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

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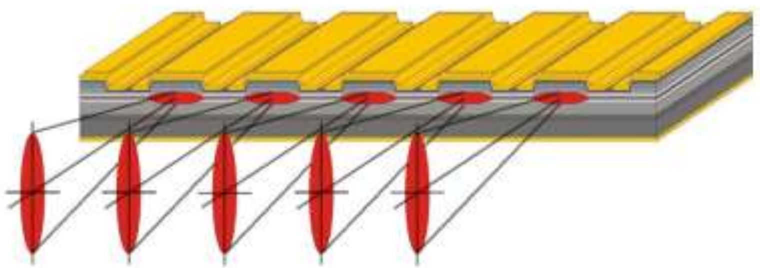
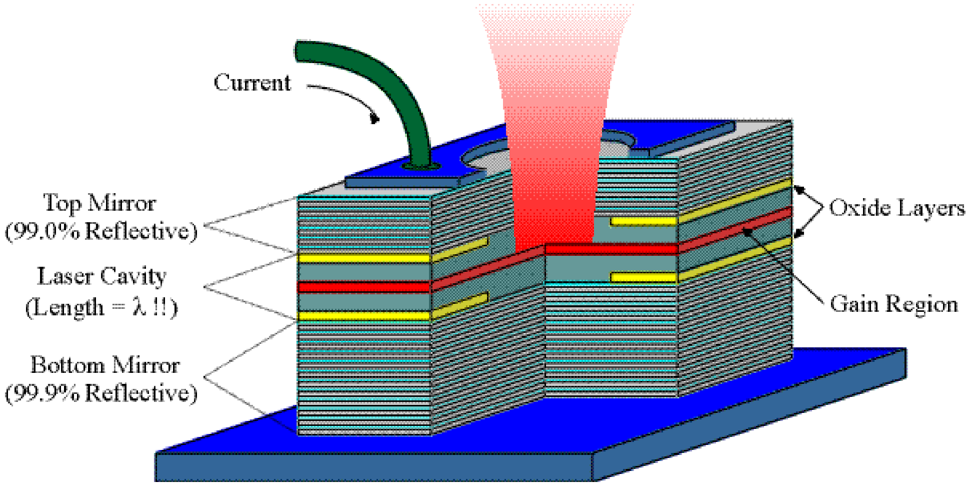
# Introduction: manufacturing challenges for MOVPE of semiconductor laser diodes



