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# Estimation of the Inhomogeneity of the Current Density and Temperature Distribution in the Structures of Bipolar and Heterobipolar High-Frequency and Ultrahigh-Frequency Transistors by Recombination Emission

© V.A. Sergeev[1], I.V. Frolov[1], A.A. Kazankov[2]

[1] Kotel'nikov Institute of Radio Engineering and Electronics (Ulyanovsk Branch),
Russian Academy of Sciences, Ulyanovsk, Russia
[2] Ulyanovsk State Technical University, Ulyanovsk, Russia
e-mail: ilya-frolov88@mail.ru

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The parameters of recombination emission arising in the structures of bipolar transistors in pulsed and stationary operating modes are investigated. The brightness distribution profiles of the recombination emission of the structure, which made it possible to evaluate the inhomogeneity of the current density distribution along the metallization tracks, were obtained when bipolar transistors were turned on in diode mode. Using KT504A transistors as an example, it is shown that the brightness profiles of the recombination emission of the emitter junction in the diode regime are well described by expressions for the distribution of current density along the metallization tracks.

**Keywords:** Bipolar and heterobipolar transistors, recombination emission, current distribution, inhomogeneity.

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Powerful bipolar and heterobipolar (heterojunction bipolar transistor - HBT) high-frequency and ultra-high-frequency transistors are widely used in modern electronic equipment and operate, as a rule, in thermal and electrical modes close to the limit, in which the distribution of temperature and current density in the comb structures of such devices becomes significantly heterogeneous as a result voltage drop across current-carrying metallization [1–3]. It is not possible to measure current density and temperature distributions in semiconductor device structures directly. The method of indirectly assessing the heterogeneity of the current density distribution from the voltage drop on the metallization tracks [1] is destructive and labor-intensive. An effective tool for these purposes can be the registration of recombination luminescence (RL), since the intensity of RL is proportional to the current density in the local region of the structure and in HBT structures it decreases almost linearly with increasing temperature [4,5]. However, in well-known works on the study of RL HBT [4,5] estimates of the heterogeneity of the distribution of current density and temperature over the structure area and the characteristics of the spatial resolution of the experimental setups and techniques used are not given.

To record the distribution of RL over the area of instrumental structures with a spatial resolution of the order of $1\,\mu$m, an experimental setup has been developed, consisting of a LevenhukD320L microscope, a cooled FL-20BW monochrome CMOS camera, a UnionTestUT3005ED linear power supply, and a computer. Measurements of the brightness profiles of the RL were carried out as follows. The transistor under study with an open crystal, mounted on a radiator, was located on the microscope stage. The current through the emitter junction of the transistor was set by a linear power supply, while the RL of the structure was focused by a lens and recorded by a camera. The spectral sensitivity range of the camera is 300−1100 nm, the maximum sensitivity is achieved at a emission wavelength of 495 nm. The software allows to set the camera exposure time from $3\,\mu$s to 3600 s. Monochrome images received from the camera, with a resolution of $5472 \times 3648$ pixels and a bit depth of 16 bit, are stored in the computer memory [6].

Fig. 1 shows the RL spectrum of the KT504A transistor, measured with an OceanOpticUSB2000 spectrometer with a fiber-optic input at an emitter current of 200 mA. The spectrum has two pronounced maxima: at a wavelength of

