Advanced optical testing of 3D devices

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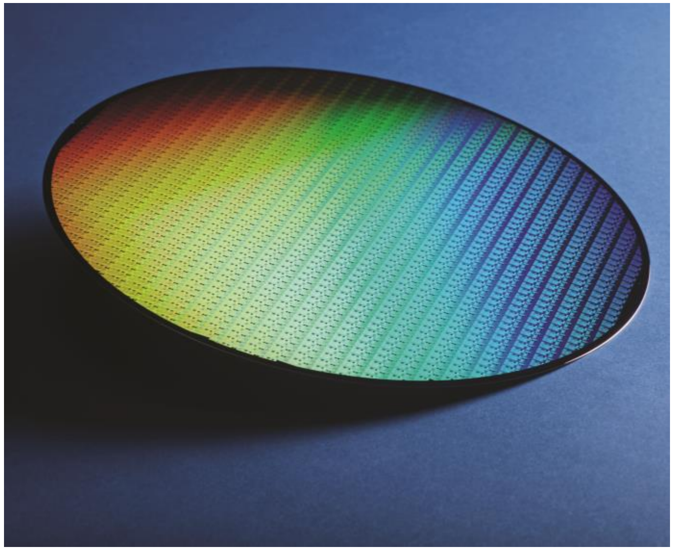
Outline

- Company Presentation
- Optical Metrology Options for 3D devices:
  - Raman and Spectral Photoluminescence (SPL)
  - En-Vision
  - Model-Based Infrared Reflectance (MBIR)
- Conclusions

Basic facts about Semilab

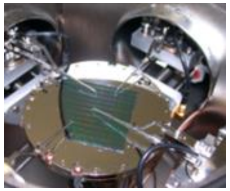
Main activity: Development, manufacturing and marketing of metrology equipment for the semiconductor and photovoltaic industries.

- Laboratory, office and manufacturing space: 17,000 m^2, about 3,900 m^2 in the subsidiaries
- More than 800 employees worldwide
- 110 physicists employed worldwide
- 30 employees holding a PhD in physics
  - 16 physicists, 1 engineer in Hungary
  - 11 physicists, 2 engineers abroad
- 11 employees attending at PhD studies (all in Hungary)
- Patents: wholly owned – 90, applications – 8, licensed – 41
- ~ 400 tools with automated wafer handling installed in semiconductor production
  - 130 tools in 300 mm fabs
- 34 different product lines, 110 products with various configurable options



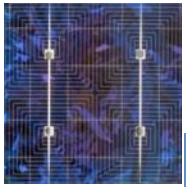
History of the Semilab Group

1990: Founded by researchers as a spin-off from the Research Institute for Technical Physics of the Hungarian Academy of Sciences



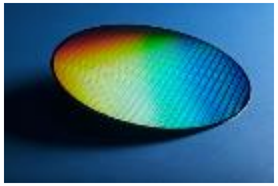
2004-2010: Photovoltaic area

- **90% annual growth (industry growth ~ 40%)**
- **Dominant player in front-end electrical metrology**



2004-2014: Semiconductor area

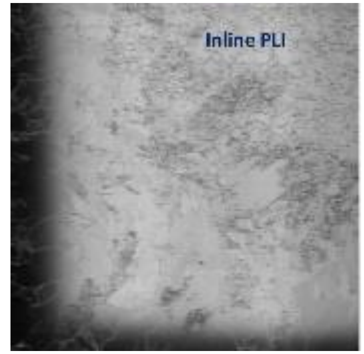
- **Growth by company and technology acquisitions**
- **5th biggest pure-play metrology company**
- **Building significant customer base in FPD industry**



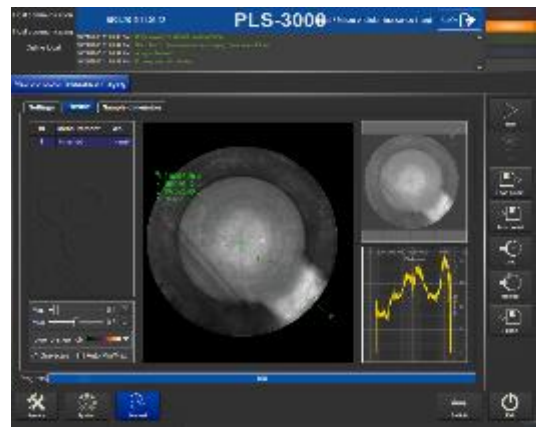
Semilab PL overview

Integrated PL; Indirect gap material (Si):

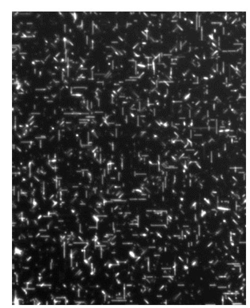
- **PV** : 6000 wph full wafer 1Mpix imaging, ispection and sorting.
  - As cut wafers: efficiency forecast
  - Processed high efficiency cells surface passivation monitoring (US patent)
- **Semi:**
  - 300mm Full wafer imaging 150um with resolution
    - Contamination troubleshooting
    - Passivation monitoring
    - Decorated slip deection
  - Micro defect band PL imaging:
    - Trench process defectivity inspection
    - Implant / Anneal defects inspection



