

Simple operation scheme of graphene-based biosensor

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Gapless and gapped graphene encapsulated with a semiconductor substrate and a biomolecule-antigen Ab, with which the tested biomolecule-antigen Ag is brought into contact, is considered as a biosensor. The conditions under which the connection of Ag to Ab changes the type of conductivity of encapsulated graphene have been determined. The process of changing the type of conductivity is illustrated graphically.

Keywords: SiC substrate, antibody (bioreceptor), antigen (biomarker).

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On account of the growing interest in graphene-based biosensors [1–9], the authors of [10,11] have proposed simple models of a resistive sensor with single-layer graphene (SLG) encapsulated between two plates: a massive semiconductor substrate and an antibody biomolecule Ab (or a bioreceptor). An antigen biomolecule Ag (or a biomarker), which needs to be identified by a biosensor, is brought into contact with the antibody, inducing a change in conductivity of encapsulated graphene (see Fig. 1 in [10]; diagrams of actual setups were given in [5,7,12]). The authors of [10] used the known dangling bond model that characterizes the adsorption of a macromolecule on graphene [13]; in [11], the problem was simplified considerably by substituting the set of dangling bonds with just two bonds: HOMO (higher occupied molecular orbital) and LUMO (lowest unoccupied molecular orbital). In the present study, a simple operation scheme of a graphene-based sensor based on the concepts detailed in [10,11,13] is proposed. We tried to present it with minimum recourse to mathematics by making use of graphical illustrations.

Green's function $G(\omega, \mathbf{k})$ for SLG encapsulated between the substrate and an antibody takes the following form [10]:

$$G^{-1}(\omega, \mathbf{k}) = \omega - \varepsilon_D - tf(\mathbf{k}) - \Lambda_{sub}(\omega) - \Lambda_{Ab}(\omega) + i(\Gamma_{sub}(\omega) + \Gamma_{Ab}(\omega)). \quad (1)$$

Here, ω is the energy variable; ε_D is the Dirac point energy; t is the energy of electron hopping between nearest-neighbor carbon atoms in graphene; and $f(\mathbf{k}) = \pm 3|\mathbf{k}|a/2$ is the dispersion function for SLG in the low-energy approximation, where a is the distance between nearest neighbors in graphene and \mathbf{k} is the wave vector measured from the Dirac point. The functions of plate-induced broadening and shift of graphene levels are $\Gamma_{sub(Ab)}(\omega) = \pi V_{sub(Ab)}^2 \rho_{sub(Ab)}(\omega)$ and $\Lambda_{sub(Ab)}(\omega) = (P/\pi) \int_{-\infty}^{\infty} d\omega' [\Gamma_{sub(Ab)}(\omega')/(\omega - \omega')]$, re-

spectively, where $V_{sub(Ab)}$ is the matrix element of interaction of graphene with the substrate (antibody), $\rho_{sub(Ab)}(\omega)$ is the density of states of the substrate (antibody), and P denotes the principal integral value.

As for the density of states of the semiconductor substrate, we set $\rho_{sub}(\omega) = \rho_s = \text{const}$ at $|\Omega| \geq E_g/2$ and 0 at $|\Omega| < E_g/2$, where $\Omega = \omega - \omega_0$ and E_g is the substrate band gap with the center of it corresponding to energy ω_0 (Haldane–Anderson model [10]). Thus, we obtain $\Gamma_{sub}(\Omega) = \pi V_{sub}^2 \rho_{sub}(\omega)$ and $\Lambda_{sub}(\Omega) = \rho_s V_{sub}^2 \ln |(\Omega - E_g/2)/(\Omega + E_g/2)|$. The density of states of Ab dangling bonds may be written as

$$\rho_{Ab}(\omega) = \sum_i N_i \rho_i(\Omega_i), \quad \rho_i(\Omega_i) = \gamma_i / \pi(\Omega_i^2 + \gamma_i^2),$$

