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Nanophoton Generator of Picosecond Pulses

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Abstract: *Results of theoretical analyses of possibility of generations of periodic picosecond pulses of voltage are presented. This process is possible under condition of external electromagnetic radiation only. As an active element of such generator may be heterojunction in which the relaxation instability of electron concentration is developed. The possible variant of heterostructure and its static and time depended electric characteristics are demonstrated. Parameters of heterostructure and operating regimes can be select so that pulses of voltage will be in terahertz range.*

Keywords: *nanophotonics, generation, heterojunction, relaxation instability, picosecond pulses, terahertz frequency range, indium antimonide, bismuth.*

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1. Introduction

In papers [1, 2] were demonstrated that under some conditions in region near heterojunction between materials with different properties may develop the specific instability named as relaxation instability. Earlier this effect was suggested to be used for generation of electromagnetic waves of terahertz frequency range [3, 4].

Creation of such generator based on indium antimonide nanowires matrix is complex task that not solve before now. Here we present more simple construction that, as we hope, may be to realize with less difficulty.

2. Potential relief and static electric characteristics of heterostructure

As follow from results of papers [1, 2] for creation of conditions for relaxation instability development there is enough the structure consists of three heterojunctions that be formed the potential relief as presented on fig. 1. The left and right regions of this potential belonging to areas $[x_0, x_e)$ и $(x_c, x_1]$ correspond to contacts. Points x_e, x_j, x_c represent the conditional ("metallurgical") boundaries of heterojunctions.

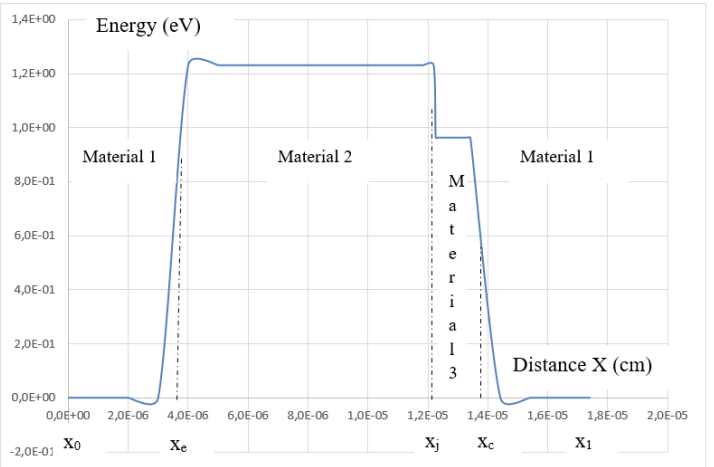


Fig. 1. Potential relief for electrons under zero voltage

For description of charge transport in this structure we will use the multicomponent model [5]. Suppose that electron gas is the mix of two components: component a is the electrons with energy more than maximum of potential; component b – is the electrons with energy less than maximum of potential. Then approximate one-dimensional equations for concentrations (n_a, n_b) and current densities (j_a, j_b) of such electrons may be wrote as [1, 2, 5]

$$\partial n_a/\partial t + e^{-1}\partial j_a/\partial x = -\hbar^{-1}(F_a - F_b)(n_a + n_b),$$
$$\partial n_b/\partial t + e^{-1}\partial j_b/\partial x = -\hbar^{-1}(F_b - F_a)(n_a + n_b). \quad (1)$$

Here e is the elementary charge; $\hbar$ is the reduced Planck constant; $F_{a,b}$ are the chemical potentials of a and b electrons.

Addition to equations (1) for self-consistent description of charge transport in heterostructure the Schrödinger and Poisson equations are necessary [2, 5]. The rations between electron concentrations, current densities and theirs

waves functions, chemical potentials and temperature are need. The rations between potential relief of heterostructure and electrostatic potential, zone structure and electron affinities of different materials and so on are necessary too. All these formulas and definitions are presented in papers [2, 5].

Equations (1) may be rewrite as

$$\partial n/\partial t \; + e^{-1}\partial j/\partial x = 0,$$

$$\partial(n_a - n_b)/\partial t \; + e^{-1}\partial(j_a - j_b)/\partial x = -(2/\hbar)(F_a - F_b), \qquad (2)$$

where $n = n_a + n_b$, $j = j_a + j_b$. First from equation (2) is the electron flux density conservation law, and second equation describe the dynamic of electrons chemical potentials difference.

Considering that temperature T is constant and neglecting by tunneling, we write

$$\partial n_{a,b}/\partial t = \Theta^{-1}\alpha_{a,b}\,\partial F_{a,b}/\partial t, j_{a,b} \approx -\sigma_{a,b}\,\partial F_{a,b}/\partial x. \qquad (3)$$

Here

$$\Theta = kT, \alpha_{a,b} = \Theta\partial n_{a,b}/\partial F_{a,b} > 0, \;\; \sigma_{a,b} \; = -\partial j_{a,b}/\partial(\partial F_{a,b}/\partial x) > 0, \quad (4)$$

k is the Boltzmann constant.

