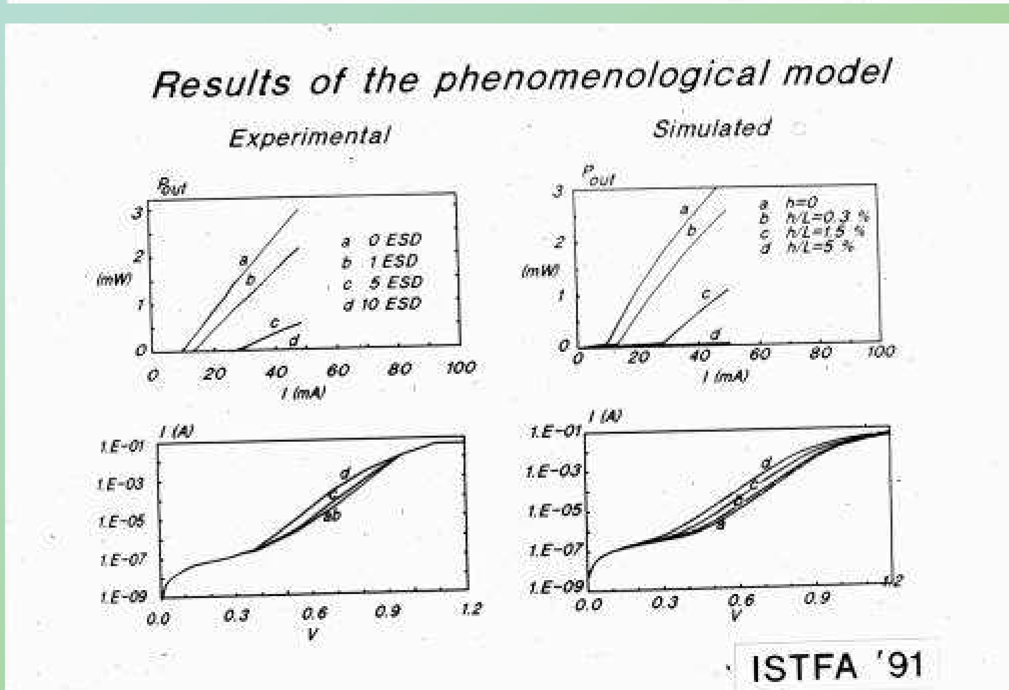


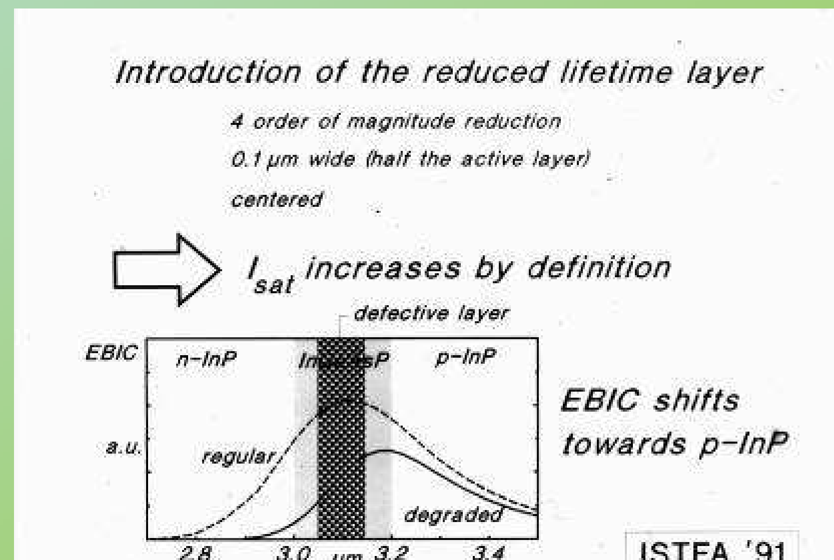


First step: a phenomenological model, and a set of parameters to trim



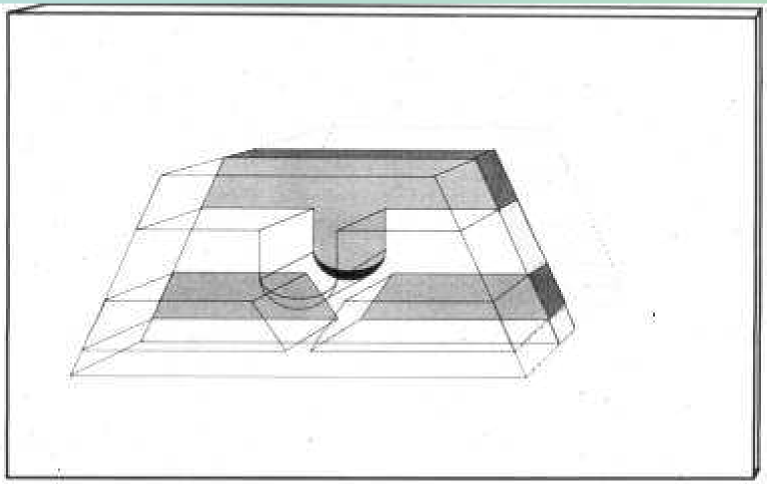
A layer of defects MUST exist confined inside the 1000 Å thick, 3 μm wide, active region, running for hundreds micrometers.



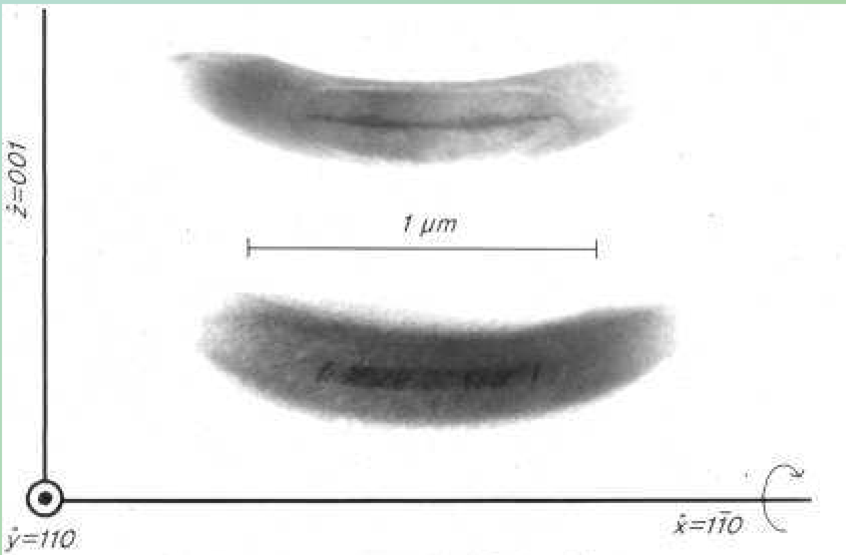


You should show it
and explain its formation
under ESD stress.

Here it is!



Thin section across the EL black segment



Bright field 300 keV

ISTFA '91

Further ion milling

Defects are present only in the middle of a regular lattice ellypsoid.

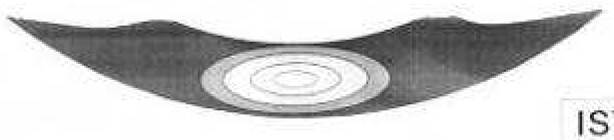
ISTFA '91

TEM confirms the hypothesis of the structural model.

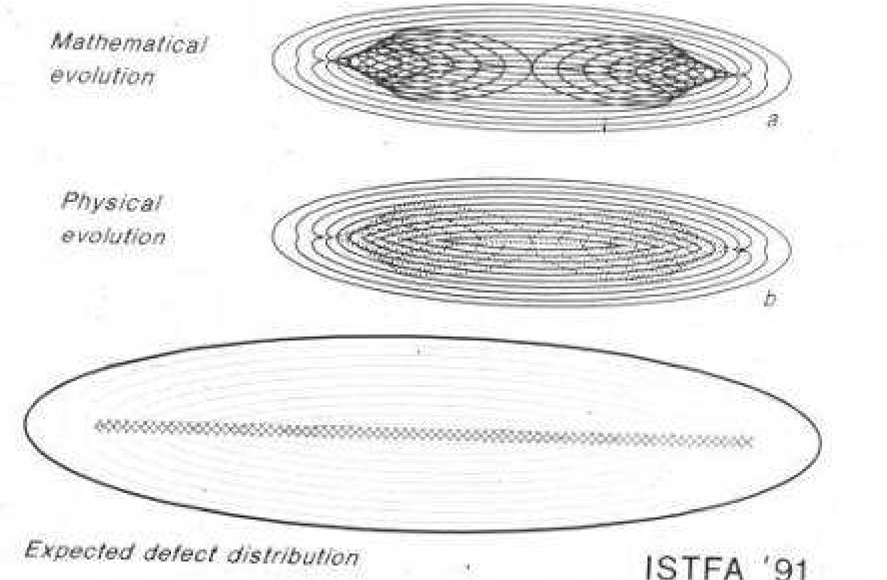
But: how can ESD induce those defects?

