Journal of Theoretical and Applied Physics, **4**-3, 11-14 (2010)

The effect of Landau subbands broadening on transport of disordered four-terminal graphene nanodevice

A. Jafari[1], A. Ahmadkhan Kordbacheh[2,*]

[1]*Department of Physics, Azad University, Karaj branch, Karaj, Iran*
[2] *Department of Physics, Iran University of Science and Technology, Tehran, Iran*

Received: 3 June 2010/Accepted: 15 September 2010/ Published: 20 December 2010

Abstract

In this paper, we have studied the transport properties of disordered four-terminal graphene nanodevice in the presence of perpendicular magnetic field, using Landauer approach and tight binding model. The results of our investigation imply that in the presence of random disorder the transport of the system decreases because of Anderson localization. Furthermore, the broadening widths of landau subbands become large in the presence of random disorder and magnetic field. The existence of divacancy and magnetic field creates additional band between landau levels, this appeared by increasing the transmission of the injected electron. In addition we found that the coupling between two vacancies due to "vacancy molecule" and bonding between them can be tuned by the magnetic field. These theoretical studies can be useful to design the electronic nanodevice.

***PACs*:** 77.80.Vp; 74.62.En; 73.23.Ad
Keywords: *Transport properties; Four-terminal grapheme; Magnetic field; Divacancy; Random disorder*

1. Introduction

Graphene (single layer of graphite) demonstrates interesting electronic properties due to its unique structure [1]. It has been shown recently that charge carriers in graphene are massless Dirac fermions with effective "velocity of light" $(10^6\, m/s)$ [2]. The unusual transport properties of graphene arise from its liner E-k relation from low energies near the six corners of two-dimension hexagonal Brilloun zone. Similar to 2D Schrodinger electrons, states in a perpendicular uniform magnetic field *B* form highly degenerated discrete Landau levels (LLs) [3]. When the magnetic flux is getting larger, these levels form the Landau sub bands because of the Harper broadening. In the presence of disorders, LLs broadening into Landau subbans, gives rise to the quantum Hall effects [4]. However, as all the other materials, real graphene device also includes some disorder. Disorder in graphene may have diverse source like vacancies, impurities, absorption of an impurity atom or random potential introduced by the irregularities of the gate edge [5]. Disorder not only acts as a source of scattering but also change the local distribution of charge. One of the important defects in graphene is a single vacancy caused by the loss of one or several nearest atoms; vacancies are natural defects in graphene lattice and can also be externally induced by ion-beam irradiation and imperfect cutting [6]. In this paper we consider the effects of random disorder and divacancy (two single vacancies) on the transport properties in four-terminal graphene nanodevice when a perpendicular magnetic field is applied. Based on the critical role that two-dimensional four-terminal devices have played in semiconductor nanotechnology, four-terminal graphene nanodevices should also play an important role in any graphene based electronic circuits. Due to its high electronic quality, a four-terminal graphene nanodevice has also attracted the interest of technologists who see it as a way of constructing ballistic transistors. In addition to the practical importance of these four-terminal graphene devices, these systems make a useful framework to study the effects of lattice defects on the electron transport in the device [7].

2. Modelling

We consider the system as a central conductor region, connected to four leads L, R, T, and B (Fig. 1). We describe the conductor and the leads by tight - binding model with one π - electron per atom. The tight - binding Hamiltonian of the system can be written as: [8]

$$H = \sum_i \varepsilon_i\, a_i^+ a_i + t \sum_{i,j} e^{i\varphi_{ij}}\, a_i^+ a_j + \sum_i V\, a_i^+ a_i \qquad (1)$$

where $\boldsymbol{a_i}$ and $\boldsymbol{a_i^+}$ are the annihilator and creator operator of the electron, respectively and $\boldsymbol{\varepsilon_i}$ is the *ith* atomic on-site energy interpreted as the potential part of energy and *t* is the hopping integral between the nearest

*Corresponding author:Amirhossein Ahmadkhan Kordbacheh;
E-mail: akordbache@iust.ac.ir
Tel: (+98) 21 77240540
Fax: (+98) 21 77240497

neighbours that may refer to the kinetic part of the energy. In the absence of defect, $\boldsymbol{\varepsilon_i}$ is taken to be zero and t = 2.7 eV [9].

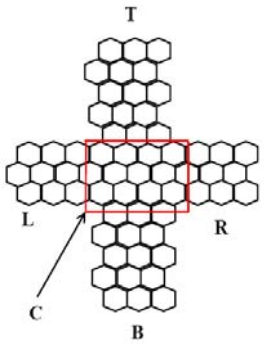

Fig. 1. Lattice configuration of four-terminal graphene nanodevice. Central region (boxed) is the conductor region, C, which is attached to four leads L, T, B and R.

