Optical characterization of semiconductor

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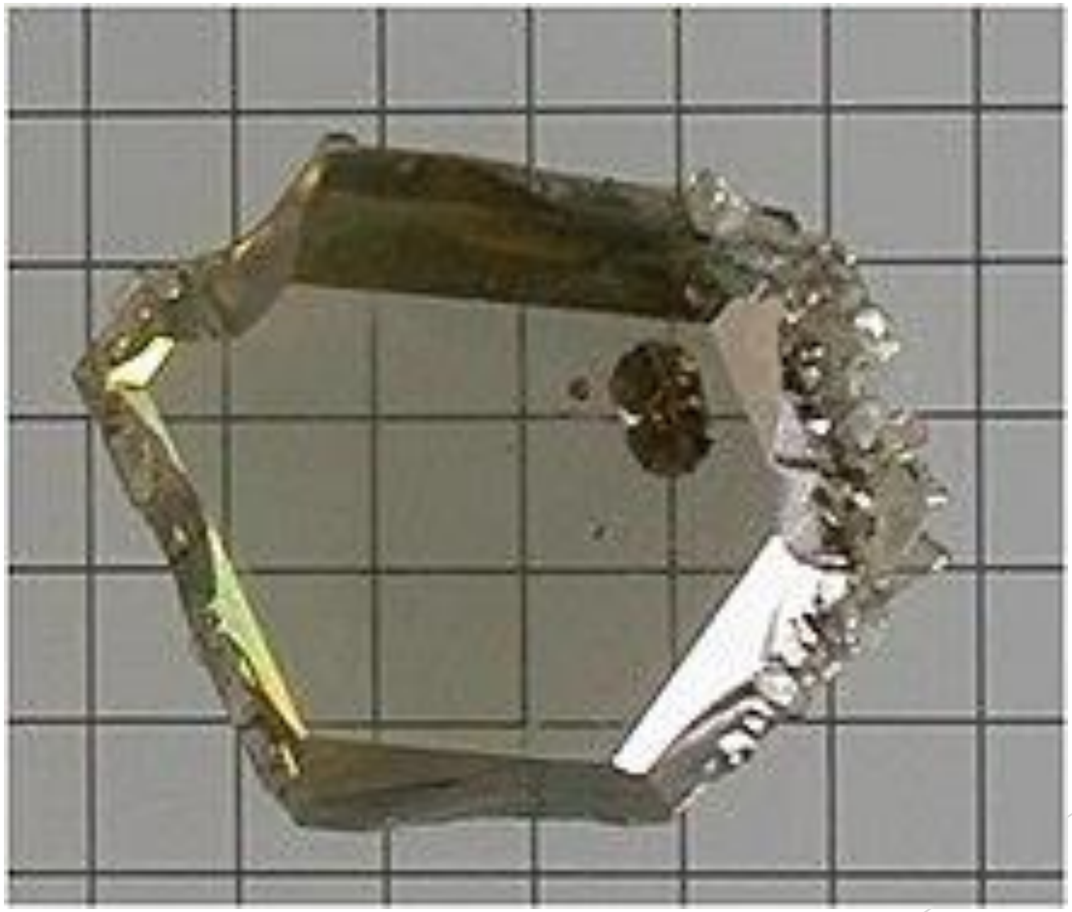


To fully characterize the material we used a range of complimentary methods

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

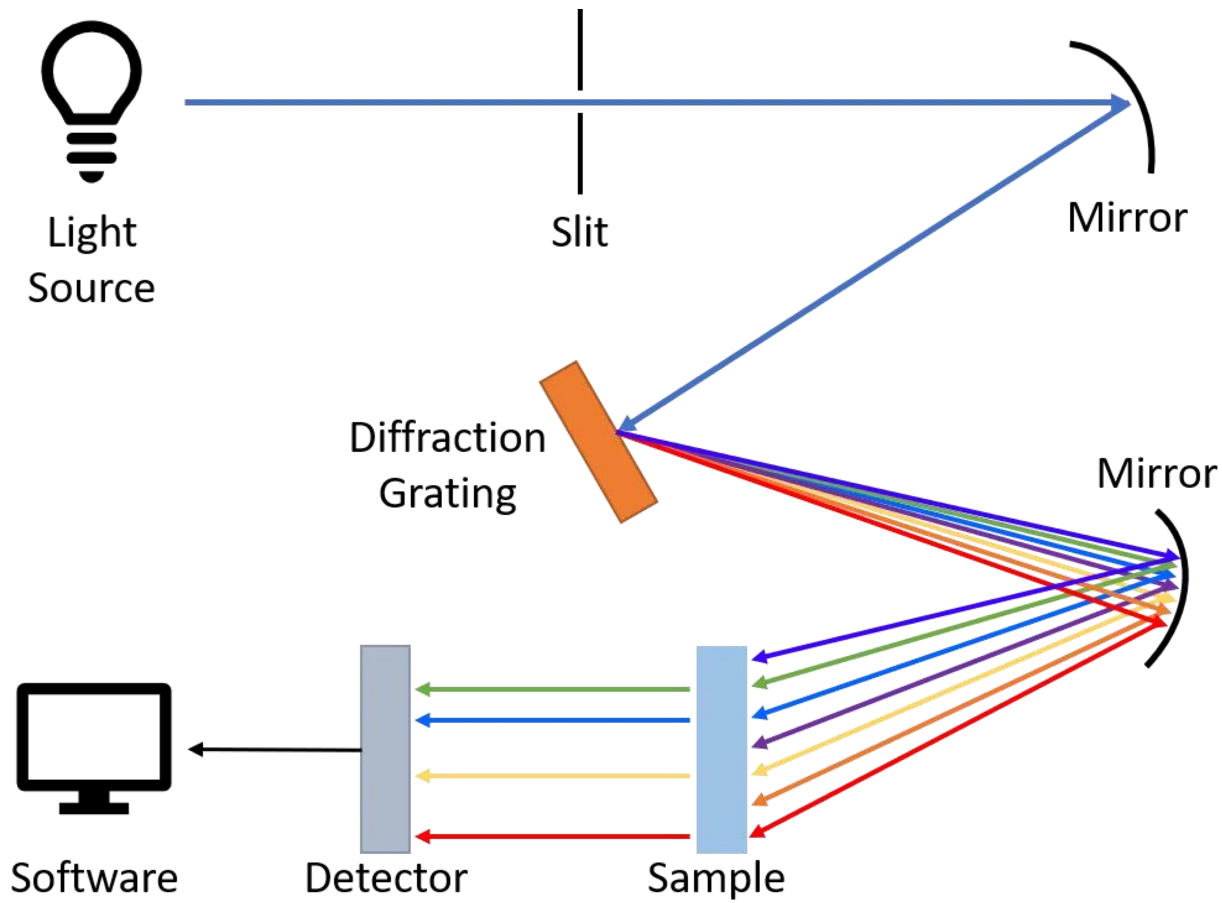
1. Energy gap of the material and in general band structure
2. Refractive index
3. Dopants and defects
4. Lattice vibrations (phonons)
5. Electron plasma escillations (plasmons)
6. Excitons, trions and other complex excitations

Optical characterization of semiconductors, advantages

Usually undistructive, equipment relatively cheap and accessible

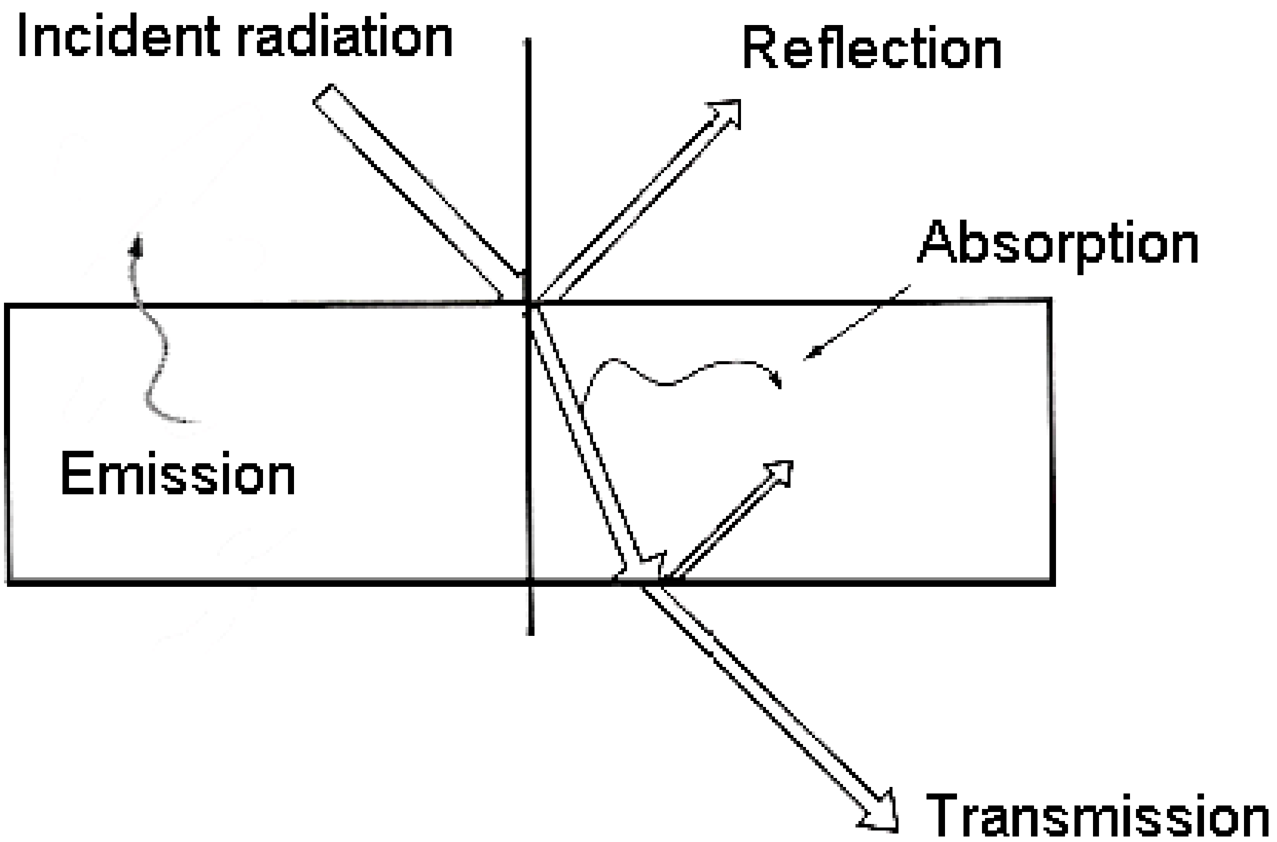
Insight into electronic structure of semiconductors

