

# Modeling of GaAs MEMS for RF Power Measurement in Telecommunications

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**Abstract:** This report discusses the design of Thermo-mechanical converter that creates heart of the RF power sensor microsystem which can be used for transmitted power measurement in telecommunications. The conception of absorbed power measurement is based on thermal conversion, where absorbed RF power is transformed into thermal power, inside a thermally isolated system. Micromechanical Thermal Converter (MTC) spatial temperature dependences, thermal time constant and power to temperature characteristics are calculated from the heat distribution. The temperature changes induced in the MTC by electrical power dissipated in the HEMT (High Electron Mobility Transistor) are sensed using the temperature sensor. The temperature distribution, over the sensing area, and mechanical stress was optimized by studying different MTC sizes, and layouts of the heater and temperature sensor.

**Key-Words:** Thermal Converter, Thermo-mechanical simulations, MEMS, Power sensor, GaAs microsystems

## 1 Introduction

Transmitted power is the main quantity measured in RF systems. The classical approach to transmitted power measurement is based on the measurement of absorbed power waves (incident and reflected) that requires sophisticated multiple power meter structures and need complex calibration.

A better method of the absorbed power measurement is based on thermal conversion where, absorbed radio frequency (RF) power is transformed into thermal power inside of a thermally isolated system.

High thermal isolation can be reached by the design of free micromechanical plate which is as thin as possible.

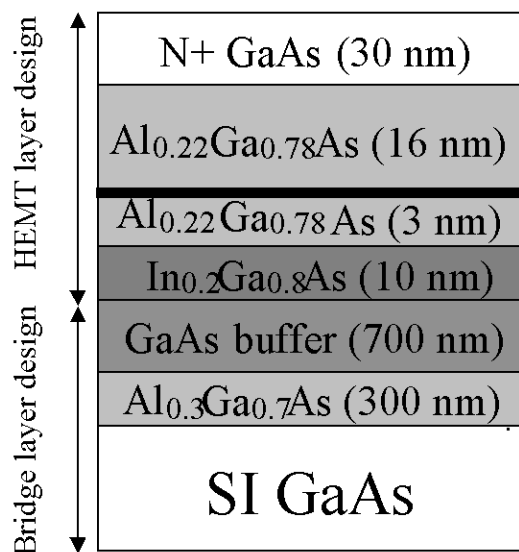


Fig. 1. Heterostructure layer design used for the HEMT and bridge technology

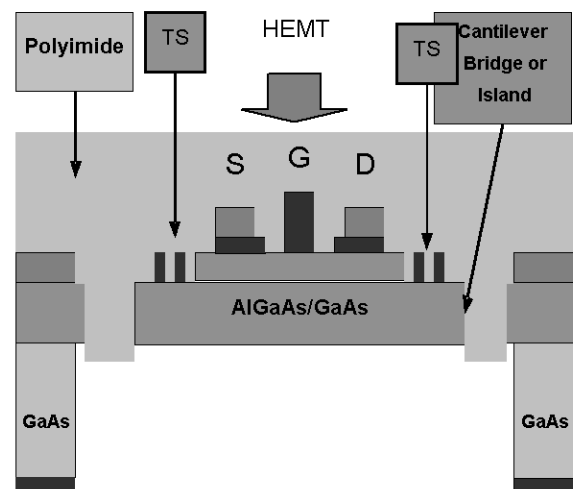


Fig. 2. Schematic cross-section through the polyimide-fixed MTC structure to be integrated with HEMT as heater and poly-Si/Pt thin film resistor as temperature sensor TS

A new GaAs based MTC technological approach creates optimal conditions for both the monolithic integration of active HEMT heater and thermal isolation of the microwave sensor elements. Thermo-mechanical numerical modelling and simulation have a significant influence on the optimal topology of the Micromechanical Thermal Converter. The main characteristics which optimise the MTC are the temperature distribution over the sensing area, time response, sensitivity analysis and evaluation of the mechanical stresses.

MTC structures with a different sizes and arrangements of the heater and the temperature sensor was studied.

