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Thermoelectric model of a heterojunction bipolar transistor taking into account the voltage drop on the current-carrying metallization

[1,2]**Vyacheslav A. Sergeev,** [1]**Alexander M. Hodakov**

[1]Kotelnikov Institute of Radioengineering and Electronics of RAS, Ulyanovsk Branch, http://www.ulireran.ru/

Ulyanovsk 432071, Russian Federation

[2]Ulyanovsk State Technical University, https://www.ulstu.ru/

Ulyanovsk 432027, Russian Federation

E-mail: sva@ulstu.ru, hod22am@mail.ru

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Abstract: **A 3D thermoelectric model has been developed to calculate the temperature field in the comb structure of a heterojunction bipolar transistor formed on the surface of a rectangular semiconductor crystal 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 due to voltage drop on the resistance of current-carrying metallization. The model is based on the solution of the thermal conductivity equation together with a system of equations for the distribution of the potential for metallization of the emitter track and the current density under the track in the COMSOL Multiphysics software environment. It is shown that as a result of the combined effect of the voltage drop on the resistances of the emitter tracks, the inhomogeneity of the temperature field in a crystal with limited dimensions and the strong dependence of the emitter current density on temperature, the temperature and current density distributions along the emitter tracks change character: from monotonously and weakly decreasing from the beginning of the track to the end in the isothermal approximation, these distributions become non-monotonic and significantlyheterogeneous. At the same time, the maximum current density and temperature with an increase in the operating current shifts from the beginning to the center of the tracks. It has also been found that with the crystal sizes unchanged, an increase in the length of the tracks leads to a certain decrease in the coefficient of inhomogeneity of the temperature distribution.**

Keywords: **heterojunction bipolar transistor, current density, temperature, inhomogeneity**

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Contents

1. INTRODUCTION

Along with the active development of MOSFET and HEMT microwave transistors, powerful bipolar (BT), including heterojunction (HBT), microwave transistors are widely used in modern radio and telecommunications equipment [1-4]. Devices of this class are the least reliable in the composition of modern radio-electronic systems for various purposes, since they operate in the most severe thermal and electrical modes. This class of devices is characterized by the presence of strong positive thermal feedback and the manifestation of the effects of 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 consequence, to acceleration of degradation mechanisms and failures of devices.

One of the most common geometries of the structures of modern high-power BT and HBT is a strip or comb geometry with a parallel arrangement of elementary transistors (cells) HBT (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 matrix of HBT elementary transistors. Due to the positive temperature coefficient of the emitter current, currents of higher density will flow through the central HBT cells with a higher temperature,

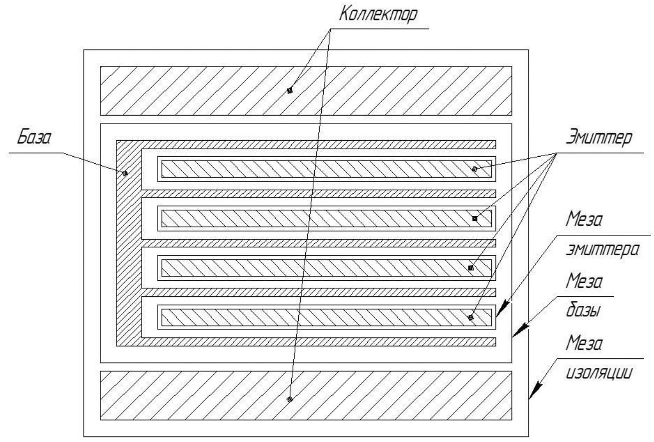


Fig. 1. *Topology of the active region of HBT* [4].

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

To reduce the nonuniform temperature distribution and solve these thermal problems, various variants of one-dimensional geometry design are used, including changing the length of the emitter in the HBT cells [7] and changing the distance between

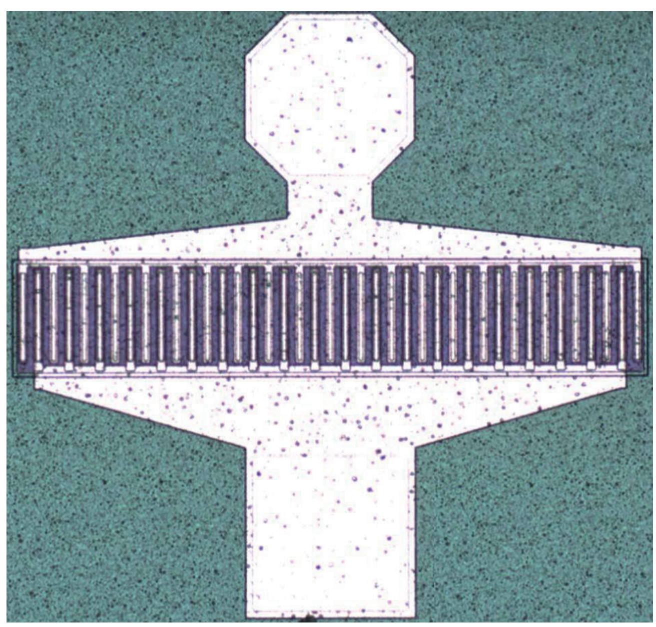


Fig. 2. *Comb structure of a HBT with 20 elementary transistors* **[7].**

the emitters between the HBT cells [8], which reduces the temperature difference along the direction of the emitter width.