Optical absorption measurement



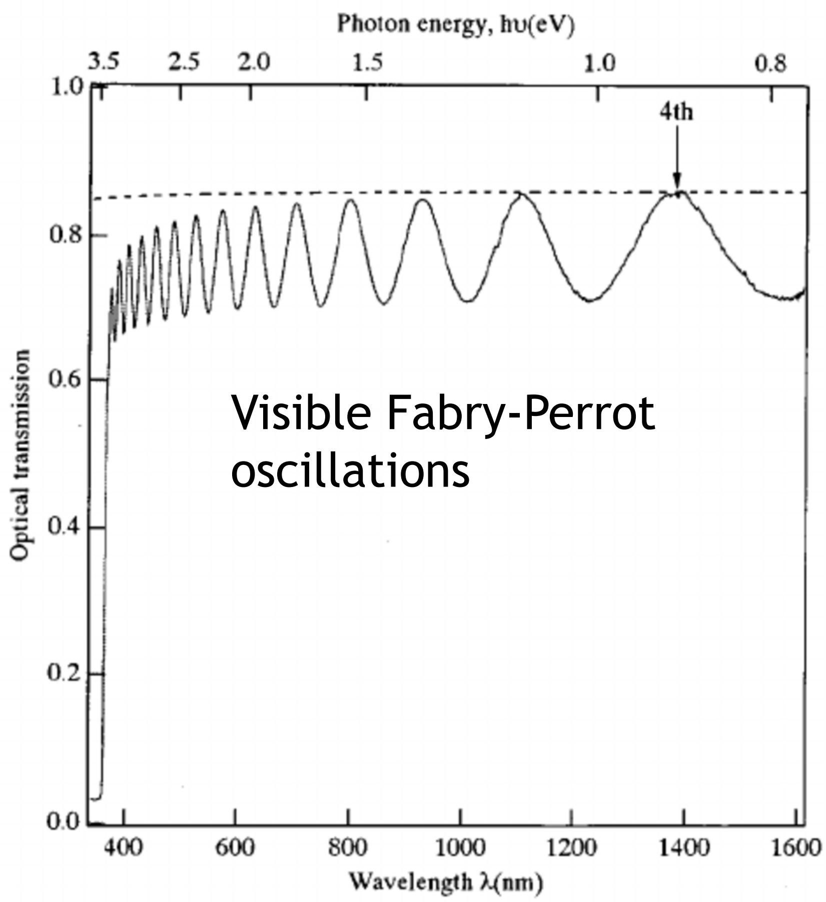
In order to measure high absorption coefficient we need very thin sample

Optical absorption



Corrections for reflected light must be made

Transmission spectrum of plane parallel sample of Gallium Nitride



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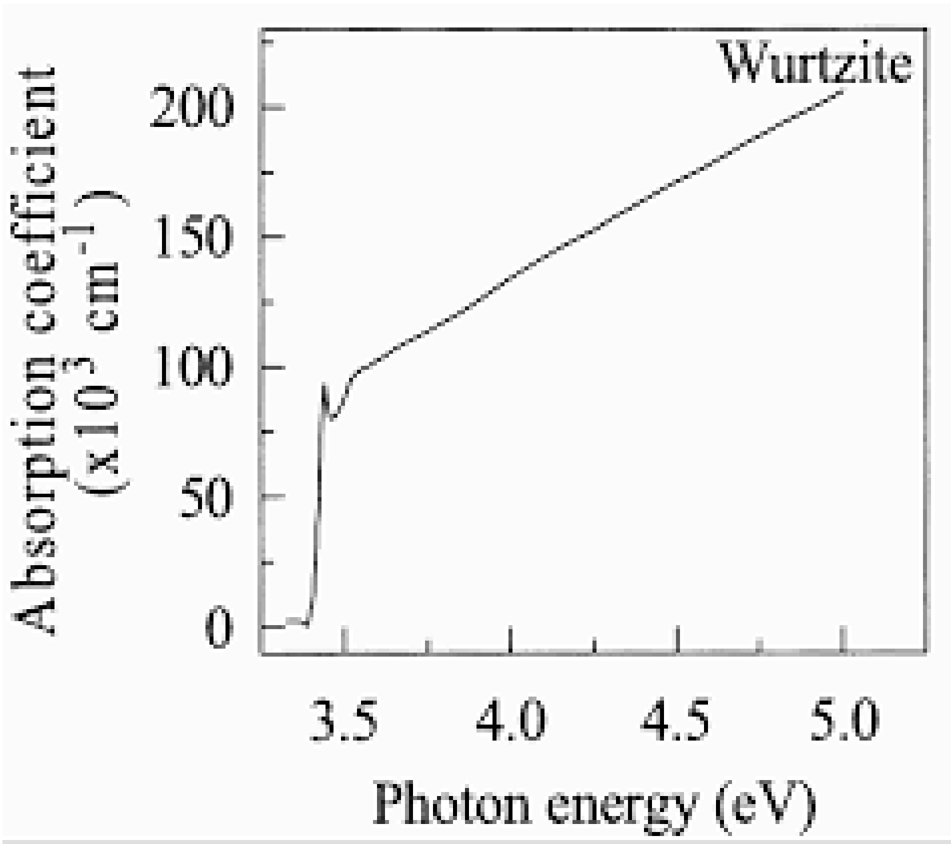
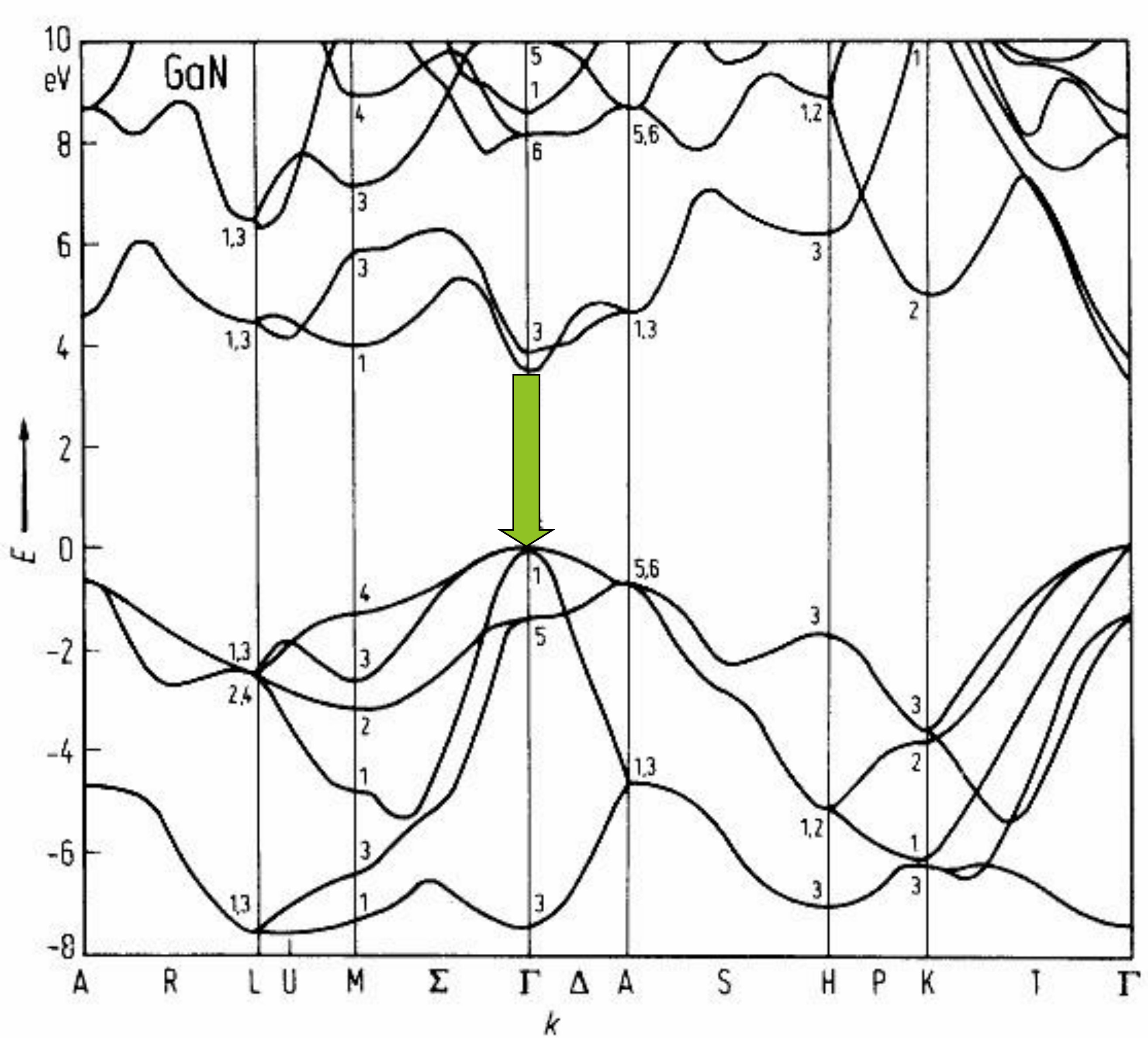
$$I(x) = I_0 e^{-\alpha x}$$