Inline pl image of 1560mm as cut wafer;



Macro Pl image of 300mm semi wafer

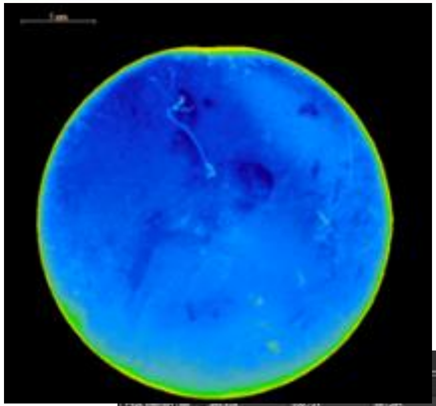


Micro PL defect image of implanted wafer; FOV 130x150µm

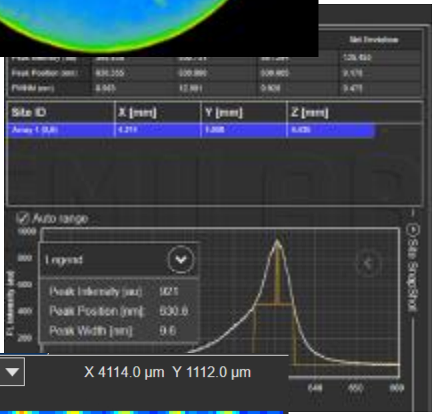
Semilab PL overview

Spectroscopic PL; Compound materials:

- full wafer scanning:
  - EPI monitoring
  - LED / Laser structures Composition monitoring
  - MQW emission monitoring



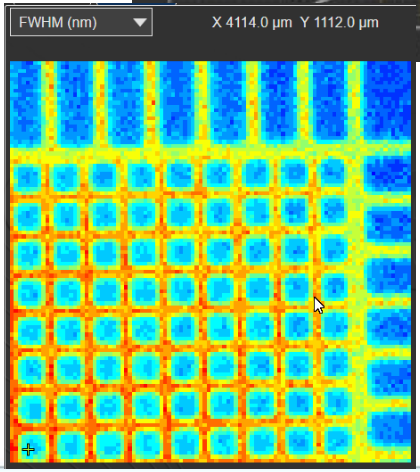
GaN EPI on saphire wafer PL map 2”



PL spectra of MQW structure

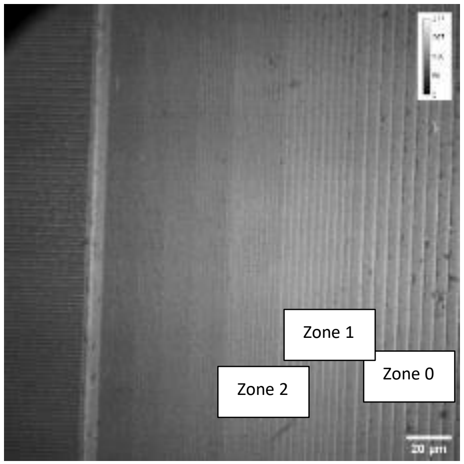
- Micro spot point measurement:
  - Measure on dedicated area of patterned wafer

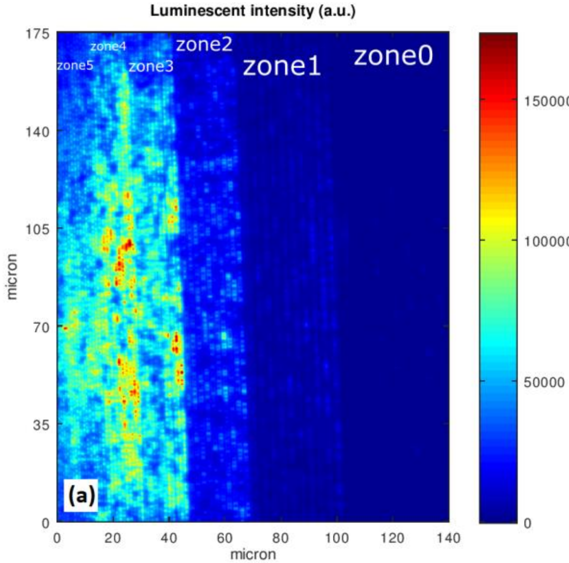
- Micro spot micro scanning:
  - Micro devices process control
  - Etching quality control
  - Defect rewiev

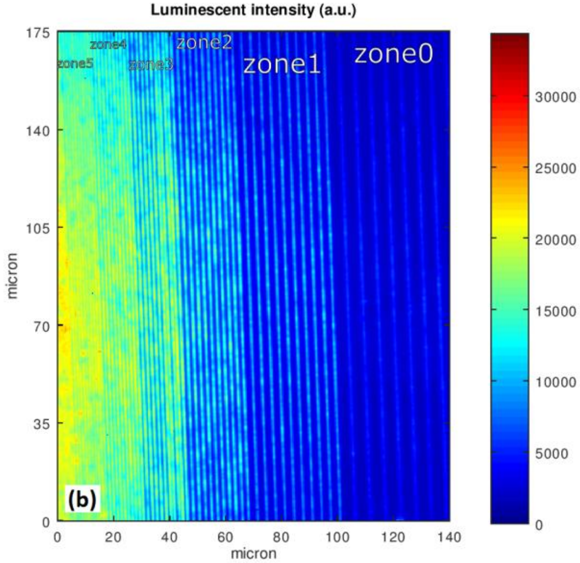


Micro PL map of pixellated structure (5 μm x 5 μm pixel size, 1 μm spatial resolution)

