MOCVD of InGaAsP/InP and InGaAlAs/InP based device structures: full replacement of ex-situ process calibration by advanced in-situ metrology

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Motivation

Growth rate calibration:

- ex-situ X-ray diffraction (Pendellösung fringing): << ±1%
- in-situ reflectance oscillation: ±1% (if nk is known accurately)

➔ **Use XRD/fringing as reference for determining accurate nk at growth temperature for InP, InGaAs, InGaAsP, …!**

Lattice match calibration (InGaAs, InGaAsP, InGaAlAs on InP):

- ex-situ XRD measures with accuracy $\Delta a/a = \pm 50$ppm
- in-situ wafer bow measures with accuracy $\Delta a/a = \pm 300$ppm

➔ **Improve wafer bow resolution to at least ±100ppm!**

Composition calibration (InGaAsP, InGaAlAs on InP):

- ex-situ PL XRD measures band-edge wavelength: $\Delta\lambda = \pm 0.5$nm
- in-situ reflectance analysis measures 'effective band-edge wavelength': $\Delta\lambda_{eff} = \pm 5$nm

➔ **Improve in-situ composition calibration to** $\Delta\lambda_{eff} = \pm 1$nm**!**

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1. GROWTH RATE CALIBRATION

Improving nk (InP) by using XRD growth rates

InP test structure:

InP // 100nm InP buffer / 0.5nm GaP / 500nm InP / 20nm InGaAs / 400nm InP cap

for XRD — for in-situ R (removed for XRD)

Step #1: grow structure and measure in-situ reflectance

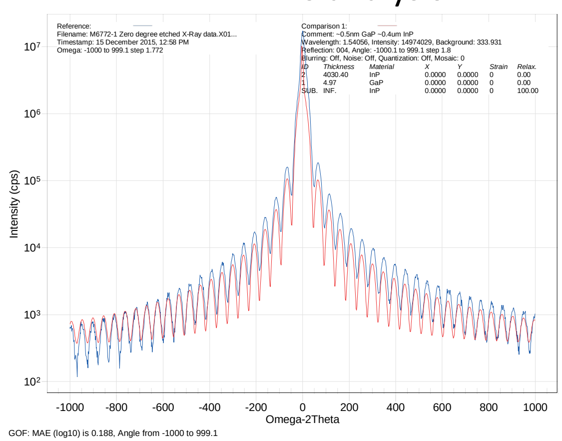
Step #2: etch away InGaAs and InP cap (creating ideal structure for XRD)

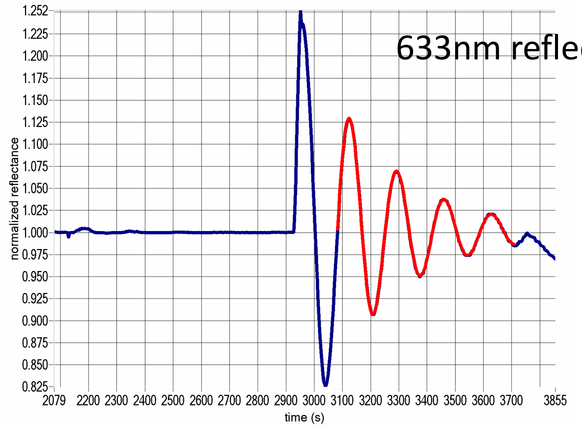
Step #3: XRD thickness ➔ calculate RT XRD „growth rate" from growth time

Step #4: correct „XRD growth rate" $r_{XRD}(T_g)$ with thermal expansion coeff.

Step #5: analyse in-situ reflectance with known $r_{XRD}(T_g)$ ➔ **nk (T_g)**

XRD RADS analysis





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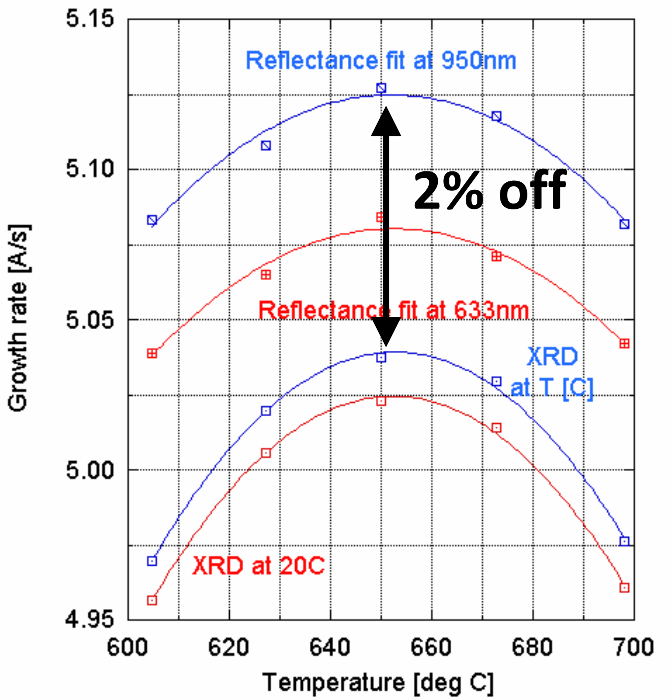
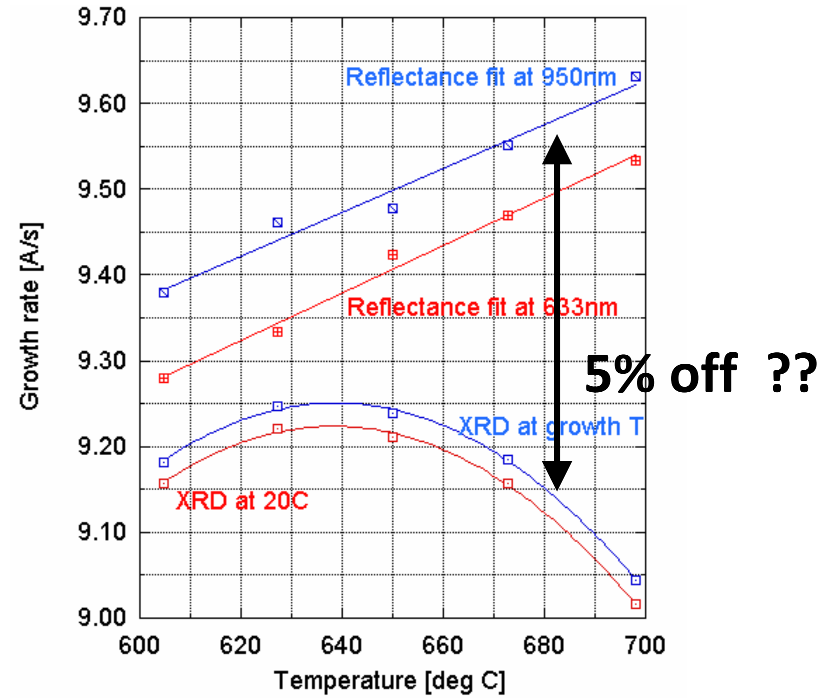
In-situ growth rate calibration – where we started:





