THz optical Hall-effect and MIR-VUV ellipsometry characterization of 2DEG properties in AlGaN/GaN HEMT structures

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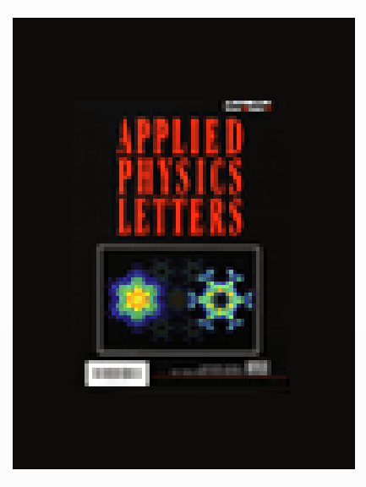

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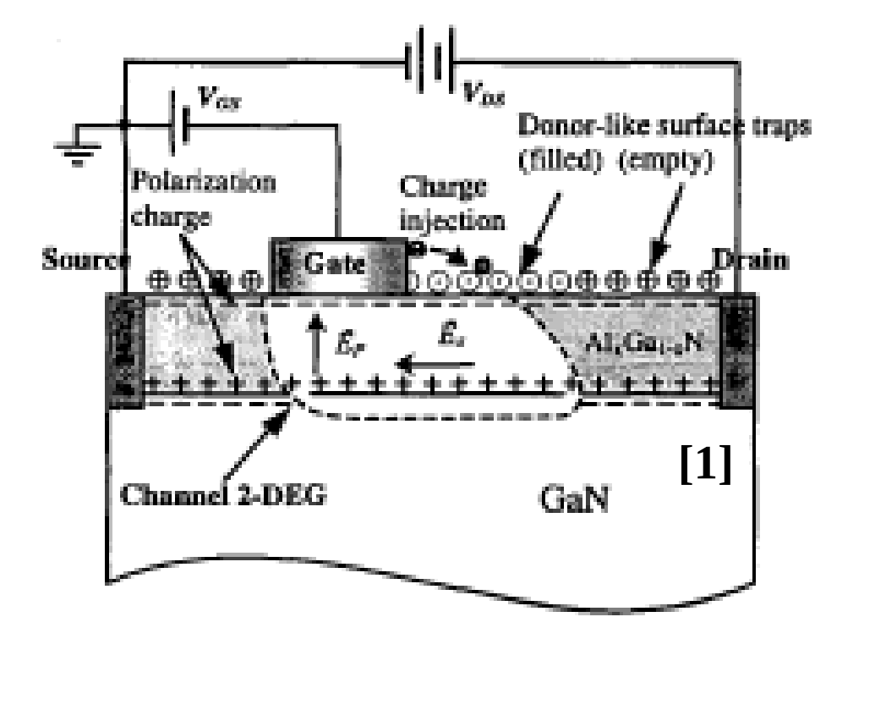
Our Message

- **Free-charge carrier mobility, sheet density, and effective mass of a 2DEG are determined in a AlGaN/GaN heterostructure using the THz-Optical Hall-Effect at room temperature.**
- **Complementary Mid-IR and NIR-VIS-VUV spectroscopic ellipsometry measurements for constituents layer thickness, phonon mode and free-charge carrier parameters.**
- **The electron effective mass in the 2DEG is determined to be (0.23 ± 0.03) m_0.**
- **High-frequency sheet density and carrier mobility parameters are in good agreement with results from DC electrical Hall effect measurements, indicative for frequency-independent carrier scattering mechanisms of the 2D carrier distribution.**

2DEGs in HfO_2 passivated AlGaN/GaN HEMTs

Passivation of surface traps changes 2DEG properties in AlGaN/GaN HEMTs!



