Graphene based spin field effect transistor

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Abstract

A spin field effect transistor (FET) is proposed by utilizing a graphene nanoribbon as the channel. Similar to the conventional spin FETs, the device involves ferromagnetic metals as a source and drain; they, in turn, are connected to the graphene channel. Due to the negligible spin-orbital coupling in the carbon based materials, the bias can accomplishes spin manipulation by means of electrical control of electron exchange interaction with a ferromagnetic dielectric attached to the nanoribbon between source and drain. The numerical estimations show the feasibility of graphene-based spin FET if a bias varies exchange interaction on the amount around 5 meV. It was shown that the device stability to the thermal dispersion can provide the armchair nanoribbons of specific width that keeps the Dirac point in electron dispersion law.

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Conventional electronics makes use of the electron charge that faces major technical limitations in the continued path to device downscaling. Spintronics operates by controlling the electronic spin state. A typical operation of spintronic logic device or spin-FET transistor as conceived by Datta and Das assumes three principle operations: (1) spin injection into the device active channel, (2) spin manipulation by the applied bias, and (3) spin detection at the device drain. In turn, the feasibility of such spin manipulation imposes some limitations on the semiconductor channel of the length $L$. The main restrictions are (i) requirement for the long enough spin-phase relaxation time $T_2$ so that spin phase should not be lost while an electron travels with mean velocity $v$ through semiconductor channel, i.e. $T_2 > L/v$ and (ii) independence of spin phase rotation on electron velocity, i.e. it should be stable for thermal dispersion of electron energy. Note that the electric field spin manipulation via Rashba effect assumes a strong spin-orbital coupling, which conflicts with fast spin decoherence. Involving the holes with enhance Rashba effect (compared with electron spin) not only shortens spin coherence but also breaks a stability to the energy dispersion because of non-linear spin-splitting dependence on hole velocity.

In this work we show that the aforementioned problems can be avoided in the spin-field transistor based on a different conception that utilize specific properties of the graphene sheet. The device design assumes the ferromagnetic source and drain, which resemble conventional spin transistor (Fig. 1). However spin rotation occurs in graphene nanoribbon, which provides the electron exchange interaction with non-metallic ferromagnetic layer attached to a graphene surface. This exchange interaction can be treated as an effective magnetic field $G$ so that a spin-polarized electron traveling through the graphene during the time $\Delta t$ turns around the $G$ on the angle $\theta = G\Delta t/\hbar$. If external electric field applied perpendicular to the graphene sheet will change the $G$ by the $\Delta G$, the spin rotation varies like $\Delta \theta = \Delta G\Delta t/\hbar$ that can perform the spin-valve function at sufficiently large $\Delta \theta$.

In order to utilize such spin-manipulation in spin-FET, the system must meet certain additional criteria. First, a spin coherence time $T_2$ must be long enough compared to traveling time $\Delta t$, so that decoherence does not influence $\theta$. In the case of graphene, the extremely small spin-orbital coupling can fix a long enough $T_2 \gg \Delta t$ that solves a problem of spin decoherence. Then, the thermal scattering of the electron energy at finite temperature $T$ must not influence the spin rotation. Note that in the case of Datta-Das device, this problem was solved due to proportionality of spin-rotation rate to electron velocity that results in
compensation of thermal scattering on electron energy under the quadratic dispersion law \( \varepsilon_k \sim k^2 \). In our case the drift time \( \Delta t = L/v \) inverses to electron velocity \( v \) in the channel under the ferromagnetic layer of the length \( L \). So in the case of the linear dispersion law in graphene ribbon\(^8\)\(^9\) the electron velocity \( v \) does not subjected to thermal scattering that preserves a broadening of the \( \theta \). Finally, the applied bias must provide a changing of the effective field \( G \). Applying the ferromagnetic materials with giant magnetoelectrical effect\(^10\) will provide the spin-rotation sensitivity to electric field. Consider this possibility in detail.

The problem of spin injection as well as spin detection in graphene are now in a progress\(^11\)\(^12\) so we focus on the analysis of spin dynamics in graphene. Although an applied bias induces some band spin splitting we neglect this effect hereinafter; besides we neglect the spin-orbital coupling that has been estimated as extremely small one, \( \sim 1 \) \( \mu eV \)\(^13\). Graphene consists on honeycomb flat lattice of carbon atoms with two atoms \( A \) and \( B \) per unit cell.

