Far-infrared photodetection in graphene nanoribbon heterostructures with black-phosphorus base layers

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Abstract. We propose far-infrared photodetectors with the graphene nanoribbon (GNR) array as the photosensitive element and the black phosphorus (bP) base layer (BL). The operation of these GNR infrared photodetectors (GNR-IPs) is associated with the interband photogeneration of the electron–hole pairs in the GNR array followed by the tunneling injection of either electrons or holes into a wide gap bP BL. The GNR-IP operating principle is akin to that of the untravelling-carrier photodiodes based on the standard semiconductors. Due to a narrow energy gap in the GNRs, the proposed GNR-IPs can operate in the far-, mid-, and near-infrared spectral ranges. The cut-off photon energy, which is specified by the GNR energy gap (i.e., is dictated by the GNR width), can be in the far-infrared range, being smaller that the energy gap of the bP BL of $\Delta_c \approx 300$ meV. Using the developed device models of the GNR-IPs and the GNR-IP terahertz photomixers, we evaluate their characteristics and predict their potential performance. The speed of the GNR-IP response is determined by rather short times: the photocarrier try-to-escape time and the photocarrier transit time across the BL. Therefore, the GNR-IPs could operate as terahertz photomixers. The excitation of the plasma oscillations in the GNR array might result in a strong resonant photomixing. © The Authors. Published by SPIE under a Creative Commons Attribution 4.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI. [DOI: 10.1117/1.OE.60.8.082002]

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1 Introduction

The quantization of the energy spectrum in the graphene nanoribbon (GNR) arrays, obtained by partitioning of the graphene layer (GL), results in the transformation of the two-dimensional gapless spectrum of the electrons and holes to the spectrum consisting of the sets of one-dimensional subbands. Such a quantization also leads to the formation of the energy gap in the GNRs. $^{1-8}$ The transformation of the energy spectrum brings about substantial modifications of the radiation absorption characteristics of the GNRs compared with the uniform GLs.

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These modifications include the appearance of the absorption resonances associated with the radiative transitions between the hole sub-bands tops and the electron sub-bands bottoms and the appearance of the absorption “red” edge. These features of the GNR radiation absorption can be used in different infrared optoelectronic devices. The incorporation of the black-phosphorus (bP) layers, exhibiting the interband absorption of the photons with the energies from $\hbar \Omega \simeq 300$ to $2000$ meV depending on the bP layer thickness, opens new prospects. The heterostructures, in which GLs or GNR arrays are integrated with the bP layers, can exhibit additional functionalities. This is due to the special GL and GNR and the bP layers’ band alignment (the Dirac point in the GLs and GNRs corresponds to the energy gap in the bP) and relatively narrow energy gap ($\Delta G \simeq 300$ meV) in the bP layers with a sufficiently large number of atomic sheets. The GL- and GNR-heterostructures with the black-arsenic (bAs) layers having even smaller band gaps demonstrate similar properties.

The GNR infrared photodetectors have been (GNR-IPs) proposed and analyzed previously using the interband transitions. In those IPs, the carrier photogeneration leads to an increase in the GNR longitudinal conductivity. In contrast, here, we consider the GNR-based vertical IPs using the radiation interband absorption in the GNR arrays. We focus our analysis on the GNR-IPs with the undoped (weakly doped) GNR array sandwiched between the top cap layer (CL) doped by donors (with the donor surface density $\Sigma_d$) and the bP base layer (BL) doped by acceptors (with the surface density $\Sigma_a$). The BL is lying on the contact layer (substrate) of $p^+$-type (see Fig. 1). The CL can be either the n-bP BL or made of other materials, in particular, hexagonal boron nitride (hBN). An example is the GNR-IP based on n-bP/GNR/p-bP/p$^+$-bP heterostructure or on an n-hBN/GNR/p-bP/p$^+$-bP heterostructure. The GNR array is supplied by the side n-type contact to each GNR, so that the GNR array with the contact forms a fork-like structure as shown in Fig. 1. The donors in the CL and acceptors in the BL can be spatially distributed uniformly across these layers or be concentrated in the delta-doped sheets. The GNR array plays the role of the photoemitter replacing the GL-photoemitter.

The GNR-IP operation is associated with the emission of the photoexcited holes from the GNR due to tunneling into p-BL contributing to the terminal current.

For the detection of radiation with $\hbar \Omega > 300$ meV, one can use more or less standard photodiodes using the interband transitions in bulk bP layers. We limit our consideration to the photon energies $\hbar \Omega < \Delta_G$, where $\Delta_G \approx 300$ meV is the energy gap in the bP BL. The band diagram of the GNR-IP with n-CL and p-BL is shown in Fig. 2. Such a choice of the device structure is associated with a relative smallness of the valence band off-set $\Delta_V$ at the GNR/bP interface in comparison with the pertinent conduction band off-set $\Delta_C$. This implies that the IPs of the n-bP/GNR/p-bP/p$^+$-bP type can have smaller cut-off photon energy (in the far-infrared or even in the terahertz ranges) compared to the IPs of the p-bP/GNR/n-bP/n$^+$-bP type. The GNR-IPs based on heterostructures of the latter type can be considered analogously.

At $\Sigma = \Sigma_d - \Sigma_a + \kappa_{BL} V/4 \pi e W > 0$, where $\kappa_{BL}$ and $W$ are the BL dielectric constant and thickness, respectively, and $V$ is the bias voltage, the Fermi level in the GNRs is in the conduction band, i.e., $\epsilon_{F,\text{GNR}} > 0$ [see Fig. 2(a)].

The operation principle of the GNR-IPs resembles that of the unitraveling-carrier photodiodes with a bulk absorbing layer serving as the emitter with the diffusive supply of the carriers injected into the BL.

