Optical characterization of semiconductor

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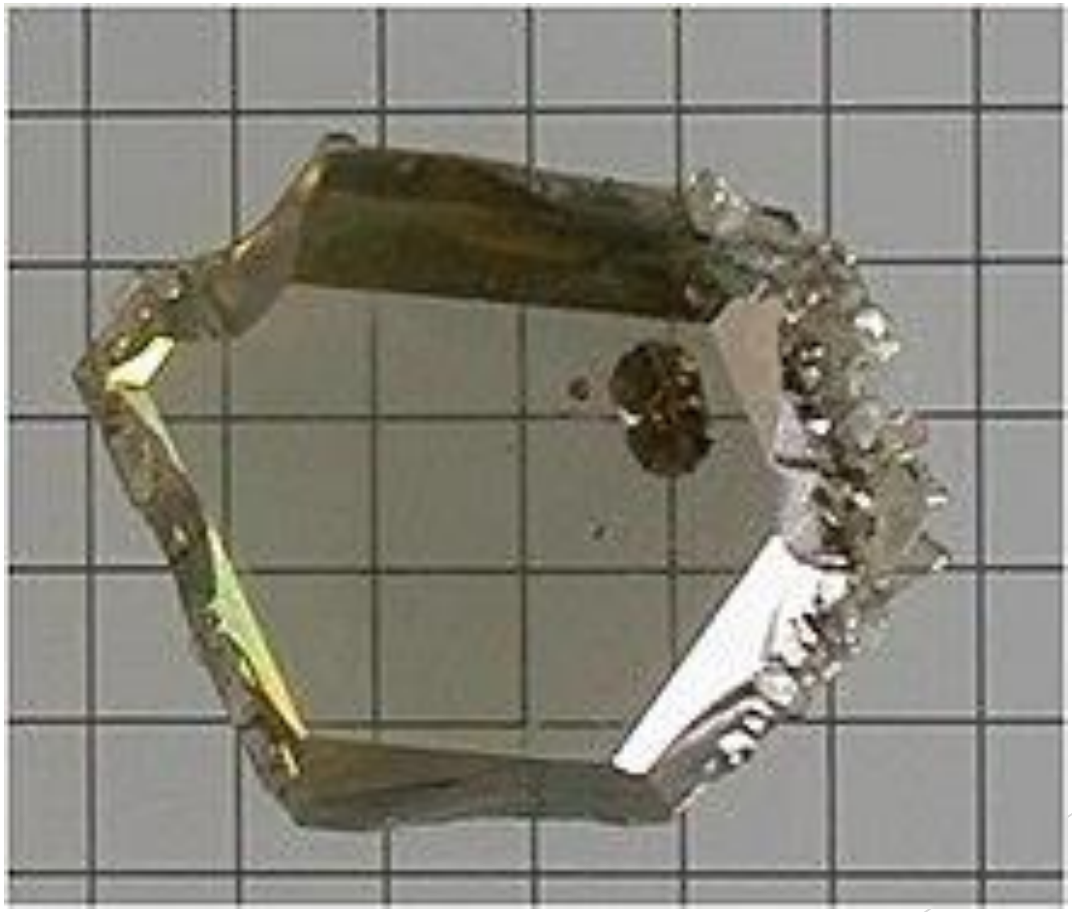


To fully characterize the material we used a range of complimentary methods

Typically we use:
X-ray diffraction to determine type of crystal lattice, chemical composition, quality of the material
SIMS (secondary ion mass spectroscopy)- chemical composition
EDS (Energy-dispersive X-ray spectroscopy) chemical composition
RBS (Rutherford Back Scattering) chemical composition
TEM (Transmission Electron Spectroscopy) –thicknesses of thin layers, defects microstructures
SEM (Scanning Electron Spectroscopy)–micro and mezo-structures
XPS (X-ray photoelectron spectroscopy) surface composition

Optical characterization, what for?

Optical characterization of semiconductors, what we can measure:

1. Energy gap of the material and in general band structure
2. Refractive index
3. Dopants and defects
4. Lattice vibrations (phonons)
5. Electron plasma oscillations (plasmons)
6. Excitons, trions and other complex excitations

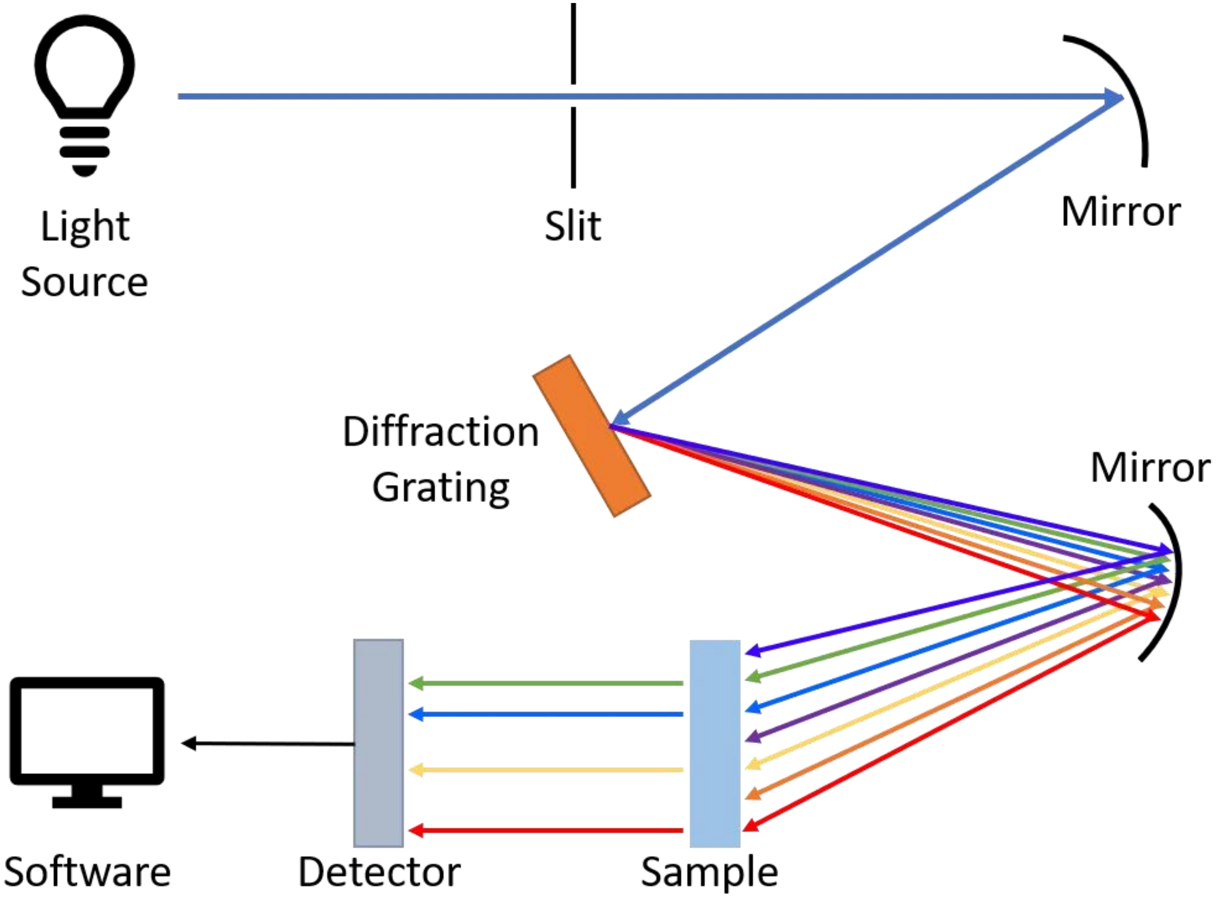
Optical characterization of semiconductors, advantages

Usually non-destructive testing", equipment relatively cheap and accessible

Insight into electronic structure of semiconductors

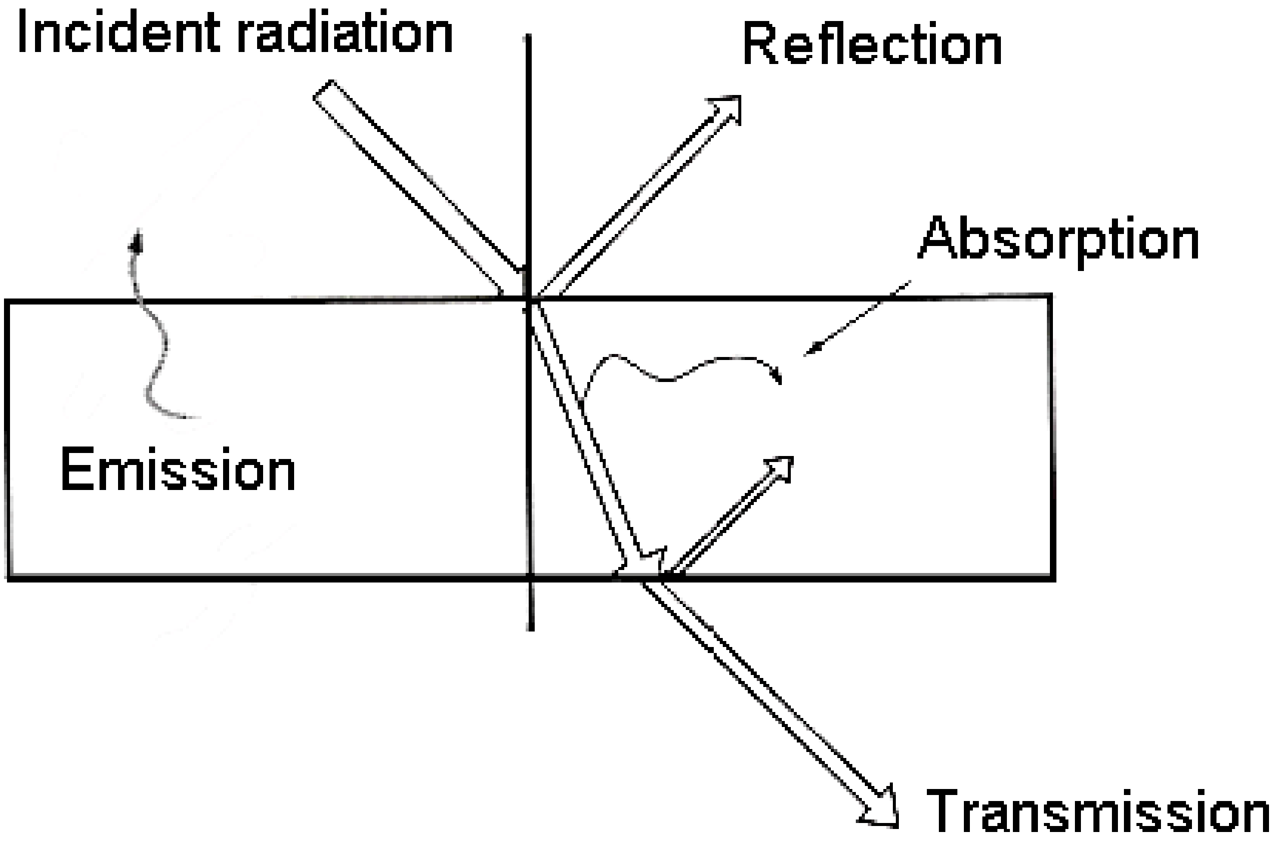
Direct relations to optoelectronics

Optical absorption measurement

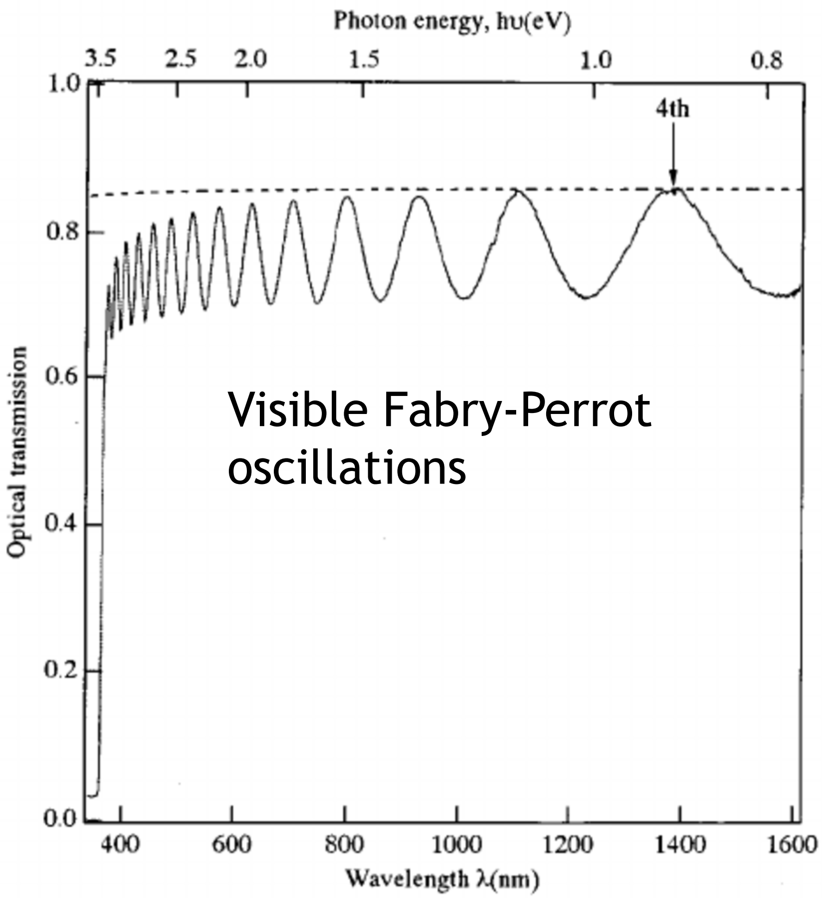


In order to measure high absorption coefficient we need very thin sample,
Otherwise we would not be able to measure high absorption coefficients.

