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Dynamic thermoelectric model of a heterojunction bipolar transistor taking into account the voltage drop on the emitter metallization tracks

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Abstract: **A dynamic 3D thermoelectric model has been developed to calculate the temperature field and emitter current density in the comb structure of a heterojunction bipolar transistor (HBT) with the length of the emitter metallization paths comparable to the size of the crystal, taking into account the inhomogeneous distribution of current density under the emitter paths caused by a voltage drop on the resistance of the current-carrying metallization. The model is based on an iterative solution in the COMSOL Multiphysics software environment of a non-stationary heat equation together with a system of equations for the distribution of electric potential along the emitter path and the current density under the path. It is shown that during the action of the heating power pulse in the HBT, the distribution of temperature and current density along the emitter tracks change character, respectively, from homogeneous and monotonically decreasing to non-monotonically changing. At the same time, the maximum temperature and current density reach stationary values with a rate significantly exceeding the rate of overheating increase with homogeneous heating of the structure, and the maxima of temperature and current density in the process of self-heating shift from the beginning to the center of the tracks. The proposed model can be used to evaluate the thermomechanical stresses in the structure of the HBT and the limiting electrical parameters in the pulsed modes of operation of the HBT.**

Keywords: **heterojunction bipolar transistor, dynamic thermoelectric model, current density, temperature, inhomogeneity**

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1. INTRODUCTION

Along with the active development of MIS and HEMT microwave transistors, modern radio and telecommunications equipment widely uses high-power bipolar (BT), including heterojunction (HBT), microwave transistors [1-4]. Devices of this class are the least reliable as part of modern radio-electronic systems for various purposes, since they operate in the most severe thermal and electrical conditions. This class of devices is characterized by the presence of a strong positive thermal feedback (PTF) and the manifestation of the effects of an inhomogeneous and unstable distribution of current density, power and temperature in transistor structures [5-7], which lead to local overheating and thermomechanical stresses of the structure and, as a result, to the acceleration of degradation mechanisms and instrument failures.

One of the most common geometries of the structures of modern high-power BTs and HBTs is a strip or comb geometry with a parallel arrangement of elementary transistors (cells) of HBTs (see **Fig. 1** [4] and **Fig. 2** [7]). Self-heating of each HBT cell by dissipated power and thermal coupling between neighboring cells lead to an uneven temperature profile of the HBT elementary transistor matrix. Due to the positive temperature coefficient of the emitter current, currents of higher density will flow through the central cells of the HBT with a higher temperature, which

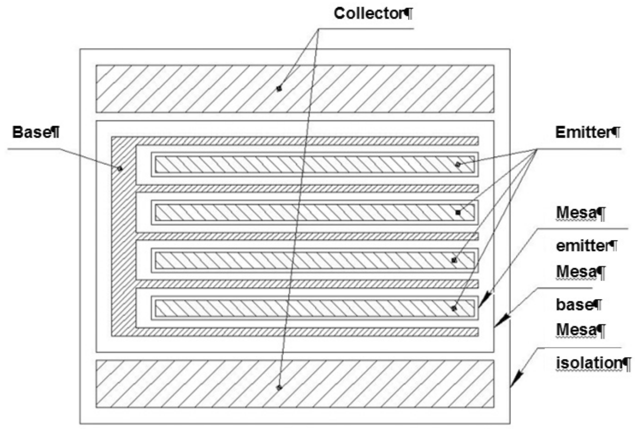

Fig. 1. *Topology of the HBT active region* [4].

leads to an increase in heat release, which can ultimately lead to thermal breakdown or degradation of the device [8, 9], which is especially strong. manifests itself at high levels of injection [10].

In order to reduce the uneven temperature distribution and solve these thermal problems, various options for one-dimensional geometry design are used, including changing the length of the emitter in HBT cells [7] and changing the distance between emitters between HBT cells [8], which allows to reduce the temperature difference between individual cells.

