Infrared Ellipsometry – a Novel Characterization Method for Group-III Nitride Device Heterostructures

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Outline

Spectroscopic Ellipsometry in the IR spectral range is presented as a **feasible and novel tool** for contactless and nondestructive determination of **free-carrier and crystal-structure properties of complex semiconductor heterostructures** designed for device applications. In the past years, the group-III nitride material system (Al, Ga, In)N has gained tremendous importance, since these materials are suitable for the fabrication of advanced optoelectronic devices operating from the near-infrared up to the ultraviolet spectral range.

Analysis of ellipsometry data from 300 to 6000 cm^{-1} can precisely provide the **spectral dependence and anisotropy of thin-film dielectric functions**. Thus, **fundamental material quantities**, such as phonon mode frequencies and broadening parameters, static dielectric constants, as well as free-carrier parameters are determined, even for films with some ten nanometer thickness only. This sensitivity is unreached by Raman scattering or IR intensity measurements.

Using IR ellipsometry, the characterization of light-emitting device structures based on group-III-nitrides is demonstrated. An **infrared dielectric function database**, which was established by analysis of simpler heterostructures, is used for the investigation of the complex structures. Information on **concentration and mobility of free carriers in *n*- and *p*-type regions, thickness, alloy composition, strain, and crystalline quality** of individual device constituents are accessible.

Data analysis

Model dielectric function in the mid-IR:
Factorized model allowing for anharmonic phonon-plasmon coupling effects

$$e_j(w) = e_{\infty,j}\,\frac{\prod_{i=1}^{l+1}\left(w^2 + ig_{LPP,ij}w - w_{LPP,ij}^2\right)}{w\left(w + ig_{p,j}\right)\cdot\prod_{i=1}^{l}\left(w^2 + ig_{TO,ij}w - w_{TO,ij}^2\right)}$$

$j \equiv$ "∥", "⊥" to c axis

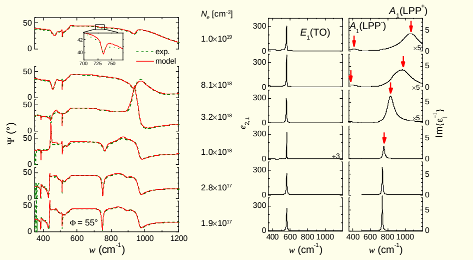
with
$$w_{LPP,ij} = \left\{\tfrac{1}{2}\left[w_{p,j}^2 + w_{LO,j}^2 + (-1)^i\sqrt{\left(w_{p,j}^2 + w_{LO,j}^2\right)^2 - 4w_{p,j}^2 w_{TO,j}^2}\right]\right\}^{1/2}$$

$w_{TO}(g_{TO})$	TO mode frequency (broadening)	$w_{LPP}(g_{LPP})$	LO-phonon-plasmon coupled mode frequency (broadening)
$w_{LO}(g_{LO})$	LO mode frequency (broadening)		
$w_p(g_p)$	plasmon frequency (broadening)	e_∞	high-frequency dielectric constant

Infrared optical data base

Free carriers

e.g. differently Si-doped a-GaN films



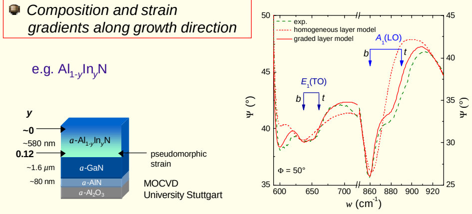
Plasmon frequency and plasmon broadening →

- *Concentration and mobility of free carriers (if effective mass assumed)*
- *Effective carrier mass (when using carrier concentration value from Hall-effect measurements)*
- *Sensitivity to thin carrier depletion layers*