Since the electric field in the p-BL is high, all the holes injected from the GNR can reach the $p^+$ substrate. As a result, the current is determined solely by the injection from the GNR.
[as schematically shown in Fig. 1(a)], so that the specific of the hole transport in the p-BL (ballistic or drift) does not affect the steady-state characteristics. However, the hole transit time across the p-BL can be fairly different in the cases of ballistic and drift transport (see Sec. 4). In this regard, the situation is analogous to that in the unitraveling-carrier photodiodes.

2 Main Equations

The electron and hole, $e^{-}(p)$ and $e^{+}(p)$, energy spectra in GNRs can be presented as the sets of the one-dimensional sub-bands\textsuperscript{6-8} [see Fig. 2(b)]

$$\varepsilon_{n}^{\pm} = \pm v_{W} \sqrt{p^{2} + \left(\frac{\pi \hbar}{d}\right)^{2} n^{2}}, \quad (1)$$

where $p = p_{y}$ is the carrier momentum along the GNR (in the $y$ direction), $v_{W} \approx 10^{5}$ cm/s is the characteristic carrier velocity in GLs (and GNRs), and $n = 1, 2, 3, \ldots$ is the index of the sub-band in the valence band (lower sign) and the conduction band (upper sign). The energy spectrum given by Eq. (1) corresponds to the GNR energy gap $\Delta = \frac{2\pi v_{W} \hbar}{d}$ and the carrier effective mass (near the sub-band’s top and bottom) $m = \frac{\Delta}{2 v_{W}^{2}}$. At $d = 15$ to 90 nm, in agreement with the experimental data,\textsuperscript{3} one obtains $\Delta \approx (300 - 30)$ meV and $m \approx (0.01 - 0.002)m_{0}$,\textsuperscript{7} where $m_{0}$ is the electron mass in vacuum.

Under the steady-state irradiation by the photon flux $I_{\Omega}$ with the photon energy $\hbar \Omega$, the average photocurrent density $\langle j_{\Omega} \rangle$ and the GNR-IP responsivity $R_{\Omega} = \langle j_{\Omega} \rangle/\hbar \Omega I_{\Omega}$ are given by (see also the Appendix)

$$\langle j_{\Omega} \rangle = e \beta_{\Omega} \Theta_{\Omega} I_{\Omega}. \quad (2)$$

Here, $e$ is the electron charge, $\beta_{\Omega}$ is the ratio of the flux of the incident photons absorbed in the GNR array due to the interband transitions to the flux of the incident photons $I_{\Omega}$ (the average photon interband absorption coefficient of the GNR), and $\Theta_{\Omega}$ is the probability of the photoexcited holes escape from the GNR. As seen from Eq. (2), the photocurrent in the GNR-IPs with the vertical injection is determined not only by the absorption coefficient, but also by the escape probability of the photoexcited carriers (holes) $\Theta_{\Omega}$ (as in the interband GL-IDs, see also references therein). For the normal radiation incidence, the GNR array interband absorption coefficient is given by\textsuperscript{6,8}

$$\beta_{\Omega} = \beta \left(\frac{2d}{\pi D}\right) \left(\frac{\Delta}{\hbar \Omega}\right) S_{\Theta} \sum_{n=1}^{\infty} \mathcal{F}_{n} \left(\frac{\hbar \Omega}{\Delta}\right). \quad (3)$$

Here, $\beta = \pi e^{2}/c \hbar \sqrt{\kappa}$ $\approx \pi/137 \sqrt{\kappa}$, $c$ is the speed of light, $\kappa$ is the refractive index determined by the dielectric constants of the CL and BL, $\varepsilon_{CL}$ and $\varepsilon_{BL}$, respectively, and the factor $d/D$ is the fraction of the GNR-IP area covered by the GNR array (the GNR aspect ratio). The function
\[ S_{\Omega} = \frac{\exp\left(\frac{\hbar \Omega}{2}\right)}{2 \left[ \cosh \left(\frac{\hbar \Omega}{2}\right) + \cosh \left(\frac{\epsilon_{\text{GNR}}}{\hbar \Omega}\right) \right]} \]

accounts for the Pauli principle for the interband transitions in the GNR (with the Fermi energy \( \epsilon_{\text{GNR}} \) counted from the Dirac point at the temperature \( T \)), whereas the function

\[
F_n(X) = \frac{1}{\sqrt{2\pi} \Gamma} \int_{-\infty}^{\infty} \frac{d\xi}{\sqrt{\xi^2 - n^2}} \exp \left[ -\frac{(\xi - X)^2}{2\rho^2} \right]
\]

(5)

describes the probability of the interband transitions in the GNR with the electron and holes states given by Eq. (1) and the Gaussian broadening (or smearing) of these states due to the collisions, characterized by \( \gamma = \Gamma/\Delta \), where \( \Gamma \sim \hbar/\tau \) with \( \tau \) being the electron and hole momentum relaxation time.

The quantity \( \Theta_{\Omega} \) in Eq. (2) is the tunneling escape probability of the photoexcited holes having the energy \( \epsilon_{\Omega} = (\hbar \Omega - \Delta)/2 \) to escape from the GNR.