r of InP (T=600C - 700C):

- in-situ reflectance and XRD gives the same basic trend of growth rate
- R(633nm) ➔ r offset about +1%
- R(950nm) ➔ r offset about +2%

r of InGaAs (T=600C - 700C):

- in-situ reflectance gives linear and XRD gives parabolic trend with T
- R(633nm) ➔ r offset >= +1 … 4% ??
- R(950nm) ➔ r offset >= +2 … 5% ??

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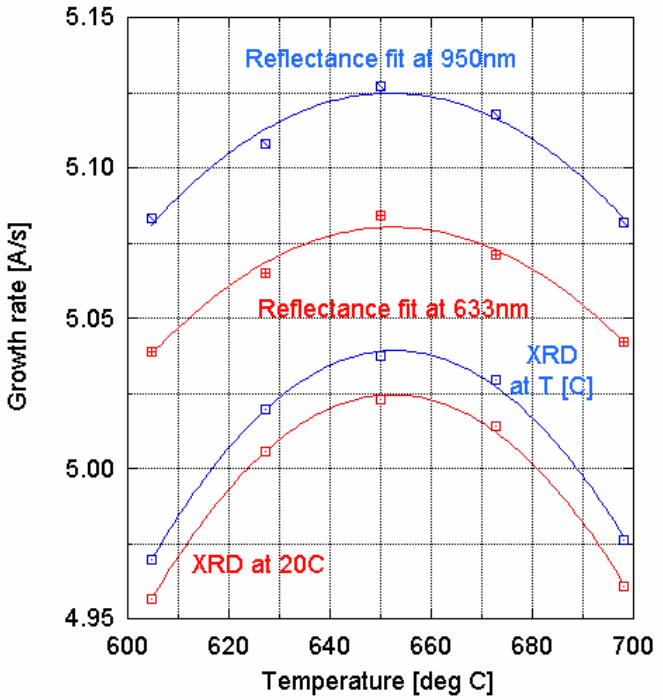
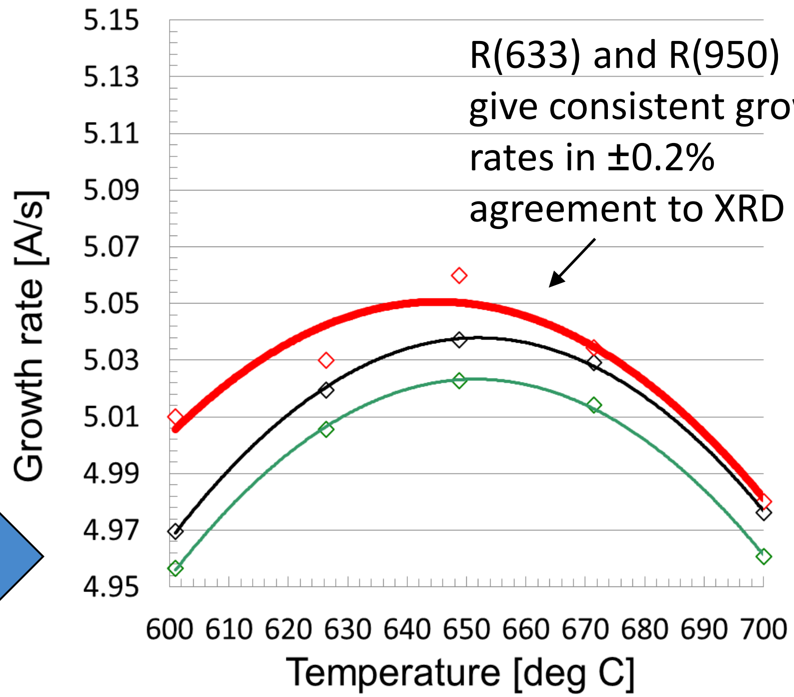
In-situ growth rate calibration – result for InP





Analysis with old nk(T)

- in-situ reflectance and XRD gives the same basic trend of growth rate
- R(633nm) ➔ r offset about +1%
- R(950nm) ➔ r offset about +2%

Analysis with XRD gauged nk(T)

- 0.2% consistency now between 633nm/950nm nk data ➔ 2WL-Fit
- 0.3% consistency between XRD and in-situ at T>620C

