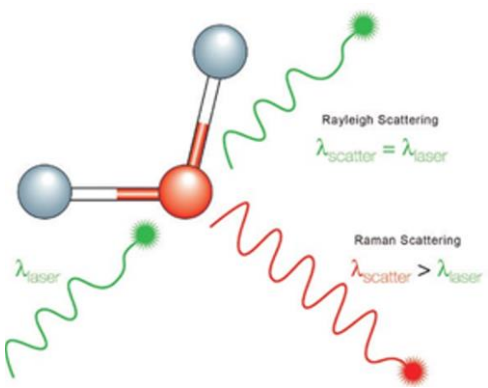
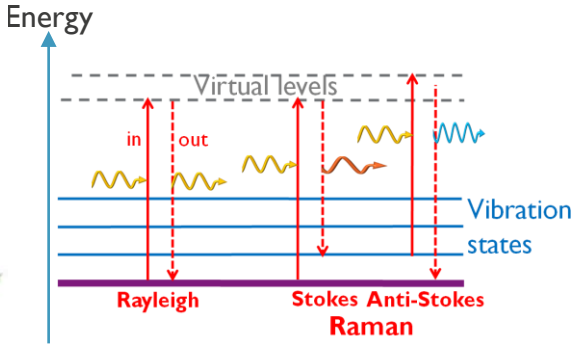
# RAMAN AND PL FOR NANOSCALE MATERIALS CHARACTERIZATION AND METROLOGY

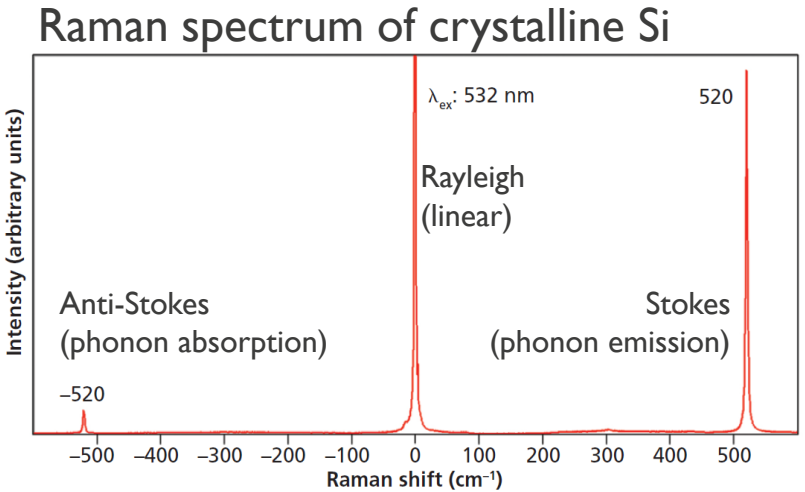
# BASICS OF RAMAN SPECTROSCOPY

- Nonlinear optical technique
→ measures light emitted with a (slightly) lower/higher energy than incident



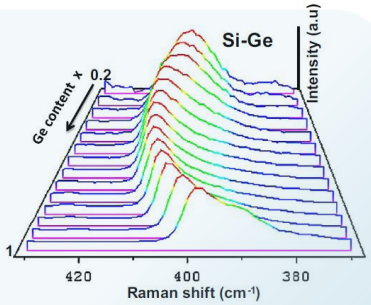




- Si spectrum:
  - Rayleigh (linear scattering)
  - Stokes (emission of 1 phonon)
  - Anti-stokes (absorption of 1 phonon)



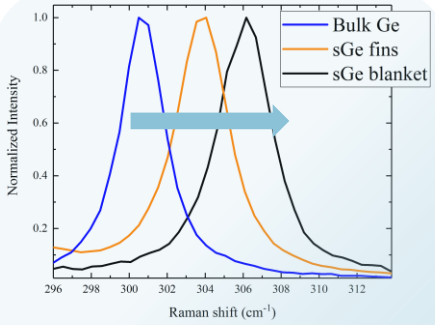
# VALUES OF RAMAN SPECTROSCOPY

### Average composition

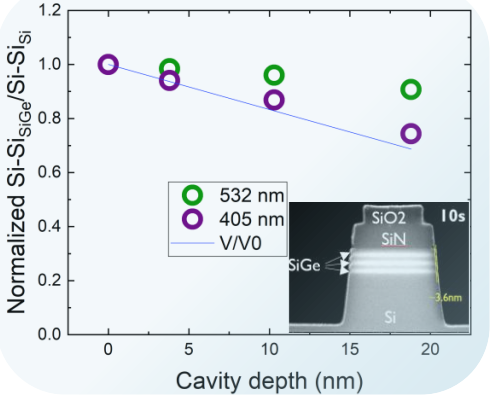



Rouchon J. Crys. Growth **392** 66 2014

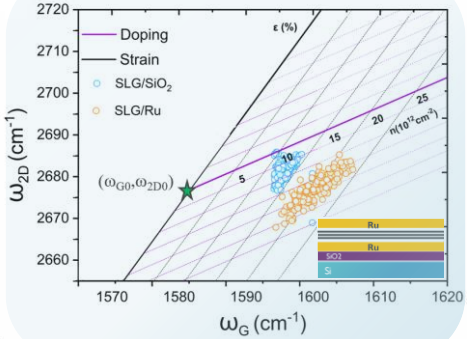
### Average stress



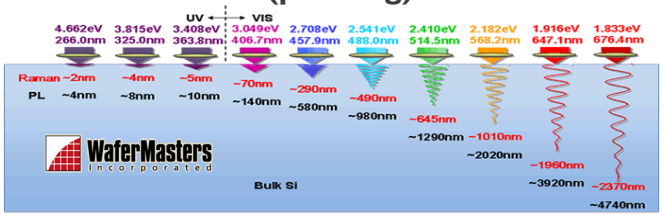

### Geometry/CD




### Doping

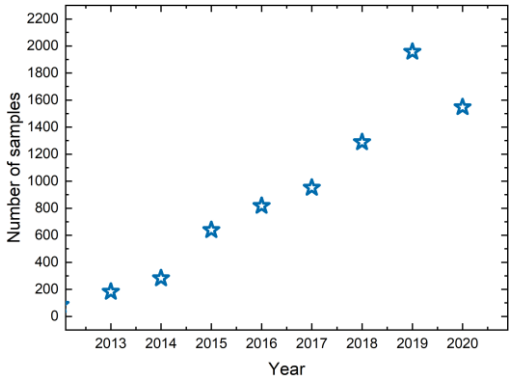



### Different probing depths possible (profiling)



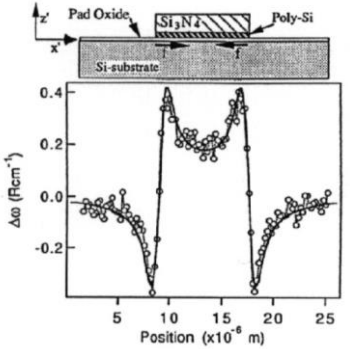

- Optical:
  - Fast
  - Non-contact
  - Good lateral resolution (~ 1 μm)
  - Capable of probing in depth
- Sensitive to:
  - Material
  - Composition
  - Stress
  - Geometry

