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Graphene Nanoribbon Phototransistor: Proposal and Analysis

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1. Introduction

Photodetectors for far infrared (FIR) and terahertz (THz) ranges of spectrum are conventionally made of narrow-gap semiconductors and quantum-well structures. In the former case, interband transitions due to the absorption of photons are used. The operation of the detectors based on quantum-well structures is associated with the electron or hole intraband (intersubband) transitions [1, 2]. Some time ago, quantum-dot and quantum-wire detectors were proposed [3, 4] and realized by many groups. The utilization of *graphene*, i.e., a monolayer of carbon atoms forming a dense honeycomb two-dimensional crystal structure [5, 6] opens up tempting prospects in creation of novel devices. in particular, novel photodetectors. One of the most promising metamaterials for FIR and THz detectors is a patterned graphene which constitutes an array of graphene nanoribbons (GNRs). The energy gap between the valence and conduction bands in GNRs as well as the intraband subbands can be engineered varying the shape of GNRs, in particular, their width, which can be defined by lithography. This opens up the prospects of creation of multicolor photodetectors. In this paper, we propose a graphene nanoribbon phototransistor (GNR-PT) and evaluate its performance using the developed device model.

2. Device structure and model

The detector proposed has a structure of GNR field-effect transistor consisting of an array of GNRs with the side source and drain contacts (to each GNR) sandwiched between the highly conducting substrate and the top gate electrode. The operation of devices with similar structure were explored recently (see, for instance, [7, 8, 9, 10, 11]). The structure of GNR-PT under consideration is schematically shown in Fig. 1. For the sake of definiteness, we consider a GNR-PT with optical input from the bottom of the structure assuming that the substrate and the layer sandwiching the GNR array are transparent. Graphene nanoribbons exhibit the energy spectrum of electrons and holes with a gap between the valence and conduction bands depending on the nanoribbon width d: $\varepsilon_n^{\mp}(p) = \pm v\sqrt{p^2 + (\pi\hbar/d)^2 n^2}$. Here $v \simeq 10^8$ cm/s is the characteristic velocity of the electron (upper sign) and hole (lower sign) spectra, p is the momentum along the nanoribbon, $\hbar$ is the reduced Planck constant, and $n = 1, 2, 3, ...$ is the subband index. This spectrum corresponds to the band gap $\Delta = 2\pi\hbar/d$ between the valence and conduction bands and to a specific density of states in the conduction and valence bands as a function of the energy. The source-drain current along the GNRs associated with the electrons propagating from the source to the drain and overcoming the barrier in the center section of the channel (beneath the top gate). The height of the barrier for electrons can be found considering the balance of the photogenerated and thermal holes in the section of the channel beneath the top gate. As a result, one obtains the following equation for the photocurrent $\Delta J = J - J^{dark}$:

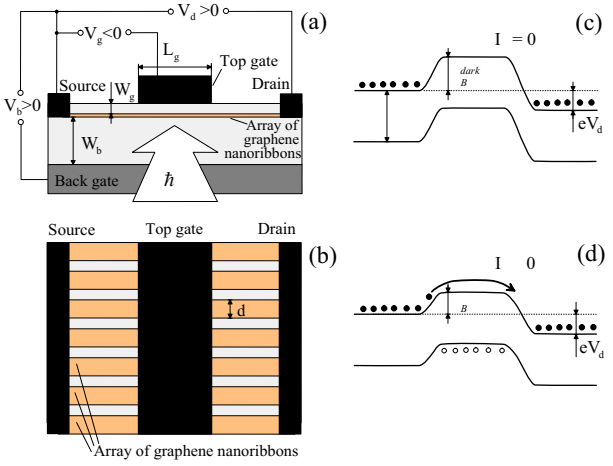

Figure 1: Schematic view of GNR-PT structure side (a) and top (b) views, and band diagrams under dark condition (c) and under irradiation (d). Circles in panels (c) and (d) corresponds to electrons and holes.

$$\Delta J \simeq \left(\frac{e^2 V_b}{k_B T}\right)\left[\frac{1-\exp(-eV_d/k_B T)}{1+\exp(-eV_d/k_B T)}\right]\left(\frac{W}{W_b}\right) L_g G_\omega. \quad (1)$$