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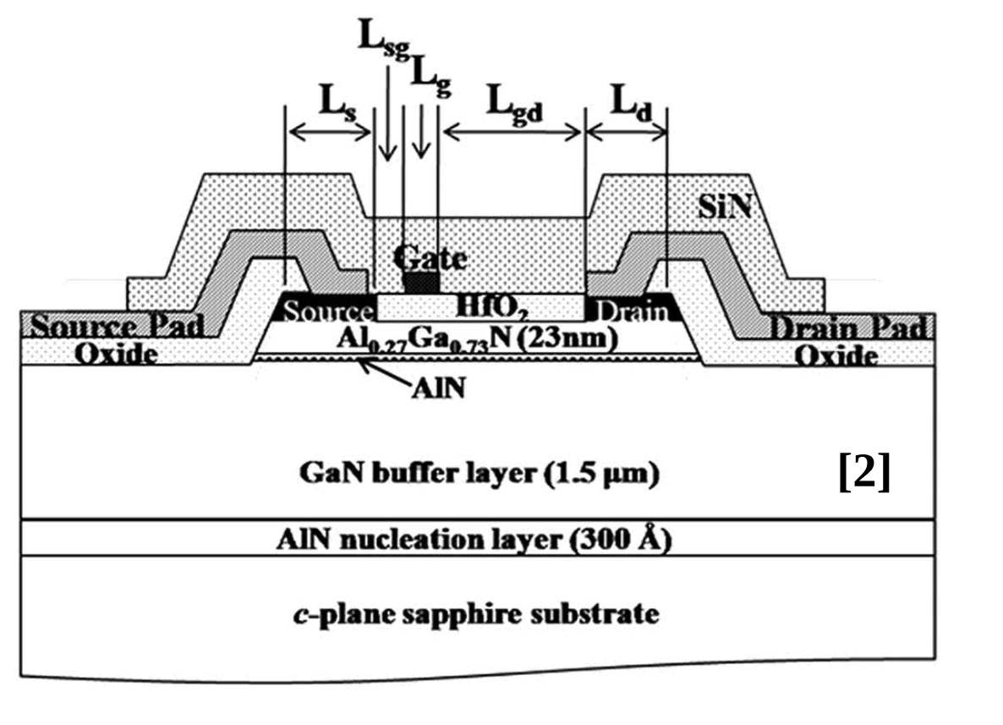
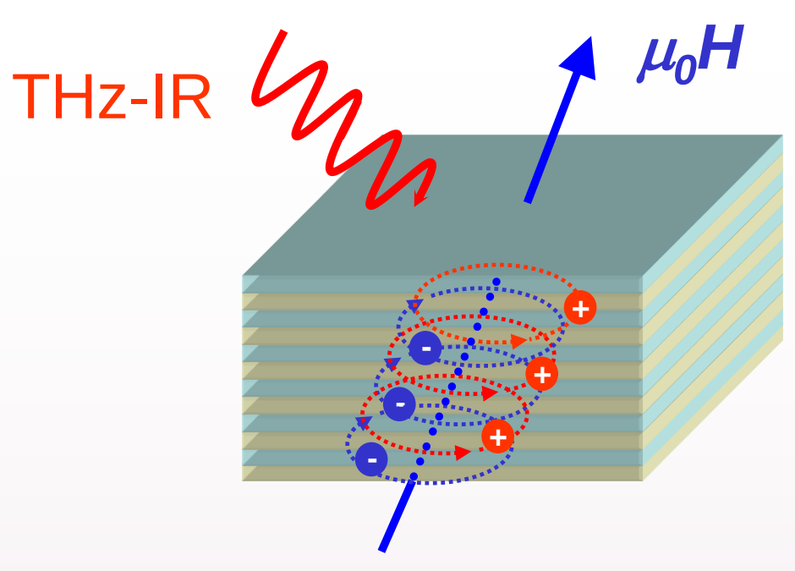


[2]

- Optimization of device performance requires access to the buried 2DEG for determination of charge carrier concentration, mobility and effective mass!!
- Electrical methods (electrical Hall-effect, Shubnikov-de Haas, cyclotron resonance) require fabrication of complete devices, electrical contacts and can not be utilized at future device's operation frequencies (GHz-THz)