*laser bar (edge emitting laser diodes, EEL)*

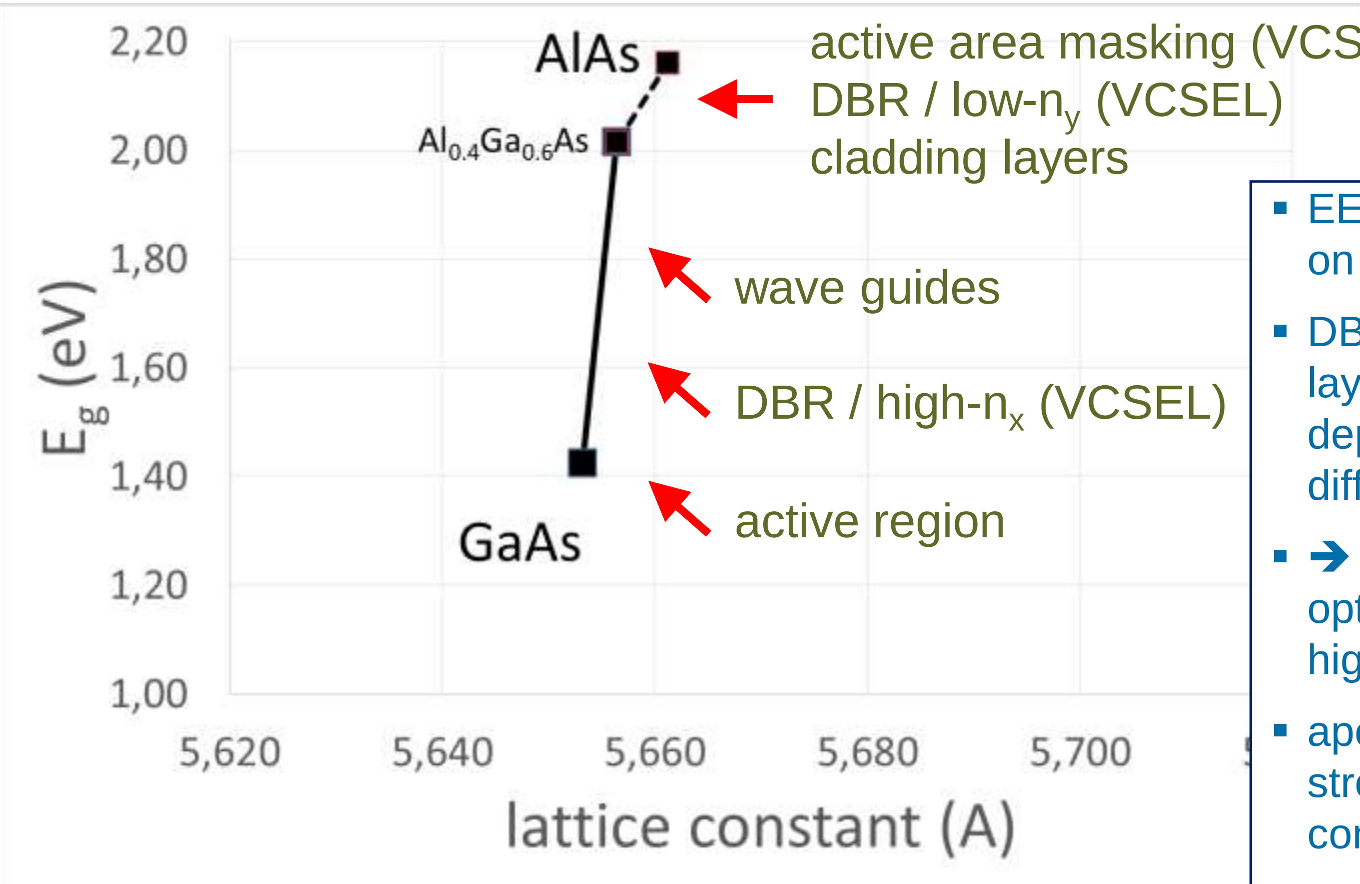



*surface emitting laser (VCSEL)*