### Constant rise in measurement requests



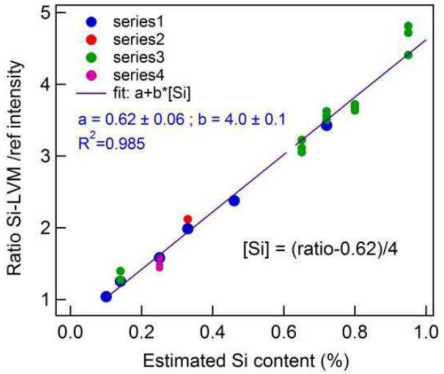
# 30 YEARS OF RAMAN EXPERTISE AT IMEC

## Average stress measurements



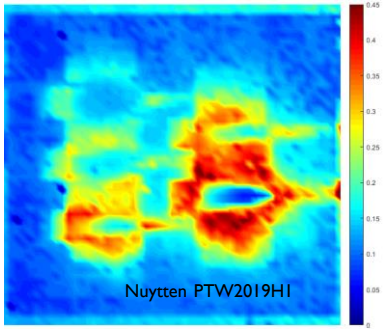

De Wolf J. Appl. Phys. **71** 898 (**1992**)
De Wolf, Semicond. Sci. Technol. 11 139 (1996) – **720 citations**

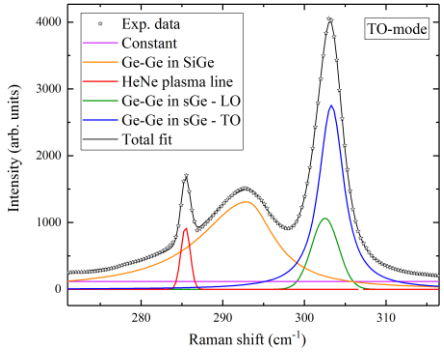
## Ultralow Si content



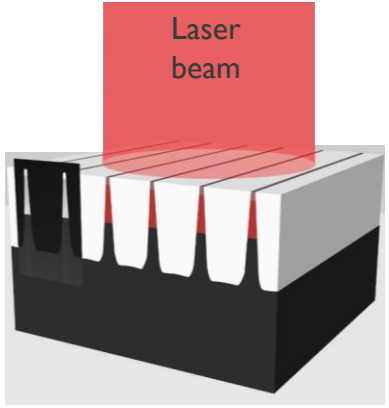

De Wolf ECS Trans. **86** 397 (2018)

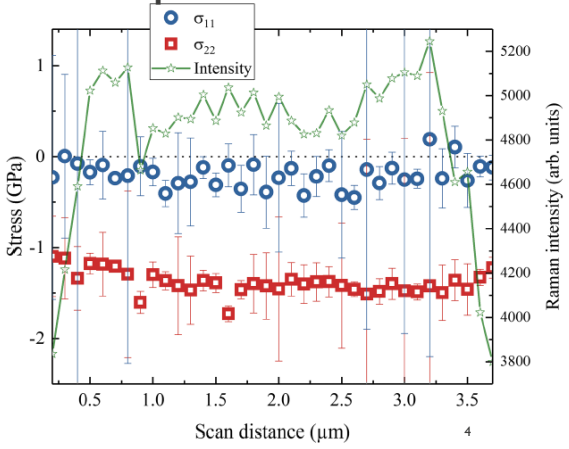
## Automated data treatment, fitting and plotting

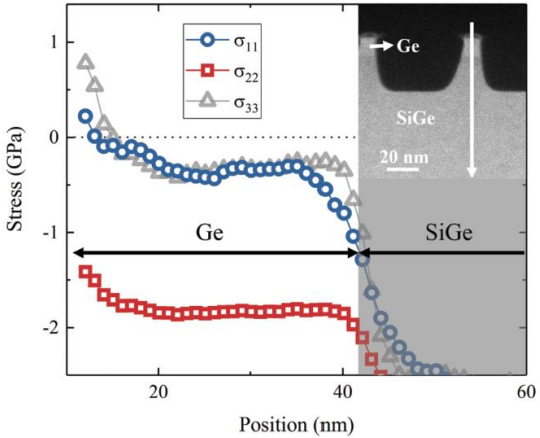



## Stress/composition in 3D confined volumes



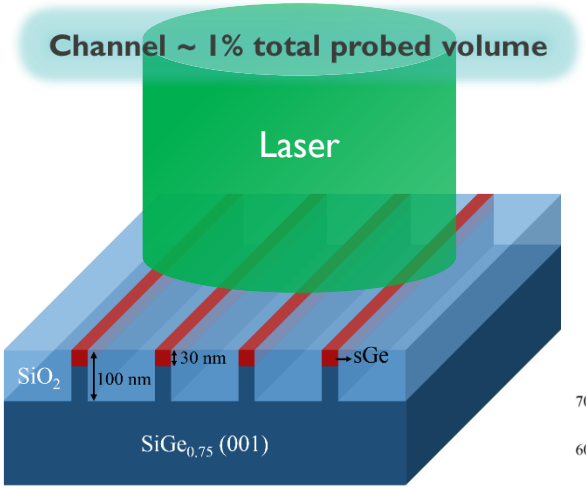



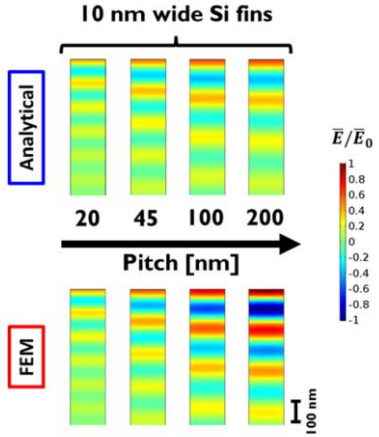



# STRESS AND CD ANALYSIS OF CONFINED VOLUMES

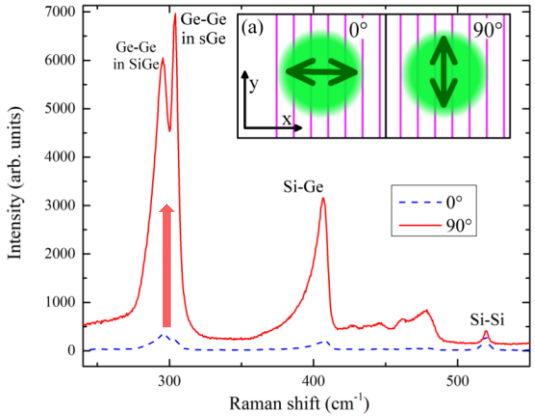
# NANOFOCUSING OF LIGHT

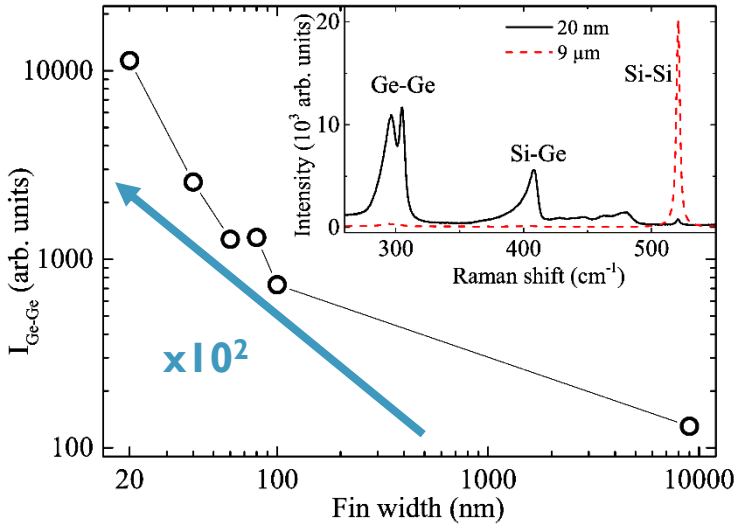
## ENABLING DEEP SUB-WAVELENGTH STRUCTURES TO STAND OUT




