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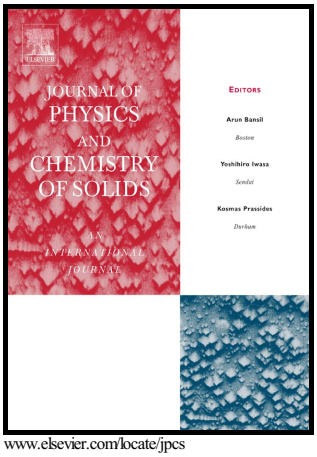

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Effect of Energy Band Gap in Graphene on Negative Refraction through the Veselago Lens and Electron Conductance

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A remarkable property of intrinsic graphene is that upon doping, electrons and holes travel through the monolayer thick material with constant velocity which does not depend on energy up to about 0.3 eV (Dirac fermions), as though the electrons and holes are massless particles and antiparticles which move at the Fermi velocity v_F. Consequently, there is Klein tunneling at a $p-n$ junction, in which there is no backscattering at normal incidence of massless Dirac fermions. However, this process yielding perfect transmission at normal incidence is expected to be affected when the group velocity of the charge carriers is energy dependent and there is non-zero effective mass for the target particle. We investigate how away from normal incidence the combined effect of incident electron energy ϵ and band gap parameter Δ can determine whether a $p-n$ junction would allow focusing of an electron beam by behaving like a Veselago lens with negative refractive index. We demonstrate that there is a specific region in $\epsilon-\Delta$ space where the index of refraction is negative, i.e., where monolayer graphene behaves as a metamaterial. Outside this region, the refractive index may be positive or there may be no refraction at all. We compute the ballistic conductance across a $p-n$ junction as a function of Δ and ϵ and compare our results with those for a single electrostatic potential barrier and multiple barriers.

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I. INTRODUCTION

Graphene is a virtually two-dimensional (2D) sheet of carbon atoms which is nearly transparent and a considerably strong material for its light weight, high thermal and electrical conductivity. It is an allotrope of carbon atoms with 2D properties. The atoms are packed densely in a regular sp^2 bonded atomic scale chicken wire hexagonal pattern. Creating high quality graphene is a complex process which prevented it from being easily available[1–3]. However, recent work found that by analyzing graphene's interfacial adhesive energy, it is possible to separate graphene from the metallic background on which it is grown. With the experimental realization of graphene, the focus now is to obtain a thorough understanding of its electronic and photonic properties. In this regard, one of the most intriguing challenges of graphene is a comprehensive understanding of the transmission[4–10] of charged particles across a potential barrier or a potential step.

In the case for transmission of an electron through a higher barrier than its incoming energy, the electron turns into a hole within the barrier region, with its momentum directed in the reversed direction, resulting in a negative refractive index[11–19] causing the electron beam to focus at a point, thereby producing a Veselago lens. There is always some probability for the electron to tunnel onto the other side of the barrier, which we have calculated in this paper. Our transmission probability is then employed in our calculation of the conductance[20–22]. The behavior of the transmission coefficient as well as the conductance changes dramatically when an energy band gap is introduced in graphene which may be achieved either by placing the 2D monolayer on a substrate or exposing it to circularly polarized light[23,24].

The rest of our paper is organized as follows. In Sec. II, the σ_z model Hamiltonian is used to solve the Hamiltonian equation for the wavefunction in the various regions with a prescribed constant potential. Using the continuity condition for the wavefunction at an interface between regions, the transmission probability is calculated. This is carried out for a potential step, as well as for one and two electrostatic potential barriers. In Sec. III, we present numerical results for the transmission coefficient, and the conductance using the analytic results in Sec. II. We conclude our paper with some relevant remarks in Sec. IV.