Far-infrared magnetooptical generalized ellipsometry determination of free-carrier parameters in semiconductor thin film structures

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M5.32

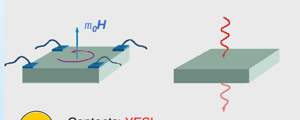
Our message

New: far-infrared magnetooptic generalized ellipsometry:

Determination of the free-charge-carrier parameters effective electron mass, mobility, and concentration independent from each other by (far) infrared magneto optic generalized ellipsometry.

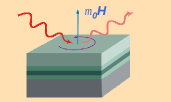
How to determine free charge carrier parameters concentration, mass, and mobility in layered structures?

Hall effect + **Ir-absorption**



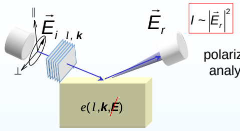
Contacts: YES!
Heterostructures: DIFFICULT!

Fir MO-ellipsometry



Contacts: NO!
Heterostructures: YES!

Experimental setup



polarization state generator (PSG)

polarization state analyzer (PSA)

Model-dielectric function

Polar lattice contribution

Electronic contribution	Infrared-active phonon modes	Alloy-induced modes	Free-carrier contribution

$$e_j(w,H)=e_{\infty,j}\cdot\prod_{i=1}^{l}\frac{w^2+ig_{LO,ij}w-w^2_{LO,ij}}{w^2+ig_{TO,ij}w-w^2_{TO,ij}}\cdot\prod_{k=1}^{m}\left(1+\frac{idg_{kj}\,w-dw^2_{kj}}{w^2+ig_{AM,kj}w-w^2_{AM,kj}}\right)-e_j^{(FC-MO)}(w,H)$$

- Infrared-active phonon modes:
  $\omega_{TO/LO}$ – TO/LO phonon mode frequency
  $\gamma_{TO/LO}$ – TO/LO broadening parameter

- alloy-induced modes:
  (ω_{TO} - ω_{LO} << ω_{TO} , ω_{LO})
  $\delta\omega_k=\omega^2_{LO,k}-\omega^2_{TO,k}$, $\gamma_{AM,k}=\gamma_{TO,k}$, and
  $\omega_{AM,k}=\omega_{LO,k}$

- Free-carrier contribution:
  $w_{p,j}\propto z_j = (N/m^*_j)^{0.5}$ – plasma frequency
  $g_{p,j}\propto x_j = (m^*_j\mu_j)^{-1}$ – scattering tensor
  N – free-carrier concentration
  m^*_j – free-carrier effective mass tensor
  μ_j – free-carrier mobililty tensor

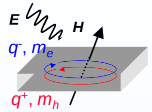
$$e_j^{(FC-MO)}(w,H=0)=\frac{w^2_{p,j}e_{\infty,j}}{w(w+ig_{p,j})}$$

Magnetooptical free-carrier effects

Free carrier movement in slowly time-dependent magnetic field H

$$\boldsymbol{m}^*\left(\frac{m_e}{q}\right)(g+\partial_t)\boldsymbol{v}=\left[\boldsymbol{E}+\frac{H}{c}(\boldsymbol{v}\times\boldsymbol{h})\right]$$

Coulomb Lorentz



$\boldsymbol{m}^*_{e,h}$: Free-carrier effective mass tensor
$g_{e,h}$: Free-carrier scattering tensor (inverse relaxation time)
$q^{+,-}$: Free-carrier charge
$\boldsymbol{H}$: Magnetic field vector $\boldsymbol{H} = H(h_1, h_2, h_3)$
$\boldsymbol{E}$: Electric field vector of the incident light

DF tensor

$$e^{(FC-MO)}(w,H)=-\langle w_p^{*2}\rangle\left[(w^2\boldsymbol{I}+iwg)-i\langle w_c\rangle\begin{pmatrix}0&-h_3&h_2\\h_3&0&-h_1\\-h_2&h_1&0\end{pmatrix}\right]^{-1}$$

Plasma (frequency) tensor $\langle w_p^{*2}\rangle\equiv N\frac{e^2}{m_e}\boldsymbol{m}^{-1}$

Cyclotron (frequency) tensor $\langle w_c\rangle\equiv q\left(\frac{H}{m_e}\right)\boldsymbol{m}^{-1}$

***H* causes non-symmetric properties of the dielectric function tensor!**

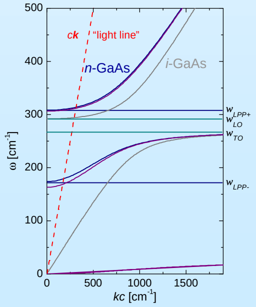
Magnetooptic tensor for $\boldsymbol{B}=\mu_0(0,0,H)$
(Faraday Configuration)

$w_c = m_0H(q/m^*)$ – cyclotron frequency,
m_0 – free electron mass,
w_p^* – unscreened plasma frequency, and
g_p – plasmon broadening parameter

$$e^{(FC-MO)}(w)=\begin{pmatrix}e_{xx}&ie_{xy}&0\\-ie_{xy}&e_{xx}&0\\0&0&e_{zz}\end{pmatrix}$$

$$e_{zz}(w)=-w_p^{*2}\frac{1}{w(w+ig_p)}\qquad e_{xy}(w)=-w_p^{*2}\frac{w_c}{w((w+ig_p)^2-w_c^{\,2})}\qquad e_{xx}(w)=-w_p^{*2}\frac{w+ig_p}{w((w+ig_p)^2-w_c^{\,2})}$$

