Micro-Raman Spectroscopy of Individual Phonon Modes in Strained Silicon

E. Schaler, A. Tarun, M. Motohashi, N. Hayazawa & S. Kawata
Nanophotonics Laboratory, RIKEN (Institute of Physical and Chemical Research), Wako, Japan

We present a novel approach for measuring the degree and orientation of strain within the strained silicon (ε-Si) regions of transistors in Intel dies. Employing Raman spectroscopy techniques to identify measureable differences in the Raman shift and spectral width between Si and ε-Si samples enables the direct calculation of material strain as a function of these scattering properties. Innovative polarization of incident light permits the parameterization and quantification of the degree strain in three dimensions: polarizing laser light into radial and azimuthal configurations results in the independent excitation of dominant transverse (TO_1 / TO_2) and longitudinal (LO) optical signals within the sample, respectively. Results reveal differences in the peak Raman shift between radial and azimuthal polarized light, and imply unequal degrees of strain in the LO and TO phonon modes. Conventional transistors employ quantities of ε-Si – produced by layering Si on SiGe – to reduce atomic forces that interfere with electron propagation through such semiconductors. The quantification and eventual optimization of this ε-Si in transistors can have a profound impact on chip design by enabling further increases in transistor speed and reductions in power requirements. The approach can also be extended to other materials for micro- and nano-scale characterization of strain.

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Nanophotonics Laboratory, RIKEN (Institute of Physical and Chemical Research), Wako, Saitama, Japan

ABSTRACT

We present a novel approach for measuring the degree and orientation of strain within the strained silicon (ε-Si) regions of transistors in Intel dies. Employing Raman spectroscopy techniques to identify measureable differences in the Raman shift and spectral width between Si and ε-Si samples enables the direct calculation of material strain as a function of these scattering properties. Innovative polarization of incident light permits the parameterization and quantification of the degree strain in three dimensions: polarizing laser light into radial and azimuthal configurations results in the independent excitation of dominant transverse (TO_1 / TO_2) and longitudinal (LO) optical signals within the sample, respectively. Results reveal differences in the peak Raman shift between radial and azimuthal polarized light, and imply unequal degrees of strain in the LO and TO phonon modes. Conventional transistors employ quantities of ε-Si – produced by layering Si on SiGe – to reduce atomic forces that interfere with electron propagation through such semiconductors. The quantification and eventual optimization of this ε-Si in transistors can have a profound impact on chip design by enabling further increases in transistor speed and reductions in power requirements. The approach can also be extended to other materials for micro- and nano-scale characterization of strain.

INTEREST IN & IMAGING OF TRANSISTORS

Intel Microchip

- Demand for advances in processing speed
- 90nm & 65nm chipsets utilize ε-Si in transistors
  - Electrons flow more easily through ε-Si than Si (greater space between atoms)
  - Increased transistor operation rates

How can the direction and degree of strain be measured in these transistors?

- Quantification of strain in 3D
- Optimization of strain in 3D for improved performance and efficiency

Strained Silicon (ε-Si)

- Formed by layering Si over SiGe
  - Si:Ge ratio directly controls the lattice constant (LC) of the SiGe crystal
  - Si crystal layer (smaller LC) is strained by the SiGe (larger LC)
- Strain observed via Raman spectroscopy
  - Raman peak shift and spectral width directly reveal strain in sample:

$$\sigma = -0.25 \cdot 10^{9} \times \Delta\tilde{\nu}\ ,\ \ \Delta\tilde{\nu} = \text{peak shift}\ [1]$$

$$\sigma = E\varepsilon$$

- Polarization of light will confine observation to known phonon modes
  - Radial Polarization (**TO** + LO)
  - Azimuthal Polarization (**LO**)