Hypothesis: *Sudden optical power dissipation*

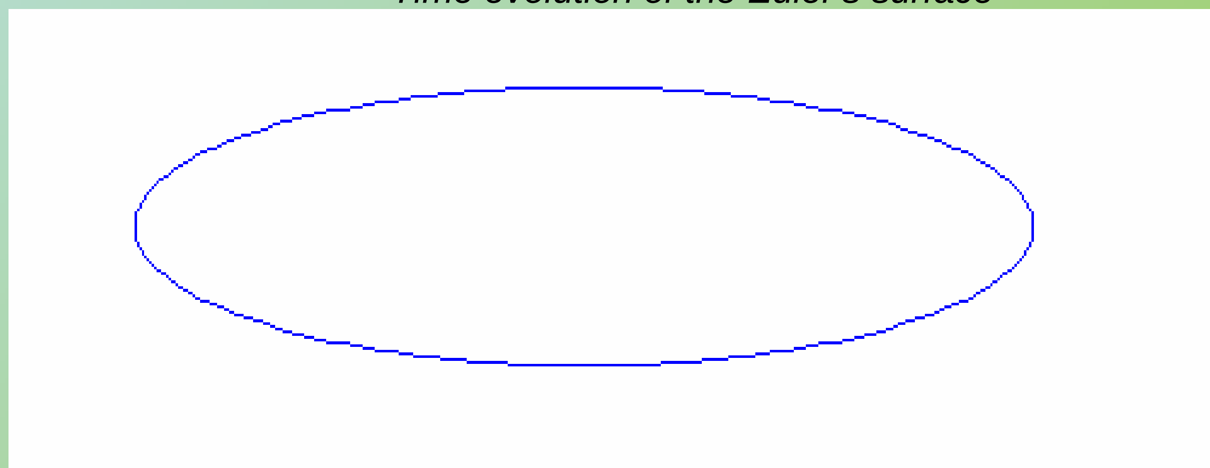
Local melting and regrowth.



ISTFA '91



Time evolution of the Euler's surface



This failure analysis was the prompt to propose, in 1995, the "Rules of the Rue Morgue": a prayer for scientific methods in both procedures and hypotheses within the reliability community.

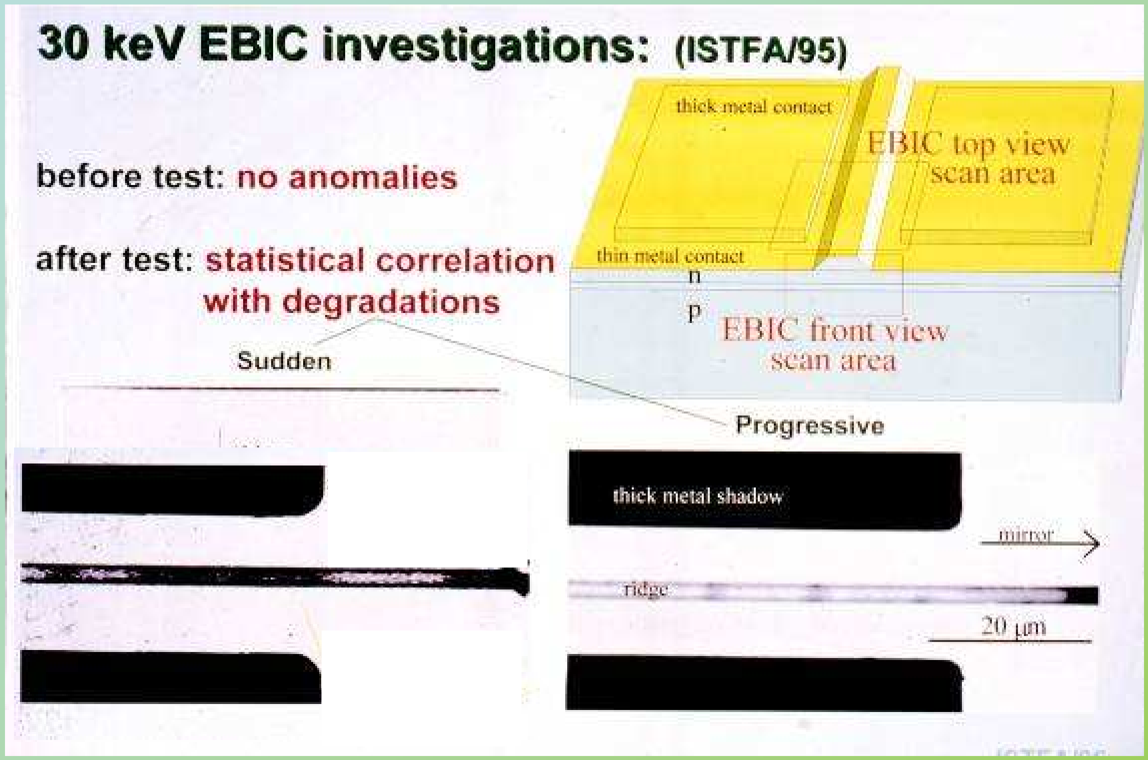
The ’90s: The pump lasers for EDFAs (and, later, for Raman)

New technologies: Quantum Wells, Strained Lattice.
New wavelengths: 980 nm
High current, high power: new mechanisms expected

And a new failure mode:
sudden failures, even after thousand hours of regular life

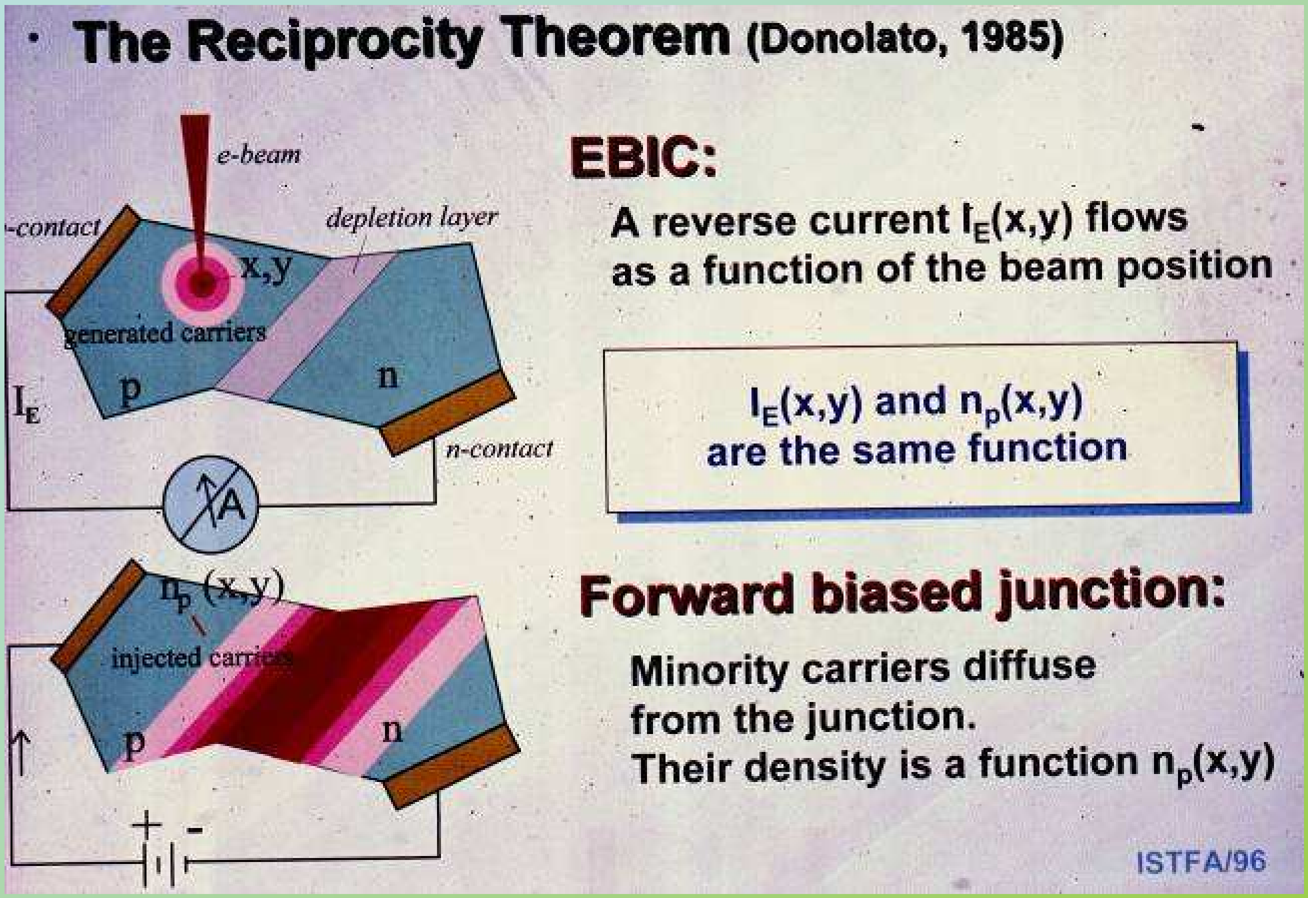
An extremely subtle feature of the failure mode: sudden failures occurred according to an *exponential distribution*, that is at constant rate. It is the fingerprint of *casual* events…