The values $\alpha_{a,b}$ have a dimension of concentration and are the electron concentrations in the case of Boltzmann statistics. The values $\sigma_{a,b}$ are the conductivities of electrons which allows, using the ratios

$$\mu_{a,b} = \sigma_{a,b}/\alpha_{a,b}\,, \qquad (5)$$

introduce the generalized mobilities $\mu_{a,b}$.

From equations (2) taking into account definitions (3) – (5) will obtain

$$\begin{gathered}\alpha_+\partial F_+/\partial t + \alpha_-\partial F_-/\partial t = (\Theta/e)\partial[\sigma_+\partial F_+/\partial x + \sigma_-\partial F_-/\partial x]/\partial x,\\ (\alpha_a\alpha_b/\alpha_+)\partial F_-/\partial t - (\Theta/e)\partial[(\alpha_a\alpha_b\mu_a\mu_b/\sigma_+)\partial F_-/\partial x]/\partial x = \\ = (\Theta/e)\{(e\mathrm{n}/\hbar)F_- - (\partial j/\partial x)[\alpha_a\alpha_b(\mu_a - \mu_b)/\alpha_+\sigma_+] - \\ -(j/2)\partial(\sigma_+/\sigma_-)/\partial x\}, \qquad (6)\end{gathered}$$

and the ratio is right

$$j = -(\sigma_+/2)\partial F_+/\partial x - (\sigma_-/2)\partial F_-/\partial x. \qquad (7)$$

Here

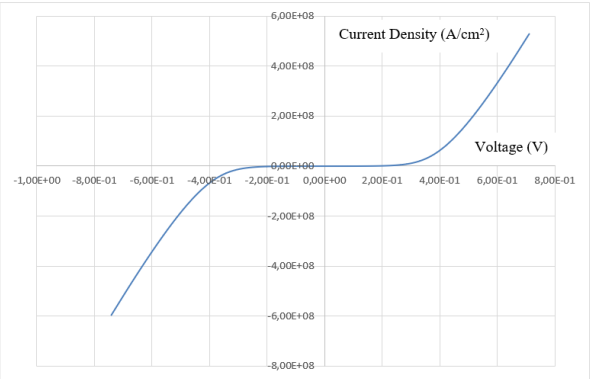
$$F_\pm = F_a \pm F_b, \alpha_\pm = \alpha_a \pm \alpha_b, \sigma_\pm = \sigma_a \pm \sigma_b. \qquad (8)$$

The chemical potentials on contacts must be equal to bias voltage with the reverse sign and multiplied to elementary charge. Therefor in points x_0 and x_1 we will assume

$$F_{-}(x_{0,1}) = 0, F_{+}(x_0) = 0, F_{+}(x_1) = -2eV, \quad (9)$$

where V is difference of the potentials between contacts.

a)



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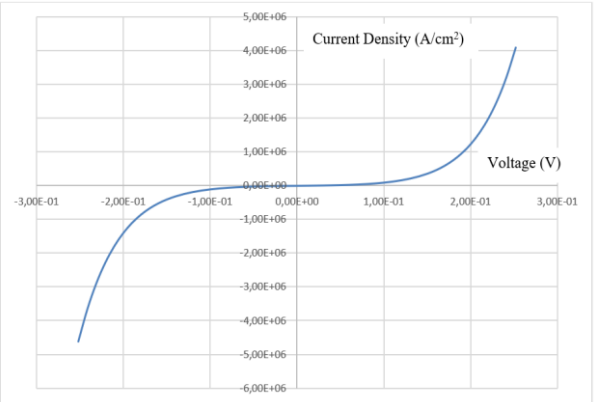


Fig. 2. Current-Voltage Characteristics of structure, presented on Fig. 1:
a – full characteristic, b – characteristic under low voltage

Detail analyses of static current-voltage characteristics of structure demonstrated on fig. 1 and factors defining their features is presented in book [2]. On fig. 2 the current-voltage characteristic of structure is shown. Nonlinear characteristic under low voltage is caused by nonequilibrium of electron gas.

Source of nonequilibrium is the current that flow perpendicular to heterojunction in point x_j. In accordance with equations (6) in static case when $j = j_0 = const$ the level of nonequilibrium may be calculate by approximate formula

$$F_-(x_j) = ej_0 r_j, \tag{10}$$

where

$$r_j = (\hbar/e^2)/(n(x_j)d_j), d_j^{-1} = -(1/2)\partial(\sigma_+/\sigma_-)/\partial x. \tag{11}$$

Value r_j is specific resistance of heterojunction in point x_j, d_j is effective width of this heterojunction, value $r_0 = \hbar/e^2 \approx 4{,}11\ k\Omega$ often referred to as fundamental resistance.

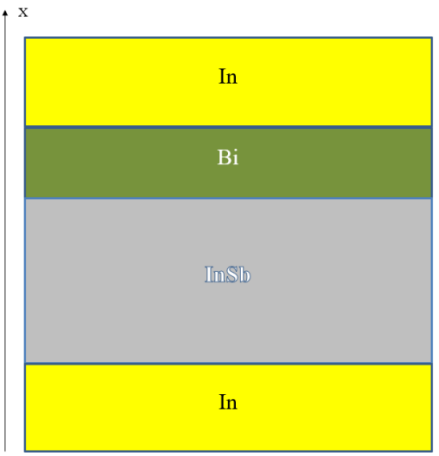


Fig. 3. Possible material realization of structure, presented on Fig. 1

Calculation of current-voltage characteristic was carried out at room temperature $T = 300\ K$ for structure in which as material 1 was indium (In), as material 2 was indium antimonide (InSb) and as material 3 was bismuth (Bi) as demonstrated on fig. 3. Influence of size effects to electron concentration and electron mobilities was taken to account [6, 7].