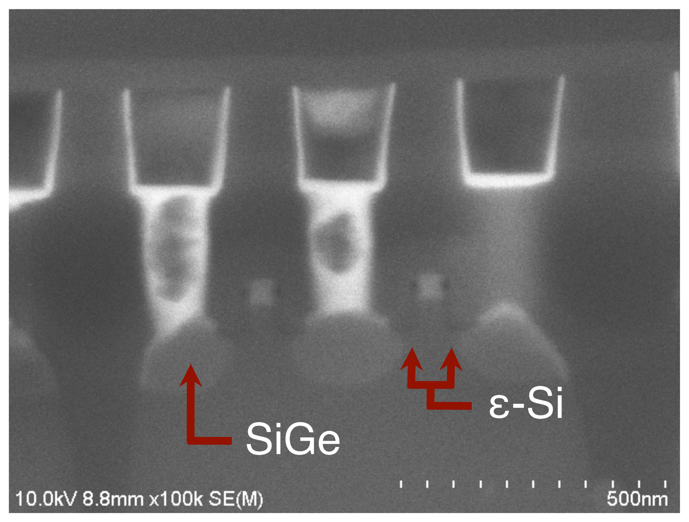


Figure 1. SEM cross-sectional image of a 90nm Intel transistor.

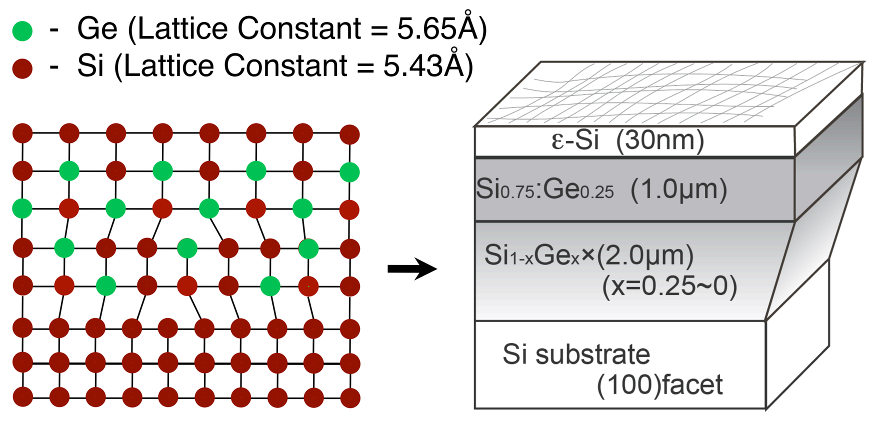
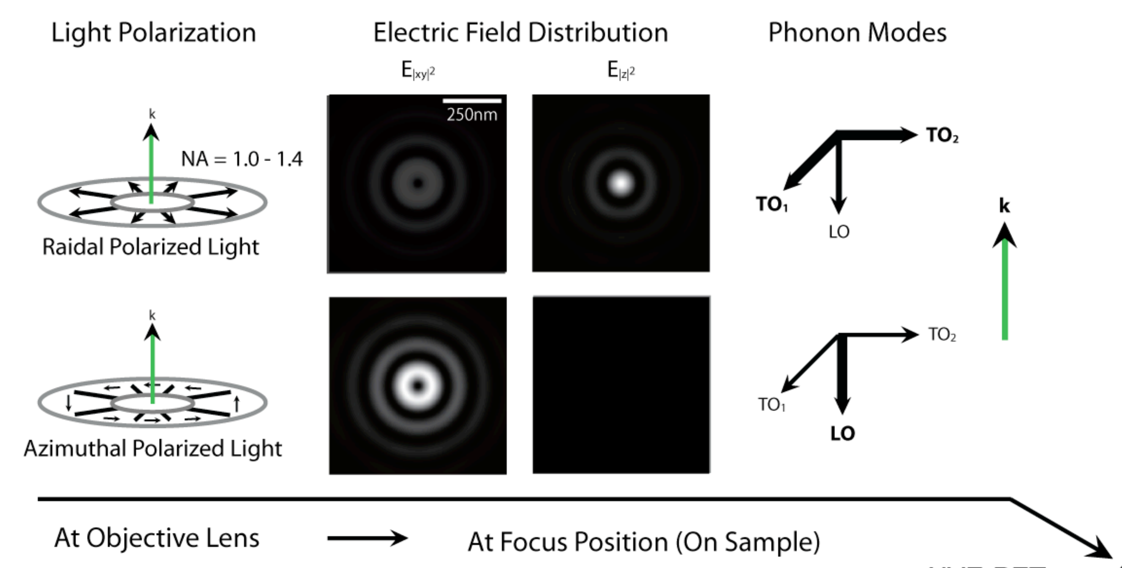
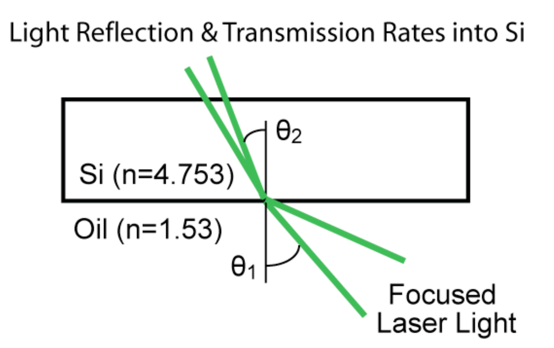