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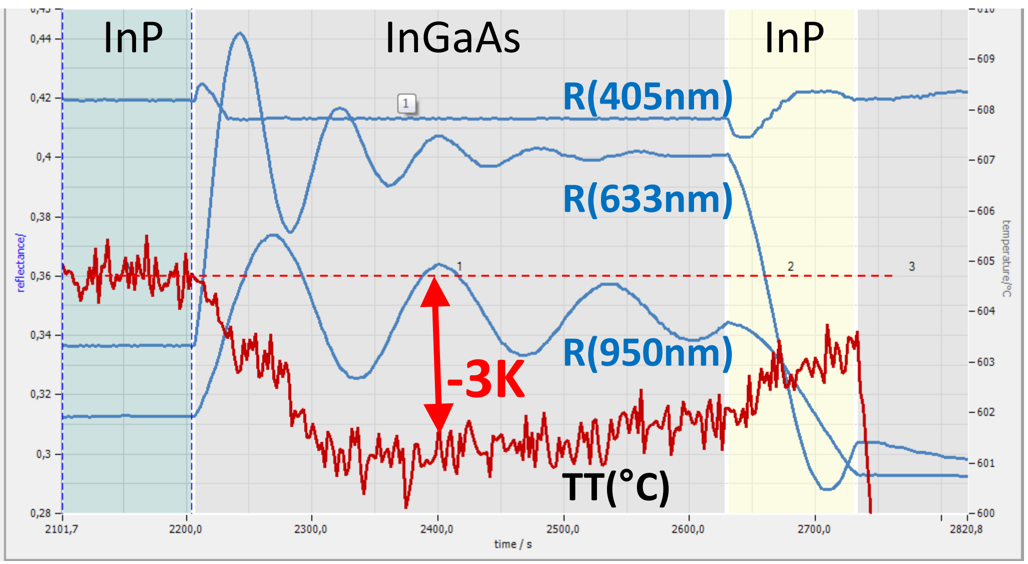
Improving nk (InGaAs) by using XRD growth rates

InGaAs test structure: **InP // 100nm InP buffer / 500nm InGaAs / 50nm InP cap**
for XRD and for in-situ R

Step #1: grow structure and measure in-situ reflectance
Step #2: XRD thickness ➔ calculate RT XRD „growth rate" from growth time
Step #3: correct „XRD growth rate" $r_{XRD}(T_g)$ with thermal expansion coeff.
Step #4: analyse in-situ reflectance with known $r_{XRD}(T_g)$ ➔ **nk (T_g)**



T_{wafer}:
PH_3 ➔ AsH_3 ➔ PH_3
604.3°C ➔ 601.5°C ➔ 603.5°C

XRD – averaged GR!

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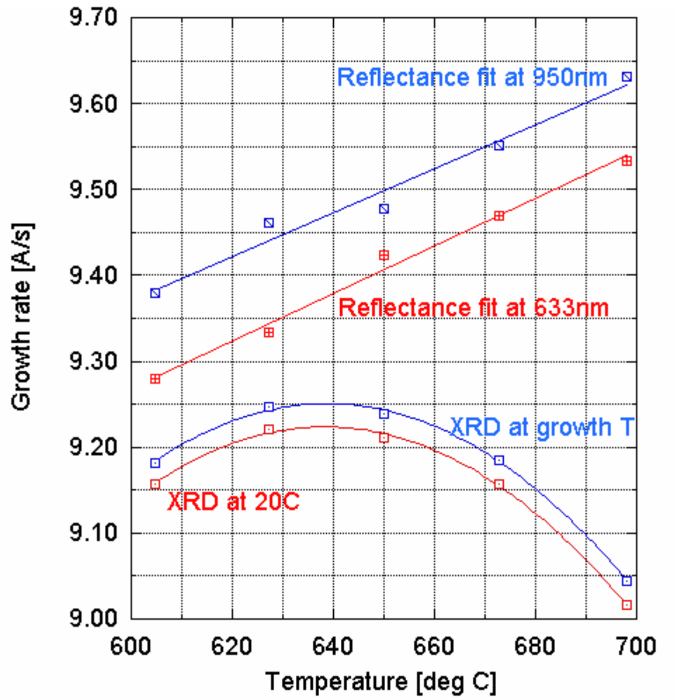
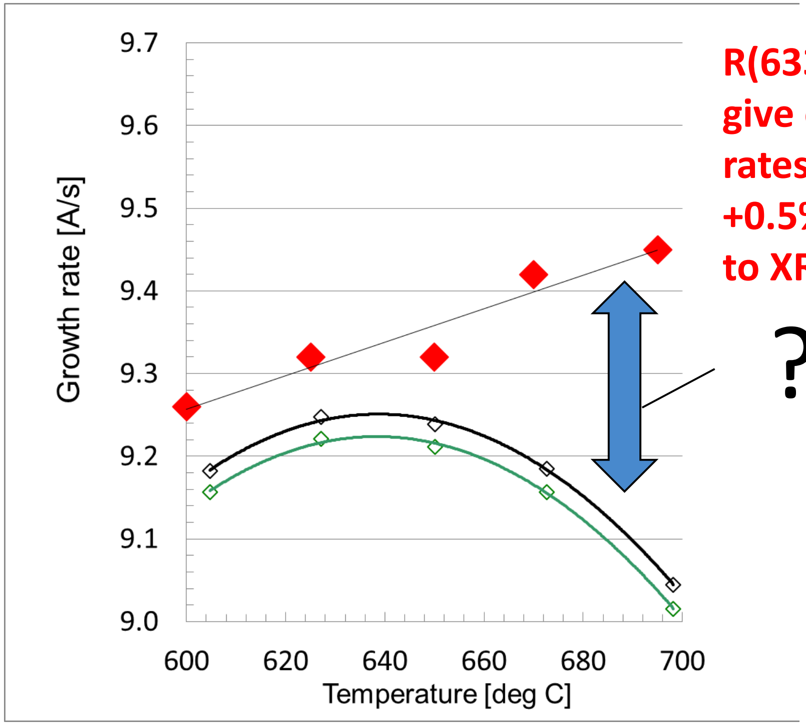
In-situ growth rate calibration – result for InGaAs





R(633) and R(950) both give consistent growth rates only with +0.5% … 3% offset to XRD

?