## 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!

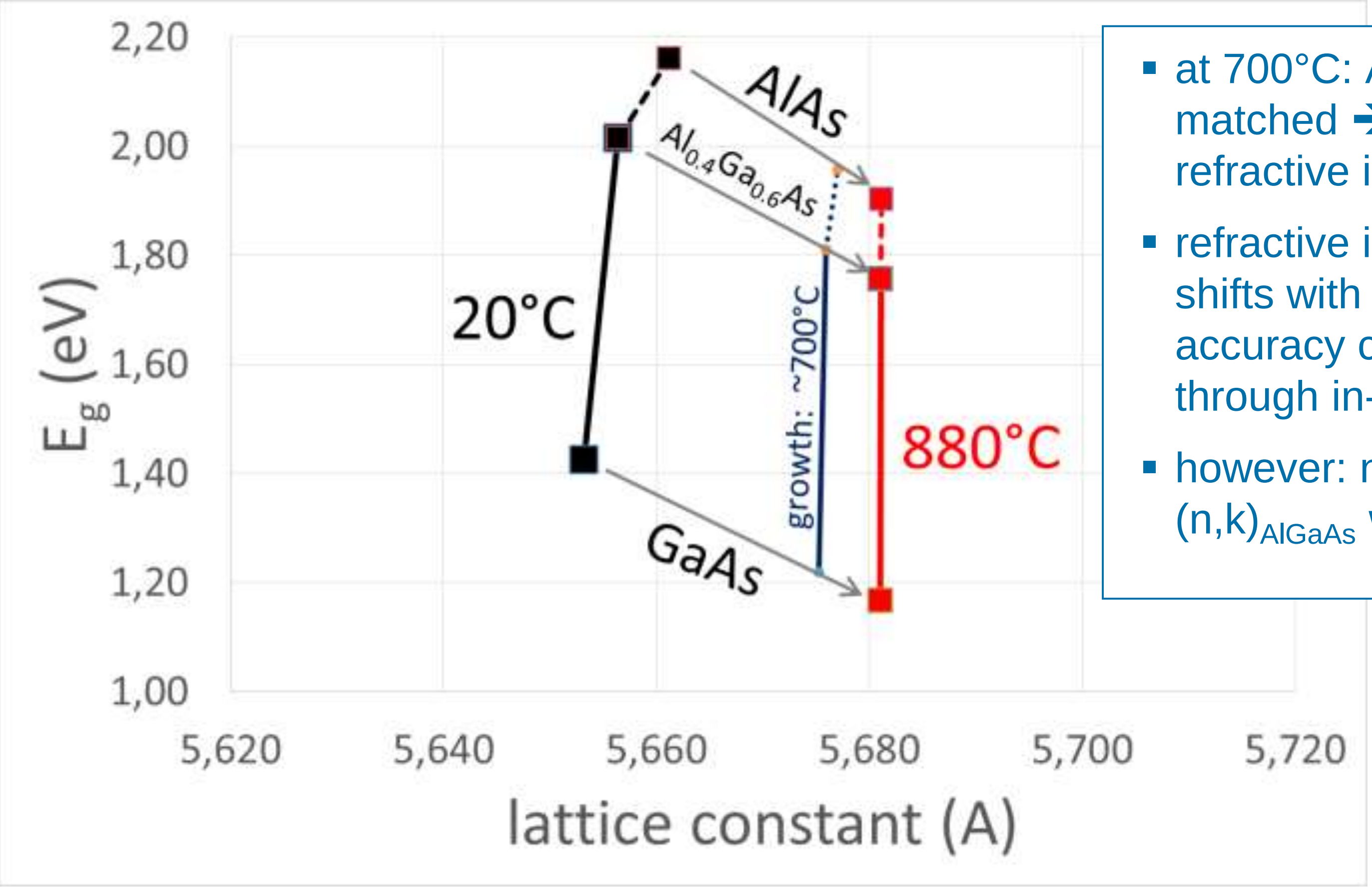
# Introduction: AlGaAs in epitaxial laser structures