In the vicinity of Fermi energy \( \varepsilon_F = 0 \) the effective mass approximation assumes that the spinless wave function takes the form of a four-vector \((\psi_A, \psi_B, \psi'_A, \psi'_B, )\), where \( \psi_A \) and \( \psi_B \) \([\psi'_A \text{ and } \psi'_B]\) are the amplitudes at the sublattices \( A \) and \( B \) in the valley \( K = \frac{2\pi}{3a}(1,1) \) \([K' = \frac{2\pi}{3a}(-1,1)]\); \( a = \sqrt{3}a_{C-C} = 0.249 \) nm is a length of lattice vector, \( a_{C-C} \) the distance between the neighbor carbon atoms. In the vicinities of valley \( K \), the Hamiltonian for the envelope wavefunctions takes the form\(^14\)

\[
H_K = \hbar v \begin{pmatrix} 0 & -i\partial/\partial x - \partial/\partial y \\ -i\partial/\partial x + \partial/\partial y & 0 \end{pmatrix},
\]

where \( v \simeq 10^8 \) cm/s is a velocity of the electron at Fermi energy\(^15\). Hamiltonian \( H_{K'} \) for the \( K' \) valley differs from Eq. (1) by opposite in sign \( i \). In general case Hamiltonian represents the direct sum

\[
H_0 = H_K \oplus H_{K'}.
\]

Electronic transport will be considered through an armchair nanoribbon directed along the \( y \) axis so that a wave number \( k_y \) attributes to a quantum numbers of the electron. The problem of eigenstates of armchair nanoribbons can be correctly developed in terms on \( kp \) approach with Hamiltonian \([2]\) by applying appropriate boundary conditions\(^2\). One of the remarkable feature of such solutions appears at particular nanoribbon width \( L_x = (3p+1)a \) with integer \( p > 0 \) that keeps the Dirac point at zero energy despite the electron confinement.
It can be shown that the energy band structure in such a case describes

\[ E_{m,k_y} = \pm \frac{\hbar v_a}{a} \sqrt{(k_y a)^2 + \left(\frac{2\pi m}{6p + 3}\right)^2} \]  

with integer \( m \). The \( m = 0 \) corresponds to gapless linear dispersion law alike to the case of bulk graphene; the edge of first excited bands with \( m = 1 \) possesses the energy \( E_{1,0} = \frac{2\pi \hbar v}{3(2p+1)a} \). Note that at reasonably narrow ribbon the energy \( E_{1,0} \) can significantly exceed the thermal energy at room temperature. For example, at \( L_x = 7.72 \text{ nm} \) \( (p = 10) \) one can find \( E_{1,0} = 260 \text{ meV} \). This estimation shows that the lowest subband with linear dispersion law can determine an electronic transport through graphene nanoribbon even at room temperature.

Now let us take into account the electron exchange interaction with magneto-ordered layer attached to the top side of the graphene nanoribbon. We assume that a magnetic structure is formed by the magnetic ions with non-compensated spin moments \( S_{\lambda,j} \) localized at sites \( \lambda \) of the unit cell \( j \). Corresponding exchange integrals \( J(R_{\lambda,j}) \) crucially depend on overlap of graphene electron wavefunction with localized magnetic ions; thus the only nearest neighbor unit cells have to be taken into account when one sums up over the \( j \). Hamiltonian of exchange interaction takes the form

\[ H_{ex} = \frac{1}{N} \sum_{j=1}^{N} \sum_{\lambda} J(R_{\lambda,j}) S_{\lambda,j} s, \]  

where \( s \) is an electron spin, \( N \) the number of unit cells attached to nanoribbon. It is naturally to introduce the molecular fields (in energy units) acted on electron spin in nanoribbon,

\[ G_{\lambda} = \frac{1}{N} \sum_{j=1}^{N} J(R_{\lambda,j}) \langle S_{\lambda,j} \rangle \]  

that stem from the exchange interaction with magnetic ions of certain type \( \lambda \), the \( \langle S_{\lambda,j} \rangle \) is a mean value of spin moment. Further elaboration of the Eq. (5) needs detailed specification of the structure that is not a scope of this letter. We only want to stress the dependence of exchange fields \( G_{\lambda} \) from both exchange integrals and magnetic moments of sublattices that will prompt the different mechanisms of \( G_{\lambda} \)'s manipulation. In the context of this approximation, the final expression for the exchange Hamiltonian takes the form of Zeeman energy

\[ H_{ex} = Gs, \]
where $G = \sum \lambda G_\lambda$ is a total effective field in energy units. Note that $G$ can run to some non-zero amount for any magnetic ordered materials, i.e. ferromagnetics, ferrimagnetics or even antiferromagnetics if the magnetic ions, which possess the opposite directed spins are differently situated with respect to graphene sheet.

