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Strain Analysis in Scaled Si Transistors by Simulation-Hybrid UV Raman Microscopy

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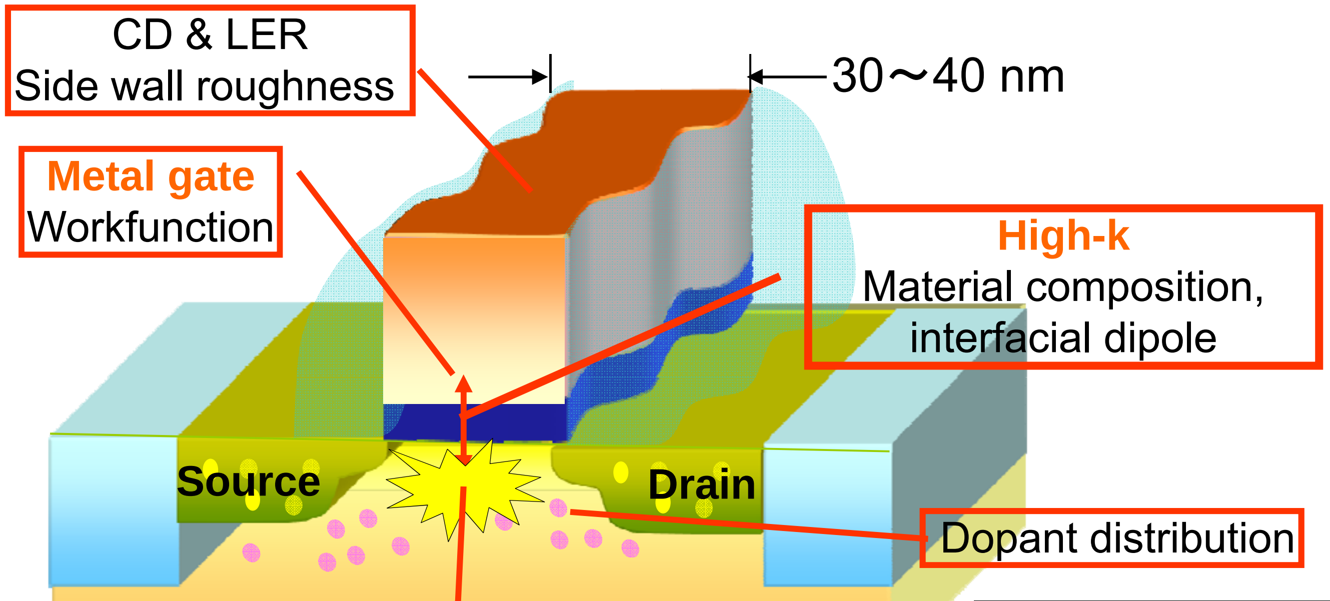
Requirements for CMOS measurement/characterization

Nanoscale material characterizations are required.

- **New materials in nanoscale devices results in complicated interfaces.**
- **Variability increases and reliability decreases.**



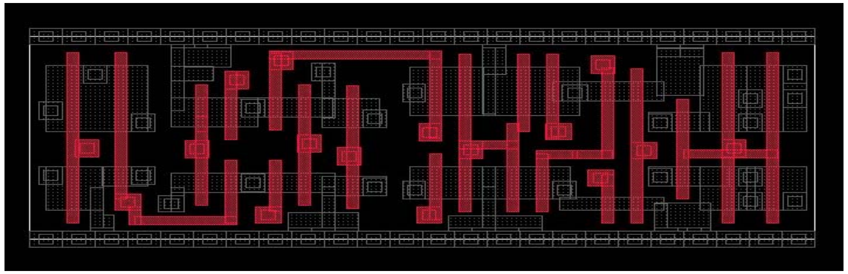
CD & LER
Side wall roughness

Metal gate
Workfunction

High-k
Material composition,
interfacial dipole

Dopant distribution

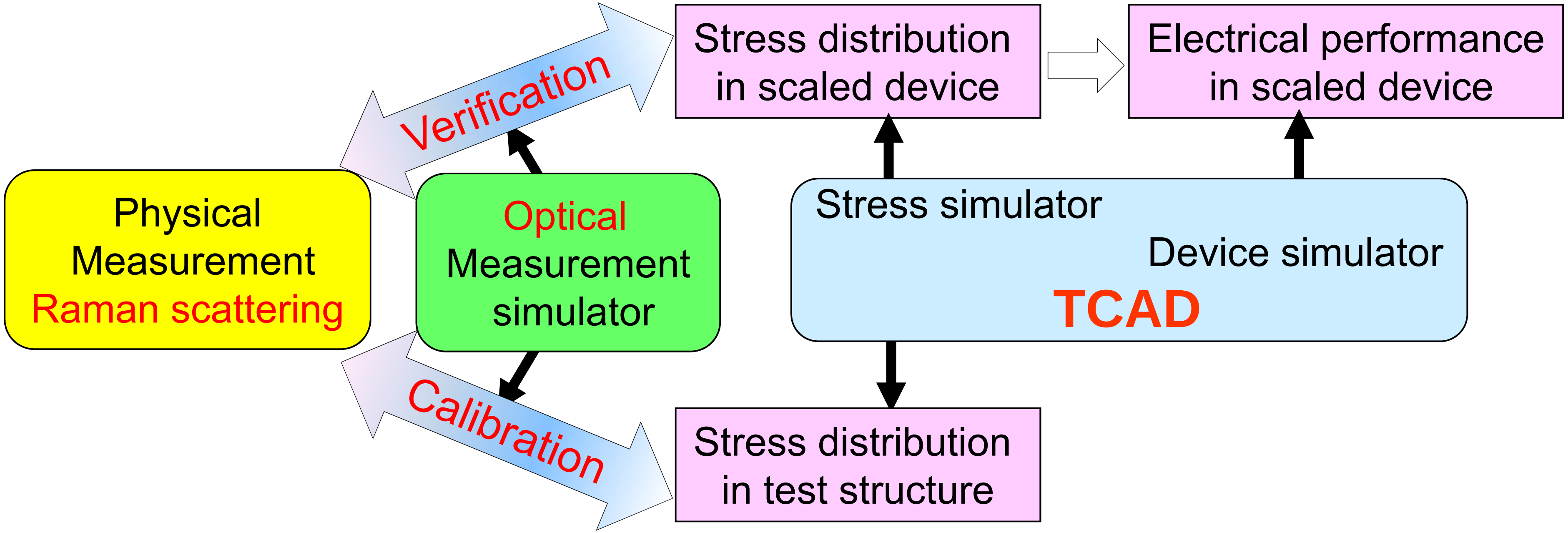
Mechanical Strain
Strain distribution



Strain distribution depends on layout.

- Simple physical measurement cannot meet the requirement.

Simulation-Hybrid Stress Measurement



Stress distribution in scaled device

Electrical performance in scaled device

Verification

Physical Measurement Raman scattering

Optical Measurement simulator

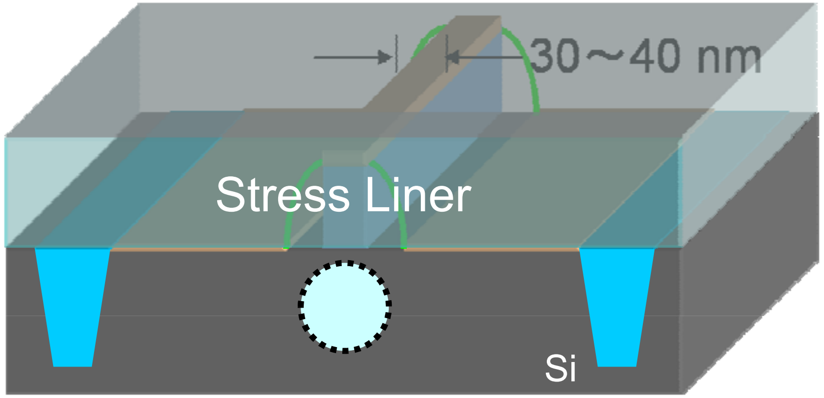
Stress simulator

Device simulator

TCAD

Calibration

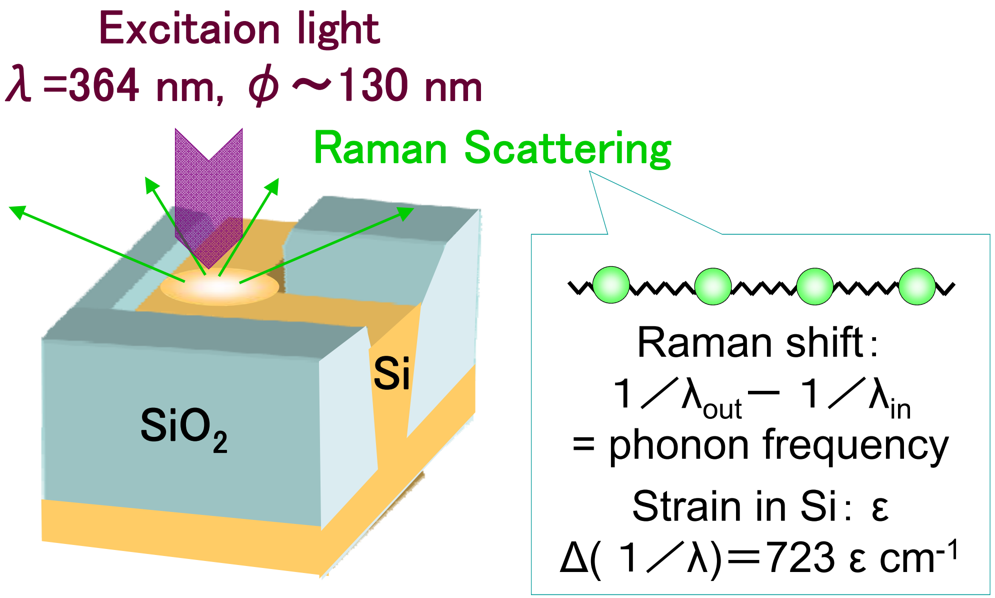
Stress distribution in test structure



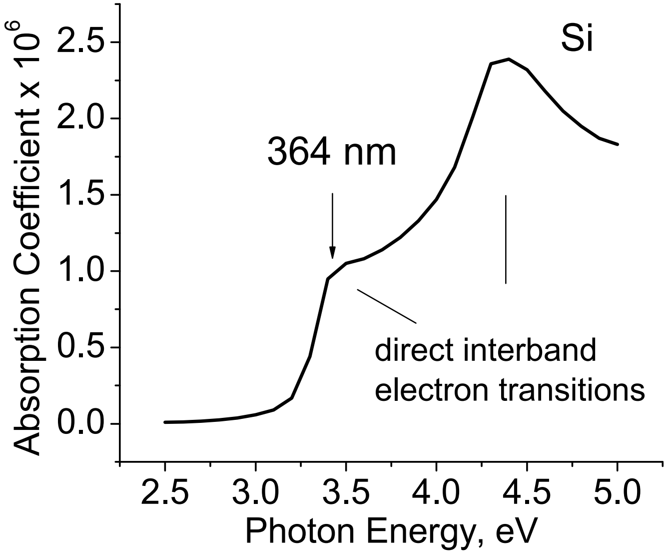
Contents

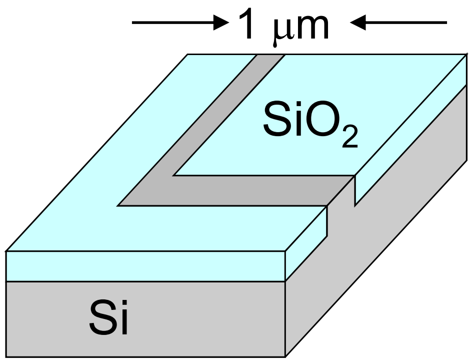
- Ability of polarized UV Raman micro-spectroscopy in combination with stress simulation and optical simulation
- Strain analysis in scaled Si transistors by stress simulation calibrated with Raman measurements
- Detection of forbidden Raman modes using high-NA optics
- Summary