EnVision - GaAs/InGaP structures with incorporated InGaAs MQW



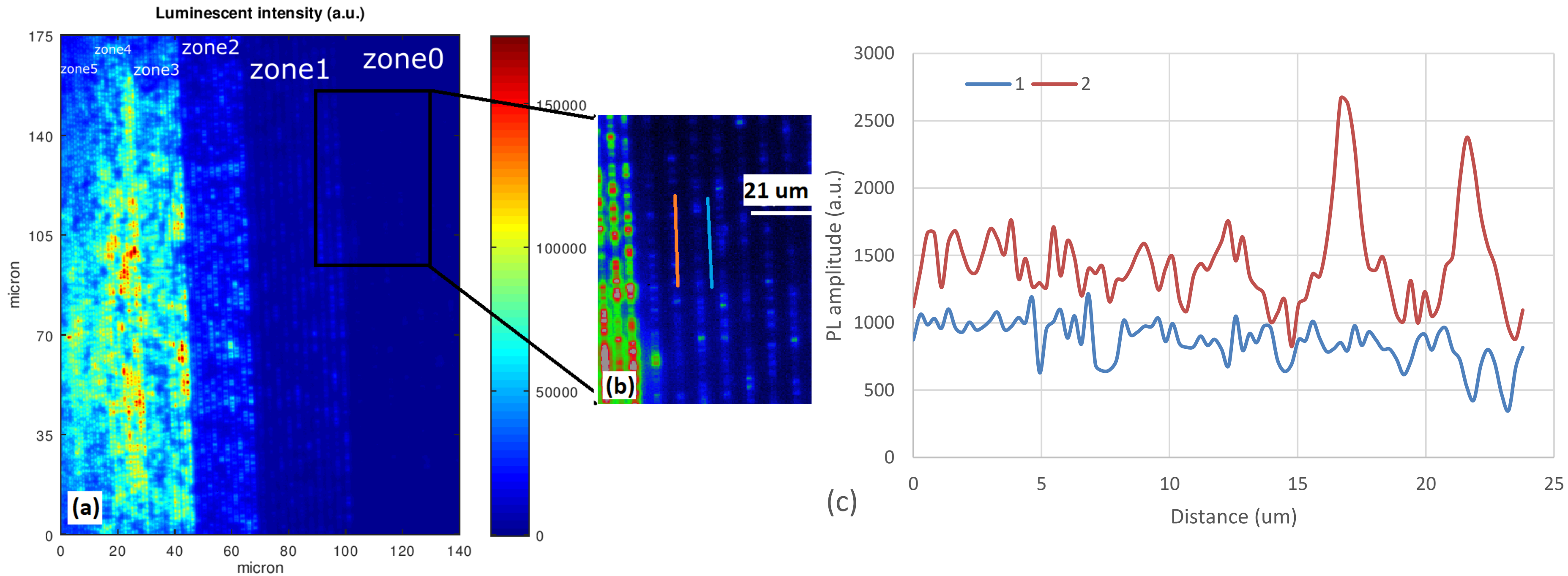




- configuration A: PL emission between 1000-1300 nm is recorded. The laser power density was 0.3 kW/cm2
- configuration B: PL signal between 1300-1700 nm is recorded. The laser power density was 2 kW/cm2.

(a) PL image measured in Configuration A (1000-1300 nm). Much stronger PL signal intensity on zone 5 (narrower fins) compared to zone 0 (wider fins). (b) PL image acquired in Configuration B (1300-1600 nm). The main PL emission of the fins is at ~1040 nm (based on spectral PL measurements).

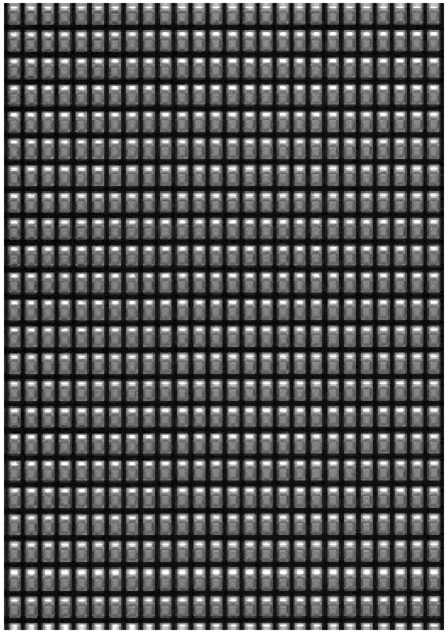
EnVision - GaAs/InGaP structures with incorporated InGaAs MQW