In the presence of defect, on-site energy can be changed. In the case of random disorder, *v* is randomly selected in the interval -1 eV to 1 eV for random atom sites and a vacancy is simulated by setting its on-site energy to infinity. Because of the existence of the magnetic field, a phase φ_{ij} is added in the hopping element [4]. Where φ_{ij} is given by the line integral of the vector potential from *i* site to *j* site, the magnetic flux through the area *S* in units of the flux quantum $\phi_0 = ch/e$ is:

$$\frac{1}{\phi_0}\int dS \cdot B = \frac{e}{ch}\oint dl \cdot A = \sum_{arounds} \phi_{i,j}, \quad (2)$$

In what follows, we show how to calculate the transmission of the system. We calculate the transmission coefficient of the electron injected into the system using Green's function formalism [8]. The transmission coefficient of the electron from lead *p* to lead *q* is then expressed as:

$$T = Tr\left(\Gamma_q G_c^r \Gamma_q G_c^r\right), \quad (3)$$

This expression shows the electron tunnelling flux both from the source (*p* electrode) to the drain (*q* electrode). The system has four leads, resulting in a conductor Green function of the form:

$$G_c^r = \left[(E + i\eta)I - Hc - \sum\nolimits_L^r - \sum\nolimits_R^r - \sum\nolimits_T^r - \sum\nolimits_B^r \right], \quad (4)$$

where Σ_q denotes the self-energy due to the coupling between the conductor and lead *q* and the coupling matrices are expressed as:

$$\Gamma_n = i\left[\sum\nolimits_n^r - \sum\nolimits_n^a \right] \quad (5)$$

In this work we have calculated all results by ignoring the effects of temperature, spin-orbit interaction, electron-electron correlation, electron-phonon interaction, etc. In this model it is also assumed that the four side-attached leads have negligible resistance.

3. Results and Discussion

It is well known that in a metal or semiconductor, defects play an important role: they act as scattering centres and locally modify the conduction-band carrier density. One of the defects in graphene is random disorder. We now consider a four-terminal device in the presence of random disorder, including impurities randomly concentrated in some atoms that influence the on-site energy of random atoms. It is known that all electrons become localized in the presence of random disorder, a phenomenon known as Anderson localization [10,11]. In the systems, random disorder localizes all states, led to the transmission coefficient to be decreased.

Fig. 2 shows the transmission coefficient of a pure and a disordered four-terminal junction from lead L to R. The fine peaks in the pure curve are Van Hov singularities (VHSs) [12] corresponding to extreme points in the energy bands. The new peaks in the transmission curve correspond to the disorder states. The disorder states are quasilocalized states caused by the random disorder. The quasilocalized states can be found in the scanning tunneling spectroscopy (STS) images or low bias scanning tunneling microscopy (STM) images [15]. The injected electron will be reflected when its energy is equal to the energy level of the quasilocalized states.

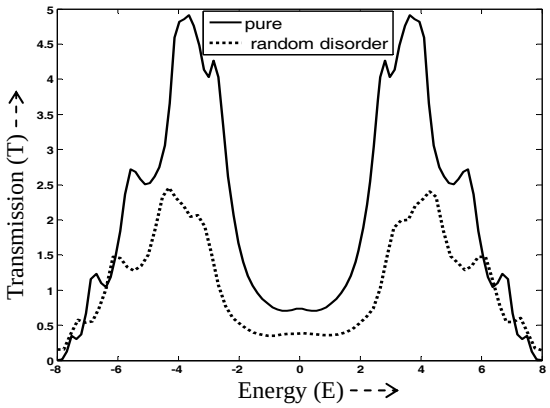

Fig. 2. The transmission coefficient of electron injected to the four-terminal device. The solid line is the transmission coefficient in pure case; dotted line is transmission coefficient in the presence of random disorder.

In Fig. 3, magnetic field and random disorder are applied to the system simultaneously. In fact, both random disorder and the magnetic field can affect the transmission coefficient in the system.

In the presence of a magnetic field the states of graphene are described in terms of Landau levels. At

low energies, when the Dirac fermion description is valid, the energy levels are given by:

$$E_{\pm} = \pm\sqrt{2}\,\delta l_B^{-1}\sqrt{n}, \qquad (6)$$

and defined $l_B = \sqrt{\hbar/eB}$, $\delta = \frac{3ta}{2}$ and n=1, 2,…. Notice that the cyclotron energy is much larger than the Zeeman energy, thus, we disregard the Zeeman energy.