Optical Hall-Effect

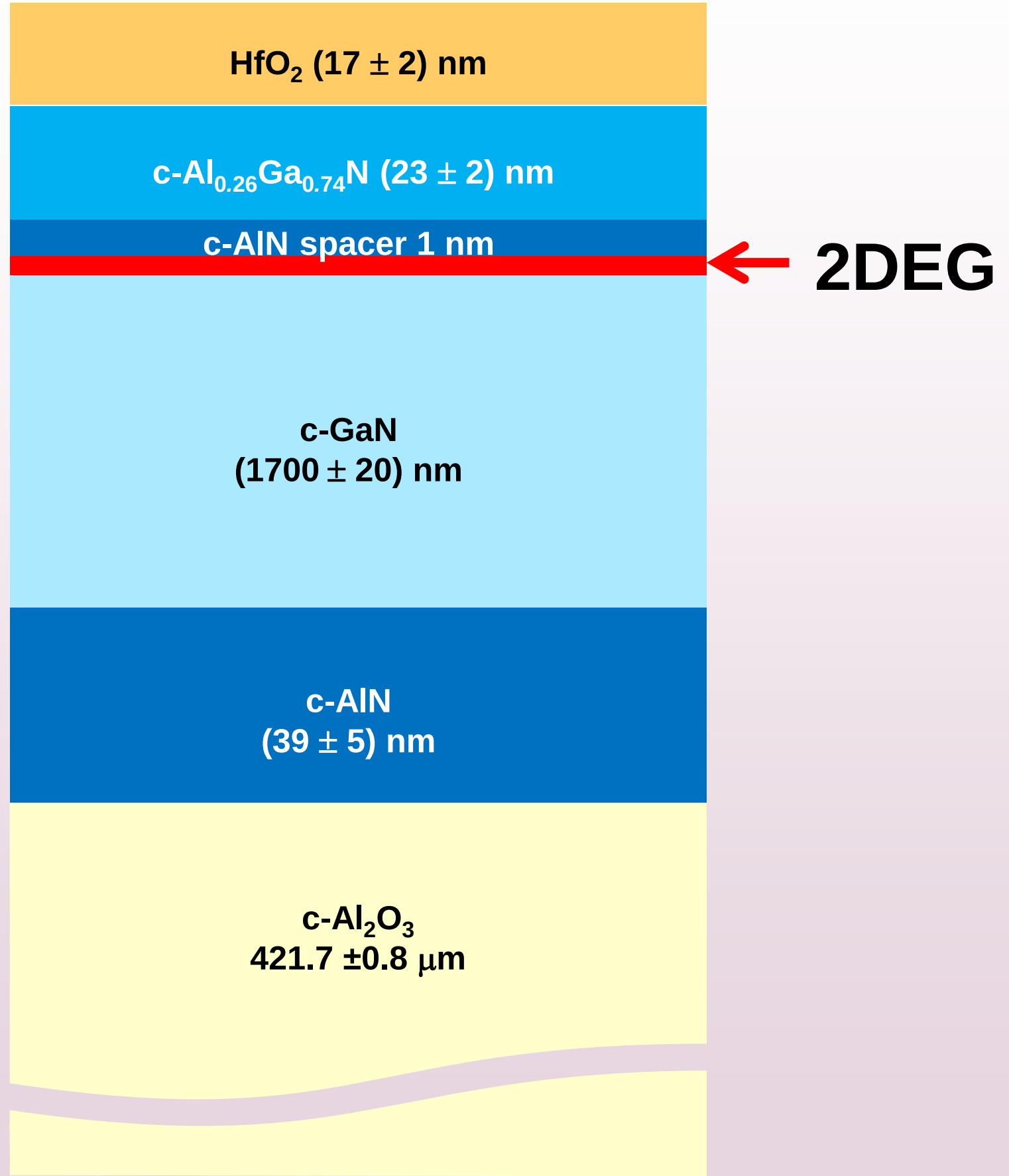
Generalized ellipsometry in combination with external magnetic fields:

- unbound charge carrier resonances in spatially confined structures in the THz frequency domain
- buried conducting channel directly accessible without electrical contacts
- performed at room temperature
- performed at future device operation frequencies (THz), i.e. studying of frequency dependent scattering mechanisms at operation frequencies possible

[1] Zhang *et al.*, *Electron Devices Meeting, 2001. IEDM Technical Digest. International* , pp.25.5.1-25.5.4, 2001, [2] J. Shi *et al.*, Appl. Phys. Lett. **95**, 042103 (2009).

Model

Layer stack model and accessible parameters



NIR-Vis-VUV

- thickness of all layers (except substrate and AlN spacer)
- dielectric function and transition energies of c-$Al_{0.26}Ga_{0.74}N$
- dielectric function and band gap energy of HfO_2

IRSE

- dominated by phonon mode contributions from c-sapphire and c-GaN buffer
- subtle features imposed by c-$Al_{0.26}Ga_{0.74}N$ and c-AlN seed layer
- limited sensitivity for layer thicknesses (except GaN buffer)
- influence of 2DEG channel negligible
- determination of volume free charge carrier contributions

THz-Optical Hall-Effect

- Fabry-Pérot interference pattern dominated by the thickness of the substrate (421.7 ±0.8 μm)
- single layer thicknesses cancel out mathematically in model calculation for thicknesses<<wavelength and are irrelevant for model analysis
- only free charge carrier response contributes to spectrum of difference between data taken at magnetic field strengths +H and -H

Optical Hall-Effect –Theory

Layer model calculations provide DF:

Electronic contribution — **THz … IR modes** — **Disorder-induced modes** — **Free-carrier contribution**

$$\varepsilon_j(\omega,H)=\varepsilon_{\infty,j}\cdot\prod_{i=1}^{l}\frac{\omega^2+i\gamma_{LO,ij}\omega-\omega_{LO,ij}^2}{\omega^2+i\gamma_{TO,ij}\omega-\omega_{TO,ij}^2}\cdot\prod_{k=1}^{m}\left(1+\frac{i\delta\gamma_{kj}\,\omega-\delta\omega_{kj}^2}{\omega^2+i\gamma_{AM,kj}\omega-\omega_{AM,kj}^2}\right)-\varepsilon_j^{(FC-MO)}(\omega,H)$$

Static dielectric constant — **Phonon mode frequencies and broadening parameters** — **Impurity mode parameters**

Magnetic field *H* causes non-symmetric properties of the IR Dielectric Function tensor:

$$\boldsymbol{\varepsilon}^{(FC-MO)}(\omega)=-\langle\omega_p^{*2}\rangle\left[\left(\omega^2+i\omega\boldsymbol{\gamma}\right)\boldsymbol{I}-i\omega\langle\omega_c\rangle\begin{pmatrix}0&-h_3&h_2\\h_3&0&-h_1\\-h_2&h_1&0\end{pmatrix}\right]^{-1}$$

→ Decoupling of m_{eff} and free charge carrier concentration
→ identification of carrier type (n/p-type)
→ determination of free charge carrier concentration, mobility and effective mass possible !!

