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Analysis and comparison of characteristics of the uncooled millimeter-wave diode detectors within a generalized theoretical model

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Within the framework of a generalized theoretical model of the uncooled millimeter-wave diode detectors, an analysis and comparison of their achievable characteristics was carried out. The approach is based on the tunnel model of current transfer. A one-dimensional structure that consists of a semiconductor/dielectric barrier layer between two electrodes is considered. The scattering of charge carriers in the barrier layer is assumed to be insignificant. Direct detection of a weak millimeter-wave signal is theoretically studied. Expressions for the current, the conductance, the curvature coefficient of the diode are derived. Possible families of the considered class of detectors are determined, their achievable characteristics are analyzed. It is shown that all detectors of the considered class can be divided into two families with qualitatively different behavior of the curvature coefficient in dependance on the diode conductance. It is obtained that the current sensitivity of the diodes that belong to the first family cannot exceed 20 A/W, while diodes of the second family can achieve $\sim$ 500 A/W. However, this value is significantly lower at a zero-bias condition, when only $\sim$ 30 A/W can be practically obtained for the second family diodes. The results of this work can be useful at choosing the diode type for a specific practical problem.

Keywords: millimeter waves, direct detection, uncooled diode detector, semiconductor structure, tunnel current transport model.

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Introduction

Uncooled millimeter-wave detectors are widely used to solve certain scientific and practical tasks, such as radio imaging [1,2], spectroscopy [3], diagnostics of materials [4], wireless power transmission [5] etc.

Generally the detector is one or several non-linear elements included in a transmission line [6]. A transmission line could be a metal waveguide, a coplanar line, an antenna. A non-linear element converts a high-frequency signal into a low-frequency signal.

When describing the detecting properties of non-linear elements, it is convenient to separately consider the elements with a different number of electrodes: two (diodes), three etc. Among the millimeter-wave detector diodes the most universal and common is a Schottky barrier diode [7]. Other types of diodes are being actively developed and used: a inversed diode [8], a resonant-tunneling [9], a heterobarrier one [10] etc. The last two−three decades were marked by success in design of a millimeter wave detector based on a field transistor [11], which is an example of a three-electrode non-linear element.

Diversity of detector diodes generates need for their classification in order to compare the achievable characteristics and to analyze the possibility of use for solving specific practical tasks. Currently available papers of review nature [12,13] focus on listing the available types of diodes and their realizations without analysis of an inner link between the mechanisms of electronic transport of the considered class of devices. This makes you think about chances of existence of other types of detector diodes and, therefore, find the data given in the review papers incomplete.

The objective of this paper is to develop an approach to classification and analysis of the achievable characteristics of potential families of uncooled diode millimeter-wave detectors based on using a single theoretical model.

1. Theoretical model

A one-dimensional structure is considered, which may include both dielectric/semiconductor and metal layers. The first and the last layers serve as electrodes, i. e. are well-conducting layers made of either a heavily-doped semiconductor or from metal. The conductance of electrodes is such that their voltage drop may be neglected compared to voltage drop in the intermediate layers that may jointly be called a barrier layer. It is assumed that the structure is crystalline. However, the work results will not change, if the dielectric and metal layers are amorphous.

An expression for current density in a one-dimensional crystalline structure has the following general appearance [14]:

$$j = -e \sum_{n=1}^{N(z)} \int_{V_{\mathbf{k}}(z)} \frac{d\mathbf{k}}{4\pi^3} v(n, \mathbf{k}, z) g(n, \mathbf{k}, z), \qquad (1)$$

where $v(n, \mathbf{k}, z)$ — electron velocity; $g(n, \mathbf{k}, z)$ — distribution function determined in such a manner that value $\frac{dz\,d\mathbf{k}}{4\pi^3} g(n, \mathbf{k}, z)$ is equal to the number of electrons per unit of surface area in n-th permiited energy zone in the element of the phase space volume $dz\,d\mathbf{k}$ with a center in point z, $\mathbf{k}$; e — elementary charge; $\mathbf{k}$ — wave vector; z — spatial coordinate. Summation is carried out in all permitted energy zones from 1 to $N(z)$. The integral is taken for all values of the wave vector in the first Brillouin zone $V_{\mathbf{k}}(z)$.