Optical absorption



Transmission spectrum of plane parallel sample of Gallium Nitride



Visible Fabry-Perrot oscillations

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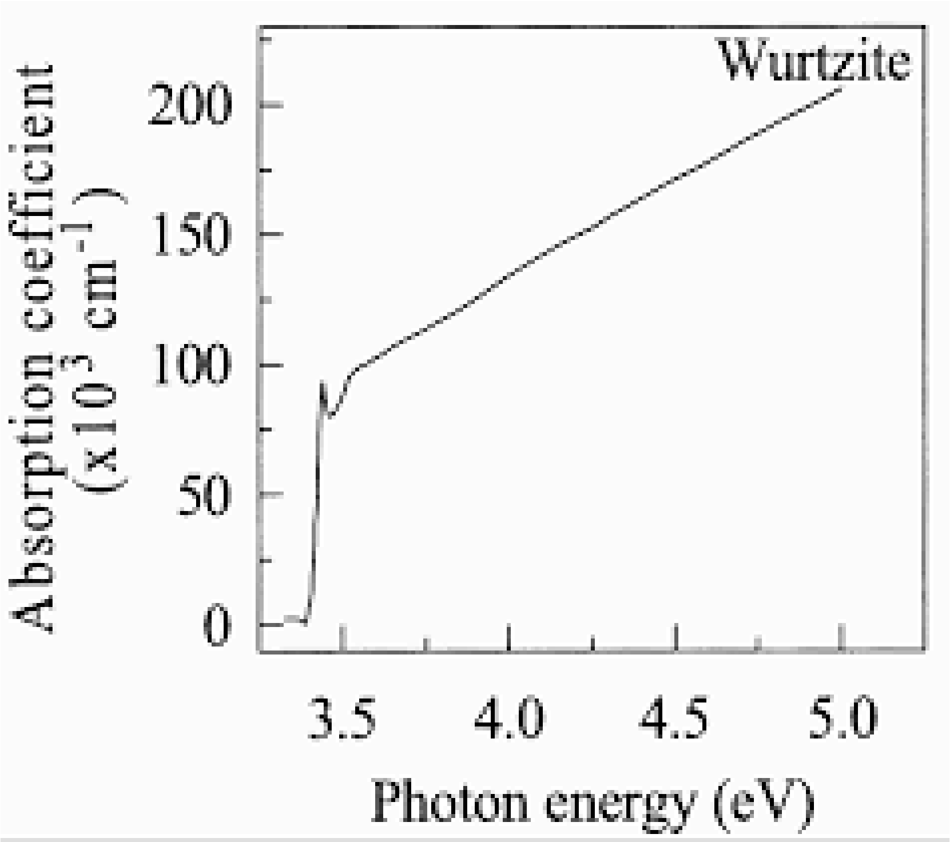
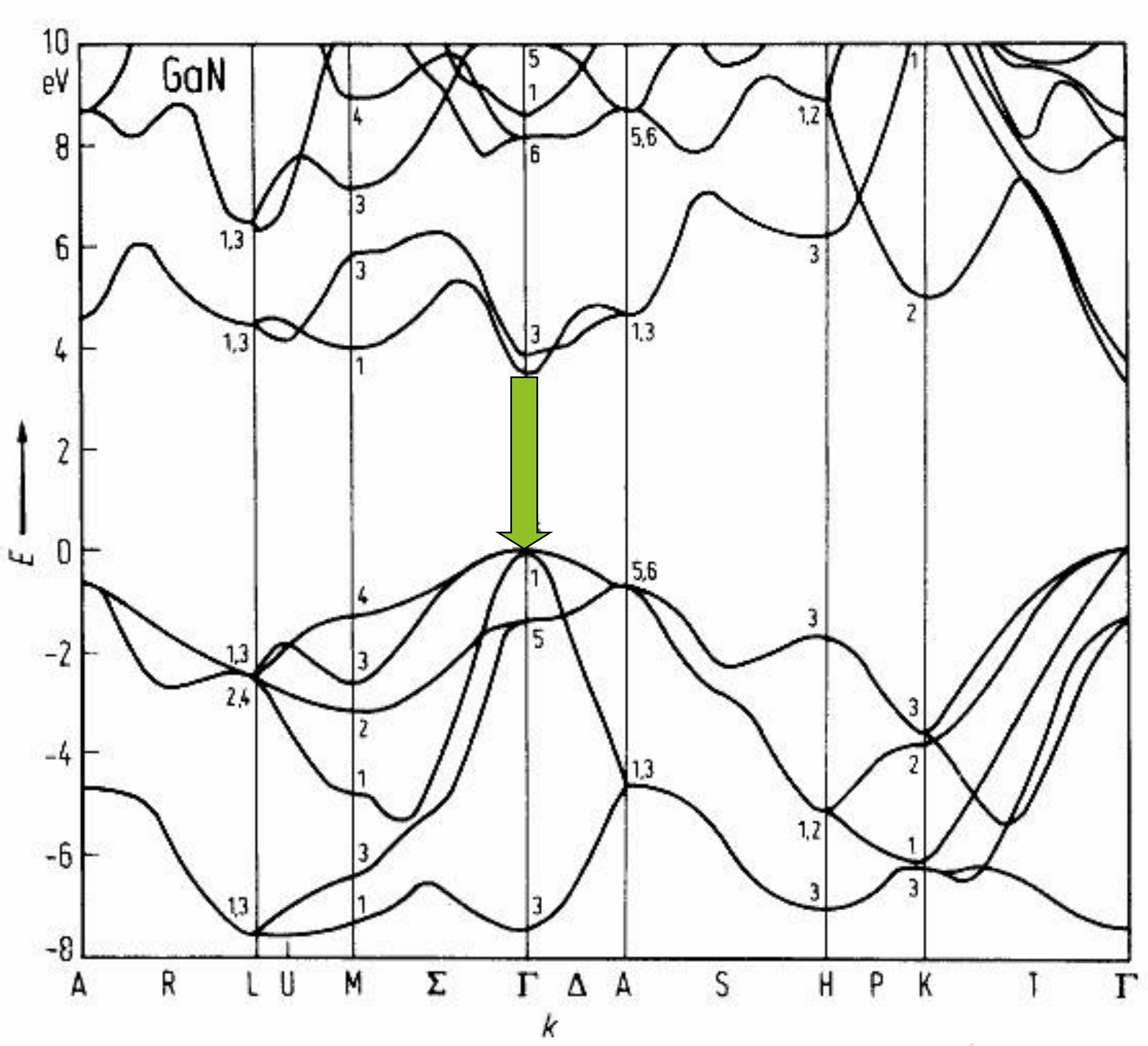
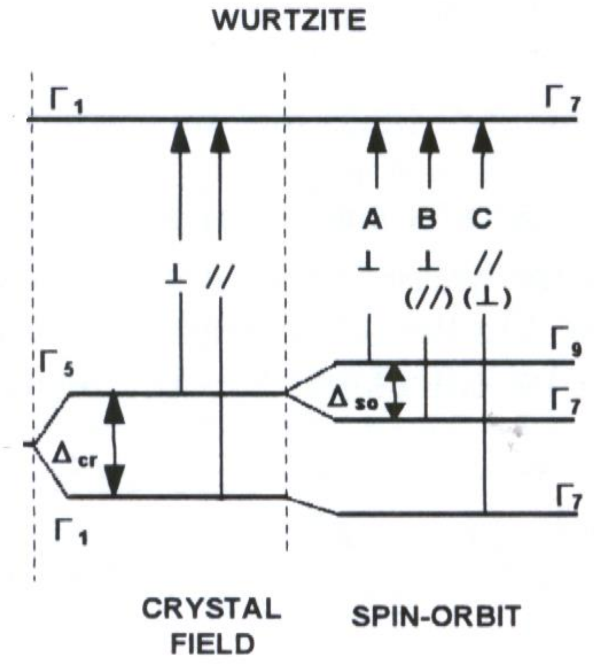
$$I(x) = I_0 e^{-4\pi\kappa x/\lambda_0}$$