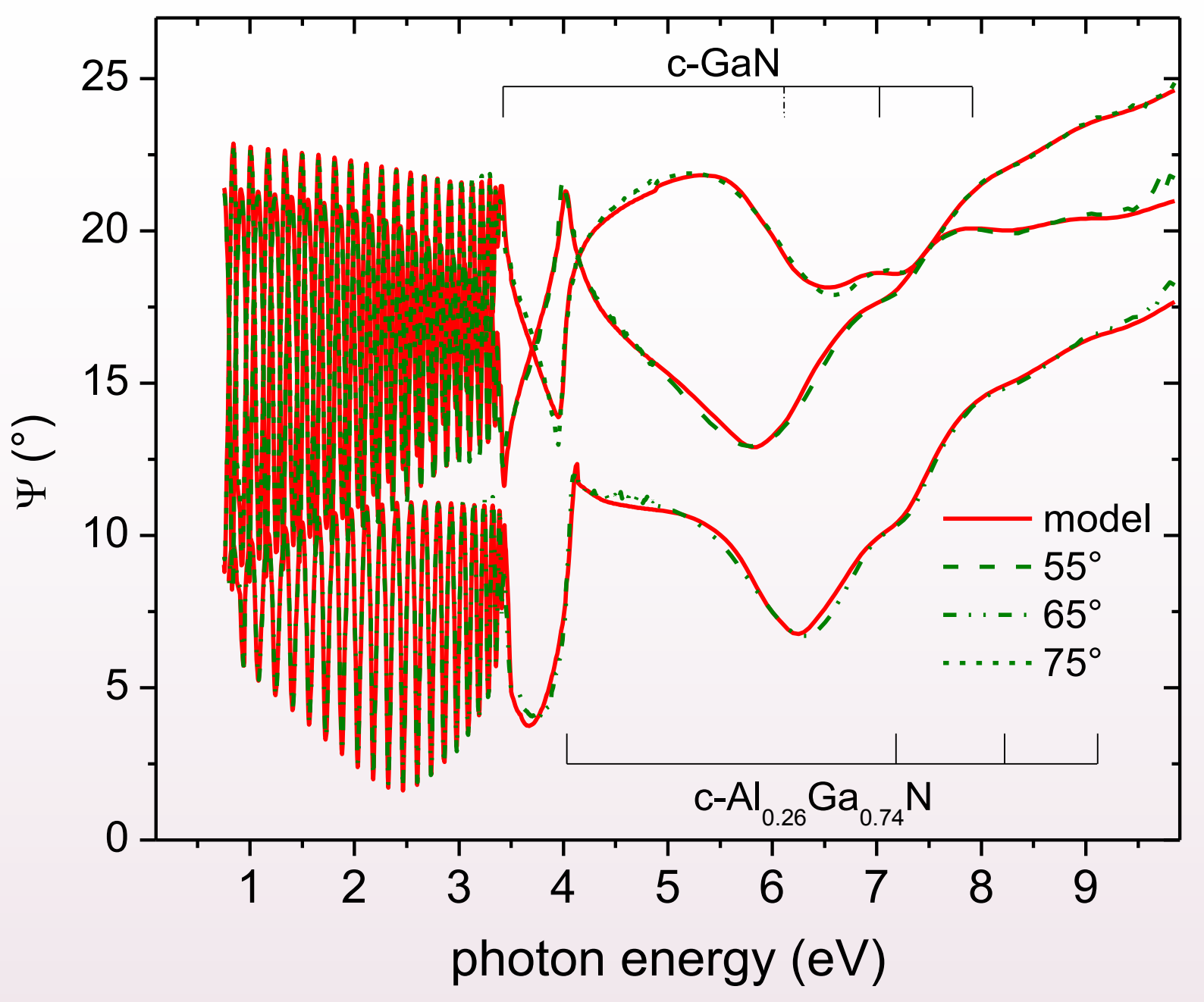
Plasma (frequency) tensor $$\langle\omega_p^{*2}\rangle\equiv N\frac{q^2}{m_e}\boldsymbol{m}^{-1}$$

