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Concept of infrared photodetector based on graphene–graphene nanoribbon structure

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HIGHLIGHTS

- We study the mechanisms of photoconductivity in graphene layer-graphene nanoribbon-graphene layer (GL-GNR-GL) structures.
- We develop the device model for GL-GNR-GL photodiode.
- The GL-GNR-GL photodiodes can effectively detect infrared and terahertz radiation at room temperature.

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ABSTRACT

We study the mechanisms of photoconductivity in graphene layer–graphene nanoribbon–graphene layer (GL–GNR–GL) structures with the *i*-type gapless GL layers as sensitive elements and *I*-type GNRs as barrier elements. The effects of both an increase in the electron and hole densities under infrared illumination and the electron and hole heating and cooling in GLs are considered. The device model for a GL–GNR–GL photodiode is developed. Using this model, the dark current, photocurrent, and responsivity are calculated as functions of the structure parameters, temperature, and the photon energy. The transition from heating of the electron–hole plasma in GLs to its cooling by changing the incident photon energy can result in the change of the photoconductivity sign from positive to negative. It is demonstrated that GL–GNR–GL photodiodes can be used in effective infrared and terahertz detectors operating at room temperature. The change in the photoconductivity sign can be used for the discrimination of the incident radiation with the wavelength 2–3 μm and 8–12 μm.

1. Introduction

Due to the gapless energy spectrum, graphene [1] absorbs electromagnetic radiation from the terahertz to ultraviolet spectral range (see, for instance, Refs. [2–4]). The fairly high quantum efficiency of the interband transitions in graphene [2] and particularly in multiple-graphene layer structures [5] promotes the creation of novel effective infrared (IR) and terahertz (THz) photodetectors. Several concepts of IR/THz photodetectors, utilizing graphene single-and multiple layer structures as well as graphene nanoribbon structures (photoconductors, photodiodes, and phototransistors), have been proposed, evaluated, and studied experimentally [6–15]. In the photodiodes and phototransistors based on graphene nanoribbon structures considered previously [8,16], these structures play the role of the absorbing region. However, to achieve appropriate responsivity in such devices, a large number of relatively long GNRs (about the wavelength of incident radiation) or special optical antenna are required. In this paper, we consider graphene photodetectors which comprise two undoped (*i*-type) gapless graphene layers (GLs) (absorbing regions supplied by the side contacts) and connected with each other by a graphene nanoribbon (GNR) or an array of GNRs with a finite band gap (undoped wide-gap barrier region of the *I*-type). The device structure of such a graphene layer–graphene nanoribbon–graphene layer (GL–GNR–GL) photodiode under consideration and its energy diagram are shown in Fig. 1. In this device, the incident radiation is absorbed by GLs. This results in an increase in the electron and hole densities in these regions. The latter leads to an increase of the thermionic

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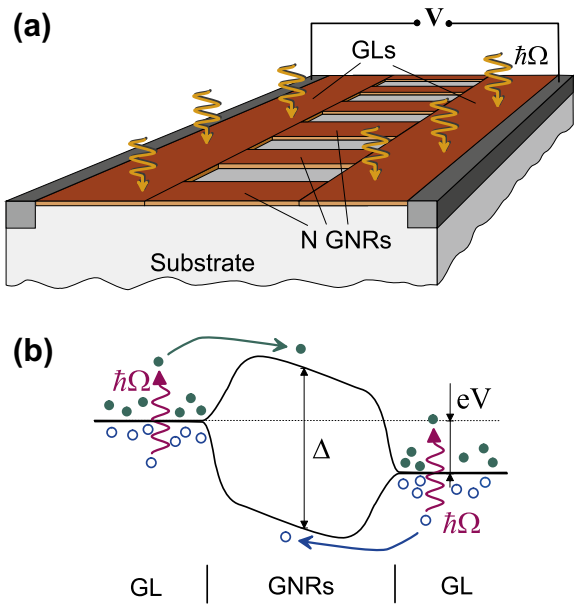

Fig. 1. Schematic views of (a) GL–GNR–GL photodiode and (b) its energy diagram under bias voltage V (wavy arrows correspond to interband transitions due to absorption of photons in GLs, smooth arrows indicate propagation of electrons and holes above the pertinent barriers in GNRs).

electron and hole currents across the energy barrier formed in GNRs, i.e., to the appearance of the photocurrent. The presence of the GNR(s) and the pertinent energy barrier provides an opportunity to control (reduce) the dark current. In illuminated GLs, a marked portion of the absorbed optical energy goes to the electron and hole energies. This can normally result in a heating of the electron–hole system and, hence, in an extra increase in the current over the barrier. The variation of the current associated with the deviation of the electron and hole temperature T from its equilibrium value T_0 can be pronounced. However, the situation can be even more complex. At elevated ($T_0 \gtrsim 100$ K) temperatures, in contrast to what is going on at low temperatures [6], the interband transitions associated with optical phonons can be the dominant mechanism of the recombination [17]. The energy relaxation of electrons and holes in GLs can also be mainly due to interaction with optical phonons [18]. As a result, the optical photons emitted by the photogenerated electrons and holes can accumulate in GLs. This implies the heating of the optical phonon system. The deviation of the optical phonon system from equilibrium can also affect the interband generation–recombination processes. The latter can lead to both the heating the the electron–hole system and its cooling depending on the energy of incident photons $\hbar\Omega$ adding complexity to the photodetector spectral characteristics. Thus, the accounting for the optical phonon heating appears to be indispensable [19,20].