Analysis with old nk(T):

- in-situ reflectance gives linear and XRD gives parabolic trend with T
- R(633nm) → r offset about +1%
- R(950nm) → r offset about +2%

Analysis with XRD gauged nk(T)

?

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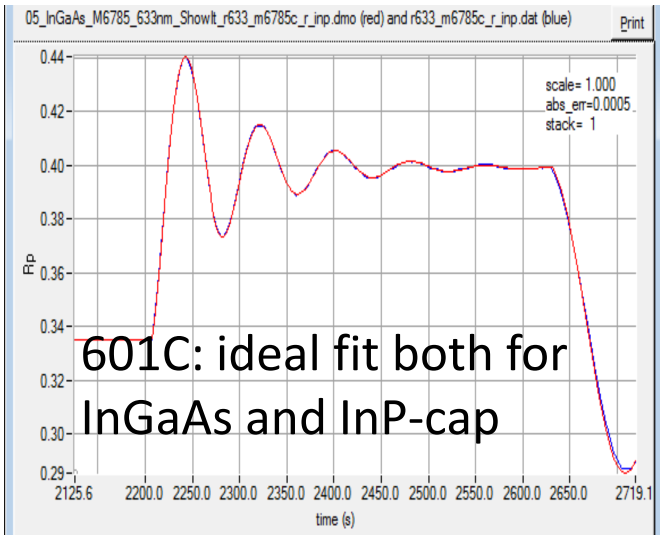
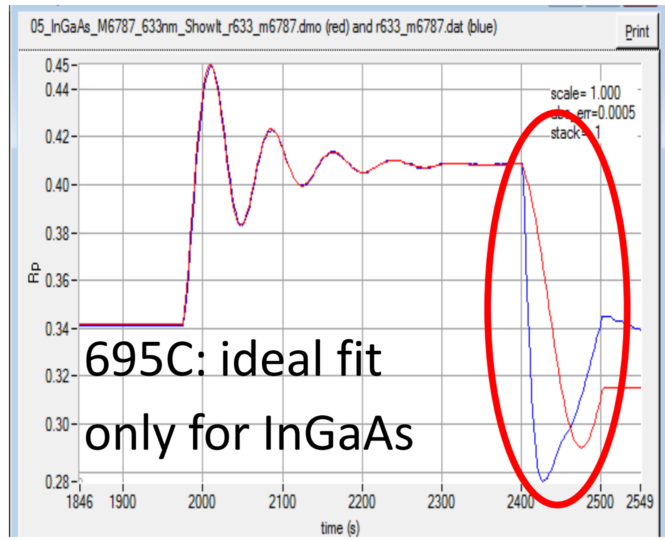
Improving nk (InGaAs) by using XRD growth rates





blue lines – measured

red lines – fitted

At higher T_g the InP-cap causes a strong interface reaction reducing InGaAs thickness ➔ RT ex-situ XRD gives reduced thickness!

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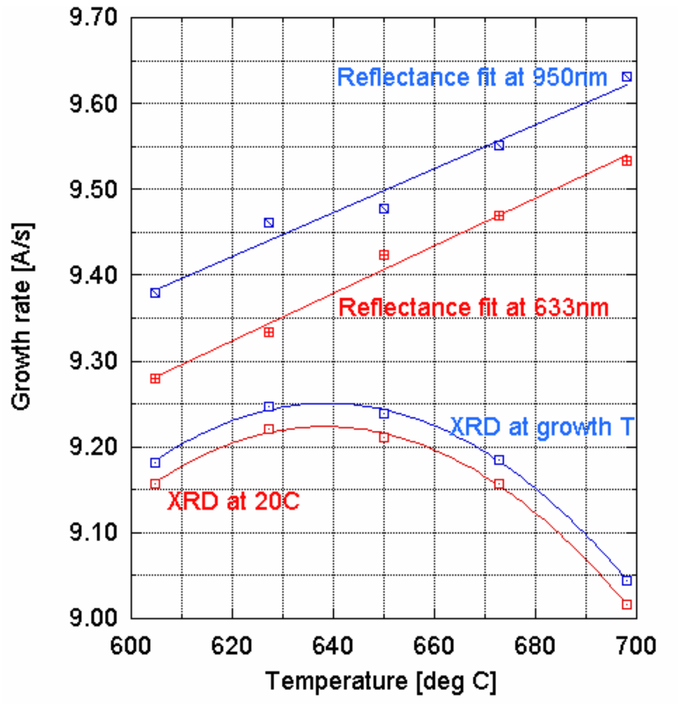
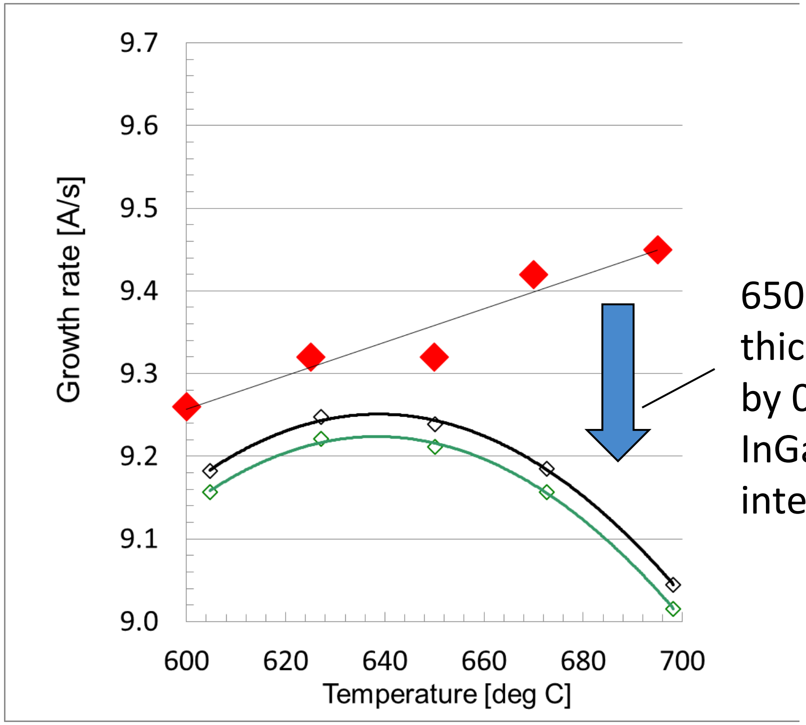
In-situ growth rate calibration – result for InGaAs