- Raman response dictated by geometric properties: critical dimension, pitch
- Allows for isolation of the signal of the ROI
- All strengths of Raman are re-enabled at the nanometer scale
- Opens path for Raman dimensional metrology



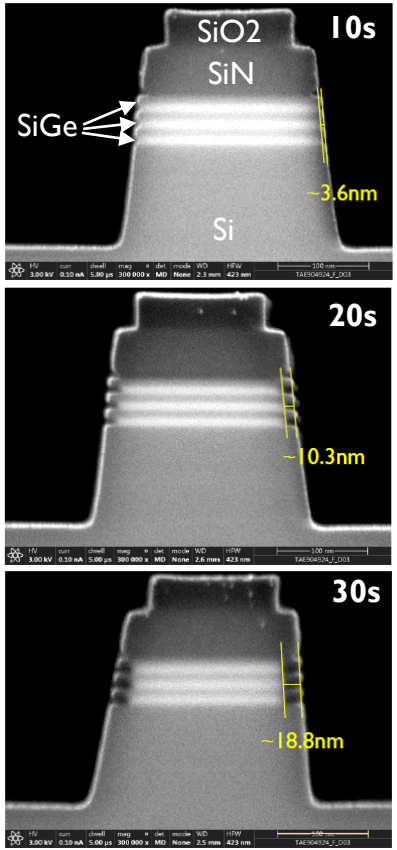


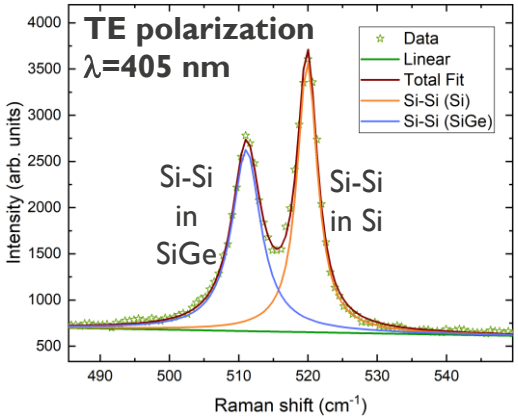
Kuhn FCMN 2013
Nuytten Appl. Phys. Lett. **106** 033107 (2015)
Bogdanowicz Appl. Phys. Lett. **108** 083106 (2016)
Nuytten APL Mat. **6** 058501 (2018)
Gawlik Appl. Phys. Lett. **113** 063103 (2018)