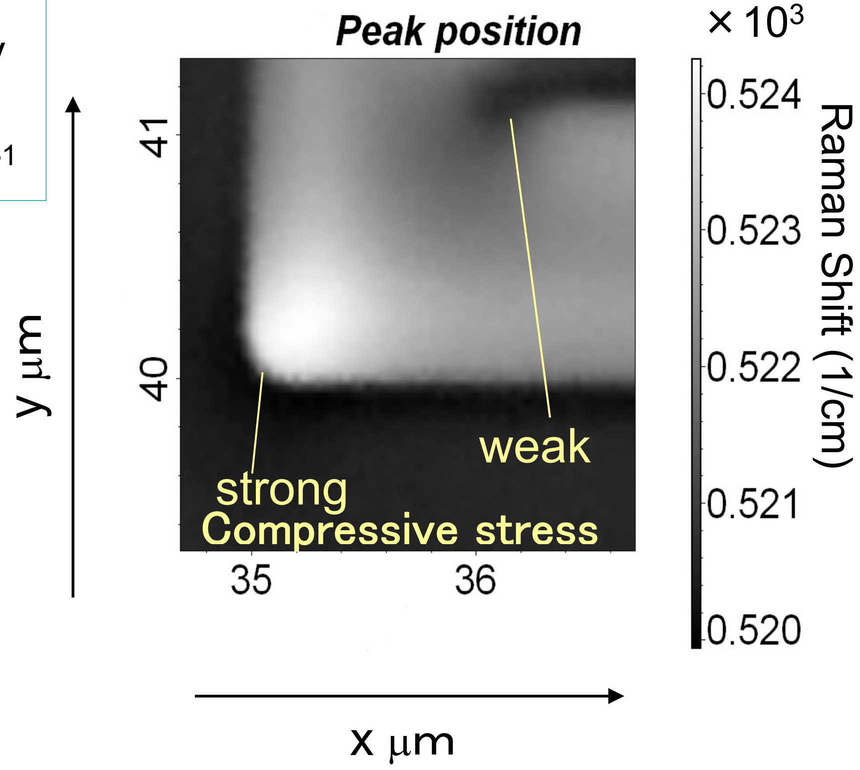
Visualization of stress distribution by confocal Raman microscope



Raman shift：
$1/\lambda_{out} - 1/\lambda_{in}$
= phonon frequency
Strain in Si：ε
$\Delta(1/\lambda) = 723\,\varepsilon\ \mathrm{cm}^{-1}$



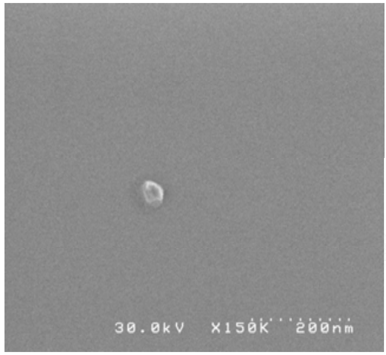




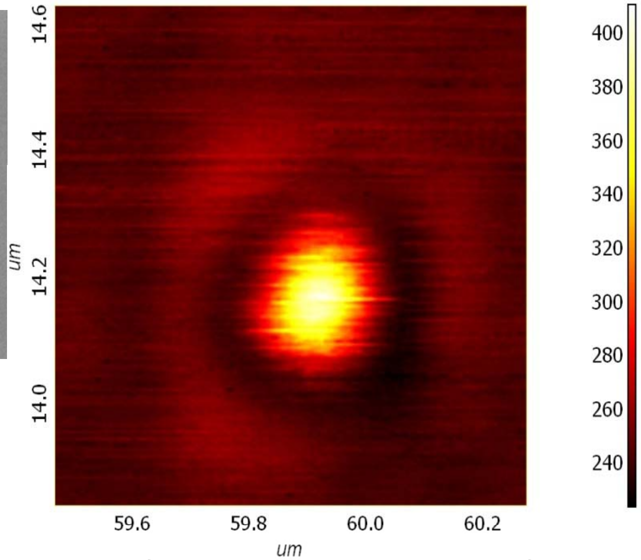
2D Raman mapping

Spatial resolution

A 30nm Al dot



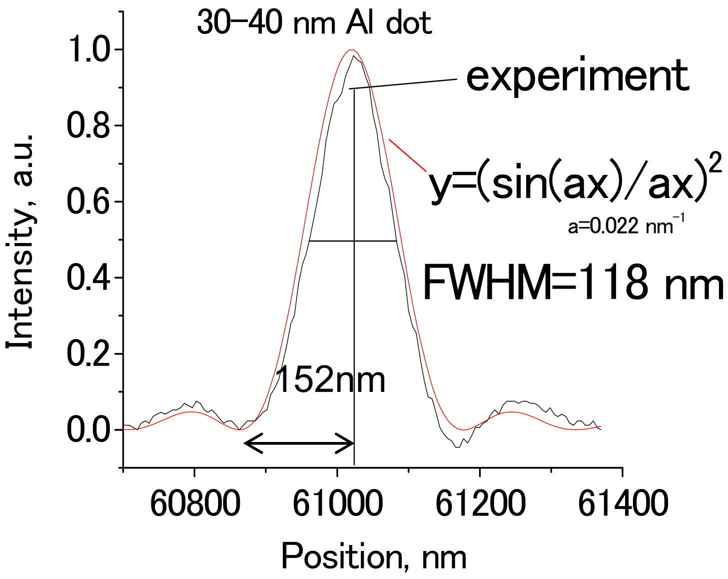
SEM pictiure of
an Al dot (30 nm)



A confocal scanning image of light
scattering by the 30nm Al dot

High NA objective lenses

NA=1.3 （oil immersion）



Point spread function of the system

- Confocal scanning microscopic image of light scattering by Al dots fabricated with e-beam lithography on SiO_2

→Spatial resolution 120-150nm: diffraction limit

Pros and Cons for Raman measurement

UV Raman scattering (364 nm)

Advantage

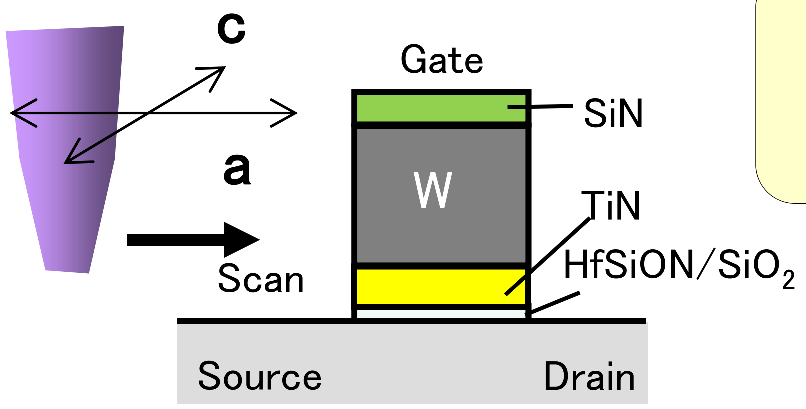
- Non-destructive
- Spatial resolution ～ 150 nm
- Small penetration depth ～ 10 nm
- Simulation is feasible

Disadvantage

- Strain/Stress tensor has six components; a single value of Raman shift is insufficient.
- Spatial resolution is not enough.

Polarization dependence
analysis with simulation

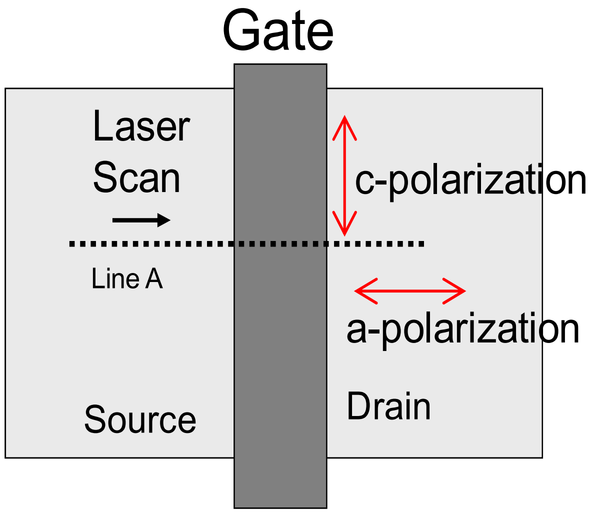
Polarized Raman measurements in a metal gate structure