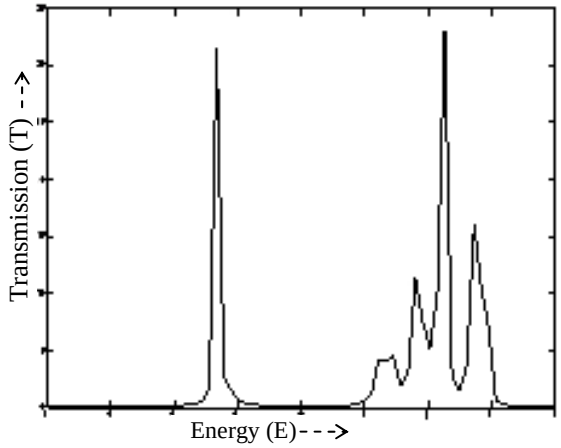

Fig. 3. The transmission coefficient of electron injected to the four-terminal device in the presence of magnetic field and random disorder.

Both random disorder and the magnetic field can affect the transport properties in the system. There are two important length scales: random disorder causes electron scattering, leading to an electron mean-free path (ℓ_e) and the magnetic field introduces a magnetic length (ℓ_B). Electronic states in a Landau level (LL) can be viewed as cyclotron motions of an electron around orbits of radius (ℓ_B) centered at different location. The transmission coefficient increases when the electron energy can receive to the energy of the Landau level, and decreases when the distribution of disorder sites led to Anderson localization. Generally the area under the transmission curve increases in comparison to the pure case because Landau levels broaden into Landau subbands and creates additional conduction channels. One can see that the curve associated to the disordered system and in the presence of magnetic field, has an asymmetric behavior.

The reason for this asymmetric behavior is related to the anisotropic system in the presence of magnetic field and nonequivalence sites in the presence of random disorder [11,13].

In Fig. 4, we plot the transmission coefficient of electrons from lead L to R (zigzag edge) in four-terminal device under the influence of divacancy.

We find that the area under the transmission curve that indicate the conduction of the system, decrease in the presence of divacancy, because removing two atoms in crystal affects the band structure and as a result affects the conduction channels and decrease the conduction in comparison with the pure case. We find that divacancy creates two peaks in the transmission coefficient at energies above and below the Fermi energy. Creating a vacancy in one site is similar to lowering the electronic density of states and increasing the electronic density on all the neighboring sites around the vacancy sites. This peaks appearing symmetrically around Fermi energy are due to the bounding and anti – bounding states [14].

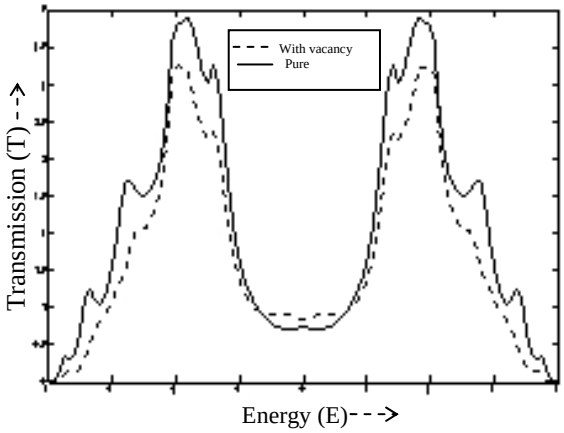

Fig. 4. The transmission coefficient of electron injected to the four-terminal device. The solid line is the transmission coefficient in pure case; dashed line is transmission coefficient in the presence of divacancy.

In Fig. 5, magnetic field and divacancy are applied to the system simultaneously. The existence of divacancy along with the magnetic field creates additional band between landau levels. In fact the number of bands increase in comparison with the case that magnetic field is applied without divacancy.

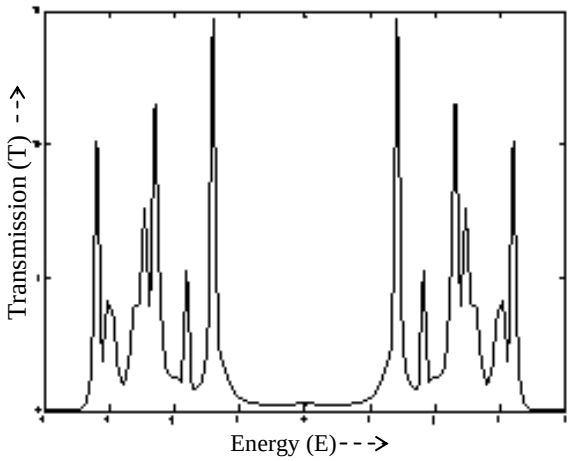

Fig. 5. The transmission coefficient of electron injected to the four-terminal device in the presence of magnetic field and divacancy

We find that two close vacancies may couple to each other, forming a “vacancy molecule” tuned by the magnetic field. The coupling between the wave function of two vacancies is verified to be determined by the distance between them and by the magnetic field. If the two single vacancies are introduced far from each other in lattice, they can’t coupled each

other, then we assume that inter-vacancy distance (d) is small ($d \approx a$, where a is the distance between two neighboring carbon atoms). The bonding between these vacancies can be tuned by magnetic field; this effect is appeared by creating a peak in Fermi energy when the magnetic field and divacancy are applied to the system simultaneously (see Fig. 6).

