Optical Characterization Methods

Julio A. N. T. Soares
Materials Research Laboratory
University of Illinois

Materials Research Laboratory

amc.mrl.Illinois.edu

Optical characterization

Light properties

Light-matter interactions

Instrumentation and methods

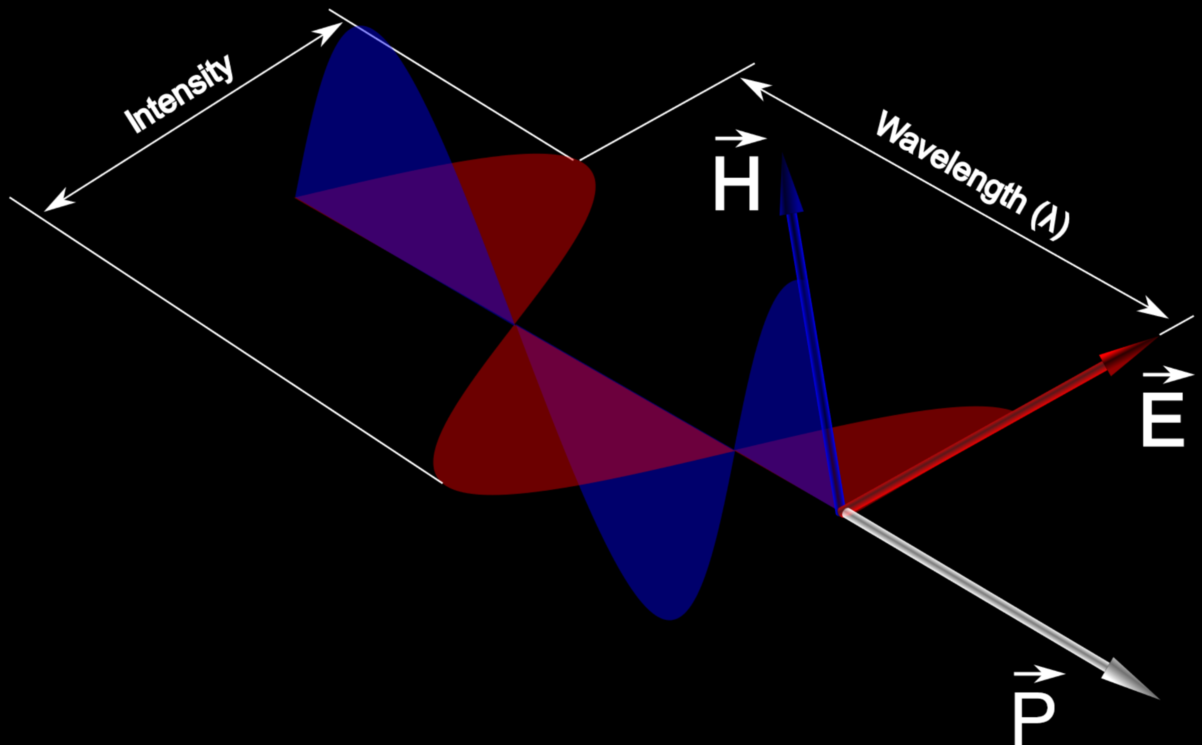
Applications

Strengths and limitations

Complementary techniques

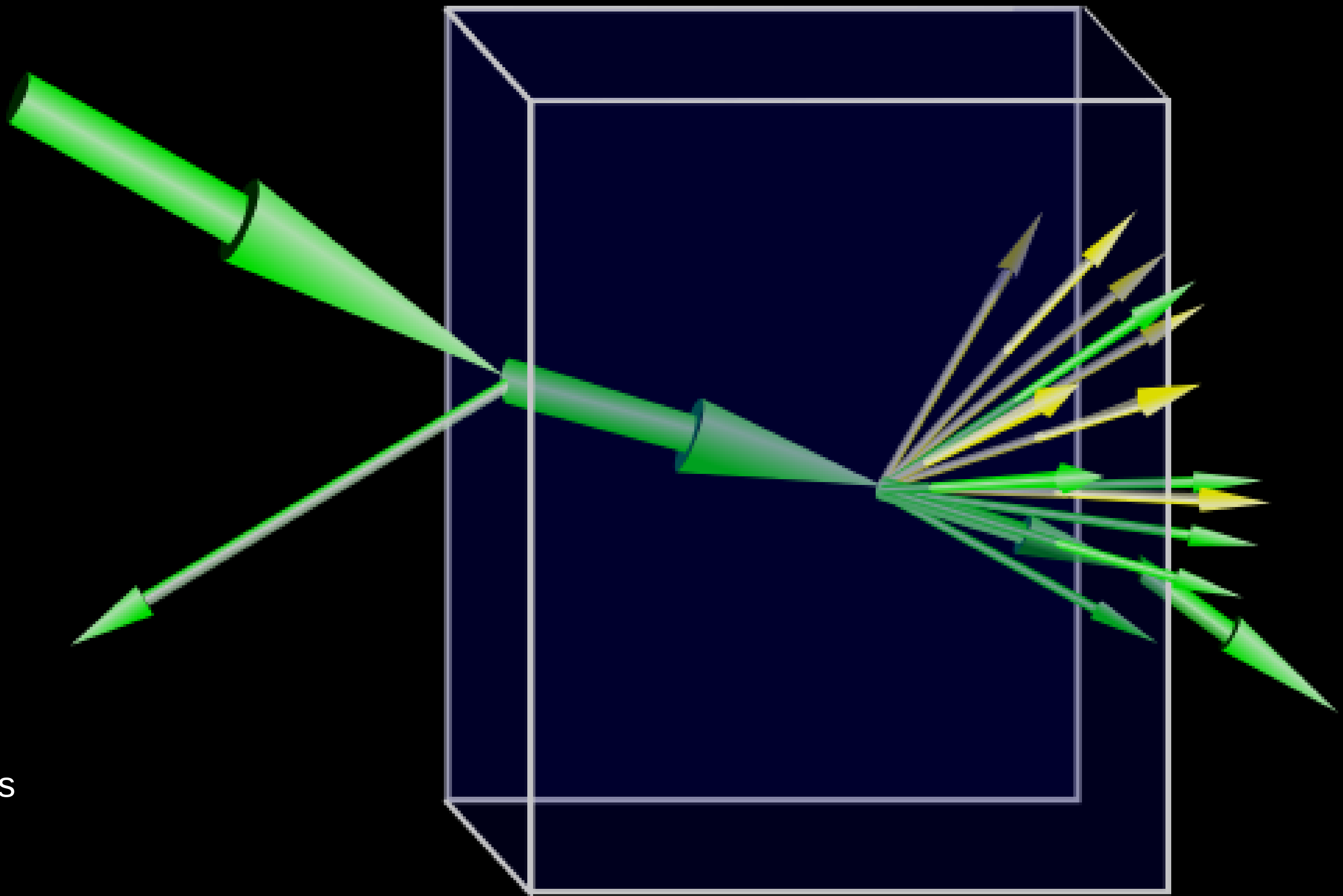
Light properties

- Direction of propagation
- Electric field direction or polarization
- Photon energy or wavelength
- Intensity
- Speed (constant in vacuum = 299,792,458 m/s = 670,616,632 mph)



Light interactions

- Transmission
- Reflection
- Absorption
- Emission
- Scattering
- Refraction



Non-linear effects
- SFG
- SHG
- DFG
- Multi-photon absorption

Light – matter interaction

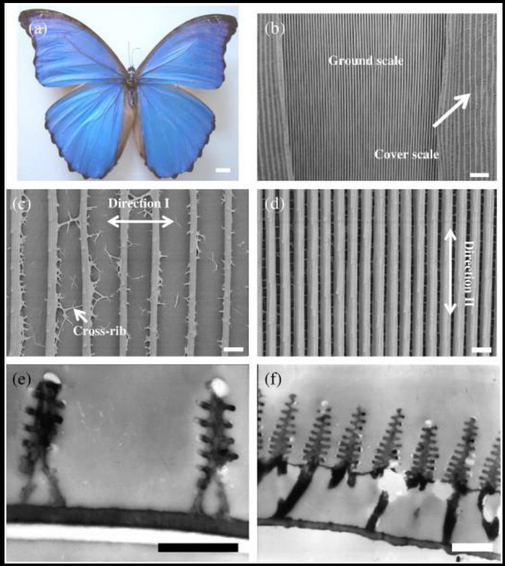
Size

Lattice structure, dopants

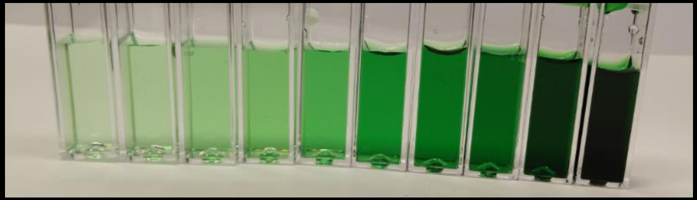
Temperature

Stress

Microstructure

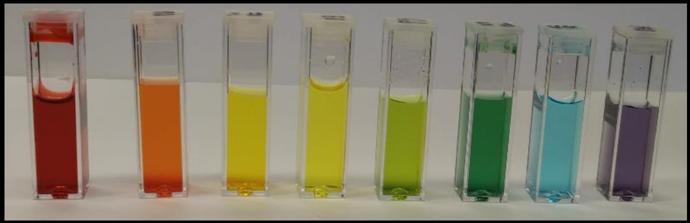


Concentration



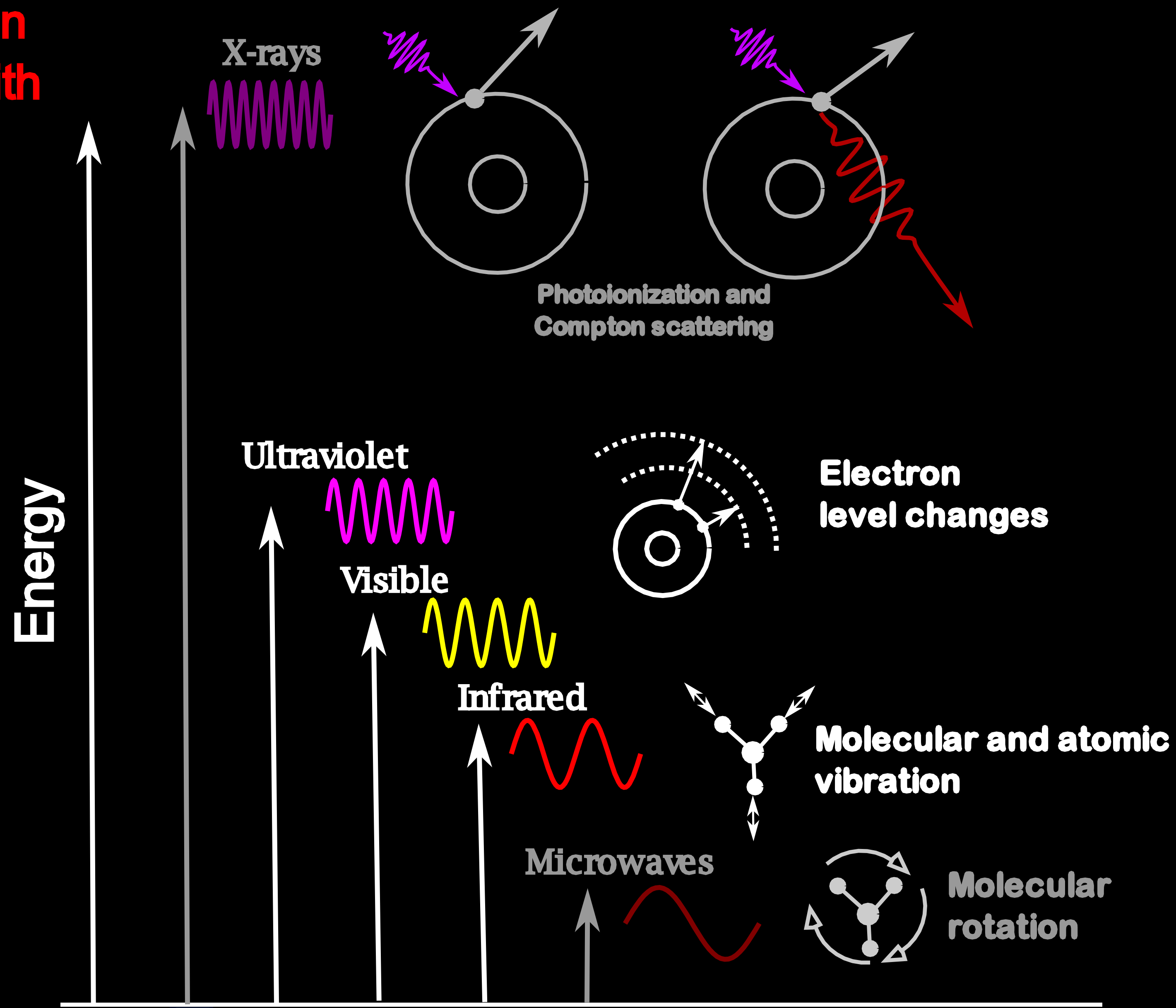
Thickness

Composition

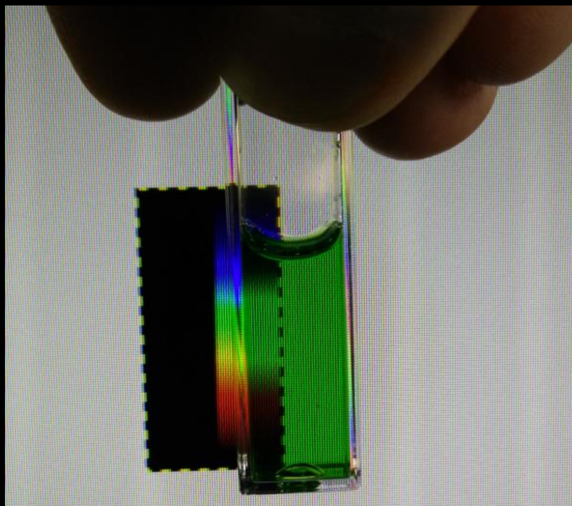


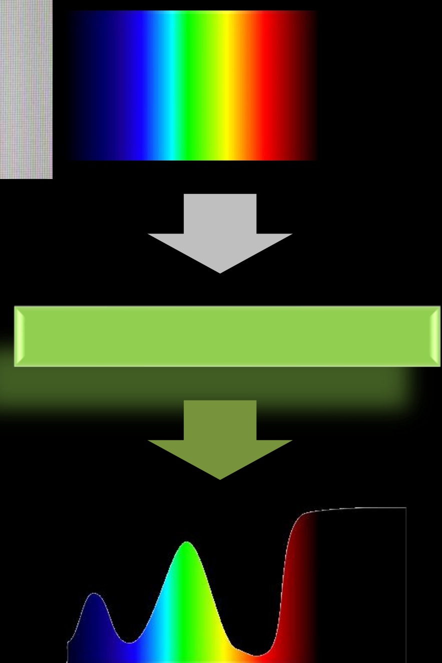
Light interactions

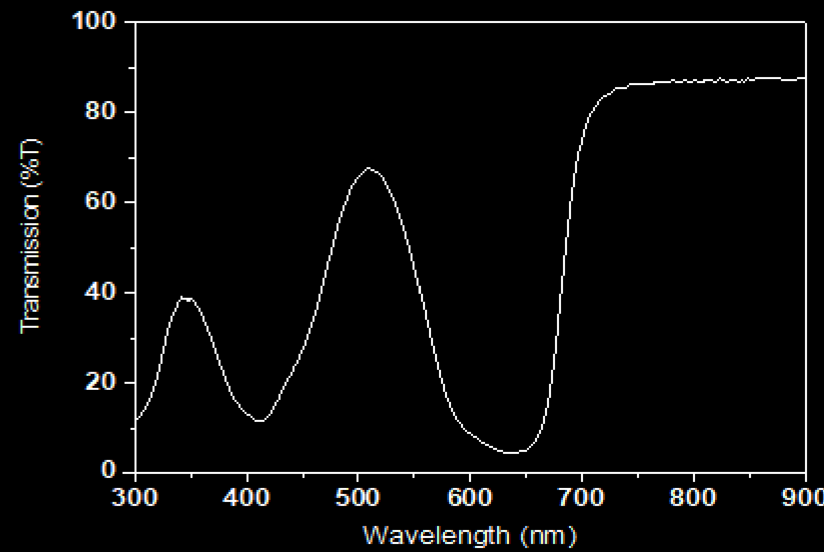
The interaction of radiation with matter

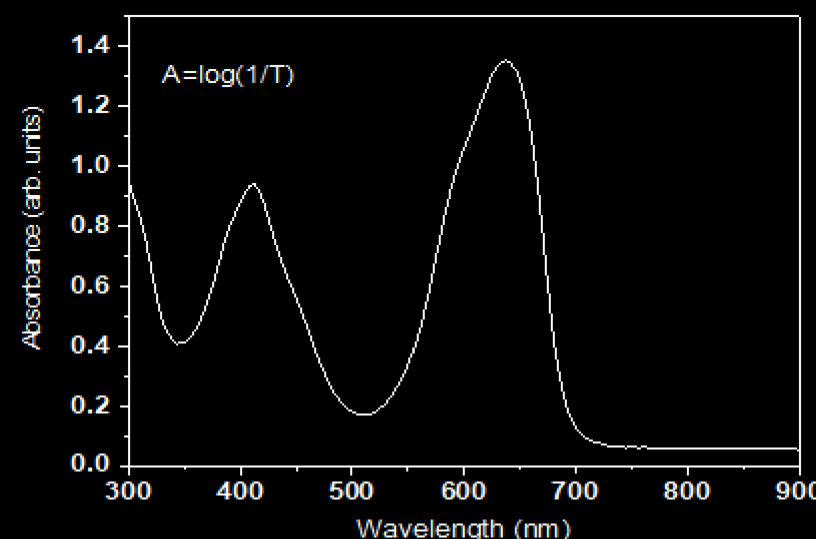


Spectroscopy





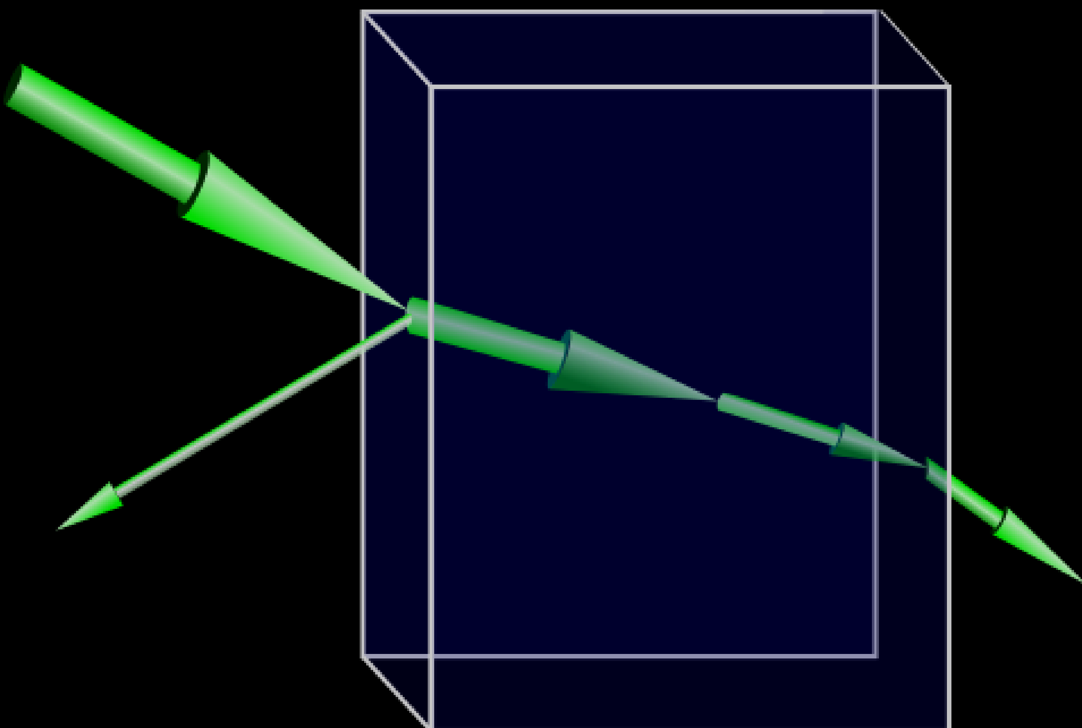




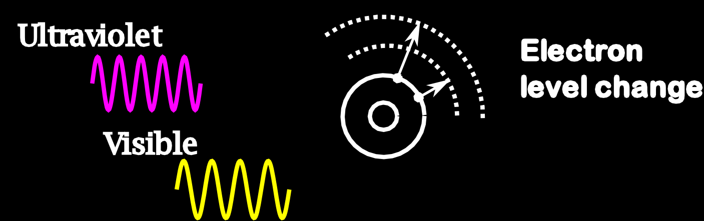
Transmission, Reflection, Absorption

What is measured:

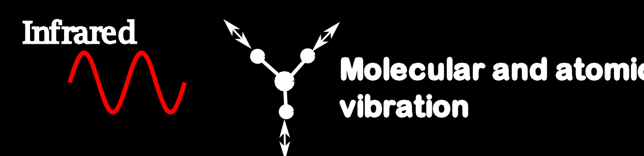
The transmitted and reflected light intensity as a function of the incident photon energy, which depends on the material's electronic, atomic, chemical and morphological structure.



UV-Vis-NIR

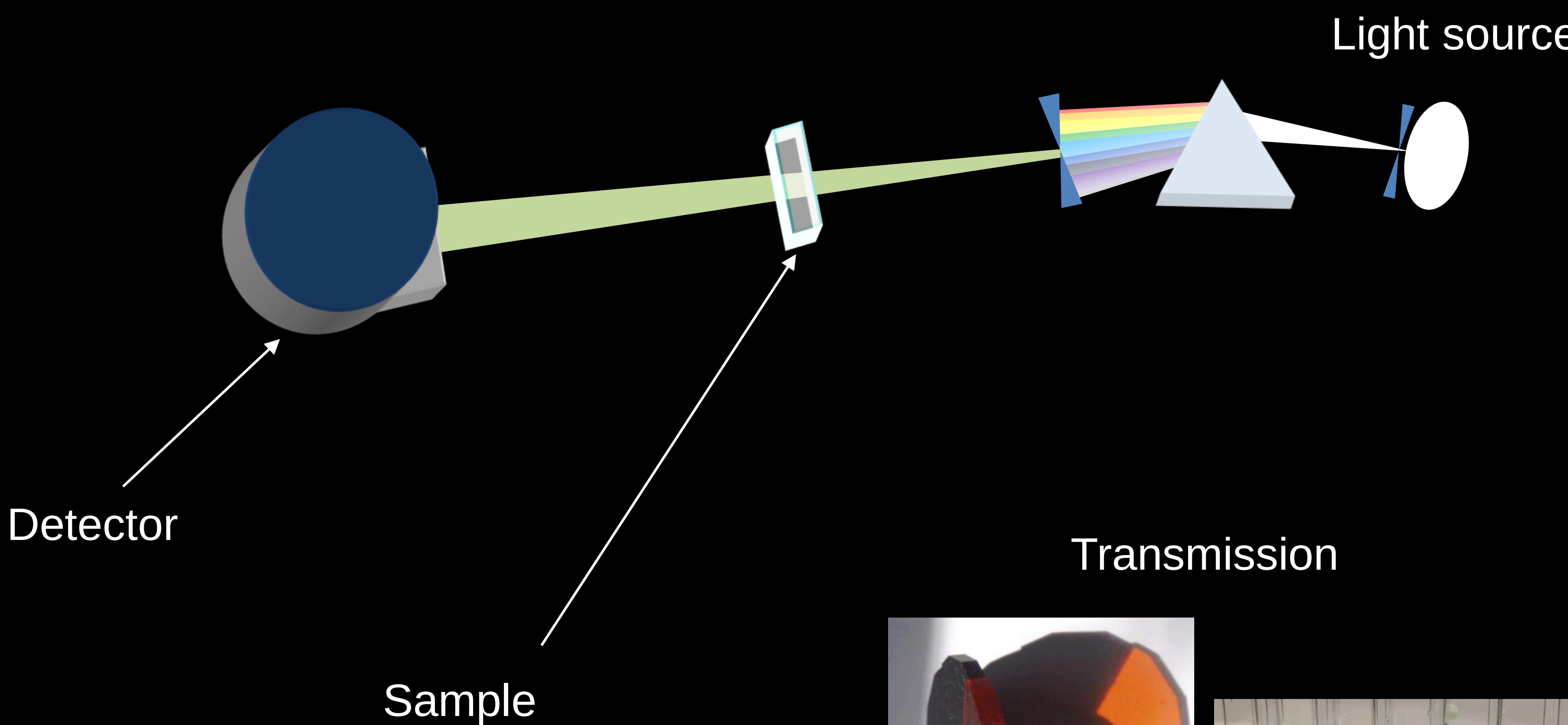


FTIR

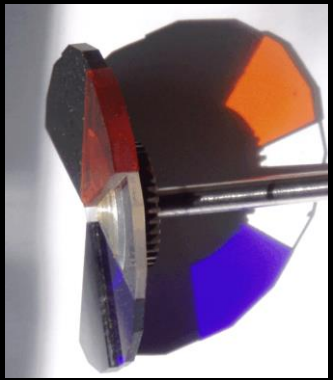


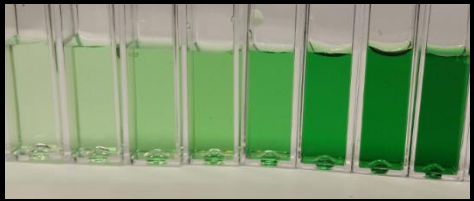
Spectrophotometry (UV-VIS-NIR)

Instrumentation:



Transmission





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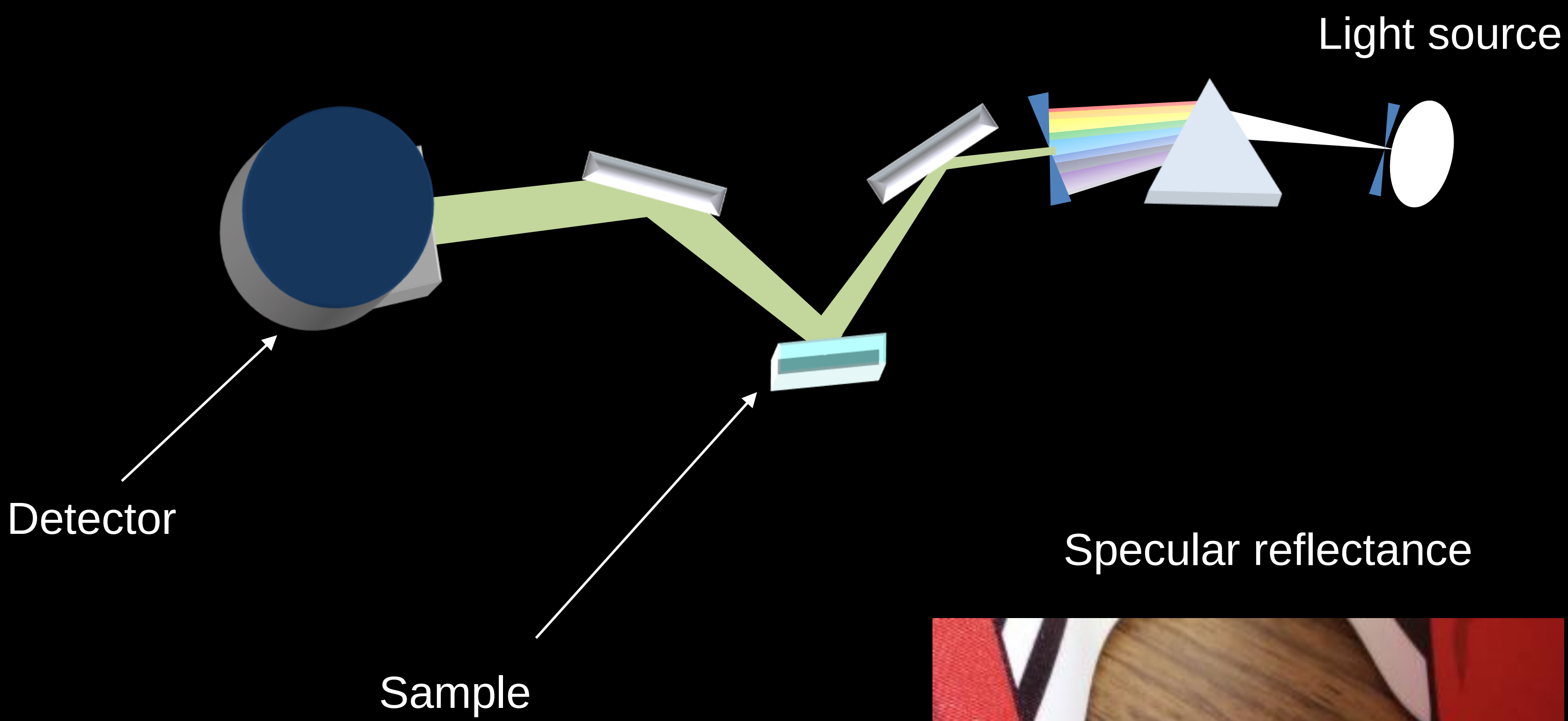
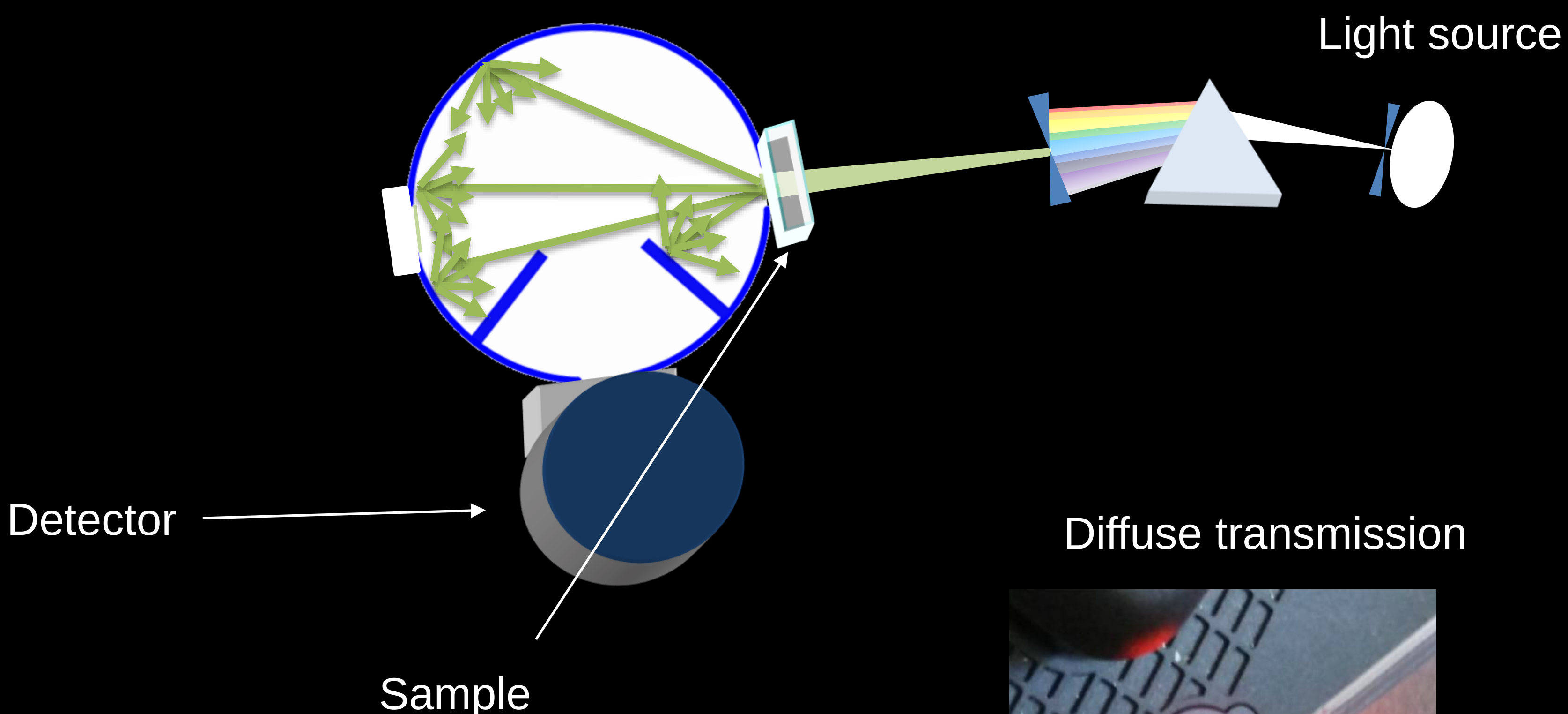


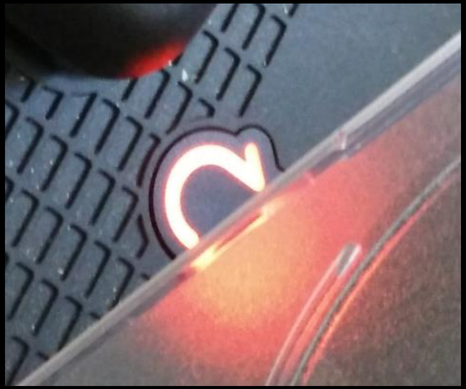
Specular reflectance

Spectrophotometry (UV-VIS-NIR)

Instrumentation:

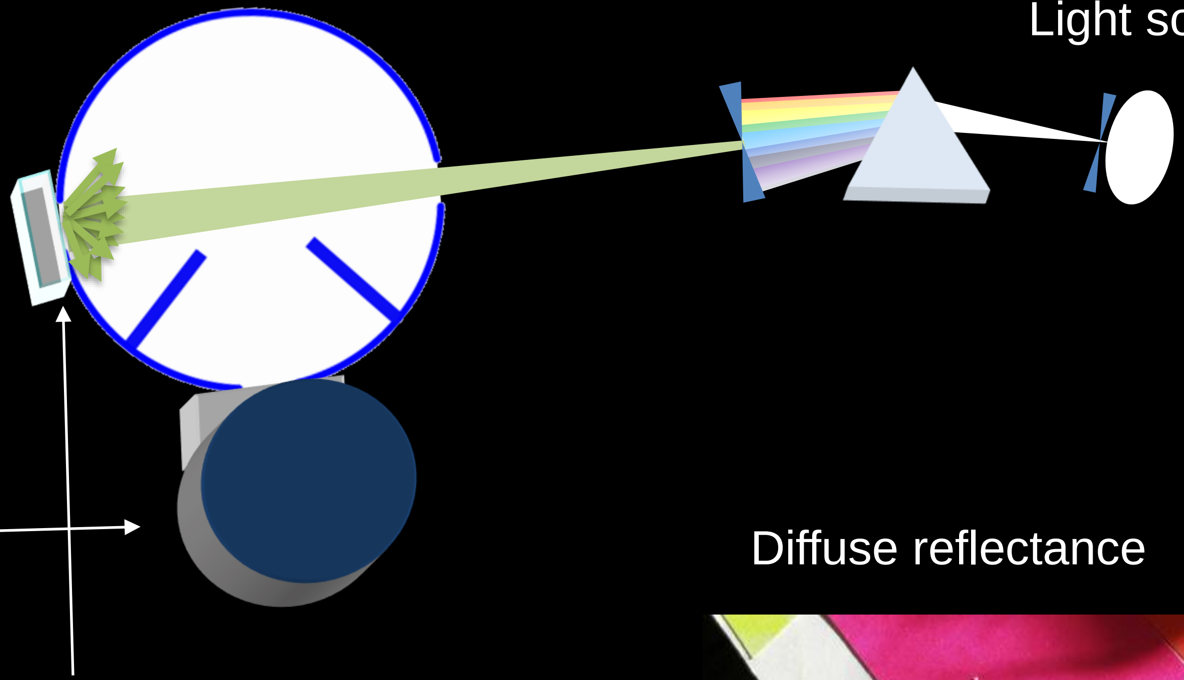


Diffuse transmission



Spectrophotometry (UV-VIS-NIR)

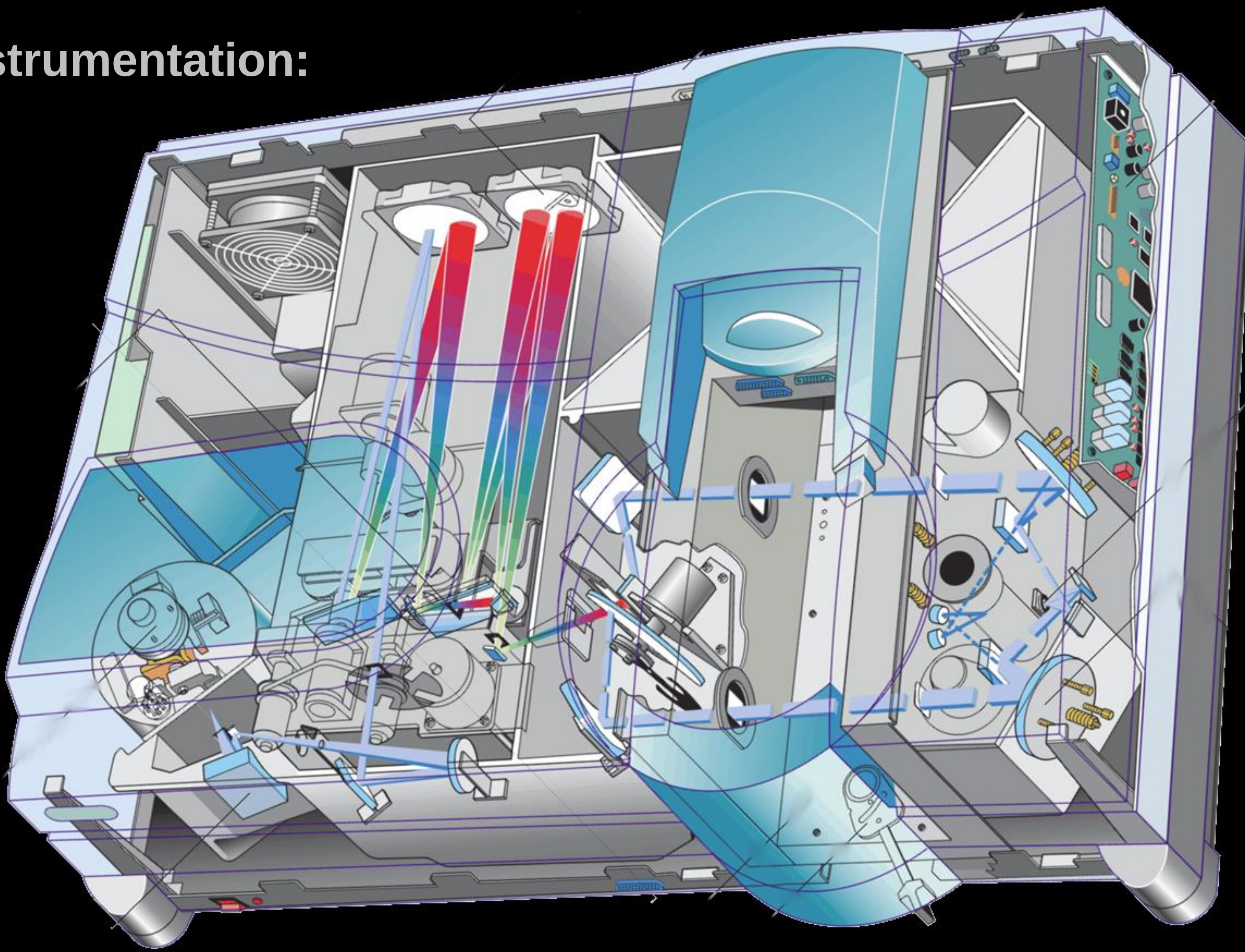
Instrumentation:



Diffuse reflectance

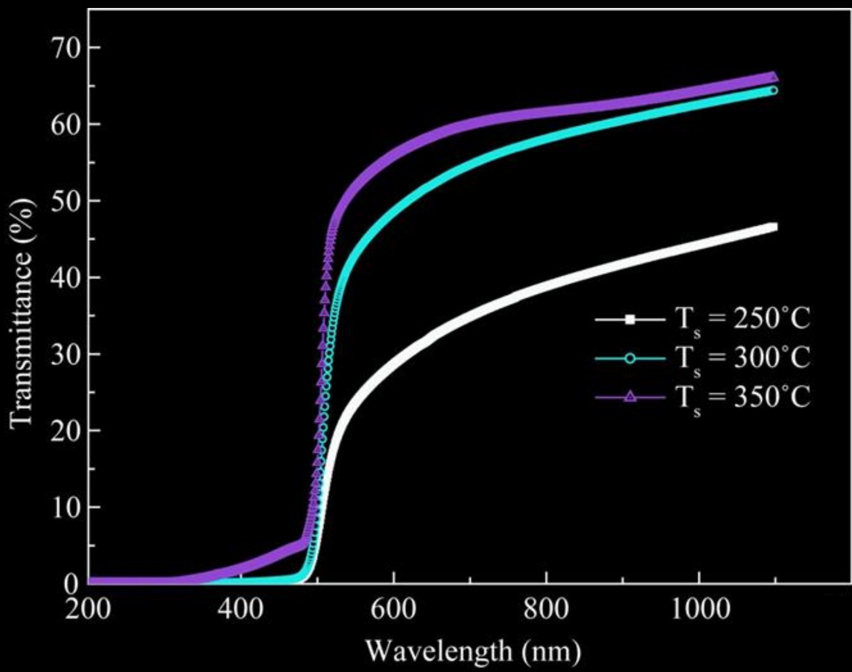
Spectrophotometry (UV-VIS-NIR)

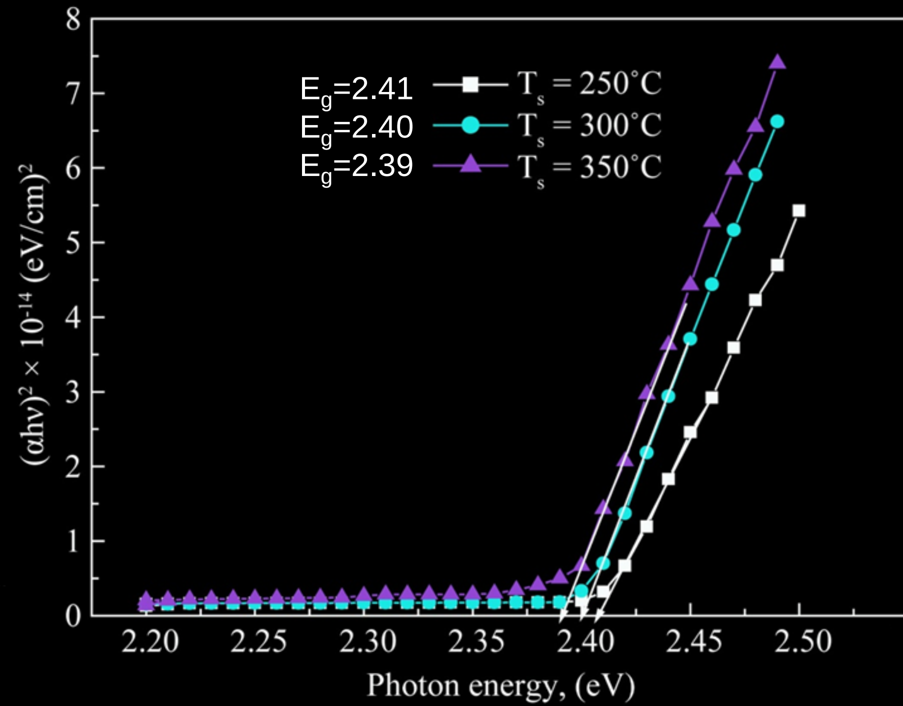
Instrumentation:



Agilent Technologies

Spectrophotometry (UV-VIS-NIR)





Optical band gap determination of CdS thin films as a function of growth substrate temperatures

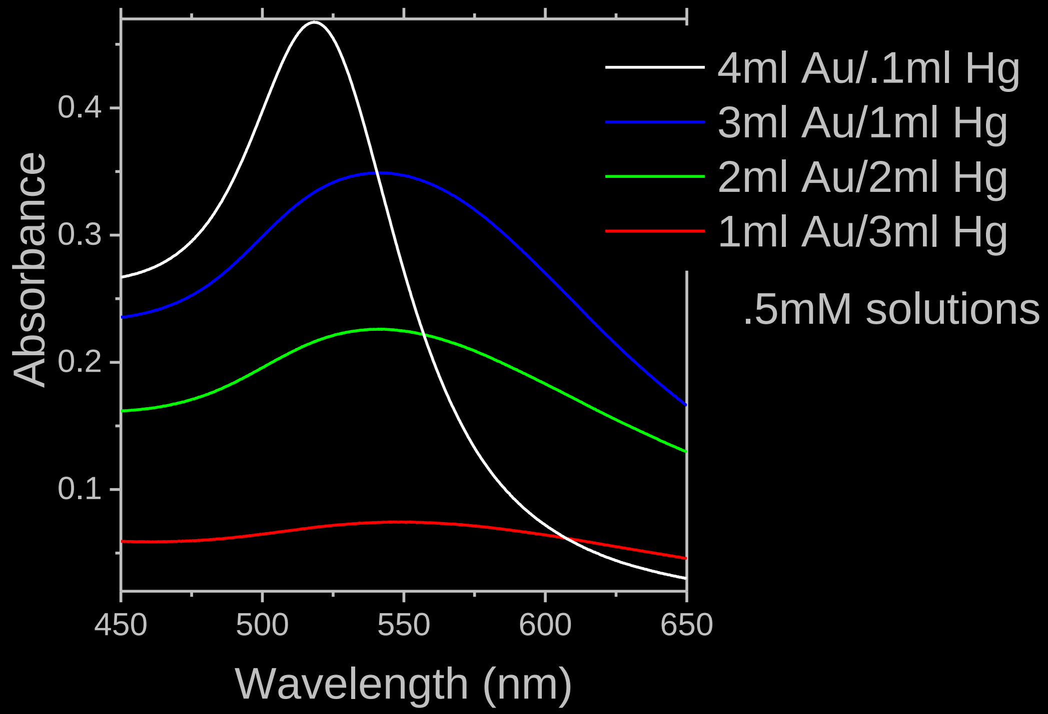
Tauc's relation:

$$\alpha h\nu = A\left(h\nu - E_g\right)^m$$

m = 0.5 for direct and 2 for indirect allowed transitions.