Let the boundary between the first electrode and the barrier layer have the coordinate $z = 0$, and the boundary between the second electrode and the barrier layer — coordinate $z = d$, where d — barrier layer thickness. Values of current density in electrodes in an arbitrary small proximity to the specified boundaries in accordance with equation (1) are given by the following expressions:

$$j = -e \int\limits_{V_{\mathbf{k},1}} \frac{d\mathbf{k}}{4\pi^3} v_1(\mathbf{k}) g_1(\mathbf{k}), \tag{2a}$$

$$j = -e \int\limits_{V_{\mathbf{k},2}} \frac{d\mathbf{k}}{4\pi^3} v_2(\mathbf{k}) g_2(\mathbf{k}), \tag{2b}$$

where lower indices 1 and 2 number the electrodes. Charge transfer in the electrodes is determined by a single energy zone, therefore expressions (2a) and (2b) exclude summation by n.

Let us imagine the integral for three-dimensional area $V_{\mathbf{k},1(2)}$ in the form of an integral of two-dimensional area $S_{\mathbf{k}_\perp,1(2)}$ and an integral of one-dimensional area $L_{k_z,1(2)}(\mathbf{k}_\perp)$, where $\mathbf{k}_\perp$ — wave vector projection on a plane perpendicular to axis z, k_z — wave vector projection on a direction along the axis z. Since $v_{1(2)}(\mathbf{k}_\perp, k_z) = -v_{1(2)}(\mathbf{k}_\perp, -k_z)$ [14], we get the expression

$$j = -\frac{e}{4\pi^3} \int\limits_{S_{\mathbf{k}_\perp,1(2)}} d\mathbf{k}_\perp \int\limits_{L^+_{k_z,1(2)}(\mathbf{k}_\perp)} dk_z v_{1(2)}(\mathbf{k}_\perp, k_z)$$
$$\times [g_{1(2)}(\mathbf{k}_\perp, k_z) - \bar{g}_{1(2)}(\mathbf{k}_\perp, k_z)], \tag{3}$$

where $\bar{g}_{1(2)}(\mathbf{k}_\perp, k_z) = g_{1(2)}(k_\perp, -k_z)$, $L^+_{k_z,1(2)}(\mathbf{k}_\perp)$ — subset of $L_{k_z,1(2)}(\mathbf{k}_\perp)$, which meets the condition $k_z > 0$.

By definition the electron velocity $v(\mathbf{k}_\perp, k_z) = dE(\mathbf{k}_\perp, k_z)/d(\hbar k_z)$ [14], where $E(\mathbf{k}_\perp, k_z)$ — electron energy, $\hbar$ — reduced Planck's constant. After the velocity expression is included in equation (3) and integration by k_z changes to integration by E we get the following expression for current density:

$$j = -\frac{e}{4\pi^3\hbar} \int\limits_{S_{\mathbf{k}_\perp,1(2)}} d\mathbf{k}_\perp \int\limits_{L_{E,1(2)}(\mathbf{k}_\perp)} dE[g_{1(2)}(\mathbf{k}_\perp, E)$$
$$- \bar{g}_{1(2)}(\mathbf{k}_\perp, E)]. \tag{4}$$

When expression (4) was derived, it was assumed that energy E was a one-to-one function k_z, i. e. charge transfer in electrodes depended on electrons located in the same valley. In case when in process of charge transfer in electrodes several equivalent valleys participate, the current value should be multiplied by the corresponding number of valleys.

Let us further assume that electrons falling on the barrier layer are in thermodynamic equilibrium state, i. e.

$$g_1(\mathbf{k}_\perp, E) = f_1(E), \tag{5a}$$

$$\bar{g}_2(\mathbf{k}_\perp, E) = f_2(E), \tag{5b}$$

where $f_{1(2)}(E)$ — Fermi–Dirac distribution function.

To find the distribution function of electrons exiting the barrier layer, let us assume that in the barrier layer the scattering is insignificant or totally absent. I.e. the condition of preserving the projection of electron wave vector $\mathbf{k}_\perp$ and its energy E when the electron passes through the barrier layer is met. Then the following expressions may be obtained:

$$\bar{g}_1(\mathbf{k}_\perp, E) = (1 - P_1(\mathbf{k}_\perp, E)) f_1(E) + P_1(\mathbf{k}_\perp, E) f_2(E), \tag{6a}$$

$$g_2(\mathbf{k}_\perp, E) = (1 - P_2(\mathbf{k}_\perp, E)) f_2(E) + P_2(\mathbf{k}_\perp, E) f_1(E), \tag{6b}$$

where $P_{1(2)}(\mathbf{k}_\perp, E)$ — probability of electron passage with initial parameters $(\mathbf{k}_\perp, E)$ from an electrode $1(2)$ to an electrode $2(1)$. After substitution of expressions (5a), (5b) and (6a), (6b) in (4) we find

$$j = -\frac{e}{4\pi^3\hbar} \int\limits_{S_{\mathbf{k}_\perp,1(2)}} d\mathbf{k}_\perp \int\limits_{L_{E,1(2)}(\mathbf{k}_\perp)} dE[f_1(E)$$
$$- f_2(E)] P_{1(2)}(\mathbf{k}_\perp, E). \tag{7}$$

