Graphene Bilayer Field-Effect Phototransistor for Terahertz and Infrared Detection

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A graphene bilayer phototransistor (GBL-PT) is proposed and analyzed. The GBL-PT under consideration has the structure of a field-effect transistor with a GBL as the channel and the back and top gates. The positive bias of the back gate results in the formation of conducting source and drain sections in the channel, while the negatively biased top gate provides the potential barrier which is controlled by the charge of the photogenerated holes. The features of the GBL-PT operation are associated with the variations of both the potential distribution and the energy gap in different sections of the channel when the gate voltages and the charge in the barrier section change. Using the developed GBL-PT device model, the spectral characteristics, dark current, responsivity and detectivity are calculated as functions of the applied voltages, energy of incident photons, intensity of electron and hole scattering, and geometrical parameters. It is shown that the GBL-PT spectral characteristics are voltage tuned. The GBL-PT performance as photodetector in the terahertz and infrared photodetectors can markedly exceed the performance of other photodetectors.

I. INTRODUCTION

At present, infrared detectors are mostly based on narrow-gap semiconductors utilizing the interband transitions. Technologies utilizing HgCdTe and InSb are well developed for infrared detection and imaging [1, 2]. The necessity of further extension of the wavelength range covered by photodetectors and imaging devices on their base, widening of their functionality, as well as cost reduction of the production by using a mature processing technology has stimulated the development of quantum-well infrared photodetectors (QWIPs) based on A3B5 compound systems and SiGe alloys and utilizing inter-subband (intraband) transitions (see, for instance, [2, 3]). Quantum-dot and quantum-wire infrared photodetectors (QDIPs and QRIPs) were also proposed [4, 5] and realized by many groups. The utilization of graphene layers and graphene bilayers [6, 7] opens up real prospects in the creation of novel photodetectors. The most important advantage of graphene relates to the possibility to control in a wide range the energy gap by patterning of the graphene layer into an array of narrow strips (nanoribbons) [8, 9]. The energy gap in graphene bilayers can be varied by the transverse electric field [10, 11, 12, 13] in different gated heterostructures. The graphene-based photodetectors can exhibit relatively high quantum efficiency (due to the use of interband transitions) and be easily integrated with silicon readout circuits. A photodetector for terahertz (THz) and infrared (IR) radiation based on a field-effect transistor structure with the channel consisting of an array of graphene nanoribbons was proposed and analyzed recently [14]. In this paper, we discuss the concept of a THz/IR photodetector with the structure of a field-effect transistor with a graphene bilayer as the device channel and photosensitive element. Using the developed device model, we calculate and analyze the detector characteristics. We demonstrate that such a graphene bilayer phototransistor (GBL-PT) can operate as very sensitive and voltage tunable THz/IR photodetector at elevated temperatures.

II. MODEL

The GBL-PT under consideration has a structure similar to that of a GBL-field-effect transistor [15] shown schematically in Fig. 1a. The GBL channel placed over a highly conducting substrate is supplied with the source and drain contacts. The substrate plays the role of the back gate which provides the formation of a two-dimensional electron gas (2DEG) in the channel when the back gate is biased positively with respect to the source and drain: \( V_b > V_d > 0 \). There is a top electrode serving as the top gate which is biased negatively (\( V_t < 0 \)). Here, \( V_b, V_t, \) and \( V_d \) are the back-gate, top-gate, and source-drain voltages, respectively. The negative bias of the top gate results in a depletion of the section of the channel beneath the top gate (which in the following are referred to as the gated section), so that the channel is partitioned into two highly conducting sections (source and drain sections) and the depleted gated section. In the gated section the potential barrier for electrons is formed. This barrier controls the injected electron current from the substrate to drain. The GBL-PT band diagram under the bias voltages corresponding to the operation conditions is shown in Fig. 1b. We shall assume that the back gate (substrate) and the top gate are sufficiently transparent for the incoming radiation. The GBL-PT operation is associated with the variation of the source-drain electron current under illumination when the electron-holes pairs are generated in the depleted sections. The photogenerated electrons are swept out to the conducting section (as

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Threshold voltages are given by the energy gaps in the source, drain, and gate regions, namely at $V_{th} = \left( E_g - \Delta \right)$ for electrons from the source and drain sides, respectively, and $V_{th}^d = \left( E_g - \Delta_d \right)$ for holes. One can see that $E_g^d / \Delta_d \approx 4d / a_B$. The latter value is rather small in the case of gate layers made of SiO$_2$ and is very small in the case of gate layers with elevated dielectric constant (say, HfO$_2$).