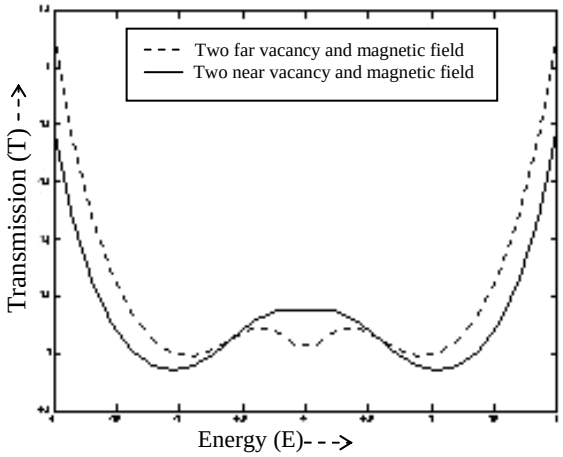

Fig. 6. The transmission coefficients in the vicinity of the Fermi energy in the presence of magnetic field and divacancy. The solid line is the transmission coefficient in the presence of two near vacancies and magnetic field ($d \approx 4a$); the dashed line is the transmission coefficient in the presence of far vacancies and magnetic field ($d \approx a$).

4. Conclusion

Based on Landauer approach and using tight-binding model, the influence of two kinds of defects, random disorder and divacancy in the presence of perpendicular magnetic field, on the transport properties of a four-terminal graphene nanodevic, has been studied. We investigated the Anderson localization of fermions at the Dirac point in a four-terminal graphene with random type of disorder and found that the states in the system with random disorder are localized. Also our results suggest that the LLs degeneracy is lifted in the presence of random disorder, LLs are broadened into Landau subbands therefore the transmission coefficient of electrons increases. We find that divacancy creates bounding and anti-bounding states around Fermi energy due to the increasing electronic density on neighboring sites. On the other hand, existence of two single vacancies, with small distance between them, in the presence of magnetic field, produce "vacancy molecules" by coupling between their wave function. This feature could make such a quasi-2D carbon-based junction a possible candidate for garphene nanoelectronic devices such as instance electronic circuits, quantum computers and ballistic transistors.

References

[1] Y. Zhang, Y.-W. Tan, H. L. Stormer, P. Kim, Nature (London) **438**, 201(2005).
[2] K. S. Novoselov, A. K. Geim, S. V. Morozov, D. Jiang, M. I. Katsnelson, I. V. Grigorieva, S. V. Dubonos, A. A. Firsov, Nature (London) **438**, 197(2005).
[3] K. Wakabayashi, M. Fujita, H. Ajiki, M. Sigrist, Phys. Rev. B**59**, 8271(1999).
[4] A. R. Wright, J. Liu, M. Zhongshui, Z. Zeng, W. Xu, C. Zhang , Microelect. J. **40**, 716 (2009).
[5] Y. Niimi, T. Matsui, H. Kambara, K. Tagami, M.Tsukada, H. Fukuyama, Phys. Rev. B **73**, 085421 (2006).
[6] Y. Kobayashi, K.-I. Fukui, T. Enoki, K. Kusakabe, Phys. Rev. B **73**, 125415 (2006).
[7] N. Goel, S. J. Chung, M. B. Santos, K. Suzuki, S. Miyashita, Y. Hirayama, Physica E **21**, 761 (2004).
[8] S. Datta, Electronic Transport in Mesoscopic Systems (Cambridge University Press, Cambridge, 1995).
[9] L. Chico, L. X. Benedict, S. G. Louie, M. L. Cohen, Phys. Rev. B **54**, 2600 (1996).
[10] I. V. Gornyi, A. D. Mirlin, D. G. Polyakov, Phys. Rev. Lett. **95**, 206603 (2005).
[11] P. W. Anderson, Phys. Rev. **109**, 1492 (1958).
[12] T. W. Odom, J. L. Huang, P. Kim, and C. M. Lieber, J. Phys. Chem. B **104**, 2794 (2000).
[13] D. N. Sheng, L. Sheng, and Z. Y. Weng Phys. Rev. B **73**, 233406 (2006).
[14] M. Igaml, T. Nakanishi, T. Ando, J. Phys. Soc. of Jap. **68**, 3146 (1999).
[15] Y. Kobayashi, K.-I. Fukui, T. Enoki, K. Kusakabe, Phys. Rev. B **73**, 125415 (2006).