J. Surf. Eng. Mat. and Adv. Tech. **3**, 43 (2013)

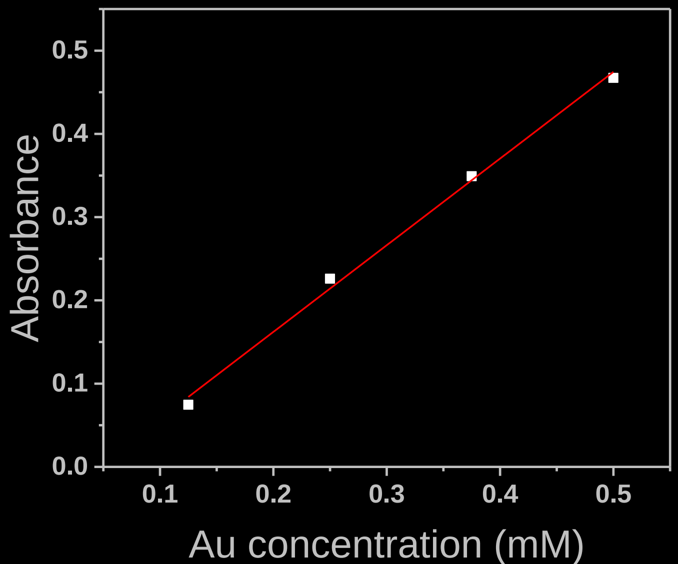
Spectrophotometry (UV-VIS-NIR)



Beer-Lambert Law

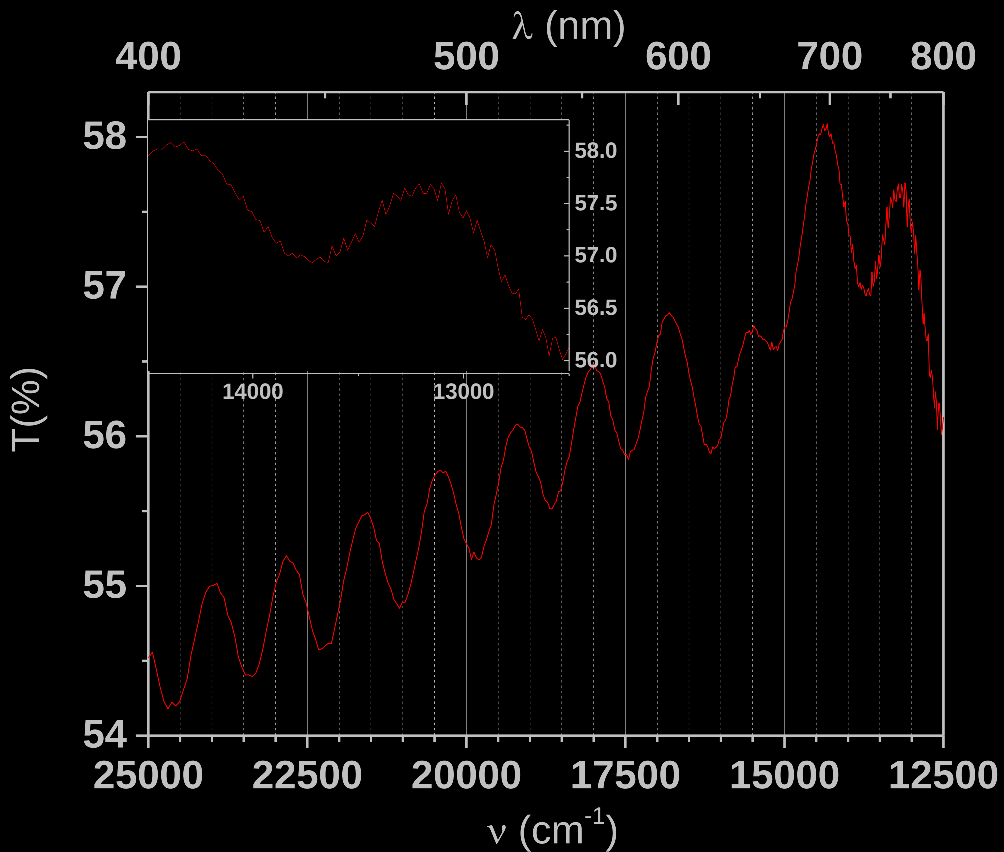
$Abs = K \ell c = a \ell$

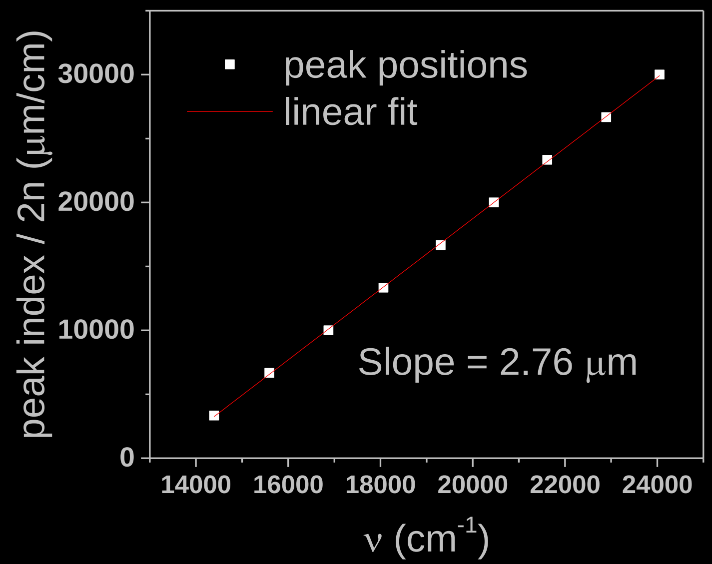
$Abs = \log (1/T)$

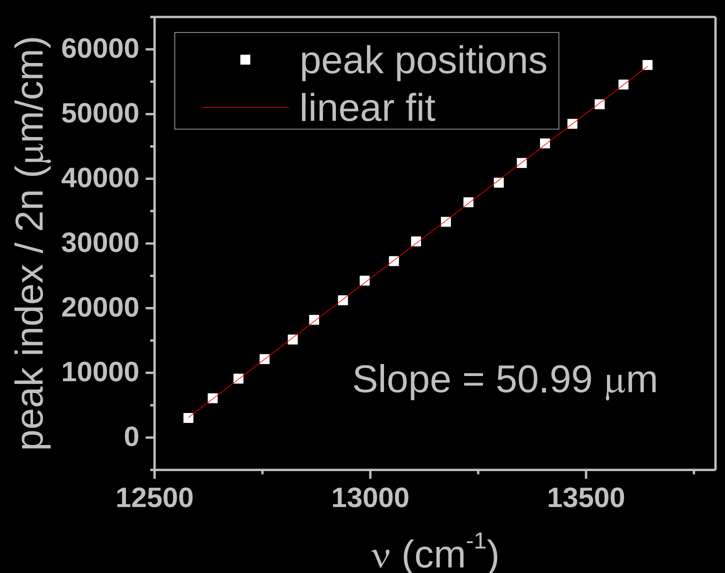


Using absorbance to determine Au/Hg concentration in water solutions

Spectrophotometry (UV-VIS-NIR)





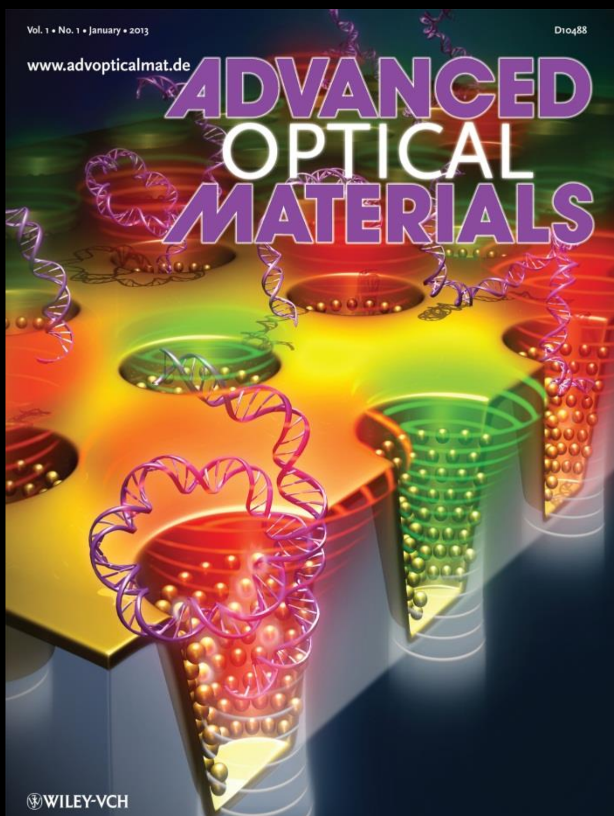


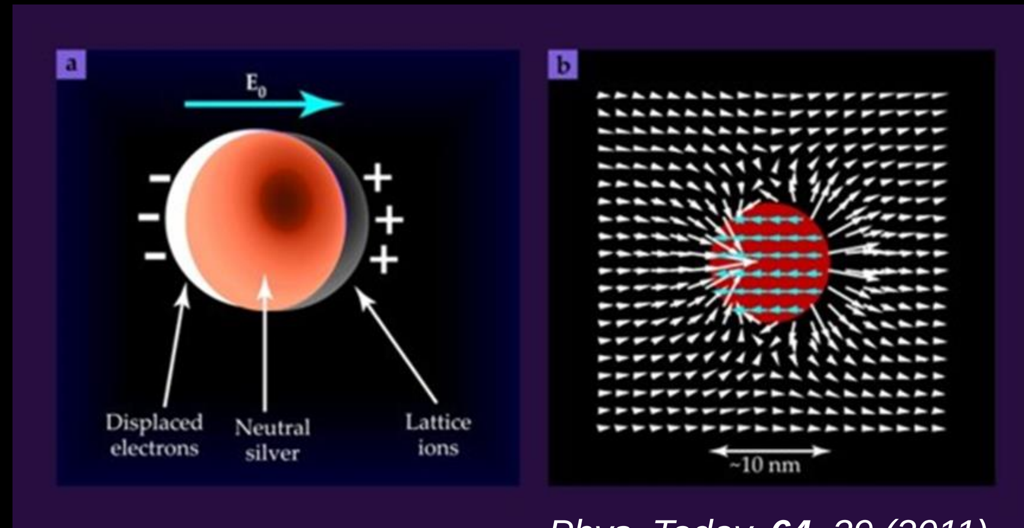
Using transmission interference fringes to determine thickness

Spectrophotometry (UV-VIS-NIR)

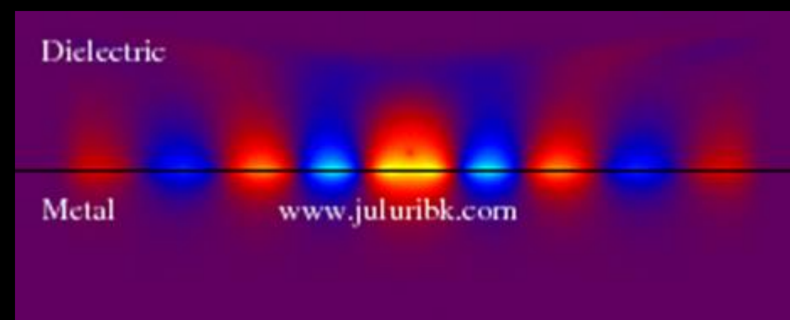
Excitations in materials

- Plasmons



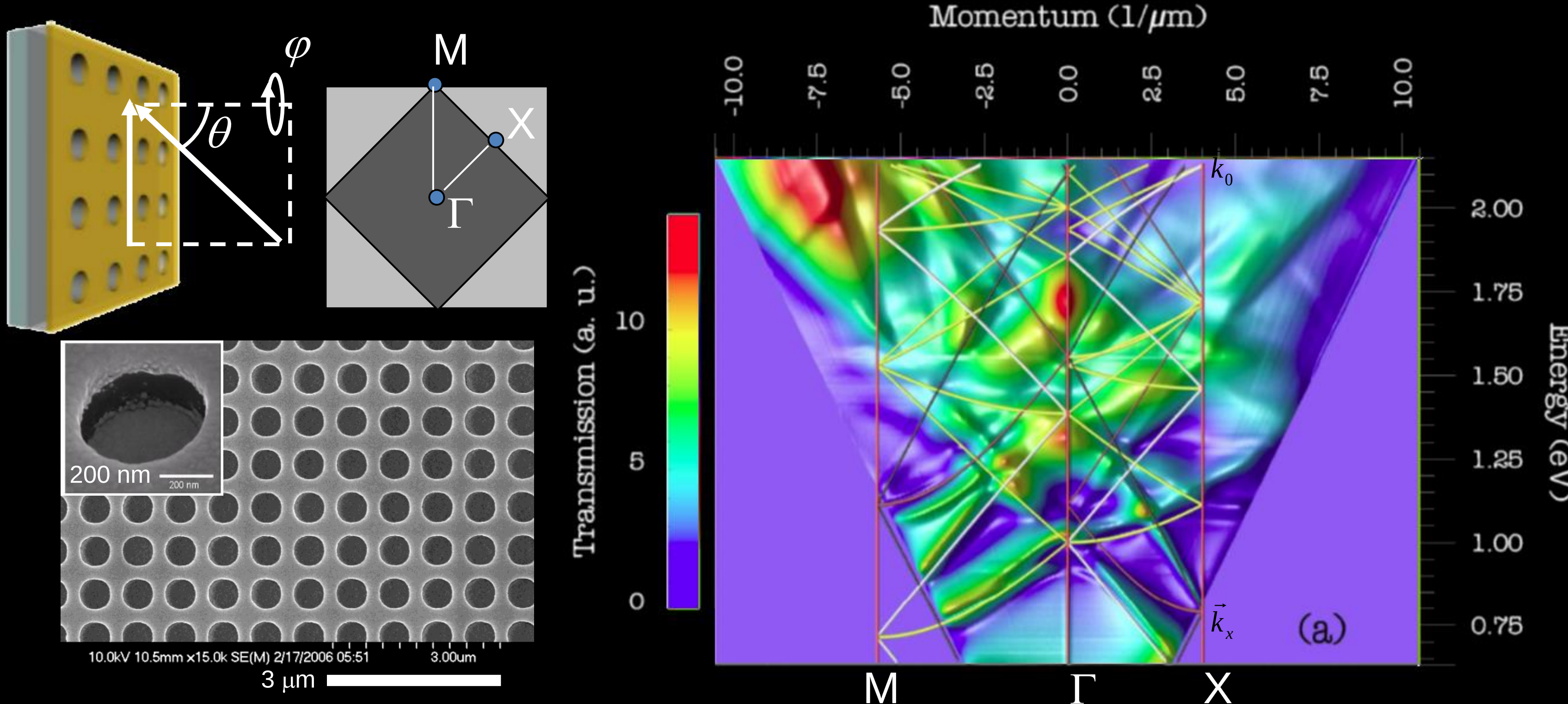


Phys. Today, ***64***, *39 (2011)*



Plasmons are quanta of collective motion of charge-carriers in a gas with respect of an oppositely charged background. They play a significant role on transmission and reflection of light.

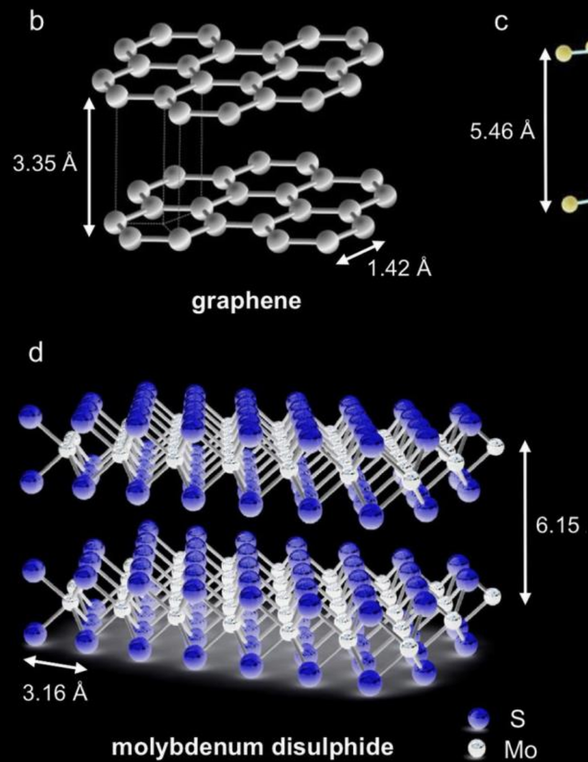
Spectrophotometry (UV-VIS-NIR)

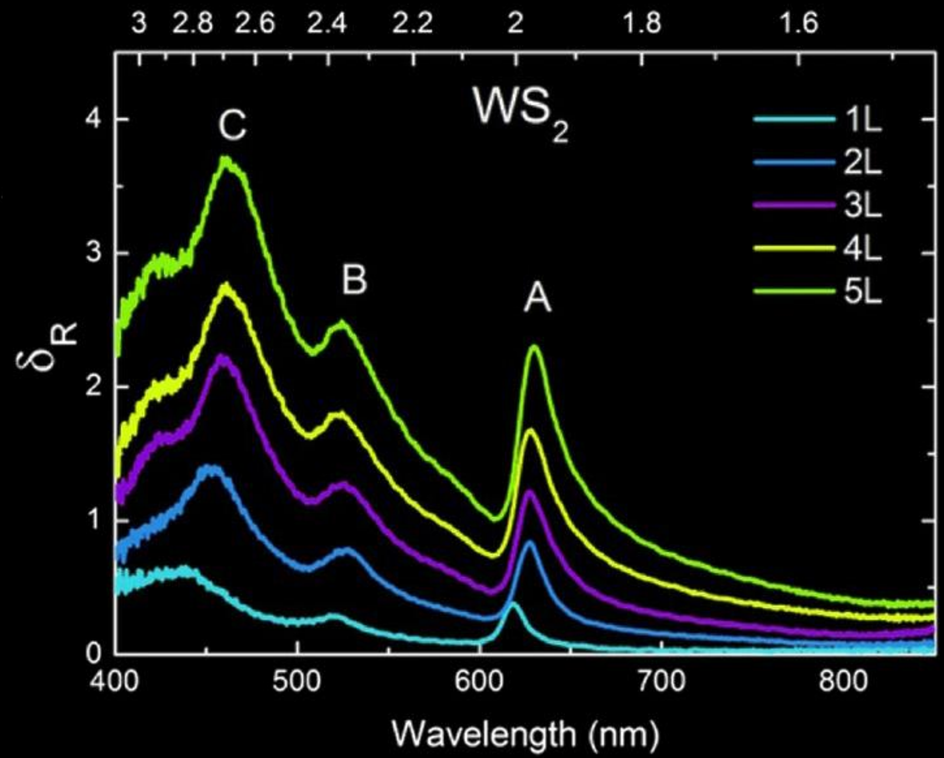


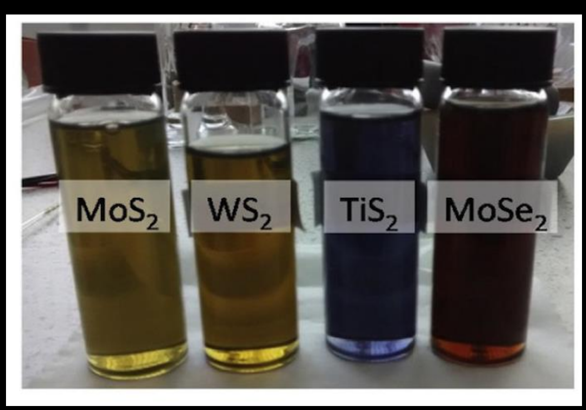
Optics Express **13**, 5669 (2005)

Plasmonic crystal Brillouin zone from the transmission spectra measured for many different angles of incidence.

Spectrophotometry (UV-VIS-NIR)

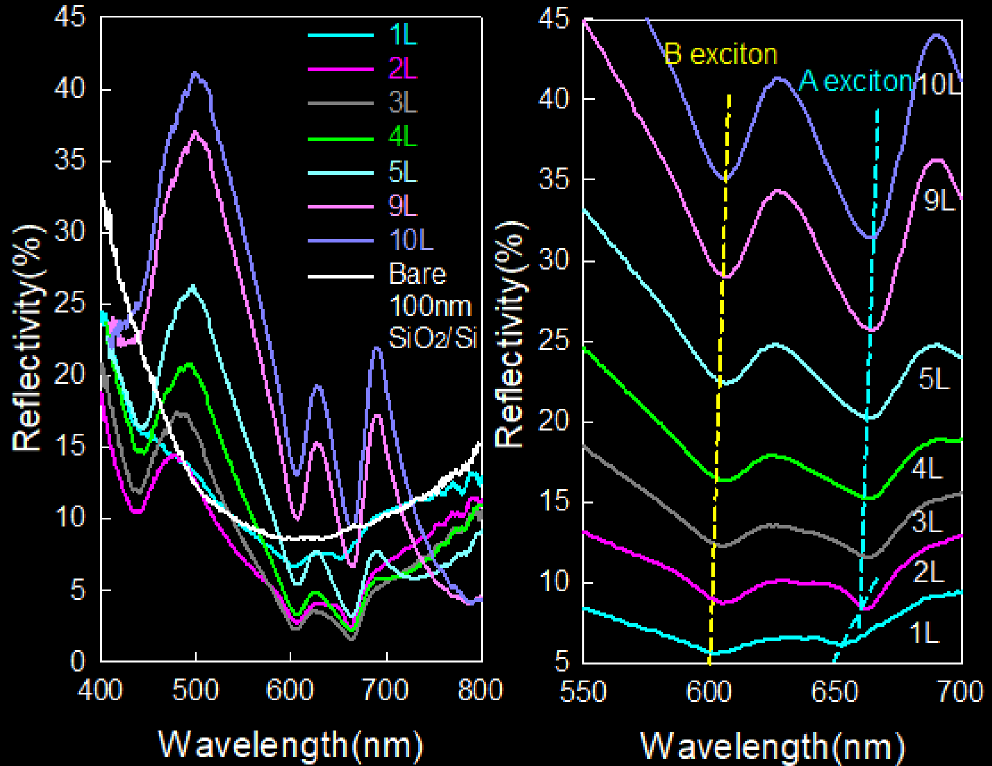


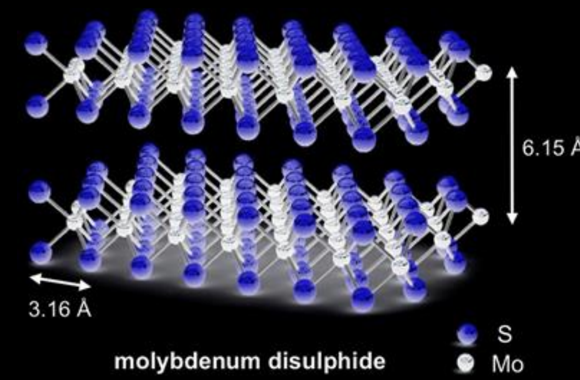




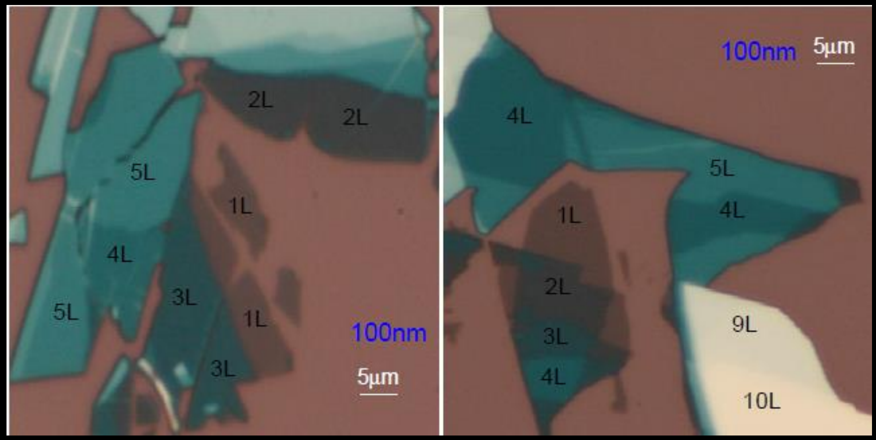
Applied Materials Today **8**, 68 (2017)

Spectrophotometry (UV-VIS-NIR)



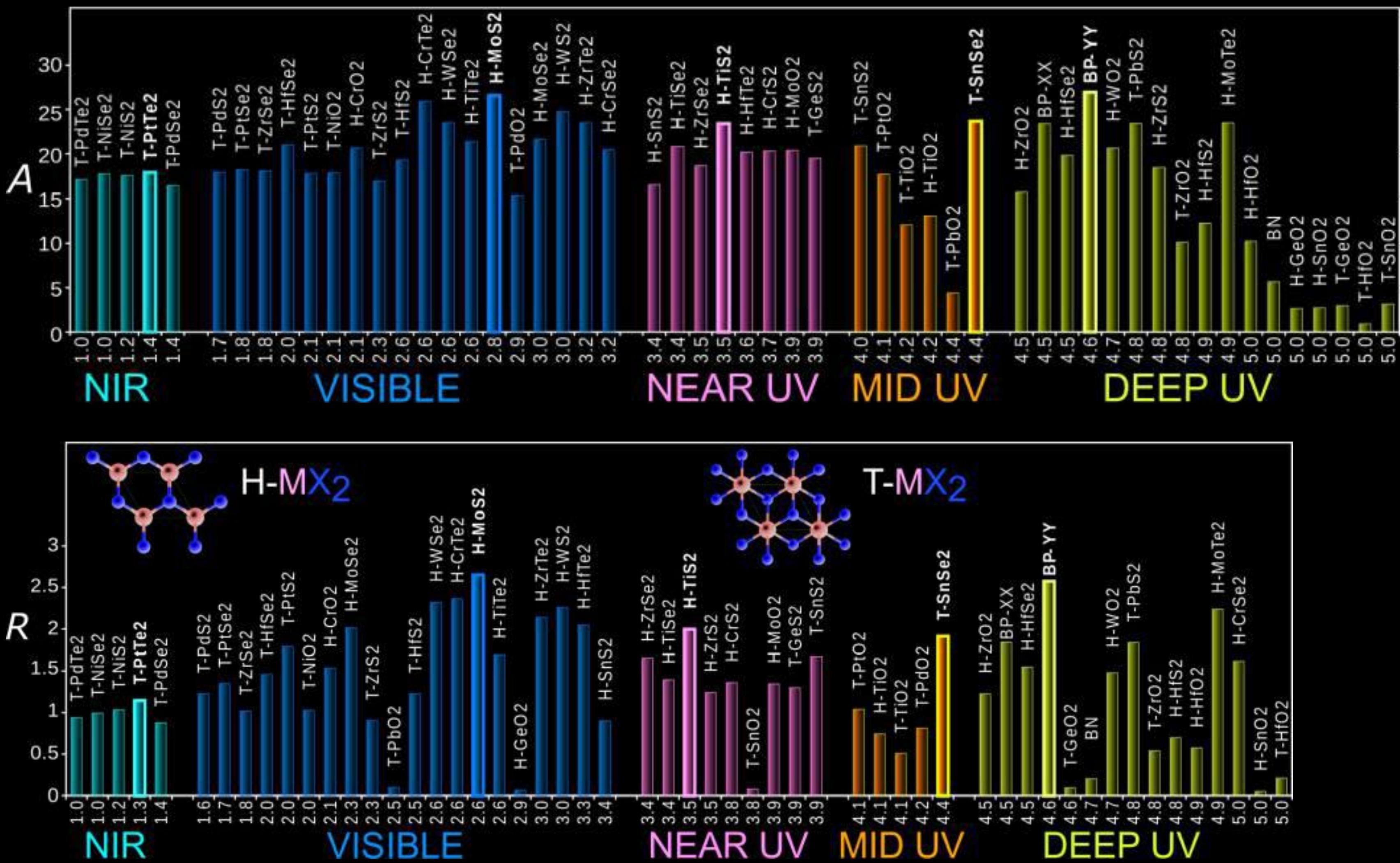


Applied Materials Today **8**, 68 (2017)



Optical Materials Express, 332858 (2018)

Spectrophotometry (UV-VIS-NIR)

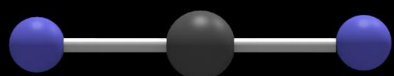


ACS Nano **12**, 10880 (2018)

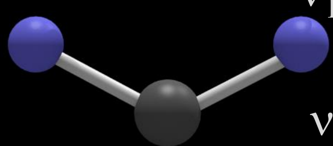
Fourier Transform IR spectroscopy (FTIR)

Normal vibrational modes in molecules:

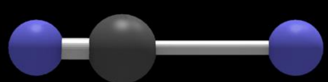
CO_2 (4 modes)



$\nu_1 = 1388\ cm^{-1}$

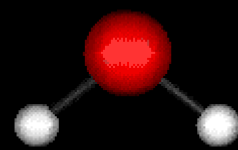


$\nu_2 = 667\ cm^{-1}$

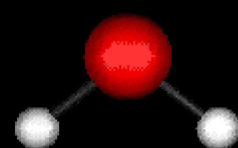


$\nu_3 = 2349\ cm^{-1}$

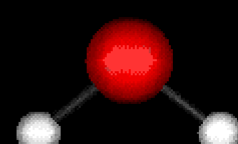
H_2O (3 modes)



ν_1 (**3657 cm^{-1}**)

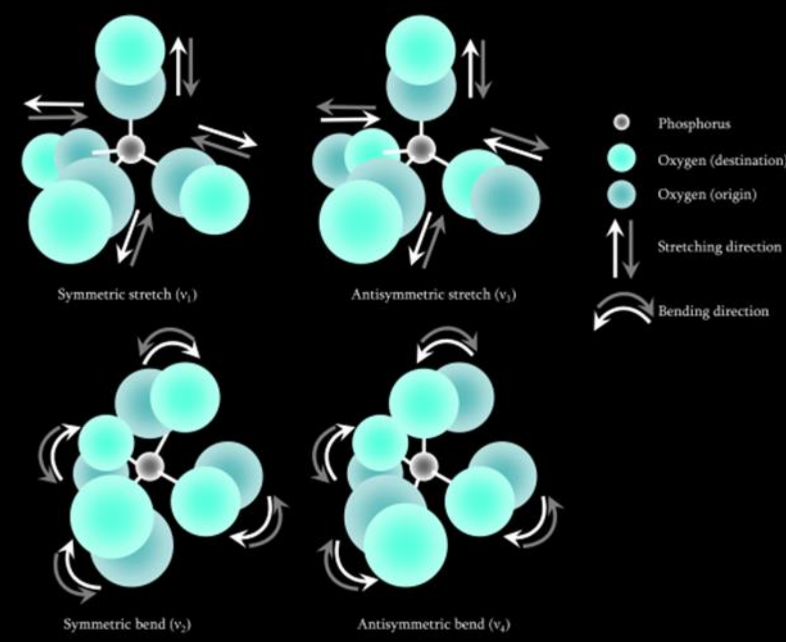


ν_2 (**1595 cm^{-1}**)



ν_3 (**3756 cm^{-1}**)

PO_4 (9 modes)

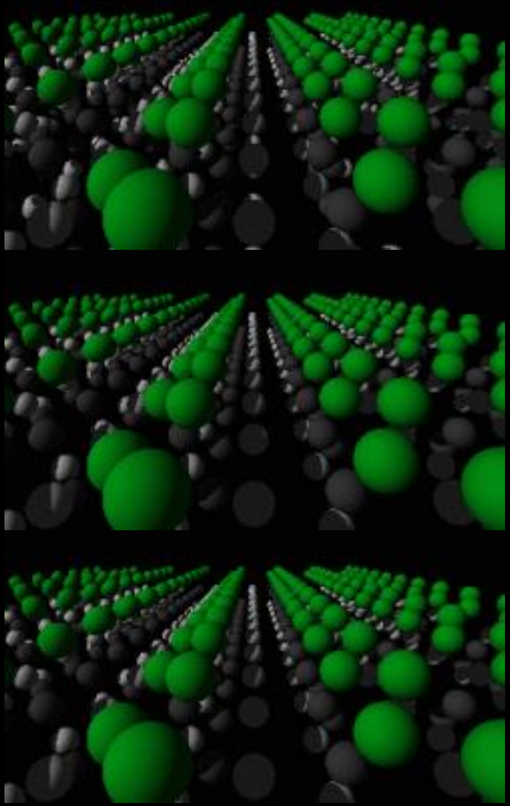


Number of modes:
3N-6 for non-linear molecules
3N-5 for linear molecules

Fourier Transform IR spectroscopy (FTIR)

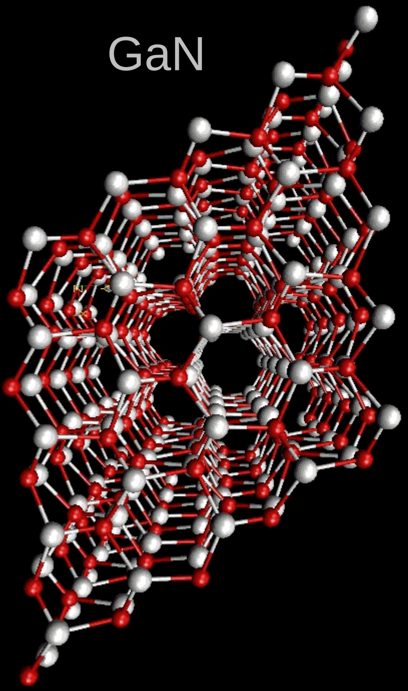
Normal vibrational modes in solids:

Sb/GaAs(110)



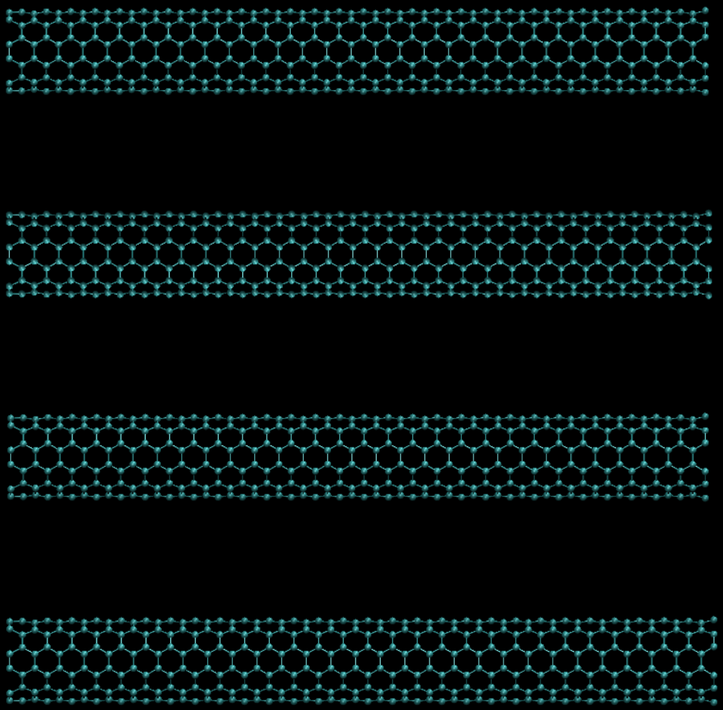
http://www.physik.tu-berlin.de/institute/IFFP/richter/new/research/surface-phonons.shtml

GaN



http://www.phonon.fc.pl

SWCNT



T. A. Beu and A. Farcaş 2016 *EPL* **113** 37004

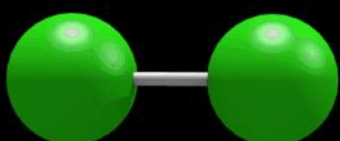
Fourier Transform IR spectroscopy (FTIR)

IR active vibrations

The intensity of a vibrational absorption depends on the strength of the transition dipole momentum, so a vibration mode j will be "IR active" only when $\left(\frac{\partial \vec{\mu}}{\partial Q_j}\right)_0 \neq 0$.

Cl_2

$\nu_1 = 558$ cm^{-1}

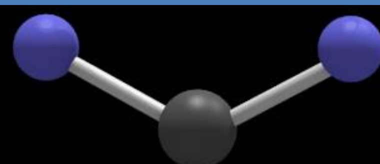


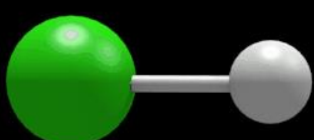
CO_2

$\nu_1 = 1388$ cm^{-1}

IR Inactive

$$\left(\frac{\partial \vec{\mu}}{\partial Q_j}\right)_0 = 0$$

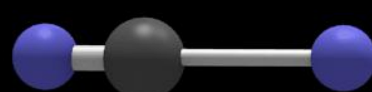




$\nu_2 = 667$ cm^{-1}

IR Active

$$\left(\frac{\partial \vec{\mu}}{\partial Q_j}\right)_0 \neq 0$$



HCl

$\nu_1 = 1443$ cm^{-1}

$\nu_3 = 2349$ cm^{-1}

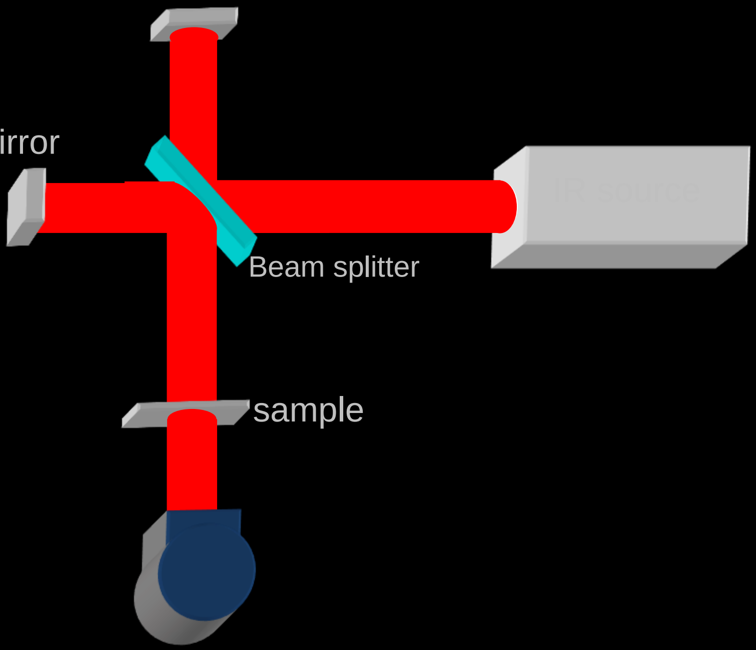
Z. Naturforsch. 58a, 36 (2003); IOP Concise Physics - Molecular Photophysics and Spectroscopy, David L Andrews

Fourier Transform IR spectroscopy (FTIR)

The Nobel Prize in Physics 1907
Albert A. Michelson

"for his optical precision instruments and the spectroscopic and metrological investigations carried out with their aid"

The Nobel Foundation

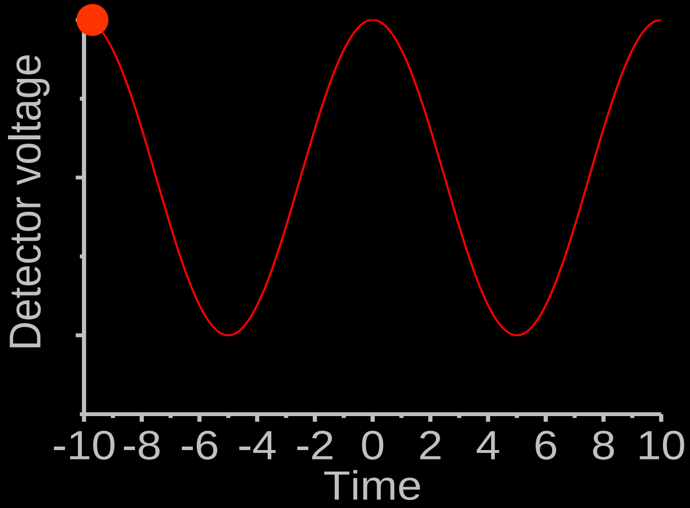


Instrumentation:

The FTIR uses a Michelson interferometer with a moving mirror, in place of a diffraction grating or prism.