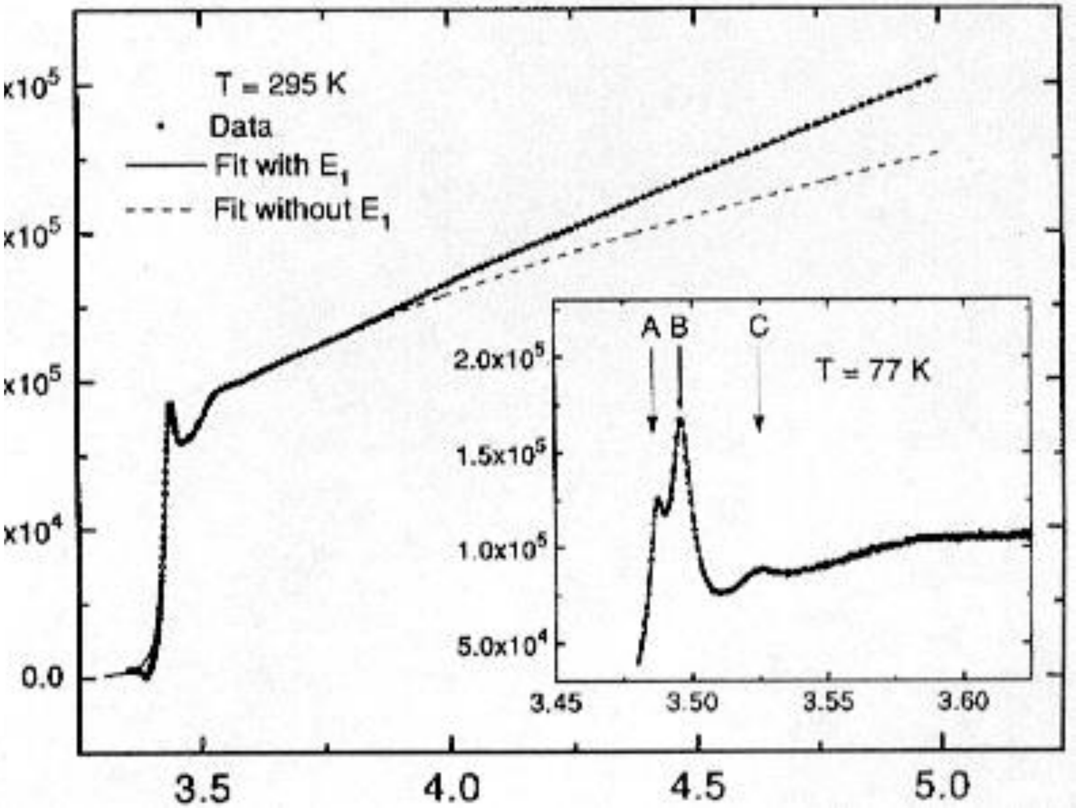


GaN – band structure



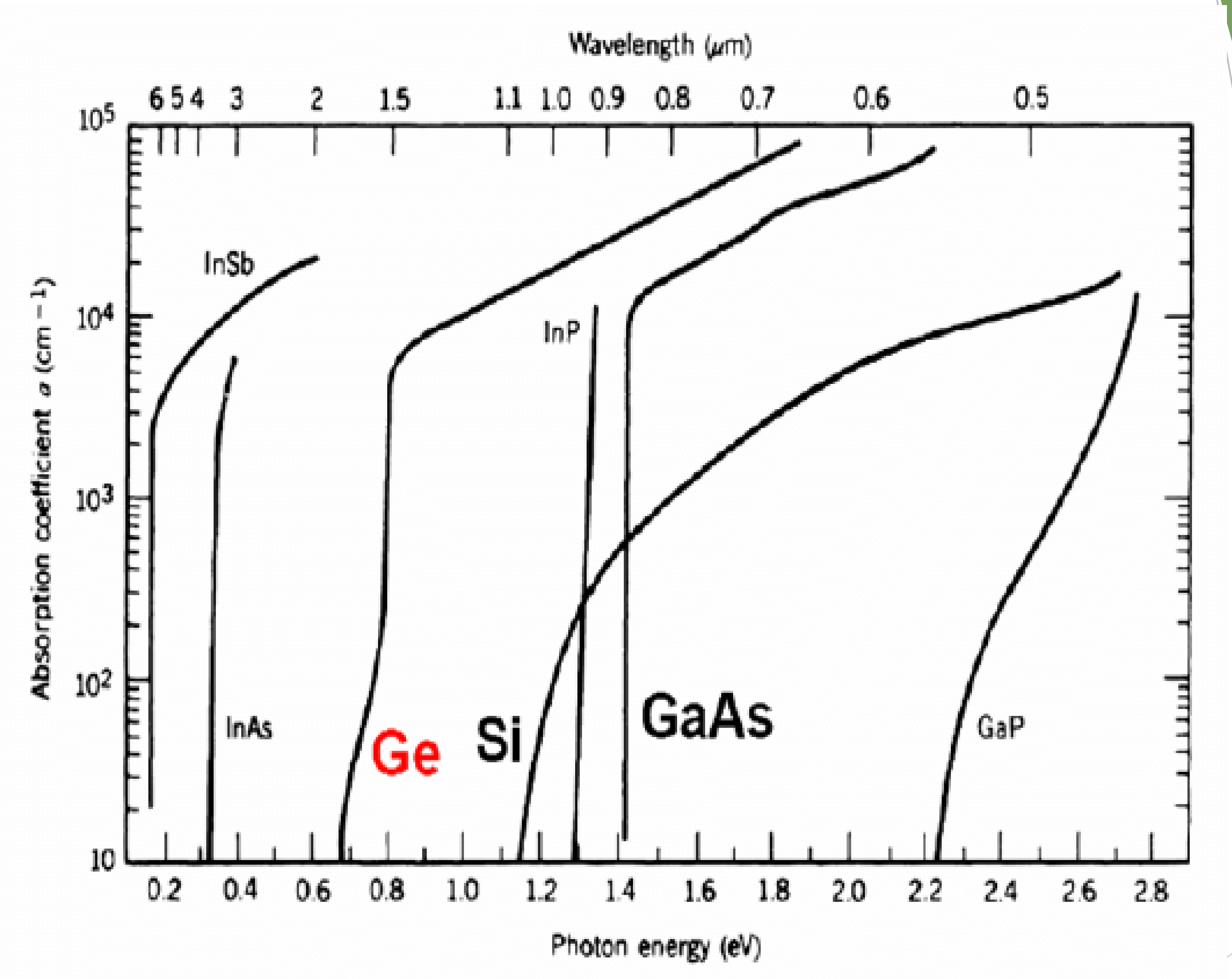
Details of the absorption spectrum of GaN
0.4 μm GaN layer on sapphire





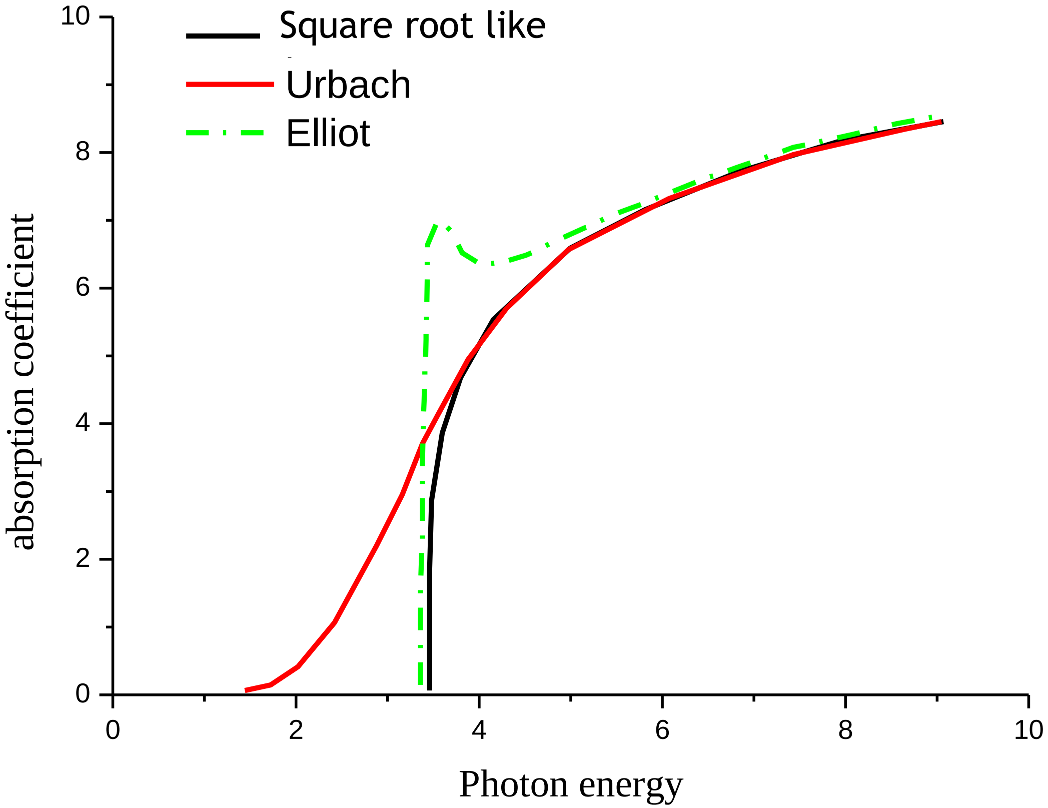
As the results you can get:
Energy of excitons
Shape of the absorption edge
You need thin layers for this measurement

GaP , Si and Ge indirect semiconductors



G. E. Stillman, V. M. Robbins, N. Tabatabaie, "III-V compound semiconductor devices: optical detectors," *IEEE Trans. Electron. Devices*, vol.31, no. 11, pp. 1643-1655, Nov. 1984.

The shape of the absorption edge provide provide an additional information on material

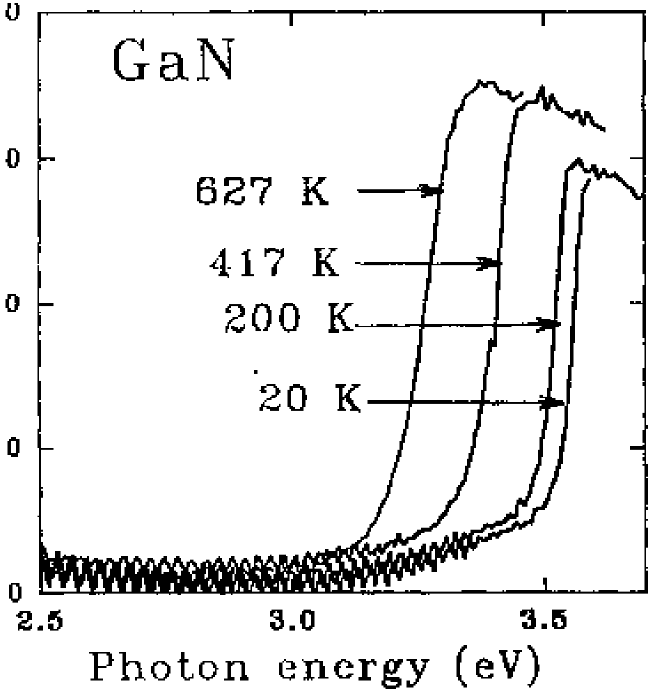


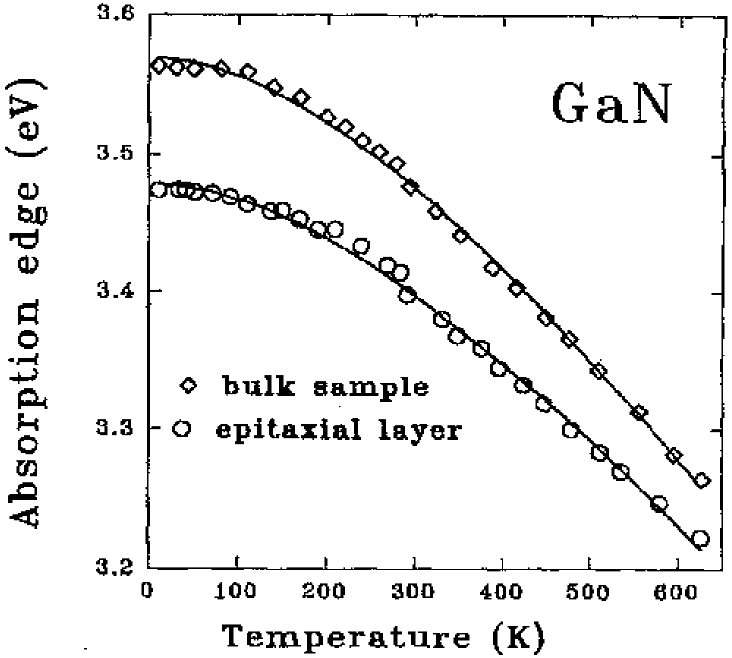
Urbach – disorder related
Elliot – excitonic

Temperature dependence of the absorption edge

Standardly, the Energy gap shrinks with the temperature

Lattice dilatation and electron-phonon interaction

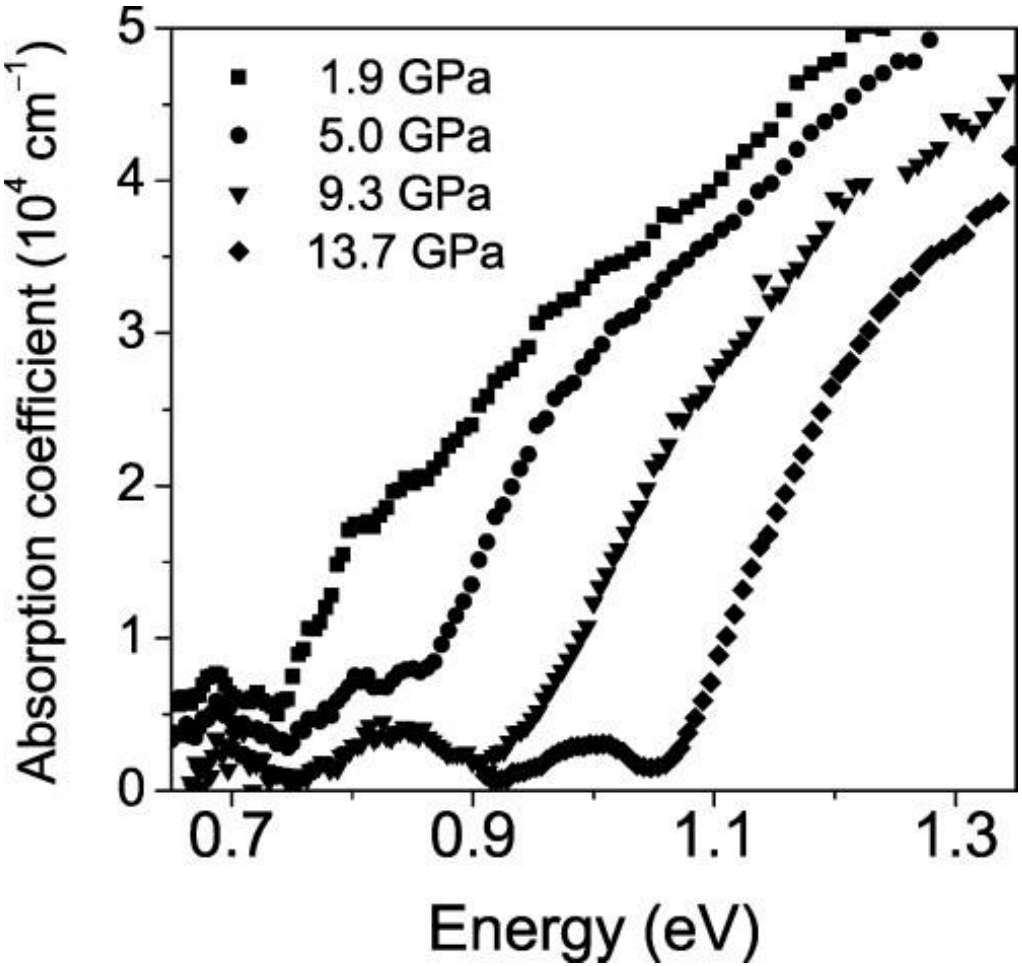




$$E_g = E_{h0} - \frac{\gamma T^2}{T+\beta}$$

Pressure effects on the absorption Edge (band gap) of InN

As a standard, Energy gap increases with the applied hydrostatic pressure.