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

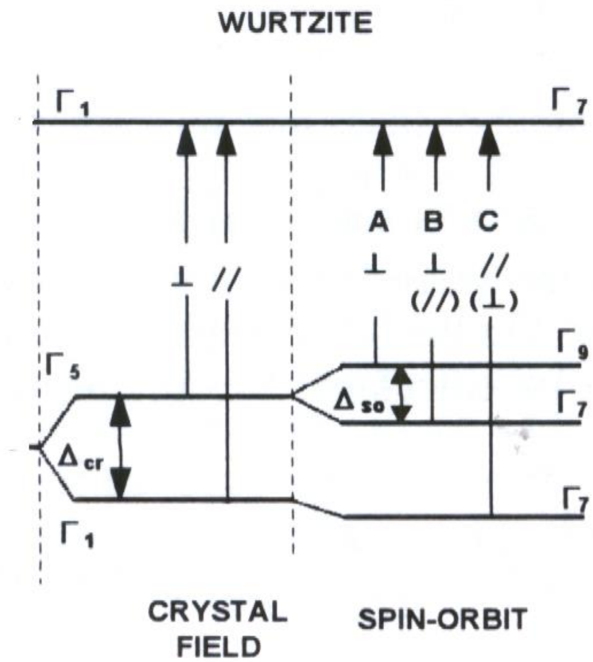


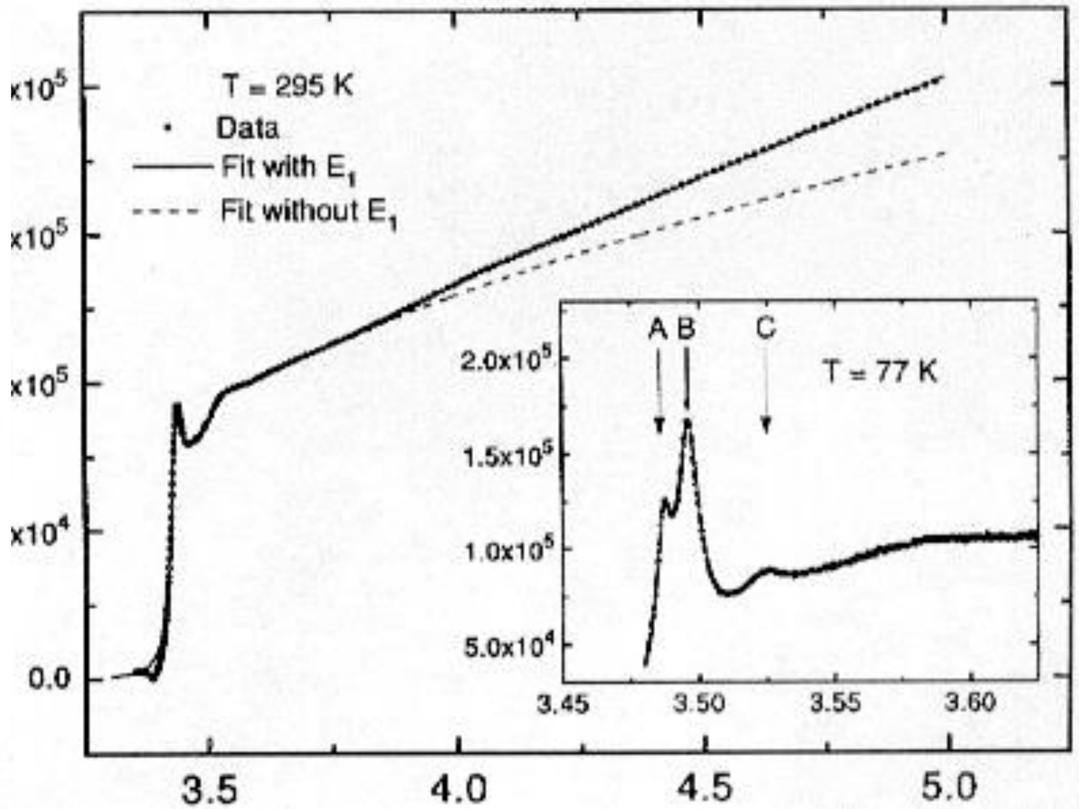
αd= 0-5. for easy measurements

GaN – band structure



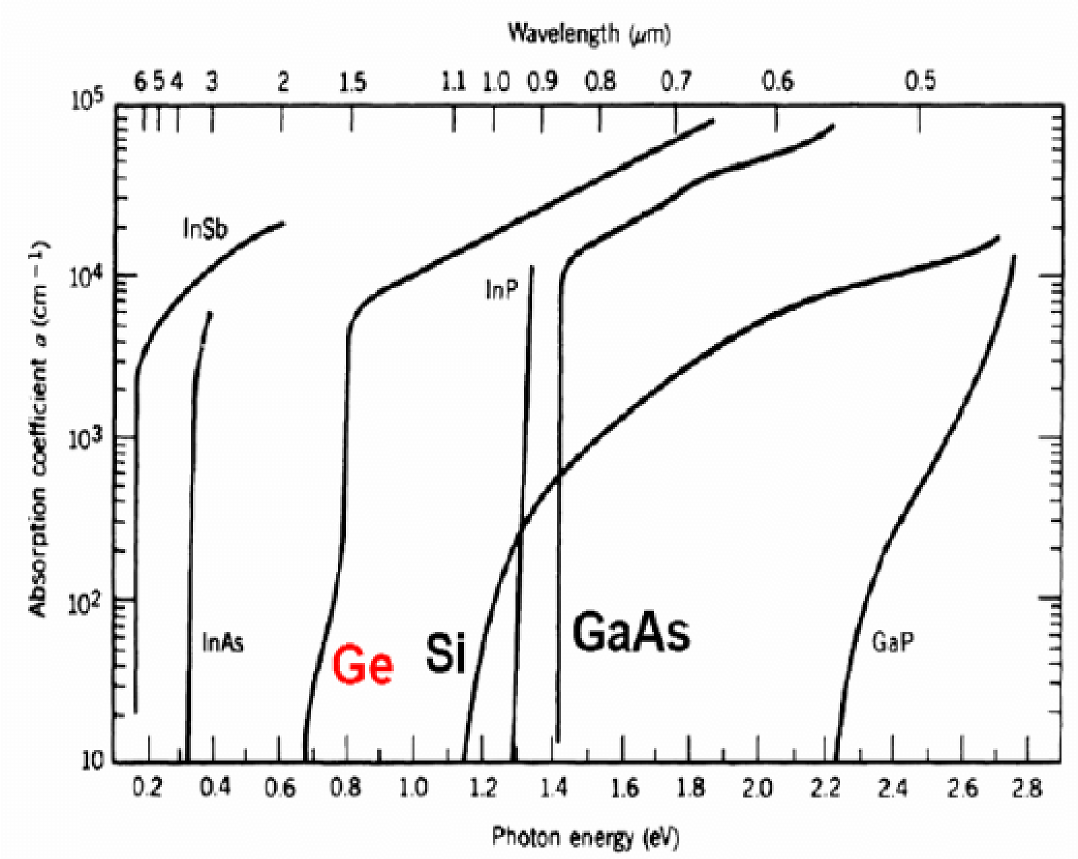
Details of the absorption spectrum of 0.4 μm GaN layer on sapphire





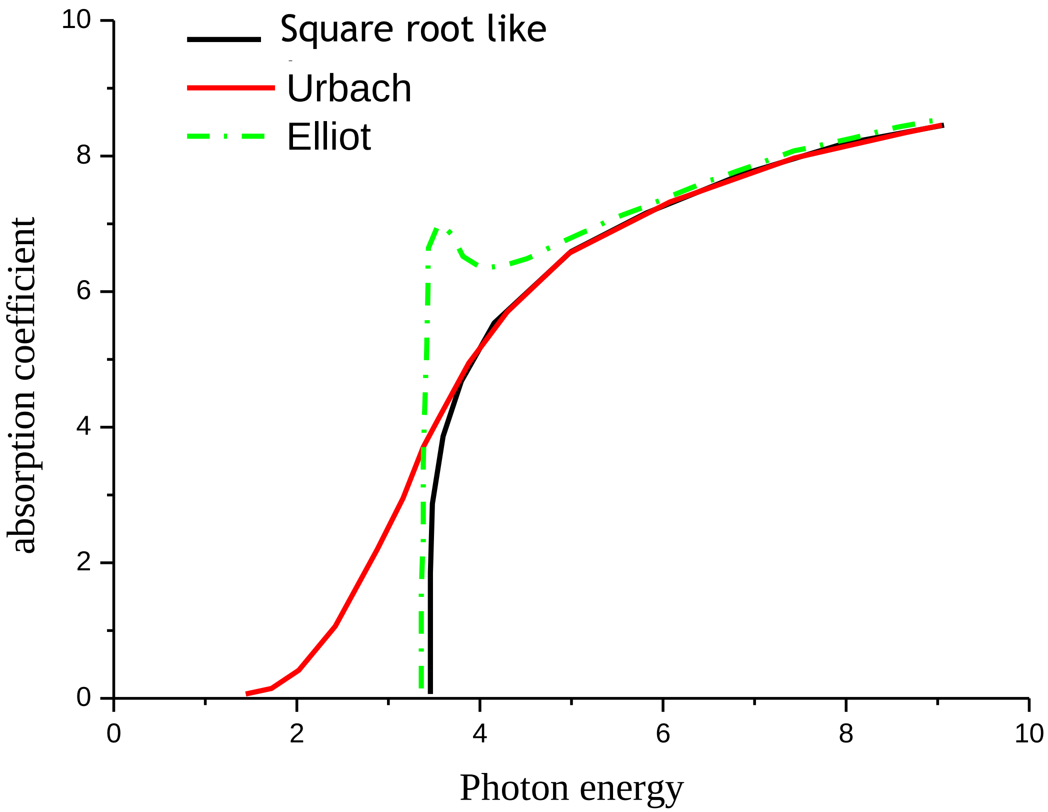
As the results you cna get:
Energy of excitons
Shape of the absorption edge
You need thin layers for this measurement

Absorption edges for various semiconductors



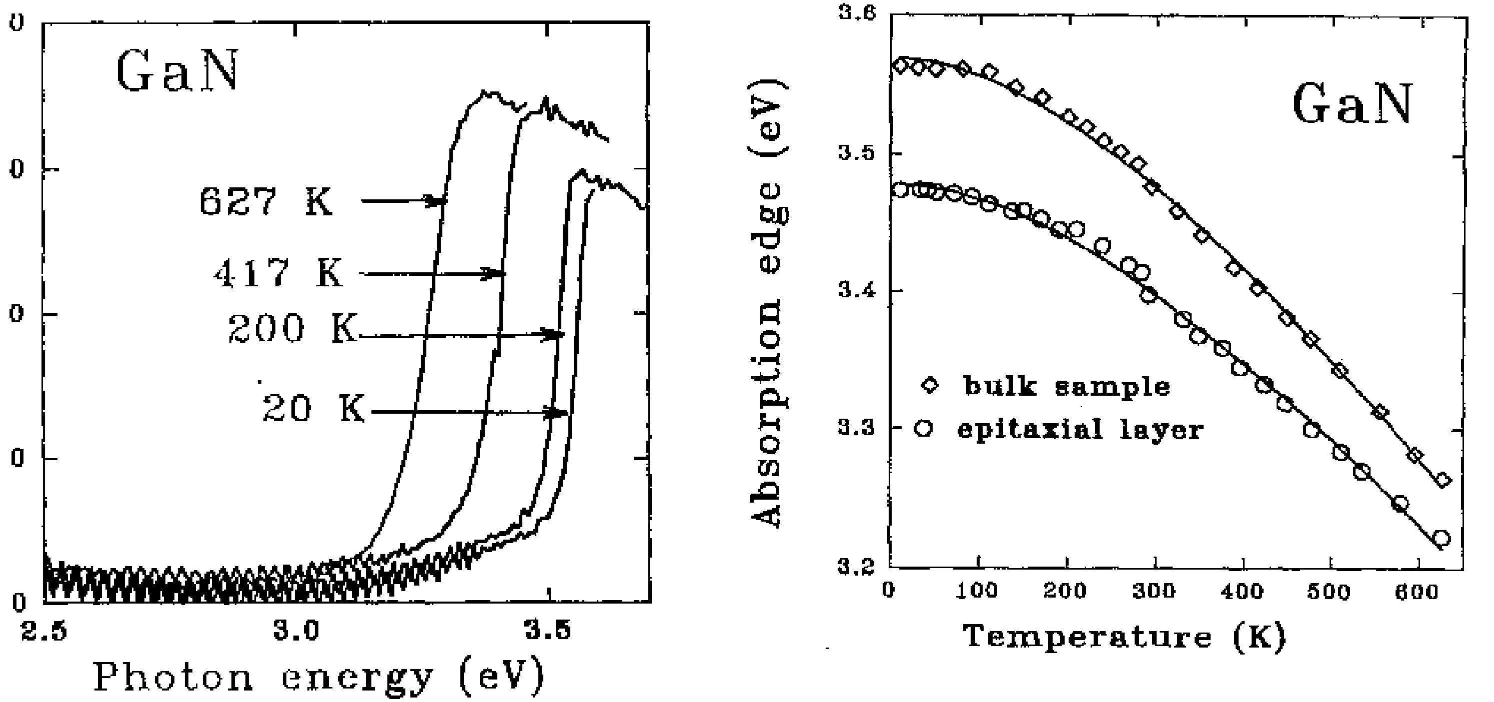
G. E. Stillman, V. M. Robbins, N. Tabatabaie, "III-V compound semiconductor devices: optical detectors," *IEEE Trans. Electron. Devices*, vol.31, no. 11, pp. 1643-1655, Nov. 1984.

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



Urbach – disorder related
Elliot – excitonic

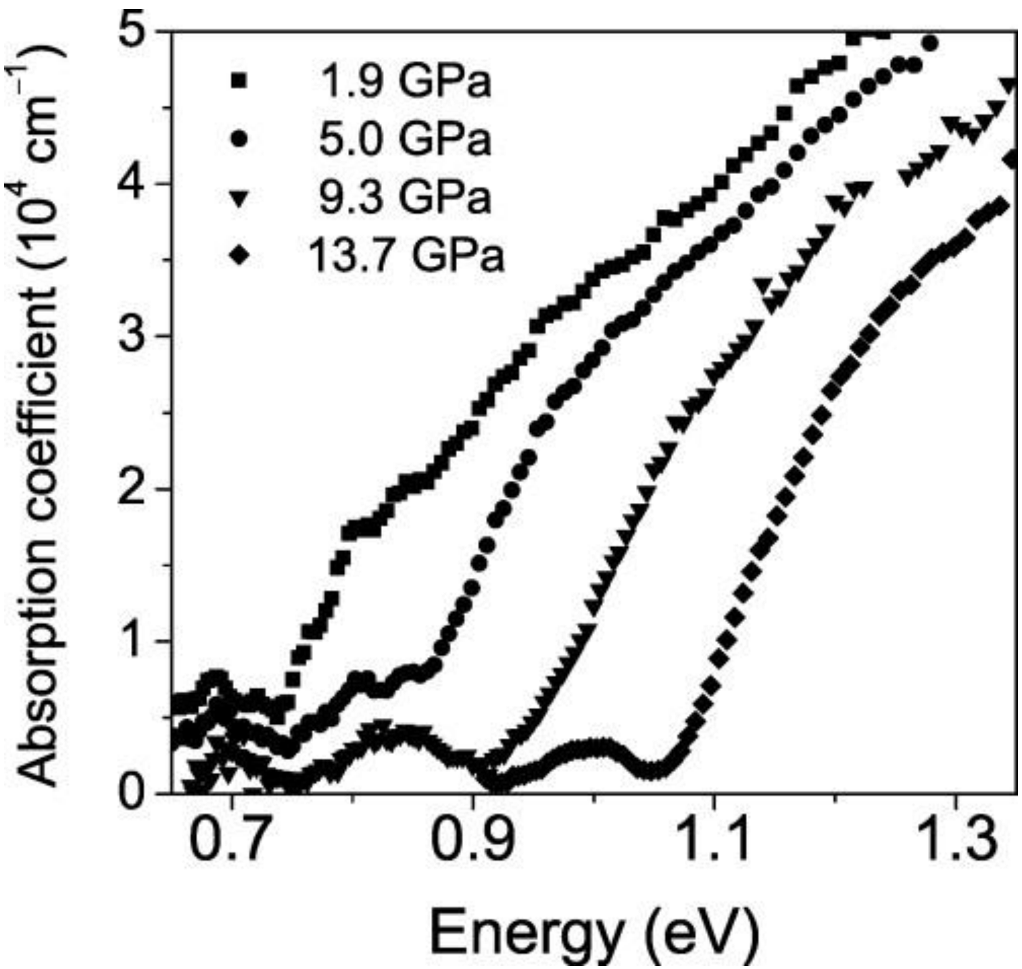
Temperature dependence of the absorption edge