III. DARK CURRENT

The source-drain current created by the electrons injected from the source and drain section into the gated section is given by

$$J = \beta J_m \left[ \exp \left( \frac{\varepsilon^s - \Delta^s}{k_B T} \right) - \exp \left( - \frac{\varepsilon^d - \Delta^d}{k_B T} \right) \right].$$

Here $\Delta^s$ and $\Delta^d$ are the heights of the potential barriers for electrons from the source and drain sides, respectively, and

$$J_m = e \sqrt{2m(k_B T)^{3/2}} \frac{\pi^{1/2}h^2}{\nu T}.$$ 

The factor $\beta$ is the fraction of the injected electrons passed through the gated section despite their scattering on impurities and acoustic phonons. Solving the 2D kinetic Boltzmann equation for the electron distribution function in this section, one can obtain $\beta \approx 1$ in the ballistic regime of the electron transport across the gated section ($\nu T < 1$ or $L_t \ll \sqrt{2k_B T/m/\nu}$), and $\beta \approx \sqrt{\pi/\nu T}$ in the collision-dominated regime ($\nu T \gg 1$), where $\tau = L_t \sqrt{m/2k_B T}$ is the effective ballistic transit time across the gated section of electrons with the thermal velocity $v_T = \sqrt{2k_B T/m}$, and $L_t$ is the length of the top gate [13].

In the dark conditions, $\Delta^s = \Delta^s_0$ and $\Delta^d = \Delta^d_0$ with

$$\Delta^s_0 = -\frac{e(V_b + V_t)}{2}, \quad \Delta^d_0 = \frac{e(V_b + V_t)}{2} - \varepsilon^s_k - \varepsilon^d_k + eV_d$$
FIG. 2: Dark current $J_0$ as a function of back-gate voltage $V_b$ (at $V_t = -V_b[1 + (a_B/4 + 2d)/W]$) at different temperatures $T$.

$$J_0 \simeq -\frac{e(V_b + V_t)}{2} + \exp\left(-\frac{a_B}{8W} eV_d\right) eV_d. \quad (6)$$

Using Eqs. (3), (4), and (6), we arrive at the following formula for the dark current:

$$J_0 \simeq \beta J_m \left[ \exp\left(\frac{a_B}{8W} \frac{eV_b}{k_BT}\right) - 1 \right] \exp\left[\frac{e(V_b + V_t)}{2k_BT}\right] \left[ 1 - \exp\left(-\frac{eV_d}{k_BT}\right) \right]$$

$$\simeq \beta J_m \exp\left[-\frac{e(V_{th} - V_t)}{2k_BT}\right] \left[ 1 - \exp\left(-\frac{eV_d}{k_BT}\right) \right]. \quad (7)$$

Figure 2 shows the dependence of the dark current $J_0$ on the back-gate voltage $V_b$ provided that the top-gate voltage is maintained to be $V_t = V_{th} = -V_b[1 + (a_B/4 + 2d)/W]$. This corresponds to the highest barrier in the gated section at which the interband tunneling can still be neglected, in particular, owing to a small density of thermal holes in this section. It is assumed that $d = 0.36$ nm, $a_B = 4$ nm, $W = 20$ nm, $\beta = 0.1$, and $V_d > k_BT/e$. Nonmonotonic behavior of the dark current-voltage characteristics shown in Fig. 2 can be attributed to the interplay of an increase of electron density in the source (drain) section with increasing $V_b$ and an increase in the height of the potential barrier in the gated section when both $V_b$ and $|V_t|$ simultaneously increase.

IV. PHOTOCURRENT AND RESPONSIVITY

As a result of illumination with the photon energy $\hbar\omega > E_g$, the photogenerated holes are accumulated in the gated section. Their density $\Sigma$ can be found from the following equation governing the balance between the photogeneration of holes and their escape to the source and drain sections:

$$G_{\omega} = \frac{\beta e J_m}{e} \exp\left(-\frac{d}{2W} \frac{eV_t}{k_BT}\right) \exp\left[\frac{e(V_b + V_t)}{2k_BT}\right] \left[ 1 + \exp\left(-\frac{eV_d}{k_BT}\right) \right]. \quad (8)$$