Bulk Polaritons



Polariton dispersion for transverse polaritons:

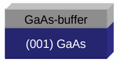
$$\boldsymbol{k}\times[\boldsymbol{k}\times\boldsymbol{E}]+\left(\frac{w}{c}\right)^2 e(w,\boldsymbol{k})\boldsymbol{E}=0$$

D. L. Mills, E. Burstein, *Polaritons: the electromagnetic modes of media*, Rep. Prog. Phys. 37, 817 (1974).

Example:
Bulk polaritons in GaAs

i-GaAs – uncoupled polaritons
n-GaAs – coupled phonon plasmons, polaritons
n-GaAs + $m_0(0,0,H)$ – coupled phonon helicons, polaritons

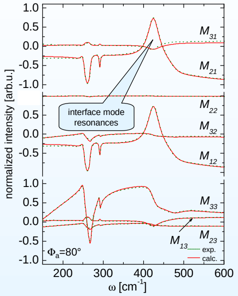
Example 1: *n*-GaAs-*i*-GaAs



~ 700nm un-doped GaAs-buffer layer
n-type (Te doped) GaAs substrate

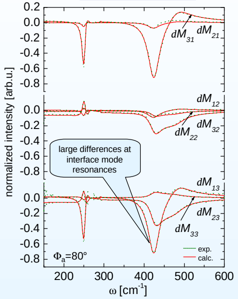
Fir-mo generalized ellipsometry

m_0H=0T



Mueller matrix elements normalized to M_{11}. Dominant structures originate from the excitation of interface modes. The GaAs TO and LO phonon mode can be recognized at ~268 and ~291 cm^{-1}.

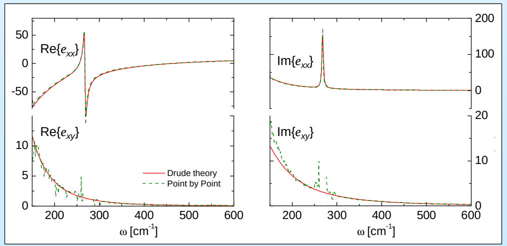
m_0H= ±2.3T



The differences of the Mueller matrix elements measured at m_0H=-2.3T and m_0H=2.3T represent the magnetic field induced changes of the ellipsometry data.

Fir dielectric tensor

First measurement of the complex fir magnetooptic Drude Tensor!



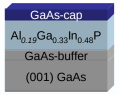
Excellent agreement of the model and the point by point data. The e_{zz} spectra are virtually identical to the e_{xx} spectra and therefore omitted here.

m* = 0.072 *m*₀
N = 1,6x10^{18} cm^{-3}
m = 2200 cm^2/(Vs)

Very good agreement agreement of the effective electron mass at N = 1,6x10^{18} cm^{-3} with Shubnikov de Haas measurements and **k**·**p** calculations.

M. Schubert, T. Hofmann, and C.M. Herzinger, J. Opt. Soc. Am. A **20** February (2003)

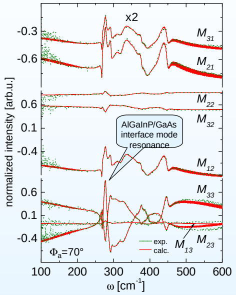
Example 2: *n*-GaAs/*n*-AlGaInP/*i*-GaAs



~ 70 nm *n*-type (Te-doped) GaAs-cap
1868 nm *n*-type (Te-doped) $Al_{0.19}Ga_{0.33}In_{0.48}P$ epilayer
~ 20 nm undoped GaAs buffer and substrate

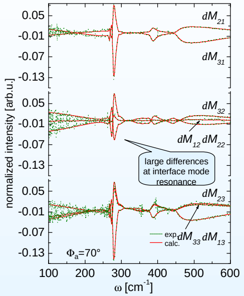
Fir-mo generalized ellipsometry

m_0H=0T



Mueller matrix elements normalized to M_{11}. Most of the structures are due to the excitation AlP-, InP-, or GaP-like phonon modes (*see M5.33 also*).

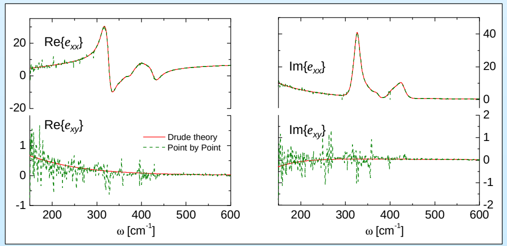
m_0H= ±2.2T



The differences of the Mueller matrix elements measured at m_0H=-2.2T and m_0H=2.2T represent the magnetic field induced changes of the ellipsometry data.

Fir dielectric tensor

First effective mass determination for highly disordered AlGaInP!



Excellent agreement of the model and the point by point data. The e_{zz} spectra are virtually identical to the e_{xx} spectra and therefore omitted here.

m* = 0.12 *m*₀
N = 6.7x10^{17} cm^{-3}
m = 339 cm^2/(Vs)

New Data: First measurement of m* in highly disordered AlGaInP. Good agreement with **k*p** calculations.

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