Fast and highly accurate in-situ calibration of AlGaAs ternary composition for MOVPE-based growth of edge-emitting diode lasers

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Introduction: manufacturing challenges for MOVPE of semiconductor laser diodes

Manufacturing of AlGaAs based lasers:

- stringent specifications: e.g. emission wavelength of final laser device ±1nm
- Properties of waveguiding layers (AlGaAs) crucially defines device performance
- homogeneity and reproducibility of growth process ➔ high yield!
Introduction: AlGaAs in epitaxial laser structures

- **Active area masking (VCSEL aperture)**
- **DBR / low-$$n_y$$ (VCSEL) cladding layers**
  - Wave guides
  - DBR / high-$$n_x$$ (VCSEL)
  - Active region

- **EELs**: performance depends on waveguiding (AlGaAs)
- **DBRs**: $$Al_xGa_{1-x}As/Al_yGa_{1-y}As$$ layer pairs → performance depends on refractive index difference ($$n_x/n_y$$)
- Trade-off with: low DBR optical absorption (exact $$x$$ in high-$$n$$ $$Al_xGa_{1-x}As$$ !)
- Aperture layer oxidation rate strongly depends on Al content (e.g. 95 to 98%)

⇒ AlGaAs composition with ±0.5% accuracy needed!
Introduction: AlGaAs during MOVPE growth (~700°C)

- at 700°C: AlAs is ~perfectly lattice matched → no strain effects to in-situ refractive index n,k of AlGaAs
- refractive index n, similarly to $E_g$, shifts with x → promising high accuracy composition measurement through in-situ reflectance
- however: non-linear change of $(n,k)_{AlGaAs}$ with wafer temperature!

**Target:** wafer temperature ($\pm 1K$); in-situ $n,k_{AlGaAs}$ ($\pm 0.002$) → in-situ AlGaAs composition with accuracy ($\pm 0.5\%$)
Outline

1. MOCVD calibration runs with optimized stack structure and accurate $T_{\text{wafer}}$

2. Ex-situ X-Ray diffraction (XRD) analysis $\Rightarrow$ composition $x$ and growth rate $r$

3. Self-consistent analysis of in-situ data $\Rightarrow$ $nk(x,T)$ database referenced to XRD

4. Replacing time-consuming ex-situ calibration by fast, accurate and fully automated in-situ reflectance

Summary & Outlook
Calibration runs for growing XRD test structures

- growth performed in production scale MOVPE (12x4"
- every AlGaAs layer is sandwiched between GaAs
- thick GaAs interlayers! → 633nm FPOs damped out
- 3 wavelength reflectance (633/405/950nm) + wafer temp.
Ex-situ XRD analysis of composition x and growth rate r

<table>
<thead>
<tr>
<th>Run A</th>
<th>Target</th>
<th>XRD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layer</td>
<td>Thickness</td>
<td>x</td>
</tr>
<tr>
<td>GaAs</td>
<td>750</td>
<td>0</td>
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<tr>
<td>Al(0,3)GaAs</td>
<td>450</td>
<td>0,3</td>
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<tr>
<td>GaAs</td>
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<td>450</td>
<td>0,5</td>
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<tr>
<td>GaAs</td>
<td>750</td>
<td>0</td>
</tr>
<tr>
<td>Al(0,8)GaAs</td>
<td>450</td>
<td>0,8</td>
</tr>
<tr>
<td>GaAs</td>
<td>750</td>
<td>0</td>
</tr>
<tr>
<td>AlAs</td>
<td>450</td>
<td>1</td>
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</tbody>
</table>

- reference layer stack compositions by ex-situ rocking curve analysis (XRD)
- fine structure of rocking curve fitted for layer thickness measurement

→ growth rates known from ex-situ XRD
→ post-growth analysis of in-situ reflectance
→ assigning x(XRD) to nk_{AlGaAs} (in-situ)
XRD gauged n and k database of AlGaAs

- With known XRD growth rates n and k have been determined by FPO analysis with an accuracy of ±0.002 (for 633nm) in the full x=0…100% composition range and in the full 600°C…710°C surface temperature range.

- Emissivity corrected 950nm pyrometry in conjunction with handheld calibration radiation source (AbsoluT) \( \rightarrow \) wafer temperature \( T_g \) is exactly assigned.
Routine AlGaAs process calibration by in-situ reflectance

<table>
<thead>
<tr>
<th>Run F:</th>
<th>GaAs</th>
<th>AlAs</th>
<th>GaAs</th>
<th>Al~70%</th>
<th>GaAs</th>
<th>x~60%</th>
<th>GaAs</th>
<th>x~40%</th>
<th>GaAs</th>
</tr>
</thead>
</table>

- Automated composition (x) and growth-rate (r) fit on calibration stack: measured (blue), fit (red)
**Routine AlGaAs composition calibration by in-situ reflectance**

Single wavelength (633nm) in-situ reflectance analysis gives:
- AlGaAs composition with accuracy of ±0.5%
- growth rates with ±1% variation from XRD

<table>
<thead>
<tr>
<th>Layer</th>
<th>Target</th>
<th>ex-situ XRD</th>
<th>in-situ</th>
<th>in-situ</th>
<th>in-situ</th>
<th>in-situ</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>d (nm)</td>
<td>x</td>
<td>r (nm/s)</td>
<td>x</td>
<td>r(nm/s)</td>
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<tr>
<td>GaAs</td>
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</table>
Routine AlGaAs process calibration by in-situ reflectance

Using all 3 wavelength for combined (633/405/950nm) in-situ reflectance analysis of growth rates / layer thickness gives:

- In-situ growth rates with even better (±0.3%) precision (here: $d_{\text{in-situ}}=457.1\text{nm}$; $d_{\text{XRD}}=458.8\text{nm}$)
- The scatter in XRD growth rates, e.g. for GaAs layers in the same stack, is larger (±0.6%)! … due to correlation effects in multi-layer analysis?
Summary:

- **AlGaAs** ➔ We have demonstrated:
  
  *in-situ* determination of
  
  \( x(0\%\ldots100\%) \) with \( \pm 0.5\% \) precision (formerly: 2\% \ldots 3\%)

  growth rate \( r \) with \( \pm 0.3\% \) precision (formerly: 1\% \ldots 3\%)

Outlook #1:

➔ we will continue with AlGaInP (e.g. 650 nm)

... by combining strain balancing

(in-situ wafer bow meas.)

with high-accuracy

reflectance analysis. ➔
Outlook #2: VCSEL process SPC
Example: 980nm InGaAs/AlGaAs VCSEL (x=12%/90% DBRs)
based on A.Mutig, PhD thesis, TU Berlin, 2010

R spectrum: at $T_g$ shifted to longer wavelength!

New AlGaAs nk-database: used for simulating 650°C in-situ data ➔ intended (grading) and non-intended (r-drifting) VCSEL process changes show-up clearly and characteristically ➔ to be fed into SPC/MES!