Analytics and Metrology for Locally Strained Silicon in CMOS devices

Michael Hecker, Liang Zhu, Carsten Georgi, Inka Zienert, Jochen Rinderknecht, Holm Geisler, and Ehrenfried Zschech
AMD Saxony LLC & Co. KG, Dresden

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2007 Int. Conference on Frontiers of Characterization and Metrology for Nanoelectronics

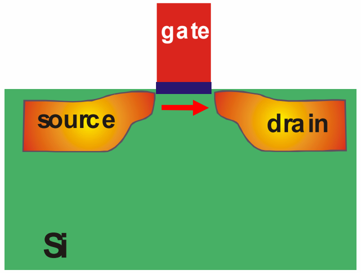
Outline of talk

I. Strain in Si structures

II. Strain metrology

III. Focus: NanoRaman

I. Strain in Silicon Structures



propagation delay

$$t_d = C\,U_d / I_d \longrightarrow I_{d,sat} \sim \mu / (L \cdot T_{ox})$$

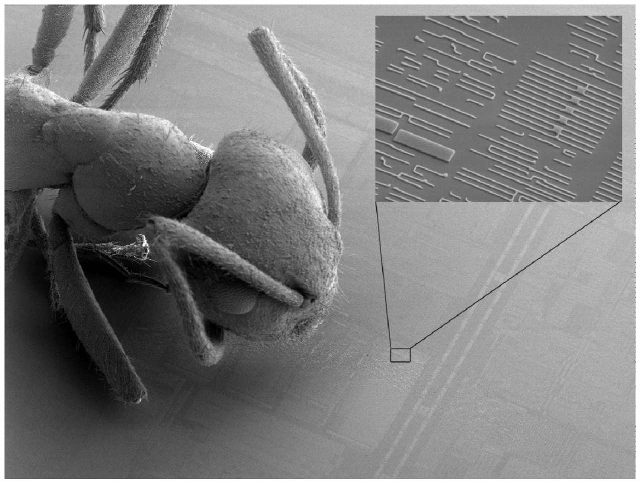
carrier mobility

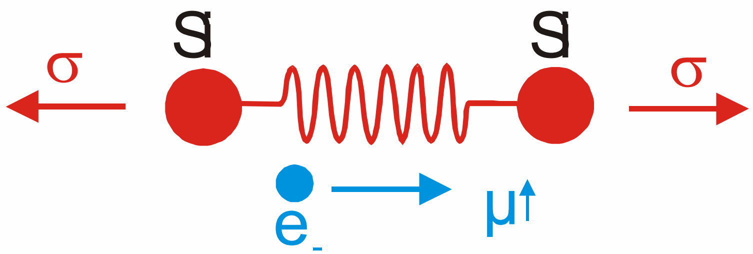
gate oxide thickness

gate length

historical approach
- shrink gate length
- shrink gate oxide thickness

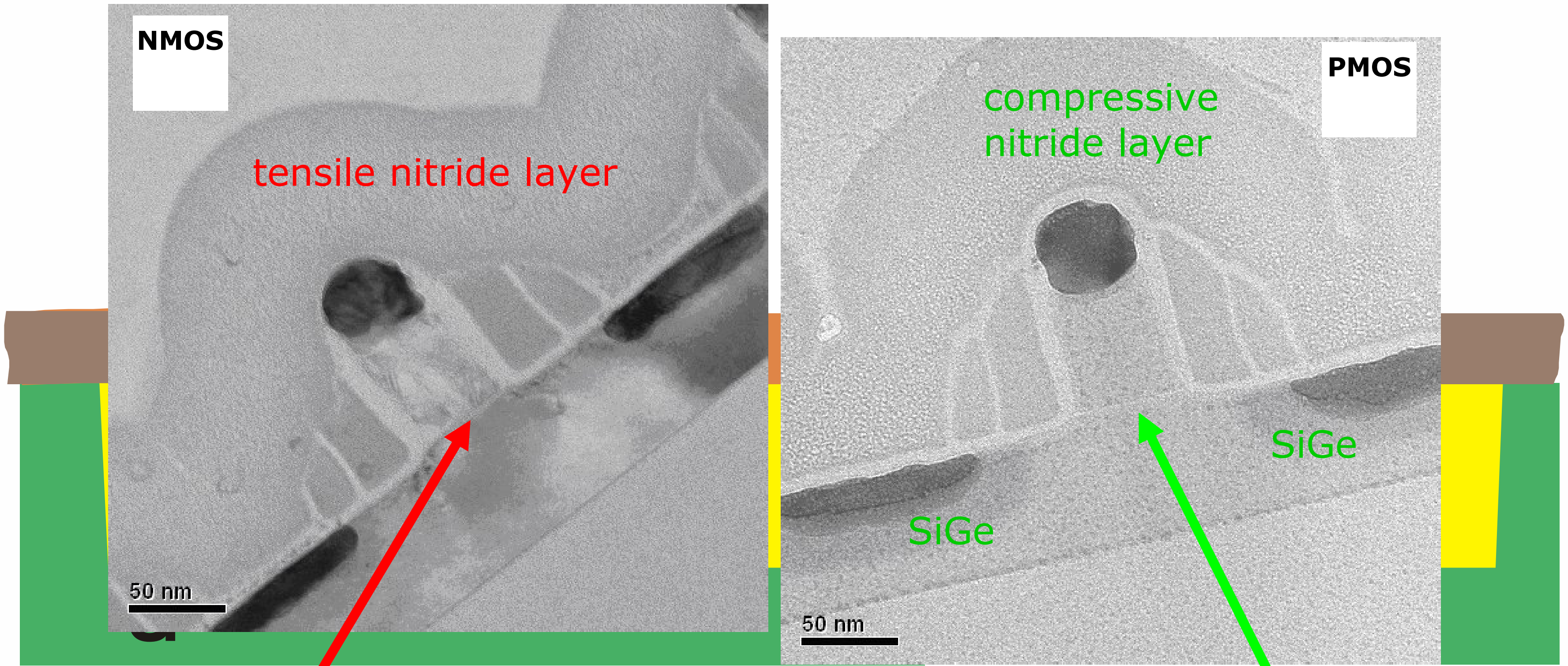
alternative, today's approaches
- higher carrier mobility (μ) in transistor channel.





local strain – dedicated strain
at transistor channel

NMOS　　　　　PMOS



electrons -> tensile

σ_{xx} = +1 GPa -> μ ↑ 30%

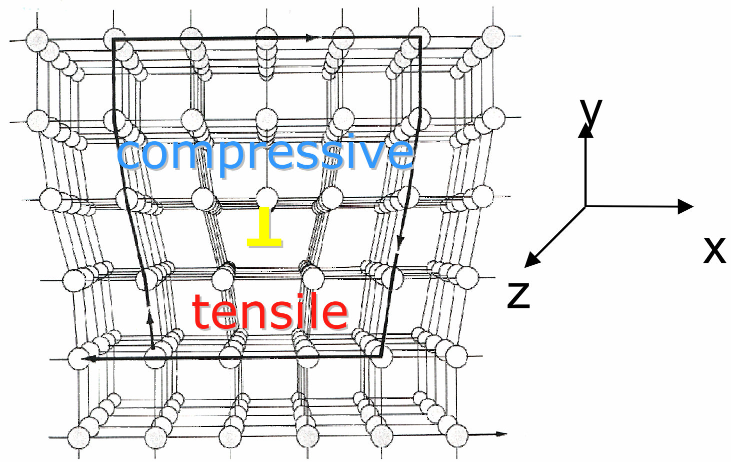
holes -> compressive

σ_{xx} = -1 GPa -> μ ↑ 70%

calc. numbers: piezoresistance effect (Krivokapic et al., Sol. State Techn. 2004)

