TOMODACHI STEM @ Rice University

Final Presentation (March 18, 2016)

Strain Direct Mapping by Using Carbon Nanotube Strain Sensor

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RICE Unconventional Wisdom

東京大学 THE UNIVERSITY OF TOKYO

Can you see material deformation?

Q: Which is *DANGEROUS* deformation ??

Both are *DANGEROUS* deformation!

Material deformation → Strain

What if we could see *STRAIN* ?

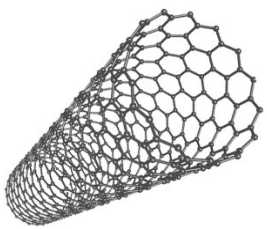
Structural health monitoring

- Non-destructive
- Non-contact
- Simple

→ **Ideal strain measurement methods**

Strain-sensing smart skin “S^4” method

Mechanisms

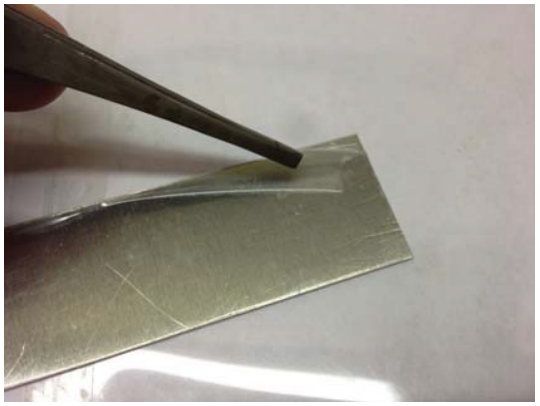


Single-walled
Carbon nanotubes

Light

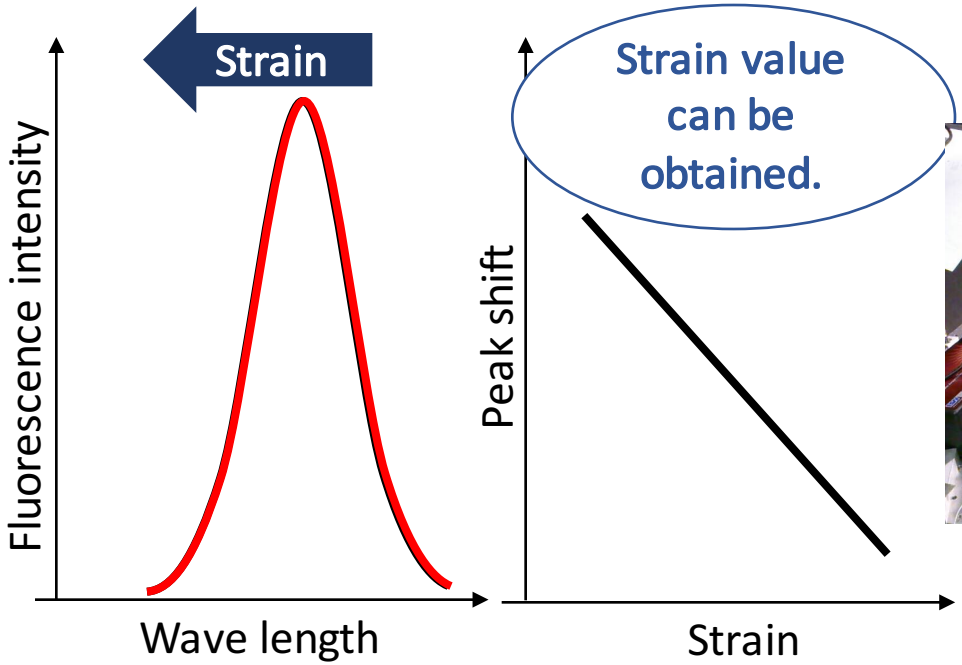
Fluorescence

different wave length



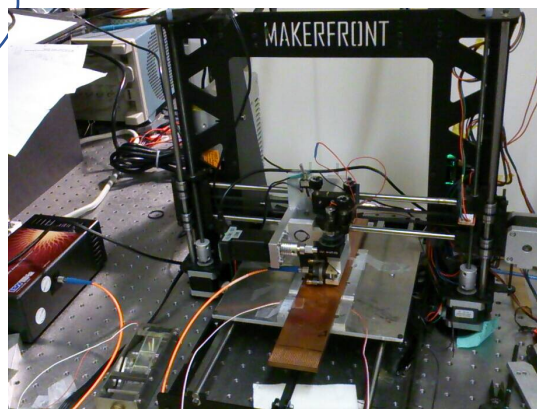
Carbon nanotubes
+
Polymer

Strain-sensing smart skin



Strain value can be obtained.

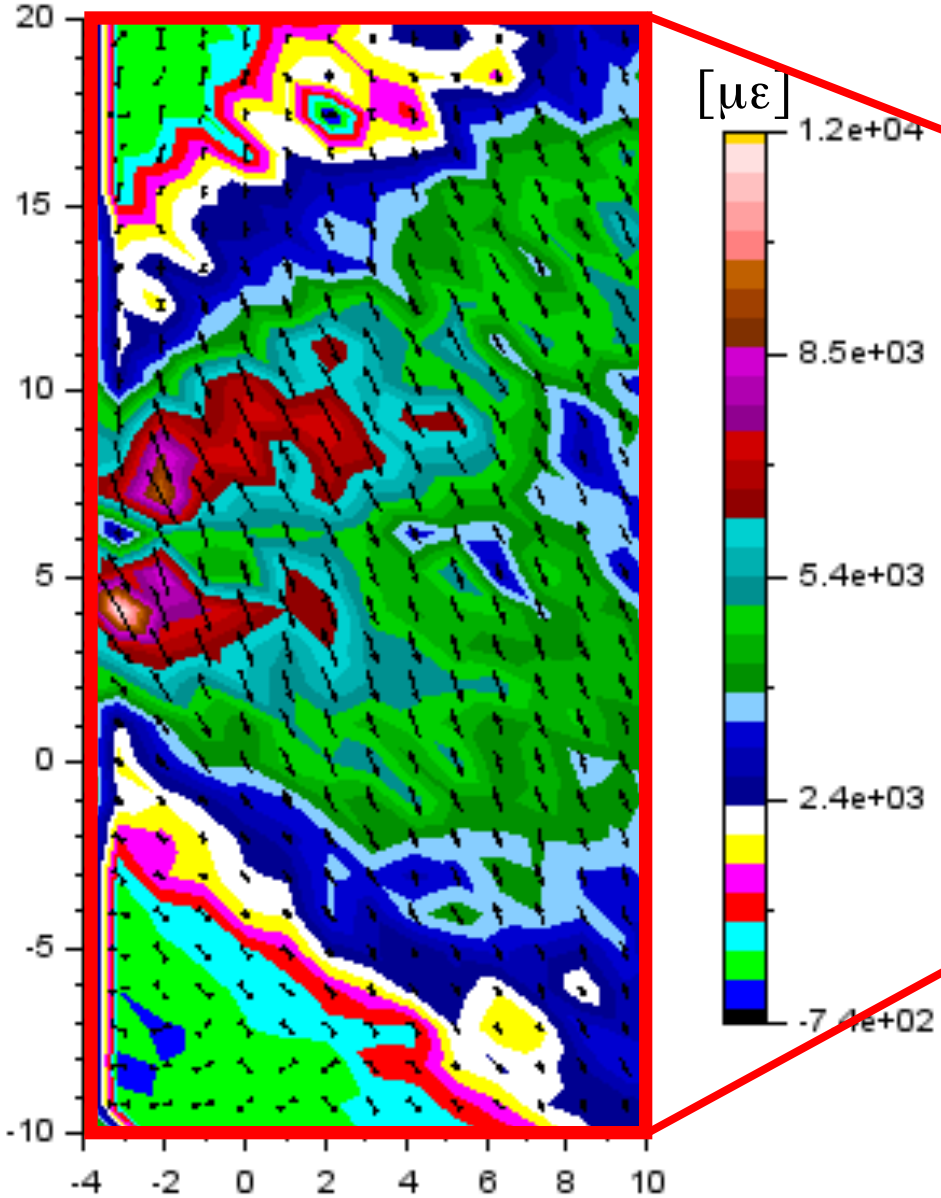
Strain scanner



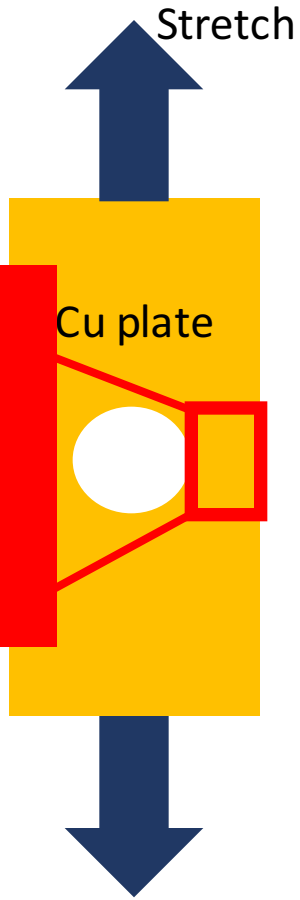
Scanning material surface

Strain map
(Picture of material deformation)

Principle strain maps

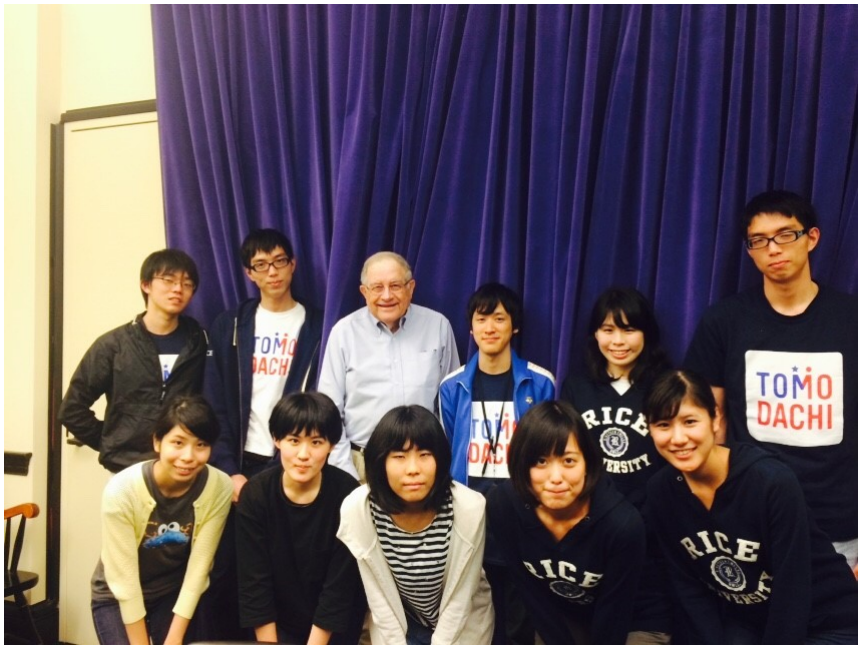


Maximum strain distribution was successfully obtained.



