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Goos-Hänchen shift in monolayer graphene with electrostatic barriers

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We analysed the electron transport and Goos-Hänchen (GH) lateral shifts in graphene. We discuss recent studies on the GH shift in monolayer graphene. We describe the theoretical framework for calculating the GH shift and its electronic analogue in monolayer graphene. Further we discuss the enhancement in the GH shift corresponding to the resonant positions arising due to quasi-bound states formation in the presence of well-formed in the double barrier structure.

Keywords: Goos-Hänchen shift, Monolayer graphene, Electrostatic barriers, Tunable transmission

INTRODUCTION

The Goos-Hänchen (GH) shift is a phenomenon in which the lateral displacement of a beam of light occurs as it is reflected off a surface. This effect was first observed in the context of optics and has since been found to occur in a variety of physical systems [1-3]. In recent years, the GH shift has been studied in the context of graphene, a two-dimensional material consisting of a single layer of carbon atoms arranged in a hexagonal lattice. Graphene exhibits a number of unique electronic and optical properties [4-9], and the GH shift in graphene has been found to have some particularly interesting and useful characteristics. The GH shift in graphene arises due to the strong interaction between light and electrons in the material. As a beam of light enters graphene, it excites the electrons and creates a surface plasmon polariton (SPP), which is a collective oscillation of the electron density. This SPP interacts with the incident light and causes it to experience a lateral shift as it reflects off the surface. Understanding and controlling the GH shift in graphene has important implications for the development of new technologies, such as ultra-compact photonic circuits and sensors. Additionally, the GH shift provides a unique tool for studying the electronic and optical properties of graphene and other two-dimensional materials.

The Goos-Hänchen (GH) shift in monolayer graphene can be understood within the framework of the surface plasmon polariton (SPP) theory. When light enters graphene, it can excite an SPP, which is a collective oscillation of the electron density on the surface of the material. This SPP can then interact with the incident light and cause a lateral shift in its reflection angle. The GH shift can be calculated using the Fresnel coefficients, which describe the reflection and transmission of light at an interface between two materials with different refractive indices. In the case of graphene, the Fresnel coefficients depend on the angle of incidence and the polarization of the incident light, as well as the doping level and Fermi energy of the material. This shift in graphene can be enhanced by controlling the doping level and Fermi energy of the material. For example, doping graphene with impurities can increase the density of states and enhance the interaction between the incident light and the SPP, leading to a larger GH shift.

In addition to its practical applications, the GH shift in graphene can also provide insights into the fundamental properties of two-dimensional materials. For example, the GH shift can be used to probe the electronic properties of graphene and to study the coupling between light and matter in low-dimensional systems. Overall, the GH shift in monolayer graphene is a fascinating phenomenon with a wide range of potential applications in photonics and nanotechnology. In addition to the Goos-Hänchen (GH) shift, monolayer graphene exhibits another type of lateral shift known as the Imbert-Fedorov (IF) shift [10]. The IF shift is similar to the GH shift in that it arises from the interaction between light and surface plasmon polaritons (SPPs) in the material, but it differs in the way that it is calculated and its physical origin.

The IF shift arises when light reflects off a surface with a non-uniform refractive index profile. In the case of graphene, this non-uniformity can arise due to the presence of a strain gradient or a spatially

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varying doping profile. The IF shift can be described as the lateral displacement of the reflected beam relative to the incident beam, and it depends on the angle of incidence and the polarization of the incident light, as well as the refractive index profile of the material. The IF shift in graphene has been experimentally observed in a number of studies. For example, it has been shown that the presence of a strain gradient in graphene can lead to a significant IF shift, which can be controlled by applying a mechanical strain to the material. Similarly, the IF shift can be enhanced by doping graphene with impurities or by patterning the material into a non-uniform structure. Like the GH shift, the IF shift in graphene has potential applications in the development of new photonic devices and sensors. The ability to control the lateral displacement of light in graphene could be useful for designing ultra-compact and highly sensitive photonic circuits, as well as for studying the fundamental properties of low-dimensional materials.

Theoretical framework

The Fresnel coefficients can be used to calculate the Goos-Hänchen (GH) shift at the interface between two media, such as strained graphene and air. The Fresnel coefficients describe the reflection and transmission of electromagnetic waves at the interface and depend on the refractive indices of the two media. In the case of strained graphene, the refractive index of graphene is affected by the mechanical strain, which changes the electronic properties of the material. The refractive index of strained graphene can be calculated using the following formula $n = 1 - \delta + i\alpha$, where δ is the real part of the refractive index, which is affected by the mechanical strain, and α is the imaginary part, which accounts for the absorption of light by the material.