The thermoelectric AC power sensor and microwave power sensor were analysed by Jaeggy and Kopystinski [6, 7] by using CMOS IC technology. The heater was defined with a polysilicon resistor and a Polysilicon/Aluminium thermopile was used as temperature sensor. Unfortunately, these sensors can not be integrated with III-V compound semiconductors. The Gallium Arsenide based Micro-Electro-Mechanical Systems have some advantages over the well-understood Silicon micromachined microsensors. The most significant advantages are some intrinsic material properties such as lower thermal conductivity, high temperature performance, heterostructure quantum effects, etc. The technology of high electron mobility transistors (HEMT) was also developed for the GaAs based structures.

These advantages of the GaAs based power sensor have been demonstrated in the work of Dehé [8]. A concept of the power sensor was based on a thin (1.5  $\mu\text{m}$ ) undoped AlGaAs/GaAs membrane. NiCr thin film resistors were integrated as heaters and GaAs thermocouples as temperature sensors [8]. However, the presented sensor was principally only another approach to the classical principle of the passive heater scheme for the measurement of absorbed power.

## 2 Governing the equation

### Conduction

The steady-state heat conduction equation shown below is solved for temperature distribution for specified thermal boundary conditions on temperature and heat flux

(including insulation, natural convection, and radiation). The Fourier equation for temperature distribution can be written as follows:

$$\text{div}(\lambda \text{grad} T) = \rho c \frac{\partial T}{\partial t} - p, \quad (1)$$

where  $\lambda$  [ $\text{W m}^{-1} \text{K}^{-1}$ ] is coefficient of thermal conductivity,  $\rho$  mass [ $\text{kg m}^{-3}$ ],  $c$  [ $\text{J kg}^{-1} \text{K}^{-1}$ ] thermal capacity and  $p$  specific heat [ $\text{W m}^{-3}$ ]. Coefficient of thermal conductivity is not constant in broad temperature differences however, in most MEMS applications can be taken as constant.

The value of heat flux can be expressed as:

$$q = -\lambda \cdot \text{grad} T \quad [\text{W.m}^{-2}], \quad (2)$$

$$q(r, t) = -\lambda \nabla T(r, t) \quad (3)$$

Transcribing above mentioned equation to Cartesian coordinate we get:

$$q_x = -\lambda_x \frac{\partial T(x, y, z, t)}{\partial x} \quad (4)$$

$$q_y = -\lambda_y \frac{\partial T(x, y, z, t)}{\partial y} \quad (5)$$

$$q_z = -\lambda_z \frac{\partial T(x, y, z, t)}{\partial z} \quad (6)$$

For isotropic materials  $\lambda_x = \lambda_y = \lambda_z$ .

If the solid body is heated up by constant power generation and cooled down constantly by surrounding environment then the temperature distribution will fix. For Cartesian coordinate the temperature distribution can be obtained by solving following equation:

$$\nabla^2 T(r, t) + \frac{Q(r, t)}{\lambda} = \frac{1}{\alpha} \frac{\partial T(r, t)}{\partial t} \quad (7)$$

For Cartesian coordinate the Laplace operator is given as:

$$\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2} \quad (8)$$

$\alpha$  in equation (7) is thermal diffusivity [ $\text{m}^2/\text{s}$ ] and mathematically can be expressed as:

$$\alpha = \frac{\lambda}{\rho c}, \quad (9)$$

### Convection

The ambient of thermal MEMS devices are often various gases or liquids. Thus the convection effects should be also taken into account in some cases (it depends on specific dimensions and shapes of the device; in many cases the convection is neglectable).

Heat transfer in gases or liquids has different physical character then in solid body. Individual particles can move mutually.

The density of heat flux under the convection is given [5]

$$q = \alpha \cdot \Delta t = \alpha(t_{st} - t_t) \quad [\text{W} \cdot \text{m}^{-2}], \quad (10)$$

where  $\alpha$  [ $\text{W} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ ] is heat transfer coefficient given by criteria equation (see below),  $t_{st}$  is wall temperature of solid body,  $t_t$  is gas or liquid surrounding temperature and  $A$  contact area.