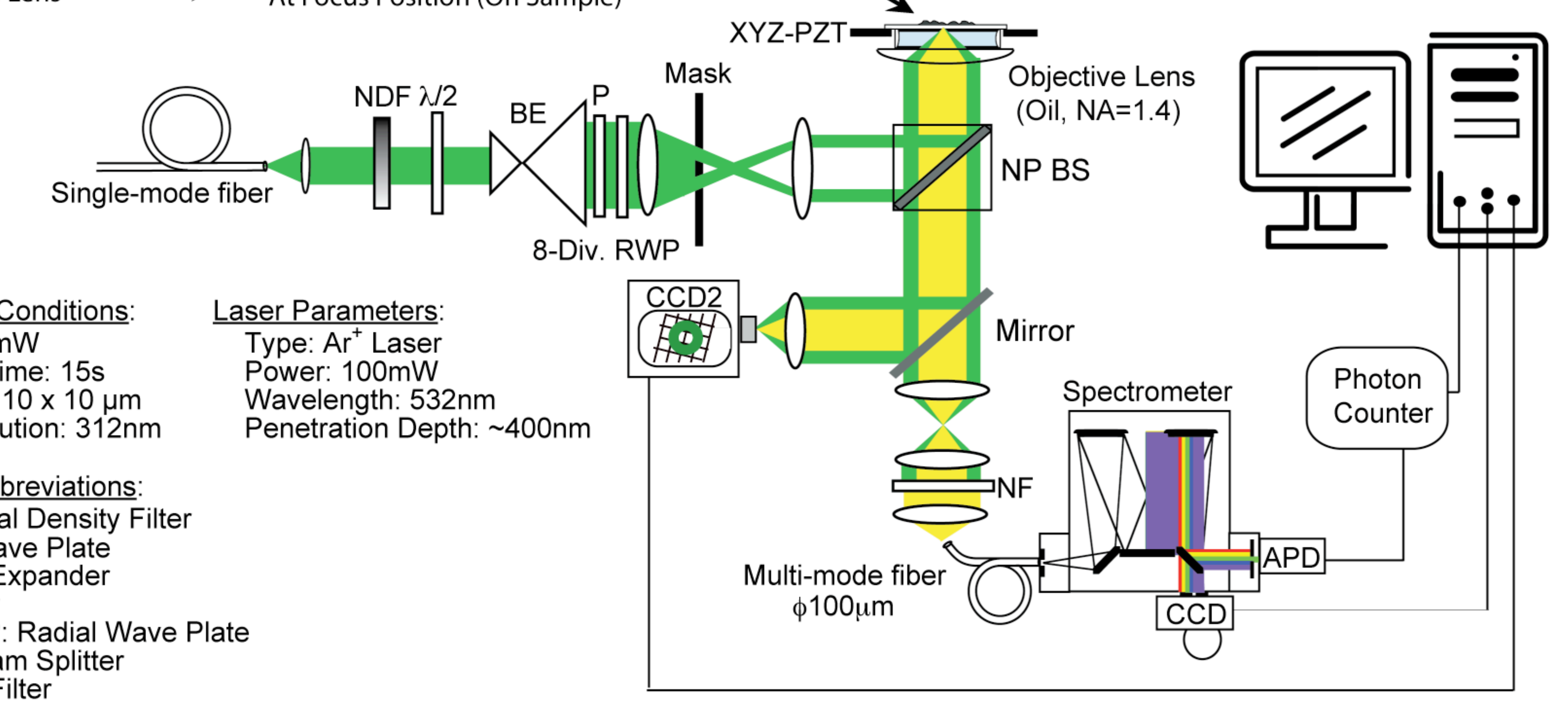
Figure 2. Cross-section of ε-Si sample. [2]

