Control of transmission in disordered graphene nanojunctions through stochastic resonance

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We investigate electronic transport in graphene nanojunctions and find that the transmission (or the conductance) can exhibit a nonmonotonic behavior with respect to variation in the strength of disorder, mimicking a stochastic resonance. The general setting for this remarkable phenomenon is where the graphene device possesses localized states in the absence of disorder, i.e., the localized edge states specific to graphene. A small amount of disorder can then break the localization and lead to an enhancement in the transmission. For strong disorder, Anderson localization [Phys. Rev. **109**, 1492 (1958)] sets in, causing the transmission to decrease. The phenomenon is robust and can occur with or without magnetic field. © *2010 American Institute of Physics*. [doi:10.1063/1.3460291]

Graphene, a sheet of honey-comb lattice of carbon atoms, has attracted much recent attention.[1] High electron mobility[2] and effectively relativistic motions make graphene appealing to various device applications ranging from nanoelectronics to state-of-art nanobiodevices such as *p*-*n* junctions and transistors, spintronics, flexible and transparent photonic devices, cellular interfaces, DNA sequencing, and DNA transistors. In experimental studies and device research, various impurities and dislocations are intrinsically present or are artificially doped into graphene. It is of paramount interest to investigate the effect of such disorders on the electronic transport properties in graphene-based nanodevices. In this regard, recent works have revealed that, for transport through a graphene nanoribbon, a disorder potential induced by charged impurities or edge roughness effectively forms quantum dots along the ribbon, which can open up the band gap[3,4] or induce localization of electron states to turn the ribbon into an insulator.[5] Large conductance fluctuations have been observed in weakly disordered graphene.[6] For quantum Hall effect, the Hall plateaus can be destroyed by disorder through the float-up of extended levels toward the band center.[7] Distinct conductance plateaus have been found in graphene *p*-*n* junctions made of weakly disordered nanoribbons in the presence of magnetic field.[8]

It has been known that disorder or noise in physical and biological systems can sometimes enhance the system performance through the mechanism of stochastic resonance (SR).[9] While in micro/nanoelectronic devices, disorder usually results in enhanced scattering during electron transport and induces localization,[10] under certain conditions disorder can increase the transmission.[8,11] In Ref. 12, the geometrical effect of structural nanoconstrictions on the transport properties of otherwise ideal zigzag graphene ribbons has been studied, with the finding that the zero-bias current is robust but the curve shape of the conductance is sensitive to the constriction geometry and edge defects. In this letter, we focus on graphene nanojunctions and address the question: can the conductance be maximized by a proper amount of disorder? Our main result is an affirmative answer and a qualitative explanation. In particular, the necessary condition for this SR-like phenomenon is found to be the occurrence of some type of localized states in the absence of disorder. This, for example, can be Landau-level states in the presence of a magnetic field, which is common for many two-dimensional electron-gas systems, or it can be the spatially localized edge states along part of the zigzag boundary in a graphene junction. A small amount of disorder then perturbs the localized state and "opens up" transmitting channels, leading to an enhanced transmission. When the disorder becomes strong, another common type of localization, Anderson localization,[10] sets in, reducing the transmission. Transmission thus reaches a maximum for an intermediate level of disorder, giving rise to the SR phenomenon. The mechanism suggests that the SR can occur in graphene nanojunctions, regardless of the presence of a perpendicular magnetic field, which has indeed been verified numerically. While SR is a robust phenomenon in disordered or noisy systems, to our knowledge, its occurrence in graphene nanojunctions and the underlying mechanism based on the localized states have not been reported prior to our work.

We use the tight-binding model and the Landauer–Büttiker formalism in combination with the nonequilibrium Green's function method to calculate the conductance and the local density of states (LDS)[13,14] for our disordered graphene system.[7,8,15] For graphene nanojunction, the left (right) lead has a potential $E_L(E_R)$. Due to the applied potential, in the device region the on-site energy varies linearly with the location as follows: $\varepsilon_i = E_L + (E_R - E_L)x_i/d_1 + \xi_i$ expressed in units of hopping energy t, where d_1 is the length of the device region, x_i is the abscissa of site i, and the energy ξ_i associated with the disorder is uniformly distrib-

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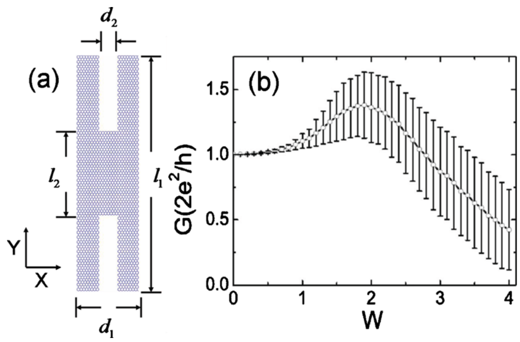

FIG. 1. (Color online) (a) Schematic illusion of H-shaped graphene junction. The device parameters are $l_1=152a_0$, $l_2=56a_0$, $d_1=22.5a$, and $d_2=7.5a$, where $a_0=1.42$ Å is the atom separation, and $a=\sqrt{3}a_0=2.46$ Å is the lattice constant. (b) Conductance G as a function of disorder W for $E_L=-0.1$, $E_R=-0.9$, and $\phi=0.0127\phi_0$. An ensemble of 1000 disorder realizations are computed for obtaining reliable statistics. The same holds for all computations of G in the paper.

