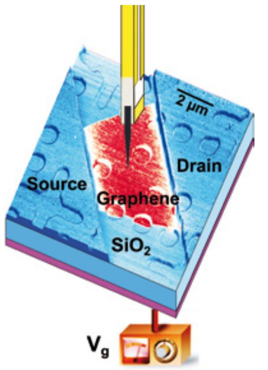
Charge-carrier puddles in graphene

What is the spatial extent over which a localized charge perturbs the density of the free charge carriers (electrons or holes) in a two-dimensional electron gas? In graphene – a remarkable 2D material where the charge carriers have zero mass – the capacity to screen background charges depends very strongly on the charge-carrier density. When the carrier density decreases, self-consistent screening theory predicts that the effect of electrostatic inhomogeneities can become very long-range. Scanning Tunnelling Microscopy is a powerful technique for investigating this question.

In vacuum or an insulator, in accordance with Coulomb's law, electrostatic interactions are extremely long range, with no characteristic length scale. Inside a conductor, the free charge-carriers move to screen any inhomogeneities of the potential landscape and Coulomb's law is quenched by an extra, exponential-decay term. This term defines a characteristic screening length, over which electrostatic inhomogeneities are smoothed out.

Fig. 1: The tip of a Scanning Tunnelling Microscope probes features in the graphene's density of states which contain information about the local concentration of free-carriers, that is, the local electrostatic potential. The graphene's conductance can be probed independently by two lateral metallic contacts (source and drain). The overall carrier density is adjusted by the capacitive coupling to a back gate (V_g) below the graphene.



Inhomogeneities in the electrostatic environment are of paramount importance for the device performances of 2D electron gases. The electric-potential inhomogeneities are usually caused by nearby, randomly distributed fixed charges, for example in the substrate. The question is then to understand the ability of a conductor to screen variations of the electrostatic background. In conventional 2D electron gases, such as found at the interfaces in semiconducting heterostructures, the ability to screen a fixed charge background does not change with the carrier density. Whatever the concentration of free carriers, the regions of locally lower or higher potential associated with isolated "puddles" (small lakes) of local excess electron or hole density, remain the same in size.

Graphene (a single sheet of carbon atoms) is different. The reason is that, unlike in the usual 2D carrier gases, its charge carriers (both electrons and holes) behave as if they have no mass. Here, it has been predicted that, at the point of vanishing carrier density, the electrostatic screening length should diverge. The carriers form into separated "puddles" whose size diverges and the electrostatics recovers a bare Coulomb-like behaviour. In other words, charge neutral graphene should behave somewhat like an insulator.

To pin down the above prediction experimentally, we have mapped charge-carrier puddles, that is variations of the local electric potential, with sub-nanometre resolution in a graphene device. This was done using a cryogenic Scanning Tunnelling Microscope (STM), see Fig. 1. The main experimental difficulty stems from the fact that the graphene sheet is in a device geometry, meaning that large parts of the substrate (SiO_2) are insulating and thus invisible to the STM technique. This was overcome by combining *in situ* the two rather antagonistic methods of Atomic Force Microscopy (AFM) and STM.

The overall carrier density in the sample of graphene under study is adjusted by applying a potential from a gate electrode situated below the graphene. When and how the graphene is driven to charge neutrality by this gate potential is independently determined by measuring how well the graphene conducts current laterally: when the resistance is maximal, the sample is charge neutral.

The experiment accurately confirmed the above predictions: as graphene goes charge neutral, the potential inhomogeneities grow substantially and in agreement with theory (Fig. 2). Yet, there is a saturation of the size of the inhomogeneities as the carrier density decreases towards zero. This is because, although it may be charge neutral overall, a sheet of graphene is not so at the nanoscale in the presence of a random impurity potential: There are puddles of negatively charged electrons and positively charged holes. A detailed comparison of our experimental results with self-consistent screening theory, done in collaboration with theoretician colleagues of the National University of Singapore, shows very good agreement.

The above-described scenario of the graphene response to charge impurities is implicitly assumed in the prevailing microscopic models, which very successfully describe a large set of electronic transport properties of graphene-based devices. This experiment is the first to check that the underlying assumptions indeed hold, at the microscopic level.

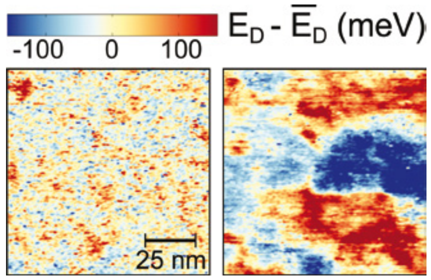


Fig. 2: Two maps displaying variations of the local Dirac point energy E_D, that is the local electrostatic potential at different back-gate voltages. At strong hole doping (a), the carrier puddles are short range and of small amplitude. Near global charge neutrality (b), the variations of the potential are very large, both in lateral extent and in amplitude.

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FURTHER READING...

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