In-situ curvature measurements applied to MOVPE-based growth of edge-emitting diode lasers

A. Maaßdorf[1)], O. Schulz[3)], M. Zorn[2)], J.-T. Zettler[3)], and M. Weyers[1)]

[1)]*Ferdinand-Braun-Institut, Leibniz-Institut für Höchstfrequenztechnik, Gustav-Kirchhoff Str. 4, 12489 Berlin, Germany*

[2)]*Jenoptik Diode Lab GmbH, Max-Planck-Str. 2, 12489 Berlin, Germany*

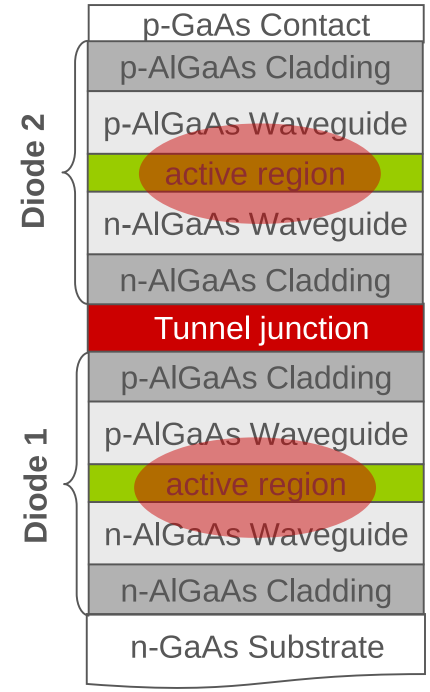
[3)]*LayTec AG, Seesener Str. 10-13, 10709 Berlin, Germany*

Outline

- Motivation: Strain in III-V devices?
- In-situ metrology measurement setup
- Growth and characterization of strain compensated III-V structures:
  - Test sample studies
    - $Al_{0.85}GaAs_yP_{1-y}$ for high power IR laser diodes (730 nm … 1180 nm)
    - InGaP for red emitting laser diodes (635 nm ... 670 nm)
  - Implementation of strain compensating (SC) $Al_{0.85}GaAs_yP_{1-y}$ layers in edge emitting diode lasers:
    - Super large optical cavity lasers (SLOC) with SC
    - 2-stage bipolar cascade laser (BCL) with SC
- Summary

Motivation: Strain in III-V devices?

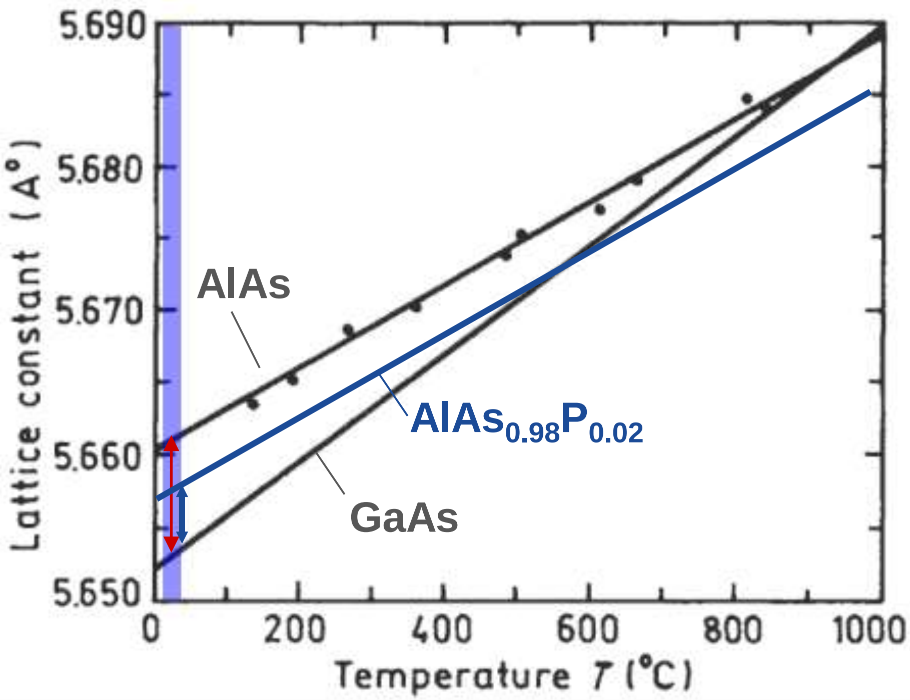
- MOVPE based growth of near infrared edge-emitting diode lasers
- Al_xGaAs-based waveguide (WG, x=0.4) and cladding layers (CL, x=0.85)
- Need for higher output powers (808 nm emission)
  - Option A
    - Increased vertical intensity distribution across cavity
    - Lower facet load → longer cavities
  - Option B
    - Distribute light emission across several lasing stages → bipolar cascade laser (BCL)
    - Increased overall thickness d > 5 µm, mean Al > 48%
- **Increased wafer bow becomes critical in terms of acceptance limits during processing&packaging:**
  - Stepper lithography → out-of-focus problems
  - Required for terrace-free cleaved laser facets → wafer thinning 450 µm → 120 µm increases curvature by factor 14
  - 10 mm laser bar soldering