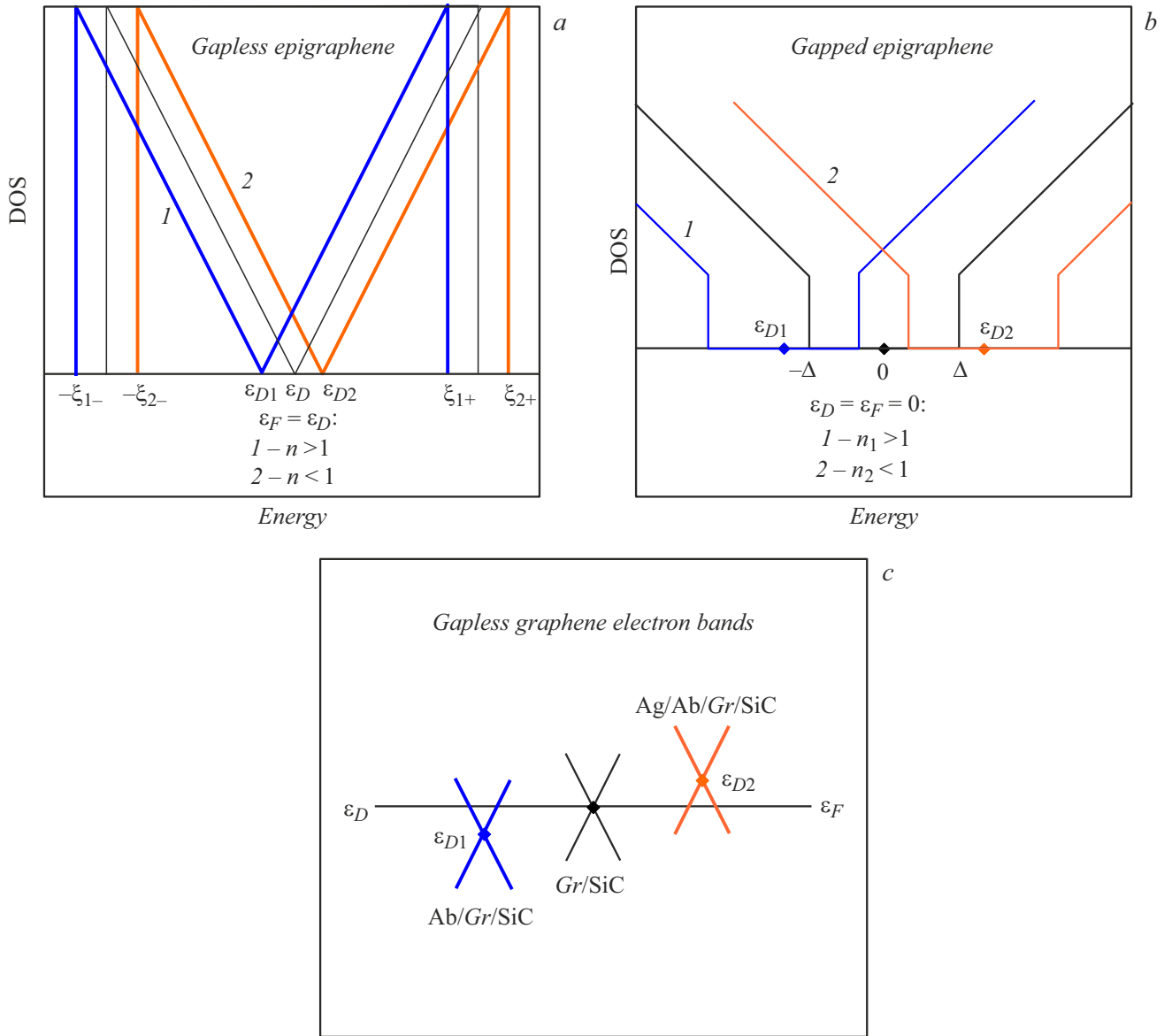
where N_i is the concentration of dangling bonds type i with energy ε_i ; $\Omega_i = \omega - \varepsilon_i$; and $\gamma_i = \text{const}$ is the intrinsic half-width of the i th dangling bond [10]. Therefore,

$$\Gamma_{Ab}(\omega) = \pi \sum_i N_i V_i^2 \rho_i(\Omega_i), \quad \Lambda_{Ab}(\omega) = \sum_i N_i \lambda_i(\Omega), \quad \lambda_i(\Omega) = \frac{\Omega_i V_i^2}{\Omega_i^2 + \gamma_i^2}. \quad (2)$$