2. GL–GNR–GL photodiode model and the pertinent equations

We consider the undoped device structure shown in Fig. 1 with a symmetrical electron–hole system i.e., the GLs and GNRs are undoped. The width of GNRs is chosen to provide necessary energy gap Δ; It is assumed that the intraband absorption in GLs and the interband absorption in GNRs are insignificant (this issue is discussed in the end of the paper). The intercarrier scattering time is sufficiently short to provide fast maxwellisation (fermisation) of the photogenerated electrons and holes. We also believe that the intraband and interband (generation and recombination) relaxation is associated with optical phonons (of one type), that corresponds to a high temperature (room or somewhat lower temperatures) operation.

In such a situation, the electron and hole distribution functions in GLs are equal and given by $f = \{\exp[(\varepsilon - \varepsilon_F)/T] + 1\}^{-1}$. Here $\varepsilon = v_W p$ is the energy of electrons and holes with the momentum p, $v_W = 10^8$ cm/s is the characteristic velocity of the GL energy spectrum, ε_F is the quasi-Fermi energy, and T is the effective temperature (in the energy units). In the case under consideration, the optical phonon system can also be far from equilibrium, so that the distribution function of optical phonons $\mathscr{N}_0$ can markedly deviate from its equilibrium value $\mathscr{N}_0^{eq} = [\exp(\hbar\omega_0/T_0) - 1]^{-1}$, where $\hbar\omega_0 \simeq 200$ meV is the energy of optical phonon in GLs.

The quasi-Fermi energy of the electron–hole plasma ε_F, its effective temperature T, and the number of optical phonons $\mathscr{N}_0$ obey the equations presented as [19,20]

$$R_0^{inter} = G_\Omega, \tag{1}$$

$$\hbar\omega_0\left(R_0^{inter} + R_0^{intra}\right) = G_\Omega \hbar\Omega, \tag{2}$$

$$\hbar\omega_0\, R^{decay} = \hbar\Omega\, G_\Omega. \tag{3}$$

These equations govern the balance of the electron–hole pairs, the balance of the energy of the electron–hole system, respectively, as well as the optical phonon balance. Here, R_0^{inter}, R_0^{intra}, and R^{decay} are the rates of the pertinent processes. Eq. (3) explicitly takes into account that all the energy received by the system from radiation goes eventually to the thermostat. Neglecting the effect of Pauli blocking at the interband optical transitions, the rate of optical generation of electron–hole pairs is given by [21]

$$G_\Omega = \pi\alpha\ \tanh\left(\frac{\hbar\Omega}{4T}\right) I. \tag{4}$$

Here, I is the photon flux of radiation and $\alpha \simeq 1/137$ is the fine structure constant (so that the absorption coefficient is equal to $\pi\alpha \simeq 0.023$).

As previously [19,20], for the terms R_0^{inter} and R_0^{intra}, we use the following simplified expressions:

$$R_0^{inter} = \frac{\Sigma_0}{\tau_0^{inter}}\left[(\mathscr{N}_0 + 1)\exp\left(\frac{2\varepsilon_F - \hbar\omega_0}{T}\right) - \mathscr{N}_0\right], \tag{5}$$

$$R_0^{intra} = \frac{\Sigma_0}{\tau_0^{intra}}\left[(\mathscr{N}_0 + 1)\exp\left(-\frac{\hbar\omega_0}{T}\right) - \mathscr{N}_0\right]. \tag{6}$$

Here, $\Sigma_0 = \pi(T_0/\hbar v_W)^2/6$ is the equilibrium electron and hole density, $\tau_0^{inter} \propto \tau_0^{intra} \propto \tau_0$ are the times of the interband and intraband phonon-assisted processes, and τ_0 is the characteristic time of spontaneous emission of optical phonon. Some difference in τ_0^{inter} and τ_0^{intra} is mainly associated with the features of the density of states. In equilibrium, i.e., at $\mathscr{N}_0 = \mathscr{N}_0^{eq}, \varepsilon_F = 0$, and $T = T_0$, from Eqs. (6) and (7) one obtains $R_0^{inter} = R_0^{intra} = 0$.

The rate of optical phonons decay due to the anharmonic contributions to the interatomic potential, resulting in the phonon–phonon scattering and in the decay of optical phonons into acoustic phonons and is assumed to be in the following form:

$$R_0^{decay} = \frac{\Sigma_0\left(\mathscr{N}_0 - \mathscr{N}_0^{eq}\right)}{\tau_0^{decay}}, \tag{7}$$

where τ_0^{decay} is the pertinent characteristic time. Considering high heat conductivity of GLs [22], the lattice temperature, i.e. the temperature of acoustic phonons, is assumed to be equal to the temperature of the contact T_0.

3. Variations of effective temperature and quasi-Fermi energy under illumination

Solving Eqs. (1), (3), and (7), we obtain