For the lengths

$$L_e = x_j - x_e, L_c = x_c - x_j \tag{10}$$

accepted the values $L_e = 72{,}0\ nm, L_c = 12{,}3\ nm$. They were selected so that dimensional quantization significantly reduces the electrons concentration in bismuth, but, at the same time, resistance of the device passive regions at low voltages would be much less than the resistance of the heterojunction r_j.

3. Conditions of relaxation instability development

Let for researched heterostructure some constant current density j_0 and voltage V_0 are correspond to stationary solution $F_{\pm}^0$ of task (6), (9). Let small fluctuations $F_{\pm}^1$ from this solution arose for some reason. Then

$$F_{\pm} = F_{\pm}^0 + F_{\pm}^1, \tag{11}$$

and conditions

$$\left|F_{\pm}^1\right| \ll \left|F_{\pm}^0\right|. \tag{12}$$

are satisfied.

In the areas $x \in (x_e, x_j) \cup (x_j, x_c)$ that do not include the small neighborhoods of the heterojunctions in the points x_e, x_j and x_c from equations (6) and (7) we obtain the approximate equations

$$\begin{gathered}
\alpha_+ \partial F_+^1/\partial t + \alpha_- \partial F_-^1/\partial t = -(2\Theta/e)(\partial j^1/\partial x), \\
(\alpha_a\alpha_b/\alpha_+)\partial F_-^1/\partial t - (\Theta/e)(\alpha_a\alpha_b\mu_a\mu_b/\sigma_+)\partial^2 F_-^1/\partial x^2 = \\
= -\tau_0^{-1} n_0 F_-^1 - (F_-^0/2\hbar)(\alpha_+ F_+^1 + \alpha_- F_-^1) - \\
-(\Theta/e)(\partial j^1/\partial x)[\alpha_a\alpha_b(\mu_a - \mu_b)/\alpha_+\sigma_+], \\
j^1 = -(\sigma_+/2)\partial F_+^1/\partial x - (\sigma_-/2)\partial F_-^1/\partial x,
\end{gathered} \tag{13}$$

where

$$\tau_0 = \hbar/\Theta. \tag{14}$$

All coefficients here are calculate under conditions $F_{\pm}^1 = 0$.

At some point x in considered area let assume

$$F_{\pm}^1(x,t) = F_{\pm}^1(q)\exp\{-\gamma t\}\cos(qx). \tag{15}$$

Substituting expression (15) into equations (13) and preserving terms that linear by deviations from stationary solution leads to the system of two homogeneous algebraic equations of the first order for amplitudes $F_{\pm}^1(q)$

$$\begin{gathered}
\gamma(\alpha_a\alpha_b/\alpha_+)F_-^1 - (q^2\Theta/e)(\alpha_a\alpha_b\mu_a\mu_b/\sigma_+)F_-^1 - \\
-\tau_0^{-1} n_0 F_-^1 - (F_-^0/2\hbar)(\alpha_+ F_+^1 + \alpha_- F_-^1) + \\
+(q^2\Theta/2e)(\mu_a - \mu_b)(\alpha_a\alpha_b/\alpha_+\sigma_+)(\sigma_+ F_+^1 + \sigma_- F_-^1) = 0, \\
\gamma(\alpha_+ F_+^1 + \alpha_- F_-^1) - (q^2\Theta/e)(\sigma_+ F_+^1 + \sigma_- F_-^1).
\end{gathered} \tag{16}$$

System (16) have nontrivial solutions if its determinant equal zero only, from which follows

$$\gamma^2 - \gamma\tau_0^{-1}\vartheta + \tau_0^{-2}\Delta = 0, \tag{17}$$

where

$$\vartheta = \xi_a^2 + \xi_b^2 + \beta, \Delta = \xi_a^2\xi_b^2 + \left(\beta_b\xi_a^2 + \beta_a\xi_b^2\right) - (\tau_0/\tau_F)\left(\xi_a^2 - \xi_b^2\right), \quad (18)$$

$$\xi_{a,b} = qL_{a,b}, \beta = \beta_a + \beta_b, \beta_{a,b} = n_0/\alpha_{a,b}, \tau_F = \hbar/F_-^0, \quad (19)$$

$$L_{a,b} = (\hbar\mu_{a,b}/e)^{\frac{1}{2}} \quad (20)$$

are the lengths of a and b electrons relaxations to the state of chemical equilibrium.

The value τ_F may be interpreted as an average transit time of nonequilibrium electrons through heterojunction. Indeed, from expressions (19), (10) and (11) follow that

$$\tau_F = d_j/v_j(x_j),$$

where

$$v_j(x_j) = j_0/en(x_j)$$

is average speed of electrons in heterojunction.

