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Ying He, Fan-Ming Zhang, and Xi Chen

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Response to "Comment on 'Guided modes in graphene waveguides'" [Appl. Phys. Lett. 96, 186101 (2010)]

Ying He,[1] Fan-Ming Zhang,[1] and Xi Chen[1,2,a)]
[1]*Department of Physics, Shanghai University, 200444 Shanghai, People's Republic of China*
[2]*Departamento de Química-Física, UPV-EHU, Apdo 644, 48080 Bilbao, Spain*

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First, we thank Villegas and Tavares[1] for their interests in our recent paper on the guided modes in graphene waveguides.[2] Second, we should emphasize that based on the analogy of optical waveguide we define the guide modes by the number of the nodes of the spinor wave function, $\Psi=[\psi_A(x), i\psi_B(x)]^T$, where the spinor components ψ_A and $i\psi_B$ represent electrons and holes, respectively. In Ref. 2, we pay our attention to the guided modes of free electrons and holes in the graphene waveguide, rather than the probability density $\rho(x)=|\psi_A(x)|^2+|i\psi_B(x)|^2$, or the whole confined state ψ. The solution in the graphene waveguide considered here corresponds to the type of standing waves inside the waveguide,[3] which suppresses the Klein tunneling due to the electron-hole conversion at the interface. That is, there are no hole states available outside. Thus, it is necessary to study the details on the guide modes of free electrons and holes represented by the corresponding components of spinor wave function, instead of the single probability density, though the probability density $\rho(x)$ is important quantity and also has symmetry in such waveguide structure. In addition, it is also shown in Ref. 2 that the electrons and holes have different velocities, while the results given by the probability density cannot distinguish the electrons and holes inside the waveguide. All these facts motivate us to investigate the electron

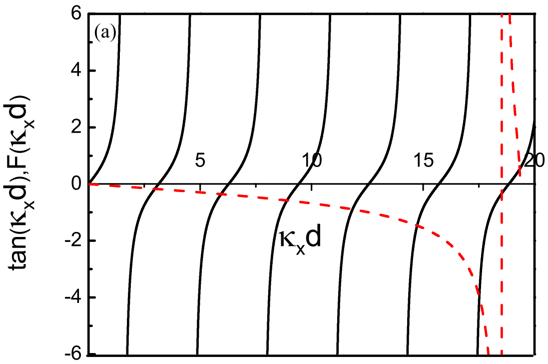

FIG. 1. (Color online) Graphical determination for guided modes where the parameters are $V_0=50$ meV, $d=200$ nm, and $E=55$ meV.

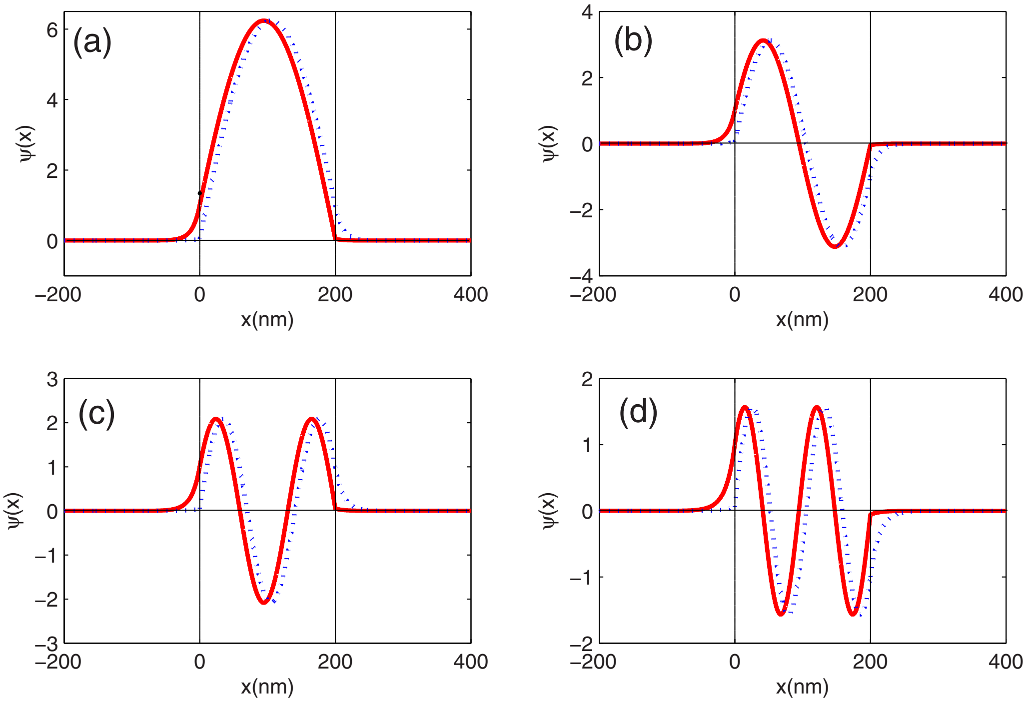

FIG. 2. (Color online) The corresponding wave function of the four lowest modes in Fig. 1.

[a)] Author to whom correspondence should be addressed. Electronic mail: xchen@shu.edu.cn.

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and hole states separately in both classical motion $(ss'=1)$ and Klein tunneling $(ss'=-1)$ cases.

Third, the authors in Ref. 1 claimed that the parameters taken for the case of classical motion $(ss'=1)$ were really confusing. To clarify it, we plot the graphical determination of the guided modes, according to the dispersion equation in Fig. 1(a) of Ref. 1. For the energy $E=55$ meV, there are seven intersections, as shown in Fig. 1. The corresponding seven guided modes defined by the components ψ_A and $i\psi_B$ are also shown in Fig. 2, where for simplicity only four lowest guided modes such as fundamental, first-order, second-order, and third-order modes are shown here. It is true that for the given parameters, the third-order mode appears. However, the third-order mode is still absent for other parameters in Ref. 2. It is worthwhile to point out that the absences of fundamental mode in Klein tunneling case and the third-order mode in classical motion case are strongly dependent on the width d and incident energy E, which are similar to the situations in guide modes of negative-refractive-index waveguide.[4] That is to say, the fundamental and third-order modes do not always disappear in Klein tunneling and classical motion cases for any parameters. Thus, one should be careful to make the conclusion on the absence of fundamental and other modes.

Last but not least, we have currently noticed the link between Klein paradox and negative refraction in left-handed metamaterials.[5] This underlying physics convinces us to simulate these peculiar properties of graphene waveguide with optical metamaterial waveguide, since the absence of fundamental mode has been already found in negative-refractive-index waveguide.[4]

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