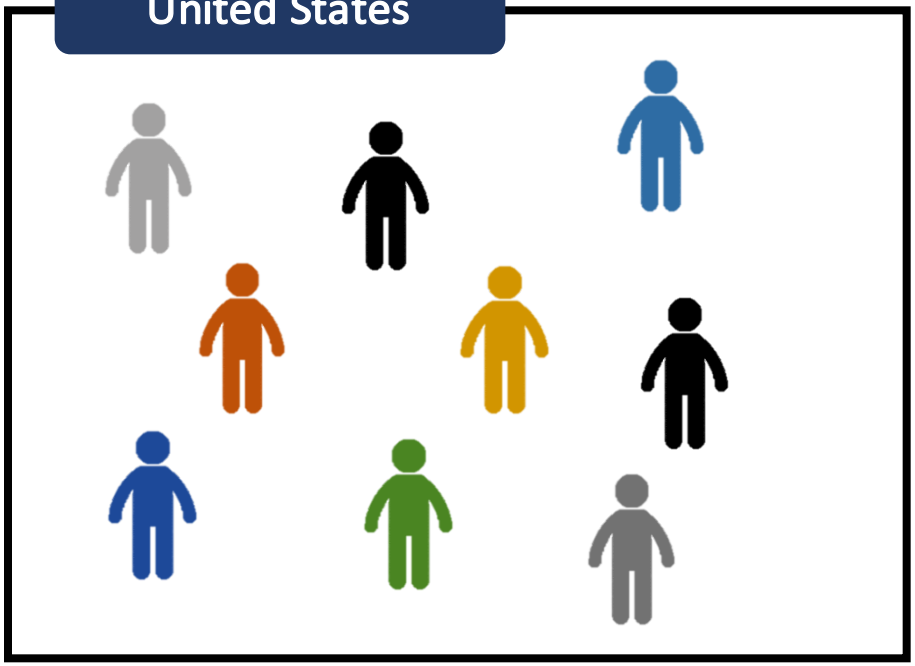
Applicable to structural health monitoring

Experiences @ Houston

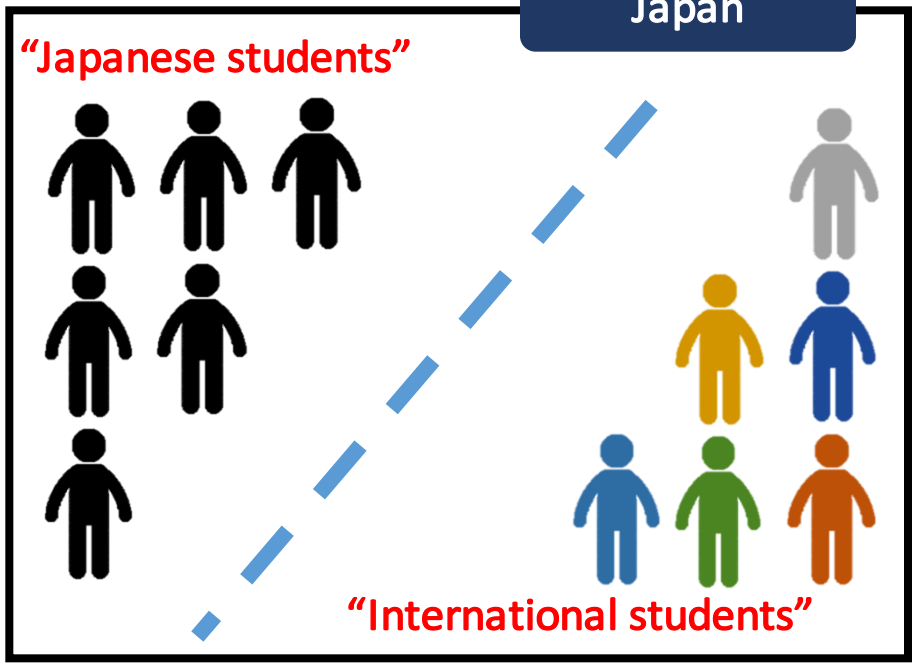


Diversity in research lab.

United States



Japan



Why important?

Diverse people

↓

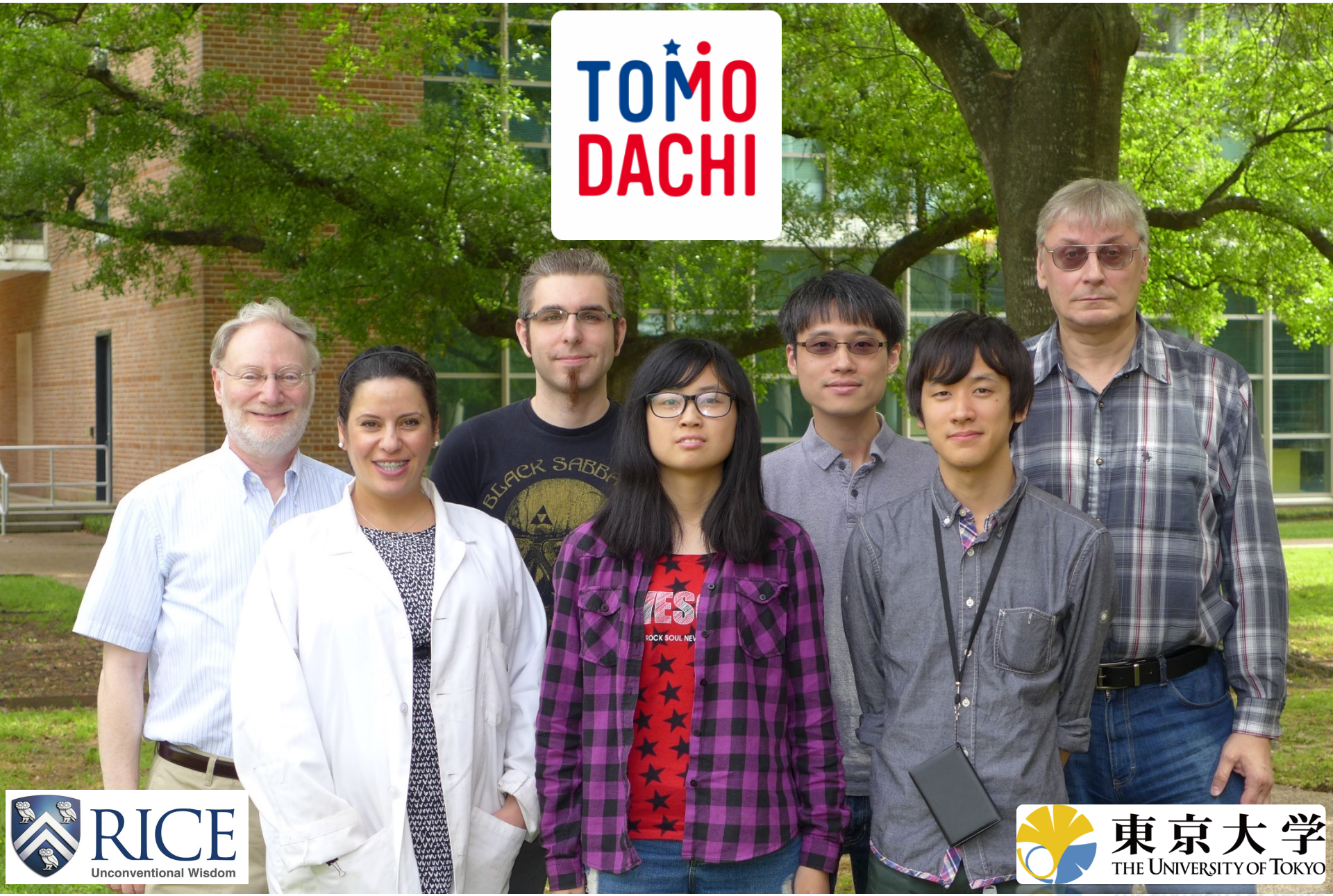
Diverse ideas

↓

Better ideas

- **Racially homogeneous society**
  (Ours ⇔ Others)
- **Language barrier**

Tolerance for diversity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Appendix

What I have done @ Rice

(1) Strain / Stress map
(2) Local work hardening map
(3) Theoretical model formulation

Theoretical model (1)

Observed spectral shift

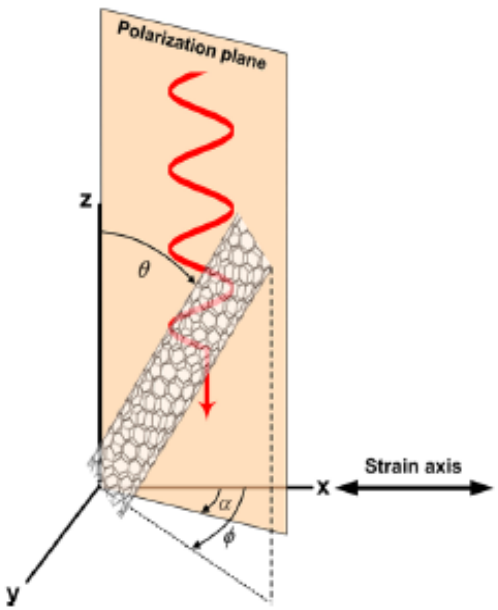
$$\Delta\nu_{observed} = \int_0^{2\pi}\int_0^{\pi} f(\theta,\phi)\Delta\nu(\theta,\phi,\alpha)\sin^3\theta\cos^2(\phi-\alpha)d\theta d\phi$$