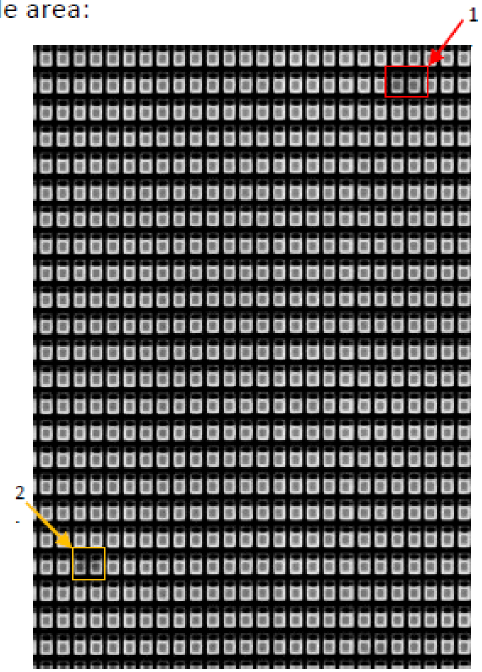
(a) The PL image is measured in Configuration A (1000-1300 nm). Much stronger PL signal intensity on zone 5 (narrower fins) compared to zone 0 (wider fins). (b) zoom-in of zone 0 – the fin structure if full with dark regions corresponding to defects. (c) Profile line along a fin (orange line) and in-between fins (blue line). PL amplitude between fins is lower compared to, but not zero.

Mapping

Example area:

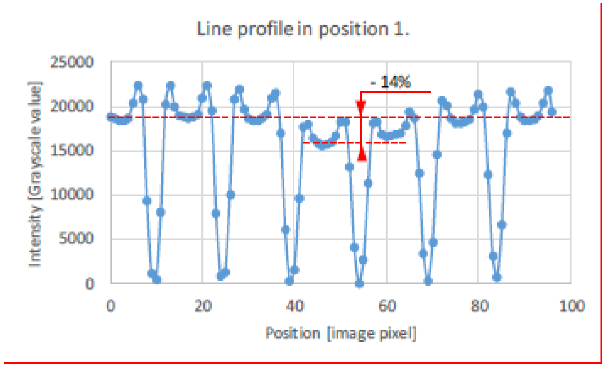


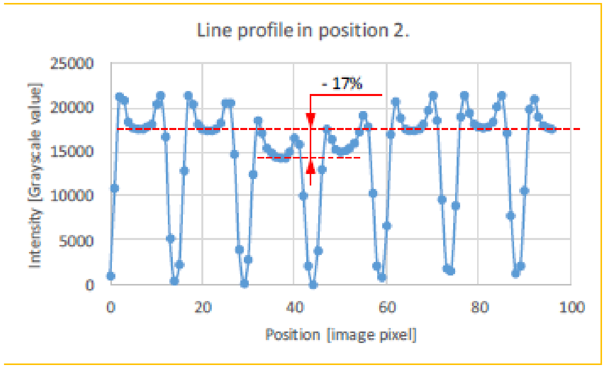
Reflection image



Photoluminescence image

No difference on reflection image in the same position as 1. & 2.

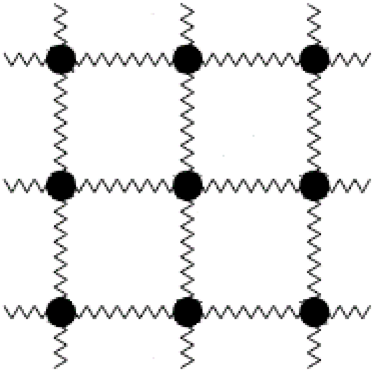




Raman effect: inelastic scattering of light with a material.

Raman spectrum: a unique (vibrational) fingerprint for a given material.

The frequency of a vibration depends on the bond strength and mass, while the number of bands (peaks) in a spectrum depends on the symmetry of the crystal.



Harmonic oscillator: $\omega \sim (k/\mu)^{1/2}$

k: force constant
μ: reduced mass

Vibrations are sensitive to changes of physical properties as well as to changes of external parameters.

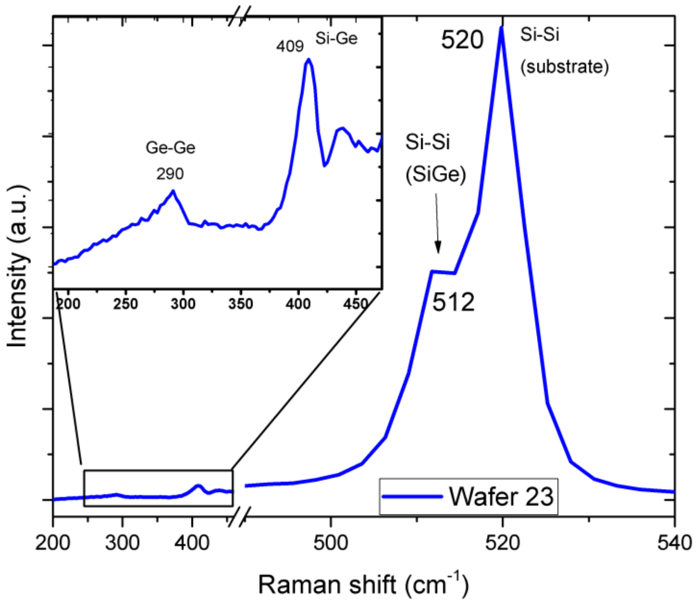
Raman spectroscopy is a probe for:
-identifying materials or types of bonding
-investigating strain in thin films
-investigating composition and doping of a solid, etc.

