Engineering of electronic transmission in novel graphene super lattice by the means of dirac gap and fermi velocity

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Abstract

The transmission spectrum and conductance of a graphenesuperlattice (GSL) have been studied theoretically by using the adopted transfer matrix method. Heterostructured substrate and series of grounded metallic planes placed over graphene sheet are used to induce periodically modulated Dirac gap and Fermi velocity barrier. As a main result, we found that the number of periods, energy gap and Fermi velocity barrier have considerable effect on transmission probability and conductance of the GSL. Our results reveal tunable transmission and conductance in GSLs which have promising applications in optoelectronic devices such as graphene based filter and switches. Copyright © 2017 VBRI Press.

Keywords: Graphene superlattices, periodic fermi velocity, gap modulation, conductance.

Introduction

Graphene, with high mobility, tunable electrical properties, and good interface parameters, presents a proper alternative to usual semiconductors superlattices and provides attractive effects such as resonant tunneling, miniband transport, Wannier–Stark localization [**1**] which cause terrific transport characteristics. However, due to the lack of energy gap in pristine graphene electronic band structure, the Klein tunneling prevents Dirac electrons in graphene from being confined by an electrostatic potential, which impedes its use in electronic devices.In order to overcome this limitation, several schemes have been proposed which leads to suppression of Klein tunneling and confinement of the Dirac electrons in graphene. For instance, energy gap in graphene can be induced by doping [**2-4**], substrate [**5-7**], strain [**8-10**], quantum confinement effects [**11-14**], spatial modulation of Dirac gap and external periodic potentials [**15-18**]. Resonant tunneling devices based on GSL have attracted considerable interests in nanoelectronic [**19**, **20**]. On the other hand, novel phenomena in GSL such as anisotropic propagation of carriers [**21**] and extra Dirac point [**22**] have not extensively investigated. Chiral nature of carriers causes strongly anisotropic renormalization of their group velocity leading to super collimation [**23**]. Motivated by these amazing properties and device applications, recently many efforts have been devoted to investigate transport properties of GSL theoretically and experimentally [**24-26**]. Moreover, the role of the Fermi velocity and band gap of the GSL, separately, on transport properties were studied by numerous groups [**27-29**]. In this letter, we present a theoretical study to analyze the role of energy gap and Fermi velocity barriers simultaneously on transmission and conductance of GSL with Kronig–Penney type electrostatic potential due to strong anisotropy near the Dirac point leading to the super-collimation phenomenon. Our results show that Fermi electrons transport and transmission band gap can modulate readily by energy gap and Fermi velocity barriers. This trend is benefit to designing high performance devices such as electronic filters [**30**].

Experimental

A schematic diagram of GSL has been shown in **Fig. 1.** L is the length of GSL. Also, *d* is the period of GSL. Composed substrate, open different energy gaps in different regions of the graphene sheet as quantum well and barrier, denoted by Δ_W and Δ_B, by breaking symmetry. Moreover, according to Lorentz invariant theory composed substrates can also modify Fermi velocity in graphene. The Fermi velocity in each region will be denoted by υ_W and υ_B. *W* and *B* subscripts indicate well and barrier region, respectively. Also $\upsilon_c = \upsilon_B/\upsilon_W$ is the Fermi velocity correlation between barrier and well. We use Kronig-Penny model for investigation of GSL performance. Also, grounded metallic planes are placed over graphene sheet which induce a periodic velocity barrier. These metallic planes do electron-electron interaction weaker; therefore reduce Fermi velocity in the relevant region [**31**].

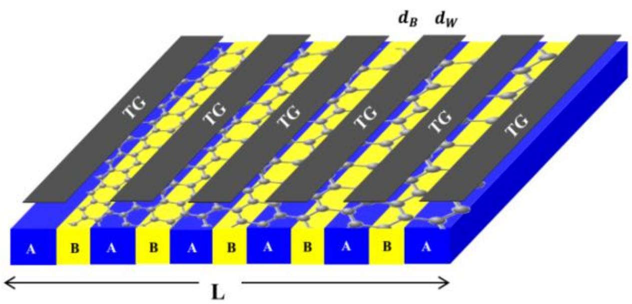

Fig. 1. (Color online) Schematics view of the gapped GSL. Heterostructured substrate, shown by A, B shift ups Dirac cones and opens of the bandgap in relevant region of GSL, respectively. Also, different Fermi velocity in well and barrier make periodic Fermi velocity barrier in GSL. Top gates (TG) are metallic planes, positioned over grpahene, are responsible for creating Fermi velocity barrier, d_B and d_W are width of barrier and well, respectively.

