Introduction of *μm*- and *nm*-sized Semiconductor Raman scattering

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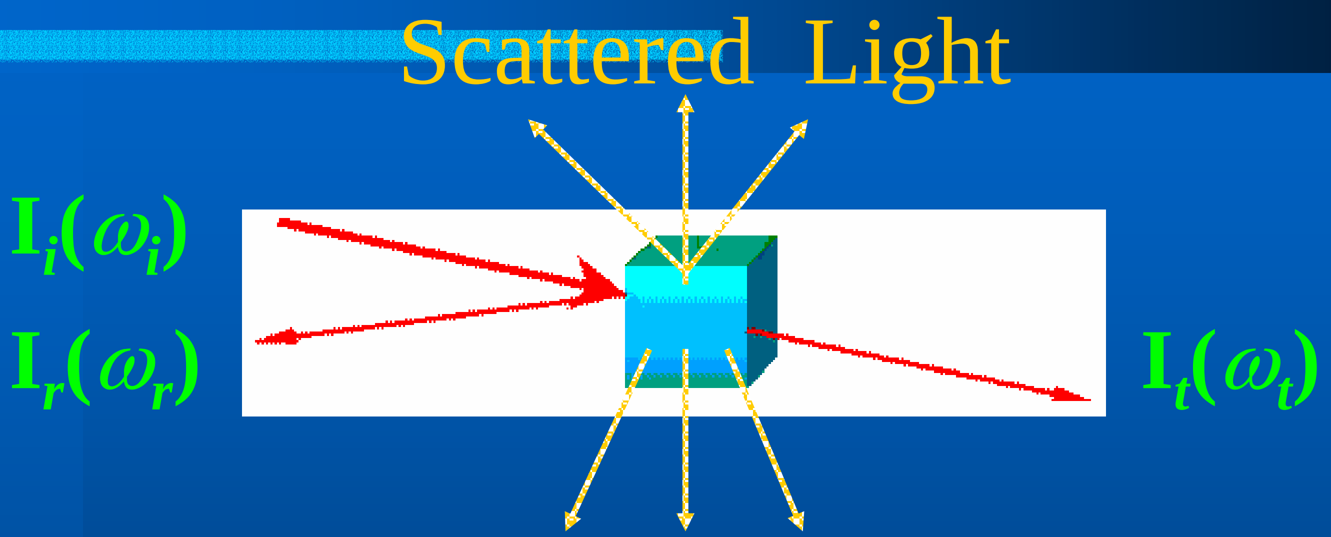
Outline

- Introduction Semiconductor Raman Scattering
- Example: Strain and Concentrations
- Raman Scattering of Nano-Sized Semiconductor (Dot, Wire and Layers)
- Summary

What is Raman?

- Sir Chandrasekhara Venkata Raman
- 1930 Nobel Price Winner

What is Light Scattering?



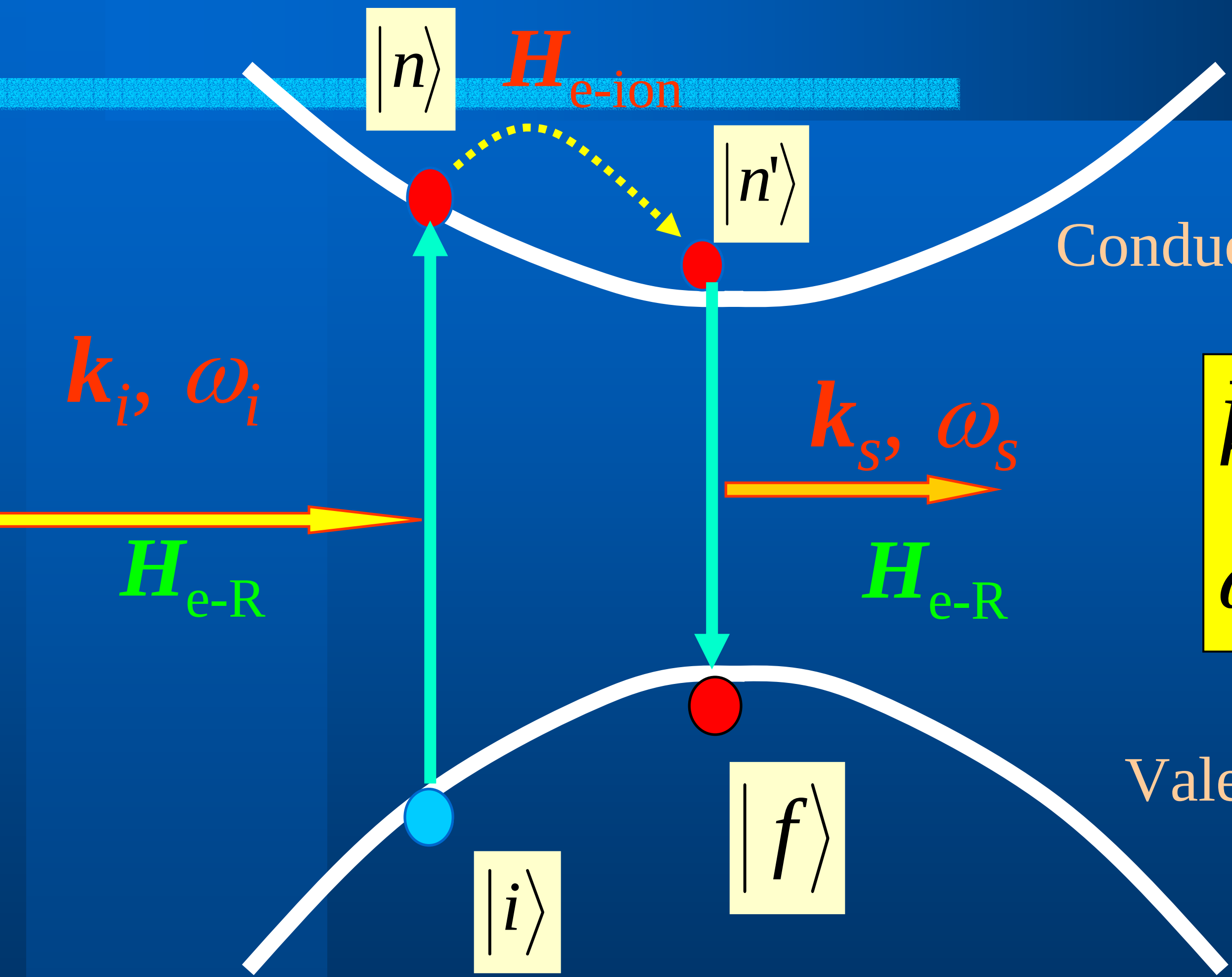
Mie Scattering: Particles,

Rayleigh Scattering: Particles $(10^{-2}\sim10^{-3})I_i$

Brillouin Scattering: Acoustic Phonon $(10^{-6}\sim10^{-9})I_i$

Raman Scattering: Optical Phonon $(10^{-6}\sim10^{-9})I_i$

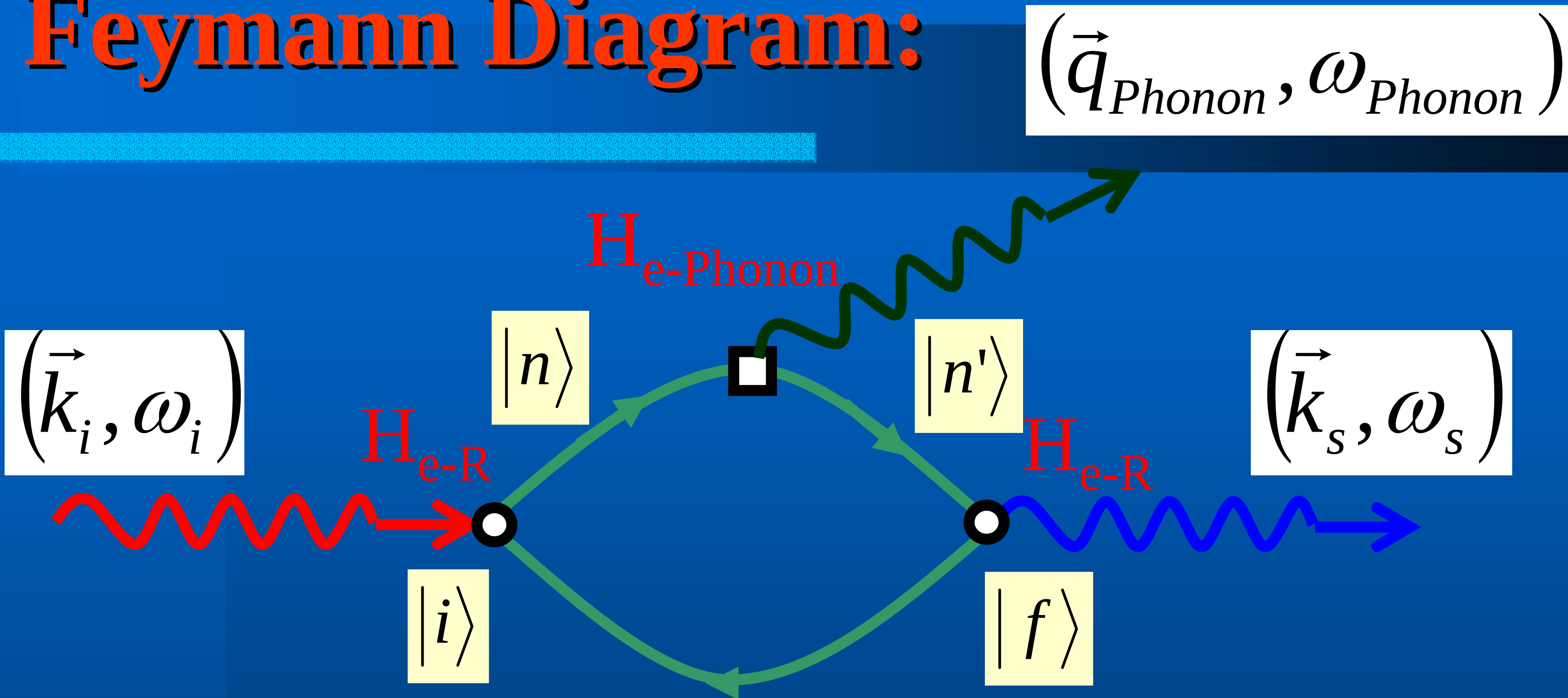
Quantum Mechanics Picture:



$$\vec{k}_i = \vec{k}_s \pm \vec{q}_{Phonon}$$

$$\omega_i = \omega_s \pm \omega_{Phonon}$$

Feymann Diagram:



$$\frac{d^2\sigma}{d\Omega d\omega} \propto \left| \sum_{n,n'} \frac{\langle f | H_{e-R} | n' \rangle \langle n' | H_{e-Phonon} | n \rangle \langle n | H_{e-R} | i \rangle}{\left(\hbar\omega_s - E_{n'} + i\Gamma_{n'}\right)\left(\hbar\omega_i - E_n + i\Gamma_n\right)} \right|^2$$

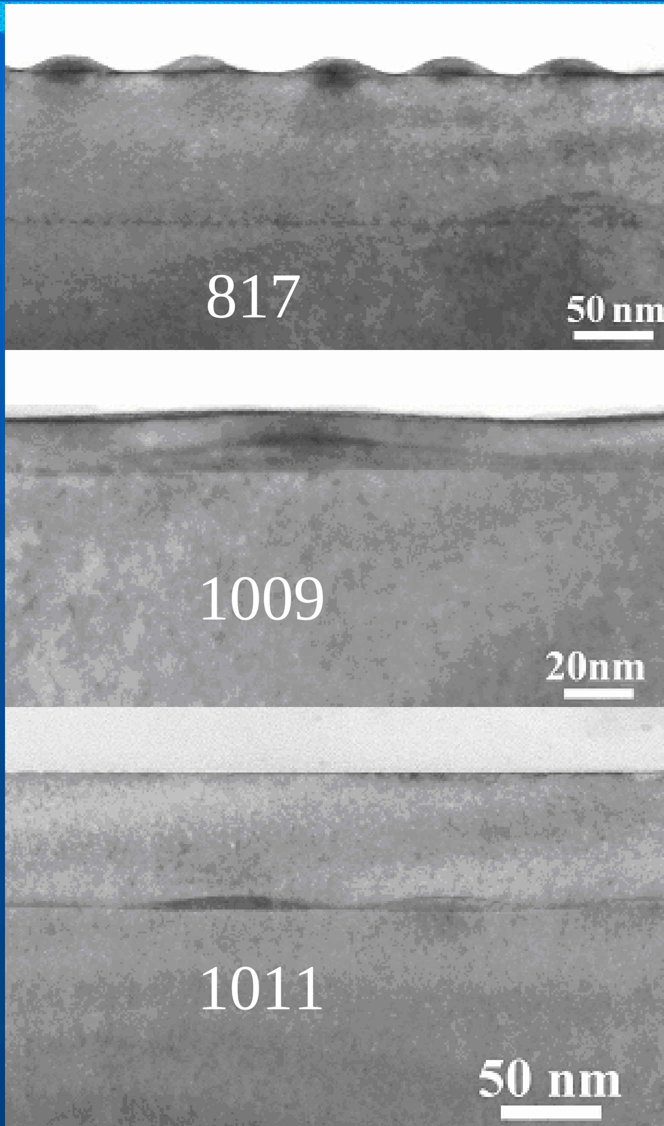
Raman Lineshapes:

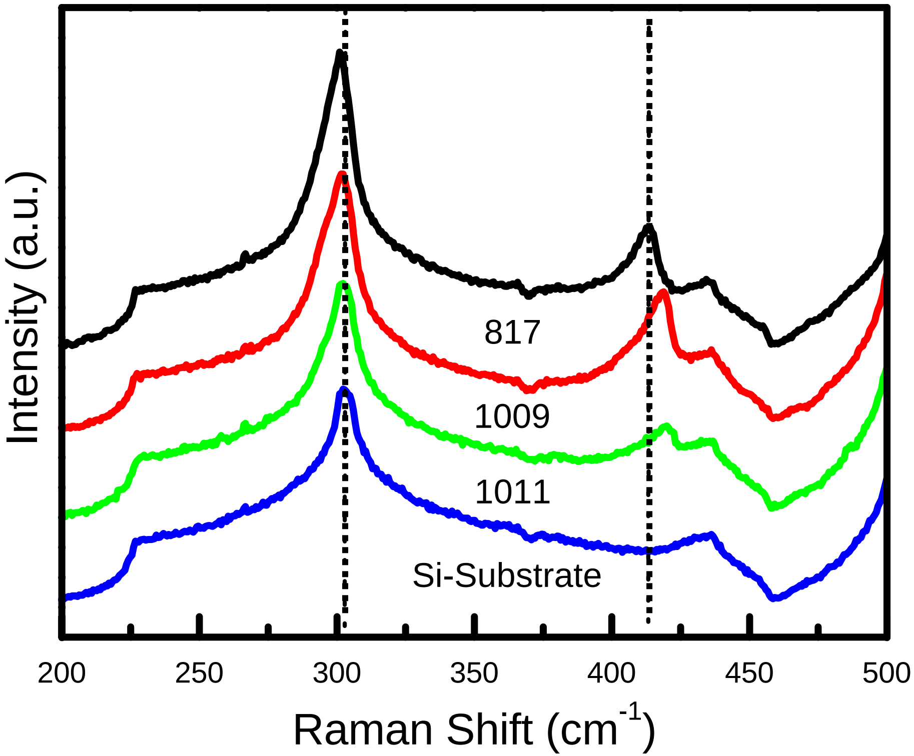
- Gaussian
- Lorentzian
- Fano
- Asymmetry
- ???

1. Raman Shift
2. Linewidth

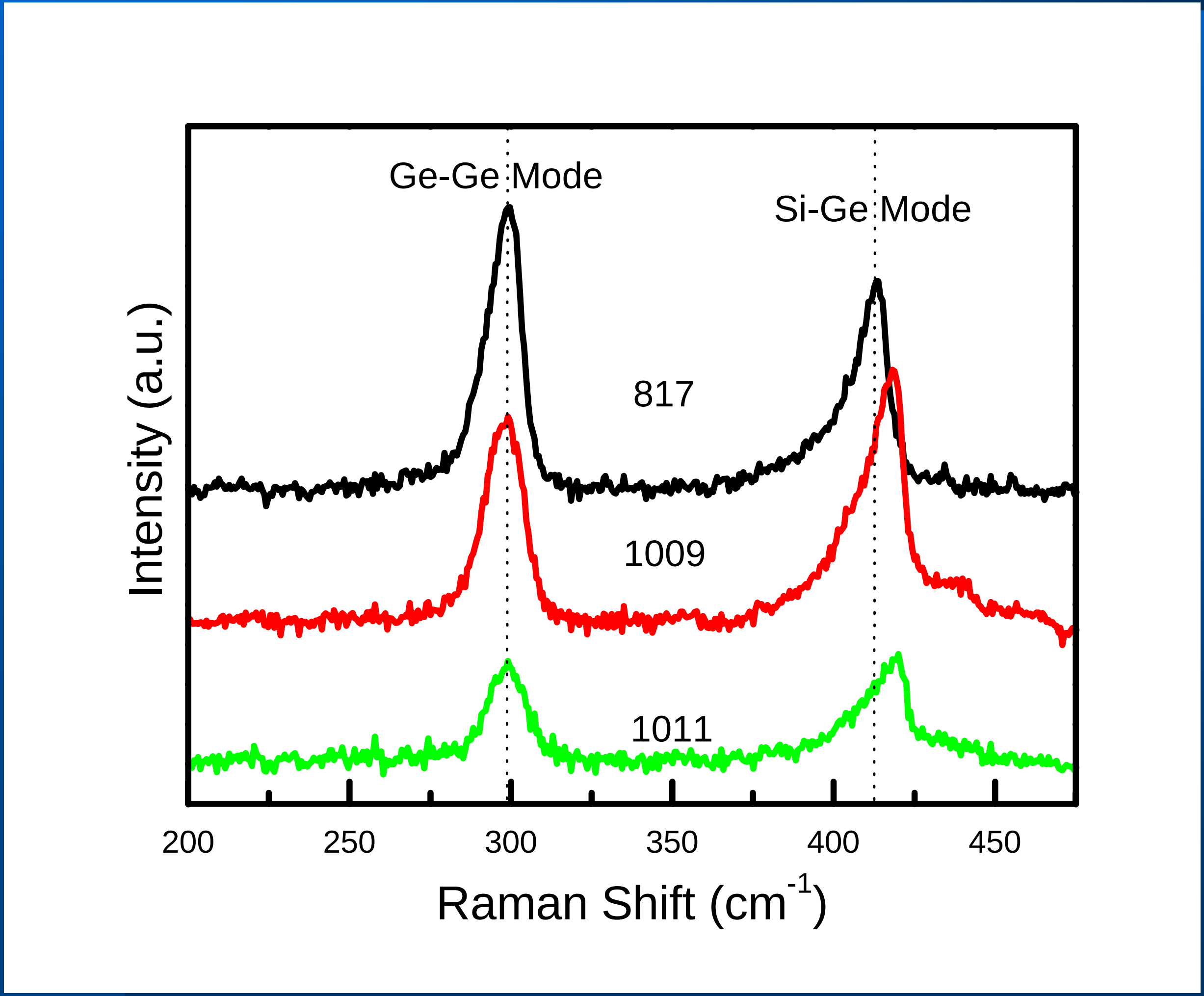
$$\frac{d^2\sigma}{d\Omega d\omega} \propto \left| \sum_{n,n'} \frac{\langle f | H_{e-R} | n' \rangle \langle n' | H_{e-Phonon} | n \rangle \langle n | H_{e-R} | i \rangle}{\left(\hbar\omega_s - E_{n'} + i\Gamma_{n'}\right)\left(\hbar\omega_i - E_n + i\Gamma_n\right)} \right|^2$$

SiGe Alloy Dot on Si(001)



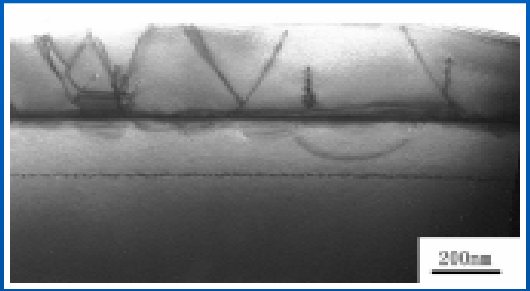


Strain in Embeded Layer

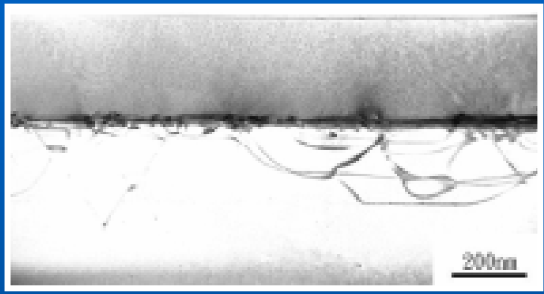


MBE Grown Relaxed SiGe alloy

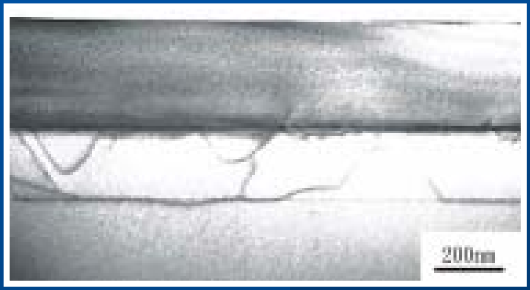
LT-Si 600 ^{o}C(＃319)



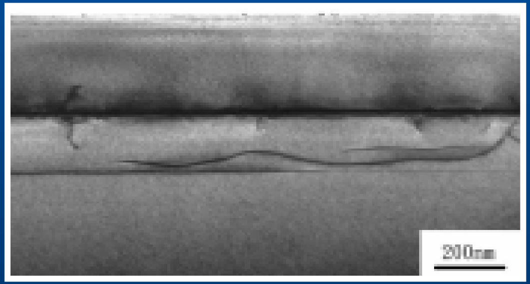
LT-Si 550 ^{o}C (＃320)



LT-Si 500 ^{o}C (＃323)

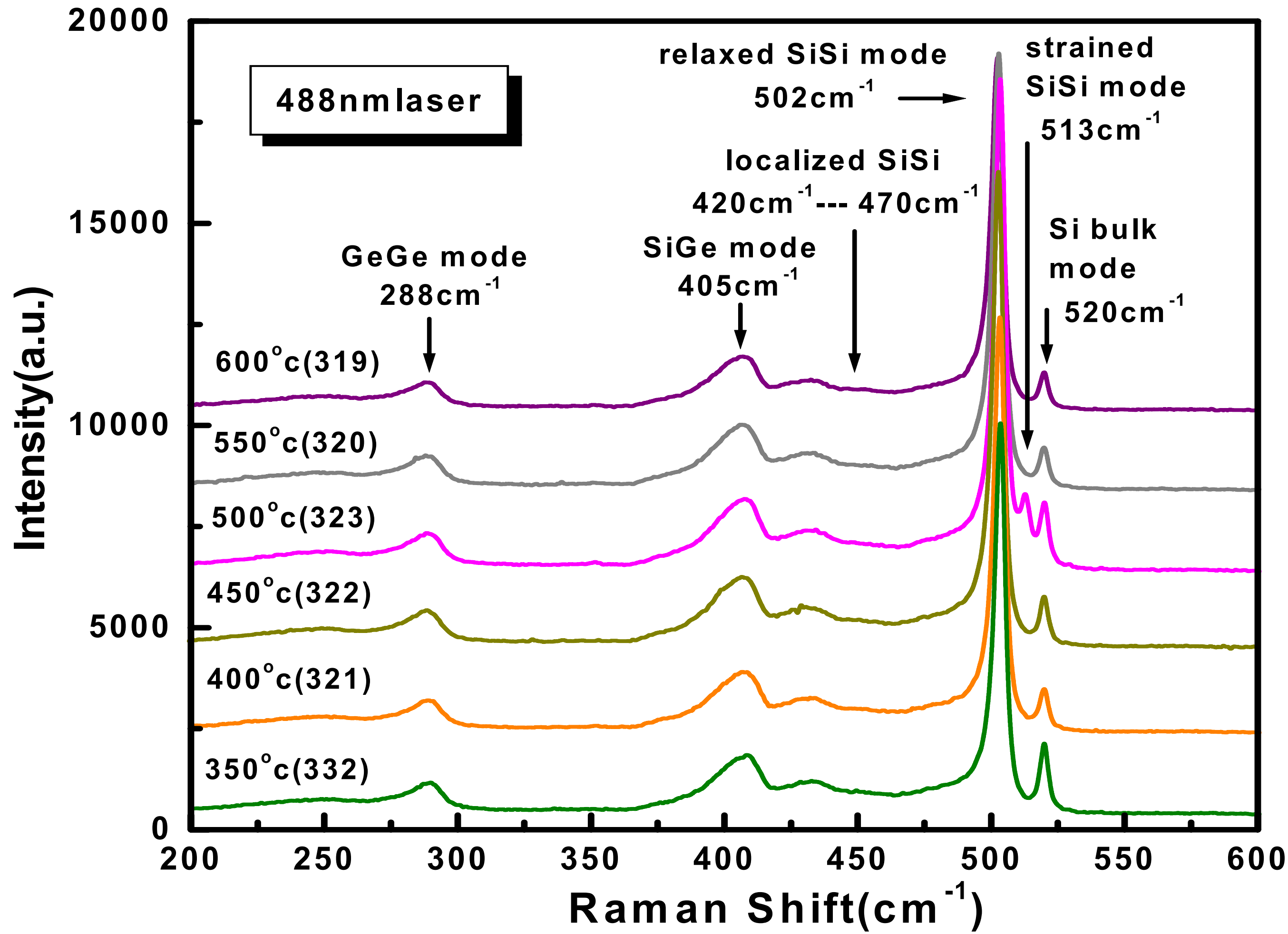


LT-Si 450 ^{o}C (＃322)