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

This article presents a 3D thermoelectric model for calculating the temperature field in the comb structure of the HBT, taking into account the combined influence of all the factors listed above of the inhomogeneous distribution of current and temperature in the instrument structure, including the inhomogeneous distribution of current density under the emitter tracks as a result of voltage drop on the resistance of current-carrying metallization.

2. THERMOELECTRIC MODEL

To determine the temperature field in the semiconductor structure of the HBT, a 3D thermoelectric model was constructed, the scheme of which is shown in **Fig. 3**. The design of the transistor structure is a rectangular semiconductor crystal with dimensions $l_x \times l_y \times l_z$ and 4 emitter metallization tracks of size $a_e \times L_e \times h_e$ each located on its upper surface.

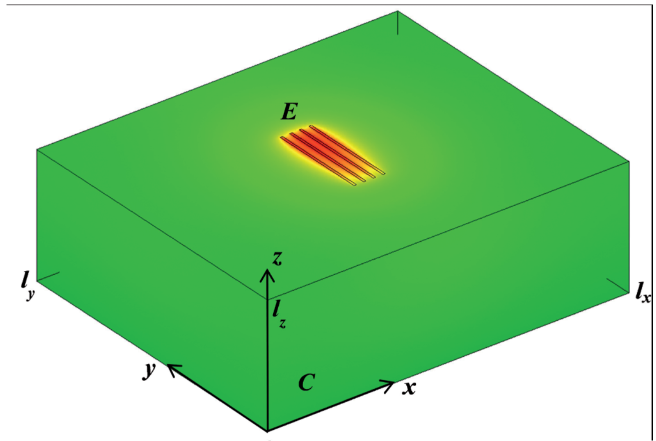


Fig. 3. *Scheme of the HBT structure model: E is emitter, C is a semiconductor crystal.*

The temperature distribution over the HBT structure is found from the solution of the stationary equation of thermal conductivity

$$\nabla_{x,y,z}\left(\lambda(T)\nabla_{x,y,z}T(x,y,z)\right)=0, \qquad (1)$$

where λ is the thermal conductivity coefficient of the crystal.

Boundary conditions of the thermal conductivity problem: the 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; the power density is set on the upper surface in the emitter region of the structure:

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

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

To find the current density along the emitter path, we write down the following system of equations. According to the voltage-ampere characteristics of the transistor

$$J_e(x,y) = J_{e0}\left(T(x,y)/T_0\right)^3 \times \\ \times \exp\left\{\frac{-E_g + e\left(U_e - \varphi_e(x,y) - rS_e n^{-1} J_e(x,y)\right)}{kT(x,y)}\right\}, \quad (3)$$

where J_{e0} is weakly temperature-dependent parameter, U_e is direct voltage drop at the emitter *p-n* junction, E_g is band gap width of a semiconductor, *e* is electron charge, φ_e is emitter metallization potential, *r* is input ohmic resistance of the transistor, *k* is Boltzmann constant.

As a condition for the inclusion of a transistor in an electrical circuit, we will consider the condition of constancy of the total emitter current I_e. This means that for any temperature distribution T(x, y, l_z) over the active region of the semiconductor structure, a restrictive equality must be fulfilled:

$$\iint_{S_e} J_e(x,y,l_z)\,dx\,dy = I_e. \quad (4)$$

Let's limit ourselves to an approximation, assuming the emitter tracks are narrow, that is, we neglect the effect of pushing the emitter current to the lateral edges of the tracks along the coordinate *x*. Then the equations for the distribution of the potential φ_e and current density J_{em} over the metallization of the emitter track will be written as:

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

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

with boundary conditions:

$$J_{em}(0) = I_e/h_e a_e, \quad (7)$$

$$J_{em}(L_e) = 0, \quad (8)$$

$$\left.\frac{d\varphi_e}{dy}\right|_{y=y_{eb}} = -\frac{I_e}{\sigma_{em} h_e a_e}, \quad (9)$$

$$\left.\frac{d\varphi_e}{dy}\right|_{y=y_{ee}} = 0, \quad (10)$$

where y_{eb} and y_{ee} are coordinates of the beginning and end of the track, σ_{em} is the specific conductivity of the metallization of the emitter track.