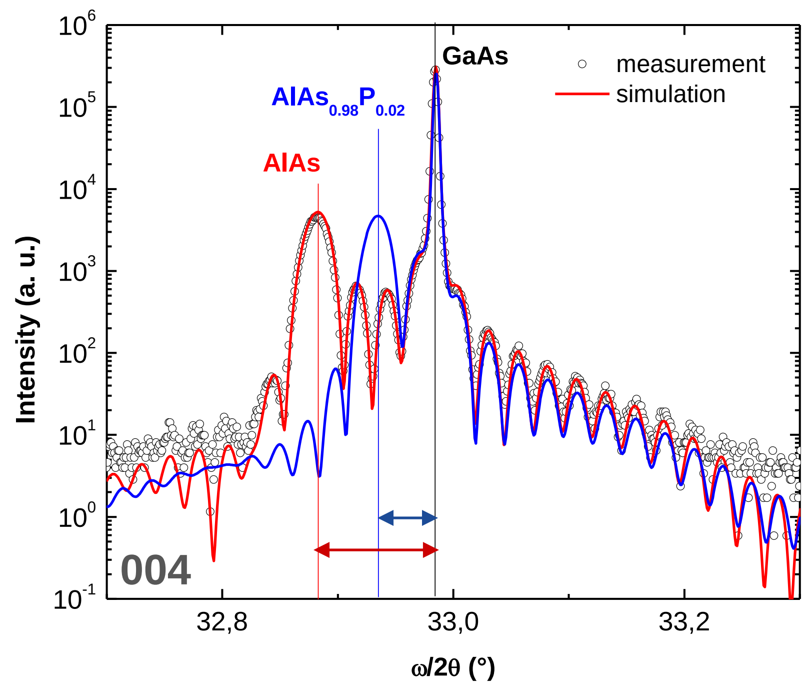


Motivation: Strain in III-V devices?

- AlAs is almost perfectly lattice matched to GaAs:
  - RT: Δa/a = 0.14 %

→http://www.ioffe.rssi.ru/SVA/NSM/Semicond/AlGaAs/
M. Ettenberg, R. J. Paff, *J. Appl. Phys.*, 41, no.10, pp.3926-3927 (1970)





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Motivation: Strain in III-V devices?

- AlAs is almost perfectly lattice matched to GaAs:
  - RT: Δa/a = 0.14 %
  - 750°C: Δa/a = 0.022 %

→ Thermal expansion mismatch

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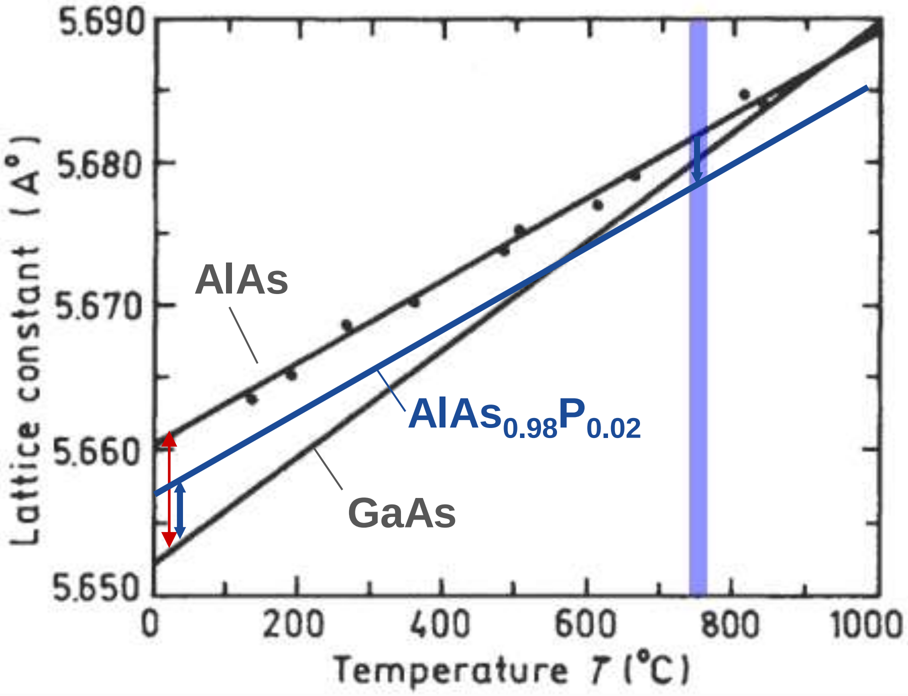
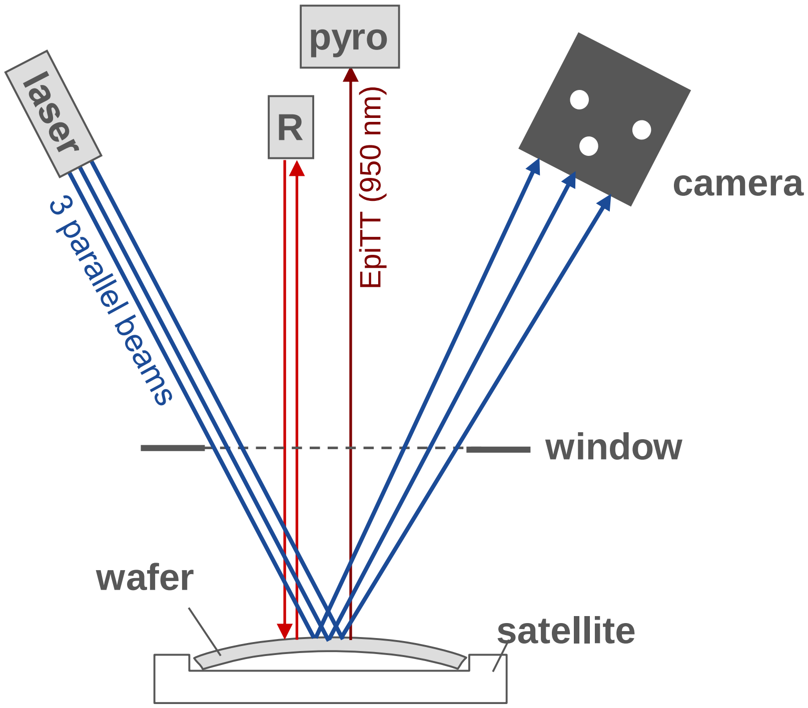