Spectral shift (individual SWNTs)

$$\Delta\nu(\theta,\phi,\alpha) = \Delta\nu_{max}(\cos^2\beta - \mu\sin^2\beta) \propto \varepsilon$$

$$\Delta\nu_{observed} = \frac{\Delta\nu_{max}}{8}(3-\mu)$$

$$\Delta E_{11} = h\Delta\nu = 3(-1)^{mod(n-m,3)+1}t_0(1+\mu_{SWNT})\cos(3\theta)\cdot\varepsilon$$



For (7,6)-(7,5) separation

$$\varepsilon = \frac{8}{3-\mu}\frac{h}{3t_0(1+\nu_{SWNT})\left(\cos 3\theta_{(7,6)} + \cos 3\theta_{(7,5)}\right)}\left(\Delta\nu_{(7,6)} - \Delta\nu_{(7,5)}\right)$$

Theoretical model (2)

Observed spectra shape

$$S_{observed} = \int_0^{2\pi}\int_0^{\pi} f(\theta,\phi)P\left(\nu-\nu_0-\Delta\nu(\theta,\phi,\alpha)\right)\sin^3\theta\cos^2(\phi-\alpha)d\theta d\phi$$

Peak function (individual SWNTs)

Gaussian distribution

$$P = A\exp\left(-\frac{\left(\nu-\nu_0-\Delta\nu(\theta,\phi,\alpha)\right)^2}{w^2}\right)$$

Lorentzian distribution

$$P = \frac{A}{\pi}\frac{\frac{1}{2}\Gamma}{\left(\nu-\nu_0-\Delta\nu(\theta,\phi,\alpha)\right)^2+\left(\frac{1}{2}\Gamma\right)^2}$$

$$\begin{cases} \varepsilon = \dfrac{8}{3-\mu}\dfrac{h}{3t_0(1+\nu_{SWNT})\left(\cos 3\theta_{(7,6)}+\cos 3\theta_{(7,5)}\right)}\left(\Delta\nu_{(7,6)}-\Delta\nu_{(7,5)}\right) \\ \quad = \dfrac{8C_1}{3-\mu}\left(\Delta\nu_{(7,6)}-\Delta\nu_{(7,5)}\right) \\ \varepsilon = C_2\Delta\lambda_{observed}^{(7,6)-(7,5)} \end{cases}$$

$$\mu = 3-\frac{8C_1}{C_2}\frac{\Delta\nu_{(7,6)}-\Delta\nu_{(7,5)}}{\Delta\lambda_{observed}^{(7,6)-(7,5)}}$$

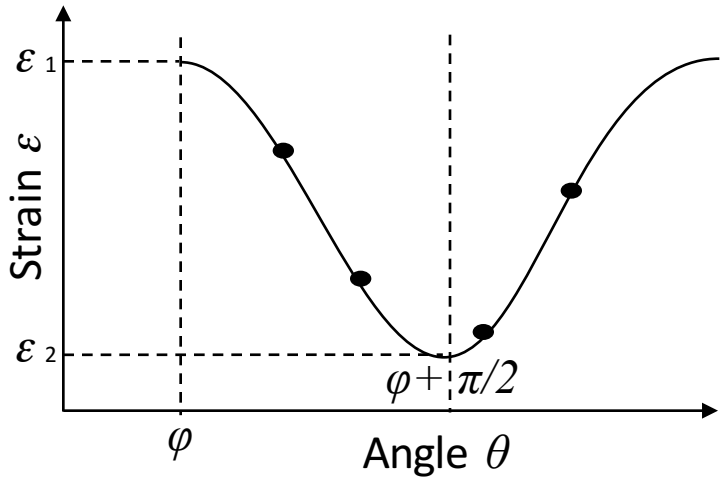
Poisson ratio can be obtained more precisely.

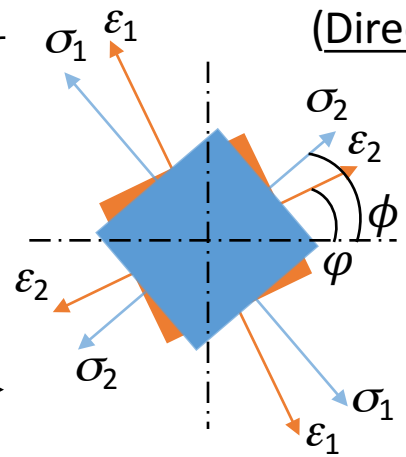
Methods

Strain Data Fitting Model

Theory of Elasticity

$$\varepsilon = \frac{1-\nu}{2}\varepsilon_1 + \frac{1+\nu}{2}\varepsilon_1 \cos(2\theta + 2\varphi)$$





Principle Stress

(Magnitude)

$$\begin{Bmatrix}\sigma_1\\ \sigma_2\end{Bmatrix} = \frac{\sigma_{11}+\sigma_{22}}{2} \pm \sqrt{\left(\frac{\sigma_{11}-\sigma_{22}}{2}\right)^2 + \sigma_{12}^2}$$

(Direction)

$$\phi = \frac{1}{2}\tan^{-1}\left(\frac{2\sigma_{12}}{\sigma_{11}-\sigma_{22}}\right) + \varphi$$

Stress / Strain map can be made.

Strain → Stress Transformation

$\sigma_{ij} = E_{ijkl}\varepsilon_{kl}$(Hooke's low)

⬇ Symmetry of Young's modulus tensor

$$\begin{bmatrix}\sigma_{11}\\ \sigma_{22}\\ \sigma_{12}\end{bmatrix} = \begin{bmatrix}E_{1111} & E_{1122} & 2E_{1112}\\ E_{1122} & E_{2222} & 2E_{2212}\\ E_{1112} & E_{2212} & 2E_{1212}\end{bmatrix}\begin{bmatrix}\varepsilon_{11}\\ \varepsilon_{22}\\ \varepsilon_{12}\end{bmatrix}$$

Work hardening mapping

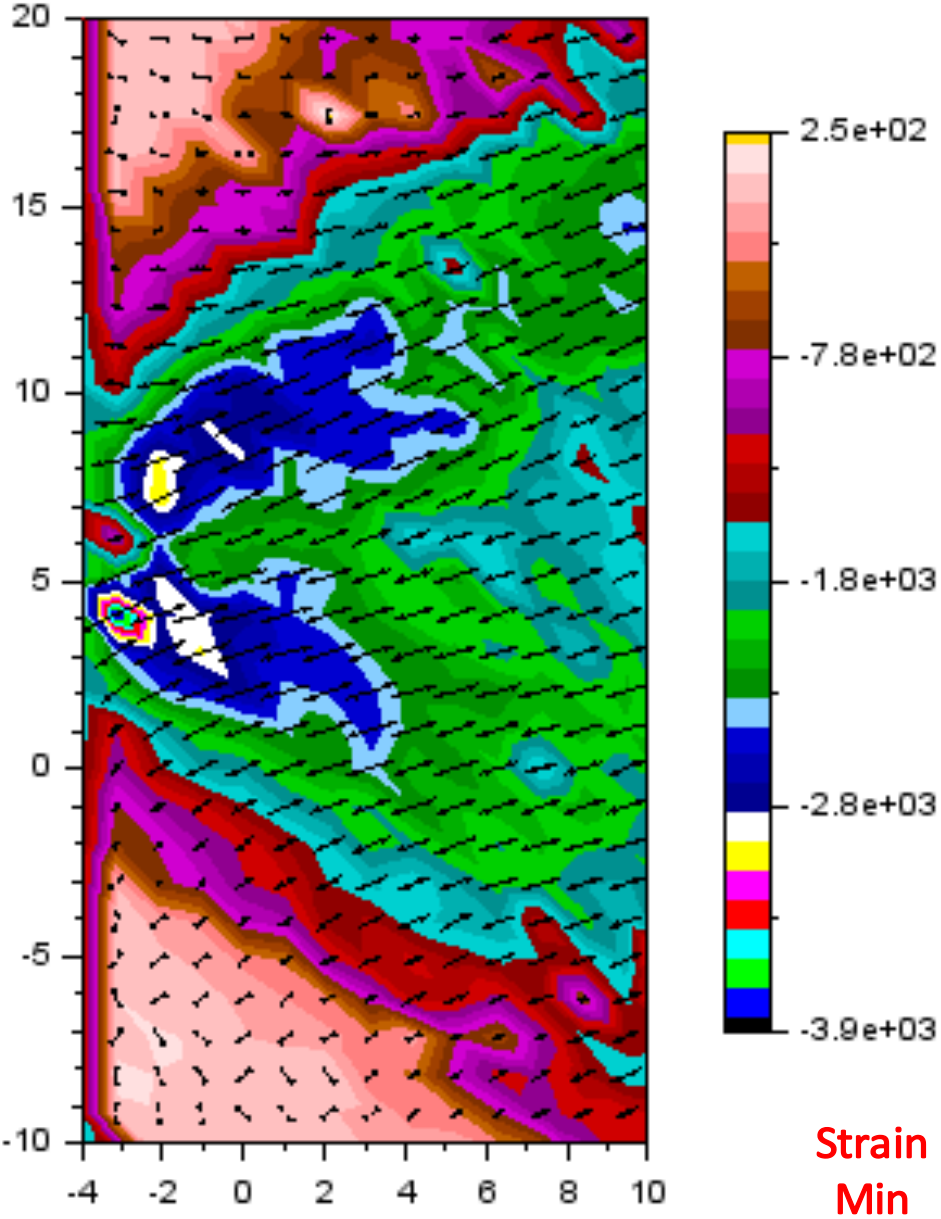
Elastic deformation
Poisson ratio: Constant

⬇ **Work hardening**

Plastic deformation
Poisson ratio: Increase

Initial plastic deformation is detectable.