Values ϑ and τ_0 are positive, therefore (see book [8]) it is possible three types of singularities of equations (13) only:

– stable nodal point when $0 < 4\Delta < \vartheta^2$, and $Im(\gamma_{1,2}) = 0, Re(\gamma_{1,2}) > 0$;
– stable focus point when $\vartheta^2 < 4\Delta$, and $Im(\gamma_{1,2}) \neq 0, Re(\gamma_{1,2}) > 0$;
– saddle point when $\Delta < 0$, and $Im(\gamma_{1,2}) = 0, Re(\gamma_1) > 0, Re(\gamma_2) < 0$.

Stable focus point correspond to existence of relaxed periodic oscillations in structure with frequencies

$$\omega_{1,2} = Im(\gamma_{1,2}) = \pm(1/2\tau_0)[-(4\tau_0/\tau_F)\left(\xi_a^2 - \xi_b^2\right) - (\xi_a^2 - \xi_b^2)^2 - \\ -2(\beta_a - \beta_b)\left(\xi_a^2 - \xi_b^2\right) - \beta^2]^{1/2}, \quad (21)$$

and decrement

$$\lambda = Re(\gamma_{1,2}) = (1/2\tau_0)(\xi_a^2 + \xi_b^2 + \beta). \quad (22)$$

It is possible only if the following conditions are satisfied

$$q \neq 0, \quad (23)$$

$$\mu_a \neq \mu_b \quad (24)$$

and

$$(4\tau_0/\tau_F)\left(\xi_a^2 - \xi_b^2\right) < -\{[\left(\xi_a^2 - \xi_b^2\right) + (\beta_a - \beta_b)]^2 + 4\beta_a\beta_b\}. \quad (25)$$

Condition (23) require the existence of space-periodic perturbations of chemical potentials of electrons in the structure. For example, such perturbations may be caused by external electromagnetic wave with small amplitude in wavelength range less than red boundary of absorption.

Conditions (24) refer to local generalized mobilities in point and do not refer to mobilities in different materials directly. Values $\mu_a(x)$ and $\mu_b(x)$ in the case of nanometer sizes of structure layers significantly depend from many factors that determine the probabilities of electrons stochastic scattering under different energies. Taking these factors into account is very difficult task. Therefore, for certainty of further estimations we will assume that near the heterojunction placed in point x_j,

$$\mu_a > \mu_b. \tag{26}$$

If inverse inequality will satisfied, then in further expressions will necessary to change signs of all currents densities.

From formulas (10), (11), (19) and (25) follows the expression for boundary current density for relaxed oscillations development

$$j_\omega = (\Theta/4er_j)\{[(\xi_a^2 - \xi_b^2) + (\beta_a - \beta_b)]^2 + 4\beta_a\beta_b\}/|\xi_a^2 - \xi_b^2|. \tag{27}$$

Value j_ω is positive. If inequality (26) is true, then relaxed oscillations of chemical potentials and electron concentrations in structure will develop when $j < -j_\omega$, in alternative case they will develop when $j > j_\omega$.

Saddle region correspond to relaxation instability of chemicals potentials and electron concentrations in structure. Necessary conditions of relaxation instability development are inequalities (23), (24) and next inequality

$$(\tau_0/\tau_F)(\xi_a^2 - \xi_b^2) > \xi_a^2\xi_b^2 + \beta_b\xi_a^2 + \beta_a\xi_b^2, \tag{28}$$

that define boundary current density of this effect

$$j_\varkappa = (\Theta/er_j)(\xi_a^2\xi_b^2 + \beta_b\xi_a^2 + \beta_a\xi_b^2)/|\xi_a^2 - \xi_b^2|. \tag{29}$$

As well as j_ω value $j_\varkappa$ is positive. If inequality (26) is true, then relaxation instability in structure will develop when $j > j_\varkappa$, in alternative case it will develop when $j < -j_\varkappa$.

Value of current density equal $j_\varkappa$ is the bifurcation point for system of equations (13). Except for the solution described exponentially rapid relaxation of small perturbations of difference of electron chemical potentials with decrement

$$\gamma_1 = (1/2\tau_0)\{(\xi_a^2 + \xi_b^2 + \beta) + [(\xi_a^2 + \xi_b^2 + \beta)^2 - \\ -4\xi_a^2\xi_b^2 - 4(\beta_b\xi_a^2 + \beta_a\xi_b^2) + (4\tau_0/\tau_F)(\xi_a^2 - \xi_b^2)]^{\frac{1}{2}}\}, \tag{30}$$

when $|j| > j_{\varkappa}$ appear the solution that describe them exponentially rapid increasing with increment

$$\varkappa = -\gamma_2 = (1/2\tau_0)\{[(\xi_a^2 + \xi_b^2 + \beta)^2 - 4\xi_a^2\xi_b^2 - 4\left(\beta_b\xi_a^2 + \beta_a\xi_b^2\right) + \\ +(4\tau_0/\tau_F)\left(\xi_a^2 - \xi_b^2\right)]^{1/2} - \left(\xi_a^2 + \xi_b^2 + \beta\right)\}. \quad (31)$$

As for electron concentrations the simple estimations are true

$$n_a \approx n_{a0}\exp\{F_-^1/2kT\}, n_b \approx n_{b0}\exp\{-F_-^1/2kT\}, \quad (32)$$

therefore, if condition (26) is satisfied, that a-electron concentration increase fasterly than difference of chemical potentials.