Here $\beta$, is the fraction of the holes injected from the gated section into the source and drain sections (i.e., into the contact sections) but not reflected back owing to the scattering ($\beta$ is determined not only by the hole collision frequency in these section but also by the rate of recombination in these sections and the contacts), $\Sigma_t = 2mk_BT/\pi \hbar^2$, and $G_{\omega}$ is the rate of photogeneration of electrons and holes owing to the absorption of the incident THz/FIR radiation. This quantity depends on the intensity of radiation $L_\omega$, the absorption quantum efficiencies $\alpha_\omega$, $\alpha_{s,d}^\omega$, and $\alpha_{s,d}^\pi$ in the pertinent sections, and their lengths. The absorption quantum efficiencies in question are given by [16]

$$\alpha_\omega = \frac{\pi e^2}{c\hbar} \frac{\hbar\omega + 2\gamma_1}{\hbar\omega + \gamma_1} \Theta(\hbar\omega - E_g), \quad (9)$$

$$\alpha_{s,d}^\omega \simeq \frac{\pi e^2}{\hbar c} \frac{\hbar\omega + 2\gamma_1}{\hbar\omega + \gamma_1} \Theta(\hbar\omega - E_g^{s,d}) B_{\omega}, \quad (10)$$

where $c$ is the speed of light, $\gamma_1 \simeq 0.4$ eV is the band parameter, $\Theta(\hbar\omega)$ is the unity step function reflecting the energy dependence of the density of states near the fundamental edge of absorption. To take into account some smearing $\gamma$ of this edge, we set $\Theta(\hbar\omega) = [1/2 + (1/\pi) \tan^{-1}(\hbar\omega/\gamma)]$. The factor $B_{\omega}$ in Eq. (10) reflects the Burstein-Moss effect [17]:

$$B_{\omega} = \left[ 1 + \exp\left(-\frac{\hbar\omega - E_g^{s,d} - 2\varepsilon_F^{s,d}}{2k_BT}\right) \right]^{-1} \times \left[ 1 + \exp\left(-\frac{\hbar\omega + E_g^{s,d} + 2\varepsilon_F^{s,d}}{2k_BT}\right) \right]^{-1}$$

$$\simeq \left[ 1 + \exp\left(-\frac{\hbar\omega - E_g^{s,d} - 2\varepsilon_F^{s,d}}{2k_BT}\right) \right]^{-1}. \quad (11)$$

For the THz/FIR radiation with $E_g \lesssim \hbar\omega \ll \gamma_1$, Eq. (9) yields $\alpha_\omega \simeq \alpha = 2\pi e^2/c\hbar = 2\pi/137$. However, the absorption coefficient in the source and drain section can be rather small due to the Burstein-Moss effect. This occurs if the 2D electron gas in these sections is degenerate ($\varepsilon_F^{s,d} \gg k_BT$) and the photon energy does not markedly exceed the energy gap. Indeed, at $\hbar\omega \gtrsim E_g \simeq 2E_g^{s,d}$, considering that $E_g^{s,d}/\varepsilon_F^{s,d} \simeq 4d/a_B < 1$, from Eq. (10) one obtains $\alpha_{s,d}^{\pi} \simeq \alpha \exp(-\varepsilon_F^{s,d}/k_BT) = \frac{\pi e^2}{\hbar c} \frac{\hbar\omega + 2\gamma_1}{\hbar\omega + \gamma_1} \Theta(\hbar\omega - E_g^{s,d}) B_{\omega}$.
The following formula:

\[ \alpha \exp[-(a_B/8W)(eV_b/k_BT)] \ll \alpha. \]

Disregarding therefore the absorption of radiation in the source and drain section and considering that the absorption of radiation in the source and drain section (virtually in equal portions). Then, using Eq. (15), the GBL-PT responsivity defined as

\[ R_\omega = \frac{\alpha e}{\hbar \omega} \Theta\left(\hbar \omega - \frac{ed(V_b - V_i)}{2W}\right) \exp\left(\frac{a_B eV_b}{8W k_BT}\right) - 1 \]

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The charge of the photogenerated holes in the gated section gives rise to lowering of the potential barrier by the value

\[ \Delta s_d - \Delta s_0 = -\frac{4\pi e^2W}{k} \Sigma. \]

Considering Eqs. (4), (7), and (13), the variation of the source-drain current under illumination \( \Delta J = J - J_0 \), i.e., the value of the photocurrent can be presented by the following formula:

\[ \Delta J = J_0 \frac{4\pi e^2W}{k k_BT} \Sigma. \]