Criteria equation can be found in literature in following form for instance [5]:

$$Nu = f(Re, Gr, Pr, \dots), \quad \text{where} \quad (11)$$

$$Nu = \frac{\alpha L}{\lambda_{tek}}, \quad Re = \frac{c \cdot L}{\nu},$$

$$Pr = \frac{\nu}{a} = \frac{\eta \cdot c_p}{\lambda}, \quad Gr = \gamma \cdot \Delta t \cdot \frac{g L^3}{\nu^2},$$

$$Pe = \frac{c \cdot L}{a} = Re \cdot Pr$$

Criteria equation for natural convection can be expressed in the form [5]:

$$Nu = C \cdot (Gr \cdot Pr)^n, \quad (12)$$

$C$  and  $n$  constants depends on the value of the product  $Gr \cdot Pr$  according tab. 1:

| Gr.Pr                                | C     | n     |
|--------------------------------------|-------|-------|
| $< 1 \cdot 10^{-3}$                  | 0,45  | 0,0   |
| $1 \cdot 10^{-3} \cong 5 \cdot 10^2$ | 1,18  | 0,125 |
| $5 \cdot 10^2 \cong 2 \cdot 10^7$    | 0,54  | 0,25  |
| $2 \cdot 10^7 \cong 1 \cdot 10^{13}$ | 0,195 | 0,333 |

Tab. 1 – value of  $C$  and  $n$  depends on  $Gr \cdot Pr$

### Radiation

For MEMS devices operating in room temperature the heat losses caused by radiation can be usually neglected. Radiation can have significant effect for the devices working much above 400 K on the other hand. Therefore for such devices the verification of radiation effect should be proved.

Heat losses caused by radiation is given by Stefan-Boltzmann emissive low:

$$P_{Rad} = \varepsilon_{1,2} \cdot C_0 \cdot A \sigma T^4 \quad [\text{W}] \quad (13)$$

where

$$\varepsilon_{1,2} = \frac{1}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1} \quad (14)$$

$\varepsilon$  is emissivity of gray body,  $A$  is the body surface and  $\sigma$  is Stefan-Boltzmann constant =  $5.67 \cdot 10^{-8} [\text{W} \cdot \text{m}^{-2} \cdot \text{K}^{-4}]$ .

## 3 Micromechanical Thermal Converter technology and 3-D model

The MTC structures used in the thermally based MEMS devices are mostly designed as free space standing structures. To increase the

thermal resistance values, they have to be designed with the thickness as thin as possible. The technology of new GaAs micromechanical island structure starts with the MBE or MOCVD growth of GaAs heterostructures on semi-insulating substrates (SI-GaAs) (Fig. 2). Then, a front-side processing technology is performed to define Source (S), Drain (D) and Gate (G) of the HEMT. The GaAs surface is completed by Ti (50 nm) / Au (150 nm) metallic transmission lines, which enable connections to the heater and TS.

Next step is a surface micromachining of cantilever, bridge or island by a masked non-selective wet or plasma etching of the heterostructures up to SI GaAs. A surface micro-machining is followed by deposition and subsequent thermal forming of a thin top polyimide layer. Finally, a three-dimensional patterning of the micro-mechanical structures is defined by a deep back-side selective reactive ion etching of SI-GaAs through the openings in mask, using AlGaAs together with the polyimide as an etch-stop layer. Thin polyimide layer is deposited after the bulk GaAs micromachining and enables the micromechanical structures to be mechanically fixed and thermally isolated in a space.