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

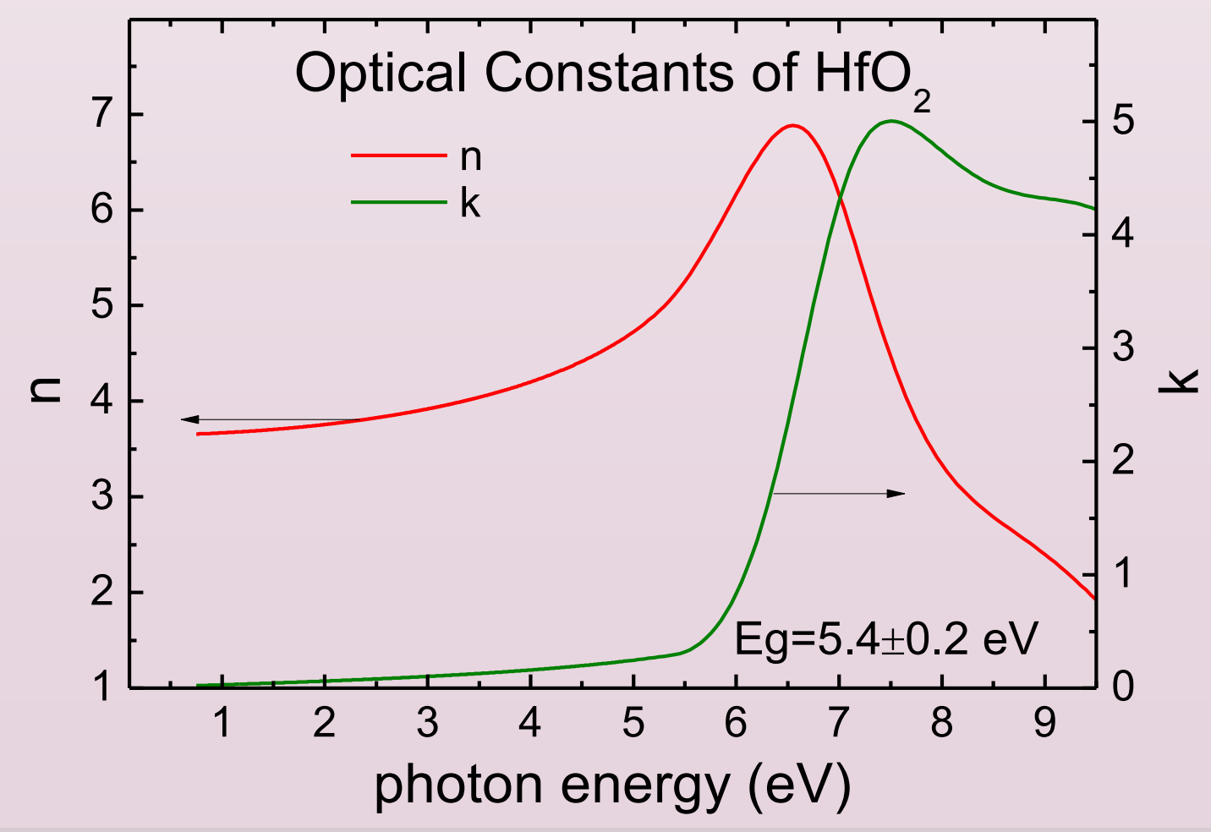
[3] T. Hofmann *et al.*, Thin Solid Films**,** (2010), *in press*, doi:10.1016/j.tsf.2010.11.092