LT-Si 400 ^{o}C (＃321)

TEM圖由台大凝態中心
鄭鴻祥教授提供



L-W Lei et.al. ICPS 2002

Strain & Ge Content of Alloy

Raman Shift of $Si_{1-x}Ge_x$ Alloy for $x < 0.4$:

$$\omega_{SiSi} = 520.5 - 62x - 815\varepsilon$$

$$\omega_{SiGe} = 400.5 + 14.2x - 575\varepsilon$$

$$\omega_{GeGe} = 282.5 + 16x - 385\varepsilon$$

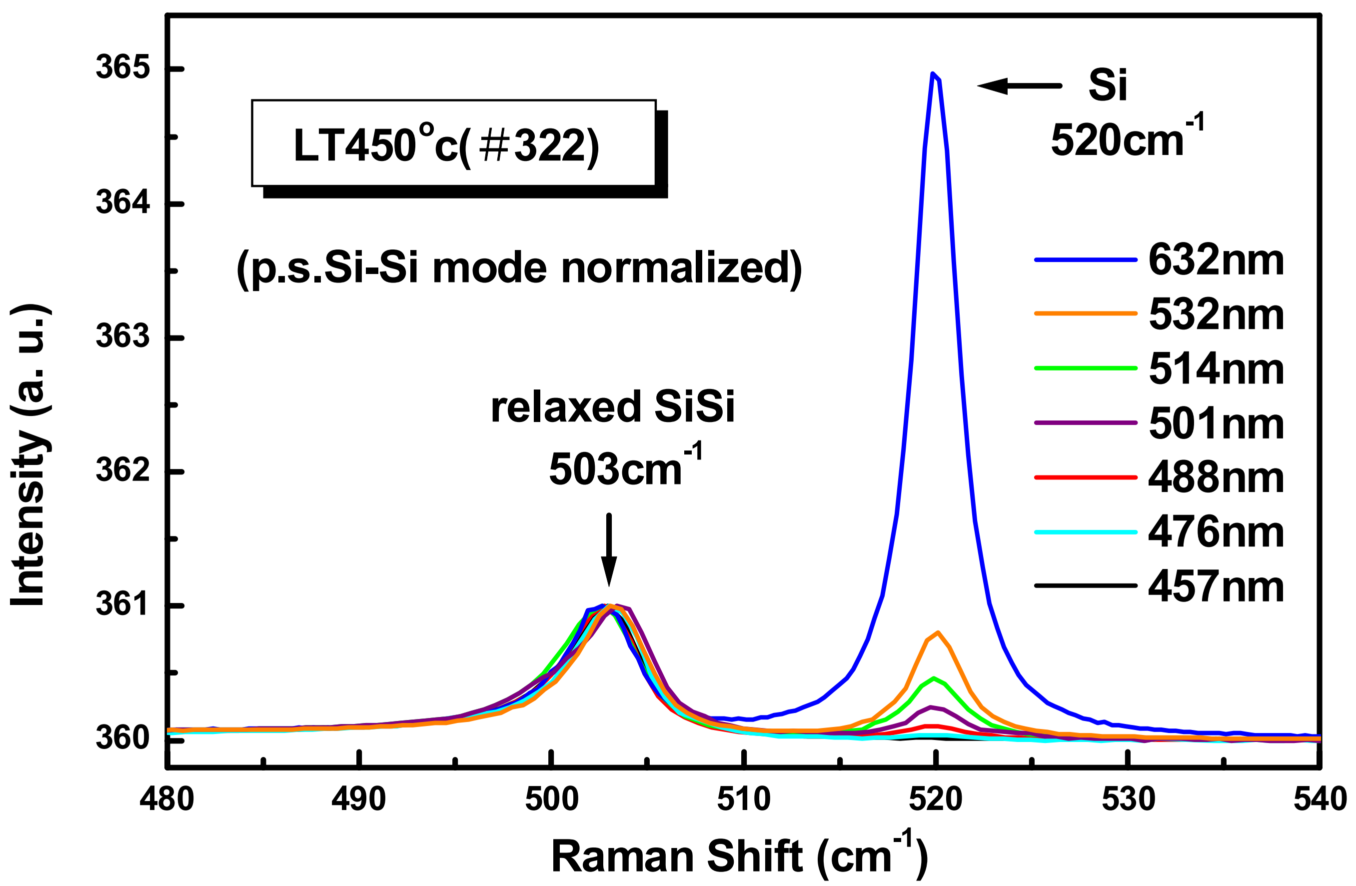
$$\varepsilon = \delta l / l$$

J. Groenen, et.al. Appl. Phys. Lett. (1997)

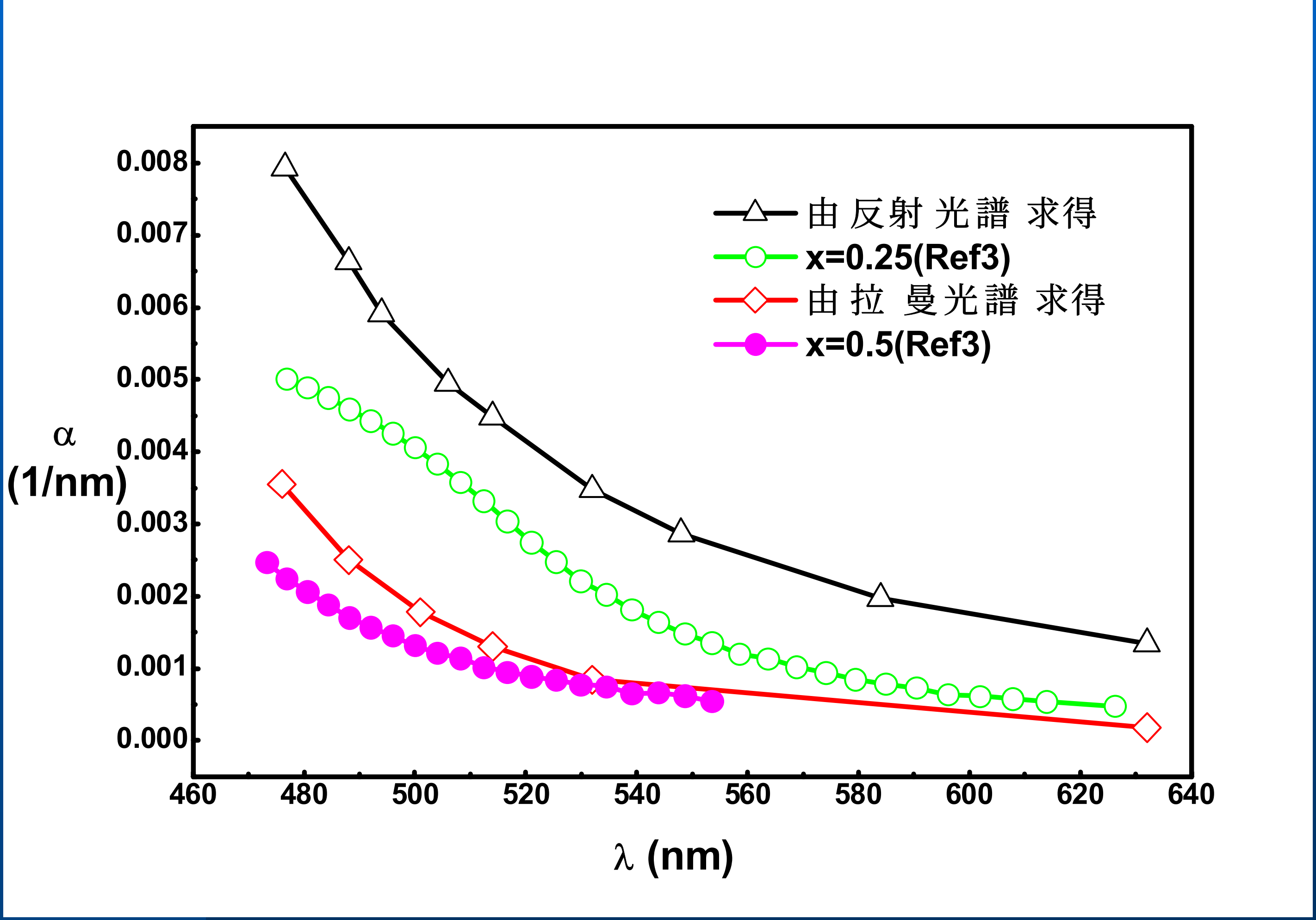
	457nm		488nm		514nm	
sample	x	Σ (%)	x	Σ (%)	x	Σ (%)
#319 (LT600°c)	0. 3 ±0.03	-2.1 ±0.06	0. 3 ±0.03	-1.9 ±0.06	0. 3 ±0.02	-0.04 ±0.003
#320 (LT550°c)	0. 3 ±0.03	-2.3 ±0.06	0. 3 ±0.02	-2.1 ±0.03	0. 3 ±0.02	-0.7 ±0.003
#323 (LT500°c)	0. 3 ±0.03	-1.6 ±0.06	0. 3 ±0.02	-1.4 ±0.03	0. 3 ±0.02	-1.6 ±0.003
#322 (LT450°c)	0. 3 ±0.03	-0.7 ±0.06	0. 3 ±0.03	-1.4 ±0.06	0. 3 ±0.03	-3.1 ±0.006
#321 (LT400°c)	0. 3 ±0.03	-2.3 ±0.06	0. 3 ±0.03	-1.6 ±0.06	0. 3 ±0.02	-2.1 ±0.003
#332 (LT350°c)	0. 3 ±0.03	-1.6 ±0.06	0. 3 ±0.03	-1.4 ±0.06	0. 3 ±0.03	-2.6 ±0.006