Lattice dilation and electron-phonon interaction

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

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



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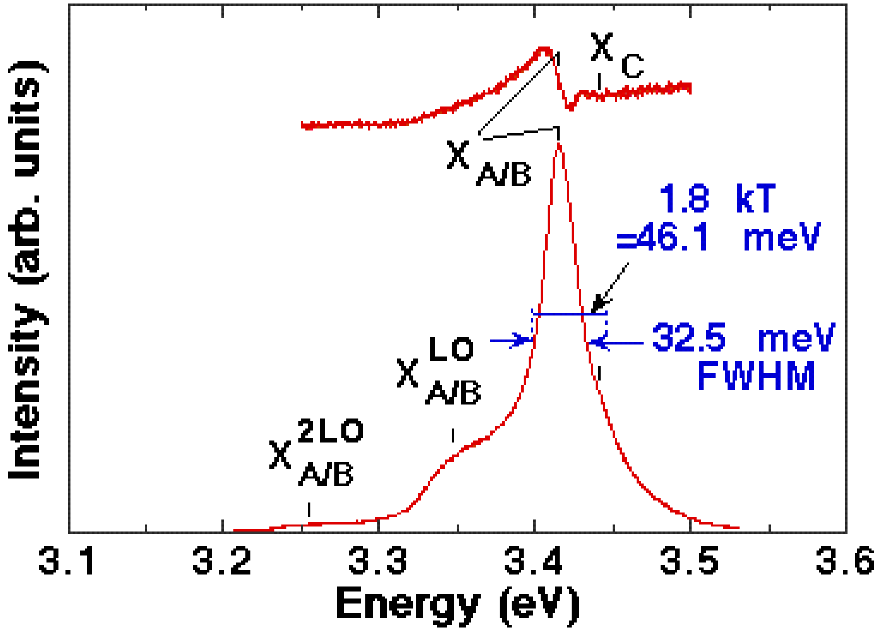
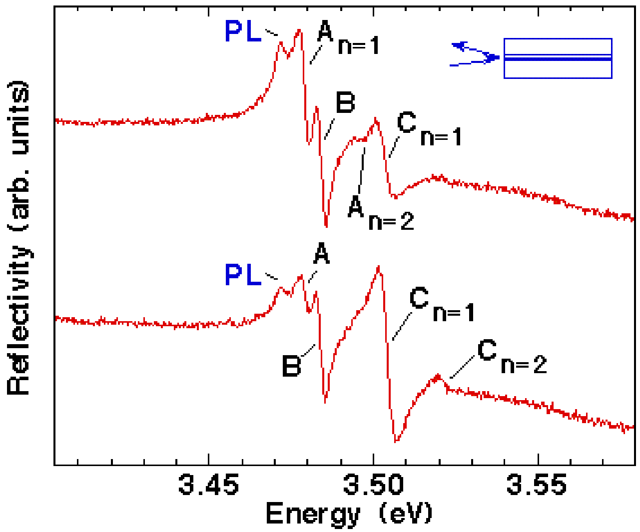
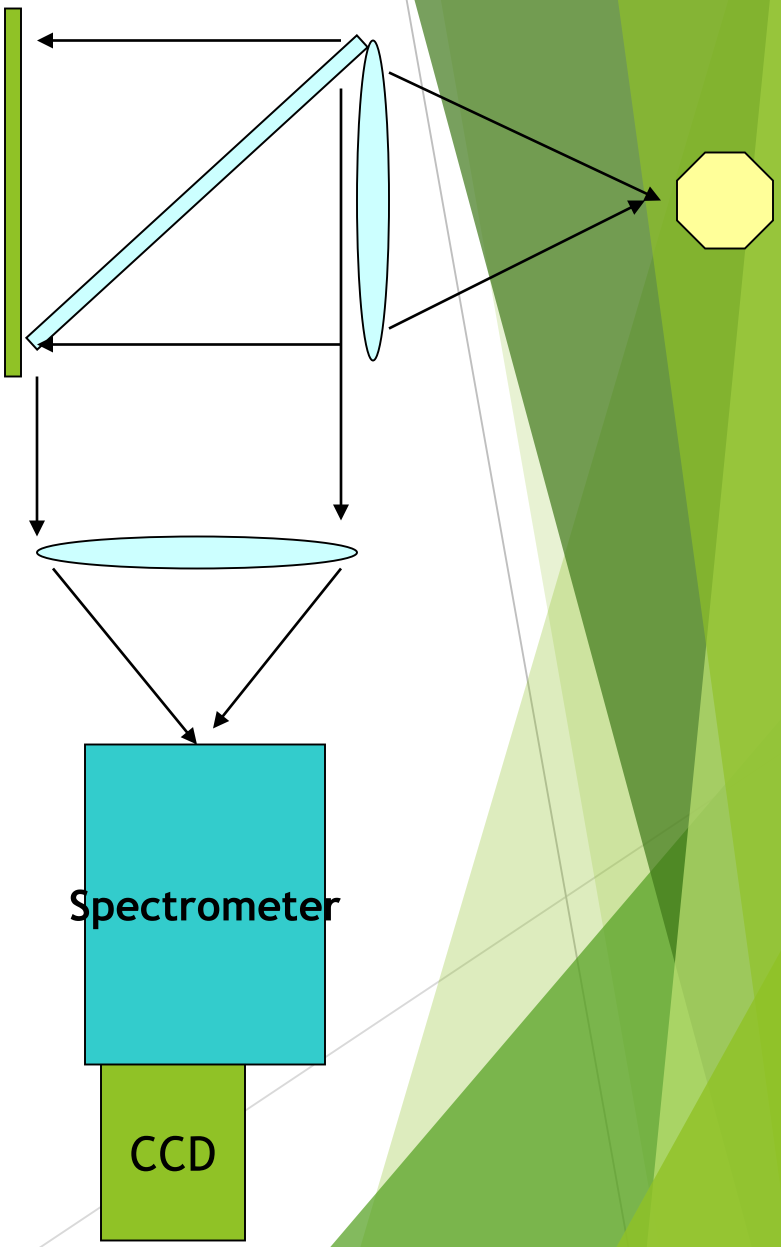
Optical reflectance