The layer system shown in fig. 1 represents HEMT design. Silicon delta-doped layer is formed in the Al<sub>0.22</sub>Ga<sub>0.78</sub>As barrier layer, and it is separated by 3 nm-thick undoped Al<sub>0.22</sub>Ga<sub>0.78</sub>As spacer layer from the

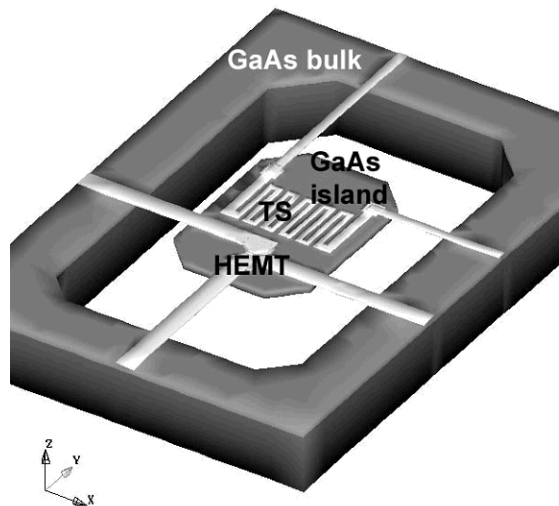


Fig. 3. Model of the Island MTC structure. GaAs island is “floating” in Polyimide 1μm thick layer (not visible). The meander-shaped TS is also shown. Z-direction is 20times magnified.

In<sub>0.2</sub>Ga<sub>0.8</sub>As channel. GaAs/Al<sub>0.3</sub>Ga<sub>0.7</sub>As (700 / 300 nm) heterostructure buffer layer under channel was designed to define the thickness of the MEMS structure.

Subsequent technology benefits is that microwave controlled circuit can also be integrated within the MTC microstructure.

Fig. 3 demonstrates model of GaAs island structure which has been proposed to increase a sensor thermal resistance. The GaAs island floats in 1 μm thin polyimide layer. The polyimide membrane (225 μm x 360 μm) mechanically fixes and thermally isolates the GaAs thin plate which is 175 μm long and 125 μm wide. The GaAs substrate rim has been designed 10 μm thick and 50 μm wide analogous to previous model.

## 4 Results

The power to temperature (P-T) conversion characteristics of the MTC structures, were investigated by simulation and were compared with the real micro-machined devices. High electro-thermal conversion efficiency defined by extracted thermal resistance values ( $R_{th}$ ) 24 K/mW was obtained for island MTC (figure 4). The 3D graph gives good overall visualization of the temperature distribution (fig.5) in the island MTC structure caused by the power

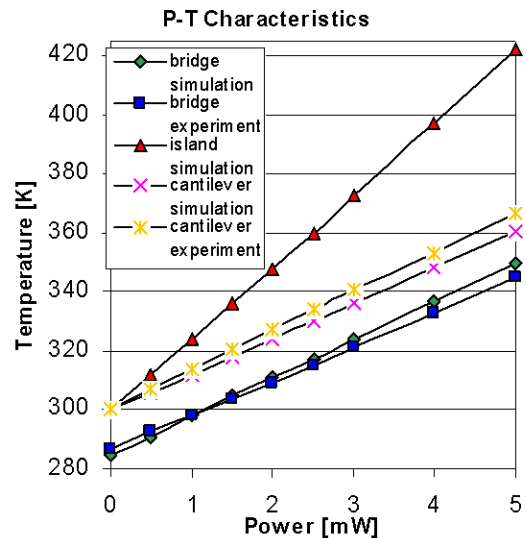


Fig. 4. Simulated island, cantilever and bridge P-T characteristics. Comparison with real micro-machined MTC device. Ambient temperature for bridge MTC was 285 K whereas other two MTCs ambient were 300 K.

dissipation generated by the HEMT heater. Shading and Z-direction value represents temperature distribution for 2 mW power HEMT dissipation. The thermal boundary conditions were defined for side walls of GaAs substrate. These sides were kept at the room temperature of 300K while other sides were adiabatic. The island is “floating” in the polyimide layer that mechanically fix and thermally isolates the MTC structure. Polyimide layer is not shown on the figure, but was considered in the simulation.

The thermal analyses were performed for both vacuum ambient and non-convective gaseous medium around the MTC structure. The heat losses, due to radiation, were viewed as negligible.

