Lecture and Tutorials of "Introduction to Graphene and 2D Materials"

This class builds upon the "E_M1 Advanced Solid State Physics" lecture and develops an introductory-level insight into the main concepts and the rich phenomenology of graphene and other two-dimensional materials, leading up to the recent advancements in moiré superlattices. In particular, the class aims to introduce all the main concepts and techniques that are needed for the study of the key experimental literature on the emergent field of moiré materials, with a strong bias towards low-temperature electronic experiments.

Lecture:

Lecturer: Prof. Dr. Dmitri K. Efetov, E-mail: dmitri.efetov@lmu.de
Mon. 8:30am – 10:00am, Geschw.-Scholl-Pl. 1 (N)/Kleiner Physiksaal (N 020)

Start: 15.04.2024 - End: 15.07.2024

Tutorials:

Dr. Martin Lee, E-mail: martin.lee@lmu.de
Tutorial 1: Fri. 8:30am - 10:00am, Geschw.-Scholl-Pl. 1 (N) / Kleiner Physiksaal (N 020)
Tutorial 2: Fri. 10:30am - 12:00am, Geschw.-Scholl-Pl. 1 (N) / Kleiner Physiksaal (N 020)

Start: 26.04.2024 - End: 19.07.2024

Tutorials and grading:

Your total grade will be composed of your active participation in the lecture and tutorial (30%), a presentation with questions that you'll give about a research topic based on several research papers (50%) and 3 exercise sheets that will be solved by the students in the tutorials (20%).

Credit: 6 ECTS.

Recommended text books and study materials:

Mikhail I. Katsnelson: " The Physics of Graphene" (Cambridge University Press).

Phaedon Avouris, Tony F. Heinz, Tony Low: "2D Materials: Properties and Devices" (Cambridge University Press).

Hideo Aoki, Mildred S. Dresselhaus: "Physics of Graphene" (Springer).

Steven M. Girvin, Kun Yang: "Modern Condensed Matter Physics" (Cambridge University Press).

Thomas Heinzel: "Mesoscopic Electronics in Solid State Nanostructures" (Wiley-VCH).

Lecture materials and notes are provided PDFs/PowerPoint slides that will be updated every week.

Tentative schedule and course description:

1. Lecture 15.04 – Introduction of the rich phenomenology of graphene and 2D materials

2. Lecture 22.04 – Tight binding band-structure of graphene, bilayer graphene, hBN and TMDs
(Exercise 26.04) – Discussion and setting of the dates of the presentations.

3. Lecture 29.04 – Dirac equation, relativistic massless electrons, pseudo-spin texture
(Exercise 03.05) – Seminar session

4. Lecture 06.05 – Nano-fabrication, nano-characterization and cryogenic techniques
(Exercise 10.05) – Seminar session

5. Lecture 13.05 – Electronic transport (Drude), 2-terminal vs. 4-terminal measurements, van der Pauw technique, I/V and dI/dV, contact resistance, electric field effect, Hall effect and carrier density extraction, effect of disorder, electron mobility, mean free path, substrate effects.
(Exercise 17.05) – Return and solution of the homework 1

6. Lecture 27.05 – Consequences of the Dirac equation, Klein tunneling, C2T symmetry protected Dirac cones, SU(4) spin/valley symmetric properties of graphene, symmetry breaking (ZOOM or move to next days).
(Exercise 31.05) – Seminar session

7. Lecture 03.06 – Relativistic Quantum Hall effect in graphene, π-Berry's phase, Landau Fan diagram, Cyclotron resonance of massless fermions, Zeeman splitting and QH ferromagnetism (ZOOM or move to next days).
(Exercise 07.06) – Seminar session

8. Lecture 10.06 – Graphene-like models as starting point for topologically non-trivial phases, Berry's phase, Haldane model, topological invariants, topological Insulators
(Exercise 14.06) – Return and solution of the homework 2

9. Lecture 17.06 – Displacement field driven strong electronic interactions in AB and ABC graphene, introduction to flat band physics, symmetry breaking, half metallicity, superconductivity
(Exercise 21.06) – Seminar session

10. Lecture 24.06 – Band engineering with 1D and 2D super potentials, moiré patterns in graphene on hBN, Hofstadter butterfly, twisted bilayer graphene, Bistrizer-MacDonald model, twisted and lattice-mismatched moiré TMD bilayers
(Exercise 28.06) – Seminar session

11. Lecture 01.07 – Magic angle twisted bilayer graphene – correlated insulators, magnetism, cascade of phase transitions
(Exercise 05.07) – Return and solution of the homework 3

12. Lecture 08.07 – Magic angle twisted bilayer graphene – topology, quantum geometry, unconventional superconductivity, strange metallicity
(Exercise 12.07) – Seminar session

13. Lecture 15.07 – Other emergent moiré systems, t-MoTe2/MoTe2, ABC graphene/hBN, fractional Chern insulators
(Exercise 19.07) – Seminar session

<u>Exercises:</u>

1. 29.04 - 17.05 – Tight binding, Dirac equation, massless electrons, valley degeneracy and pseudo-spin texture, DOS calculation, conversion of carrier concentration to Fermi energy etc.

2. 27.05 – 14.06 – Electronic transport, consequences of the Dirac equation, Klein tunneling, conversion of FWHM into disorder broadening, derivation of LL dispersion vs. carrier concentration and energy etc.

3. 17.06 – 05.07 – Quantum Hall effect, Topological phases, Haldane model, superlattices etc.