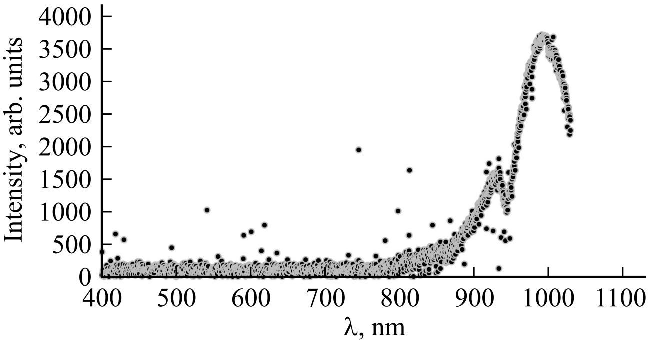

**Figure 1.** RL spectrum of KT504A transistor.

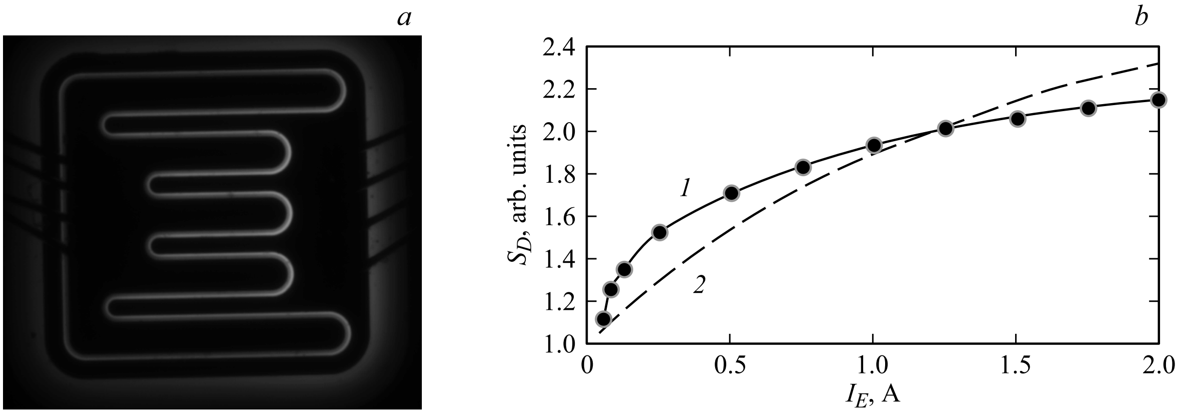

**Figure 2.** (*a*) RL intensity profile of the KT504A transistor at a current of 1.5 A in diode mode, (*b*) dependence of the coefficient of heterogeneity of the RL intensity distribution along the emitter track on the emitter current: *1* — measurement result, *2* — calculation result.

930 and 1005 nm. It has been experimentally specified that there is this form of the RL spectrum in silicon bipolar transistors of other types, in particular, KT809A, KT903A. The main maximum at a wavelength of 1005 nm is determined by the optical band gap of silicon $E_{\text{gopt}} \sim 1.205\,\text{eV}$, and the maximum at a wavelength of 930 nm — by the energy difference $\Delta E_{\max}$ corresponding to the maxima of the population of electron states in the conduction band and holes in the valence band silicon: $\Delta E \sim E_{\text{gopt}} + 2kT \sim 1.26\,\text{eV}$, where $k$ — is Boltzmann constant, $T$ — is an absolute temperature.

Figure 2, *a* shows the intensity distribution profile of the RL structure in the diode regime of the emitter junction of the transistor at a current of 1.5 A. It is can be seen from the figure that the RL intensity, and hence the emitter current density, decreases from the end of the emitter tracks to their base (correspondingly, from the base of the basic tracks to their end). This ratio of RL brightnesses is presented over the entire range of specified currents. There was a similar RL distribution in the comb structures of transistors of the KT809A and KT903A types. To assess the heterogeneity of the RL intensity distribution along the tracks, we introduce the heterogeneity coefficient $S_D = E_1/E_2$, where $E_1$ — RL intensity at the end of the central emitter track, $E_2$ — RL intensity near the base of the central emitter track. Graphs of the dependence of the heterogeneity coefficient $S_D(I_E)$ on the total emitter current of the transistor, varying in the range 0.15−2.0 A, are shown in Fig. 2, *b*. During measurements, the camera exposure time was set from 10 s at a current strength of 2 A to 3600 s at a current strength of 0.15 A. As can be seen from the graph, in the mode of diode switching of the emitter junction, the dependence of the heterogeneity coefficient $S_D(I_E)$ is monotonically increasing.