In what follows, we consider weak binding of encapsulated graphene with plates; i.e., it is assumed that $\Gamma_{sub(Ab)}(\omega) \ll t$. If, as in [10], the values of $\Gamma_{sub(Ab)}(\omega)$ are considered negligible compared to $\Lambda_{sub(Ab)}(\omega)$, density of states $\rho_{\Delta}(\omega)$ of encapsulated graphene with a gap within energy range $(-\Delta, \Delta)$ of the electron spectrum may be written as

$$\rho_{\Delta}(\omega) = \begin{cases} \frac{2|w|}{\xi^2}, & R \geq |w| \geq \Delta, \\ 0, & |w| < \Delta, \quad |w| > R, \end{cases} \quad (3)$$

where $w = \omega - \varepsilon_D - \Lambda_{Ab}(\omega)$, $\varepsilon_D \approx \varepsilon_D^0 + \Lambda_{sub}(\varepsilon_D^0)$ is the Dirac point energy of single-layer epitaxial graphene (ε_D^0 is the Dirac point of free-standing graphene), $R = \sqrt{\Delta^2 + \xi^2}$,



Shift of the model density of states (*a, b*) and band spectrum (*c*) of epigrahene brought into contact with antibody Ab (*1*) and antibody Ab interacting with antigen Ag (*2*). It is assumed that Dirac point ε_D of epigrahene in the initial state coincides with the Fermi level of the semiconductor substrate (model silicon carbide polytype), so that there is no charge transfer between the substrate and SLG. At stage *1*, electrons are transferred from Ab to epigrahene, resulting in carbon atom occupation number $n > 1$. At stage *2*, the electrons are transferred from epigrahene to the Ab+Ag complex, and the carbon atom occupation number assumes the value of $n < 1$. *a* — Gapless epigrahene: $\varepsilon_{D1(D2)}$ — Dirac point energy at stage *1* (*2*); lower and upper boundaries of the continuous spectrum region $\xi_{1\mp(2\mp)} = \varepsilon_{D1(D2)} \mp \xi$. *b* — Gapped epigrahene: 2Δ — band gap; energies of the bottom of the valence band and the top of the conduction band $R_{1\mp(2\mp)} = \varepsilon_{D1(D2)} \mp R$ lie outside the boundaries of the figure at the chosen scale. *c* — Changes in the initial band spectrum (middle figure) at stages *1* and *2*; *Gr* — graphene.

and $\xi = \sqrt{2\pi\sqrt{3}t}$. The values of 2Δ in epigrahene are on the order of 0.1–0.3 eV [11]. At $\Delta = 0$, density of states $\rho_0(\omega)$ of gapless epigrahene assumes the characteristic M-shaped form.

Relying on the assumption of weak plate–graphene binding, we set that $w \approx \omega - \varepsilon_D - \Lambda_0$, $\Lambda_{sum} = \Lambda_{Ab} + \Lambda_{Ag}$. At zero temperature, the occupation number of an atom of encapsulated graphene is $n_\Delta = \int_{-R}^{\varepsilon_F} \rho_\Delta(\omega) d\omega$, where ε_F is

the Fermi level. Let us assume that the position of the Fermi level of the system is set by the massive substrate. The estimates for SiC polytype substrates indicate that the graphene gap is located inside the band gap of polytypes. In the present study, we omit the analytical expressions for n_Δ and go straight to the discussion (see the figure).

The figure shows a simplified diagram of operation of a resistive biosensor. In the initial state, the sensor is SLG formed on the surface of a „model“ SiC polytype with

the middle of its band gap ω_0 coinciding with Dirac point ε_D of epigraphene. If the polytype is undoped, which implies that $\varepsilon_F = \omega_0$ (as in [5,10,11,13], we assume that the position of the Fermi level in the biosensor structure is dictated by the SiC substrate), there is no charge transfer between the substrate and SLG due to the fact that $\varepsilon_F = \omega_0 = \varepsilon_D$ (the case with $\omega_0 \neq \varepsilon_D$ was discussed in [10,11]). This means that the occupation number of carbon atoms in epigraphene is $n = 1$, and the free carrier density is $\nu = (n - 1)/\bar{S}_i = 0$, where \bar{S}_i is the average area per dangling bond; thus, the diffusion (non-quantum) current through epigraphene is zero. Epigraphene would have hole and electron conductivity at $n < 1$ and $n > 1$, respectively.