Results: $x = 0.30$, $\Sigma = -0.16\%$

Spectra excited by various Energies



Absorption Coefficient



GeSi/Si Micro-Horns

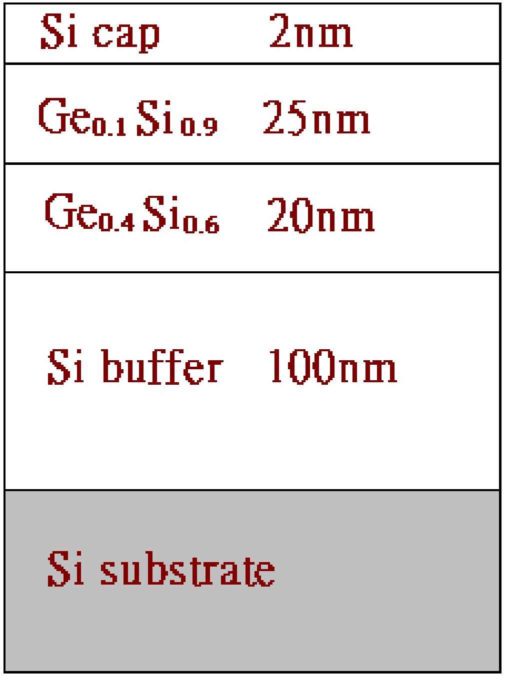


Fig.1 sample before etching

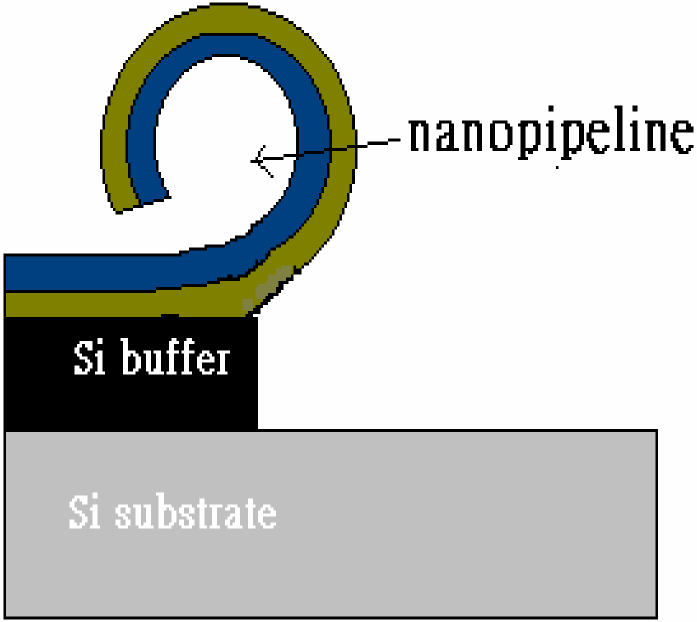
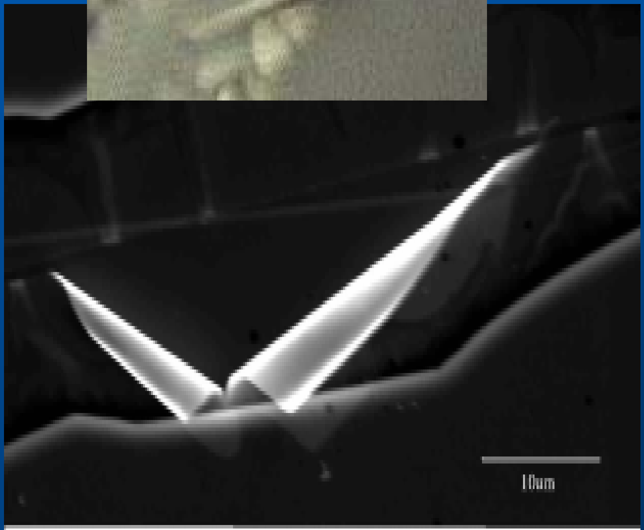
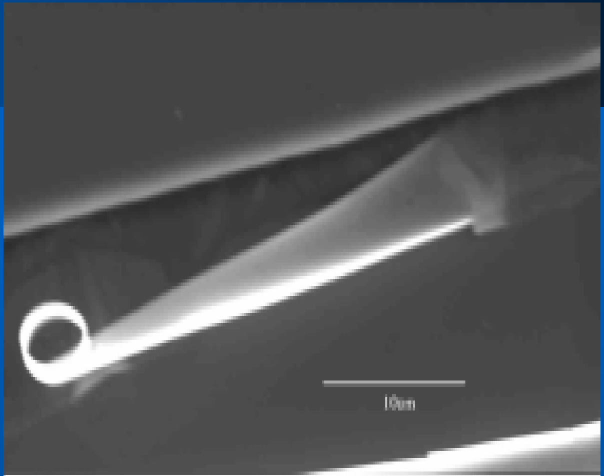


Fig.3 nanopipline has formed

Micro-Horn Images

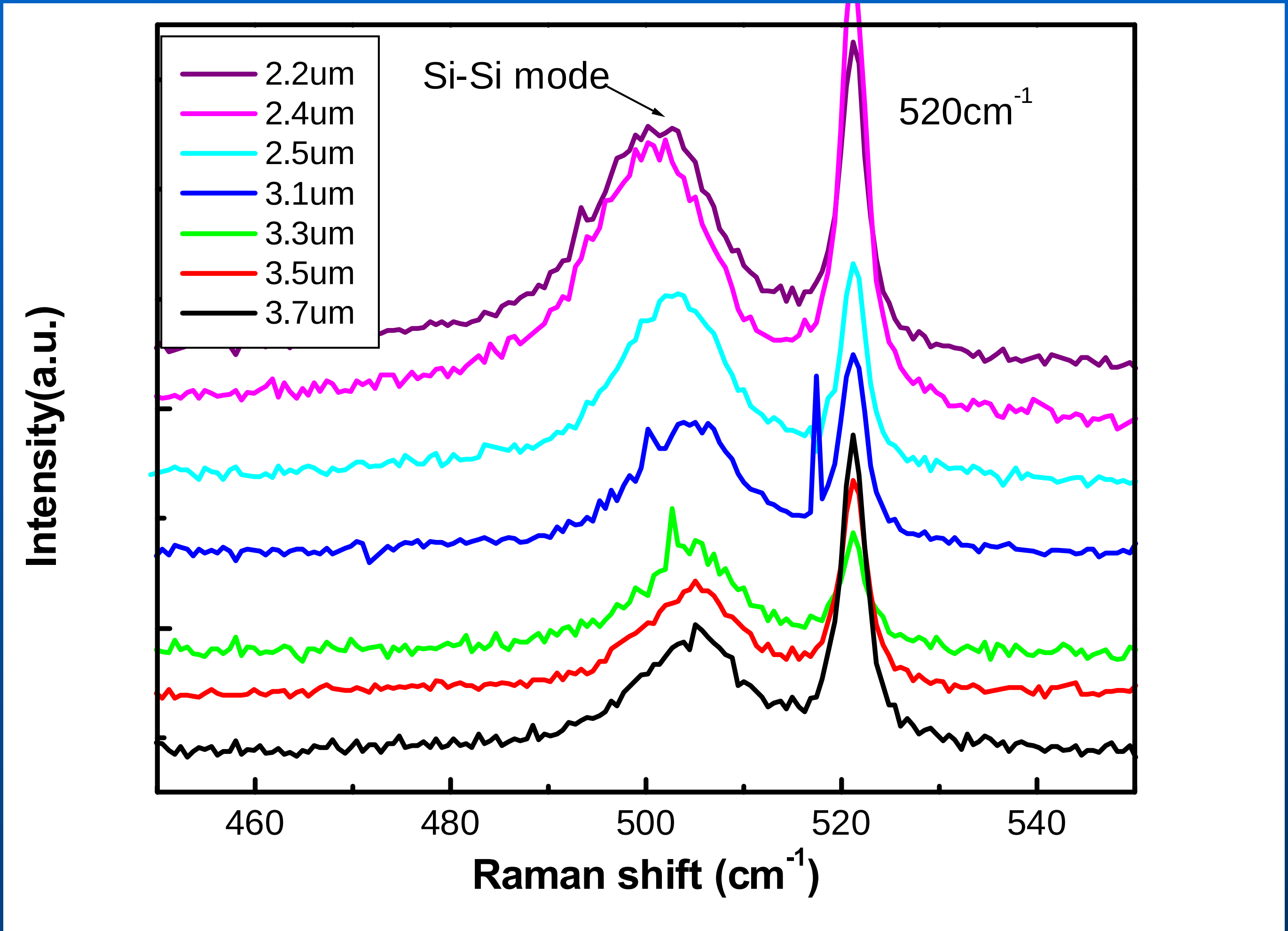


Sample 725

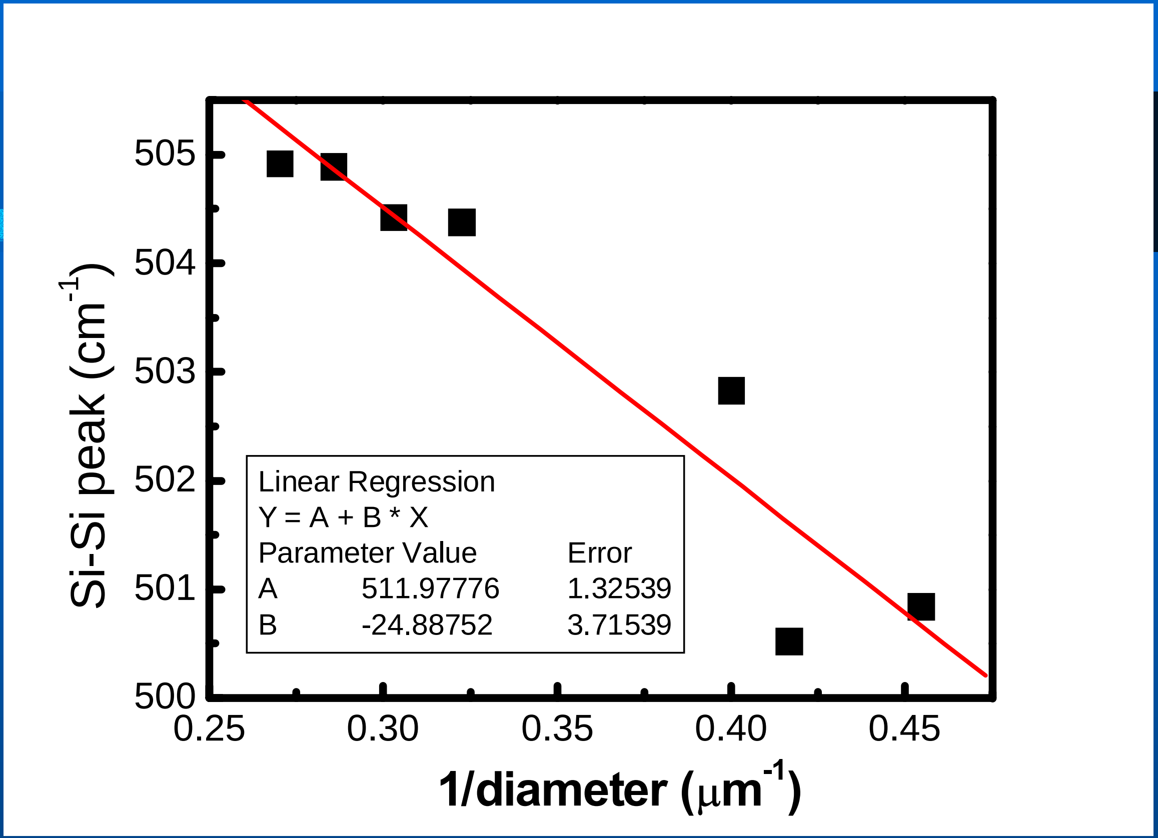


Sample 725

Raman Spectra:



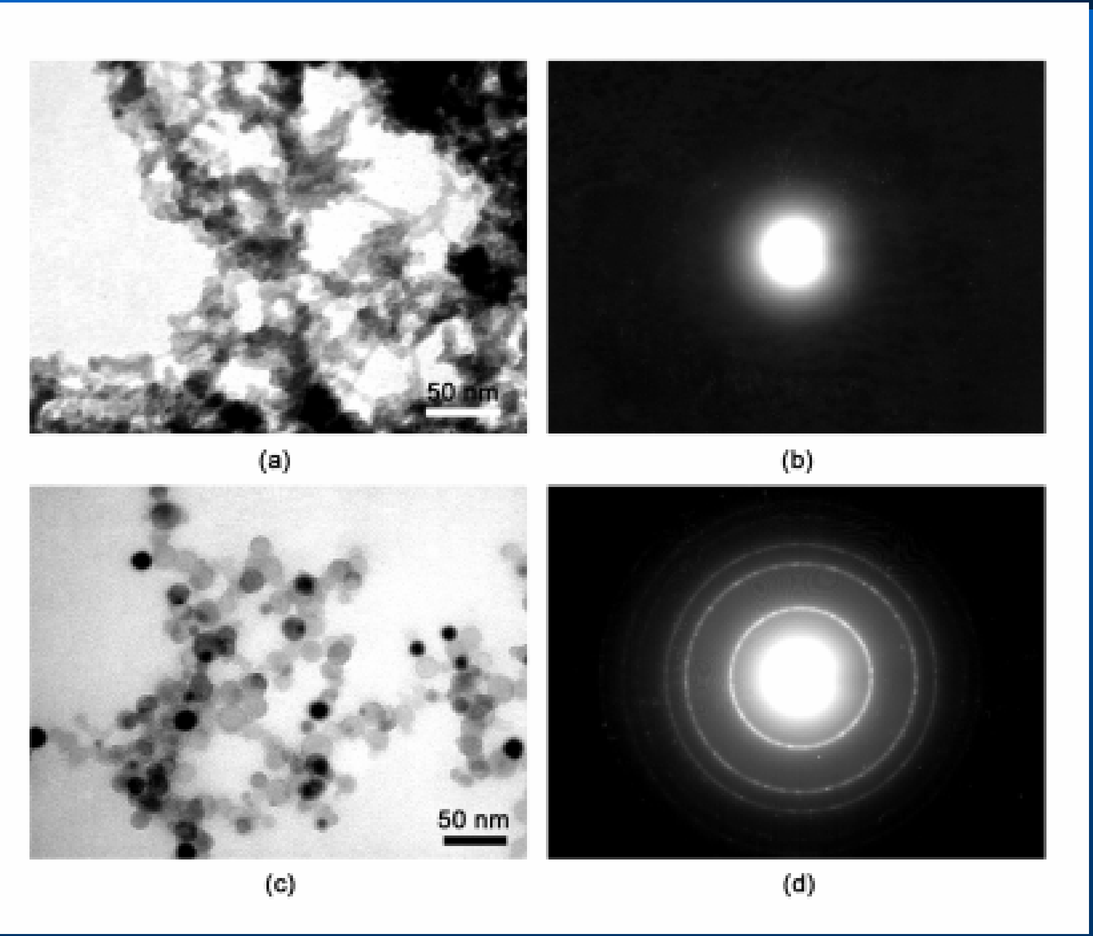
Strain & 1/D



$$\omega_{Si-Si} = 520.5 - 62x - 815\varepsilon - C \cdot \frac{1}{D}$$

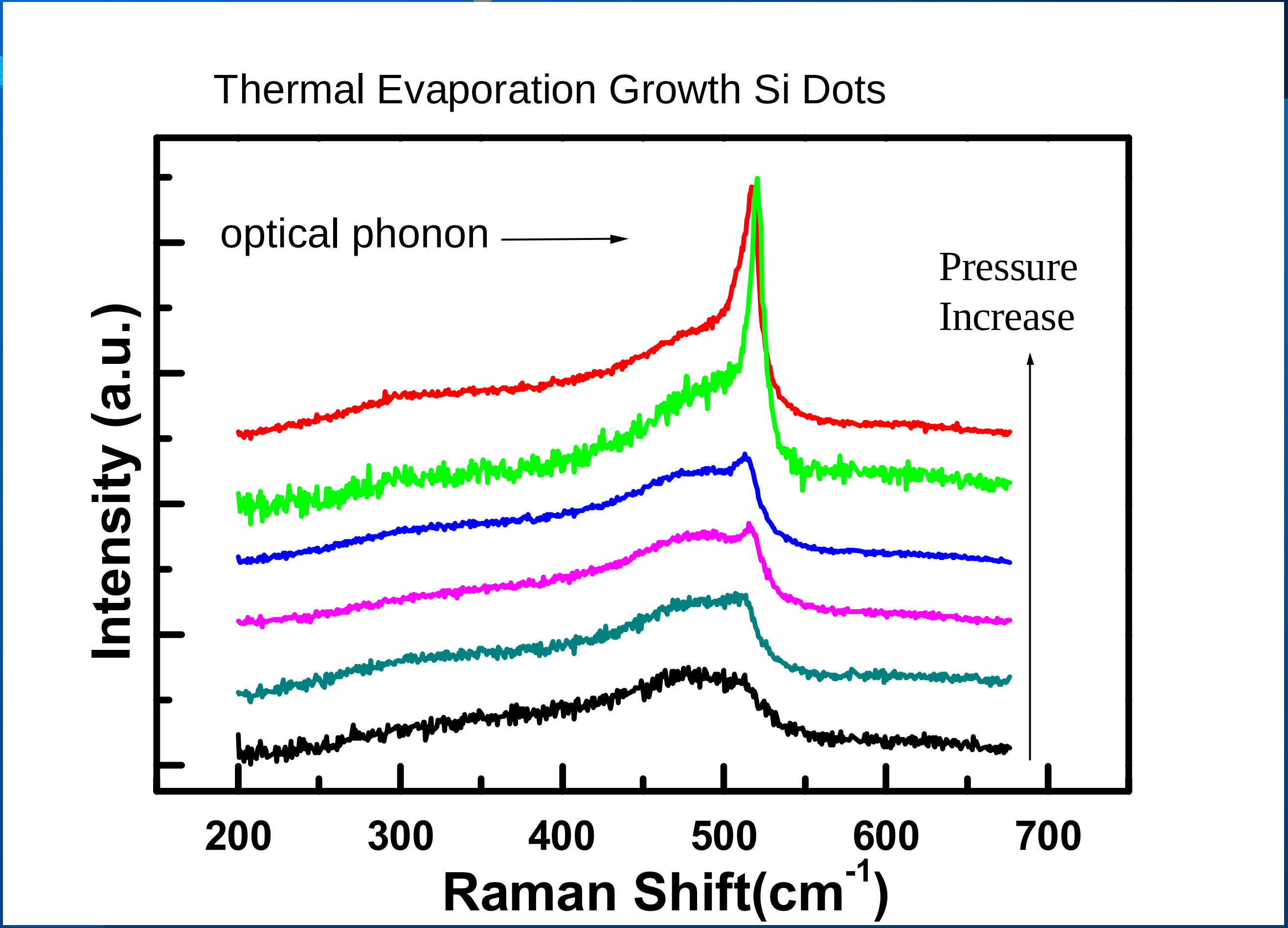
C=24.89

Spherical Si Quantum Dots



Y-C Liao, *et.al.*, Appl. Phys. Lett. 77, 4328 (2000).
C-W Lin, *et.al.*, J. of Appl. Phys. 91, 1525 (2002).

Raman Study of Si Dots' Size



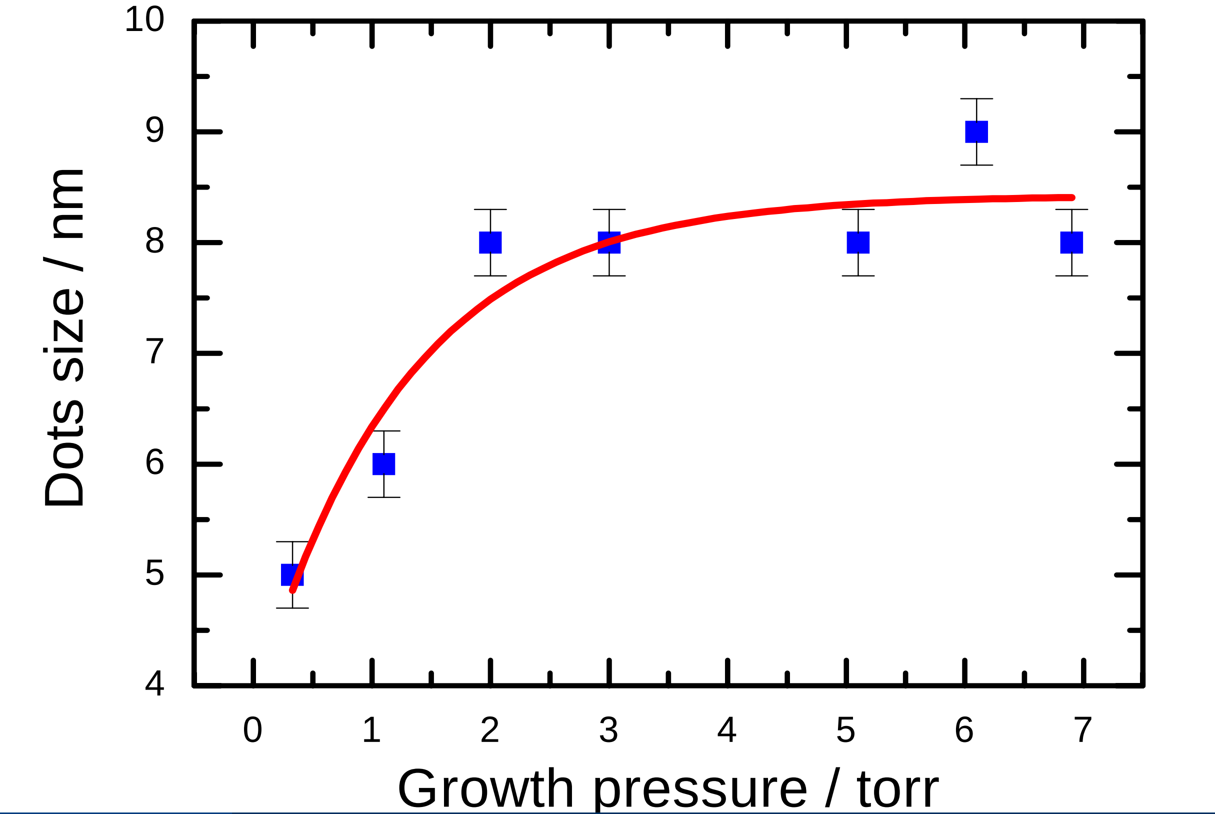
D.-Y. Chien, *et.al.*, ICORS 2002

Size of Dots:

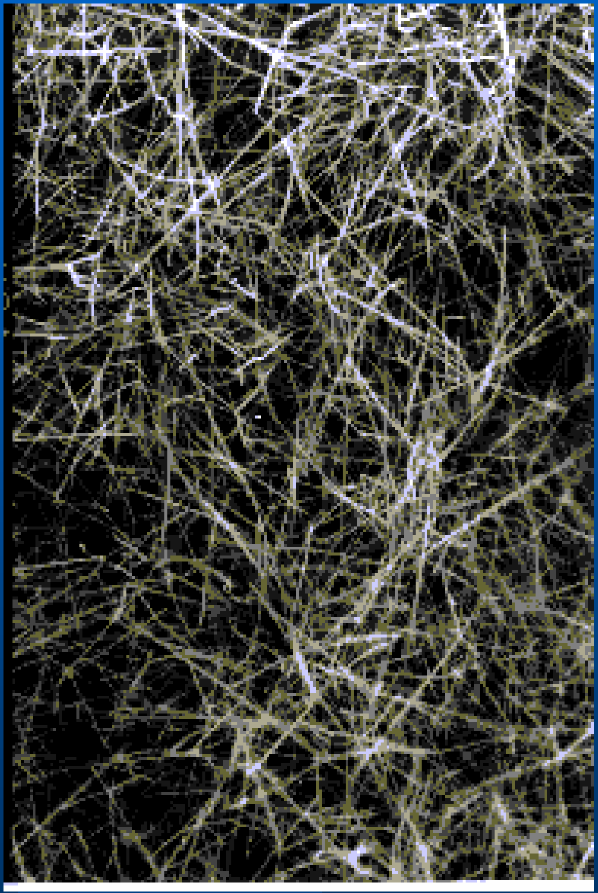
$$I(\omega) = \int_0^1 \frac{d^3q\left|C(0,\vec{q})\right|^2}{[\omega - \omega(q)]^2 + (\Gamma_0/2)^2}$$

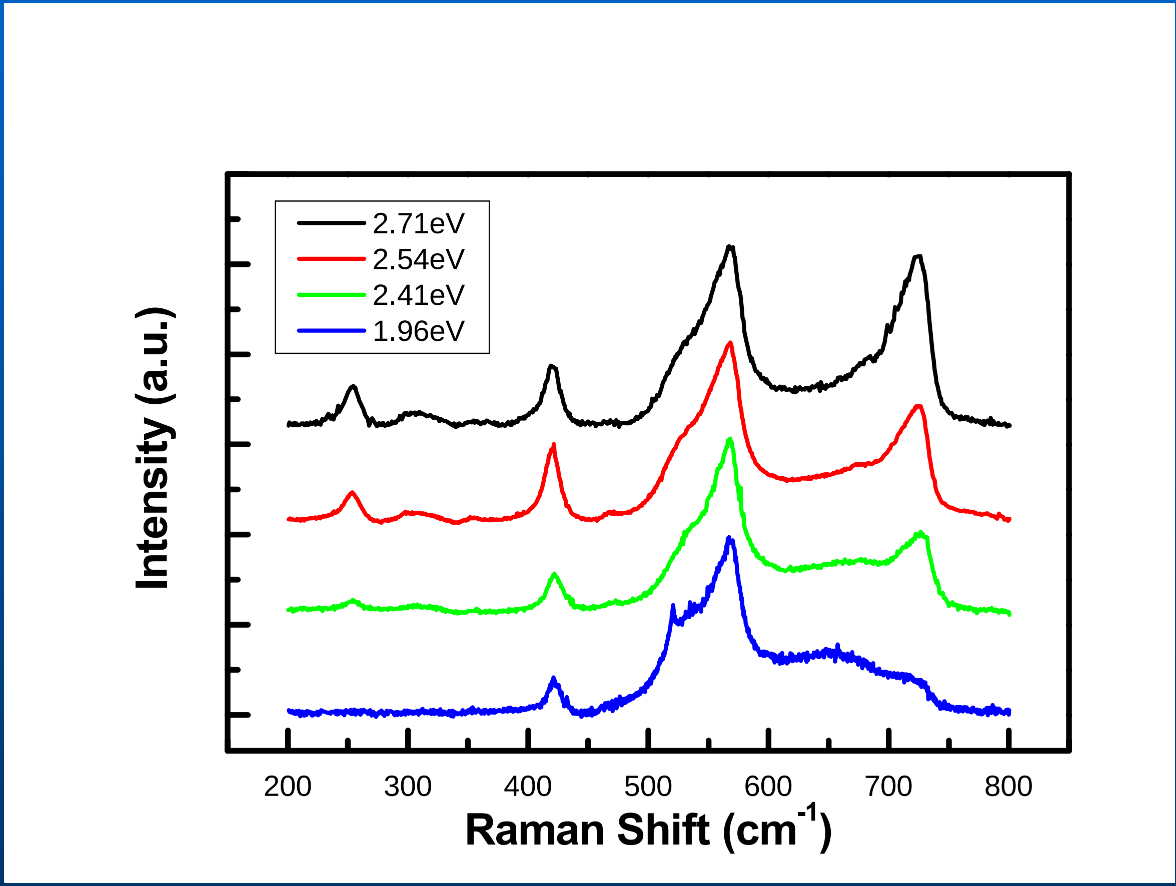
$$\omega(q) = [A + B\cos(\pi q/2)]^{1/2}$$