Experimental Results

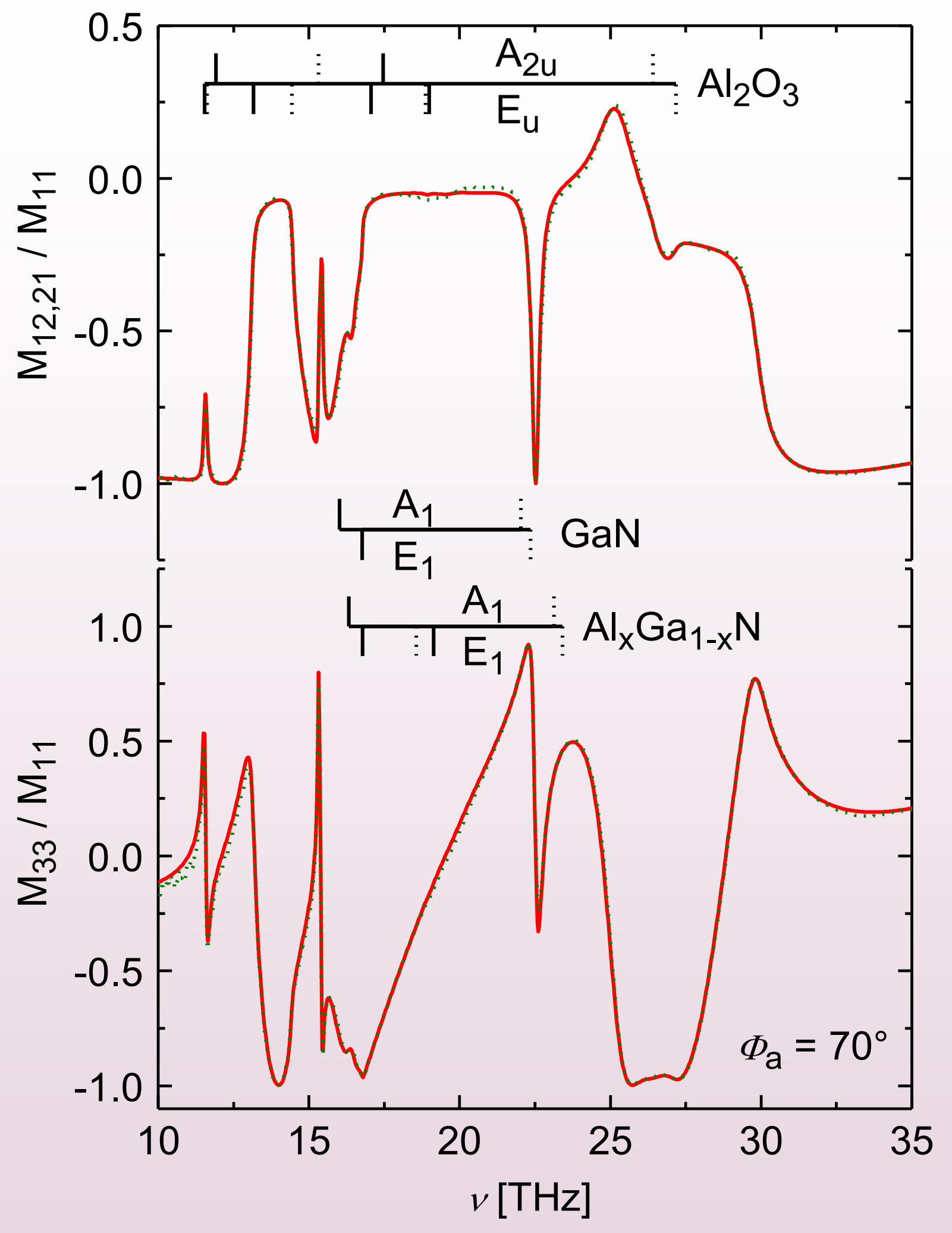
NIR-Vis-UV-VUV SE



determination of layer thicknesses
2-oscillator model (TL+L) for HfO_2 (E_g=5.4±0.2 eV)