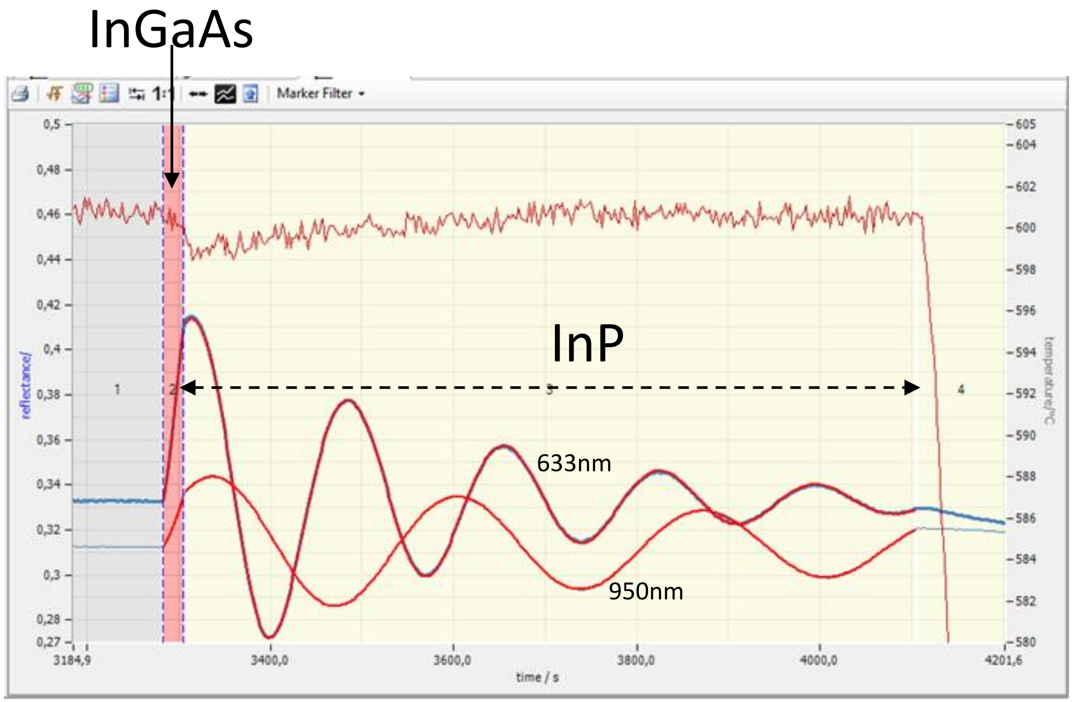
Analysis with old nk(T):

- in-situ reflectance gives linear and XRD gives parabolic trend with T
- R(633nm) ➔ r offset about +1%
- R(950nm) ➔ r offset about +2%

Analysis with XRD gauged nk(T)

- 0.1% consistency now between 633nm/950nm nk data ➔ 2WL-Fit
- >650C the InP cap apparently reduces the InGaAs thickness below

In-situ growth rate calibration – 2λ growth rate fits



blue lines – measured

red lines – fitted

Consistent and XRD referenced nk data combined with 2λ-fits:

- Even very thin layers (here the InGaAs contrast layer under the InP) can be accurately fitted → d_{InGaAs} = 17.5nm // d_{InP} = 401.8nm

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2. Lattice Match Calibration

... after resolution of in-situ wafer curvature measurement had been improved for CCS reactors from ~3km^{-1} ➔ 0.3km^{-1}