Strain


20
15
10
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-5
-10
-4
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0
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2.5e+02
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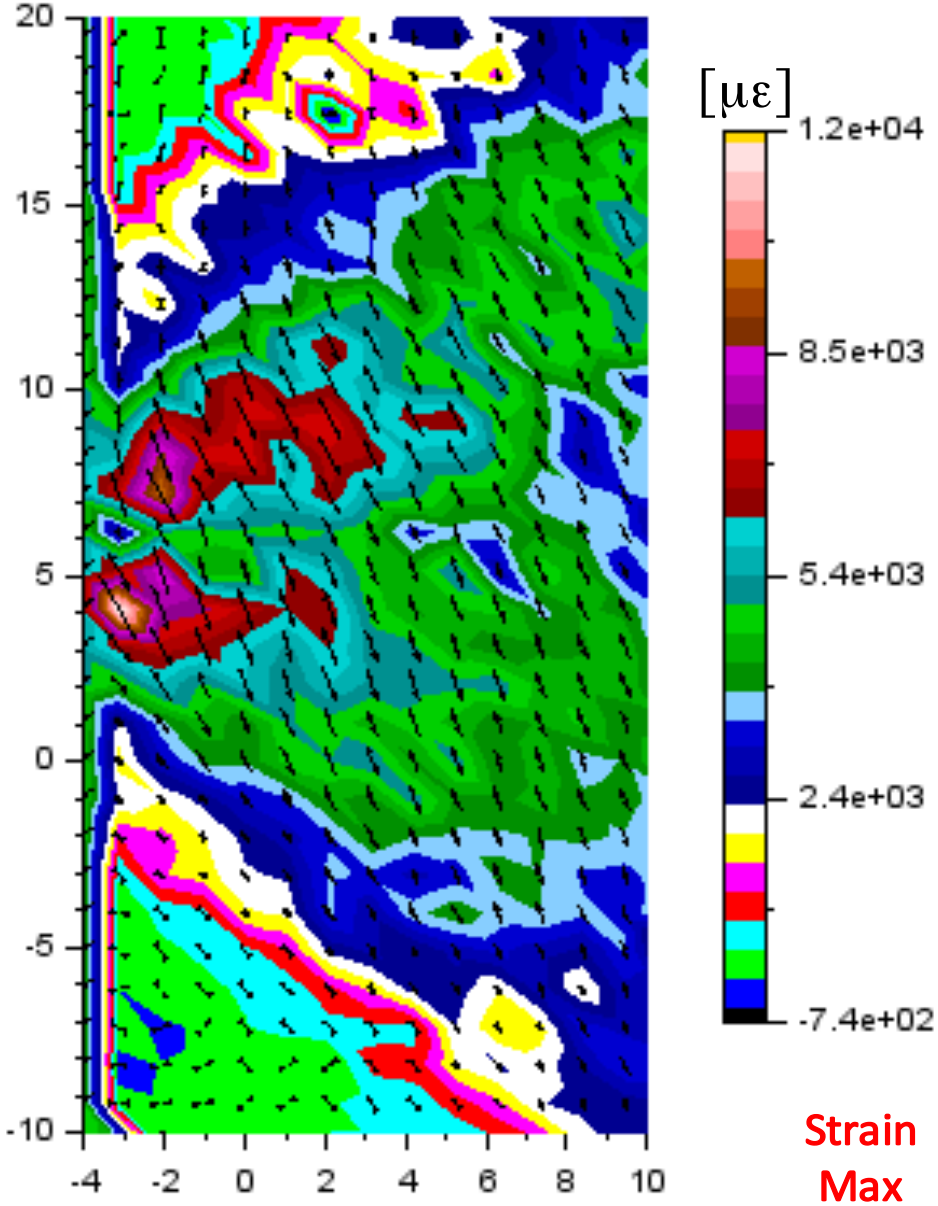
-1.8e+03
-2.8e+03
-3.9e+03
Strain Min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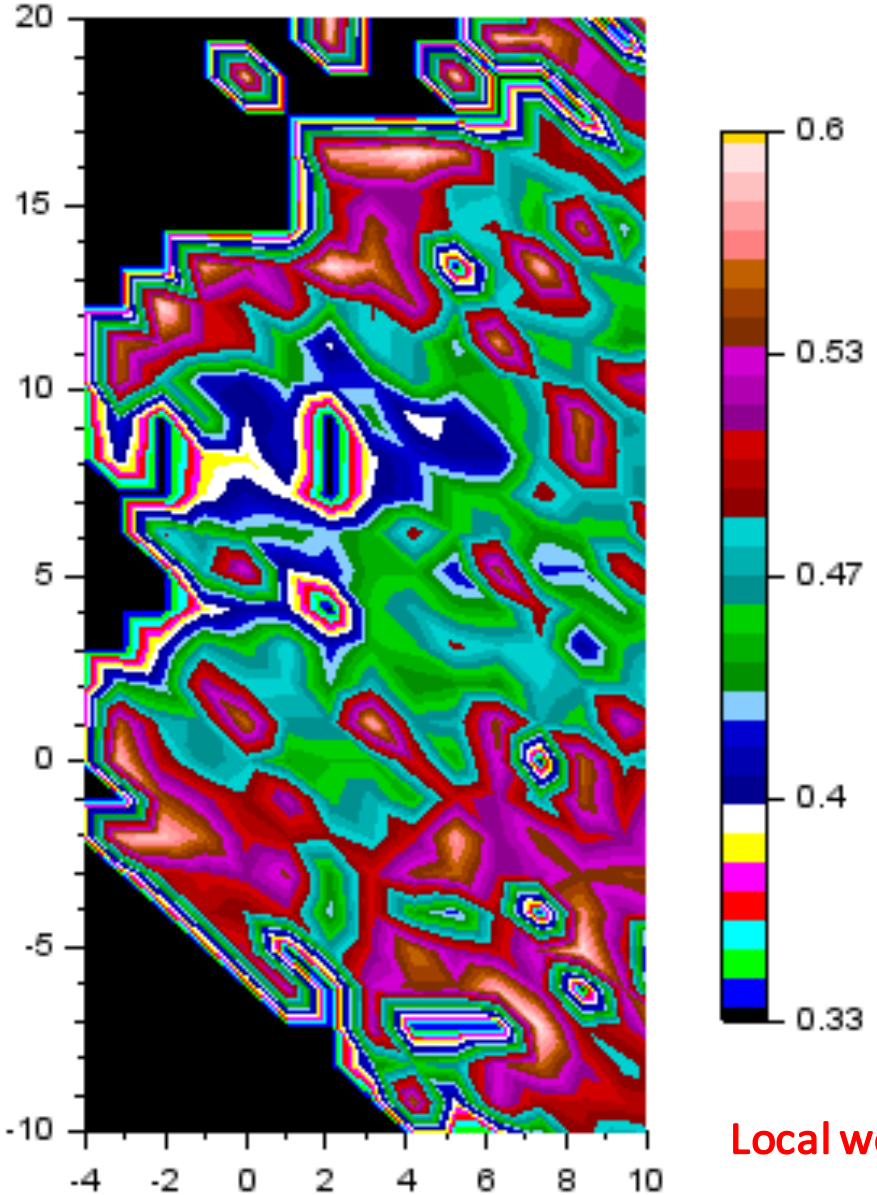
8.5e+03
5.4e+03
2.4e+03
-7.4e+02
Strain Max

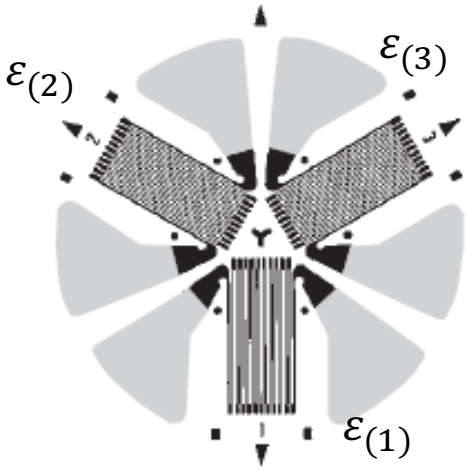
Local work hardening map

Colored region show damaged part



Local work hardening

Strain gage rosettes



Consisting of 3 strain gage with different angle

$$\begin{cases} \varepsilon_{(1)} = \dfrac{\varepsilon_1 + \varepsilon_2}{2} + \dfrac{\varepsilon_1 - \varepsilon_2}{2}\cos(2\theta) \\ \varepsilon_{(2)} = \dfrac{\varepsilon_1 + \varepsilon_2}{2} + \dfrac{\varepsilon_1 - \varepsilon_2}{2}\cos 2\left(\theta + \dfrac{\pi}{3}\right) \\ \varepsilon_{(3)} = \dfrac{\varepsilon_1 + \varepsilon_2}{2} + \dfrac{\varepsilon_1 - \varepsilon_2}{2}\cos 2\left(\theta + \dfrac{2\pi}{3}\right) \end{cases}$$

$$\begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \end{Bmatrix} = \frac{\varepsilon_{(1)} + \varepsilon_{(2)} + \varepsilon_{(3)}}{3} \pm \frac{\sqrt{2}}{3}\sqrt{\left(\varepsilon_{(1)} - \varepsilon_{(2)}\right)^2 + \left(\varepsilon_{(2)} - \varepsilon_{(3)}\right)^2 + \left(\varepsilon_{(3)} - \varepsilon_{(1)}\right)^2}$$

Principle strain can be determined based on 3 data with different angle.

$$\theta = \frac{1}{2}\tan^{-1}\left(\frac{\sqrt{3}\left(\varepsilon_{(3)} - \varepsilon_{(2)}\right)}{2\varepsilon_{(1)} - \varepsilon_{(2)} - \varepsilon_{(3)}}\right)$$