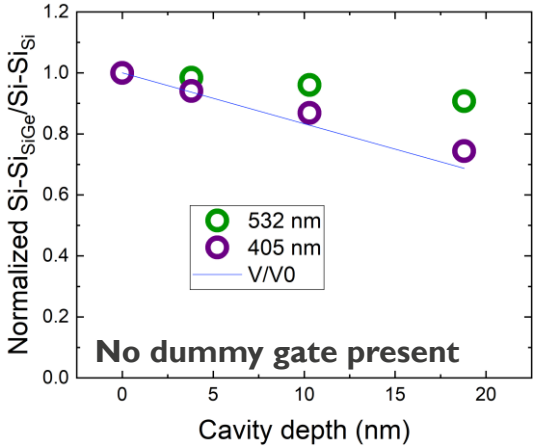

imec

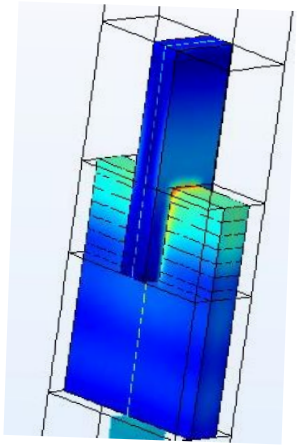
# CAVITY DEPTH

**Nanosheet/Forksheet/CFET technology**



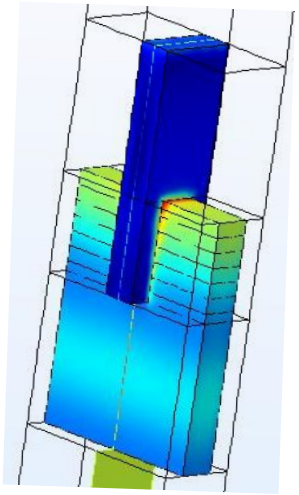



$E_{TE}$

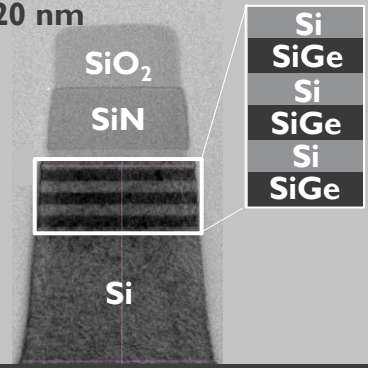
Wavelength= 405 nm

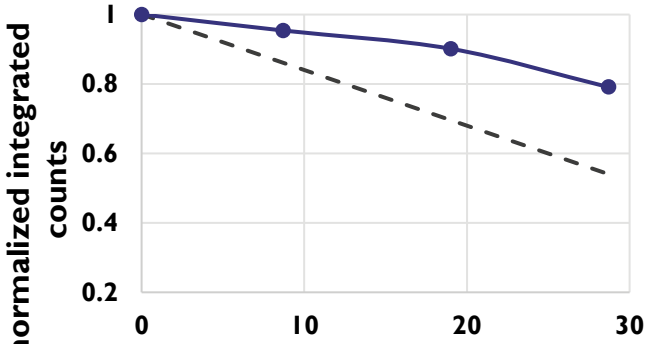


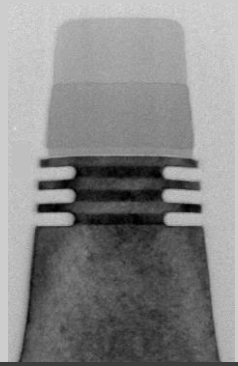
$E_{TE}$

Wavelength= 532 nm

CD~120 nm
Pitch=520 nm



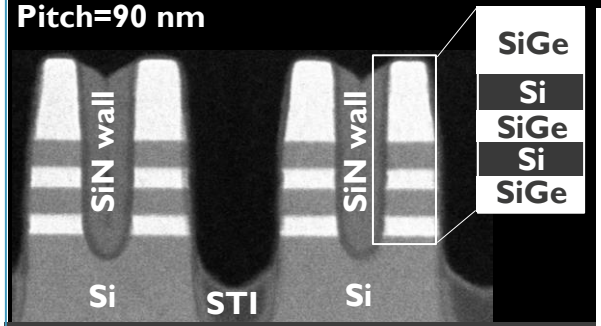
Cavity : 0 nm
$V_{SiGe}=V_0$

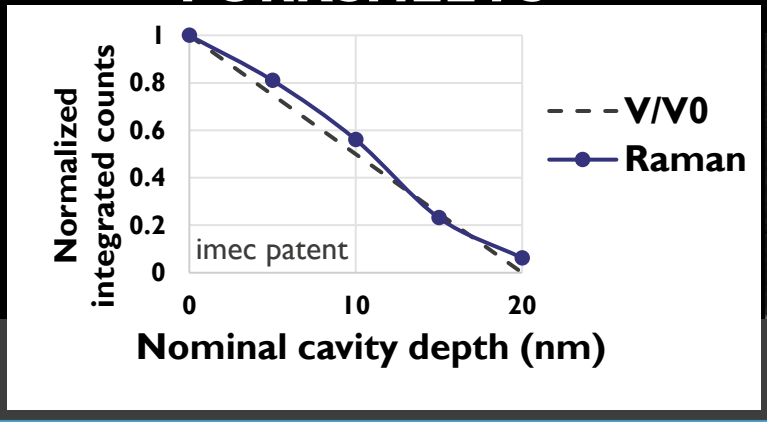
Cavity: 28.7 nm
$V_{SiGe}/V_0=0.54$

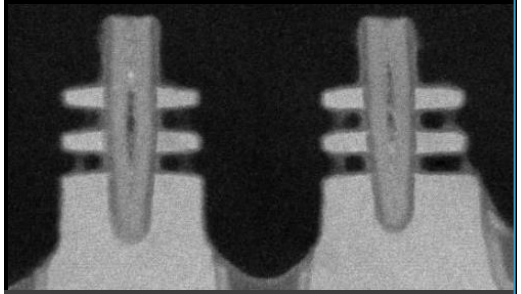
# NANOSHEETS

# FORKSHEETS

CD~50 nm
Pitch=90 nm



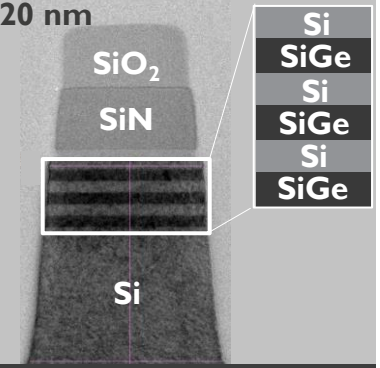



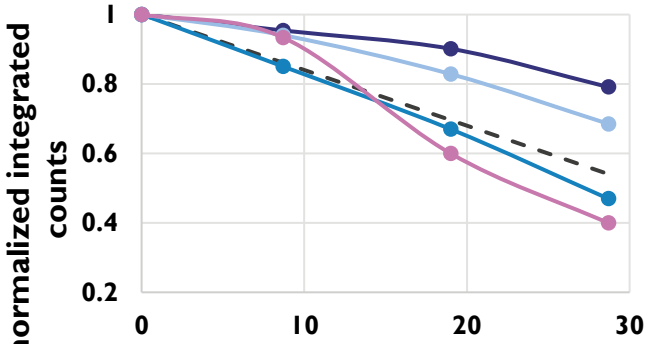



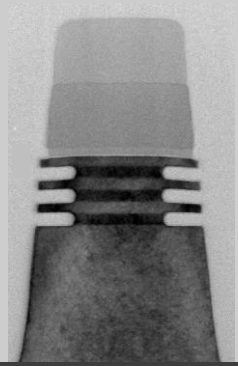
Cavity : 0 nm
$V_{SiGe}=V_0$

Cavity ~ 20 nm
$V_{SiGe}\sim 0$

CD~120 nm
Pitch=520 nm



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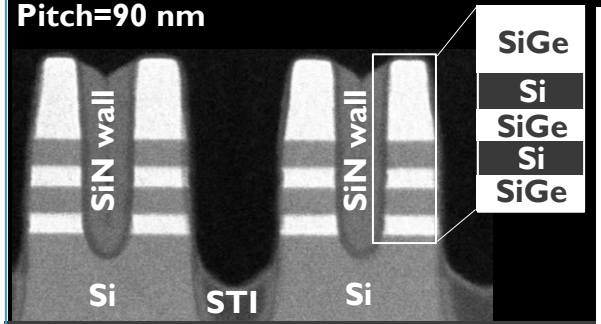
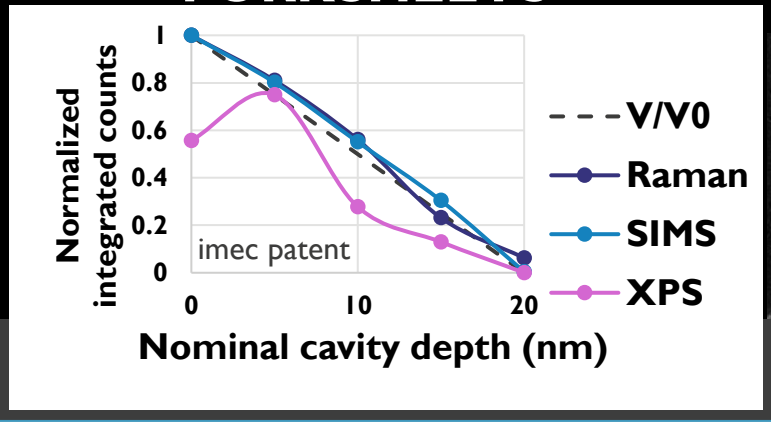
$V_{SiGe}/V_0=0.54$