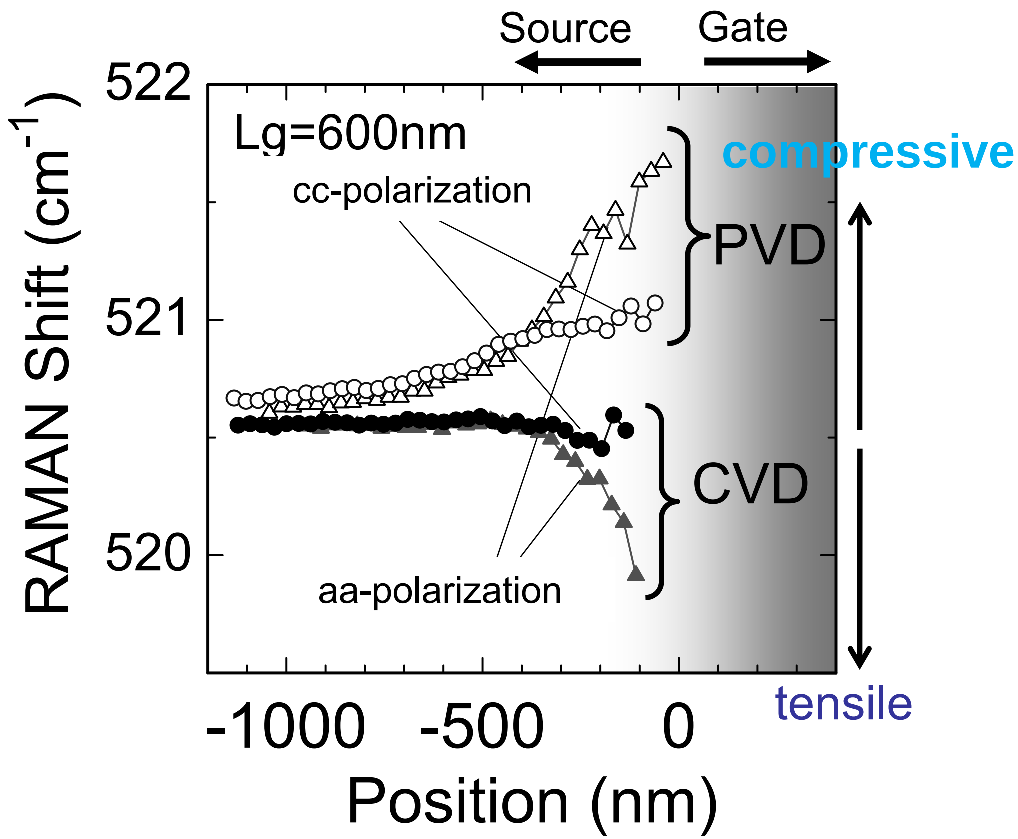


Gate length=600 nm, H=70 nm

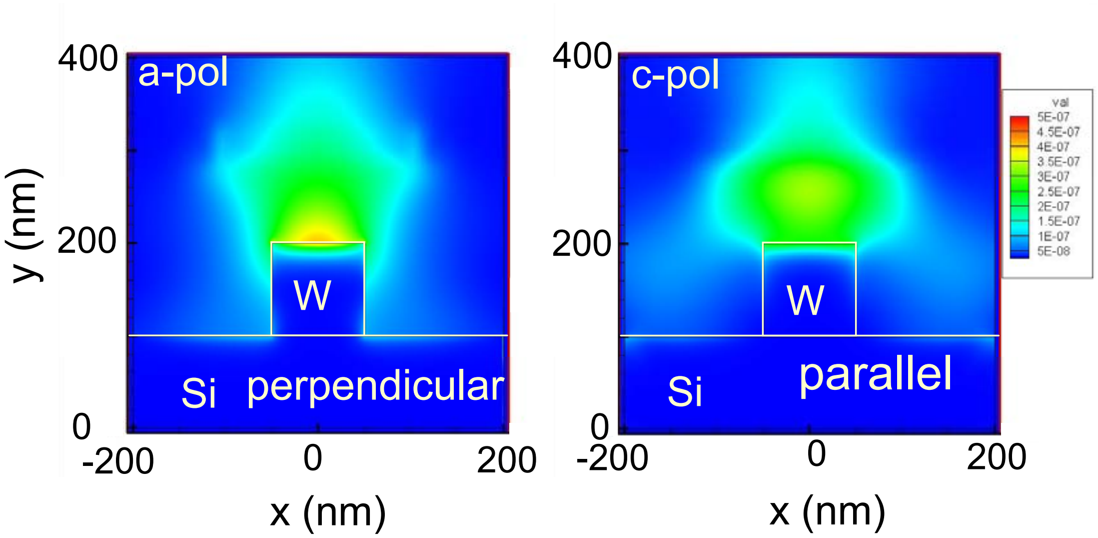
x *y*-polarization configuration

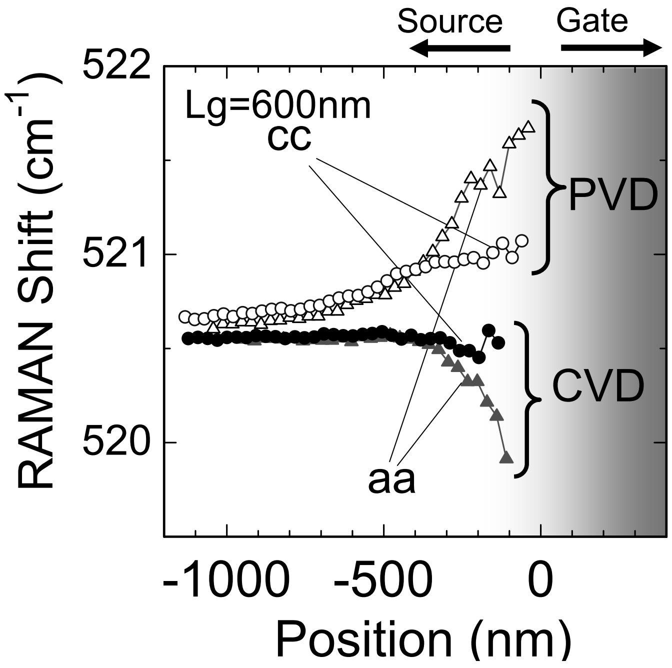
excitation ↗ ↖ detection



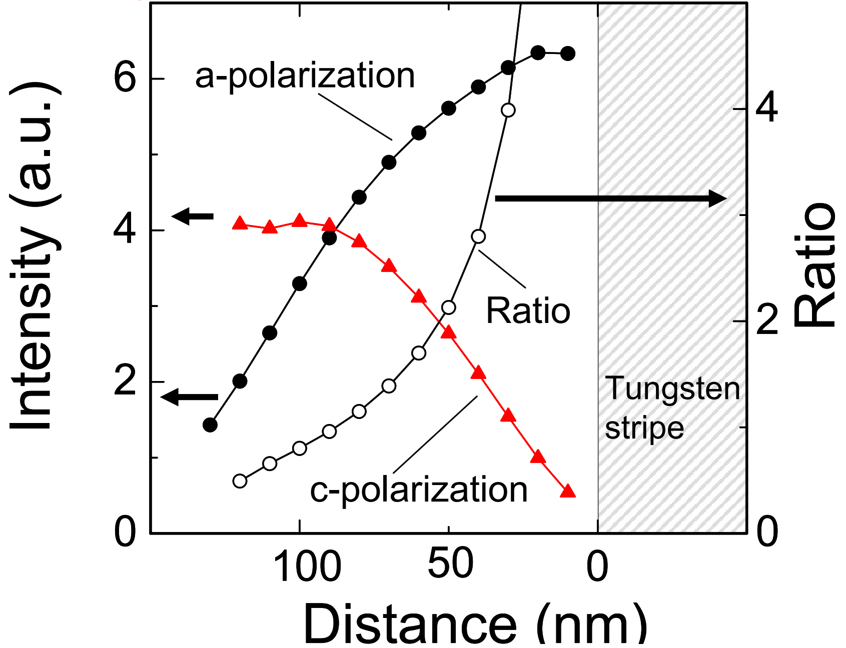


Excitation light intensity distribution calculated with FDTD simulation





The light intensity at 5-nm below the Si surface

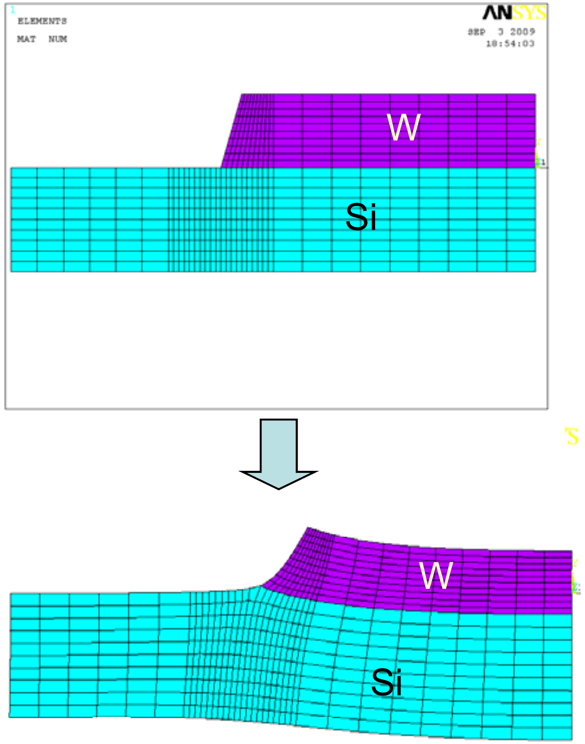


The stress induced Raman shift for the *aa*-configuration is much larger than that for the *cc*-configuration

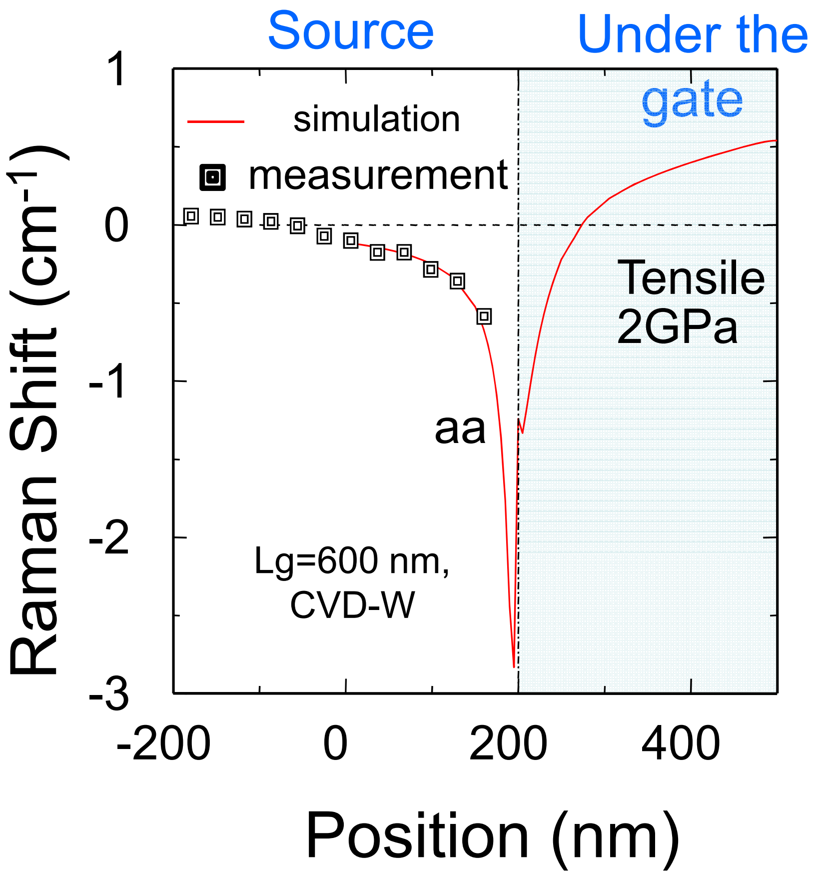
The stress is localized very close to the gate edge (~ 50nm)

even higher spatial resolution than the diffraction limit of the excitation probe

FEM stress simulation



Deformation of the structure after applying the initial tensile stress (2GPa)

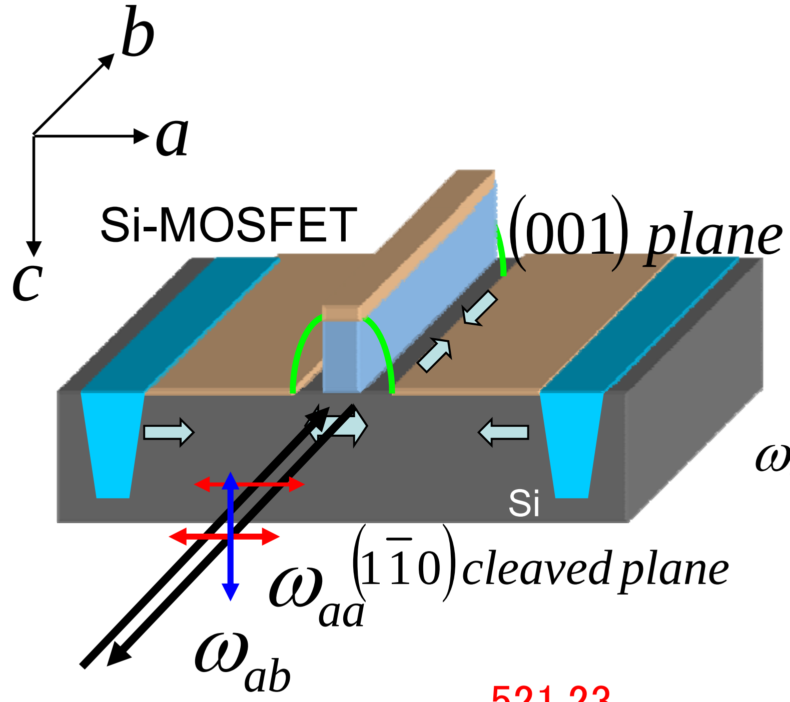


The distribution of the Raman shift calculated using the FEM stress simulation results.