Corresponding to condition (28) instability of stationary task solution for electron chemical potentials develop in the case when the average transit time of nonequilibrium electrons through heterojunction area τ_F will become less than effective time of chemical potentials difference relaxation to zero

$$\tau_{rel} = \tau_0|\xi_a^2 - \xi_b^2|/(\xi_a^2\xi_b^2 + \beta_b\xi_a^2 + \beta_a\xi_b^2), \quad (33)$$

Thus, nonequilibrium electrons do not have time to relax in heterojunction neighborhood and them concentration in adjacent areas is increase.

If the initial equations (6), (7) were linear that the relaxation instability will leads to catastrophic decreasing of structure resistance, increasing of current and to irreversible electrical breakdown. Nonlinear dependance of electron concentrations from chemical potentials (see formulas (32)) and expressions (10), (11) make it possible the scenario in which increasing of concentrations will stop before the irreversible electrical breakdown will happen and difference F_-^1 will achieve nonzero but finite value [9]. As a result of such process the complex singular point named saddle-nodal will formed from which under some conditions the limit cycle will developed.

4. Stimulated generation of periodic picosecond pulses

As follow from condition (23) for relaxation instability or relaxed oscillations realization it is necessary small space-periodic perturbation of chemical potentials. Such perturbation may be created by external electromagnetic radiation with wavelength less than red boundary of absorption in structure. In this case the electron concentration and chemical potentials will change by internal photoeffect.

Boundary current density of relaxation instability and increment of instability increasing defined by expressions (29) and (31). At room temperature the estimations are true: $\Theta \approx 0{,}026\ eV;\ 1/2\tau_0 \approx 19{,}8\ THz; L_{a,b} \sim 10^{-6}\ cm;\ \beta, \beta_{a,b} \sim 1$. If

the width of heterojunction in point x_j is about lattice constant of indium antimonide (0,648 nm) then under zero voltage $r_j \sim 10^{-6}\ \Omega \times cm^2$.

From these estimations follow that if wavelength

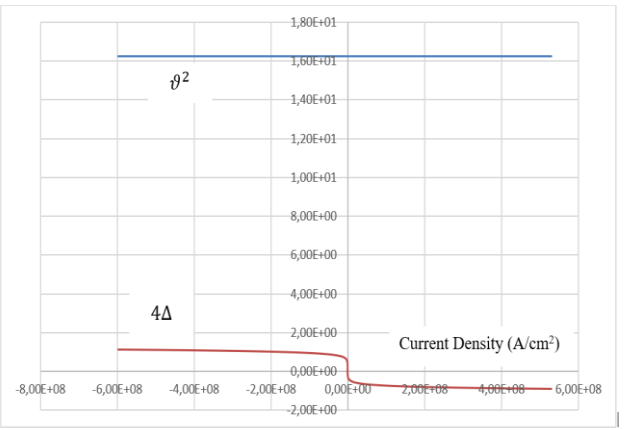
$$\lambda = 1/q \tag{34}$$

of stimulating radiation satisfies inequalities

$$\lambda \gg L_{a,b} \rightarrow \xi_{a,b} \ll 1, \tag{35}$$

then boundary current density $j_\varkappa$ is about $10^4\ A/cm^2$.

To ensure the picosecond duration of instability development the expression in figure bracket in formula (31) must be no less than 0,1. It may be reach by increasing of operating current density to one or two orders compared to $j_\varkappa$ and by maximum decreasing wavelength λ for the goal to increase values of $\xi_{a,b}$.



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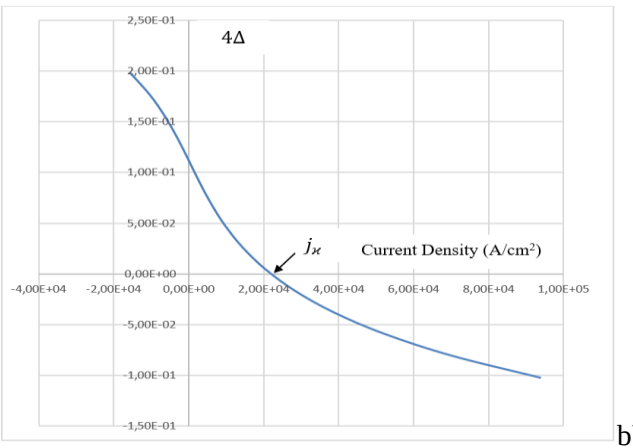


b)

Fig. 4. Parameters θ^2 *and* 4Δ as functions of current density under condition $\lambda = 598\ nm$

On fig. 4 the typical behavior of parameters θ^2 and 4Δ as functions of current density is demonstrated. It can be seen (see fig. 4 a) that region of relaxed oscillations ($4\Delta > \vartheta^2$) is practically unattainable under reasonable values of current densities. Opposite the region of relaxation instability ($\Delta < 0$) is achievable easily. Boundary current density $j_\varkappa$ equal $2{,}83 \times 10^4\ A/cm^2$ when wavelength λ of stimulating radiation equal $598\ nm$ that correspond to voltage equal $0{,}06\ V$ (see fig. 2 b).

