



TWISTED BILAYER GRAPHENE

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ABSTRACT

This review paper discusses tunneling properties of charge carriers through bilayer graphene nanostructures and throws some light on a special structure called twisted bilayer graphene (TBG). Transmission coefficient, tunneling lifetime, Fano resonance and many other interesting phenomena in bilayer graphene system have been discussed. Effect of external electric field on these properties has also been discussed. The main objective, however, is to encourage researchers to study these properties in case of TBG in a similar way so as to open a new field in this direction and design more efficient electronic devices.

KEYWORDS: Twisted Graphene Bilayer, Transmission Coefficient, Tunneling Life-Time, Hamiltonian, Fano Resonance.

1. INTRODUCTION

Graphene [1] is a flat monolayer of densely packed Carbon atoms arranged in a hexagonal lattice. Due to its unique properties, it has attracted immense interest from researchers [2-5] in both theoretical and experimental field. Charge carriers in this material have an approximately linear electron spectrum near the Fermi energy at two inequivalent points of the Brillouin Zone, resulting in massless, chiral, relativistic fermions governed by a two-dimensional Dirac equation [6,7], the velocity of light replaced by the Fermi velocity. This leads to a number of unusual electronic properties such as high electronic mobility and quantum Hall effect [8]. The presence of Dirac like quasi particles in graphene is also expected to lead to perfect transmission through potential barriers, a phenomenon known as Klein Tunneling [9].

The chiral nature of graphene is a fascinating property that has the potential to revolutionize nanoelectronics and related fields. In addition to the Klein tunneling phenomenon, the conservation of the pseudospin of the charge carriers in graphene could have significant implications for electronic and optical device applications. Furthermore, the ability to manipulate the chirality of graphene could allow for the design of advanced electronic devices with unique properties. To investigate such phenomena, researchers have investigated different graphene-based microstructures including p-n junctions [10], single and double barriers [4, 11], and superlattices [5]. The study of these microstructures is essential for further understanding of the fundamental physics of graphene and its potential application. Overall the unique properties of graphene based microstructures make it a highly promising material to use in electronic, photonic and sensor devices and it is likely to continue to be the focus of intense research in near future.

Twisted graphene bilayer (TGB) consists of two sheets of graphene rotated with respect to each other at a specific magic angle. The angle of rotation determines the size of the Moiré pattern, which is a superlattice structure that arises from the

overlapping of the two graphene lattices. This Moiré pattern can significantly affect the electronic properties of TGB, giving rise to flat bands and correlated insulating phases at certain angles [12, 13]. One of the most important electronic properties of TGB is the presence of chiral tunneling which arises from the observation of pseudospin in chiral particles and leads to the suppression of backscattering. Recent studies have shown that TGB exhibits this chiral tunneling effect at certain twist angles and gate voltages, providing opportunities for the design of novel electronic devices such as tunnel transistors and tunnel diodes [12, 14-16]. Also TGB has been shown to exhibit superconductivity at certain twist angles and doping levels, which could have implications for the development of high-temperature superconductors [12, 17]. Overall, the unique electronic properties of TGB make it a promising material for a wide range of applications in areas such as electronics and quantum computing.

2. ELECTRONIC BAND STRUCTURE OF TBG

A twisted graphene bilayer is made up of AB-Bernal stacked bilayer graphene with a twist angle θ between the top and bottom layers, around a common (A1B2) vertical axis as shown in the following Fig. 1(a).

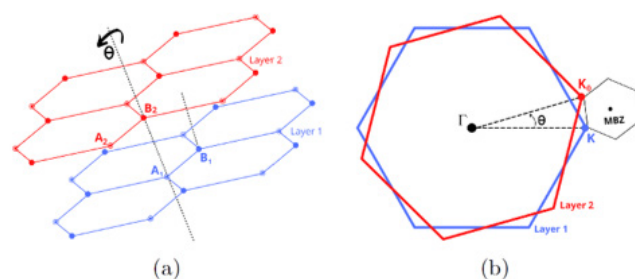


FIG. 1

Owing to the relative rotation of the Bernal bilayer graphene, a periodic Moiré superlattice is generated and the corresponding Moiré Brillouin zone (MBZ) is depicted schematically in