$\Delta L = n\lambda$ => constructive interference

$\Delta L = (n+1/2)\lambda$ => destructive interference



Fourier Transform IR spectroscopy (FTIR)

The Nobel Prize in Physics 1907
Albert A. Michelson

"for his optical precision instruments and the spectroscopic and metrological investigations carried out with their aid"

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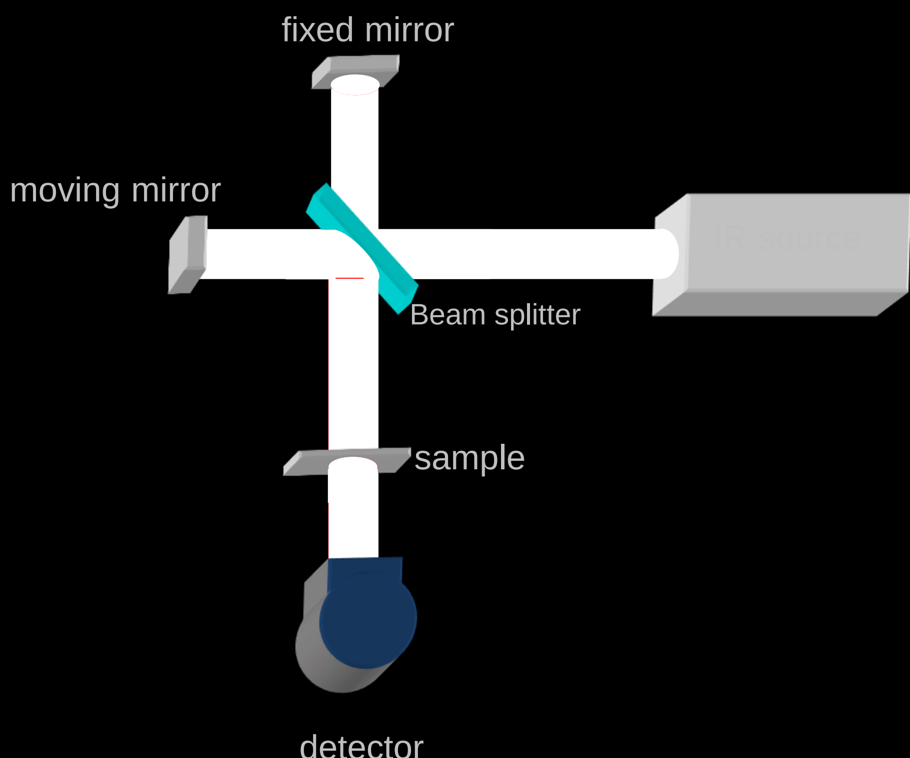

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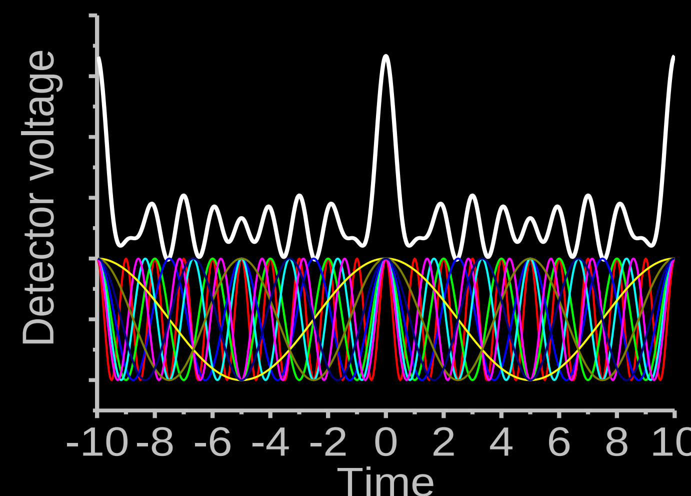
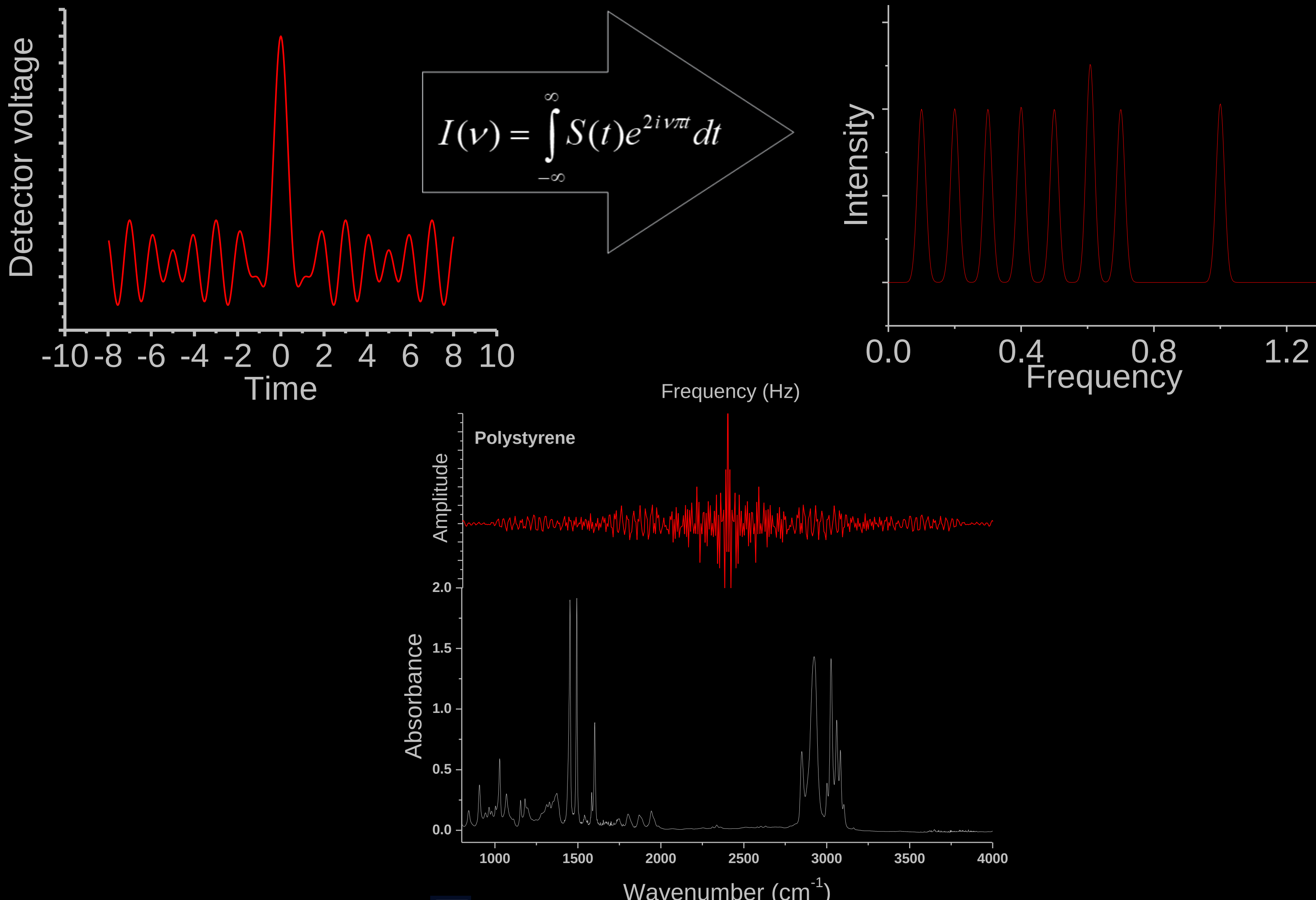
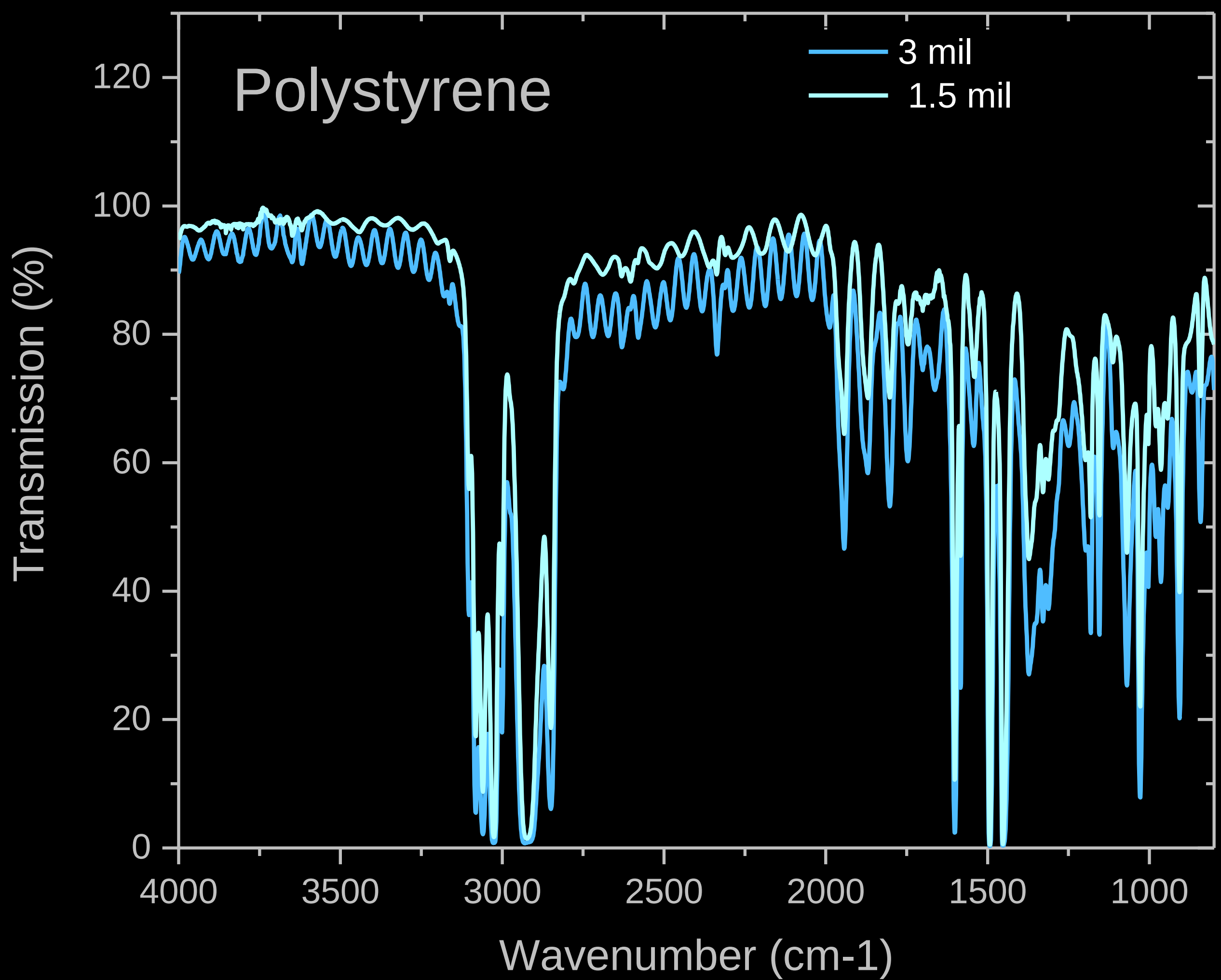


Fourier Transform IR spectroscopy (FTIR)



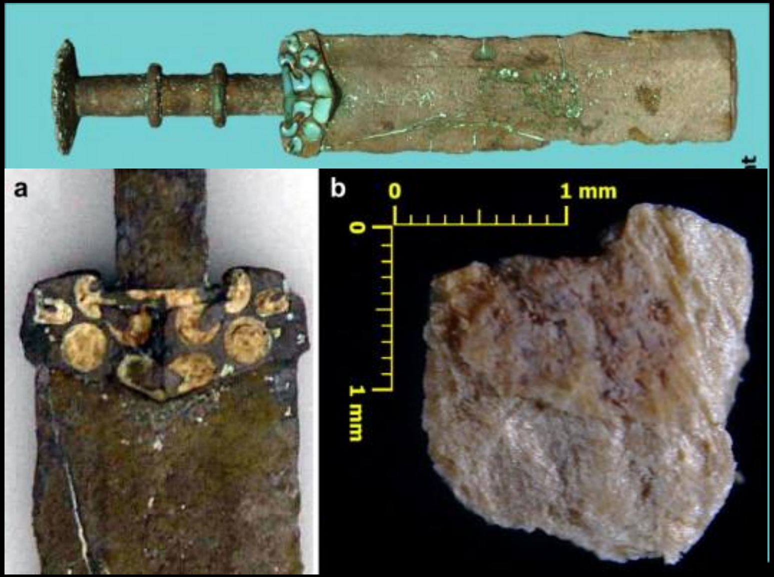
Fourier Transform IR spectroscopy (FTIR)

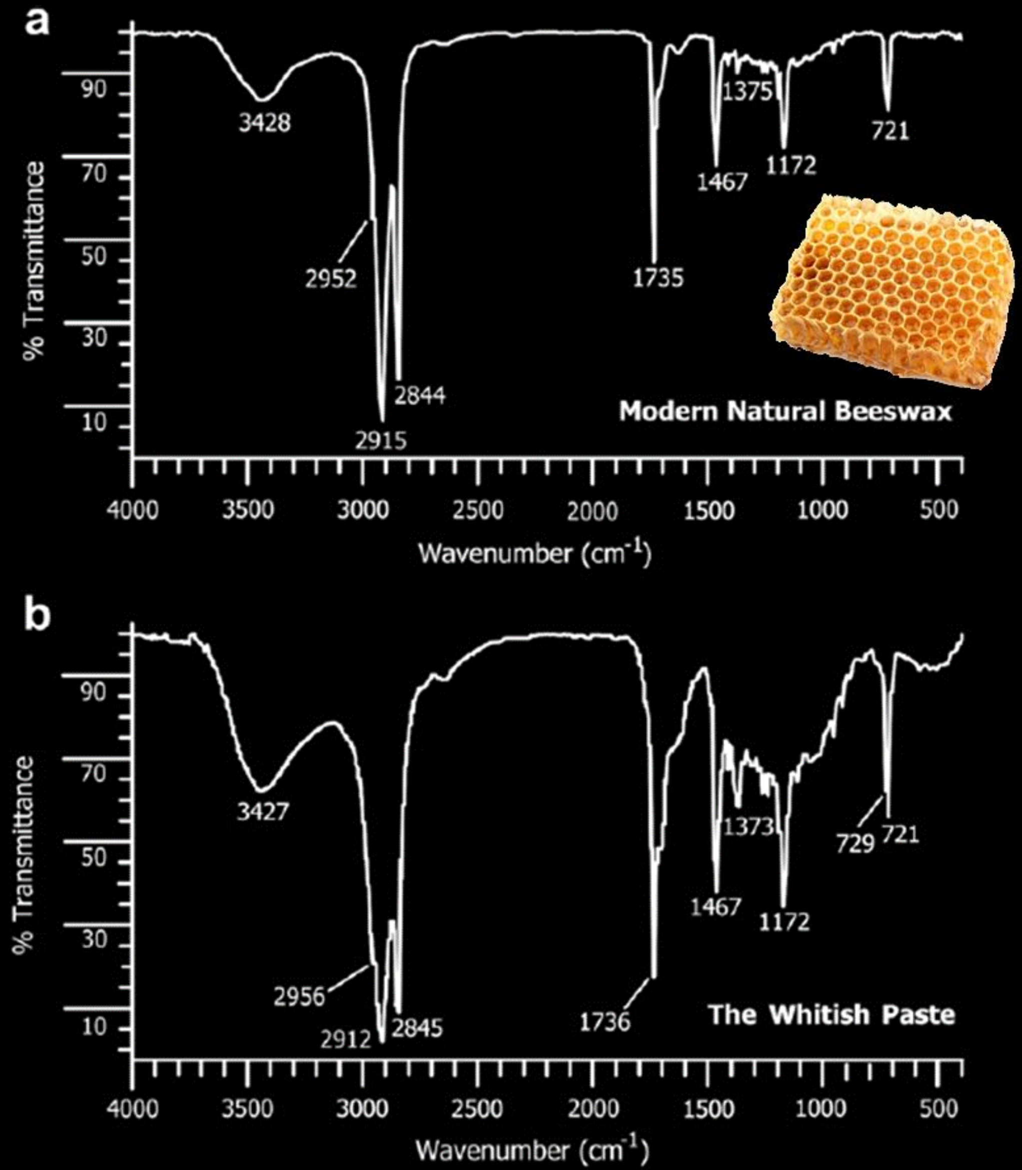


Fourier Transform IR spectroscopy (FTIR)

FTIR can be used to identify components in a mixture by comparison with reference spectra.

Discovery of beeswax as binding agent on a 6th-century BC Chinese turquoise-inlaid bronze sword
Wugan Luo, Tao Li, Changsui Wang, Fengchun Huang





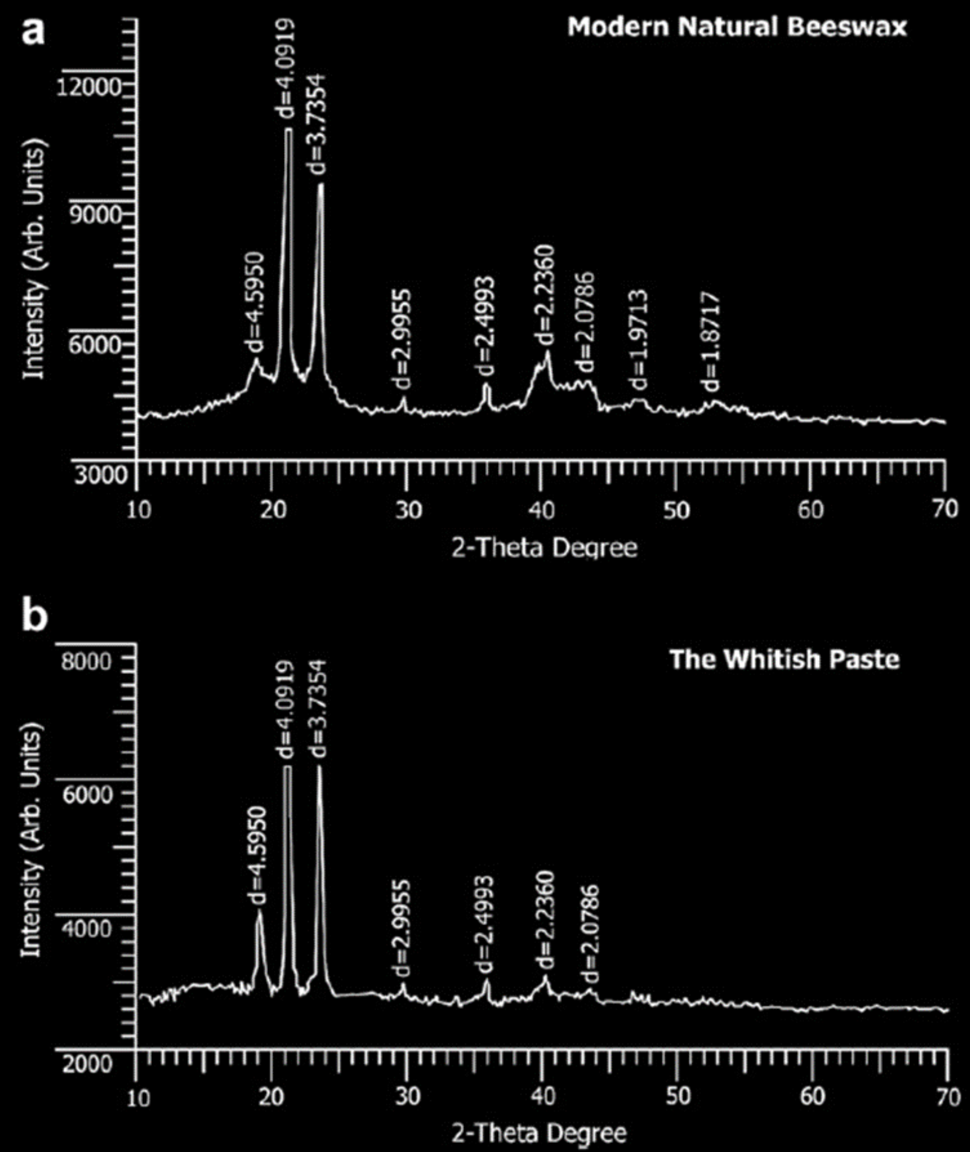
J. of Archaeological Sci. **39** (2012), 1227

Fourier Transform IR spectroscopy (FTIR)

Fingerprinting:

FTIR can be used to identify components in a mixture by comparison with reference spectra.

Complementary characterization techniques, like XRD can provide conclusive evidence for the identification.

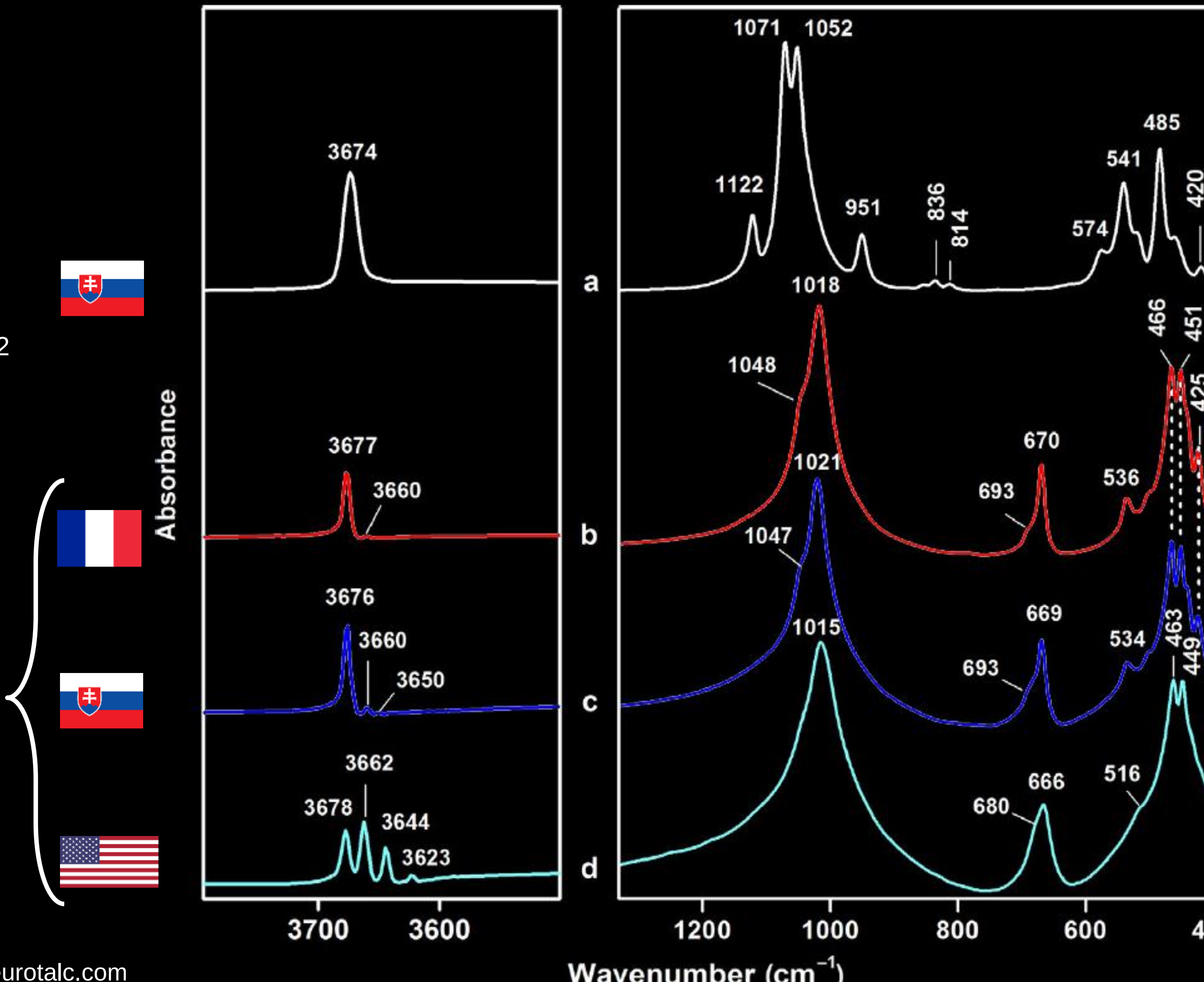


J. of Archaeological Sci. **39** (2012), 1227

Fourier Transform IR spectroscopy (FTIR)

$Al_2Si_4O_{10}(OH)_2$

$Mg_3Si_4O_{10}(OH)_2$

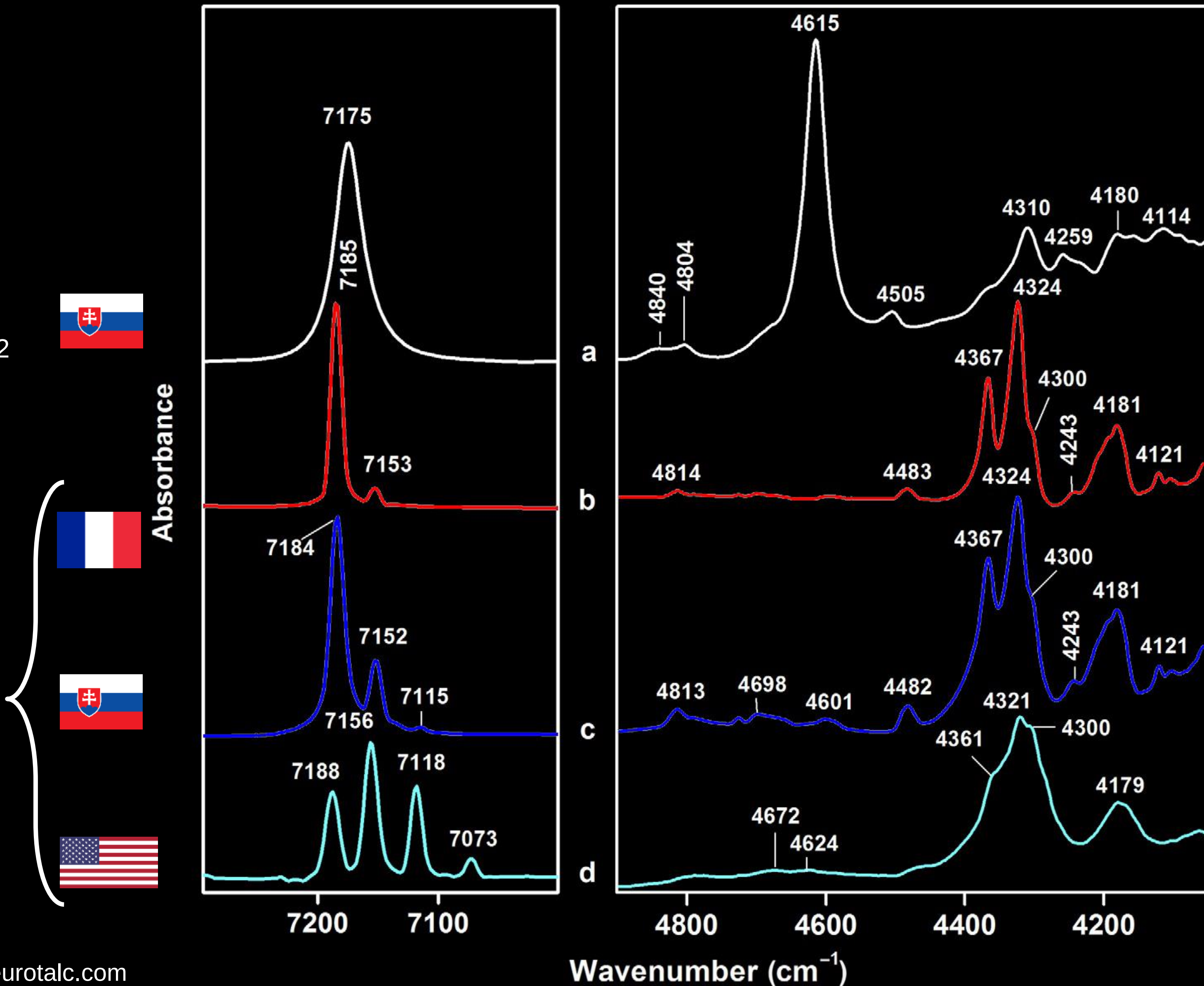


Images from Wikipedia and eurotalc.com
Spectra from *Developments in Clay Science*, Vol. 8. Ch. 5

Spectrophotometry (UV-VIS-NIR)

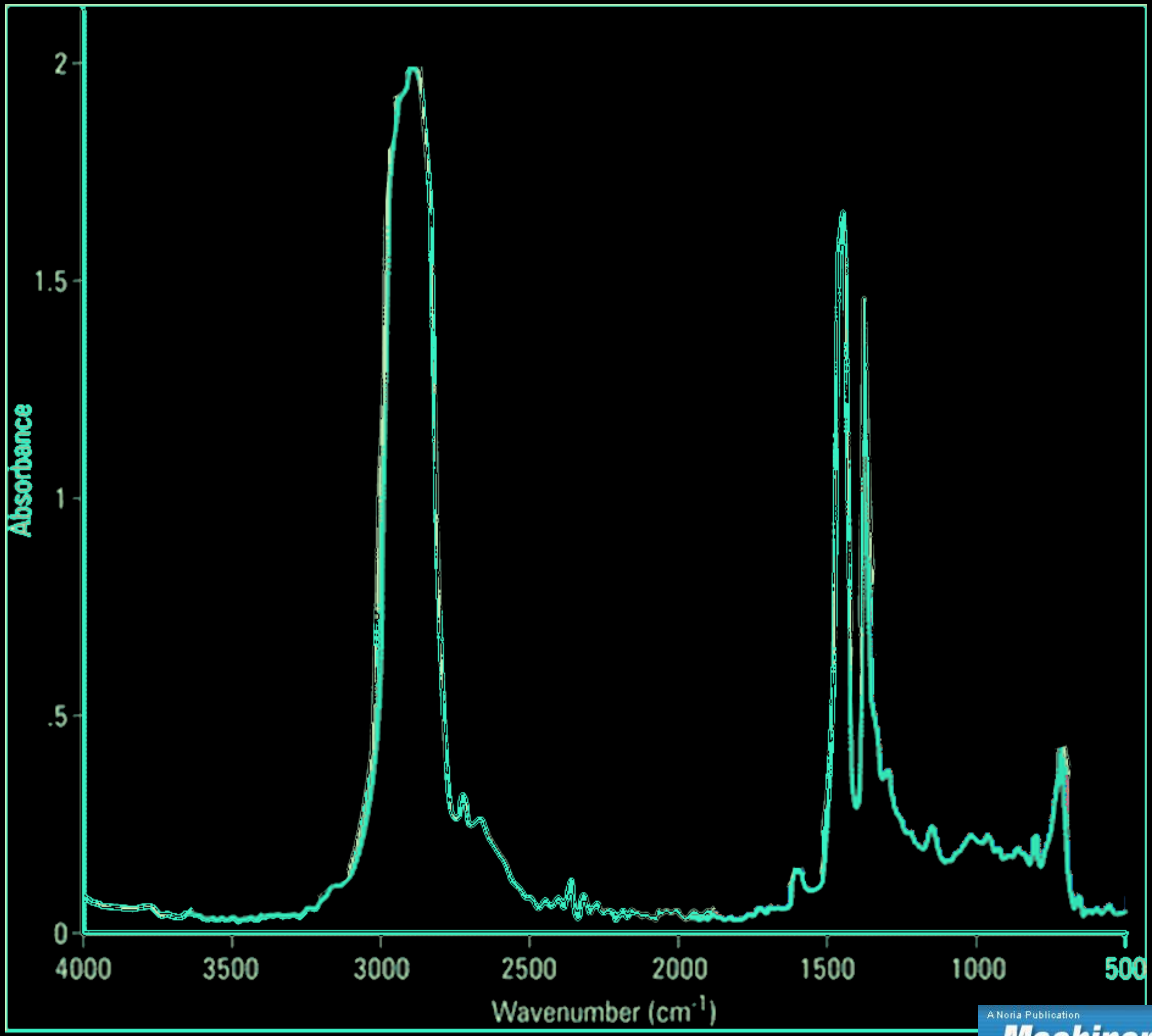
$Al_2Si_4O_{10}(OH)_2$

$Mg_3Si_4O_{10}(OH)_2$

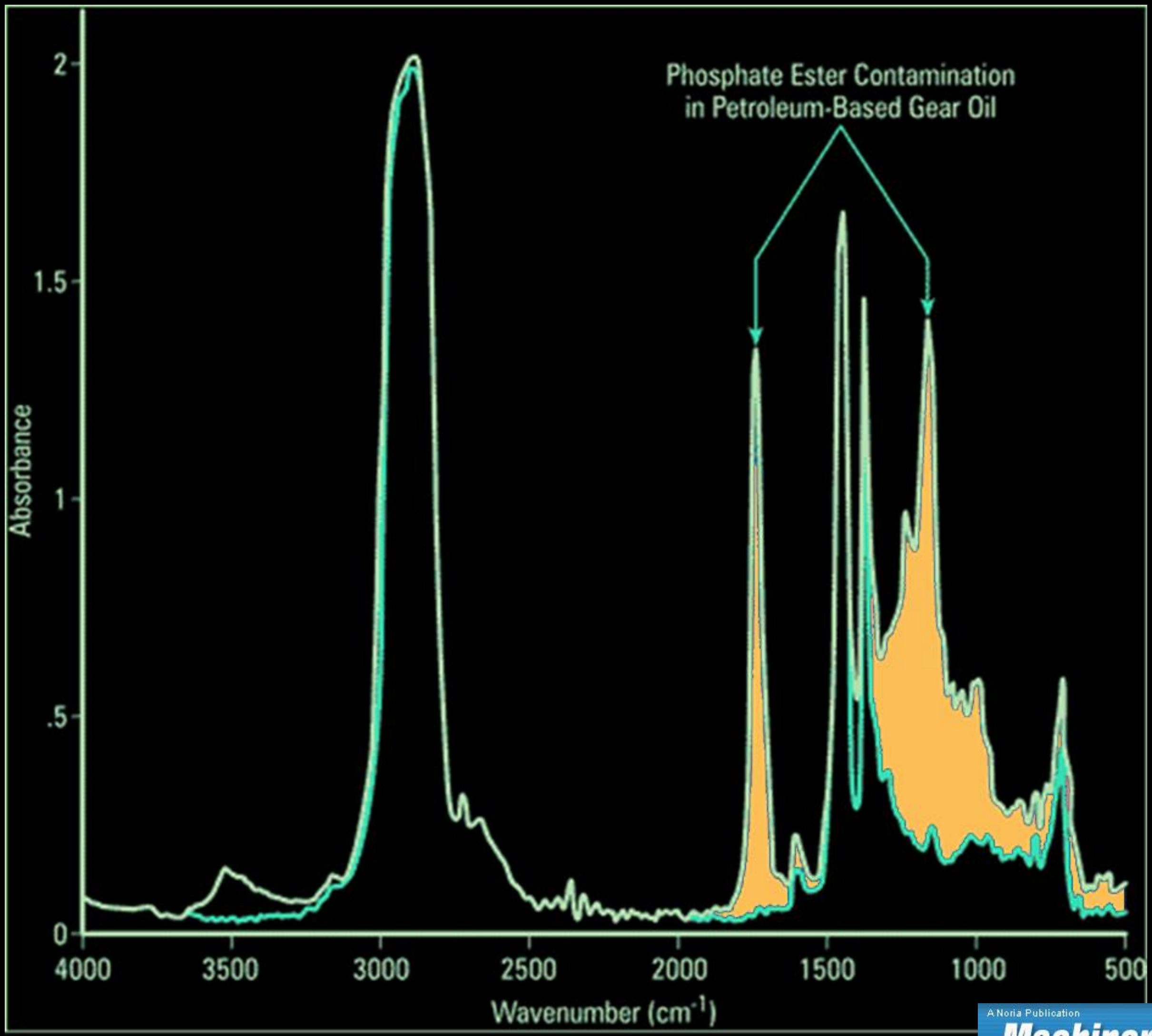


Images from Wikipedia and eurotalc.com
Spectra from *Developments in Clay Science*, Vol. 8. Ch. 5

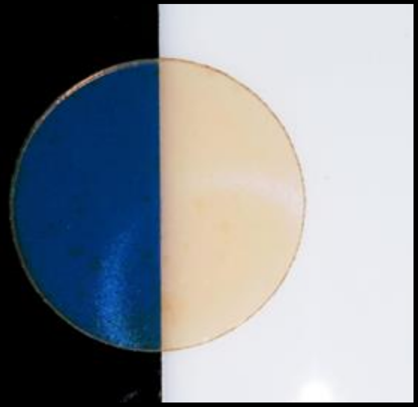
Fourier Transform IR spectroscopy (FTIR)



Fourier Transform IR spectroscopy (FTIR)



Spectrophotometry (UV-VIS-NIR) and FTIR



Limitations:

- Reference sample is often needed for quantitative analysis.
- Many contributions to the spectrum are small and can be buried in the background.
- Usually, unambiguous chemical identification requires the use of complementary techniques.
- Limited spatial resolution.

Strengths:

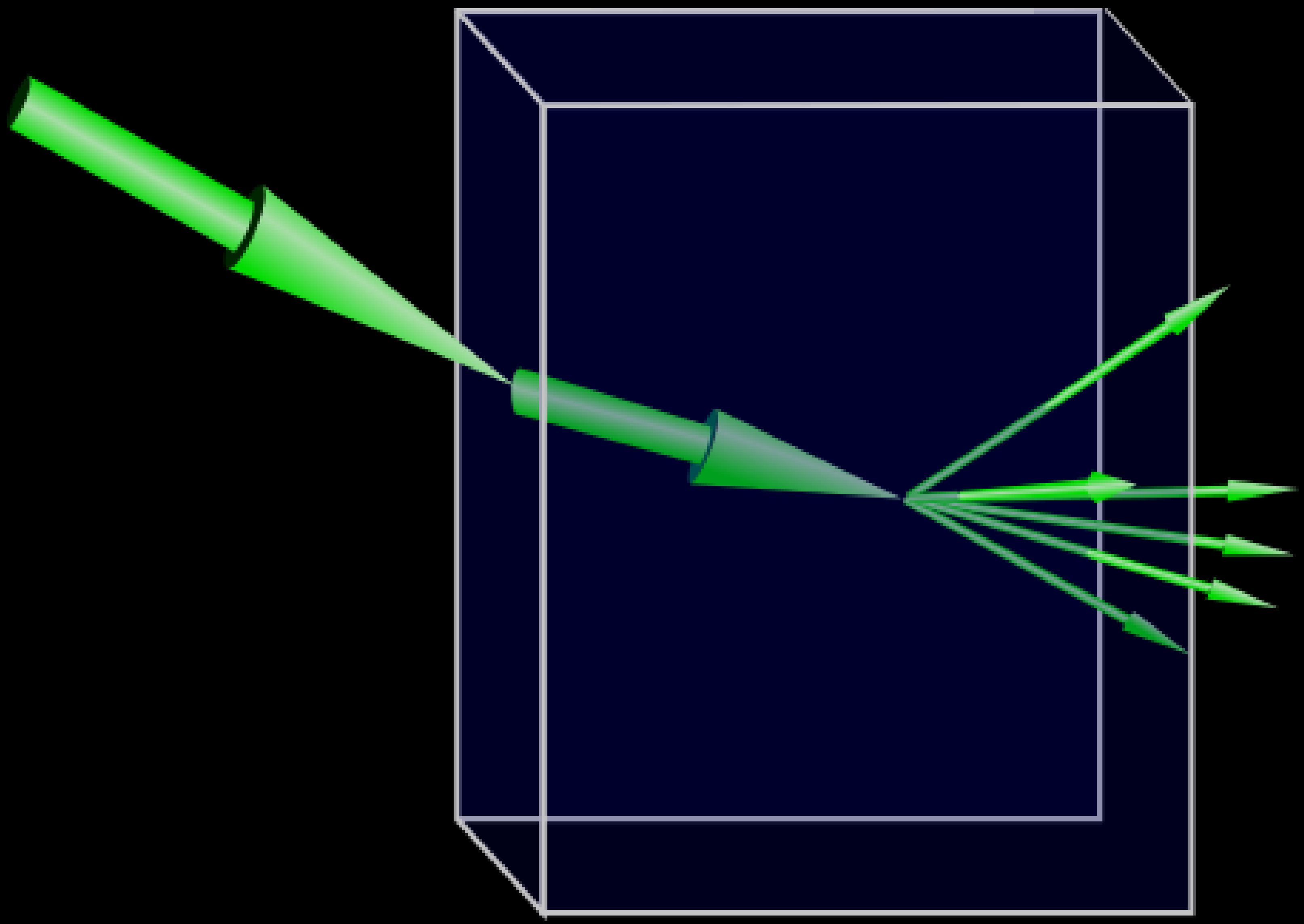
- Very little or simple sample preparation.
- Simplicity of use and data interpretation.
- Short acquisition time, for most cases.
- Non destructive.
- Broad range of photon energies.
- High sensitivity (~ 0.1 wt% typical for FTIR).

Complementary techniques:

Raman, Electron Energy Loss Spectroscopy (EELS), Extended X-ray Absorption Fine Structure (EXAFS), XPS, Auger, SIMS, XRD, SFG.

nanocomposix.com

Light scattering



Light scattering

Sir Chandrasekhara Venkata Raman

The Nobel Prize in Physics 1930 was awarded to Sir Venkata Raman *"for his work on the scattering of light and for the discovery of the effect named after him"*.

The Nobel Foundation

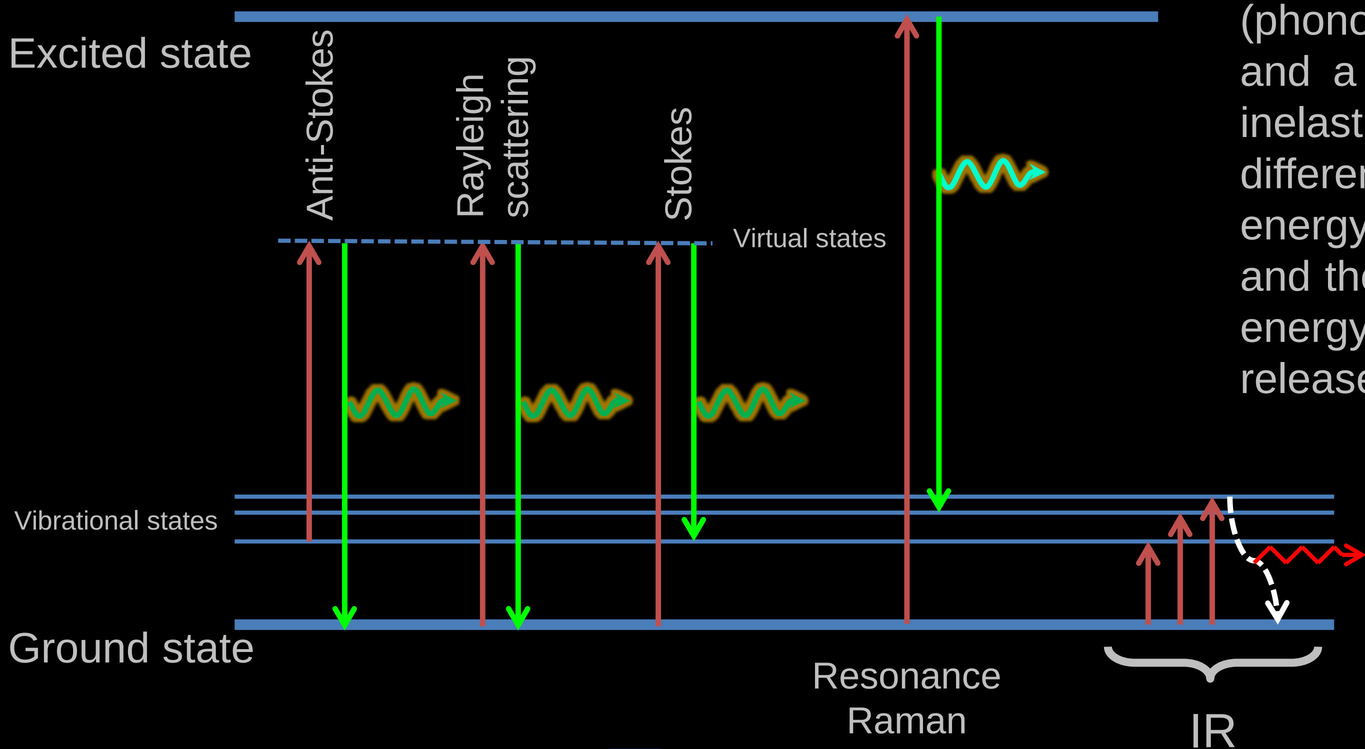
Raman spectroscopy

What is measured:

The light inelastically scattered by the material.

Basic principle:

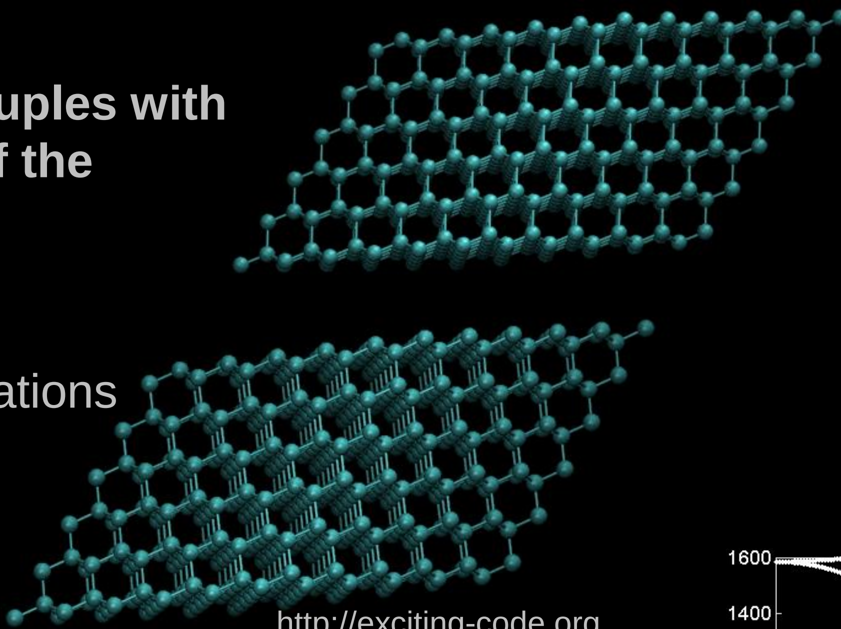
The impinging light couples with the lattice vibrations (phonons) of the material, and a small portion of it is inelastically scattered. The difference between the energy of the scattered light and the incident beam is the energy absorbed or released by the phonons.



Raman spectroscopy

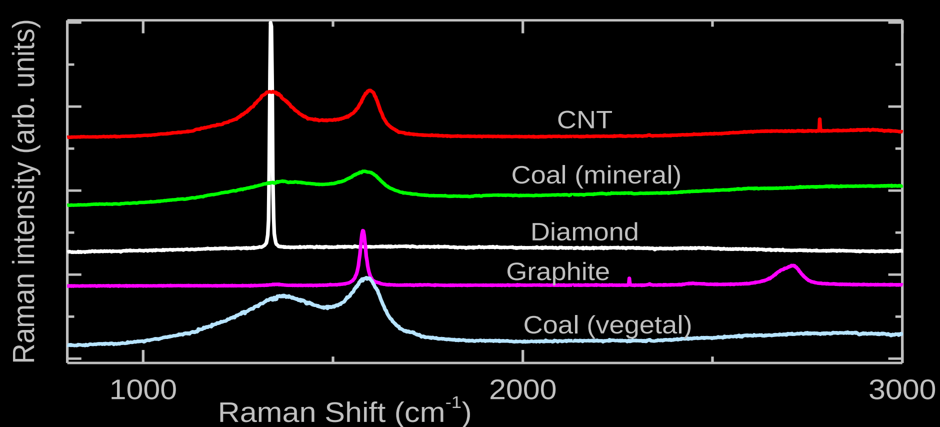
Impinging light couples with vibration modes of the material:

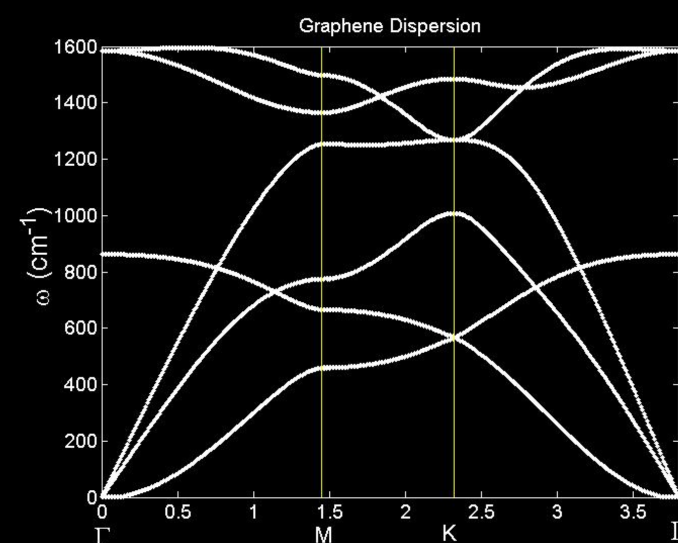
- Phonons
- Molecular vibrations



http://exciting-code.org

atomic structure
chemical composition
physical state
temperature.





http://flex.phys.tohoku.ac.jp/~pourya

Raman spectroscopy

Inelastic scattering:

The dependence of the polarizability tensor $\vec{\alpha}$ on the normal coordinate Q associated with a normal vibrational mode of a material, for small amplitude oscillations near the equilibrium can be written:

$$\alpha = \alpha_0 + \left(\frac{\partial \alpha}{\partial Q}\right) Q = \alpha_0 + \alpha' Q$$

For a harmonic oscillation ($Q = Q_0 \cos \omega t$) and $E = E_0 \cos \omega_0 t$, the time dependence of the induced dipole momentum μ' will be:

$$\mu' = \alpha_0 E_0 \cos \omega_0 t + \frac{1}{2} \alpha' Q_0 E_0 [\cos(\omega_0 - \omega)t + \cos(\omega_0 + \omega)t]$$

meaning that the dipole oscillates with three frequencies simultaneously, corresponding to the three possible scattering modes (Rayleigh, Stokes Raman and anti-Stokes Raman)

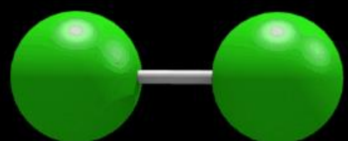
Fourier Transform IR spectroscopy (FTIR)

IR active vibrations

The intensity of a vibrational absorption depends on the strength of the transition dipole momentum, so a vibration mode j will be "IR active" only when $\left(\frac{\partial \vec{\mu}}{\partial Q_j}\right)_0 \neq 0$.

