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Thermal deformation model of the submodule of the X-band output power amplifier

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Abstract. **The results of 3D modeling in the Comsol Multiphysics software environment and calculation of temperature and thermal deformation fields of GaAs crystals of monolithic integrated circuits (MIC) of microwave amplifiers as part of the submodule of the X-band output power amplifier (OPA) and their contact connections with the substrate in pulse modes of operation with different duty cycles are presented. It is shown that the maximum temperature and thermomechanical stresses in the MIC crystal in the dynamic mode of operation significantly exceed the calculated values for the stationary mode and strongly depend on the pulse duty cycle of the power dissipated by the MIS. Thermomechanical stresses take the maximum value in some narrow region near the boundary of the adhesive connection of the MIC crystal with the mounting plate; this maximum value strongly depends on the temperature coefficient of expansion (TCE) of the adhesive and takes the lowest value when the TCE of the adhesive is equal to the TCE of the GaAs crystal.**

Keywords: **thermal deformation, a microwave amplifier, the duty cycle of the pulse**

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Contents

1. INTRODUCTION

The main element base of modern submodules of output power amplifiers (OPAs) of receiving and transmitting modules of active phased phased array antennas are solid-state monolithic integrated circuits of microwave power amplifiers on GaAs or GaN crystals [1,2]. To obtain the required output power in the OPA, the summation of the microwave power of two or more MICs is usually used. The efficiency of modern OPA, as a rule, does not exceed 20-25%, and the power released in the MIC leads to their significant heating. The inhomogeneous heating of the MIC and the difference in the temperature coefficients of the material of the contact joint and the MIC crystal lead to large thermomechanical stresses in the area of the contact joint of the MIC with the substrate. The efforts of the developers are aimed at reducing the overheating of the MIC during operation, but reducing the average temperature of the substrate does not eliminate the problem of local dynamic overheating of the MIC in pulse modes of operation. Thermal models and thermal modes of operation of the OPA X-band were considered in many works [3-5]. However, estimates of the thermomechanical stresses occurring in MIC crystals and in the region of their contact connections with a substrate in pulsed operating modes have not been given in the literature. At the same time, these thermal deformations are one of the main reasons for the increase in the thermal resistance of the contact joint as a result of the accumulation of microcracks [6] and gradual (degradation) failures of the OPA.

2. THERMODEFORMATIONAL MODEL OF THE OPA SUBMODULE

The object of research in this paper is the submodule of the X-range OPA, the thermal model of which is considered by us in [7]. With a OPA efficiency of 20%, the pulse power dissipated by the OPA MIC is 60 W, and the average for the period of radio pulses is 12 W. With an uniform distribution of power between the MIC, each MIC dissipates 6 W of average power. The power dissipated by other OPA elements can be neglected.

The geometry of the OPA thermal model is presented in **Fig. 1** in the form of two identical rectangular GaAs MIC crystals with sides of size $b \times a$ and thickness δ, fixed on a copper heat sink plate of thickness h using an adhesive layer of thickness δ_s and with a thermal conductivity coefficient λ_s; the dimensions of the MIC crystal $b \times a \times \delta = 4.29 \times 4.94 \times 0.1$ mm; the dimensions of the mounting plate $17 \times 46 \times 5.5$ mm. To calculate and analyze

