# Graphenes: The Ultimate Electronic Flatlands

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Graphene is a one-atom-thick layer of carbon atoms arranged in a honeycomb structure (Fig. 1). It can be thought of as a single atomic layer of the graphite found in lead pencils. In 2004 Andre Geim and Konstantin Novoselov were able to isolate it and to study its physical properties. They discovered that graphene has truly exceptional qualities: it is stronger than steel and it conducts electricity much more efficiently than copper. Geim and Novoselov's 2004 discovery was seminal: it started a new field of research that is currently the most active in physics, and was recognized with the 2010 Nobel prize. A recent analysis of search terms on *Nature* magazine's website ranked "graphene" first, followed by "HIV" and "cancer."

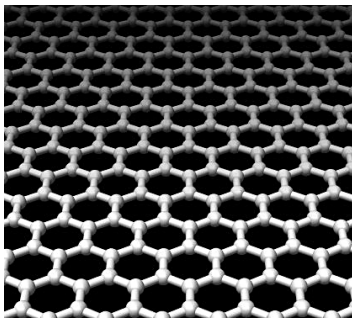

***Figure 1:*** *Graphene.*

One of the features of graphene that has attracted so much attention among physicists is the fact that the electrons behave as massless ultrarelativistic electrons. This has allowed the study in graphene of ultrarelativistic effects that could not be studied otherwise. The electronic properties of graphene, in particular its exceptional conductivity, make it also extremely interesting for technological applications.

Since 2004 new graphene-based materials, such as bilayer graphene, have been realized. Bilayer graphene is formed by two stacked layers of graphene. These new graphene-based materials also have unique electronic properties that are currently studied very actively and still poorly understood. It appears that in bilayer graphene the electron-electron interactions play a much more important role than in single layer graphene. In addition, in bilayer graphene the electronic properties, i.e. its band structure, can be modified qualitatively via external fields. To better understand how the interplay of electron-electron interactions and external electric fields affect the properties of bilayer graphene we have calculated how the electrons in bilayer graphene reacts to an external (parallel) AC electric field taking into account both the interactions

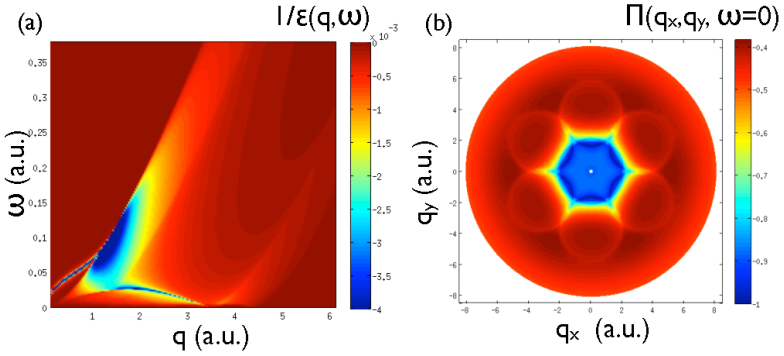


***Figure 2:*** *(a) Color plot that shows one over the dielectric function as a function of inverse wavelength (q) and frequency (ω). The most prominent new feature is the lower blue arch that indicates the presence of a novel "resonant ripple." (b) Response function for ω = 0 of the electron-liquid in bilayer graphene to an external electric field. Adapted from [1].*

and the presence of a static perpendicular electric field. The question that we addressed is analogous to the question of how ripples form and propagate in a pond of water: our "water" is the "liquid"-like state formed by the electrons in bilayer graphene.

Using SciClone, we have discovered that in bilayer graphene, in the presence of a vertical electric field, the ripples in the electron-liquid are very different than in unbiased bilayer graphene [1]. This is shown by the color plot in Fig. 2(a) that effectively shows the amplitude of the ripples in the electron-liquid of bilayer graphene as a function of inverse wavelength ($q$) and frequency ($\omega$). The most prominent new feature, absent when the perpendicular electric field is set to zero, is the appearance of a particularly strong "ripple" for values of $q$ and $\omega$ along the lower blue arch in the figure. We have also calculated how the intensity of the ripples depend on the direction of propagation, as shown in Fig. 2(b).

Another important topic that we are studying is how disorder, always present in real systems, affects the properties of graphenes. There is compelling evidence that in graphene and bilayer graphene charge impurities are the dominant source of disorder. In the presence of charge impurities the electron-liquid in bilayer graphene breaks up in puddles as shown in Fig. 3(a). To characterize theoretically the properties of a system in the presence of disorder it is necessary to consider many (thousands or more) disorder realizations and then appropriately average the results. This is a task that can only be accomplished using parallel computers. With SciClone we have calculated the transport properties of bilayer graphene [2, 3] and found that they depend in a very anomalous way on the density of charge impurities ($n_{imp}$) and the average electron density $\langle n \rangle$ as shown in Fig 3(b). This figure shows that bilayer graphene, in the presence of a perpendicular electric field, can exhibit four very different regimes (I, II, III, IV) and that, counterintuitively, in this system an increase of the disorder can result in an increase of the conductivity (as we go from region III to region IV along a horizontal line).

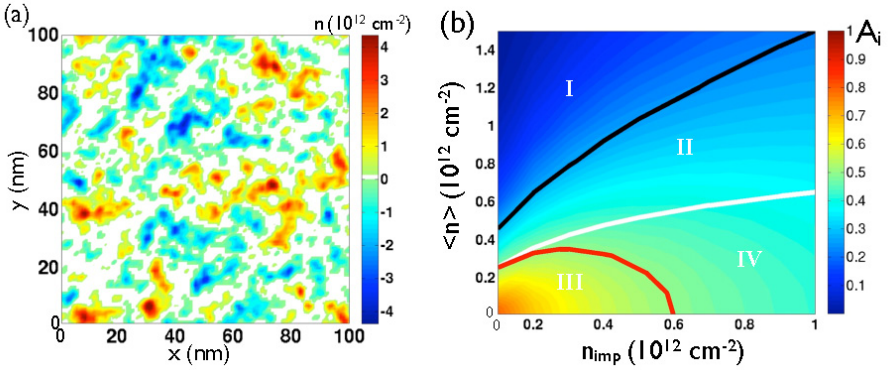


***Figure 3:*** *(a) Electron density profile of bilayer graphene in the presence of a perpendicular electric field and charge impurities. Blue indicates regions where there is a lack of electrons (hole-regions); red regions have an excess of electrons; white regions have an electron density of zero. (b) Color plot that shows the fraction of the area ($A_i$) in which the electron density is zero as a function of the impurity density $n_{imp}$ and average electron density $\langle n \rangle$. In region III, $A_i > 50\%$ and so in this region the system is expected to be an insulator, whereas in regions I, II, and IV, $A_i < 50\%$ so in these regions the system is expected to behave as a metal. Adapted from [2].*


[1] C. Triola and E. Rossi. Collective modes of bilayer graphene. In preparation.

[2] E. Rossi and S. Das Sarma. Inhomogenous electronic structure, transport gap, and percolation threshold in disordered bilayer graphene. *Phys. Rev. Lett.*, 107:155502, Oct. 2011.

[3] Qiuzi Li, E. H. Hwang, E. Rossi, and S. Das Sarma. Theory of 2d transport in graphene for correlated disorder. *Phys. Rev. Lett.*, 107:156601, Oct. 2011.