Fig. 1(b), along with the Brillouin zones (BZs) of individual graphene layers [18]. Moreover, the formation of the Moiré superlattice also directly leads to the expansion of the unit cells of TGB. The twisting not only results in the Moiré pattern, but also leads to a relative shift of the two Dirac cones. The resulting relative shift of the Dirac points on the different layers is defined as $\Delta K = 2|K| \sin \theta/2$ where $|K| = 4\pi/3a_0$ is the momentum-space dependence determined by the graphene lattice constants in real-space $a_0 = \sqrt{3}a \approx 0.25$ nm. The interaction of electrons between the two graphene sheets and the coupling of their respective Dirac cones in the BZ leads to a redistribution of the electronic band structure, which is similar to that of single-layer graphene with a linear dispersion near the Fermi surface. The electronic band structure of TGB is mainly formed along the anticrossing Dirac cone [13]. The overlap of the electronic band structure between the upper and lower layers of graphene causes the electronic band structure of TGB to exhibit saddle points in the density of state (DOS).

3. TRANSMISSION SPECTRUM OF BILAYER GRAPHENE TUNNELING STRUCTURES

Transmission spectrum of Bilayer graphene structures was studied theoretically by C. Sinha and R. Biswas [19] in the year 2011. The coupling between the layers in the graphene bilayer (GBL) transforms the massless Dirac fermions into massive chiral particles, having a parabolic energy spectrum, and thus the system can be considered (structurally) as a quasi-two-dimensional (2D) system different from the pure 2D system. The charge carriers in the bilayer graphene have a parabolic energy spectrum and are described by the following off-diagonal Hamiltonian:

$$H = \left[-\frac{\hbar^2}{2m} \begin{pmatrix} 0 & (k_x - ik_y)^2 \\ (k_x + ik_y)^2 & 0 \end{pmatrix} + V(x) \right]$$

where k_x and k_y are the quasiparticle wave vectors along the x- and y-axes, respectively, in the plane of the graphene layer.

In case of a GBL, unlike the monolayer, the Dirac spinors in both the well and the barrier regions are represented by a linear superposition of the evanescent states and the propagating states. Such representation of the charge carriers in GBL bears an important implication in the sense that the possibility of occurrence of the Fano resonances (FRs) in the transmission spectrum is inherent in it. The FR that arises due to the coherent superposition of the discrete and continuum states might be a particular characteristic of the GBL tunneling spectra and is supposed to be absent in the graphene monolayer (GML) transmission spectrum, particularly in the coherent regime. The Fano-type resonance is widely known to occur in many branches of physics and chemistry, including the mesoscopic systems. The asymmetric Fano resonances (FRs) was noted for the first time in the coherent ballistic transmission spectrum of bilayer graphene tunneling structures.

The observed FRs were found to be highly direction sensitive and tunable by controlling the barrier width and the external electric fields. The presence of a narrow region of antiresonance

within the tunneling band that arises due to the destructive interference between the discrete and continuum states leads to fragmentation of the tunneling band and might be responsible for producing the negative differential conductivity (NDC) in the system. The Stark effect was noted to be much more pronounced for the evanescent states than that for the extended states. The findings might be quite useful for the exploitation of bilayer graphene in the field of nanotechnology. The numerical results and findings of tunneling properties in case of graphene bilayer should prompt one to study the case of Fano resonance in case of twisted bilayer graphene (TBG) approaching in a similar way with a little modification in the form of the Hamiltonian accordingly.

4. TUNNELING PROPERTIES IN A BIASED BILAYER GRAPHENE NANOSTRUCTURES

Tunneling properties in a biased bilayer graphene nanostructure were studied for the first time by our group [20] in the year 2011. The potential profile along the x-axis in presence of an external homogenous electric field (E') applied between $x = 0$ and $x = L$ ($a+2b$) is given by,

$$V(x) = V_0 - eE'x \text{ for } (N-1)d < x < Nd - a \\ = eE'x \text{ elsewhere,}$$

where $d = a + b$, 'a' and 'b' are the well and barrier widths; $N = 1$ for the first barrier and 2 for the second; V_0 being the constant potential barrier height chosen as the conduction band discontinuity between two consecutive bilayer graphene strips.

In the case of BG (unlike the monolayer), transmission through the barriers occurs via the evanescent as well as the continuum states. The quantum interference between these two channels might lead to the so called Fano resonance (FR) in the transmission spectra. The study of such resonance phenomenon finds applications in sensors, lasing, switching and nonlinear devices. This Fano resonance was addressed in the ballistic transmission of the BG.

The study also reported the tunneling lifetime in a biased bilayer graphene for the first time in the literature. The tunneling time of charge carriers in a graphene-based system plays a very crucial role in the preparation of very high speed nano electronic devices [34], particularly in the oscillators and memory devices. Further, the key information about the tuning of the tunneling current, a vital issue for the device modeling, comes from the knowledge of the dependence of the tunneling lifetime on the electric field and other structure parameters.