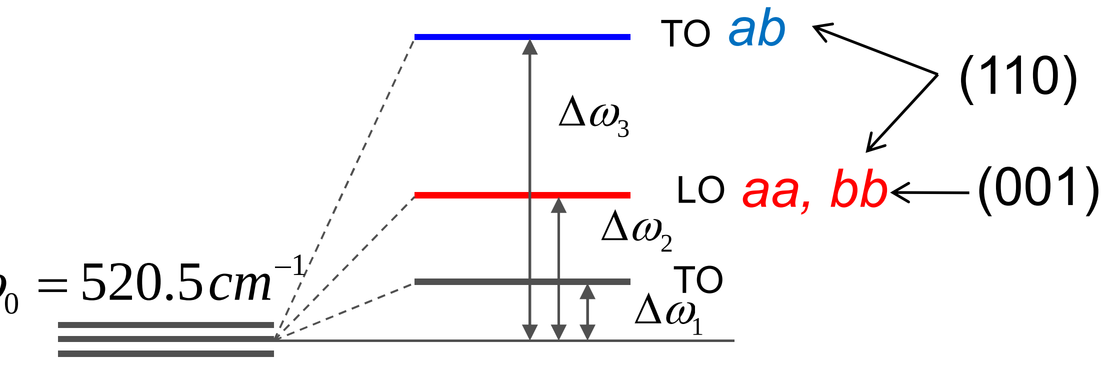
The experimental data for the CVD-W gate (Lg=600nm)can be fitted with the initial stress of 2GPa.

The stress in the channel region under the gate can be estimated.

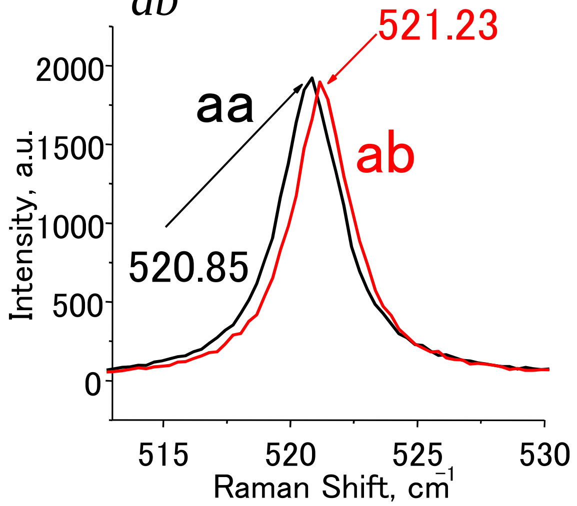
Polarized UV Raman measurement on (110) surface



Anisotropic stress,
e.g. [110] uniaxial stress



1LO and 2TO phonon modes



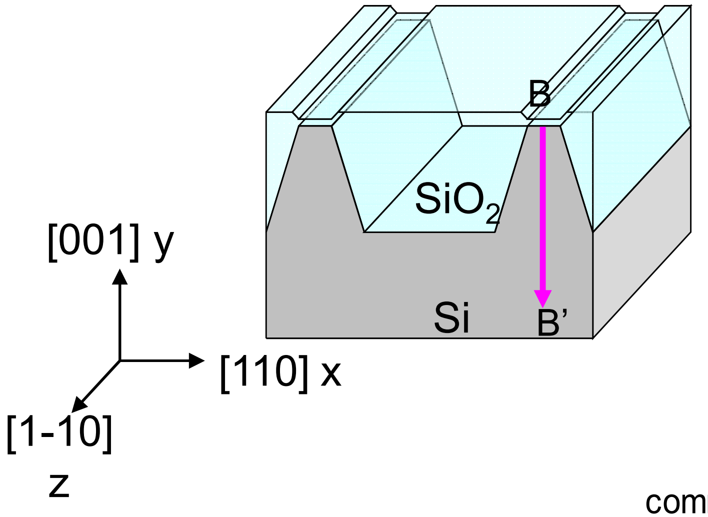
at the bottom of STI

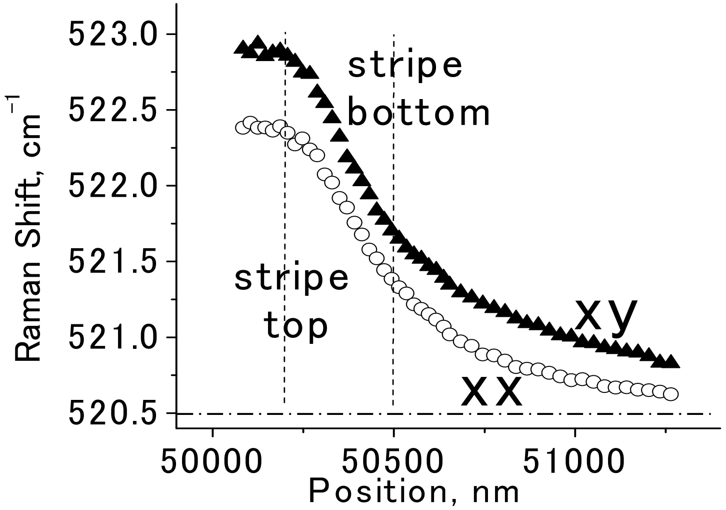
If shear stress is neglected
on the cleaved surface

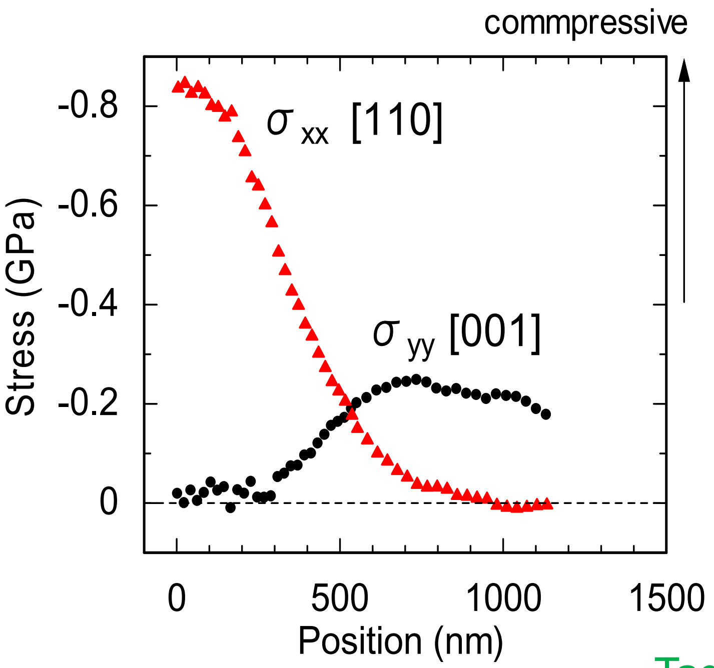
$$\boxed{\begin{aligned}\Delta\omega_{aa} &= C_1\sigma(100) + C_2\sigma(110)\\ \Delta\omega_{ab} &= C_3\sigma(100) + C_4\sigma(110)\end{aligned}}$$

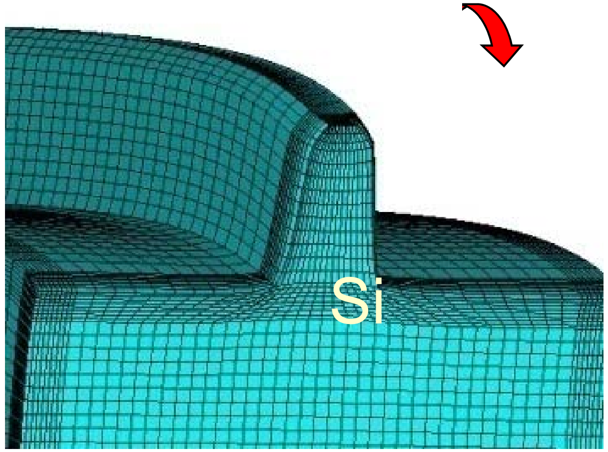
$C_1 = [qS_{11} + (p + q)S_{12}]/2\omega_0$,
$C_2 = (pS_{11} + 2qS_{12})/2\omega_0$,
$C_3 = [(p + q)S_{11} + (p + 3q)S_{12} + rS_{44}]$,
where S_{11}, S_{12}, and S_{44} are compliance constants of Si, and p,q,r are phono deformation potentials.

Stress distribution in STI on (1-10) cross sectional surface









The upper part of the cleaved surface bends toward the front.

Tada, et.al, J. Appl. Phys. **107** (2010) 113539.