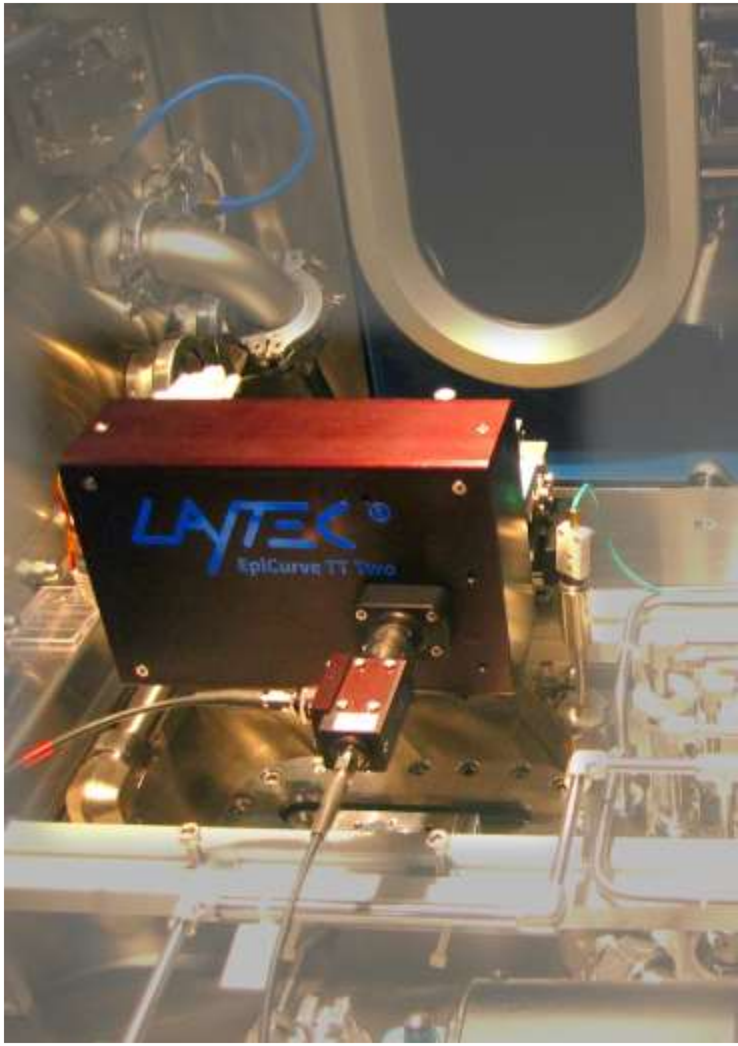
Decrease mismatch at RT:
→ Increase mismatch at T_{growth}

Evaluate strain at T_{growth}:
→ Measure in-situ curvature

Setup

- Planetary 5×4“ AIX2400G3
- Precursors: TMGa, TMAl, TMIn, AsH3, PH3, ...
- LayTec EpiCurveTT AR