Cl_2

$\nu_1 = 558$ cm^{-1}

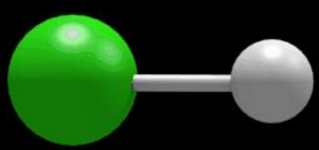


CO_2

$\nu_1 = 1388$ cm^{-1}

IR Inactive

$$\left(\frac{\partial \vec{\mu}}{\partial Q_j}\right)_0 = 0$$



$\nu_2 = 667$ cm^{-1}

$\nu_3 = 2349$ cm^{-1}

IR Active

$$\left(\frac{\partial \vec{\mu}}{\partial Q_j}\right)_0 \neq 0$$

HCl

$\nu_1 = 1443$ cm^{-1}

Z. Naturforsch. 58a, 36 (2003); IOP Concise Physics - Molecular Photophysics and Spectroscopy, David L Andrews

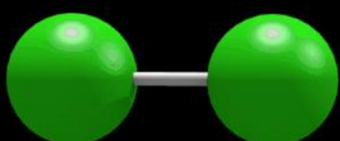
Raman spectroscopy

Raman active vibrations

The intensity of the Raman scattering linked to a vibrational state depends on the change in the polarizability tensor $\left(\frac{\partial \vec{\alpha}}{\partial Q_j}\right)_0 \neq 0$

Cl_2

$\nu_1 = 558\ cm^{-1}$



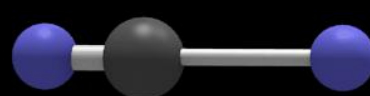
CO_2

$\nu_1 = 1388\ cm^{-1}$

Raman active

$\left(\frac{\partial \vec{\alpha}}{\partial Q_j}\right)_0 \neq 0$

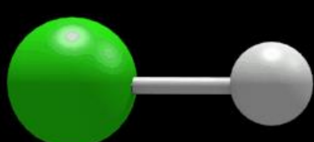
$\nu_2 = 667\ cm^{-1}$



$\nu_3 = 2349\ cm^{-1}$

Raman Inactive

$\left(\frac{\partial \vec{\alpha}}{\partial Q_j}\right)_0 = 0$



HCl

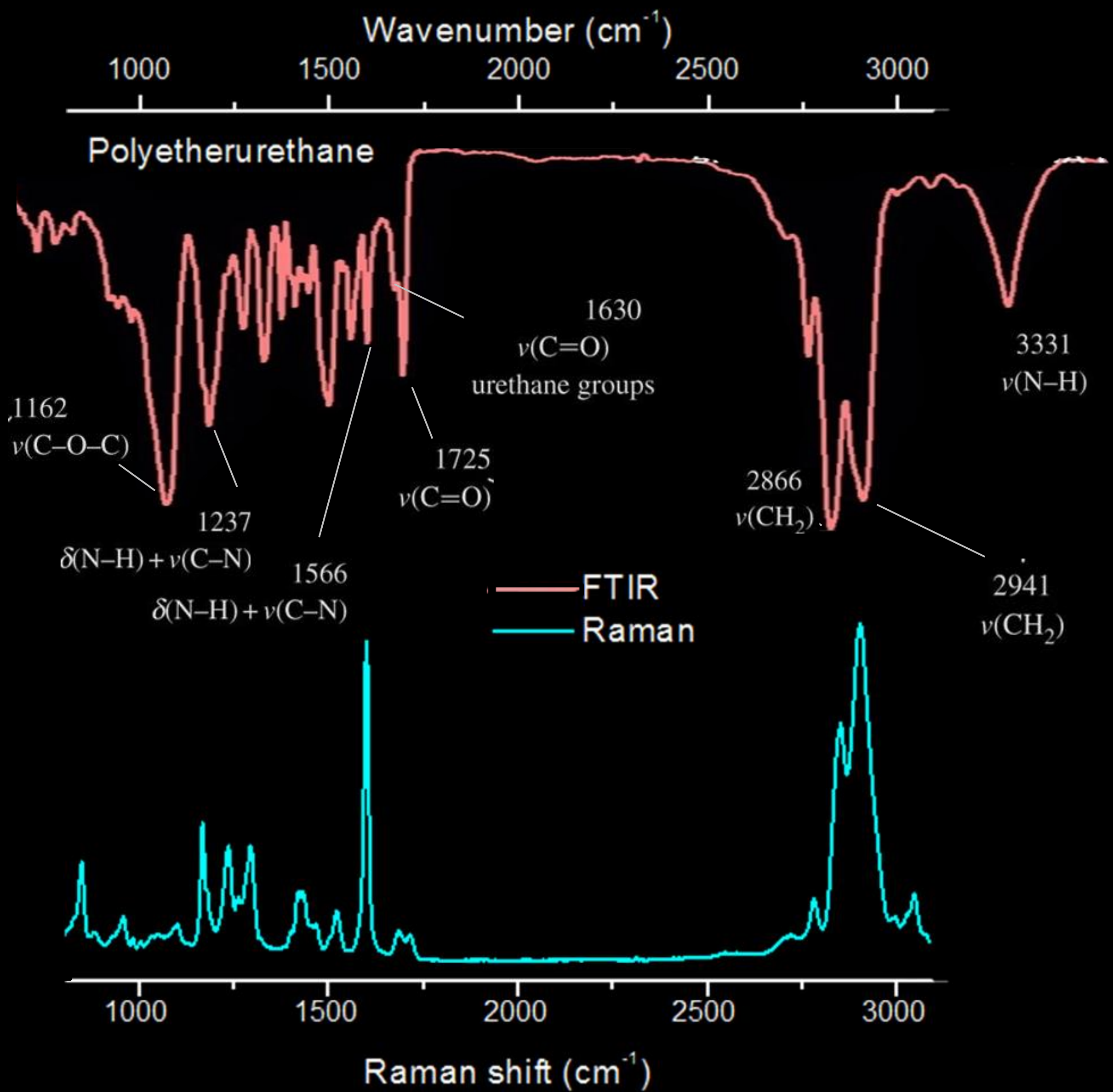
$\nu_1 = 1443\ cm^{-1}$

Z. Naturforsch. 58a, 36 (2003); IOP Concise Physics - Molecular Photophysics and Spectroscopy, David L Andrews

Raman spectroscopy

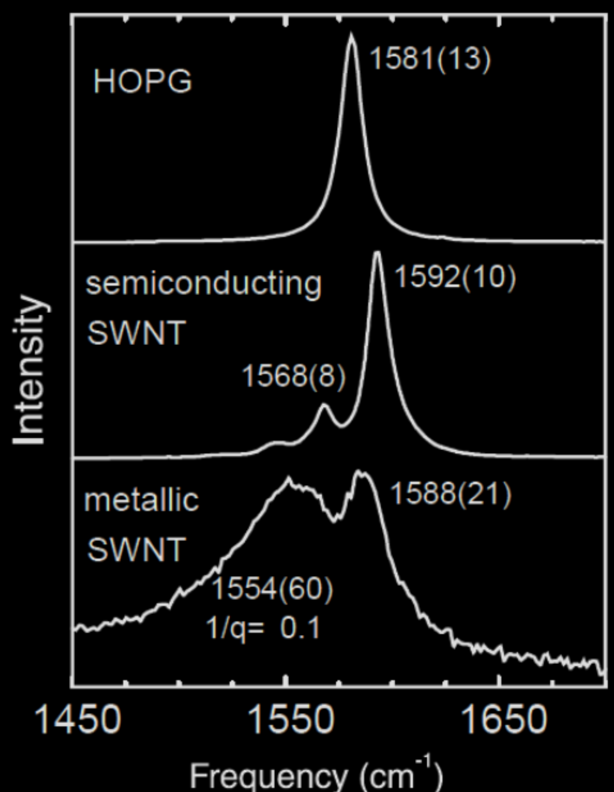
FTIR and Raman:

The two techniques are complementary (different selection rules).

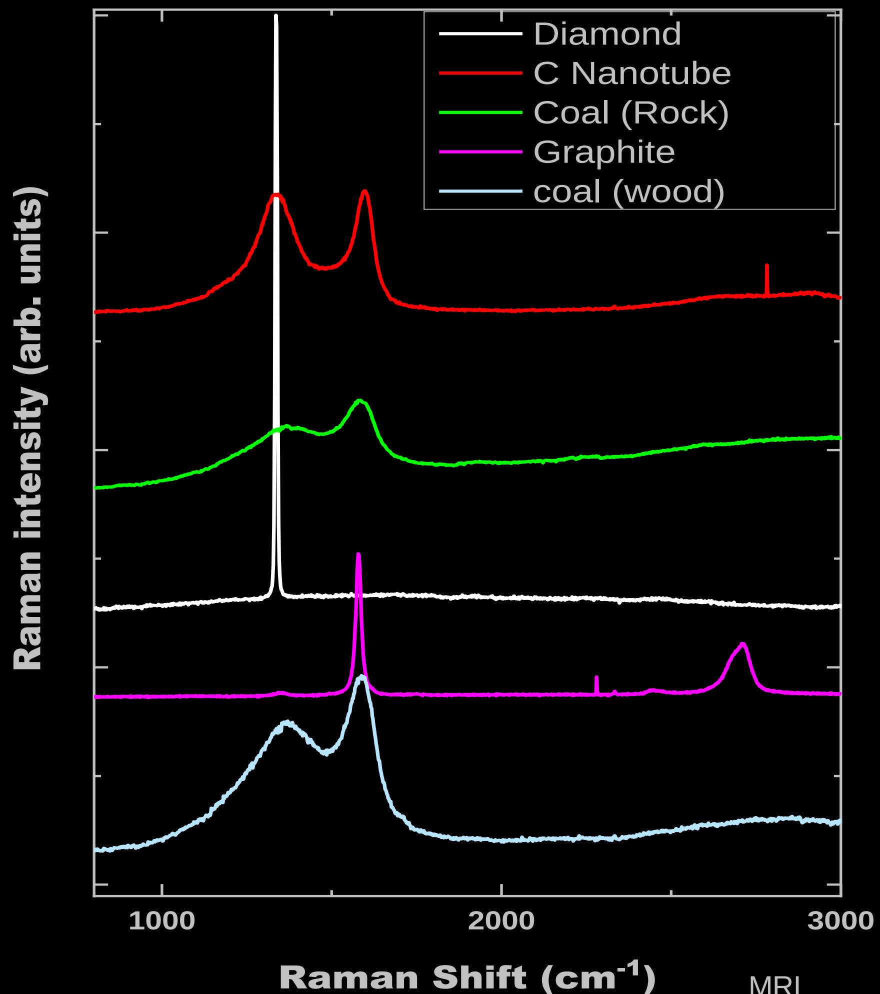


Raman spectroscopy

Molecular and crystalline structure characterization



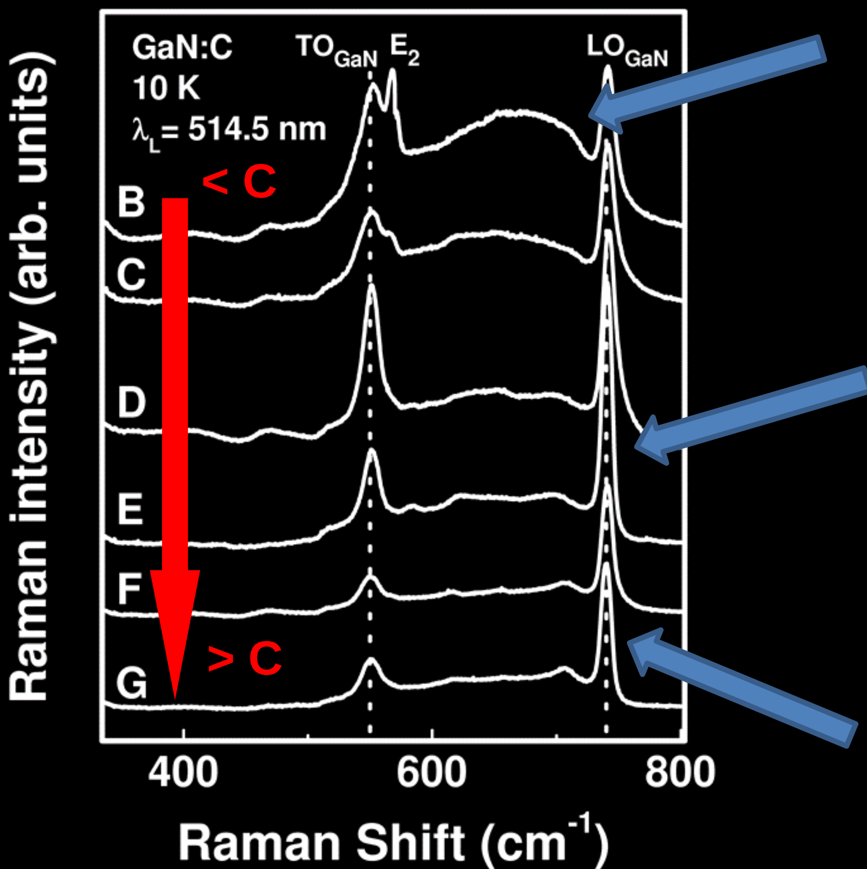
Physics Reports, 409 (2005), 47



MRL

Raman spectroscopy

Molecular and crystalline structure characterization



PHYSICAL REVIEW B **68**, 155204 (2003)

Presence of N vacancies yields poor crystallinity

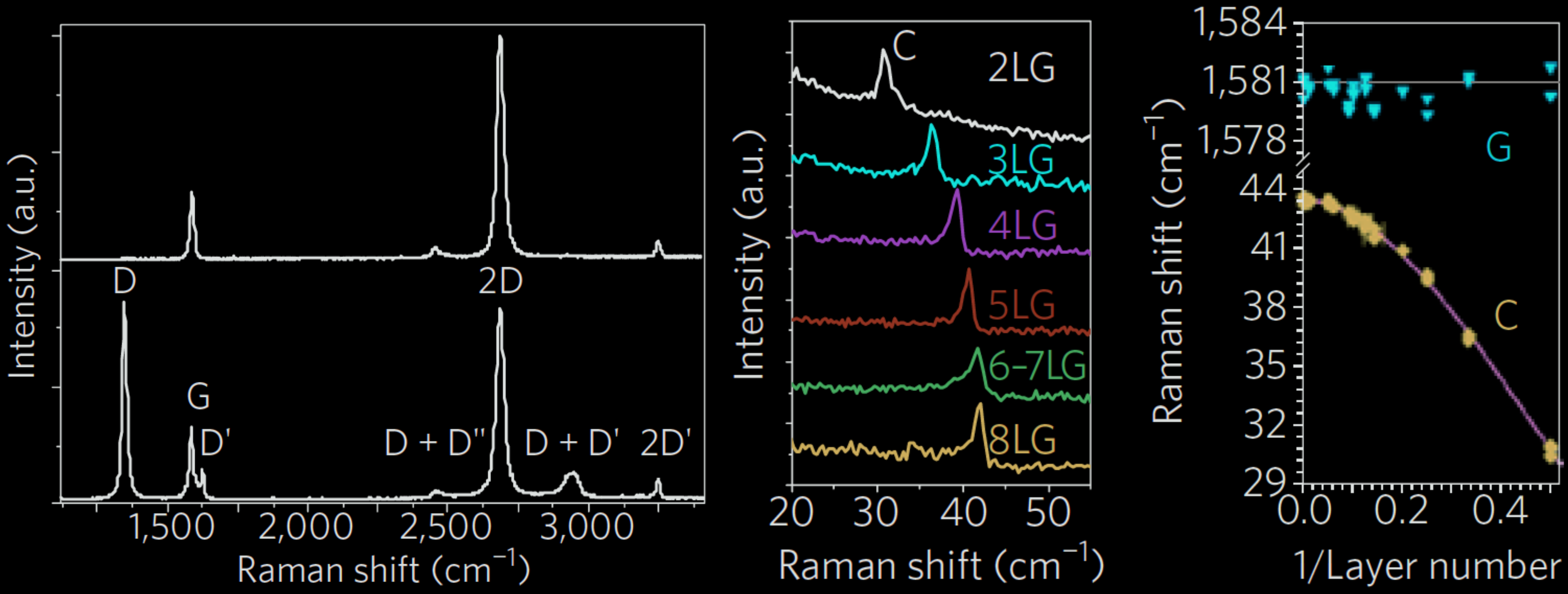
Substitutional C fills N vacancies improving the crystallinity

C incorporates interstitially causing a degradation of the crystal lattice

Raman spectroscopy

Crystalline structure defect characterization

Graphene

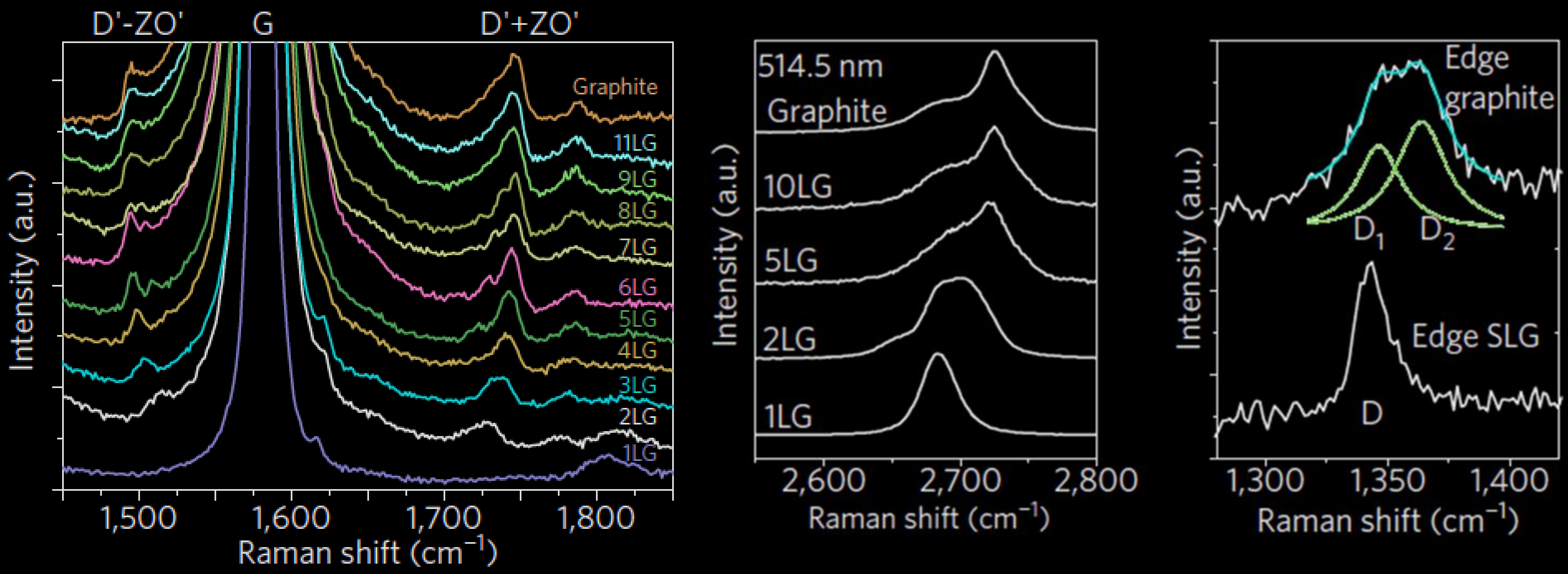


Nature Nanotech. ***5,*** *235* (2013)

Raman spectroscopy

Crystalline structure defect characterization

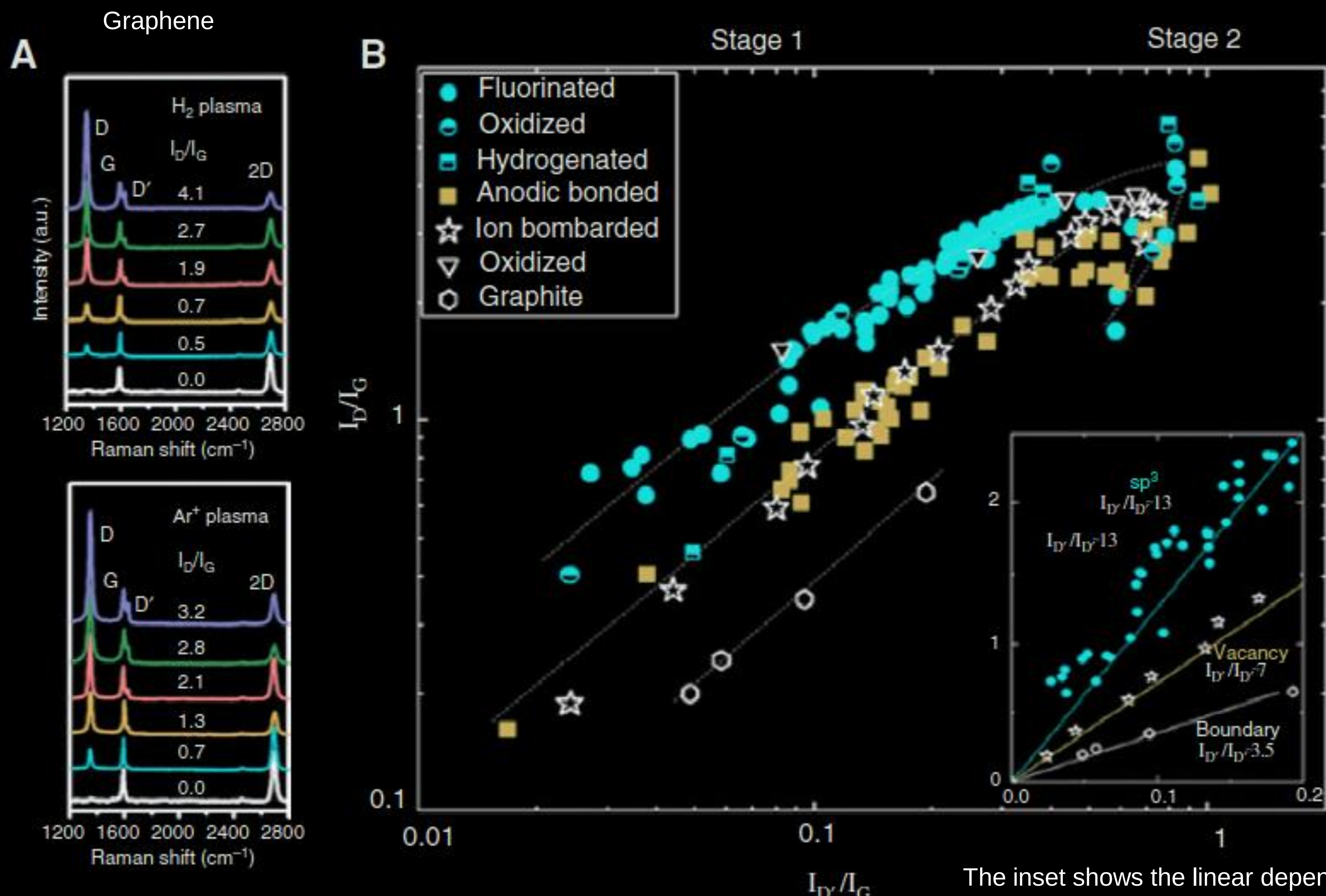
Graphene



Nature Nanotech. ***5,*** *235* (2013)

Raman spectroscopy

Crystalline structure defect characterization

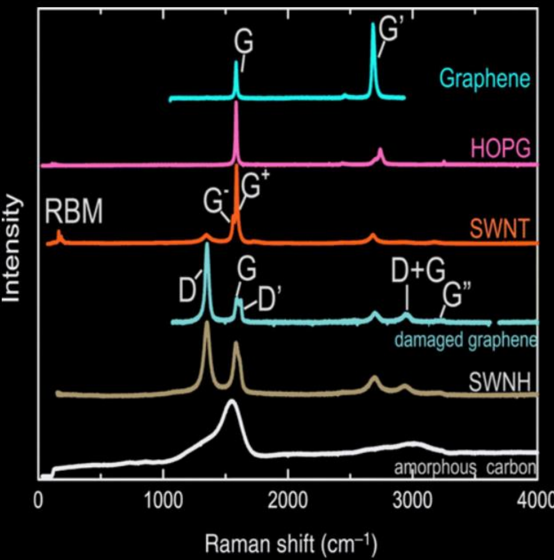


The inset shows the linear dependence between the two parameters at low defect concentration.

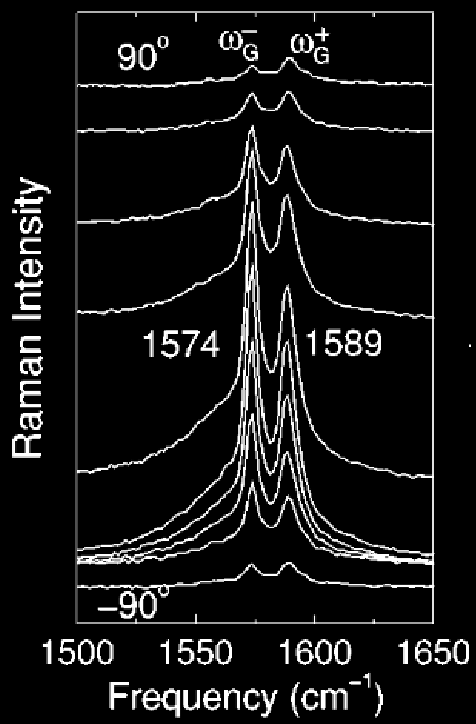
Nanophotonics **6,** 1219 (2017)

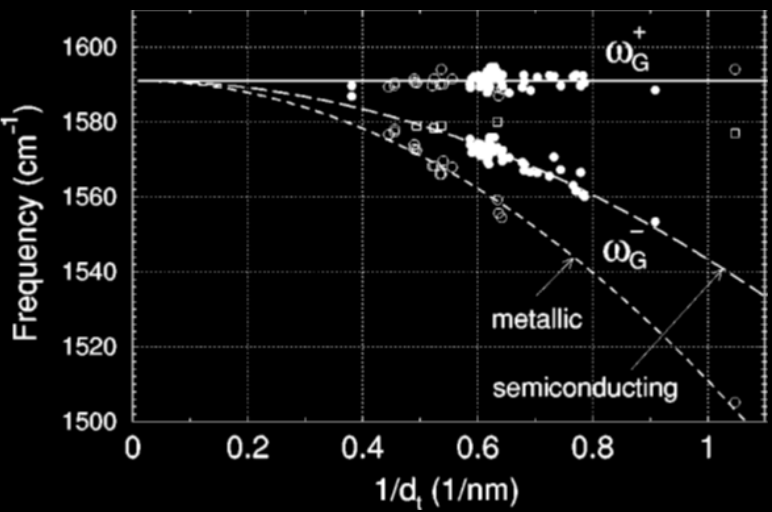
Raman spectroscopy

Type of single wall carbon nanotubes (SWNT)



Advances in Physics **60,** 413 (2011)



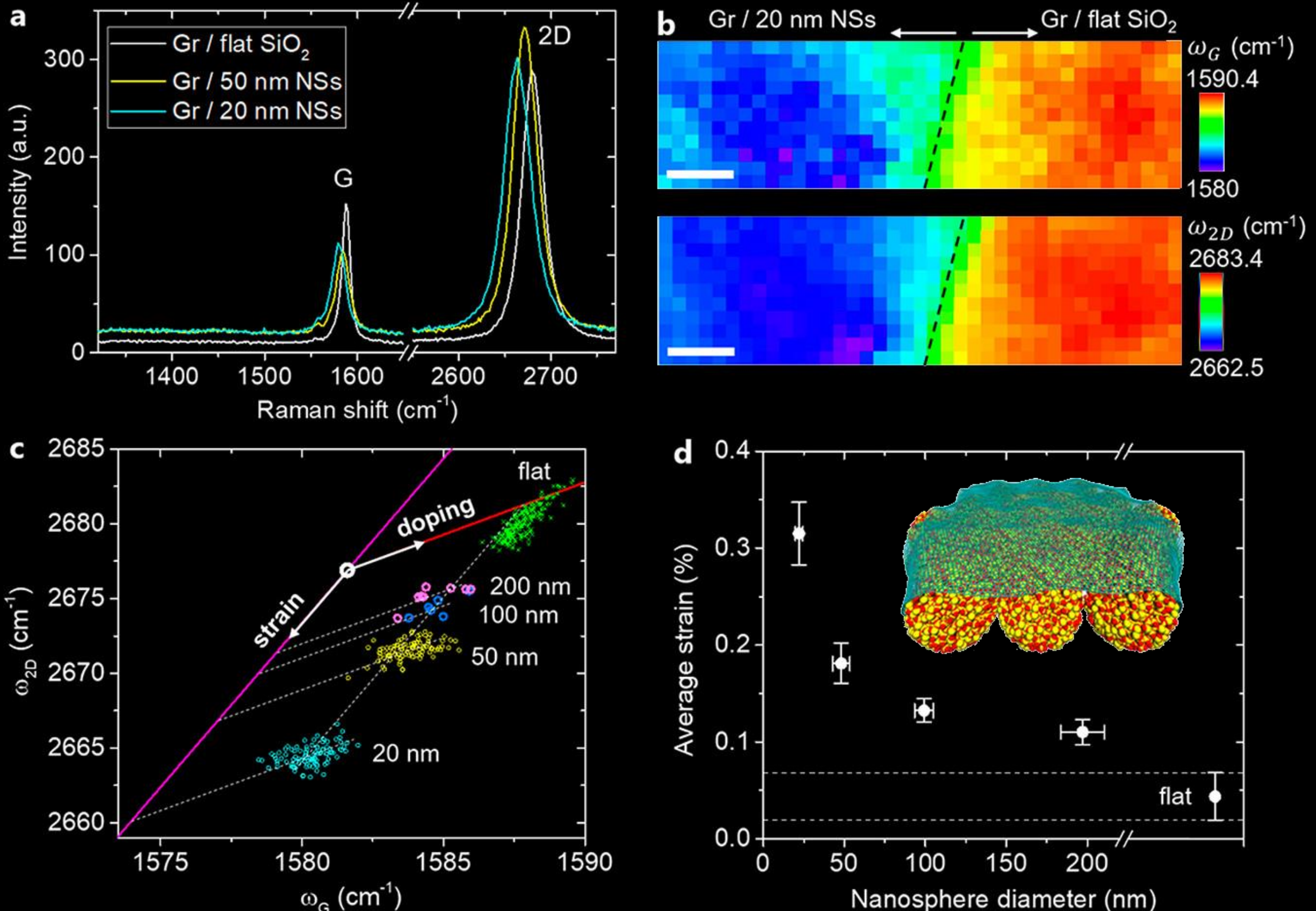


Phys. Rev. B **65**, 155412 (2001)

G' = 2D
G'' = 2D'

Raman spectroscopy

Strain



Nano Lett. **18**, 2098 (2018)

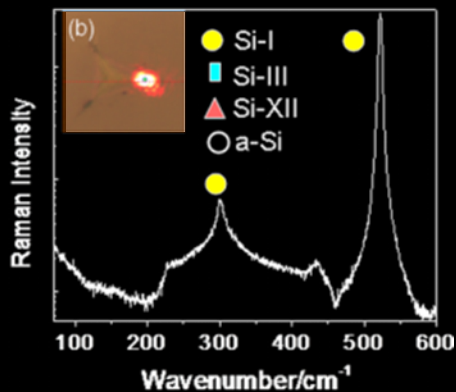
Raman spectroscopy

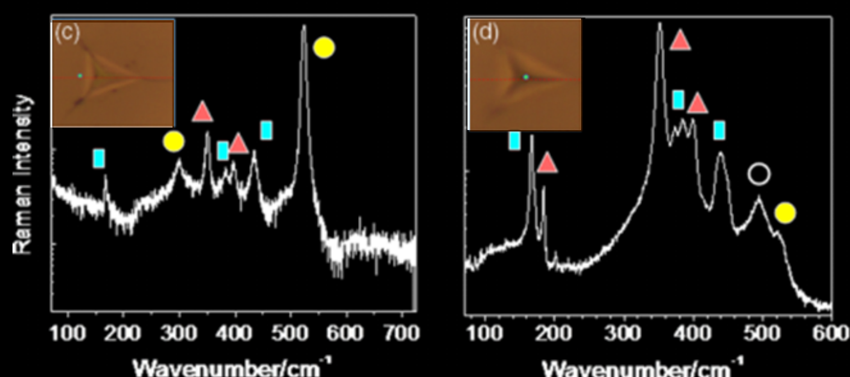
Phase transitions

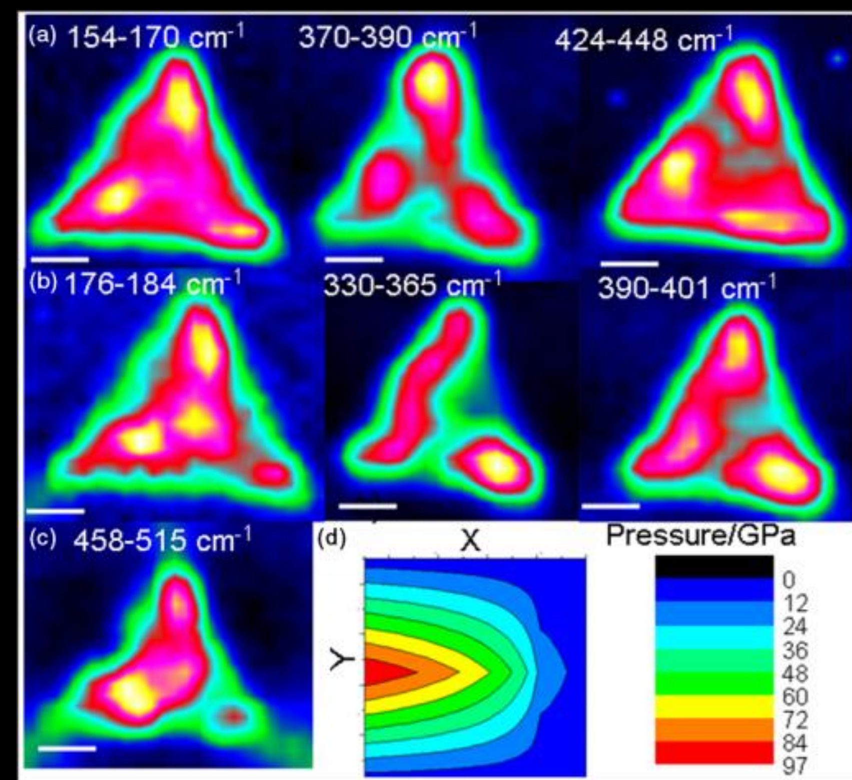
(a) Different Raman Modes

Si-I (cm^{-1})†	Si-III (cm^{-1})†	Si-XII (cm^{-1})†
300, 520	166, 171	182
a-Si (cm^{-1})†	384	352
475, 510	432, 463	397

† Ref 2,3

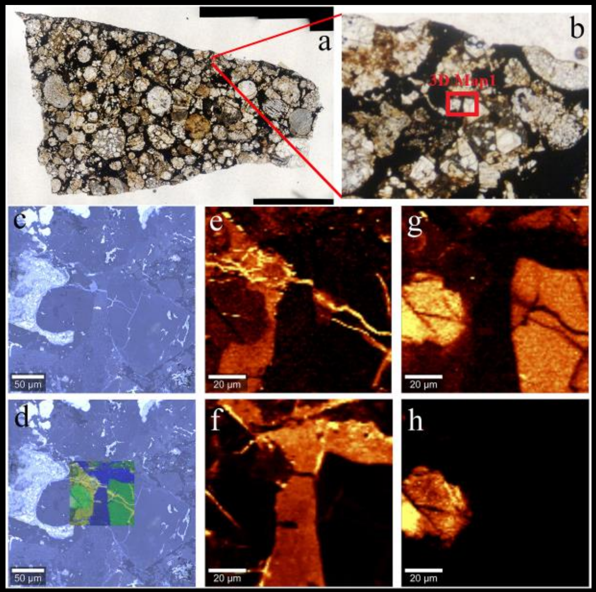




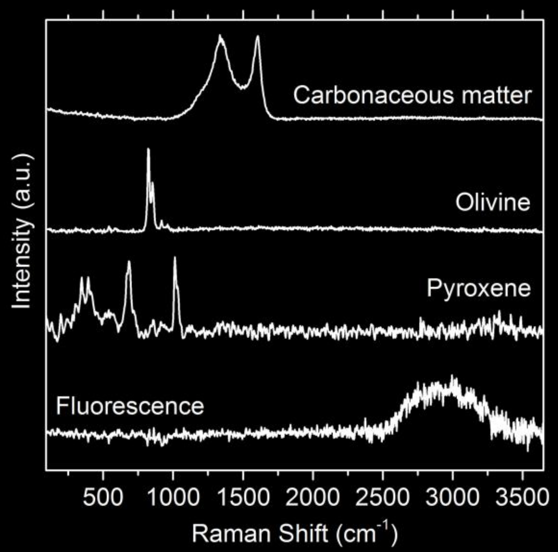


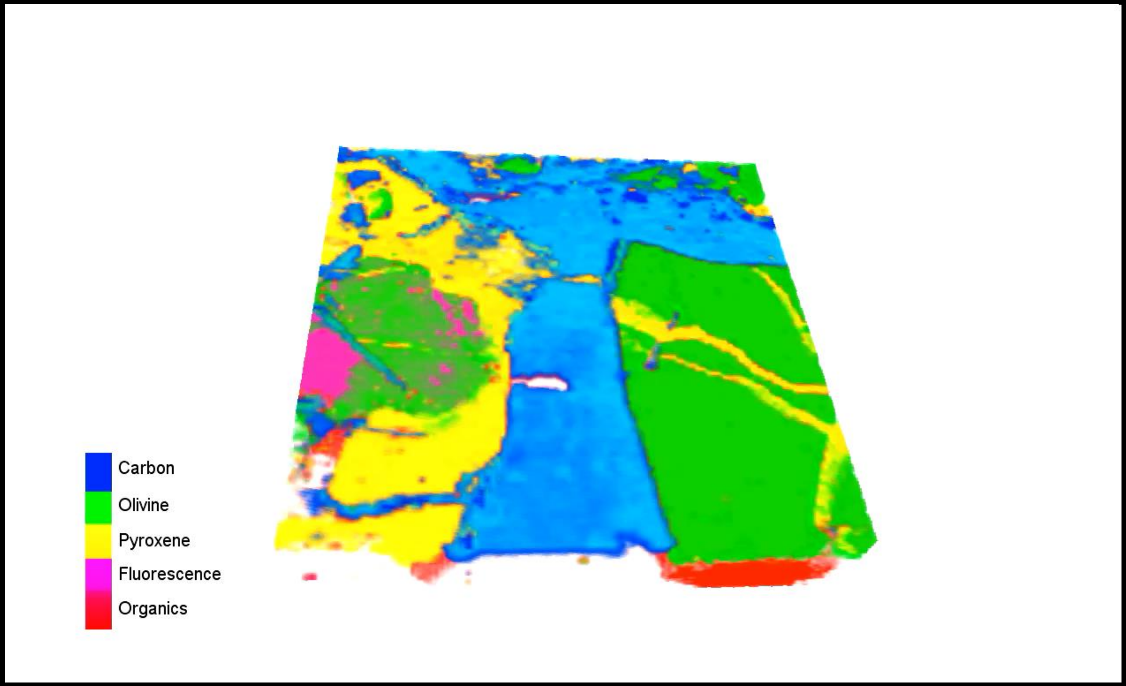
J. Raman Spectroscopy **41,** 334 (2010)

Raman spectroscopy



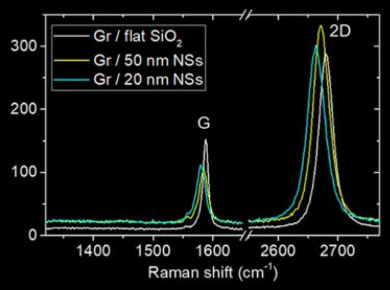
Chemical composition
Component identification
Components distribution

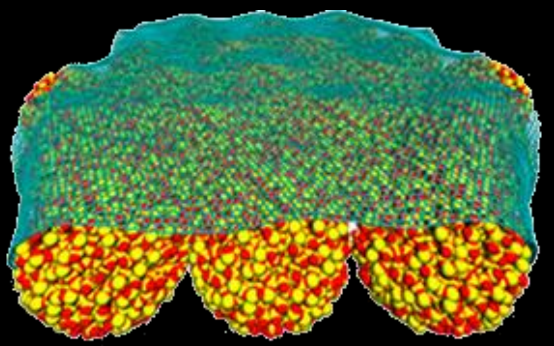




Earth and Space Science **5** (8), 380 (2018) DOI: (10.1029/2018EA000369)

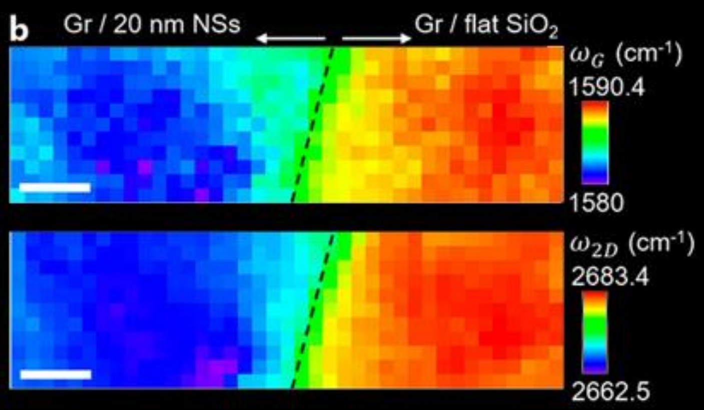
Raman spectroscopy





Primary Strengths:

- Very little sample preparation.
- Structural characterization.
- Non destructive technique.
- Chemical information.
- Complementary to FTIR.



Primary Limitations:

- Expensive apparatus (for high spectral/spatial resolution and sensitivity).
- Weak signal, compared to fluorescence.
- Limited spatial resolution (diffraction limited).

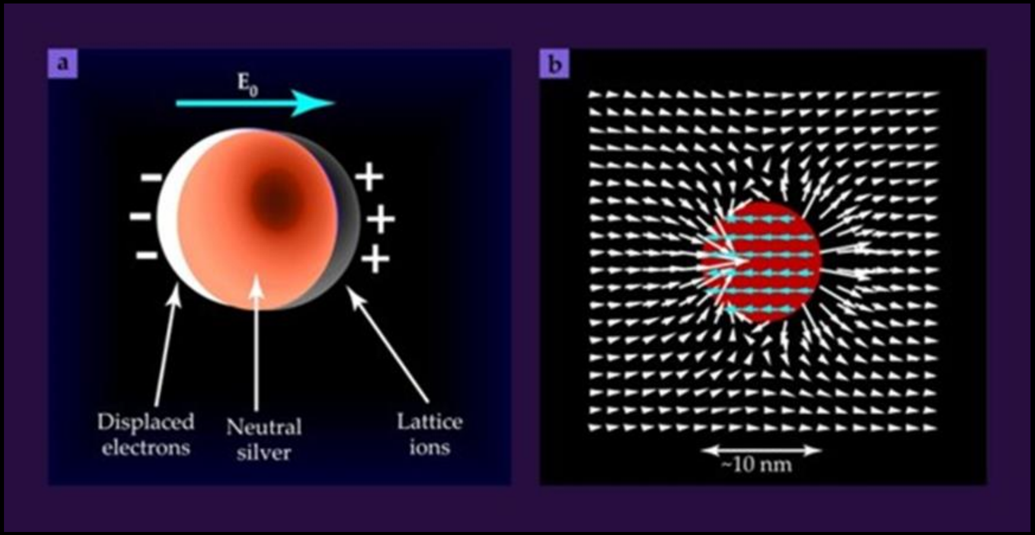
Complementary techniques:

FTIR, EELS, Mass spectroscopy, EXAFS, XPS, AES, SIMS, XRD, SFG.