We estimate \( \Theta_{\Omega} \) as

\[
\Theta_{\Omega} \approx \frac{1}{1 + \frac{\tau_{\text{relax}}}{\tau_{\text{esc}}} \exp\left(\frac{3/2 E_{\text{tunn}}}{E_{\text{GNR}}}\right)}.
\]

(6)

Here, \( \eta_{\Omega} = 1 - \hbar \Omega/2 \Delta \), \( E_{\text{tunn}} = 4\sqrt{2m_{z} \Delta \gamma^{3/2}}/3e \hbar \) is the characteristic tunneling field, \( m_{z} \) is the hole effective mass in the BL in the direction perpendicular to the atomic sheets, \( \tau_{\text{relax}} \) is the relaxation time of the photoexcited holes in the GNR due to the recombination and the energy relaxation on acoustic phonons, and \( \tau_{\text{esc}} \) is the photoexcited holes’ try-to-escape time. The electric field at the GNR array plane \( E_{\text{GNR}} \) determining the shape of the tunneling barriers depends on the potential drop \( V \) between the collector and the GNR. Considering the BL doping and neglecting the quantum capacitance, \( \Sigma_{\Omega} \approx \frac{\hbar}{\tau_{\text{relax}}} \), we arrive at the following equation:

\[
E_{\text{GNR}} \approx \frac{V}{W} + E_{\alpha} - E_{\beta}.
\]

(7)

Here, \( E_{\alpha} = 4\pi e \Sigma_{\alpha}/\kappa_{\text{BL}} \) and \( E_{\beta} = 4\pi e \Sigma_{\beta}/\kappa_{\text{BL}} \).

Setting \( \Delta \gamma = 100 \) meV and \( m_{z} \approx 0.28m_{0} \), \( \Sigma_{\Omega} \approx 1.19 \times 10^{5} \) V/cm. For \( \Sigma_{\alpha} = 2.2 \times 10^{12} \) cm\(^{-2} \) and \( \kappa_{\text{BL}} = 4 \), we obtain \( E_{\alpha} \approx 1 \times 10^{6} \) V/cm.

### 3 Spectral Characteristics of the GNR-IP Responsivity and Detectivity

According to Eq. (2), the GNR-IP responsivity \( R_{\Omega} \)—one of the main IP characteristics—can be presented as

\[
R_{\Omega} = \frac{2 e \beta S_{\Omega} \Theta_{\Omega}}{\pi \hbar \Omega} \left( \frac{d}{D} \right) = \frac{2 e \beta S_{\Omega} \Theta_{\Omega}}{\pi} \left( \frac{\Delta}{\hbar \Omega} \right) \sum_{n=1}^{\infty} \frac{F_n}{(\hbar \Omega/\Delta)}.
\]

(8)

Here,

\[
R_{\Omega} = \frac{e \beta S_{\Omega} \Theta_{\Omega}}{\hbar \Omega} \left( \frac{d}{D} \right).
\]

(9)

Figure 3 shows the spectral characteristics of the GNR-IP responsivity calculated for parameters of the GNR-IP structure (\( \Delta \), \( \Gamma \), \( \epsilon_{\text{GNR}} \), and \( T \)). The following parameters are assumed: \( \beta = 1.15 \times 10^{-2} \), \( \kappa = 4 \), \( \Delta \gamma = 100 \) meV, \( \tau_{\text{relax}}/\tau_{\text{esc}} \approx 0.1 \), \( E_{\text{tunn}} \approx 1.19 \times 10^{5} \) V/cm \((m_{z} \approx 2.5 \times 10^{-28} \text{ g})\), and \( E_{\text{GNR}} = 1 \approx 10^{5} \) V/\( \mu \text{m} \). The temperature is assumed to be \( T = 26 \) meV \((T \approx 300 \) K\) except for Fig. 3(d). The parameter \( \Gamma \) was assumed to be \( \Gamma = 1 \) and 5 meV, which corresponds to the realistic momentum relaxation times \( \tau \approx 6.25 \times 10^{-13} \) and \( 1.25 \times 10^{-13} \) s,
respectively. At $\Delta = 100 \text{ meV}$, the range of the Fermi energies $\epsilon_{\text{GNR}}^F = 25$ to $50 \text{ meV}$ corresponds to the $\Sigma_d - \Sigma_a \approx (1.8$ to $4.4) \times 10^{12} \text{ cm}^{-2}$. For the degenerate electron gas in the GNRs (sufficiently large $\Sigma$), the Fermi energy in the GNRs $\epsilon_{\text{GNR}}^F \approx \Delta (\Sigma_d^2/2)^{1/2} \propto \Sigma/\Delta$ (see the Appendix).

At $\Delta = 75 \text{ meV}$, the range of the Fermi energies $\epsilon_{\text{GNR}}^F = 25$ to $50 \text{ meV}$ corresponds to $\Sigma_d - \Sigma_a \approx (2.4$ to $5.9) \times 10^{12} \text{ cm}^{-2}$.

As seen from the comparison of the dependences for GNR-IPs with those for the GL-IP (without the partitioning of the GL into the GNRs, i.e., with $\Delta = 0$, and presented by the dotted lines) shown in Figs. 3(a) and 3(b), the former can exhibit much higher $R_\Omega$ when $\hbar \Omega \sim \Delta$.

As follows from Figs. 3(c) and 3(d), an increase in the Fermi energy $\epsilon_{\text{GNR}}^F$ and in temperature $T$ leads to a smaller responsivity. This is attributed to stronger restrictions for the radiative interband transitions imposed by the Fermi principle [described by the factor $S_\Omega$ given by Eq. (4)].

The GNR-IP detectivity is given by

$$D^{*}_{\Omega} = \frac{R_\Omega}{\sqrt{4j_0}}. \quad \text{(10)}$$

where $j_0$ is the dark-current density. As follows from Eq. (10), the shape of the spectral characteristic of the detectivity repeats that for the responsivity ($D^{*}_{\Omega} \propto R_\Omega$). Since $D^{*}_{\Omega}$ depends also on the dark-current density $D_\Omega \propto 1/\sqrt{j_0}$, it is sensitive to the parameters determining the tunneling of equilibrium carriers from the GNR into the BL, first of all, to the energy states near the Fermi energy $\epsilon_{\text{GNR}}^F$. Considering that the probability of the hole tunneling escape from their Fermi energy can be presented as [compare with Eq. (6)]

$$\Theta_0 \propto \exp \left( -\frac{\eta_0^{3/2} \Gamma_{\text{tunn}}}{E_{\text{GNR}}^F} \right), \quad \text{(11)}$$

where $\eta_0 = 1 \pm \epsilon_{\text{GNR}}^F/\Delta_V$ (the sign "+" corresponds the situation when the Fermi level is in the conduction band, so that the GNR array is charged predominately by electrons, and the sign "−" corresponds the situation when the Fermi level is in the GNR valence band), in the most interesting case ($\Sigma > 0$, i.e., the GNR Fermi level is in the conduction band) for the dark-current density we obtain.

