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Strain filter with gate control in a gapped graphene junction

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ABSTRACT

We study transport properties of massive Dirac electrons tunneling through a strained barrier in graphene junction. The interplay of strained barrier and gap opening in graphene is focused. As an interesting result, we find that the applied strain in the barrier would cause a maximum conductance for some strain values leading to "strain filtering effect". Perfect strain filter is predicted at the Fermi level approaching the energy gap. The selected strain value is found to be tunable by the gate voltage at the barrier. The strain filtering effect does not occur when graphene is gapless. The gate-controlled strain filter is almost linearly dependent on gate voltage for large strain. Our work reveals the potential of graphene for application of strain sensor or filter device.

1. Introduction

Graphene, a monolayer of graphite, has become a promising material for nanotechnology [1–5], after discovered [6]. Graphene transistor operated at 100–300 GHz was reported [1] and the first graphene-based integrated circuit has been realized [7]. One of the special electronic properties is that its charged carriers mimic the behavior of the two-dimensional Dirac fermions where the speed of light is replaced by its Fermi velocity [8,9]. In general, Dirac electrons in graphene act like massless fermions, satisfying energy–momentum relation of $E = v_F p$ where E, $v_F \sim 10^6$ m/s and p are energy, Fermi velocity and momentum, respectively. Dirac electrons in monolayer graphene may become massive by means of substrate-induced band gap [10,11] which may yields energy–momentum relation, $E = \sqrt{(v_F p)^2 + \Delta^2}$, where $m = \Delta/v_F^2$ plays the role of a relativistic mass. Graphene grown on hexagonal boron nitride (h-BN) substrate may yield energy gap of about 53 meV [11], due to difference in energy levels in sublattice A and B. Graphene is a good nano-material having elastic property sustaining uniaxial strain beyond 20% [12,13]. Mechanical strain would generate filed-like vector potential with the same magnitude but opposite signs $-(+)$ for electrons in $k-$ $(k'-)$ valleys [14–17]. The band structure would be shifted in the momentum space by strain field. Pseudo magnetic field greater than 300 T was observed in graphene nanobuble grown on a platinum (1 1 1) surface [18]. The electronic band structure can be controlled by external applied strain, applicable for nano-electro-mechanical devices [19–21] such as pressure sensor device [20] and strain sensor [21]. As one of topics of interest, electronic currents passing through strain barrier in gapless graphene junctions have drawn much attention [16,17,22–29]. The interplay of strain and real vector potential leads to valley polarization [22,23]. Adding Zeeman field into the barrier also gives rise to spin and valley polarizations [17,24]. The Josephson junction with strain barrier was recently studied [24,25].

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In gapped graphene, electrons are massive-like Dirac fermions. Their velocity may be tunable by varying their energy, unlike that in gapless graphene that electron's velocity does not change. The transport properties in gaped graphene system have drawn much attention [30–34]. In this paper, we investigate Dirac electron tunneling through a strained barrier in which they are massive, possibly induced by substrate [11]. Effect of the interplay of mass and applied strain on the conductance of junction is focused. We will show that "strain filtering effect" may occur when the charged carriers are massive. This result may be important for strain sensor device.

2. Model and scattering process

The electronic model, normal graphene (NG)/strain-graphene (Strain-G)/normal graphene (NG), is depicted in Fig. 1(a)–(c). Graphene is assumed to be grown on a substrate, for example h-BN-substrate [11], to induce band gap of 2Δ, while in the barrier with thickness L, there is modeled as no energy gap because of no interaction between graphene and the substrate. Uniaxial strain in armchair direction is assumed to be applied only into the barrier. The uniaxial strain in the armchair direction may create pseudo vector potential only in the x-direction as of the form [14–17,22–24]

$$\vec{A}_{\text{pseudo}}(y) = \lambda \frac{c}{e v_{\text{F}}} \langle \delta, 0 \rangle \Theta(y) \Theta(L-y), \tag{1}$$

where $\Theta(y)$ is a unit step function, $\lambda = 1(-1)$ stands for electrons in $k-$ $(k'-)$ valleys and "c" is speed of light. The formula of strain-induced energy interaction "$\delta = 3.37 t_0 \times strain$" is adopted, based on the formula in Refs. [17,24], where $t_0 \cong 2.7$ eV is hoping energy [35]. In the barrier, charged carrier is also tuned by gate voltage $-V_G$ to get the potential function defined as $U(y) = eV_G \Theta(y)\Theta(L-y)$. The current of the junction is assumed to flow in the y-direction.

