Compositional and strain metrology in nanoscale structures using Raman spectroscopy

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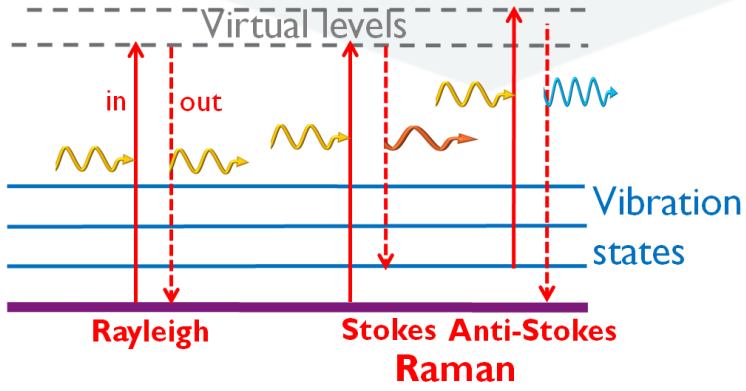
imec

Outline

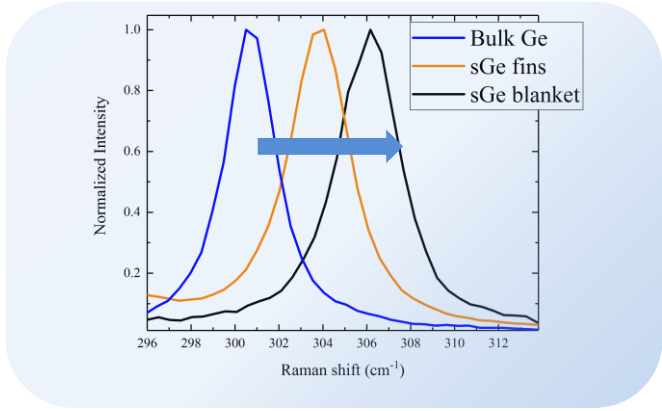
- **Raman spectroscopy as a tool for stress and compositional metrology**
- **Nanofocusing of light**
- **Stress measurements**
- **Composition measurements**

Raman as stress and composition gauge

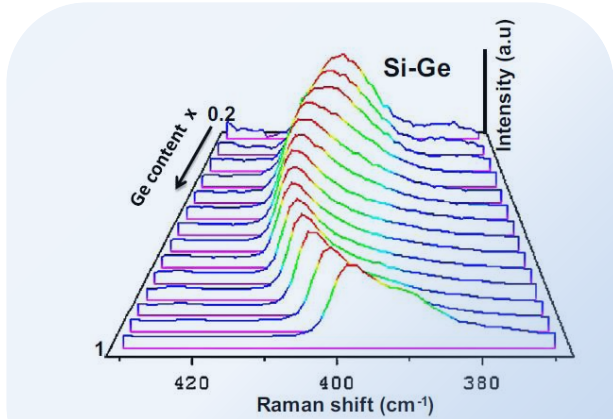
Raman spectroscopy (RS) probes lattice vibrations (phonons), whose energy levels shift:



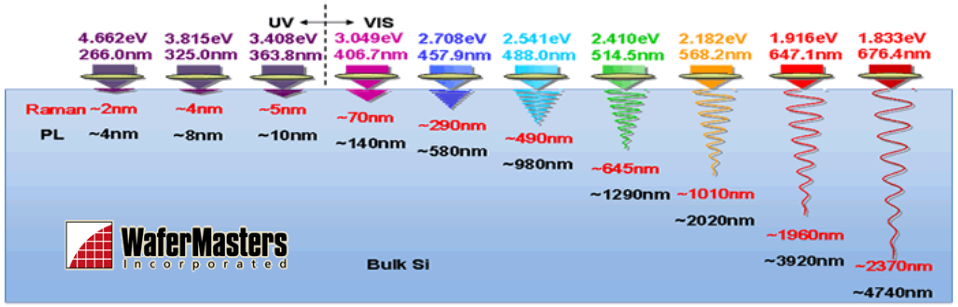
when mechanical stress is applied...