- 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, similiarly 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 (±1K); in-situ $n,k_{AlGaAs}$ (±0.002)

**➔ in-situ AlGaAs composition with accuracy (±0.5%)**

# Outline

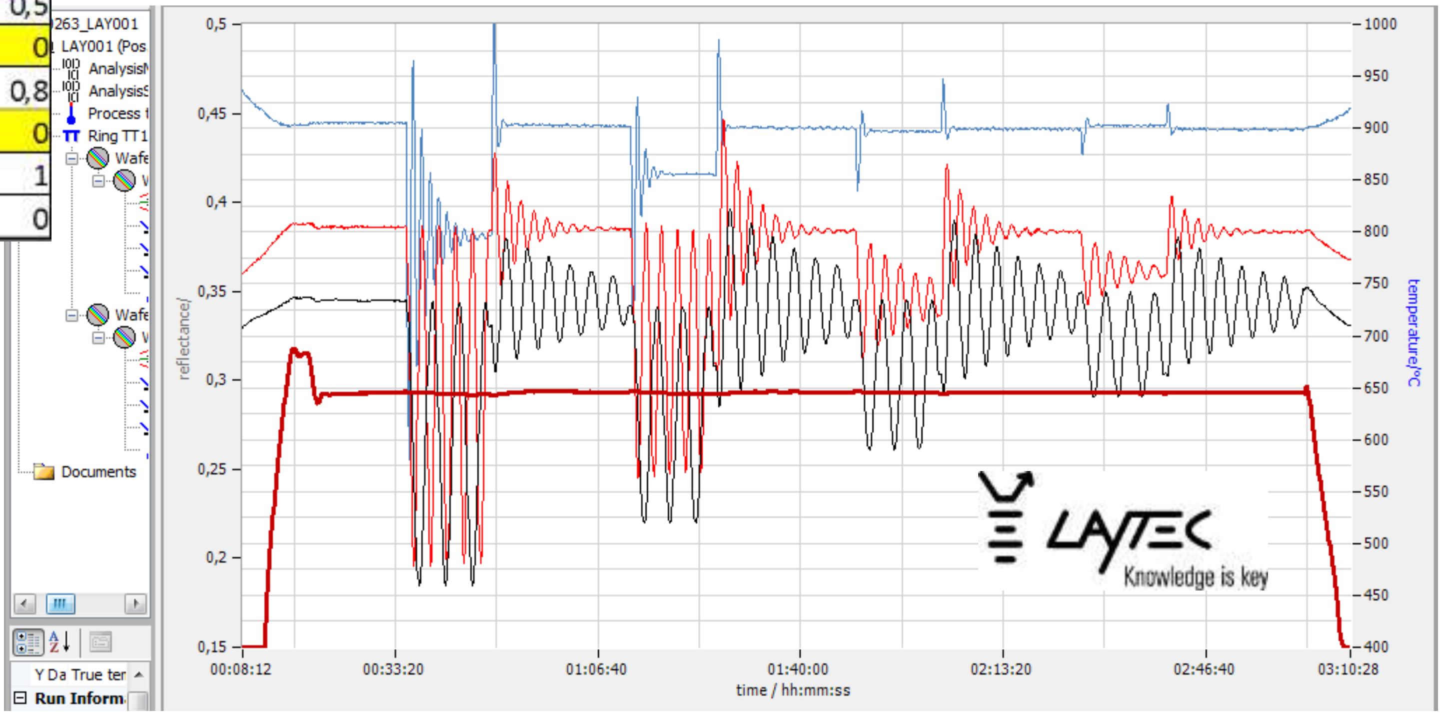
1. MOCVD calibration runs with optimized stack structure and accurate $T_{wafer}$
2. Ex-situ X-Ray diffraction (XRD) analysis ➔ composition x and growth rate r
3. Self-consistent analysis of in-situ data ➔ nk(x,T) database referenced to XRD
4. Replacing time-consuming ex-situ calibration by fast, accurate and fully automated in-situ reflectance