…but casual events are not likely to generate *internal* defects, as shown by EBIC, similar to the evidence from progressively degraded devices.



Is EBIC meaningful? Does that glorious technique fail on these new devices?

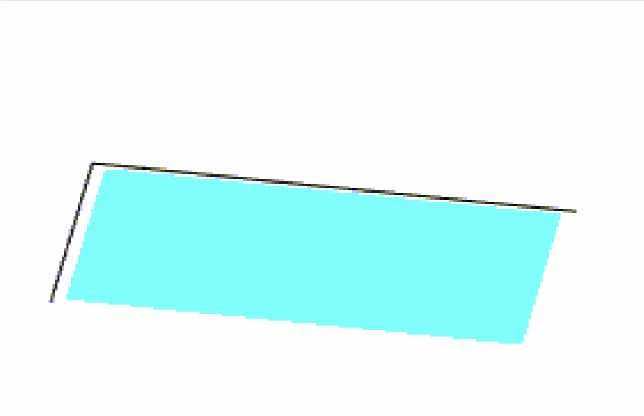
One year to give EBIC back its honour.

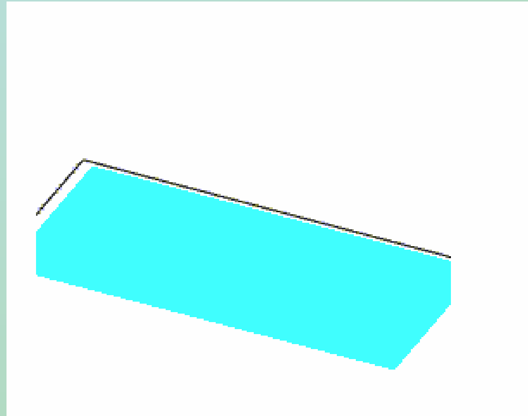


Where EBIC is possible, it maps the efficiency of the junction in injecting carriers, when forward biased.

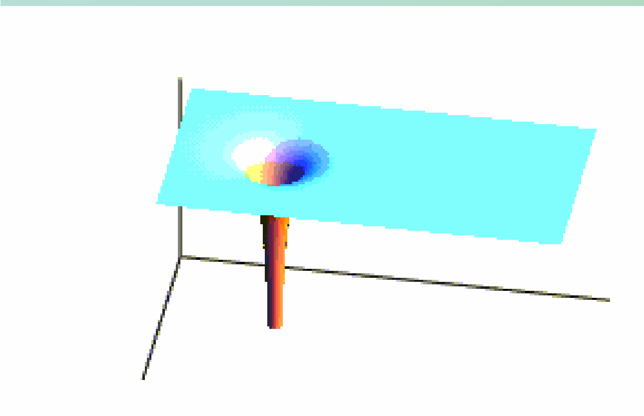
How can defects suddenly hit a laser, after a long silent time?

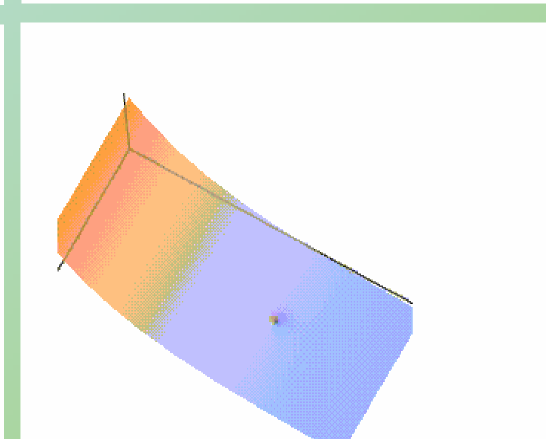
The REDR (Recombination Enhanced Defect Reaction) mechanism:



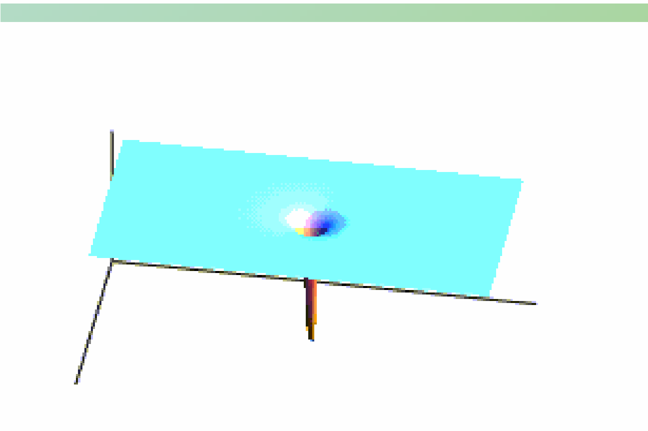


Defects flowed by minority carriers diffusing from a forward biased junction will reach the depletion layer within a time proportional to the exponential of the distance





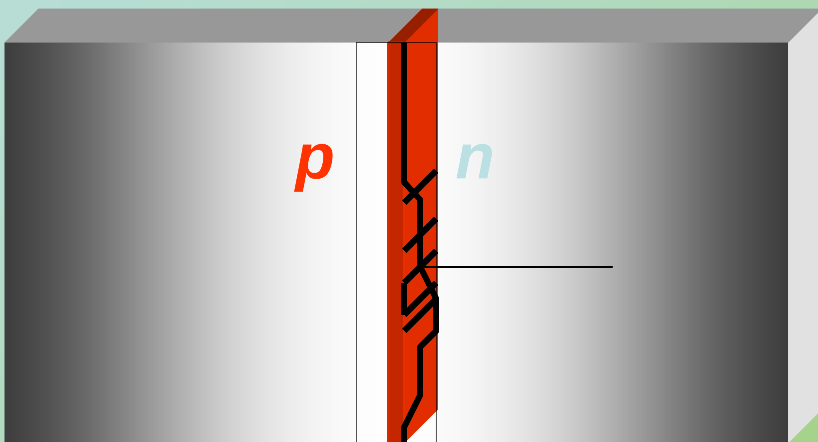
They will affect the diode only at that time.