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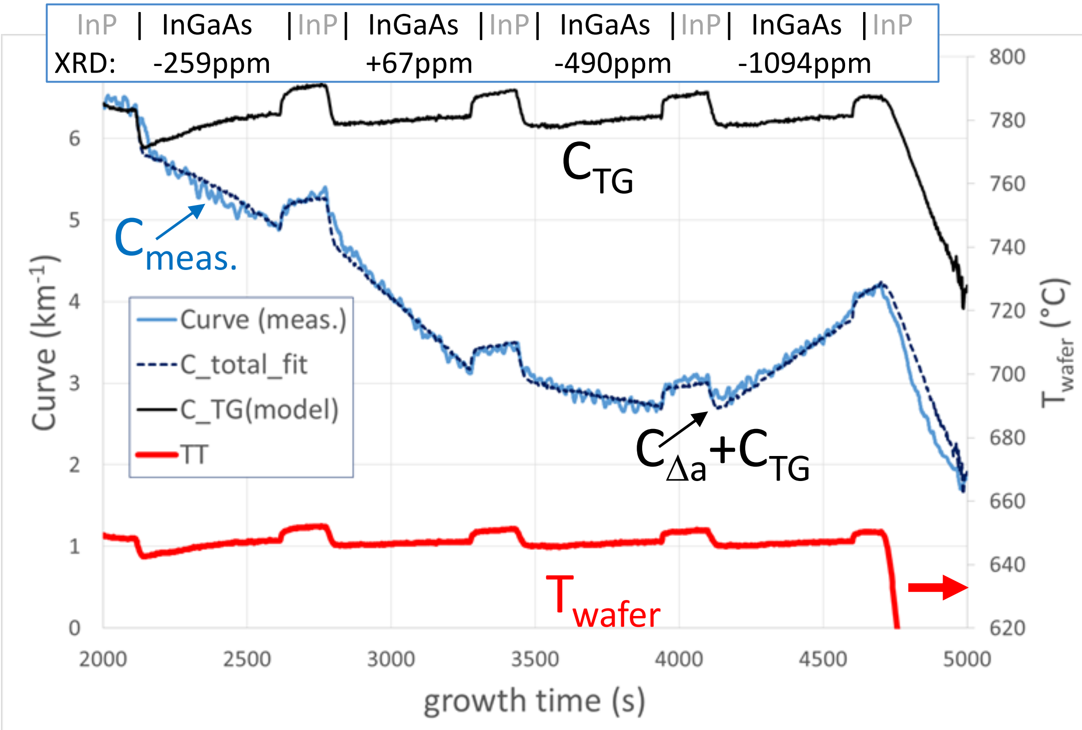
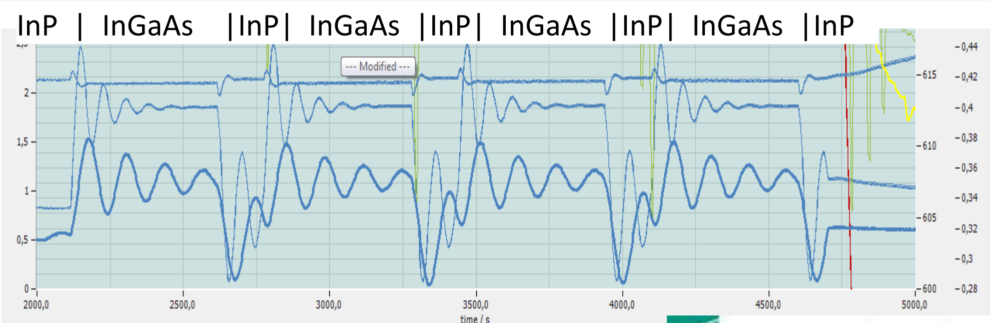
In-situ wafer bow for lattice matching of InGaAs/InP



Wafer bow is sensitive to small lattice mismatch, but: precursor gas changes cause change in wafer surface temperature

➔ full simulation of wafer bow response has to include vertical temperature gradient (TG, wafer back-side / wafer-front-side)



Reflectance of all 4 InGaAs layers at all 3 wavelength is identical! ➔ InGaAs refractive index and growth rate is NOT sensitive to small lattice mismatch!

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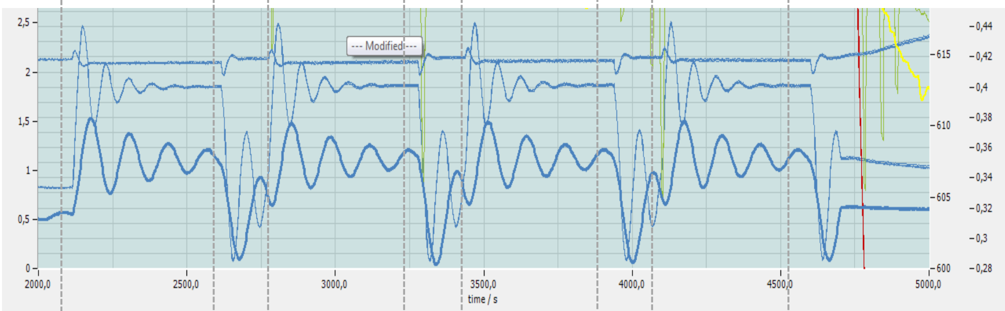
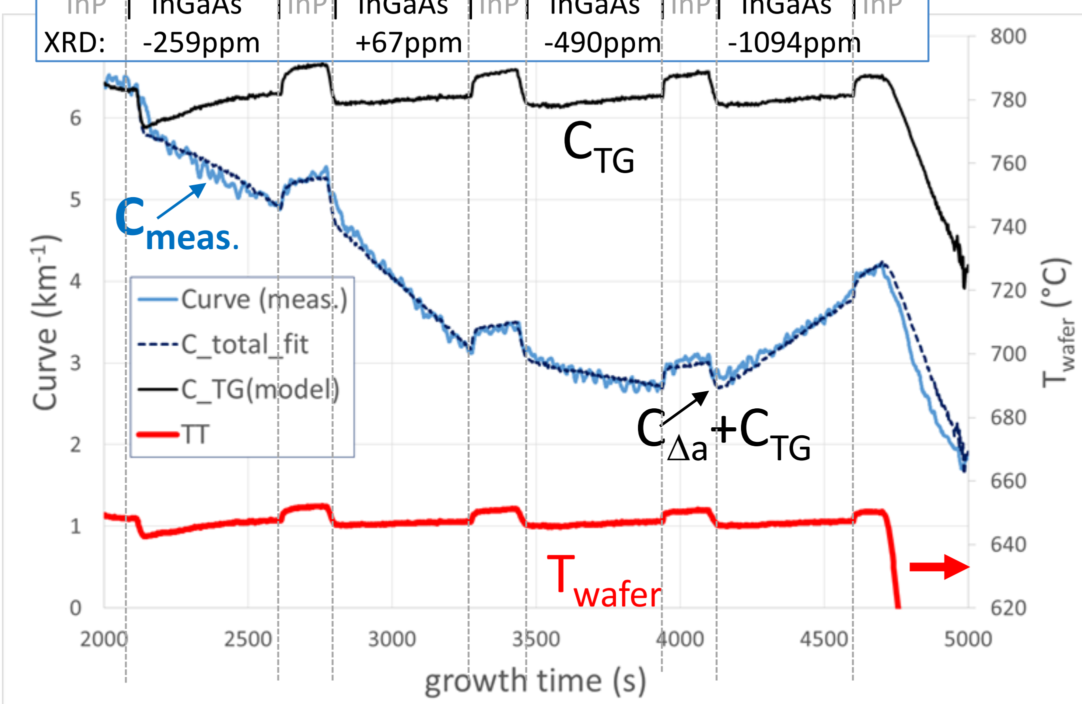
In-situ wafer bow for lattice matching of InGaAs/InP

InP	InGaAs	InP	InGaAs	InP	InGaAs	InP	InGaAs	InP
XRD:	-259ppm		+67ppm		-490ppm		-1094ppm	



Reflectance of all 4 InGaAs layers at all 3 wavelength **is identical**!