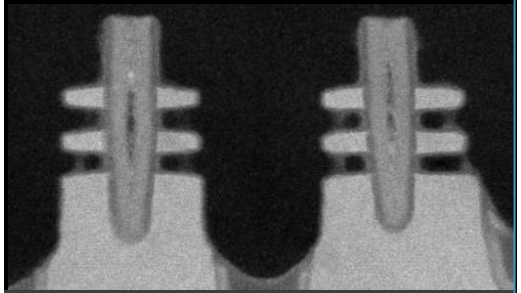
# NANOSHEETS

# FORKSHEETS

CD~50 nm
Pitch=90 nm



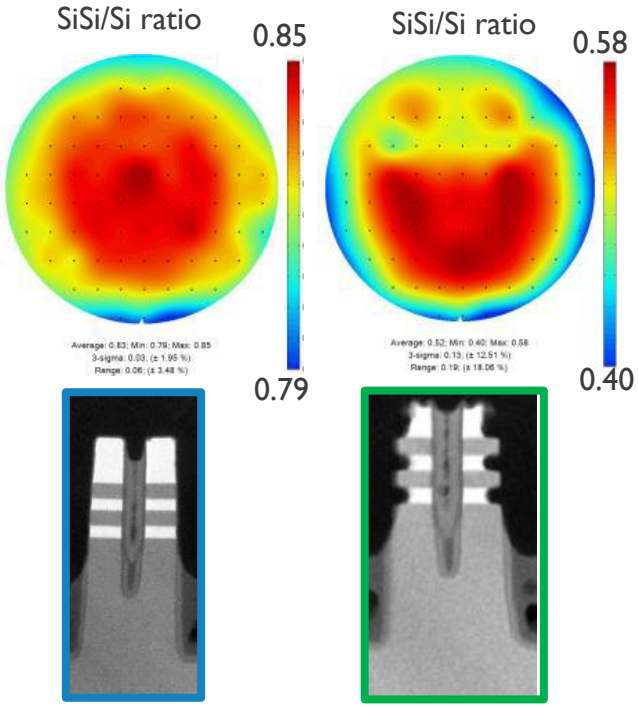



Cavity : 0 nm
$V_{SiGe}=V_0$

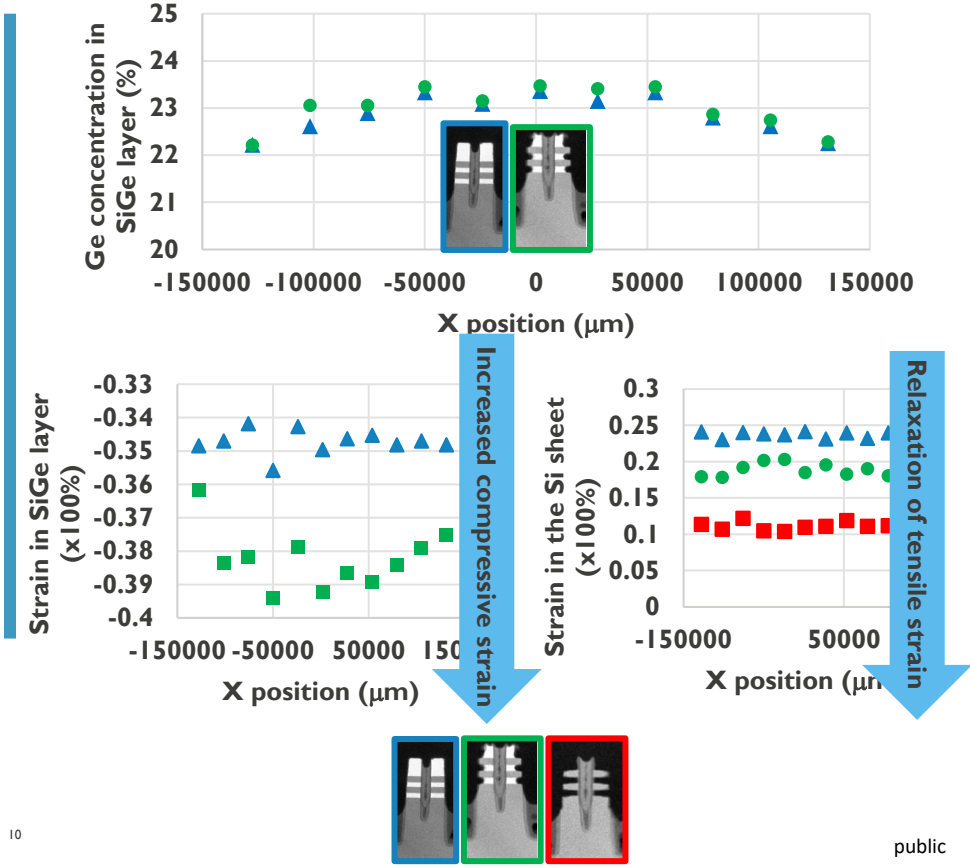
Cavity ~ 20 nm
$V_{SiGe}\sim 0$

# APPLICATION ON FULLY AUTOMATED TOOLS

## Cavity depth

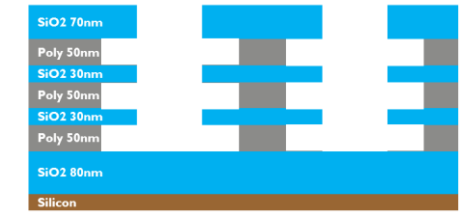


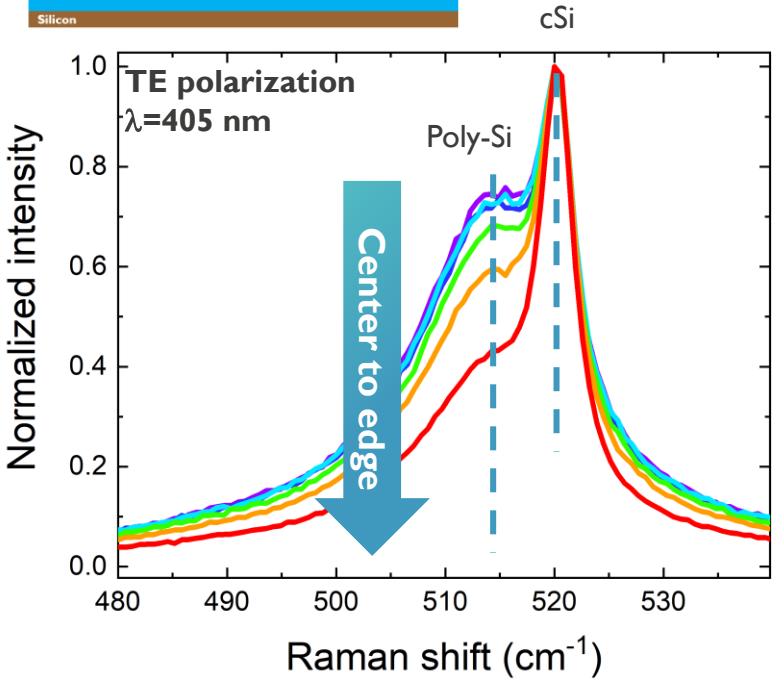

## SiGe composition & strain

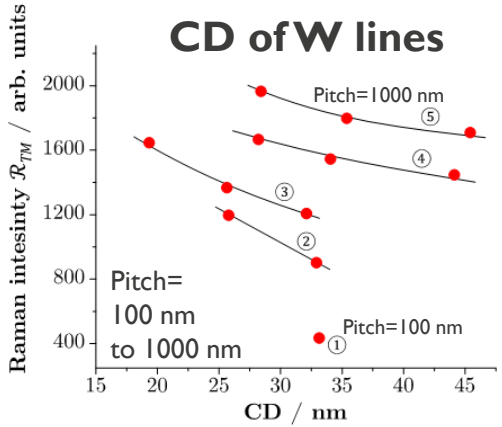


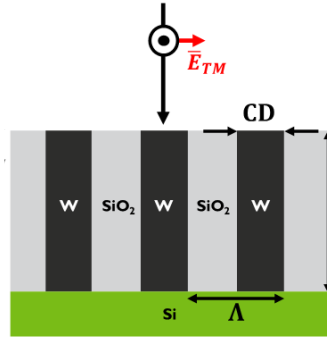

imec NOVA PROCESS INSIGHT

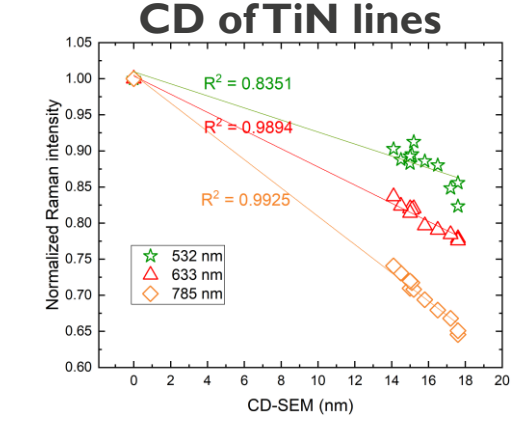
# UNIVERSAL APPLICATION SUITE

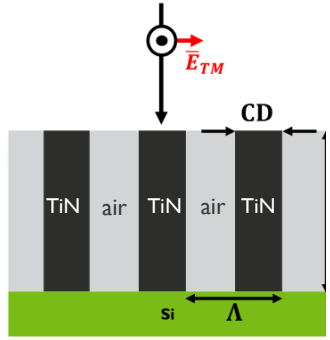


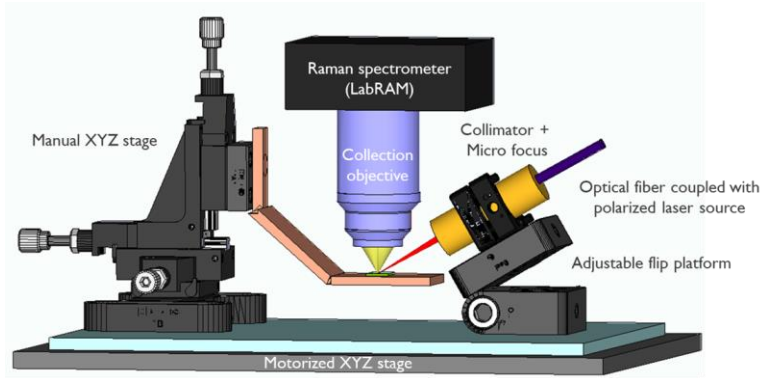

Gawlik Appl. Phys. Lett. **117** 043102 (2020)

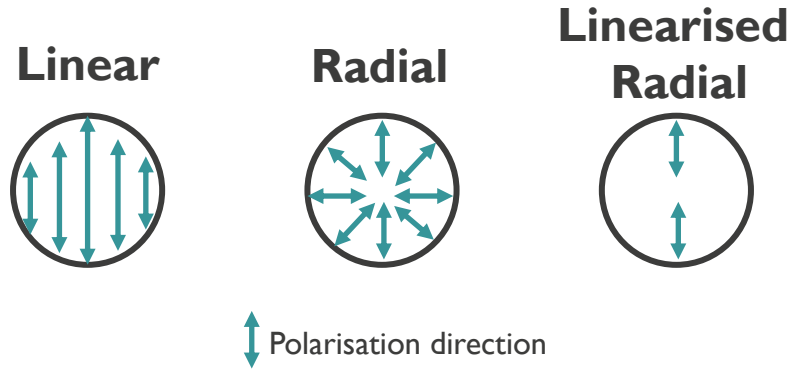
# RECENT RAMAN DEVELOPMENTS:
# OFF-AXIS RAMAN
# AND
# USE OF LINEARIZED RADIAL POLARIZATION

# NANOSCALE STRESS MEASUREMENTS

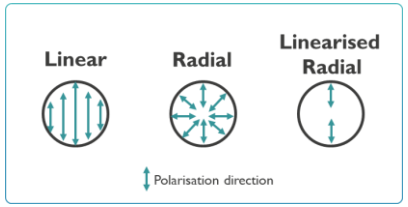