Transient on/off power characteristics for island structure are depicted on fig. 6. At the beginning there was power of 2mW switched ON. In the time of 2ms the power was switched OFF. Thermal time constant of the island structure arrangement is 2ms. There are two transients on the fig. 6. Upper is the temperature of the heater and the bottom dependence reflect average temperature of TS. Stress and displacement magnitude evaluation were simulated using MemMech simulator.

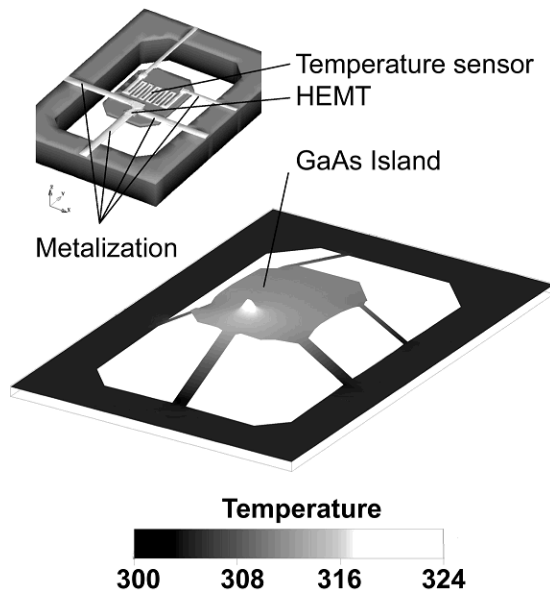


Figure 5. 3-D plots of temperature distribution of the island MTC structure for power dissipation of 2mW. The island is “floating” in polyimide layer that mechanically and thermally isolates the MTC structure. Polyimide not shown.

Outer substrate rim was set as rigid (non moveable). Fig. 8 shows the most extreme island structure displacement dependence on the power dissipation in the z-axis direction. The value represents the difference between the substrate surface and the displaced island.

## 5 Conclusion

Spatial temperature dependences, thermal time constant, thermal stress and displacement and power to temperature characteristics were calculated from the heat distribution. Temperature distribution, mechanical stresses and displacements of GaAs MEMS device have been simulated using CoventorWare. Using FEM simulations, the layout of HEMT transistor, temperature sensor and MTC shapes and dimensions were also optimized.

Power to temperature (P-T) conversion characteristics of the MTC devices was determined. The high electro-thermal conversion efficiency, defined by extracted thermal resistance values ( $R_{th}$ ) 24 K/mW, was achieved for island structure. As compared with the experiment, the thermal resistance values are congruent.

Photograph of “floating” Island MTC structure

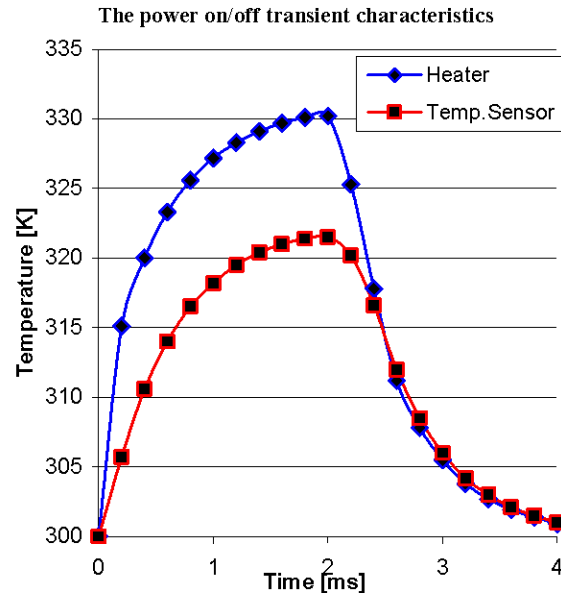


Fig. 6. The power on/off transient characteristics for island MTC structure for power ON of 2mW. At the beginning there was power of 2mW switched ON. In the time of 2ms the power was switched OFF.

is on figure 7. Top polyimide layer was removed in order to see the surface of island.