To combine Dirac mass [30–34] and strain effect [14–17] on transport property, the Hamiltonian used to describe the motion of electrons near the Dirac point in the system may be given by the following

$$\hat{H}_\lambda = v_{\text{F}} \vec{\sigma} \cdot \hat{\vec{p}} + \lambda \sigma_z M(y) + \sigma_0 U(y) + \lambda \frac{e v_{\text{F}}}{c} \vec{\sigma} \cdot \vec{A}_{\text{pseudo}}, \tag{2}$$

where $\vec{\sigma} = \langle \sigma_x, \sigma_y, \sigma_z \rangle$ are standard vector of Pauli spin matrices acting on pseudo-spinor field ψ, energy gap function is $M(y) = \Delta\Theta(-y) + \Delta\Theta(y-L)$ and σ_0 is a 2×2 unit matrix. The momentum operators is usually given as $\hat{\vec{p}} = -i\hbar \langle \partial/\partial x, \partial/\partial y, 0 \rangle$. Plane wave solution can be determined using Eigen equation

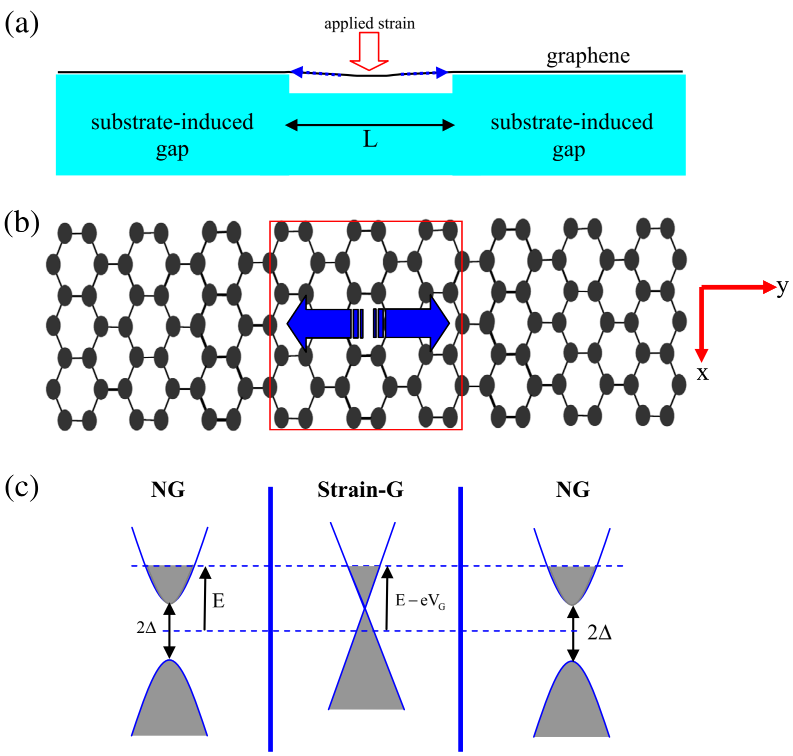

Fig. 1. Schematic illustrations of (a) junction of graphene on substrate-induced band gap with applied strain in the thickness of barrier L, (b) local strain at the barrier being applied in the armchair direction and (c) electronic band structure normal and strained-regions. The gate voltage, excited energy and energy gap are given by $-V_G$, E and $E_{gap} = 2\Delta$, respectively. The current flows in the y-direction, or in the armchair direction.