In the vicinity of the Dirac points, the GSL electronic structure can be described by the Dirac-like equation. The effective 2D Dirac Hamiltonian for a gapped GSL is written as

$$H = -i\hbar(v_F(\sigma.p)) + V(x)\hat{1} + \Delta(x)\sigma_z \,, \qquad (1)$$

where, σ is a vector given by the Pauli matrices $\sigma = (\sigma_x, \sigma_y)$, $\rho = (\rho_x, \rho_y)$ is the in-plane momentum operator, $\Delta(x)$ is the graphene energy gap, $V(x)$ is position dependent electrostatic potential. This is assumed to be uniform along the y-direction and to vary along the x-direction. According to Bloch's theorem, the electronic dispersion for infinite periodic structure, GSL is straightforward to obtain that the dispersion relation is given by

$$\cos(k_x l) = \cos(k_B a)\cos(k_W b) + \frac{k_y^2\hbar^2 v_B v_W - (E-V(x)_B)^2(E-V(x)_W)^2 + \Delta}{\hbar^2 v_F k_B k_W}\sin(k_B a)\sin(k_W b) \qquad (2)$$

Transmission probability, T, is given by $T = 1 - \left|\frac{\mathcal{T}_{21}}{\mathcal{T}_{22}}\right|^2$ where $\mathcal{T}_{21}$, $\mathcal{T}_{22}$ are two elements of transfer matrix, $\mathcal{T}$, and the $\mathcal{T}$-matrix for multibarrier potential can be written as

$$\mathcal{T}_n = R_W^{-n}(d)\,[R_W(d)\mathcal{T}(0)]^n \qquad (3)$$

where, n is the number of period. The zero-temperature conductance's given by [**32**]

$$G = 2geW/v_F h^2 \int_{-\pi}^{\pi} \mathcal{T}(E_F, \alpha, v_b)\cos\alpha \, d\alpha \qquad (4)$$

where, $G_0 = 2e^2/h$, $g = 4$ is the degeneracy of electron states in graphene. W is the sample width that we choose it as d_B.

Results and discussion

Fig 2.a shows the transmission profile of GSL. From figure it is clear that gaps created in transmission spectrum are modulated by energy gap opened in barrier region. The reason is suppression of Klein tunneling with increasing barrier height. For lower incident energy (E) only one transmission gap created for higher barrier energy gap (barrier height). Secondary gap appears for higher incident energy; also it is observed that the width of secondary gap is increased and blue-shifted with increasing incident energy. Wide gap is created for incident energies bigger than 100 meV where barrier height is very low (close to zero). These results show that the effect of barrier height or barrier band gap for certain value of well band gap is remarkable where low energy of incident Dirac electron is considered. According to Lorentz theory, metal strip adjacent graphene sheet induces a Fermi velocity barrier. From **Fig 2.b**, oscillation in transmission spectrum is increased with decreasing v_c. In contrast, for higher values of v_c, oscillation diminishes and energy gap increased. The number of extra Dirac points change if the difference in the Fermi velocity ratio is sufficiently high (i.e. Fermi velocity of barrier is sufficiently height).Therefore, Dirac gap and Fermi velocity barrier is key parameters to controlling resonant tunneling in GSL that benefit to design better resonant tunneling devices.

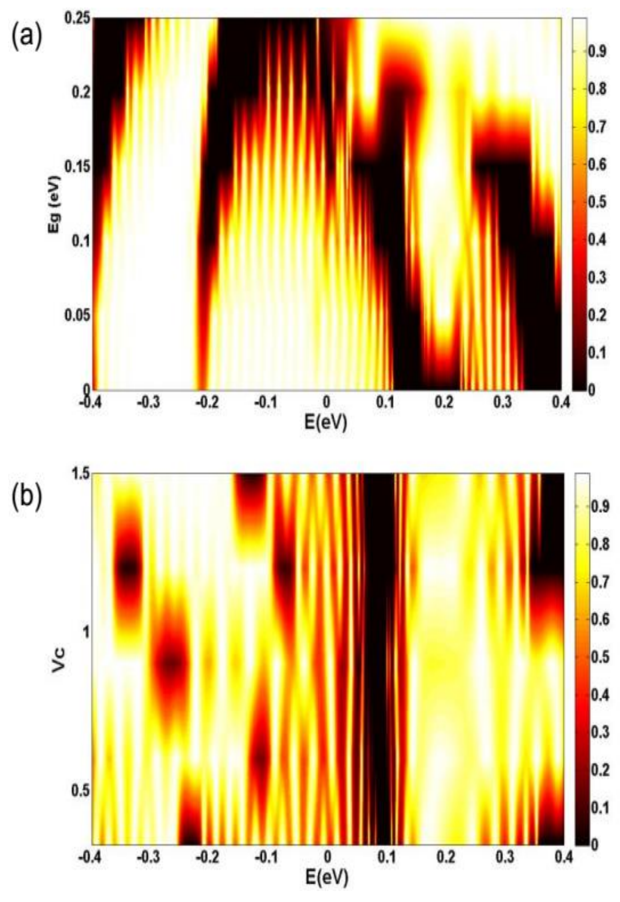

Fig. 2. (Color online) Contour plot of the electron transmission versus the incident energy E for (a) different barrier energy gaps, Δ_B, (b) Fermi velocity ratio (V_c). $d_W = d_B = 50\ nm$ and N=15, $\Delta_B = 0.1\ eV$.