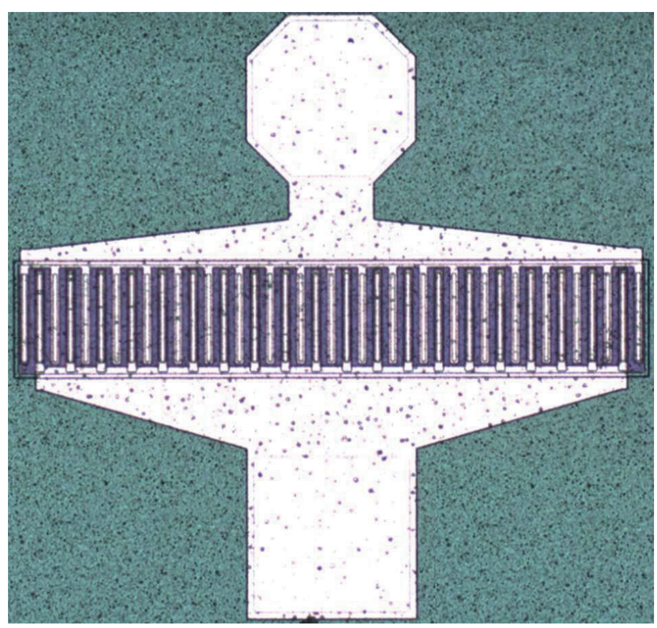

Fig. 2. *Comb structure of HBT with 20 elementary transistors* [7].

In well-known works, thermoelectric processes in comb-like HBT structures were considered without taking into account the voltage drop on the current-carrying tracks of emitter metallization, which leads to a significant inhomogeneous distribution of the emitter current density, and hence the power dissipation density along the emitter tracks [11-13].

In [14], we considered a stationary thermoelectric model of the HBT microwave transistor structure, taking into account the voltage drop on the current-carrying tracks of the emitter metallization. It is shown that the distributions of temperature and current density along the emitter tracks of the structure change their character: from monotonically and weakly decreasing from the beginning of the track to the end in the isothermal approximation, these distributions become nonmonotonic and essentially inhomogeneous. In addition, the maximum current density and temperature shift from the beginning to the center of the track with an increase in the operating current. Note that for semiconductor structures, it is not the absolute deviation of the local temperature of the structure from the average value that is critically important, but the gradient of temperature change, which determines the level of thermomechanical stresses and the dynamics of electromigration processes in the elements of the structure [15].

In radio-electronic systems of HBT microwave transistors, as a rule, operate not in stationary, but in pulsed modes with the duration and duty cycle of the pulses varying over a wide range. In this case, it is obvious that during the action of the dissipated power pulse, the distribution of current density and temperature in the structure will be transformed. This article presents a 3D thermoelectric model for calculating the temperature field and the distribution of the emitter current density in the comb structure of the GBT, taking into account the joint influence of all the above factors of the inhomogeneous distribution of current and temperature in the device structure, including the inhomogeneous distribution of the current density under the emitter tracks as a result of the voltage drop across resistance of current-carrying metallization.

2. THERMOELECTRIC MODEL

Fig. 3 shows the geometry of the HBT semiconductor structure model used in calculating the temperature fields, which is a rectangular semiconductor crystal with dimensions $l_x \times l_y \times l_z$, with emitter metallization tracks located on its upper surface with dimensions $a_e \times L_e \times h_e$. The crystal is placed on an ideal heat sink with temperature T_0. As in [14], assuming the emitter tracks to be narrow, we neglect the effect of pushing the emitter current to the side edges of the tracks along the coordinate x.

The temperature field in the HBT structure $T(x,y,z,t)$ at an arbitrary time t in the process of self-heating of the structure by a heating power pulse is found from the solution of the non-stationary heat conduction equation

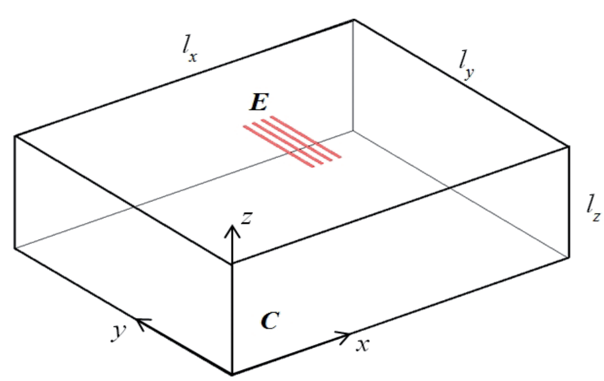

Fig. 3. *Geometry of the HBT structure model: E – emitter, C - semiconductor crystal.*

$$c(T)\,\rho(T)\frac{\partial T}{\partial t}+\nabla_{x,y,z}\left(\lambda(T)\nabla_{x,y,z}T\right)=0, \qquad (1)$$

where c, ϱ, λ – coefficients of heat capacity, density and thermal conductivity of the crystal material, with the following boundary conditions:

- side surfaces and the upper surface of the crystal are thermally insulated;
- the temperature of the lower surface of the crystal is equal to the temperature of the heat sink T_0;
- on the upper surface in the region of the emitter of the structure, the heating power density is given, which is determined by the formula:

$$q_e(T)=-\lambda(T)\frac{\partial T}{\partial z}\bigg|_{z=l_z}=\begin{cases}J_e(T)U_c,(x,y)\in S_e\\ 0,(x,y)\in S-S_e\end{cases}, \qquad (2)$$

where S, $S_e = na_eL_e$ – area of the upper surface of the crystal and its active region, n – number of emitter tracks, J_e, U_c – emitter current density and collector voltage.

As an initial condition for the temperature in solving equation (1), a uniform temperature distribution over the HBT structure was taken

$$T(x,y,z,0) = T_0. \qquad (3)$$

Emitter current density distribution J_e under the track of the emitter metallization of the structure is found from the solution of the following system of equations:

$$J_e(T)= \\ =J_{e0}(T/T_0)^3\exp\left\{\frac{-E_g+e\left(U_e-\varphi_e-rS_en^{-1}J_e(T)\right)}{kT}\right\}, \qquad (4)$$

where J_{e0} – parameter weakly dependent on temperature, U_e – direct voltage drop across the emitter *p-n* junction, E_g – semiconductor bandgap, e – electron charge, φ_e – emitter metallization potential, r – transistor input ohmic resistance, k – Boltzmann's constant;

$$\frac{dJ_{em}(y)}{dy}=-\frac{J_e(y)}{h_e}, \qquad (5)$$

$$\frac{d\varphi_e(y)}{dy}=-\frac{J_{em}(y)}{\sigma_{em}}, \qquad (6)$$

$$J_{em}(y_{eb})=I_e/h_ea_e, \qquad (7)$$

$$J_{em}(y_{ee})=0, \qquad (8)$$

$$\frac{d\varphi_e}{dy}\bigg|_{y=y_{eb}}=-\frac{I_e}{\sigma_{em}h_ea_e}, \qquad (9)$$

$$\frac{d\varphi_e}{dy}\bigg|_{y=y_{ee}}=0, \qquad (10)$$

where I_e – total emitter current, J_{em} – current density by emitter track metallization, y_{eb} and y_{ee} – track start and end coordinates, σ_{em} – specific conductivity of emitter track metallization.

To ensure the condition for switching on the transistor in an electrical circuit (constancy of the total emitter current I_e) it is necessary that the equality be satisfied:

$$\iint_{S_e}J_e(x,y,t)\,dx\,dy=I_e. \qquad (11)$$

3. SOLUTION OF THE PROBLEM AND RESULTS OF CALCULATIONS

The model non-stationary problem (1)-(11) was solved by the method of successive time intervals [16], that is, the entire time of the heat transfer process was divided into a number of intervals $\Delta t = t_j - t_{j-1}$, within which the non-stationary heat conduction equation was solved with the initial power density $q_{ej}(x,y,l_z,t_{j-1})$ and temperature $T_j(x,y,l_z,t_{j-1})$ distributions, found as a result of solving on previous interval. The values of the potentials U_e and φ_e were found by a numerical iterative method, a similar algorithm of which is presented in [17]. As an initial approximation of the dependence $J_e^0(y)$ in the iterative process, the current density values calculated by the formula [18] were chosen:

$$J_e^0(y)=\frac{2\varphi_{T_0}}{L_ea_eR_e}\cdot\frac{C^2}{\cos^2\left[C(1-y/L_e)\right]}, \qquad (12)$$

where $\varphi_{T_0} = \frac{kT_0}{e}$ – temperature potential at T_0 = 300 K, the value of which is equal to 26 мВ; R_e – metallization resistance of the emitter track, and the constant C is found from the solution of the equation $C\text{tg}C = R_e I_e / 2n\varphi_{T0}$.