EXPERIMENTAL CONFIGURATION





N.A	θ_1	θ_2	R_P	T_P	R_S	T_S
1.4	66.21	17.13	1.2%	98	57	42
1.2	51.66	14.62	11	89	43	57
1.0	40.81	12.14	17	83	36	64



Experimental Conditions:
Power: 1.6mW
Exposure Time: 15s
Scan Area: 10 x 10 μm
Scan Resolution: 312nm

Laser Parameters:
Type: Ar+ Laser
Power: 100mW
Wavelength: 532nm
Penetration Depth: ~400nm

Equipment Abbreviations:
NDF: Neutral Density Filter
λ/2: Half Wave Plate
BE: Beam Expander
P: Polarizer
8-Div. RWP: Radial Wave Plate
NP BS: Beam Splitter
NF: Notch Filter

Figure 3. Experimental Setup (Far-Field Raman Spectroscopy) & Light Polarization Overview [2] [3]

ε-SI RESULTS & INTERPRETATION

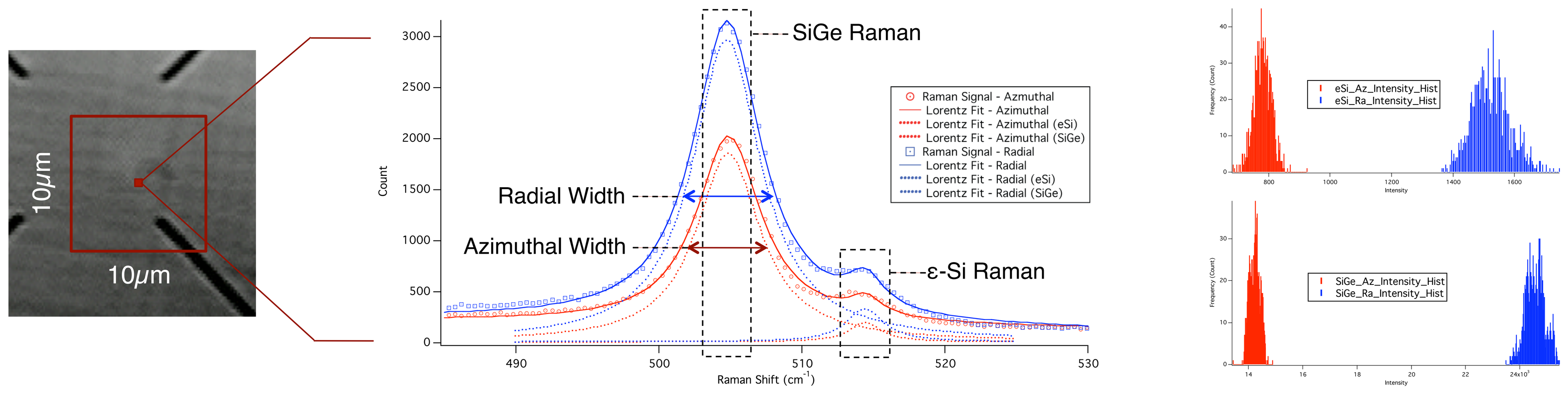


Figure 4. Optical image of ε-Si sample. Sample observation spectra (azimuthal and radial light polarization configurations) and subsequent fitting using a Lorentz curve.