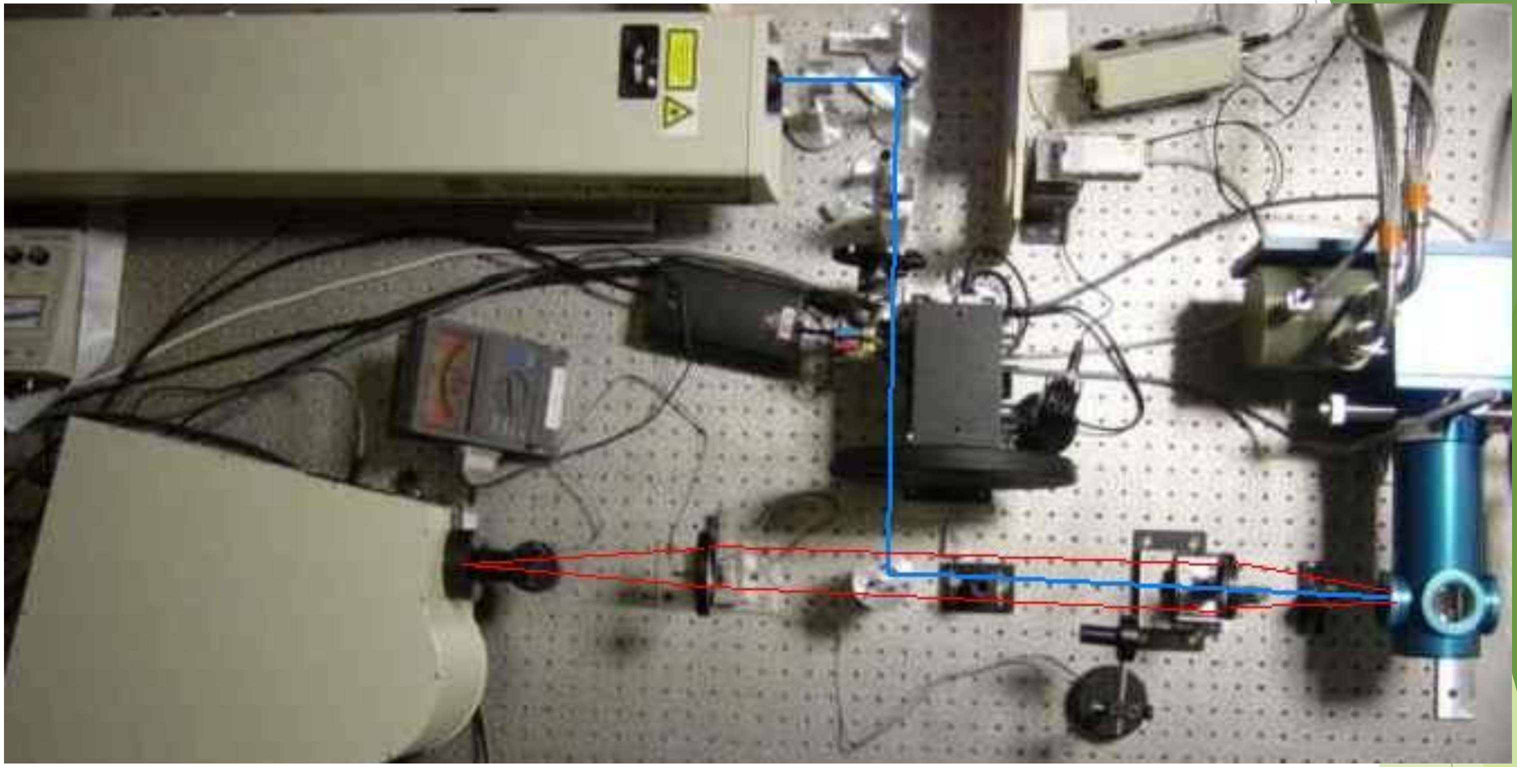
No need to thin down the sample





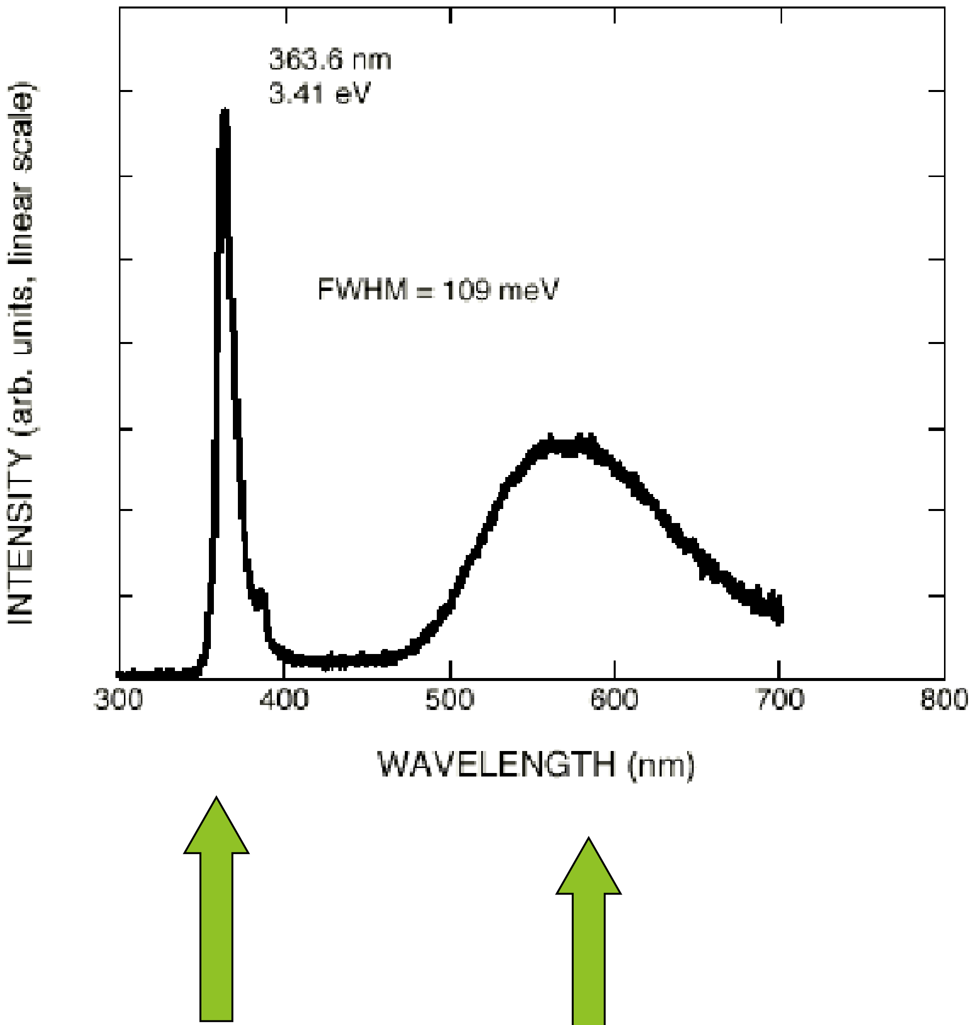


Photoluminescence



Very simple (usually) measurement system
Easy introduction of external perturbations like: T,p, B, E
Light source, usually laser
Well equipped spectrometer is needed.

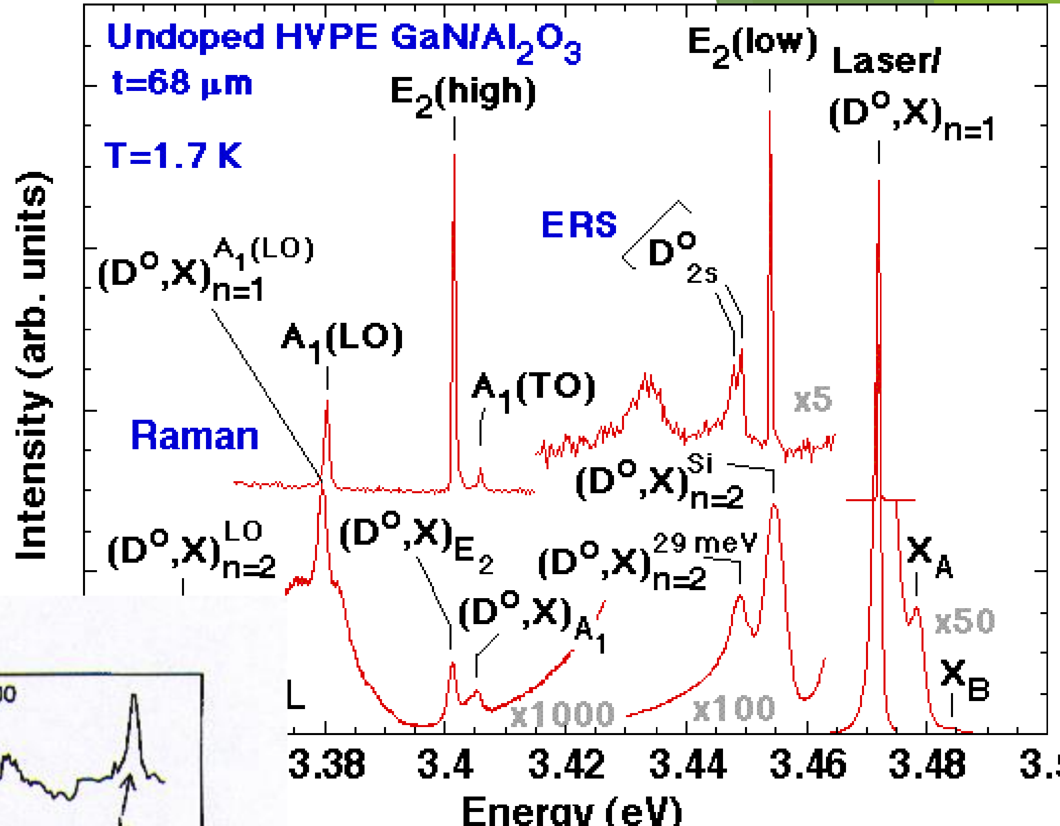
Photoluminescence



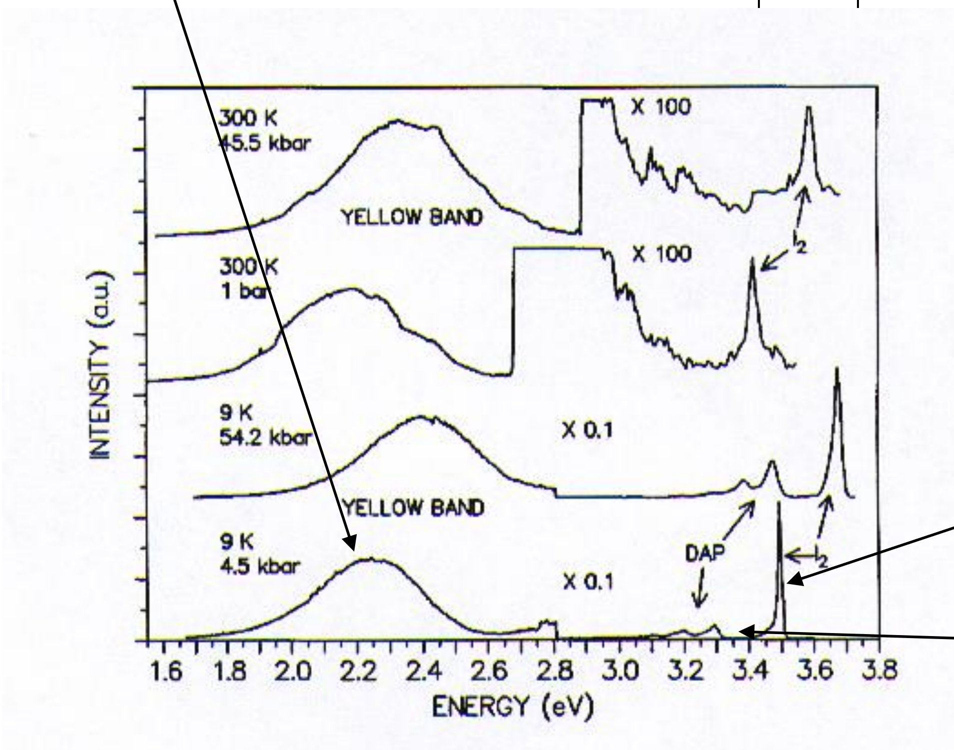
Shallow states, energy gap

Deep states

Photoluminescence



Deep levels



excitons

Donor acceptor pairs

Photoluminescence energy depends on temperaturę and strain of the material

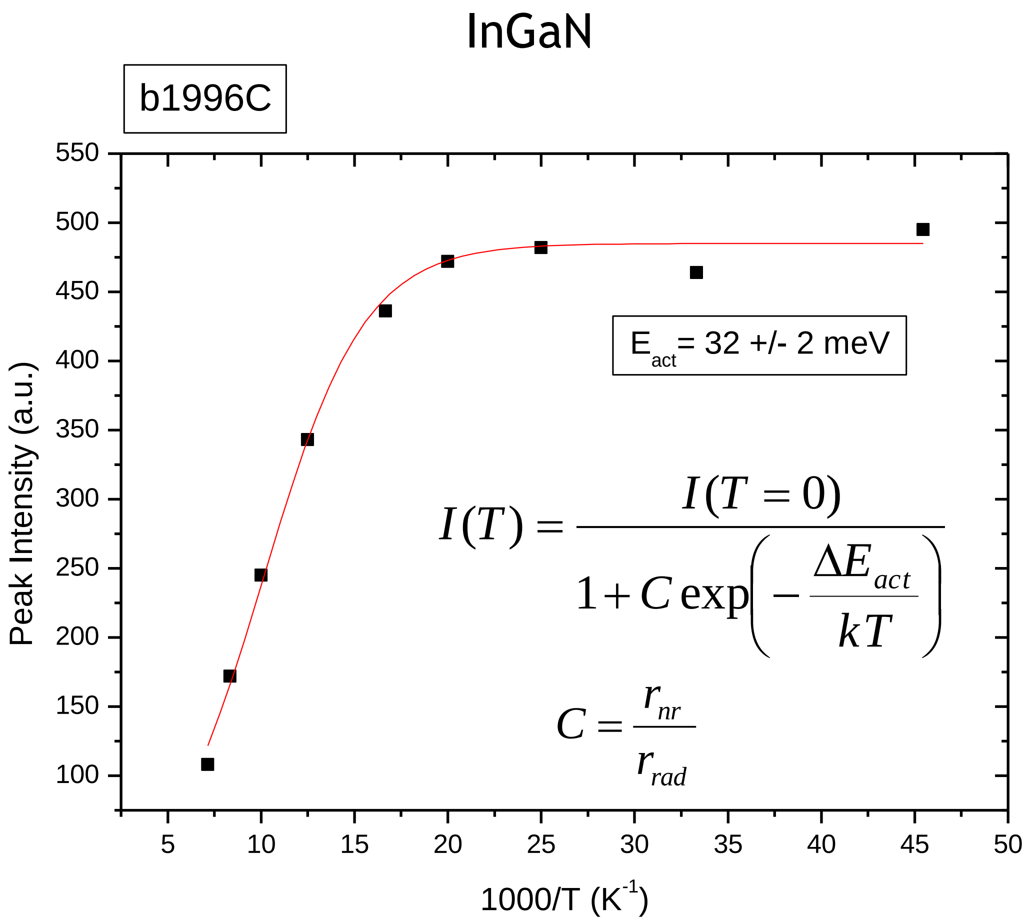
Strain and deformation potentials: C, D

$$E^{\partial} = E^{\partial,0} + C\left(\varepsilon^{xx} + \varepsilon^{\lambda\lambda}\right) + D\varepsilon^{zz}$$