The conditions imposed upon the properties of the distribution function in electrodes (5a), (5b) and (6a), (6b), and the condition of absent scattering in the barrier layer practically reduce the considered current transfer model to a tunnel model [15] with an additional simplifying assumption on preservation of the wave vector projection $\mathbf{k}_\perp$ as the electron passes through the barrier layer.

Since $\mathbf{k}_\perp$ and E are maintained when the electron passes via the barrier layer, outside of the set $S_{\mathbf{k}_\perp} = S_{\mathbf{k}_\perp,1} \cap S_{\mathbf{k}_\perp,2}$ or $L_E(\mathbf{k}_\perp) = L_{E,1}(\mathbf{k}_\perp) \cap L_{E,2}(\mathbf{k}_\perp)$ the equation $P_{1(2)}(\mathbf{k}_\perp, E) = 0$ should be identically satisfied. Taking into account the specified conditions, one may rewrite (7) in the form convenient for further analysis

$$j = \frac{e}{4\pi^3\hbar} \int\limits_{S_{\mathbf{k}_\perp}} d\mathbf{k}_\perp \Big\{ \int\limits_{L_{E,2}(\mathbf{k}_\perp)} dE\, f_2(E) P_2(\mathbf{k}_\perp, E)$$
$$- \int\limits_{L_{E,1}(k_\perp)} dE\, f_1(E) P_1(\mathbf{k}_\perp, E) \Big\}. \tag{8}$$

Starting from expression (8), let us count the electron energy in the electrode from Fermi level in this electrode; in this case $f_1(E) = f_2(E) \equiv f(E)$.

To calculate the differential conductance of structure $G = dj/dV$ it is necessary to find out the shape of current dependence on voltage $j(V)$. Let us note that the fields of integration, as well as the distribution function in (8) do not depend on the applied voltage. The dependent value is only the probability of electron passage through the barrier layer $P_{1(2)}(\mathbf{k}_\perp, E, V)$. Let us imagine this function in the form of a single rectangular pulse

$$P_i(\mathbf{k}_\perp, E, V) = \theta(E - E_{i,s}(\mathbf{k}_\perp, V)) - \theta(E - E_{i,f}(\mathbf{k}_\perp, V)), \tag{9}$$

where $\theta(E - E_{i,s(f)}(\mathbf{k}_\perp, V))$ — Heaviside function, $E_{i,s(f)}(\mathbf{k}_\perp, V)$ — upper and lower boundaries of the energy authorized for transition through the barrier layer, $i = \{1, 2\}$. Let us assume that the position of the boundaries linearly depends on the applied voltage:

$$E_{i,s(f)}(\mathbf{k}_\perp, V) = E_{i,s(f),0}(\mathbf{k}_\perp) + \alpha_{i,s(f)}(\mathbf{k}_\perp)eV, \tag{10}$$

where

$$E_{i,s(f),0}(\mathbf{k}_\perp) = E_{i,s(f)}(\mathbf{k}_\perp, 0),$$
$$\alpha_{i,s(f)}(\mathbf{k}_\perp) = dE_{i,s(f)}(\mathbf{k}_\perp, V)/d(eV),$$

where

$$\alpha_{1,s(f)}(\mathbf{k}_\perp) \geq 0, \quad \alpha_{2,s(f)}(\mathbf{k}_\perp) \leq 0,$$
$$|\alpha_{1,s(f)}(\mathbf{k}_\perp)| + |\alpha_{2,s(f)}(\mathbf{k}_\perp)| = 1.$$

Differentiating (8) by voltage with account of (9) and (10) and integrating by energy, we find

$$G = \frac{e}{4\pi^3\hbar} \int\limits_{S_{\mathbf{k}_\perp}} d\mathbf{k}_\perp \sum_{i=1}^{2} \big\{ |\alpha_{i,s}(\mathbf{k}_\perp)| f\big(E_{i,s}(\mathbf{k}_\perp)\big) - |\alpha_{i,f}(\mathbf{k}_\perp)| f\big(E_{i,f}(\mathbf{k}_\perp)\big) \big\}. \tag{11}$$

In expression (11) it is assumed that for those $\mathbf{k}_\perp$, where $E_{i,s(f)}(\mathbf{k}_\perp) \notin L_{E,i}(\mathbf{k}_\perp)$, the parameter $\alpha_{i,s(f)}(\mathbf{k}_\perp) = 0$.