The Fresnel coefficients for the reflection and transmission of electromagnetic waves at the interface between strained graphene and air can be expressed as $r = (n_1 - n_2)/(n_1 + n_2)$ and $t = 2n_1/(n_1 + n_2)$, where n_1 is the refractive index of strained graphene and n_2 is the refractive index of air. With this, the GH shift can be calculated using $\Delta x = -2\mathrm{Im}(t/r)\ \partial\theta(q/k)$, where Im is the imaginary part, $\partial\theta(q/k)$ is the derivative of the surface plasmon wave vector with respect to the incident angle, and q and k are the wave vectors of the surface plasmon and incident light, respectively.

Electronic analogue of Goos-Hänchen-like shift in graphene

Many optics like behavior of ballistic electrons in graphene have been demonstrated due to the quantum-mechanical wave nature of electrons [4]. In graphene, electrons near the Fermi level, namely the transport electrons no more obey quadratic dispersion law, a typical characteristic of their nonrelativistic nature, but rather obey a linear dispersion relation, an archetype of the ultra-relativistic massless particles. The transport of such massless Dirac fermions in the presence of an electrostatic potential barrier is analogous to negative refraction through meta materials [9]. It was shown that a precise focusing can be achieved by fine-tuning the densities of carriers on either side of the barrier. This can be used to turn the electrostatic barrier (or n-p-n junction) into a Veselago lens for electrons.

Further, the unique electronic and transport properties of graphene including anomalous quantum hall effect and Klein tunnelling has opened very new exciting prospects in terms of analogy between optics and electron propagation in ballistic regime. Many optics-like phenomena such as collimation, Fabry Perot interference and Bragg reflection have been predicted with graphene-based structures. Further, quantum Goos-Hänchen effect has been investigated at the single graphene interface and in graphene based electric and magnetic barriers which are analogous to the phenomenon of the lateral shift of the light beam total internally reflected from dielectric surface [10-22]. However, in general the magnitude of quantum Goos-Hänchen shift is of the order of Fermi wavelength which impedes its direct measurement and broad applications. Later on, Chen *et al*. investigated the lateral shifts for Dirac fermions in transmission through monolayer graphene barrier, based on a tunable transmission gap [21, 22]. This shift has same physical origin that is due to the beam reshaping since each plane wave component undergoes different phase shift, however it has nothing to do with the evanescent waves which play an all important role in the lateral shift of total internally reflected wave function. For this reason, this shift can be termed as Goos-Hänchen-like (GHL) shift. It can be considered as an electronic analogue of the lateral shifts of light beam transmitted through a meta-material slab. Very recently a giant Goos-Hänchen shift has been reported for electron beam tunnelling through graphene double barrier structures [18, 19]. It is found that inside the transmission gap for the single barrier, the shift displays sharp peaks with magnitude up to the order of electron beam width which may be utilized to design valley and spin beam filters. A detailed investigation of the physics behind such giant Goos-Hänchen shift is required.

Theory: tunable transmission gap and GHL shift for single electrostatic barrier in monolayer graphene

We consider the massless Dirac fermions with the Fermi energy E and incidence angle ϕ with respect to the x axis incident upon a barrier of height V_0 and width d. Since the charge carriers in graphene are formally described by Dirac like Hamiltonians, the wave functions in region I (x<0), region II (0<x<d) and in region III (x>d) are obtained as:

$$\psi_I = \begin{pmatrix} 1 \\ se^{i\phi} \end{pmatrix} e^{i(k_x x + k_y y)} + r \begin{pmatrix} 1 \\ -se^{-i\phi} \end{pmatrix} e^{i(-k_x x + k_y y)}$$

$$\psi_{II} = a \begin{pmatrix} 1 \\ s'e^{i\theta} \end{pmatrix} e^{i(q_x x + q_y y)} + b \begin{pmatrix} 1 \\ -s'e^{-i\theta} \end{pmatrix} e^{i(-q_x x + q_y y)}$$

$$\psi_{III} = t \begin{pmatrix} 1 \\ se^{i\phi} \end{pmatrix} e^{i(k_x x + k_y y)}$$

Eq. (1)

Here k_x and k_y are the parallel and perpendicular wave vector components outside the barrier while q_x and q_y are the corresponding components inside the barrier. Using Eq. (1) the transmission coefficient is determined as:

$$T = \frac{4k_x^2 q_x^2}{k_x^2 q_x^2 + \left(k_y^2 + k_F k_F^{'}\right)^2} e^{-2iq_x d}$$

Here k_F and $k_F^{'}$ are the Fermi wave vectors outside and inside the barrier region, respectively. In the next section we present the result and analysis of transmission and GHL shift using above expression.

RESULTS AND DISCUSSION

Tunable transmission gap & Goos-Hänchen shift for single and double electrostatic barrier

We calculated the tunable transmission gap occurring in the presence of single electrostatic barrier in graphene, and the associated Goos-Hänchen-like (GHL) shift. This is shown in Figs. 1 (a) and (b). Further, we obtained the shift in the presence of a double electrostatic barrier and showed that inside the tunable transmission gap for the constituent single barrier, the shift displays giant, sharp peaks at the position of the bound states formed due to the well between the two barriers.