Temperature

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

Thermal Decay of the photoluminescence



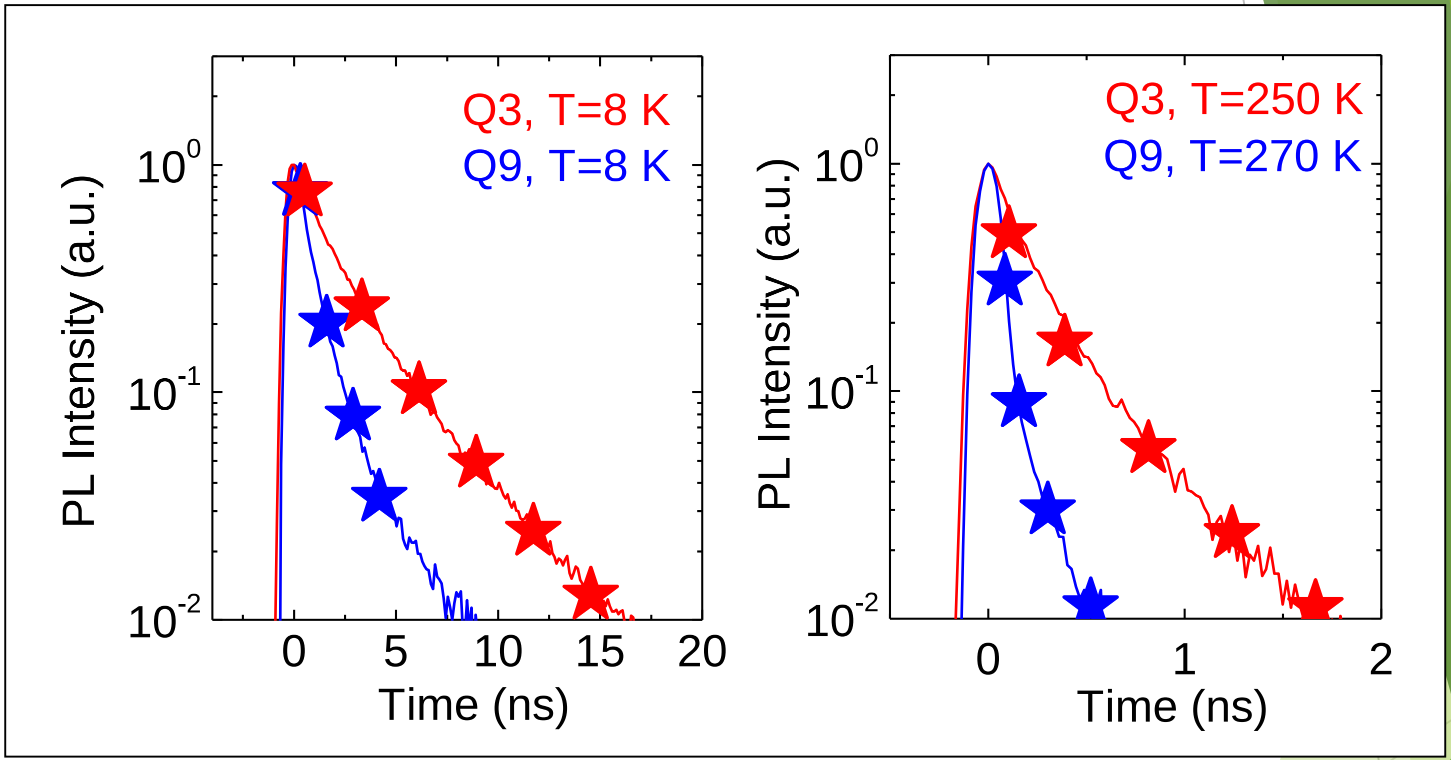
$$I(T) = \frac{I(T=0)}{1 + C\exp\left(-\frac{\Delta E_{act}}{kT}\right)}$$

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

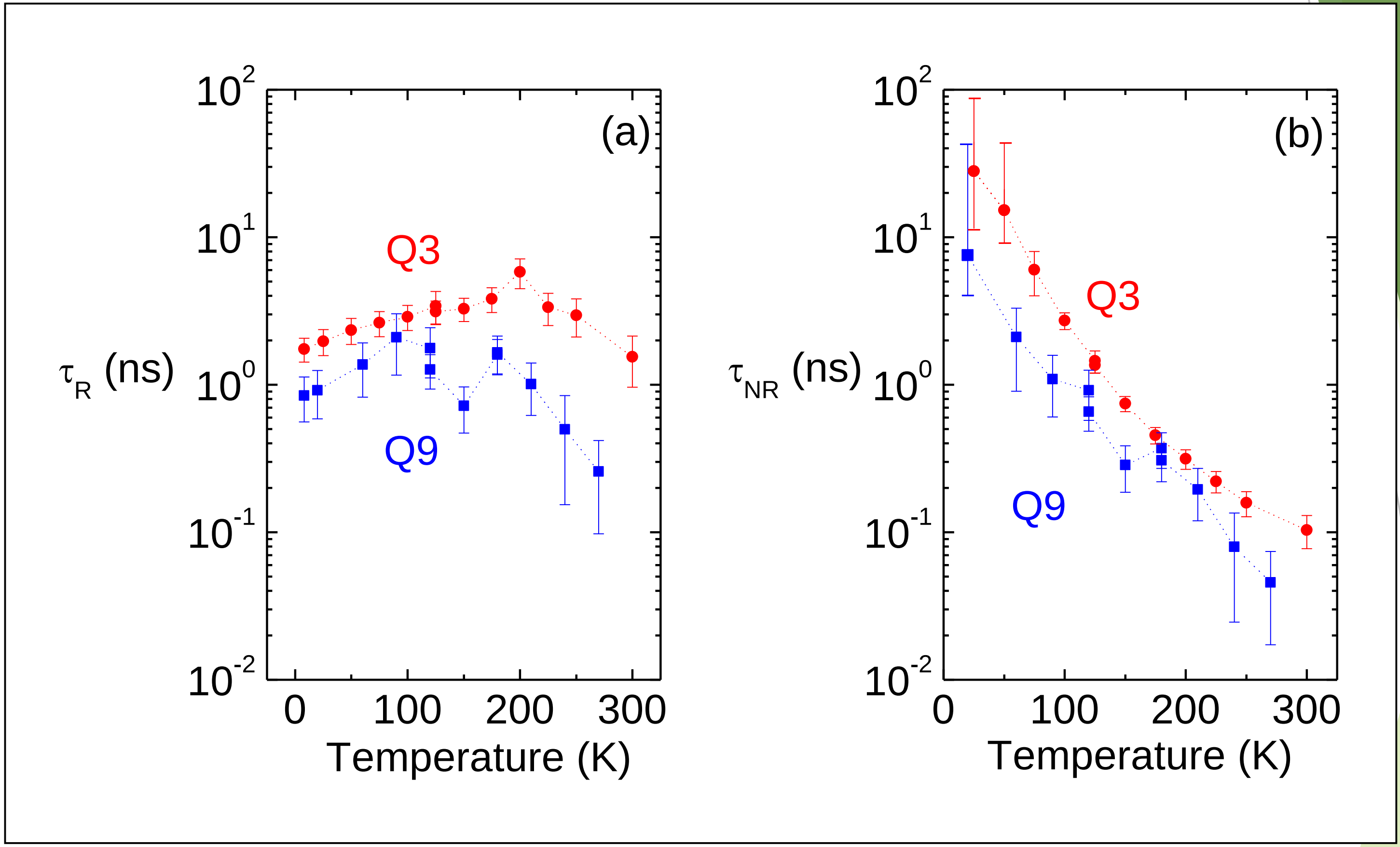
Brings information about the characteristic energies involved, exciton binding Energy, localization energy, donor/acceptor energies.

Non-radiative recombination

Time resolved photoluminescence (femtosecond lasers, streak camera)

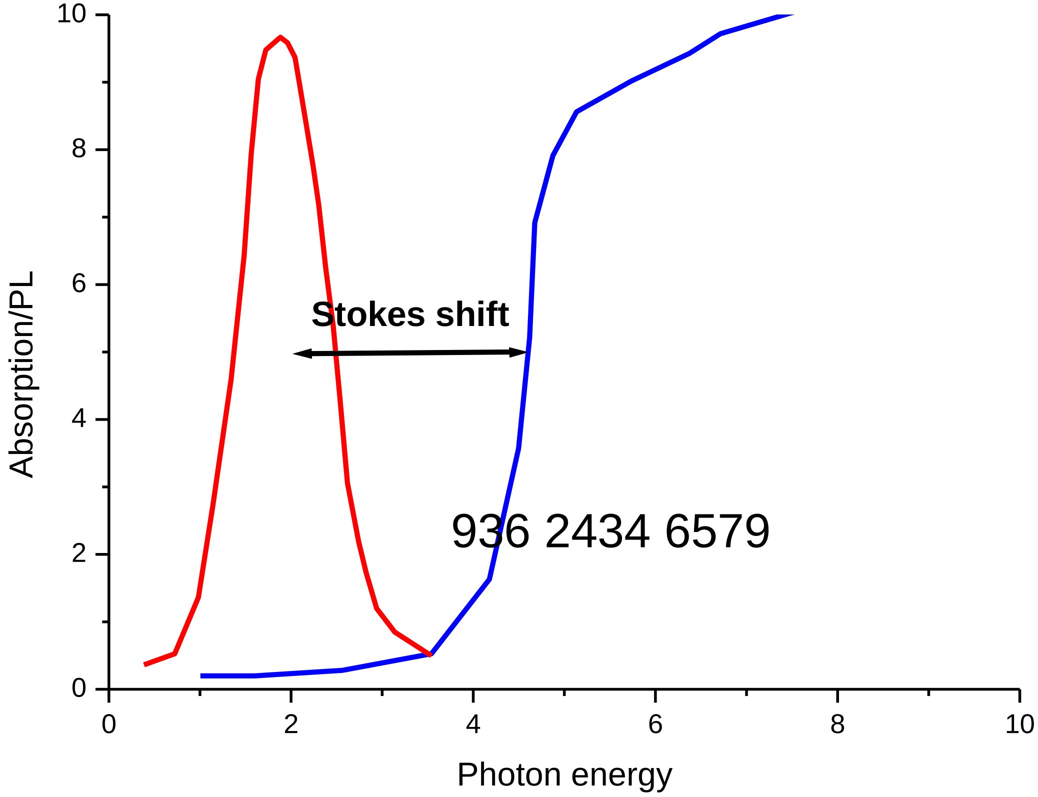


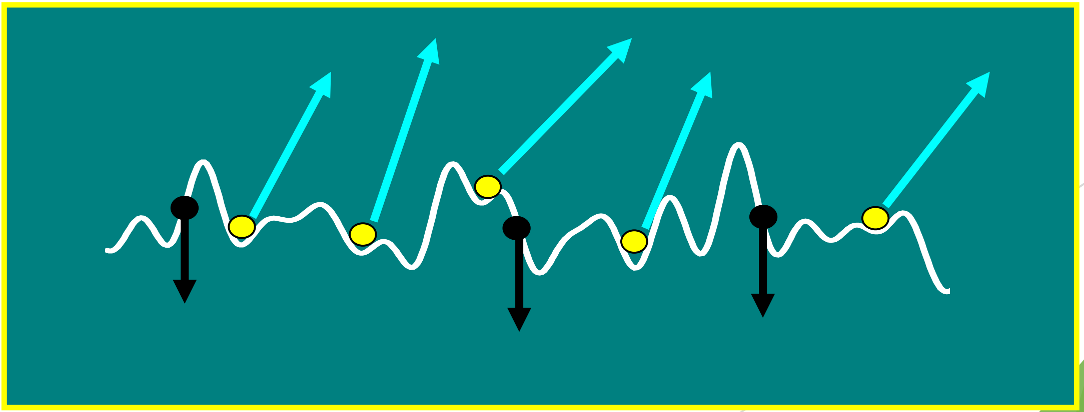
Determination of radiative and non-radiative recombination times.



Determination of radiative and nonradiative recombination Times using time resolved PL as a function of

Stoke’s shift the measure of carrier localization.