Externally, it seems a sudden event

REDR in SL laser diodes: a *possible* root for sudden failures

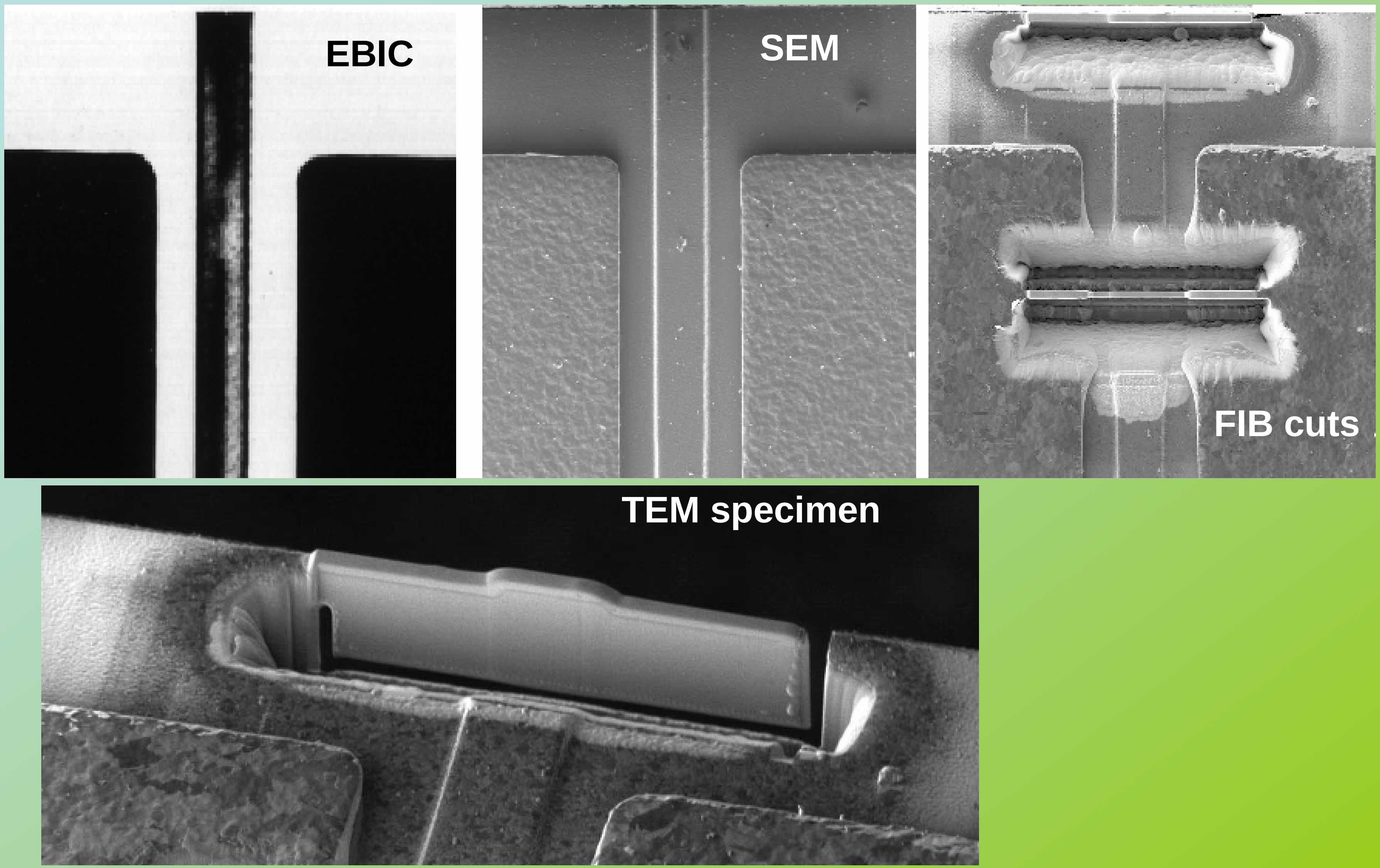
In Strained Lattice Double Heterostructures (SQW InGaAs/AlGaAs laser): fast *strain release* after the delayed arrival of the gliding defect



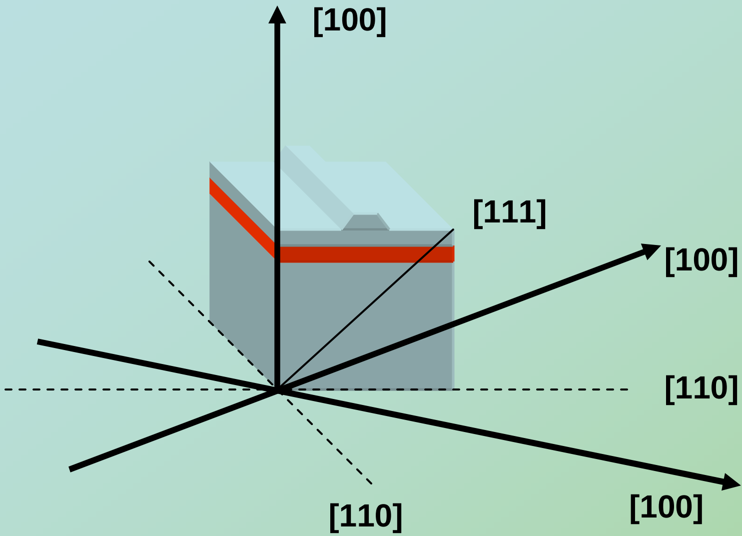
Expected findings:

- **Current sinking by non-radiative recombination**
- **Displacement of the current threshold**
- **Long dark strips in EBIC**
- **Network of *misfit* dislocations ([110] preferential)at FIB/TEM**