Raman shift distribution

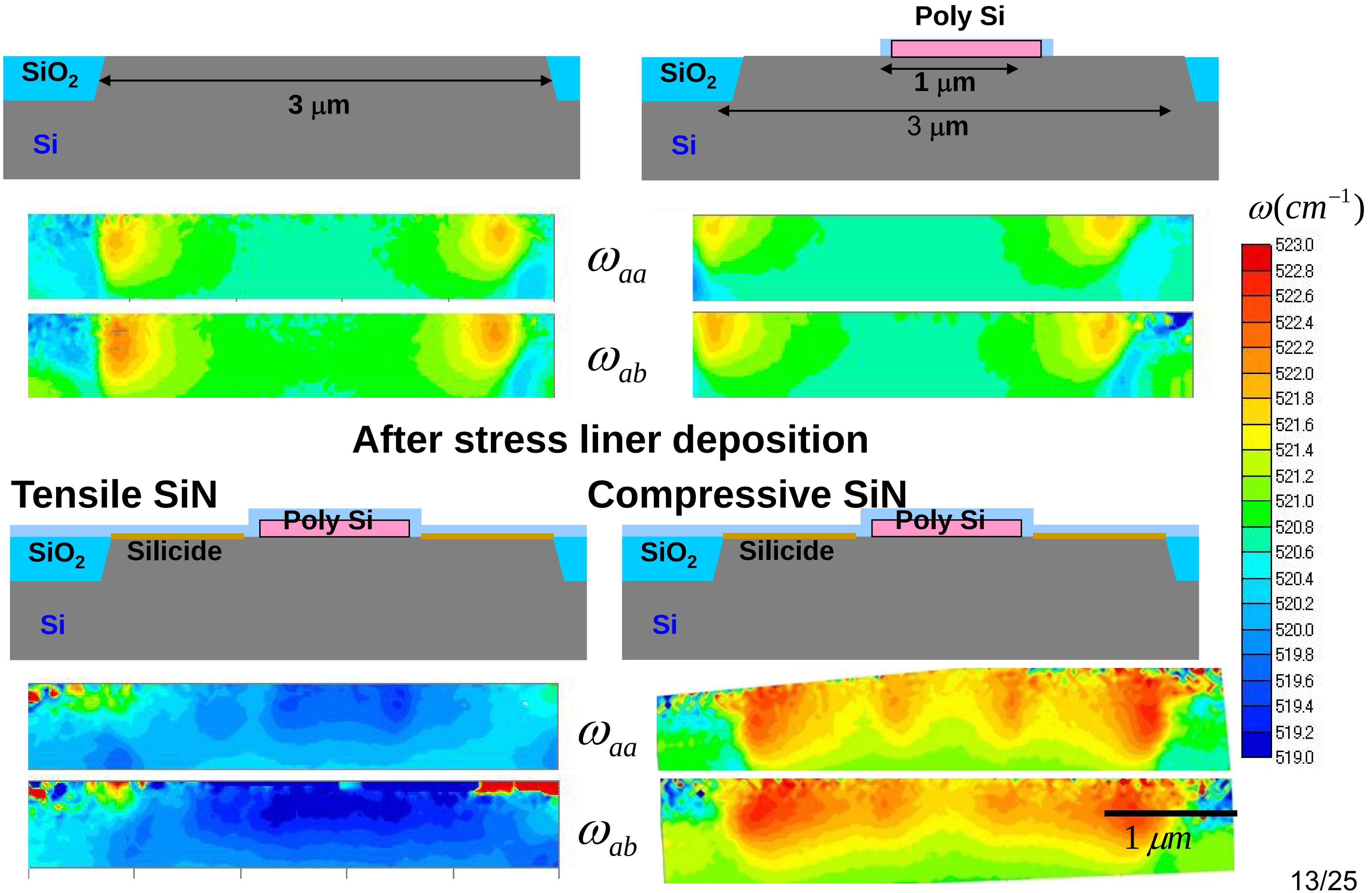
After gate oxidation

After SD annealing with gate

After stress liner deposition

Tensile SiN

Compressive SiN

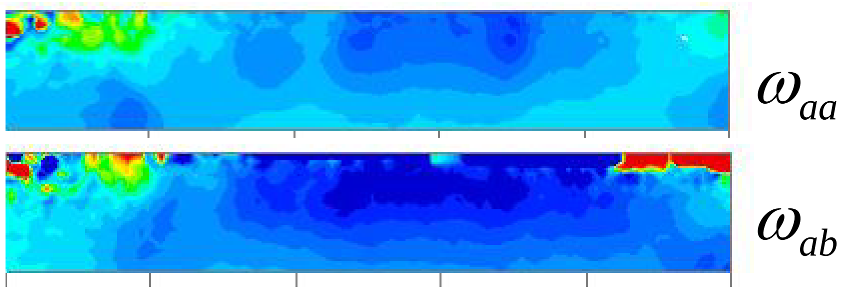


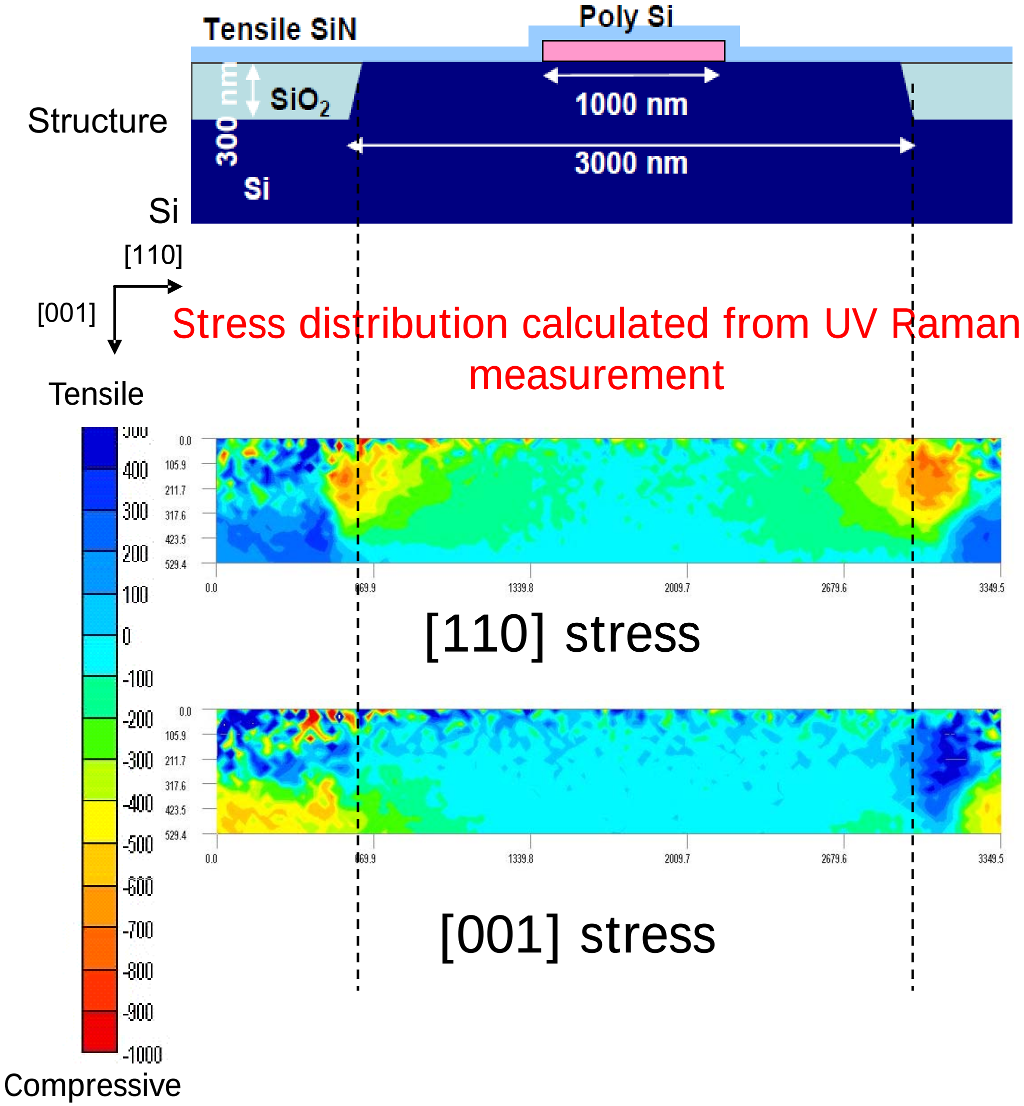
Stress measurement by polarized UV Raman mapping

$$\Delta\omega_{ab}=C_1\sigma(100)+C_2\sigma(110)$$
$$\Delta\omega_{ab}=C_3\sigma(100)+C_4\sigma(110)$$

Tensile SiN

2D distribution of Raman shift



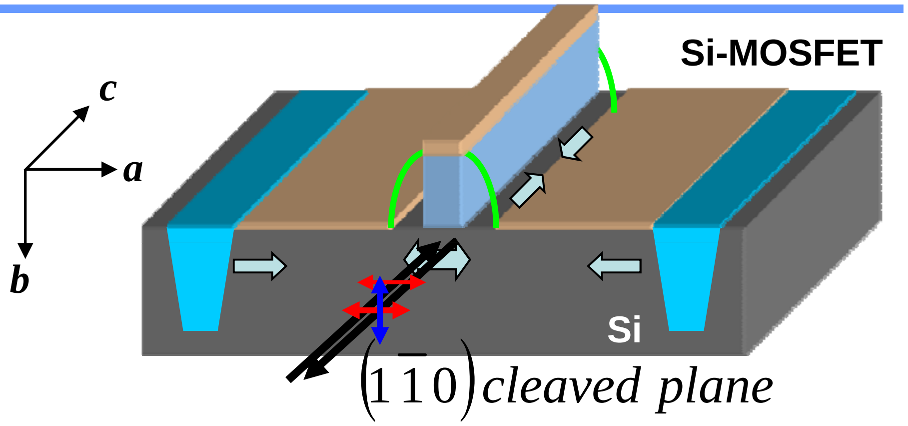


Stress distribution calculated from UV Raman measurement

[110] stress

[001] stress

Calibration using Raman spectroscopy analysis



Stress Simulation

Strain tensor (ε_{ij})

$$\begin{vmatrix} p\varepsilon_{11}+q(\varepsilon_{22}+\varepsilon_{33})-\lambda & 2r\varepsilon_{12} & 2r\varepsilon_{13} \\ 2r\varepsilon_{21} & p\varepsilon_{22}+q(\varepsilon_{33}+\varepsilon_{11})-\lambda & 2r\varepsilon_{23} \\ 2r\varepsilon_{31} & 2r\varepsilon_{32} & p\varepsilon_{33}+q(\varepsilon_{11}+\varepsilon_{22})-\lambda \end{vmatrix} = 0$$

$\omega_i^2 = \lambda_i + \omega_0^2$ (i = 1, 2, and 3)

p, *q*, and *r* are phonon deformation potentials of Si.

Calculated Raman shift map

ω_{aa} ω_{ab}

Measured Raman shift map

ω_{aa} ω_{ab}

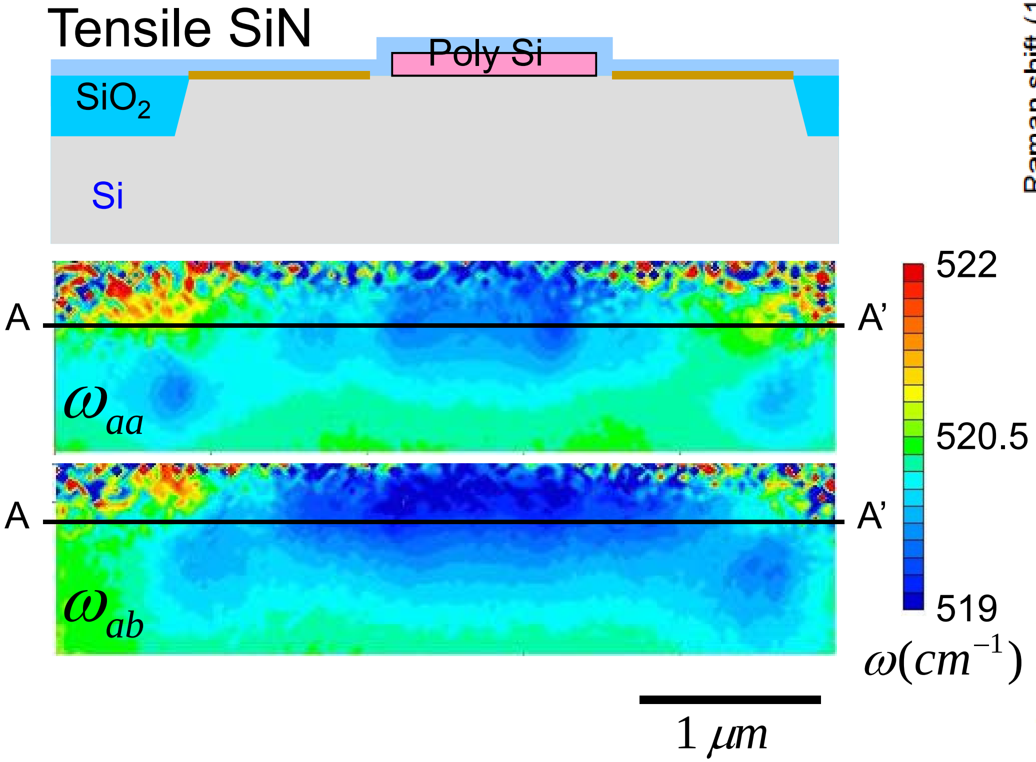
Comparison

Calibration
of material parameters

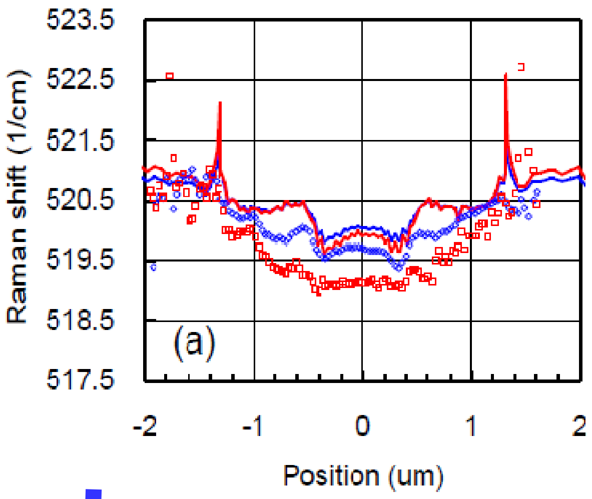
Cross-sectional Distribution

Structure: nMOSFET with tensile stress liner

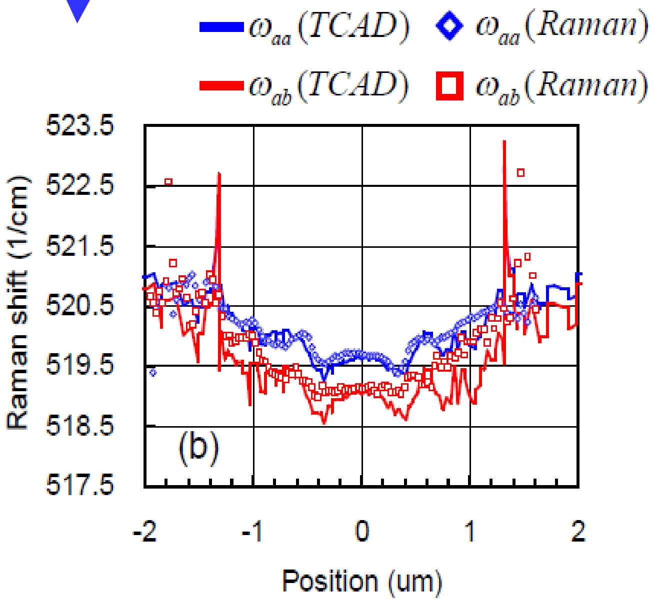
2D distribution of Raman shift



Measured Raman shift variation
along A-A' and calculated
using all tensor components