## IMPROVE PRACTICALITY OR PRECISION OF ANISOTROPIC STRESS MEASUREMENTS

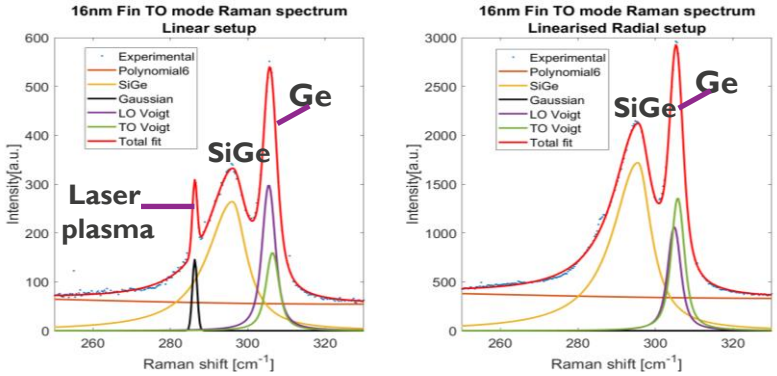
- Decoupling of $\sigma_{11}$ and $\sigma_{22}$ requires deconvolution of LO and TO
- Selection rules dictate TO only excited by $E_z$
- High precision measurements = large out-of-plane polarization component $E_z$
- Standard solution: oil immersion – no in-line potential



# STRESS MEASUREMENT AND VALIDATION

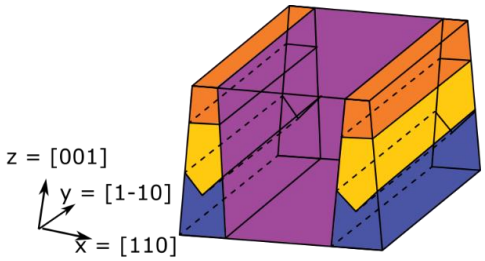



| Setup | TO/LO |
|---|---|
| Linear setup | 0.6 ± 0.2 |
| Linearised radial setup | 1.2 ± 0.3 |


| Linear | Linearised radial |
|---|---|
| $\sigma_x = -1.47 \pm \mathbf{0.05}\ GPa$<br>$\sigma_y = -1.48 \pm \mathbf{0.05}\ GPa$ | $\sigma_x = -1.45 \pm \mathbf{0.03}\ GPa$<br>$\sigma_y = -1.45 \pm \mathbf{0.03}\ GPa$ |

**Biaxial in-plane stress**




| Linear | Linearised radial |
|---|---|
| $\sigma_x = -0.45 \pm \mathbf{0.05}\ GPa$<br>$\sigma_y = -2.29 \pm \mathbf{0.05}\ GPa$ | $\sigma_x = -0.48 \pm \mathbf{0.02}\ GPa$<br>$\sigma_y = -2.26 \pm \mathbf{0.02}\ GPa$ |