calculated stress in transistor channel: impact of embedded SiGe

<u>model:</u>
continuous distribution
of virtual interface dislocations



-> <u>general stress state in PMOS channel:</u>

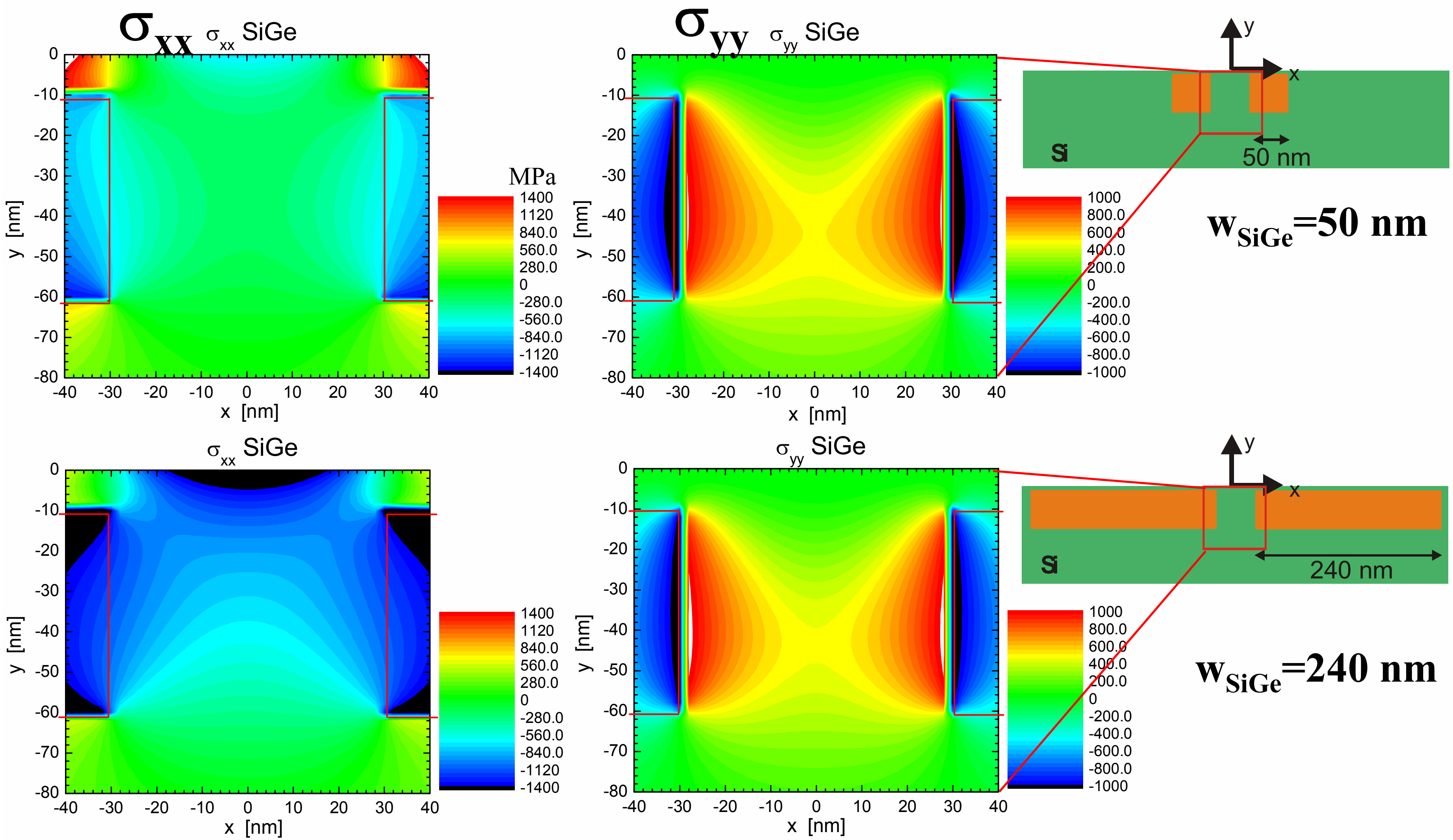
σ_{xx} << 0 -> high μ-sensitivity
σ_{yy} >> 0 -> low μ-sensitivity
σ_{zz} > 0 -> high μ-sensitivity

$$\Delta\mu_{<110>}/\mu \approx (-0.72\,\sigma_{xx} + 0.01\,\sigma_{yy} + 0.66\,\sigma_{zz})/\mathrm{GPa}$$

hole mobility enhancement in p-Si

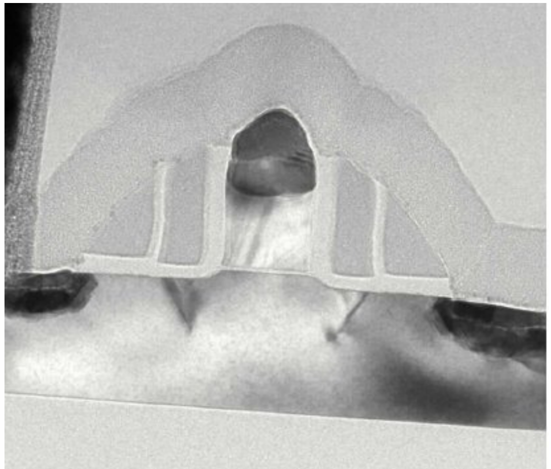
[Smith, Phys. Rev 94 (1954); Thompson, IEEE 51 (2004)]

impact of cavity geometry on SiGe stress

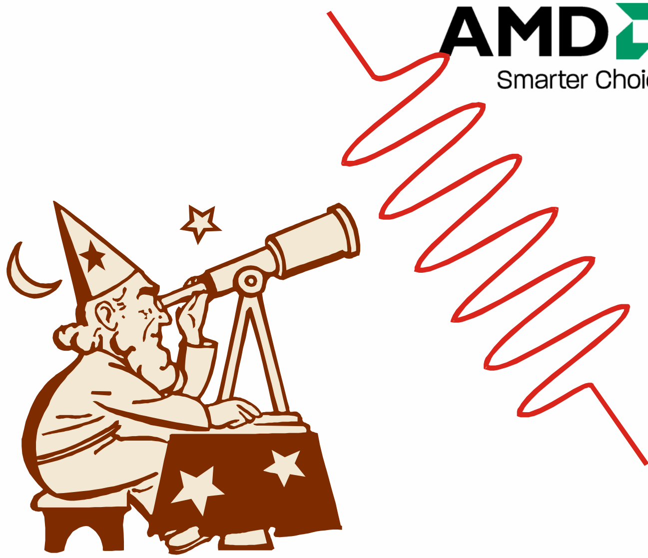


Hecker, Geisler: Mat. Sci. Pol. 25, 7 (2007)

II. Strain metrology

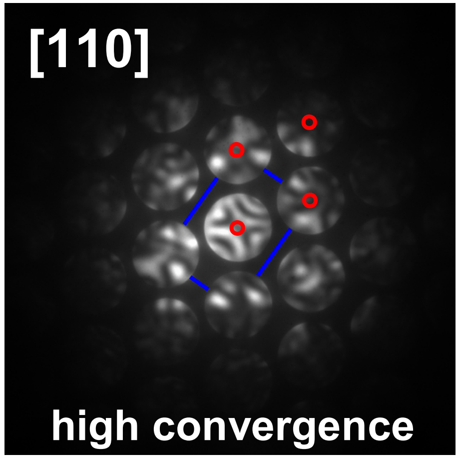


dislocations in NMOS
of 90 nm devices
(source: D. James, Chipworks, 2005)



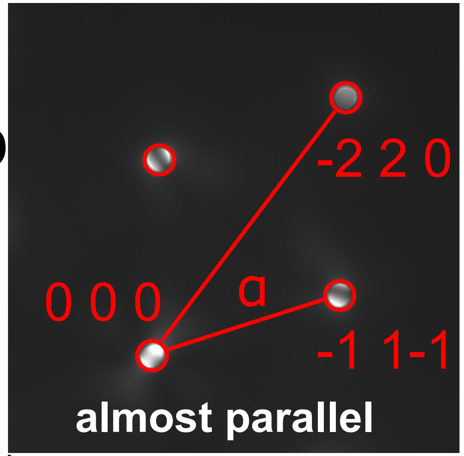
wafer curvature	: stress = force/area (Stoney eqn.)
X-ray	: lattice parameter (Bragg eqn.)
TEM	: lattice parameter (CBED, NBD, HRTEM)
Photoluminescence	: strain -> band gap change
Raman	: strain via lattice vibrations

