THESIS DEFENSE: Exploring graphene artificial superlattices and hydrodynamic plasmons

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Graphene has revolutionized the field of condensed matter physics over the last two decades, emerging as an outstanding research platform. This is because graphene electrons behave as massless Dirac fermions, displaying properties typical of relativistic particles, and because of its extraordinary opto-electronic characteristics, such as an exceptional electron mobility, high tunability with electrostatic gating and broadband light absorption. More recently, the discovery of correlated physics in graphene moire superlattices has led to a torrent of new investigations and results in the community. Moire superlattices are generated by stacking Van der Waals layers with a relative twist, originating a new and longer periodicity that modifies the electronic band structure. In principle, one could also engineer artificially such superlattices, with the benefit of a complete flexibility to create any kind of lattice. In the first part of this Thesis, we introduce a new nanopatterning technique allowing us to pattern Van der Waals materials on a scale comparable to moire superlattices, but with no restrictions in the lattice design. Our technique is based on ion-beam milling of suspended membranes and is able to imprint periodic features in graphite electrodes with less than 20 nm period. These periodic features serve to generate a superlattice potential in single layer graphene that modifies its band structure, which is demonstrated through electronic transport measurements. We employ our nanopatterning process to study more complicated lattice structures, which are not accessible by twisting layers. Our technique allows us to propose a feasible experimental setup to engineer isolated electronic flat bands, that could potentially lead to correlated phenomena, by inducing a superlattice potential in gapped bilayer graphene. This will allow to engineer a new class of solid-state Fermi-Hubbard model simulators, similar to those in moire semiconductors.
Owing to the long distances graphene electrons can propagate without loosing their momentum, even at room temperature, it was recently shown that they can behave as a hydrodynamic fluid, for a significant and experimentally accessible range of parameters. This fluid-like behaviour is driven by the electron-electron collisions. Phenomena typical to liquids, such as viscosity, has been studied in graphene devices, drawing considerable interest from the scientific community. In the second part of this Thesis, we employ terahertz graphene plasmons - a collective excitation of the electron density - to explore the transition

from the collisionless regime, where electron-electrons do not play a role in the dynamical response of graphene, to the hydrodynamic regime. We demonstrate that the dynamica response of an electron liquid to an oscillating electric potential is different depending o whether the excitation frequency is larger or smaller than the frequency of electron-electro collisions. In electronic Fermi liquids, this is the equivalent of the zero to first sound transitio observed in neutral Fermi liquids such as He-3. Finally, we implement a phase-resolved TH scattering nearfield system, that allows high signal-to-noise ratio imaging in the THz regim with few tens of nanometers resolution. We apply this technique to image THz acousti plasmons in charge neutral graphene, for the first time

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