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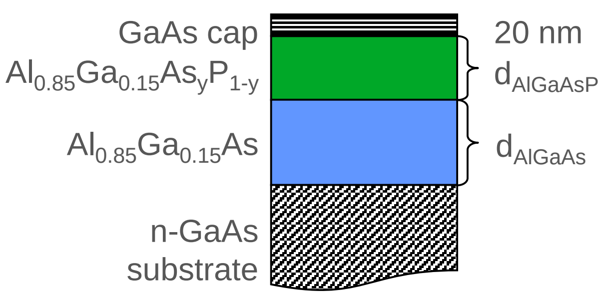
Setup

- Planetary 5×4“ AIX2400G3
- Precursors: TMGa, TMAl, TMIn, AsH3, PH3, ...
- LayTec EpiCurveTT AR

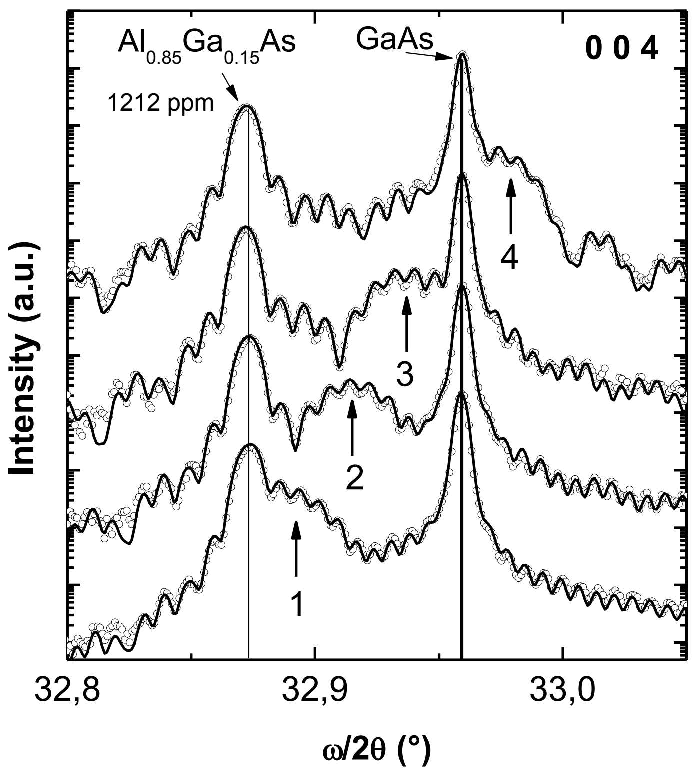
- Test sample structure:

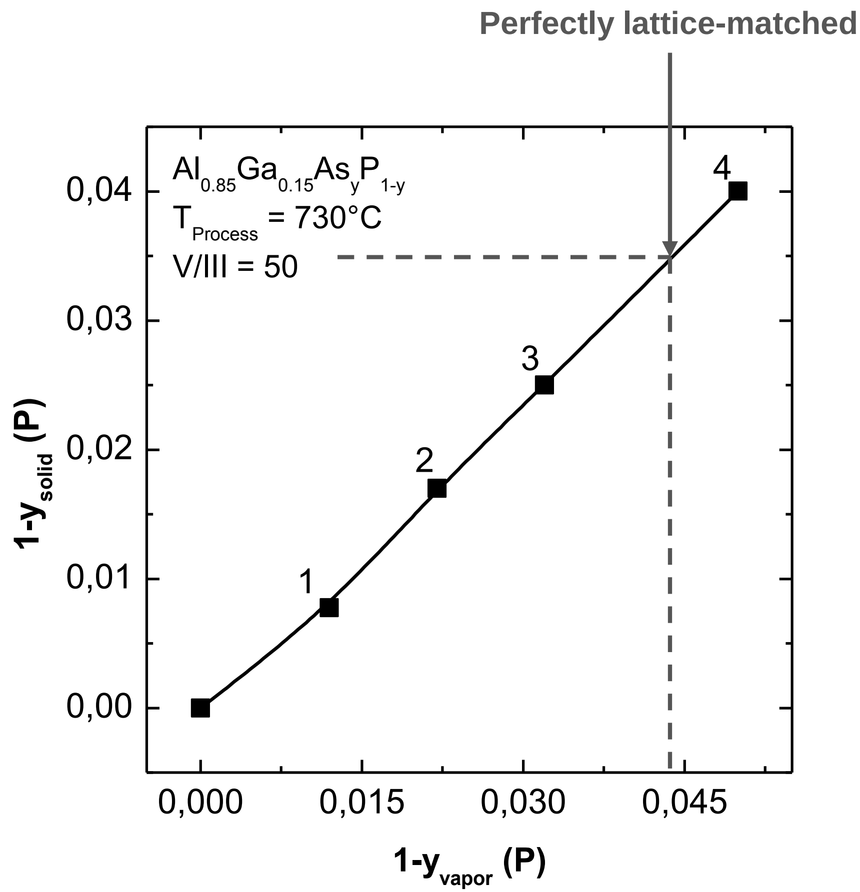


$$d_{AlGaAs} + d_{AlGaAsP} = 650\ nm$$

Growth of $Al_{0.85}Ga_{0.15}As_yP_{1-y}$: test samples

- d_{AlGaAs} = 500 nm, $d_{AlGaAsP}$ = 150 nm
- Variation of phosphorus mole fraction