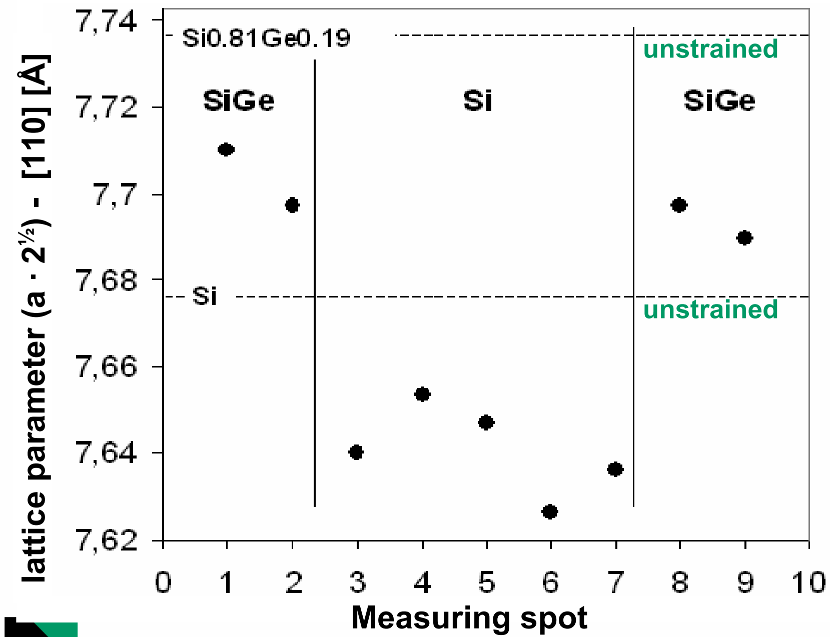
strain measurement by TEM

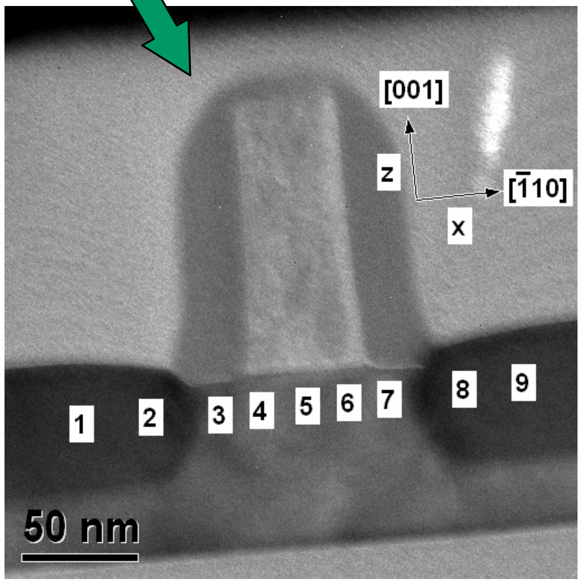


CBED

NBD







Engelmann, Heinemann, Zschech: IMC16, 990 (2006)

Raman strain measurement

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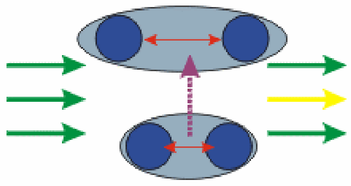
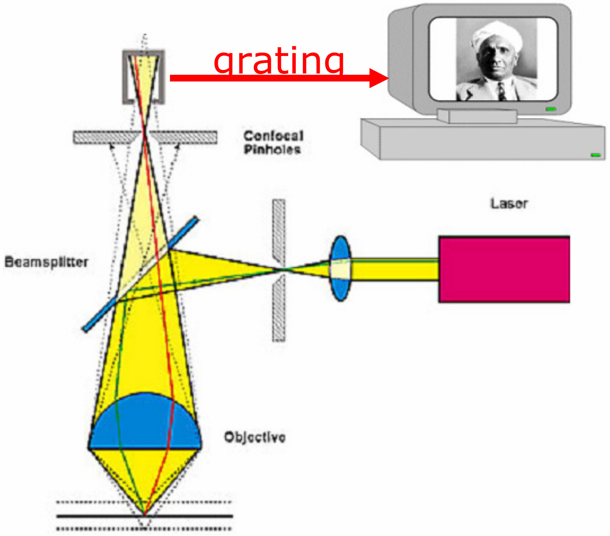
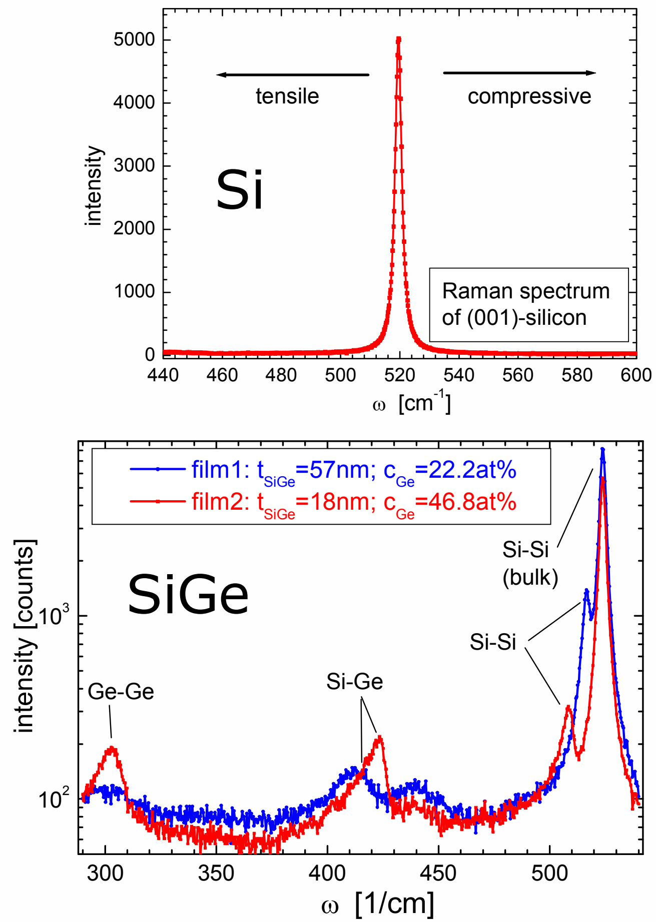
Raman-principle



confocal microscope



Raman measurement



- nondestructive
- fast
- spatial resolution < 1µm

film stack for Raman calibration: sSOI/SiGe

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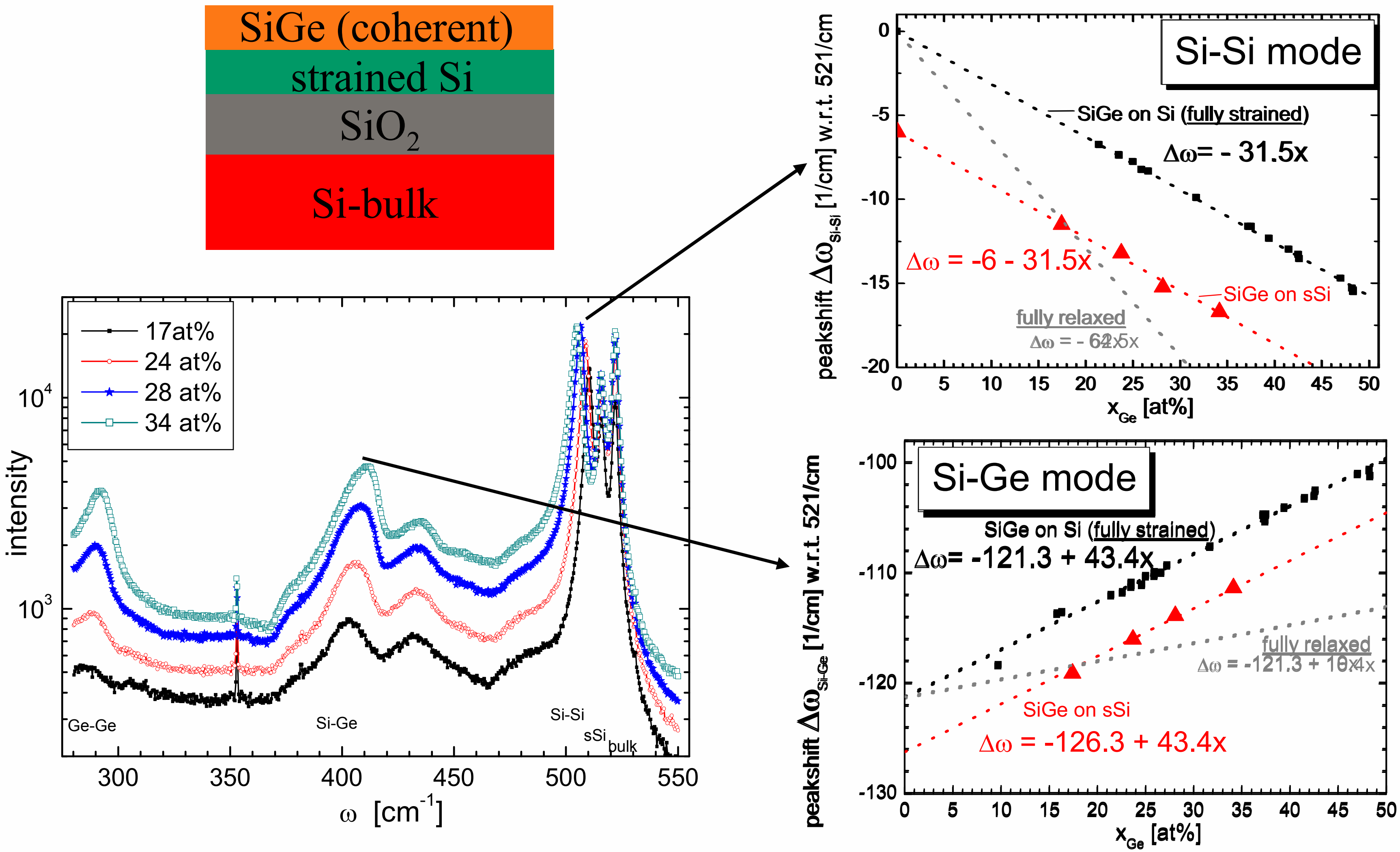