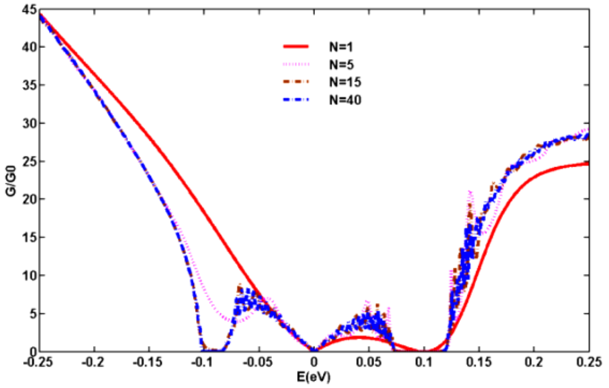

Fig. 3. (Color online) The effective conductance G^* as a function of incident energy for different N.$d_w, d_g = 50\ nm$,Δ_g= $0.1\ eV$ and $V_c = 1.3$.

Fig. 3. presents the number of periodicity role on GSL conductance. For large number of periodicities duo to increased interference effects caused by lots of boundaries, oscillations are increased in conductance. Also, with increasing N, due to interband coupling of adjacent wells, transmission picks constitute minibands. The width of this minibands almost independent of N. From figure conductance grows with increasing incident energy. Overall conductance of smaller GSL is higher than larger ones. With increasing N, picks of conductance become sharper and their width are narrower.

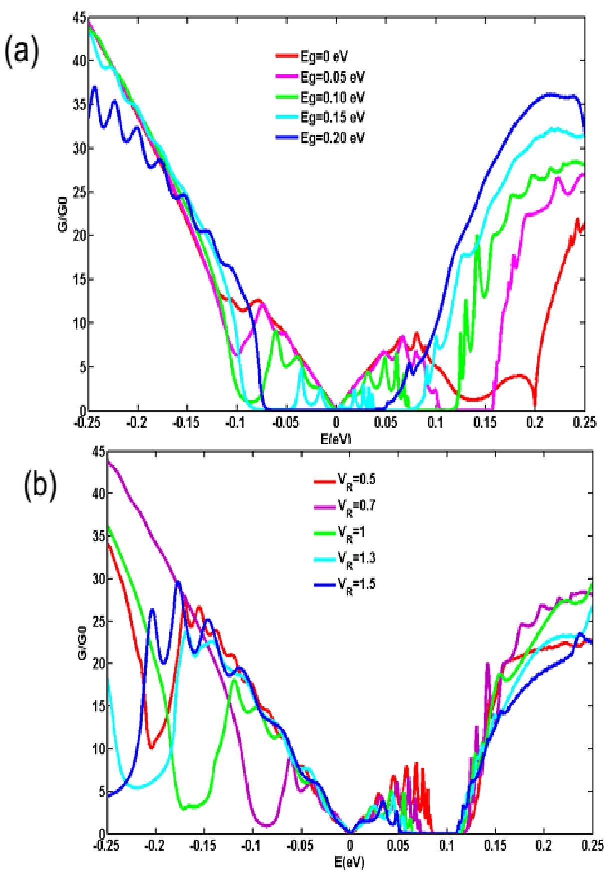

Fig. 4. (Color online) The effective conductance G^* as a function of incident energy for different (a)energy gap(Δ_g) and $V_c = 1.3$, (b) Fermi velocity ratio, Δ_g= 0.1 eV.$d_w = d_g = 50\ nm$.

Fig 4.a depicts the effect of barrier band gap, Δ_B, on conductance of GSL. It can be seen that the conductance has smooth trend for higher band gaps. Lower barrier band gaps cause the conductance to show multi peak treatment. From **Fig 4.b** it is observed that increasing Fermi velocity barrier, shifts the conductance stop region to lower energies that is because it moves the resonant states to higher energies. For negative incident energies Conductance has higher pick amplitudes for almost all values of V_c . a lot of narrow small peaks are observed for very low incident positive energies where V_c is very small (red curve). By increasing the amount of V_c, these peaks are shifted to higher values of incident energies. Our finding has very good agreement with Vasilopoulos et.al results [**33**]. Torres *et al.* studied the effect of structure parameters of GSL on angle-resolved conductivity [**34**]. They found how the creation of minibands affects the conductivity. The advantage of our work compared to their work is considering the effect of one dimensional periodic potential (V(x)) and$\Delta(x)$, the graphene energy gap, that provide a useful tool to control the carrier transport in GSL.

Conclusion

In summary, we theoretically studied the conductance of GSL structure made by patterning graphene on nanostructured substrate and top grounded- gates. The effects of parameters like number of periods, *N*, ratio of Fermi velocity, V_c, Dirac barrier , Δ_B, have been analyzed in details. Our theoretical study offers a novel way in the control of the performance of the graphene-based nanoelectronic devices.

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