Lecture 10. Properties of Graphene and Graphene Oxide

The purpose of the lecture: to provide information on the properties of graphene and graphene oxide.

Expected results: to know the properties of graphene and graphene oxide.

Electronic Properties of Graphene

Wallace, in 1947, used the two-dimensional honeycomb structure of graphene to obtain information on the properties of graphite and developed the band theory of graphite. In his analyses he assumed that since the spacing of lattice planes of graphite is large (about 0.337 nm) compared with the hexagonal spacing in the layer (0.142 nm), as a first approximation, the interactions between the planes may be neglected and may be supposed that conduction takes place only in the layers and this assumption makes subsequent analyses applicable to graphene.

Discovery of graphene made it possible to experimentally explore the nature of graphene's conductivity and verify the exotic electrical properties initially predicted—in particular, that its mobile electrons behave as if they were massless, relativistic fermions.

Each carbon atom in graphene's honeycomb lattice forms strong covalent bonds with its neighbors, with one unbound electron on each carbon atom left over to interact and move around the carbon atoms across the two-dimensional crystal lattice. The electronic π-band structure of graphene derived from its crystal structure governs the behavior of its electrons and describes the energy dependence of that electronic motion, that is, how a particle's energy changes with its momentum along valence and conduction bands. The band structure picture of graphene can be considered as the starting point to understand the amazing electronic properties of graphene.

Band Structure of Graphene

The hexagonal crystal structure of graphene consists of two interpenetrating triangular sublattices A and B. Figure 1 shows the honeycomb lattice structure of graphene and its lattice vectors, reciprocal lattice vectors, and the first Brillouin zone. The two different but equivalent carbon sublattices in the crystal structure of graphene give graphene its unique electronic band structure and the unusual behavior of charge carriers in graphene.

To understand the behavior of electrons in a crystal, it is important to consider the electronic dispersion relation called the E-k relation, or the energy–momentum dispersion relation. Considering only the nearest neighbors in the honeycomb lattice of graphene and using a simple tight-binding approach for electrons in graphene, the energy band structure of graphene is obtained. Figure 2 shows the electronic dispersion in graphene or the electronic band structure of graphene.

The upper conduction band (π* band) and the lower valence band (π band) meet or touch, with a perfect symmetry between the upper band and the lower band, at discrete points in graphene, (at the K or K′ point in the first Brillouin zone) and as the bands approach each other the dispersion of those bands is linear. The energy bands in the vicinity of the K or K′ point in the first Brillouin zone show a linear dispersion relation of energy versus momentum, that is, $E = \hbar v_F k$, where v_F represents the Fermi velocity and is equal to 106 m/s. The linear dispersion curve implies that the electron's effective mass, a parameter that accounts for the interaction of electron with the lattice, vanishes, that is, becomes zero throughout a large range of momentum values in the crystal lattice, and hence the velocity of the electrons confined on graphene remains constant, a transport property similar to the massless particles like photons. The electron behaves more like a photon than a conventional massive particle whose energy–momentum dispersion is parabolic and given by $E = \hbar^2 k^2/2m^*$, where m* is the effective mass of electron. The linear dispersion relation for graphene close to the K or K′ points is similar to the two-dimensional Dirac equation for relativistic massless particles (photons) except that for graphene the Fermi velocity of electrons or holes replaces the speed of light, which appears in the relativistic Dirac equation. The K points at the corners of the graphene Brillouin zone where the empty conduction band and the filled valence band meet are

called Dirac points. There are six Dirac points (two sets of unequal Dirac points K and K′) located at the six corners of the graphene Brillouin zone. The conduction and valence bands are represented by two Dirac cones with touching points that cross linearly at the neutrality point or Dirac point where E(k) = 0 = EF (Fermi level energy).

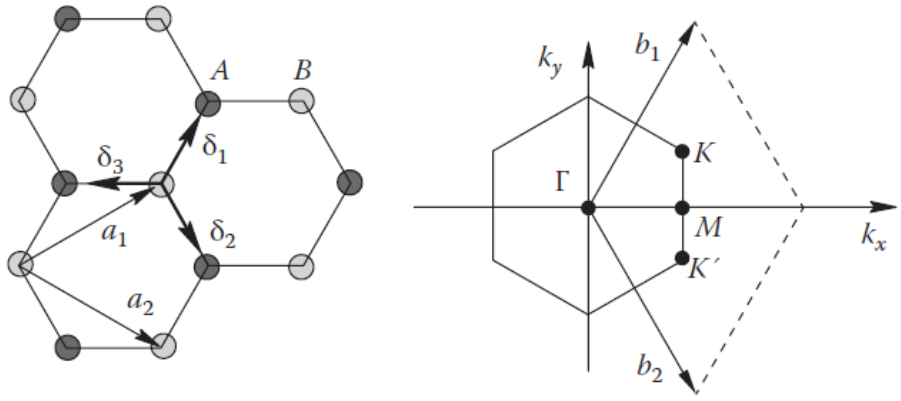

FIGURE 1. (a) Lattice structure of graphene made out of two interpenetrating triangular lattices (*a*1 and *a*2 are the lattice unit vectors and δi, i = 1, 2, 3 are the nearest neighbor vectors). (b) Corresponding Brillouin zone. The Dirac cones are located at the K and K′ points

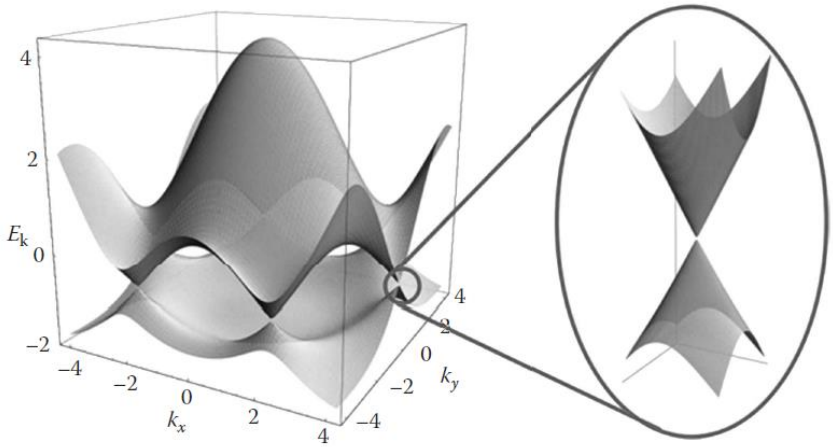

FIGURE 2. The electronic band structure of graphene where graphene's valence and conduction bands are represented by two Dirac cones with touching points that cross linearly at the Dirac point

Electronic Properties of Graphene

Graphene possesses a number of amazing electronic properties as a consequence of its 2D honeycomb crystal lattice. Some of the unique electronic properties of graphene are highlighted next.

Measurement of the intrinsic transport properties of graphene have shown that graphene possesses high charge carrier mobilities. In their initial studies on fewlayer graphene, Novoselov et al. obtained charge mobility values between 3000 and 10,000 cm2 V−1 s−1. The mobilities were practically independent of absolute temperature, T, indicating that they were still limited by scattering on defects. Mobilities in excess of 200,000 cm2 V−1 s−1 at high electron densities of ~2 Ч 1011 cm−2 have been measured for a suspended single-layer mechanically exfoliated graphene. A high quality of 2D crystal of graphene implies an unusually low density of defects, which typically serve as the scattering centers that inhibit charge transport. High carrier mobilities show that charge transport is essentially ballistic on the micrometer-scale at room temperature.