When epigraphene is brought into contact with an antibody (the first step in the sensor operation process), Dirac point ε_D shifts to $\varepsilon_{D1} \approx \varepsilon_D + \Lambda_{Ab}$. At $\Lambda_{Ab} < 0$, this shift, which is illustrated in panel *a* of the figure, leads to the transfer of electrons from Ab to epigraphene, an increase in occupation number ($n > 1$), and the emergence of free electrons with density $\nu_e = (n - 1)/\bar{S}_i > 0$; the drift conductivity is $\sigma_1 = e\nu_e\mu_e$, where μ_e is the electron mobility and e is the elementary charge. Let us now add antigen Ag to Ab, which results in the shift of Dirac point ε_{D1} to $\varepsilon_{D2} \approx \varepsilon_{D1} + \Lambda_{Ag}$. If $\Lambda_{Ag} > |\Lambda_{Ab}|$ (the shift induced by the introduction of Ag exceeds the shift caused by Ab), the Dirac point shifts up the energy scale (this is illustrated for gapless graphene in panel *a* of the figure). This shift is equivalent to a reduction in occupation number n due to the withdrawal of electrons from epigraphene to the Ab+Ag complex. Hole conductivity $\sigma_h = e\nu_h\mu_h$ with hole density $\nu_h = (1 - n)/\bar{S}_i > 0$, where μ_h is the hole mobility, is established as a result. More accurate estimates were given in [10].

The above analysis is relevant to gapless epigraphene. Moving on to gapped epigraphene (see panel *b* of the figure), we find that a shift of $\Lambda_{Ab} < 0$ and $|\Lambda_{Ab}| > \Delta$, where Δ , as above, is the half-width of the gap, is needed to produce free electrons when antibody Ab is brought into contact with epigraphene. When Ag is subsequently added to Ab, the emergence of free holes is possible only with $\Lambda_{Ag} > 2\Delta$. Thus, the presence of a gap reinforces the requirements for changing the conductivity type in biosensor operation; i.e., it reduces its sensitivity. However, it should be noted that the presence of local levels in the gap relaxes the above requirements (this case is not considered here). It should also be emphasized that the process wherein Ab induces hole conductivity in epigraphene and the subsequent addition of Ag induces electron conductivity may be analyzed in exactly the same manner. Using formula (3) for $\varepsilon_F = \varepsilon_D = 0$, one may show easily that $\Delta n = 1 - 2\Lambda(R - \Delta)/\xi^2$. Since $\Delta \sim 0.2\text{--}0.3\text{ eV}$ and $\xi \sim 10\text{ eV}$, we may set $\Delta = 0$ and $R = \xi$ for our estimates. At stage 1, where $\Lambda \equiv \Lambda_{Ab} < 0$, we find $n_\Delta > 1$; at stage 2 with $\Lambda \equiv \Lambda_{Ag} > 0$, we obtain $n_\Delta < 1$. Let us present the carrier density as $\nu = \Theta(n - 1)/S_1$, where $S_1 = 3\sqrt{3}a^2/4$ is the area per graphene atom and

$\Theta = S_1/\bar{S}_i$ is the concentration of Ab dangling bonds. Then, $\nu \sim 5 \cdot 10^{12}\text{ cm}^{-2}$ at $\Lambda/\xi \sim 0.1$ and $\Theta \sim 10^{-2}$.

Thus, according to the proposed scheme, it is necessary to measure the current flowing through graphene sequentially for structures *Gr*/SiC, *Ab/Gr*/SiC, and *Ag/Ab/Gr*/SiC and, if possible, establish such conditions under which the current in epigraphene is zero in the initial state and is supported by opposite-sign carriers in the last two structures. In general, a change in conductivity type in a sensor is possible if Ab is a donor (acceptor) for epigraphene, while the (Ab+Ag) complex is, on the contrary, an acceptor (donor) (see panel *c* of the figure). In this case, the bond between the Ab and Ag molecules should be sufficiently strong (i.e., be a de Gennes covalent bond; see [14] for details).

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Conflict of interest

The authors declare that they have no conflict of interest.

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