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Infrared photodetectors based on graphene van der Waals heterostructures

V. Ryzhii [a,b,c,*], M. Ryzhii [d], D. Svintsov [e], V. Leiman [e], V. Mitin [a,f], M.S. Shur [g], T. Otsuji [a]

[a] Research Institute of Electrical Communication, Tohoku University, Sendai 980-8577, Japan
[b] Institute of Ultra High Frequency Semiconductor Electronics of RAS, Moscow 117105, Russia
[c] Center for Photonics and Infrared Engineering, Bauman Moscow State Technical University, Moscow 111005, Russia
[d] Department of Computer Science and Engineering, University of Aizu, Aizu-Wakamatsu 965-8580, Japan
[e] Laboratory of 2D Materials' Optoelectronics, Moscow Institute of Physics and Technology, Dolgoprudny 141700, Russia
[f] Department of Electrical Engineering, University at Buffalo, Buffalo, NY 1460-1920, USA
[g] Department of Electrical, Computer, and Systems Engineering, Rensselaer Polytechnic Institute, Troy, NY 12180, USA

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ABSTRACT

We propose and evaluate the graphene layer (GL) infrared photodetectors (GLIPs) based on the van der Waals (vdW) heterostructures with the radiation absorbing GLs. The operation of the GLIPs is associated with the electron photoexcitation from the GL valence band to the continuum states above the inter-GL barriers (either via tunneling or direct transitions to the continuum states). Using the developed device model, we calculate the photodetector characteristics as functions of the GL-vdW heterostructure parameters. We show that due to a relatively large efficiency of the electron photoexcitation and low capture efficiency of the electrons propagating over the barriers in the inter-GL layers, GLIPs should exhibit the elevated photoelectric gain and detector responsivity as well as relatively high detectivity. The possibility of high-speed operation, high conductivity, transparency of the GLIP contact layers, and the sensitivity to normally incident IR radiation provides additional potential advantages in comparison with other IR photodetectors. In particular, the proposed GLIPs can compete with unitravelling-carrier photodetectors.

1. Introduction

Successful development of the van der Waals (vdW) heterostructures [1] based on stacking of two-dimensional (2D) crystals and graphene layers (GLs) promises a significant progress in infrared (IR) and terahertz (THz) optoelectronics [2,3]. The unique properties of GLs provide an opportunity to create new effective photodetectors operating in a wide range of photon energies [4–13]. Supplementing their design by the band structure engineering using 2D-materials for the barrier layers opens up new prospects in further enhancement of the detector performance. Recently, new IR and THz detectors using GL-vdW heterostructures were proposed and evaluated:

(i) THz photodetectors based on a double-GL structure, in which the *intraband* inter-GL resonant transitions are assisted by IR or THz photons [14]. The resonant nature of such transitions, in which the electron momentum is conserved [15–19], promotes their elevated probability and, hence, the elevated quantum efficiency. These photodetectors require inclined radiation incidence or a radiation coupler (grating structure).
(ii) THz and IR photodetectors based on the GL-vdW heterostructures using the photon-assisted *interband* transitions between the neighboring GLs [20].
(iii) THz detectors based on the GL-vdW heterostructures operating as hot-electron bolometers using the effect of the emission from GLs of the electrons, heated by the THz radiation, due to the *intraband* (Drude) absorptions in GLs [21].

In this paper, we propose and evaluate the IR photodetectors based on the GL-vdW heterostructures with different numbers of the active undoped GLs placed between the emitter and collector and separated by the inter-GL barriers (GLIPs). These photodetectors are using the *interband* photoexcitation of the electrons in GLs from the valence band states to the exited states slightly below or higher than the barrier edge. The photoexcited electrons transfer (by tunneling through the barrier top or directly) to the continuum

* Corresponding author at: Research Institute of Electrical Communication, Tohoku University, Sendai 980-8577, Japan.
E-mail address: v-ryzhii@riec.tohoku.ac.jp (V. Ryzhii).

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states above the barrier and propagate through the barrier layers. The GL-vdW double-GL photoconductive device with the emitter and collector GLs separated by the barrier and using a similar mechanism was recently proposed [22] fabricated and measured [23]. However, as we demonstrate below, the insertion of the inner GLs, which provides the extra electron photoemission and capture, can lead to a dramatic increase in the GLIP responsivity. This is due to the photocurrent gain associated with the redistribution of the electric field in the heterostructure and leading to amplification of the electron injection from the emitter. Thus the GLIPs in some sense resemble quantum-well infrared photodetectors (QWIPs) typically using III-V materials and extensively studied, fabricated, and used in applications during two decades [24–27]. Such a similarity is due to the propagation of the photoexcited electrons over the barriers with their fraction being captured back to the bound states (in GLs and QWs, respectively). A relatively low capture probability results in the elevated values of the detector responsivity. Apart from this, in both GLIPs and QWIPs the detector detectivity increases with an increasing number of GLs and QWs (see, for example, [24]).