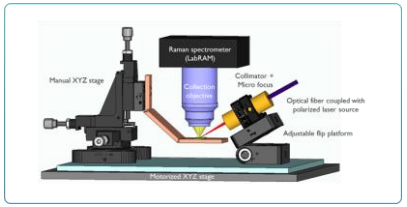
**Uniaxial stress**

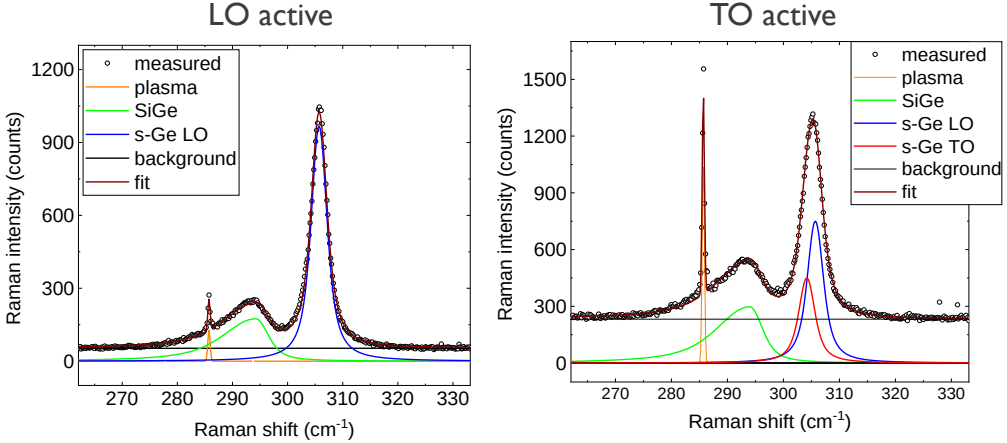
**Improved precision in stress measurement**

imec

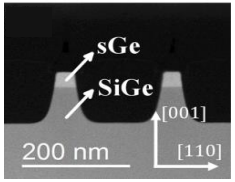
V. Prabhakara, T. Nuytten, H. Bender , W. Vandervorst, S. Bals and J. Verbeeck, Opt. Express **29** 34531 (2021)

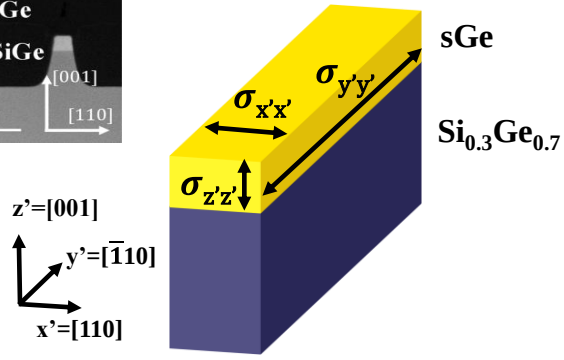
# STRESS MEASUREMENTS WITH FCOR

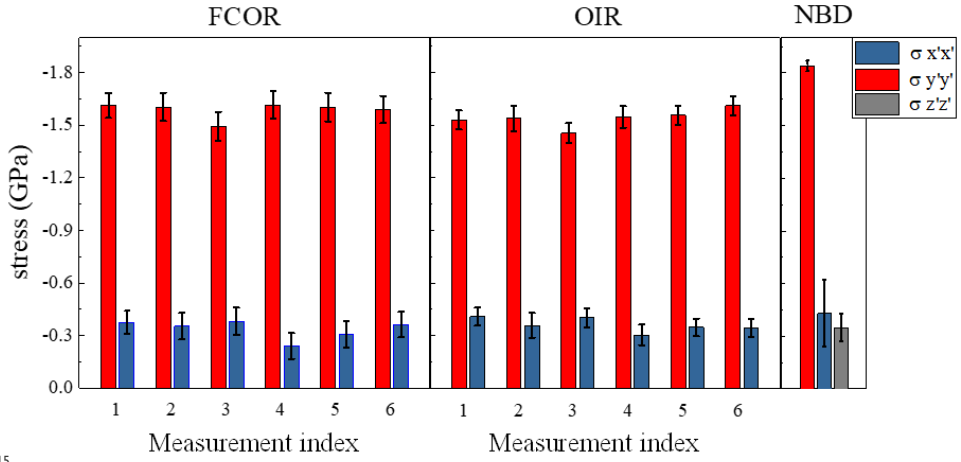



- LO- and TO-active spectra are acquired independently
- In-plane stress extracted with similar precision
- Validated by OIR and NBD
- Truly non-invasive stress characterization

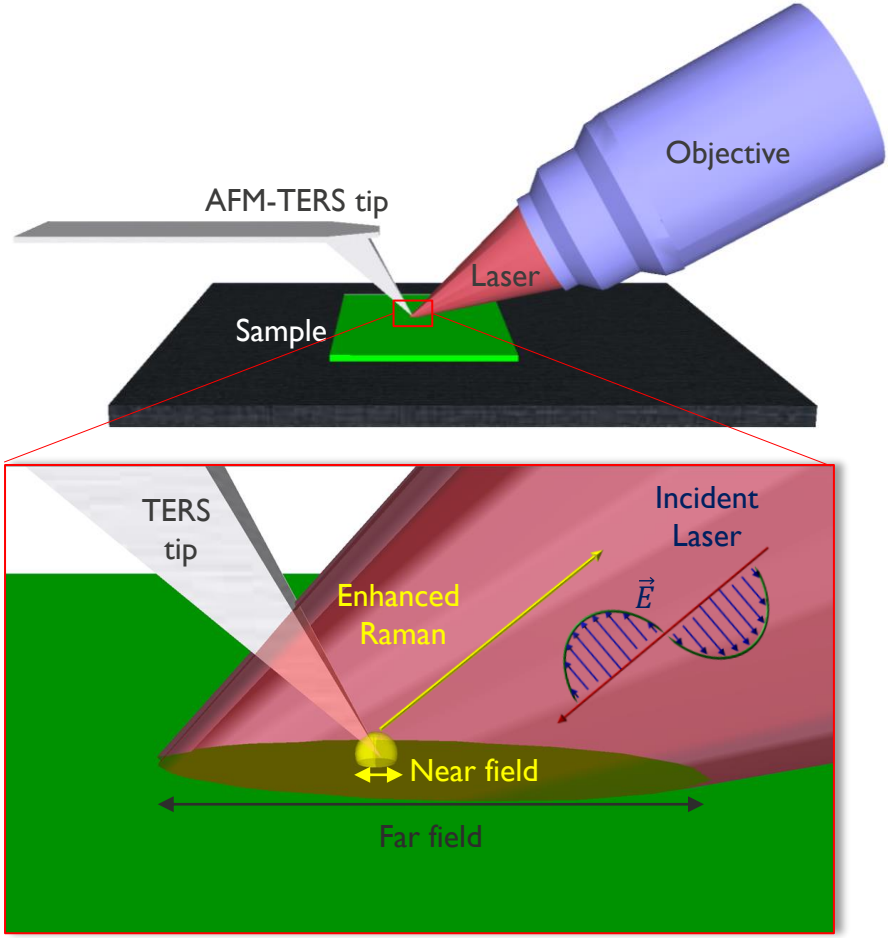


# TERS/TEPL FOR NANOSCALE RESOLUTION

# TIP ENHANCED RAMAN SPECTROSCOPY

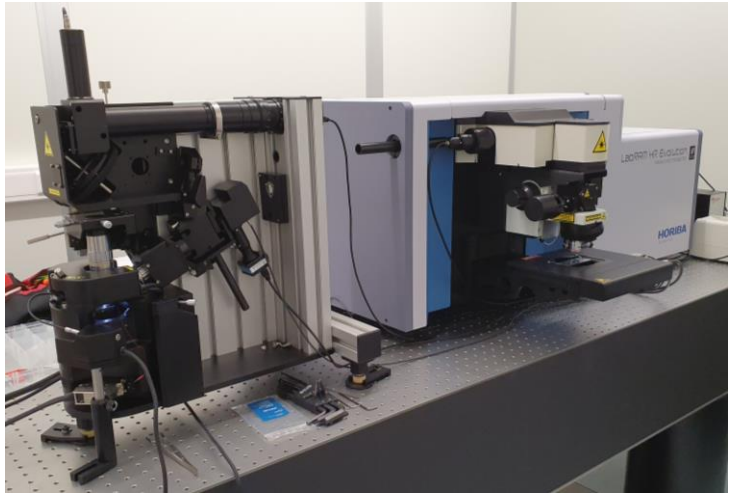



Concept

- Raman intensity α $E^4$
- Incident laser excites a localized surface plasmon at the tip apex
- Plasmonically enhanced field increases the Raman intensity near the tip apex
- Intensity enhancement depends on tip properties, laser polarization and choice of substrate