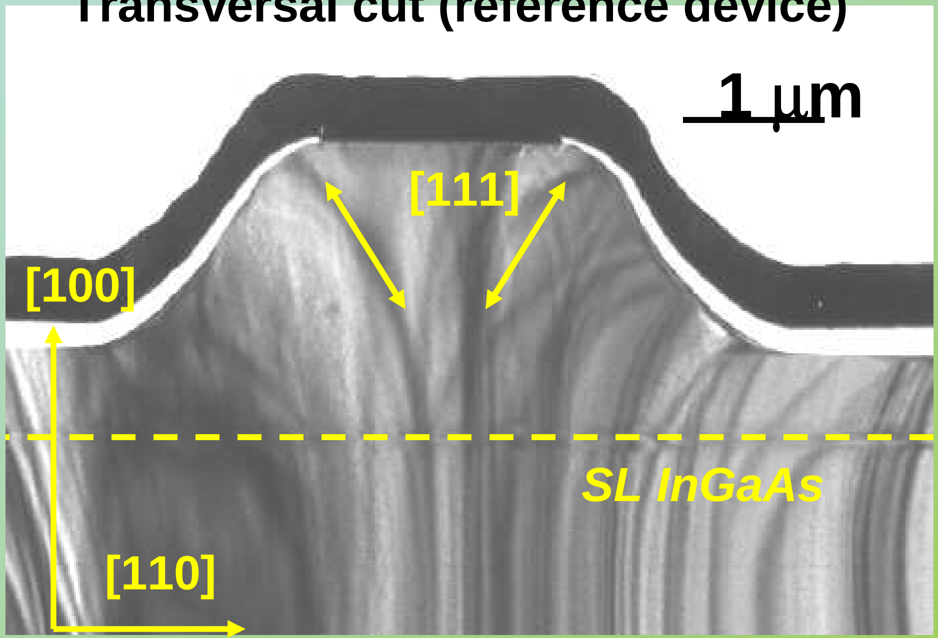
EBIC-driven FIB/TEM



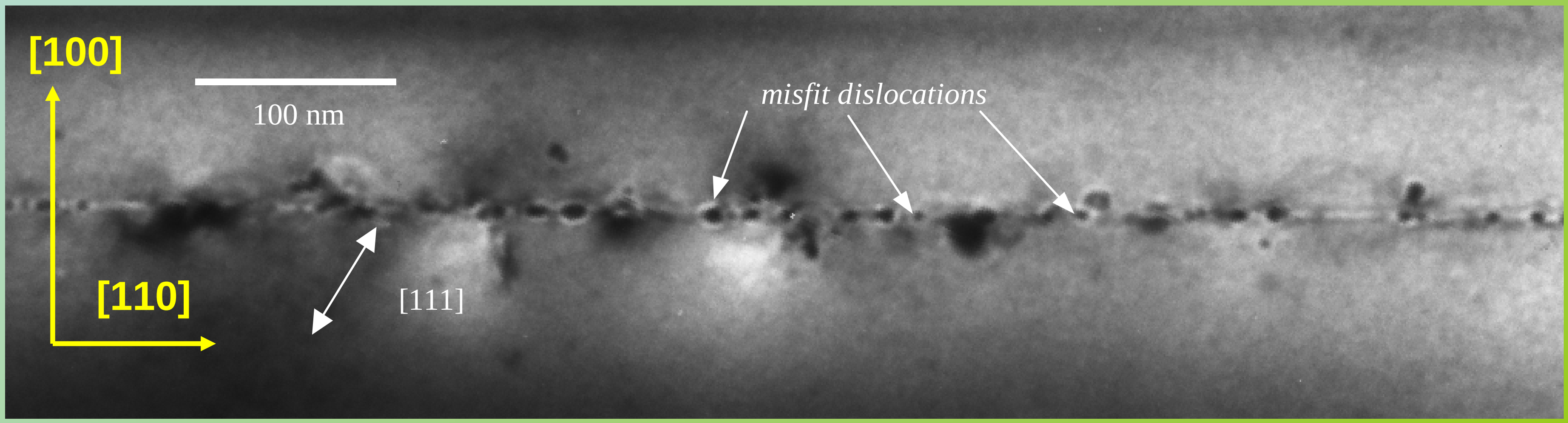
TEM results



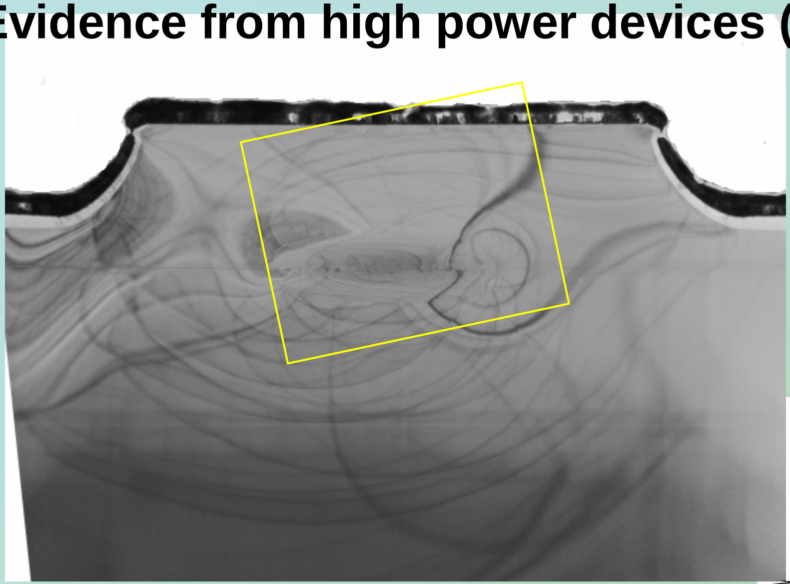
Transversal cut (reference device)



Longitudinal cut



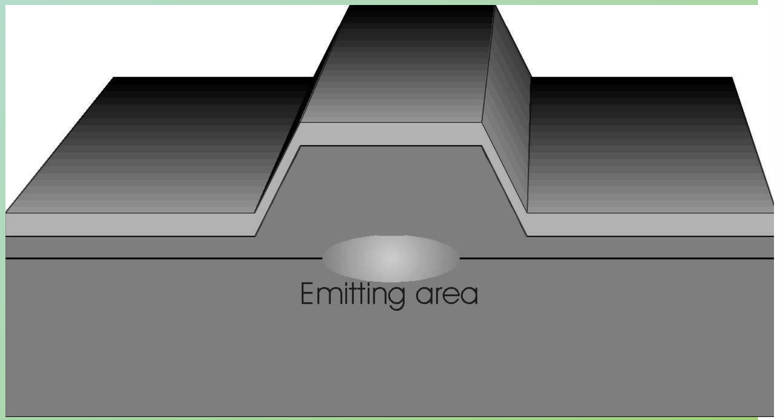
Evidence from high power devices (ESREF2000)

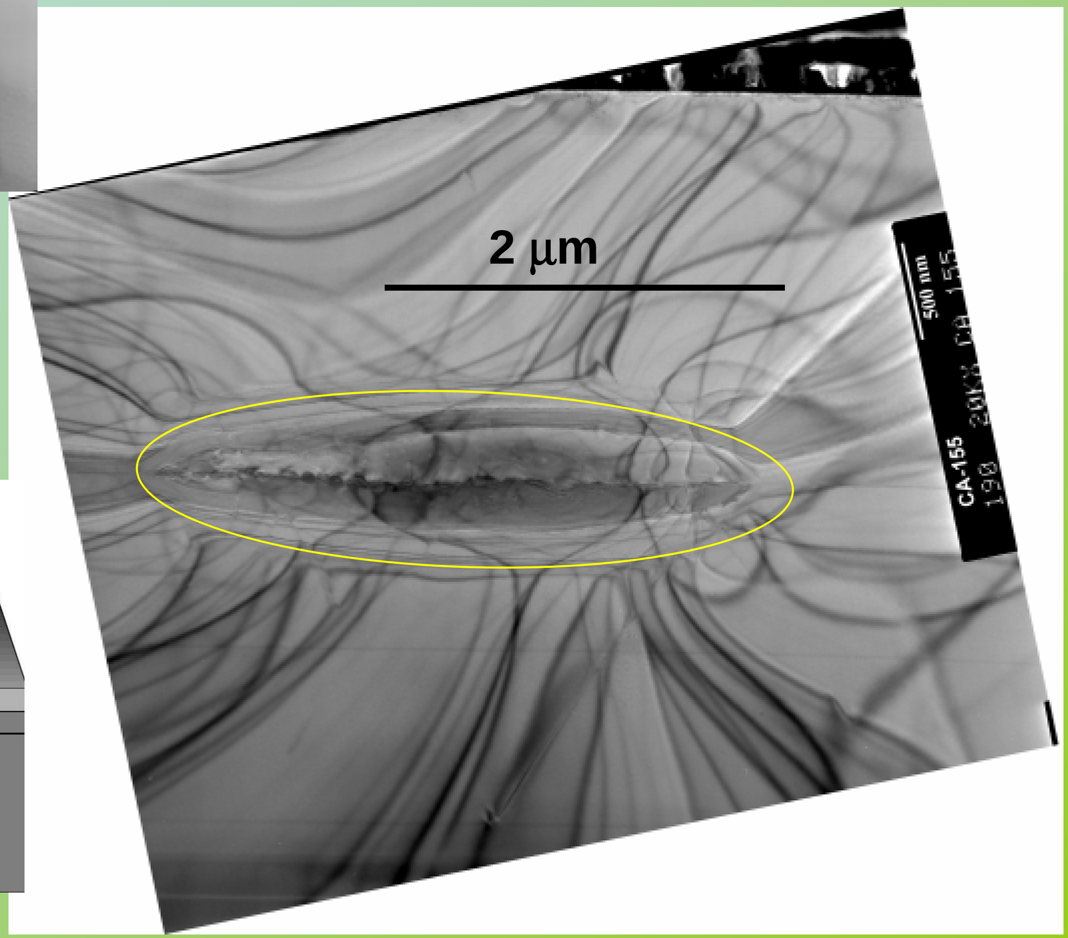


Overstressed sample: no evident, extended dislocation patterns,

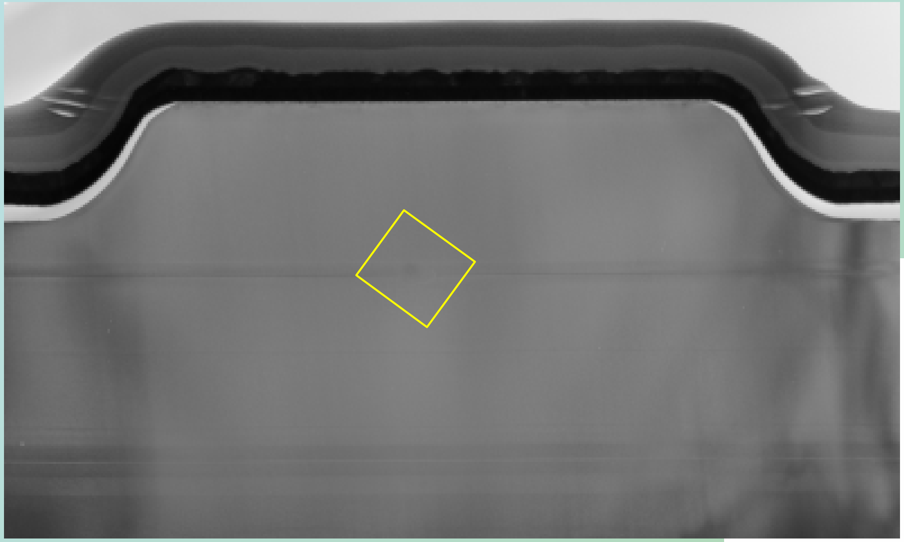
but a limited region of strange contrast...