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Optical reflectance

Photoluminescence

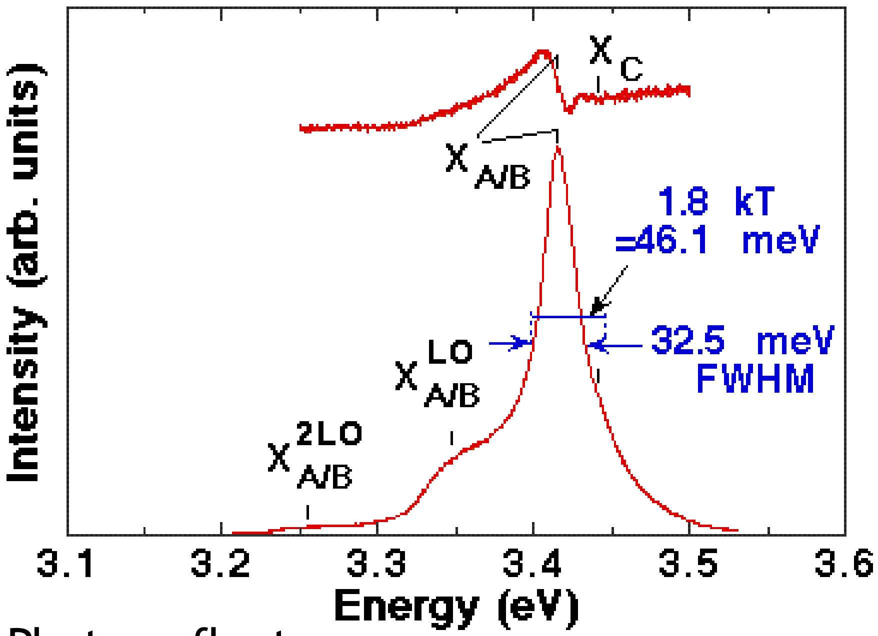
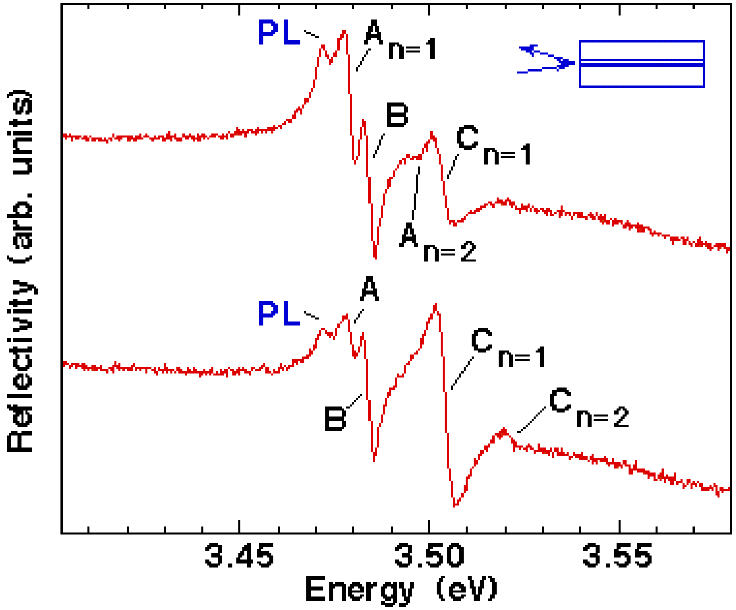
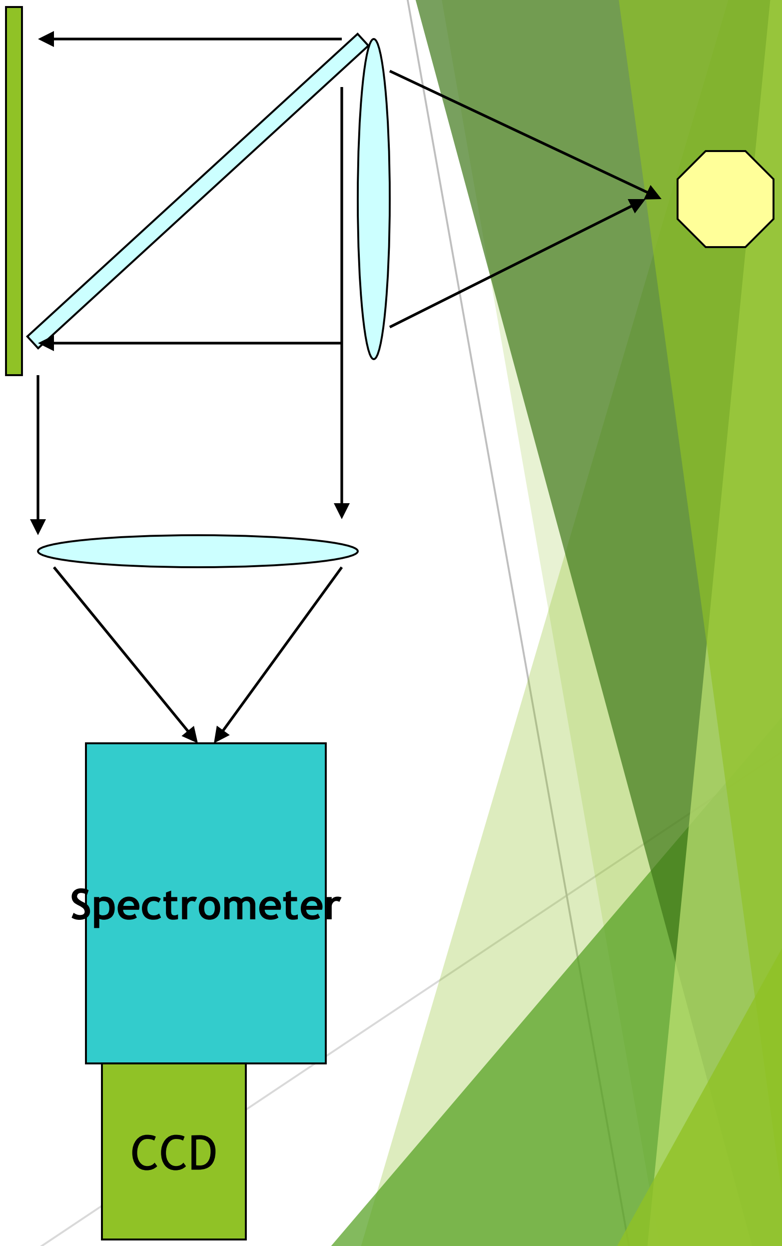