The total Hamiltonian is a sum, $H = H_0 + H_{ex}$, that include the commutating operators taken from the Eq. (2) and Eq. (6). According to Fig. 1, the effective exchange field is directed along to $x$-axis so that the eigenenergy of electron depends on electron spin projection $\xi = \pm 1/2$ on the axis $x$:

$$E_\xi = \hbar v k_y + G_x \xi.$$  

(7)

Eq. (7) shows that an electron of some fixed energy and with different spin orientations $\xi = +1/2$ and $\xi = -1/2$ possesses a difference in wave vectors $k_y(\xi = -1/2) - k_y(\xi = +1/2) = G_x/\hbar v$. Thus at the end of the graphene nanoribbon of the length $L_y$ this produce the spin phase rotation $\theta = G_x L_y/\hbar v$. If an applied bias in z-direction mediates the change $\Delta G_x$ of the effective field along the whole nanoribbon, the spin rotation will progressive change,

$$\Delta \theta = \Delta G_x L_y/\hbar v.$$  

(8)

This result is in accordance of our qualitative discussion. Note that $\Delta \theta$ is not depended on $k_y$ i.e. it is robust with respect to electron thermal dispersion.

It can be noted two mechanisms of electric field influence on the effective field $G$. First, the dielectric polarization in an external electric field is accompanied by ions shifts inside the crystal unit cell. If such shift concerns the magnetic ions, it will result in variation of exchange integrals and, therefore, exchange field $G$. Other possibility can be realized in the case of multiferroic materials with giant magneto-electric effect\textsuperscript{10,16,17} where the total magnetic moment $\sum \langle S_\lambda, j \rangle$ is strongly depended on electric polarization.

Now we can estimate the magnitude of the exchange field variation $\Delta G$ needed to the effective device operation. Note that spin coherence length in graphene was recently found as long as 1 $\mu$m.\textsuperscript{18} Thus, under the applying of graphene nanoribbon of 100 nm length, the variation $\Delta G \simeq 5$ meV leads to spin rotation changing $\Delta \theta \simeq 1$. The spin-controlled current through the device represent the oscillating function on the $\Delta G$.

Let us introduce the transmission coefficient $T_+$ for the electrons, which reach the drain with spin directed along the $y$-axis (Fig. 1). Similarly, one can introduce the $T_-$ for anti-
directional spin and magnetization vectors. The total transmission of the device is

\[ T = \frac{1}{2} T_0 + \langle s_y \rangle \Delta T, \]  

(9)

where \( \langle s_y \rangle \) is a mean value of electron spin projection on the y-axis, \( T_0 = T_+ + T_- \), \( \Delta T = T_+ - T_- \). In the case of ballistic transport \( \langle s_y \rangle = \frac{1}{2} \cos \theta \). As mentioned above, the spin rotation is \( \theta = \theta_0 + \Delta \theta \) with \( \theta_0 = (2n + 1) \pi \), which is independent on applied bias and integer \( n \). This results in \( \langle s_y \rangle = -\frac{1}{2} \cos \Delta \theta \) so that maximal transmission amplitude \( \Delta T \) arrives at \( \Delta \theta \) variation from 0 to \( \pm \pi \). Naturally, the finite coherence length \( L_C \) will reduce the \( \Delta T \) by the factor \( \exp(-L_y/L_C) \). Fig. 2 illustrates the expected dependencies of the device transmission on the variable part of the exchange field \( \Delta G \) and the channel length \( L_y \).

In summary, a conception of spin-FET based on hybrid structure, which incorporates the graphene nanoribbon with attached ferromagnetic dielectric is proposed. The advantage of such hybrid structure is a long electron spin coherence in graphene and constant electron velocity through the nanoribbon of specific width. As a result, the ferromagnetic dielectric can control spin rotation and implement the function of spin-FET if an effective exchange field is controlled by applied bias. Apparently the multiferroic materials are probably most appropriate candidates for such structure.

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Figure captions

Fig. 1. Schematic illustration of the spin-FET based on the graphene nanoribbon (circles with bonds) and ferromagnetic dielectric (FMD) hybrid structure. Ferromagnetic source (S) and drain (D) has collinear magnetic moments (large arrows) directed with $y$-axis, ferromagnetic dielectric directs its magnetization (circle with dot) along $x$-axis. The figure illustrates the situation when electron spin (small arrow) inverse its direction due to interaction with ferromagnetic dielectric that suppresses the conductance of the device (spin-valve is closed). When an applied bias (along $z$-axis) $V_g$ alters the electron interaction with ferromagnet, the electron reaches the drain with arbitrary spin orientation, i.e. it has a finite probability to pass into the drain with the same spin projection (spin-valve is unclosed).

Fig. 2. Device transmission as a function of (a) exchange field in energy units under the length $L_y = 100$ nm and (b) a channel length under the $\Delta G = 10$ meV. The coherence length $L_C = 500$ nm and ratio $T_-/T_+ = 0.1$ are applied for both pictures.
Fig. 1: Semenov et al.
Fig. 2: Semenov et al.