→ Adding ~3.5% of phosphorus to $Al_{0.85}$GaAs leads to exact lattice matching to GaAs at room temperature

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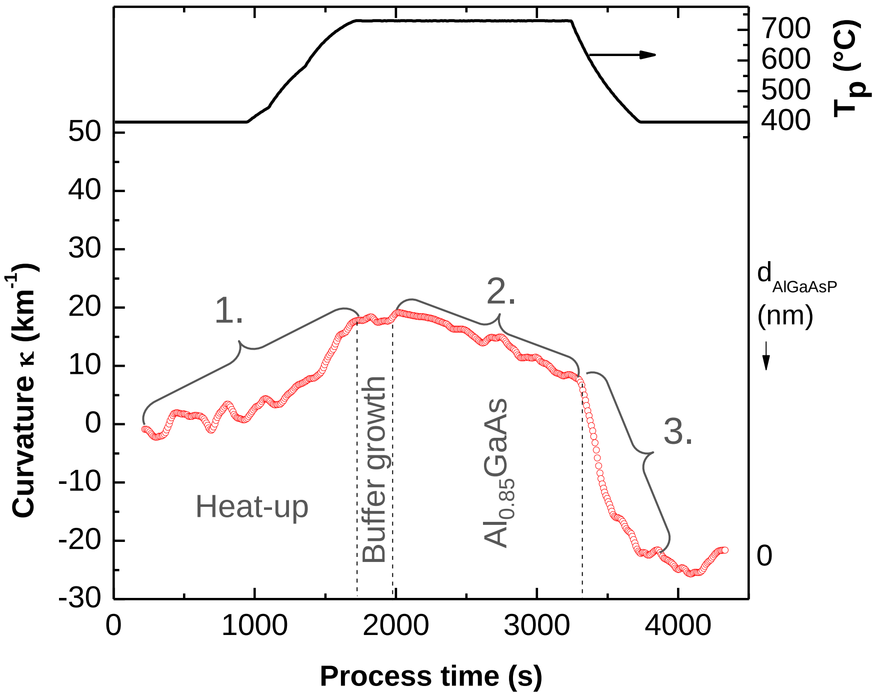
Growth of $Al_{0.85}Ga_{0.15}As$: test samples

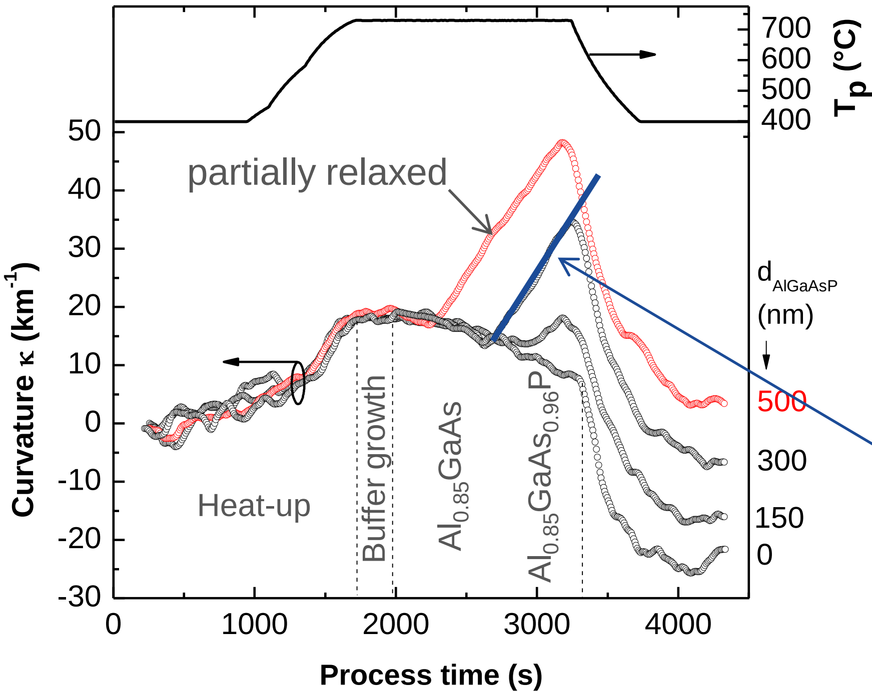
- $Al_{0.85}$GaAs reference



1. Heat up:
   Concave wafer bow due to thermal gradient over substrate
2. Growth:
   Layer growth under compressive strain due to lattice mismatch
3. **Cool down:**
   Thermal expansion mismatch