Analysis of inhomogeneous layers

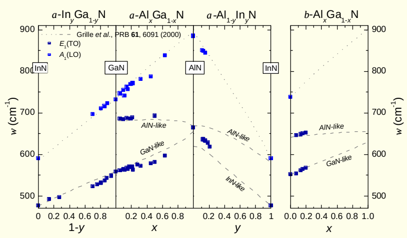
- *Composition and strain gradients along growth direction*

e.g. $Al_{1-y}In_yN$



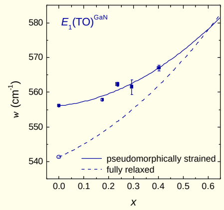
Phonons

Composition dependence of phonon mode frequencies



Strain dependence of phonon mode frequencies

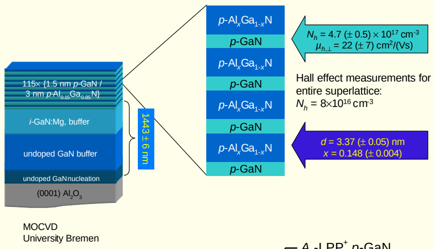
e.g. a-$Al_xIn_{0.12}Ga_{0.88-x}N$

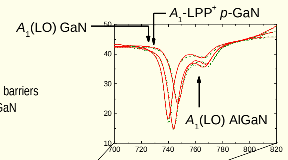


Frequencies and broadenings of IR-active phonons →

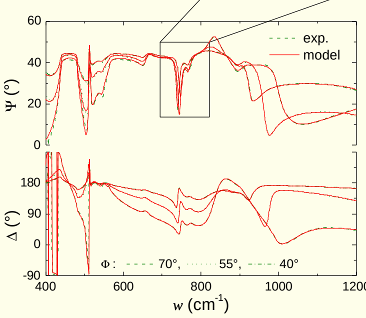
- *Mode behavior (one-, two-mode behavior etc.)*
- *Separation of the influences of composition and strain on frequencies*
- *Detection of weak disorder-activated modes*

Superlattice structures



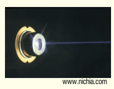


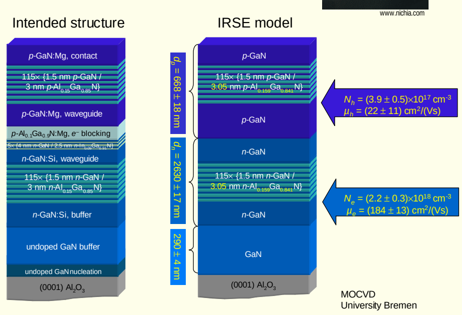
Assumptions:
no free carriers in AlGaN barriers
$m_h = 0.8 \times m_0$ for p-type GaN

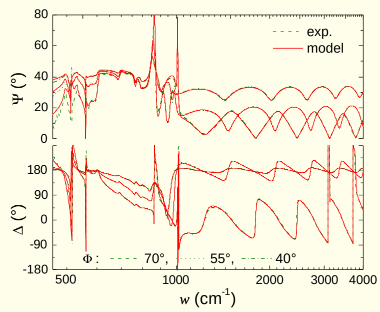


Device heterostructures

e.g. blue light emitting laser diode structure

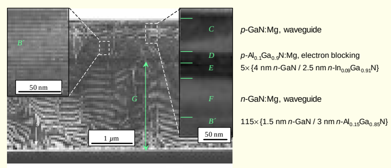






	intended value	IRSE	TEM
d_p [nm]	698	668 ± 18	665 ± 7
d_n [nm]	2975	2920 ± 17	2879 ± 29
$d_{B'/115}$ [nm]	4.5	4.55 ± 0.05	4.54 ± 0.05
x	0.15	0.159 ± 0.005	
N_e [10^{18} cm^{-3}]	1 – 2	2.2 ± 0.3	
μ_e [cm^2/(Vs)]		184 ± 13	
N_h [10^{17} cm^{-3}]	2	3.9 ± 0.5	
μ_h [cm^2/(Vs)]		22 ± 11	

TEM image



The contactless and non-destructive IR-optical characterization of complex multilayer structures provides information on

- *concentration and mobility of free carriers in p- and n-type regions*
- *localization of pn-junction*
- *thicknesses,*
- *composition,*
- *strain, and*
- *crystalline quality*

of individual heterostructure constituents.

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