The original program included an appeal to the COMSOL Multiphysics interactive software environment. As in [14], an InGaP/GaAs GBT with a crystal size of 300×250×100 microns and an active transistor structure with four gold emitter tracks with a width a_e = 2 microns and a thickness of h_e = 0.5 microns was chosen as the calculated base object of the study, while the length of the tracks during calculations varied and was set within L_e = (40÷80) microns. The functional dependences on the temperature of the thermophysical characteristics c, ϱ, λ of the crystal material were selected from the COMSOL program materials database. The temperature of the ideal heat sink T_0 was assumed to be 300 K.

In order to compare the calculation results with the results of calculations based on the stationary model, numerical calculations based on the proposed dynamic model are given for a variant of the transistor operating mode at I_e = 40 мА, U_c = 7 В. The initial value of the offset voltage at the emitter junction U_e = 1.2 В. The total current of the transistor structure was considered evenly distributed between the emitter metallization tracks.

Figures 4 and **5** show the dynamics of changes in the maximum and average temperature of the structure, as well as the maximum emitter current density of the HBT structure during the action of a heating power pulse.

Approximating the change in the maximum and average overheating of the structure by a function of the form $\Delta T(1 - \exp(-t/\tau_T))$, where τ_T thermal time constant that determines the rate of increase of overheating, according to the obtained dependences, it is possible to estimate the change in the rate of increase of overheating as a result of inhomogeneous current distribution under the action of positive thermal feedback in

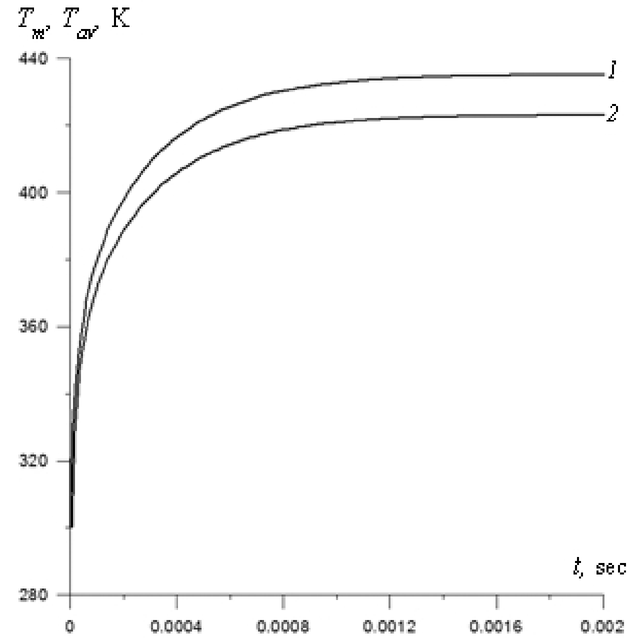

Fig. 4. *Change in the maximum (1) and average (2) temperature of the active region: I_e = 40 mA, U_c = 7 V; a_e = 2 μm, L_e = 60 μm, h_e = 0.5 μm.*

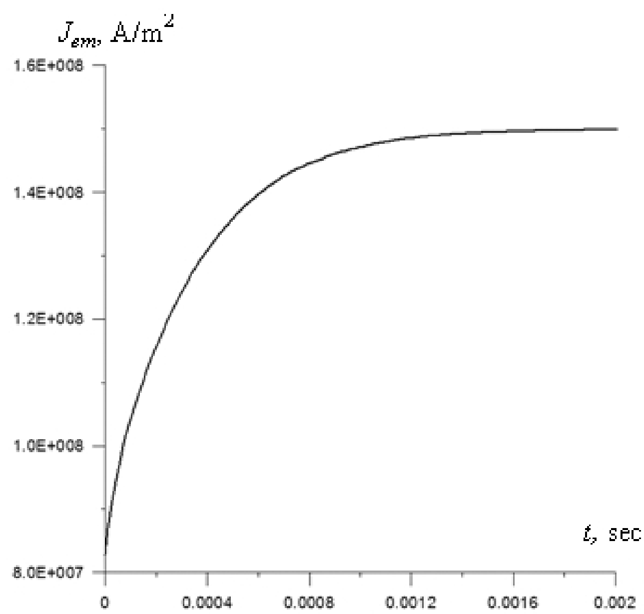

Fig. 5. *Changing the maximum emitter current density: I_e = 40 mA, U_c = 7 V; a_e = 2 μm, L_e = 60 μm, h_e = 0.5 μm.*