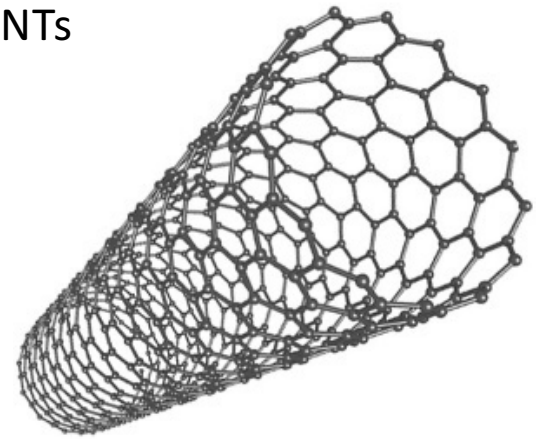
Problems

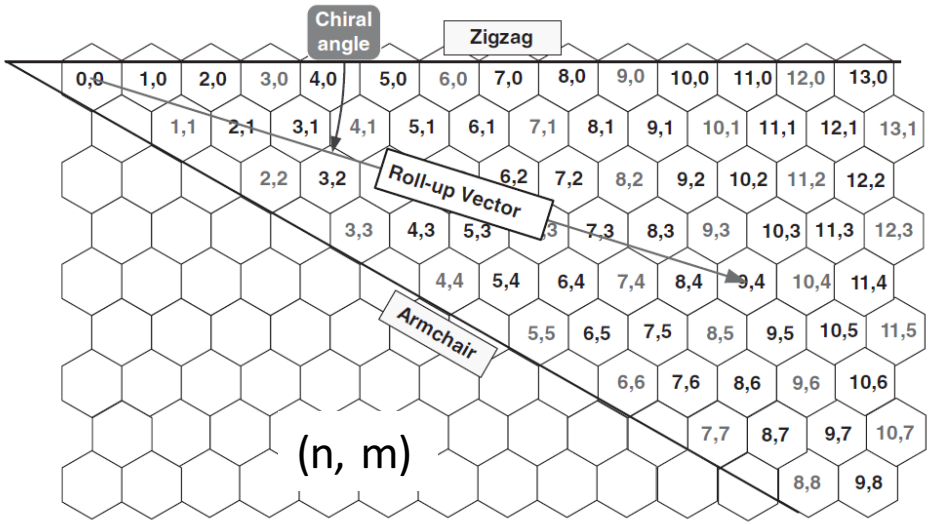
- Low accuracy (small # of data)
- Space is necessary (larger than SWNTs)
- Difficulties on deciding 0 of angle
- Stiffness & thermal conductivity of materials could be altered locally.

These can be solved by using SWNTs strain sensor.

Single-walled carbon nanotubes

SWNTs





Rolling up graphene sheet into cylindrical shape

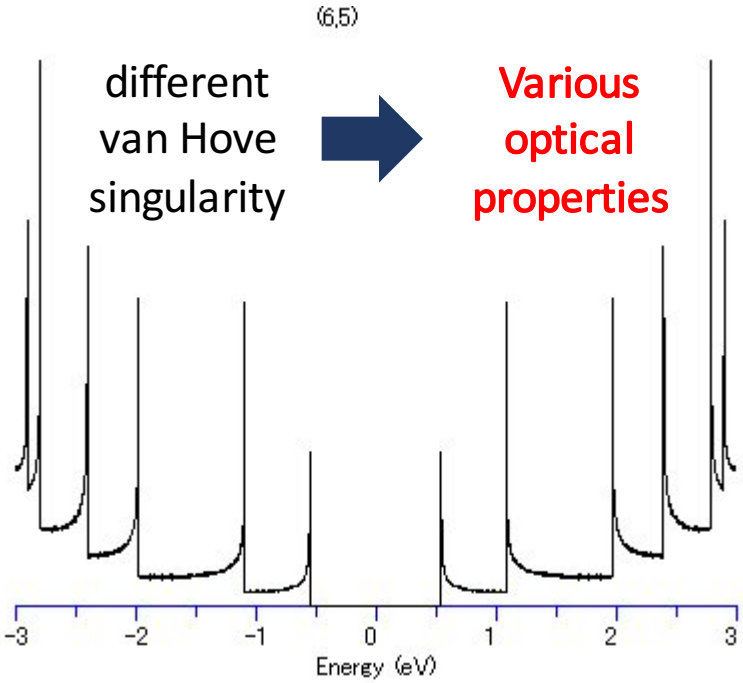
Quasi-1D structure

Various superior properties

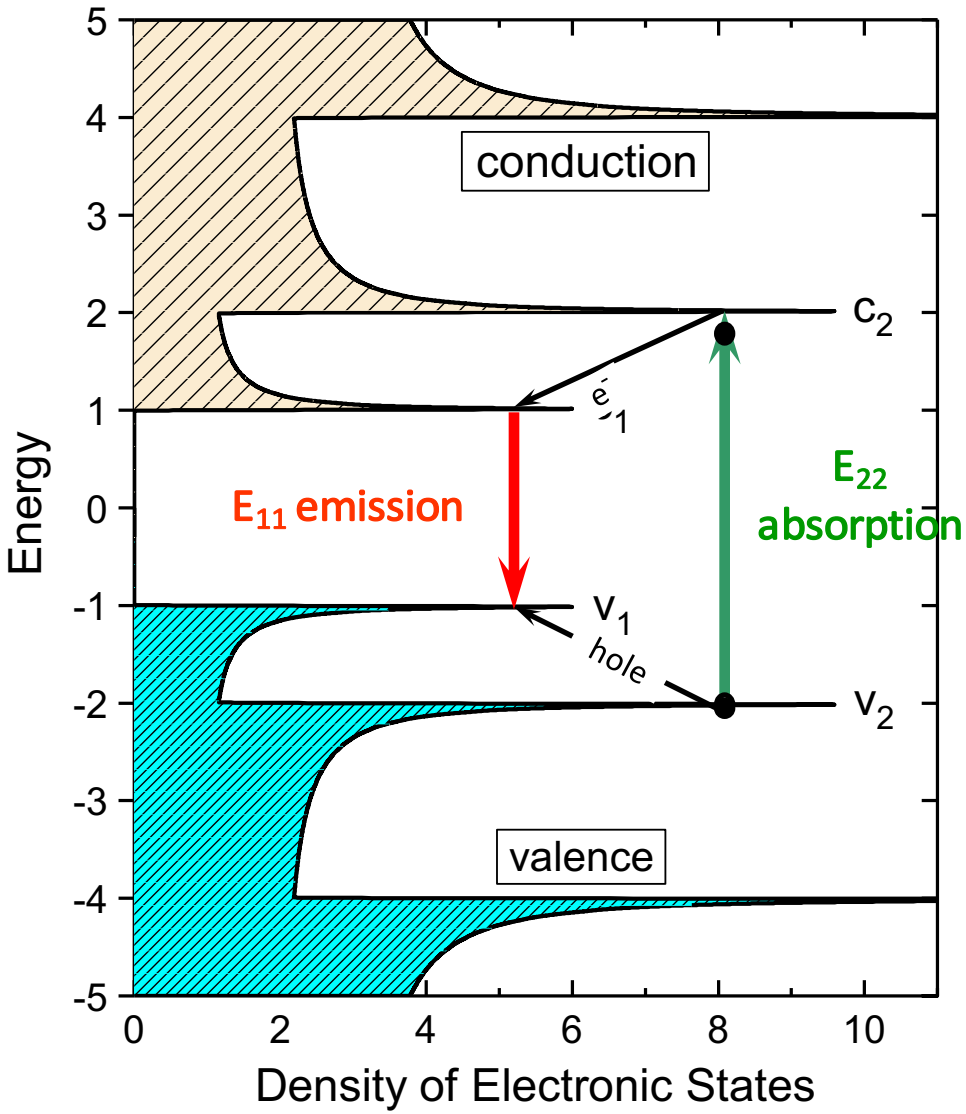
<u>Chirality and electronic structure</u>

$(n-m)\ mod\ 3 = 0 \rightarrow$ Metal

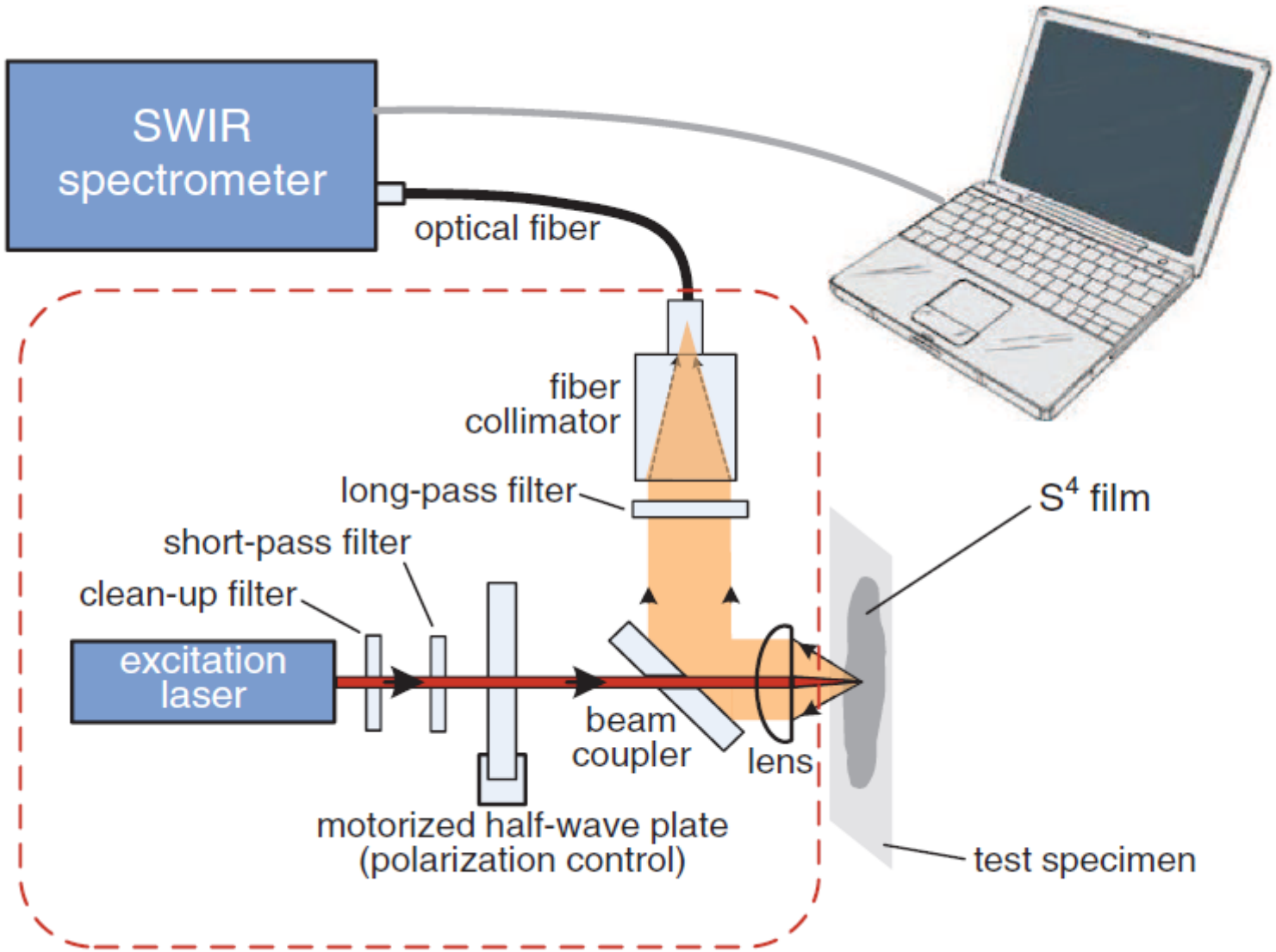
$(n-m)\ mod\ 3 \neq 0 \rightarrow$ Semiconductor