To describe the obtained dependencies, let us review the expression for the current density $J_E(x)$ under the emitter track in the comb structure of a bipolar transistor, obtained in the isothermal approximation, for the case of diode regime:

$$J_E(x) = \frac{2\varphi_T}{[R_{BM} + R_{EM}]S_E} \cdot B_1^2 \cos^{-2}\left[B_1\left(\frac{x}{L_{\text{EM}}} + B_2\right)\right], \tag{1}$$

where $S_E$ — the area of the emitter metallization track, the constants $B_1$ and $B_2$ are found from solving the system of transcendental equations:

$$B_1 \operatorname{tg} B_1 B_2 = -R_{EM} I_E / 2\varphi_T, \tag{2a}$$

$$B_1 \operatorname{tg}[B_1(1 + B_2)] = R_{BM} I_E / 2\varphi_T, \tag{2b}$$

where $R_{EM}{=}L_{EM}\rho_{EM}/d_{EM}a_{EM}$ and $R_{BM}{=}L_{BM}\rho_{BM}/d_{BM}a_{BM}$ — resistance, $L_{EM,BM}$, $a_{EM,BM}$, $d_{EM,BM}$ — length, width and thickness, $\rho_{EM,BM}$ — resistivity of the material of the emitter and base metallization tracks, respectively, $I_E$ – current flowing into the emitter track, $\varphi_T = kT_n/e$ — thermal potential at transition temperature $T_n$, $e$ — electron charge, $x$ — coordinate of the emitter track, measured from its base.

Since the RL intensity is proportional to the emitter current density, the heterogeneity coefficient $S_D(I_E)$ can be expressed from (1) through the ratio of the current densities at the end and at the base of the emitter track:

$$S_D(I_E) = \frac{J_E(L_{EM})}{J_E(0)} = \frac{\cos^2[B_1 B_2]}{\cos^2[B_1(1 + B_2)]}. \tag{3}$$

Solving the system of equations (2) for the constants $B_1$ and $B_2$, limiting to linear terms in the expansion tg and substituting the resulting expressions into (3), we obtain

$$S_D(I_E) \approx \frac{1 + (R_{BM}/(R_{BM} + R_{EM}))(R_{BM} I_E/2\varphi_T)}{1 + (R_{EM}/(R_{BM} + R_{EM}))(R_{EM} I_E/2\varphi_T)}. \tag{4}$$

For further calculations, let us note that the KT504A transistor has a base track width of approximately 1.9 times less than the emitter width and, other parameters being equal, $R_{BM} \sim 1.9R_{EM}$. Equation (4) may then be written in the form

$$S_D(I_E) \approx \frac{1 + 1.25(R_{EM}I_0/2\varphi_T)(I_E/I_0)}{1 + 0.35(R_{EM}I_0/2\varphi_T)(I_E/I_0)}, \qquad (5)$$

where $I_0$ — some fiducial value of the total emitter current of the transistor.

The experimental dependences $S_D(I_E)$ are well described by expression (5) for $I_0 = 1\,\text{A}$ and $(R_{EM}I_0/2\varphi_T) \sim 1.5$ (dashed line in Fig. $2, b$). Considering that the structure of the KT504 transistor has five emitter tracks, the condition $(R_{EM}I_0/2\varphi_T \sim 1.5$ at $\varphi_T \sim 0.026\,\text{V}$ corresponds to the resistance of the emitter track $R_{EM} \sim 0.40{-}0.45\,\Omega$, which is consistent with the values obtained previously for similar structures [1]. With an average ratio of the length of the emitter track $L_{EM}$ to the width of $a_{EM}$ in the structure of the KT504A transistor equal to 7, and with a resistivity of aluminum of the order of $3 \cdot 10^{-8}\,\Omega$ m, this corresponds to the thickness of the metallization $0.7{-}0.8\,\mu$m.

Thus, the value of the RL heterogeneity coefficient $S_D(I_E)$, measured at a certain rated emitter current, is an informative parameter not only for diagnosing current distribution heterogeneity, but also for indirectly assessing the resistance of current-carrying metallization tracks in a transistor structure. With a known resistance of the tracks of current-carrying metallization, this parameter can be used to assess the heterogeneity of the structure temperature through the value of the thermal potential.

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### Conflict of interest

The authors declare that they have no conflict of interest.

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