->calibration for defect-free films

X-ray strain measurement

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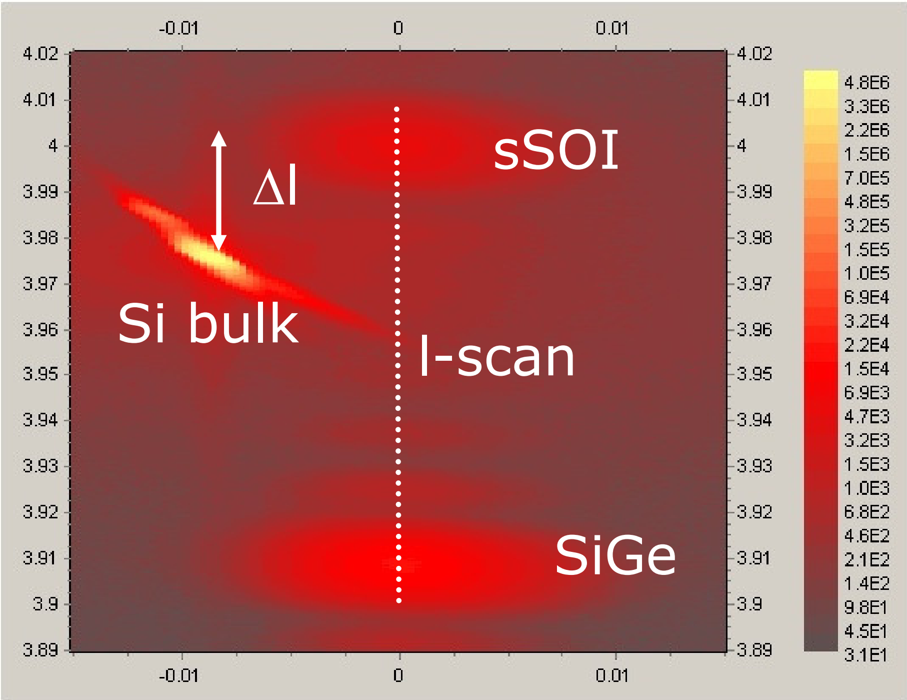
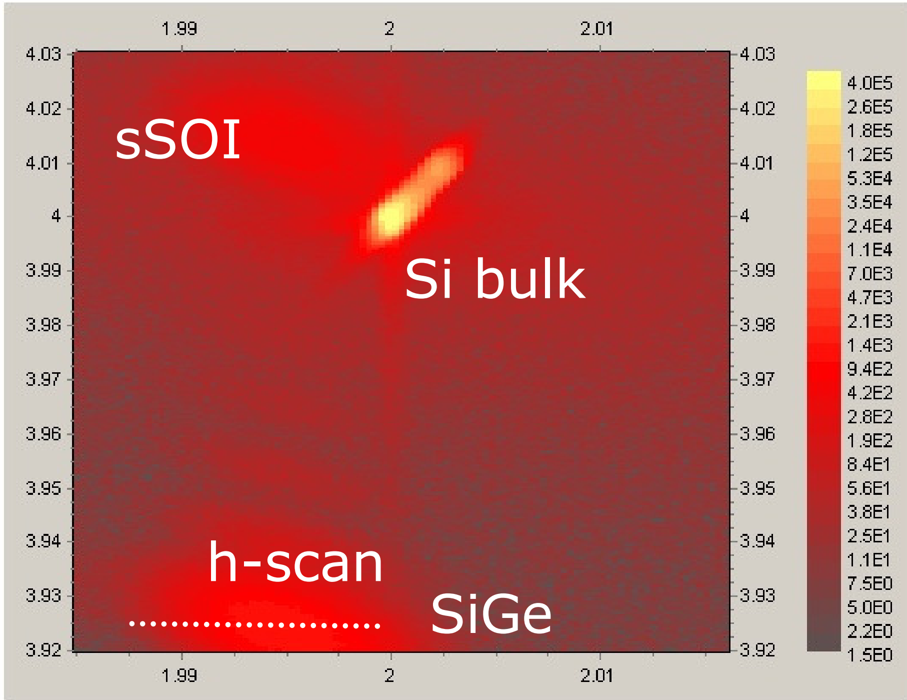
004 map



004: strain normal to surface

224 map



224: in-plane strain

Δl -> sSOI strain
-> Raman strain parameters
σ = -235 MPa cm $\Delta\omega$

“quick” measurements -> l-scan, h-scan
detailed information -> reciprocal space map

III. Nano-optics and field enhancement

The Lycurgus Cup

reflected / transmitted light
(TEM: 50 nm Au particles)

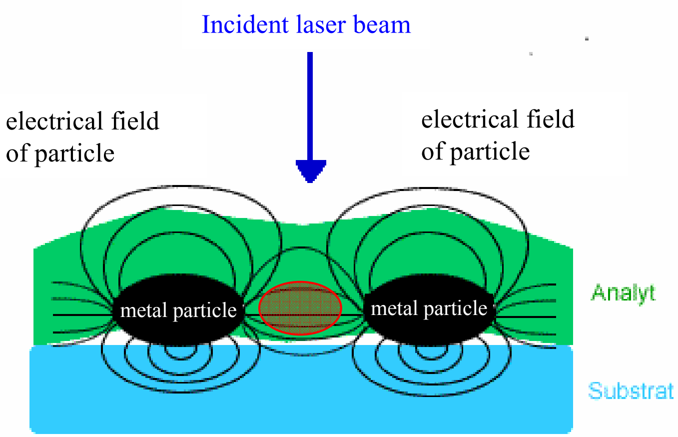
particle-related field enhancement due to:

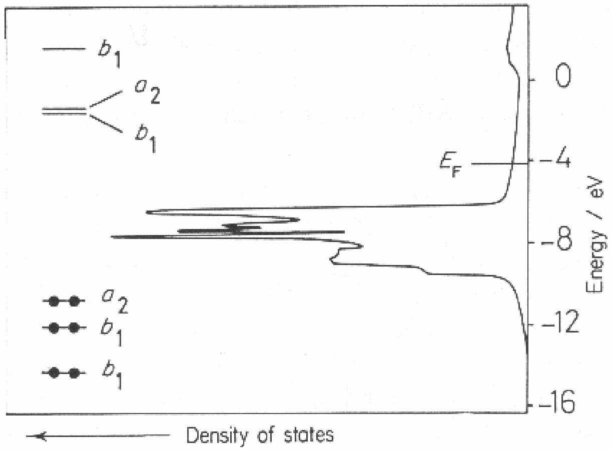
electromagnetic effect

surface plasmons
-> antenna effect
-> high efficiency of
plasmon excitation
in Ag, Au

chemical effect

increased polarizability due to
charge transfer
metal -> sample





Surface enhanced Raman scattering (SERS) close to Ag particles

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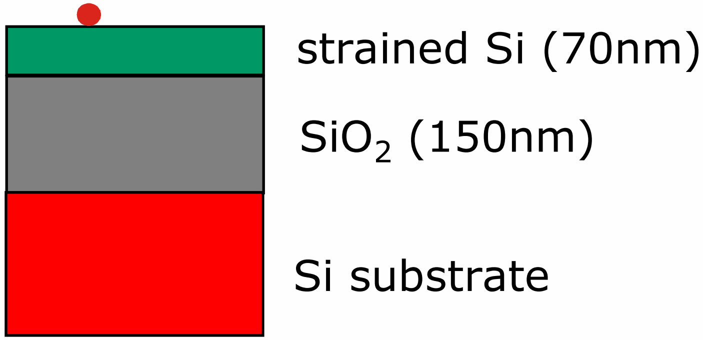
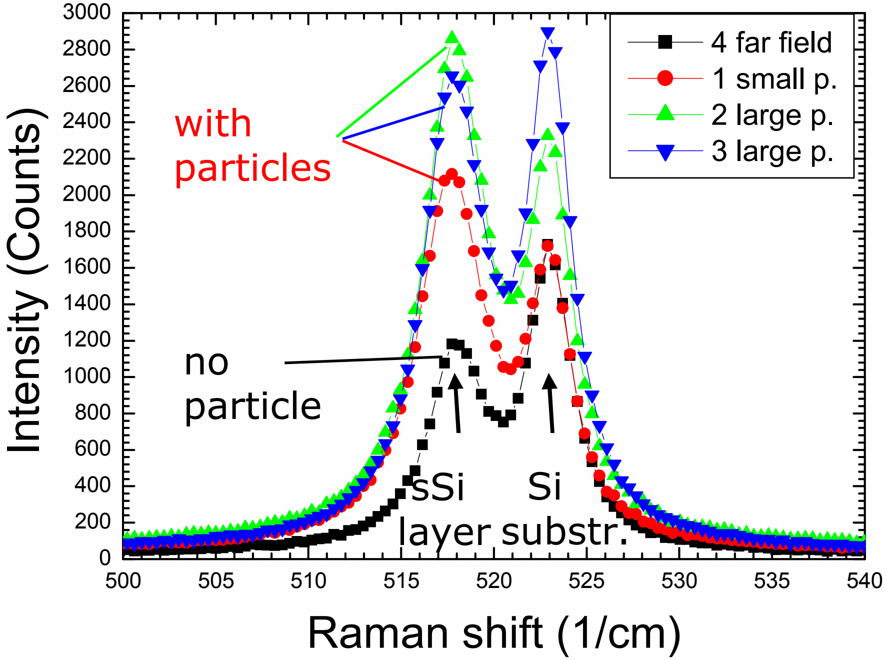
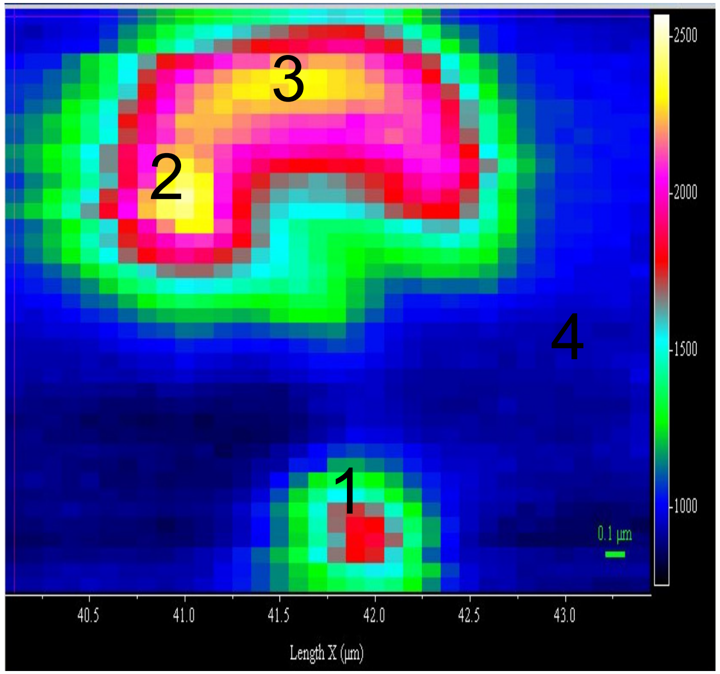