Surface Plasmons

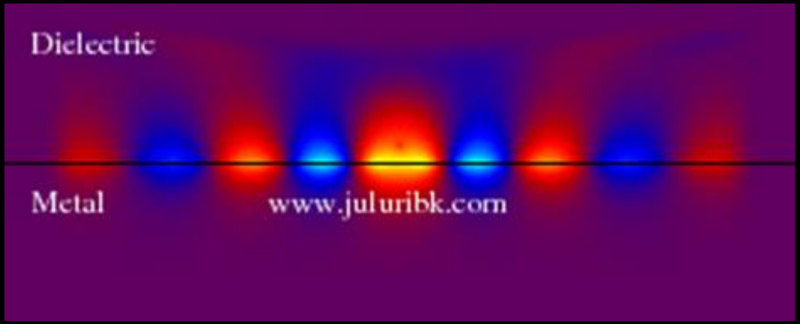
Excitations in materials

- Plasmons



Phys. Today, ***64***, *39 (2011)*

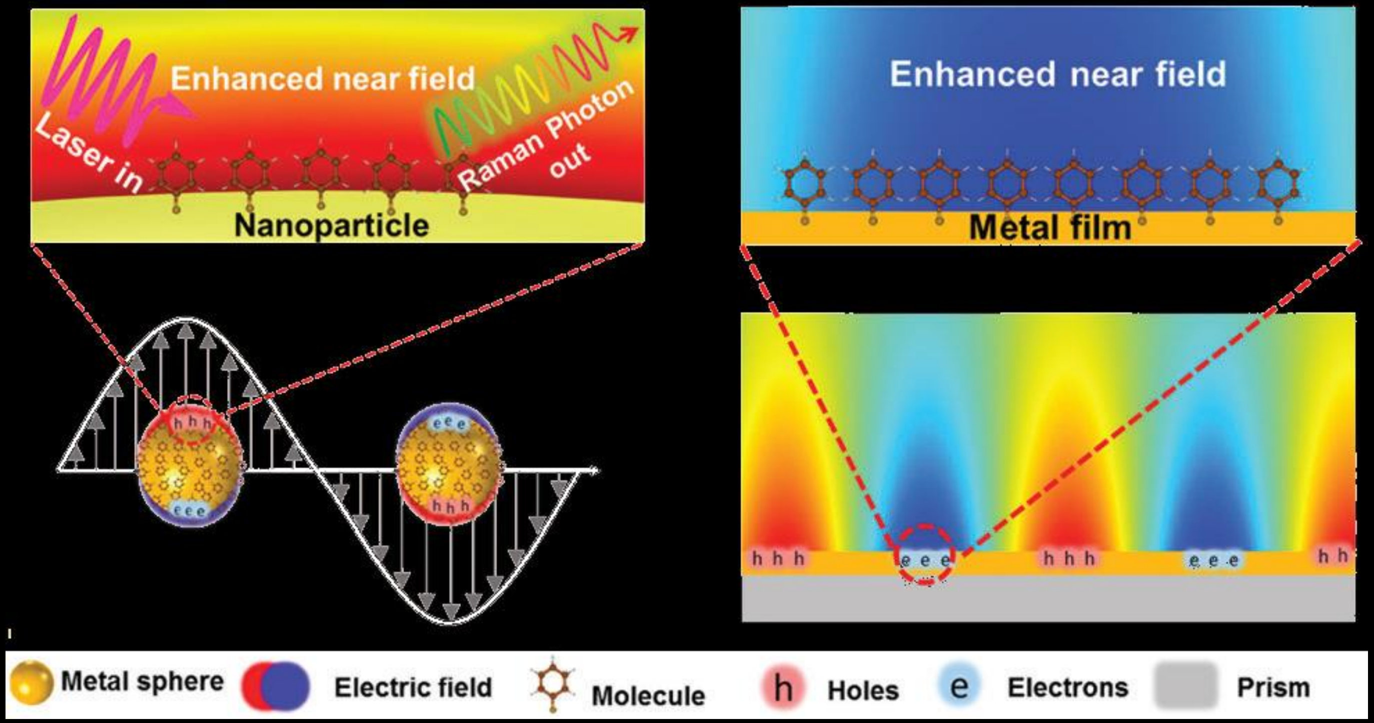
Plasmons are quanta of collective motion of charge-carriers in a gas with respect of an oppositely charged background.



They can be driven by photons at resonance to build large standing wave electric fields.

That leads to a strong enhancement of Raman scattering, proportional to fourth power of the E field strength.

Surface Enhanced Raman Spectroscopy (SERS)

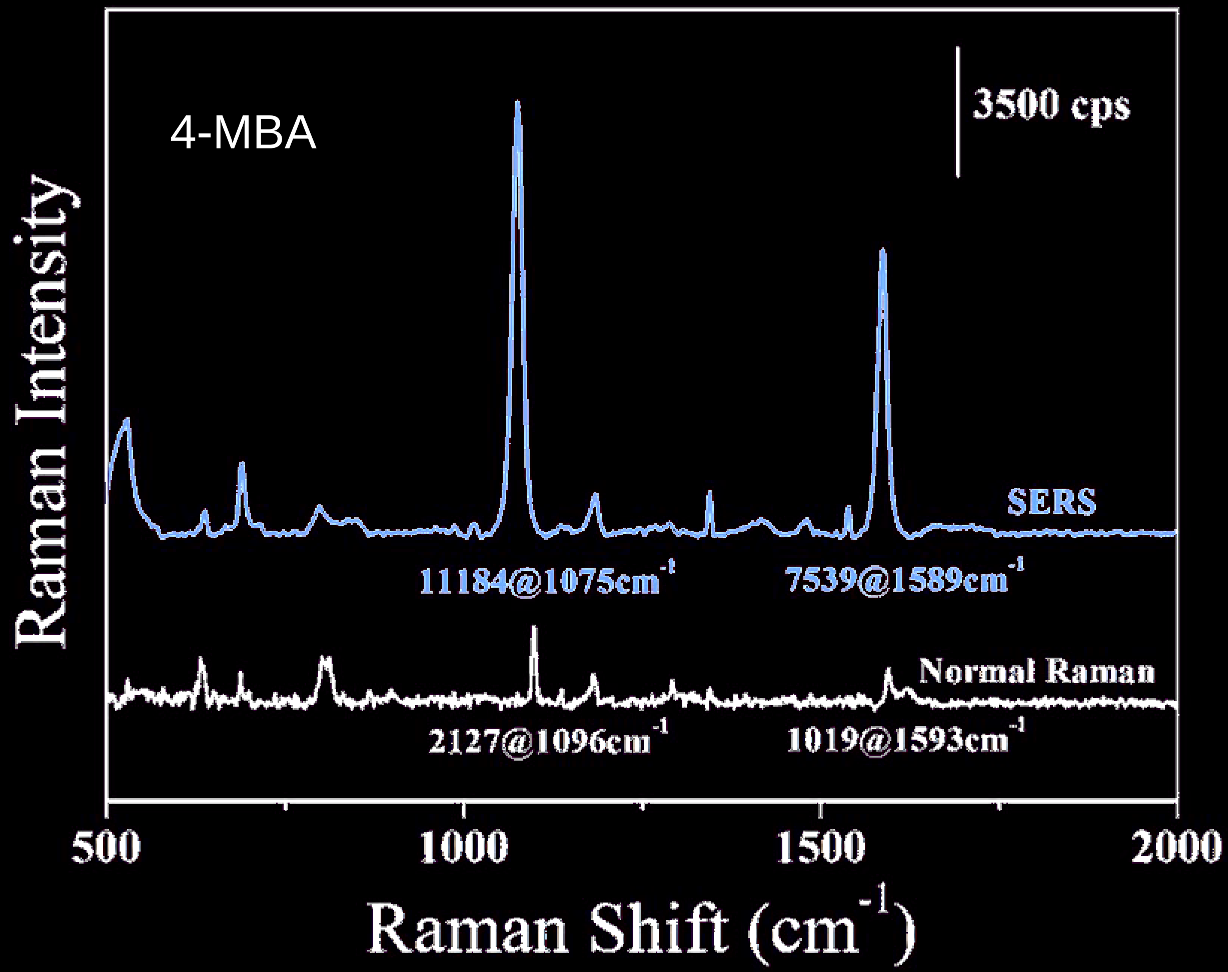


Chem. Rev. **117**, 5002, (2017)

Typically achieved with corrugated gold/silver surface or gold/silver nanoparticles with molecules of interest attached.

Capable of boosting Raman signal up to **14 Orders of Magnitude** or more! *Science* **275**, 1102 (1997)

Surface Enhanced Raman Spectroscopy (SERS)



Anal. Methods, **6**, 9547 (2014)

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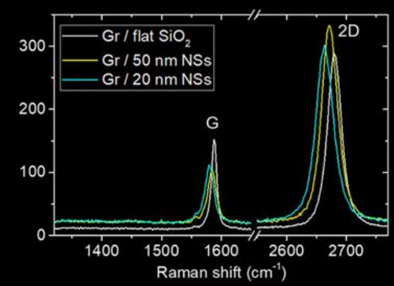
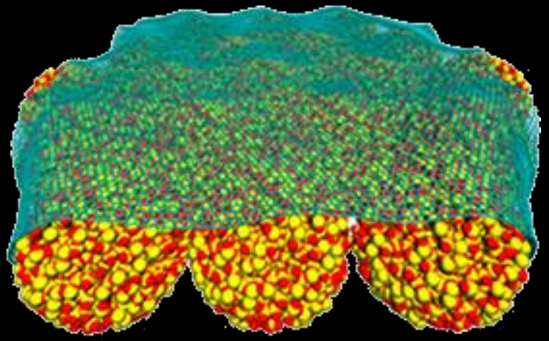
Raman spectroscopy





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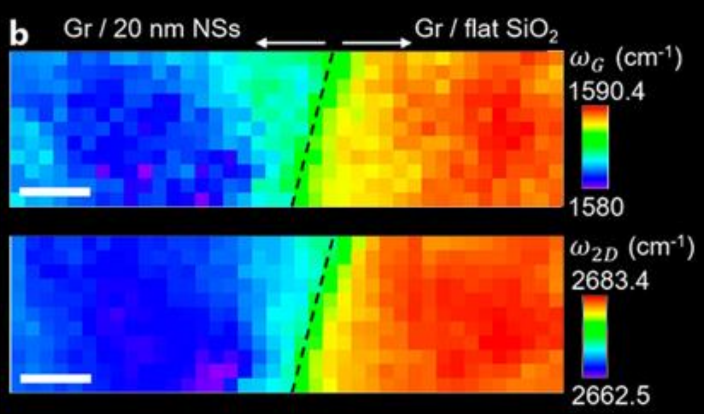

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- Weak signal, compared to fluorescence.
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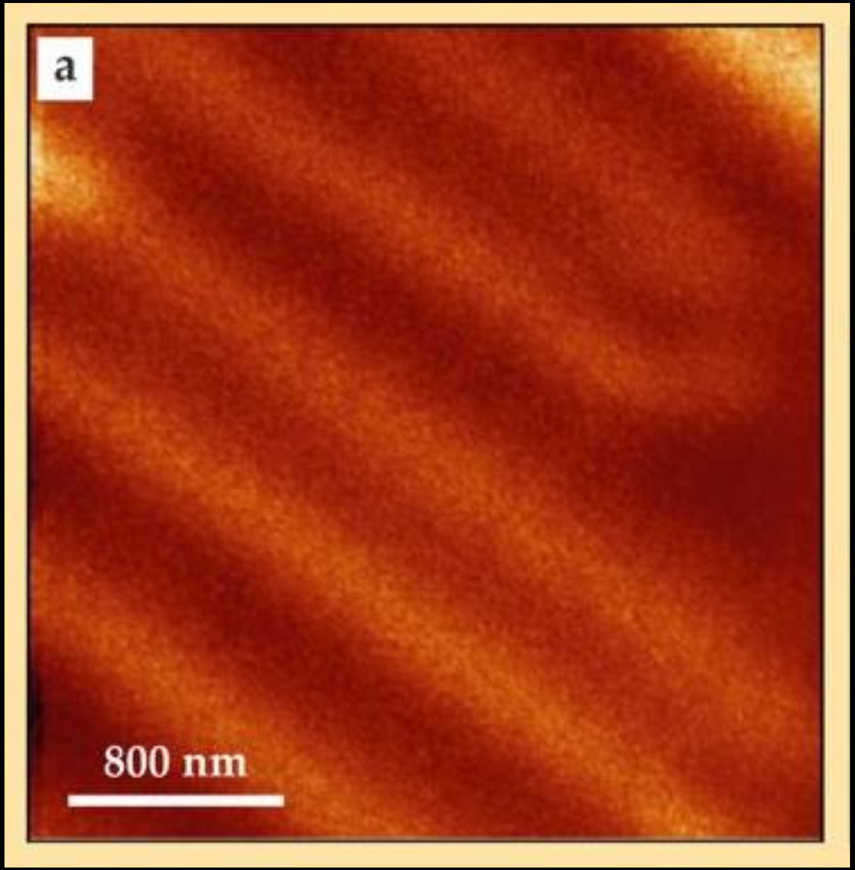
Complementary techniques:

FTIR, EELS, Mass spectroscopy, EXAFS, XPS, AES, SIMS, XRD, SFG.

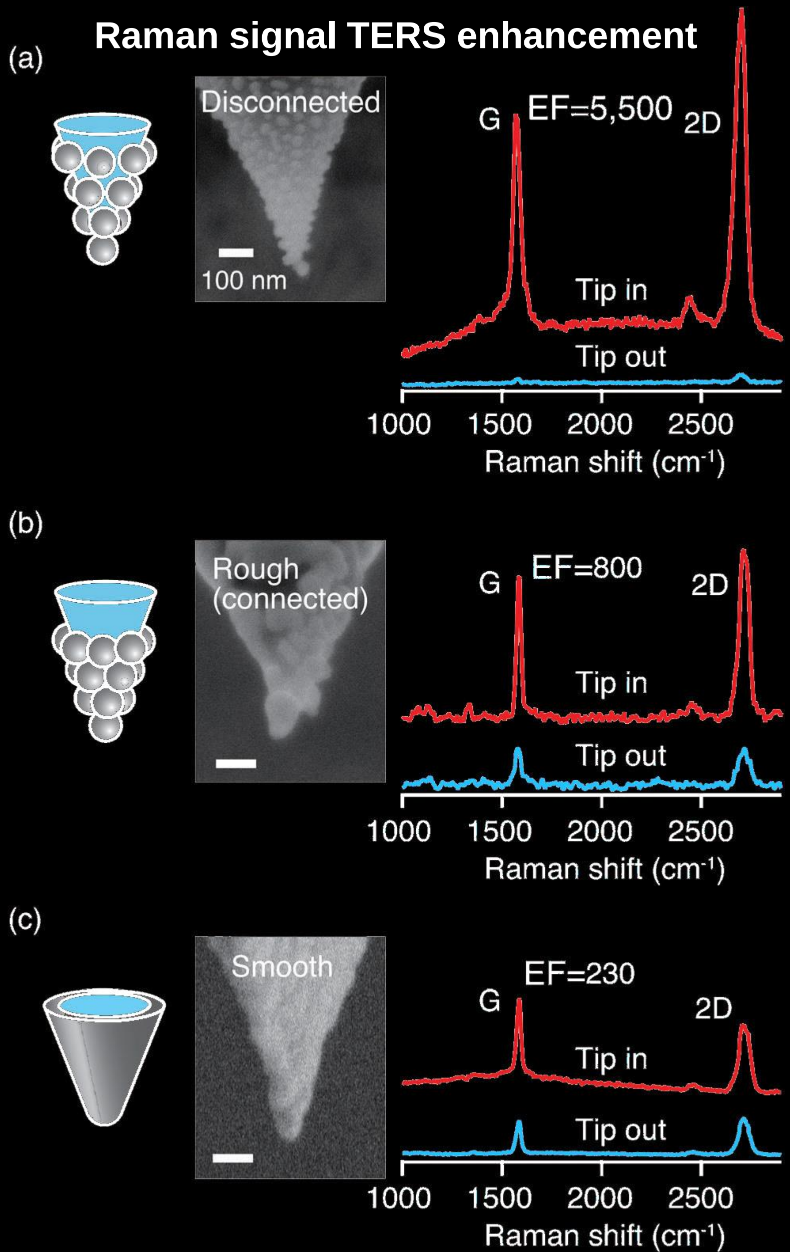
Confocal Raman Microscopy



Confocal Raman Image
Carbon Nanotubes

Phys. Rev. Lett. **103**, 186101 (2009)

Tip Enhanced Raman Spectroscopy (TERS)

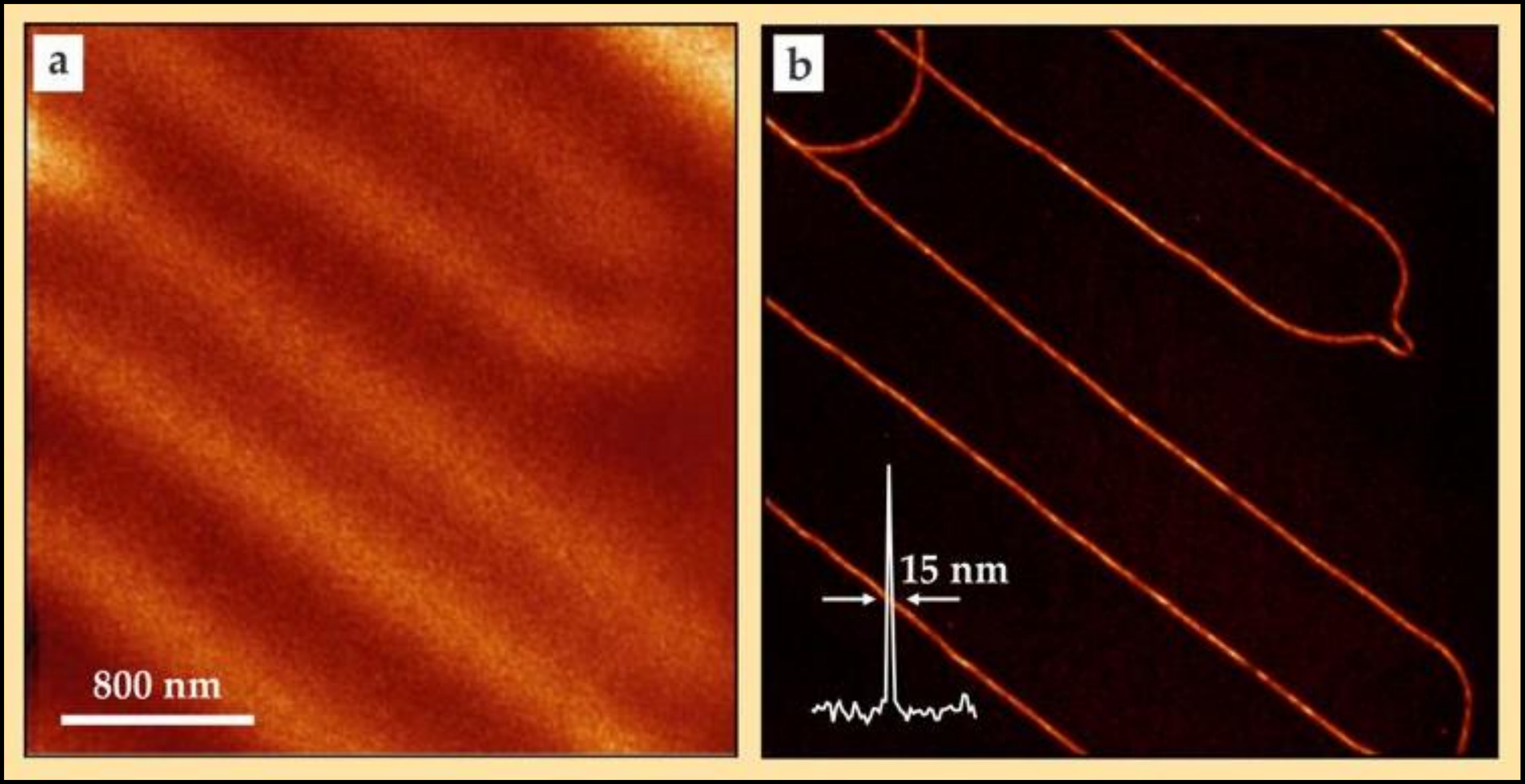


This also works with a single metalized sharp tip, such as an STM or AFM tip!

Not only do you get the electric field enhancement, but now the source of the Raman signal is extremely localized.

Chem. Soc. Rev. **46**, 4077 (2017)

Tip Enhanced Raman Spectroscopy (TERS)

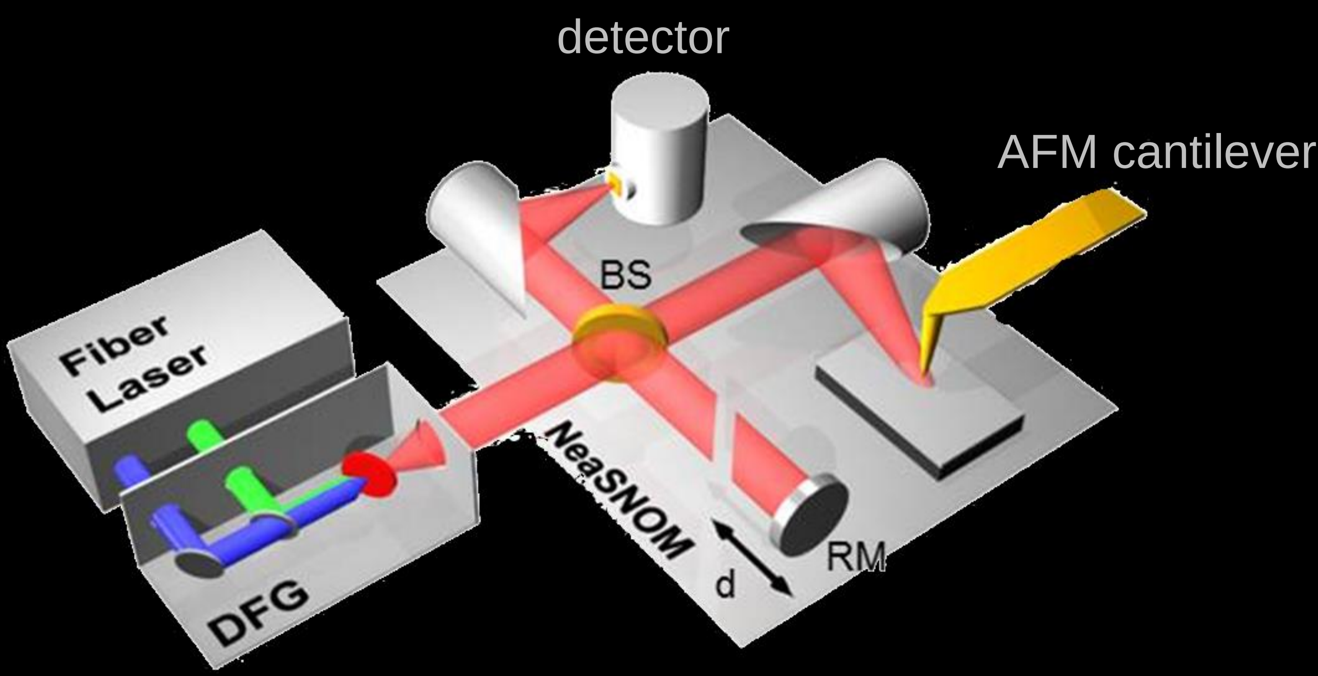


Confocal Raman Image ***Tip Enhanced Raman Image***

Carbon Nanotubes

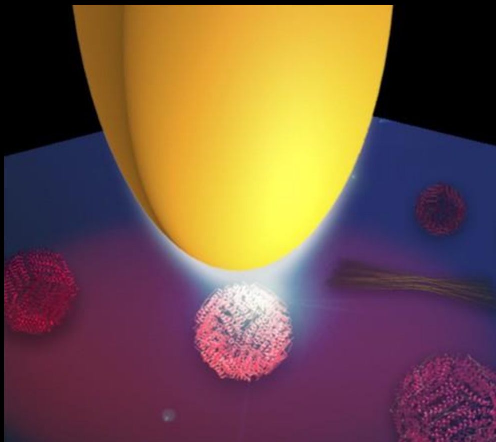
*Phys. Rev. Lett.*__103__, 186101 (2009)

Near-field scanning optical nanospectroscopy



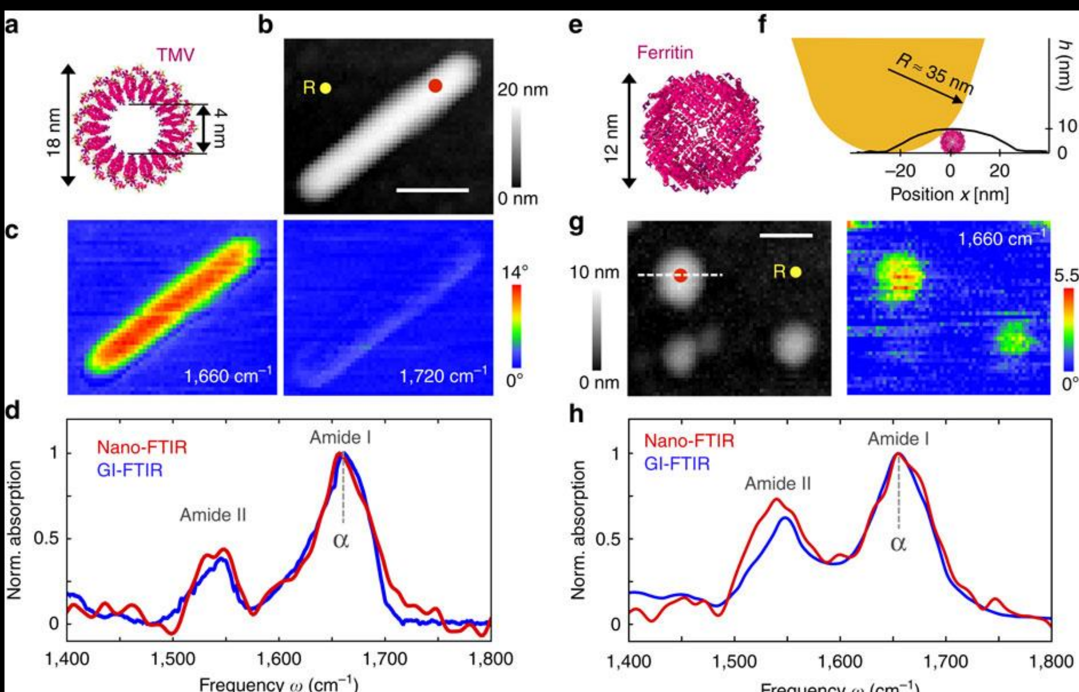
Near-field scanning optical nanospectroscopy

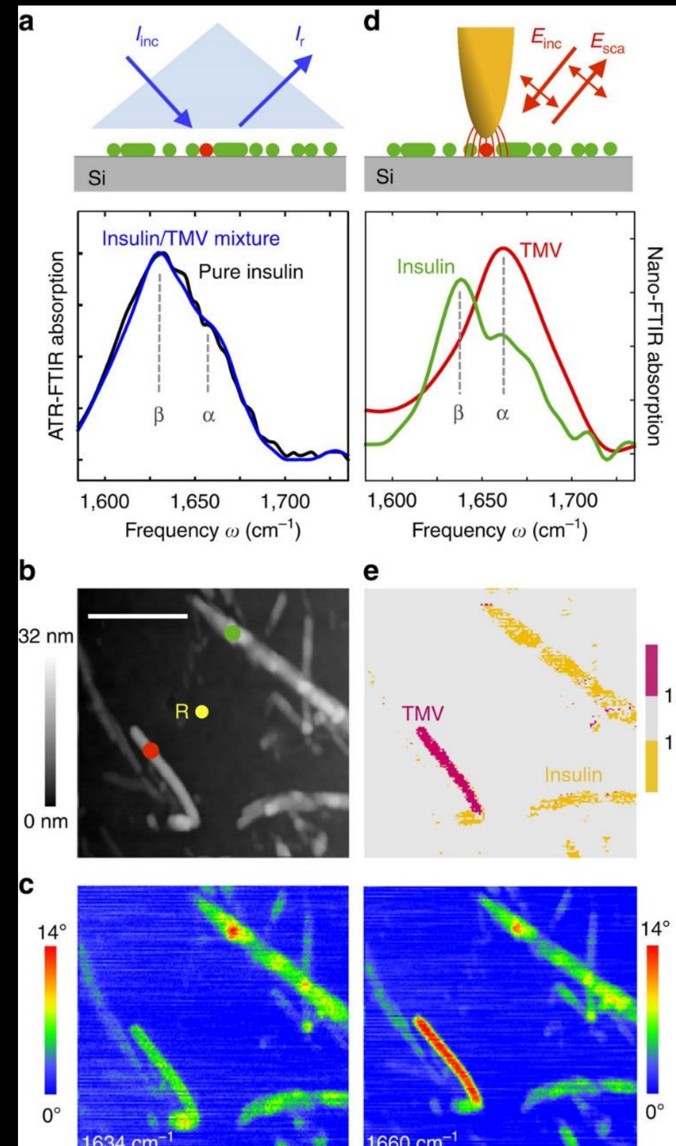
Nano-FTIR



nature

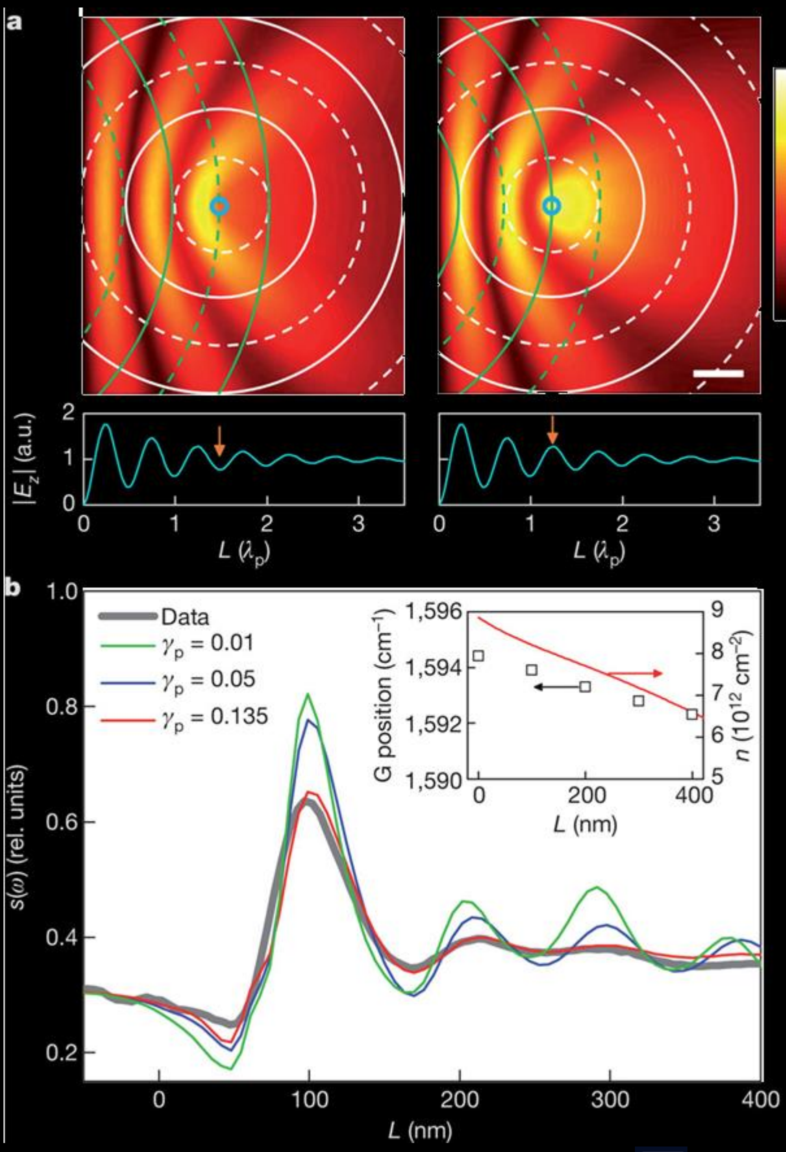
Nature Communications **4**, 2890

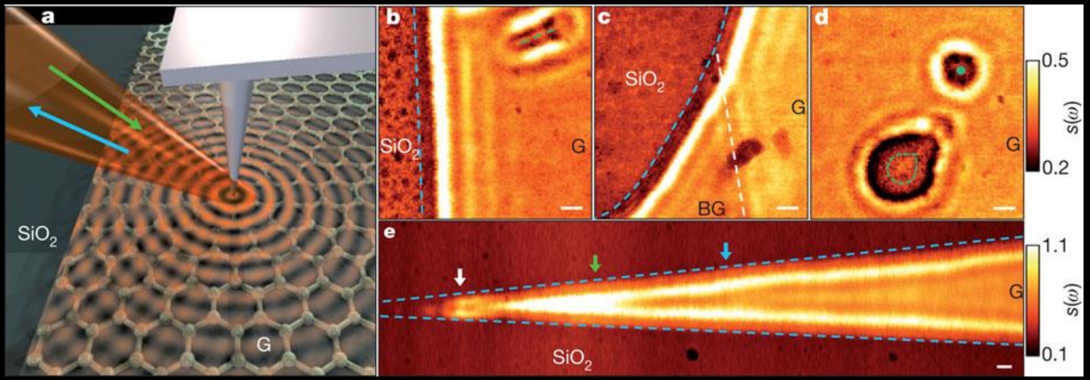




Near-field scanning optical nanospectroscopy

Nano-FTIR





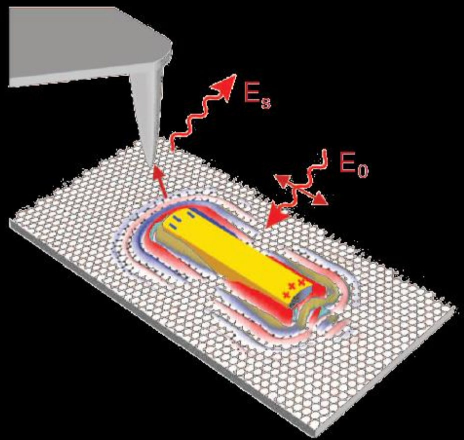
Nature **000**, 1-4 (2012) doi:10.1038/nature11253

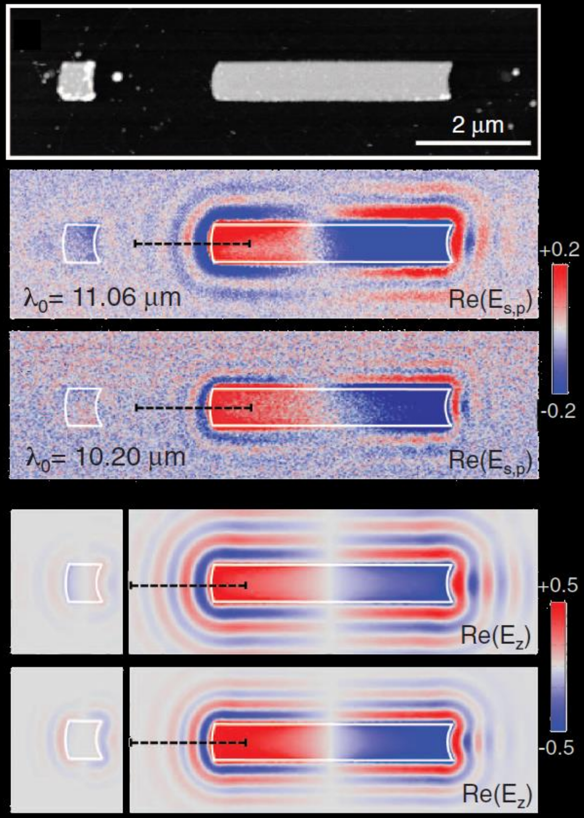
nature

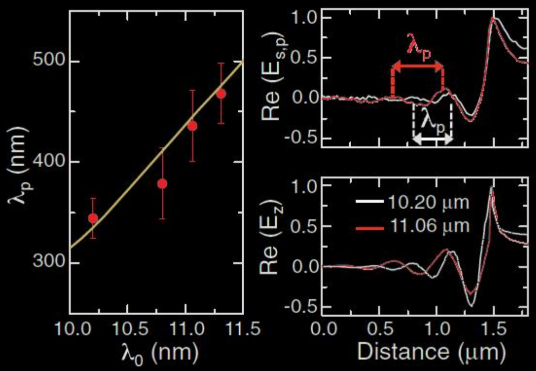
https://www.youtube.com/watch?v=mcom2uN1TR4

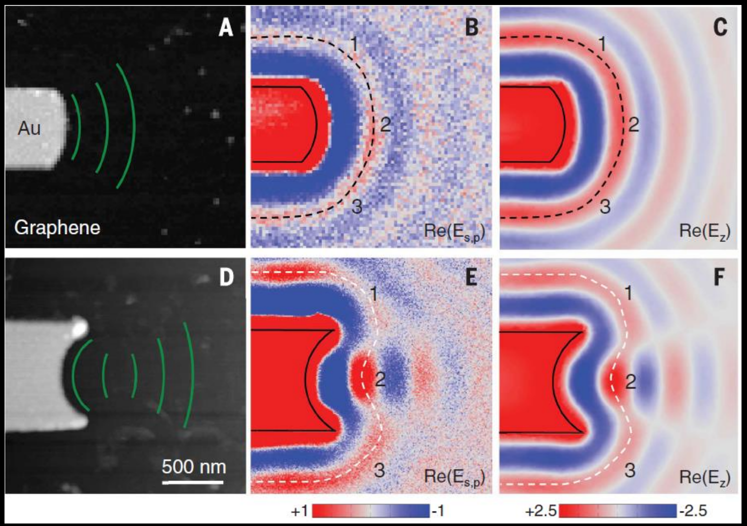
Near-field scanning optical nanospectroscopy

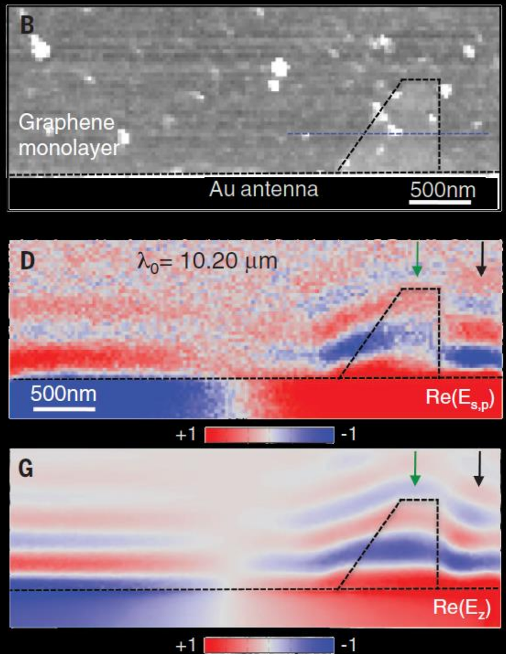
Nano-FTIR











Science **344**, 1369

Near-field scanning optical nanospectroscopy

Strengths:

- No sample preparation.
- Non destructive technique.
- Sub diffraction limit resolution (20 nm).

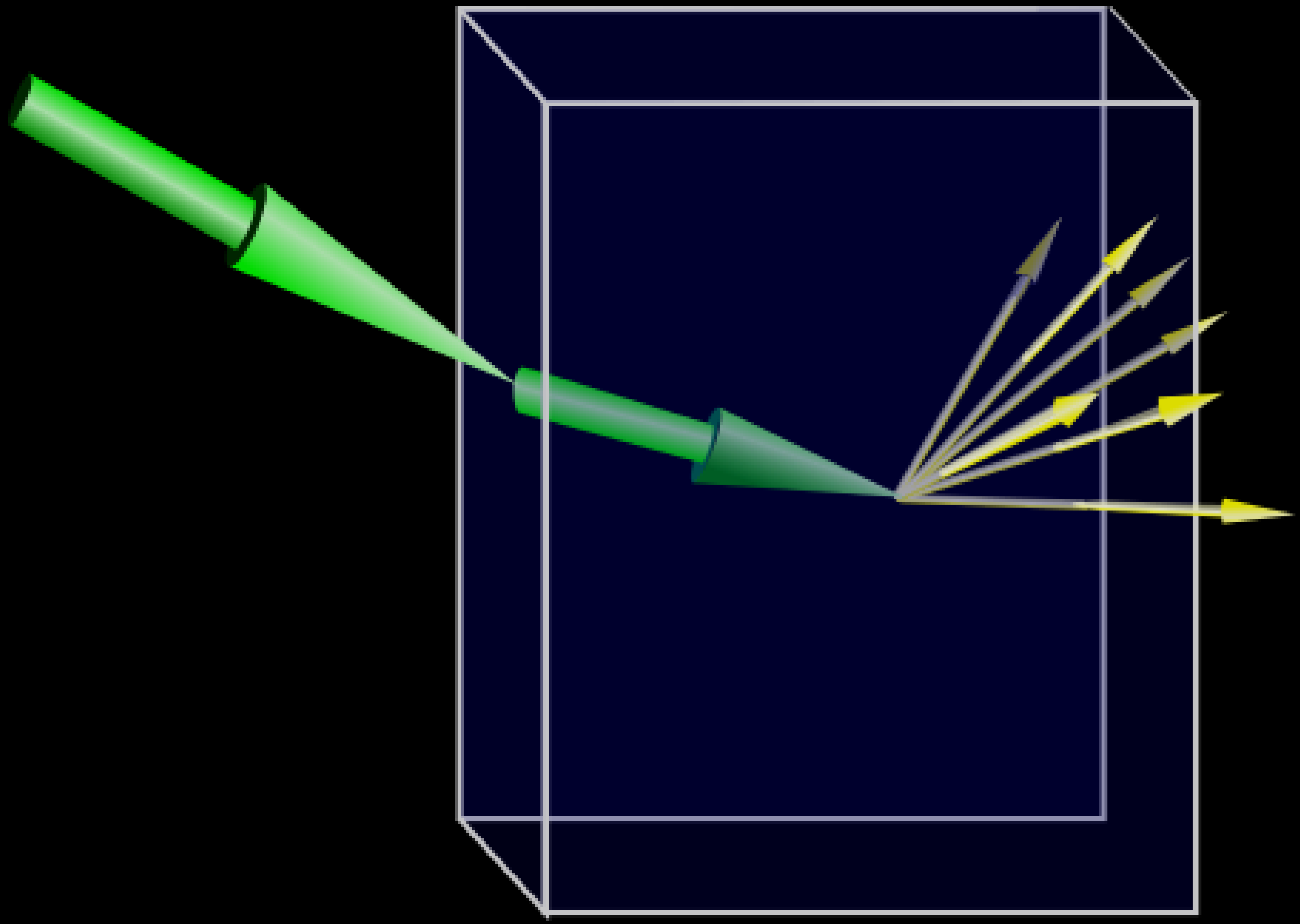
Requirements and limitations:

- Slow data acquisition.
- Limited to fairly flat samples (AFM-like).
- Interaction between tip and sample may make analysis difficult.

Complementary techniques:

AFM, SEM,TEM, Confocal microscopy.

Luminescence



Luminescence

Lifetime: Phosphorescence, fluorescence

Mechanism: Photoluminescence, bioluminescence, chemoluminescence, thermoluminescence, piezoluminescence, etc.

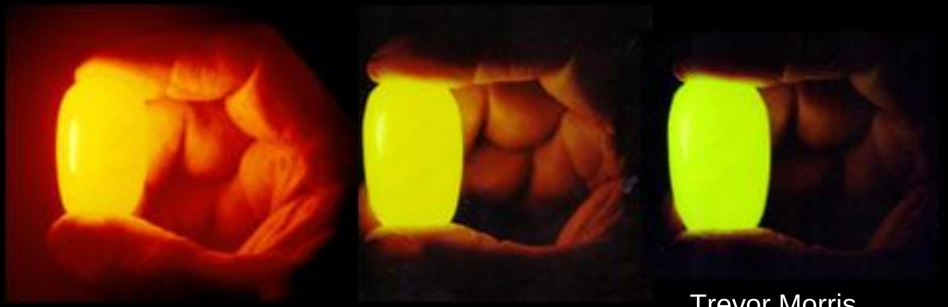
Disney Pixar

Charles Hedgcock ©

Profilephotocovers.com

Radim Schreiber

Profilephotocovers.com



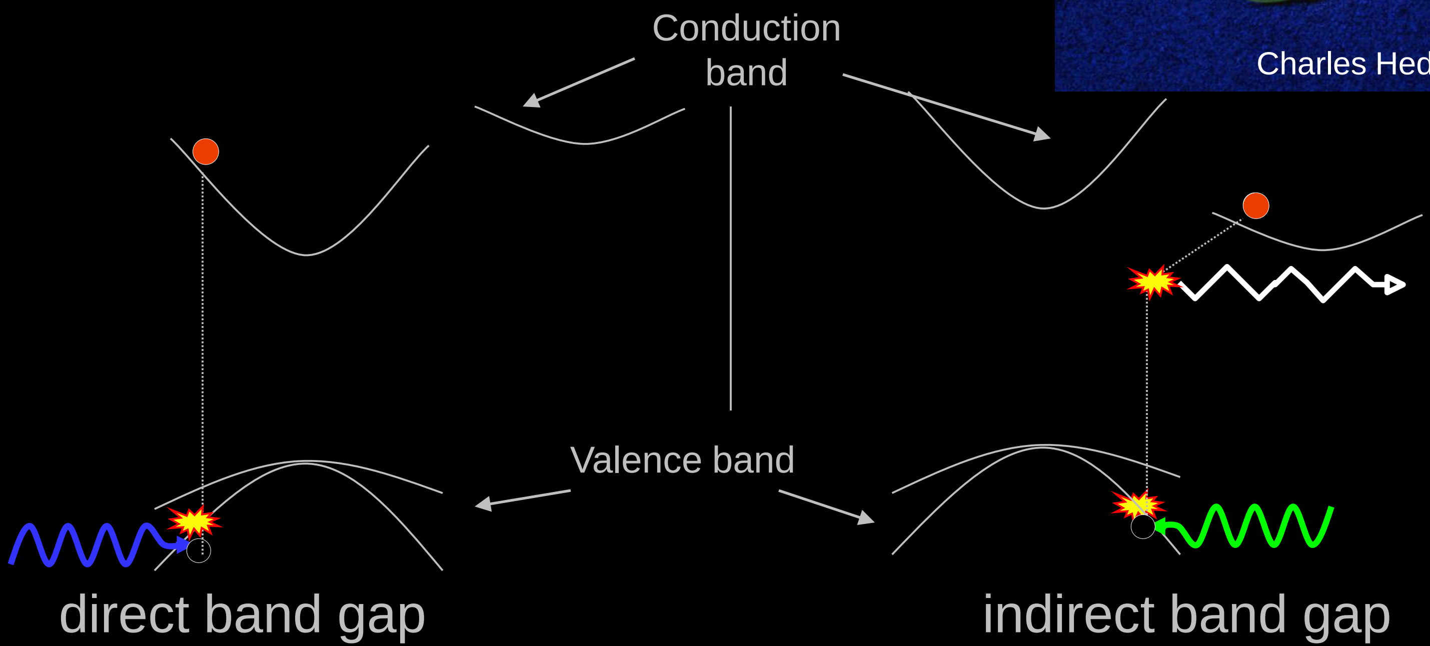
Trevor Morris

Photoluminescence

What is measured:

The emission spectra of materials due to radiative recombination following photo-excitation.