$$\left|C(0,\vec{q})\right|^2 \cong e^{-q^2L^2/4}$$



Raman Spectra of GaN Wire

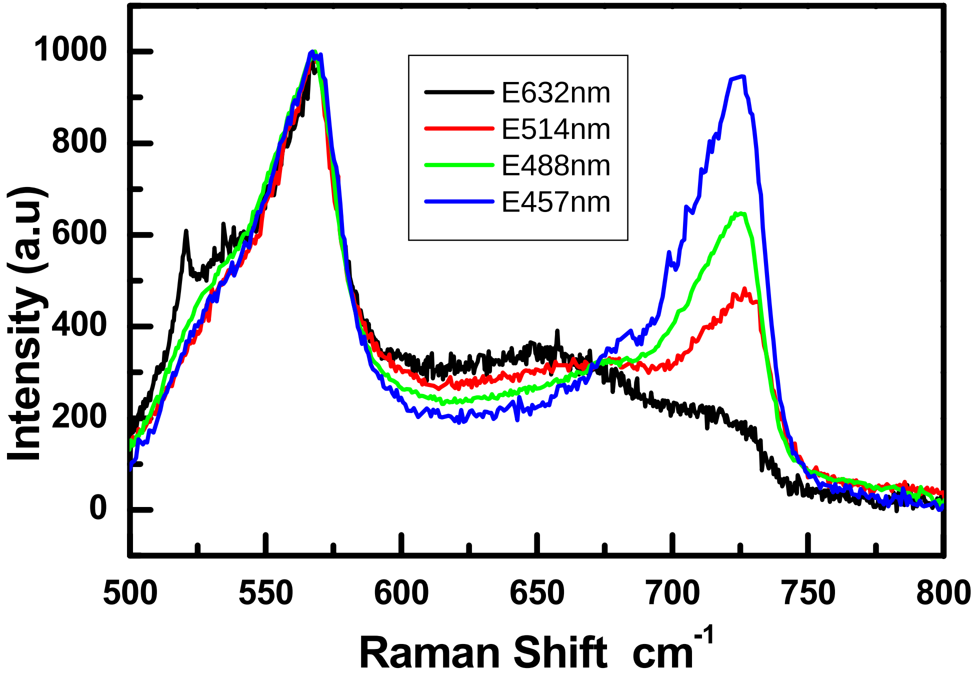




H-L Liu, *et.al.*, Chem. Phys. Lett. 345, 245-251 (2001)

LO-Phonon and Plasma Coupling

$$I(\omega) = \int_0^{q_{max}} dqF(q) \cdot q^2 S(\omega, q)\,\mathrm{Im}\left(\frac{-1}{\varepsilon(\omega, q)}\right)$$



CDF and IIF Mechanism

$$I(\omega) = \int_0^{q_{\max}} dq F(q) \cdot q^2 S(\omega, q) \, \mathrm{Im}\left(\frac{-1}{\varepsilon(\omega, q)} \right)$$

$$S_{CDF}(q,\omega) \propto (1 - e^{-\hbar\omega/k_B T})^{-1} \cdot \left(\frac{(\omega_{LO}^2 - \omega^2)}{(\omega_{TO}^2 - \omega^2)} \right)^2$$

$$S_{IIF}(q,\omega) \propto (1 - e^{-\hbar\omega/k_B T})^{-1}$$

$$F(q) = \left(\frac{4\pi}{q^2 + q_{FT}^2} \right)^2$$

Coupled Dilectric Constant:

$$\varepsilon(q,\omega) = \varepsilon_\infty + \chi_{Phonon} + \chi_{Linhard}(q,\omega)$$

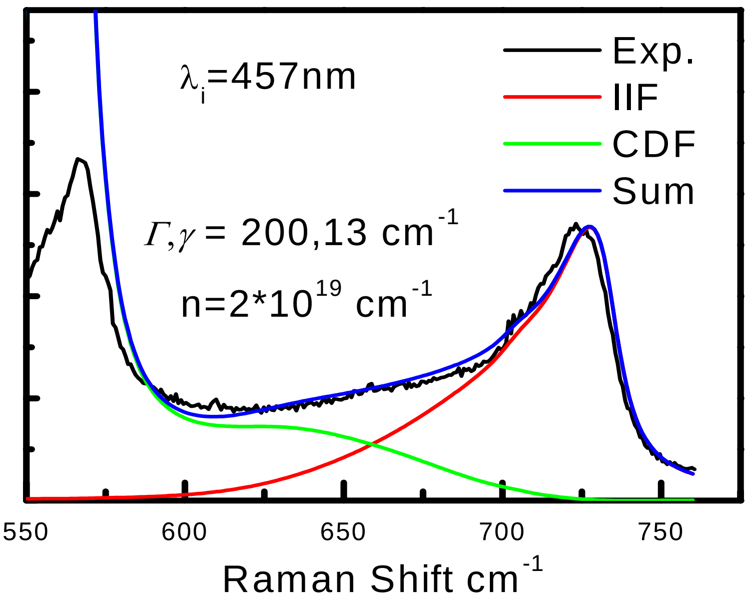
$$\chi_{Phonon} = \varepsilon_\infty \frac{\omega_{LO}^2 - \omega_{TO}^2}{\omega_{TO}^2 - \omega^2 - i\omega\gamma}$$

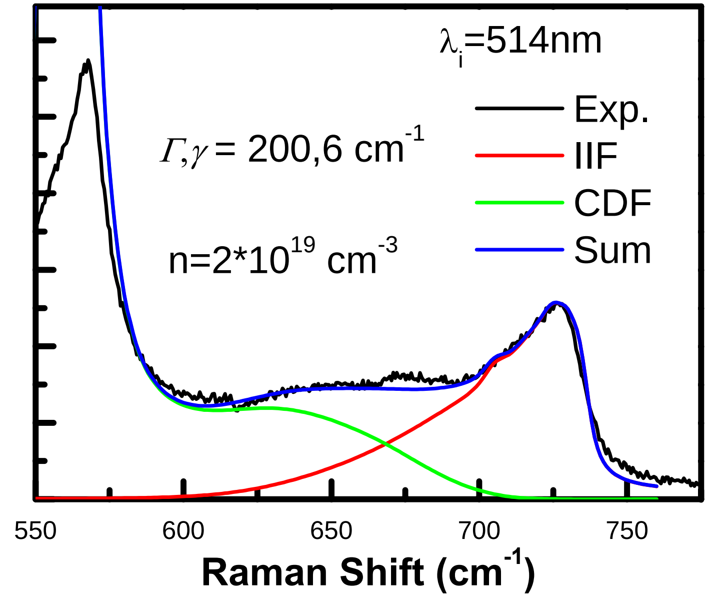
Lattice-Vibration Contributions

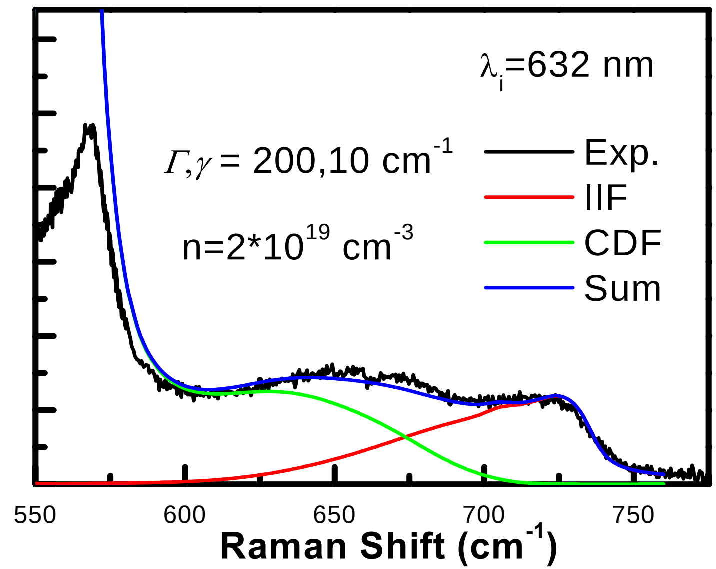
$$\chi_{Linhard}(q,\omega) = \frac{(1 - i\Gamma/\omega)[\chi^0(q,\omega + i\Gamma)]}{1 + (i\Gamma/\omega)[\chi^0(q,\omega + i\Gamma)/\chi^0(q,0)}$$