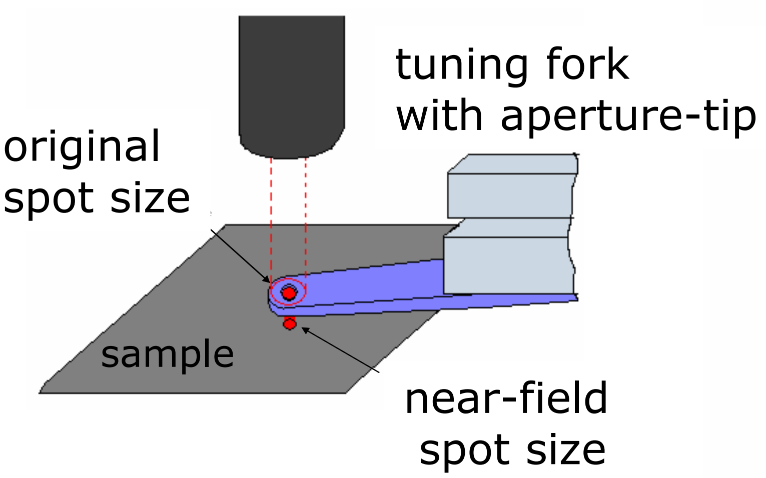


1: layer: +91% substrat −10%
2: layer: +153% substrat +23%
3: layer: +134% substrat +65%

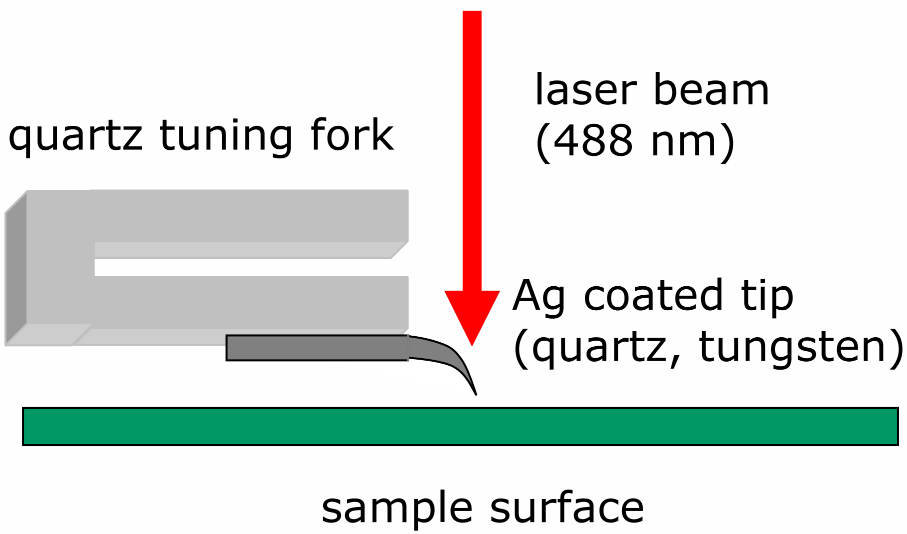
L. Zhu et al.: Mat. Sci. Pol. 25, 19 (2007)

From surface enhanced to Tip Enhanced Raman Scattering (TERS)

(1) aperture based

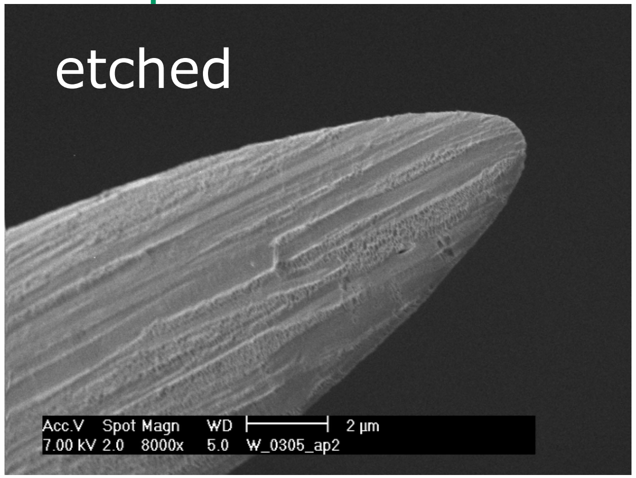


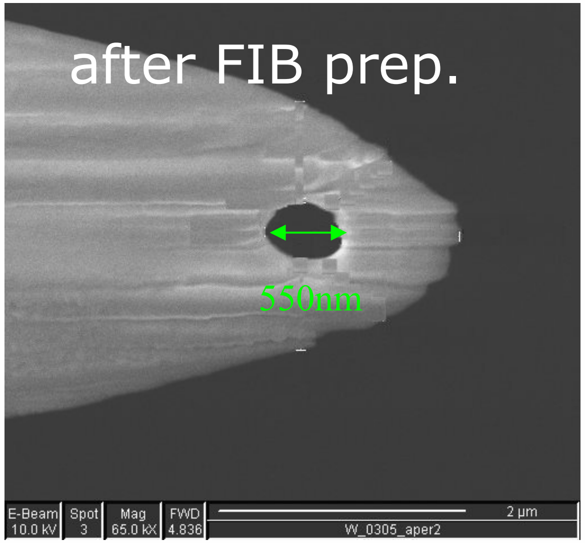
(2) apertureless (TERS)