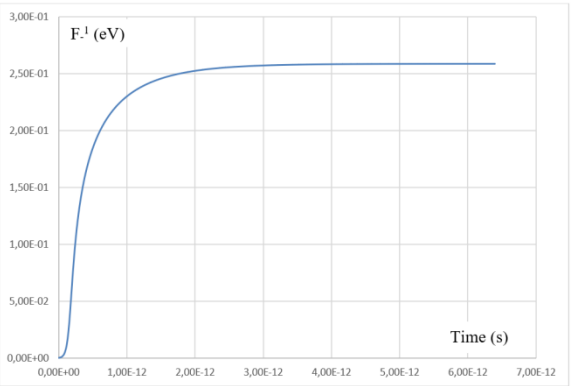


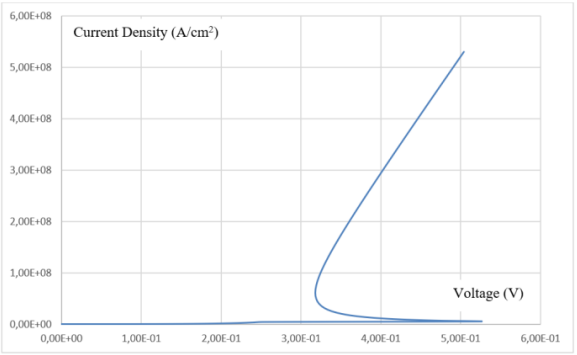
Fig. 5. Value F_-^1 near the heterojunction in point x_j as a function of time after short pulse of stimulating radiation with $\lambda = 598\ nm$

At wavelength equal $598\ nm$ and current density equal $4{,}10 \times 10^6\ A/cm^2$ ($V = 0{,}252\ V$) the increment of perturbation increasing is $32{,}6\ THz$. If stimulating radiation acts a very short period of time much less than $\tau_\varkappa = 1/\varkappa \approx 3{,}06 \times 10^{-14}\ s$ then function $F_-^1(t)$ near the heterojunction reaches the limit value F_{-max}^1 equal $0{,}259\ eV$, as demonstrated on fig. 5, and stabilized in this level.

Note that the value F_{-max}^1 on fig. 5 is the same order as a bias voltage and conditions (12) at $(t - t_0) \gg \tau_\varkappa$ not satisfy. Hereinafter, it is accepted that initial moment of time $t_0 = 0$. Presented results were obtained by numerical solution of task where in initial moment of time amplitude of perturbation was equal $0{,}00026\ eV$ only and satisfy to conditions (12). Numerical experiment demonstrated that if condition (12) satisfied in initial moment of time that value F_{-max}^1 do not depend from amplitude of perturbation practically.

In papers [4, 10] the experimental current-voltage characteristics of indium antimonide nanowires in matrix of alumina oxide with copper contacts were presented. Curves of current-voltage characteristics are nonmonotonic, they have hysteresis and jumps that analogical of demonstrated on fig. 6 b. These features may be interpreted as a result of electron gas relaxation instability in

heterojunction between nanowire and contact [1,2] stimulated by natural lighting. The rationale of such interpretation requires further careful experimental researches and calculations.



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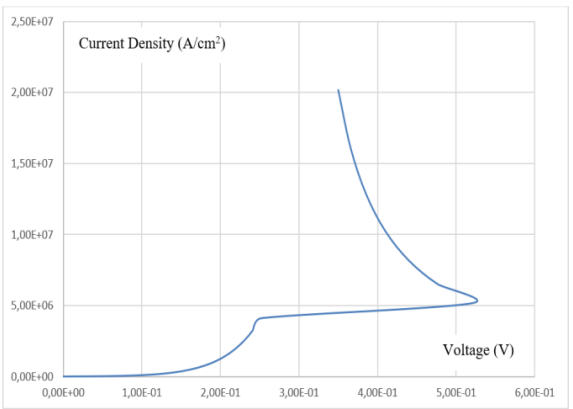


b)