Plasma-Oscillation Contributions

Fitting Results



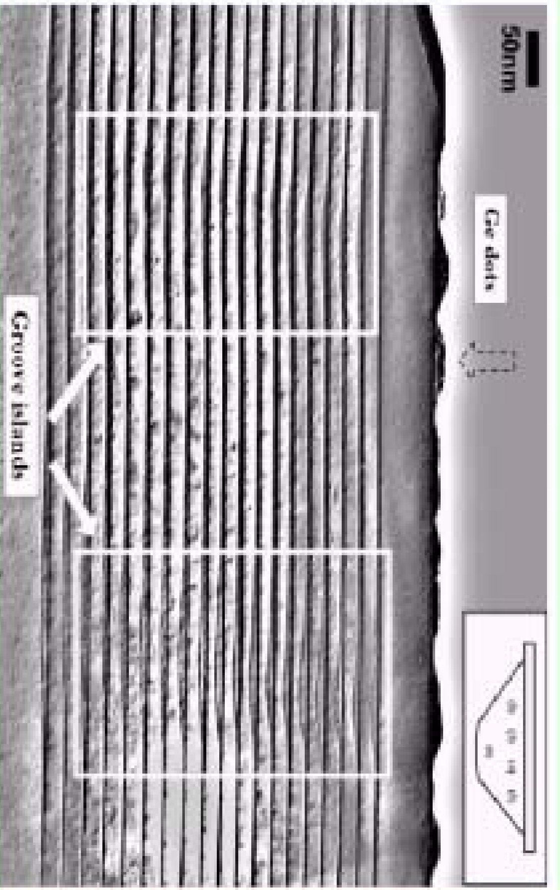


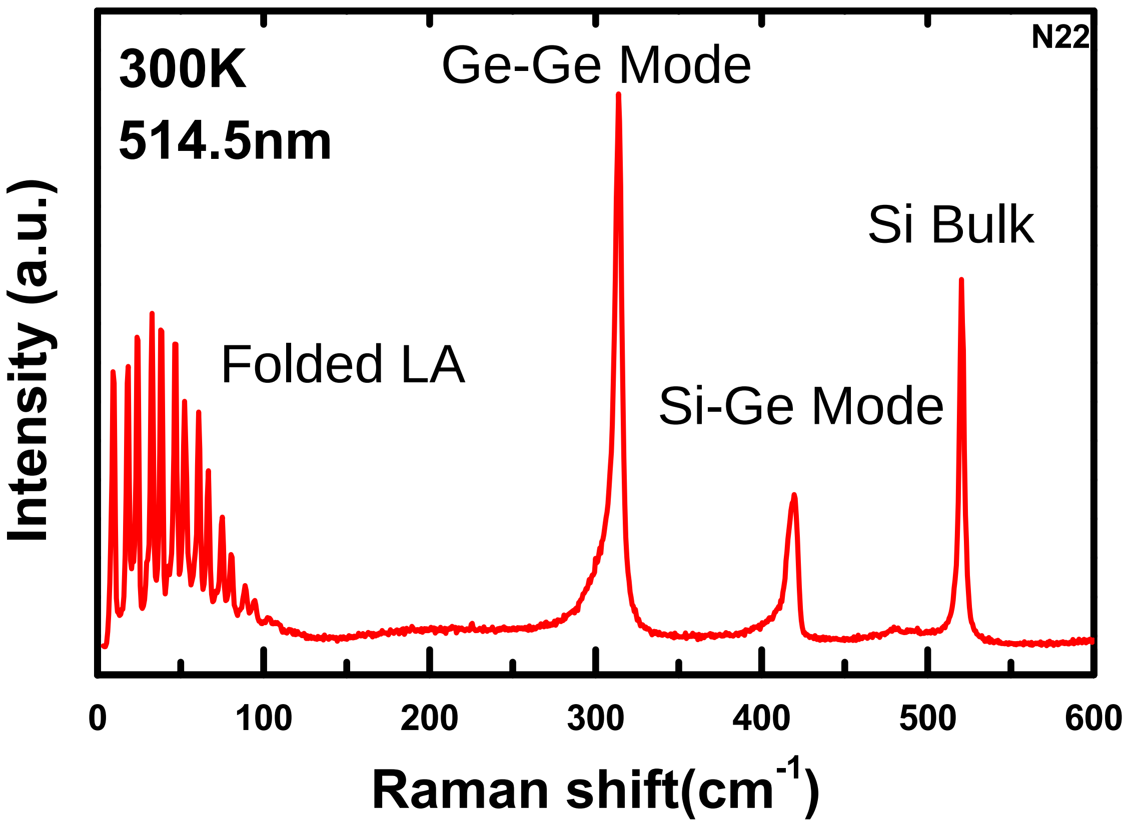


Heavy damping Γ=200 cm^{-1}

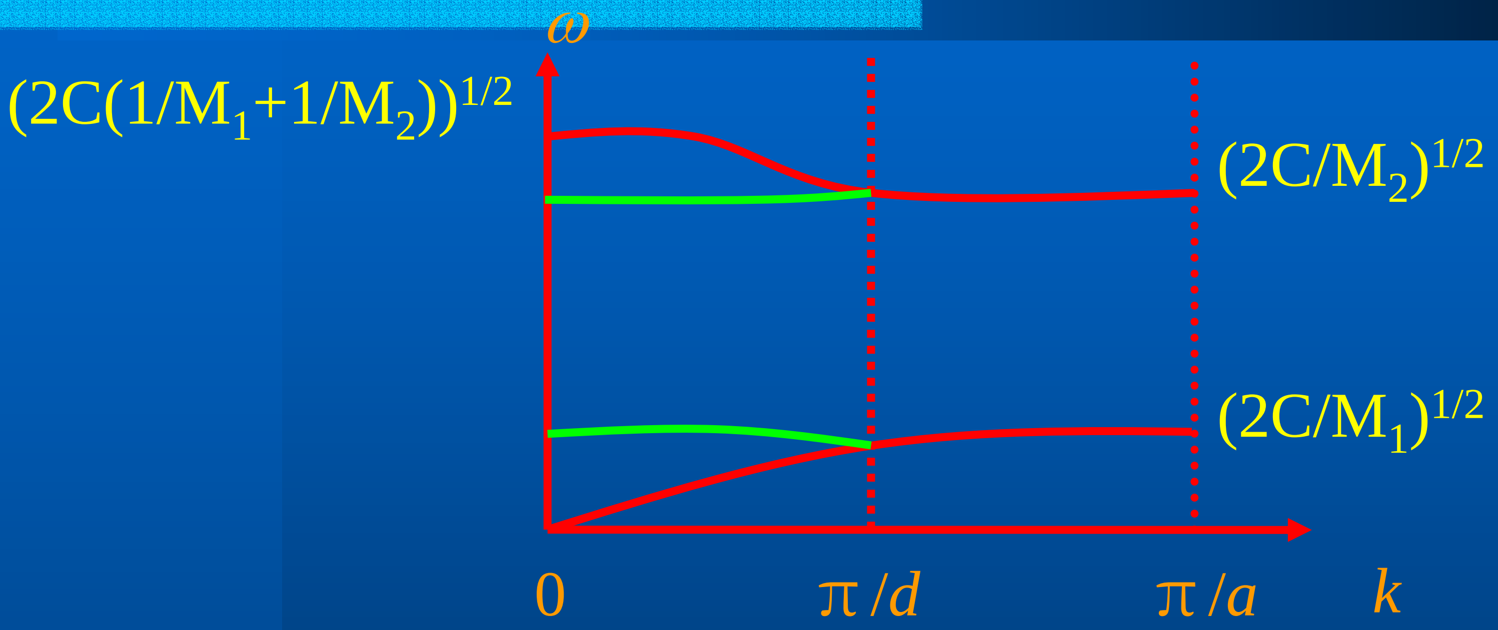
Impurity Desinty: ~$2X10^{19}$ cm^{-3}

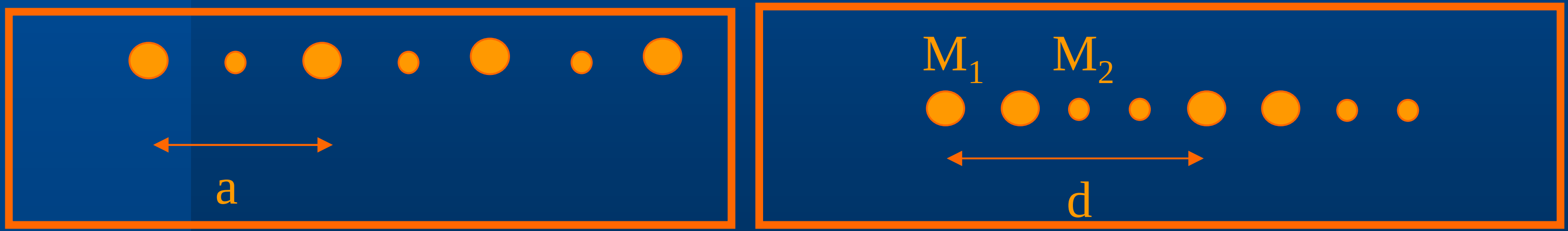
Ge/Si MBE-Grown Superlattice





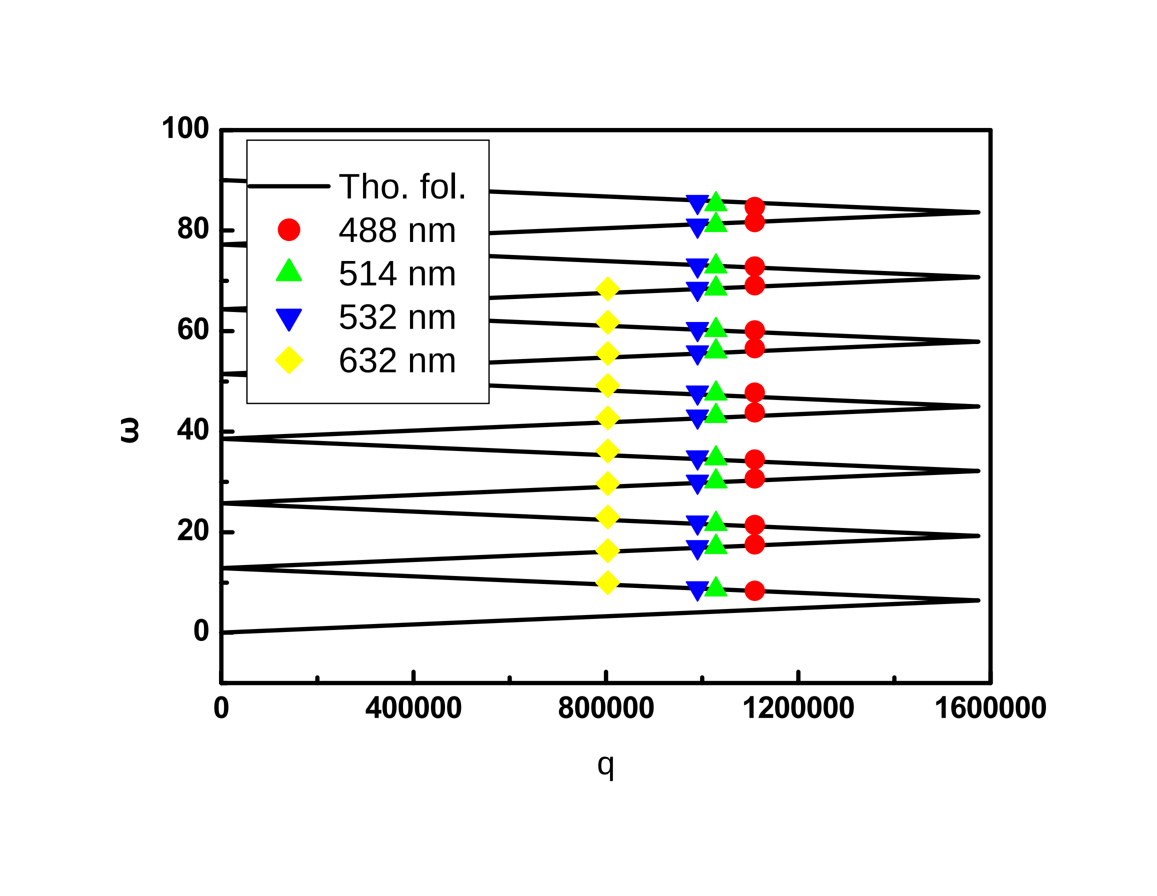
Folded LA Phonon





Thickness of Ge and Si laryer

Rytov theory

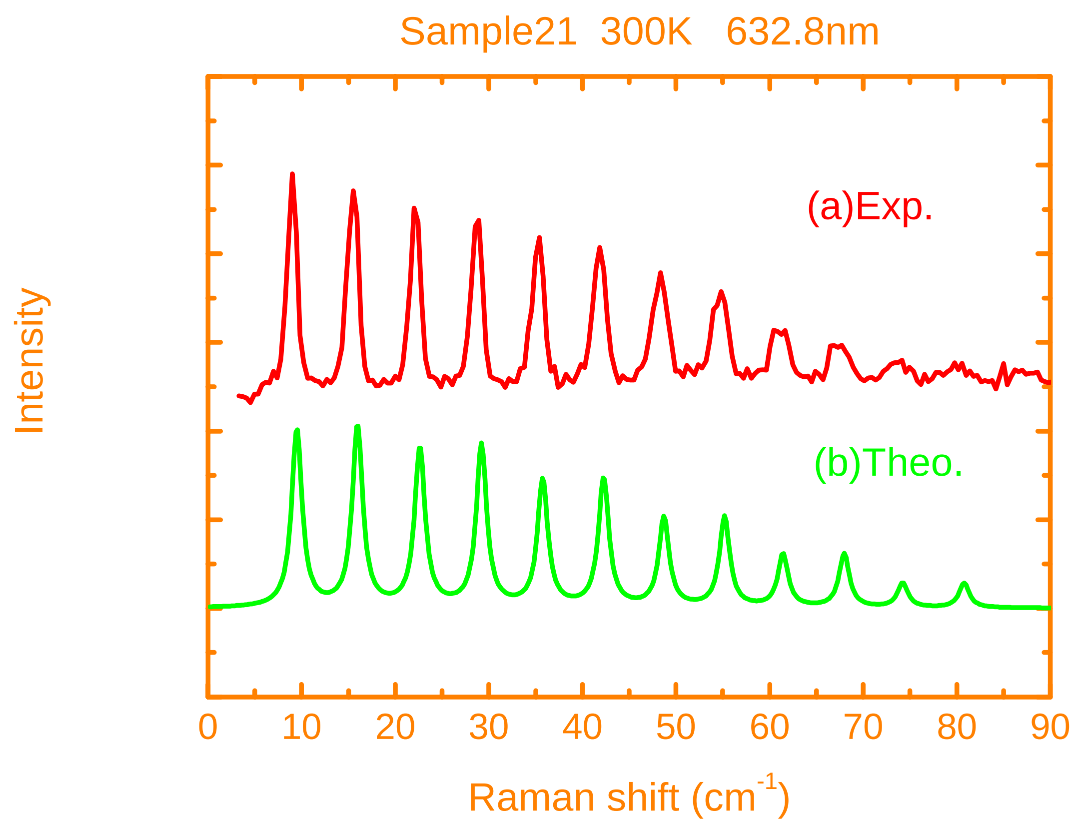


$$\omega = V_{SL}\left(\frac{2\pi m}{d} \pm q\right)$$

C.-H. Lin, C.-T. Chia and H. H. Cheng, ICOR2002

Folded LA Intensity:

$$\frac{I_m}{I_{Brill}} = \frac{(P_b^{12} - P_a^{12})}{P_0^2} \frac{\sin^2(m\pi \frac{d_1}{d})}{\pi^2 m^2} \eta$$