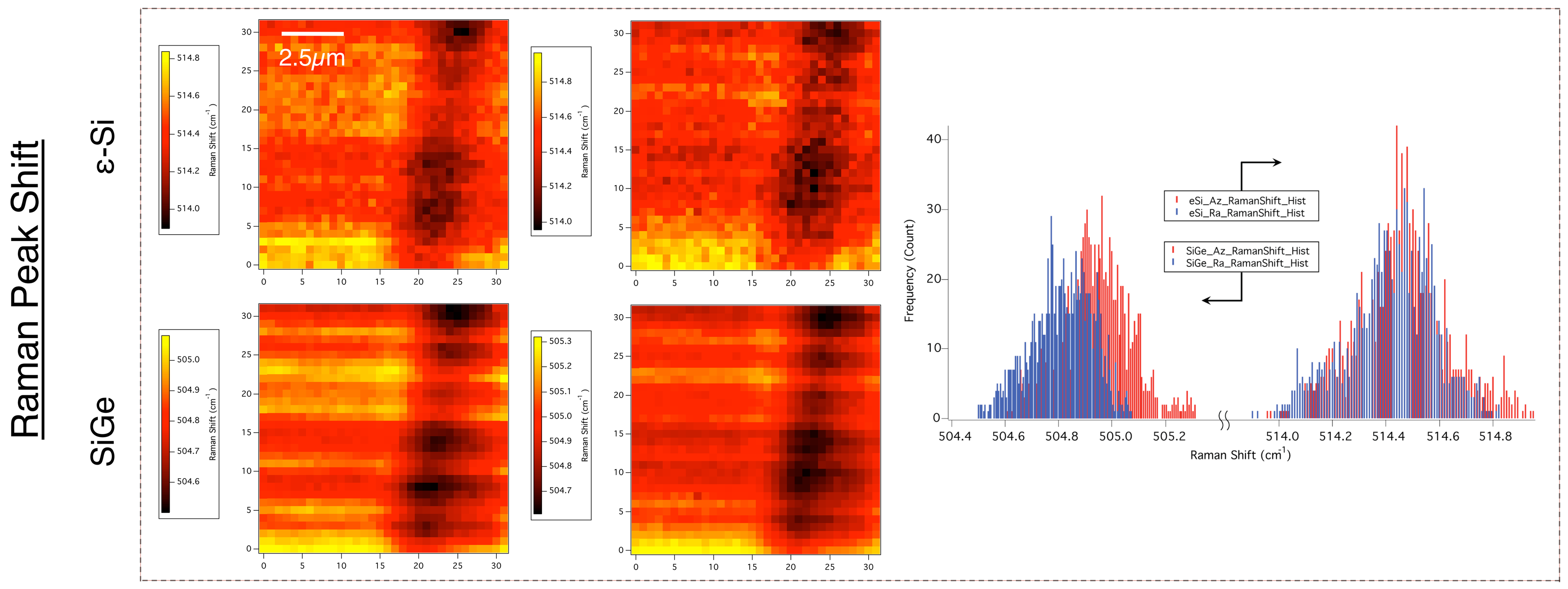


Figure 5. Raman peak shift across the sample (in both the ε-Si and SiGe).

