Physica E 72 (2015) 149–159

Contents lists available at ScienceDirect

Physica E

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

Electrostatic and magnetic fields in bilayer graphene

Ahmed Jellal [a,b,*], Ilham Redouani [b], Hocine Bahlouli [a,c]

[a] Saudi Center for Theoretical Physics, Dhahran, Saudi Arabia
[b] Theoretical Physics Group, Faculty of Sciences, Chouaïb Doukkali University, PO Box 20, 24000 El Jadida, Morocco
[c] Physics Department, King Fahd University of Petroleum and Minerals, Dhahran 31261, Saudi Arabia

HIGHLIGHTS

- The transmission probability through rectangular potential barriers and p–n junctions in the presence of a magnetic and electric fields in bilayer graphene is calculated for the full four bands of the energy spectrum.
- For energy E higher than the interlayer coupling γ_1 ($E > \gamma_1$) two propagation modes are available for transport giving rise to four possible ways for transmission and reflection probabilities.
- For the energy is less then the height of the barrier the Dirac fermions exhibits transmission resonances and only one mode of propagation is available.
- The effect of the interlayer electrostatic potential δ and different geometry parameters of the barrier on the transmission probability were studied.

ARTICLE INFO

Article history:
Received 27 November 2014
Received in revised form
27 February 2015
Accepted 29 April 2015
Available online 7 May 2015

Keywords:
Bilayer graphene
Barriers
Scattering
Transmission
Conductance

ABSTRACT

We compute the transmission probability through rectangular potential barriers and p–n junctions in the presence of a magnetic and electric fields in bilayer graphene taking into account contributions from the full four bands of the energy spectrum. For energy E higher than the interlayer coupling γ_1 ($E > \gamma_1$) two propagation modes are available for transport giving rise to four possible ways for transmission and reflection coefficients. However, when the energy is less than the height of the barrier the Dirac fermions exhibit transmission resonances and only one mode of propagation is available for transport. We study the effect of the interlayer electrostatic potential denoted by δ and variations of different barrier geometry parameters on the transmission probability.

1. Introduction

Graphene is a one atom thick single layer of carbon material, which takes the form of a planar honeycomb lattice of sp^2 bonded carbon atoms. It is the first two-dimensional (2D) crystalline material which has been experimentally realized [1]. This new material has attractive electronic properties, among them, an unusual quantum Hall effect [2,3] and optical transparency [4]. The equation describing the electronic excitations in graphene is formally similar to the Dirac equation for massless fermions which travel at a speed of the order on 10^6 m/s [5,6]. As a result graphene has a number ofattractive physical properties which makes it a good candidate for several applications. In fact its conductivity can be modified over a wide range of values either by chemical doping or through the application of a DC electric field.The very high mobility of graphene [7] makes it very attractive for electronic high speed applications [8].

Bilayer graphene consists of two single layer graphene sheets stacked in A–B stacking (also known as Bernal stacking [9]), where the A and B atoms in different layers are on top of each other. While a single layer graphene has two atoms per unit cell a bilayer graphene has four atoms per unit cell and atoms in different layers interact with each other. However, the most important interaction between the two layers is represented by a direct overlap integral between A and B atoms on top of each other, this interaction is denoted by γ_1 [12], higher order interactions between other atoms in different layers will have minor effect on the properties of the bilayer system and hence will be neglected in the present work. Many of the properties of bilayer graphene are similar to those of a single layer graphene [10,11]. However, while the energy spectrum of a single layer graphene consists of two cone shaped bands,

* Corresponding author at: Theoretical Physics Group, Faculty of Sciences, Chouaïb Doukkali University, PO Box 20, 24000 El Jadida, Morocco.
E-mail addresses: a.jellal@ucd.ac.ma, ajellal@ictp.it (A. Jellal).

http://dx.doi.org/10.1016/j.physe.2015.04.026
1386-9477/

bilayer graphene possess four bands and the lowest conduction and highest valence bands exhibit quadratic spectra and are tangent to each other near the K-points [12–15]. One of the most important applications of bilayer graphene is the fact that we can easily create and control the energy gap using a static electric field.

Recently there have been some theoretical investigations on bilayer graphene, in particular the work of Van Duppen [16] followed our recent work [17], where we developed a theoretical model that generalizes [16] and allowed us to deal with bilayer graphene in the presence of a perpendicular electric and magnetic fields. A systematic study revealed that interlayer interaction is essential, in particular the direct interlayer coupling parameter γ_1, for the study of transmission properties. Actually this interlayer coupling γ_1 sets the main energy scale in the problem. For incident energies E we found that for $E < \gamma_1$ there is only one channel of transmission exhibiting resonances while for $E > \gamma_1$ two propagating modes are available for transport resulting in four possible ways of transmission. Subsequently, we used the transfer matrix method to determine the transmission probability and associated current density. This work allowed us to investigate the current density and transmission through a double barrier system in the presence of electric and magnetic fields perpendicular to the layers and allowed us to compare our numerical results with existing literature on the subject.