The solution of the model problem (1) – (10) was found by the numerical iterative method, the algorithm of which is presented in [14]. The developed program included an appeal to the COMSOL Multiphysics interactive software environment. InGaP/GaAs HBT [4] with a crystal size of 300×250×100 microns was chosen as the calculated base object of the study. The active cell of the transistor has a comb structure with 4 emitter tracks, the dimensions of which were: width a_e = 2 μm, thickness h_e = 0.5 μm, and the length varied within L_e = (40÷80) μm. The track material is gold. The temperature dependence of the thermal conductivity coefficient of the transistor crystal material λ(*T*) was selected from the COMSOL program database. Heat sink temperature T_0 = 300 K.

As an initial approximation of the dependence $J_e^0(y)$ in the iterative process, the current density values calculated by the formula [11] were chosen:

$$J_e^0(y) = \frac{2\varphi_{T_0}}{L_e a_e R_e} \cdot \frac{C^2}{\cos^2\left[C\left(1 - y/L_e\right)\right]}, \tag{11}$$

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

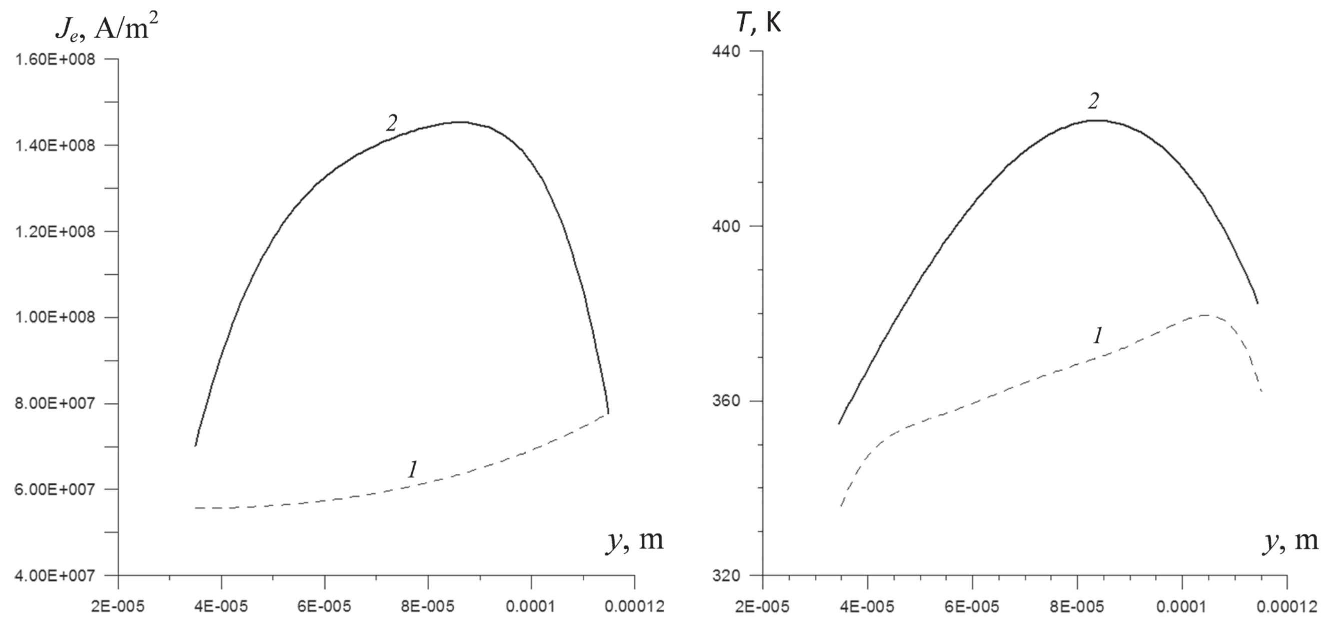
3. RESULTS AND DISCUSSION

Further results of numerical calculations are presented for a variant of the transistor operation mode at I_e = 40 mA, U_c = 7 V. Initial value U_e = 1.2 V. **Fig. 4** shows the results of modeling the distribution of emitter current density and temperature under the 3rd emitter track.

As can be seen, the temperature-dependent approximation of the emitter current density (formula 3) has a significant effect on the heterogeneity of the emitter current density and temperature distributions along the track.

Calculations have shown that the maximum value of the potential, if the length of the emitter track changes within the above limits, varies from 10.3 to 23.0 mV (less than the value), and the heterogeneity of the potential distribution increases with growth (**Fig. 5**).