The group studied the effect of an external in plane static electric field on the transmission coefficients (T) and the quasi resonant tunneling lifetime of the Dirac fermions in zero gap double barrier single well BG nanostructures. The T_c for the unbiased case was calculated using the transfer matrix method while the biased situation was solved by numerical simulation. Finally, the energy - time uncertainty relation was exploited to calculate the tunneling lifetime in the quasi resonant energy levels for the normal as well as for the oblique incidence. This review paper

suggests similar study for TBG to unfold more interesting facts about tunneling properties in this specific structure to develop a new era in the field of nanotechnology.

5. CONCLUSION

The present review paper is concluded by taking note that TBG might be a promising material to study in near future in the field of designing efficient electronic devices due to its fascinating properties in connection with the transport phenomena including Klein tunneling, Fano resonance, tunneling conductance, tunneling lifetime etc. It should be noted that the possibility to control the transmission of charge carriers in twisted graphene bilayer through double barrier structure can help designing efficient graphene-based electronic devices.

6. REFERENCES

1. K. S. Novoselov, A. K. Geim, S. V. Morozov, D.-e. Jiang, Y. Zhang, S. V. Dubonos, I. V. Grigorieva, and A. A. Firsov, *science* 306, 666 (2004).
2. Y. Zhang, Y.-W. Tan, H. L. Stormer, and P. Kim, *nature* 438, 201 (2005).
3. N. M. R. Peres, F. Guinea, and A. H. Castro Neto, *Phys. Rev. B* 73, 125411 (2006).
4. M. Katsnelson, K. Novoselov, and A. Geim, *Nature physics* 2, 620 (2006).
5. C. Bai and X. Zhang, *Phys. Rev. B* 76, 075430 (2007).
6. C. W. J. Beenakker, *Rev. Mod. Phys.* 80, 1337 (2008).
7. A. H. Castro Neto, F. Guinea, N. M. R. Peres, K. S. Novoselov, and A. K. Geim, *Rev. Mod. Phys.* 81, 109 (2009).
8. K. S. Novoselov, A. K. Geim, S. V. Morozov, D. Jiang, M. I. Katsnelson, I. V. Grigorieva, S. V. Dubonos, and A. A. Firsov, *nature* 438, 197 (2005).
9. A. K. Geim and K. S. Novoselov, *Nature materials* 6, 183 (2007).
10. V. V. Cheianov and V. I. Fal'ko, *Phys. Rev. B* 74, 041403 (2006).
11. J. M. Pereira Jr, P. Vasilopoulos, and F. Peeters, *Applied physics letters* 90, 132122 (2007).
12. Y. Cao, V. Fatemi, S. Fang, K. Watanabe, T. Taniguchi, E. Kaxiras, and P. Jarillo-Herrero, *Nature* 556, 43 (2018).
13. Y. Cao, V. Fatemi, A. Demir, S. Fang, S. L. Tomarken, J. Y. Luo, J. D. Sanchez-Yamagishi, K. Watanabe, T. Taniguchi, E. Kaxiras, et al., *Nature* 556, 80 (2018).
14. M. Yankowitz, S. Chen, H. Polshyn, Y. Zhang, K. Watanabe, T. Taniguchi, D. Graf, A. F. Young, and C. R. Dean, *Science* 363, 1059 (2019).
15. T. Ohta, A. Bostwick, T. Seyller, K. Horn, and E. Rotenberg, *Science* 313, 951 (2006).
16. W.-Y. He, Z.-D. Chu, and L. He, *Phys. Rev. Lett.* 111, 066803 (2013).
17. S. Chen, M. He, Y.-H. Zhang, V. Hsieh, Z. Fei, K. Watanabe, T. Taniguchi, D. H. Cobden, X. Xu, C. R. Dean, and M. Yankowitz, *Nature Physics* 17, 374 (2021).
18. S.-Y. Li, K.-Q. Liu, L.-J. Yin, W.-X. Wang, W. Yan, X.-Q. Yang, J.-K. Yang, H. Liu, H. Jiang, and L. He, *Phys. Rev. B* 96, 155416 (2017).
19. C. Sinha and R. Biswas, *Physical Review B* 84, 155439 (2011).
20. S. Mukhopadhyay, R. Biswas and C. Sinha, *Phys. Lett. A* 375, 2921 (2011).