Physica B 455 (2014) 26–30

Contents lists available at ScienceDirect

Physica B

journal homepage: www.elsevier.com/locate/physb

Andreev levels in a Josephson superconductor graphene superconductor nanostructure

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ARTICLE INFO

Article history:
Received 26 December 2013
Accepted 18 July 2014
Available online 19 August 2014

Keywords:
Graphene
Josephson
Density of states
Armchair edge
Zigzag edge
Green function

ABSTRACT

We obtain the bound states in superconductor-graphene-superconductor nanostructure, which are responsible for the Josephson effect. The coupling between graphene and each superconducting region is modeled as two different hopping parameters in the respective SG and GS interfaces. With the purpose of determining the local density of states and the spectrum, the Green function of the junction is calculated resolving the Dyson equation. We obtain that the number of levels depends on the width and doping of graphene region and this occurs for the two types of edge (armchair or zigzag). We investigate the behavior of the bound states as a function of the transparency. In the limit of a transparent junction, the results obtained by the Green's function method reproduce those present in the literature. In the tunnel limit the spectrum is different for armchair and zigzag edges.

1. Introduction

Josephson junctions, in which a graphene film assumes the role of a weak link between the superconductors, have been recently investigated theoretically [1–6] and experimentally [7–12]. In these junctions the D.C. Josephson effect has been observed, which is a clear signature of the coherent transport of electrons and holes through the graphene film. In addition, to investigate the critical current, Fraunhofer pattern, current voltage and current phase relations, it is necessary to investigate the effect of the graphene film edge armchair or zigzag [13,14] on the electronic transport properties. In this way, the first step is to analyze microscopically the energy spectrum considering both type of edges, for different Fermi energies and transparency values of the interfaces.

In the short junction limit $L \ll \xi$ in which the length of graphene film L is much lower than superconducting coherence length ξ, the supercurrent is mainly carried by the discrete Andreev levels [19,20]. For graphene (G)–superconductor (S) surfaces the Andreev levels split and these ones exhibit oscillations as a function of the graphene Fermi energy [16], both effects are due to valley mixing. The energy spectrum in SGS junctions has been calculated [3,4], where have been analyzed the effects of specular Andreev reflection [18], on the electronic transport properties. Phase difference between superconductors and transparency through graphene–superconductor interfaces is responsible for the splitting of energy levels.

In this work we show that by changing transparency through the interfaces for both armchair and zigzag edges, there is a splitting of the energy levels, which is different from the splitting obtained by changing phase difference. We show that the structure of the energy levels is affected by doping of the graphene film [15], and transparency through interfaces. Finally, we present some results for the short junction regime, in which the gap between the Andreev levels is enhanced.

2. System description

We determine the density of states for a SGS superconductor-graphene-superconductor Josephson junction (see Fig. 1a). This density gives information about both the continuum spectrum and Andreev levels [19], which are formed by the interference of quasiparticles. The GS and SG interfaces are made of graphene in normal and superconducting states, where the superconductivity is induced by means of proximity effect [7–9,17] through a superconducting electrode, and a phase difference φ between the superconductors is considered.

The Josephson junction is in the $x-y$ plane, the graphene–superconductor interfaces are perpendicular to the x axis. The normal region has a length W, and extends from $x=0$ to $x=-W$, which can have armchair or zigzag edges parallel to y axis (see Fig. 1b). The superconducting regions are modeled as semi-infinite mediums that extend from $x=-\infty$ to $x=-W$ and from $x=0$ to $x=\infty$.

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http://dx.doi.org/10.1016/j.physb.2014.07.038
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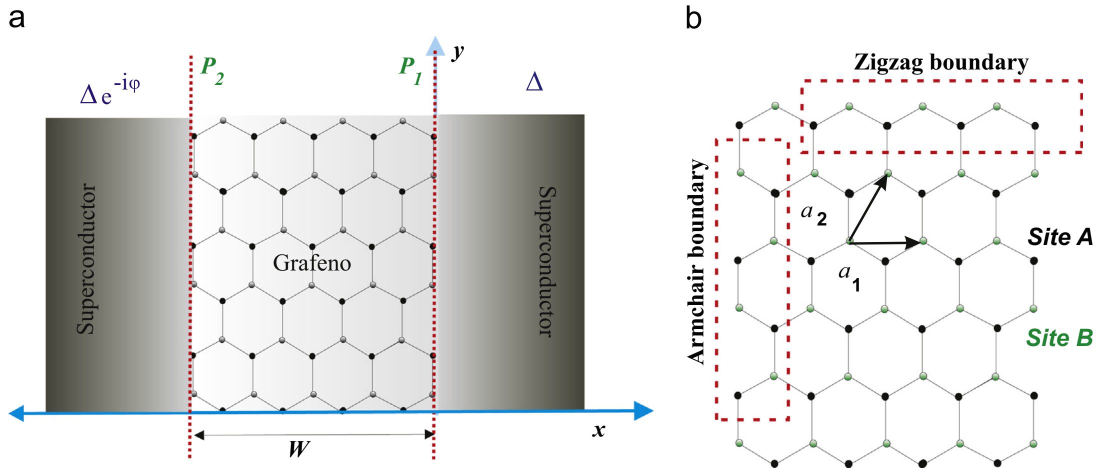

Fig. 1. (a) Josephson superconductor-graphene-superconductor junction, the width of the normal region is W. Right(Left) GS(SG) interfaces have in general, different hopping parameters $P_1(P_2)$. (b) Honeycomb lattice of graphene indicating the two types of boundaries.