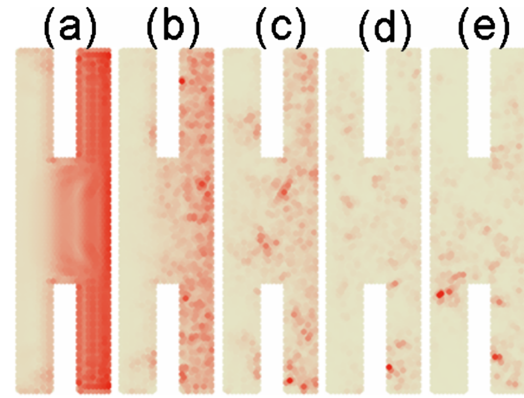

FIG. 3. (Color online) LDS patterns for typical cases in Fig. 1(b): $W=0.0$, 1.0, 1.9, 3.0, and 4.0 for (a), (b), (c), (d), and (e), respectively. The respective transmissions are 1, 1.05, 1.58, 0.73, and 0.51. The minimum and maximum LDS values of the patterns are $(3.38\times10^{-4}, 0.11)$, $(1.09\times10^{-4}, 0.34)$, $(5.64\times10^{-5}, 0.72)$, $(1.15\times10^{-5}, 1.91)$, and $(3.98\times10^{-6}, 2.25)$, respectively. The color code is normalized for each case, where dark regions in the patterns correspond to higher LDS values.

uted in the range $[-W/2, W/2]$. Depending on the potential E_L and E_R, the device can be a *p-n*, a *p-p*, or an *n-n* junction. In the presence of a magnetic field **B**, there will be a phase shift in the hopping energy given by $\phi_{ij}=\int_j^i \mathbf{A}\cdot d\mathbf{r}/\phi_0$, where the vector potential is $\mathbf{A}=(-By,0,0)$ under the Landau gauge and $\phi_0=h/e$ is the magnetic flux quanta. For convenience, we use the magnetic flux $\phi=BS$ through a hexagonal plaque as the control parameter, the area of which is $S=\sqrt{3}a^2/2=5.24$ Å^2.

We start with an H-shaped graphene junction[12] as shown in Fig. 1(a) with zigzag horizontal boundaries. Figure 1(b) shows, for a given set of the lead potential and magnetic flux ϕ, conductance G versus the disorder strength W. As W increases from 0, conductance is enhanced, indicating that a small amount of disorder can facilitate transmission. Further increase in disorder suppresses the conductance. This leads to a resonant behavior in the conductance as a function of the disorder strength. Phenomenologically, this resembles SR (Ref. 9) in that the outcome (conductance) is optimized by a proper degree of the disorder. To explore whether the resonance phenomenon is robust, we carry out systematic computations by varying the lead potential. The results are shown in Fig. 2. For most E_R values, a maximum conductance can be achieved for some optimal value of W between 2 and 3. In addition, we have tested different values of E_L for different shapes of the device and found that the resonance phenomenon persists. To gain insights into the mechanism of the resonance phenomenon, we calculate the typical LDS patterns, as shown in Fig. 3. In the absence of any disorder, under magnetic field coherent localized Landau-level states are formed in the device [Fig. 3(a)], which suppresses the transmission. A small amount of disorder perturbs the Landau-level states and bridges these states with the transmission modes in the leads, thereby enhancing the conductance. Signature of this mechanism can be seen from Fig. 3(b), where the Landau-level state loses much of its coherence and is superimposed with inhomogeneous random perturbations. However, if the disorder is too strong, it forms localized state via the mechanism of Anderson localization, where the spatial range of the localization is much smaller than the size of the junction, as shown in Figs. 3(d) and 3(e). In this case, the transmission becomes small again. With conductance increasing in the small disorder range and decreasing in the strong disorder case, there must be a maximum value for an intermediate strength of disorder which, in the case of Fig. 1(b) and Fig. 3, is located at $W\approx1.9$.