Free carrier absorption, the interaction with plasmons

Longitudinal oscillation of free carriers plasma

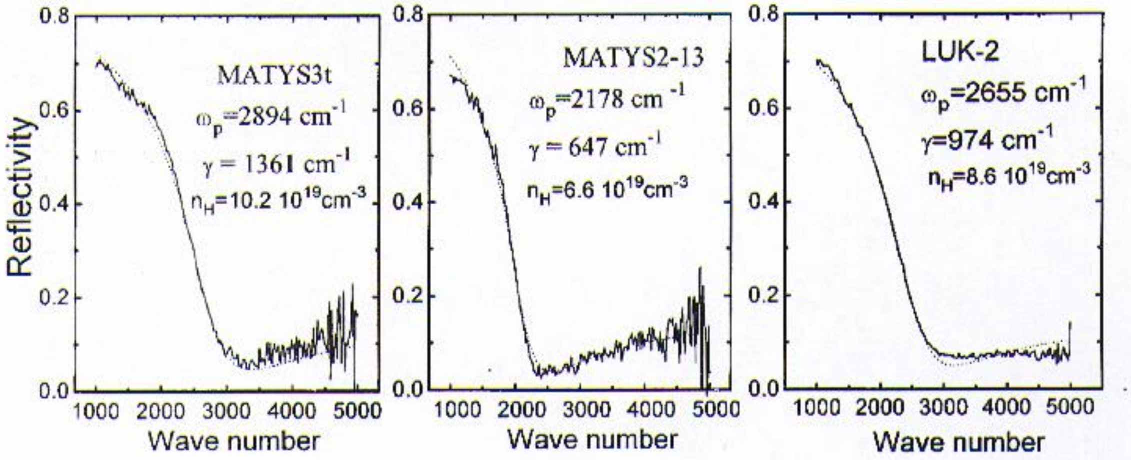


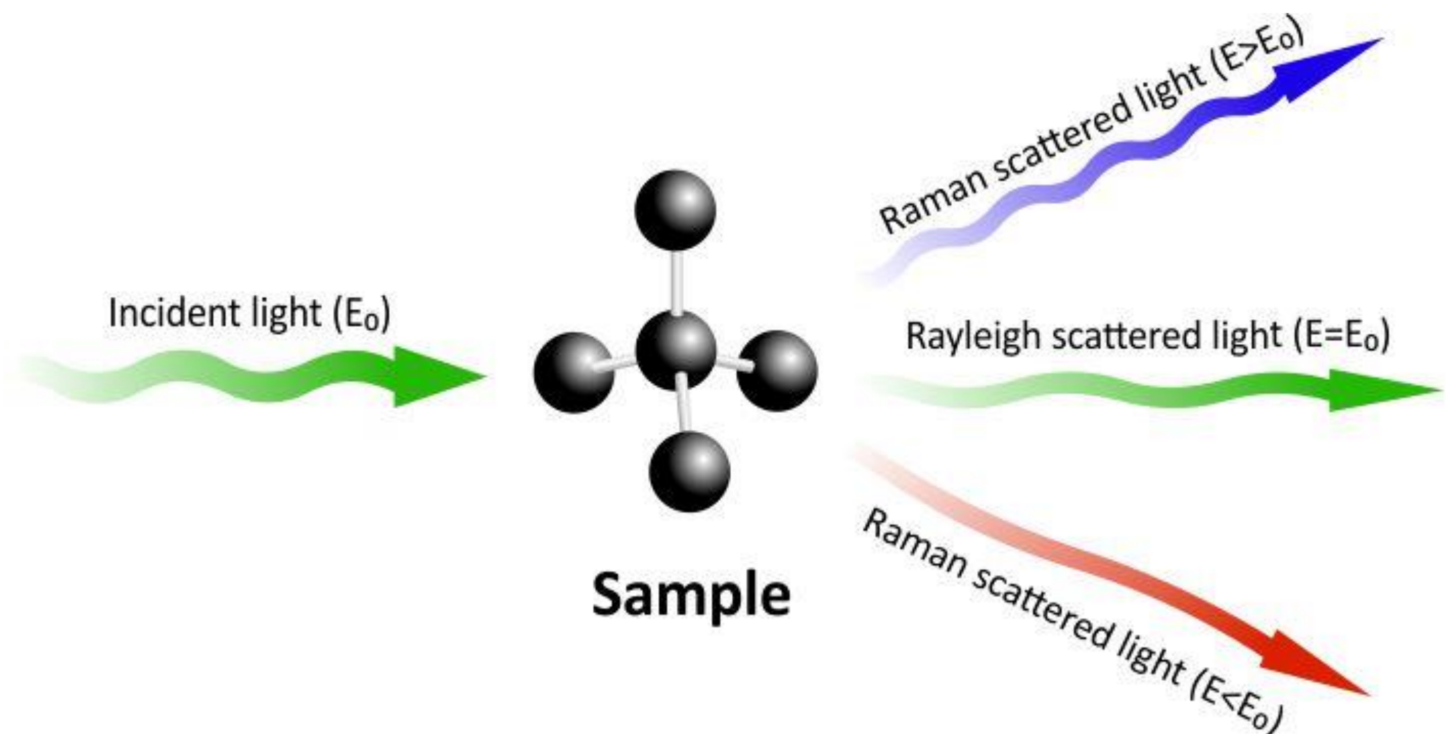
FIG. 1. Examples of reflectivity spectra for three samples of different electron concentrations. The dotted line shows the best fit of Eq. (2) to the experimental data, ωp is a plasma frequency, and γ is electron damping parameter of Eq. (4).

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

Determination of the effective mass of electrons.

Raman scattering

Measurement system similar to PL but:
Triple or single spectrometer with Notch filter
Mostly room temperature
Popular micro-Raman setups with a microscope



Phonon modes of GaN

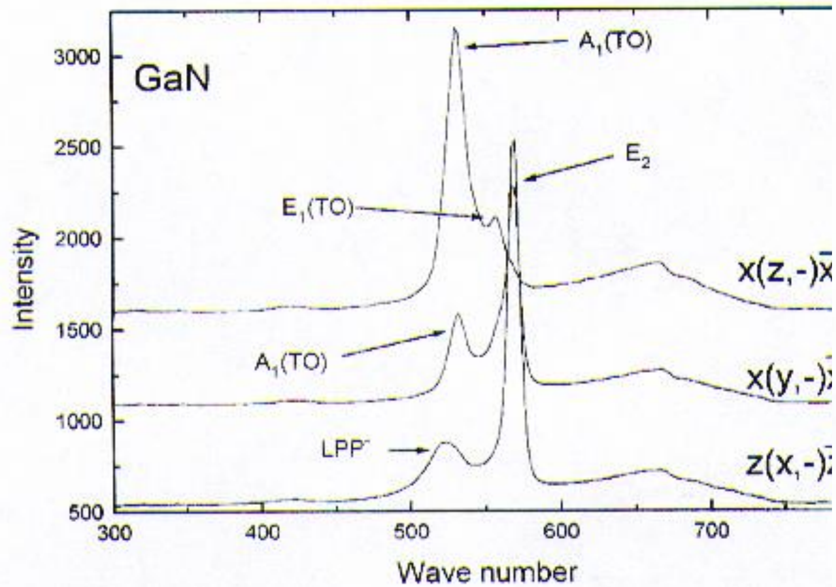


FIG. 2. Raman spectra of bulk GaN measured in various backscattering Raman configurations.

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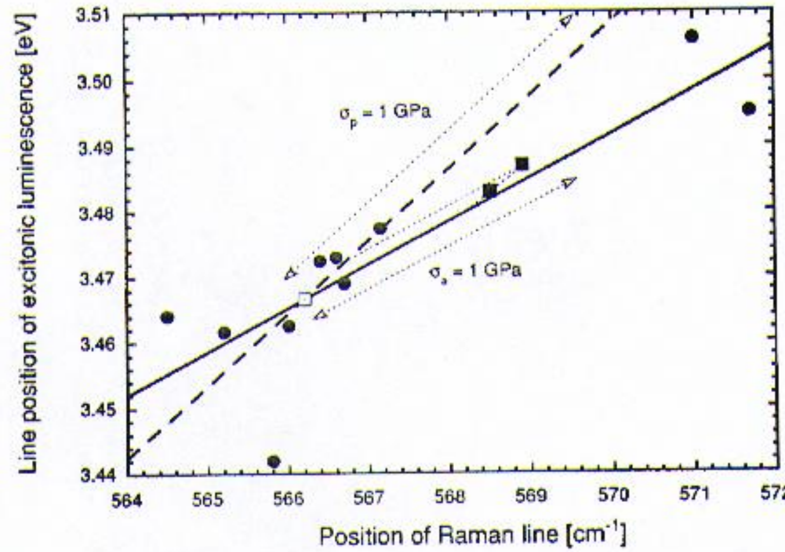
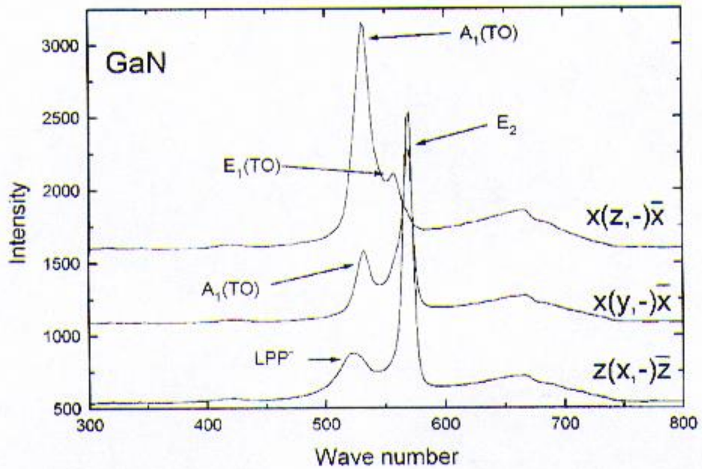


Position of Raman mode may be used as a measure of internal stress or/and the sample temperature