D.A.Long, Raman spectroscopy,
McGraw-Hill International Book Company, 1977

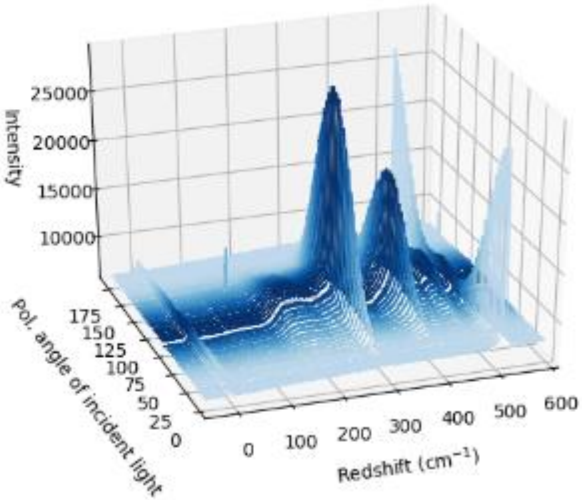
SiGe fin-FET

Ge concentrations (x) ranging between 15-30%, SiGe layer thicknesses (d) between 4-12 nm.

Penetration depth in Si at 355 nm: 10.6nm.



Typical Raman spectrum of a SiGe layer grown on Si(001). The spectrum is characterized by four main modes: SiSi (of SiGe), SiGe, GeGe, and SiSi (of substrate).



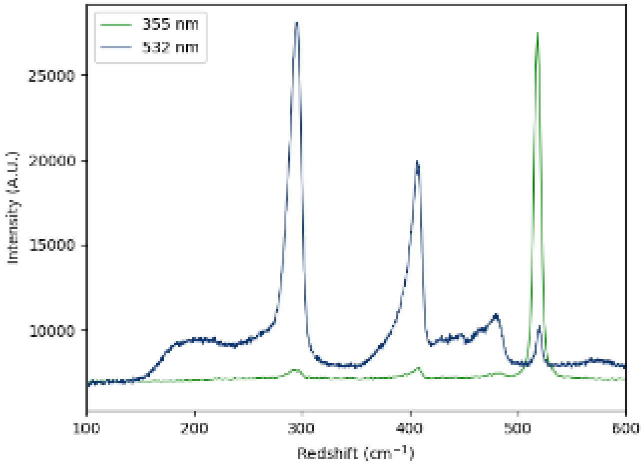
Position of the SiGe related Raman bands are a function of the Ge content.

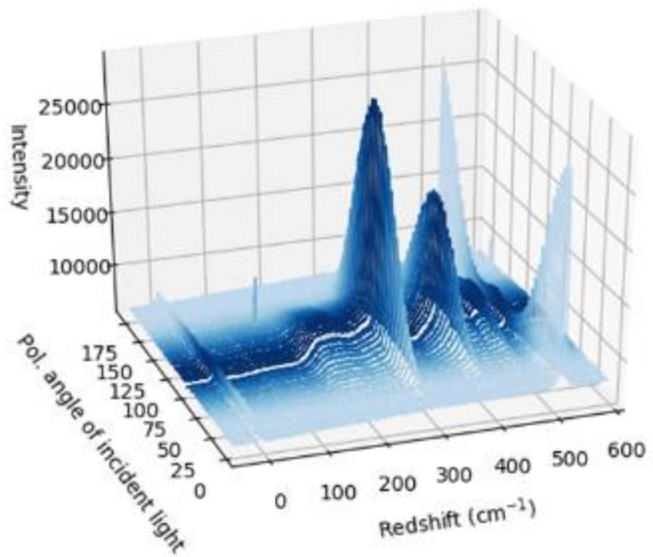
$$\omega_{\text{Si-Si}} = 521 - 68x - 815\epsilon_{\parallel}$$

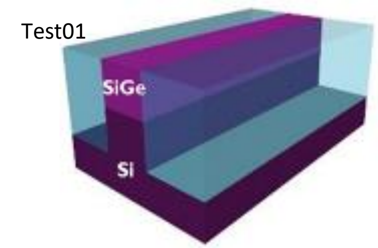
$$\omega_{\text{Si-Ge}} = 399.5 + 14.2x - 575\epsilon_{\parallel}$$