Growth of $Al_{0.85}Ga_{0.15}As_yP_{1-y}$: test samples

- Phosphorus mole fraction $1\text{-}y_{solid}$ = 4% (XRD)
- Variation of d_{AlGaAs} and $d_{AlGaAsP}$



Stoney:

$$\varepsilon_L = \frac{(\Delta\kappa/\Delta t)\cdot d_{SUB}^2}{6\cdot r_G}\times\frac{E_S}{E_L}$$

ε_L – layer strain
E_L, E_S – Young's modulus
d_{SUB} – substrate thickness
r_G – growth rate
$\Delta\kappa/\Delta t$ – curvature slope

ε = 1328 ppm → $1\text{-}y_{solid}$(703°C) = 4.5%

→ Can only offset part of the thermal mismatch induced RT wafer bow by growing tensile strained $Al_{0.85}GaAs_yP_{1-y}$ due to onset of relaxation

Growth of InGaP on GaAs (1)

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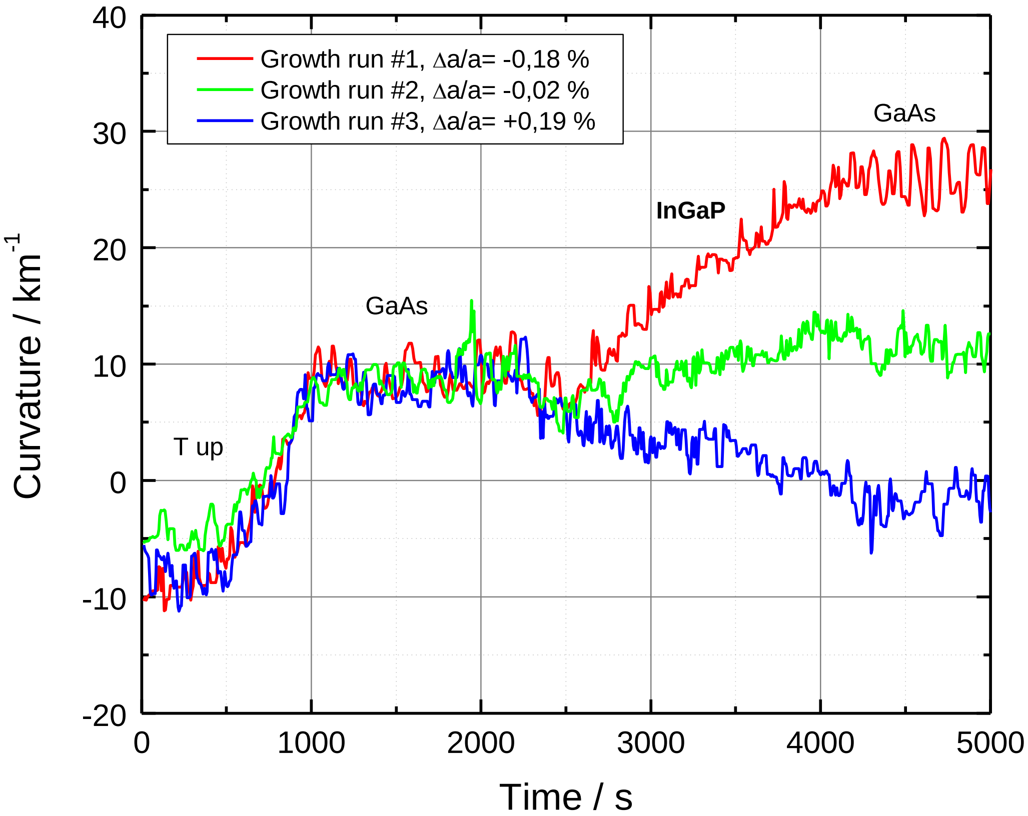
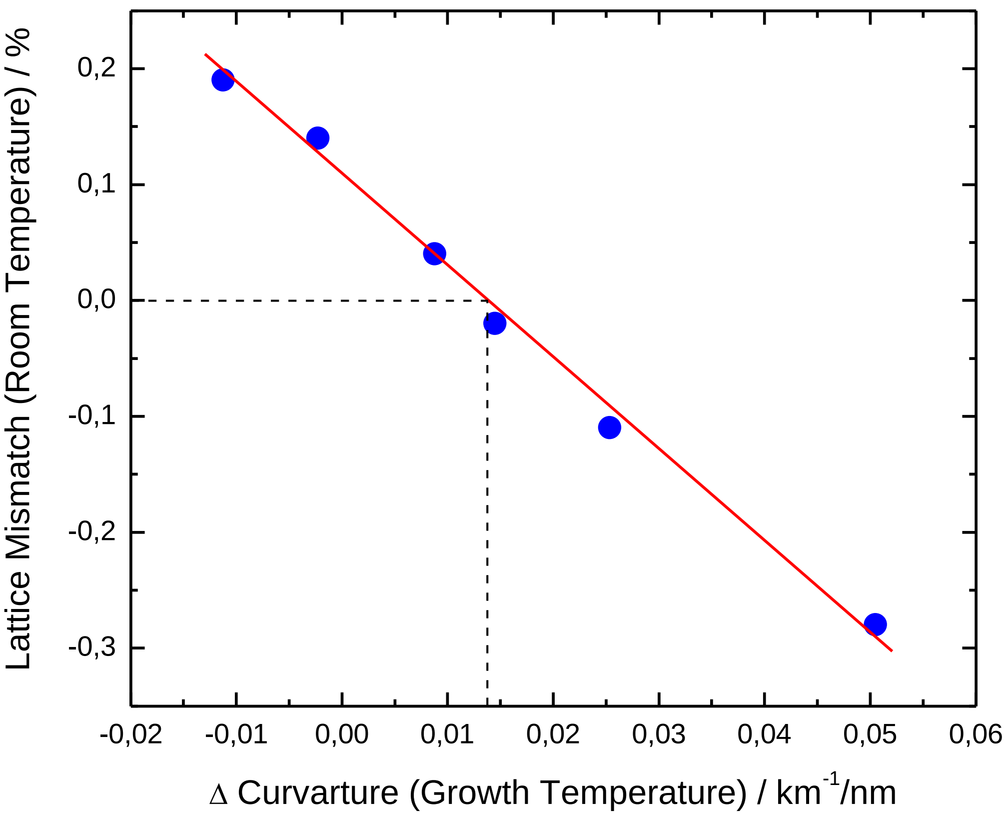