The present paper is organized as follows. In Section 2, we formulate our model Hamiltonian system and compute the associated energy eigenvalues and energy bands. In Section 3, we consider the three potential regions of the bilayer and obtain the spinor solution corresponding to each region in terms of barrier parameters and applied fields. The boundary conditions enabled us to calculate the transmission and reflection probabilities. We then studied two interesting cases corresponding to incident electron energy either smaller or greater than the interlayer coupling parameter, $E < \gamma_1$ or $E > \gamma_1$. In Section 4 we consider the first situation where $E < \gamma_1$ which exhibits a two band tunneling which then results in one transmission and one reflection channel. Then in Section 5 we consider the case $E > \gamma_1$ which leads to a four band tunneling and results in four transmission and four reflection channels. In Section 6, we show the numerical results for the conductance and investigate the contribution of each transmission channel. Finally, in Section 7, we conclude our work and summarize our main results.

2. Theoretical model

We consider a bilayer graphene consisting of two A–B stacked layers of graphene, each layer has two independent basis atoms (A_1,B_1) and (A_2,B_2), respectively, as shown in Fig. 1, where the two indices (1,2) corresponding to the lower and upper graphene layer, respectively. Every B_1 site in the bottom layer lies directly below an A_2 site in the upper layer while A_1 and B_2 sites do not lie directly below or above each other. Our theoretical model is based on the well established tight binding Hamiltonian of graphite [18] and adopt the Slonczewski–Weiss–McClure parametrization of the relevant intralayer and interlayer couplings [19] to model our bilayer graphene system. The in-plane hopping parameter, due to near neighbor overlap, is called γ_0 and gives rise to the in-plan carrier velocity. The strongest interlayer coupling between pairs of A_2–B_1 orbitals that lie directly below and above each other is called γ_1, this coupling is at the origin of the high energy bands and plays an important role in our present work. A much weaker coupling between the A_1 and B_2 sites, which are not on top of each other, and hence is considered as a higher order near neighbor interaction leads to an effective interlayer coupling called γ_3 the effect of which will be substantial only at very low energies. The last coupling parameter γ_4 represents the interlayer coupling between the same kind atoms but in different layers A_1–A_2 and B_1–B_2. The numerical values of these parameters have been estimated to be $\gamma_0 \approx 1.4$ eV for the intralayer coupling and $\gamma_1 \approx 0.4$ eV for the most relevant interlayer coupling while $\gamma_3 \approx 0.3$ eV and $\gamma_4 \approx 0.1$ eV. However, these last two coupling parameters γ_4 and γ_3 have negligible effect at high energy and consequently will be neglected in our present work [12,20].

We consider bilayer graphene in the presence of a perpendicular static electric and magnetic fields. The charge carriers are scattered by a single barrier potential along the x-direction which results in three different scattering regions denoted by I, II and III. Based on the tight binding approach we can write the Hamiltonian of the system in the long wavelength limit [21,22], and the associated eigenstates $\psi(x, y)$ as follows:

$$H = \begin{pmatrix} V^+ & v_F\pi^+ & -v_4\pi^+ & v_3\pi \\ v_F\pi & V^+ & \gamma_1 & -v_4\pi^+ \\ -v_4\pi & \gamma_1 & V^- & v_F\pi^+ \\ v_3\pi^+ & -v_4\pi & v_F\pi & V^- \end{pmatrix}, \quad \psi(x,y) = \begin{pmatrix} \psi_{A_1}(x,y) \\ \psi_{B_1}(x,y) \\ \psi_{A_2}(x,y) \\ \psi_{B_2}(x,y) \end{pmatrix}. \tag{1}$$

Here $\pi = p_x + ip_y$, $p_j = -i\hbar\nabla_j + eA_j(x, y)$ is the j-th component of in-plane momentum relative to the Dirac point,

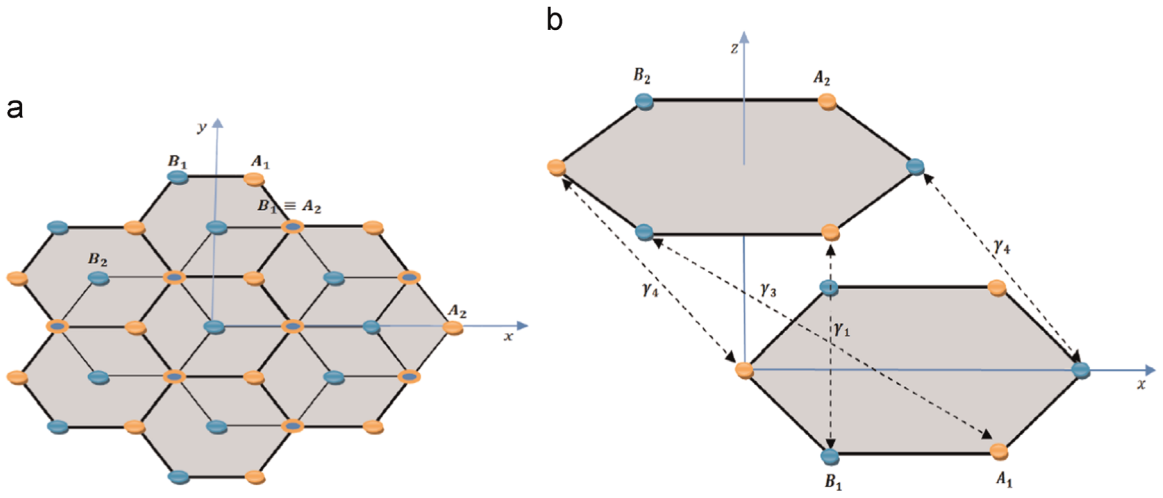

Fig. 1. Lattice structure of bilayer graphene with (A,B) atoms within the same layer.