Coefficient of heterogeneity of temperature distribution , where , are



a *b*

Fig. 4. *Distribution of current density (a) and temperature (b) under the 3rd emitter track; I_e = 40 mA, U_c = 5 V; a_e = 2 μm, h_e = 0.5 μm, L_e = 80 μm; approximation: 1 – formula 11, 2 – temperature-dependent, formula 3.*

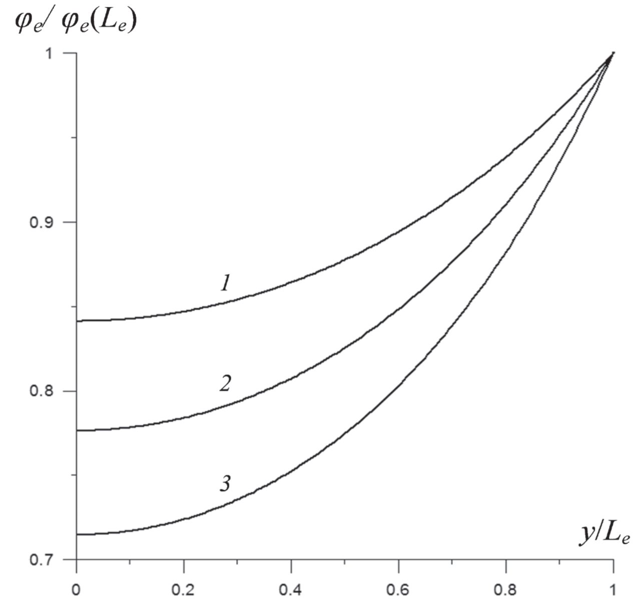


Fig. 5. *Distribution of the reduced potential along the emitter path; I_e = 40 mA, U_c = 5 V; a_e = 2 μm, h_e = 0.5 μm, L_e: 1 –40, 2 –60, 3 –80 μm.*

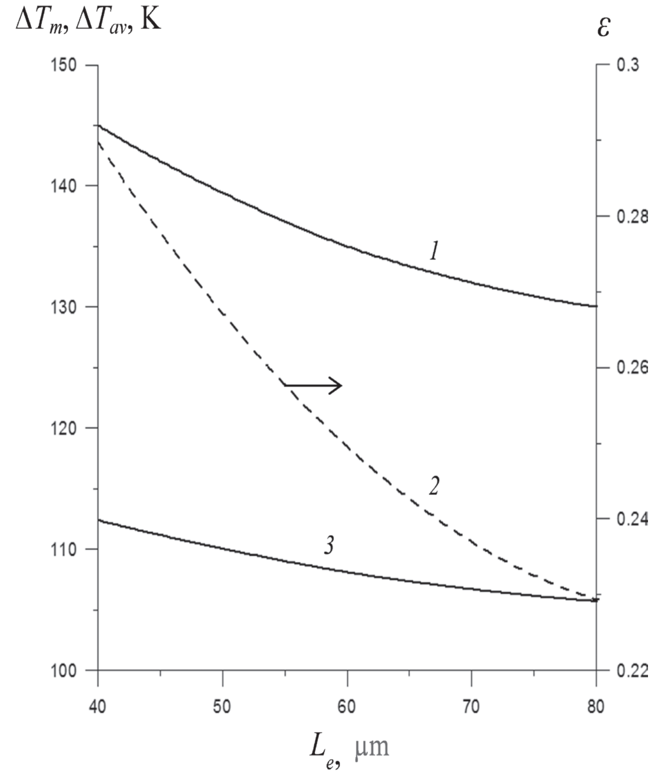


Fig. 6. *Dependence of the maximum (1), average (3) temperature increment and inhomogeneity coefficient (2) on the track length; I_e = 40 mA, U_c = 5 V; a_e = 2 μm, h_e = 0.5 μm.*

the maximum and average temperature increment, respectively, decreases with an increase in the length of the track by 1.3 times (**Fig. 6**).

4. CONCLUSION

Thus, the proposed thermoelectric model of the HBT comb structure, taking into account the inhomogeneous distribution of emitter current density as a result of voltage drop on the metallization emitter tracks and positive thermoelectric feedback acting in the HBT semiconductor structure, showed that the temperature and current density distributions along the emitter tracks change character: from monotonously and weakly decreasing from the beginning of the track to finally, in the isothermal approximation, these distributions become nonmonotonic and substantially inhomogeneous.

An increase in the heterogeneity of temperature and current density in the HBT structure leads to a decrease in the maximum functionality of the device in current and power. At the same time, the maximum current density and temperature with increasing operating current shifts from the beginning to the center of the tracks. It has also been found that with the crystal sizes unchanged, an increase in the length of the tracks leads to a certain decrease in the coefficient of inhomogeneity of the temperature distribution.

The proposed model can be used in the development of HBT structures and the assessment of their limiting functionality in terms of current and temperature.

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