Similarly we find the parameter of quadratic nonlinearity $\beta = (d^2j/dV^2)/(dj/dV)$:

$$\beta = e \frac{\int\limits_{S_{\mathbf{k}_\perp}} d\mathbf{k}_\perp \sum_{i=1}^{2} (-1)^i \{ |\alpha_{i,s}(\mathbf{k}_\perp)|^2 f'(E_{i,s}(\mathbf{k}_\perp)) - |\alpha_{i,f}(\mathbf{k}_\perp)|^2 f'(E_{i,f}(\mathbf{k}_\perp)) \}}{\int\limits_{S_{\mathbf{k}_\perp}} d\mathbf{k}_\perp \sum\limits_{i=1}^{2} \{ |\alpha_{i,s}(\mathbf{k}_\perp)| f(E_{i,s}(\mathbf{k}_\perp)) - |\alpha_{i,f}(\mathbf{k}_\perp)| f(E_{i,f}(\mathbf{k}_\perp)) \}}. \tag{12}$$

In (12) designation $f'(E) = -\frac{d}{dE} f(E)$ is introduced.

Let us stop on coefficients $\alpha_{i,s(f)}(\mathbf{k}_\perp)$, which appear in expressions (11) and (12) when using the approximation of the linear dependence of the boundaries in the area authorized for electron transition on the applied voltage (10). In some special cases it is really so, for example, when the energy boundary is a boundary of the energy zone of the electrode. In cases of non-linear dependence, the introduced linear approximation (10) is based on the condition of a weak input signal, specific for the mode of diode detection (see below).

2. Classification of detectors and analysis of their characteristics

Under the conditions of a weak input signal V_{RF}, when the ratio $V_{RF} \ll 1/\beta$ is met, the main parameters characterizing the sensitivity of the detector, are the differential conductance G and parameter of square-law nonlinearity β. This mode of instrument operation is called the square-law detection. When the threshold level of signal $V_{RF,USL} \sim 1/\beta$ is exceeded, the sensitivity of the square-law detector starts decreasing, which is related to additional absorption of power of the received signal in the nonlinearity of the current-voltage curve of third degree [16].

Analysis of expressions (11) and (12) shows that all detectors may be separated into two families with qualitatively different properties. The first detector family meets the following condition:

$$\int\limits_{S_{\mathbf{k}_\perp}} d\mathbf{k}_\perp \sum_{i=1}^{2} |\alpha_{i,s}(\mathbf{k}_\perp)| f\big(E_{i,s}(\mathbf{k}_\perp)\big) \gg \int\limits_{S_{\mathbf{k}_\perp}} d\mathbf{k}_\perp \sum_{i=1}^{2} |\alpha_{i,f}(\mathbf{k}_\perp)| f\big(E_{i,f}(\mathbf{k}_\perp)\big), \tag{13a}$$

or

$$\int\limits_{S_{\mathbf{k}_\perp}} d\mathbf{k}_\perp \sum_{i=1}^{2} |\alpha_{i,f}(\mathbf{k}_\perp)| \big(1 - f\big(E_{i,f}(\mathbf{k}_\perp)\big)\big) \gg \int\limits_{S_{\mathbf{k}_\perp}} d\mathbf{k}_\perp \sum_{i=1}^{2} |\alpha_{i,s}(\mathbf{k}_\perp)| \big(1 - f\big(E_{i,s}(\mathbf{k}_\perp)\big)\big). \tag{13b}$$

The consequence of the conditions imposed is the fact that the conductance of the barrier layer is determined only by lower (expression (13a)) or upper (expression (13b)) boundaries authorized for transition of electron energy intervals through the barrier layer. Condition (13a) is related to electron conductance; condition (13b) — to hole conductance of the structure. Further for more certainty we will consider the case of electron conductance.