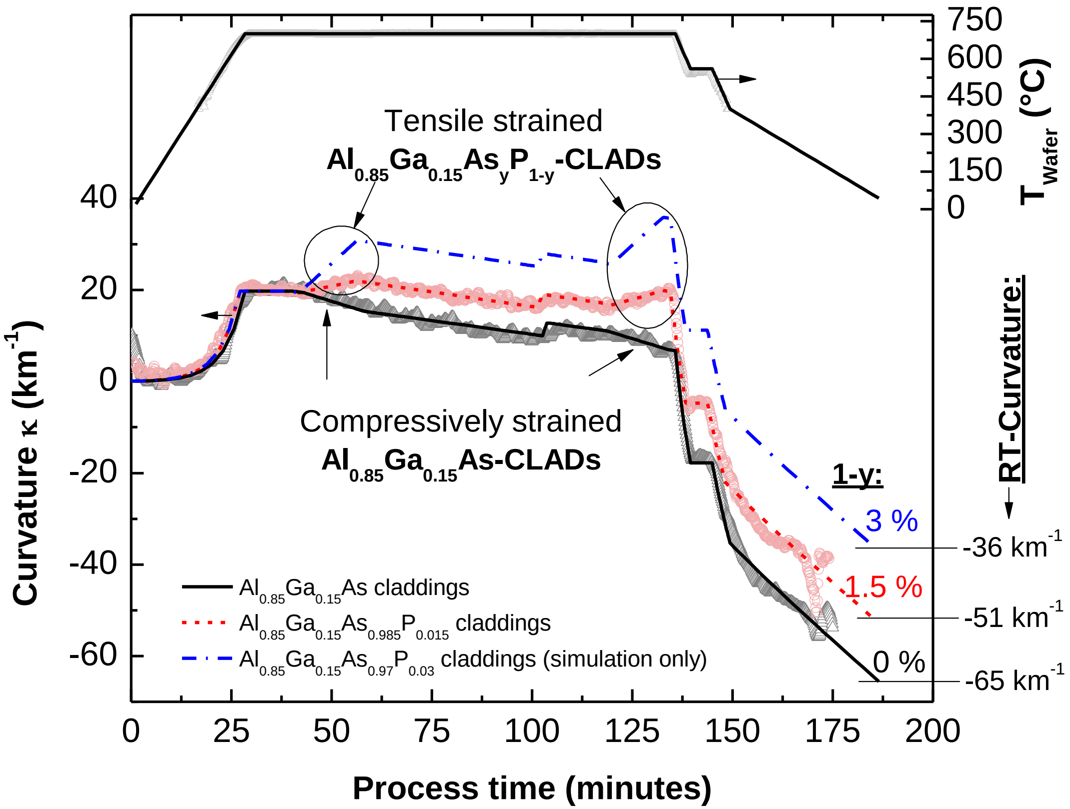
- **Indium Gallium Phosphide ($In_xGa_{1-x}P$)**
  - Indium content determines lattice constant of InGaP layers
  - Deviation of InGaP lattice constant from GaAs substrate leads to strained layers
  - Strain-dependant curvature during growth of InGaP layers enables in-situ composition measurement

Growth of InGaP on GaAs (2)