TCAD Calibration



Calibration results

Portion	Material		Intrinsic stress (MPa)		Young’s modulus (GPa)	Poisson’s ratio
			Initial	Calibrated		
STI	SiO2		－ 220	－ 400	72	0.167
Gate	Poly Si		－ 500	－ 300	145	0.280
Gate, S/D	Silicide		＋ 500	＋ 700	210	0.329
Stress liner	SiN	Tensile	＋ 1550	＋ 1250	180	0.286
		Compressive	－ 3450	－ 3500	210	0.286

＋: tensile
－: compressive

The initial mechanical stress parameters of each material

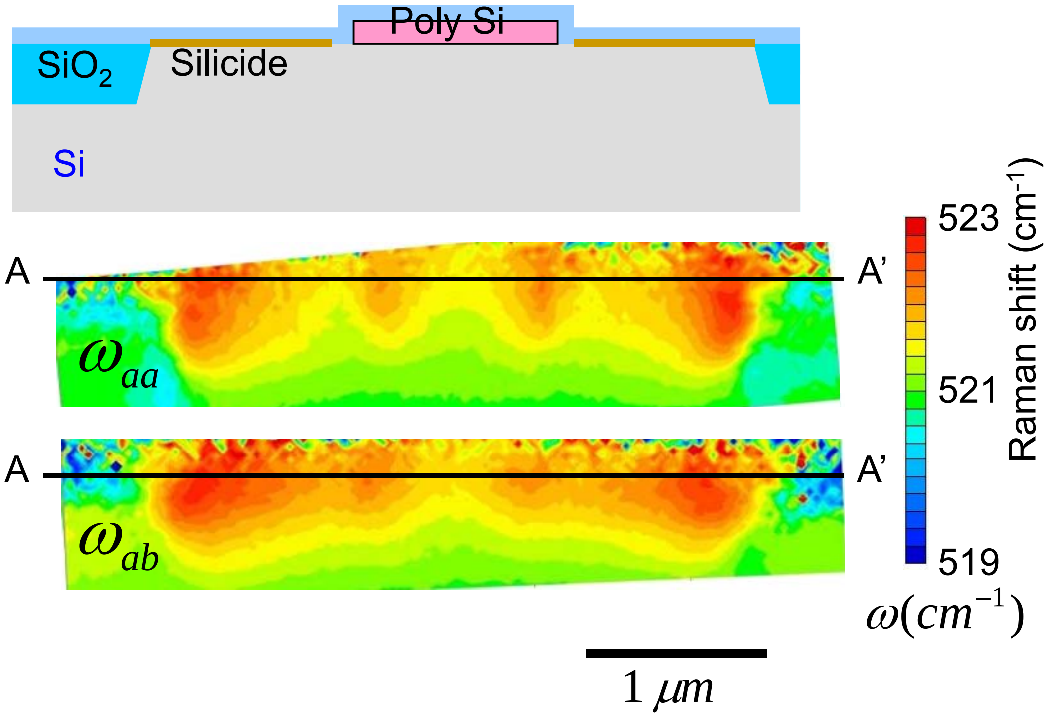
- wafer-bending measurements for intrinsic stress
- nanoindentation measurements for Young’s modulus
- the literature on Poisson’s ratio.

Cross-sectional Distribution

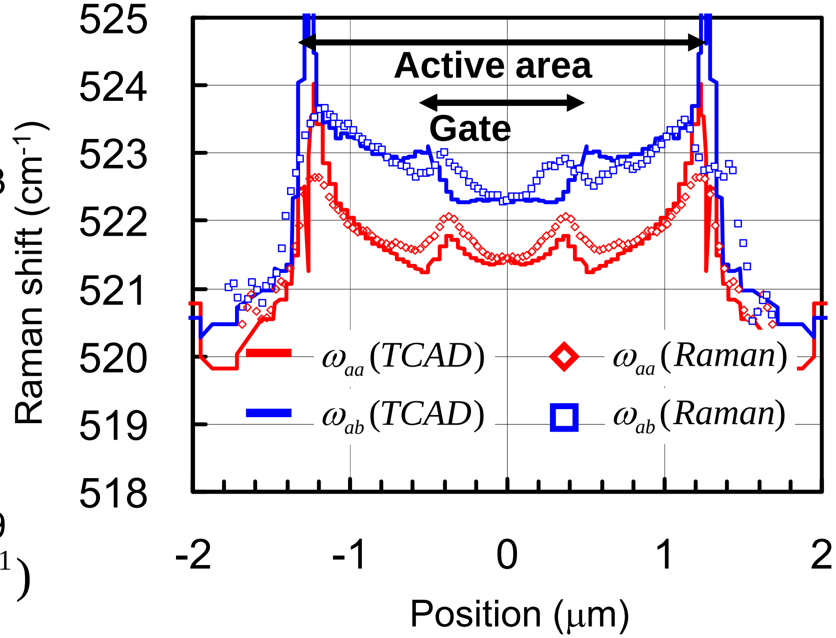
Structure: pMOSFET with compressive stress liner

2D distribution of Raman shift

Compressive SiN

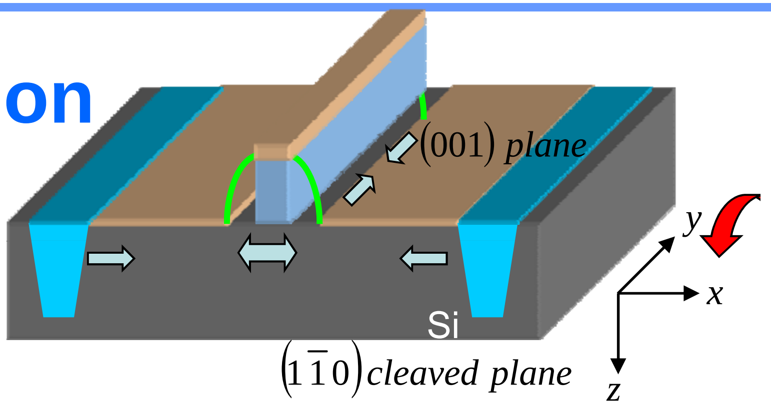


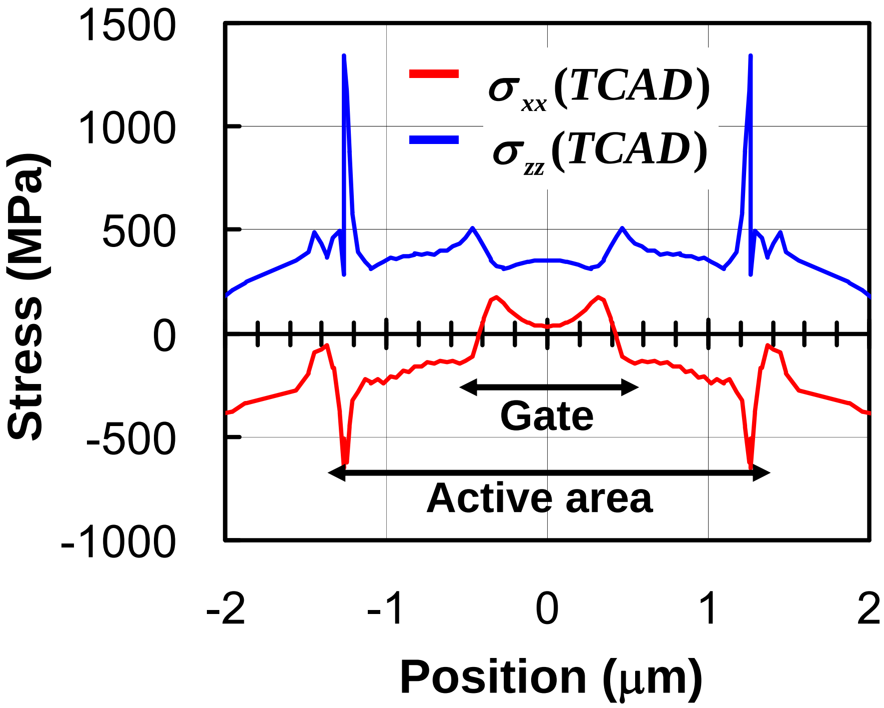
Measured Raman shift variation along A-A' and calculated using all tensor components



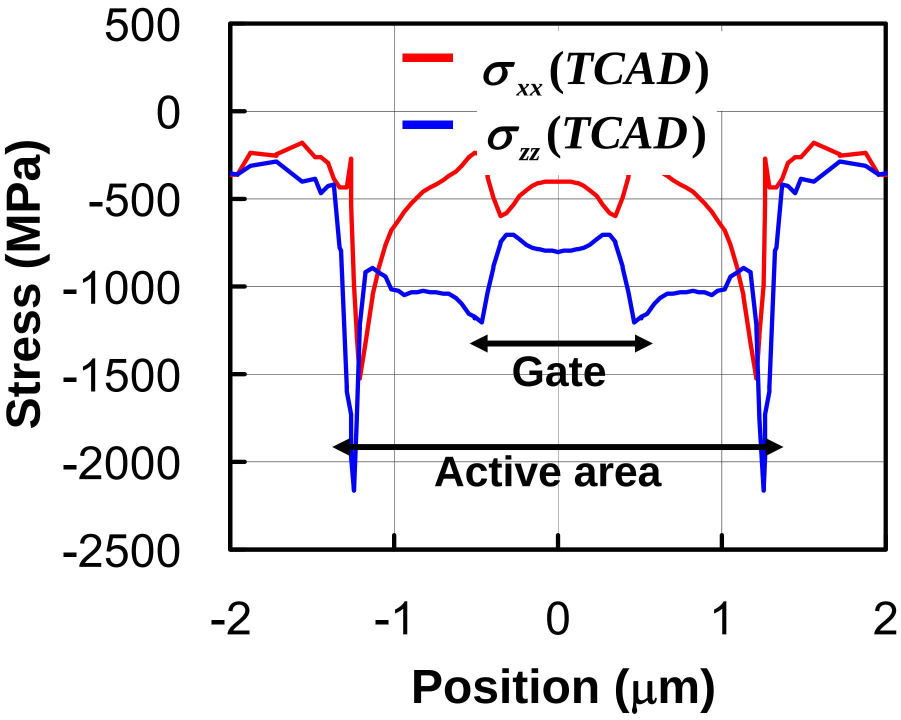
Stress distributions calculated by calibrated TCAD