---

**Fig. 3** The responsivity $R_\Omega$ versus photon energy $\hbar \Omega$ of GNR-IPs with (a) $\Gamma = 5 \text{ meV}$ and (b) $\Gamma = 1 \text{ meV}$ at different energy gaps $\Delta$ (different GNR widths), (c) $\Delta = 75 \text{ meV}$, $\Gamma = 5 \text{ meV}$, and $\epsilon_{\text{GNR}}^F = 25 \text{ meV}$ at different Fermi energies in the GNR $\epsilon_{\text{GNR}}^F$, and (d) $\Delta = 75 \text{ meV}$, $\Gamma = 5 \text{ meV}$, and $\epsilon_{\text{GNR}}^F = 25 \text{ meV}$ at different temperatures $T$. Dotted lines correspond to the GL-IP responsivity.
\[ j_0 = \frac{e}{\tau_{\text{esc}}} \left( \frac{d}{R} \right) \exp \left[ - \left( 1 + \frac{\varepsilon_{\text{GNR}}}{\Delta} \right)^{3/2} \frac{E_{\text{tunn}}}{E_{\text{GNR}}} \right]. \]  

(12)

Hence,

\[ D_\Omega^m = \mathcal{D}_\Omega^m \frac{2}{\pi} \left( \frac{\Delta}{\hbar \Omega} \right) \sum_{\kappa=1}^{\infty} \mathcal{F}_\kappa \left( \frac{h\Omega}{\Delta} \right), \]

(13)

where

\[ \mathcal{D}_\Omega = \frac{R}{\sqrt{4 ej_0}} = \frac{\beta \Theta_{\Omega}}{\hbar \Omega \sqrt{\Theta_0}} \sqrt{\frac{\tau_{\text{esc}}}{\delta \Omega}} \propto S_\Omega \exp \left[ \left( 1 + \frac{\varepsilon_{\text{GNR}}}{\Delta} \right)^{3/2} \frac{E_{\text{tunn}}}{2E_{\text{GNR}}} \right]. \]

(14)

At \( \varepsilon_{\text{GNR}}^F > 0 \), the exponential factor in Eq. (14), and hence the GNR-IP detectivity can be fairly large. Although, when \( \varepsilon_{\text{GNR}}^F \) becomes larger than \( \hbar \Omega/2 \), \( S_\Omega \) and \( \mathcal{D}_\Omega \) can exhibit a steep drop in line with the pertinent responsivity roll-off seen in Fig. 3(b). This indicated that the selection of the CL and BL parameters, where first of all their doping opens the possibilities of the GNR-IP detectivity enhancement. One needs to stress that the proper choosing of the bias voltage might also be important for the GNR-ID responsivity and detectivity.

### 4 Detection of Modulated Radiation

If the incident radiation comprises the steady-state and modulation components, \( I_\Omega \) and \( \delta I_\Omega^m \exp(-i\omega t) \), respectively, where \( \delta I_\Omega^m \) and \( \omega \) are the amplitude and frequency of the modulation components, considering the Shockley–Ramo theorem,\(^{38,39}\) the ac terminal current density is given by [see Eqs. (29) and (30) in the Appendix]

\[ \langle \delta j_{\text{osc}}^m \rangle = e \beta_\Omega \Theta_{\text{osc}}^m \frac{[\exp(i\omega \tau_{\text{tr}}) - 1]}{i\omega \tau_{\text{tr}}} \delta I_\Omega^m. \]

(15)

where

\[ \Theta_{\text{osc}}^m \approx \frac{1}{1 - i\omega \tau_{\text{esc}} \tau_{\text{relax}} \exp \left( \frac{3/2 E_{\text{tunn}}}{E_{\text{GNR}}} \right)} \]

(16)

which replaces \( \Theta_{\text{osc}} \) in Eq. (26) and \( \tau_{\text{tr}} \) is the hole transit time across the BL. The factor \( [\exp(i\omega \tau_{\text{tr}}) - 1]/i\omega \tau_{\text{tr}} \) in the right-hand side of Eq. (8) describes the hole transit-time effect (transit delay) in the BL.

As follows from Eqs. (8), (15), and (16), for the responsivity to the modulation signals, \( R_{\text{osc}}^m \equiv \langle \delta j_{\text{osc}}^m \rangle / \hbar \Omega \delta I_\Omega^m \) one can arrive at

\[ R_{\text{osc}}^m = R_{\Omega}^m \Theta_{\text{osc}}^m T_{\text{osc}}^m. \]

(17)

where

\[ T_{\text{osc}}^m = \frac{\exp(i\omega \tau_{\text{tr}}) - 1}{i\omega \tau_{\text{tr}}} \]

(18)

is the transit-time factor. Hence,

\[ \left| \frac{R_{\text{osc}}^m}{R_{\Omega}} \right| = \frac{1 + \frac{\tau_{\text{esc}}}{\tau_{\text{relax}}} \exp \left( \frac{3/2 E_{\text{tunn}}}{E_{\text{GNR}}} \right)}{\sqrt{1 + \frac{\tau_{\text{esc}}}{\tau_{\text{relax}}} \exp \left( \frac{3/2 E_{\text{tunn}}}{E_{\text{GNR}}} \right)^2 + \omega^2 \tau_{\text{esc}}^2}} \left| \frac{\sin(\omega \tau_{\text{tr}}/2)}{(\omega \tau_{\text{tr}}/2)} \right|. \]