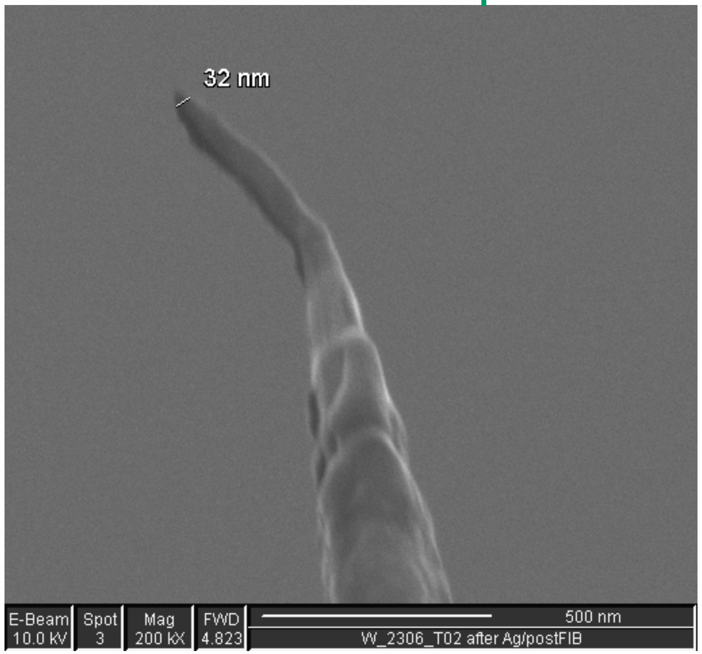
tip etching

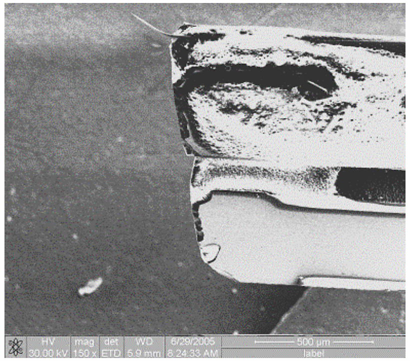
apertures





TERS tips





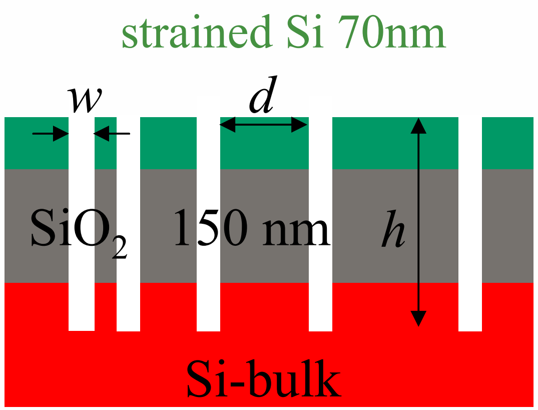
mounted on tuning fork

Y. Ritz et al.: Pract. Metallogr. 38, 403 (2006)

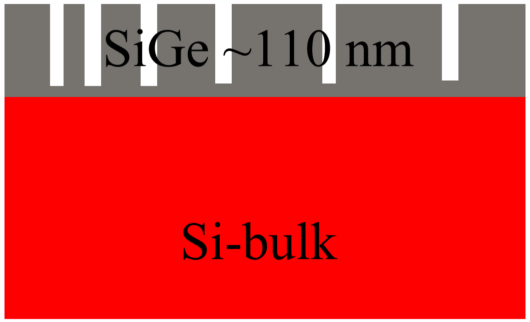
samples

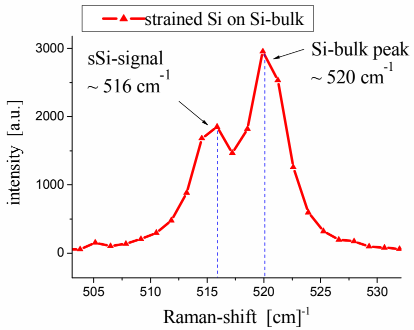
strained silicon on insulator (sSOI)

SiGe-layer fully strained on Si-bulk

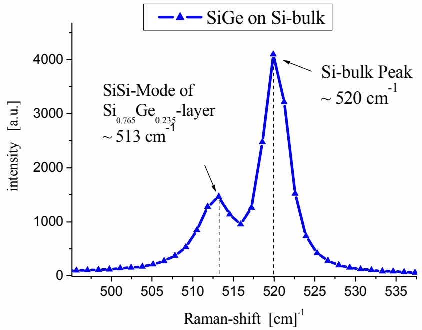


sample patterning for studies of spatial Raman resolution by FIB technique





Raman film peak Si-Si: shifted to smaller wave numbers



(1) measurements with near-field-aperture

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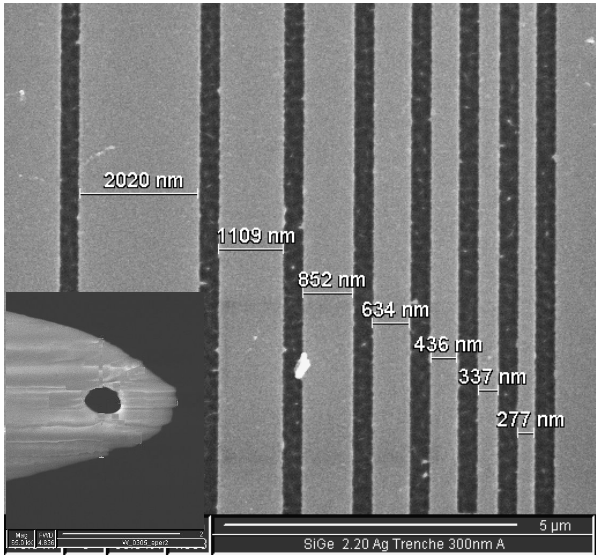

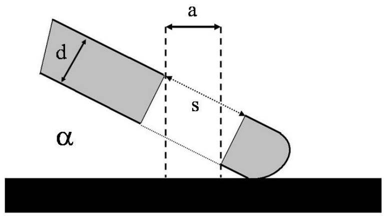

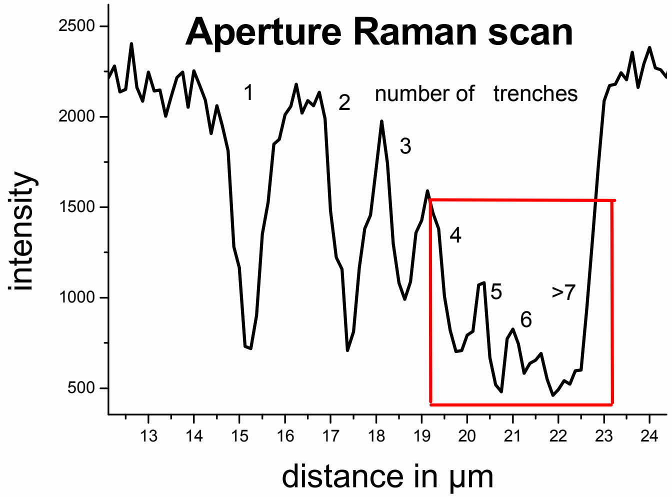

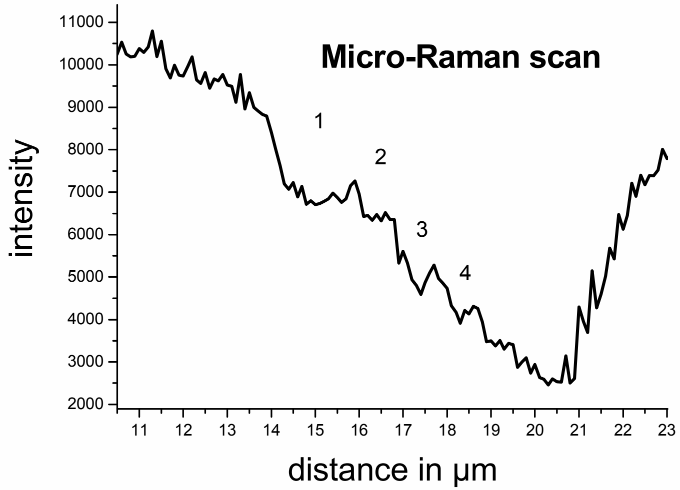

~ 300 nm spatial resolution with aperture, compared to ~ 800 nm

(2) measurements with TERS-tips

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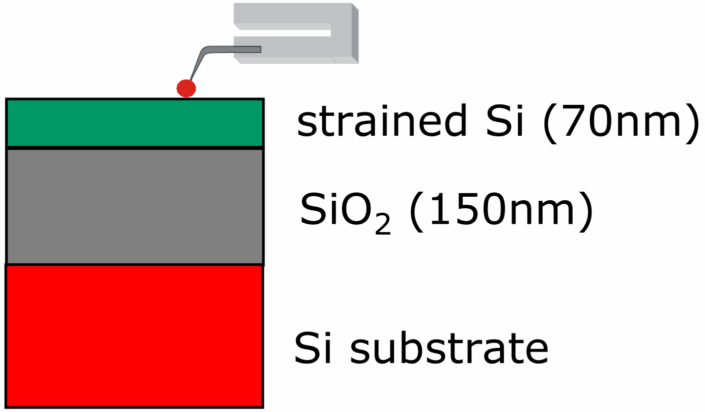