The main difference between the GLIPs and QWIPs is in the use of the interband (in GLIPs) and intraband (in QWIPs) transitions. This allows eliminating the grating structures required in the n-QWIPs for radiation coupling. In realistic GLIPs with a relatively large conduction band off-set, the proper electron photoexcitation requires higher photon energies $\hbar\Omega$ than in QWIPs. This implies that the GLIPs might generally operate at shorter radiation wavelengths than the QWIPs. However, modifying the shape of the barriers by doping of the inter-GL layers, one can achieve an effective electron photoescape at fairly low photon energies (in far-IR range). As shown in [28,29], the probability of the electron capture into the GLs can be much smaller than that for the QWs (see, for example, [30]) since doping of the QWs in the QWIPs leads to the inclusion of the electron-electron scattering mechanism of the capture. Smaller capture efficiency is beneficial for a higher detector responsivity [30] (see also, [24–27]).

The absence of the GL doping promotes lower electron emission of the thermalized electrons than that in the doped QWs and, hence, leads to a smaller dark current. Finally, the probability of the electron photoexcitation from the GLs is substantially higher than from the QWs. These GLIP features (the sensitivity to the normally incident radiation and higher photoexcitation and lower capture probabilities) provide potential advantages of the GLIPs over the QWIPs and some other photodetectors. The photodetectors based on GL-vdW heterostructures with the tunneling transparent inter-GL barrier layers considered recently [20] and the GLIPs with relatively thick layers studied in the present paper are analogous. However their operation principles are quite different: the photo-stimulated cascade tunneling between GLs in [20] and the photoexcitation of electrons to the continuum states and propagation in GLIPs. In the latter device, only a small fraction of the propagating electrons can be captured to the GLs. Such a distinction results in different spectral properties and other detector characteristics. In particular, in the GLIPs under consideration, the photoexcitation probability can be much larger than the probability of the inter-GL photo-stimulated transfer. This is due to the diminished wave function overlap in the neighboring GLs [20]. Apart from this, the GLIPs considered here and the hot-electron GLIPs using the bolometric mechanism [21] are characterized by a rather low capture probability of electrons in the continuum states [28,29]. This promotes high values of the detector responsivity [30,31] This is in contrast with the detection mechanism associated with the cascade inter-GL photo-stimulated tunneling. The spectral ranges of the photodetectors using the inter-GL photo-stimulated cascade transfer 20 and the electron heating [21] from one side and the spectral range of the GLIP operation can be essentially different. One important feature of the GLIPs is that their operation do not require the mutual alignment of the GLs.

Various device models used for studies of the vertical electron transport in QWs (and GLs) introduce the concept of an "ideal" emitter (which provides as many injected electrons as the bulk of the structure "requires"). In the framework of this concept, the electric-field distributions are assumed to be uniform. A more accurate consideration of the transport phenomena in such structures (including GLIPs) in the dark conditions and under irradiation accounts for the self-consistent electric field distributions and the nonideality of the emitter [32–38]. This paper uses this more accurate approach.

The paper is organized as follows. In Section 2, we describe the possible GLIP device structures and the GLIP operation principle. Section 3 deals with the device mathematical model. The latter includes the equation for the self-consistent electric potential and the equations governing the electron balance in the GLs. In the latter equation, the electron capture into the GLs is described phenomenologically invoking the concept of the capture parameter [30] (see, also, [26–30]. In Section 4, we derive the dark current in the GLIPs as a function of the structural parameters and the applied voltage using the model described in Section 3. In Section 5, we calculate the photocurrent (the variation of the current under the incident radiation). The expressions obtained in Sections 4 and 5 are then used in Section 6 for the derivation of the GLIP detector responsivity, photoelectric gain, and detectivity. In Section 6, we compare the GLIPs with some other IR photodetectors. In the Conclusion section, we draw the main results of the paper. In the Appendix, we discuss some simplifications of the main model.

2. Device structure and operation principle

We consider the GLIPs based on the GL heterostructure which consists of the N inner GLs clad between the $M = N + 1$ barrier layers with the top and bottom contact GLs. The conduction band offsets between the emitter GL and the barrier layer, Δ_E, as well as between the inner GLs and the barrier layers between them, Δ, are smaller than the pertinent offsets in the valence band. Generally, the materials of the emitter barrier layer and of other barrier layers can be different, so that $\Delta_E \neq \Delta$.

The top and bottom GLs are assumed to be doped to provide their sufficiently high lateral conductivity. These extreme GLs serve as the tunneling emitter (injecting electrons into the GL-heterostructure bulk) and the collector, respectively. The top and bottom GLs are supplied with contacts between which the bias voltage V is applied. We consider the GL heterostructures with either the n-type or p-type doping of both the emitter and collector GLs and undoped inner GLs and the barrier layers, i.e., the heterostructures with different types of the emitter and collector can also be treated in the framework of our model. The applied voltage in such heterostructures, stimulates the electron tunneling through the barriers with triangular tops. The thermalized electrons tunneling from the GLs and the electrons excited by the incident IR radiation propagate over the barriers.

Fig. 1(a) and 1(b) shows schematically the GLIPs based on GL-vdW heterostructures considered in [20,21] and their band diagrams. Fig. 1(c) corresponds to the GLIPs with the bound-to-continuum tunneling and photon-assisted transitions considered in the present work.

Fig. 2 shows the band diagrams of the GLIP (with the structure of Fig. 1(c)) using the interband intra-GL photoexcitation with the sequential tunneling of the photoexcited electrons (a) in dark conditions and (b) under the strong IR irradiation at the sufficiently