...or the composition changes

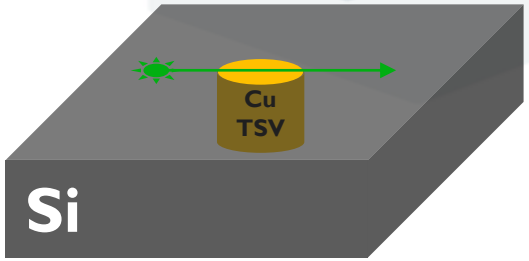


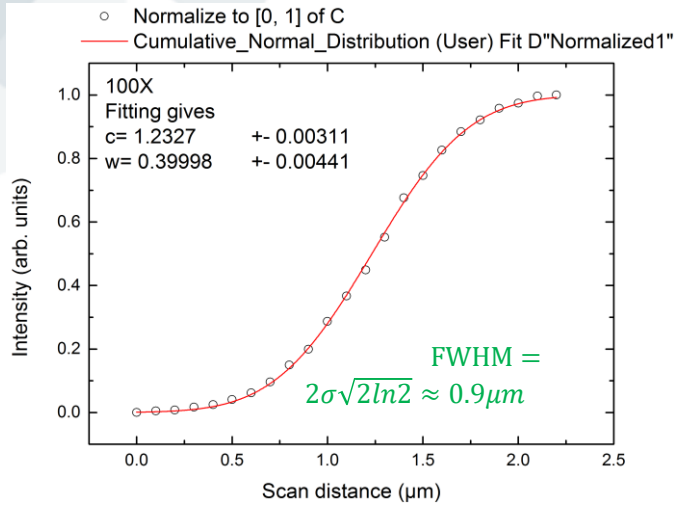
Rouchon J. Crys. Growth **392** 66 2014



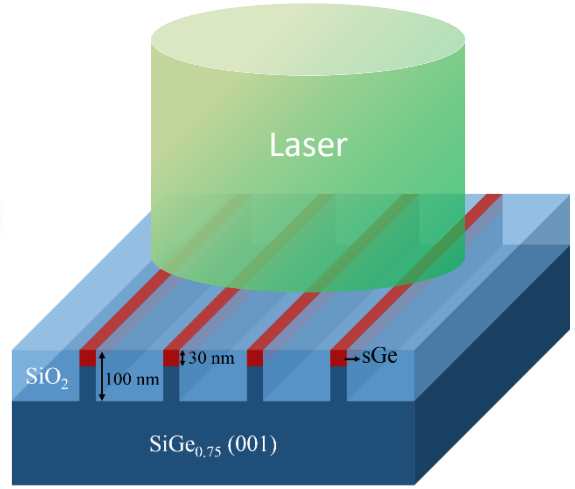
A highly versatile, fast and non-destructive technique, so ideal for high performance stress measurements in semiconductor technology

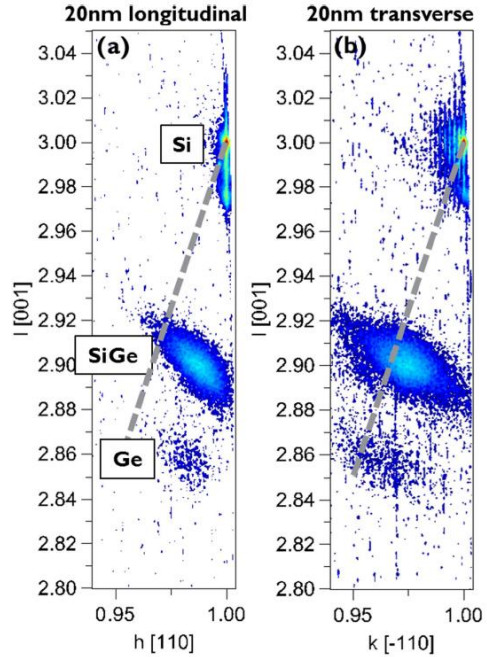
Scaling optical spectroscopy?





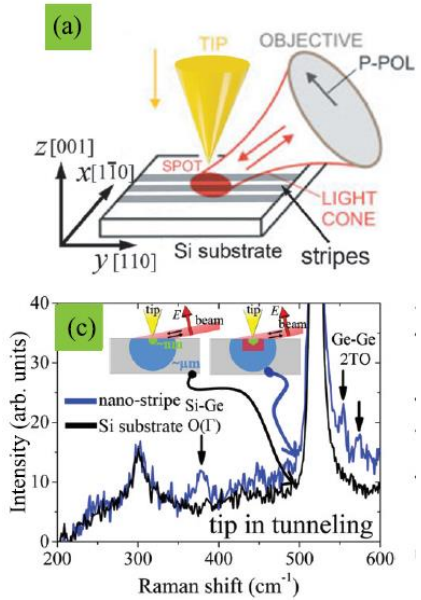
Channel ~ 1% total probed volume





Schulze Nanotechnol. **28** 145703 (2017)