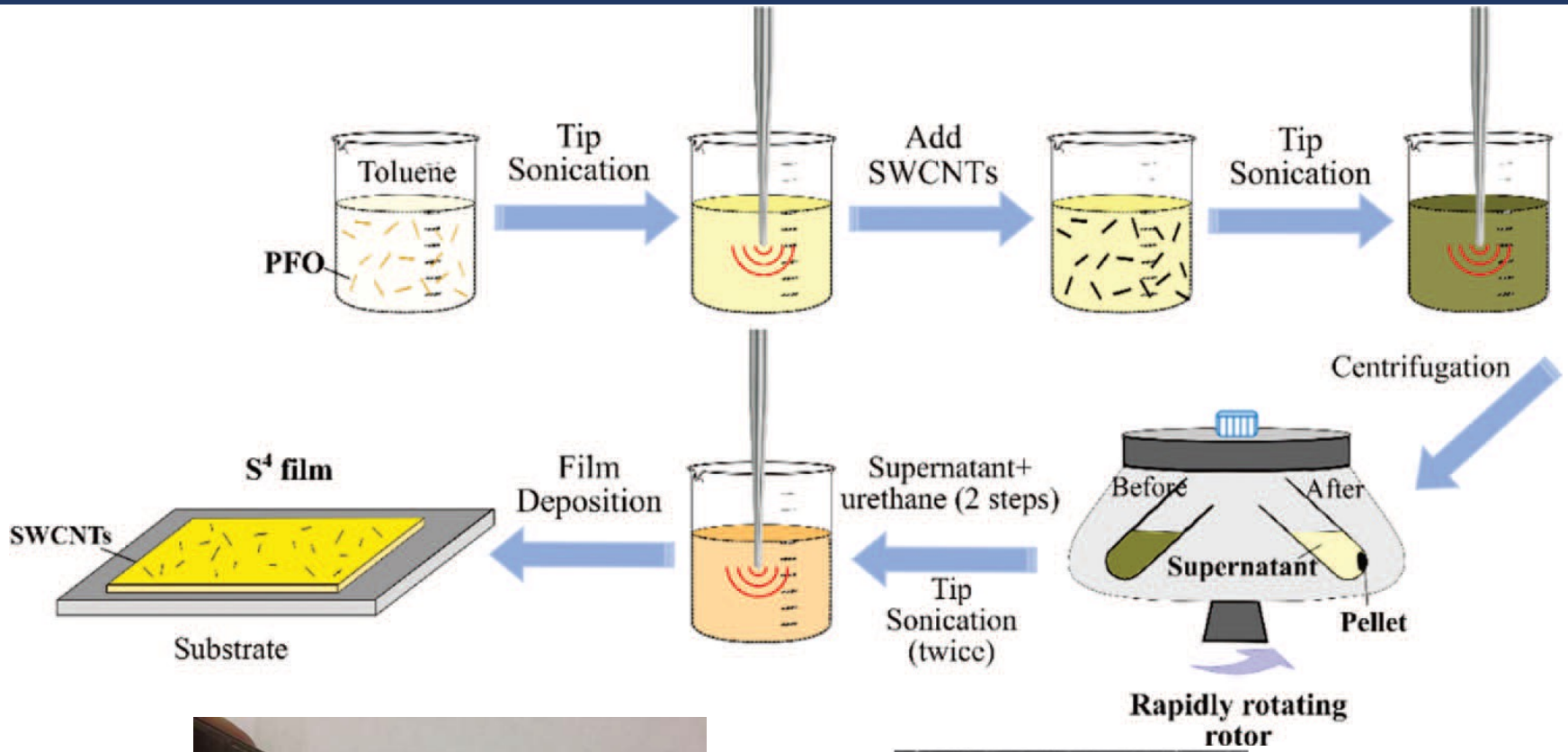
Optical property of SWNTs

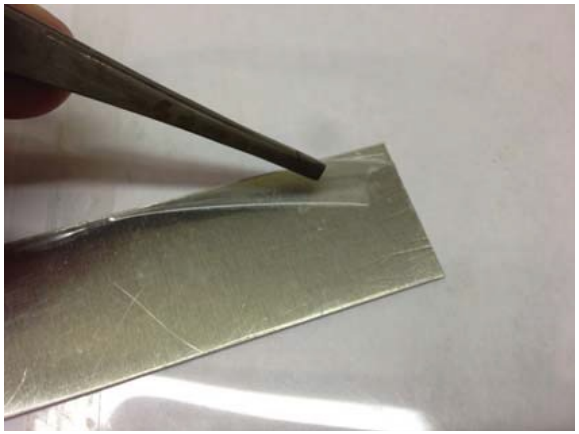


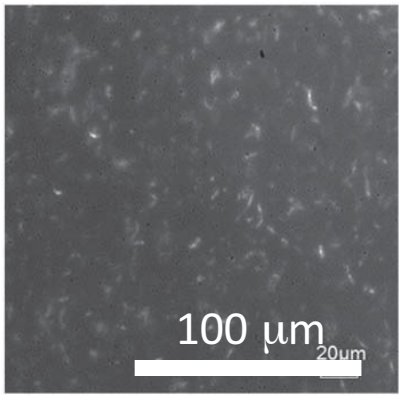
Measurement setup



SWNT dispersed polymer films

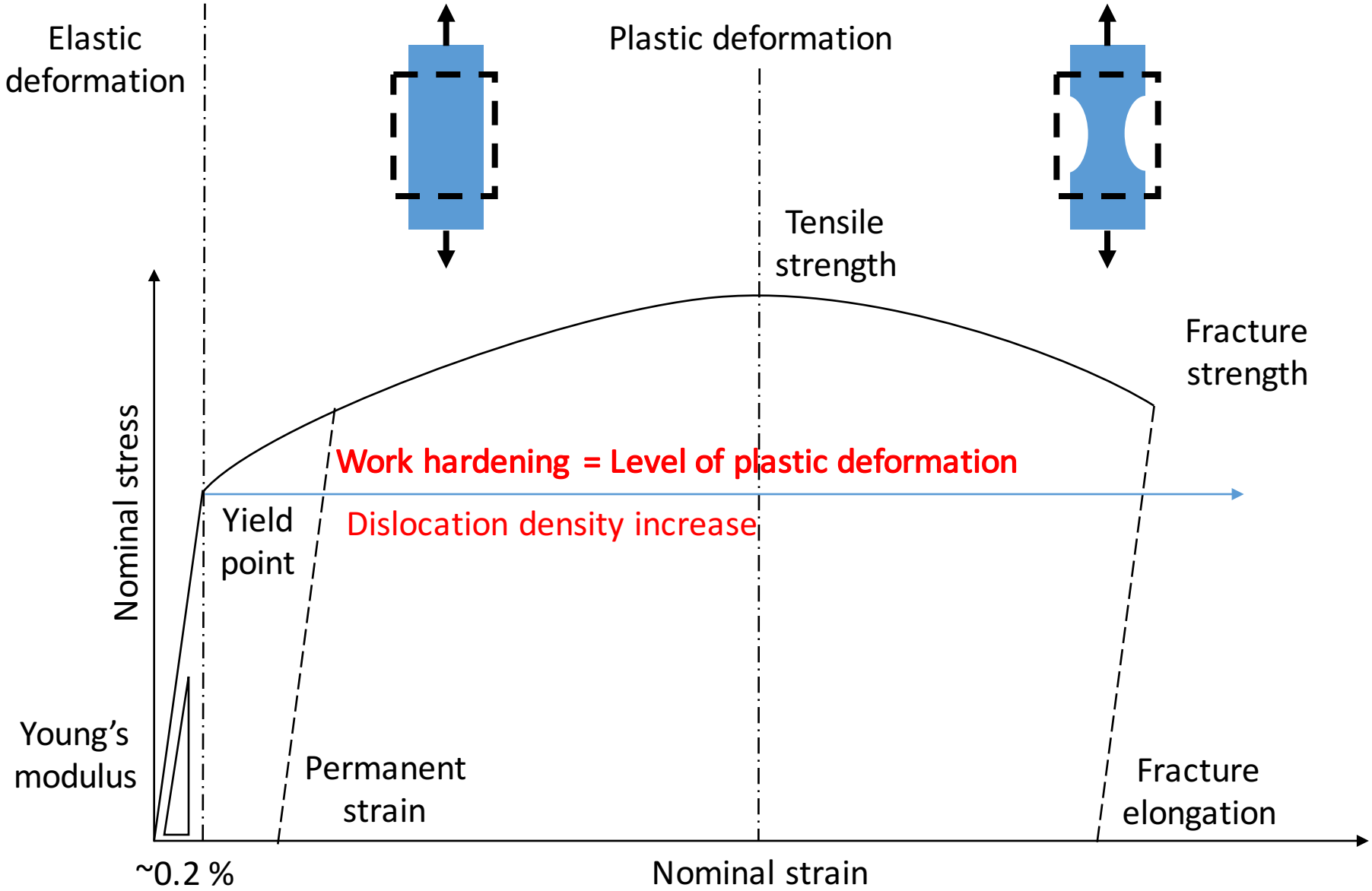




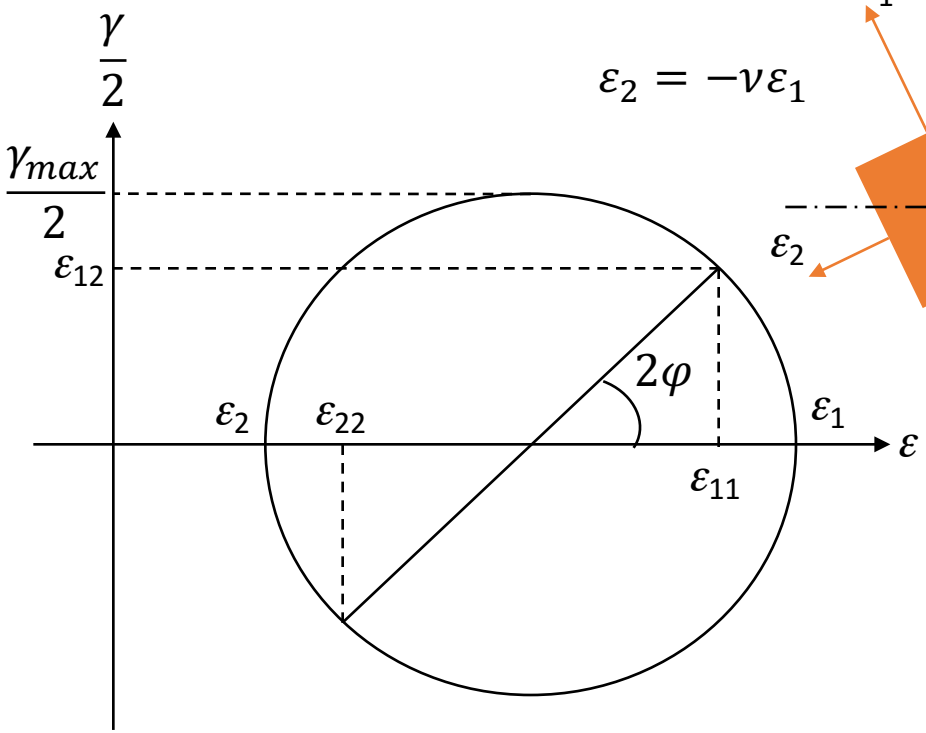


IR fluorescence microscopy images

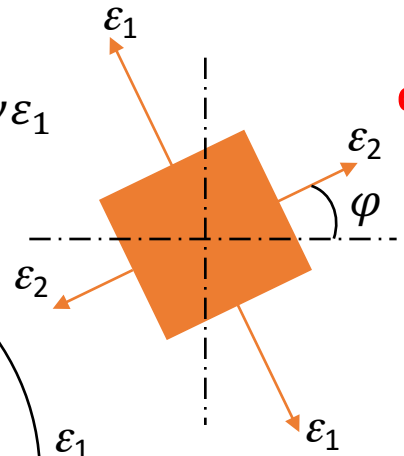
Deformation of materials



Mohr's circle

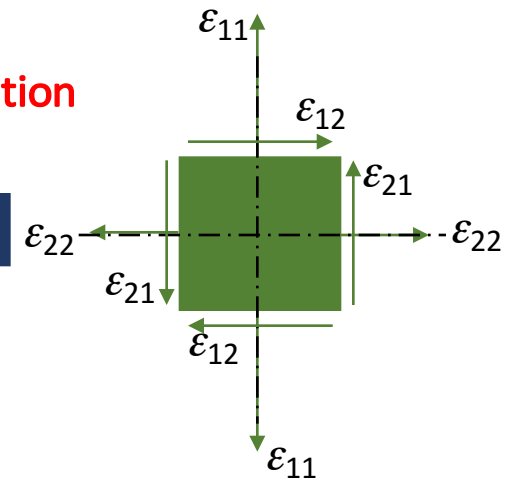


$$\varepsilon_2 = -\nu\varepsilon_1$$



diagonalization

Strain state



$$\boldsymbol{\varepsilon} = \begin{bmatrix} \varepsilon_{11} & \varepsilon_{12} \\ \varepsilon_{21} & \varepsilon_{22} \end{bmatrix} \text{(Strain tensor)}$$

$$\boldsymbol{\varepsilon x} = \varepsilon \boldsymbol{x}$$

$$(\boldsymbol{\varepsilon} - \varepsilon \boldsymbol{I})\boldsymbol{x} = \boldsymbol{0}$$

$$|\boldsymbol{\varepsilon} - \varepsilon \boldsymbol{I}| = 0$$

Equivalent

$$\left(\varepsilon - \frac{\varepsilon_1 + \varepsilon_2}{2}\right)^2 + \left(\frac{\gamma}{2}\right)^2 = \left(\frac{\varepsilon_1 - \varepsilon_2}{2}\right)^2$$