…limited by an ellipsoidal boundary, resembling the expected "hot" region around the emission area

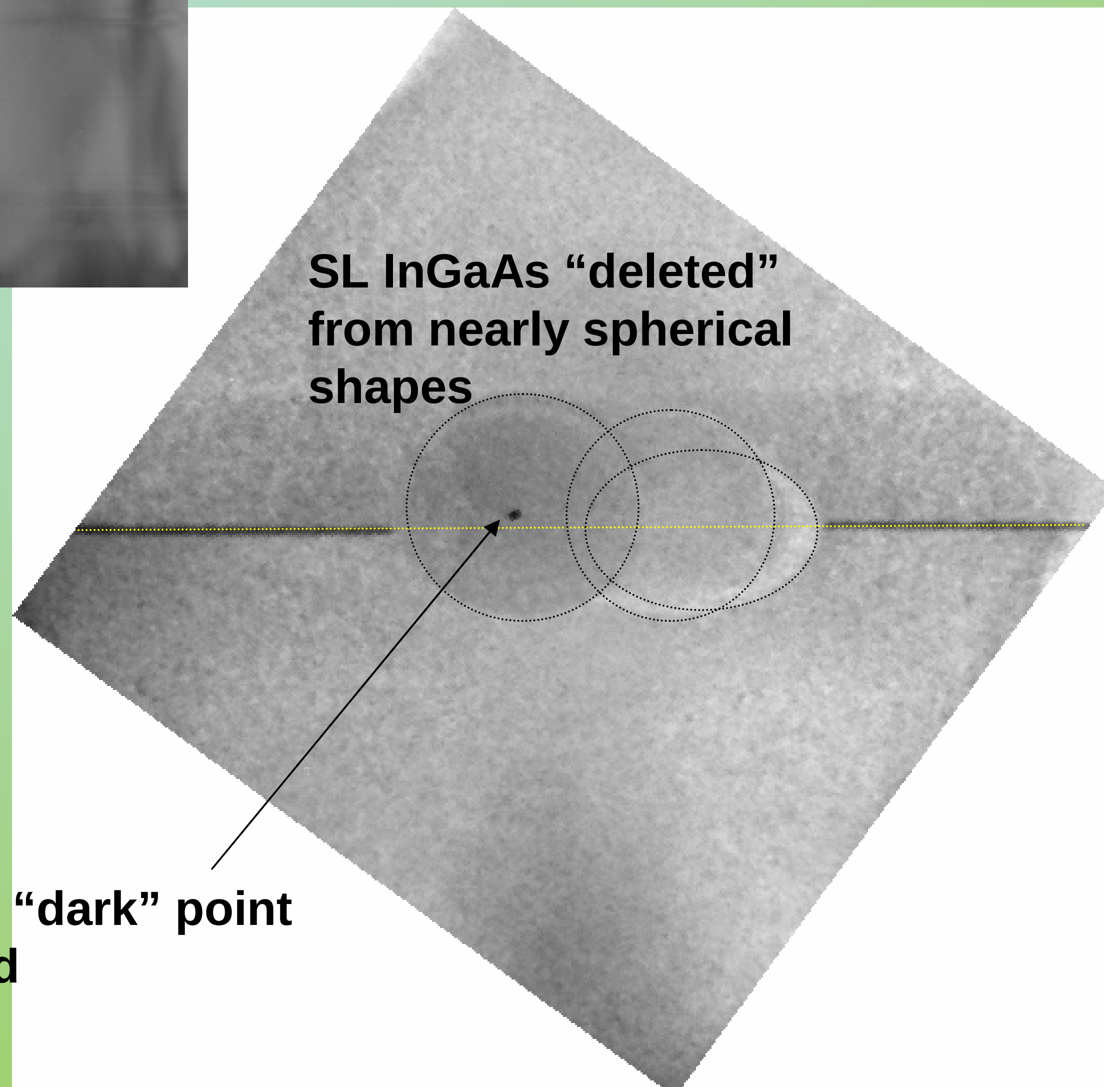




Fusion and re-crystallization, as for the "old" devices



Suddenly failed device:
nearly perfect lattice



SL InGaAs “deleted” from nearly spherical shapes

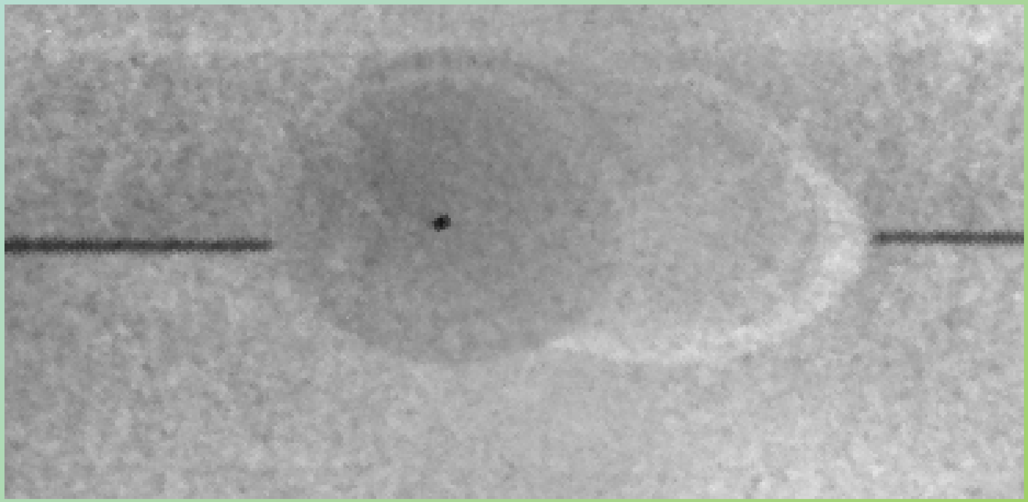
No defects even at higher magnification

1 single “dark” point centered

Suddenly failed device:

the same mechanism, but starting from a *different heath source:* a [110] line laying inside the SL InGaAs:

a typical misfit dislocation

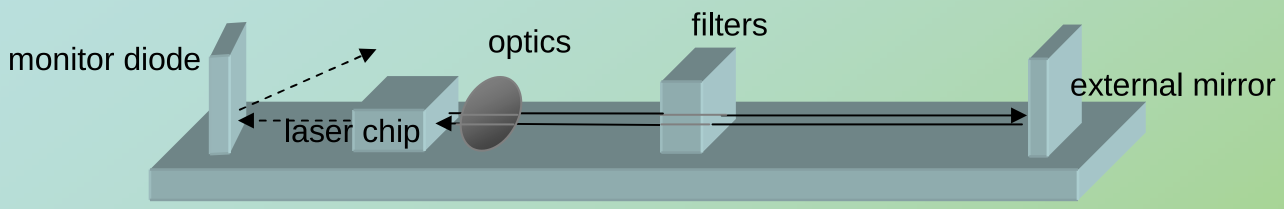


It acts as a hot rod because of its twofold energy sinking role:

1) **energy released by excess carrier recombination**
2) **photon absorbption because of local recombination-induced transparency loss**

And cannot be a native defect… → **REDR**

2000s: the external cavity tunable devices.



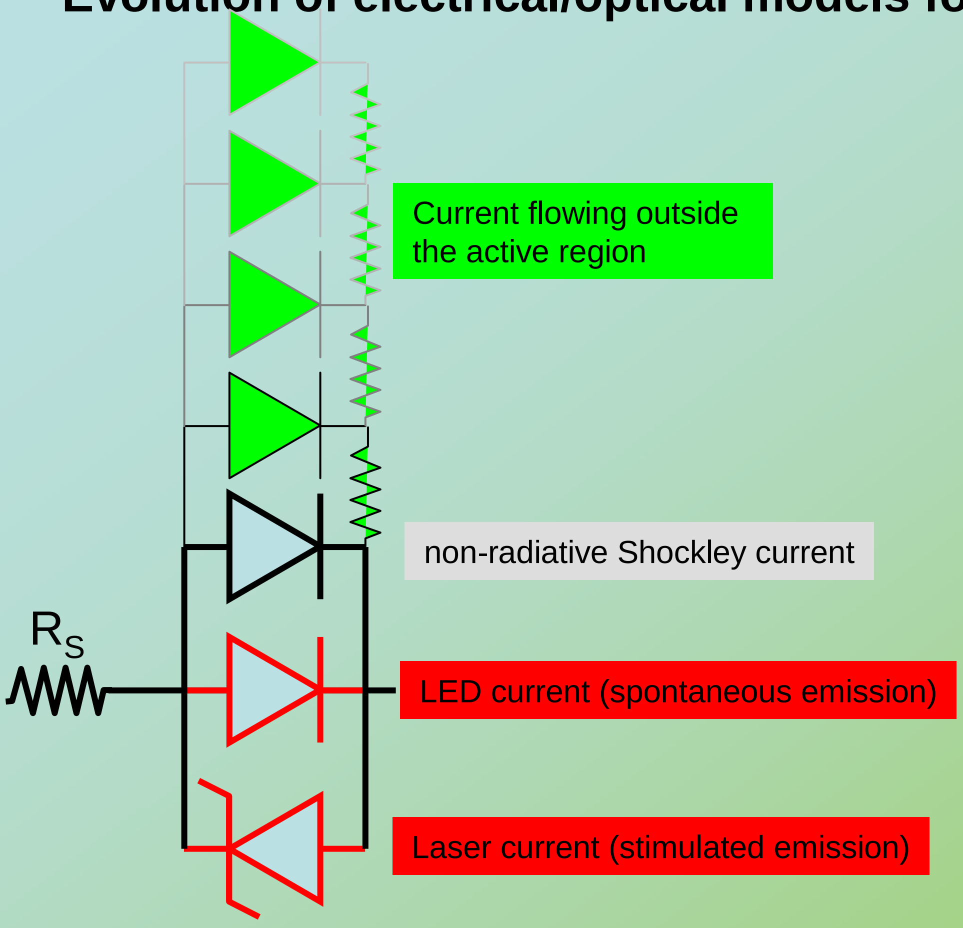
• Impossible to apply lifetest-level stress to an assembled module