for x<0.3

Tiberj, Proc. of MRS Symp. 809, 97-102, 2004

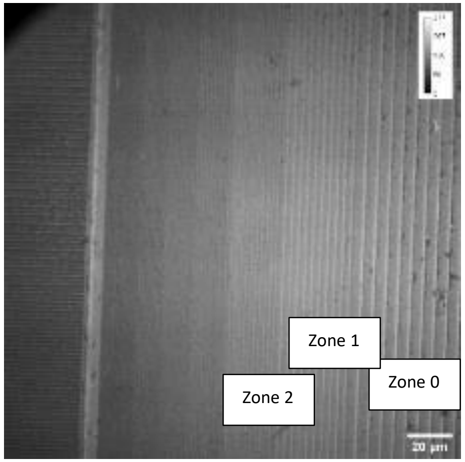


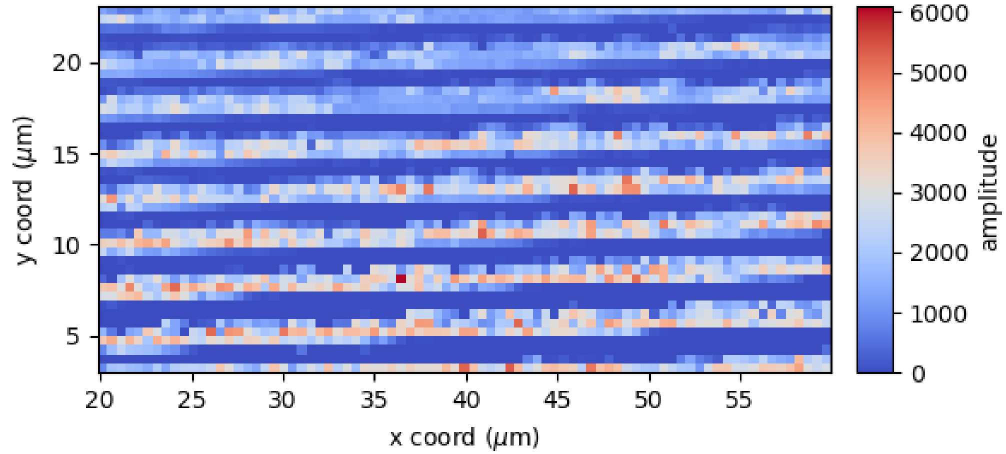




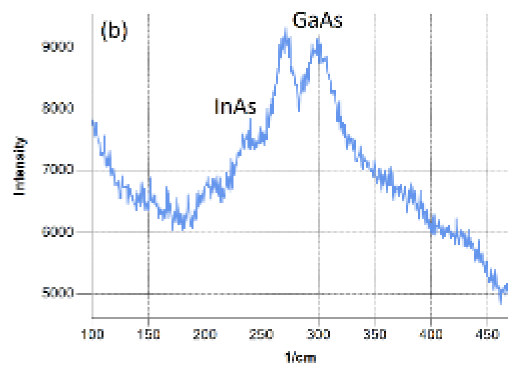
- SiGe fin Raman signal is enhanced when the fin orientation is parallel to the incident laser orientation (mainly visible for Ge-Ge and Si-Ge Raman bands at ~300 and ~400 cm-1 respectively).

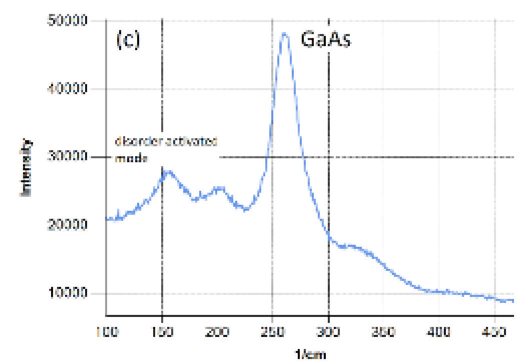
Raman - GaAs/InGaP structures with incorporated InGaAs MQW





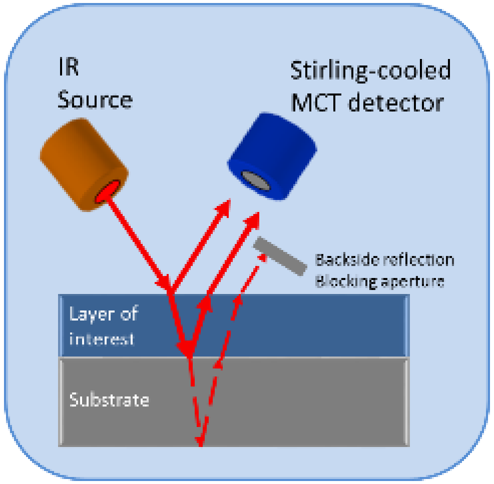
- Experimental setup: 532 nm Raman, 0.5 µm spot size. 0.5 µm spatial resolution.
- The high-resolution Raman intensity map at 160 cm^{-1} (disorder activated mode) on zone2 show an inhomogeneous Raman intensity along and between the fins.
- Raman bands of InAs (~240 cm^{-1}) and GaAs (~270 cm^{-1}) are present both in-between and on the fin structures. In addition, a new spectral band located at 160 cm^{-1} is measured only on the fins.