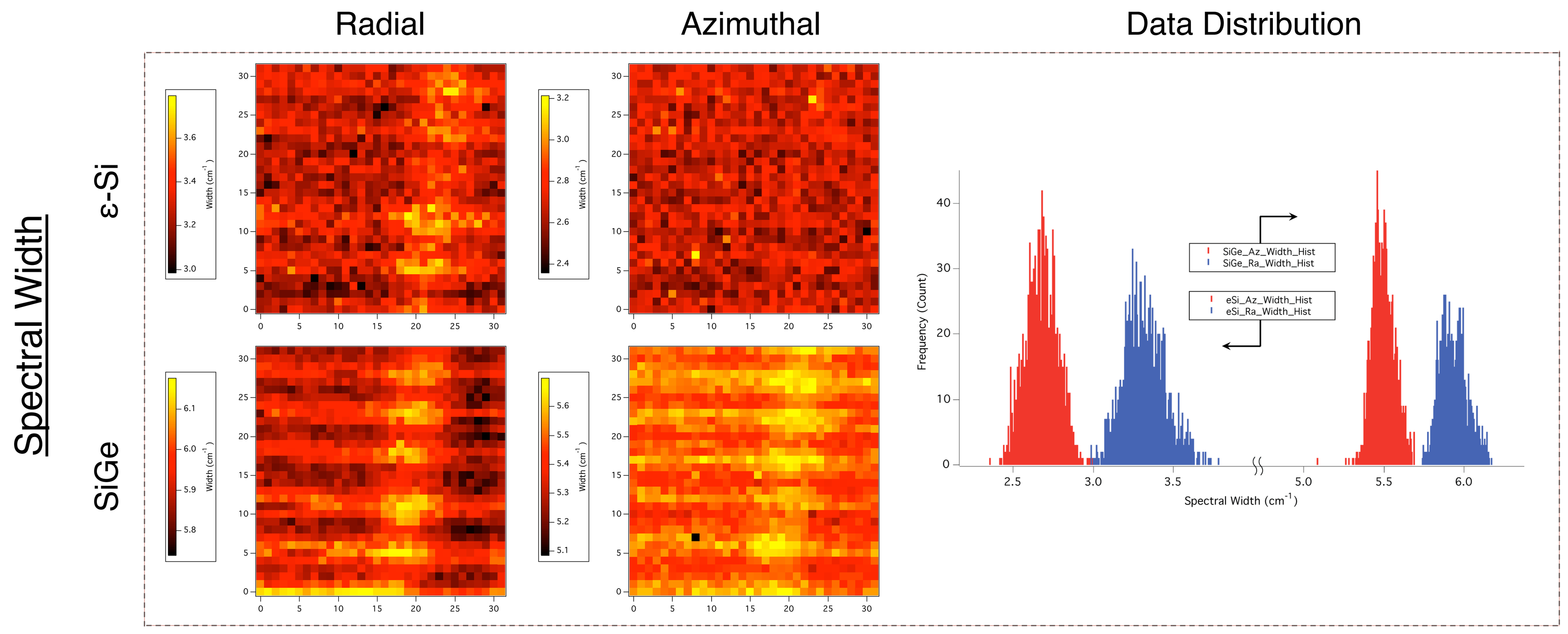


Figure 6. Spectral width across the sample (in both the ε-Si and SiGe).

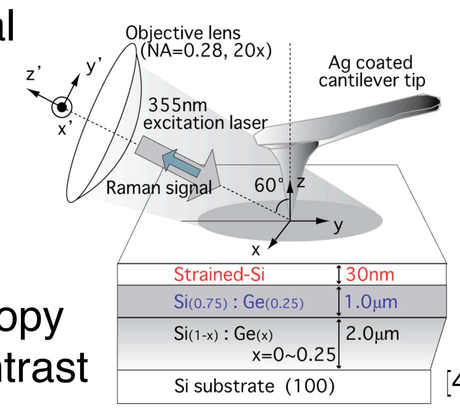
CONCLUSIONS & FUTURE DIRECTION

Significance of ε-Si Sample Results

- Distinguishable difference between ε-Si and SiGe peaks in Raman spectra
- Distribution of spectral width values is larger in ε-Si (varied strain) than in SiGe (primarily relaxed)
- SiGe Raman has a large width on the edges of large Raman peak shift regions (LO vs. LO+TO)
- ε-Si Raman has a large width on large Raman peak shift regions for radial but not azimuthal polarization (thin layer with high, locally uniform strain)

Optical Imaging of Intel Chip (Transistor)

- Towards identification and mapping of strain within ε-Si of a transistor
- Significant increases in spatial resolution beyond the diffraction limit
  - Lateral Confinement: Enhanced resolution using Near-Field Spectroscopy
  - Vertical Confinement: Enhanced focus on ε-Si layer and ε-Si/SiGe contrast



[4]

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[2] A. Tarun, *et al.* Rev. Sci. Instrum. **79**, 013706 (2008).
[3] N. Hayazawa, *et al.* Jpn. J. Appl. Phys. **46**, pp. 7995-7999 (2007).
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