If the condition (13a) is met, the maximum (positive) value of the square-law nonlinearity parameter β is achieved at $\alpha_{1,s}(\mathbf{k}_\perp) = 0\,(|\alpha_{2,s}(\mathbf{k}_\perp)| = 1)$ and $\alpha_{2,f}(\mathbf{k}_\perp) = 0\,(|\alpha_{1,f}(\mathbf{k}_\perp)| = 1)$. At opposite values $\alpha_{1(2),s(f)}(\mathbf{k}_\perp)$ the same value is achieved by absolute value, but with the opposite sign β. Let us consider the case of the positive value of parameter β. Let us also take into account the fact that in practically implemented structures meeting the condition (13a), $\int\limits_{S_{\mathbf{k}_\perp}} d\mathbf{k}_\perp f'\big(E_{1,f}(\mathbf{k}_\perp)\big) \ll \int\limits_{S_{\mathbf{k}_\perp}} d\mathbf{k}_\perp f'\big(E_{2,s}(\mathbf{k}_\perp)\big)$. As a result, for the first family of detectors we get the following expressions:

$$G = \frac{e}{4\pi^3\hbar} \int\limits_{S_{\mathbf{k}_\perp}} d\mathbf{k}_\perp f\big(E_{2,s}(\mathbf{k}_\perp)\big), \tag{14a}$$

$$\beta = e\frac{\int\limits_{S_{\mathbf{k}_\perp}} d\mathbf{k}_\perp f'\big(E_{2,s}(\mathbf{k}_\perp)\big)}{\int\limits_{S_{\mathbf{k}_\perp}} d\mathbf{k}_\perp f\big(E_{2,s}(\mathbf{k}_\perp)\big)}. \tag{14b}$$

The highest value is reached by β provided that

$$E_{2,s}(\mathbf{k}_\perp) \gg k_B T, \tag{15}$$

where T — structure temperature, k_B — Boltzmann constant. In this case

$$G \ll \frac{e^2 m^*_\perp k_B T}{2\pi^2\hbar^3}, \tag{16a}$$

$$\beta = \frac{e}{k_B T}, \tag{16b}$$

where $m^*_\perp$ — effective mass of electron in barrier layer.

The second family of the detectors is characterized by the condition opposite to (13a) and (13b), namely

$$\int\limits_{S_{\mathbf{k}_\perp}} d\mathbf{k}_\perp \sum_{i=1}^{2} |\alpha_{i,s}(\mathbf{k}_\perp)| f\big(E_{i,s}(\mathbf{k}_\perp)\big)$$

$$\sim \int\limits_{S_{\mathbf{k}_\perp}} d\mathbf{k}_\perp \sum_{i=1}^{2} |\alpha_{i,f}(\mathbf{k}_\perp)| f\big(E_{i,f}(\mathbf{k}_\perp)\big). \tag{17}$$

Therefore, conductance G may go to zero and take on negative values. Since the negative differential conductance is an unstable state of an electronic instrument, it may not be used for signal detection. Therefore, only the areas of parameters with $G > 0$ will be considered.

For the second family of detectors the maximum (positive) value of the square-law nonlinearity parameter is also achieved at $\alpha_{1,s}(\mathbf{k}_\perp)=0$ ($|\alpha_{2,s}(\mathbf{k}_\perp)|=1$) and $\alpha_{2,f}(\mathbf{k}_\perp)=0$ ($|\alpha_{1,f}(\mathbf{k}_\perp)|=1$). Expressions (11) and (12) will be recorded then as follows:

$$G = \frac{e}{4\pi^3\hbar}\int\limits_{S_{\mathbf{k}_\perp}} d\mathbf{k}_\perp \big\{ f\big(E_{2,s}(\mathbf{k}_\perp)\big) - f\big(E_{1,f}(\mathbf{k}_\perp)\big)\big\}, \tag{18a}$$

$$\beta = e\frac{\int\limits_{S_{\mathbf{k}_\perp}} d\mathbf{k}_\perp \big\{ f'\big(E_{2,s}(\mathbf{k}_\perp)\big) + f'\big(E_{1,f}(\mathbf{k}_\perp)\big)\big\}}{\int\limits_{S_{\mathbf{k}_\perp}} d\mathbf{k}_\perp \big\{ f\big(E_{2,s}(\mathbf{k}_\perp)\big) - f\big(E_{1,f}(\mathbf{k}_\perp)\big)\big\}}. \tag{18b}$$

The numerator in the expression for β reaches the highest value under the following conditions:

$$\min\nolimits_{\mathbf{k}_\perp} E_{2(1),s(f)}(\mathbf{k}_\perp) < 0, \quad |\min\nolimits_{\mathbf{k}_\perp} E_{2(1),s(f)}(\mathbf{k}_\perp)| \gg k_B T, \tag{19a}$$

$$\max\nolimits_{\mathbf{k}_\perp} E_{2(1),s(f)}(\mathbf{k}_\perp) > 0, \quad |\max\nolimits_{\mathbf{k}_\perp} E_{2(1),s(f)}(\mathbf{k}_\perp)| \gg k_B T. \tag{19b}$$

