THz Optical Hall-Effect in Multi-Valley Band Materials

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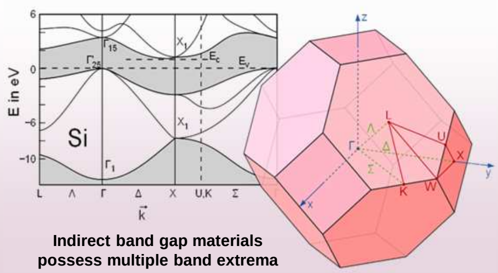
Our Message

- We employ the optical Hall-effect for contact free determination of the effective mass tensor for multi-valley band materials like silicon.
- In addition the THz optical Hall-effect enables to determine the carrier concentration and mobility for both bulk and layered silicon structures.
- The measurement geometry of the setup effects the uncertainty for the longitudinal mass parameter.
- Low temperature, high magnetic field ellipsometric measurements at small angles of incident provide higher sensitivity to longitudinal mass.

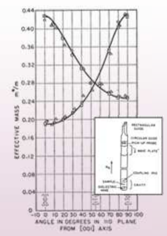
Motivation: THz Spectroscopic Ellipsometry

Indirect Semiconductors



Indirect band gap materials possess multiple band extrema

Effective Mass



Dresselhaus et al. Phys. Rev. 98, 368–384 (1955)

Long wavelength behavior of free charge carrier described by effective mass

Historical determination of effective mass-parameter: cyclotron resonance experiments

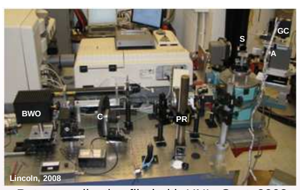
High free mean path length necessary

=> low temperature needed

THz Optical Hall-Effect - Experimental Setup

Generalized THz Ellipsometry

- rotating analyzer ellipsometry configuration
- polarization rotator to change the input polarization (PR)
- wire grid polarizer (A)
- Golay cell detector (GC)

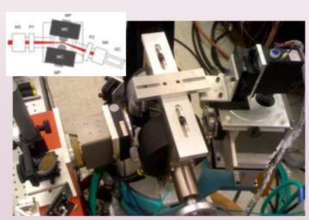


Patent application filed with UNL, Sept. 2008

Optical Hall-Effect

Current System - water cooled magnet:
- magnetic field up to 1.8 T
- angle of incidence 80

MRI "THz optical Hall effect" project:
- superconducting magnet (8 T)
- closed cycle cryogen system
- sample temperature from 4.2 K to RT
- spectral range from 0.1 to 70 THz



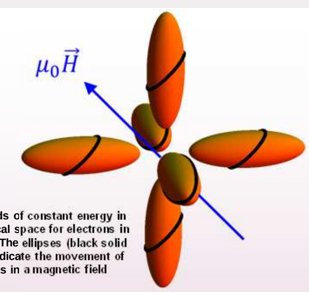
Theory

Drude Model

Classical Drude equation for charge carriers subjected to an external magnetic field:

$$\frac{\hat{m}}{q}(\gamma + \partial_t)\vec{v}_d = \vec{E} + \mu_0(\vec{v}_d \times \vec{H})$$

- silicon posses 6 non *Γ*-point minima
- 6 energy ellipsoids in reciprocal space
- energy ellipsoids parameterized by longitudinal m_l and transversal m_t effective masses



Ellipsoids of constant energy in reciprocal space for electrons in silicon. The ellipses (black solid lines) indicate the movement of electrons in a magnetic field

Magneto-Optical Dielectric Tensor

Drude equation leads to the optical response for a single charge carrier species with an arbitrary effective mass:

$$\varepsilon_{ik} = \frac{nq}{i\varepsilon_0\omega}\left[\frac{\gamma - i\omega}{q}m_{ik} + \epsilon_{ijk}B_j\right]^{-1}$$

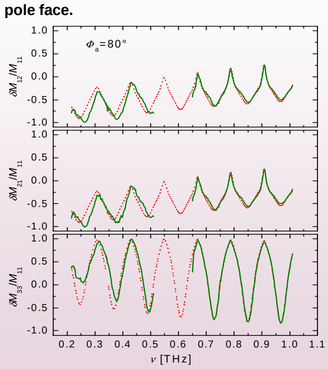
ε_{ik}	dielectric tensor	$\vec{H}, B_j$	magnetic field
$\hat{m}, m_{ik}$	effective mass	$\vec{E}$	electric field
n	carrier concentration	$\vec{v}_d$	drift velocity
q	charge	ε_0	electric vac. permeability
γ	average scattering time	μ_0	magnetic vac. permeability
ω	angular frequency	ϵ_{ijk}	levi-cevita-symbol

- free charge carrier contribution to DF for silicon is sum over six tensors!
- THz optical Hall-effect allows determination of arbitrary dielectric tensor!

Experimental Results

Generalized Ellipsometry

Sample: Double side polished <001> silicon substrate with a titanium coating on backside in order to prevent reflections from magnet pole face.



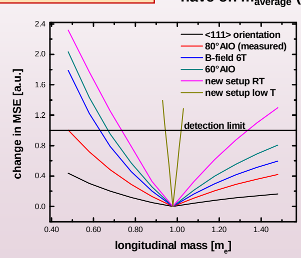
Fabry-Pérot interferences are found to enhance sensitivity to free charge carrier contributions.

Optical Hall-Effect

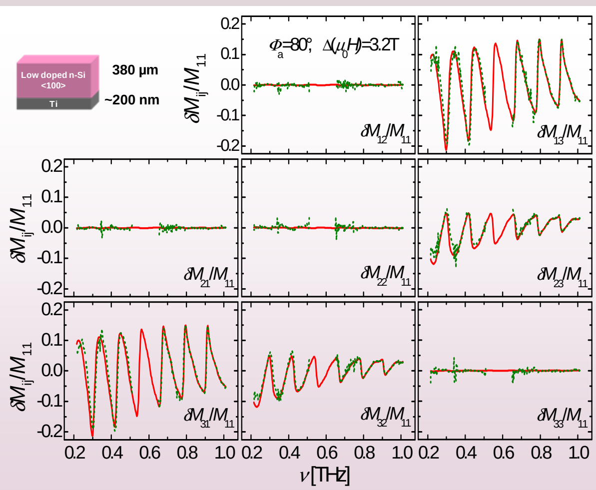
Simultaneous determination of longitudinal and transversal effective masses, carrier concentration, mobility and carrier type:

Best-model parameters:
m_l = (0.98 0.5) m_0
m_t = (0.19 0.02) m_0
n = (5.8 3.2) 10^{14} cm^{-3}
μ = (1250 200) cm^2/Vs

The large error bar on m_t origins from the fairly flat branches of these sensitivity curves, and the small uncertainty we have on $m_{average}$ (isotrop)



Terahertz optical-Hall effect for multiple valley band materials: *n*-type silicon
P. Kühne, T. Hofmann, C.M. Herzinger and M. Schubert TSF (2011)
http://dx.doi.org/10.1016/j.tsf.2010.11.087



Experimental (green) and best-fit-model calculated (red) Mueller matrix difference spectra $\delta M_{ij}=M_{ij}(B=1.6T)-M_{ij}(B=-1.6T)$ with magnetic field perpendicular to the sample surface

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