Photo-reflectance

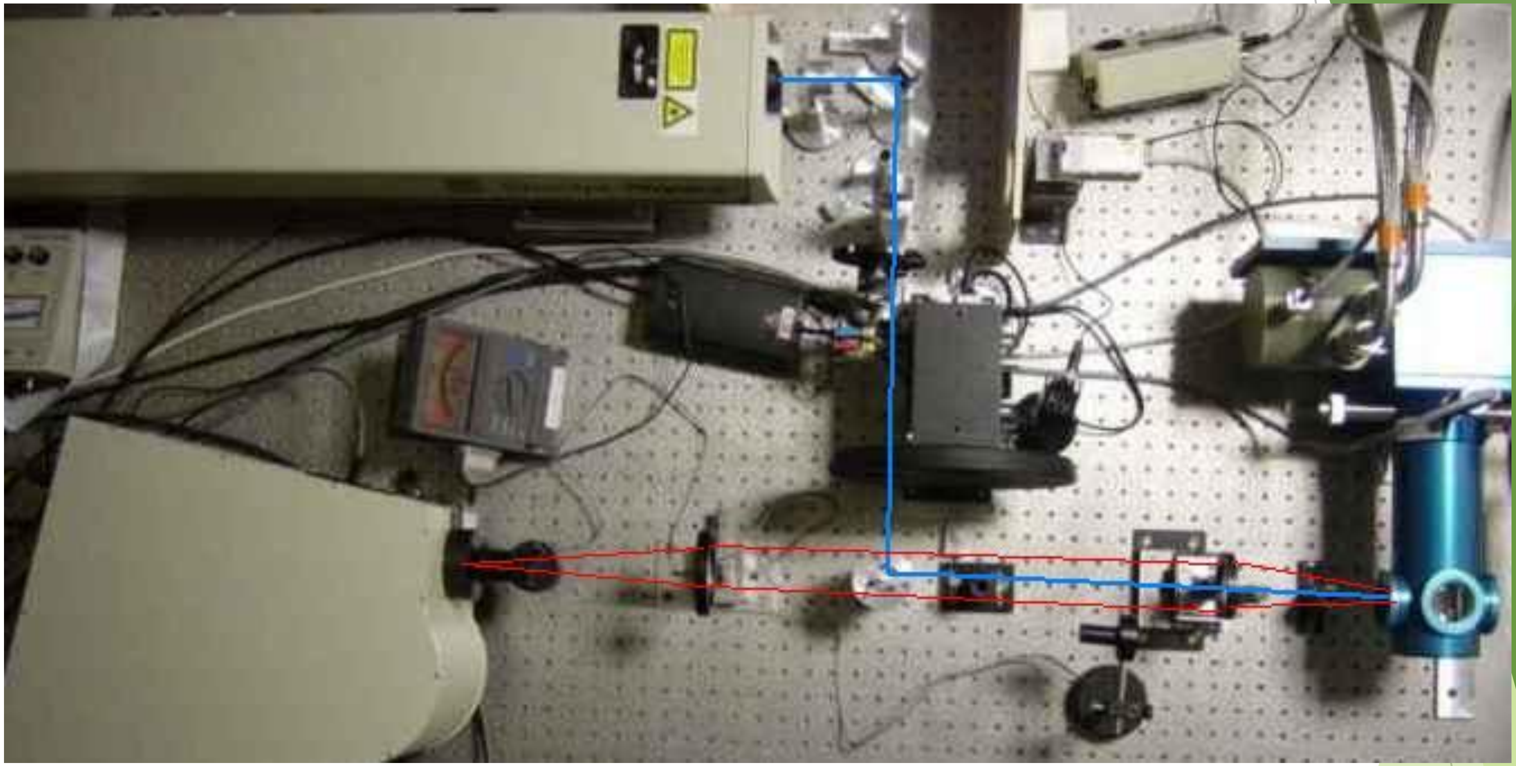




Spectrometer

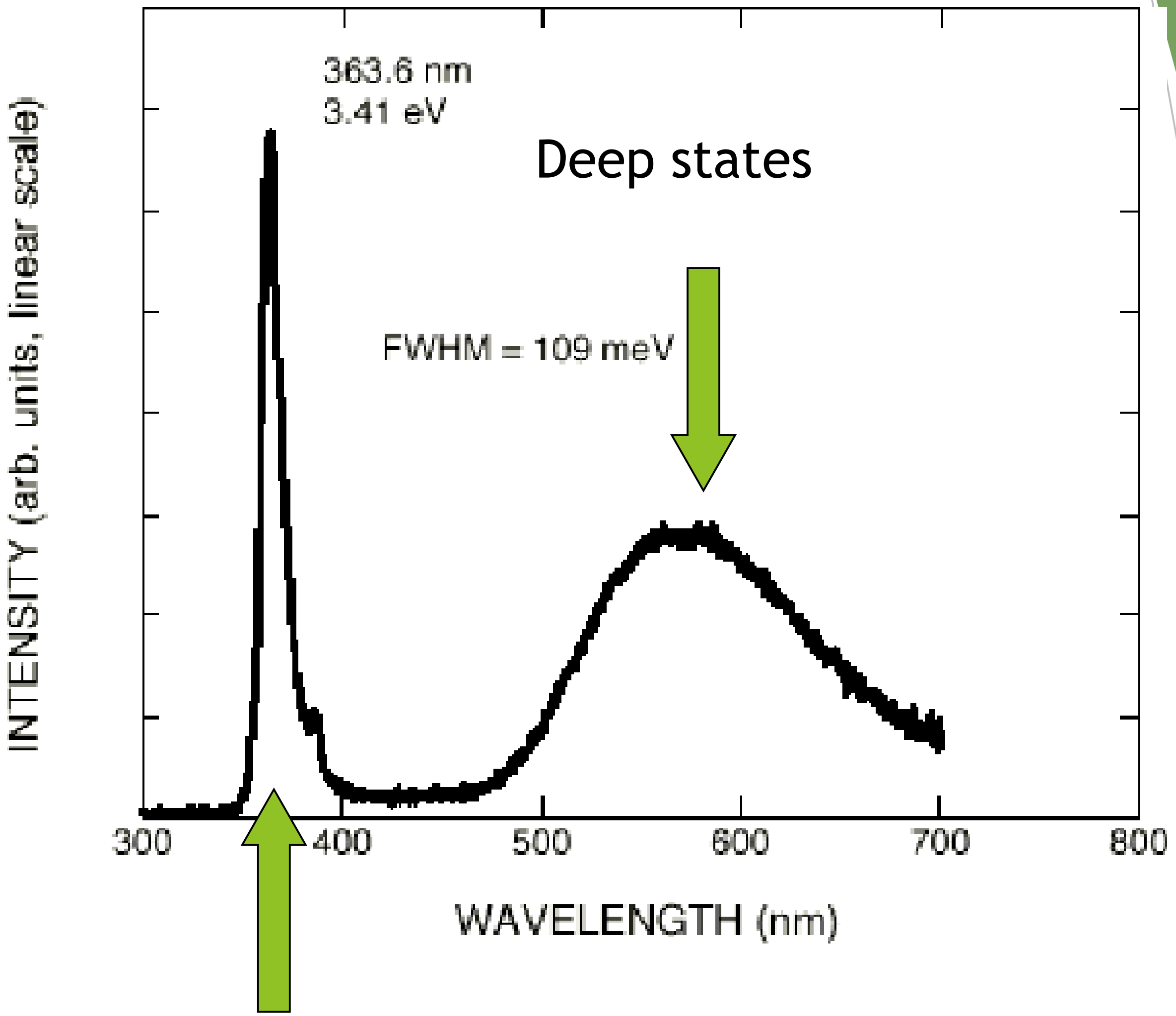
CCD

Photoluminescence



Simple measurement system.
Easy application of external disturbances (T, p, B, E).
requirements: light source – laser, detector, spectrometer.

Photoluminescence – an example GaN - crystal

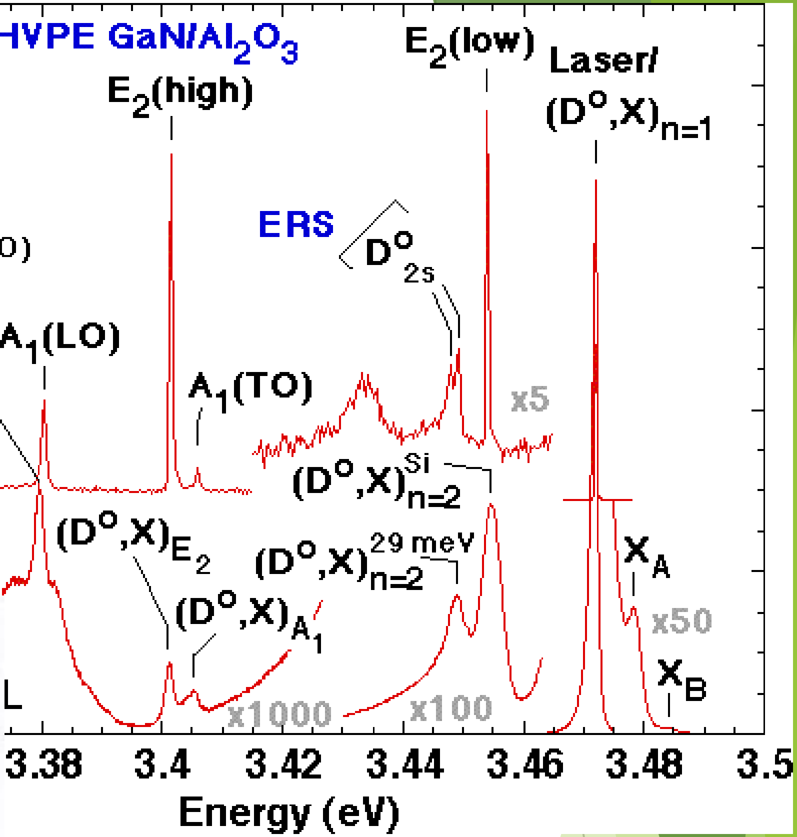


Deep states

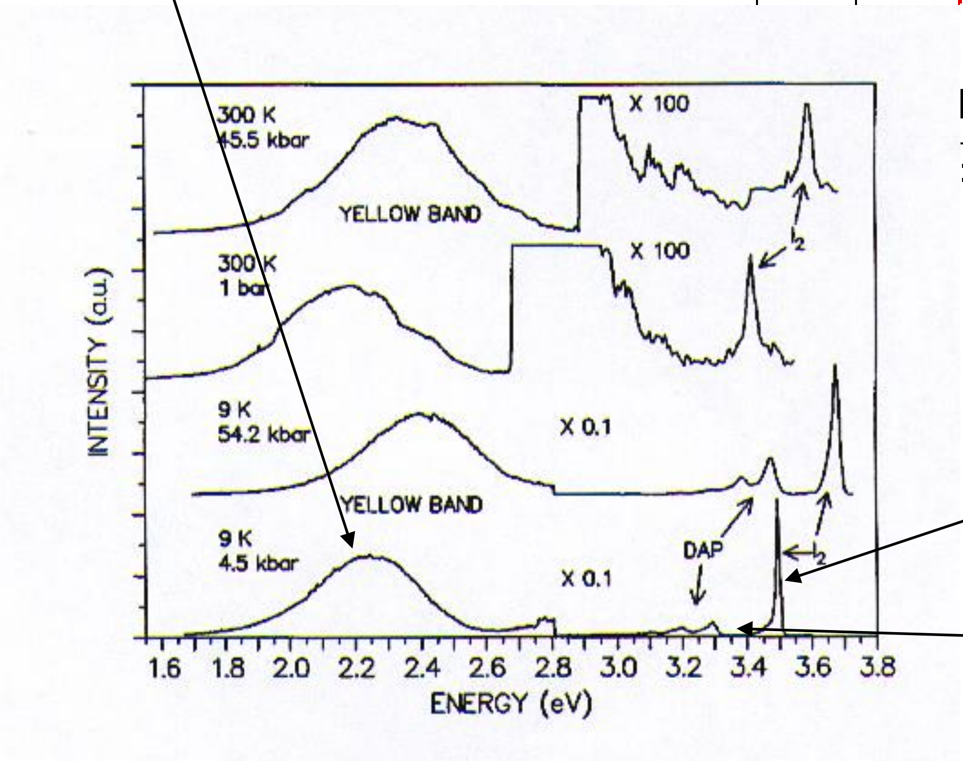
Shallow states, energy gap region

Photoluminescence

Picture can be quite complex



Deep levels



excitons

Donor acceptor pairs

Photoluminescence can provide information on strain and/or temperature of the crystal

Strain

$$E_g = E_{g,0} + C(\epsilon_{xx} + \epsilon_{yy}) + D\epsilon_{zz}$$

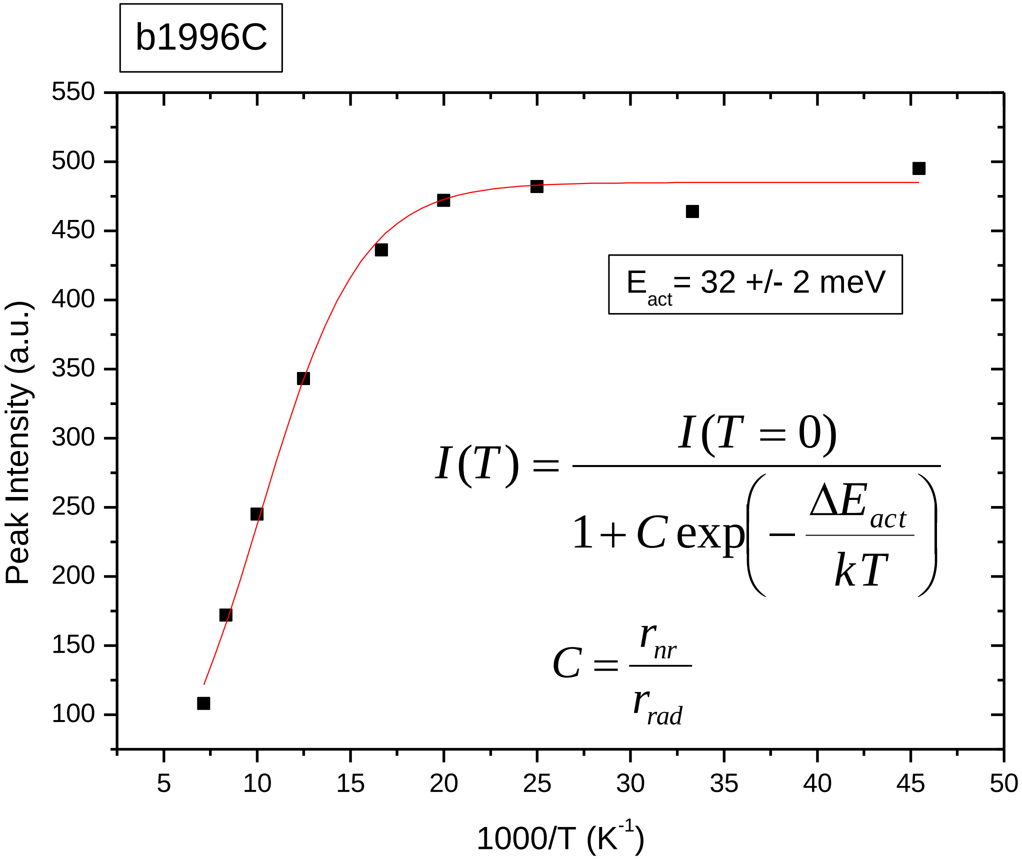
C, D deformation potentials of the crystal