(19)
According to Eq. (19), the roll-off of the relative responsivity $|R^\omega_{\Omega}/R_{\Omega}|$ with increasing modulation frequency $\omega$ is primarily determined by the transit time $\tau_\nu$ if the try-to-escape time $\tau_{\text{esc}}$ is shorter than the transit time of the holes $\tau_r$.

$$
\left| \frac{R^\omega_{\Omega}}{R_{\Omega}} \right| \approx \left| \frac{\sin(\omega \tau_\nu/2)}{(\omega \tau_{\text{esc}}/2)} \right|.
$$

(20)

### 5 Plasmonic Response

Depending on the sign of $\Sigma = \Sigma_d - \Sigma_a - \kappa_{\text{BL}} V/4 \pi e W$, the one-dimensional electron or hole gases are formed in each GNR. The collective response of these electron or hole systems can lead to pronounced plasmonic phenomena.

The ac current of the photoexcited holes emitted from the GLs causes ac hole injection from the side contacts to the GNRs. The ac current along the GNRs (in the y direction, see Fig. 1) could lead to the excitation of the plasmonic oscillations, i.e., the self-consistent spatial–temporal variation of the electron or hole density and the GNR array potential in the GNR array $\delta \phi^I_{\Omega}(y) \exp(-i \omega t)$.

This plasmonic oscillation is the standing wave formed by the plasmonic waves propagated along the GNR in the opposite directions (i.e., with the wave numbers $\pm k_z$). As a result, accounting for the plasmonic oscillations in the GNR, the averaged current density can be presented as [see the Appendix, Eq. (37)]

$$
\langle \delta j^I_{\Omega} \rangle = e \beta_{\Omega} \Theta_{\Omega} T^\omega \tan \left[ \frac{\pi \sqrt{(\omega + i/\tau)(\omega + i/\tau_d)/\omega_p}}{\pi \sqrt{(\omega + i/\tau)(\omega + i/\tau_d)/\omega_p}} \right] \delta I^\omega_{\Omega}.
$$

(21)

Here, $1/\tau_d \propto \beta_{\Omega} I_{\Omega}$ is given by Eq. (34) in the Appendix. Equation (21) yields the following equation for the responsivity:

$$
R^\omega_{\Omega} = R_{\Omega} \Theta_{\Omega} T^\omega \Theta^w_{\Omega}.
$$

(22)

Here,

$$
P^\omega = \tan \left[ \frac{\pi \sqrt{(\omega + i/\tau)(\omega + i/\tau_d)/2\omega_p}}{\pi \sqrt{(\omega + i/\tau)(\omega + i/\tau_d)/2\omega_p}} \right]
$$

(23)

is the factor describing the contribution of the plasmonic resonances [compare Eqs. (17) and (22)] and $\omega_p = \pi^2 e^2 \Sigma a / \kappa_{\text{BL}} m L^2$ is the plasmonic frequency of the carriers (holes) induced in the GNRs, where $\Sigma \approx \Sigma_a - \Sigma_d + \kappa_{\text{BL}} V/4 \pi e W$ is the hole density in the GNR array induced by the doping of the CL and BL and the bias voltage, and $m \approx \Delta / 2v^2_W$ is the hole effective mass in GNRs.

Considering the relation between $m$ and $\Delta$, we find

$$
\omega_p = \frac{\pi v_W}{L} \sqrt{\frac{2 \pi e^2 W \Sigma_a}{\kappa_{\text{BL}} \Delta}} + \frac{eV}{2 \Delta} = \frac{\pi v_W}{L} \sqrt{\frac{W E_a + eV}{2 \Delta}} = \frac{\pi v_W}{L} \sqrt{\frac{W E_{\text{GRN}}}{2 \Delta}}.
$$

(24)

Setting $E_{\text{GRN}} = 10^6$ V/cm, $\Delta = 100$ meV, $W = 0.1$ $\mu$m, and $L = 2.5$ $\mu$m, we obtain $\omega_p/2\pi \approx 1.4$ THz.

If $\omega \ll \tau^{-1}$, $\tau_d^{-1} \ll \omega_p$, one obtains $P^\omega \approx 1$, and Eq. (22) turns to Eq. (17). At the combined resonance $h \Omega/\Delta \approx 1$ and $\omega/\omega_p \approx 1$, the responsivity $|R^\omega_{\Omega}|$ exhibits a particularly high maximum.

Figure 4 shows examples of the modulation characteristics $|R^\omega_{\Omega}/R_{\Omega}|$ as functions of the modulation frequency $\omega/2\pi$. These characteristics account for the delay in the photoexcited holes escape from the GNRs, the hole transit-time delay, and the plasmonic effects.
plasmonic oscillation.

2) Those considered in Refs. 8 and 45 oscillations.

heterostructures. The electron and hole mobilities on the order of 10 cm2 V−1s−1 of the pronounced plasmonic oscillations require relatively perfect GNRs with high carrier mobility.

Both the realization of the resonant interband intersubband radiative transitions and the possibility of the terahertz range of the modulation frequencies, in particular, as the terahertz photomixers.

6 Discussion

The following parameters are assumed: \( \omega_p/2\pi = 1.5 \) and \( \omega_p/2\pi = 2.5 \) THz, \( \tau_\gamma = 0.5 \) ps, \( \tau_d = 10 \) ps, \( \tau_{\text{rec}} = \tau = 0.625 \) ps and \( \tau_{\text{rec}} = \tau = 1.875 \) ps (corresponding to \( \Gamma = h/\tau = 1 \) meV and \( \Gamma = 1/3 \) meV, respectively). The frequency dependences shown in Fig. 4 reflect the interplay of the transit-time and plasmonic effects.

