Free-Charge Carrier Properties of Graphene Layers on SiC

UNIVERSITY OF NEBRASKA-LINCOLN

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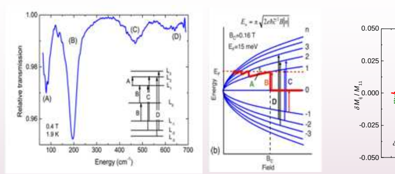
Our article, "Hole-channel conductivity in epitaxial graphene determined by terahertz optical-Hall effect and midinfrared ellipsometry," published in Appl. Phys. Lett. 98, 041906 (2011), has been selected for the February 7, 2011 issue of Virtual Journal of Nanoscale Science and Technology.

Our Message

- A rotating analyzer-type ellipsometer employing a frequency-tunable backward wave oscillator source was used for Mueller matrix measurements in the THz frequency range.
- High mobility few layer graphene (d~1 nm) is observed as a distinct damping of Fabry-Pérot interferences originating from the SiC substrate.
- The combination of THz and MIR ellipsometry allows the identification of high and low mobility graphene layers grown on C-face SiC.
- THz optical-Hall effect data are successfully used for the determination of the free electron effective mass in epitaxial graphene.
- THz ellipsometry is found to be a very useful tool for the investigation of the electrical properties of epitaxial graphene deposited on SiC substrates.

Epitaxial Graphene for THz Electronics

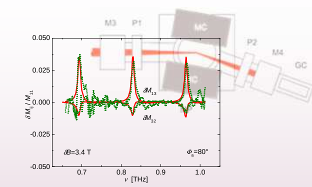
Dirac Particle Properties



- Infrared transmission spectroscopy of epitaxial graphene revealing Landau level structure
- Absorption maxima positions as a function of field is characteristic for a chiral "massless" Dirac particle

W. A. de Heer, *et al.*, *Solid State Commun.* **143**, 92 (2007).

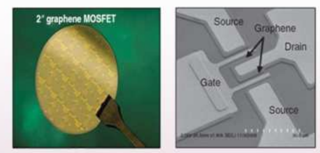
FCC Properties of Graphene on SiC



- Non-contact, optical measurements of free charge carrier mobility and sheet density in epitaxial graphene
- THz ellipsometry and the optical Hall-effect determine carrier properties at desired (THz) electronics frequencies.

T. Hofmann, *et al.*, *Appl. Phys. Lett.* **98**, 041906 (2011).

Wafer-Scale THz Field-Effect



- 50 mm graphene wafer was processed by standard lithographic techniques
- Graphene based field-effect transistors have been demonstrated to operate in the 100 GHz range

P. N. First, *et al.*, *MRS Bull.* **35**, 296-305 (2010).

Sample Description

Sublimation of Si from SiC substrates at temperatures >1200 C results in the formation of epitaxial graphene at the SiC interface.

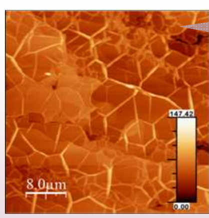
Si-Face (0001)

- Step bunching results in bi-layer formation on a 6√3 × 6√3 R30° reconstructed surface
- Low sheet charge density, low mobility graphene

C-Face (000-1)

- High sheet charge density, high mobility graphene
- Graphene layer is covered with "graphitic" layers with lower carrier concentration and mobility

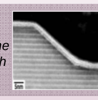
C-Face (000-1)

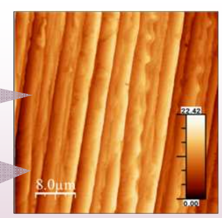


AFM topography of graphene on C-face, showing typical "giraffe pattern"

AFM topography of graphene on Si-face, showing step bunches

TEM micrograph showing graphene over a step bunch

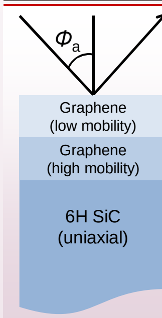




Si-Face (0001)