➔ InGaAs refractive index and growth rate is NOT sensitive to small lattice mismatch!

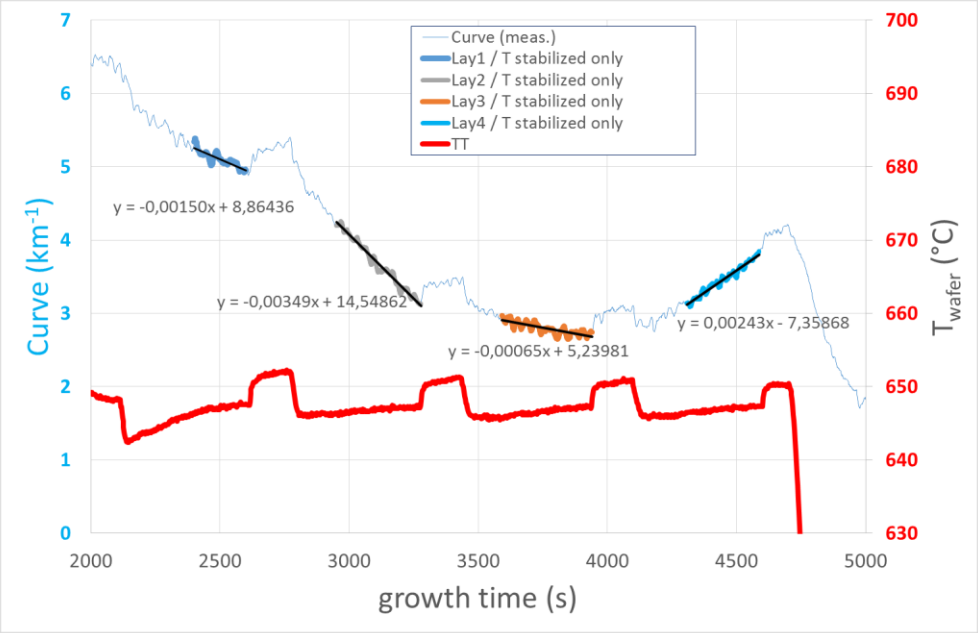


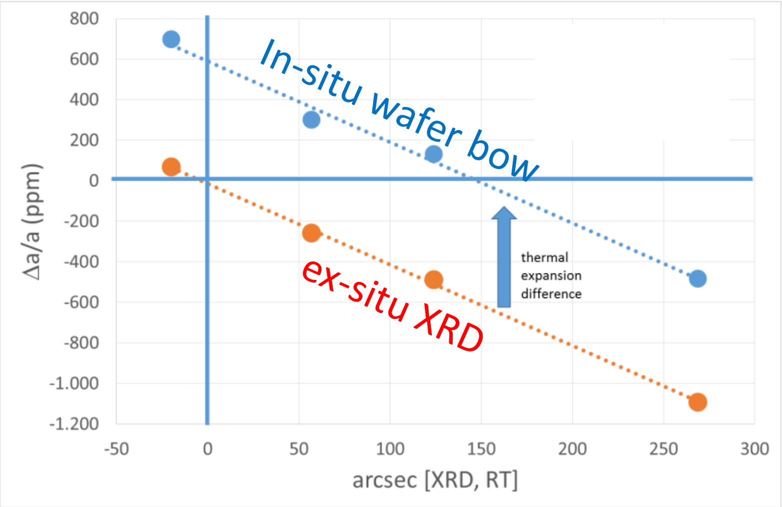
InP | InGaAs | InP | InGaAs | InP | InGaAs | InP | InGaAs | InP

Wafer bow is sensitive to small lattice mismatch, but:
precursor gas changes cause change in wafer surface temperature

➔ full simulation of wafer bow response has to include vertical temperature gradient (TG, wafer back-side / wafer-front-side)

In-situ lattice matching of InGaAs/InP: Δa/a=± 50 ppm





<u>Simplified analysis:</u> slope of wafer bow during InGaAs growth AFTER re-stabilization of T_{wafer} !

Slope of wafer bow, normalized to InGaAs growth rate, is an accurate measure of even very small lattice mismatch!

Once calibrated to XRD ➔ in-situ adjustment of lattice match!