- **Indium Gallium Phosphide ($In_xGa_{1-x}P$)**
  - Correlation of curvature change during growth to lattice mismatch determined by X-ray diffraction after growth
  - Quantitative in-situ measurement of lattice mismatch possible

Example 1: SLOC edge emitting diode laser with SC



- Stoney-based curvature transient modelling
- Replace $Al_{0.85}GaAs$-CLADs with $Al_{0.85}GaAs_{0.985}P$
- To be done: replace $Al_{0.85}GaAs$-CLADs with $Al_{0.85}GaAs_{0.97}P$

→ $Al_{0.85}GaAs_yP_{1-y}$ claddings can be used as a drop-in replacement to lower RT wafer bow without interfering electro-optical device properties

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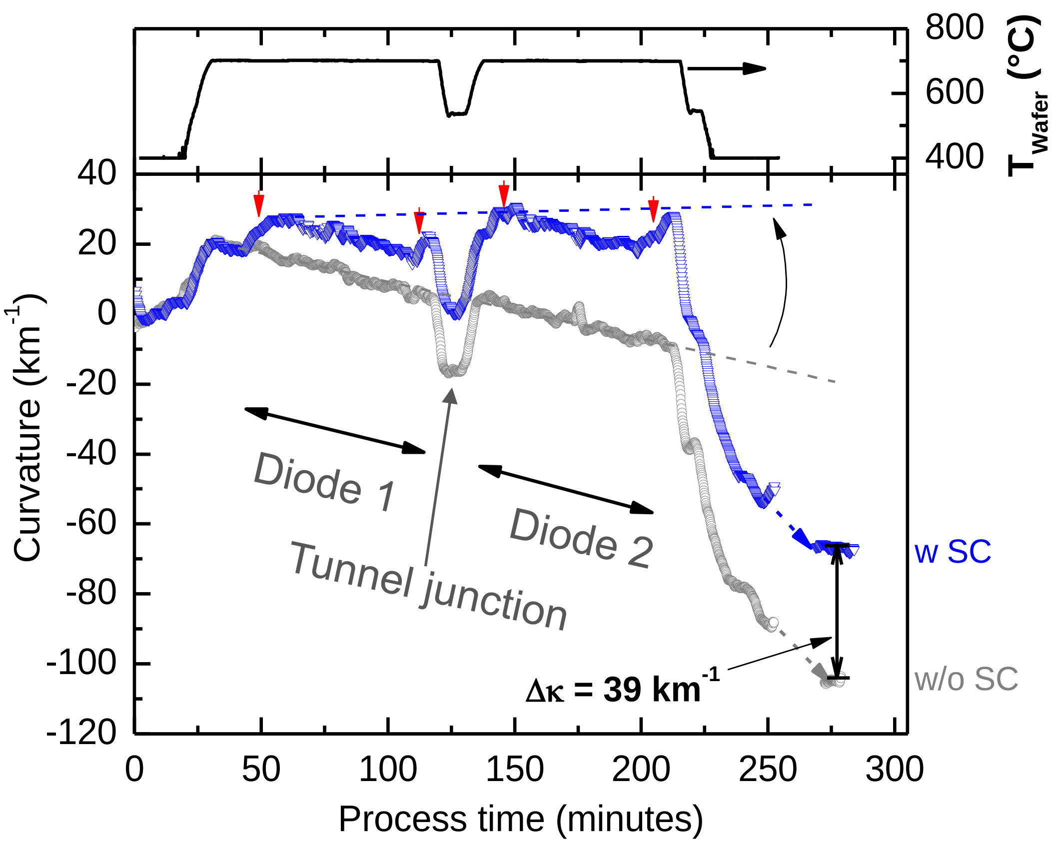
Example 2: 2-stage BCL with/without SC



- Overall thickness: 5.5 µm
- Mean Al content: 48%
- Replace $Al_{0.85}GaAs$ with $Al_{0.85}GaAs_{0.965}P$, d≤350 nm
- Tilted envelope → flat

→ Observed wafer bow reduction translates into a 10 mm laser bar smile reduction from 19 µm to 11.7 µm → less mounting induced reliability issues!

Summary

→ **Reduce RT wafer bow of thick III-V laser structures:**

- Increase lattice mismatch at growth with tensile strained AlGaAsP or InGaP
  → Tensile strain during growth is limited by onset of relaxation
- Use $Al_{0.85}GaAs_{0.965}P$ as a drop-in replacement for $Al_{0.85}GaAs$ claddings in edge-emitting diode lasers
  → EpiCurve assisted development of a distributed strain compensation scheme
  → 2-stage diode laser yielding a RT curvature reduction of $\Delta\kappa$ = 39 km^{-1}
  → Laser bar smile reduction from Δz = 19 µm to Δz = 11.7 µm
- Correlation between in-situ curvature change and ex-situ lattice mismatch
  → Faster R&D loops, early detection of production variances possible

Thank you for your attention!

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