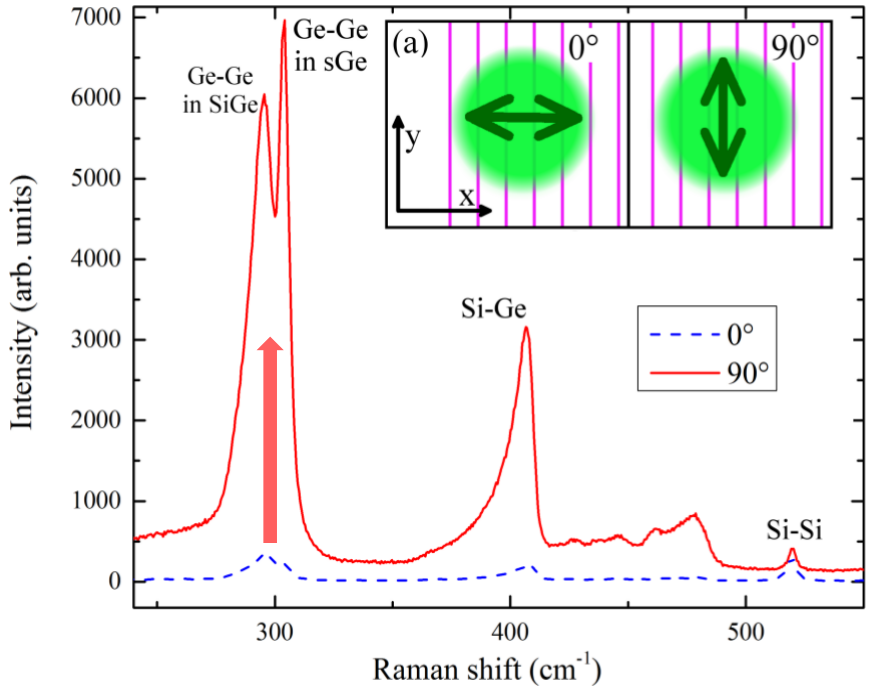
Vanacore Phys. Rev. B **88** 115309 (2013)

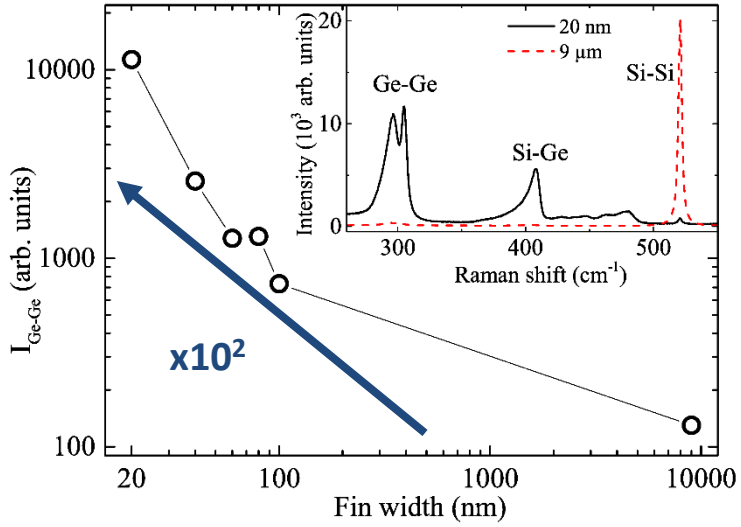


Improve the spatial resolution through:

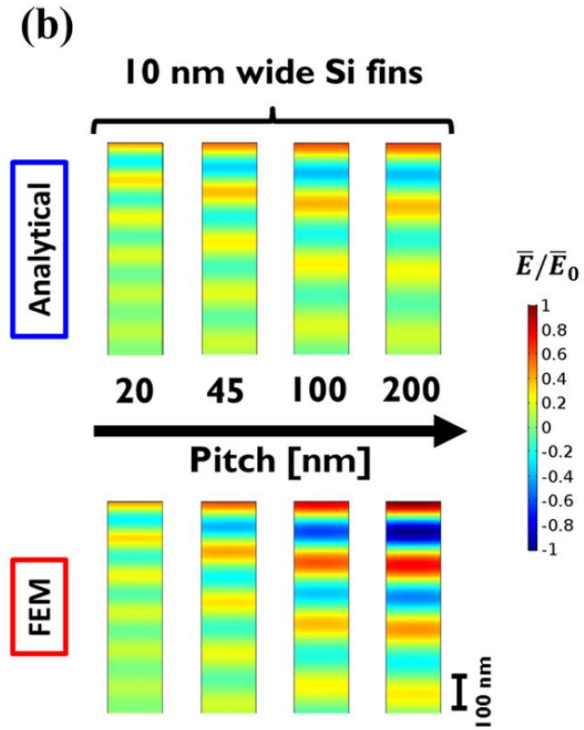
- **SNOM**
- **SERS**
- **TERS**
- **…**