Temperature

$$E_g = E_{h0} - \frac{gT^2}{T + b}$$

Thermal quenching of the photoluminescence intensity

InGaN



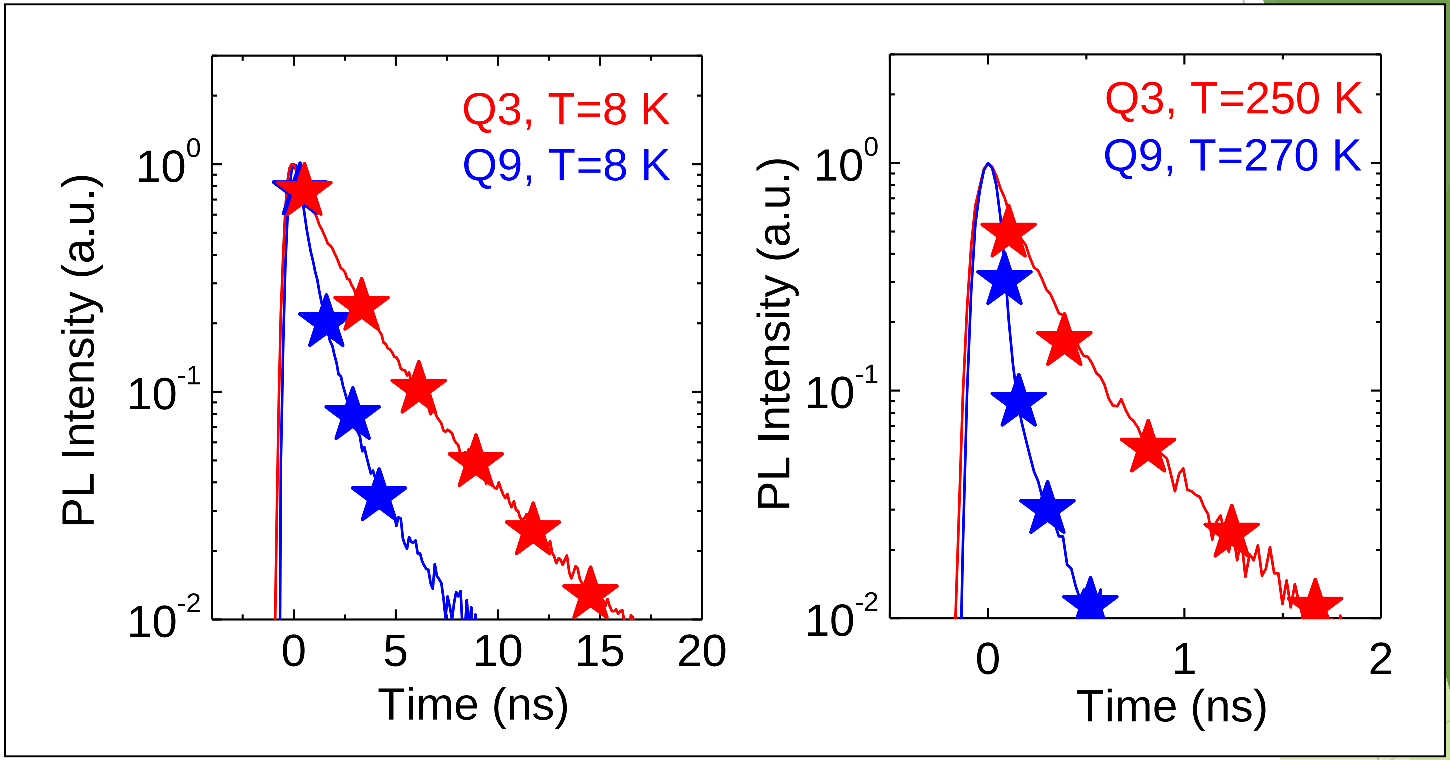
$$I(T) = \frac{I(T=0)}{1 + C\exp\left(-\frac{\Delta E_{act}}{kT}\right)}$$

$$C = \frac{r_{nr}}{r_{rad}}$$

Information on characteristic Energy scales, for example related to localization, binding Energy of excitons, donors, etc…
Also non-radiative recombination influences this proces.

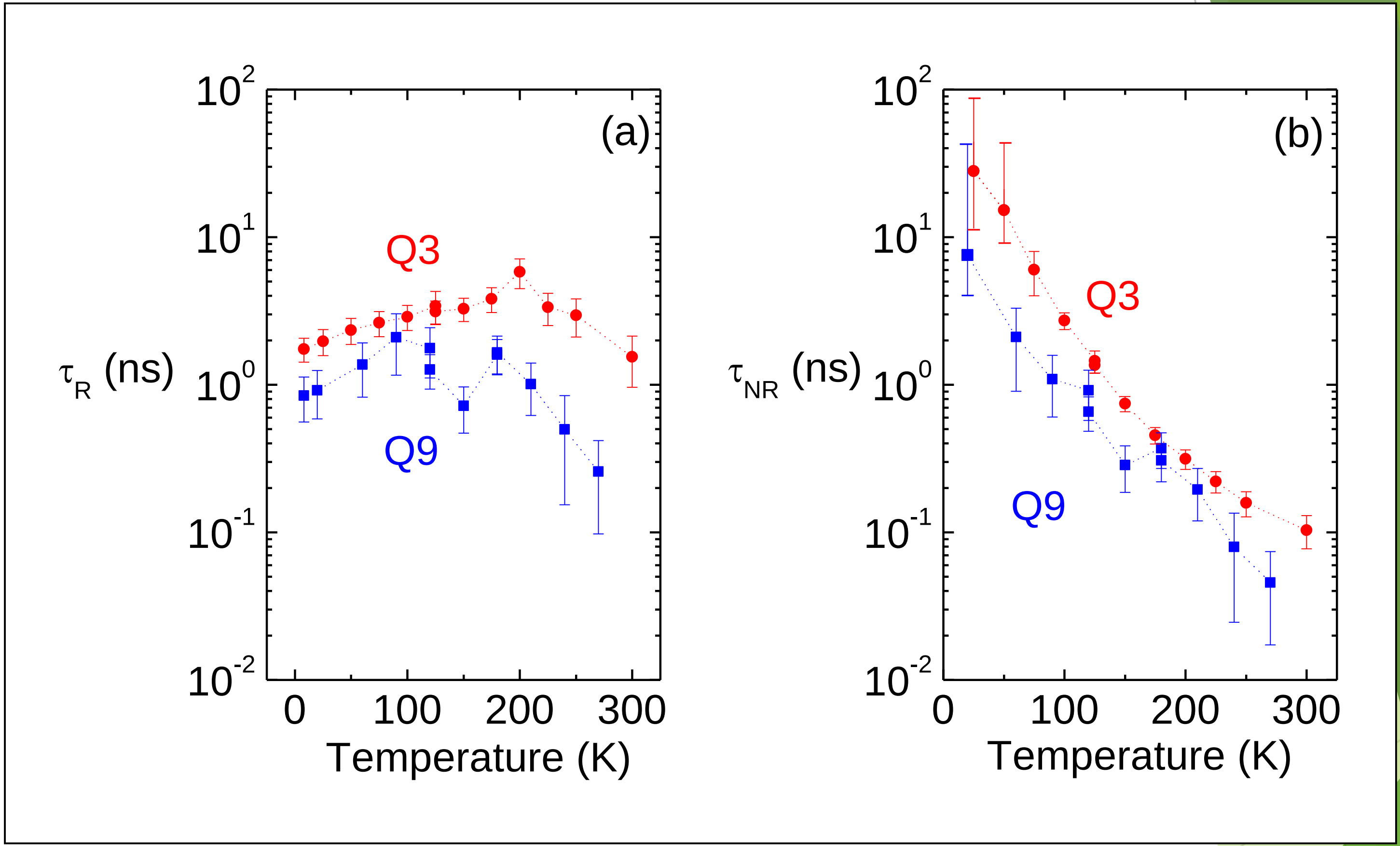
Time-resolved photoluminescence

- Fits indicated by ★, ★.



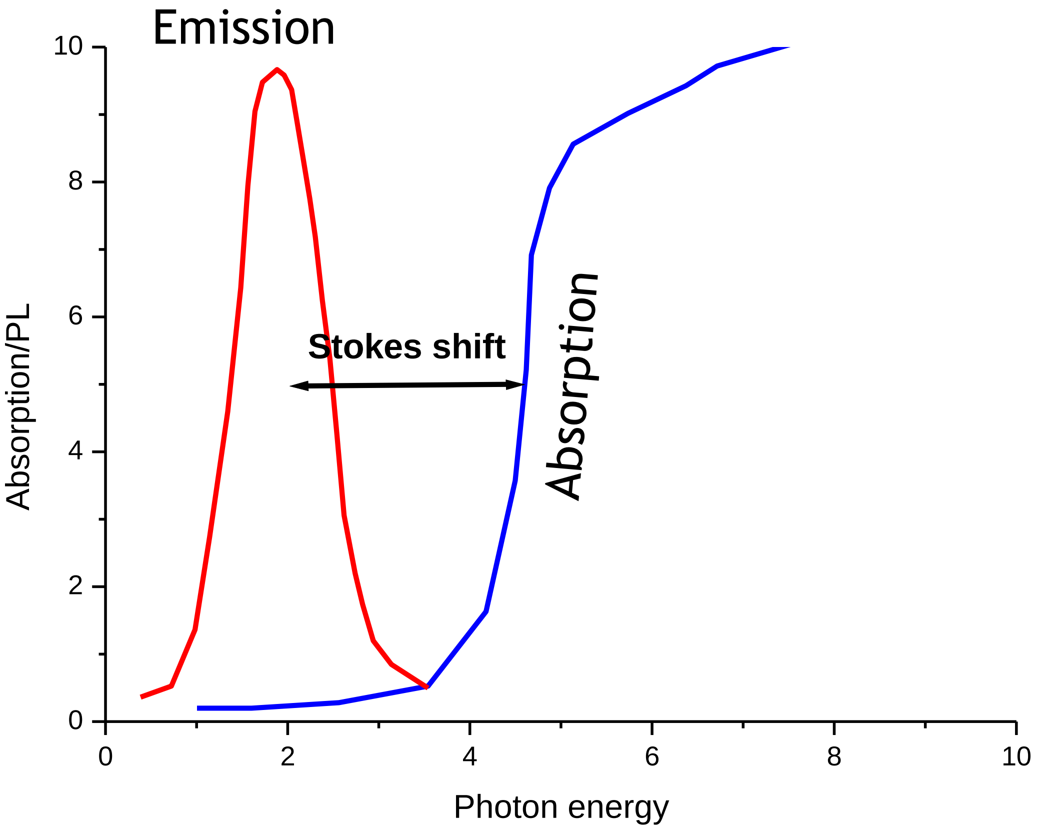
Determining the radiative and non-radiative lifetimes of carriers from the temperature dependence of photoluminescence decay.

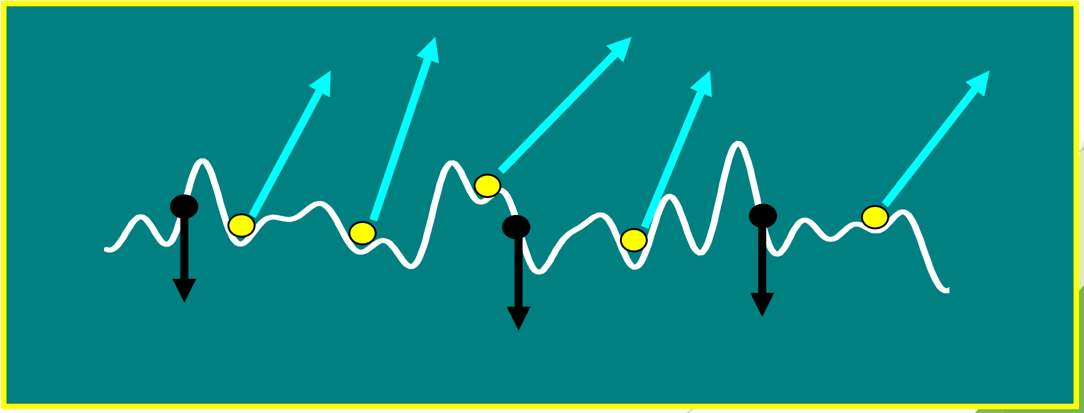
Time-resolved photoluminescence



Determining the radiative and non-radiative lifetimes of carriers from the temperature dependence of photoluminescence decay.