$$\begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \end{Bmatrix} = \frac{\varepsilon_{11} + \varepsilon_{22}}{2} \pm \sqrt{\left(\frac{\varepsilon_{11} - \varepsilon_{22}}{2}\right)^2 + \varepsilon_{12}^2}$$

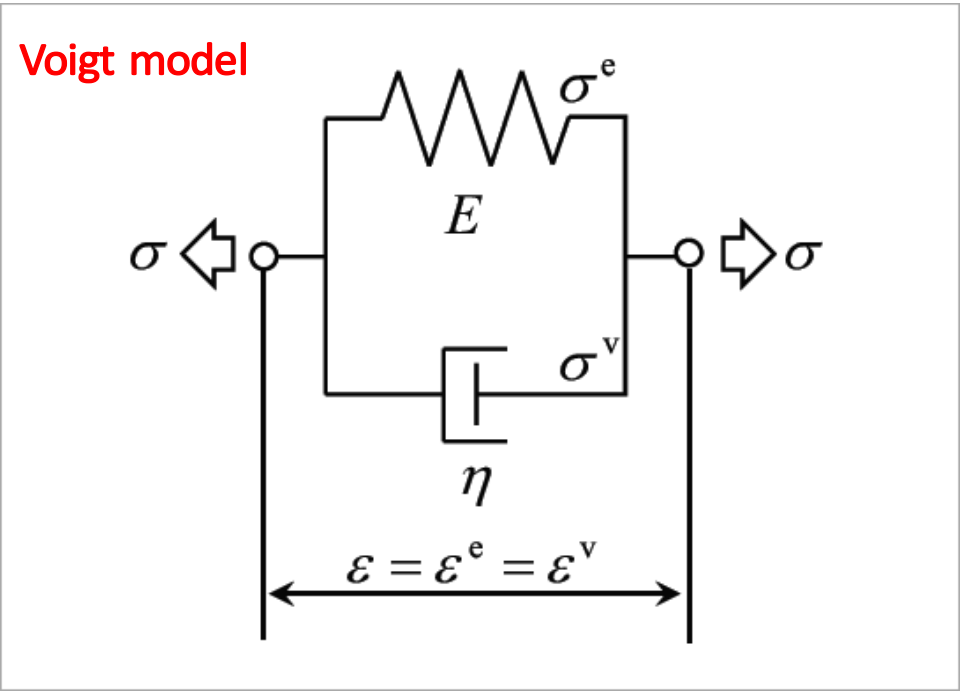
$$\varepsilon = \frac{\varepsilon_1 + \varepsilon_2}{2} + \frac{\varepsilon_1 - \varepsilon_2}{2}\cos(2\theta + 2\varphi)$$

$$\varphi = \frac{1}{2}\tan^{-1}\left(\frac{2\varepsilon_{12}}{\varepsilon_{11} - \varepsilon_{22}}\right)$$

$$\varepsilon = \frac{1 - \nu}{2} + \frac{1 + \nu}{2}\cos(2\theta + 2\varphi)$$

Dynamic measurement

Viscoelasticity of polymer film
→ Strain response delay in cycle test



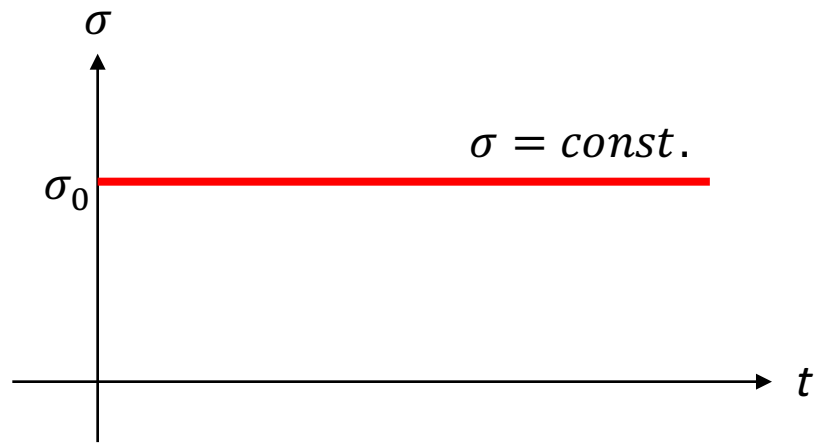
$$\sigma = \sigma^e + \sigma^v$$

$$\varepsilon = \varepsilon^e = \varepsilon^v$$

$$\sigma^e = E\sigma^e = E\varepsilon$$

$$\sigma^v = \eta\dot{\varepsilon^v} = \eta\dot{\varepsilon}$$

$$\sigma = E\varepsilon + \eta\dot{\varepsilon}$$



$$\varepsilon(t) = \frac{\sigma_0}{E}\left(1 - \exp\left(-\frac{E}{\eta}t\right)\right)$$

Input force

$$\sigma = \sigma_0 f(t)$$

$$\varepsilon(t) = f \otimes \varepsilon = \mathcal{L}^{-1}\left[\mathcal{L}[f]\mathcal{L}[\varepsilon]\right]$$

Strain response delay can be eliminated.