Nanofocusing of light





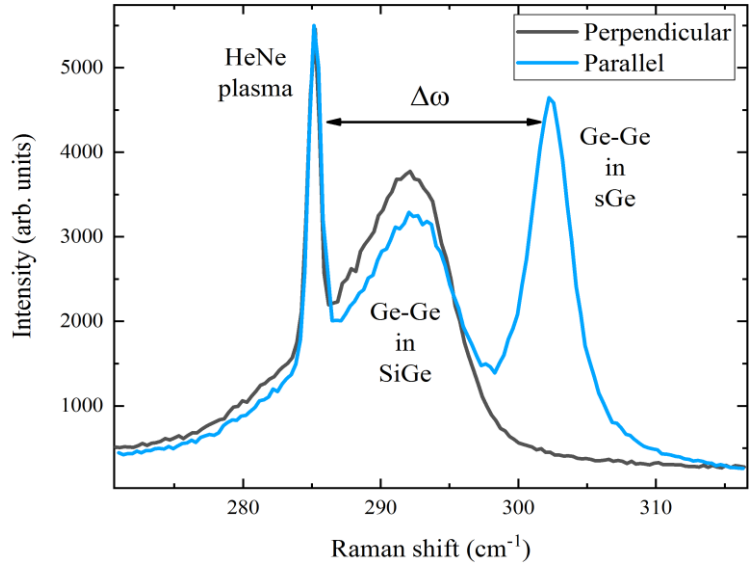
- **While the amount of material illuminated is ±constant, the Ge-Ge scattering quickly decreases with increasing fin width/pitch**

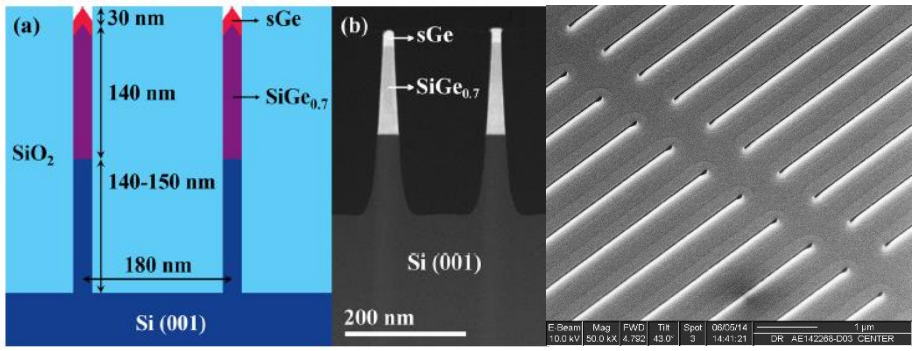


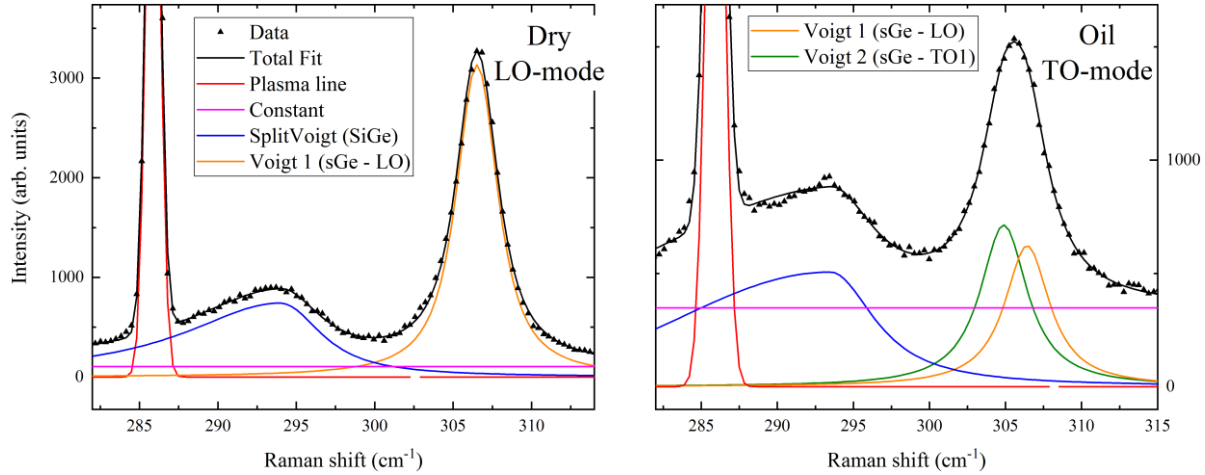
Nuytten Appl. Phys. Lett. **106** 033107 (2015)
Bogdanowicz Appl. Phys. Lett. **108** 083106 (2016)
Nuytten Adv. Eng. Mat. **19** 1600612 (2017)
Gawlik Appl. Phys. Lett. **113** 063103 (2018)

Stress measurements

- **An oil-immersion objective uses a higher NA to increase the z-polarization component of the incident light required for TO excitation**
- **Lifting of TO/LO degeneracy is now visible and both profiles can be fitted independently, allowing calculation of anisotropic biaxial stress**