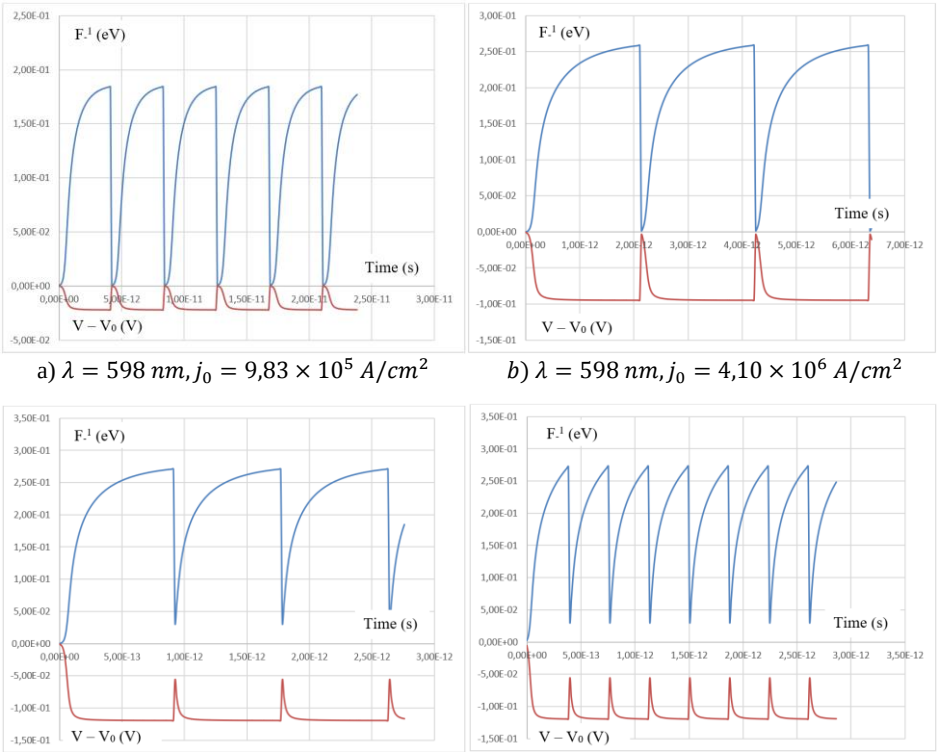
Fig. 6. Current-Voltage Characteristic of structure, presented on Fig. 1, after short pulse of stimulating radiation with $\lambda = 598\ nm$: a – characteristic under $V > 0$, b – range of characteristic with features caused by relaxation instability

When function $F_{-}^{1}(t)$ reaches the value F_{-max}^{1} increment of perturbation increasing $\varkappa$ and parameter Δ become zeros. Saddle singular point of equation (13) turns to complex singular point saddle-nodal. If any new perturbations are absent the system may to be in such neutral state infinity long time. However, any new small perturbation of electron chemical potentials will change the parameter Δ and shift the system either towards of stable nodal or towards saddle back. In any of these two cases function $F_{-}^{1}(t)$ will exponentially decrease to zero.

As such perturbation may be the permanent stimulating electromagnetic radiation. If in this case the current density j_0 is constant that when function $F_{-}^{1}(t)$ will reach values near zero stimulating radiation may move the transport

equations solution to the exponentially increased branch again and process will repeat. Thus, in the systems the periodic process (limit cycle) appears.

On fig. 7 results of calculations of function $F_{-}^{1}(t)$ near the heterojunction in point x_j and difference of voltages $V - V_0$ on structure's contacts under different values wavelengths of stimulating radiation λ and current density j_0 are presented. Results of electron concentration calculations in the same space point that F_{-}^{1} are demonstrated on fig. 8.



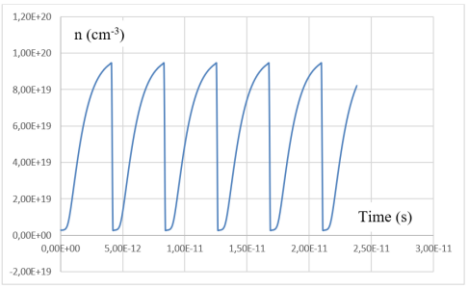
a) $\lambda = 598\ nm, j_0 = 9{,}83 \times 10^5\ A/cm^2$ *b*) $\lambda = 598\ nm, j_0 = 4{,}10 \times 10^6\ A/cm^2$

c) $\lambda = 399\ nm, j_0 = 5{,}17 \times 10^6\ A/cm^2$ d) $\lambda = 399\ nm, j_0 = 8{,}17 \times 10^6\ A/cm^2$

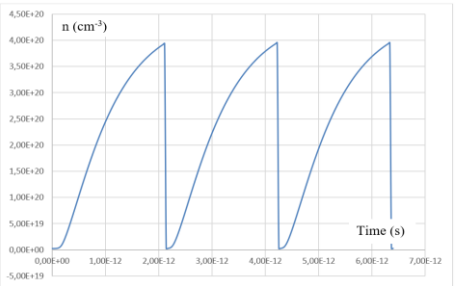
Fig. 7. F_{-}^{1} *and* $V - V_0$ as functions of time under different current densities j_0 and wavelength of simulating radiation λ

At constant current density the pulses of F_{-}^{1} appear in the structure. As a result of these pulses, we see the periodic changes of electron concentration, resistance of structure and voltage on structure's contacts. Decreasing of wavelength λ and increasing of current density j_0 are lead to decreasing of pulses period and they frequency increasing. When $\lambda = 598\ nm$ four times increasing of current density change the frequency from $244\ GHz$ to $474\ GHz$. When

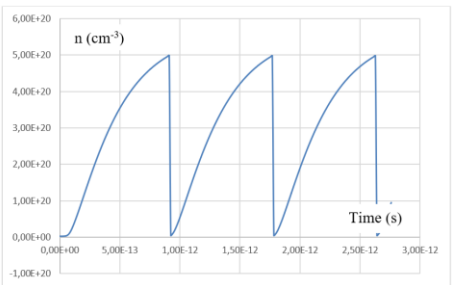
$\lambda = 399\ nm$ one and a half times increasing of current density increase the frequency from $1{,}10\ THz$ to $2{,}61\ THz$. With increasing of current density, the amplitudes of electron concentrations pulses and voltage pulses first increase and then stabilize near some values.