It should be noted that the contribution of the photogenerated electrons to the net photocurrent can be neglected because is small and the photogenerated electrons are swept out from the gated section to both the source and drain section (virtually in equal portions). Then, using Eqs. (7), (11), and (14), we arrive at

\[ \Delta J = e\frac{L_t \beta}{\beta_c} \left(\frac{8W}{a_B}\right) \exp\left(\frac{a_B eV_b}{8W k_BT}\right) - 1 \]

\[ \exp\left(\frac{d}{2W k_BT} \left[1 - \exp(-eV_d/k_BT)\right]\right) \frac{d}{2W k_BT} \left[1 + \exp(-eV_d/k_BT)\right]. \]

Here, \( C = \frac{L_t \beta}{(L_t + 2L_c)} \beta_c \) is the collision factor. At \( \hbar \omega = 10 \text{ meV} \) and \( C = 1 \), one obtains \( R_\omega = (e\alpha C/\hbar \omega) \approx 4.6 \text{ A/W}. \)

In the most interesting situation when the 2D gases in the source and drain sections are degenerate, the top gate voltage is chosen to provide relatively high barrier for electrons in the source and drain sections, and the source-drain voltage is sufficiently large, i.e., at \( eV_b > k_BT(8W/a_B) \), \( V_i = V_{ih} = -V_b[1 + (a_B/4 + 2d)/W] \), and \( eV_d > k_BT \), Eq. (16) can be reduced to the following:

\[ R_\omega \approx e\alpha C \Theta(\hbar \omega - \hbar \omega_{on}) \frac{8W}{a_B} \exp\left(\frac{a_B eV_b}{8W k_BT}\right) \left(1 - \frac{4d}{a_B}\right). \]
Here \( h\omega_{off} = E_g \approx e(V_b - V_i)/2W \gtrsim eV_b/W \) is the photon cut-off energy at which the GBL-PT responsivity reaches a maximum:

\[
\max R_\omega \sim \frac{\alpha C}{V_b} \left( \frac{8W^2}{da_B} \right) \exp \left( \frac{a_B}{8W k_B T} \left( \frac{eV_b}{k_B T} \right) \left( 1 - \frac{4d}{a_B} \right) \right).
\]  

(18)

Figure 3 shows the GBL-PT responsivity \( R_\omega \) as a function of the photon energy \( h\omega \) for different back-gate voltages \( V_b \) at different temperatures. Here and in the following figures, it is set that for each value of the back-gate voltage \( V_b \) the top gate voltage is chosen to be \( V_i = V_{th} = -V_b[1 + (a_B/4 + 2d)/W] \). The source-drain voltage is assumed to be \( V_d > k_B T/E \). In such a case, the thermionic dark current is lowered while the interband tunneling is still negligible. We assume that \( d = 0.36 \) nm, \( a_B = 4 \) nm, \( W = 20 \) nm, \( \gamma = 2 \) meV, \( \beta = 0.1 \), and \( C = 1 \). The spectral dependences shown in Fig. 3 correspond to the cut-off photon energies \( h\omega = E_g \approx eV_b/W \) (when \(|V_i| \gtrsim V_b|\).

Figure 4 shows the dependences of the responsivity maximum value \( \max R_\omega \) on the back-gate voltage \( V_b \) (and the photon energy \( h\omega_{off} \)) for the same parameters as in Fig. 3.

V. PHOTOELECTRIC GAIN AND DETECTIVITY

Considering Eq. (15) and taking into account that the photocurrent created by the photogenerated electrons and holes as such is equal to \( \Delta J_0 = eL_i\alpha \omega J_0/h\omega \), the photoelectric gain \( g = \Delta J/\Delta J_0 \) can be presented as (compare with Eq. (18))

\[
g \approx \frac{\beta}{\beta_e} \left( \frac{8W}{a_B} \right) \exp \left( \frac{a_B}{8W k_B T} \left( \frac{eV_b}{k_B T} \right) \left( 1 - \frac{4d}{a_B} \right) \right),
\]  

(19)

where all the factors in the right-hand side exceed or greatly exceed unity if \( 4d/a_B < 1 \) (\( 4d/a_B \approx 0.36 \) and \( 0.07 \) in the case of SiO_2 and HfO_2 gate layers, respectively.)