As seen from Fig. 4, \( |R^\text{v}_{\Omega}|/|R_{\Omega}| \) and hence \( |R^\text{v}_{\Omega}| \) exhibit the maxima corresponding to the plasmonic resonance \( \omega/\omega_p \). The responsivity \( |R^\text{v}_{\Omega}| \) becomes particularly large at the combined resonances \( \Omega \approx n\Delta/h \) and \( \omega/\omega_p \approx 1 \). The resonance effects under consideration are pronounced when the carrier momentum relaxation time \( \tau \) is sufficiently long.

The inclusion of the plasmonic effects enables the possibility of the GNR-IPs operation in the terahertz range of the modulation frequencies, in particular, as the terahertz photomixers.

The following parameters are assumed: \( \omega_p/2\pi = 1.5 \) and \( \omega_p/2\pi = 2.5 \) THz, \( \tau_\gamma = 0.5 \) ps, \( \tau_d = 10 \) ps, \( \tau_{\text{rec}} = \tau = 0.625 \) ps and \( \tau_{\text{rec}} = \tau = 1.875 \) ps (corresponding to \( \Gamma = h/\tau = 1 \) meV and \( \Gamma = 1/3 \) meV, respectively). The frequency dependences shown in Fig. 4 reflect the interplay of the transit-time and plasmonic effects.

As seen from Fig. 4, \( |R^\text{v}_{\Omega}|/|R_{\Omega}| \) and hence \( |R^\text{v}_{\Omega}| \) exhibit the maxima corresponding to the plasmonic resonance \( \omega/\omega_p \). The responsivity \( |R^\text{v}_{\Omega}| \) becomes particularly large at the combined resonances \( \Omega \approx n\Delta/h \) and \( \omega/\omega_p \approx 1 \). The resonance effects under consideration are pronounced when the carrier momentum relaxation time \( \tau \) is sufficiently long.

The inclusion of the plasmonic effects enables the possibility of the GNR-IPs operation in the terahertz range of the modulation frequencies, in particular, as the terahertz photomixers.

6 Discussion

Both the realization of the resonant interband intersubband radiative transitions and the possibility of the pronounced plasmonic oscillations require relatively perfect GNRs with high carrier mobilities along the GNRs or their ballistic transport, which are achievable in real GNR-based heterostructures. The electron and hole mobilities on the order of (2000 to 2500) cm2 V−1s−1 measured in GNRs43,44 are sufficiently large to support resonant interband transitions and plasmonic oscillations.

As seen from Figs. 3(a) and 3(b), the comparison of the vertical GNR-IP and GL-IP responsivities’ dotted lines in Figs. 3(a) and 3(b), \( R_{\Omega} \) and \( R_{\Omega} \), at \( h\Omega = \Delta \) yields \( R_{\Omega}/R_{\Omega} \gg 1 \). The same is valid for \( R_{\Omega}/R_{\Omega} = \text{GL-IP} \). Thus, the GNR-IPs can markedly surpass the GL-IPs in the responsivity if the GNRs are sufficiently perfect with long electron and hole momentum relaxation times, in particular, \( \tau = (1.25 \text{ to } 6.25) \times 10^{-13} \) s [corresponding to \( \Gamma = (1 \text{ to } 5) \) meV], assumed in Figs. 3(a) and 3(b).

Despite a similarity of the GNR-IP and the standard unitraveling-carrier photodiodes, there are the following distinctions enabling the advantages of the former due to the following: the operation in the far-infrared range because of a narrow energy gap in the GNRs and the BLs, an increase photexcitation efficiency associated with the resonant intersubband transitions, and a shortened escape time of the photoexcited holes.

Comparing the responsivity \( R_{\Omega} \) of the vertical GNR-IP under consideration with the responsivity \( R_{\Omega} \) of the lateral GNR-IP with the p–n–n structure having the depleted GNR array (like those considered in Refs. 8 and 45–47) and exploiting the variation of the GNR conductivity under irradiation (with the same lateral sizes), at low- and high-modulation frequencies \( \omega \) one can find, respectively, \( R_{\Omega}/R_{\Omega} \approx 2 \) and \( R_{\Omega}/R_{\Omega} \approx 2\tau_d/\tau_\gamma \). Here, \( \tau_d/\tau_\gamma \approx (L/W) \gg 1 \) is the ratio of the lateral (along the GNRs) and vertical (across the BL) transit times. The responsivity of the lateral GNR-IPs with the n-contacts and the energy barrier formed by the GNR between these contacts48,33 can include the photoconductive gain increasing their responsivity, but at the expense of a lower speed operation.
The structure of the GNR-IP can be inverted placing the BL on the device top. Such GNR-IPs can be made on the hBN substrate.

Due to the similarity of the band alignment of the GNR with the bP and bAs layers, the obtained results can be applied to the GNR-IPs with the b-As layers considering the pertinent quantitative difference in $\Delta_C$ and $\Delta_V$.

The resonant response of the GNR-IPs is revealed when the smearing of the carrier spectra is relatively small. This requires a smallness of $\gamma$ (i.e., sufficiently long momentum relaxation time $\tau$) and a small overlap of the wave functions in the neighboring GNRs. The latter implies that the spacing between these GNRs $l = (D - d)$ should not be too small. This condition looks like

$$\exp \left[ -2 \sqrt{2m_z \left( \Delta V - \Delta V / 2 \right)} (D - d) / \hbar \right] \ll 1.$$  

For the GNR-IPs operating at the photon energies $\hbar \Omega \sim 100$ meV, $d \sim 4$ nm, the above inequality is satisfied if $D - d > 0.4$ nm. This means that the spacing between the GNRs can be fairly small, so that $d / D \leq 1$ and the potential sag in the inter-GNR region is small. All these indicate that the lateral nonuniformity of the potential in the GNR array plane can be very small.