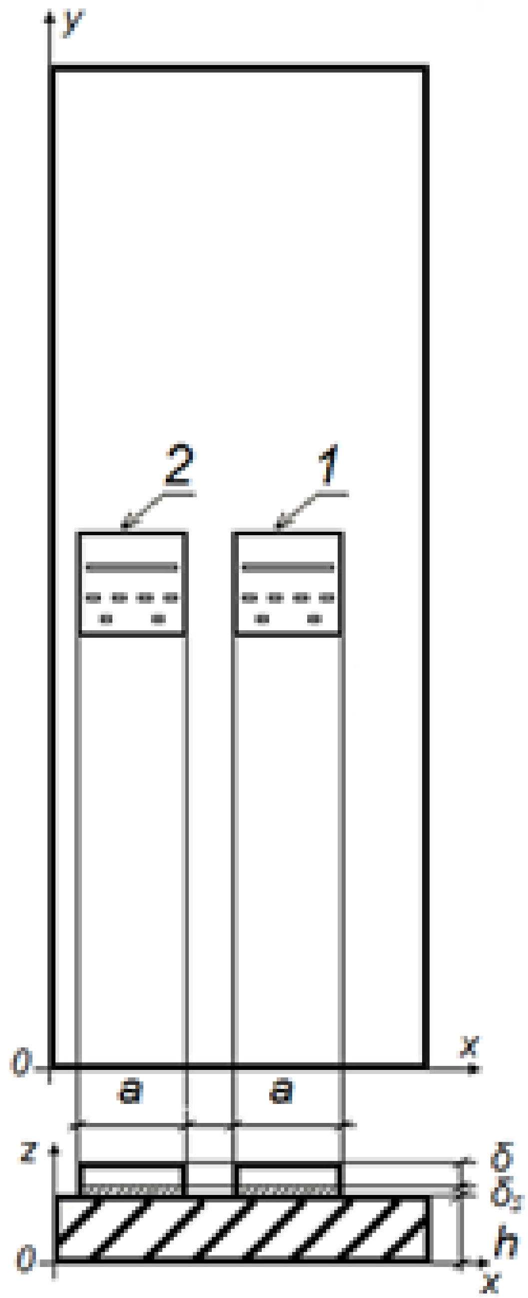


Fig. 1. *Geometry of the OPA model: 1, 2 - MIC with the location of heat sources on the crystal surface.*

the thermodeformational processes in the OPA submodule, the equation of thermoelasticity was added to the non-stationary heat equation in its mathematical thermal model [8]:

$$\mu_i \nabla^2 \overrightarrow{u_i} + (\lambda_i + \mu_i) \nabla \left(\nabla \overrightarrow{u_i}\right) - \\ -(3\lambda_i + 2\mu_i)\alpha_i \nabla \left(T_i - T_0\right) = 0,\ i = 1,\ldots,5, \quad (1)$$

where $\vec{u}_i(x,y,z,t)$ is the deformation displacement of the elements of the structure OPA; T_0 is the ambient temperature; $\lambda_i = \dfrac{v_i E_i}{(1+v_i)(1-2v_i)}$, $\mu_i = \dfrac{E_i}{2(1+v_i)}$ - Lame coefficients; E_i, v_i, α_i - modulus of elasticity, Poisson's ratio and coefficient of thermal expansion of the materials of the structure $\nabla = \nabla(x,y,z)$. All external surfaces of the elements of the OPA structure are considered free.

The numerical solution of the model problem was performed by the finite element method using the COMSOL Multiphysics software environment. The values of the mechanical characteristics of GaAs and copper were taken from the Comsol Multiphysics library. For the basic design version, silver-containing epoxy adhesive XH9960-1 from NAMICS was chosen as the adhesive, thickness δ_s = 15 microns with a temperature coefficient of expansion (TCE) α = 29e-6·K^{-1} and other mechanical and thermophysical characteristics that were found from the technical specification of the adhesive [9]. The critical temperature of the GaAs crystal is T_C = 460 K. The ultimate shear strength of the crystal for this type of glue σ_c = 13 MPa.

As shown by the calculated studies, the maximum value of the mechanical stress in the structure is concentrated in a small critical area at the edge of the adhesive joint of the MIC crystal with the mounting plate (**Fig. 2**).