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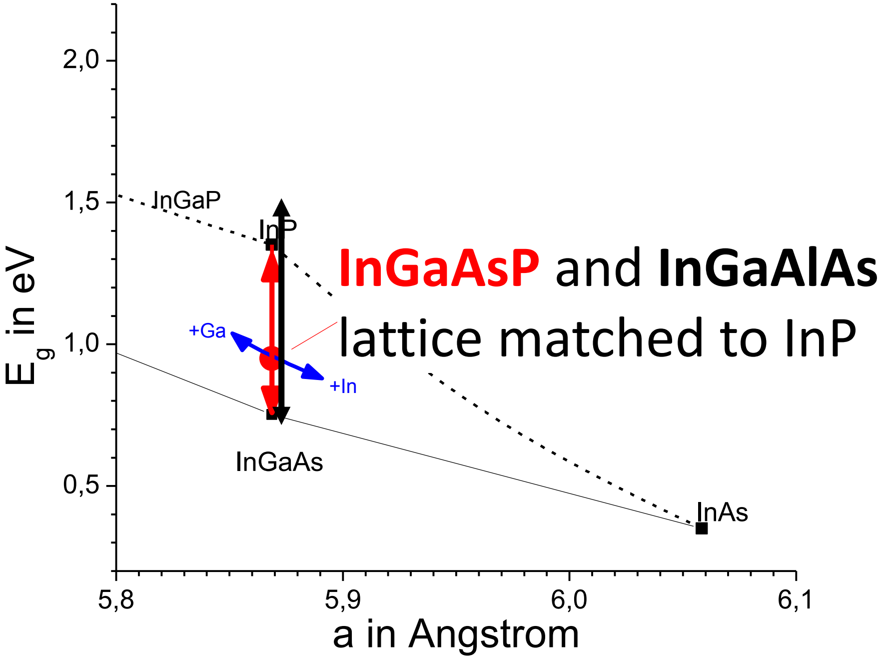
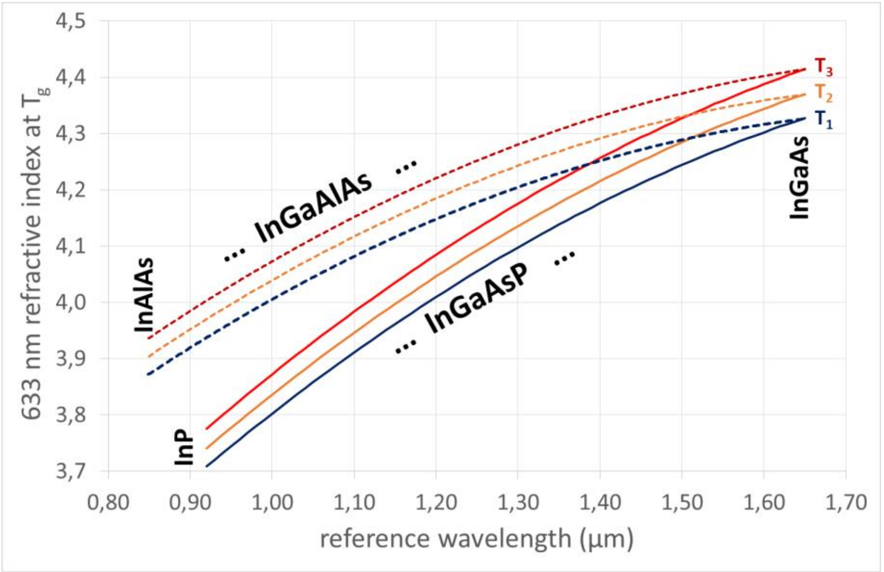
3. Composition Calibration of lattice matched quaternaries on InP

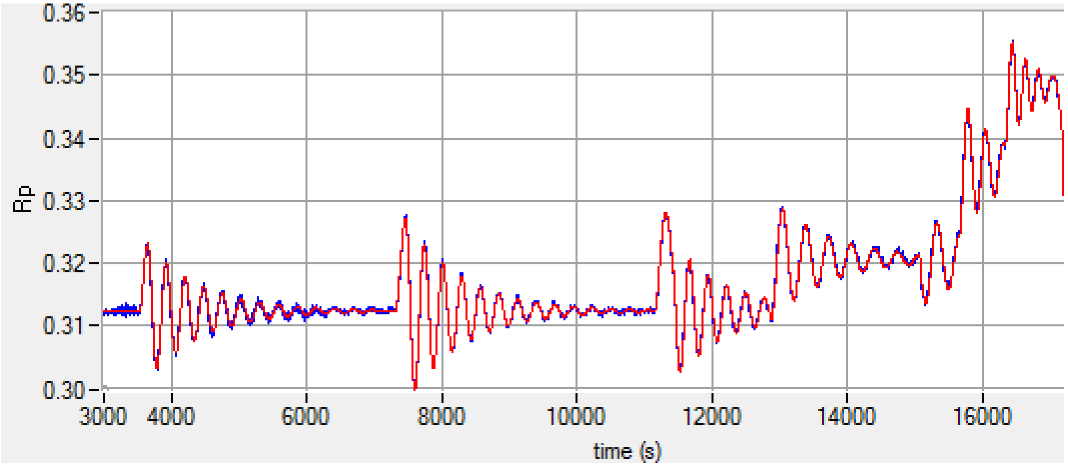
The high temperature nk of lattice matched InGaAsP and InGaAlAs directly correlate with PL emission wavelength at room-temperature





Based on XRD gauged nk of InP ➔ improved accuracy of nk (633nm) of InGaAsP and InGaAlP … but work is still in progress

Full Device analysis (HHI-Stack)



blue lines – measured

red lines – fitted

- Lattice matching of all layers verified by in-situ wafer bow
- PL emission wavelength (effective composition) measured in-situ by nk fit to the reflectance FPOs of all layers
- Composition analysis possible only for layers >~200nm
- Optimizing the analysis strategy: thickness of very thin films (5-20nm) can measured accurately by fixing nk(T) to values determined before at thicker films (of same effective composition) in the same stack

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SUMMARY

Growth rate calibration:

➔ Use XRD/fringing as reference for determining accurate nk at growth temperature for InP, InGaAs, InGaAsP, …!

DONE!

Lattice match calibration (InGaAs, InGaAsP, InGaAlAs on InP):

➔ Improve wafer bow resolution to at least ±100ppm!

DONE!

Composition calibration (InGaAsP, InGaAlAs on InP):

➔ Improve in-situ composition calibration to $\Delta\lambda_{eff} = \pm 2$nm!

In Progress!

Not yet mentioned so far: in-situ wafer temperature control better ±1K (AbsoluT calibrated to the PTB/NIST standard) is a must for all of this!

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Thank you for your attention

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