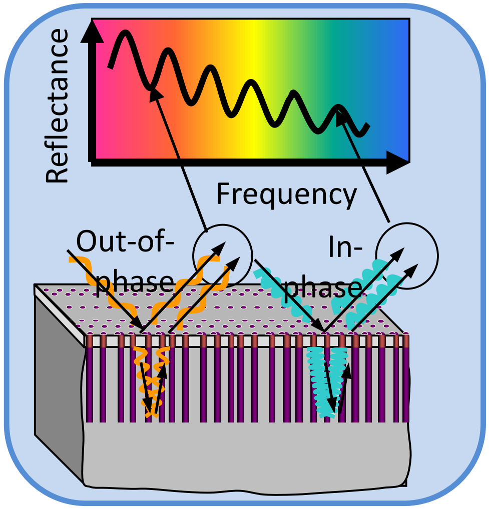




Model-Based IRR

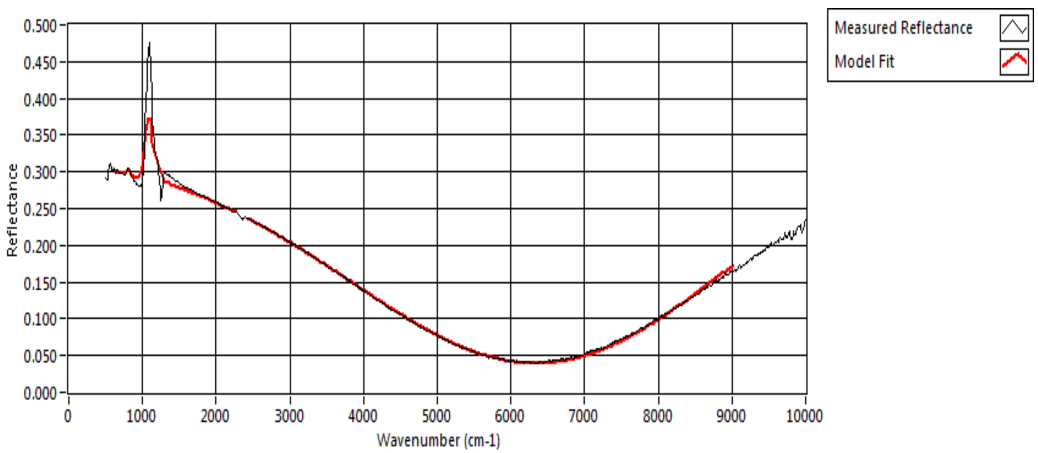
- **Effective Model Approximation**: Fins are modeled as a homogeneous or gradient layer made from the appropriate material mix
- **Model parameters**: "effective" thickness of the layer, mix composition, etc.
- **Model parameters** are calculated by fitting model spectra to measured spectra. Model parameters need to be correlated to analytical measurements.

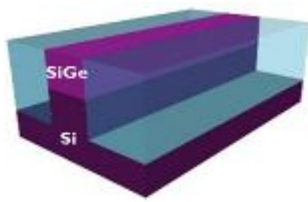


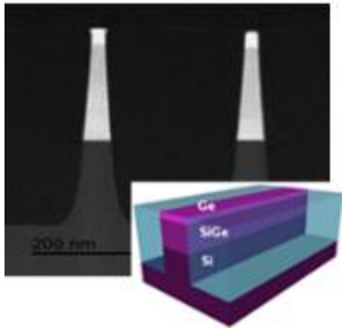


- Reflections & absorptions from trenches and films determine shape of reflectance spectrum
- Analysis of reflectance spectrum yields thickness, depth, CD, and composition

Results: Model Fit Example – Test 01 and Test 02





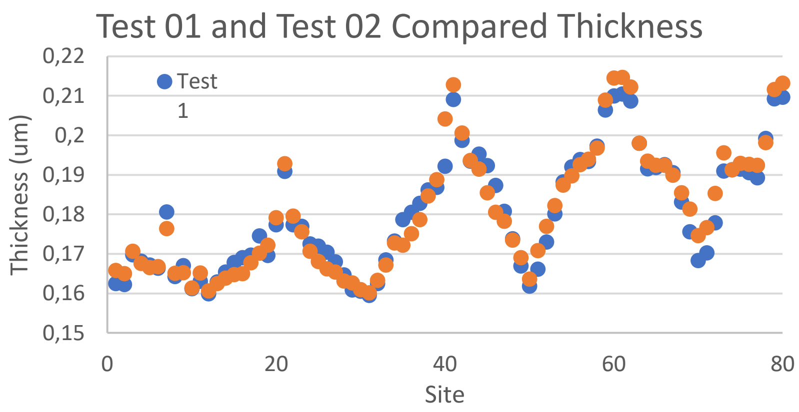


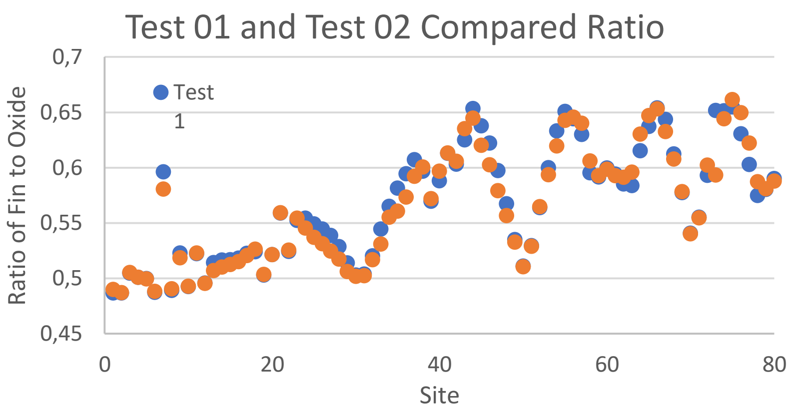
The model provides a good fit to the measured spectrum.