After stress liner deposition





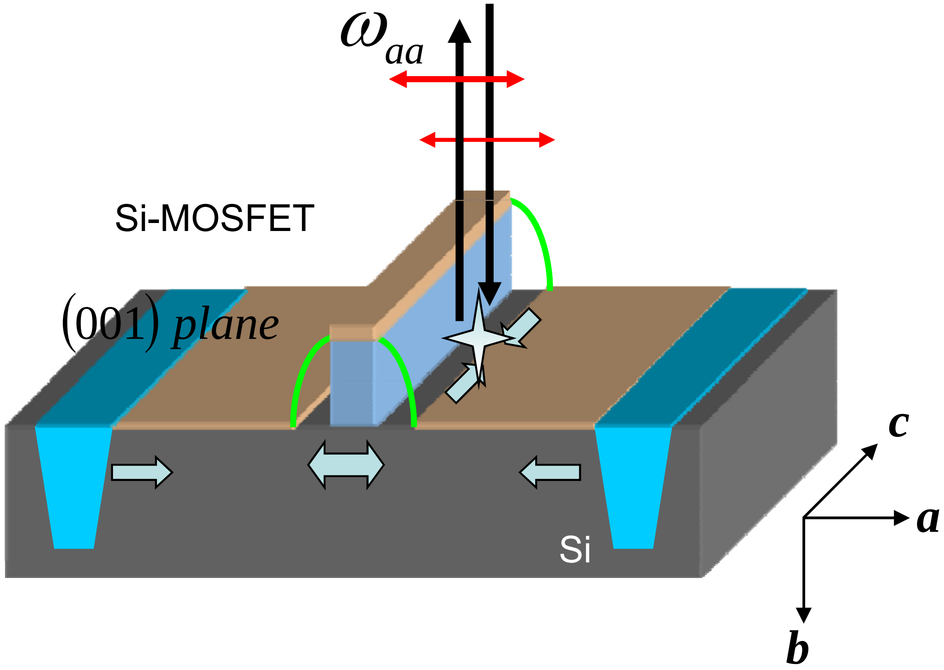
N structure

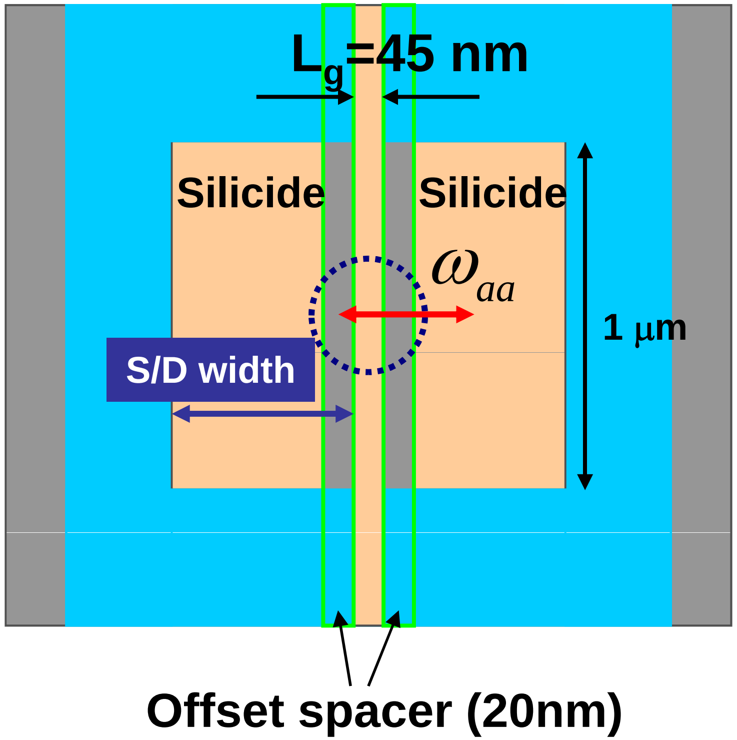


P structure

Verification in scaled device by top down Raman measurements

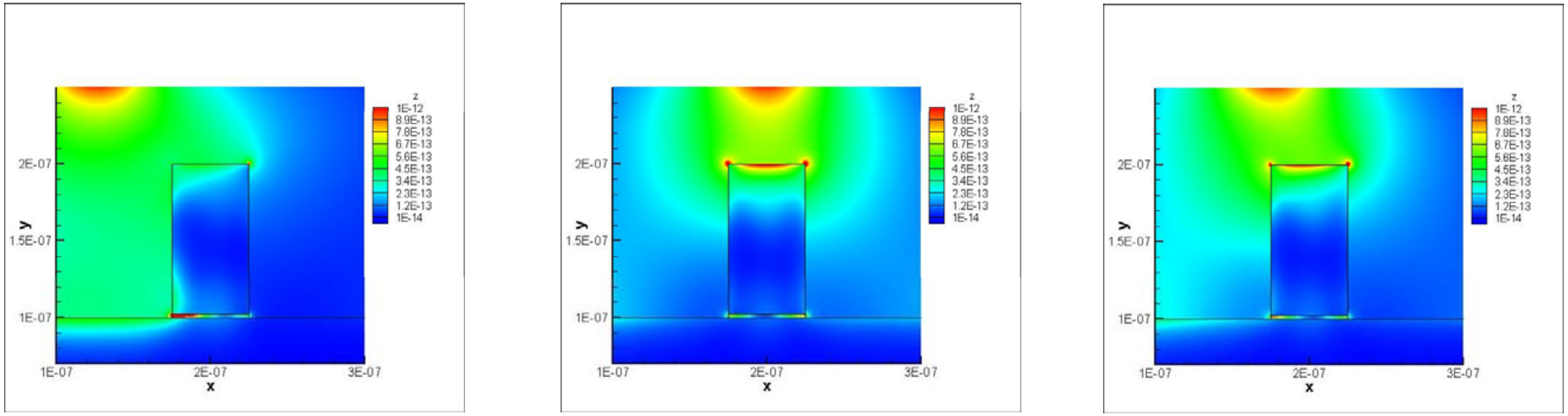
Raman signals only come from under the offset spacer region because the rests of regions are covered with metallic silicide.