In this case,

$$G = \frac{e^2}{2\pi^2\hbar^3}\{ m^*_{\perp,1} |\min\nolimits_{\mathbf{k}_\perp} E_{2,s}(\mathbf{k}_\perp)| - m^*_{\perp,2} |\min\nolimits_{\mathbf{k}_\perp} E_{1,f}(\mathbf{k}_\perp)|\}, \tag{20a}$$

$$\beta = \frac{e^3(m^*_{\perp,1} + m^*_{\perp,2})}{2\pi^2\hbar^3 G} \equiv \frac{H}{G}, \tag{20b}$$

where $H = e^3(m^*_{\perp,1} + m^*_{\perp,2})/(2\pi^2\hbar^3)$, $m^*_{\perp,1(2)}$ — effective mass of charge carriers in the plane perpendicular to axis z in the first (second) electrode. Note that conductance G may regardless of H change its value within the wide limits due to the change of $|\min_{\mathbf{k}_\perp} E_{2,s}(\mathbf{k}_\perp)|$ and $|\min_{\mathbf{k}_\perp} E_{1,f}(\mathbf{k}_\perp)|$.

Using the found expressions for G and β let us analyze the current sensitivity of the first and second detector families. Current sensitivity S_I for a square-law detector may be recorded as follows [16]:

$$S_I = \frac{\beta}{2}\frac{1}{1 + r_s G + (2\pi f c)^2 r_s/G}, \tag{21}$$

where c — capacity of the barrier layer per unit of surface area, r_s — subsequent resistance to the barrier layer per unit of surface area, f — frequency of detected signal.

For the first detector family, if the condition (16a) is met, the parameter of square-law nonlinearity β does not depend on conductance G. In this case current sensitivity (21) reaches its maximum at

$$(2\pi f c)^2 r_s \ll G \ll \min\left\{\frac{e^2 m^*_\perp k_B T}{2\pi^2\hbar^3}, \frac{1}{r_s}\right\}, \tag{22a}$$

where

$$S_I = \frac{e}{2k_B T}. \tag{22b}$$

Let us assess the conductance values compliant with the condition of (22a). Let $m^*_\perp \sim 0.1 m_0$ [17], where m_0 — mass of free electron, $c \sim 1\,\mathrm{fF}/\mu\mathrm{m}^2$, $r_s \sim 100\,\Omega\cdot\mu\mathrm{m}^2$ [7,10], $f \sim 100\,\mathrm{GHz}$. Value of the specific capacity of the diode was obtained based on the equation for the flat capacitor capacity $c = \varepsilon_0\varepsilon/d$, where $d \sim 100\,\mathrm{nm}$ [7,10], and $\varepsilon \sim 10$ [17] — dielectric permeability of barrier layer; ε_0 — electric constant. Using the taken values, we obtain $4\cdot 10^{-5}\,1/(\Omega\cdot\mu\mathrm{m}^2) \ll G \ll 10^{-2}\,1/(\Omega\cdot\mu\mathrm{m}^2)$, which means that the conductance takes on values $G \sim 10^{-4}$–$10^{-3}\,1/(\Omega\cdot\mu\mathrm{m}^2)$). Besides, current sensitivity at room temperature ($T = 293\,\mathrm{K}$) is equal to $S_I = 19.8\,\mathrm{A/W}$.

For the second detector family the current sensitivity reaches its maximum at

$$G \ll 2\pi f c \cdot \min\{1, 2\pi f r_s c\}, \tag{23a}$$

then

$$S_I = \frac{e^3(m^*_{\perp,1} + m^*_{\perp,2})}{(2\pi)^4\hbar^3 (f c)^2 r_s}. \tag{23b}$$