This model has assumed a mixed layer of Si and SiO2 on top of the substrate. The ratio of the fin to the oxide can be followed to check for width variation.

	Fin Width (nm)	20	40	60	80	100	120	150	200	300	500
Fin Length (nm)	100	✓	✓	✓	✓	✓	M1	M2	M3	M4	M6
	200	✓	✓	✓	✓	✓	✓	✓	✓	M5	M7
	300	✓	✓	✓	✓	✓	✓	✓	✓	✓	M8
	500	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	1000	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	3000	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	5000	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	10000	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Test 01 and Test 02 Comparison

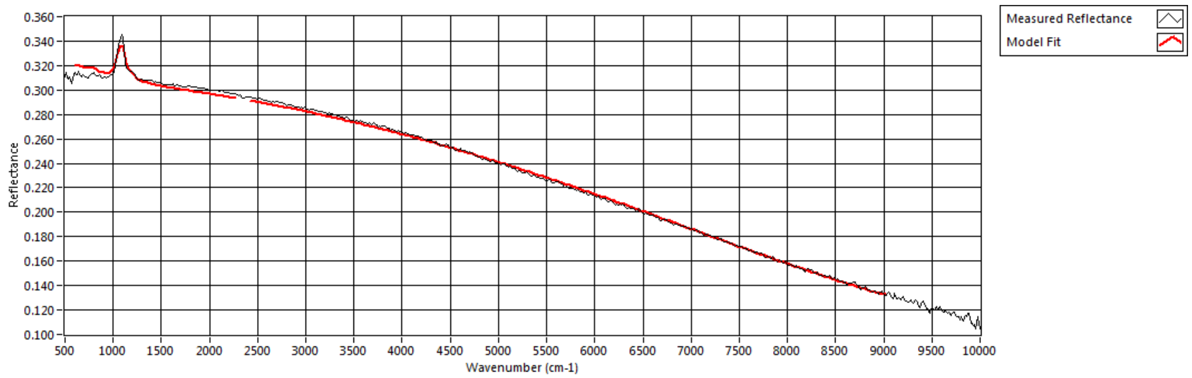


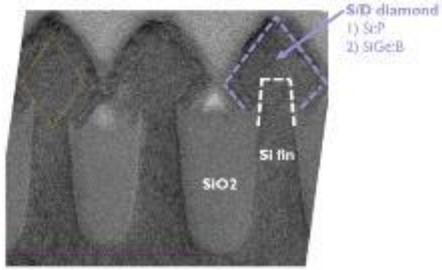


The Compared Thickness chart confirms the correlation between the thickness based of the width and length of the fin as it goes along the serpentine path.

We note that the sample 01 and 02 fin thickness and ratio results are consistent between the samples, the method is sensitive to process changes thus it would be suitable as a go/no go process method due to the high speed and reliability of optical measurements

Model Fit Example – Test 6 Fin Array





	Thickness (um)	Ratio SiO2-Si	P-Dose (E14/cm2)
Average	0.091903	39.40833	2.181013
σ %	1.07%	1.25%	3.92%

The model provides a good fit to the measured spectrum.

The model for the Test06 fin array was made with a mixed layer of Si and SiO2 such as Test 01 and 02, however another layer of doped Si was added above it.

Dynamic Repeatability – Test 01 and Test 02

	Thickness σ %	Ratio σ %
Test 01	0.16%	0.30%
Test 02	0.16%	0.63%

- The dynamic repeatability was evaluated by measuring the wafers a total of 30 times. The wafer was unloaded and loaded again between the measurements.

Conclusion Test 01 and 02:

- Measured model parameters are dependent on both fin width and length
- While one parameter (width or length) stays constant, the effective thickness is a monotonous function of the other parameter (see the sections of the thickness plot on in 4.12)
- Thus while the results are not analytical, and cannot be used for absolute measurement as the *same* effective thickness can be given by a number of width*length configurations, it can be seen that the method is sensitive to small changes for a given process

Dynamic Repeatability – Test06

	Thickness (um)	Ratio (SiO2-Si)	P-Dose (E14/cm2)
Test 06 fin	1.07%	1.25%	3.92%

- The dynamic repeatability was evaluated by measuring the wafers a total of 30 times. The sample was unloaded and loaded again between the measurements.
- Note: The repeatability of the P-Dose value may not be as low as desired due to the lower P-Dose value.

Conclusion Test 06:

- For sample test 06 the thickness, SiO2 ratio and P-dose measurements were reported.
- While the fin dimensions may also be measured by some other optical techniques the P-dose measurement capability is unique for MBIR.