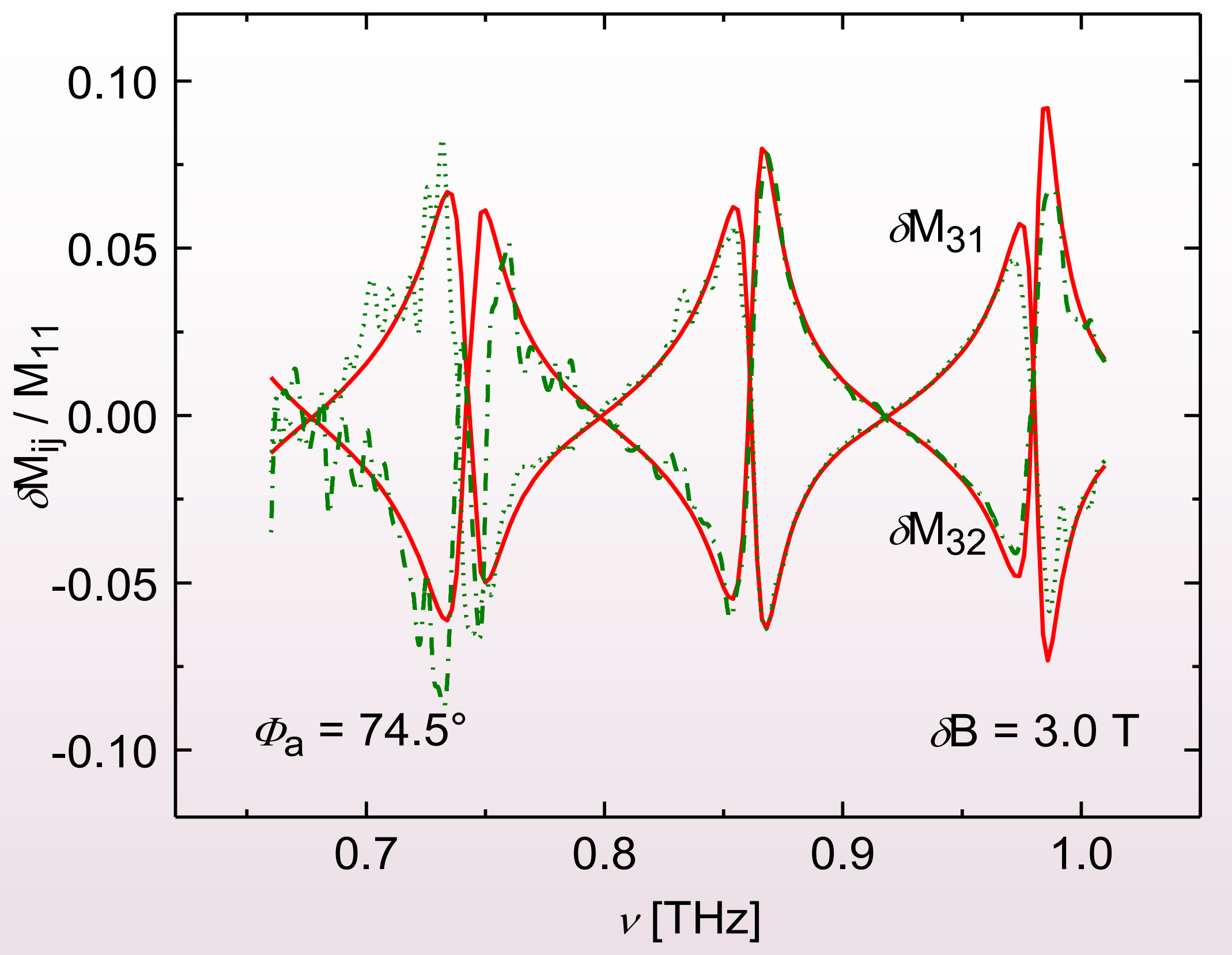


IRSE



phonon modes indicated by insets: solid: TO; dotted: LO
influence of the 2DEG is negligible
no volume free charge carriers detected

THz-Optical Hall-Effect



Room Temp. OHE 2DEG properties:
$N_s = (5 \pm 2)\cdot 10^{12}$ cm^{-2}
$\mu = (1452 \pm 250)$ cm^2/Vs
$m^* = 0.23 \pm 0.03\ m_0$

Room Temp. elec. Hall effect:
$N_s = (9 \pm 3)\cdot 10^{12}$ cm^{-2}
$\mu = (1700 \pm 200)$ cm^2/Vs

[4] S. Schöche *et al.*, Appl. Phys. Lett, **98,** (2011), *accepted*, doi:10.1063/1.3556617

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