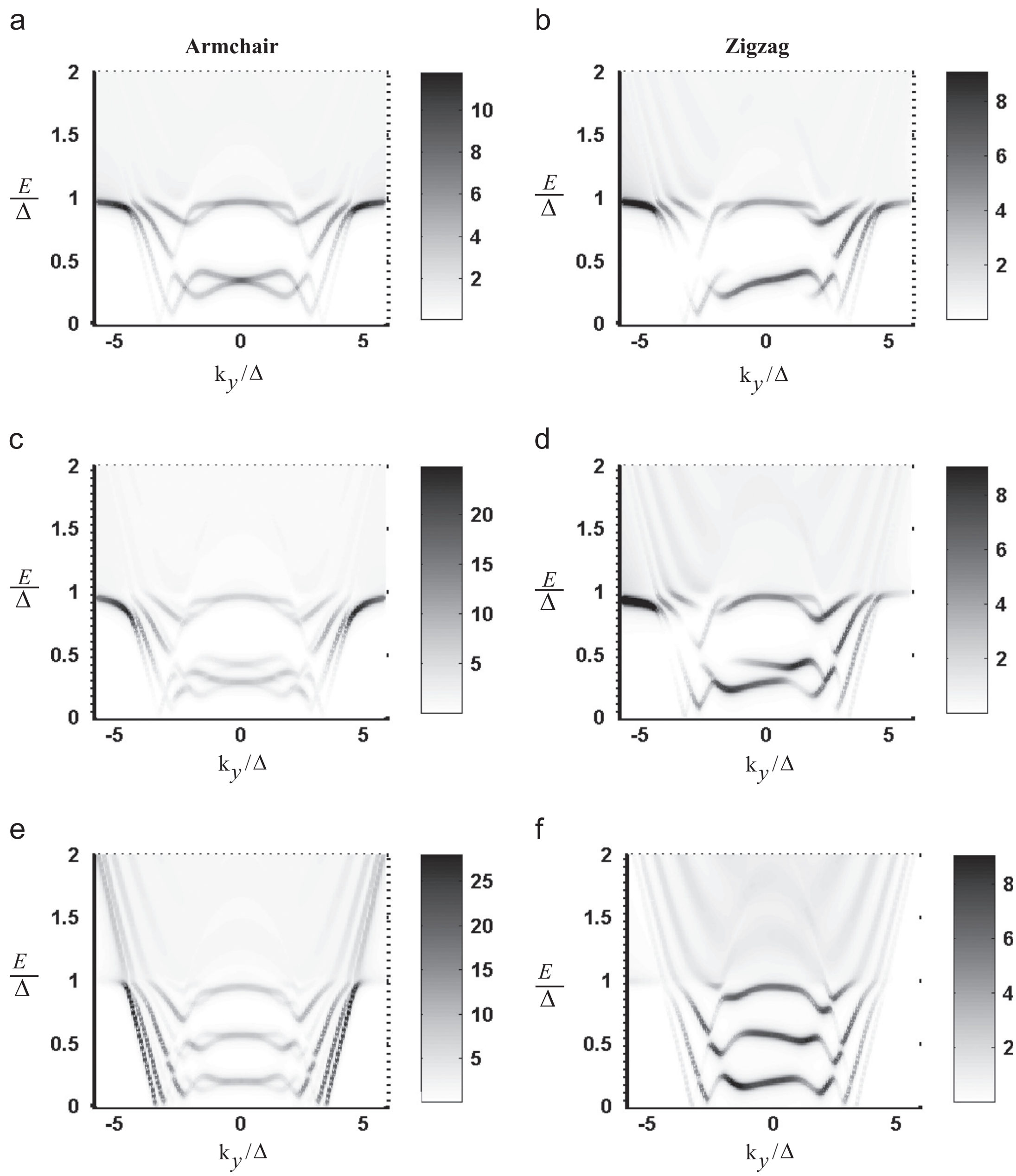

Fig. 2. Local density of states contour plot for a graphene Josephson junction with zero phase difference between the superconductors. $L/\xi = 3.464$, $E_F = 3\Delta$. Left and right graphics correspond to armchair and zigzag edges respectively. For all cases $P_1 = 1$. In (a), (b) $P_2 = 1$. In (c), (d) $P_2 = 0.7$. In (e), (f) $P_2 = 0.2$.