Summary & Outlook

# Calibration runs for growing XRD test structures

| Run A | | |
|---|---|---|
| | Target | |
| Layer | Thickness | x |
| GaAs | 750 | 0 |
| Al(0,3)GaAs | 450 | 0,3 |
| GaAs | 750 | 0 |
| Al(0,5)GaAs | 450 | 0,5 |
| GaAs | 750 | 0 |
| Al(0,8)GaAs | 450 | 0,8 |
| GaAs | 750 | 0 |
| AlAs | 450 | 1 |
| GaAs-Sub. | | 0 |

- 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.

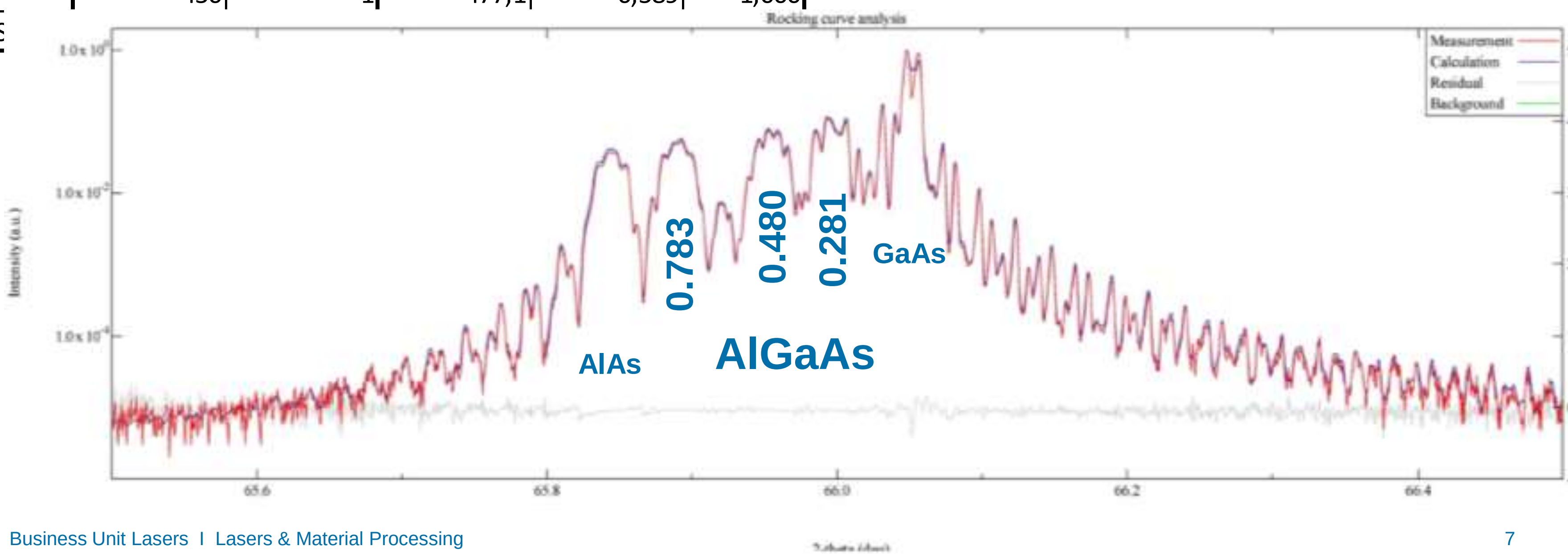


# Ex-situ XRD analysis of composition x and growth rate  r

| Run A | | | | | |
|---|---|---|---|---|---|
| | Target | | XRD | | |
| Layer | Thickness | x | Thickness | Rate (nm/s) | x |
| GaAs | 750 | 0 | 806,1 | **0,597** | 0,000 |
| Al(0,3)GaAs | 450 | 0,3 | 448,9 | 0,553 | 0,281 |
| GaAs | 750 | 0 | 805,2 | **0,596** | 0,000 |
| Al(0,5)GaAs | 450 | 0,5 | 458,4 | 0,566 | 0,480 |
| GaAs | 750 | 0 | 804,4 | **0,596** | 0,000 |
| Al(0,8)GaAs | 450 | 0,8 | 472,1 | 0,583 | 0,783 |
| GaAs | 750 | 0 | 805,5 | **0,597** | 0,000 |
| AlAs | 450 | 1 | 477,1 | 0,589 | 1,000 |
| GaAs-S | | | | | |

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

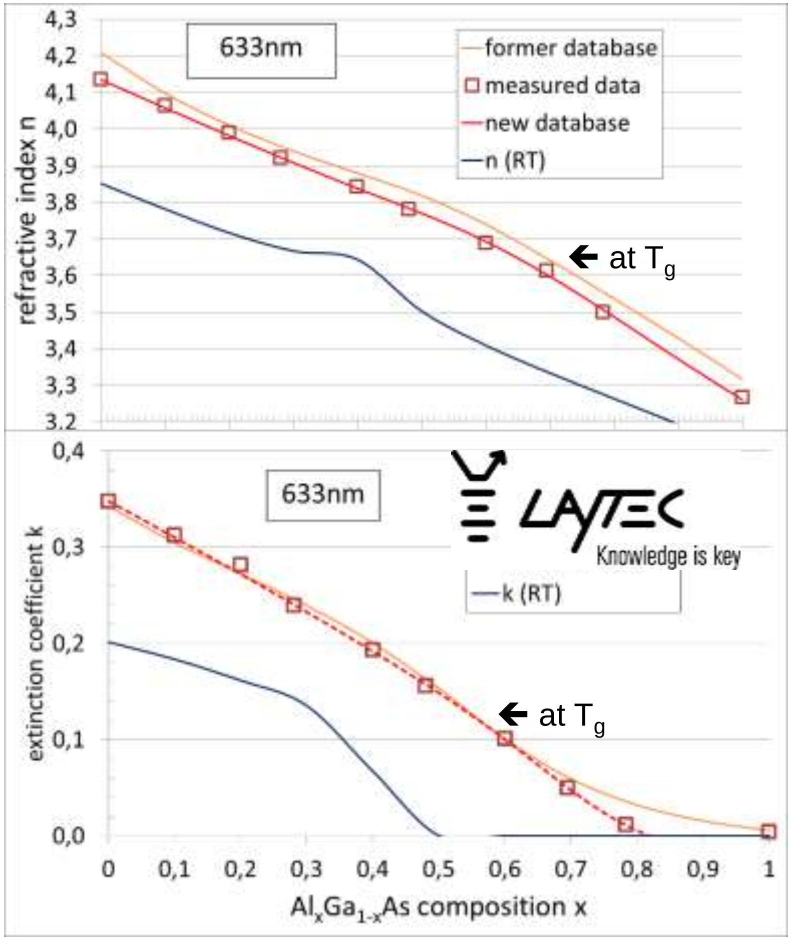
➔ growth rates known from ex-situ XRD
➔ post-growth analysis of in-situ reflectance
➔ assigning x(XRD) to $nk_{AlGaAs}$ (in-situ)