To assess the conductance value that meets the condition (23a), let us take $c \sim 30\,\mathrm{fF}/\mu\mathrm{m}^2$, $r_s \sim 100\,\Omega\cdot\mu\mathrm{m}^2$ [8,9,18], $f \sim 100\,\mathrm{GHz}$. Note that the selected capacity value is 30 times higher than the corresponding value for the instruments of the first family, which is explained by different in the barrier layer thickness: compliance with the condition (17) is implementable only for tunnel mechanism of current flow, possible at barrier level thickness of $d \sim 1-10$ nm [8,9,18]. After substitution of numerical values into expression (23a) we obtain $G \ll 2 \cdot 10^{-2}\,1/(\Omega \cdot \mu\mathrm{m}^2)$, from which it follows that $G \lesssim 10^{-3}\,1/(\Omega \cdot \mu\mathrm{m}^2)$. Value of the current sensitivity of the second family detectors at the above values of parameters and $m^*_{\perp,1(2)} \sim 0.1 m_0$ [17] may be assessed as $S_I \sim 500$ A/W, which is approximately 20–30 times higher than the achievable value of current sensitivity for the first family detectors. More detailed analysis, however, may find that the obtained high value of current sensitivity for detectors from the second family may be achieved only in the mode of diode operation with bias, when the compliance with the conditions (19) is physically implementable.

Let us define the maximum achievable value of current sensitivity of detectors related to the second family in the mode of operation without bias. First, note that for diodes operating in this mode, $\max_{\mathbf{k}_\perp} E_{2,s}(\mathbf{k}_\perp) = \min_{\mathbf{k}_\perp} E_{1,f}(\mathbf{k}_\perp) \equiv E_0$. Second, you can show that the parameter of square-law nonlinearity β is a monotonously decreasing function of parameter $\Delta E = \max_{\mathbf{k}_\perp} E_{1,f}(\mathbf{k}_\perp) - \min_{\mathbf{k}_\perp} E_{2,s}(\mathbf{k}_\perp)$, and at $\Delta E \to 0$ the parameter is $\beta \to \infty$. For this reason we focus our attention on the case

$$\Delta E \lesssim k_B T. \qquad (24)$$

If this condition is met from expressions (18a), (18b) we find

$$G = \frac{e^2 m^*_\perp \Delta E^2}{(4\pi)^2 \hbar^3 k_B T}, \qquad (25a)$$

$$\beta = \frac{4e}{\Delta E} = e\sqrt{\frac{e^2 m^*_\perp}{\pi^2 \hbar^3 k_B T G}} \equiv \frac{I}{\sqrt{G}}, \qquad (25b)$$

where

$$I = e\sqrt{e^2 m^*_\perp/(\pi^2 \hbar^3 k_B T)},$$

$$m^*_\perp = m^*_{\perp,1} m^*_{\perp,2}/(m^*_{\perp,1} + m^*_{\perp,2}).$$

Current sensitivity (21) at the same time reaches its maximum, when

$$G = \frac{\sqrt{1 + 12(2\pi f r_s c)^2} - 1}{6 r_s} \lesssim \frac{e^2 m^*_\perp k_B T}{(4\pi)^2 \hbar^3}, \qquad (26a)$$

in this case,

$$S_I = \frac{e}{4(1 + 2 r_s G)} \sqrt{\frac{e^2 m^*_\perp}{\pi^2 \hbar^3 k_B T G}}. \qquad (26b)$$

Substituting to (26a)

$$c \sim 30\,\mathrm{fF}/\mu\mathrm{m}^2, \quad r_s \sim 100\,\Omega \cdot \mu\mathrm{m}^2 \text{ [8, 9, 18]},$$

$$f \sim 100\,\mathrm{GHz}, \quad m^*_{\perp,1(2)} \sim 0.1 m_0 \text{ [17]},$$

let us find $G \sim 0.9 \cdot 10^{-2}\,1/(\Omega \cdot \mu\mathrm{m}^2)$. Using this conductance value, from (26b) we obtain $S_I \sim 30$ A/W. Therefore, in the mode of operation without bias the maximum achievable value of current sensitivity for the detectors related to the second family is compared by the order of value to the value obtained for the detectors of the first family (see estimates of expressions (22a), (22b)).

Note that at the stage of obtaining the final expressions for conductance, parameter of square-law nonlinearity and current sensitivity, used for quantitative estimates, the approximation is introduced for the constancy (independence on the electron energy) of two-dimensional (in the plane perpendicular to the direction of current flow) density of states. In case of the parabolic law of dispersion it is precisely complied with. When deviating from the parabolic law of dispersion, one may identify a section of electron energies, which provide the main contribution to current transfer, and introduce a certain average density of states value in this section, which will impact the values of the effective masses of charge carriers $m^*_{\perp,1(2)}$ and $m^*_\perp$.