Calculating the GBL-PT dark current limited detectivity as \( D^* = R_\omega/\sqrt{4e\gamma J_0/H} \), where \( H \) is the GBL-PT width (in the direction perpendicular to the current), at properly chosen relationship between \( V_b \) and \( V_i \) (as above), we arrive at the following formula:

\[
D^* \approx \frac{e\alpha C_*}{h\omega_{off}} \sqrt{\frac{H}{4eJ_m}} \left( \frac{8W}{a_B} \right) \exp \left( \frac{h\omega_{off}}{n k_B T} \right),
\]  

(20)

where \( C_* = C\sqrt{\beta_e/\beta} = [L_i/(L_i + 2L_e)]\sqrt{\beta_e} \) and \( n = (16d/a_B)/[1 + 4d/a_B] \). A point worth noting is that the factor \( n \) in the exponential dependence in Eq. (21) can be about or smaller than unity. Indeed, for \( a_B = 4 \) nm, one obtains \( n \approx 0.27 - 1 \). This provides fairly steep increase in \( D^* \) with increasing \( h\omega_{off} \).

Figures 5 and 6 demonstrate the dark current limited detectivity \( D^* \) (under the optimized conditions) as a function of the cut-off photon energy \( h\omega_{off} \) at different temperatures \( T \) and as a function of \( T \) at given values \( h\omega_{off} \). One can see that \( D^* \) can be fairly large even at room temperatures. The detectivity markedly decreases with decreasing cut-off photon energy. However, as shown in Fig. 7, in GBL-PTs with relatively high-\( k \) gate layers in which the Bohr radius can be large, a rather high detectivity can be achieved in the range of low cut-off photon energies, in particular, those corresponding to the THz range of spectrum.

VI. COMMENTS

As follows from Eq. (16) - (20) and demonstrated in Figs. 3 - 7, the GBL-PT responsivity and detectivity can be very large even at room temperatures exceeding those of QWIP and QDIPs. This is attributed to the following. First of all, the quantum efficiency of the interband
with $T = 300$ K, inequality (21) yields $T_{photogenerated holes} = \beta_{a} = (1 + (\nu_{c}/v_{T})^{2}/\pi)^{-1/2}$, and $\beta_{b} = (1 + (\nu_{c}/v_{T})^{2}/\pi)^{-1/2}$. As a result, we obtain

$$C \approx \frac{L_{t}}{2(L_{t} + 2L_{c})} \sqrt{\frac{1 + (\nu_{c}/v_{T})^{2}/\pi}{1 + (\nu_{c}/v_{T})^{2}/\pi}}$$

(22)

As follows from Eq. (21), $C$ as a function of $L_{t}$ exhibits a maximum at a certain value of the latter. If both $L_{c}$ and $L_{t}$ are large, so that the electron transport in all the sections is collision dominated, $C \approx (L_{c}/(L_{t} + 2L_{c}))/(\nu_{c}/\nu)$. When the photon energy $\hbar \omega > E_{g}^{s,d} + \varepsilon_{F}^{d,s}$, the radiation absorption in the source and drain sections can be essential. In such a spectral range, the holes photogenerated in these sections can substantially affect the net hole charge in the gated section. In this case, the quantity $G_{\omega}$ in the right-hand side of Eq. (8) should be modified to take into account the extra holes photogenerated in the source and drain sections and injected into the gated section. The contribution of the holes photogenerated in the source and drain section can result in a modification in the spectral characteristic of the responsivity at elevated photon energies according to the frequency dependence of the factor $B_{\omega}$ in Eq. (10). As a result, a duplicated maxima of $R_{\omega}$ can appear which correspond to $\hbar \omega \approx \hbar \omega_{off} \gtrsim eV_{b}/W$ and $\hbar \omega \approx \hbar \omega_{off}/2 + (a_{B}/8W)eV_{b} \approx (eV_{b}/W)(1 + (a_{B}/4d)/2) > \hbar \omega_{off}$. We considered a GBL-PT with the structure of a single FET. Actually, analogous GBL photodetectors can be made of multiple periodic GBL-PT structures. Such photodetectors can surpass the GBL-PT considered above. However, their operation can be complicated by additional features of the photogenerated holes transport. As a result, the potential distribution along the GBL channel can be nontrivial as it takes place in multiple QWIP (see, for instance, Refs. [14, 20]), so that special studies of multiple GBL-PTs are required.