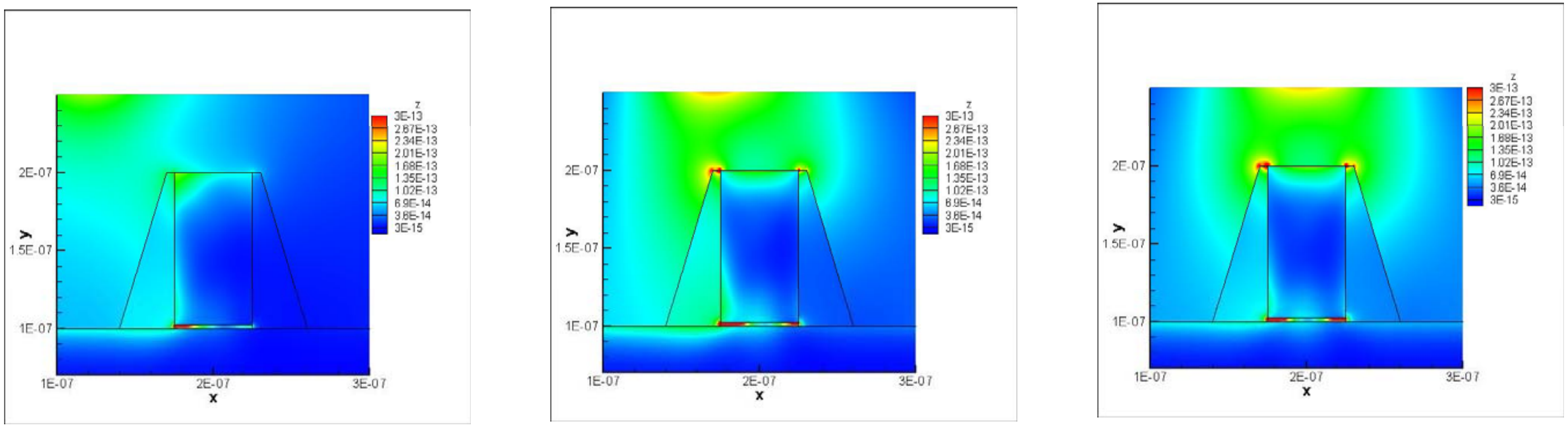


FDTD simulation for a gate structure for a-polarization

L_g= 50 nm

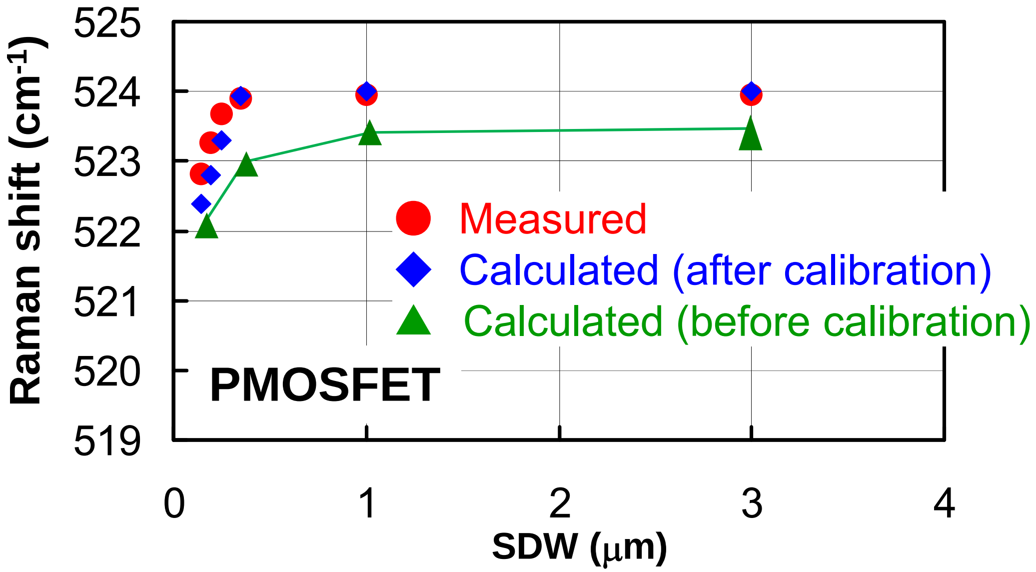


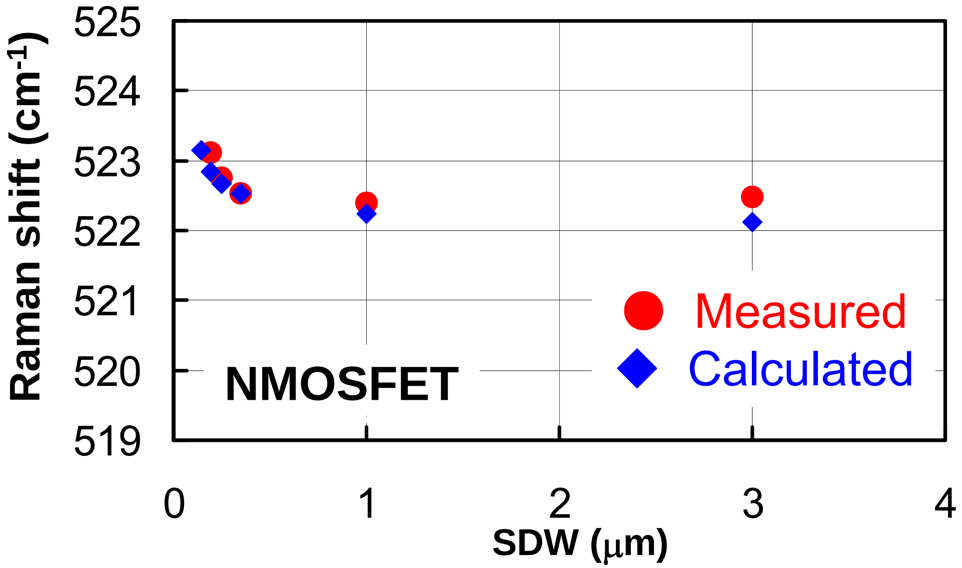
without side wall

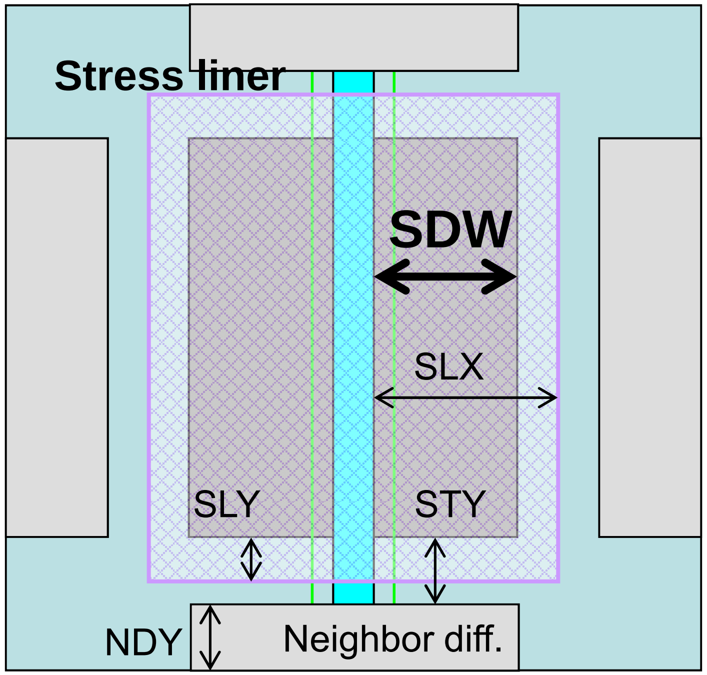


with side wall

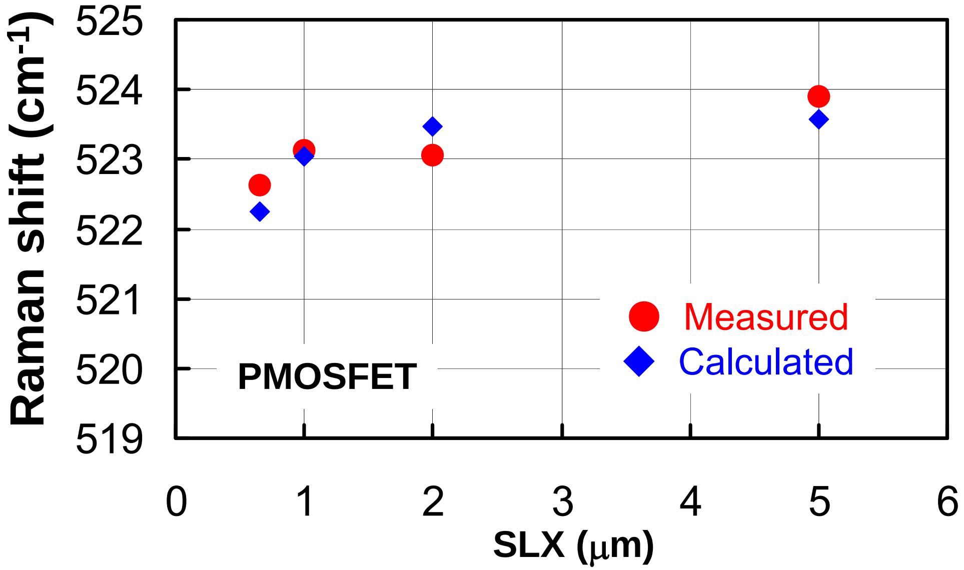
SDW dependence measured and calculated Raman shifts

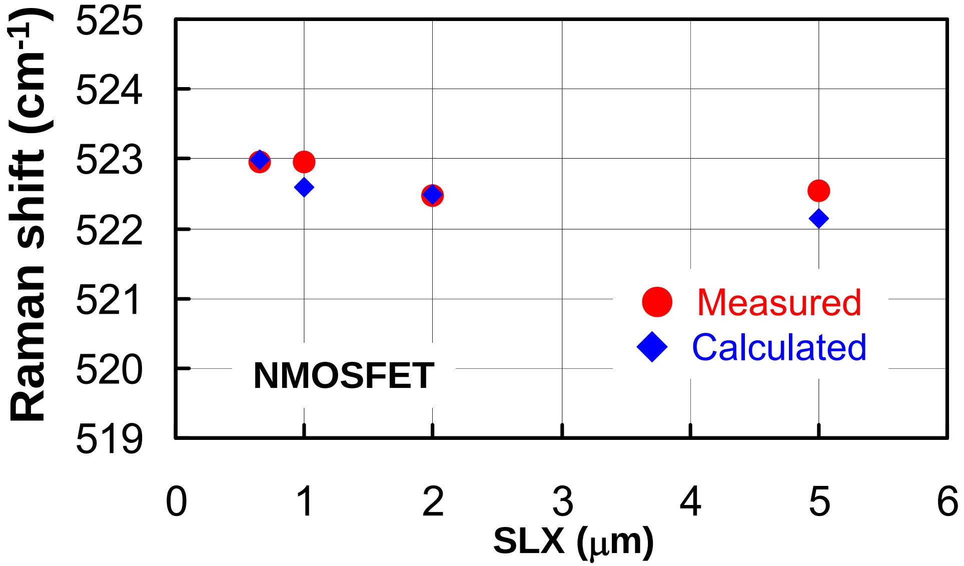


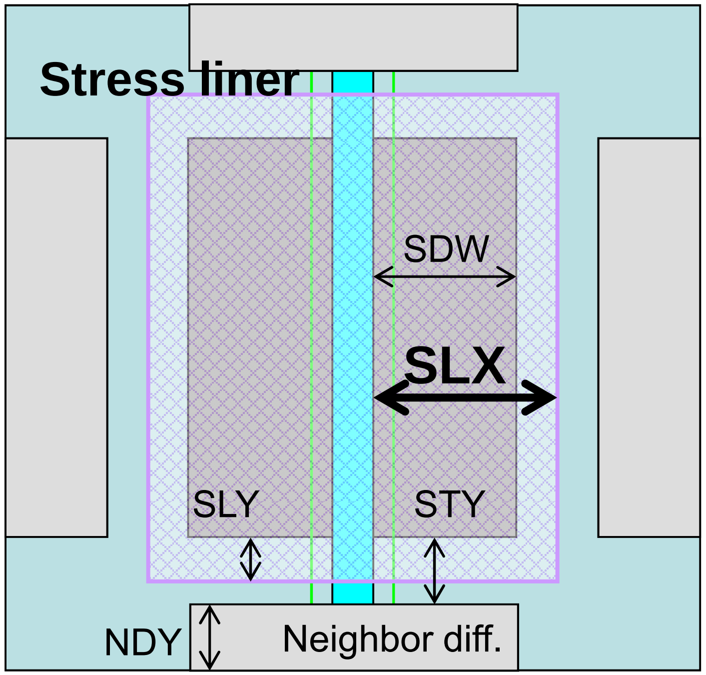




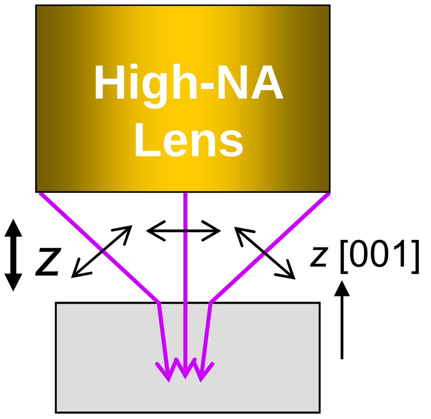
SLX dependence measured and calculated Raman shifts





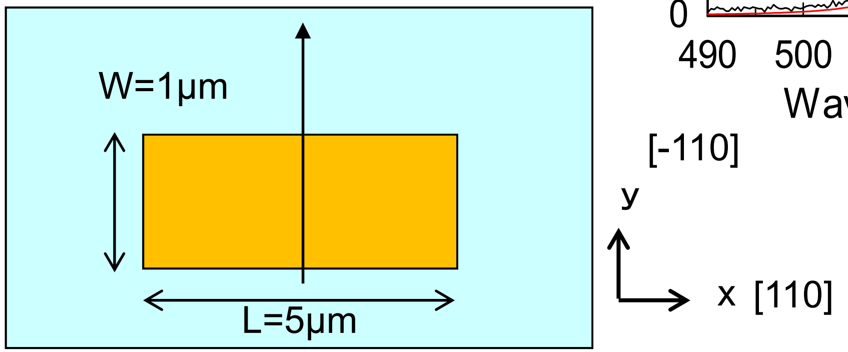


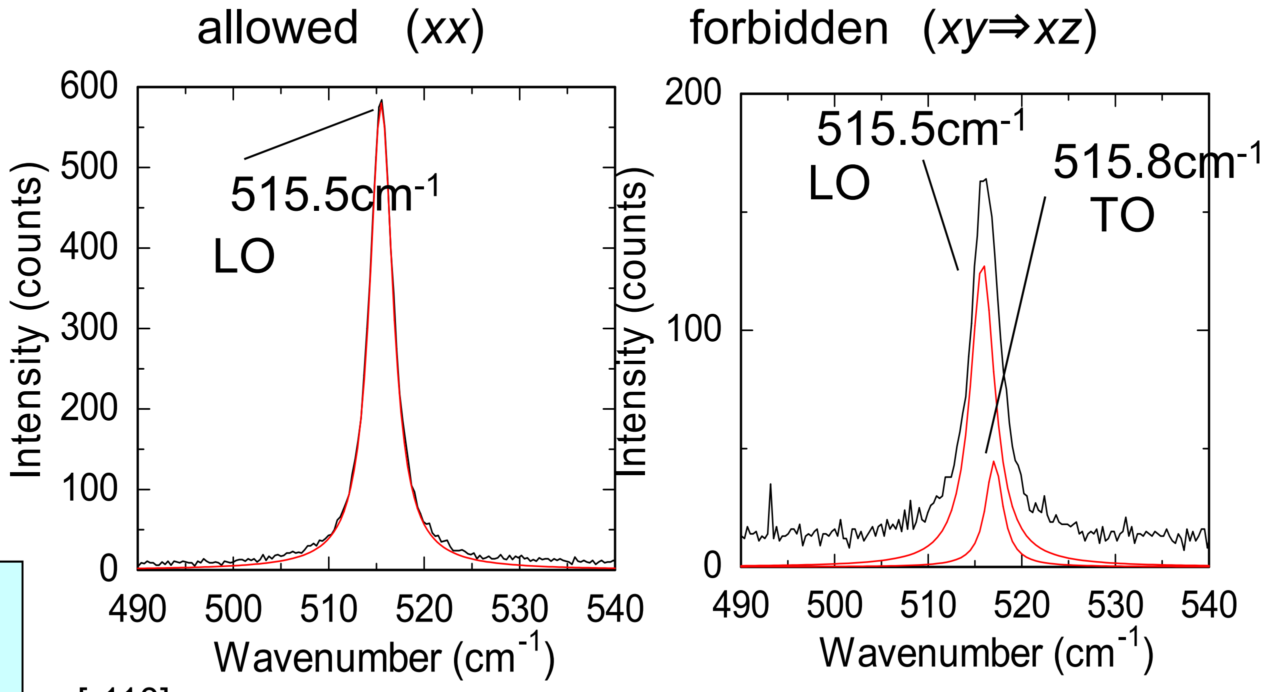
High-NA Raman measurement on Si (001) surface



z polarization component

1 µm Wide Stripe SSOI
(strained Si on Insulator)





Raman Spectrum in the middle

Middle: biaxial tensile stress
L direction 1.3GPa
W direction 1.0GPa
Edge: uniaxial tensile stress
L direction 1.4GPa
W direction 0.1GPa

Edge
L-direction stress: not relaxed
W-direction stress: relaxed

Assuming that shear stresses are negligible

Summary

- Polarized UV Raman micro-spectroscopy acquires higher ability to quantitatively analyze local strain by combination with stress simulation and optical simulation.
- Evaluation of mechanical stress in scaled Si MOSFETs using TCAD simulations calibrated by UV Raman measurements.
  - The mechanical stress parameters are calibrated by comparing Raman shift calculated from all tensor components with Raman shifts measured by polarized UV Raman spectroscopy.
  - Calibrated stress simulation agrees with the layout dependence of top-view Raman measurements.