Levenberg–Marquardt algorithm

Problem: Finding least squares

$$S(\boldsymbol{\beta}) = \sum_{i=1}^{m} [y_i - f(x_i, \boldsymbol{\beta})]^2$$

One of the most used, typical & fast optimization algorithms

Idea

$$f(x_i, \boldsymbol{\beta}_0 + \boldsymbol{\delta}) \approx f(x_i, \boldsymbol{\beta}_0) + J_i \boldsymbol{\delta}$$

$\boldsymbol{\beta}_0$: Initial guess of optimization parameter

Moving from $\boldsymbol{\beta}$ to $\boldsymbol{\beta} + \boldsymbol{\delta}$

$$J_i = \frac{\partial f(x_i, \boldsymbol{\beta}_0)}{\partial \boldsymbol{\beta}}$$

Jacobian matrix

$$S(\boldsymbol{\beta}_0 + \boldsymbol{\delta}) \approx \sum_{i=1}^{m} [y_i - f(x_i, \boldsymbol{\beta}_0) + J_i \boldsymbol{\delta}]^2 = \|\boldsymbol{y} - \boldsymbol{f}(\boldsymbol{\beta}_0) - \boldsymbol{J}\boldsymbol{\delta}\|^2$$

Finding best $\boldsymbol{\delta}$

Solution

$$(\boldsymbol{J}^T \boldsymbol{J})\boldsymbol{\delta} = \boldsymbol{J}^T [\boldsymbol{y} - \boldsymbol{f}(\boldsymbol{\beta}_0)]$$

←same as (differential = 0)

$$\left(\boldsymbol{J}^T \boldsymbol{J} + \lambda \mathbf{diag}(\boldsymbol{J}^T \boldsymbol{J})\right)\boldsymbol{\delta} = \boldsymbol{J}^T [\boldsymbol{y} - \boldsymbol{f}(\boldsymbol{\beta}_0)]$$

Levenberg-Marquardt algorithm

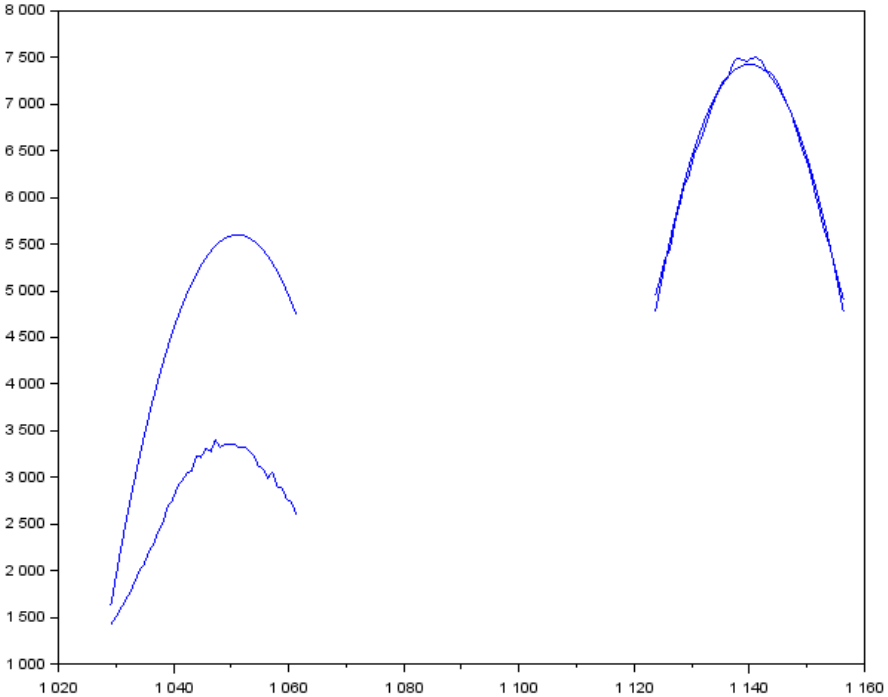
λ: Damping factor (Adjustable) → make the calculation faster.

Peak deconvolution

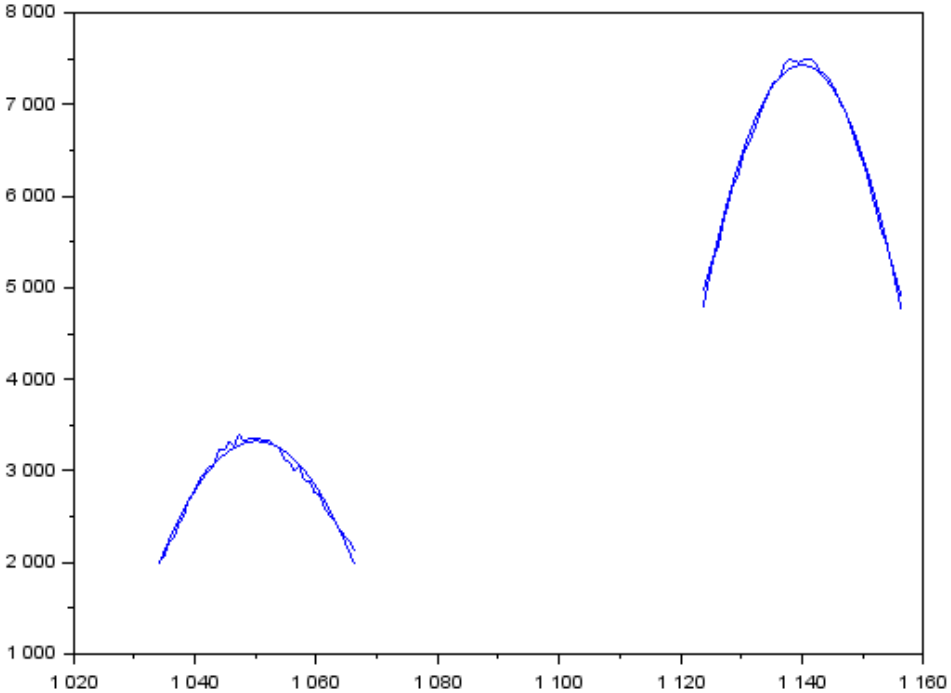
Levenberg – Maquardt algorithm
Optimized solution → depends on initial assumption

Problem: Inappropriate fitting curve could appear.
Solution: Polynomial fitting curves (→ Analytically solved)

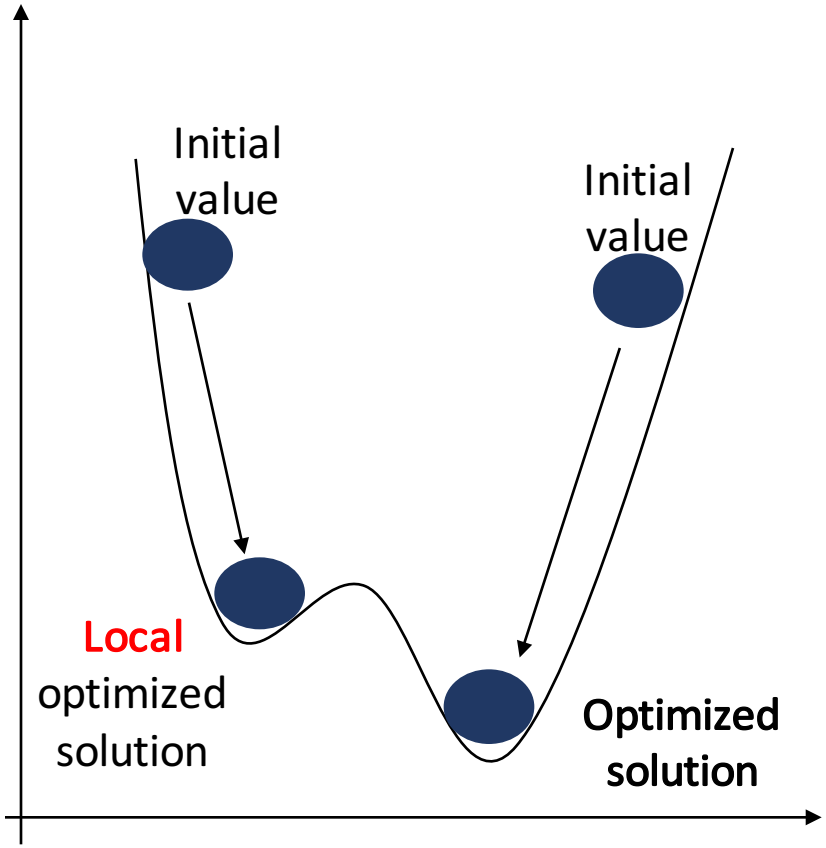
Before



After



Annealing methods



Levenberg – Maquardt algorithm
Optimized solution
→ depends on initial assumption

Problem:
Inappropriate fitting curve could appear.

Solution:
(1) Random initial value
(2) Find the most optimized one
(Annealing methods)

Future applications

(1) Structural health monitoring

(2) Application for nano-micro mechanical structures

Remained issues

(1) Material optimizations

- Degradation resistance
- Good adhesion with substrates
- Cost performance
- Spray technique

(2) System optimizations

- Data precision
- Data acquisition speed up
- Data processing speed up