

Theory of monolayer and bilayer graphene: Pseudo-spin physics

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In this talk a brief review is given on characteristic features of electronic states in graphene and its multi-layers mainly from a theoretical point of view, together with topics on roles of electron-phonon interactions studied recently.

The electron motion in graphene is governed by Weyl's equation for a neutrino or the Dirac equation with vanishing rest mass characterized by a velocity which is about 1/300 of the light velocity. The pseudo-spin wave function exhibits a sign change due to Berry's phase when the wave vector \mathbf{k} is rotated around the origin and therefore has a topological singularity at $\mathbf{k}=0$. This singularity is the origin of the peculiar behavior in the transport properties of graphene, such as the minimum conductivity in the absence of a magnetic field, the quantum Hall effect, the dynamical conductivity, and the singular diamagnetism [1], as well as the absence of backscattering in metallic carbon nanotubes [2-4]. The neutrino equation is invariant under special time-reversal operation S corresponding to the system with strong spin-orbit interaction. Because S is not the real time-reversal symmetry, it can be destroyed by various perturbations. This leads to symmetry crossover characteristic to the graphene system, manifesting itself as negative or positive magnetoresistance [5,6].

There are three different kinds of phonons contributing to electron-phonon interaction. They are long-wavelength acoustic phonons, zone-center optical phonons, and zone-boundary phonons [7]. In particular, optical phonons varies strongly as a function of the Fermi level and applied magnetic field through electron-phonon interaction [8-11], as experimentally observed [12-14]. Inter-layer interaction in bilayer graphene destroys the linear dispersion into an approximate parabolic dispersion [15]. In this system, strong asymmetry in the potential of two layers can be introduced by external fields, leading to band-gap opening and strong mixing of symmetric and antisymmetric optical phonons [16] as well as the phonon softening [17], as experimentally observed [18-20].

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