Stokes shift the measure of localization





Free carrier absorption

Longitudinal vibrations (waves) of free electron plasma

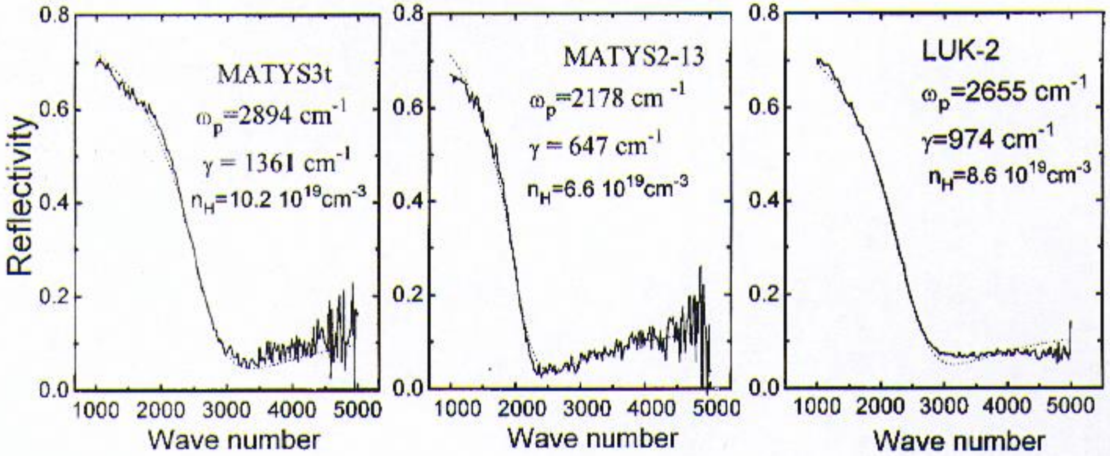


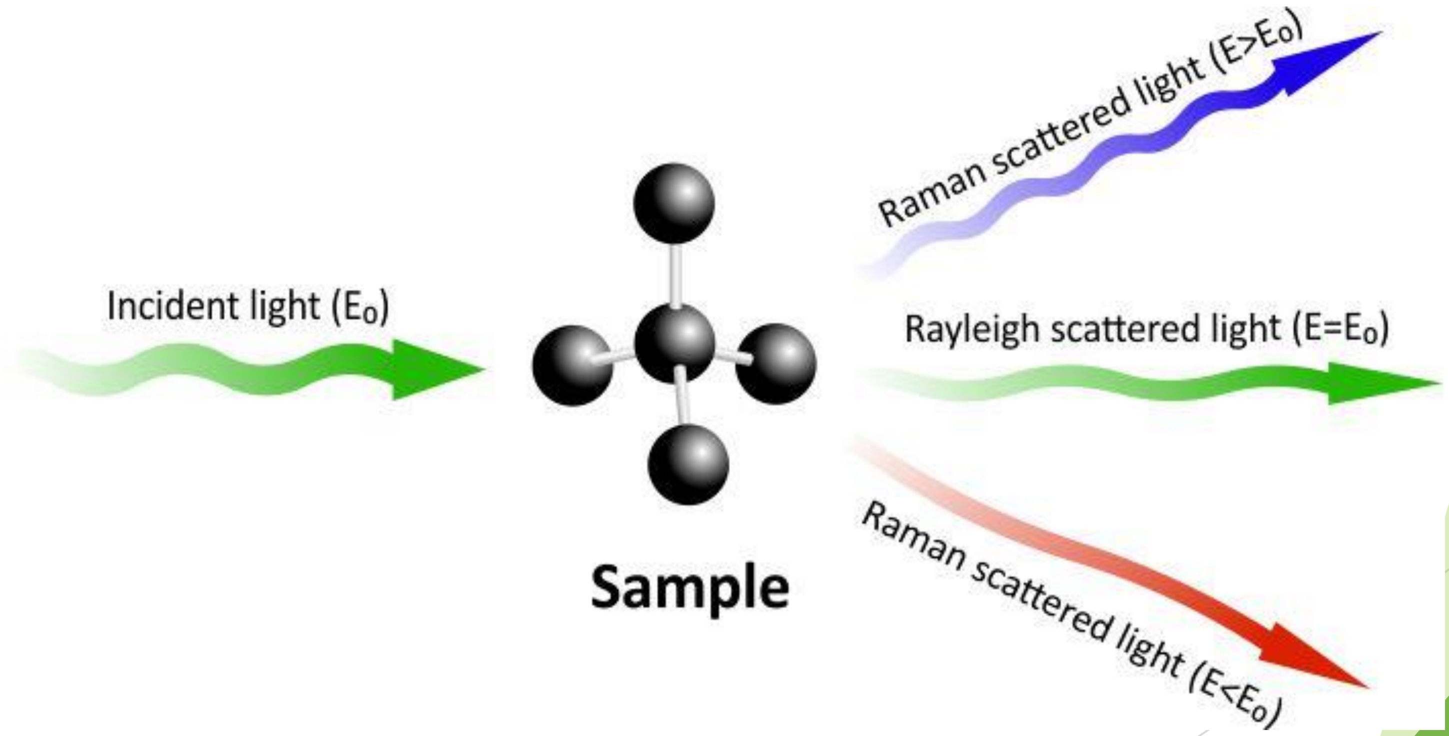
FIG. 1. Examples of reflectivity spectra for three samples of different electron concentrations. The dotted line shows the best fit of Eq. (2) to the experimental data, ωp is a plasma frequency, and γ is electron damping parameter of Eq. (4).

$$\omega_p^2 = \frac{Ne^2}{m^* \varepsilon_\infty \varepsilon_0}$$

Determination of effective mass of carriers

Raman scattering

Measurement system similar to PL but:
Triple or single spectrometer with a notch filter.
Usually at room temperature.
Popular micro-Raman setups with a microscope.



Phonon modes – lattice vibrations example - gallium nitride

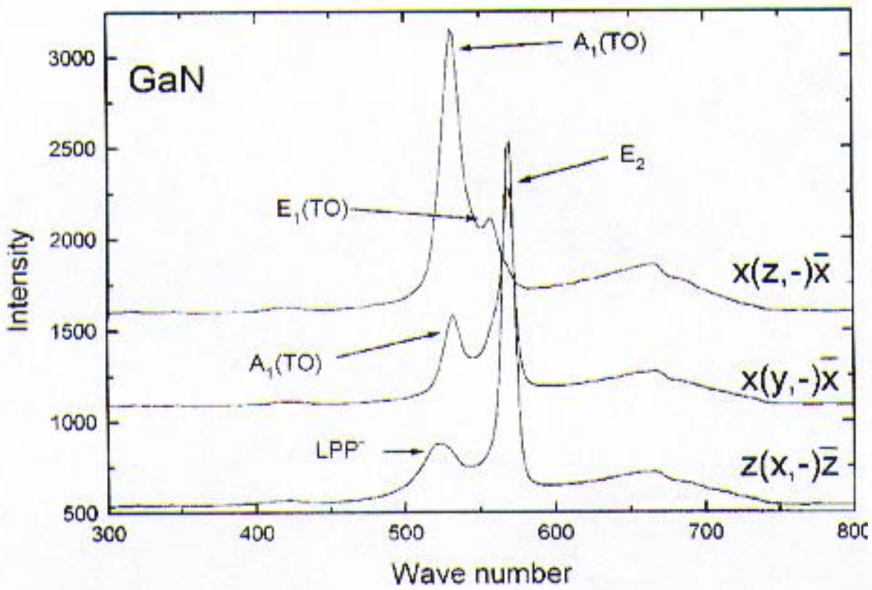


FIG. 2. Raman spectra of bulk GaN measured in various backscattering Raman configurations.

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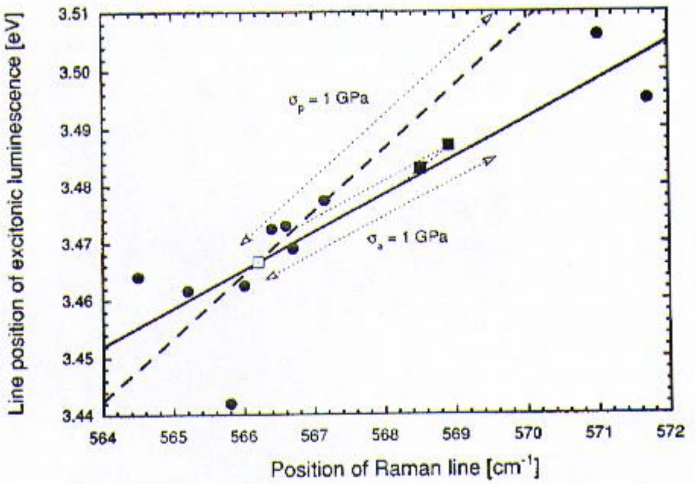

Measurement of the positions of the phonon modes enables determination of lattice temperature and thanks to plasmon phono coupling makes possible contactless determination of carrier concentration

Plasma frequency measured by light reflectance and plasmon-phonon moders – clear correspondence

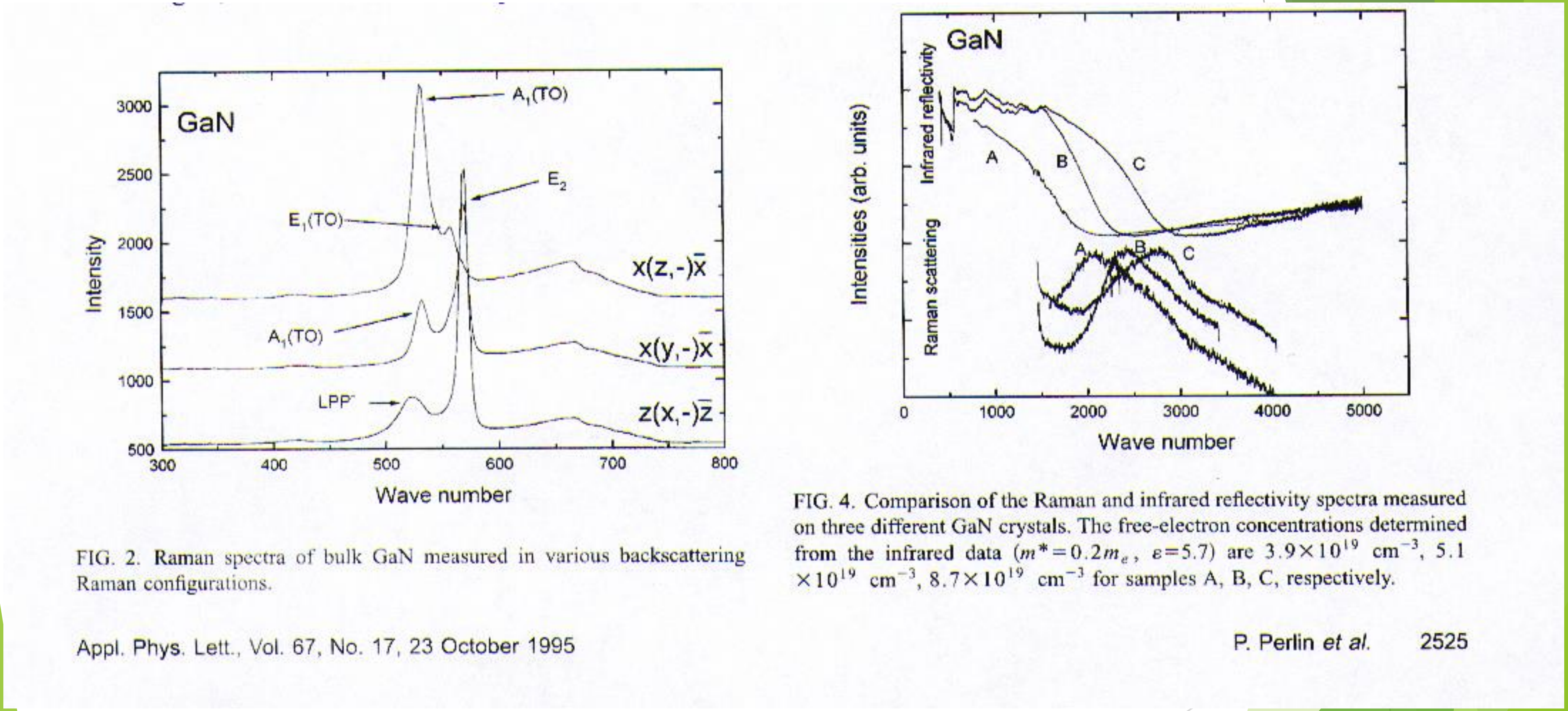

FIG. 2. Raman spectra of bulk GaN measured in various backscattering Raman configurations.

FIG. 4. Comparison of the Raman and infrared reflectivity spectra measured on three different GaN crystals. The free-electron concentrations determined from the infrared data ($m^* = 0.2m_e$, $\varepsilon = 5.7$) are 3.9×10^{19} cm^{-3}, 5.1×10^{19} cm^{-3}, 8.7×10^{19} cm^{-3} for samples A, B, C, respectively.