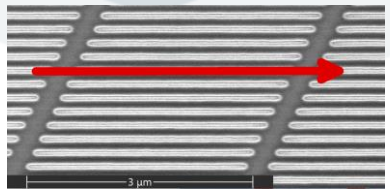


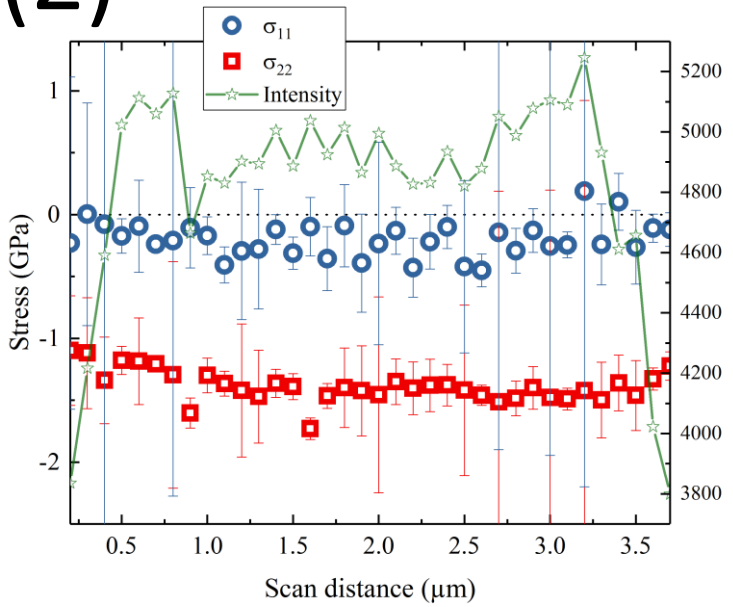




Stress measurements (2)

- **Nondesctructive measurement of anisotropic biaxial stress in finFET channels**





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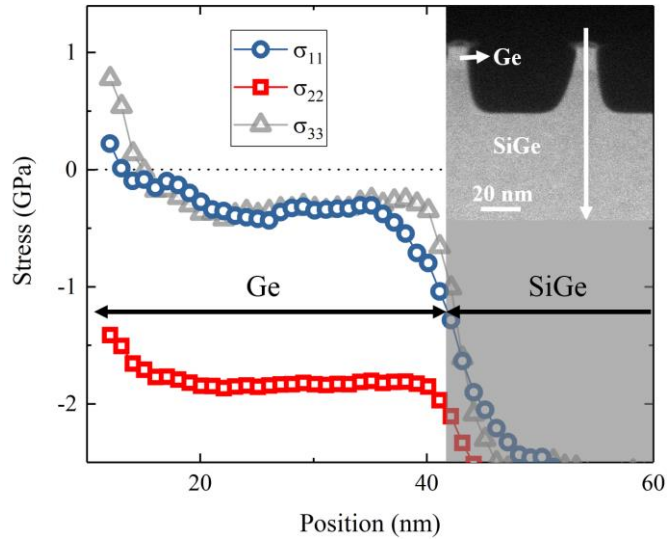
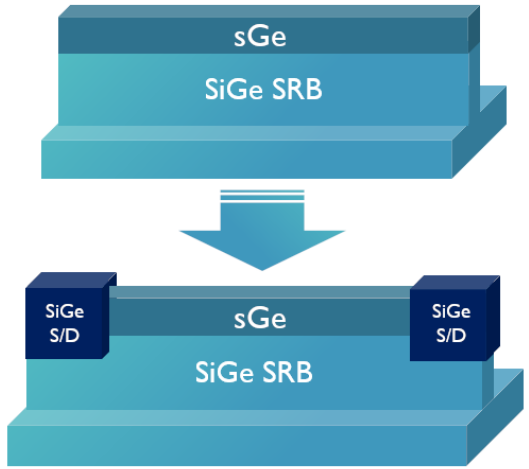
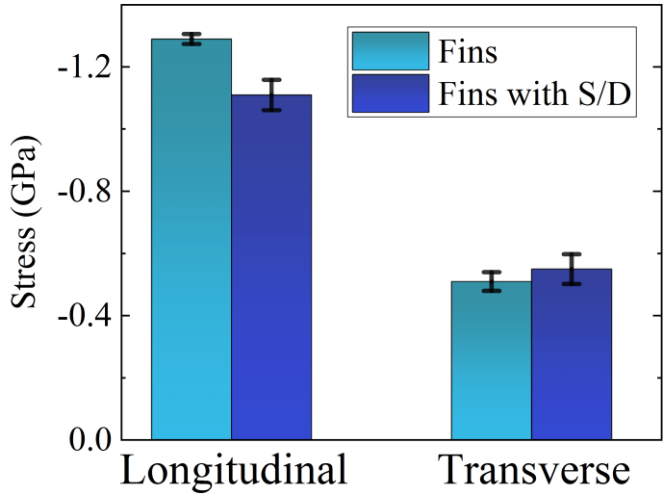