Basic principle:



Photoluminescence

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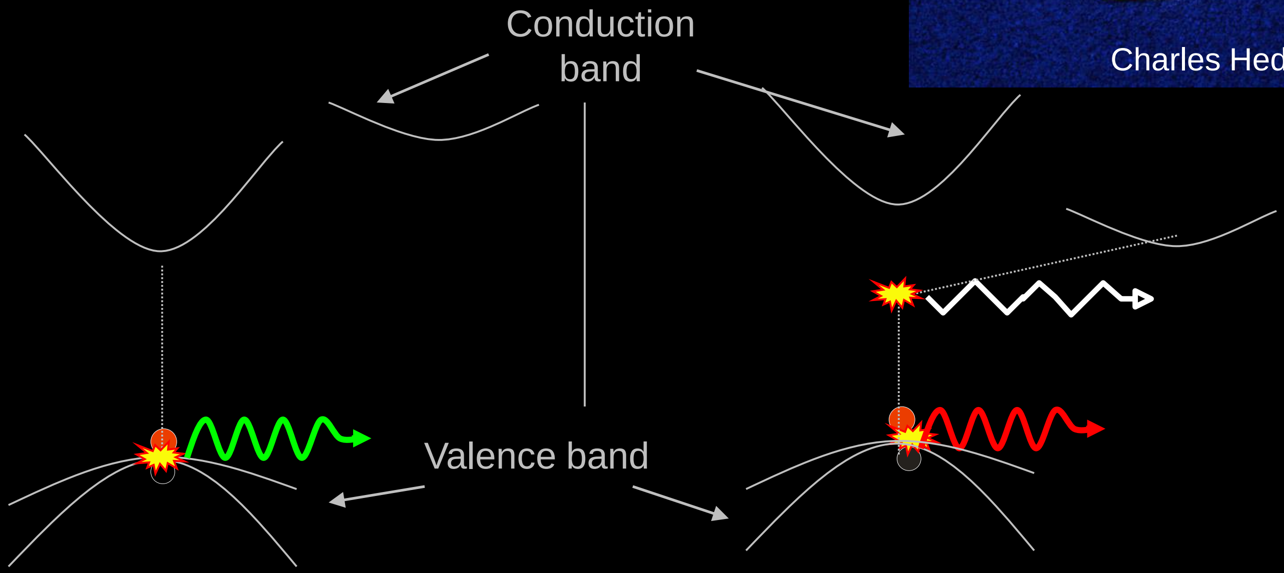
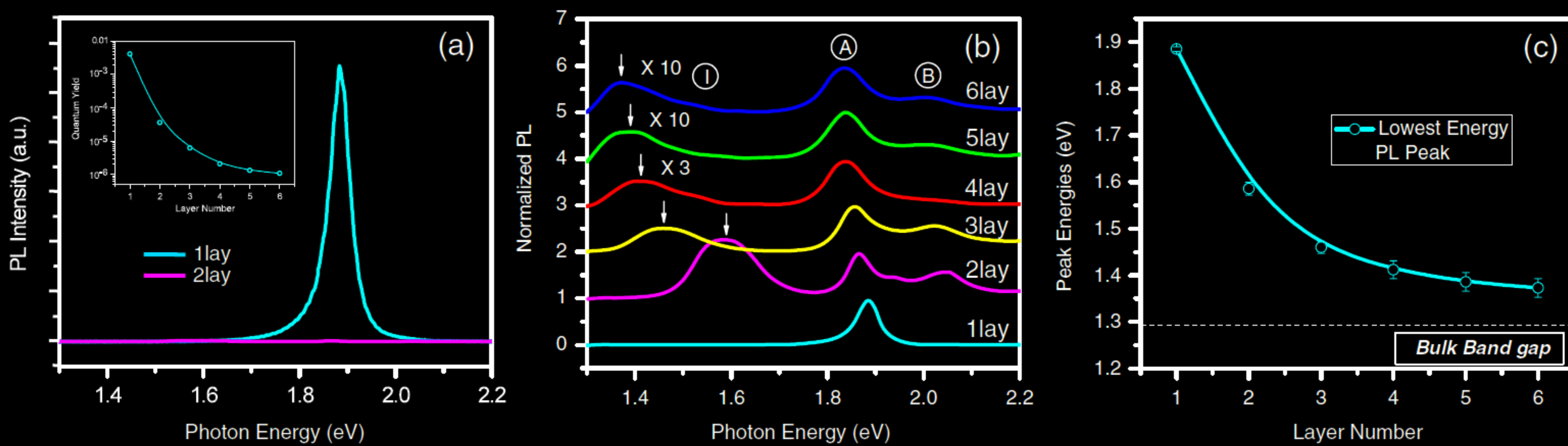


direct band gap

indirect band gap

Number of layers in 2D materials

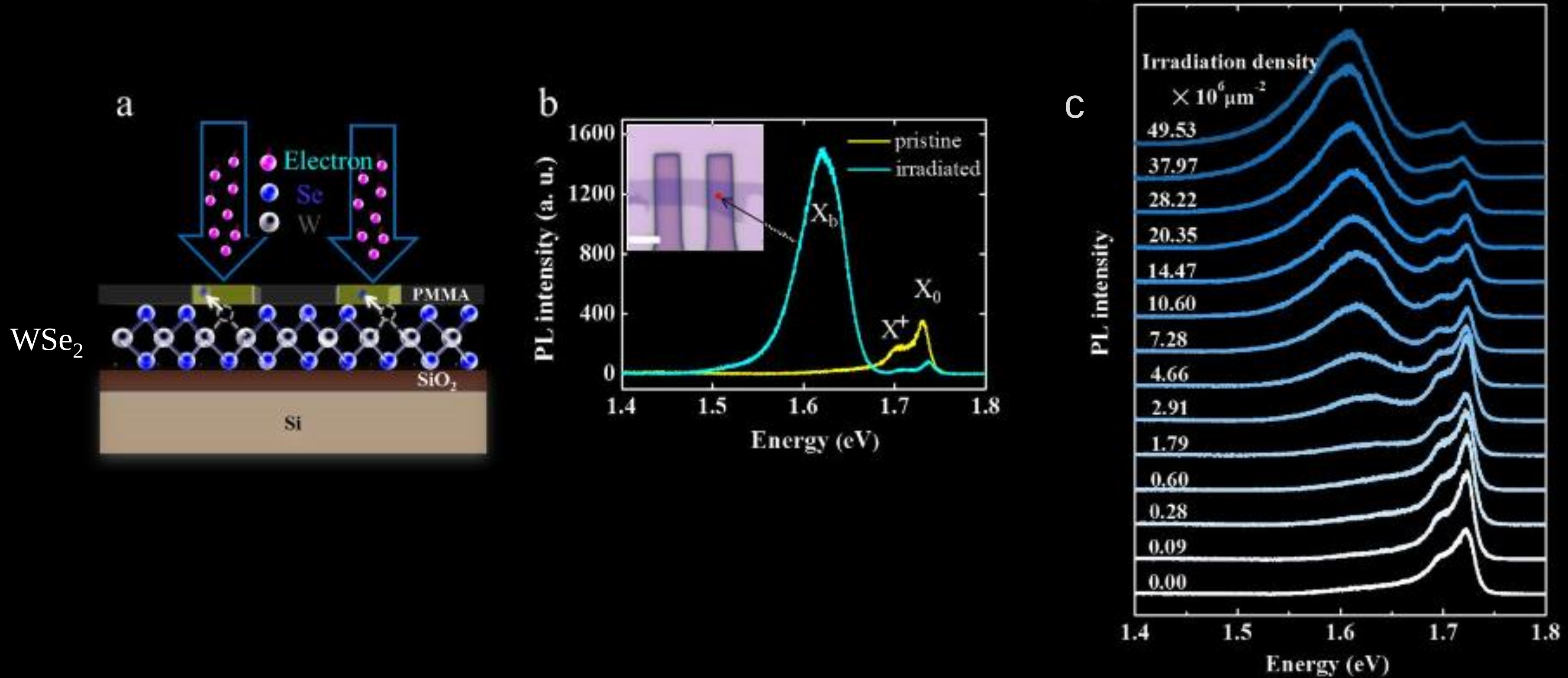
(a) PL spectra for mono- and bilayer MoS_2.
Inset: PL QY of thin layers for N = 1–6.
(b) Normalized PL spectra by the intensity of peak A of thin layers of MoS_2 for N = 1–6. Feature I for N = 4–6 is magnified for clarity.
(c) Band-gap energy of thin layers of MoS_2, inferred from the energy of the PL feature I for N = 2–6 and from the energy of the PL peak A for N = 1. The dashed line represents the (indirect) band-gap energy of bulk MoS_2.



Phys. Rev. Lett. **105**, 136805 (2010)

Defects in 2D materials

(a) Defect induced PL emission. (a) Schematic diagram of electron beam irradiation on monolayer WSe_2 sample during the EBL process.
(b) PL spectrum of pristine monolayer WSe_2 and monolayer WSe_2 after EBL.
The inset shows optical image of WSe_2 with PMMA patterned by EBL, scale bar is 5 μm
(c) PL spectra of a pristine WSe_2 under different e^- beam irradiation density.

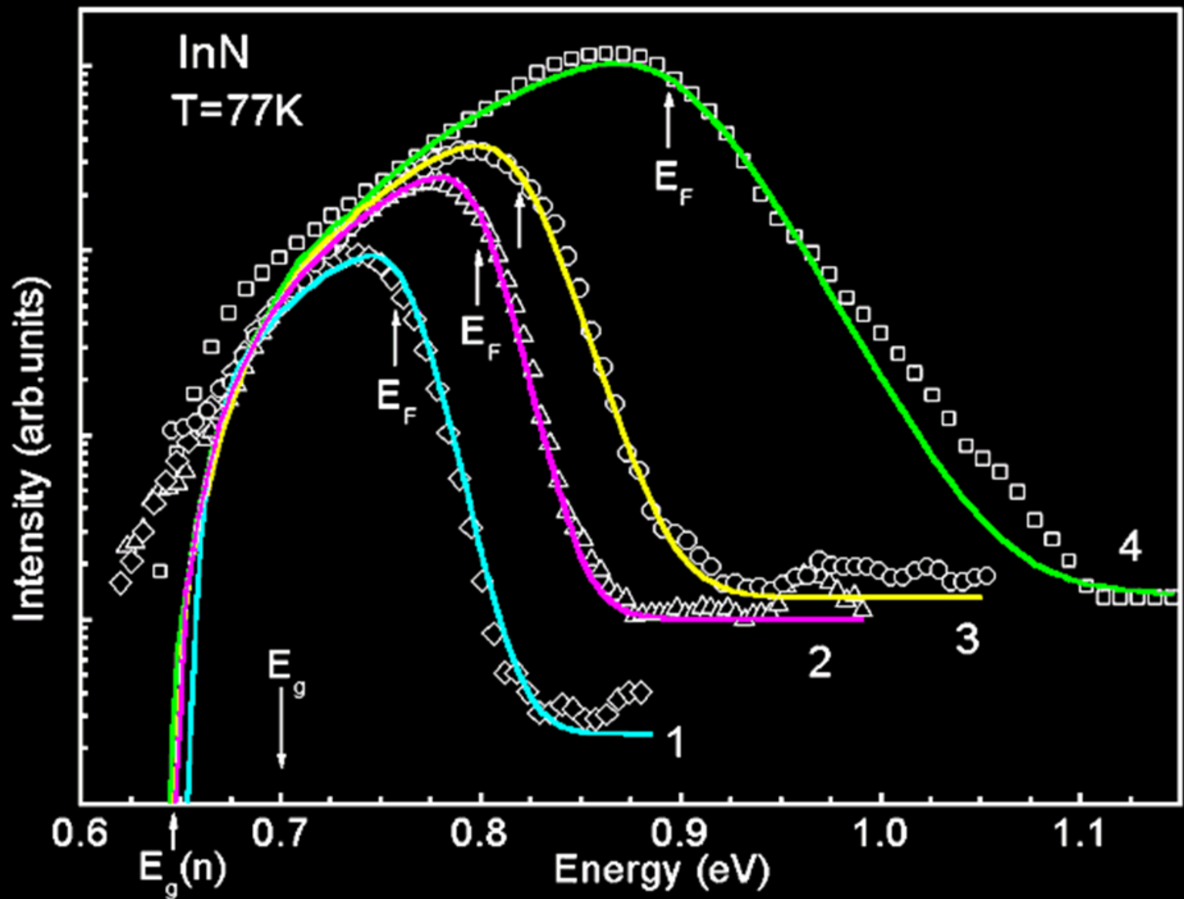


arXiv:1608.02043

Carrier concentration

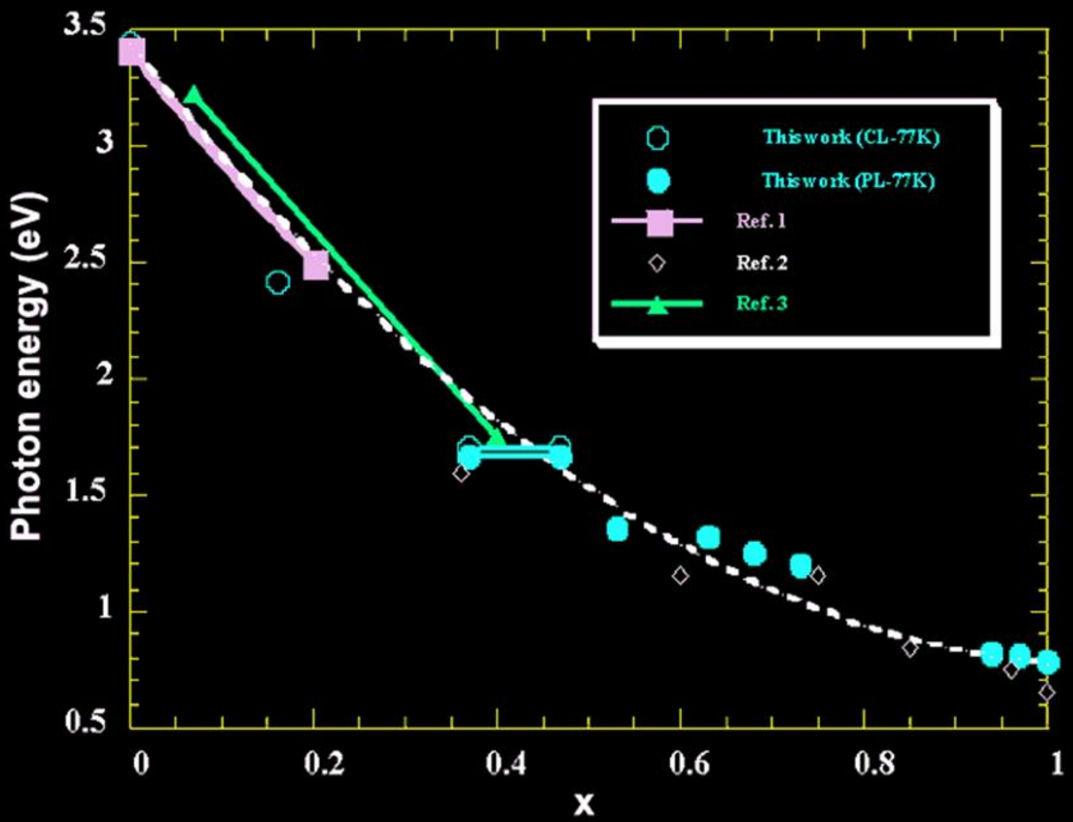
Photoluminescence spectra of InN layers with different carrier concentrations.

1 - n = 6×10^{18} cm^{-3} (MOCVD);
2 - n = 9×10^{18} cm^{-3} (MOMBE);
3 - n = 1.1×10^{19} cm^{-3} (MOMBE);
4 - n = 4.2×10^{19} cm^{-3} (PAMBE).



Phys. Stat. Solidi **(b) 230** (2002**b**), R4

Photoluminescence



Alloy composition

$In_xGa_{1-x}N$ alloys. Luminescence peak positions of catodoluminescence and photoluminescence spectra vs. concentration *x*.

The plots of luminescence peak positions can be fitted to the curve $E_g(x)=3.48 - 2.70x - bx(1-x)$ with a bowing parameter of **b=2.3 eV**

Ref.1 - Wetzel., *Appl. Phys. Lett.* **73,** 73 (1998).

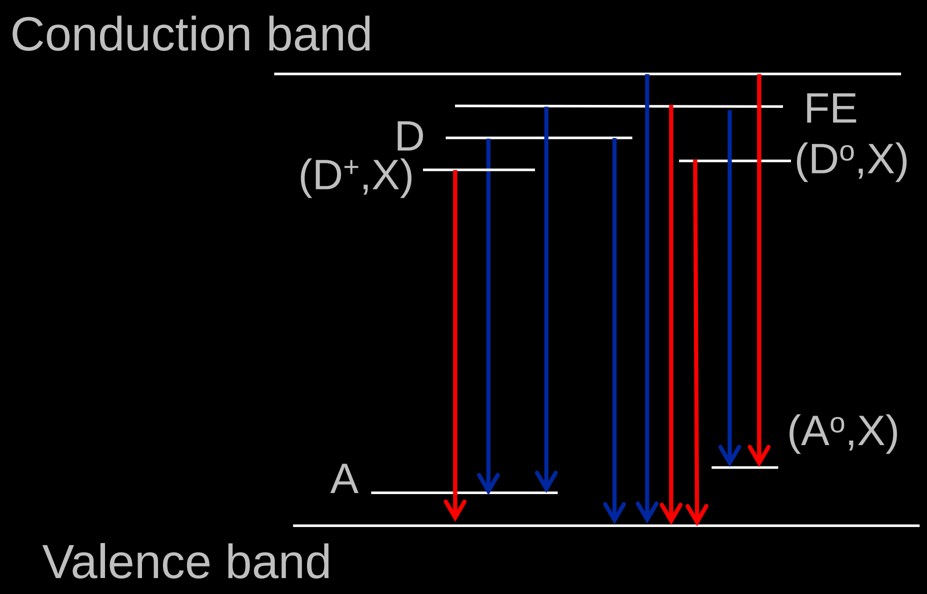
Ref.2 - V. Yu. Davydov., *Phys. Stat. Sol.* **(b) 230,** R4 (2002).

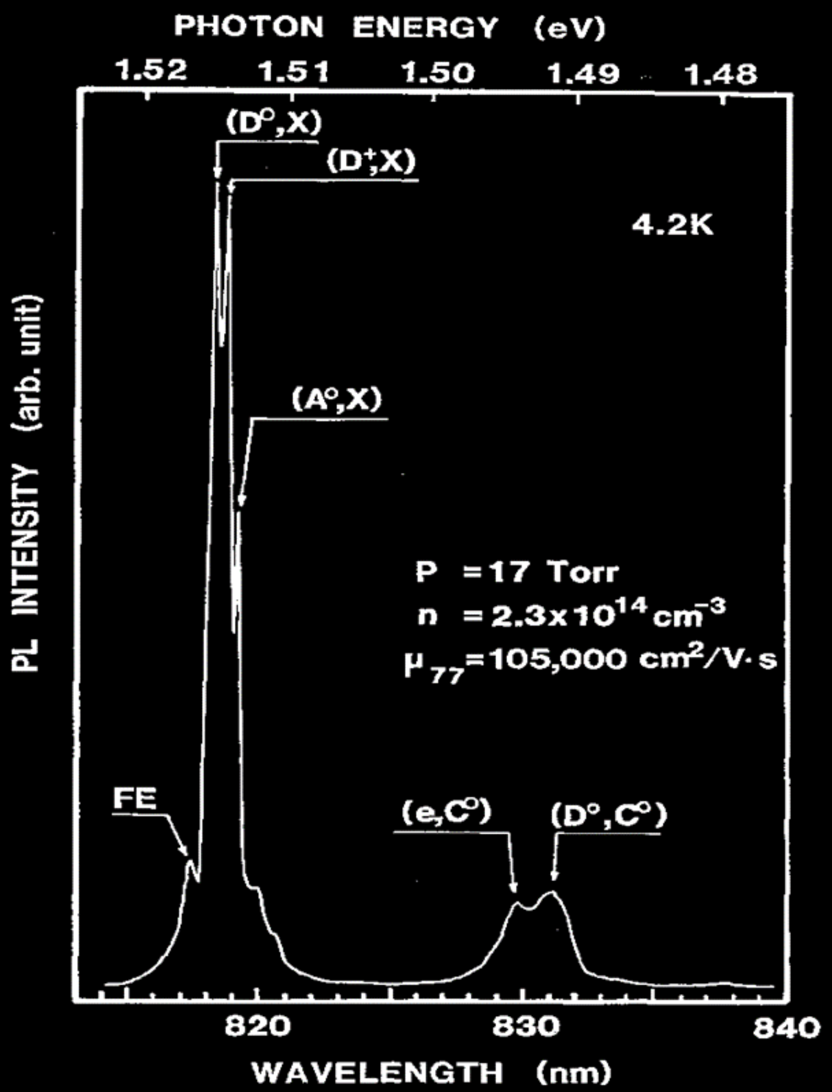
Ref.3 - O'Donnel., *J. Phys .Condens. Matt.* **13,** 1994 (1998).

Phys. Stat. Sol. **(b) 234** (2002) 750

Photoluminescence

Electronic band structure





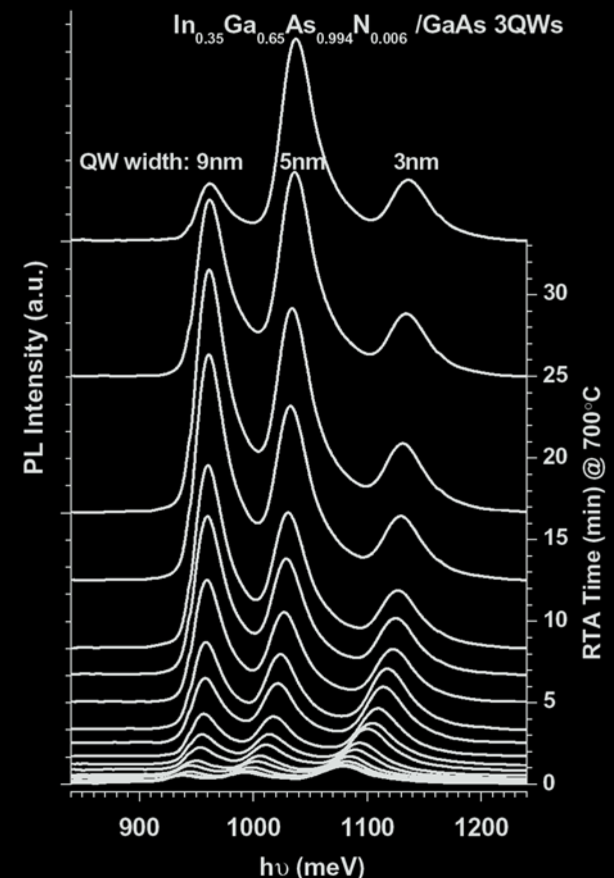
Jap. J. App. Phys. **23**, L100 (1984)

Photoluminescence

Width and quality of semiconductor quantum wells.

3-QWs

100 nm	GaAs	cap
3nm	InGaAsN	QW
35 nm	GaAs	barrier
5nm	InGaAsN	QW
35 nm	GaAs	barrier
9nm	InGaAsN	QW
100 nm	GaAs	buffer
GaAs (001) SUB		



Journal of Crystal Growth 278 (2005) 259–263

Photoluminescence

Strengths:

- Very little to none sample preparation.
- Non destructive technique.
- Very informative spectrum.

Limitations:

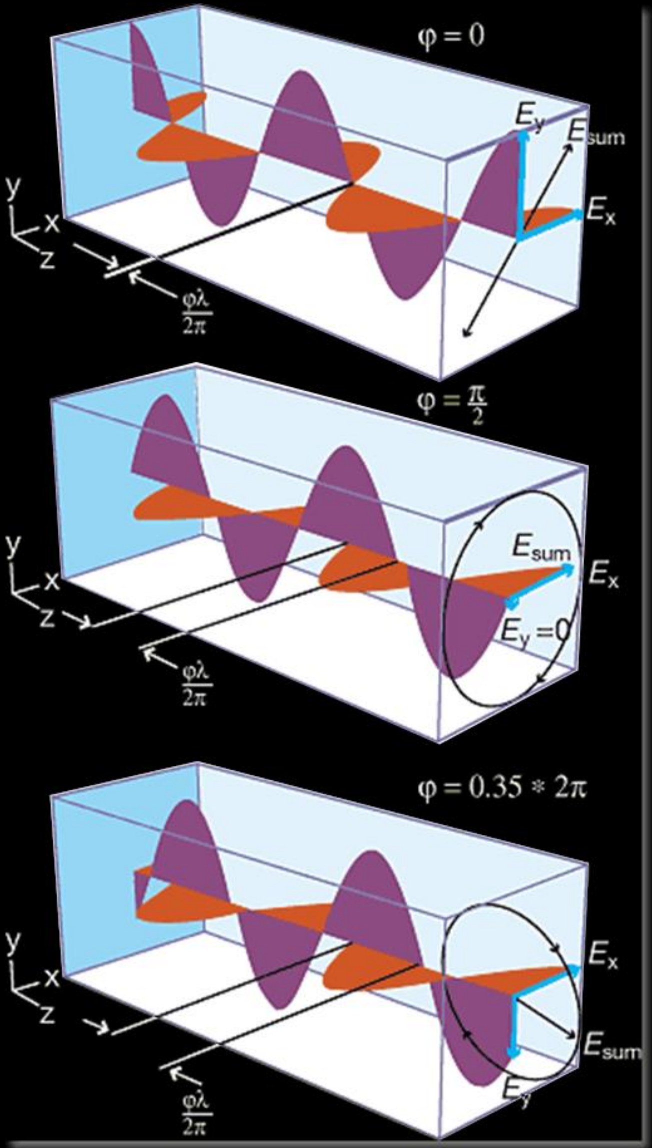
- Often requires low temperature.
- Data analysis may be complex.
- Many materials luminescence weakly.

Complementary techniques:

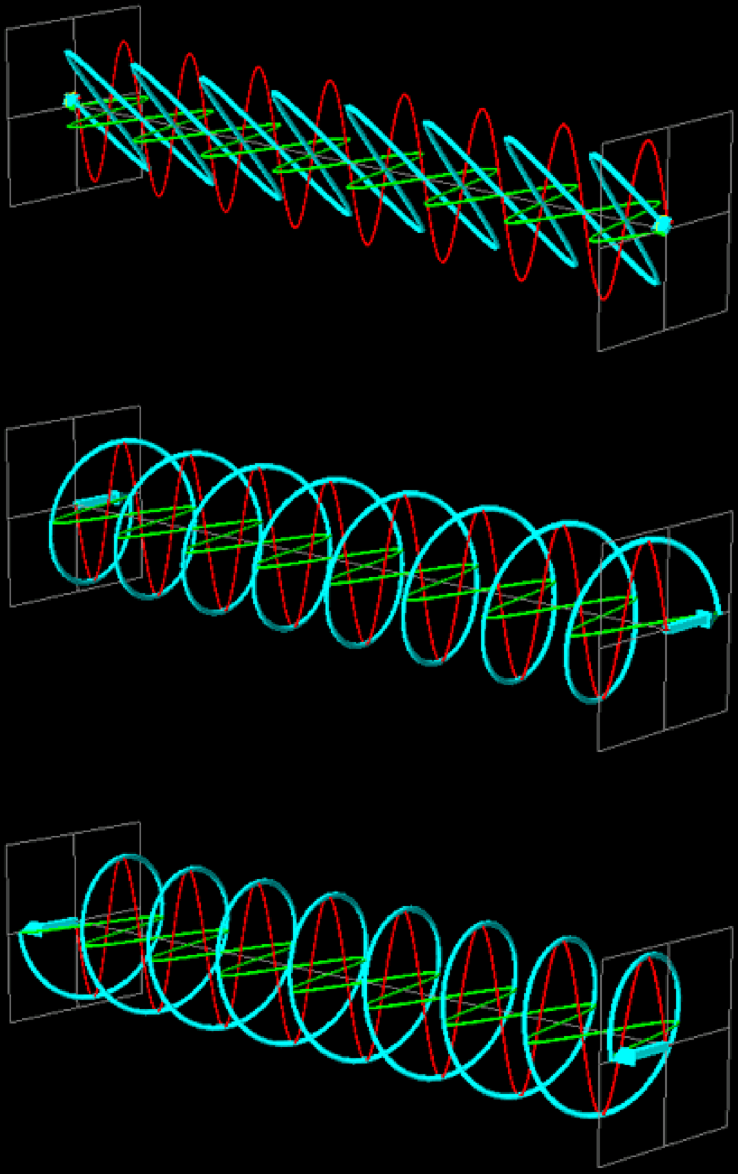
Ellipsometry, Modulation spectroscopies, Spectrophotometry, Raman.

www.glofish.com

Polarization

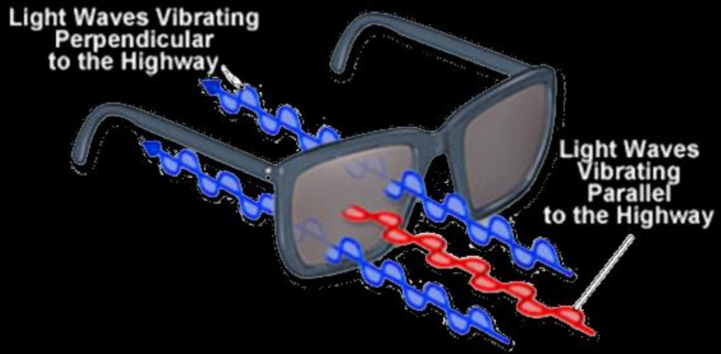


Guimond and Elmore - Oemagazine May 2004

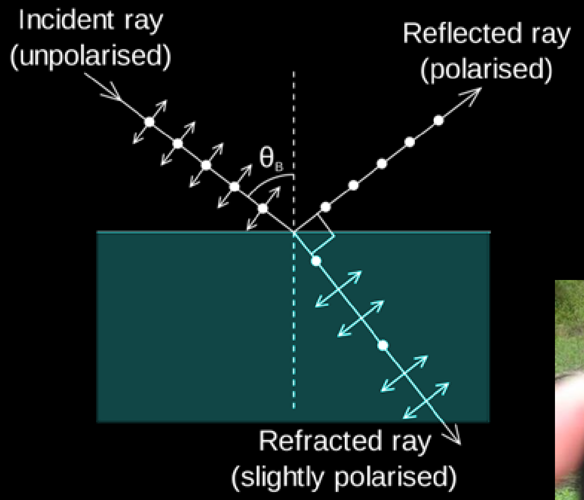


http://www.photophysics.com/

Polarization



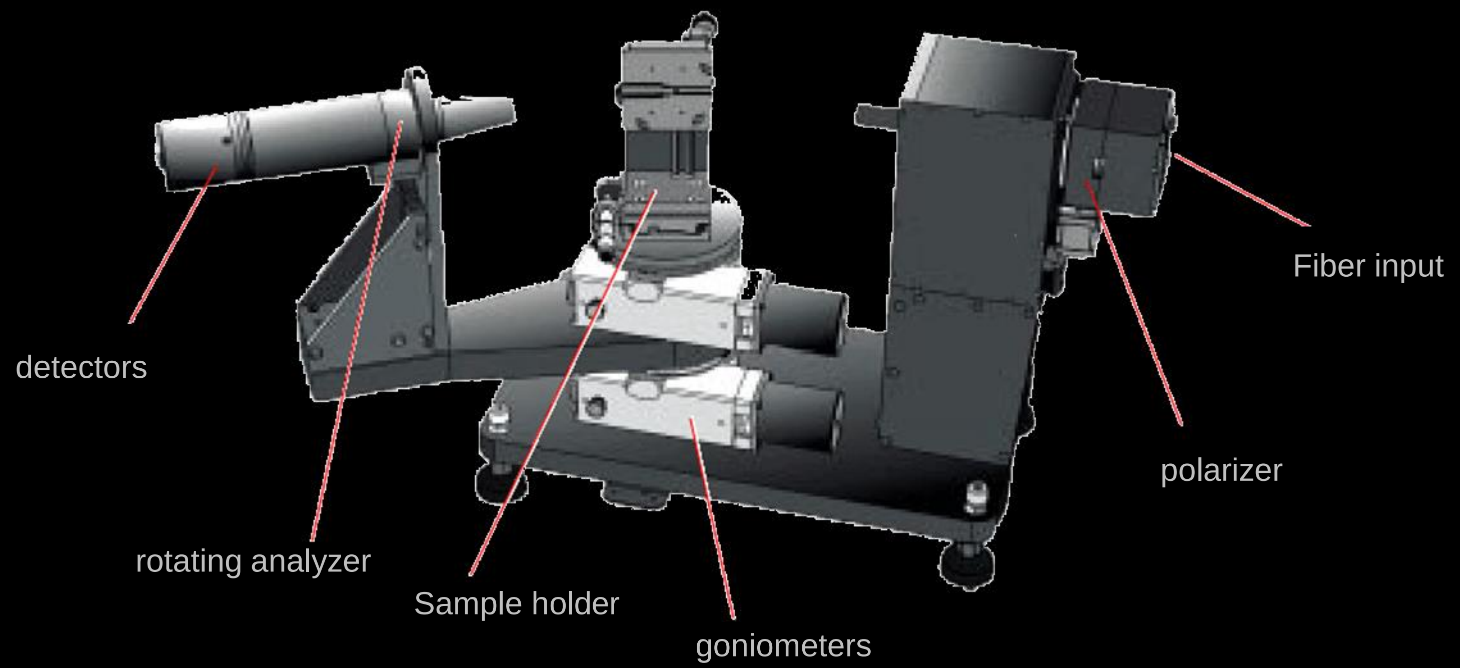
www.bobatkins.com



Ellipsometry

What is measured:

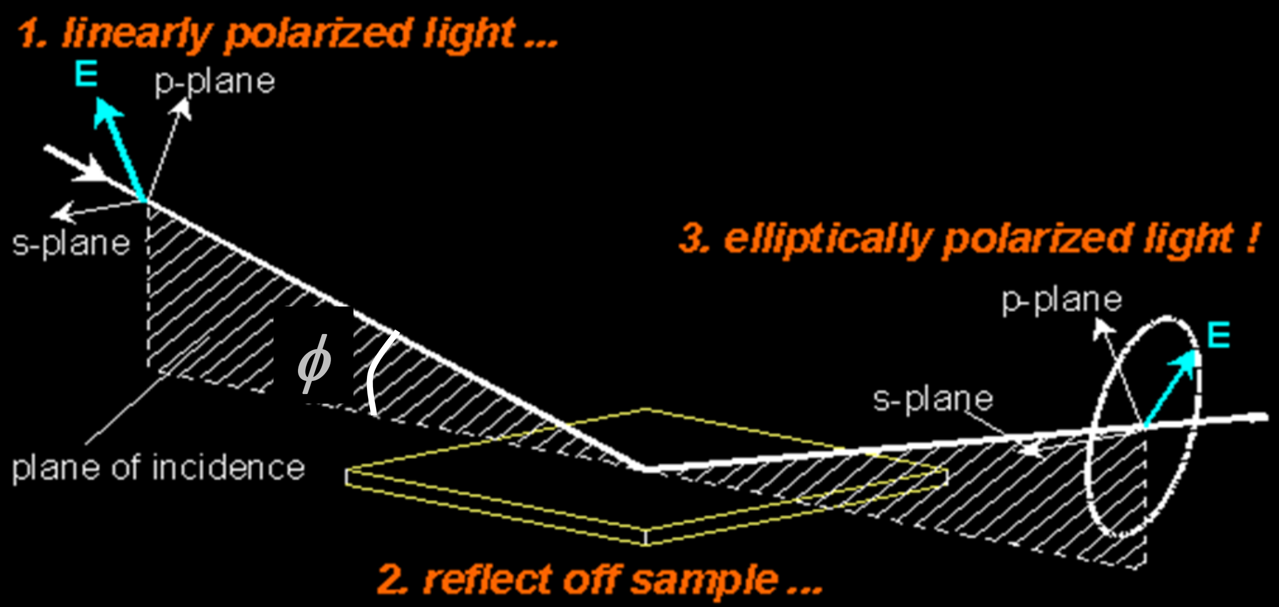
The changes in the polarization state of light upon reflection from a mirror like surface.



Ellipsometry

Basic principle:

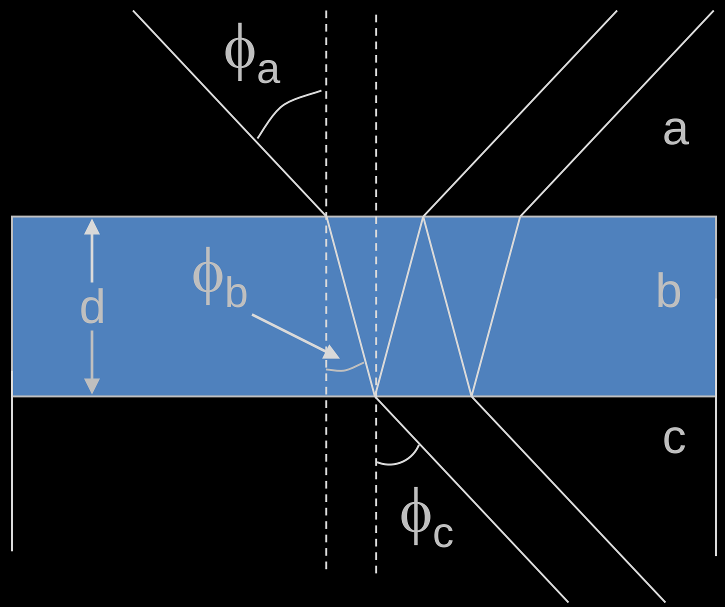
The reflected light emerges from the surface elliptically polarized, i.e. its p and s polarization components are generally different in phase and amplitude.



$$\tan(\Psi)e^{i\Delta} = \frac{\tilde{R}_p}{\tilde{R}_s}$$

J.A. Woollam Co., Inc.

Ellipsometry



$$\tilde{n} = n + ik \qquad \tilde{n}_1 \sin\phi_1 = \tilde{n}_2 \sin\phi_2$$

$$\tilde{r}_{12}^{p,s} = \frac{\tilde{n}_{2,1}\cos\phi_1 - \tilde{n}_{1,2}\cos\phi_2}{\tilde{n}_{2,1}\cos\phi_1 + \tilde{n}_{1,2}\cos\phi_2}$$

$$\tilde{R}_{p,s} = \frac{\tilde{r}_{ab}^{p,s} + \tilde{r}_{bc}^{p,s} e^{-2i\beta}}{1 + \tilde{r}_{ab}^{p,s}\tilde{r}_{bc}^{p,s} e^{-2i\beta}}$$

$$\beta = \frac{2\pi d}{\lambda}\tilde{n}_b \cos\phi_b$$

$$\tilde{R}_{p,s} = \frac{E_{p,s}^r}{E_{p,s}^i} e^{i(\delta_{p,s}^r - \delta_{p,s}^i)}$$

$$\tan(\Psi)e^{i\Delta} = \frac{\tilde{R}_p}{\tilde{R}_s} \Rightarrow \begin{cases} \tan(\Psi) = \dfrac{|\tilde{R}_p|}{|\tilde{R}_s|} \\ \Delta = \delta^r - \delta^i \end{cases}$$

Ellipsometry

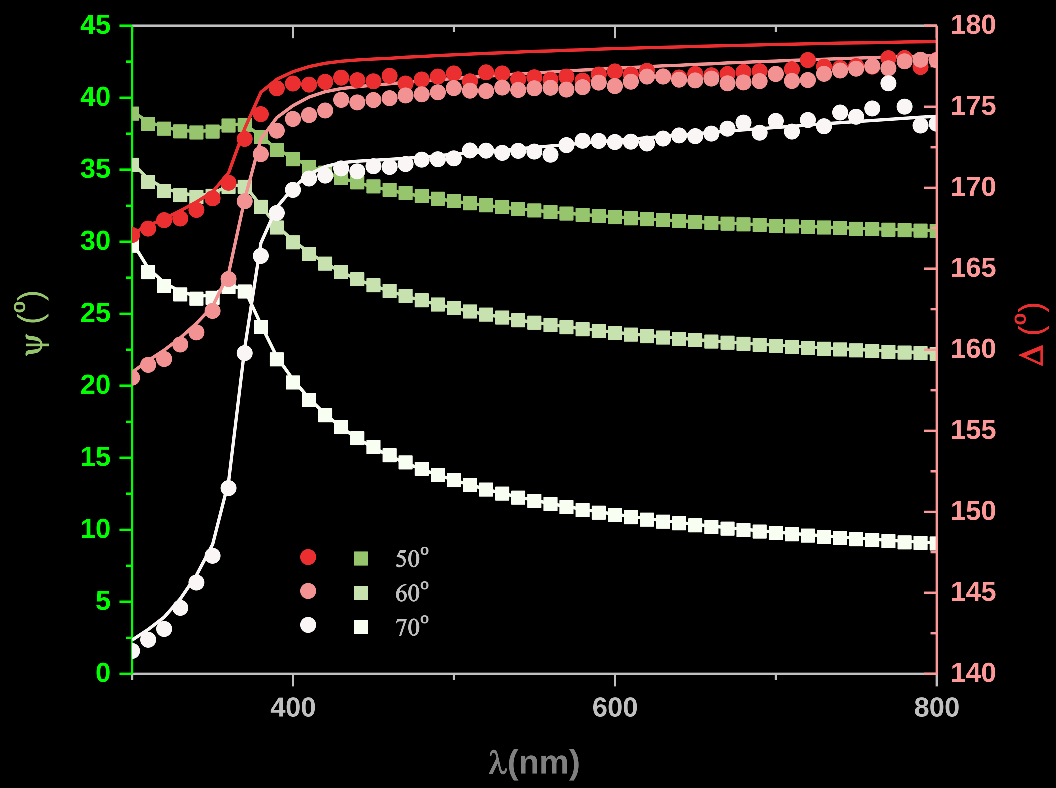
Applications

- Film thickness

SiO_2	21.1 Å
Si	

SiO_2 thickness 21.1 ± 0.5 Å

$\chi^2 = 4.31$



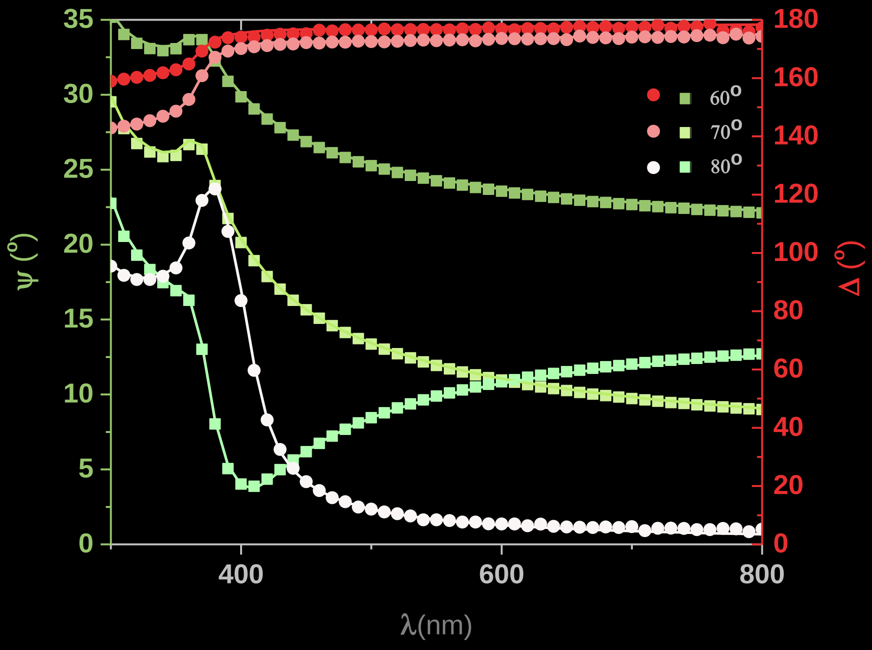
Ellipsometry

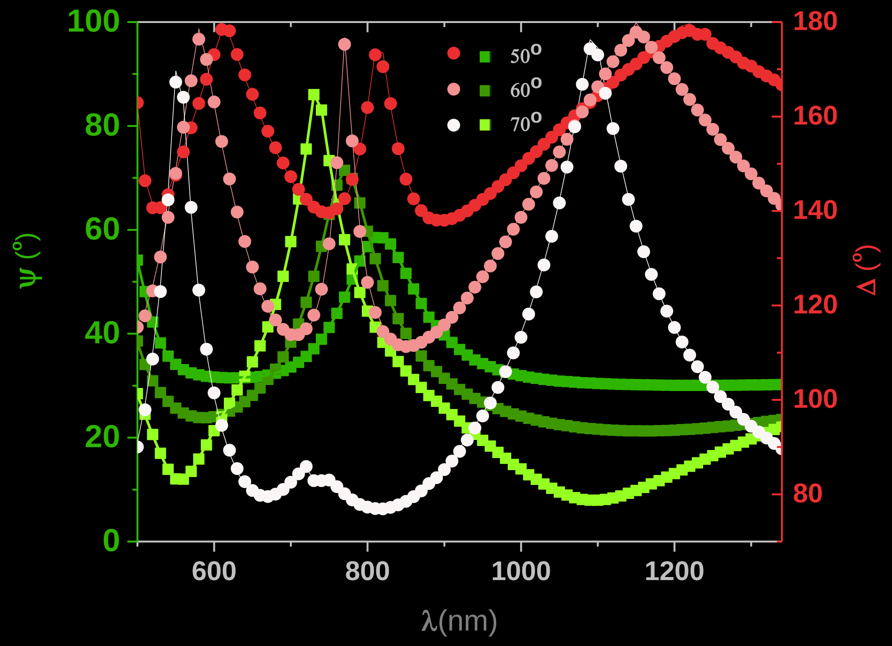
Applications

- Film thickness

SiO_2	18.7 ± 0.2 Å
Si	

SiO_2	4923.1 ± 0.2 Å
Si	

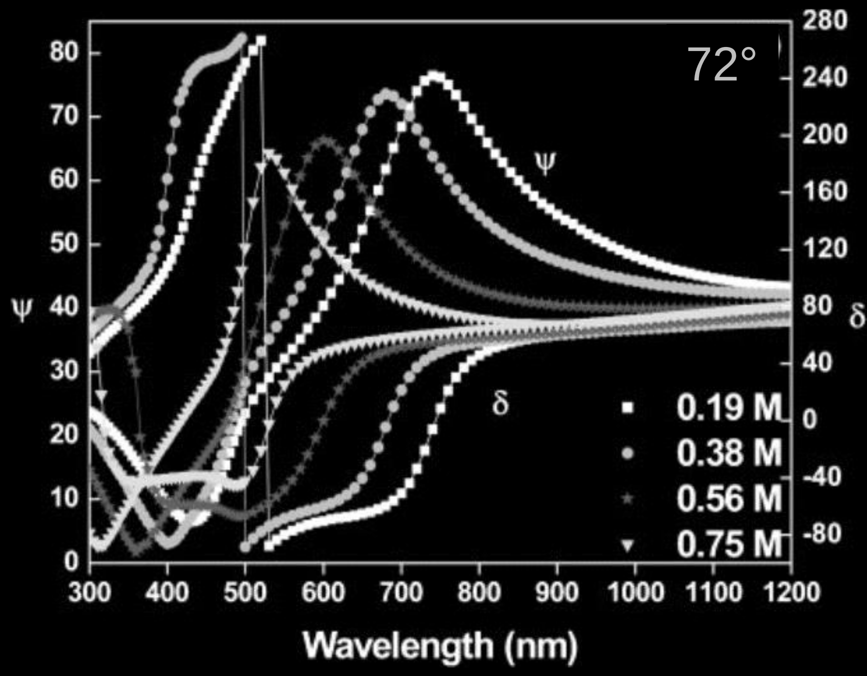




Ellipsometry

Applications

- Composition
- Surface roughness
- Film thickness



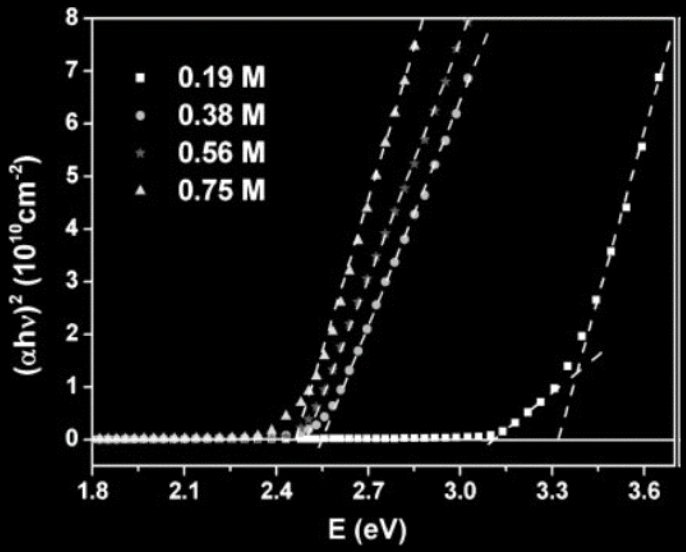
Ellipsometric $\Psi(\lambda)$ and $\Delta(\lambda)$ spectra of $Cd_{1-x}Zn_xS$ thin films deposited under the different concentration of ammonia: 0.19, 0.38, 0.56, and 0.75 M