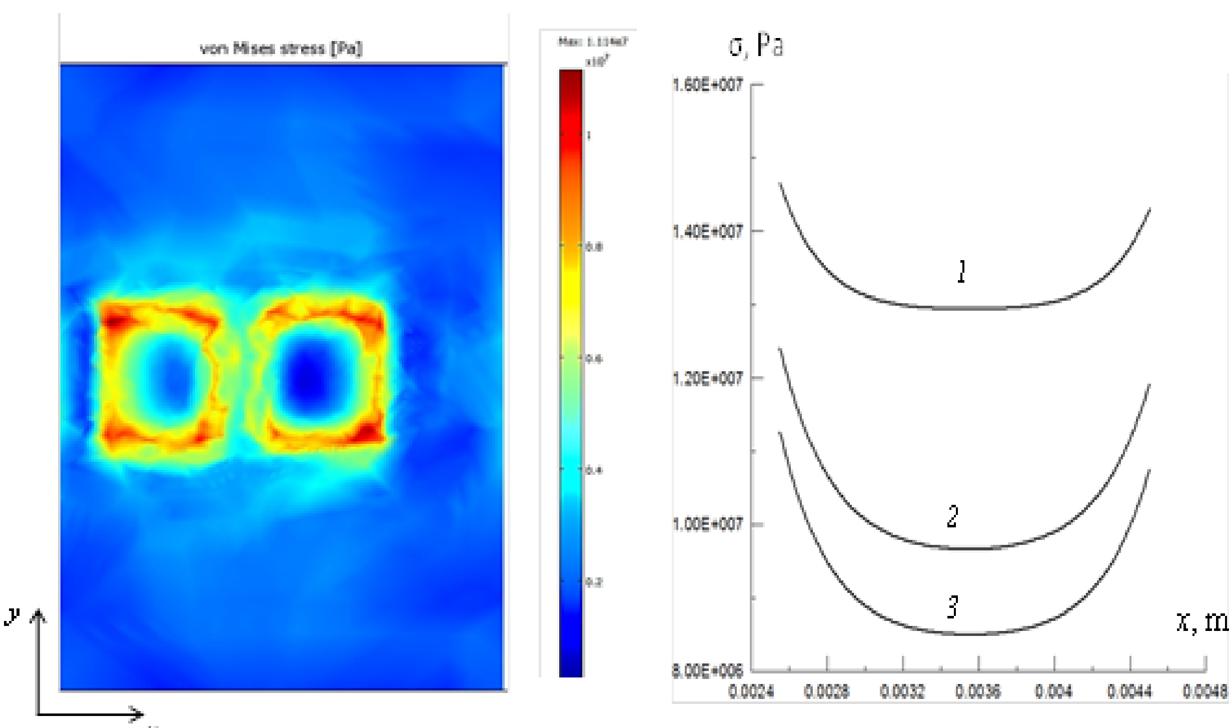
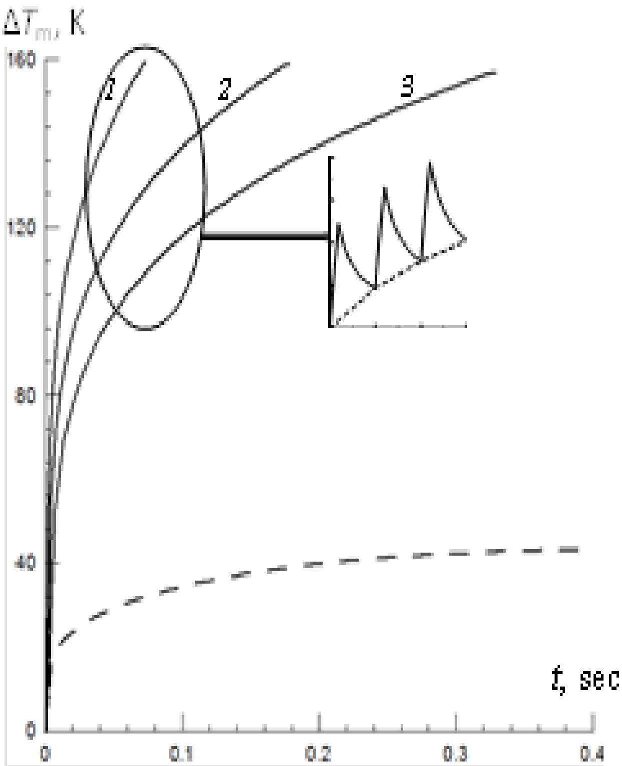


Fig. 2. *Distribution of mechanical stress in the area of the glued joint; a: 1 - 3e-6·K^{-1}, 2 - 29e-6·K^{-1}, 3 - 9e-6·K^{-1}; W = 6 W.*