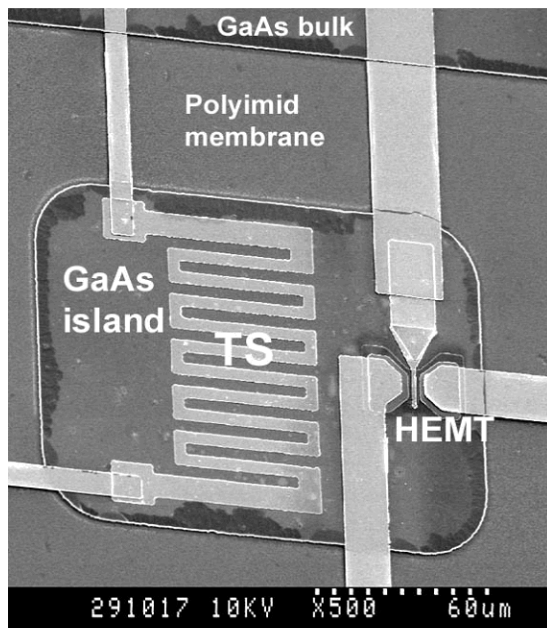


Fig. 7. Photograph of “floating” Island MTC structure. The polyimide was removed in order to see the surface of island.

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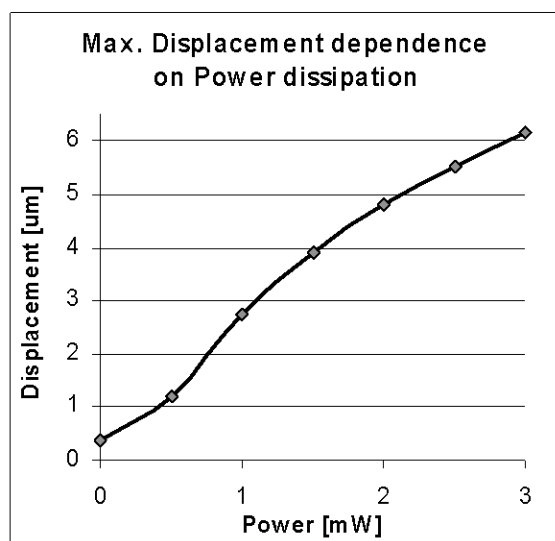


Fig. 8. Maximal Displacement dependence on Power dissipation simulated for Island structure in Z direction.

## References

- [1] T. Lalinský, J. Kuzmík, M. Porges, S. Hascík, Z. Mozolová, L. Grno, “Monolithic GaAs MESFET power sensor microsystem”, *Electronics Letters* 31, pp.1914, 1995.
- [2] J. Jakovenko, M. Husak, “MEMCAD thermal simulation of GaAs based membrane bridge”, *MME '01 Conference*, Cork, Ireland, 2001.
- [3] S.D. Senturia, *Microsystem Design*, Kluwer Academic Publisher book, 2001.
- [4] M. Elwensoekk, R. Wiegerink, *Mechanical Mikrosensors*, Springer, book, 2000.
- [5] Tai-Ran Hsu, *MEMS and Microsystems Design and Manufacture*, Mc Graw Hill, book, 2001.
- [6] Jaeggy, H. Baltes and D. Moser, “Thermoelectric AC Power Sensor by CMOS Technology”, *IEEE Electron Device Letters* 13, 1992, pp. 366
- [7] P. Kopystinski, H. Obermayer, H. Delfts, W. Hohenester, and A. Loser, “Silicon RF Power Sensor from DC to Microwave”, *Microsystem Technologies*, 1990, pp. 605.
- [8] A. Dehe, V. Krozer, B. Chen and H. Hartnagel, “High-sensitivity microwave Power Sensor for GaAs-MMIC implementation”, *Electronics Letters* 32, 1996, pp.2149-2150.
- [9] M. Husak, “Hierarchy of models in microsystems design”, *Computational Methods in Circuits and Systems Applications conference proceedings*, pp. 101 -104, 2003
- [10] M. Salehnamadi, “RMICR: Reconfigurable mesh with interchangeable column row”, *Computational Methods in Circuits and Systems Applications conference proceedings*, pp. 63 -67, 2003