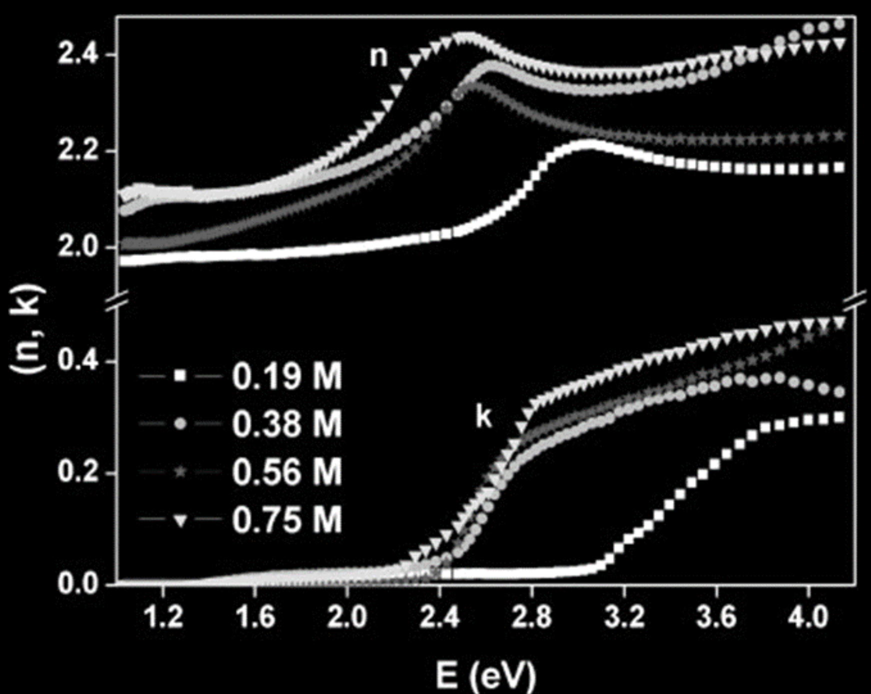
[NH4OH] (M)	Thickness (nm)	Roughness (nm)	ZnS (%)	Band-gap (eV)
0.19	42.12	23.77	99.7	3.49
0.38	73.79	7.15	45.5	2.52
0.56	50.89	5.94	32.3	2.45
0.75	18.59	4.54	5.2	2.43

Jpn. J. Appl. Phys. 49 (2010) 081202

Ellipsometry

Applications

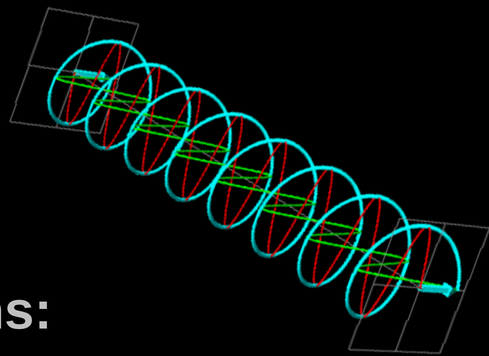




- Composition
- Surface roughness
- Film thickness
- Band gap energy
- Optical constants (dielectric function)

Jpn. J. Appl. Phys. 49 (2010) 081202

Ellipsometry

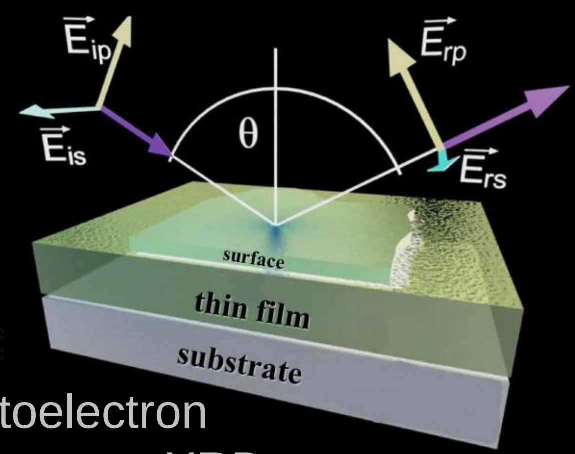


Strengths:

– Fast.
– Measures a ratio of two intensity values and a phase.
  - Highly accurate (even in low light levels).
  - No reference sample necessary.
  - Not susceptible to scatter, lamp or purge fluctuations.
  - Increased sensitivity, especially to ultrathin films (<10nm).
– Can be used in-situ.

Limitations:

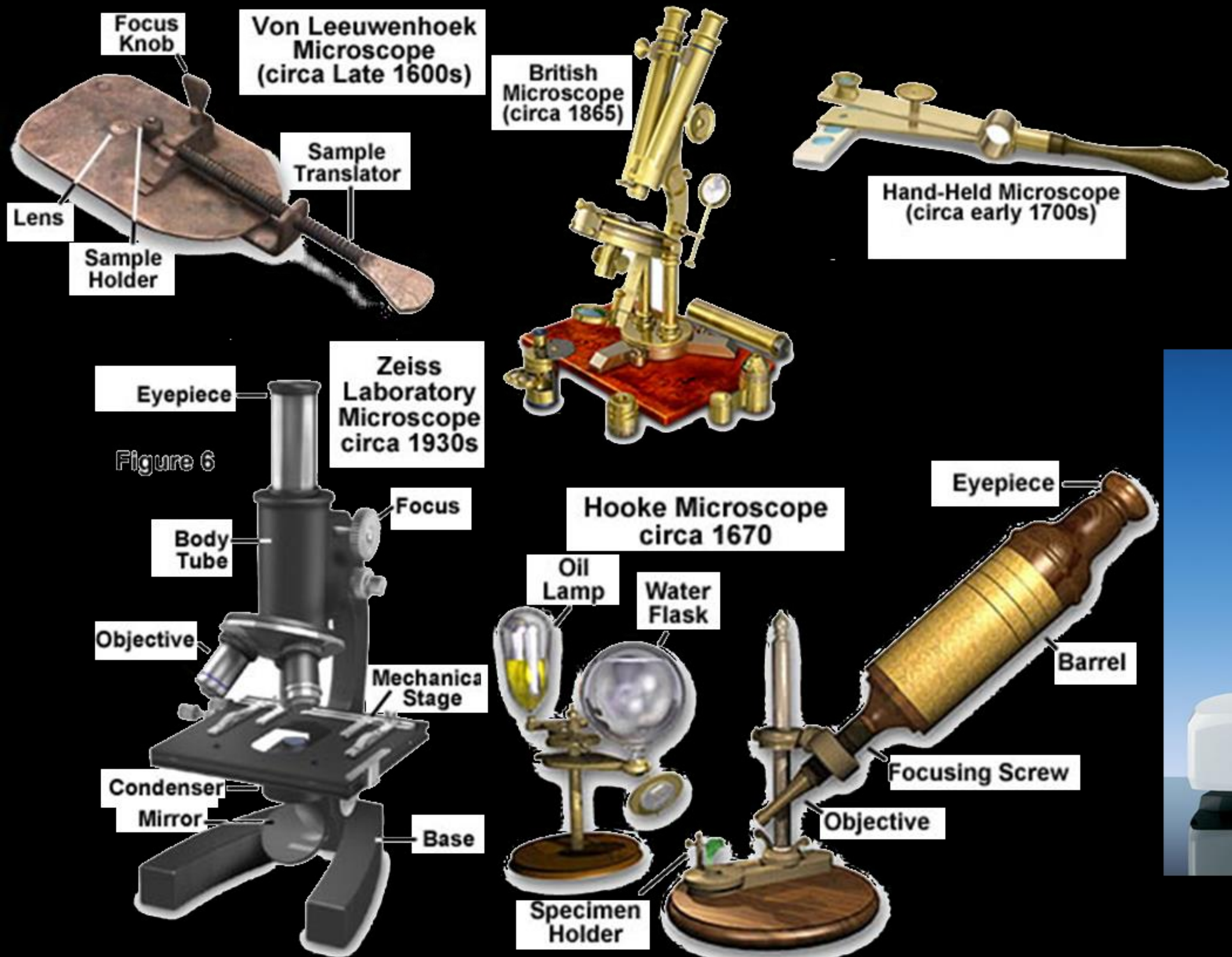
– Flat and parallel surface and interfaces with measurable reflectivity.
– A realistic physical model of the sample is required to obtain most useful information.



Complementary techniques:

PL, Modulation spectroscopies, X-Ray Photoelectron Spectroscopy, Secondary Ion Mass Spectroscopy, XRD, Hall effect.

Optical microscopy



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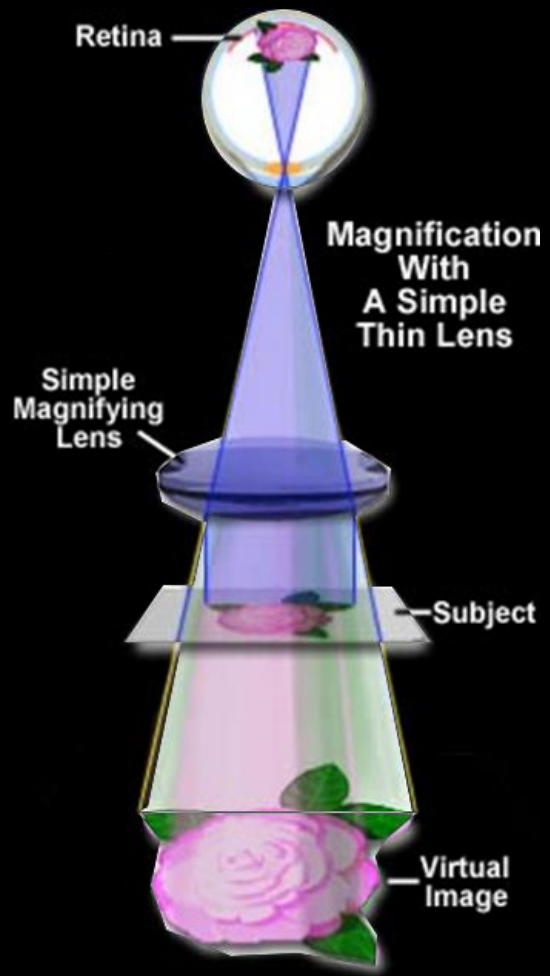
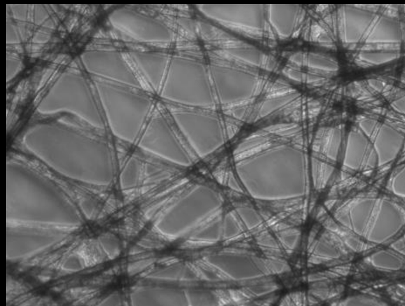
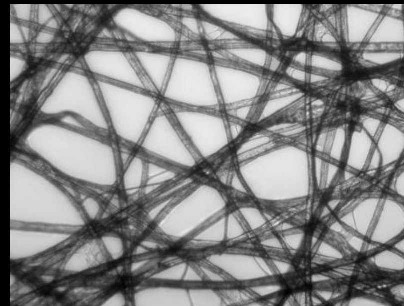
Optical microscopy

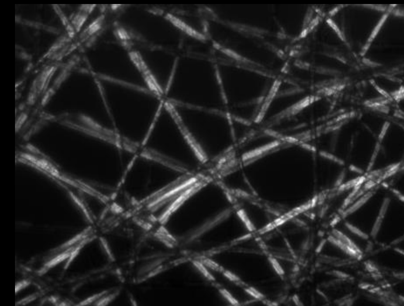
“Conventional" Optical Microscopy

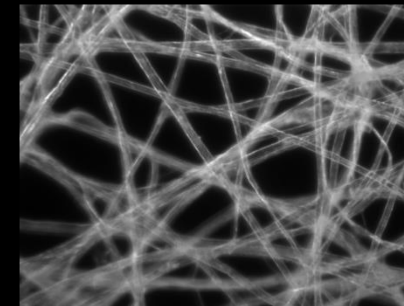


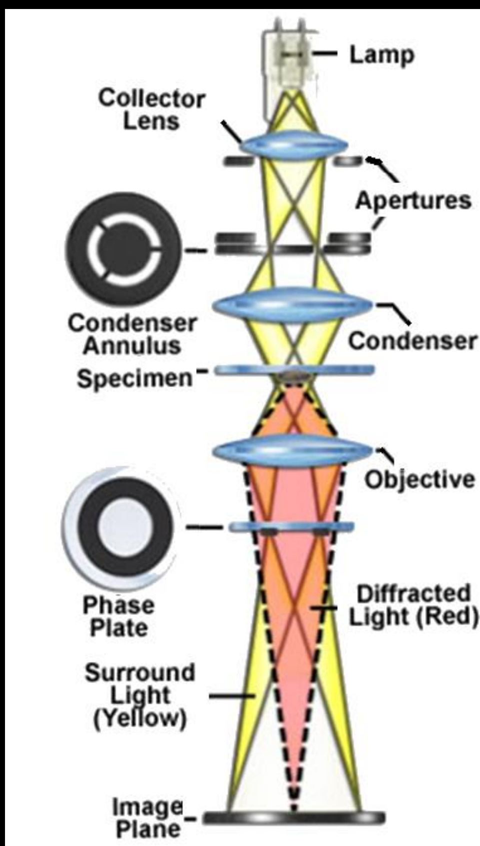
Optical microscopy

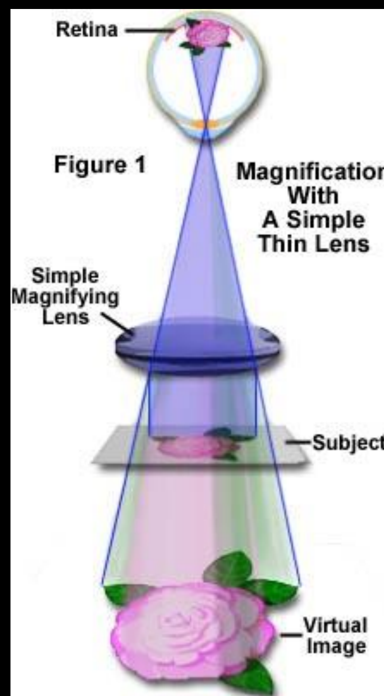


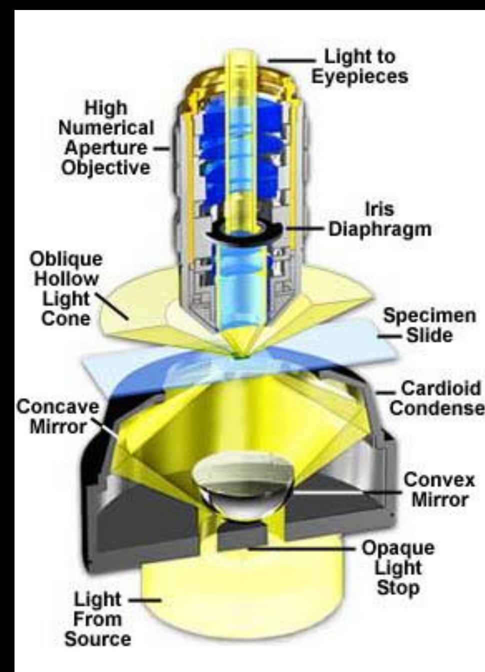


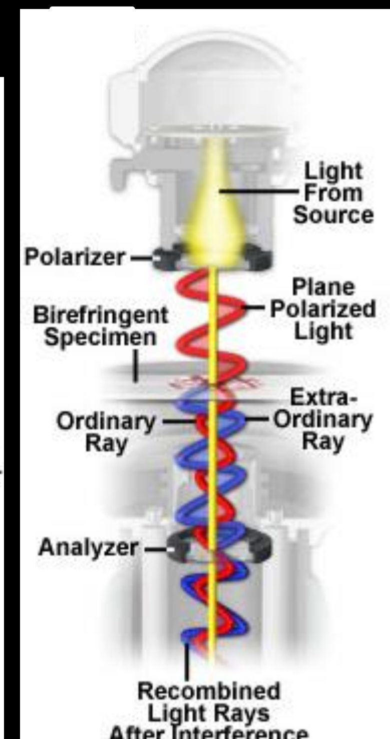












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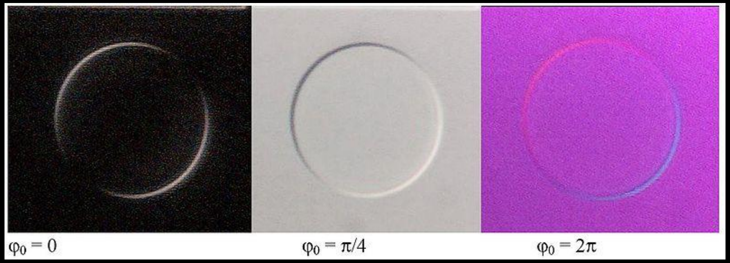
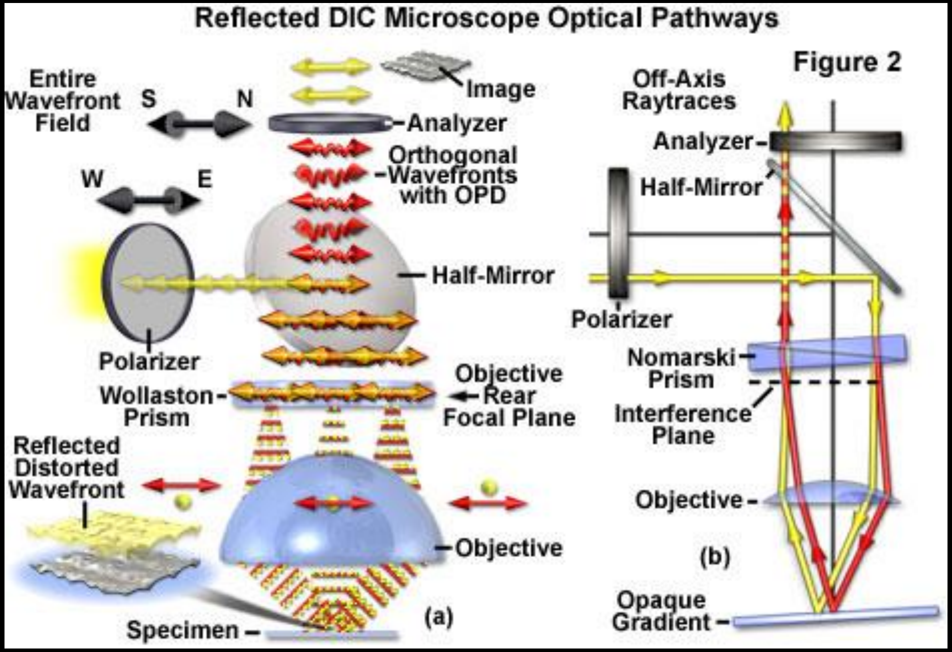
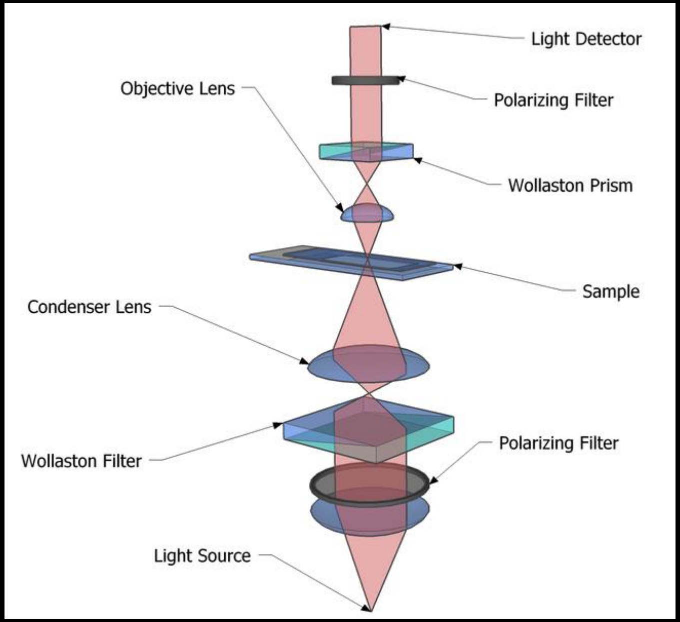
Optical microscopy

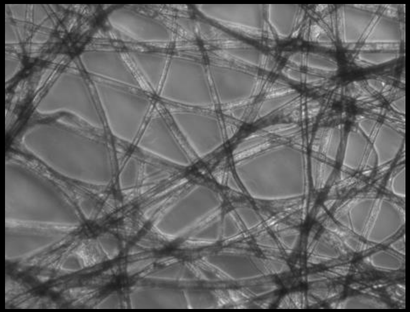




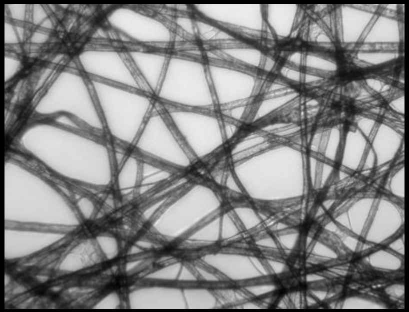


Optical microscopy

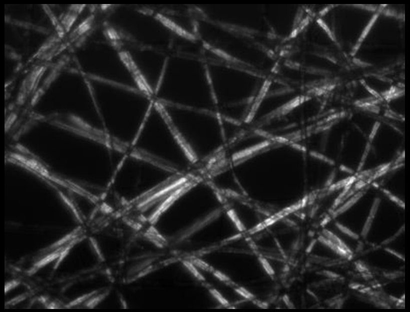
Phase contrast



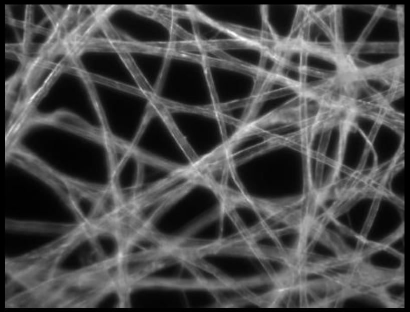
Bright field

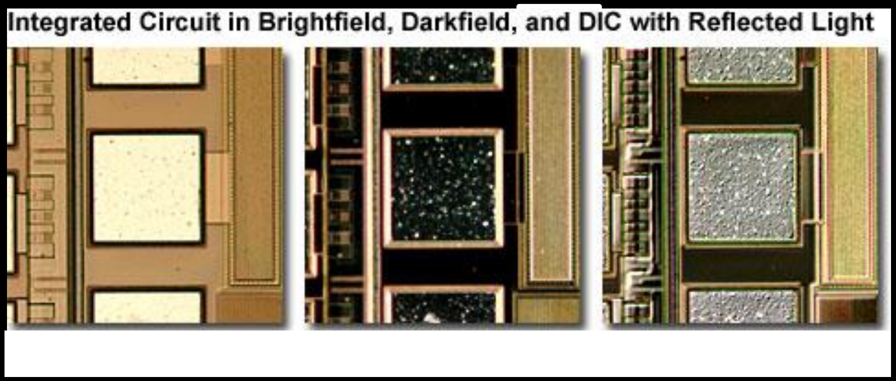


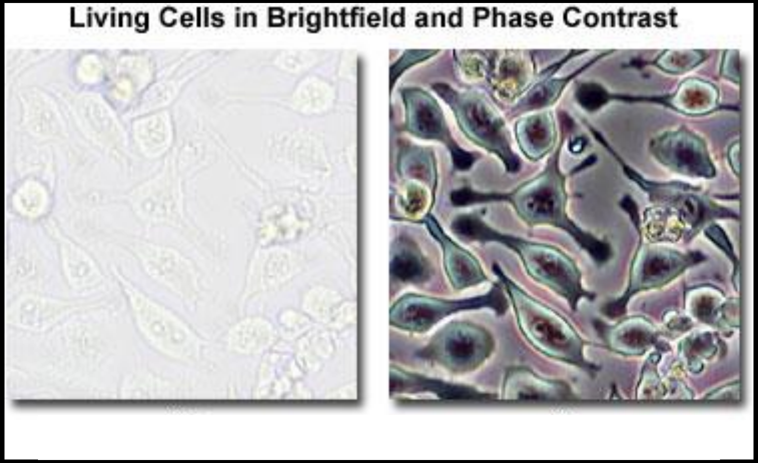
Dark field



Polarizing







Optical microscopy

Contrast-Enhancing Techniques for Optical Microscopy

Specimen Type	**Imaging Technique**
Transmitted Light	
Transparent Specimens **Phase Objects** Bacteria, Spermatozoa, Cells in Glass Containers, Protozoa, Mites, Fibers, etc.	**Phase Contrast** **Differential Interference Contrast (DIC)** **Hoffman Modulation Contrast** **Oblique Illumination**
Light Scattering Objects Diatoms, Fibers, Hairs, Fresh Water Microorganisms, Radiolarians, etc.	**Rheinberg Illumination** **Darkfield Illumination** **Phase Contrast and DIC**
Light Refracting Specimens Colloidal Suspensions powders and minerals Liquids	**Phase Contrast** **Dispersion Staining** **DIC**
Amplitude Specimens Stained Tissue Naturally Colored Specimens Hair and Fibers Insects and Marine Algae	**Brightfield Illumination**
Fluorescent Specimens Cells in Tissue Culture Fluorochrome-Stained Sections Smears and Spreads	**Fluorescence Illumination**
Birefringent Specimens Mineral Thin Sections Liquid Crystals Melted and Recrystallized Chemicals Hairs and Fibers Bones and Feathers	**Polarized Illumination**

http://micro.magnet.fsu.edu

MOLECULAR EXPRESSIONS™ Optical Microscopy Primer Specialized Techniques

Contrast-Enhancing Techniques for Optical Microscopy

Specimen Type	Imaging Technique
Reflected Light	
Specular (Reflecting) Surface Thin Films, Mirrors Polished Metallurgical Samples Integrated Circuits	**Brightfield Illumination** **Phase Contrast, DIC** **Darkfield Illumination**
Diffuse (Non-Reflecting) Surface Thin and Thick Films Rocks and Minerals Hairs, Fibers, and Bone Insects	**Brightfield Illumination** **Phase Contrast, DIC** **Darkfield Illumination**
Amplitude Surface Features Dyed Fibers Diffuse Metallic Specimens Composite Materials Polymers	**Brightfield Illumination** **Darkfield Illumination**
Birefringent Specimens Mineral Thin Sections Hairs and Fibers Bones and Feathers Single Crystals Oriented Films	**Polarized Illumination**
Fluorescent Specimens Mounted Cells Fluorochrome-Stained Sections Smears and Spreads	**Fluorescence Illumination**

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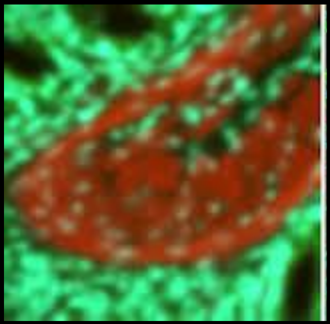
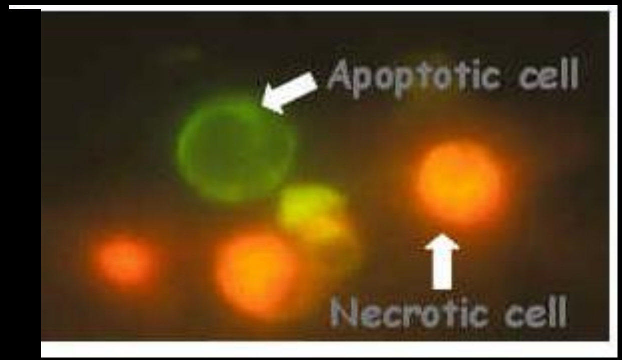
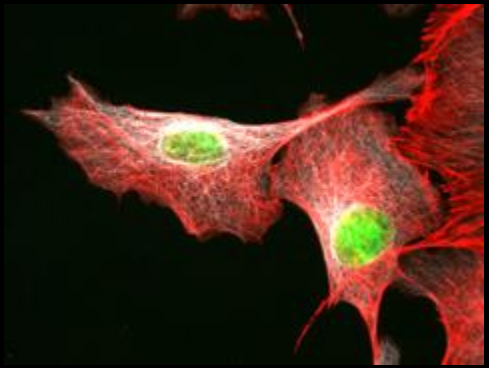
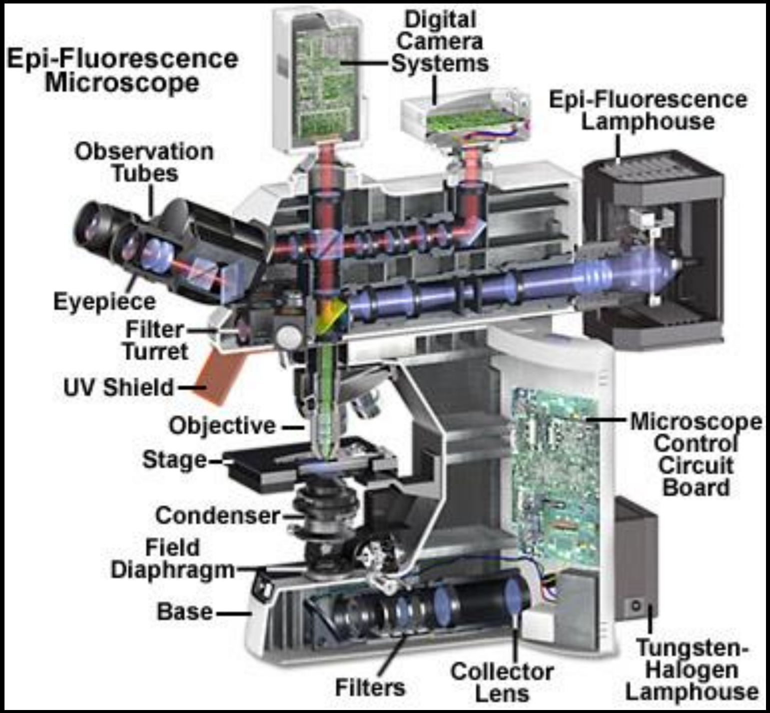
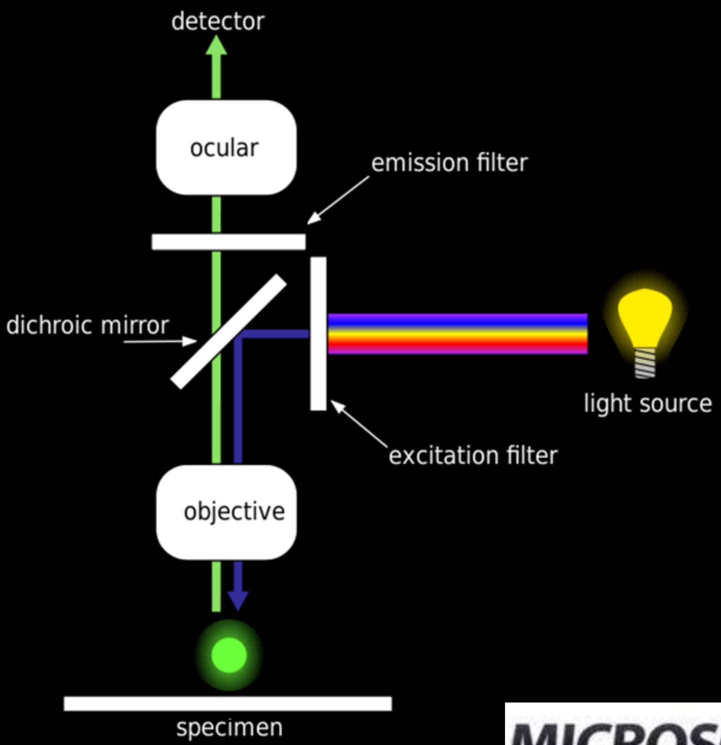
Optical microscopy











MICROSCOPYU
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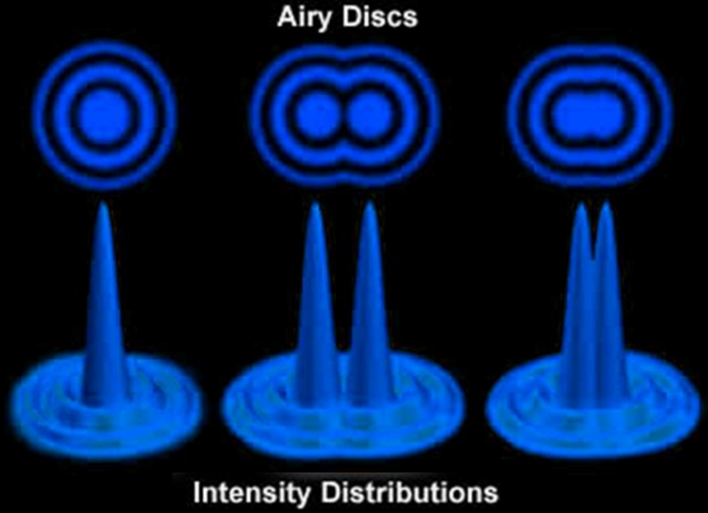
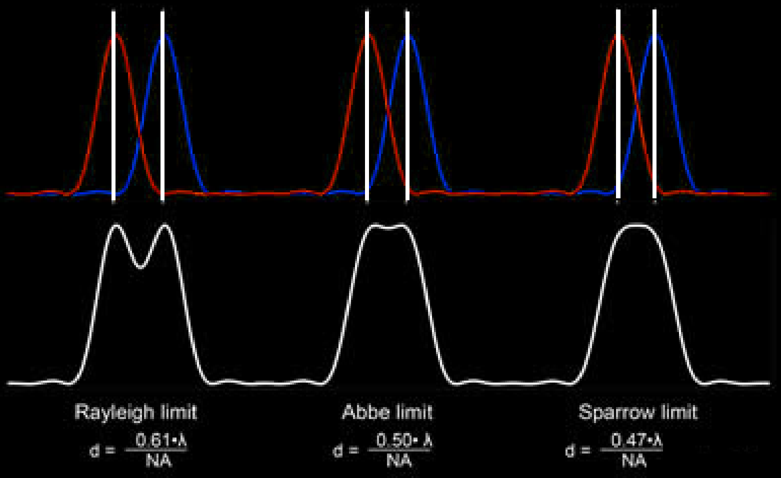
Optical microscopy

Resolution

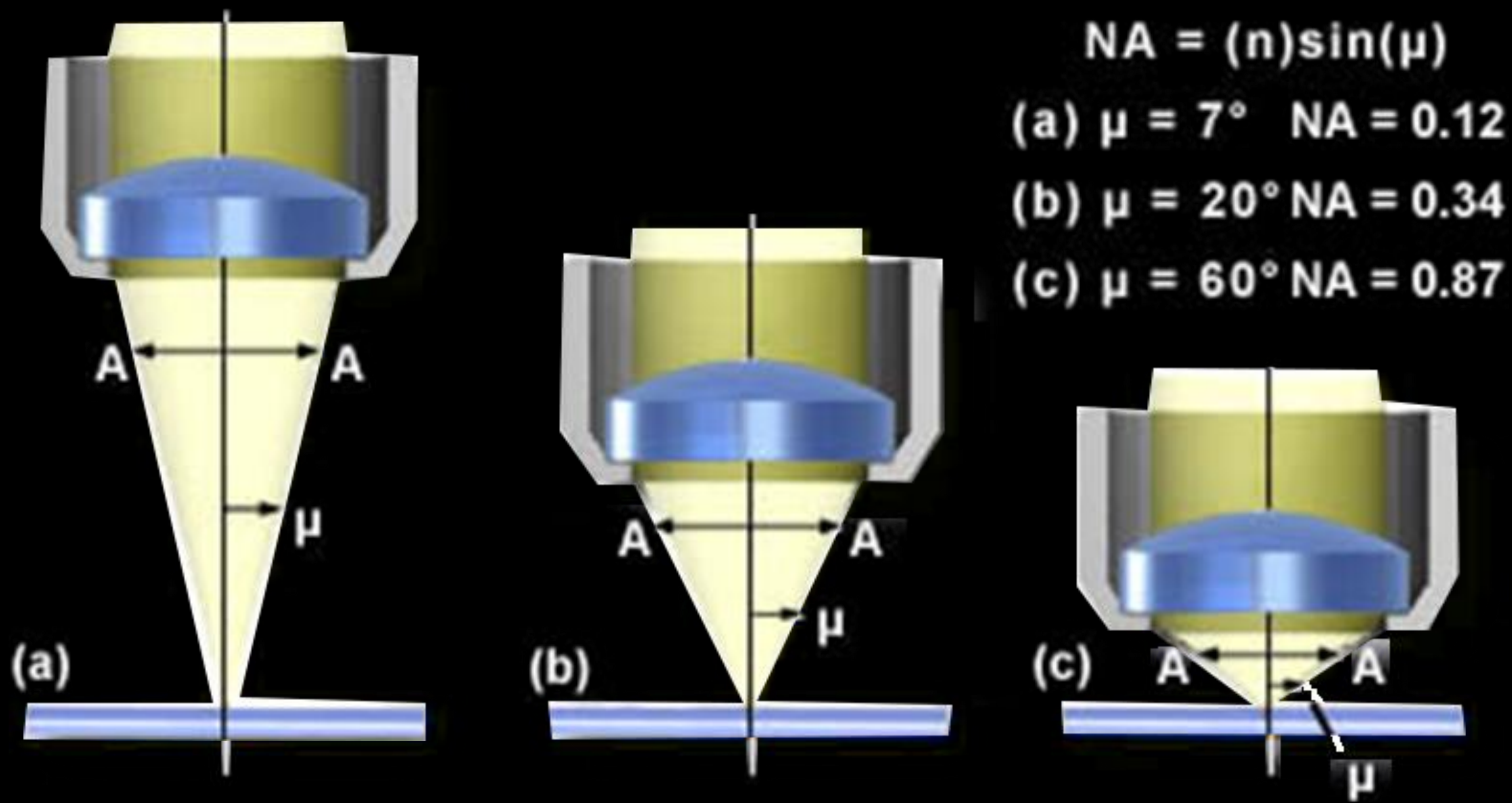




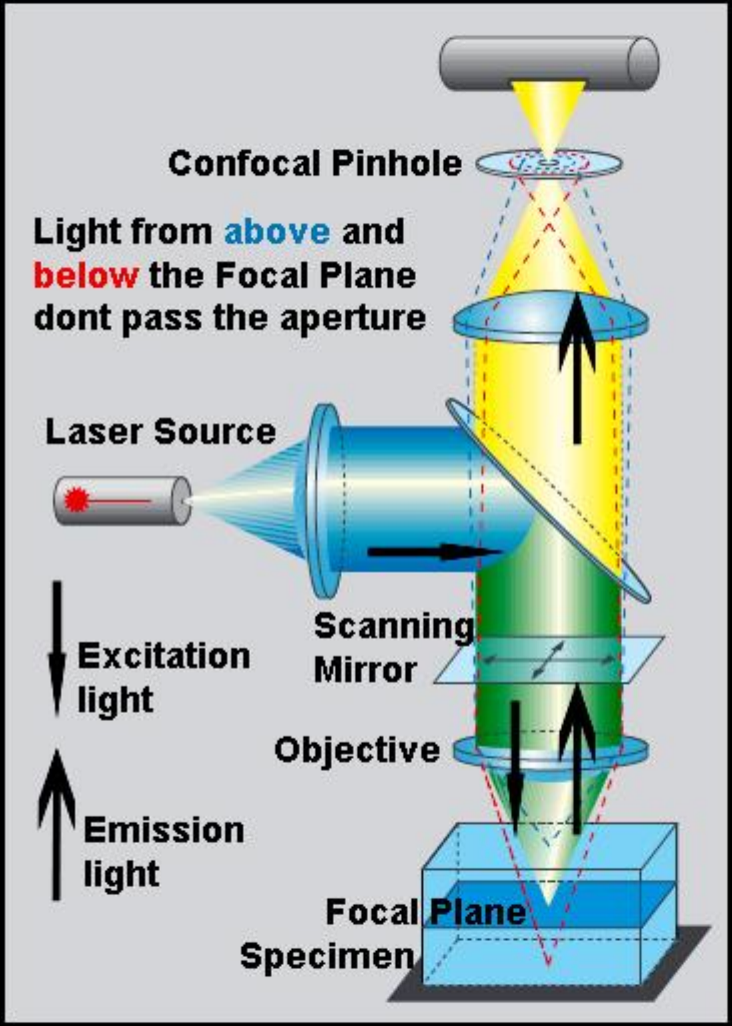
$$d \approx \frac{0.61\lambda}{NA}$$ Rayleigh criterion

$$d \approx \frac{\lambda}{NA_{col} + NA_{obj}} \approx \frac{\lambda}{2\ NA}$$ Abbé criterion

Optical microscopy



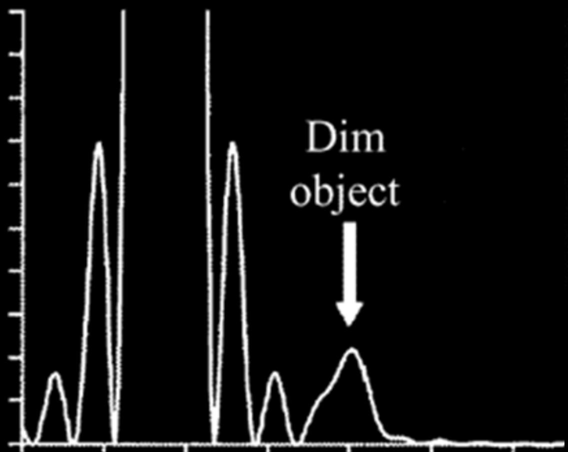
Confocal microscopy

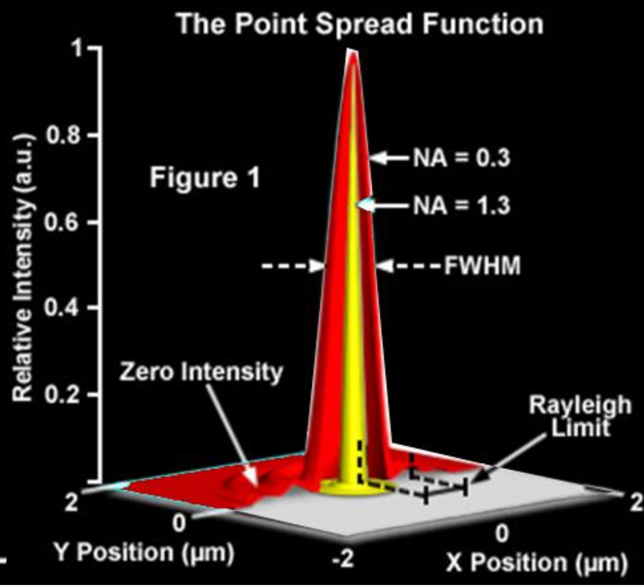


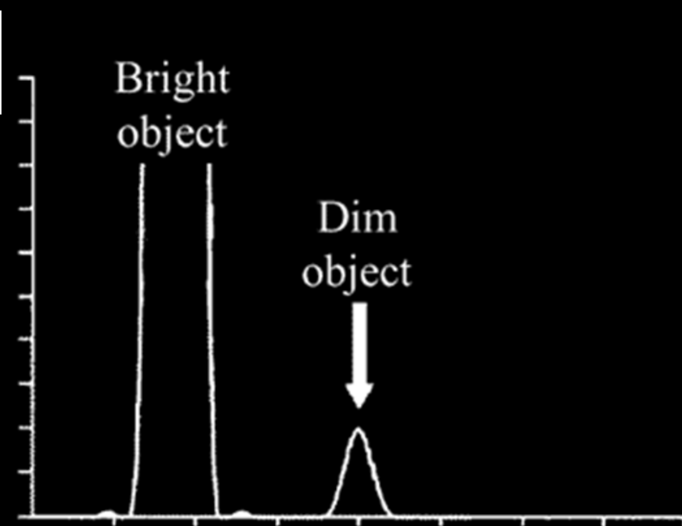
- Increased contrast => 200:1.
- Slightly increased in plane resolution (1.5 x)
- Significantly increased resolution along the optical axis.
- Scanning image formation.

