Impact of disorder and topology in two dimensional systems at low carrier densities

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by

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Contents

3 Experimental methods 63

Chapter 1

Introduction to the thesis

Two dimensional (2D) systems with low carrier density is an outstanding platform for studying a wide spectrum of physical concepts. It includes both classical and quantum phenomena. At very low carrier densities, the 2D system often becomes inhomogeneous and exhibits various classical effects such as critical behaviour of percolation mechanism [1] and enhancement of magneto-electric properties [2]. Low carrier density in 2D is also associated with the dominance of the Coulomb interaction energy over the kinetic energy which can lead to exotic phases of matter [3]. Furthermore, lowering the carrier density is the only way to tune the Fermi energy inside the band gap of a topological insulator and access its topologically protected surface states [4].

In this thesis, we study the physics at low carrier densities of GaAs/AlGaAs heterostructure and bilayer graphene. GaAs/AlGaAs heterostructure provides a model 2D system at its heterojunction to study low density phenomena arising from disorder and strong Coulomb interactions. One of the main goals of this thesis is to take advantage of the fine control over its number density and explore new phase space for the impact of disorder. This has been addressed in Chapter 4 and 5, and forms the first part of the thesis. Bilayer graphene at low carrier densities has been a subject of many experimental and theoretical works. It is a complex system with multiple transport mechanisms closely spaced in the phase space. Inside an induced band gap, disorder and its topological aspects are particularly prominent. The second part of the thesis explores a variety of electrical measurement tools to discern the nature of bilayer graphene at low densities. Before these experimental Chapters, **Chapter 2** reviews the fundamentals of these systems and their transport phenomena and **Chapter 3** describes in detail the experimental methods that have been used for this thesis work.

A two-dimensional electron system (2DES) formed in a GaAs/AlGaAs heterostructure offers an avenue to build a variety of mesoscopic devices, much of which is achieved by the capability to construct complex potential landscapes using surface gates. Trapping charge carriers in low densities on them gives the prospects for a broad range of phenomena to emerge. For example, under a plane surface gate which has driven the system to low carrier densities, electronic screening to long range disorder diminishes and leads to a disordered profile of the conduction band edge where electrons distribute very inhomogeneously [1]. This has been associated with phenomena such as metal-to-insulator transition [1,5] and charge density waves [3] enhanced by a strong magnetic field. However, the effect of a strong in-plane electric field has not been explored in this system. **Chapter 4** investigates a new direction in the phase space of strongly inhomogeneous 2DES by applying a strong in-plane electric field with a strong gate electric field and magnetic field. Surprisingly, we find a linear form of longitudinal magneto-resistance which is colossal in magnitude. We attribute this to be a classical effect of strong disorder.

A suitable periodic potential landscape in a 2DES can form a lattice of quantum dots. If the number density is lowered such that very few electrons are trapped in the quantum dots, the system can resemble an artificial crystal. By controlling its energy scales, a quantum dot lattice can be used for experimental simulations of difficult-to-study solid state systems. In this direction, **Chapter 5** studies a dual-gated GaAs/AlGaAs heterostructure, with an unprecedented control over its potential landscape, and shows the formation of a highly tunable quantum dot lattice formed electrostatically.

In bilayer graphene, the tunablity of band gap is the most striking property [6]. However, simple electrical transport and electronic compressibility measurements have revealed that a significant density of mid-gap states exist inside the band gap [7,8], thereby undermining it. It has taken sophisticated experimental techniques to come up with several pictures that can explain their existence. For example, STM measurements have shown the formation of electron-hole puddles [9] which can contribute to hopping transport through localized states, whereas ARPES measurements have shown the presence of linear bands inside the gap arising from interlayer relative twist due to structural disorder [10]. Inside the gap, 1D valley polarized propagating modes have also been shown to exist [11], owing to the topological nature of bilayer graphenes band-structure, which has been gaining increased attention recently. They are particularly interesting because of their prospect in enabling next generation valley based information processing systems [12]. Physically, these 1D channels can reside on the edges of bilayer graphene [13], grain boundaries between AB and BA stacking in its bulk [11], and interfaces between areas of inverted electric fields [14].

It is clear that the investigation of the complex phase space of gapped bilayer graphene at low densities requires a variety of measurement tools. Most of these tools, which were discussed above, are scanning probes which are inconvenient in several respects. It is thus desirable to have an electrical measurements scheme to study this phase space. For example, this would be highly convenient to characterize devices produced in batches. The second part of the thesis employs a higher order statistical moment of resistance/conductance, namely the variance of their fluctuations, to complement the averaged resistance/conductance and studies gapped bilayer graphene at low densities. In **Chapter 6**, the low density regime of gapped bilayer graphene is investigated systematically by studying its conductance and $1/f$ type resistance noise. Our results show possible evidence of percolative transport and topologically protected edge transport at different ranges of low number densities respectively. In **Chapter 7**, the same phase space has been explored by studying its mesoscopic conductance fluctuations at very low temperatures. This is the first of its kind systematic experiment in a dual-gated bilayer graphene device. Its conductance fluctuations have several anomalous features suggesting non-universal behaviour at odds with conventional disordered systems.

Finally **Chapter 8** concludes the thesis with a summary of the main results and a discussion of scope for future work. **Appendix A** gives the fabrication details of the GaAs/AlGaAs heterostructures studied in this thesis.