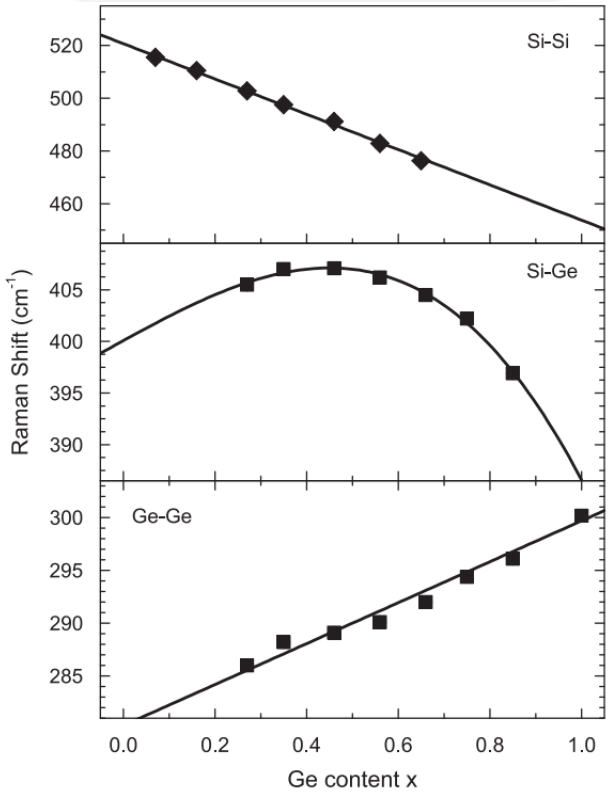




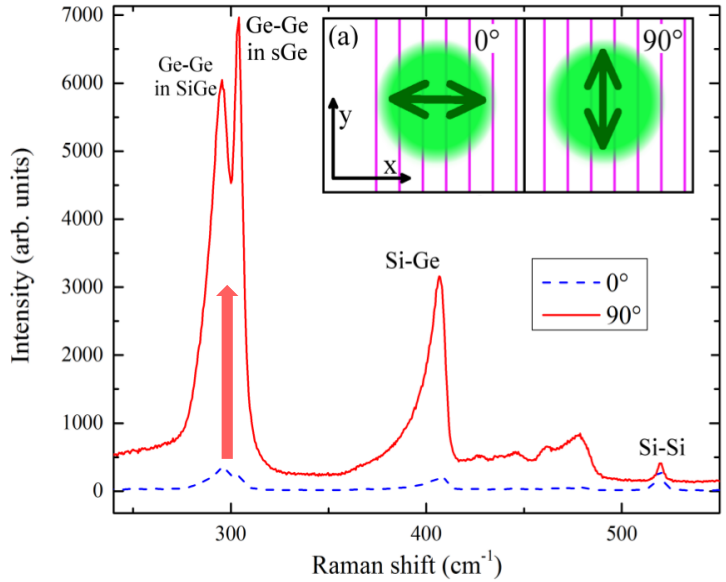
- **Insight in process-induced relaxation**

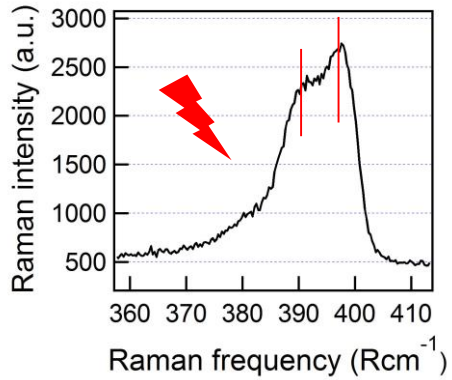
Composition measurements – peak position

Unique dependence of Raman modes on composition



Pezzoli Mat. Sci. Semic. Proc. **11** 279 (2008)