the structure compared with the case of homogeneous heating of the structure. When the structure is heated by a uniformly distributed power density $\tau_T^{\text{homogen}} = \tau_{\text{Tcr}}$, where τ_{Tcr} thermal time constant of the crystal, determined by the thermal diffusivity of the crystal material and its thickness d: $\tau_{\text{Tcr}} = d^2/\alpha$. For a GaAs crystal with a thickness of 100 microns is about 300 microseconds. From the dependencies in Fig. 4 and Fig. 5, it can be seen and numerical calculations show, that the thermal time constant $\tau_T^{\text{heterogen}}$ with inhomogeneous heating and the action of PFT is approximately 130 microseconds, that is, 2.3 times less τ_T^{homogen}, that is, the rate of change in the maximum and average overheating of the structure significantly exceeds the rate of increase in overheating with homogeneous heating of the structure. This is obviously due to the redistribution of the current density along the emitter metallization tracks and, accordingly, the power density dissipated in the HBT collector junction under the track.

From the distributions of overheating along the emitter track presented in **Fig. 6** at different times, it can be seen that in the process of HBT heating, the maximum temperature value shifts from the edge of the track to its center, i.e., to the center of the crystal.

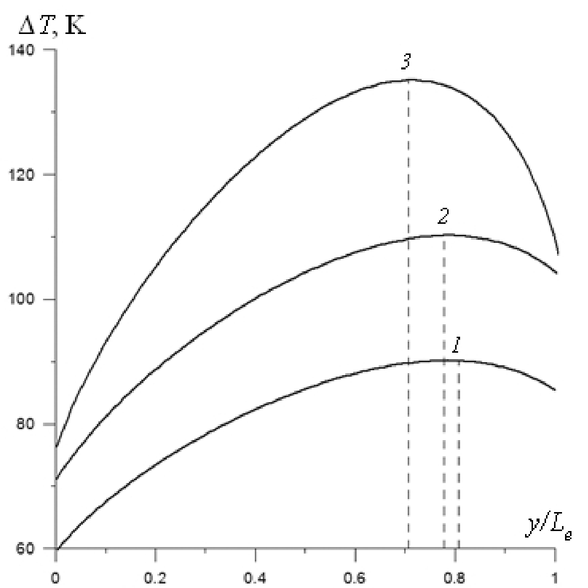

Fig. 6. *Overheating along the 3rd emitter track: I_e = 40 mA, U_c = 7 V; a_e = 2 μm, L_e = 60 μm, h_e = 0.5 μm; t: 1 – 0.15, 2 – 0.3, 3 – 2 ms.*

It should also be noted again that the proposed model did not consider the redistribution of the total current of the structure between the cells as a result of uneven heating of the cells of the HBT structure due to their different arrangement with respect to the edges of the crystal. This effect will probably lead to even greater inhomogeneity of the temperature and current density distributions in the structure and requires a separate additional analysis.

4. CONCLUSION

The developed dynamic thermoelectric model of the HBT comb structure, taking into account the inhomogeneous distribution of the emitter current density as a result of the voltage drop on the emitter metallization tracks and the positive thermoelectric feedback acting in the HBT structure, determines the rate and nature of the change in the temperature and current density distribution along the emitter tracks of the structure under the action of a pulse heating power in HBT: from monotonically and weakly decreasing from the beginning of the track to the end in the isothermal approximation, these distributions become nonmonotonic and significantly inhomogeneous. In this case, the maximum temperature and current density reach stationary values at a rate significantly exceeding the rate of increase in overheating during uniform heating of the structure, and the temperature and current density maxima in the process of self-heating of the structure shift from the beginning to the center of the tracks. The proposed model can be used in the development of HBT structures and evaluation of their limiting functionality in terms of current and temperature in the pulsed operating modes of the HBT.

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