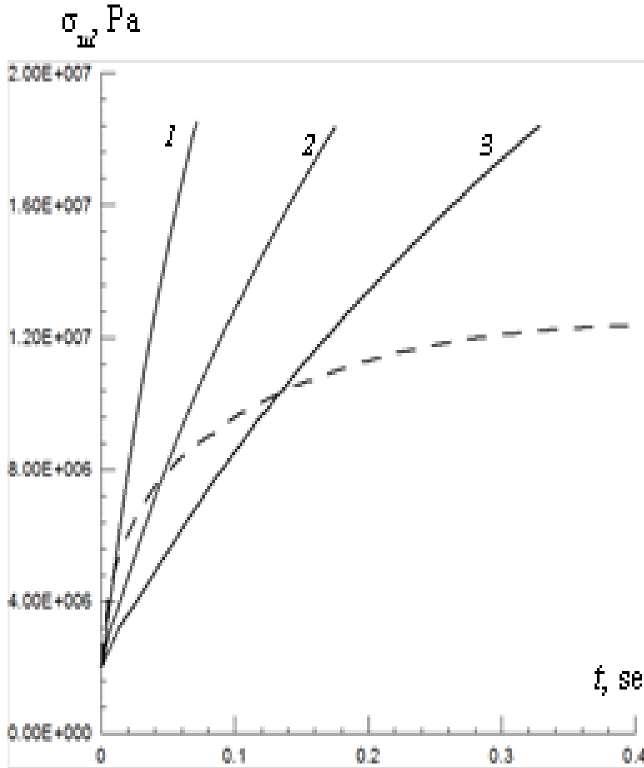


Fig. 3. *Kinetics of the overheating temperature of the center of the upper surface of the MIC crystal (a) and the maximum mechanical stress of the adhesive joint (b); pulse duration τ = 10 μs; duty cycle Q: 1 - 2, 2 - 5, 3 - 10;* T_c *= 460 K.*

Time dependence of the temperature of the center of the upper surface of the crystal MIC and the maximum stress in the critical region at the edge of the adhesive bonding of the crystal with a mounting plate, as shown in **Fig. 3.** The dashed line corresponds to the temperature behavior during dissipating in each of MIC 6 W average power during the period, and the solid lines - 30 W of pulsed power, with a pulse duration $\tau = 10$ μs and duty cycle of Q varying in the range $Q = 2 \div 10$. The maximum temperature and mechanical stress in the dynamic mode (at $Q \sim 10$) reach the limit values in just tenths of a second.

Calculations of the maximum thermomechanical stress acting in the critical region at the edge of the adhesive joint for several brands of electrically conductive adhesives used for mounting

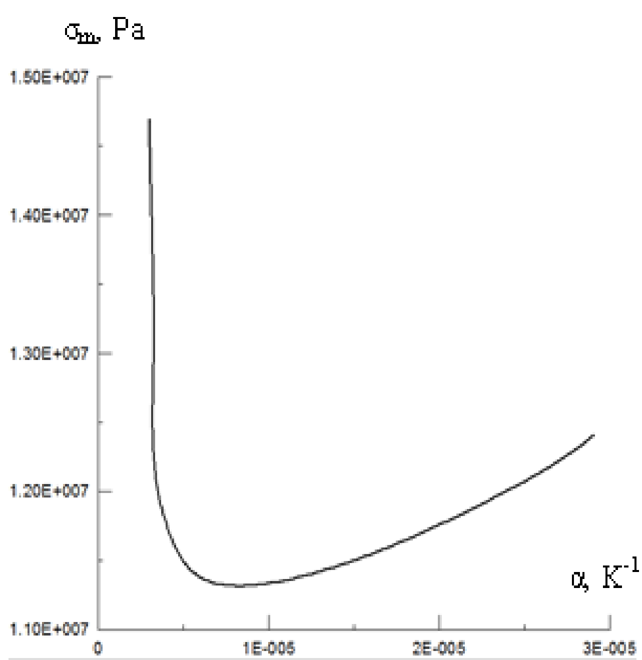


Fig. 4. *Dependence of the maximum mechanical stress on the thermal expansion coefficient at W = 6 W.*

crystals [9-11], with a TCE varying within $\alpha = (3\div30)e\text{-}6\cdot K^{-1}$, showed that the calculated curve has a minimum when the TCE of the glue and the GaAs crystal are equal (**Fig. 4**).

Even with a small decrease in the TCE of the adhesive compared to the GaAs TCE, the maximum stress in the critical area of the contact joint increases sharply, which must be taken into account when choosing the material of the contact joint.

3. CONCLUSION

Modeling of thermal and thermal processes in the submodule OPA showed that the maximum temperature and thermomechanical stresses in the crystal MIC and in contact with the substrate coupling in dynamic mode substantially exceed the calculated values for the stationary regime and highly dependent on the duty cycle of MIC dissipated power. The maximum values of the thermomechanical stresses in the area solder joints crystal MIC with a mounting plate are accepted in some narrow region near the boundary of the crystal dimension. The maximum mechanical stress σ_m strongly depends on the TCE of the glue and takes the lowest value when the TCE of the glue and the GaAs crystal are equal.

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