Korelacja krawędzi plazmowej i modów sprzężonych



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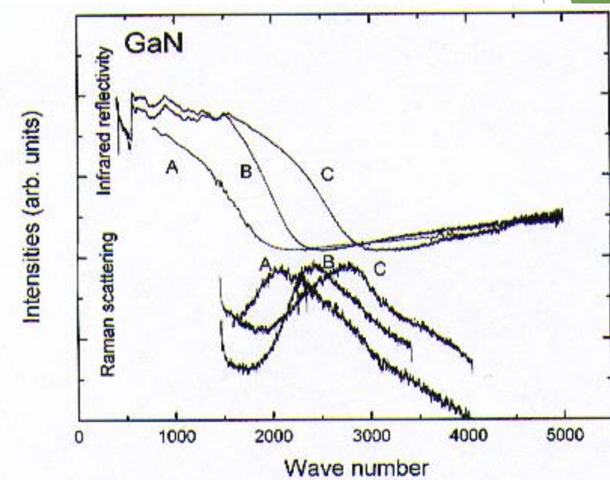
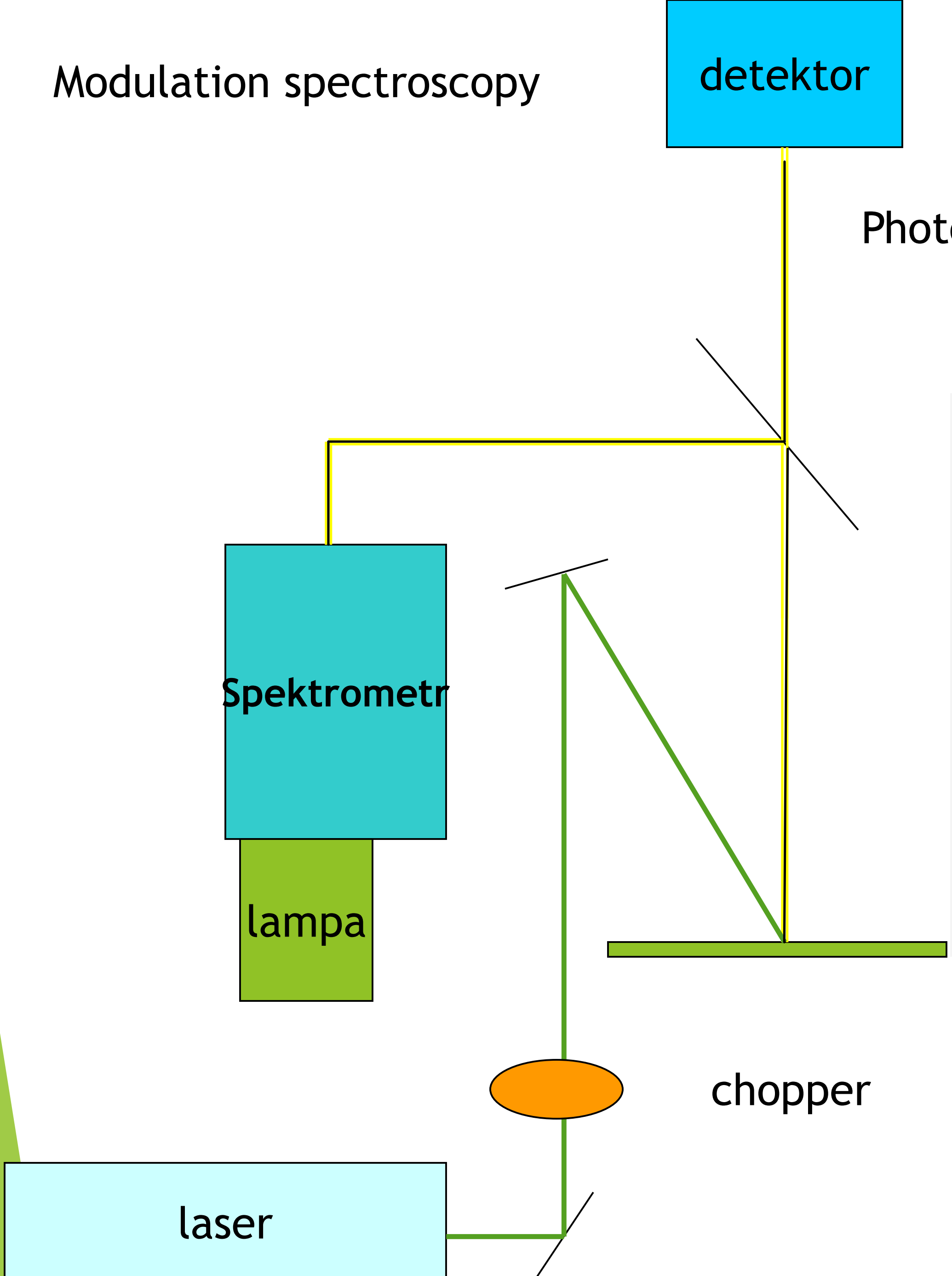
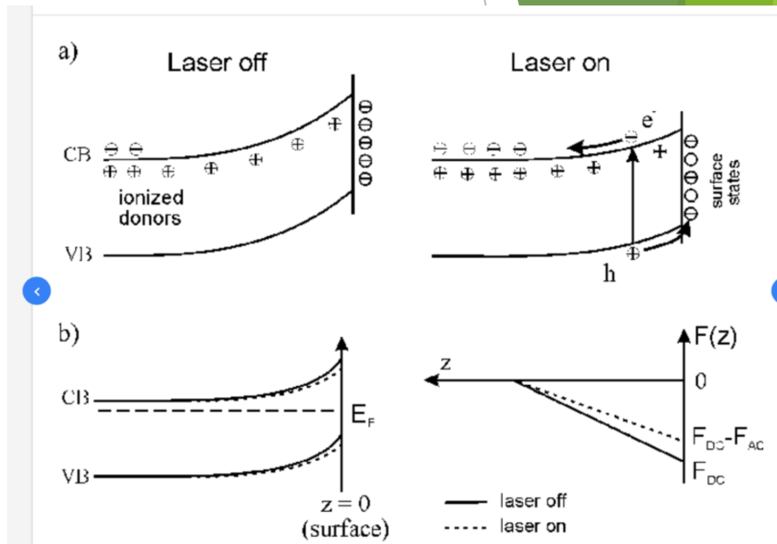


FIG. 4. Comparison of the Raman and infrared reflectivity spectra measured on three different GaN crystals. The free-electron concentrations determined from the infrared data ($m^*=0.2m_e$, $\varepsilon=5.7$) are 3.9×10^{19} cm^{-3}, 5.1×10^{19} cm^{-3}, 8.7×10^{19} cm^{-3} for samples A, B, C, respectively.

Modulation spectroscopy

Photoreflectance setup





Schematic representation of the photoreflectance effect (a), and the photoinduced changes in electronic bands and the surface bulit-in electric field (b), for an n-type semiconductor

Pomiary fotoodbicia w temperaturze pokojowej w GaN rejonie przerwy energetycznej

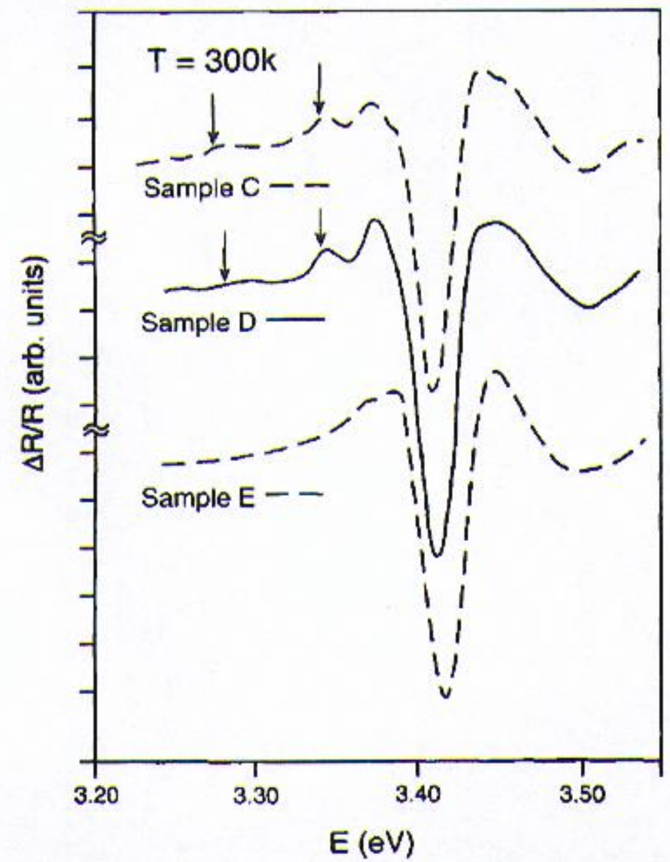
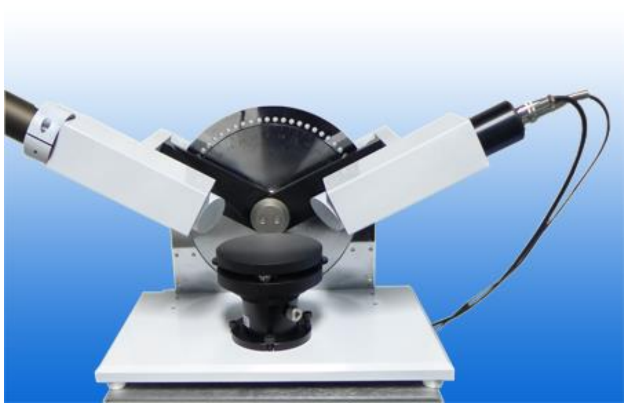
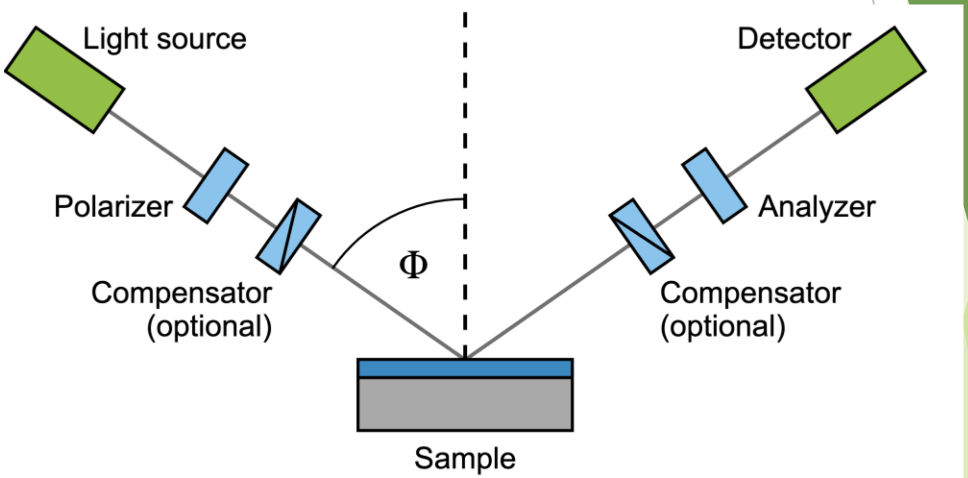


FIG. 4. PR spectra obtained at $T=300$ K for samples C, D, and E. The arrows indicate the presence of below band gap transitions which are seen in samples C and D but not in sample E.

Reflection of the polarized light- elipsometry





$$r_s = \frac{n_i \cos(\theta_i) - n_t \cos(\theta_t)}{n_t \cos(\theta_t) + n_i \cos(\theta_i)}$$

$$t_s = \frac{2n_i \cos(\theta_i)}{n_i \cos(\theta_i) + n_t \cos(\theta_t)}$$

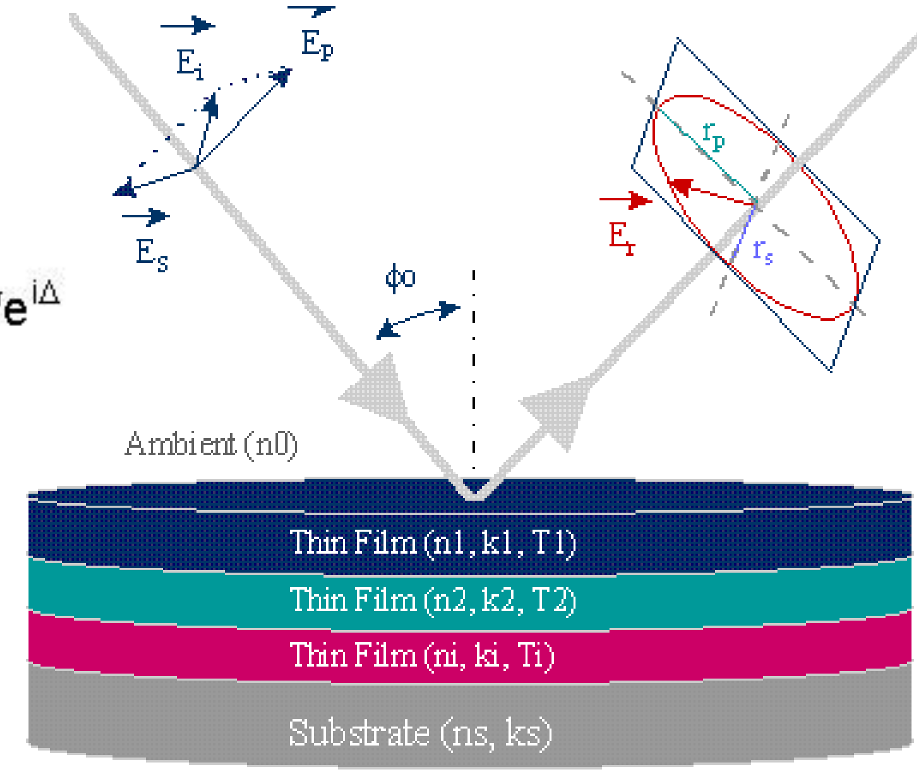
$$r_p = \frac{n_i \cos(\theta_t) - n_t \cos(\theta_i)}{n_t \cos(\theta_i) + n_i \cos(\theta_t)}$$

$$t_p = \frac{2n_i \cos(\theta_i)}{n_t \cos(\theta_i) + n_i \cos(\theta_t)}$$

Based on Fresnel equation

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

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



Determination of the layer thickness and refractive index and asbsorption (extinction).

Summary

Popular optical methods provide information such as:

Energy gap value
Exciton energies
Sample quality, location, carrier life times
Dielectric constant, refractive index
Energies of phonons.
Stresses in thin layers
Concentration of electrons