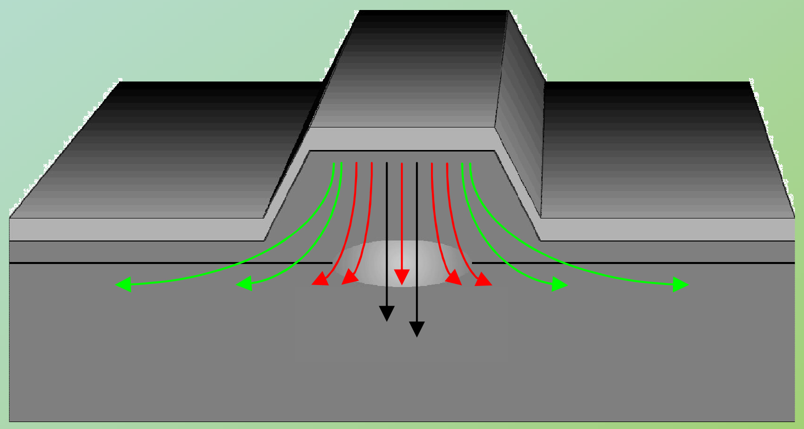
• Impossible to test the single chip: no laser emission

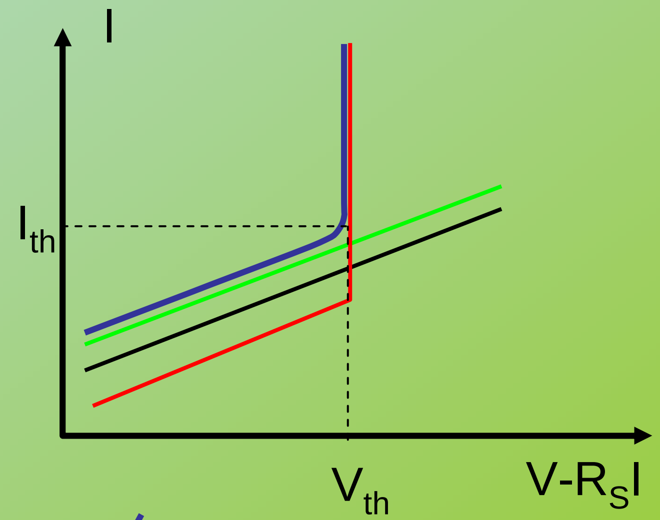
• Accelerated life tests only possible on Fabry-Perot chips: are results meaningful?

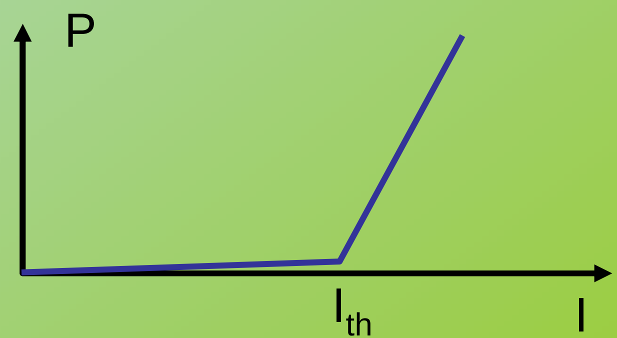
•Is chip reliability still the major issue?