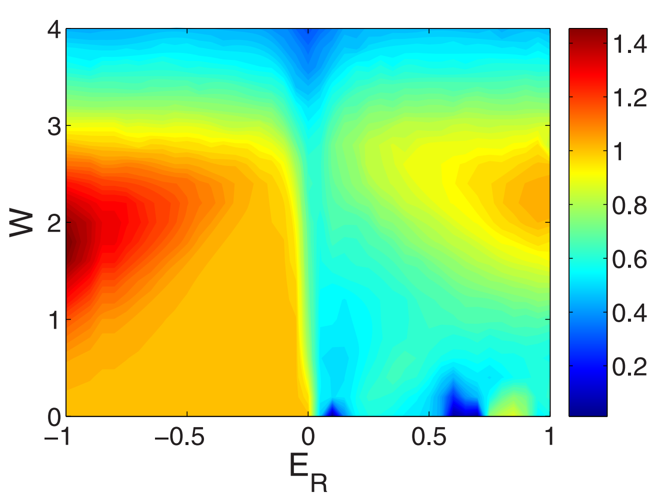

FIG. 2. (Color online) Contour plot of conductance G in the (W, E_R) parameter space for $E_L=-0.1$ and $\phi=0.0127\phi_0$.

The above mechanism of SR is through the breaking of Landau-level states when magnetic field is present. In fact, for graphene nanojunctions, another form of localization states exists even in the absence of magnetic field: edge states along the zigzag boundary. In this case, disorder can break this localization state and give rise to SR, which has indeed been observed for a class of wedge-shaped graphene junctions[12] [Fig. 4(a)]. Figure 4(b) shows the results of the averaged conductance in the (W, E_R) plane. From the figure, we can see that in the range of $-0.1<E_R<0$ and $0.05<E_R<0.35$, the conductance generally exhibits the SR behavior as the disorder strength W is increased from zero. As in the case with magnetic field, the optimal disorder strength maximizing the conductance changes with E_R, and the shape of the curve of G versus W also changes for different values of E_R. However, the feature that an appropriate disorder strength maximizes the conductance persists. For this case, unlike the breaking of Landau-level states in a magnetic field, it is the edge state that is localized. The boundary is zigzag and the two leads are gated to different potentials with

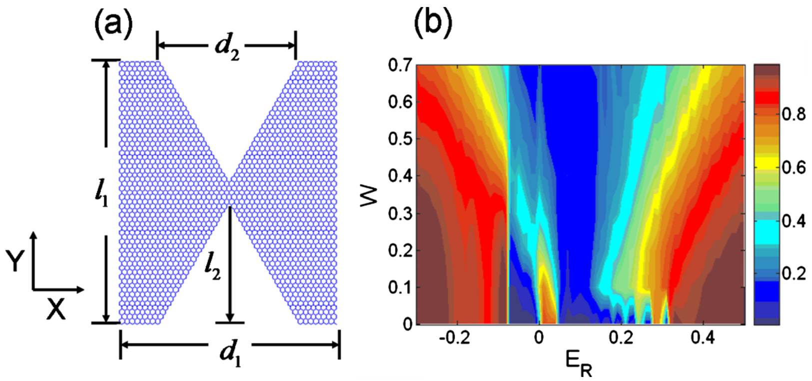

FIG. 4. (Color online) (a) Schematic illustration of a wedge-shaped graphene junction. The device parameters are $l_1=89a_0$, $l_2=41a_0$, $d_1=42.5a$, and $d_2=27a$. (b) Contour plot of G in the (W,E_R) plane for $E_L=-0.1$ and $\phi=0$.

opposite sign. Since the edge states only occur along the zigzag boundaries where the energy is about zero, it happens only in the region where $\varepsilon_i \approx 0$. Thus for this case the edge state is not only localized in the perpendicular direction to the boundary (as in the zigzag ribbon case), but also localized *along* the boundary, effectively eliminating transmission associated with this mode. To visualize the localized edge states, we calculate the LDS patterns for a typical case, as shown in Fig. 5(a), where the localization *along* the boundary is apparent, resulting in small transmission. As disorder is introduced into the system, the localized state becomes broadened, as shown in Fig. 5(b), giving rise to a higher probability for the electrons to couple to the transmission modes in the leads and leading to an enhanced conductance. For a stronger degree of disorder, Anderson localization emerges, the transmission becomes small again, as shown in Figs. 5(c) and 5(d). Also note that in this case the optimum disorder strength is much smaller, i.e., $W_{opt} \sim 0.1$ (versus $W_{opt} \sim 2$) in Fig. 2. Although the SR shown in Fig. 4(b) is stable for small variations in lead potentials and junction shapes, it generally will be washed out if the change is large.