When the electrons are incident at an angle greater than the critical angle:

$$\phi > \phi_c = \sin^{-1}\left|\frac{V_0 - E}{E}\right|$$

the wave vector inside the barrier corresponds to an evanescent wave and the transmission probability is damped exponentially. Due to this reason, there occurs an angle-dependent gap as we plot transmission as a function of incident energy. The amount of this angle-dependent gap can be evaluated analytically as $\Delta E = 2V_0 \sec\phi \tan\phi$. Further, using the transmission coefficient expression and applying the stationary phase approximation the GHL shifts of the transmitted beam through a barrier in graphene can be obtained using $\sigma_t = \delta\phi_t / \delta k_y$ corresponding to the wave vector at central incidence angle. The analytical expression for GHL shift is thus obtained as:

$$\sigma_t = d \tan\phi_0 \cdot T \cdot \left[\left(2 + \frac{k_0^2}{k_x^2} + \frac{k_0^2}{q_x^2}\right)\frac{\sin 2q_x d}{2q_x d} - \frac{k_0^2}{q_x^2}\right]$$

where $k_0^2 = k_{y0}^2 - ss' k_F k_F^{'}$, the central wave vector being k_0.

Depending on the sign of the product $ss' = \pm 1$ the GHL shifts can be negative or positive and can be enhanced by the transmission resonances. Importantly, we clearly show that the giant GHL shifts correspond to the resonant positions arising due to quasi-bound states formation in the presence of well-formed double barrier structure.

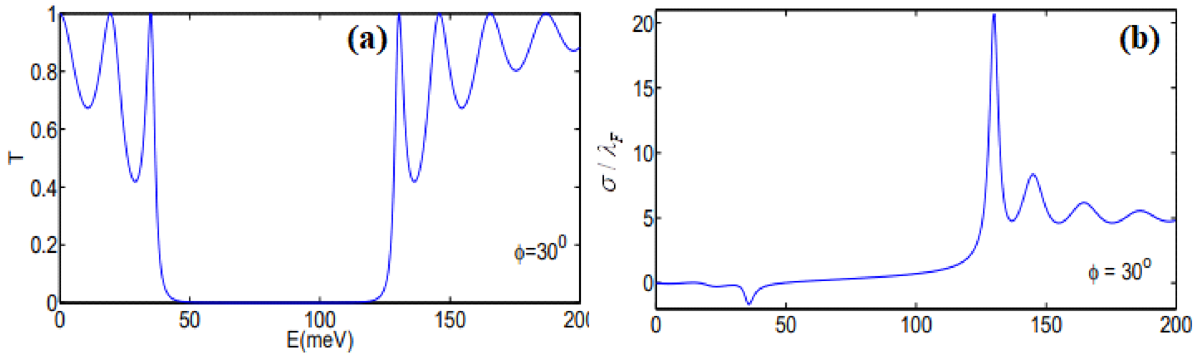

Fig. 1. Tunable transmission gap & Goos-Hänchen shift for single electrostatic barrier in monolayer graphene

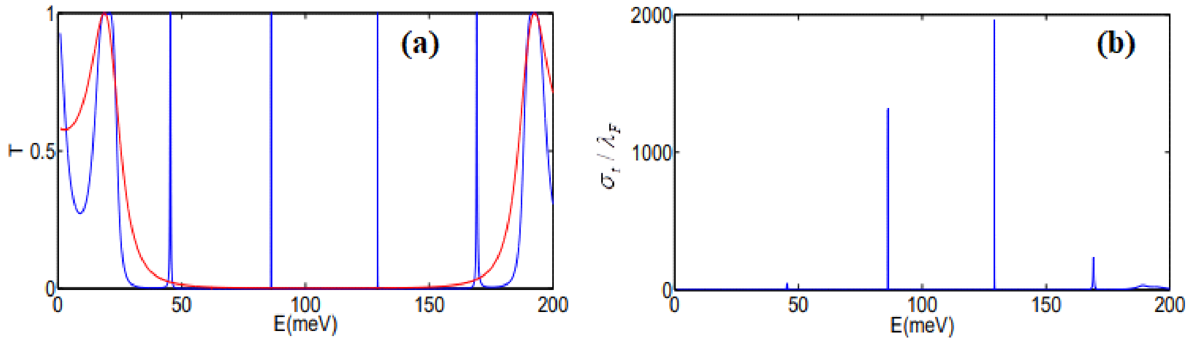

Fig. 2. Tunable transmission gap & Goos-Hänchen shift for double electrostatic barrier in monolayer graphene.

CONCLUSION

In this paper we discussed the GHL shift in monolayer graphene. Depending on the Klein tunnelling regime or classical motion regime, the GHL shifts can be negative or positive and can be enhanced by the transmission resonances. Here we point out that applying magnetic barriers with commensurate electrostatic potential will provide better tunability to the system. The vector potential of a magnetic field couples differently at the two valleys of graphene and hence can be used to obtain valley polarisation.

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