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

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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$_{0.85}$Ga$_{0.15}$As$_y$P$_{1-y}$ 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$_{0.85}$Ga$_{0.15}$As$_y$P$_{1-y}$ 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
- $\text{Al}_x\text{GaAs}$-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 $\rightarrow$ longer cavities
  - Option B
    - Distribute light emission across several lasing stages $\rightarrow$ bipolar cascade laser (BCL)
    - Increased overall thickness $d > 5 \, \mu\text{m}$, mean Al $> 48\%$

- Increased wafer bow becomes critical in terms of acceptance limits during processing & packaging:
  - Stepper lithography $\rightarrow$ out-of-focus problems
  - Required for terrace-free cleaved laser facets $\rightarrow$ wafer thinning $450 \, \mu\text{m} \rightarrow 120 \, \mu\text{m}$ 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: $\Delta a/a = 0.14\%$

http://www.ioffe.rssi.ru/SVA/NSM/Semicond/AlGaAs/
Motivation: Strain in III-V devices?

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

→ Thermal expansion mismatch


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, TMAI, TMIn, AsH3, PH3, ...
- LayTec EpiCurveTT AR
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Test sample structure:

\[
\begin{align*}
&\text{GaAs cap} \quad 20 \text{ nm} \\
&\text{Al}_{0.85}\text{Ga}_{0.15}\text{As}_{y}\text{P}_{1-y} \\
&\text{Al}_{0.85}\text{Ga}_{0.15}\text{As} \\
&\text{n-GaAs substrate} \\
&d_{\text{AlGaAs}} + d_{\text{AlGaAsP}} = 650 \text{ nm}
\end{align*}
\]
Growth of Al$_{0.85}$Ga$_{0.15}$As$_y$P$_{1-y}$: test samples

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

Adding $\sim 3.5\%$ of phosphorus to Al$_{0.85}$GaAs leads to exact lattice matching to GaAs at room temperature.
Growth of $\text{Al}_{0.85}\text{Ga}_{0.15}\text{As}$: test samples

- $\text{Al}_{0.85}\text{GaAs}$ 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$_y$P$_{1-y}$: test samples

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

\[ \varepsilon_L = \frac{\Delta \kappa / \Delta t \cdot d_{\text{SUB}}^2}{6 \cdot r_G} \times \frac{E_S}{E_L} \]

- \( \varepsilon_L \): layer strain
- \( E_L, E_S \): Young’s modulus
- \( d_{\text{SUB}} \): substrate thickness
- \( r_G \): growth rate
- \( \Delta \kappa / \Delta t \): curvature slope

\( \varepsilon = 1328 \text{ ppm} \rightarrow 1-y_{\text{solid}}(703°C) = 4.5\% \)

- Can only offset part of the thermal mismatch induced RT wafer bow by growing tensile strained Al$_{0.85}$GaAs$_y$P$_{1-y}$ due to onset of relaxation
Growth of InGaP on GaAs (1)

- **Indium Gallium Phosphide** (In$_x$Ga$_{1-x}$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 ($\text{In}_x\text{Ga}_{1-x}\text{P}$)
  - 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$_y$P$_{1-y}$ claddings can be used as a drop-in replacement to lower RT wafer bow without interfering electro-optical device properties
Example 2: 2-stage BCL with/without SC

- Overall thickness: 5.5 µm
- Mean Al content: 48%
- Replace $\text{Al}_{0.85}\text{GaAs}$ with $\text{Al}_{0.85}\text{GaAs}_{0.965}\text{P}$, $d \leq 350$ nm
- Tilted envelope $\rightarrow$ flat

$\rightarrow$ Observed wafer bow reduction translates into a 10 mm laser bar smile reduction from 19 µm to 11.7 µm $\rightarrow$ 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 $\Delta \kappa = 39 \text{ km}^{-1}$
    → Laser bar smile reduction from $\Delta z = 19 \ \mu \text{m}$ to $\Delta z = 11.7 \ \mu \text{m}$
  - 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!