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Strained graphene Josephson junction with anisotropic *d*-wave superconductivity

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ABSTRACT

Effect of proximity-induced superconductivity in the new two-dimensional structures, as graphene and topological insulator on the Andreev bound states (ABSs) and Josephson supercurrent has attracted much efforts. Motivated by this subject, we study, in particular, the influence of anisotropic Fermi velocity and unconventional *d*-wave pairing in a strained graphene-based superconductor/normal/ superconductor junction. Strain is applied in the zigzag direction of graphene sheet. In this process, effect of zero energy states and Fermi wavevector mismatch are investigated. It is shown, that strain up to 22% in graphene lattice differently affects Josephson currents in parallel and perpendicular directions of strain. Strain causes to exponentially decrease the supercurrent in the strain direction, whereas increase for other direction. We find that, in one hand, the ABSs strongly depend on strain and, on the other hand, a gap opens in the states with respect to non-zero incidence angle of quasiparticles, where a period of 2π is obtained for Andreev states. Moreover, we observe no gap for $\theta_s \neq 0$, when the zero energy states (ZESs) occur in $\alpha = \pi/4$ due to anisotropic superconducting gap. In this case, ABSs have a period of 4π.S

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1. Introduction

The exotic electronic properties of quasiparticles in two-dimensional honeycomb atomic graphene lattice [1,2] have allocated many research works to itself during the last few years. Existing two sub-lattices in graphene, that responses to pseudospin quantum number of relativistic charge carriers leads to interesting features of dispersion relation, so that at first, there is no Fermi surface at Dirac point in pristine graphene, secondly, linearity of dispersion relation in the first Brillouin zone gives rise to zero effective mass of charge carriers. One of the important properties of graphene lattice is the endurance of uniaxial mechanical strain up to 20%, leading to open an energy gap due to considerable deformation of two inequivalent Dirac points, K and K', as shown in Fig. 1(a). As primary theoretical and experimental works, the effect of reversible and controlled strain on electronic properties of graphene is investigated in Refs. [3–6]. Pereira et al. [7], using the tight-binding approach have shown that the magnitude of gap opening for deformation beyond 22% depends on the direction of strain. In this regards, another calculation has been performed by Choi et al. [8] with the result that the work function increases substantially as the uniaxial and isotropic strain increases.

Regarding the proximity-induced superconductivity in graphene achieved experimentally in Refs. [9–11], massive investigations with respect to the transport properties of superconductor/graphene structures were carried out in recent few years [12–32]. Relating with such proximity effect, formation of ABSs between two superconducting electrodes separated by a normal section on top of a graphene monolayer is described by nontrivial modification of Andreev reflection. Conventional and, specially, unconventional superconducting gap can give rise to create gapped or gapless superconductor quasi-particle excitations. However, regardless of conventional s-wave pairing graphene-based Josephson structures [33–37], it needs to pay attention to how unconventional pairing influences the transport properties (see, for example Refs. [20,24,38–41]), since, actually such pairing gap behaves in different ways with respect to electron-like or hole-like quasiparticle incidence to the gap.

Motivated by these, we investigate in this paper the effect of both strain and anisotropic d-wave pairing on ABSs and supercurrent. The supercurrent in Josephson structure was studied with strained graphene s-wave order in [42] and without graphene substrate d-wave pairing in [43]. Indeed, detecting unconventional Cooper pair coupling has a noticeable importance in high-T_C superconductivity. Experimentally developments in this area can consist the works of Wang, Li, Takano, Latyshev and et al. [44–47] and Katterwe et al. [48], where purported d-wave superconductor $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi2212) can be considered as a candidate for anisotropic pairing. The article is organized as follows: in Section 2, we present the theoretical formalism and exact analytical solutions of Dirac–Bogoliubov–de Gennes (DBdG) equation and corresponding Andreev bound state taking into account the formation of zero energy states (ZESs). In Section 3, our main numerical results are discussed. Finally, we summarize our findings in Section 4.

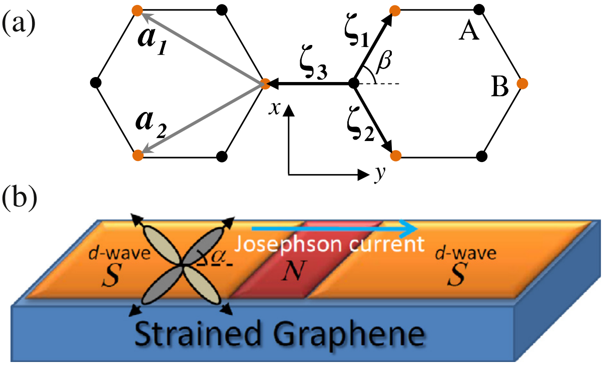

Fig. 1. (a) Sketch of lattice structure of deformed graphene due to strain. (b) Schematic of strained graphene Josephson junction, where d-wave superconductivity is induced via the proximity effect.