7 Conclusions

We proposed and evaluated interband far-infrared photodetectors with the GNR array and the bP BL—GNR-IPs. Due to the specifics of the energy spectra of graphene and bP, the GNR-IPs can operate at photon energies much smaller than 300 meV. Due to a strong interband resonant absorption in the GNRs, the GNR-IPs can surpass the interband GL-IPs and different intersub-band IPs in responsivity and detectivity. The GNR-IPs are analogous to the unitraveling-carrier photodiodes and can operate at fairly high-modulation frequencies of the incident radiation. The possibility of the excitation of plasmonic oscillations in the GNR array of the device might lead to a pronounced response when the radiation modulation frequency is close to the frequency of the plasmonic oscillations, which is typically in the terahertz range. This enables the use of the GNR-IPs as terahertz photomixers. The GNR-IP response can be particularly strong at the combined resonance—the radiation frequency corresponds to the resonant interband transitions between the sub-bands, whereas the radiation modulation frequency corresponds to the plasmonic resonance.

8 Appendix

8.1 Steady-State Photocurrent

Considering that the incident radiation comprises the steady-state and modulation components, $I_{\Omega}$ and $\delta I_{\Omega} \exp(-i\omega t)$, respectively, where $\delta I_{\Omega}$ and $\omega$ are the amplitude and frequency of the modulation component, the dc and ac components of surface density, $\Sigma_{\Omega}$ and $\delta \Sigma_{\Omega}$, of the photoexcited carriers in the GNR array averaged in the lateral directions $\Sigma_{\Omega} + \delta \Sigma_{\Omega}$ is governed by the following equations:

$$\beta_{\Omega} I_{\Omega} - \Sigma_{\Omega} \left[ \frac{1}{\tau_{\text{relax}}} + \frac{\exp(-\eta_{\Omega}^{3/2} E_{\text{tunn}} / E_{\text{GNR}})}{\tau_{\text{esc}}} \right] = \frac{d \Sigma_{\Omega}}{dt} = 0, \tag{25}$$

$$\beta_{\Omega} \delta I_{\Omega} - \delta \Sigma_{\Omega} \left[ \frac{1}{\tau_{\text{relax}}} + \frac{\exp(-\eta_{\Omega}^{3/2} E_{\text{tunn}} / E_{\text{GNR}})}{\tau_{\text{esc}}} \right] = \frac{\delta \Sigma_{\Omega}}{dt}. \tag{26}$$

The parameters in Eqs. (25) and (26) were given in the main text.

The dc components of the average current density are given by

$$\langle j_{\Omega} \rangle = \frac{e \exp(-\eta_{\Omega}^{3/2} E_{\text{tunn}} / E_{\text{GNR}})}{\tau_{\text{esc}}} \Sigma_{\Omega}. \tag{27}$$

Equations (25) and (27) yield Eq. (2) with the factors determined by Eqs. (3)–(6).
8.2 Photocurrent at Modulated Radiation

The ac component of the average terminal current density is equal to

$$\langle \delta j^\omega \rangle = \frac{e \exp(-\eta_\Omega^{3/2} E_{\text{num}}/E_{\text{GNR}})}{\tau_{\text{esc}}} \exp(i\omega \tau_\text{tr}) - 1 \right] \delta j^\omega = e\beta_\Omega T^w \delta j^w. \quad (28)$$

Here, $\tau_\text{tr}$ is the transit time of the carriers crossing the BL. This time can be estimated as $\tau_\text{tr} = W/v_S$, where $v_S$ is the average (or saturation) velocity in the BL. The factor containing $\tau_\text{tr}$ describes the effect of transit-time finiteness on the induced terminal current in line with the Shockley–Ramo theorem.\textsuperscript{38,39} Equation (28) does not account for the possible excitation of plasma oscillations (spatiotemporal variations of the carrier density in the GNR-array and of the electric field in the BL), which could result in the temporal variation of $E_{\text{GNR}}$ and in the displacement terminal current. Such a simplification of Eq. (28) is justified when $\omega$ is far from the characteristic plasma frequencies.

Equations (26) and (28) yield

$$\langle \delta j^\omega \rangle = \frac{e\beta_\Omega}{1 - i\omega \tau_{\text{esc}} + \frac{\tau_{\text{esc}}}{\tau_{\text{rel}}} \exp\left(\eta_\Omega^{3/2} E_{\text{num}}/E_{\text{GNR}}\right)} \exp(i\omega \tau_\text{tr}) \delta j^w = e\beta_\Omega \Theta_\Omega T^w \delta j^w. \quad (29)$$

where

$$\Theta_\Omega \simeq \frac{1}{1 - i\omega \tau_{\text{esc}} + \frac{\tau_{\text{esc}}}{\tau_{\text{rel}}} \exp\left(\eta_\Omega^{3/2} E_{\text{num}}/E_{\text{GNR}}\right)} \frac{T^w}{i\omega \tau_\text{tr}}. \quad (30)$$

8.3 Plasmonic Oscillations in GNR Arrays

The amplitude of the plasmonic mode potential $\delta \rho_\Omega^w$ is governed by the equation, which is the consequence of the electron transport equation along the GNR and the Poisson equation (similar to that used previously for different plasmonic structures)\textsuperscript{33,40,41}

$$\frac{d^2 \delta \rho_\Omega^w}{dy^2} + \frac{\omega(\omega + i/\tau)}{s^2} \delta \rho_\Omega^w = i(\omega + i/\tau) \frac{4\pi W \kappa_{BL} s}{\kappa_{BL} s} \delta j^w. \quad (31)$$

with the boundary conditions $\delta \rho_\Omega^w|_{y=0} = 0$ (at the contact) and $d\delta \rho_\Omega^w/d\text{d}y|_{y=L} = 0$ (at free GNR ends). Here, $s = \sqrt{4\pi e^2 W \Sigma/\kappa_{BL} m}$ is the characteristic plasma velocity in the GNR array separated from the highly conducting $\text{p}^+$ substrate by the BL of the thickness $W$, $\Sigma$ is the hole density in the GNR array, $m$ is the effective mass in the GNRs, and $L$ is the length of the GNRs (spacing between the side contacts to the GNRs).

