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Electronic properties of tri-layer graphene

Low-dimensional electronic systems allow observation of complicated condensed matter phenomena associated with electron ordering while still being relatively easy to control experimentally. The electronic properties of a 2D electron system are radically altered when subjected to strong magnetic fields; electrons are no longer unconstrained and are forced to occupy highly degenerate discrete energy levels. In this case the electron-electron interactions grow with magnetic field, $E^{e-e} \propto \sqrt{B}$ as electronic orbits are forced closer together. Increasing the magnetic field drives the system into a regime where interactions dominate over all other energy scales,resulting in in states of matter not otherwise realizable. In multilayer systems, application of an electric field breaks additional internals symmetries, giving rise to a rich phase diagram. The main difficulty in realizing such systems is to overcome the energy-level broadening caused by disorder. For this reason, 2D electron gases are usually realized in MBE (molecular beam epitaxy) grown GaAs/AlGaAs hetero-structures.

Recently our group had demonstrated extremely clean (reaching and possibly surpassing GaAs/AlGaAs) 2D electronic devices based on graphene. Graphene is an inherently 2D layer of carbon atoms. The complexity of the system can be raised by artificially stacking 2D layers bound by Van der Waals forces. These stacks can be composed of the same material (e.g. multi-layer graphene) or of different materials (graphene stacked with other 2D atomic crystals such as hexagonal boron nitride or transition metal dichalcogenides).[1]

Most of our research is done in such systems – isolated graphene layers encapsulated in boron nitride (a 2D dielectric) with electrically conducting top and bottom gates made of few-layer graphites. In such systems we have observed the fragile even-denominator fractional quantum hall (FQH) states, the exact nature of which still remains elusive. Even-denominator FQH have attracted a lot of theoretical and experimental interest for their possible applications in topological quantum computing; it is proposed that they might host a new type of quasi-particles – non-abelian anyons, whose existence was proposed in 1988 but still remain undiscovered.

So far the group's efforts have focused on studying mono- and bi-layer graphene. But the added complexity of a third graphene layer might result in new and unexpected physics, and additional degree of control. We thus propose to study trilayer graphene for this summer project. Trilayer graphene can be thought of as a coupled system of a bilayer and monolayer graphene, with hybridization between the two tunable using an external electric field. The increased complexity of the system, which nominally includes 12 degenerate Landau levels, dramatically expands the Hilbert space available for constructing many body wavefunctions. It is consequently difficult to perform numerical simulations. New, thorough experimental studies of the tri-layer phase diagram, however, can stimulate theoretical research, further guiding experimental explorations of the phase space of magnetic fields, electric fields, and layer number and orientation. Our experiments will thus hopefully initiating a feedback loop between theory and experiment to control and design many body ground states and control their excitations for quantum devices.

To date the available theoretical studies of trilayer graphene predict new fractional quantum Hall states emerging from the broken SU(3) symmetry and trigonal warping of the band structure.[2][3] The complexity of the tri-layer graphene also offers a higher degree of tunability of the electrons wave-functions compared to mono- and bi-layer graphene[4]; tuning the wave-functions allows tuning of the form of interactions in the system and possibly stabilizing more fragile states not studied before, as well as studying quantum phse transitions between different phases. To determine the electronic band structure experimentally, we will rely on quantum capacitance measurements. Quantum capacitance measurements probe the energy cost of moving charge around the bilayer, giving access to thermodynamic density of states and layer polarization. To measure the quantum capacitance of the stacked 2D layers, we sandwich them between two gates, forming a capacitor. To amplify the signal caused by the change in the (very small) capacitance, we use a transistor amplifier based on a commercial HEMT (high electron mobility transistor). The readout signal consists of the change in capacitance caused by the electronic band structure and an added parasitic contribution originating from, for instance, the wires separating the device and the amplifier. In order to register the most subtle changes in the band structure, we need to reduce this parasitic contribution; hence, it is crucial to have an amplifier in direct proximity of the device.

Project Milestones for Student

(weeks 1-2) Assemble a Van der Waals heterostructure with a tri-layer graphene active layer. Design a measurement device and fabricate it. The undergraduate already has experience making Van der Waals stacks. Start simulating the single-particle phase diagram, which ignores electron interactions.

(weeks 3-5) Get familiar with the measurement setup and software. Determine the phase diagram of the lowest energy level of the tri-layer graphene device. Compare the observed phases with the single-particle simulations, label observed fractional quantum hall states.

(weeks 6-beyond) Accumulate data, characterize the states by tracking their evolution as a function of temperature and magnetic field (in and out of plane), preparing publication quality figures for and writing the draft for a paper.

In the duration of the project, the undergraduate would improve his fabrication skills and learn to perform measurements in a high magnetic field, cryogenic environment and most importantly analysis. The graduate student will direct the required reading and assist with all steps of the experiment. The results would contribute to the undergraduate's senior thesis project; the reading would help the undergraduate to familiarize himself with the most current problems in condensed matter physics and would help him make decisions regarding graduate school applications.
Based on the unique device cleanliness that we achieve in our lab and the complexity of the tri-layer system there is a high probability of achieving a publishable result in a journal.

References

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