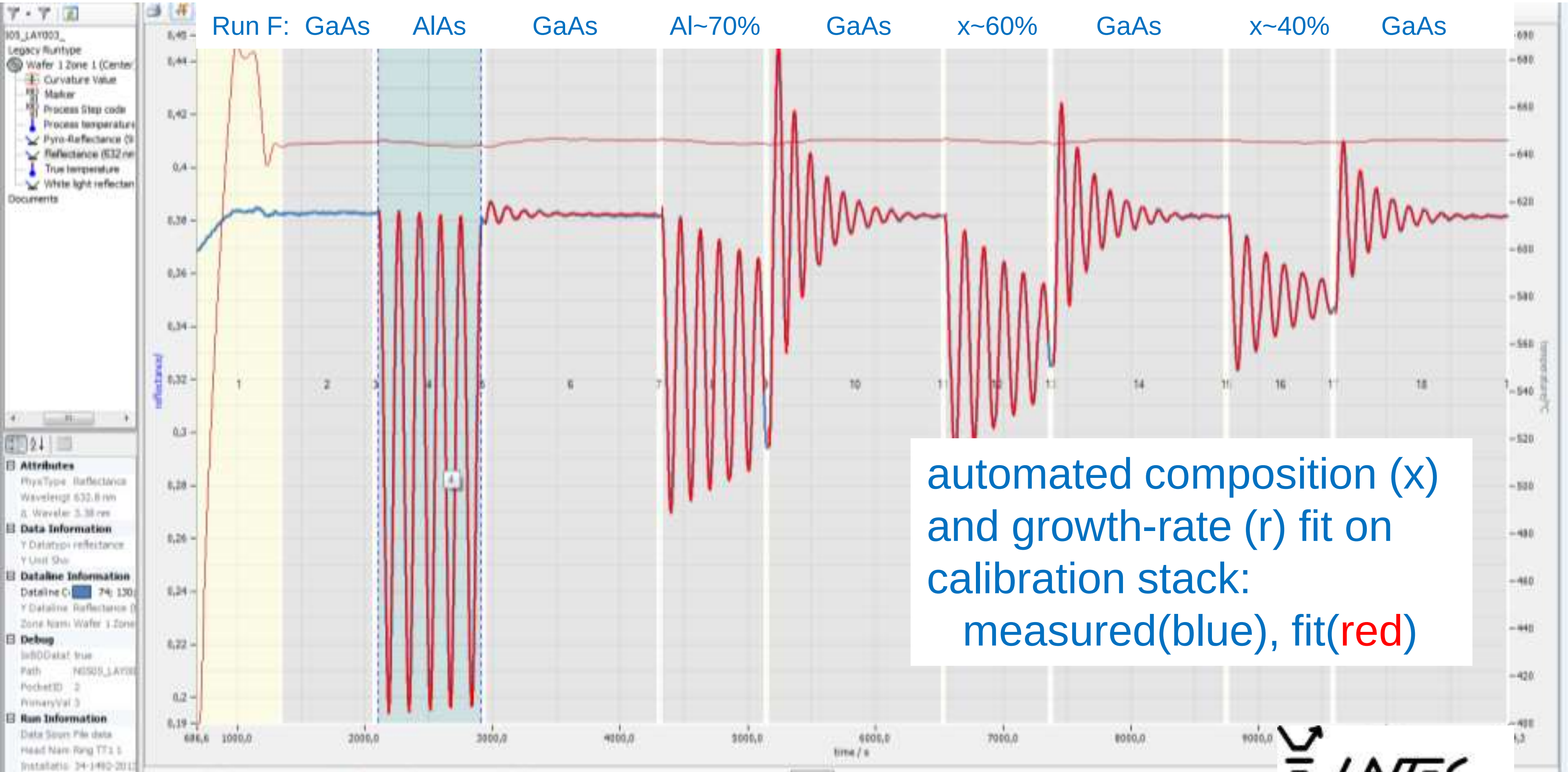
# XRD gauged n and k database of AlGaAs

- 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) ➔ wafer temperature $T_g$ is exactly assigned