$Si_{0.11}Ge_{0.89}$

$$\omega_{Si-Si} = A - Bx + b_{Si-Si}\varepsilon$$

$$\omega_{Si-Ge} = A' + B'x - C'x^2 + D'x^3 - E'x^4 + b_{Si-Ge}\varepsilon$$

$$\omega_{Ge-Ge} = A'' + B''x + C''x^2 + b_{Ge-Ge}\varepsilon$$

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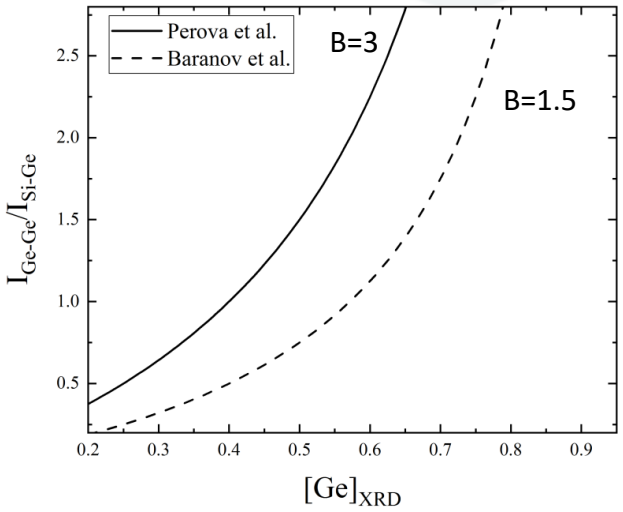
Composition measurements – peak area

Assuming random mixing, the relative intensities should scale with the relative quantities of bonds, namely $(1-x)^2$, x^2 and $2x(1-x)$ for Si-Si, Ge-Ge and Si-Ge

$$\frac{I_{Si-Si}}{I_{Si-Ge}} = \frac{A(1-x)}{2x}$$

$$\frac{I_{Ge-Ge}}{I_{Si-Ge}} = \frac{Bx}{2-2x}$$

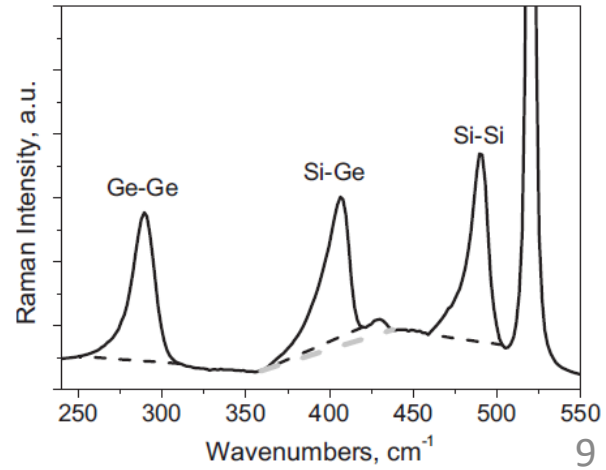


Ge-Ge and Si-Ge peaks separate so easiest to work with (but problematic for low Ge)

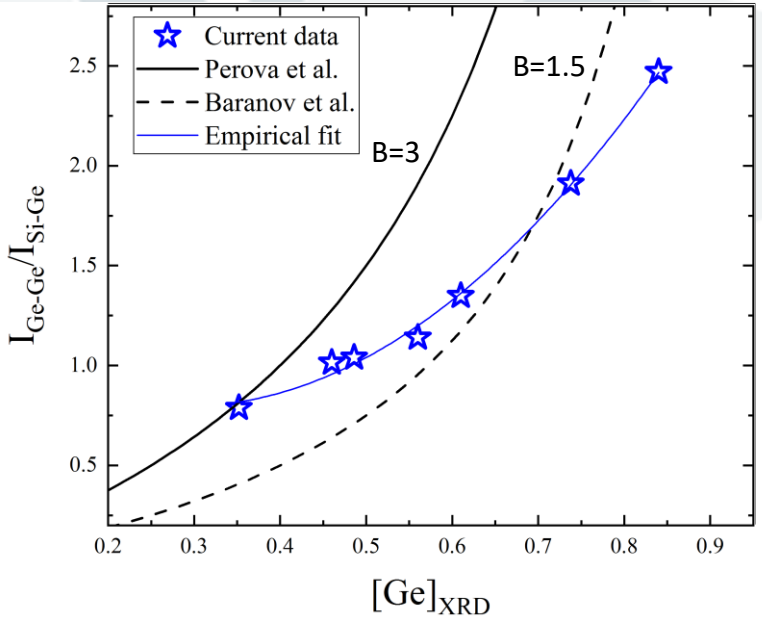
Coefficient B depends on excitation wavelength (resonance effects), spectrograph sensitivity, etc

No consensus on fitting procedure, leading to large discrepancies

Perova J. Appl. Phys. **109** 033502 (2011)