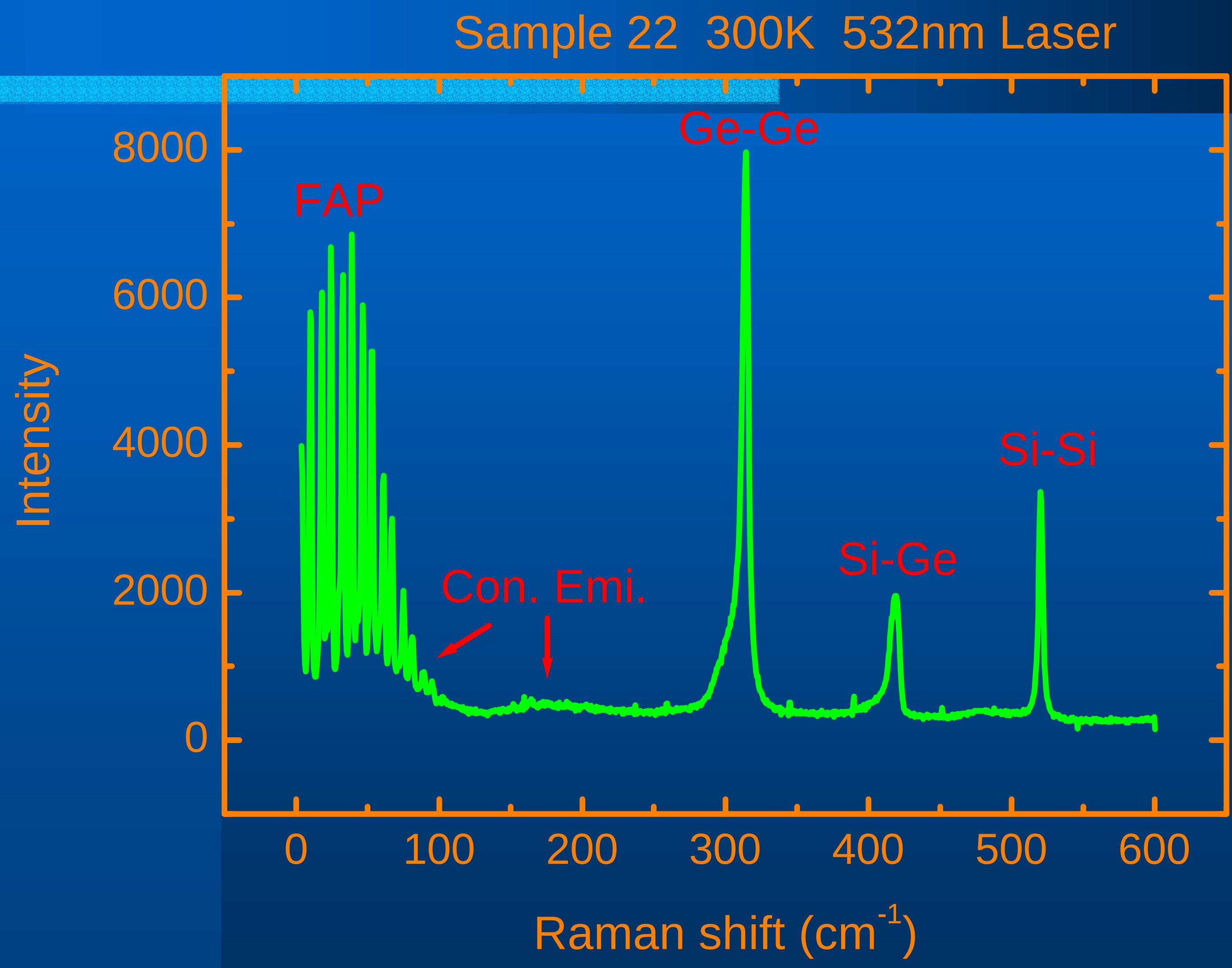


$$\eta = \frac{\omega_m (n_m + 1)}{\omega_0 (n_0 + 1)}$$

Layer Thickness

樣品21	Si厚度 (nm)	Ge厚度 (nm)	厚度比d_1/d	超晶格週期 d(nm)
TEM圖	15±2	3±2	0.83	18±4
光譜擬合	17.5±0.6	2.40±0.08	0.88	19.9±0.7
樣品22				
TEM圖	17±2	2±2	0.90	19±4
光譜擬合	15.8±0.5	2.30±0.08	0.90	18.1±0.6
樣品23				
TEM圖	20±2	2±2	0.91	22±4
光譜擬合	19.6±0.7	2.50±0.09	0.89	22.1±0.8

Continuous Emission:

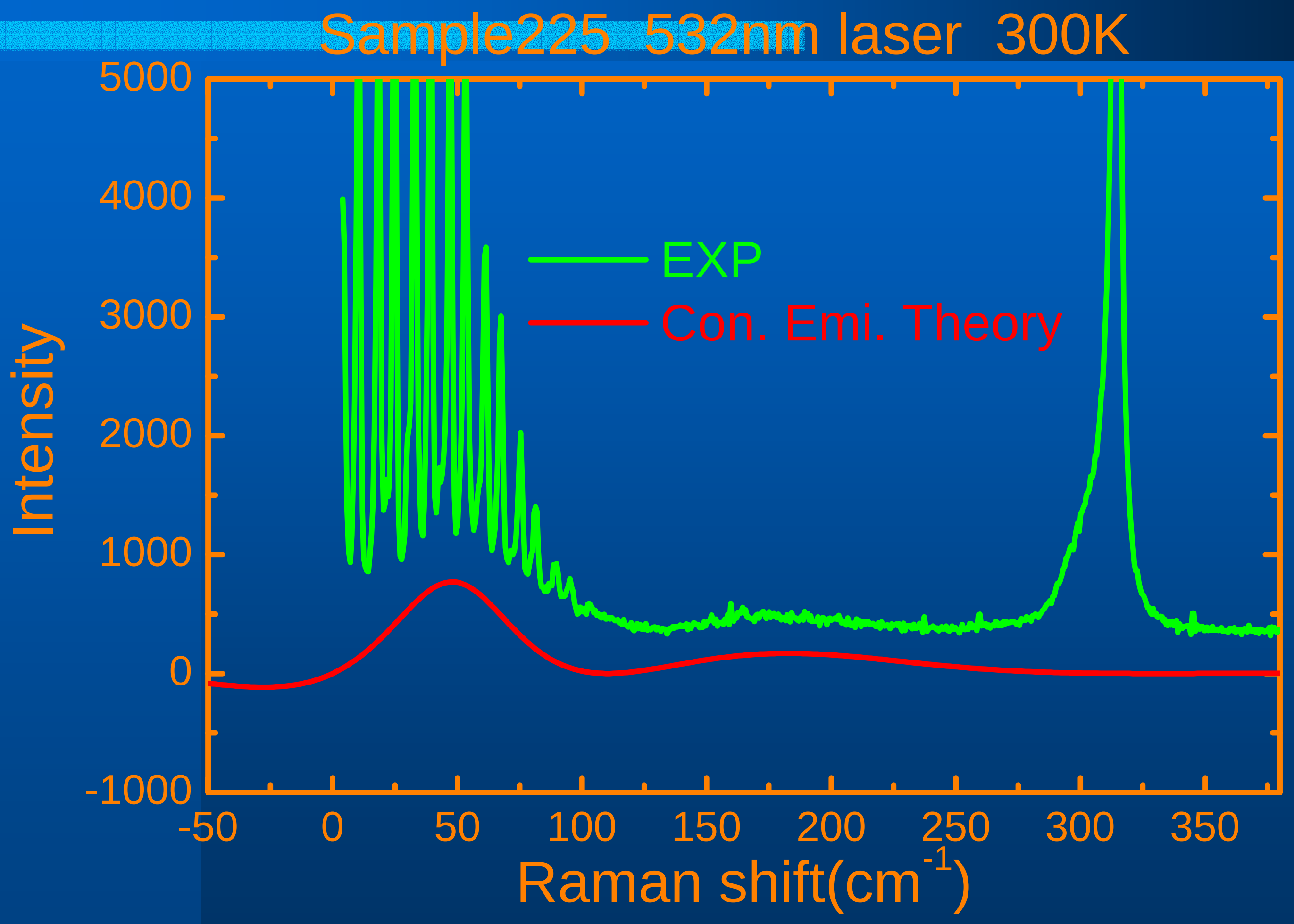


Theory of Continuous Emission:

$$I_{(\omega)} \cong \sum_{q_Z} \frac{q_z^2}{\omega_{q_Z}} \frac{\sin^2 \frac{aq_Z}{2}}{\left(\frac{aq_Z}{2}\right)^2} \times \left(n_q + 1\right) \delta\left(\omega_l - \omega_s - \omega_q\right)$$

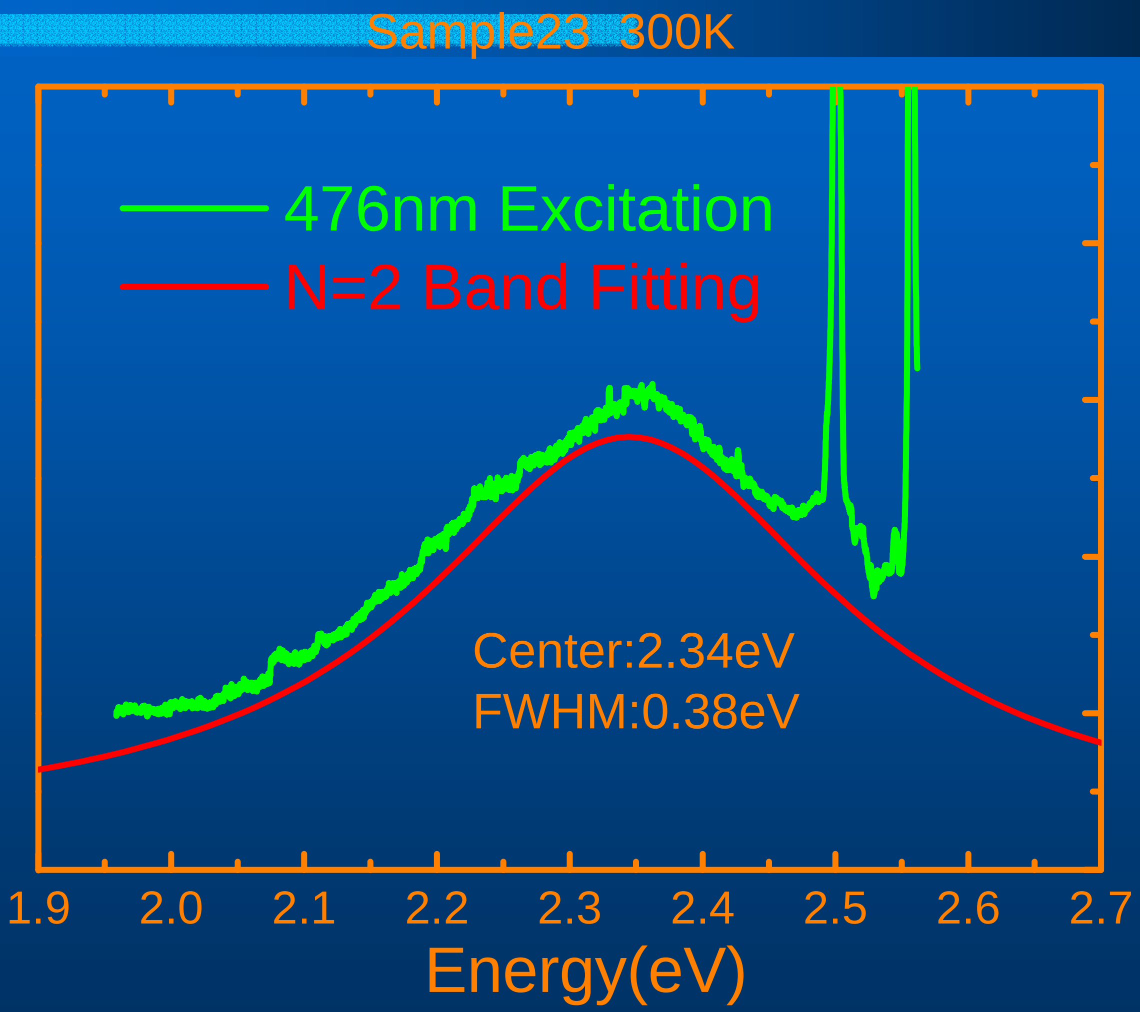
$$\times \left| \sum_N \left(\Omega_N + i\frac{\gamma_e + \gamma_h}{2}\right)^{-1} \left(\Omega_N - \omega_l + \omega_s + i\frac{\gamma_e + \gamma_h}{2}\right)^{-1} \times \frac{4N^2}{4N^2 - \left(\frac{aq_Z}{\pi}\right)^2} \right|^2$$

Continuous Emission Fitting



Resonant Energy : 2.34 eV

Room Temperature Luminescence



Summary:

Visible Lasers + Raman Spectrometers

Can completely resolve the Physics properties of semiconductor from Raman-Phonon Lineshapes.

<u>IF</u>

Right energy laser

Good-resolution spectrometer

感謝Raman實驗室成員

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