- Morphology, growth rate, and roughness are different between C-face and Si-face
- Graphene on Si-face has transition layer, graphene on C-face does not
- For a given sheet charge density, mobility of EG on Si-face less than EG on C-face

Optical Model

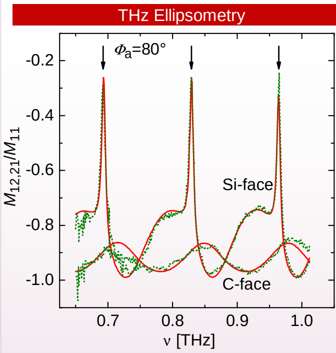


Graphene requires a two layer model, with identical fit parameters whose values vary according to the sample.

Fit parameters:
(each graphene layer)
- Mobility
- Carrier concentration (sheet density)
- Effective mass
- Magnetic field strength (when present)

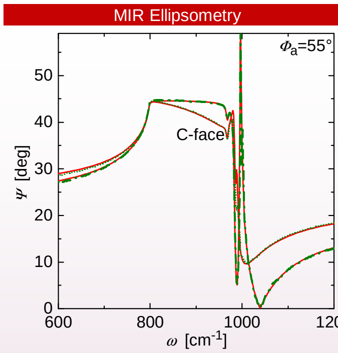
THz, MIR Ellipsometry and the Optical Hall-Effect

THz Ellipsometry



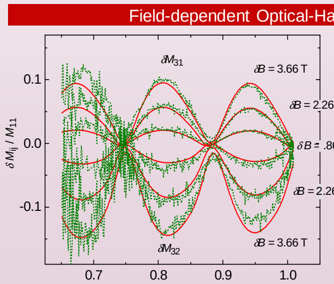
Fabry-Pérot interferences (arrows) originating from the SiC substrate are damped out for C-face grown graphene

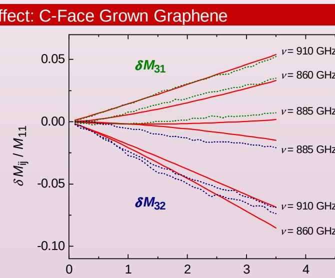
MIR Ellipsometry



Fingerprint of graphene at the rest-stahlenband of SiC – more dominant for C-face grown graphene

Field-dependent Optical-Hall Effect: C-Face Grown Graphene





Results

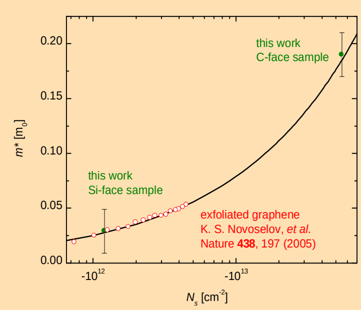
Determination of Effective Mass in Graphene

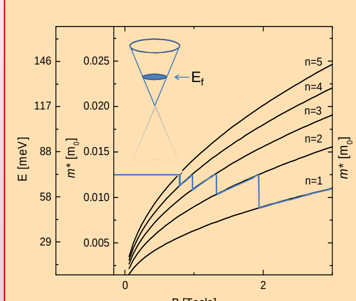
- OHE at THz frequencies allows determination of graphene effective mass consistent with Shubnikov-de Haas measurements on exfoliated graphene.
- C-Face graphene shows a field dependence of effective mass:

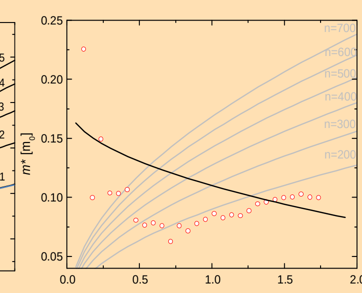
$$m^*(B) = m_a - m_b\sqrt{B}$$

m_a=0.18 and m_b=0.07 for δB<3.7T

- Quantized effective mass dependence for graphene:







6th Workshop Ellipsometry, February 21st 2011, TU Berlin

Supported by the JAW Foundation, ARO W911NF-09-C-0097, NSF DMR 0922937, NSF DMR-0907475, NSF DMR-0820521, and NSF EPS-1004094.