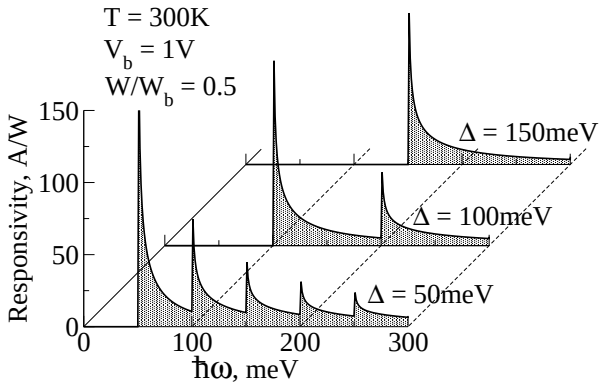

Figure 2: Responsivity, R, as a function of energy of incident photons, $\hbar\omega$, for GNR-PTs with different Δ.

Here e is the electron charge, V_b and V_d are the back gate and drain voltages, respectively, T is the temperature, k_B is the Boltzmann constant, $W = W_b W_g/(W_b + W_g)$, where W_b and W_g are the thicknesses of the layers separating the GNR array from the back and top gates, and L_g is the length of the top gate.. The rate of the photogeneration due to the interband absorption of incoming radiation is given by

$$G_\omega = \sum_{n=1}^{\infty} \frac{\beta\Delta \cdot \Theta(\hbar\omega - n\Delta)}{\sqrt{\hbar^2\omega^2 - n^2\Delta^2}} \frac{I_\omega}{\hbar\omega}, \qquad (2)$$

where I_ω is the radiation intensity, $\beta = 2\pi e^2/c\hbar \simeq 2\pi/137 \simeq 4.59 \times 10^{-2}$, c is the speed of light, $\hbar$ is the reduced Planck constant, and $\Theta(\hbar\omega - \Delta_n)$ is the unity-step function. The quantity $\beta\Delta/\sqrt{\hbar^2\omega^2 - \Delta^2}$ is the effective quantum efficiency of the GNR array. In the limit $\hbar\omega$ tends to Δ, the quantum efficiency is limited by $\beta\Delta/\Gamma$, where Γ is the "smearing" of the valence and conduction band edges due to disorder.

3. Detector responsivity

Using eqs. (1) and (2), we obtain the following formula for the detector responsivity $R = \Delta J/L_g I_\omega$:

$$R \simeq \left(\frac{W}{W_b}\right)\left(\frac{eV_b}{k_B T}\right)\left[\frac{1 - \exp(-eV_d/k_B T)}{1 + \exp(-eV_d/k_B T)}\right] \times \sum_{n=1}^{\infty} \frac{e\beta\Delta \cdot \Theta(\hbar\omega - n\Delta)}{\hbar\omega\sqrt{\hbar^2\omega^2 - n^2\Delta^2}}. \qquad (3)$$

Setting $W \simeq W_b/2$, $eV_d \gg k_B T$, $\Delta = 100$ meV, $\Gamma = 2$ meV, $V_b = 1 - 5$ V, and $T = 300$ K, we obtain $\max R \sim 50 - 250$ A/W. These values of the responsivity obtained significantly exceed those for intersubband quantum-well, -wire, and -dot photodetectors for the IR and THz ranges (see, for instance [2]). This is primarily due to higher quantum efficiency and higher photoelectric gain, which might be exhibited by GNR-PTs. The latter is associated with a long life-time of the photogenerated holes in the central section of the channel because these holes are confined in this section by relatively high barriers, so that the photoelectric gain $g \gg 1$. The maximum responsivity of GNR-PTs can also exceed the responsivity of the customary photodetectors made of narrow gap semiconductors (for example, PbSnTe and CdHgTe), whose responsivity is about a few A/W [1, 2], because the former can exhibit rather high quantum efficiency at the resonances $\hbar\omega = n\Delta$ arising due to the lateral quantization in GNRs. Figure 2 shows the spectral dependences of the responsivity, R, of GNR-PTs with different energy gaps Δ (different width of GNRs) calculated using eq. (3). It is assumed that $W/W_b = 0.5$, $V_b = 1$ V, and $T = 300$ K.

4. Conclusions

In conclusion, we developed the GNR-PT model and calculated the device characteristics. It was shown that GNR-PTs can surpass the IR and THz detectors utilizing other types of quantum structures (in particular, quantum-well, -wire, and -dot photodetectors). The GNR-PTs under consideration can exhibit substantial technological advantages, including easier integration with readout circuits, over the detectors on the base of narrow-gap semiconductors like PbSnTe and CdHgTe.

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