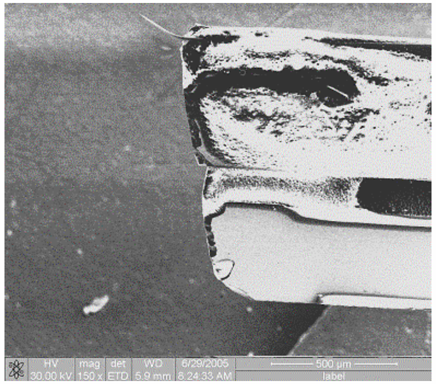

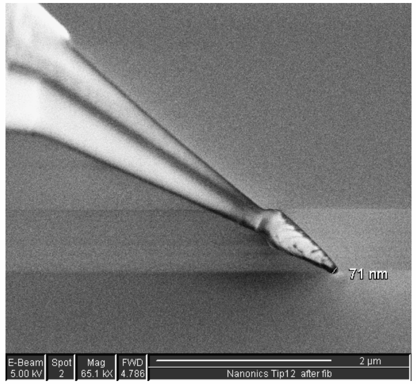

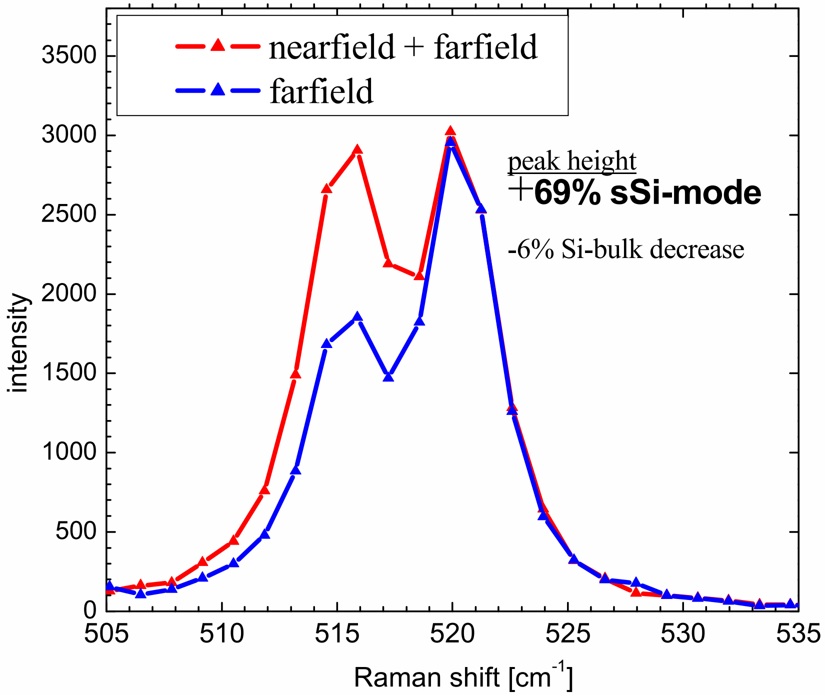

selective enhancement ~ 70%

Gaithersburg, March 28, 2007

M. Hecker et al., AMD Saxony LLC&Co. KG

Resolution of sSOI line structures below diffraction limit by TERS

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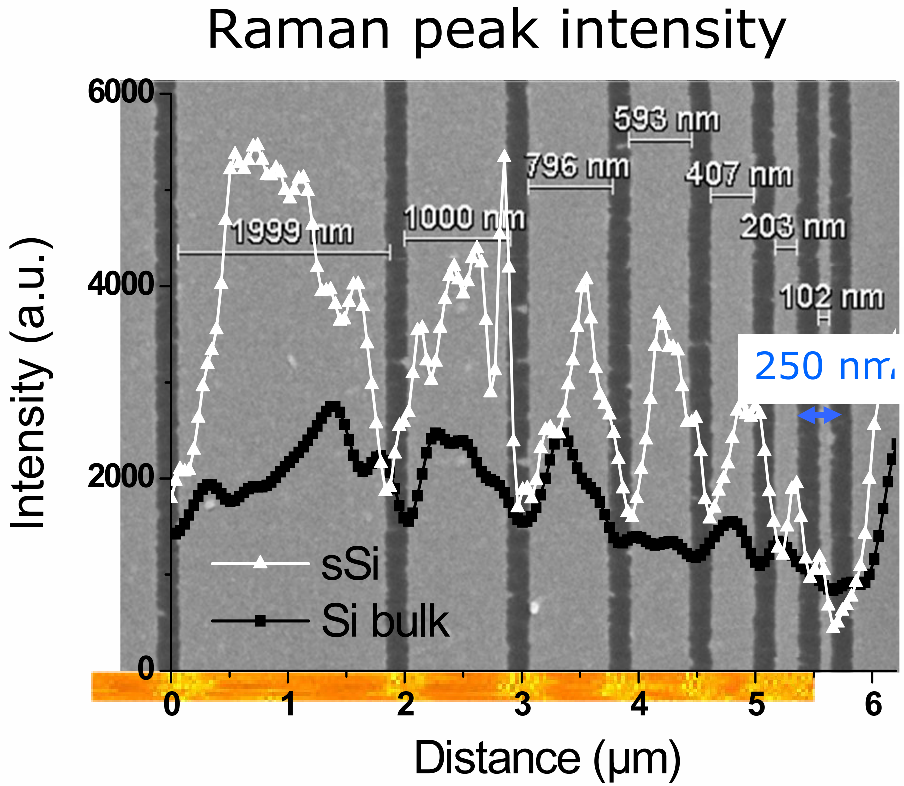
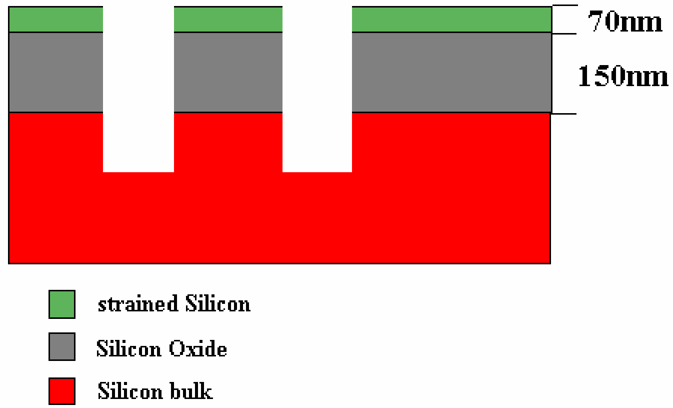




- **improved contrast**
- **more features resolved in sSi film peak intensity**
- **resolution ~ 250 nm**

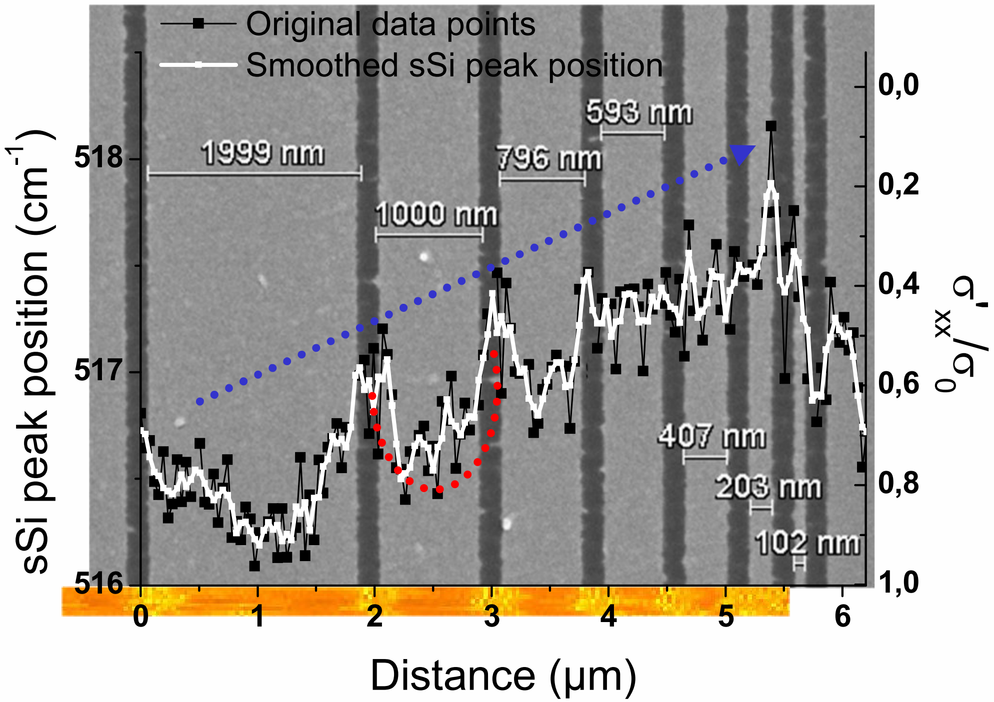
scan parameters:

488 nm laser, 10 mW, 3 s, step size 40 nm

L. Zhu et al.: Journ. Appl. Phys., submitted (2007)

strain distribution in sSOI line structures

Raman peak position

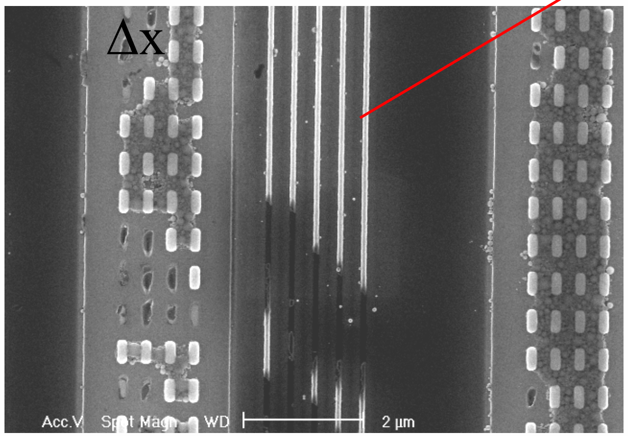


- ➢ strain profile in wider lines: relaxation at line edges visible (2000 .. 600 nm)
- ➢ tendency of higher relaxation for narrower lines visible