Composition measurements – peak position



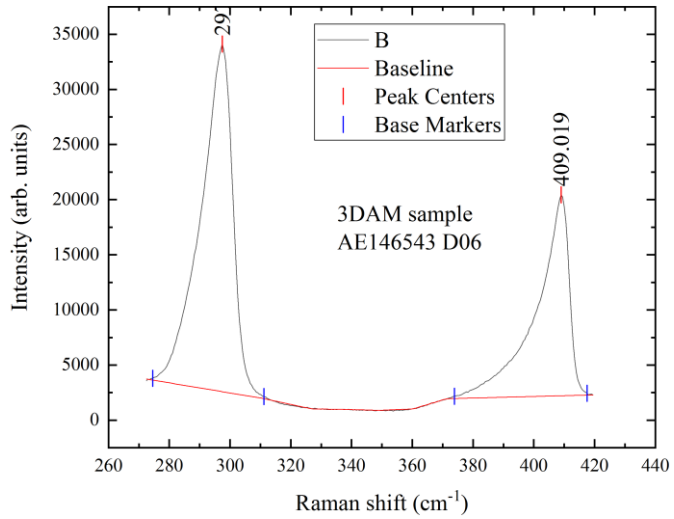
Empirical fit to bulk reference measurements

$$\frac{I_{Ge-Ge}}{I_{Si-Ge}} = 5.52x^2 - 3.20x + 1.26$$

Note: not valid beyond this [Ge] interval

No suitable coefficient B can be found for fitting of the data using

$$\frac{I_{Ge-Ge}}{I_{Si-Ge}} = \frac{Bx}{2-2x}$$



Intensity ratio is 1.70 giving

	XRD	SIMS	EDX	RAMAN
[Ge]%	70	72	72	70

Next: determine calibration samples' composition with RBS

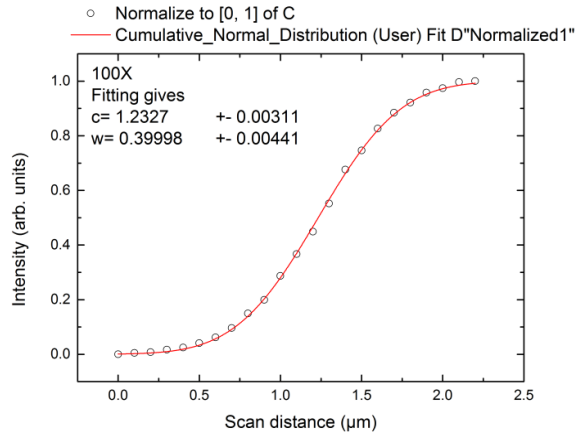
Conclusions

- **Nano-focused Raman transforms the sensitivity of vibrational spectroscopy**
- **The improved sensitivity re-enables the technique at the nanometer scale**
- **Quantitative stress and composition measurements on challenging structures**

Thank you

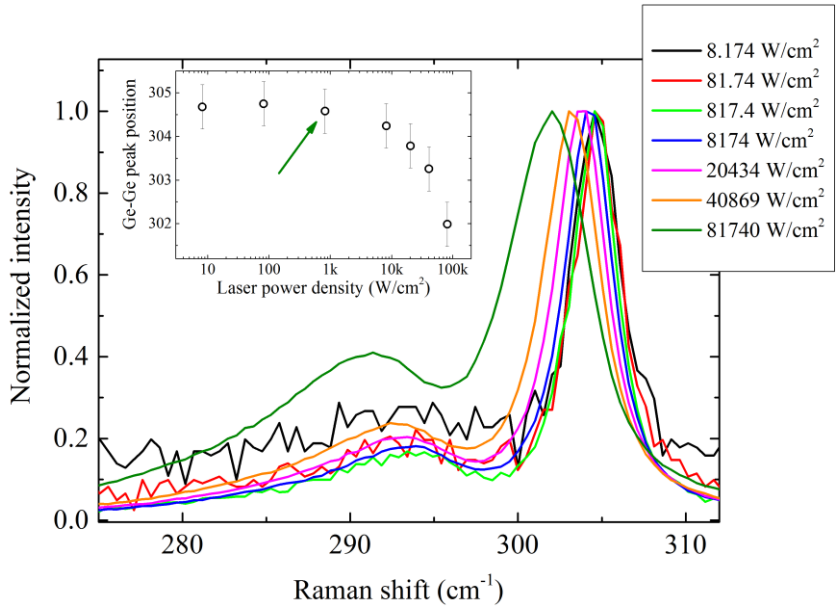
Ingrid De Wolf, Janusz Bogdanowicz, Andreas Schulze, Daisuke Kosemura, Imran Aslam, Veerle Simons, Andrzej Gawlik, Liesbeth Witters, Geert Eneman, Roger Loo, Clement Porret, Bernardette Kunert, Hugo Bender, Paola Favia, Johan Meersschaut, Thomas Hantschel, Wilfried Vandervorst, Paul van der Heide

Stress measurement caveats



$$\mathrm{FWHM} = 2\sigma\sqrt{2ln2}$$

- **In µRaman spectroscopy the laser light is focused to a very small spot (~900 nm for 532 nm and 100X0.9NA) resulting in kW/cm^2-order laser power densities for conventional Raman lasers**
- **Nanofocusing further concentrates the energy inside the structure of interest, and especially Ge has very high absorption in the visible**
- **Peak positions can only be reliable when sufficiently low laser power is used**



Composition measurement caveats