The important parameter of the diode is its impedance Z, which defines the possibility of the effective matching of the element with the transmission line. Using the equivalent scheme of the diode made of parallel-connected resistance and capacity of the barrier layer with a serial resistance thereto, one may find that [16]:

$$Z = \frac{1}{G + i2\pi f c} + r_s. \qquad (27)$$

Expression (27) makes it possible to assess the value of diode impedance for the considered families of detectors using the above values for c, r_s, f and the calculated value G. For detectors related to the first family, $Z \sim [3 - i16] \cdot 10^2 - [8 - i4] \cdot 10^2\,\Omega \cdot \mu\mathrm{m}^2$. For detectors related to the second family, $Z \sim [1 - i0.5] \cdot 10^2\,\Omega \cdot \mu\mathrm{m}^2$ in the mode of operation with bias and $Z \sim [1.2 - i0.4] \cdot 10^2\,\Omega \cdot \mu\mathrm{m}^2$ in the mode of operation without bias. For effective agreement of the diode with the transmission line in the wide band of frequencies it is necessary that $\mathrm{Re}(Z) \gtrsim |Im(Z)|$, which under certain values of parameters may be achieved for all considered types of detectors.

To estimate the limit power of the input signal $P_{RF,USL}$ (per unit of the diode structure surface area), when the conditions for implementation of the square-law detection mode are not complied with, let us use the equation

$$P_{RF,USL} \approx \frac{G}{8[1 + r_s G + (2\pi f c)^2 r_s/G] S_I^2}, \qquad (28)$$

which may be derived from the ratio between the power and the voltage of the input signal, and from the condition $V_{RF,USL} \sim 1/\beta$. Substituting to (28) the above specific values for every family of detectors c, r_s, f and the calculated values G and S_I, we find that $P_{RF,USL} \sim 3 \cdot 10^{-8} - 3 \cdot 10^{-7}$ W/μm^2 for detectors of the first family, $P_{RF,USL} \lesssim 10^{-11}$ W/μm^2 for detectors of the second family in the mode of operation with bias and $P_{RF,USL} \sim 2 \cdot 10^{-7}$ W/μm^2 in the mode of operation

Estimated values of characteristics of uncooled millimeter-wave detectors, examples of specific types of diodes

Family	Mode of operation	G, $1/(\Omega \cdot \mu\mathrm{m}^2)$	S_I, A/W	$Z, \Omega \cdot \mu\mathrm{m}^2$	$P_{RF,USL}, \mathrm{W}/\mu\mathrm{m}^2$	Examples
1	Without bias	$\sim 10^{-4}$–10^{-3}	~ 20	$\sim [300 - i1600]-[800 - i400]$	$\sim 3 \cdot 10^{-8}$–$3 \cdot 10^{-7}$	Schottky barrier diode [7], heterobarrier diode [10]
	With bias					
2	Without bias	$\sim 9 \cdot 10^{-3}$	~ 30	$\sim [120 - i40]$	$\sim 2 \cdot 10^{-7}$	Backward diode [8], resonant-tunneling diode [9]
	With bias	$\lesssim 10^{-3}$	~ 500	$\sim [100 - i50]$	$\lesssim 10^{-11}$	Tunnel diode [18]

without bias. Note that $P_{RF,USL} \propto 1/S_I^2$, therefore $P_{RF,USL}$ may be increased by decrease of S_I.

The table for both families and both modes of detector operation contains estimated value of the above analyzed parameters, and also the examples of the specific types of detector diodes with the corresponding references to a literature source.

Conclusion

In the paper within a single theoretical model the analysis was conducted, and quantitative estimates were obtained for the main characteristics of the uncooled diode millimeter-wave detectors. Analysis of expressions for conductance and parameter of square-law nonlinearity shows that all considered diodes may be divided into two families, which qualitatively differ by their detecting properties. The parameter of the square-law nonlinearity of the first family detectors is limited by value 40 A/W, while for the second family detectors this value may reach the infinity. This feature is eliminated by taking into account the spurious parameters of the diode, such as capacity and serial resistance. Nevertheless, the maximum current sensitivity of the second family detectors remains 20–30 times higher than in the first family detectors. With zero bias the maximum current sensitivity of both families of detectors is comparable and amounts to around 20–30 A/W. It is possible to specify as examples that the Schottky barrier diode and heterobarrier-based diode belong to the first family; the backward diode, resonant-tunneling diode and tunnel diode belong to the second family.

The proposed classification and the obtained estimate values of detector parameters in the considered class may be useful to select the optimal type of diode and preliminary forecasting of the achievable characteristics of the end devices, when the specific practical task is considered.

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Conflict of interest

The author declares that he has no conflict of interest.

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