In conclusion, we have discovered an SR like phenomenon for transport in disordered graphene nanojunctions. Generally, when the system possesses localized states that hamper electronic transport (e.g., edge states in the absence of magnetic field or Landau-level states under magnetic field), a small amount of disorder can perturb the localized states and, under certain circumstances, open up "channels" for electrons to be coupled to the transmission modes in the leads, thereby enhancing the conductance. For strong disorder, Anderson localization emerges and turns the junction into an insulator. This resonance phenomenon can be exploited for realistic applications of disordered graphene nanojunctions where the conductance can be controlled by the strength of disorder.

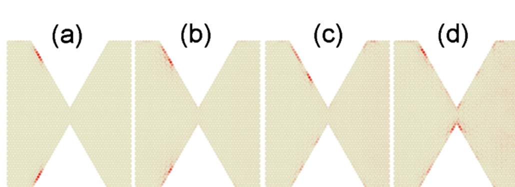

FIG. 5. (Color online) LDS patterns for different disorder strength of the junction in Fig. 4(a). The color code is normalized for each case. The disorder parameters are $W=0.0,0.1,0.5,1.0$ for (a), (b), (c), and (d), respectively. The respective transmissions are 0.53, 0.94, 0.47, and 0.40. The minimum and maximum LDS values are $(7.96\times10^{-6},4.35)$, $(1.08\times10^{-5},1.23)$, $(7.17\times10^{-6},0.58)$, and $(1.66\times10^{-6},0.46)$, respectively. The potentials are $E_L=-0.1$ and $E_R=0.3$.

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[1]K. S. Novoselov, A. K. Geim, S. V. Morozov, D. Jiang, Y. Zhang, S. V. Dubonos, I. V. Grigorieva, and A. A. Firsov, Science **306**, 666 (2004); C. W. J. Beenakker, Rev. Mod. Phys. **80**, 1337 (2008); A. H. Castro Neto, F. Guinea, N. M. R. Peres, K. S. Novoselov, and A. K. Geim, *ibid.* **81**, 109 (2009).
[2]K. I. Bolotin, K. J. Sikes, J. Hone, H. L. Stormer, and P. Kim, Phys. Rev. Lett. **101**, 096802 (2008).
[3]P. Gallagher, K. Todd, and D. Goldhaber-Gordon, Phys. Rev. B **81**, 115409 (2010).
[4]F. Sols, F. Guinea, and A. H. CastroNeto, Phys. Rev. Lett. **99**, 166803 (2007).
[5]D. Gunlycke, D. A. Areshkin, and C. T. White, Appl. Phys. Lett. **90**, 142104 (2007); A. Lherbier, B. Biel, Y.-M. Niquet, and S. Roche, Phys. Rev. Lett. **100**, 036803 (2008); D. Querlioz, Y. Apertet, A. Valentin, K. Huet, A. Bournel, S. Galdin-Retailleau, and P. Dollfus, Appl. Phys. Lett. **92**, 042108 (2008); X. Ni, G. Liang, J.-S. Wang, and B. Li, *ibid.* **95**, 192114 (2009); M. Y. Han, J. C. Brant, and P. Kim, Phys. Rev. Lett. **104**, 056801 (2010).
[6]A. Rycerz, J. Tworzydło, and C. W. J. Beenakker, EPL **79**, 57003 (2007).
[7]R. Ma, L. Sheng, R. Shen, M. Liu, and D. N. Sheng, Phys. Rev. B **80**, 205101 (2009).
[8]W. Long, Q.-F. Sun, and J. Wang, Phys. Rev. Lett. **101**, 166806 (2008).
[9]L. Gammaitoni, P. Hänggi, P. Jung, and F. Marchesoni, Rev. Mod. Phys. **70**, 223 (1998).
[10]P. W. Anderson, Phys. Rev. **109**, 1492 (1958); C. W. J. Beenakker, Rev. Mod. Phys. **69**, 731 (1997); A. D. Mirlin, Phys. Rep. **326**, 259 (2000).
[11]H. L. Martinez and J. M. R. Parrondo, Phys. Rev. E **70**, 026113 (2004); A.-M. Guo, S.-J. Xiong, Z. Yang, and H.-J. Zhu, *ibid.* **78**, 061922 (2008); Y. P. Bliokh, V. Freilikher, S. Savelev, and F. Nori, Phys. Rev. B **79**, 075123 (2009).
[12]F. Muñoz-Rojas, D. Jacob, J. Fernández-Rossier, and J. J. Palacios, Phys. Rev. B **74**, 195417 (2006).
[13]R. Landauer, Philos. Mag. **21**, 863 (1970).
[14]S. Datta, *Electronic Transport in Mesoscopic Systems* (Cambridge University Press, Cambridge, UK, 1995).
[15]I. Amanatidis and S. N. Evangelou, Phys. Rev. B **79**, 205420 (2009).