Confocal microscopy

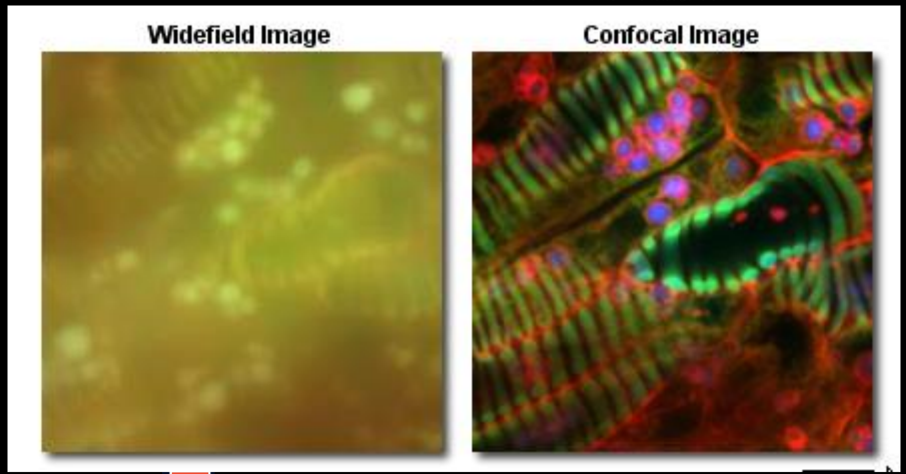
The relation of the first ring maximum amplitude to the amplitude in the center is 2% in case of conventional point spreading function (PSF) in a focal plane, while in case of a confocal microscope this relation is 0.04%.





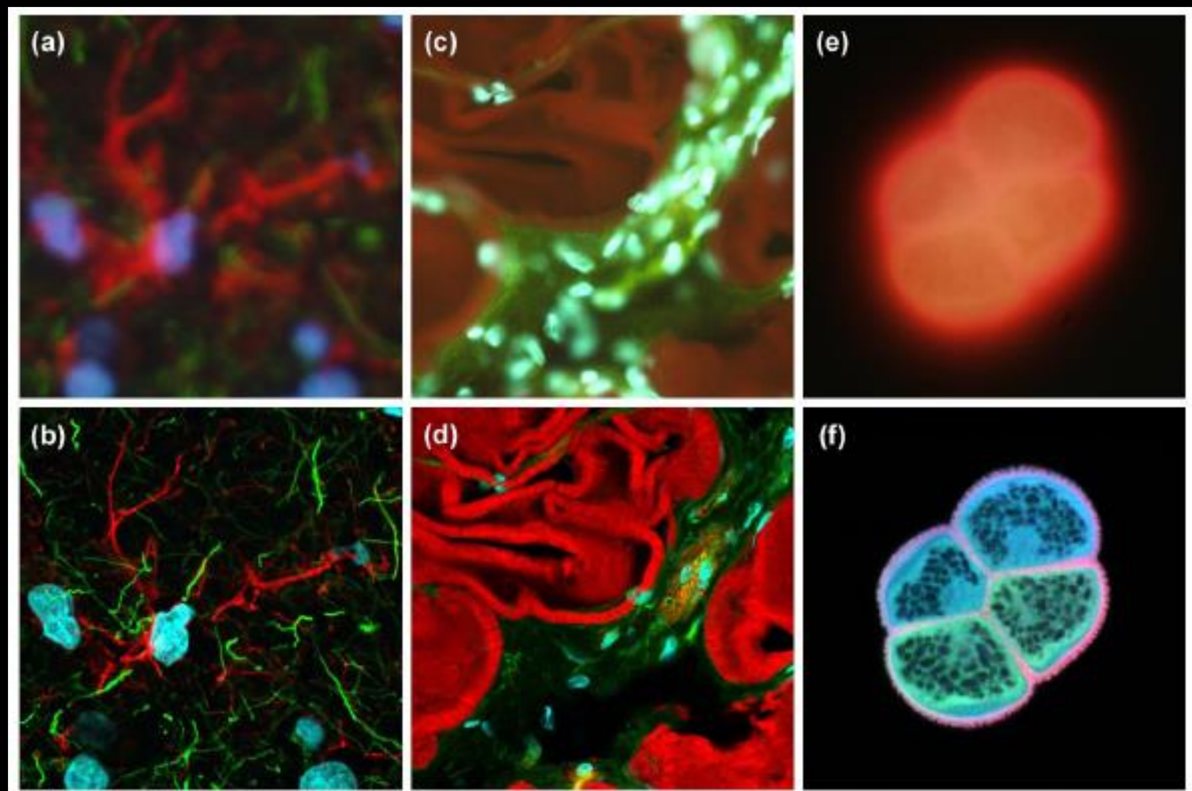


$$r_{resel} = 0.61\frac{\lambda}{n \sin\theta} = 1.22\frac{\lambda'}{D}F$$



$$r_{conf} = 0.44\frac{\lambda}{n \sin\theta} = 0.88\frac{\lambda'}{D}F$$

Confocal microscopy

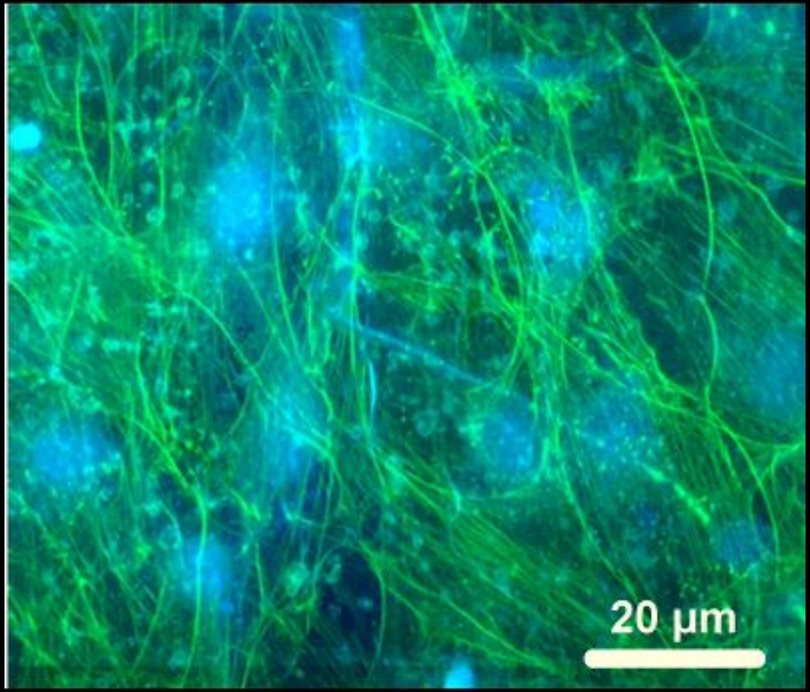


LASER SCANNING CONFOCAL MICROSCOPY

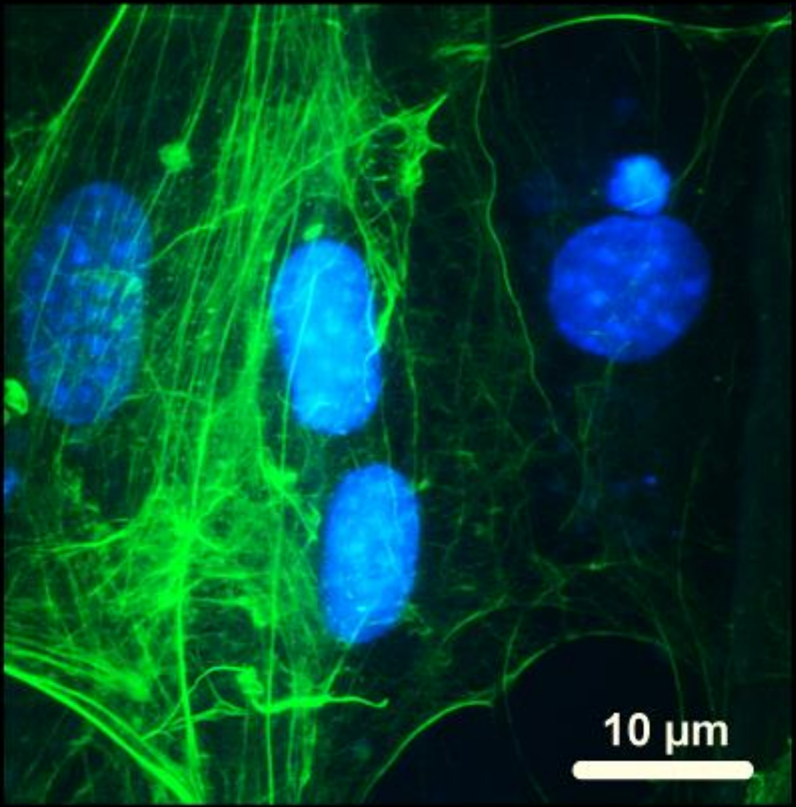
Nathan S. Claxton, Thomas J. Fellers, and Michael W. Davidson

Department of Optical Microscopy and Digital Imaging, National High Magnetic Field Laboratory,
The Florida State University, Tallahassee, Florida 32310

Confocal microscopy



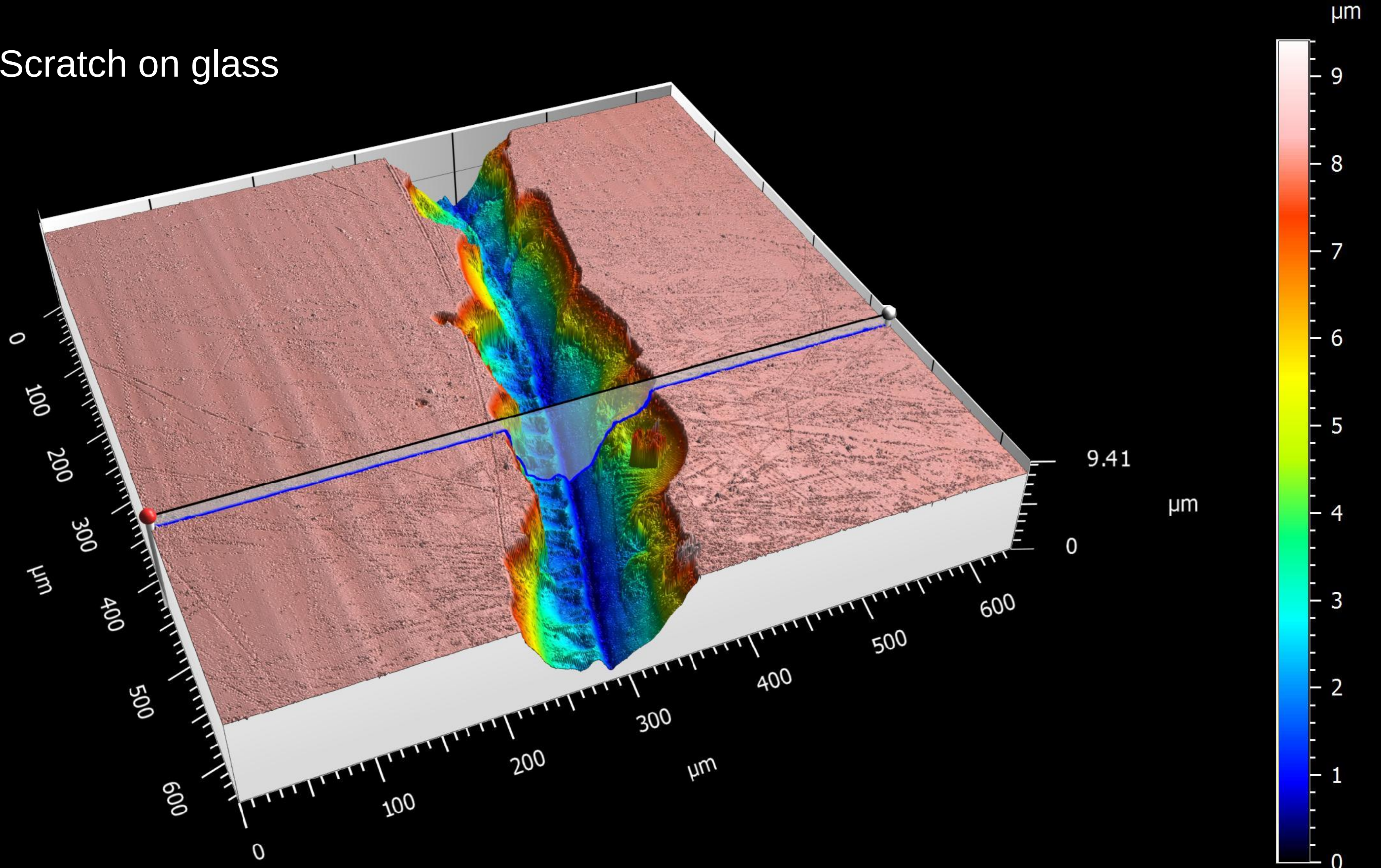
<fibroblasts network on epoxy> *data/image courtesy of Joselle McCracken, Nuzzo Group*



<cells bridge the gap> *data/image courtesy of Joselle McCracken, Nuzzo Group*

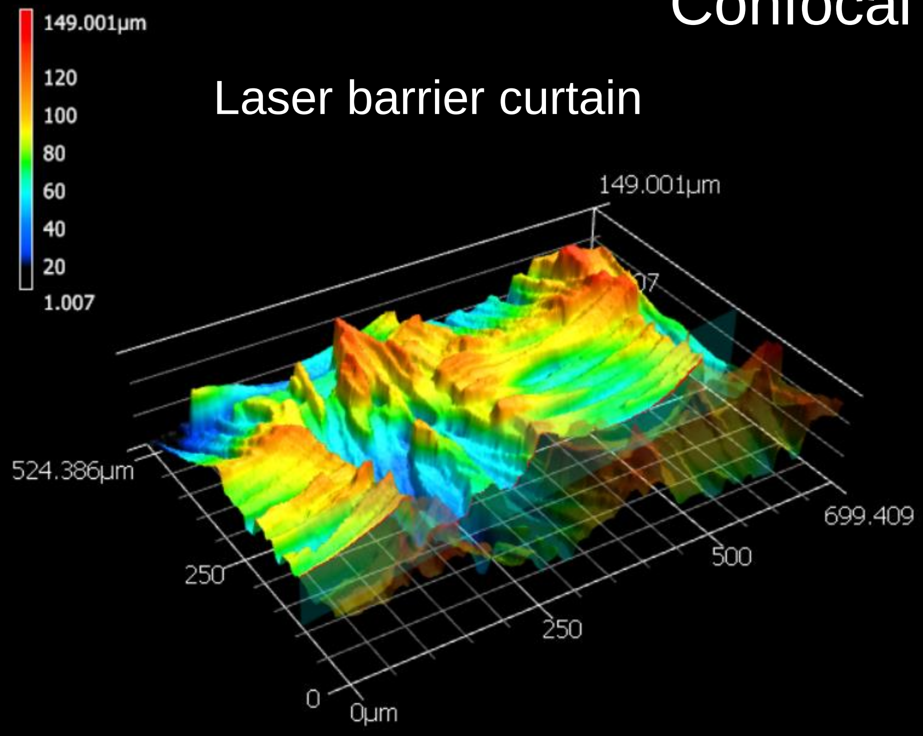
Confocal microscopy

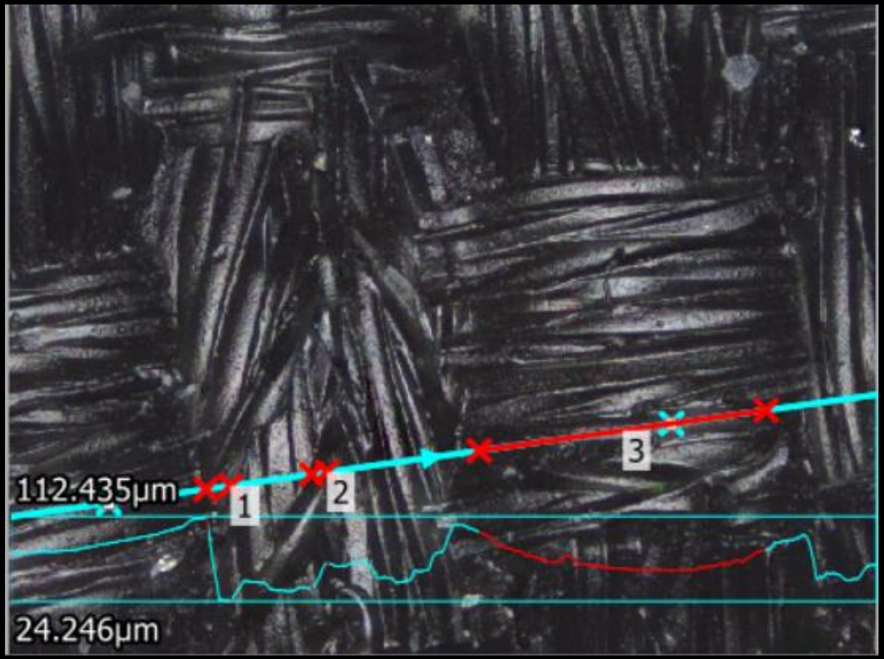
Scratch on glass

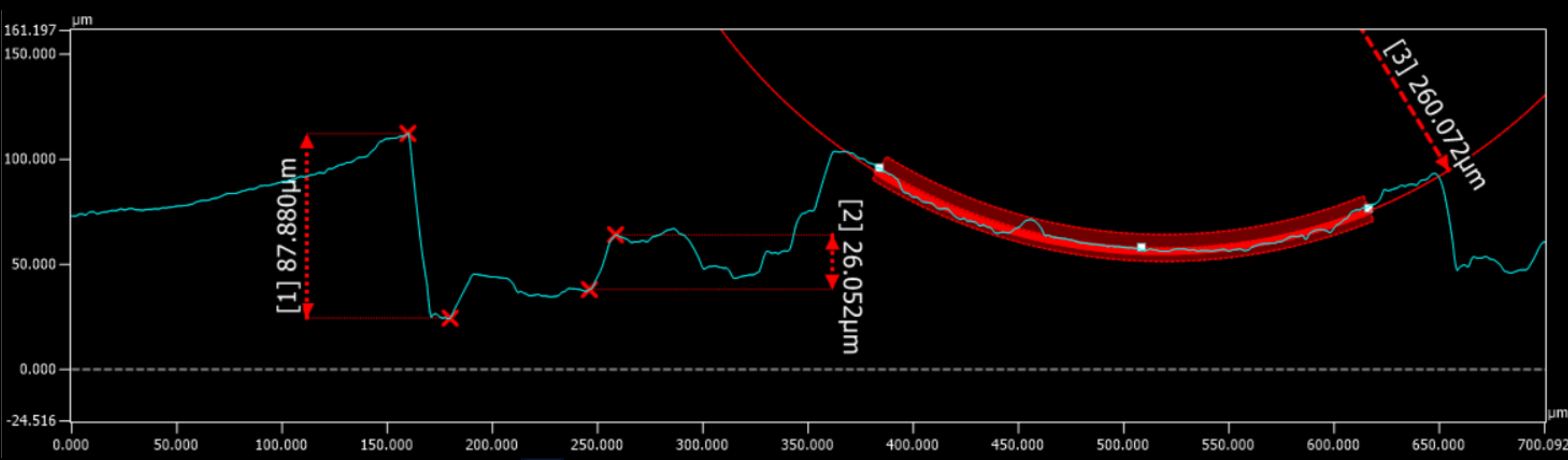


Confocal microscopy

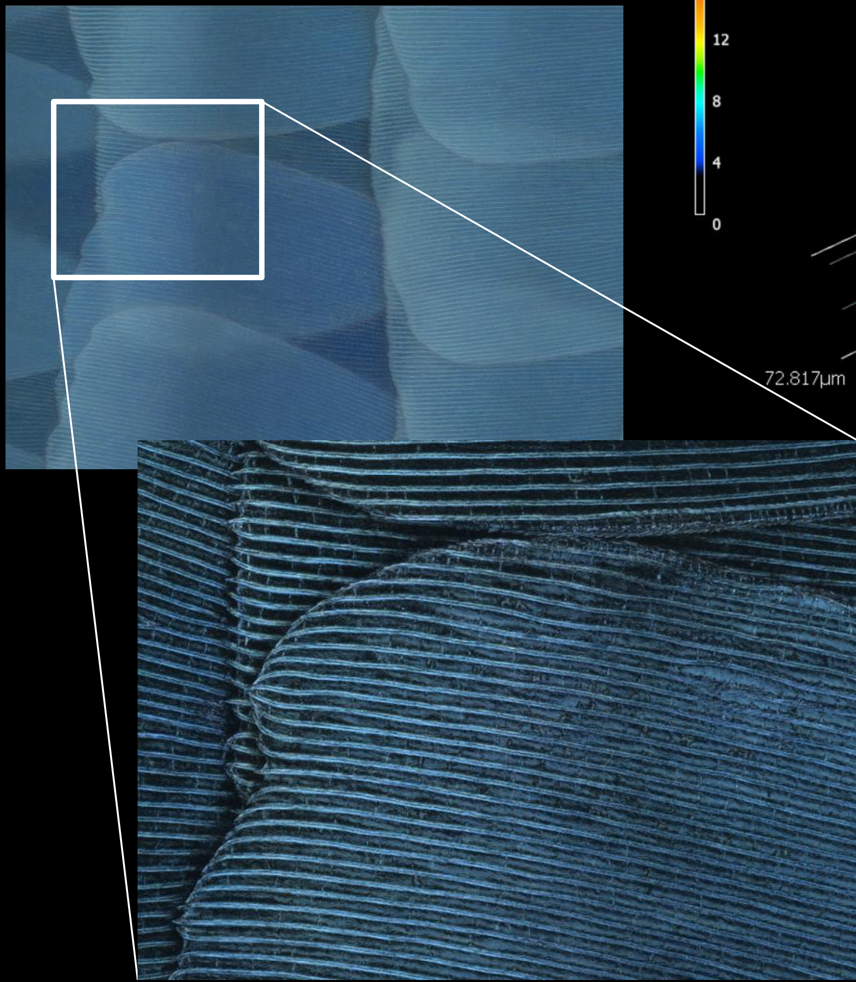
Laser barrier curtain

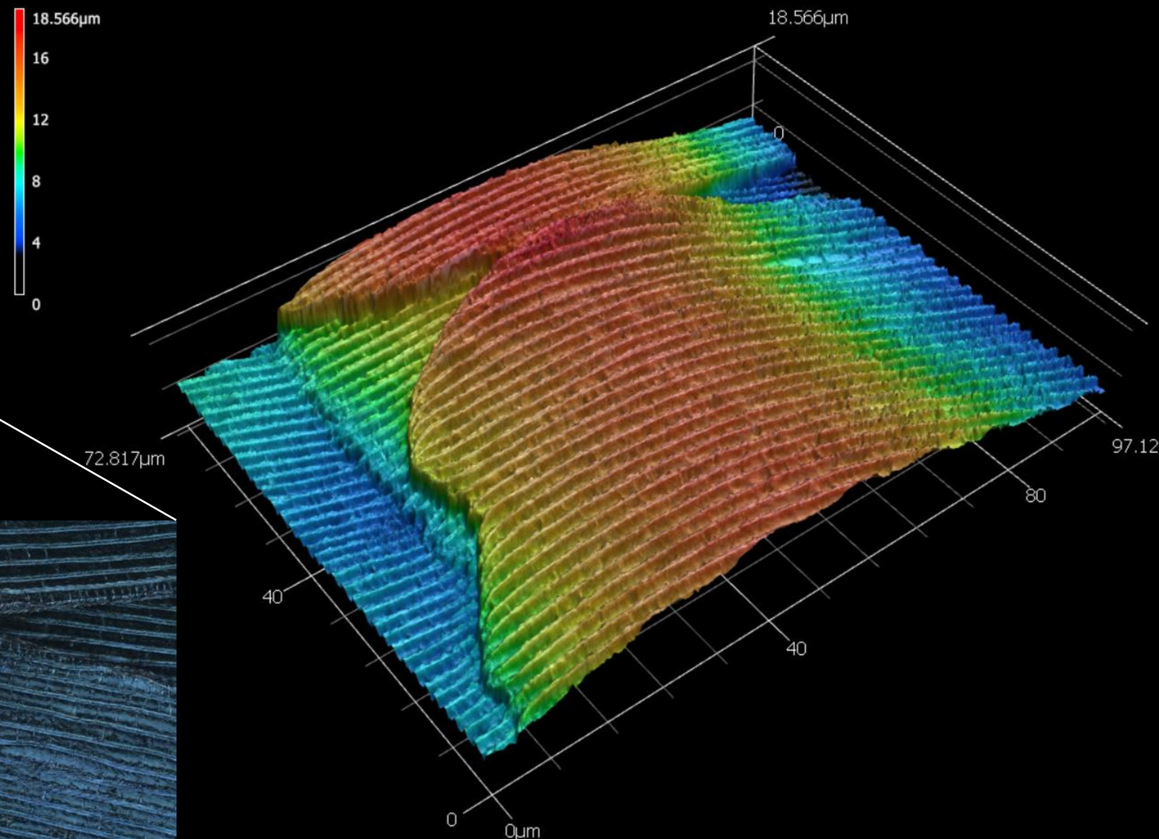






Confocal microscopy

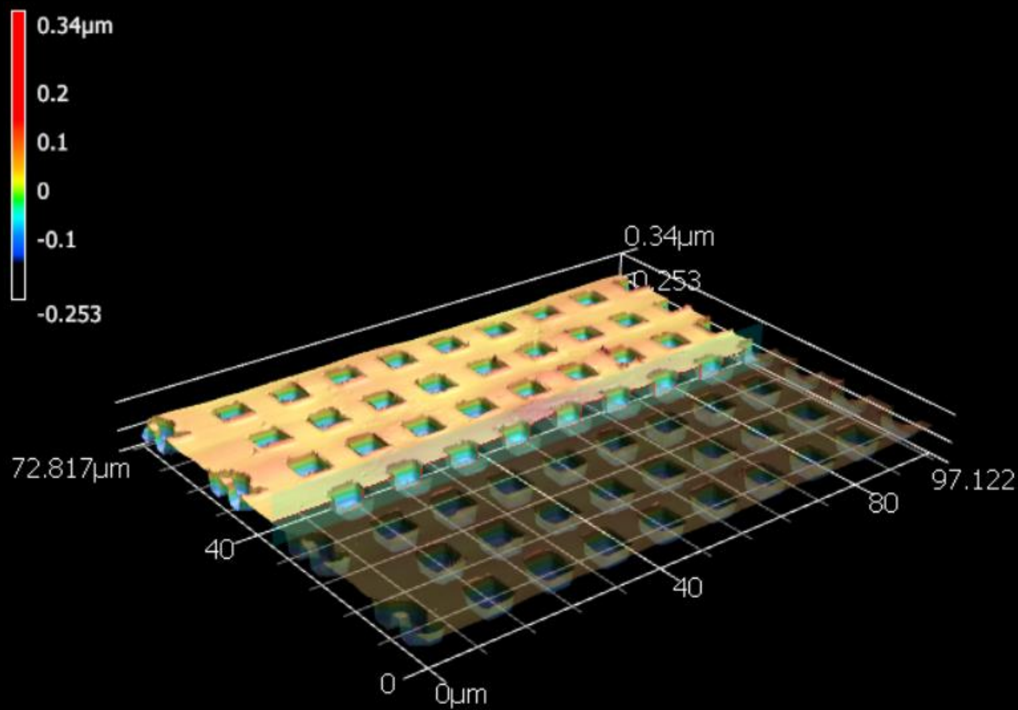


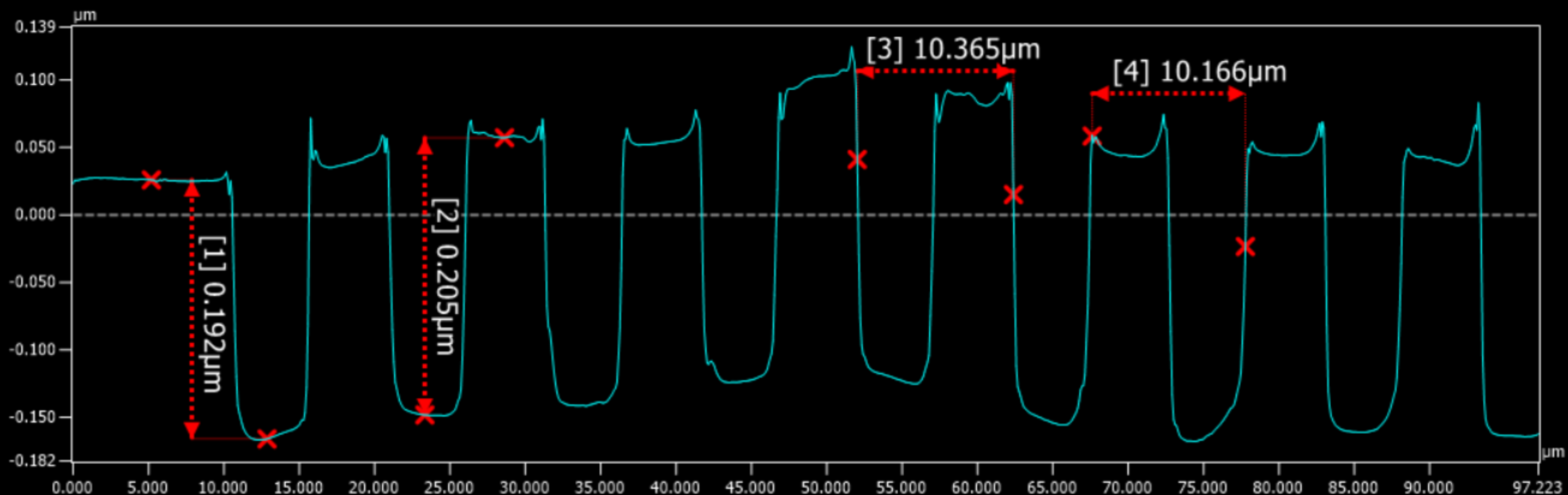


Mermaid butterfly wing

Confocal microscopy

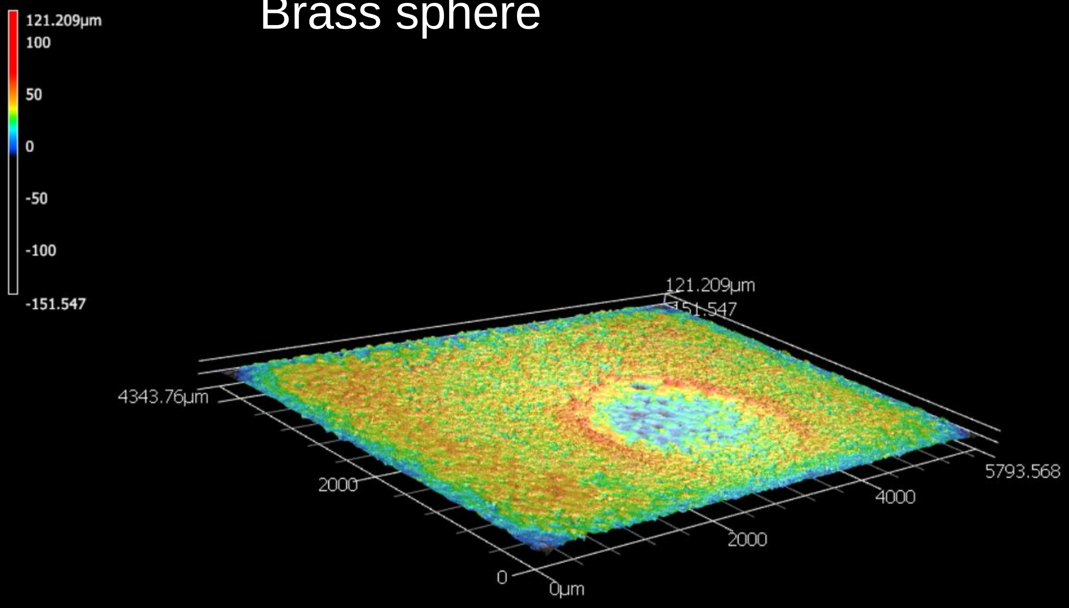
AFM calibration grating

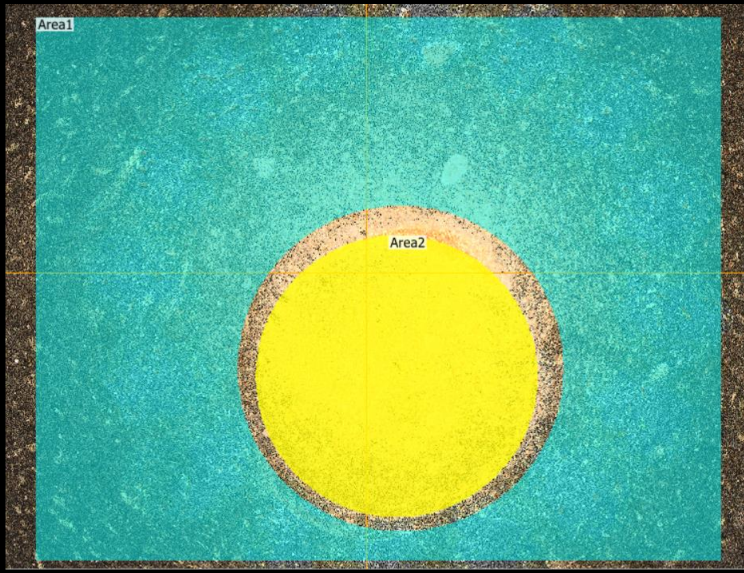


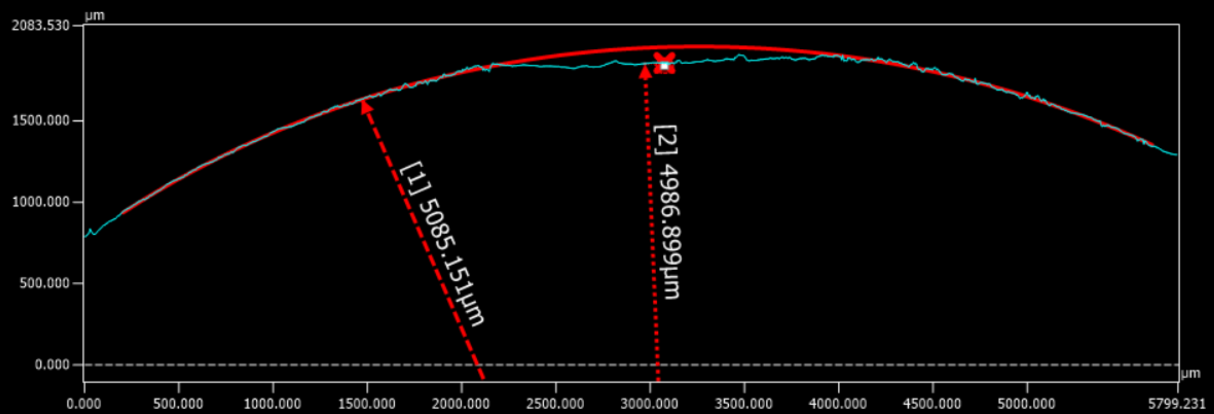


Confocal microscopy

Brass sphere







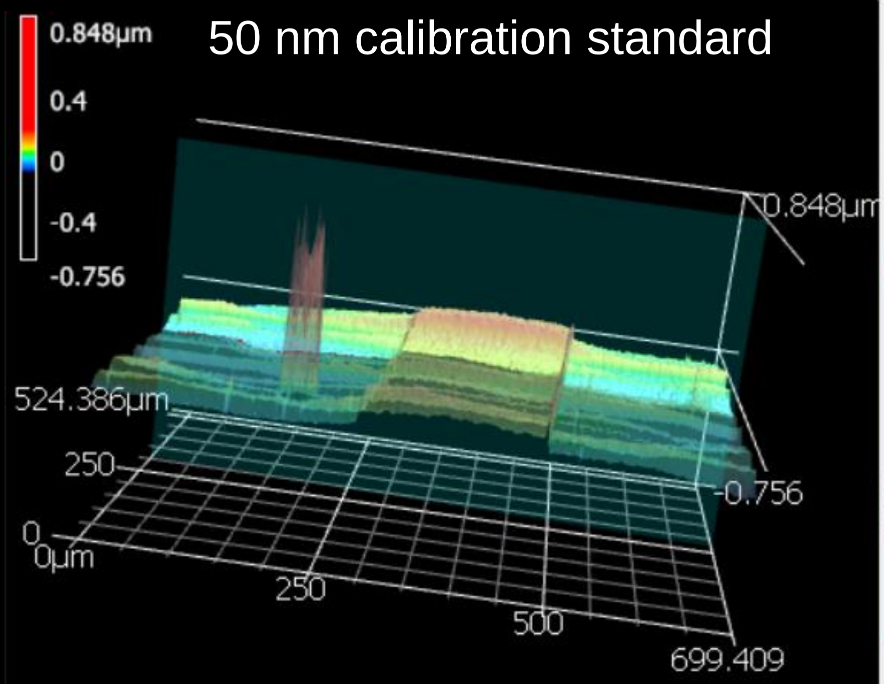
	Ra µm	Rq µm
Area1	8.159	10.616
Area2	12.537	15.763

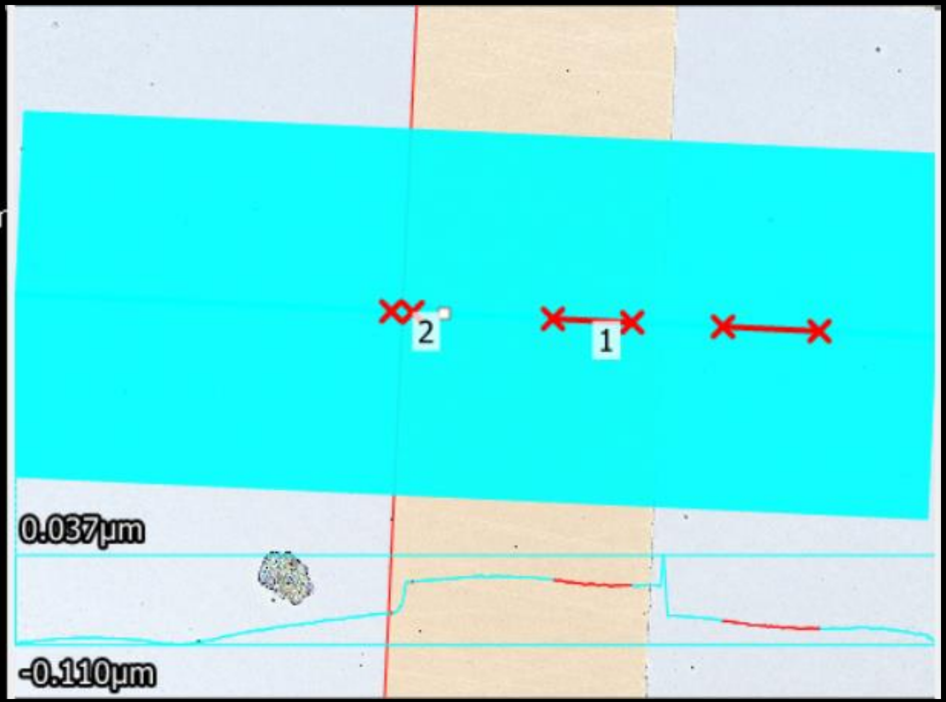
$$Ra = \frac{1}{n}\sum_{i=1}^{n}|y_i|$$

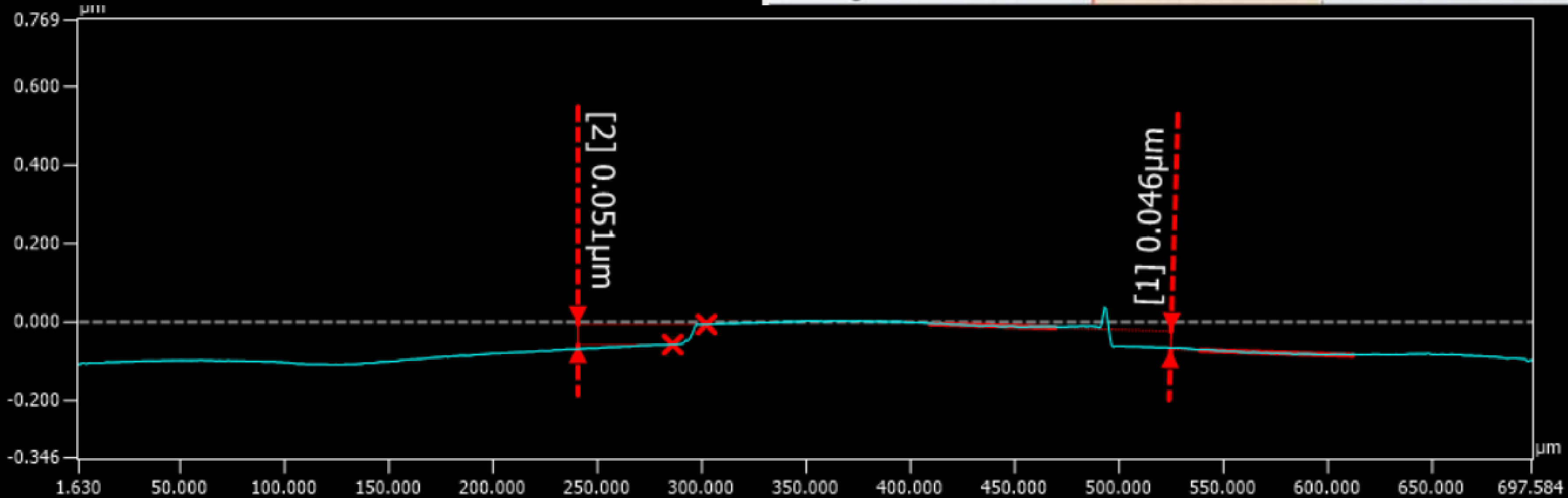
$$Rq = \sqrt{\frac{1}{n}\sum_{i=1}^{n}y_i^2}$$

Confocal microscopy

50 nm calibration standard







Confocal microscopy

Limitations:

- Image is scanned, resulting in slower data acquisition.
- High intensity laser radiation can damage some samples.
- Cost (typically 5x more than a comparable wide-field system).

Strengths:

- Optical sectioning.
  - Three-dimensional images.
  - Software localization of signal can bring z resolution to 20 nm.
- Improved contrast (200:1).
- Better resolution lateral (1.5x).
- Field of view defined by the scanning range.

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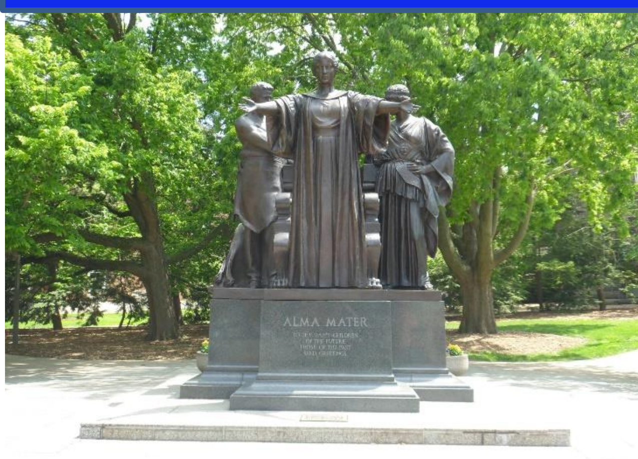
2019 SYMPOSIUM

September 5th, 2019



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