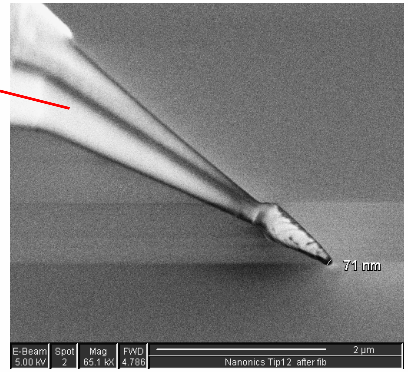
evaluation for assumption of stress conservation along line direction and partial relaxation perpendicular to lines:

$$\frac{\sigma_{x'x'}}{\sigma_0} = -0.455 \cdot \left(\omega_{sSi} - 520\ cm^{-1}\right) - 1$$

strain investigation in between SiGe cavities (test structures)

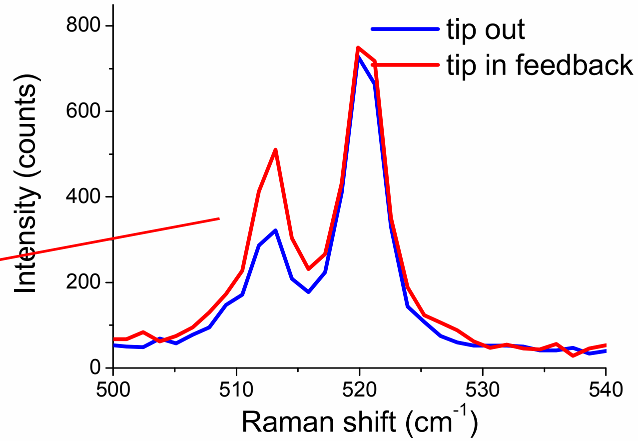


100 nm Si lines in between 300 nm SiGe cavities, scanned with FIB modified TERS tip



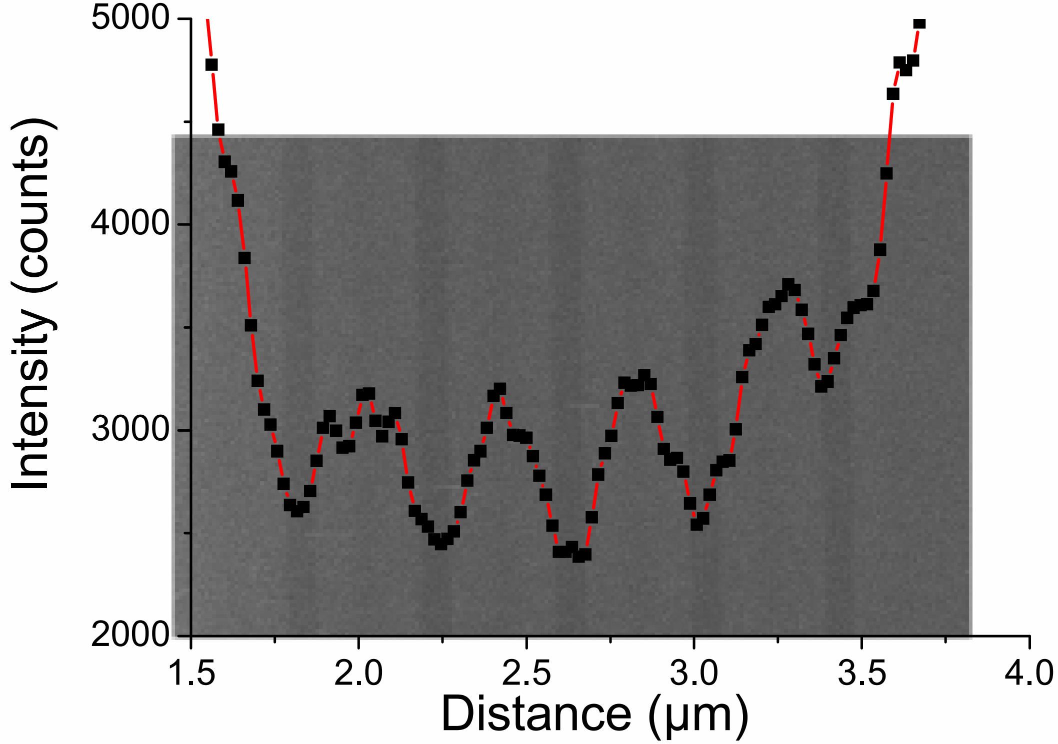
Raman measurement:

~ 50% signal enhancement



strain investigation in between SiGe cavities (test structures)

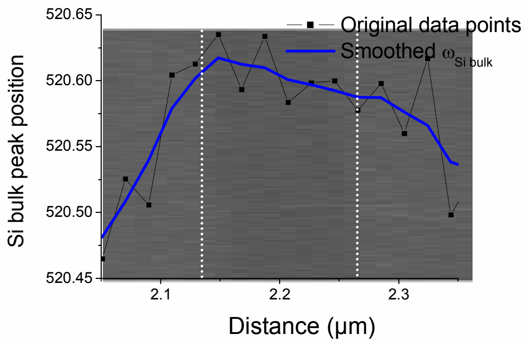
Raman peak intensity



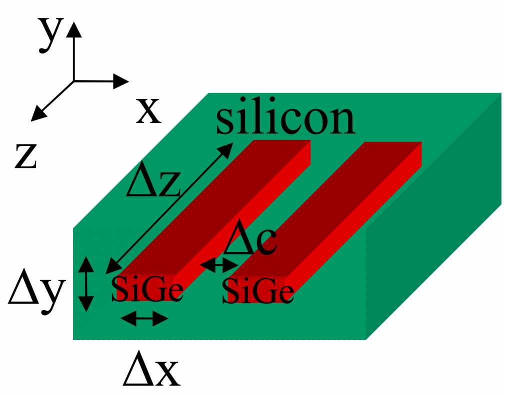
scan parameters: 488 nm laser, 10 mW, 3 s, step size 16 nm

strain in between SiGe cavities – comparison with calculation

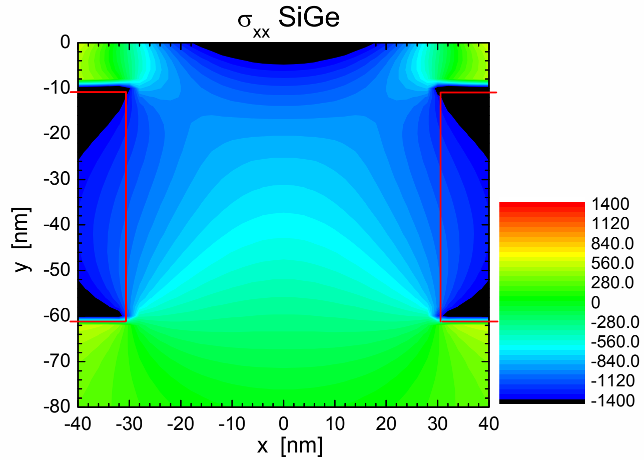
Raman data



model for strain calculation



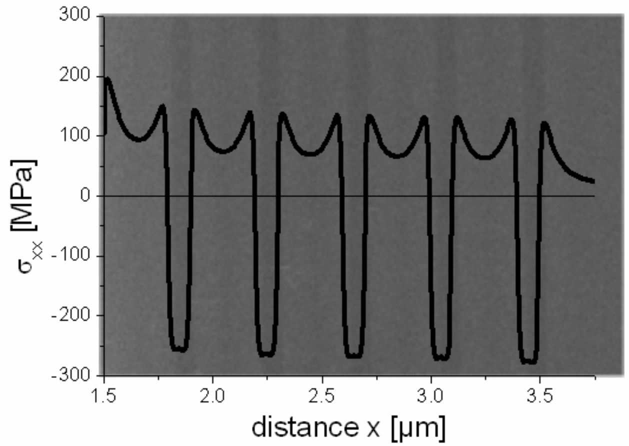
strain in channel



calculated resulting peakshift

$$\Delta\omega_{Si} = (\sigma_{xx} + \sigma_{zz}) \cdot C_1 + \sigma_{yy} \cdot C_2$$

Si peak shift due to strained Si: approx. 1cm^{-1}



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Summary for strain metrology

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☹

- X-ray: sample throughput, spatial resolution
- Raman: weak signals (near field), not all materials
- sample preparation for sub-100nm measurements critical

☺

- strain increases transistor speed -> high motivation to measure
- spatial resolution of techniques continuously scales down
- near-field Raman has potential for local strain measurements

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