VII. CONCLUSIONS

We proposed a GBL-PT and calculate its spectral characteristics, dark current, responsivity, and dark current limited detectivity. It was shown that GBL-PTs with optimized structure at properly chosen applied voltages

\[ a_{B} = 20 \text{ nm} \]
\[ W = 20 \text{ nm} \]

FIG. 7: The same as in Fig. 5 but for GBL-PT with different value of the Bohr radius $a_{B}$ (different dieletric constant of gate layers $k$). $\alpha$ is relatively large (in comparison, say, with the inter-subband transitions in single QWIPS). Second, the photoelectric gain exhibited by GBL-PTs can also be very large. This is associated with a higher energy barrier (high activation energy) for the photogenerated holes accumulated in the gated section in comparison with the activation energies for electrons in the source and drain sections. The difference between this activation energies is equal to $\epsilon_{F}^{s,d} - E_{g}^{s,d} \approx (a_{B}/8W)(1 - 4d/2a_{B})eV_{b}$. An increase in the gate voltages results in an increase of the Fermi energy of electrons in the source and drain section and, in a rise of the activation energy for the photogenerated holes leading to an increase of their lifetime. As a result, the temperature dependence of the GBL-PT detectivity is given by the factor exp($\hbar \omega_{off}/k_{B}T$) with $n < 2$ in contrast to QWIPS (optimized) for which $D^{*} \propto \exp(\hbar \omega_{off}/2k_{B}T)$ (see, for instance, Refs. [2, 3]). This might open prospects to use GBL-PTs at elevated temperatures.

The GBL-PT responsivity and detectivity can be limited by the interband tunneling of the photogenerated holes if the width of the junction between the source (or drain) section and the gated section $W^{*}$ is too small ($W^{*}$ depends on $W$ as well as $V_{b}$ and $V_{t}$). This can deteriorate the GBL-PT performance due to a decrease in the photoelectric gain associated with a shortening of the lifetime of the photogenerated holes. Estimating the probability of interband tunneling as $\exp(-\pi m^{1/2}E_{g}^{1/2}/2\sqrt{2}e\hbar \mathcal{E})$, where $\mathcal{E} \approx E_{g}/cW^{*}$, we arrive at the following condition when the tunneling of the photogenerated holes might be essential:

$$W^{*} \gtrsim \frac{a_{B}}{d} \frac{\hbar}{\pi \sqrt{2m}} \frac{\sqrt{\hbar \omega_{off}}}{k_{B}T}.$$  

(21)

For instance, for $a_{B} = 4$ nm, $\hbar \omega_{off} = 10 - 100$ meV, and $T = 300$ K, inequality (21) yields $W^{*} \gtrsim 12 - 40$ nm.

The collision factor $C$ in Eqs. (16) - (18) can influence the GBL-PT performance. It depends on the device geometrical parameters $L_{t}$ and $L_{c}$. Since the propagation of holes in the source and drain sections can be strongly affected by scattering on electrons due to their large density, the hole collision frequency in the source and drain sections $\nu_{h} > \nu$ (or even $\nu_{c} \gg \nu$). In this case, $C$ can exceed unity. This is because strong collisions of holes in the source and drain section can markedly decrease the current of the photogenerated holes from the gated section into the source section (as well as into the drain section) increasing the holes lifetime and, hence, the photoelectric gain. To follow the dependence of $C$ (and, consequently, $R_{\omega}$) on $L_{t}$ and $L_{c}$, assuming that the holes recombine primarily at the contacts, one can use the following interpolation formulas: $\beta_{a} = [1 + (\nu_{c}/v_{T})^{2}/\pi]^{-1/2}$, and $\beta_{b} = [1 + (\nu_{c}/v_{T})^{2}/\pi]^{-1/2}$. As a result, we obtain

$$C \approx \frac{L_{t}}{2(L_{t} + 2L_{c})} \sqrt{\frac{1 + (\nu_{c}/v_{T})^{2}/\pi}{1 + (\nu_{c}/v_{T})^{2}/\pi}}$$

(22)
can surpass the photodetectors of other types. The main advantages of GBL-PTs are associated with the utilization of interband transitions with relatively high quantum efficiency, high photoelectric gain, and possibility of operation at elevated temperatures. The advantages of the GBL-PT under consideration in comparison with QWIPs, QDIPs, and QRIPs, as well as with HgCdTe and InSb detectors can also be easy fabrication and integration with silicon (or graphene) readout circuits and the voltage tuning of the spectral characteristics.

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