Since the ac current $\delta j^w_\Omega$ apart from the current due to the variation of the radiation intensity includes the component arisen due to the variations of the tunneling probability associated with the change of the electric field at the GNR array $\delta E_{\text{GNR}}$ in the case of the plasmonic oscillations, Eq. (29) should be replaced by

$$\delta j^w_\Omega = e\beta_\Omega T^w \Theta_\Omega \delta I^w_\Omega - \frac{I_\Omega}{W} \Theta_\Omega \delta I^w_\Omega = e\beta_\Omega T^w \Theta_\Omega \delta I^w_\Omega - \frac{\kappa_{BL}}{4\pi W \tau_d} \delta \rho_\Omega^w. \quad (32)$$

so that Eq. (31) becomes

$$\frac{d^2 \delta \rho_\Omega^w}{dy^2} + \frac{(\omega + i/\tau)(\omega + i/\tau_d)}{s^2} \delta \rho_\Omega^w = i(\omega + i/\tau) \frac{4\pi W \kappa_{BL} s}{\kappa_{BL} s} \delta j^w_\Omega. \quad (33)$$

where

$$\frac{1}{\tau_d} = \frac{4\pi e\beta_\Omega I_\Omega}{\kappa_{BL}} \left( \frac{d\Theta_\Omega}{dE_{\text{GNR}}} \right) T^w. \quad (34)$$
Solving Eq. (33) with the above boundary conditions, we obtain

\[
\varphi^{(m)}_{\Omega} = \frac{i 4 \pi W}{\kappa_{\text{BL}}} \frac{e \beta_{\Omega} T^{(m)}}{(\omega + i/\tau_d)} \left\{ 1 - \frac{\cos \left[ \sqrt{(\omega + i/\tau_d)(\omega + i/\tau_d)(L - y)/s} \right]}{\cos \left[ \sqrt{(\omega + i/\tau_d)(\omega + i/\tau_d)L/s} \right]} \right\} \delta I^{(m)}_{\Omega},
\]

so that

\[
\langle \delta j^{(m)}_{\Omega} \rangle = \frac{i 4 \pi W}{\kappa_{\text{BL}}} \frac{e \beta_{\Omega} T^{(m)}}{(\omega + i/\tau_d)} \left\{ 1 - \frac{\tan \left[ \pi \sqrt{(\omega + i/\tau_d)(\omega + i/\tau_d)/2\omega_p} \right]}{\pi \sqrt{(\omega + i/\tau_d)(\omega + i/\tau_d)/2\omega_p}} \right\} \delta I^{(m)}_{\Omega}.
\]

where \(\omega_p = \pi s/2L = \pi \sqrt{\pi e^3 W \Sigma/\kappa_{\text{BL}} m^2 L^2}\) is the plasmonic frequency.

Adding the density of the displacement current \(\delta j^{(m)}_{\Omega} = i \omega (\kappa_{\text{BL}}/4\pi W) \delta \varphi^{(m)}_{\Omega}\) to \(\delta j^{(m)}_{\Omega}\), we find

\[
\langle \delta j^{(m)}_{\Omega} \rangle = e \beta_{\Omega} T^{(m)} \delta I^{(m)}_{\Omega} + i \frac{\kappa_{\text{BL}}}{4\pi W} \left( \omega + i/\tau_d \right) \left( \delta \varphi^{(m)}_{\Omega} \right)
\]

\[
= e \beta_{\Omega} T^{(m)} \delta I^{(m)}_{\Omega} \frac{\tan \left[ \pi \sqrt{(\omega + i/\tau_d)(\omega + i/\tau_d)/\omega_p} \right]}{\pi \sqrt{(\omega + i/\tau_d)(\omega + i/\tau_d)/\omega_p}}
\]

8.4 Fermi Energy in the GNR Array

If \(\Sigma = \Sigma_d - \Sigma_o - \kappa_{\text{BL}} V / 4\pi e W > 0\), i.e., at a stronger doping of the CL than the BL and at not too high bias voltages, the GNRs are occupied primarily by the induced electrons. At sufficiently large \(\Sigma\), the electron gas in the GNRs can be degenerate. In this case, the linear electron density in GNRs is given by

\[
\rho = \frac{1}{\pi \hbar} \int_{-\rho^F}^{\rho^F} \frac{dp}{p} = \frac{2 \rho^F}{\pi \hbar}.
\]

Here, \(\rho^F\) is the electron momentum at the Fermi energy. The average surface electron density is equal \(\Sigma = \rho/D\), so that

\[
\Sigma \approx \frac{2 \rho^F}{\pi \hbar D}.
\]

At not too high electron densities when the electrons occupy only the lowest sub-band \(n = 1\), considering Eq. (1), we have

\[
\epsilon_{\text{GNR}}^F \approx \Delta \left( \frac{\rho^F d}{2\pi \hbar} \right)^2.
\]

Hence,

\[
\epsilon_{\text{GNR}}^F \approx \Delta \left( \frac{\Sigma d^2}{4} \right)^2 \leq \Delta \left( \frac{\Sigma d^2}{4} \right)^2.
\]

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