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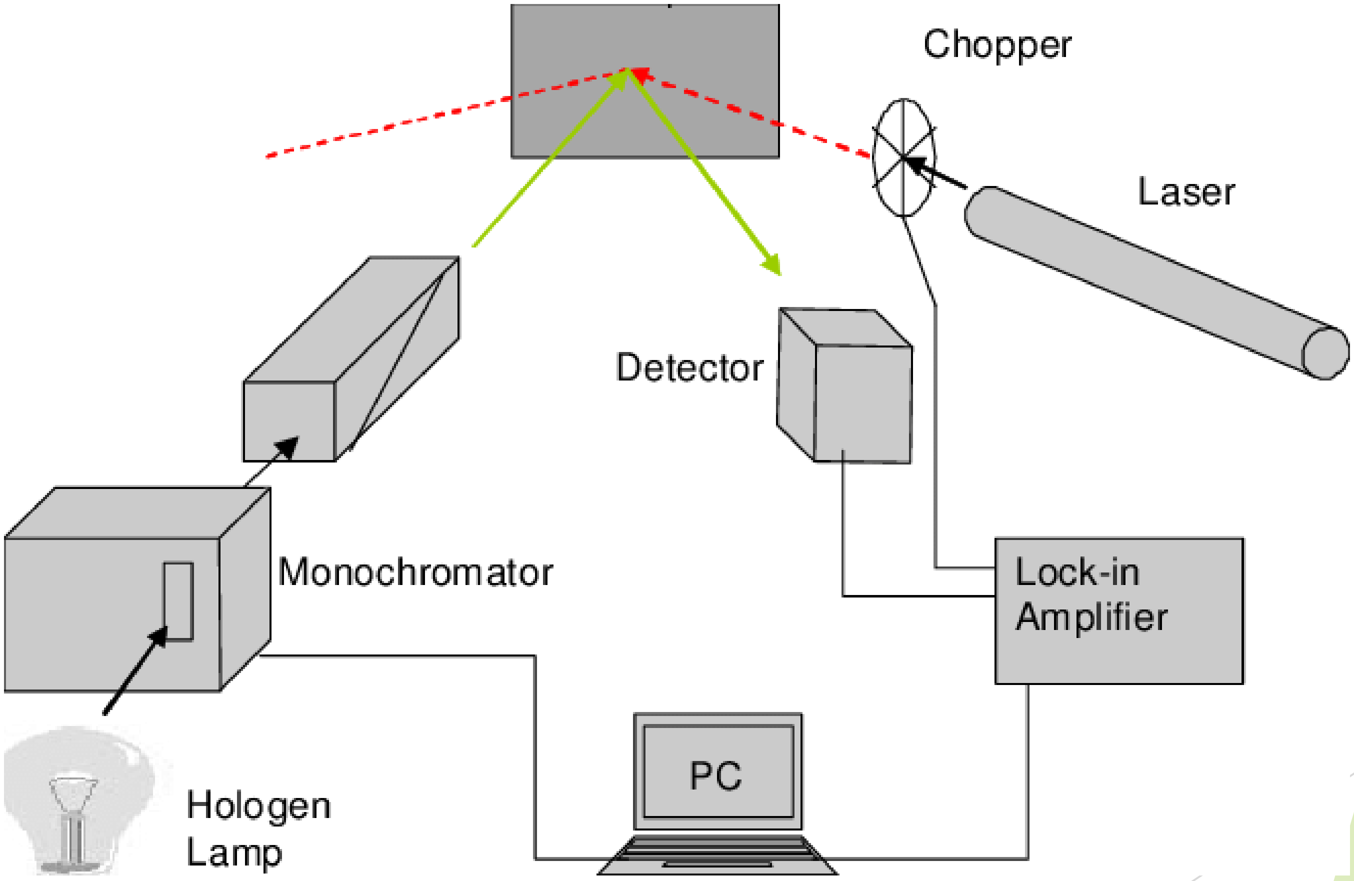
Photoreflectance measurement system

Modulated laser light being shined on the crystals changes the local electric field leading to modulatedn reflectance, increasing the sensitibvity of the measurement.



Photoreflectance spectra of GaN measured close to the energy gap position

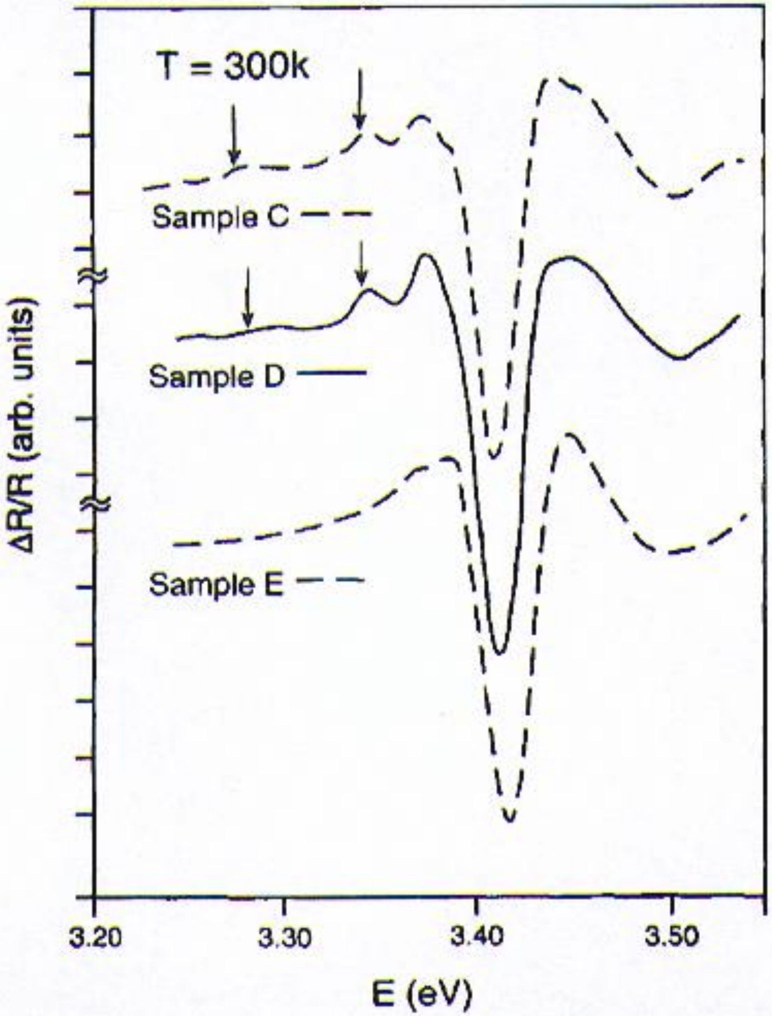
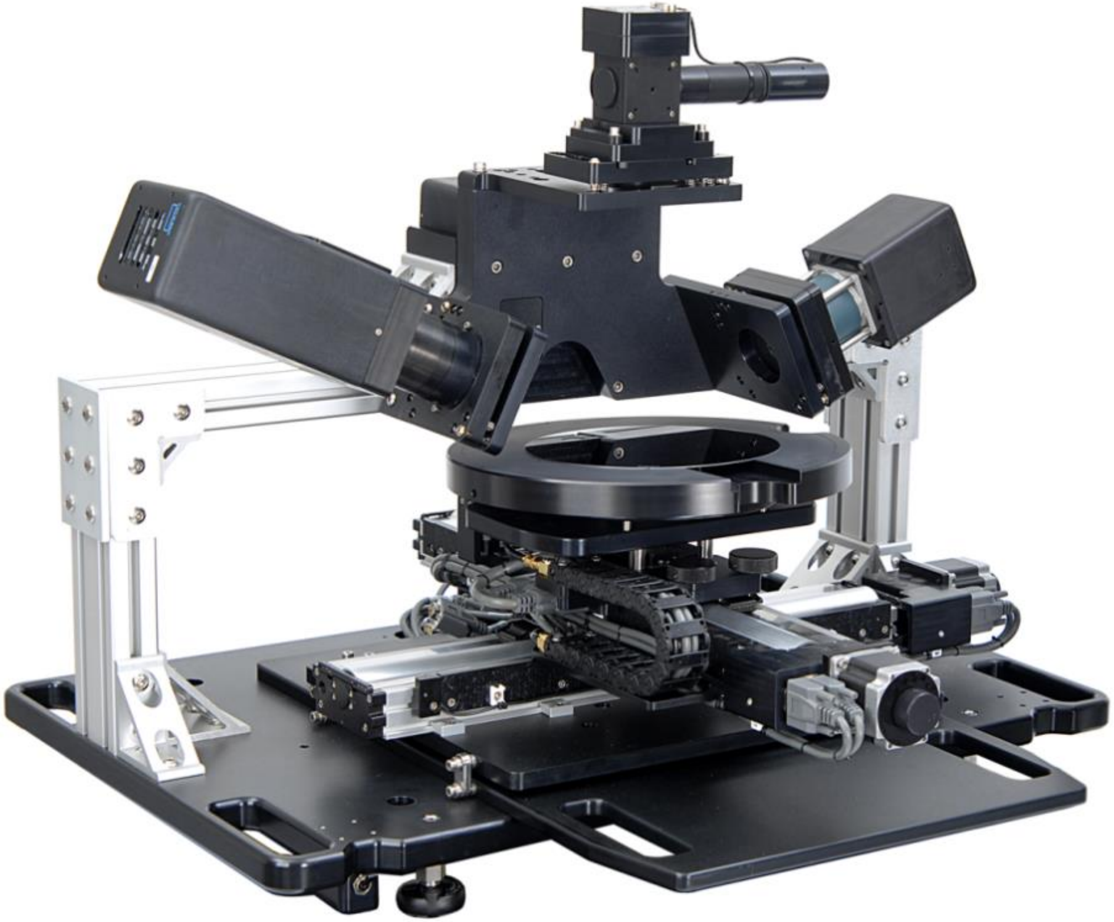


FIG. 4. PR spectra obtained at $T=300$ K for samples C, D, and E. The arrows indicate the presence of below band gap transitions which are seen in samples C and D but not in sample E.

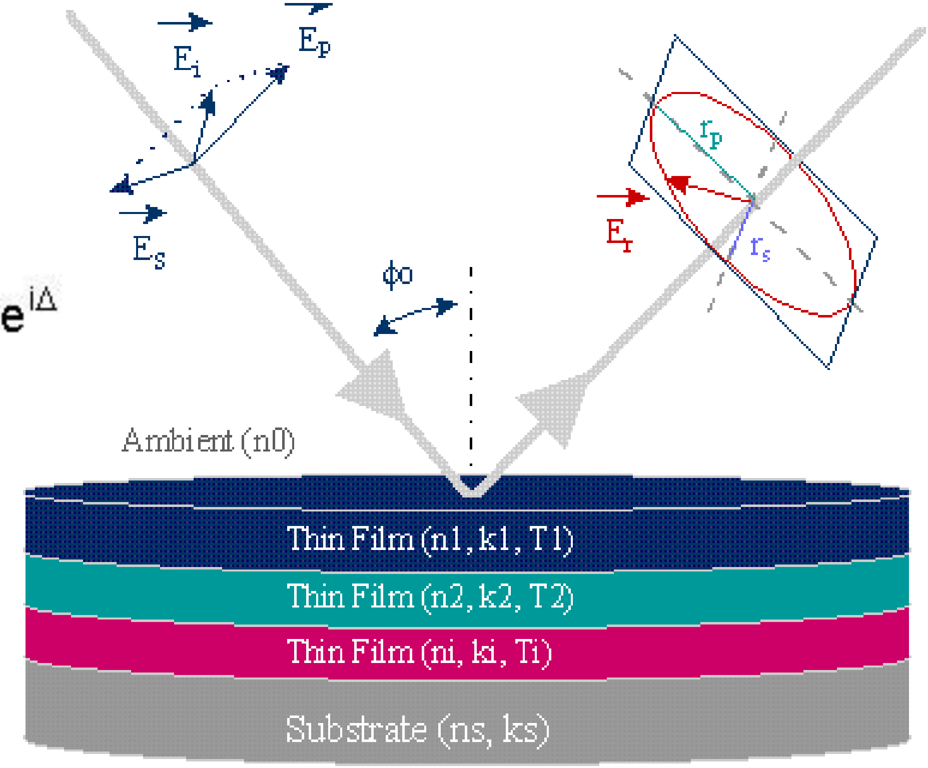
Elipsometer – basic tool for thin film characterization



Layer thicknesses, and refractive indices

Ellipsometry - measurement of phase shift between the components of the E vector (parallel and perpendicular to the plane of incidence)

$$\rho = \frac{R_p}{R_s} = \tan \Psi e^{i\Delta}$$



Measurement of thickness and refractive index of thin films.
High accuracy and ease of measurement

Summary

Popular optical methods provide information such as:

Bandgap value
Exciton energies
Sample quality, localization, carrier lifetimes
Dielectric constant, refractive index
Phonon energies
Stresses in thin films
Contactless measurement of electron concentration