# Routine AlGaAs process calibration by in-situ reflectance



# Routine AlGaAs composition calibration by in-situ reflectance

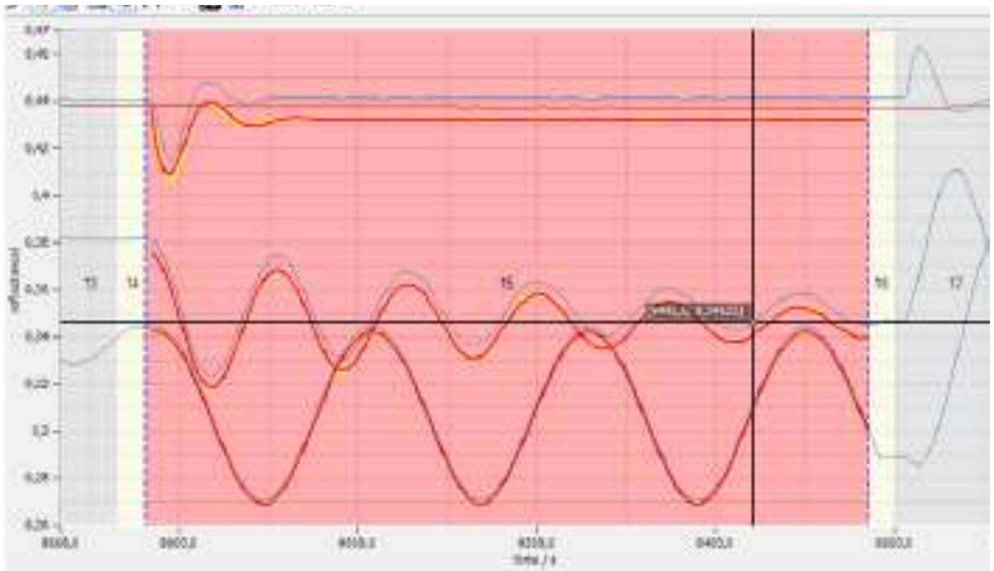
| Run F | Target | | ex-situ XRD | | in-situ | in-situ | in-situ | in-situ |
|---|---|---|---|---|---|---|---|---|
| Layer | d (nm) | x | r (nm/s) | x | r(nm/s) | x | Δr/r | Δx |
| GaAs | 750 | 0,000 | 0,5971 | 0,000 | 0,602 | 0,002 | 0,8% | 0,2% |
| Al(0,4)GaAs | 450 | 0,400 | 0,5531 | 0,402 | 0,564 | 0,402 | 2,0% | 0,0% |
| GaAs | 750 | 0,000 | 0,5964 | 0,000 | 0,602 | 0,000 | 0,9% | 0,0% |
| Al(0,6)GaAs | 450 | 0,600 | 0,5659 | 0,601 | 0,558 | 0,607 | -1,4% | 0,6% |
| GaAs | 750 | 0,000 | 0,5959 | 0,000 | 0,600 | 0,000 | 0,7% | 0,0% |
| Al(0,7)GaAs | 450 | 0,700 | 0,5828 | 0,695 | 0,577 | 0,690 | -1,0% | -0,5% |
| GaAs | 750 | 0,000 | 0,5967 | 0,000 | 0,599 | 0,000 | 0,4% | 0,0% |
| AlAs | 450 | 1,000 | 0,5890 | 1,000 | 0,598 | 1,000 | 1,5% | 0,0% |
| GaAs-Sub. | | 0,000 | | | | | | |

Single wavelength (633nm) in-situ reflectance analysis gives:

- AlGaAs composition with accuracy of ±0.5%
- growth rates with ±1% variation from XRD

# Routine AlGaAs process calibration by in-situ reflectance

Run F: GaAs | | AlGaAs (x~40%) | | GaAs



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: $d_{in\text{-}situ}$=457.1nm; $d_{XRD}$=458.8nm)
- 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%....100%) with ±0.5% precision** (formerly: 2% … 3%)

  **growth rate r with ±0.3% precision** (formerly: 1% … 3%)

## Outlook #1:

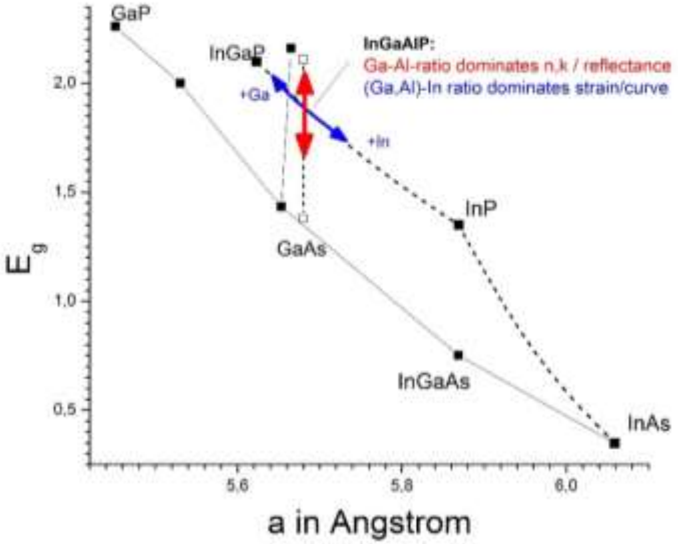
➔ we will continue with AlGaInP (e.g. 650 nm)

… by combining strain balancing

(in-situ wafer bow meas.)