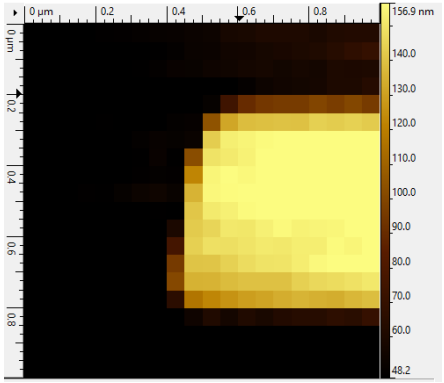
Spatial resolution

- Far field ~ $\frac{0.61\ \lambda}{\text{N.A.}}$
- Near field ~ Radius of tip apex

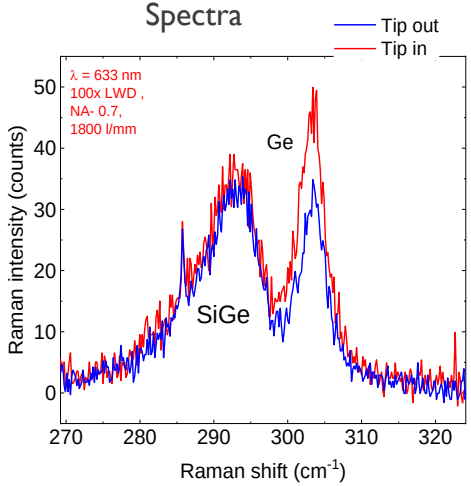


# TERS

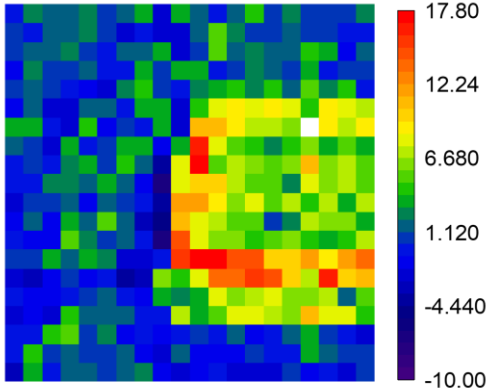
## AFM topography

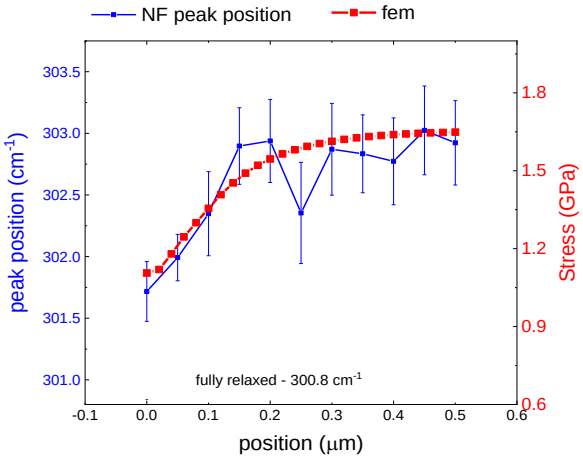


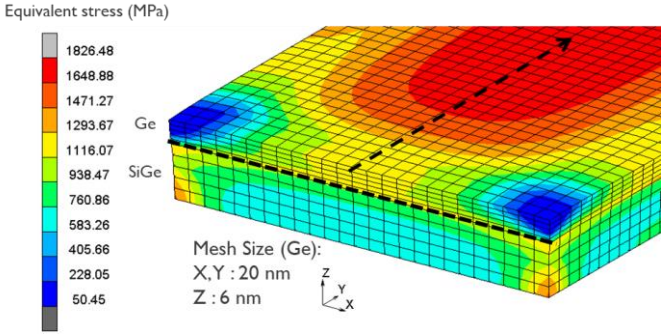

## Spectra




## Near field Intensity



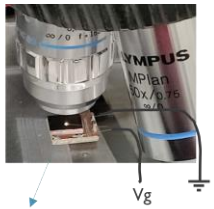



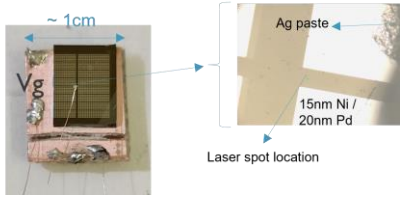
# BACK-GATED CRYO-PHOTOLUMINESCENCE OF 2D MATERIALS

## NON-DESTRUCTIVE DEFECT CHARACTERIZATION?

Defects (e.g. S-vacancies) create shallow levels in the BG that can be studied through photoluminescence. For this we need low temperature (77K), and control over all other parameters affecting the PL:

- Temperature
- Excitation power
- Back-gate bias / doping
- Extrinsic & strain factors

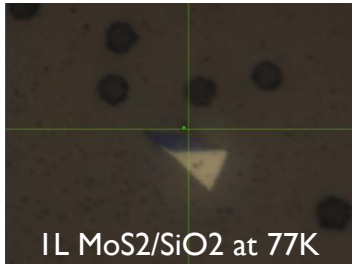


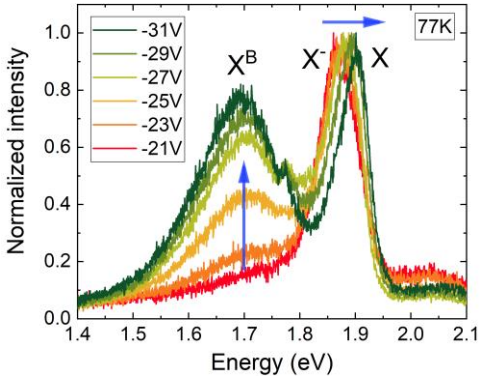




**Two setups available at imec:**

N2 sample holder
(used on Raman tools)

Lifetime meter with cryo
(less suited)




Built setup for combined back-gating and low-temperature PL, first electrostatic control and activation of defect signal on **imec synthetic material** has been demonstrated. Quantitative interpretation of results and link with electrical measurements needs development and data cycles.

Steps to take

- Quantitative defect characterization from observed behavior
- Link with mobility (device processing)
- Establish connection with S-vacancies (HRTEM)

# ACKNOWLEDGEMENT

imec

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NOVA PROCESS INSIGHT

J. Hung, R. Koret, D. Fishman, Y. Katz, N. Meir


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