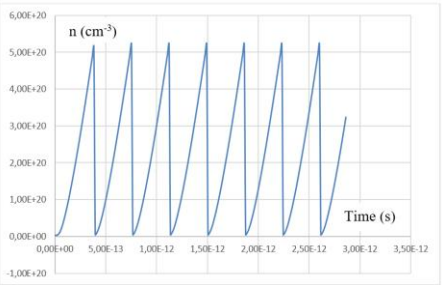
a) $\lambda = 598\ nm, j_0 = 9{,}83 \times 10^5\ A/cm^2$



b) $\lambda = 598\ nm, j_0 = 4{,}10 \times 10^6\ A/cm^2$

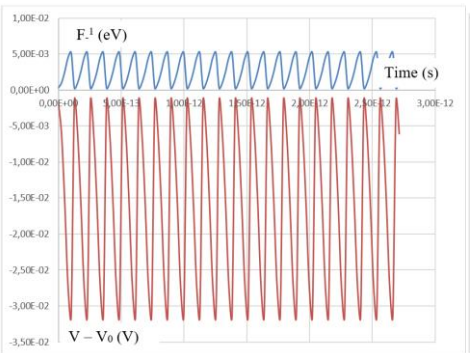


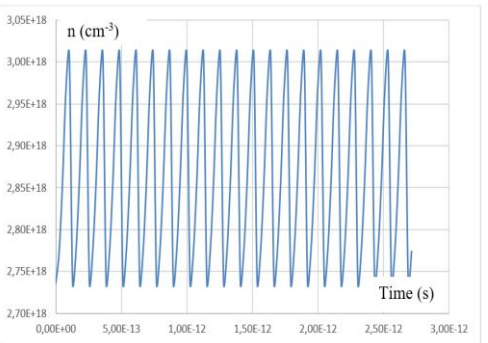
c) $\lambda = 399\ nm, j_0 = 5{,}17 \times 10^6\ A/cm^2$



d) $\lambda = 399\ nm, j_0 = 8{,}17 \times 10^6\ A/cm^2$

Fig. 8. Electron concentration n as a function of time under different current densities j_0 and wavelength of simulating radiation λ





$\lambda = 4{,}09\ nm, j_0 = 1{,}41 \times 10^7\ A/cm^2$

Fig. 9. F_{-}^{1} , $V - V_0$ and electron concentration n as functions of time for very shot wavelength

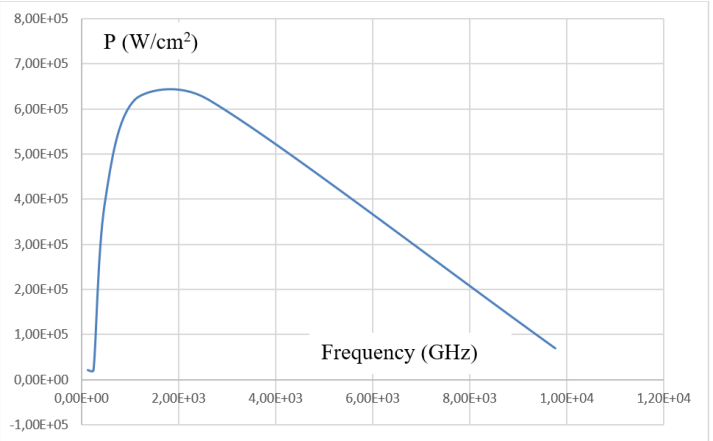


Fig. 10. Specific power as a function of pulses frequency

It is interesting to calculate the parameters of pulses when wavelength of stimulating radiation is very short. Results of such calculation for X-ray range ($\lambda = 4{,}09\ nm$) demonstrated on fig. 9. It can be seen that pulses frequency increase considerably (to $9{,}77\ THz$) but they amplitude decrease. The calculated dependance of specific power of radiation from frequency is presented on fig. 10. This curve confirms the noted trend.

5. Conclusion

Theoretical analysis of electric current flow through heterojunction shows that under some conditions in area near heterojunction may developed instability leads to fast increasing of small perturbations of electron concentration. This increasing is limited by nonlinear dependance of electron concentration from chemical potentials. The process may reach to the irreversible electrical breakdown of structure or to electron concentration stabilization in some new nonequilibrium level.

Small perturbations of electron concentration may be caused by electromagnetic radiation with wavelength less than red boundary of absorption in structure. In this paper we demonstrated that under conditions of such stimulating radiation and constant current density in heterostructure may develop the periodic process of electron concentration changes that leads to periodic pulses of voltage on structure's contacts.

Parameters of heterostructure, operating current density and wavelength of stimulating radiation can be select so that pulses will picosecond and they frequency will be in terahertz range.

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