with high-accuracy

reflectance analysis. ➔

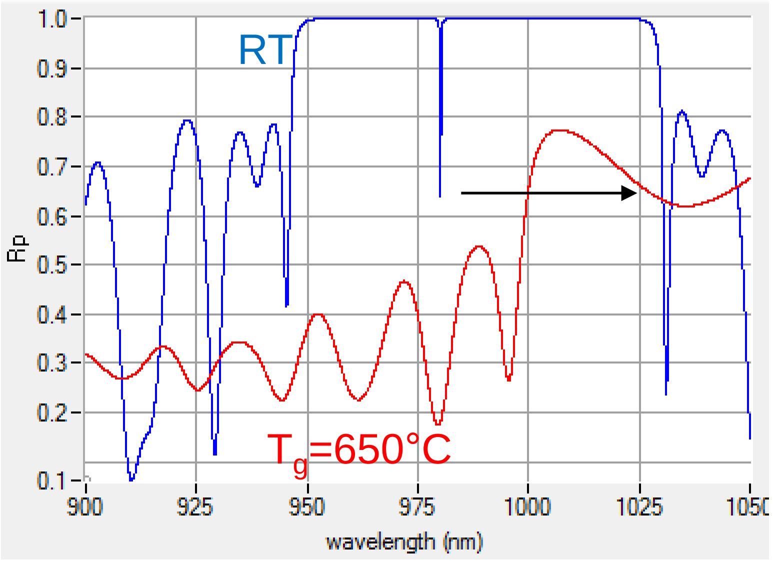


# Outlook #2: VCSEL process SPC

Example: 980nm InGaAs/AlGaAs VCSEL (x=12%/90% DBRs)

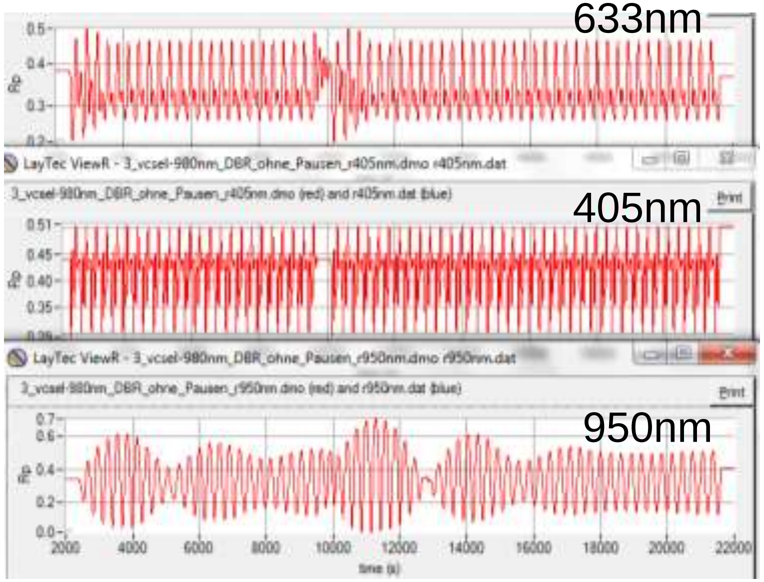
based on A.Mutig, PhD thesis, TU Berlin, 2010

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



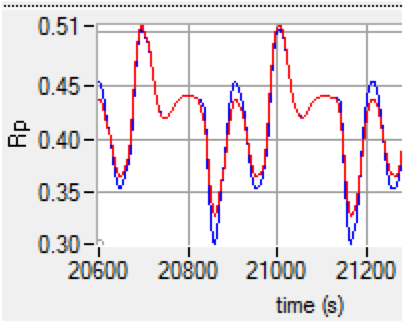

~5 hours MOCVD!

in-situ reflectance (simulated)

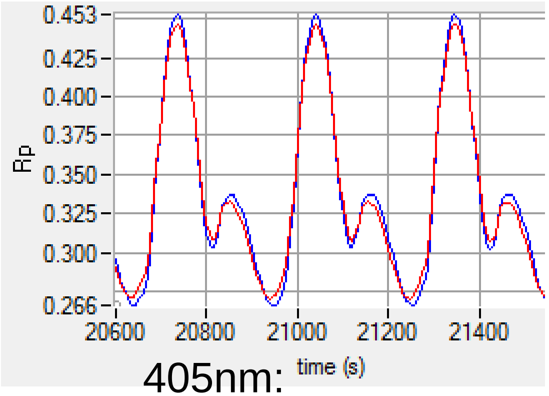



**New AlGaAs nk-database:** used for simulating 650°C in-situ data ➔ intended (grading) and non-intended (r-drifting) VCSEL process changes show-up clearly and characteristically

➔ **to be fed into SPC/MES!**




633nm:
2% growth rate drift




405nm:
Interface grading


NRC·CNRC
LAYTEC
Knowledge is key
JENOPTIK
SHARING EXCELLENCE