Evolution of electrical/optical models for laser degradation

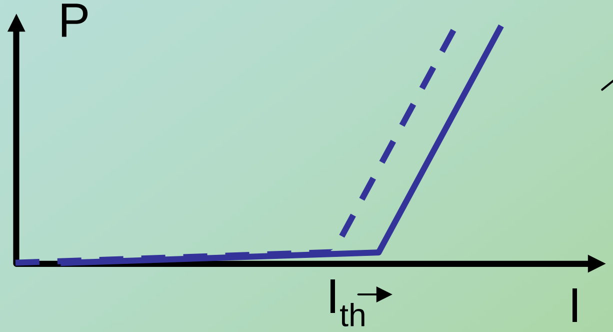


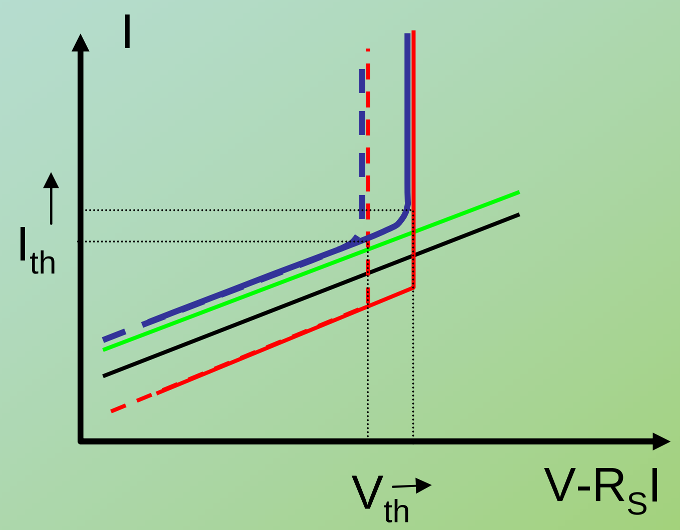




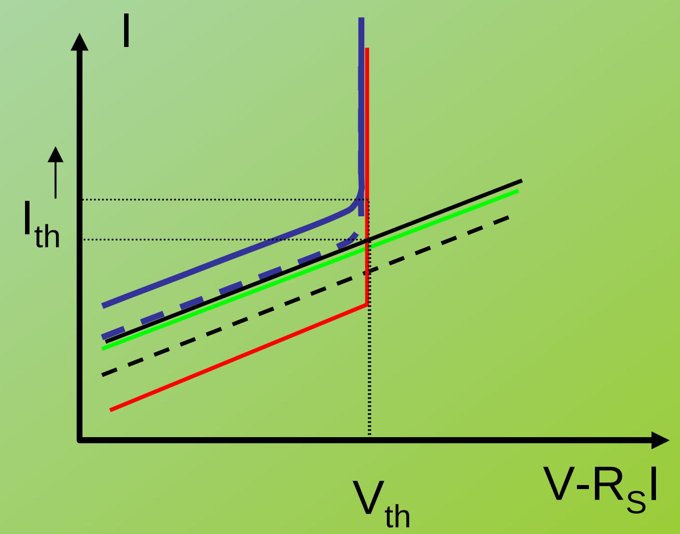


$$V_{th} \approx \frac{h\nu(eV)}{q} \approx \frac{E_g(eV)}{q}$$



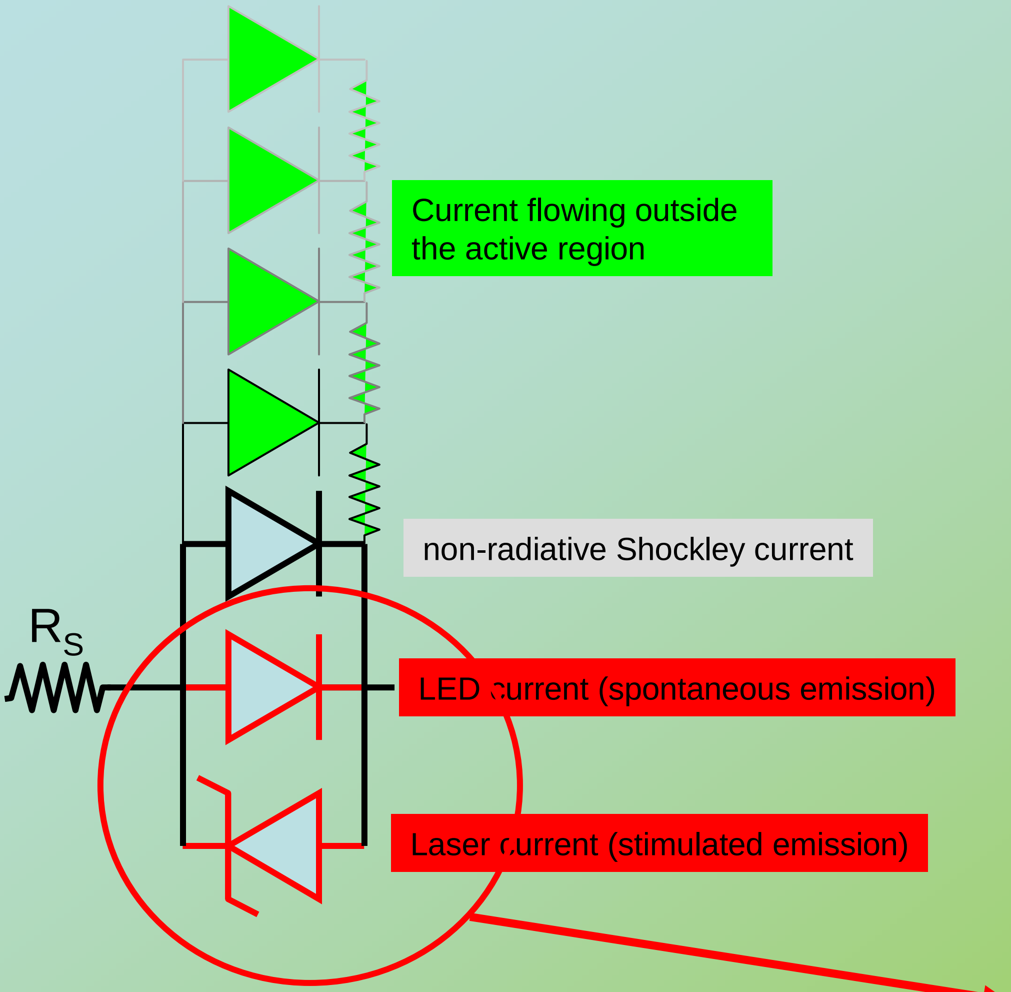


Increased facet loss



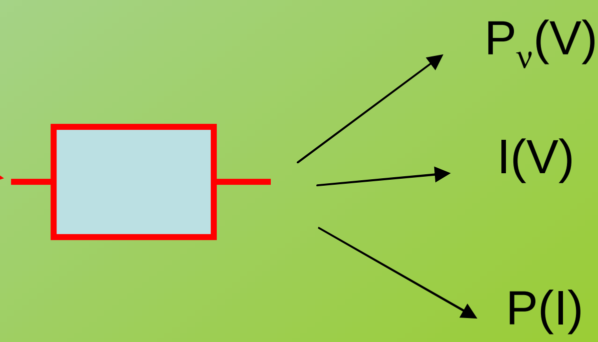
Defect growth inside the active region

The most recent evolution (2005, not published): the self-threshold model



A multimodal (spectral) model linking I, V and the spectral power.

Its calibration follows standard electric/optic measurements



An application to fit experimental figures of a single-mode ν (external tuned) QW laser

$$P_\nu(V) = ch\nu \frac{\gamma_0}{P_T\left[\exp\left(\frac{h\nu - qV}{2kT}\right)+1\right]^2 + \Omega_0\left[\exp\left(\frac{h\nu - qV}{kT}\right)-1\right]} \frac{P_{LD}}{P_T}$$

$$P_T = \alpha_e + \ln\left(\frac{1}{R_1 R_2}\right)$$ Total photon loss

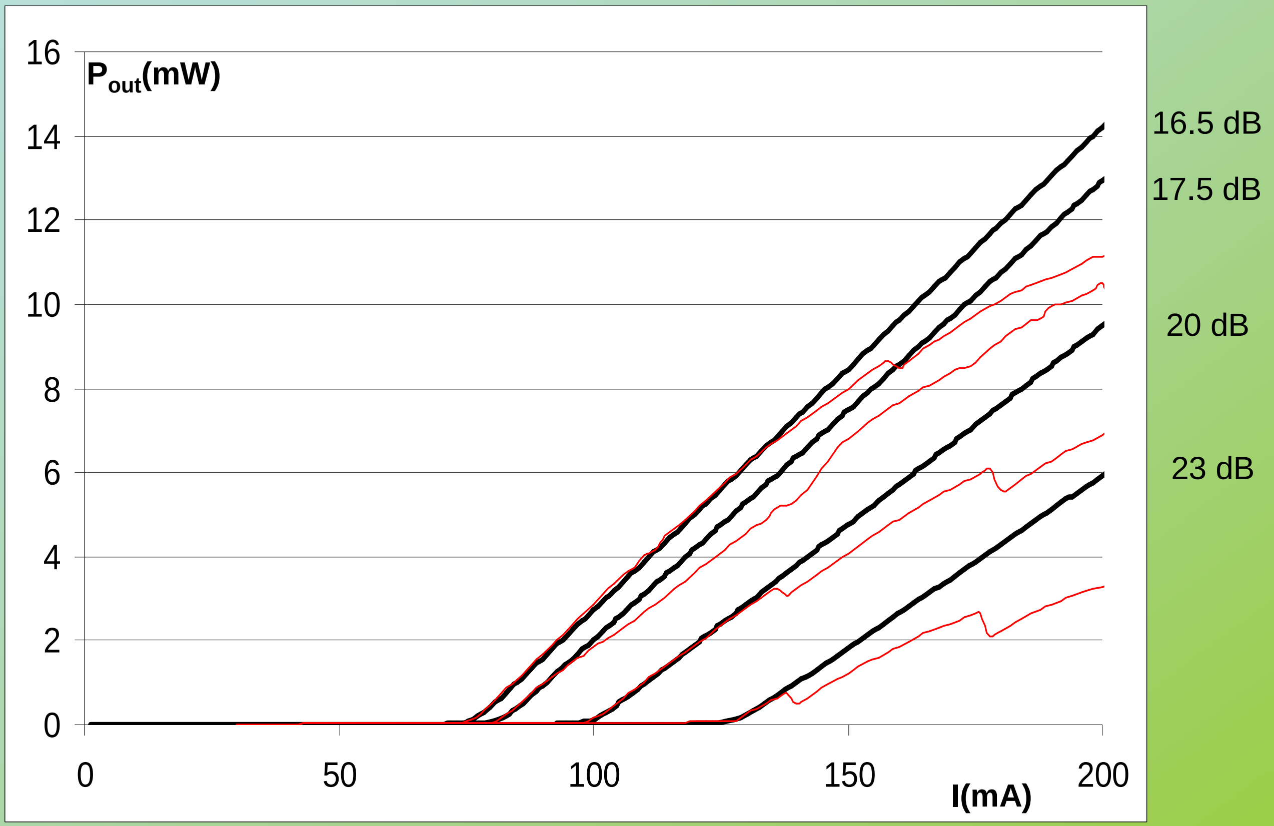
$$P_{LD} = \ln\left(\frac{1}{R_1 R_2}\right)$$ Photon loss from the only facets

$\Omega_0, \gamma_0 =$ device-specific parameters (to be measured)

$$P_\nu(V) = \frac{I_{ph}(V)}{q}\eta_q h\nu \frac{P_{LD}}{P_T}$$ η_q= quantum efficiency

$$I(V) = I_{ph}(V) + I_{s0}\exp\left(\frac{qV}{kT}\right)$$

Two characteristics at known P_T allow to calibrate the model and fit the threshold current and the optical efficiency at other loss levels



Conclusions ?

- Reliability: a never concluded job

- The race continues along the main streams of:

  - Technological Characterization
  - Technique experimentation and development
  - Specimen handling
  - Failure Physics
  - Device modeling

- See you at the next decade