Design and Characterization of new GaAs Micromechanical Thermal Converter developed for Microwave Power Sensor

Jiri Jakovenko*, Miroslav Husak*, Tibor Lalinsky**

*Czech Technical University, Dept. of Microelectronics,
Technicka 2, Prague 6, Czech Republic, jakovenk@feld.cvut.cz
**Institute of Electrical Engineering, Slovak Academy of Sciences, Bratislava, Slovakia

ABSTRACT

In this report we demonstrate the design of Thermo-mechanical converter that creates heart of the RF power sensor microsystem. The inspiration 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 intended from the heat distribution. The temperature changes induced in the MTC by electrical power dissipated in the HEMT (High Electron Mobility Tranzistor) are sensed using the temperature sensor. The temperature distribution and mechanical stress was optimized by studying different MTC sizes, and layouts of the heater and temperature sensor.

Keywords: MEMS thermal converter, thermo-mechanical simulation, GaAs power sensor

1 INTRODUCTION

Transmitted power is the most important measure considered in RF systems. Usual approach to transmitted power measurement is based on the detection of absorbed power waves (incident and reflected) that requires complicated multiple power meter structures and need complex calibration.

An improved 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 of the MTC can be reached by the design of free micromechanical plate which is as thin as possible. We have developed a new GaAs based MTC technological process, which 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 temperature distribution optimization have a significant influence on the performance of the Micromechanical Thermal Converter. MTC structures with a diverse sizes and arrangements of the heater and the temperature sensor were studied.

The thermoelectric AC power sensor and microwave power sensor were firstly analyzed by Jaeggy and Kopystinski [6, 7] by using CMOS IC technology. The

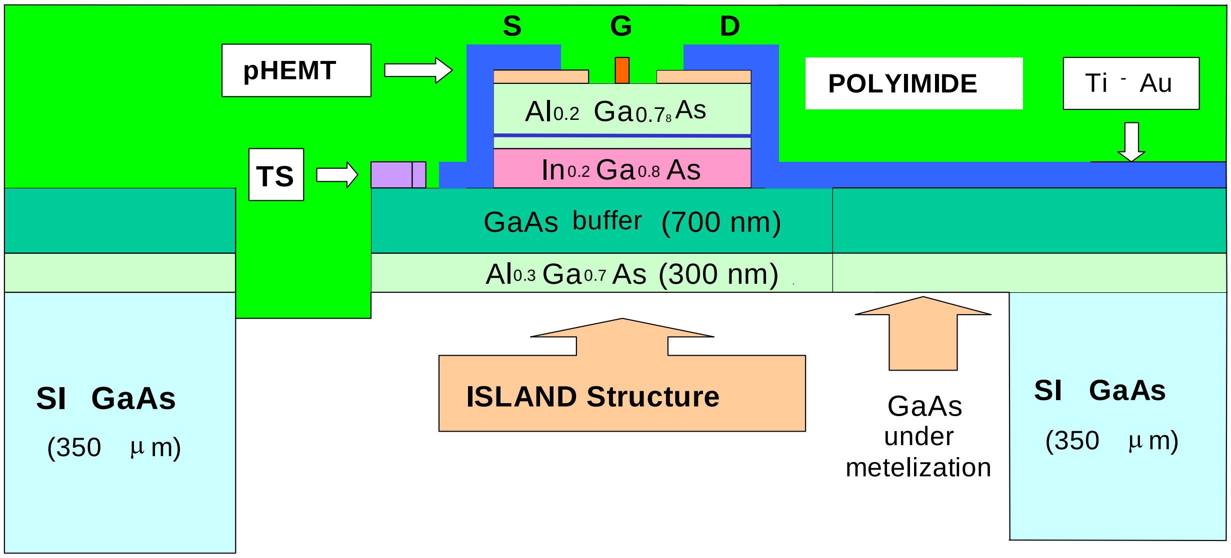

Fig. 1. Schematic cross-section through the polyimide-fixed MTC structure to be integrated with HEMT as heater and poly-Si/Pt thin film resistor as temperature sensor TS

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 considerable advantages are some intrinsic material properties such as lower thermal conductivity, high temperature performance, heterostructure quantum effects, etc. The HEMT technology has been developed for our GaAs based MEMS structures.

2 MTC TECHNOLOGY AND 3-D MODEL

In order to increase the thermal resistance values of the MTC structures, they have to be designed as a very thin plate. We have developed a new technology of GaAs micromechanical island structure. The technology process begins with the MBE or MOCVD growth of GaAs heterostructures on semi-insulating substrates (SI-GaAs) (Fig. 1). 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 allow 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.

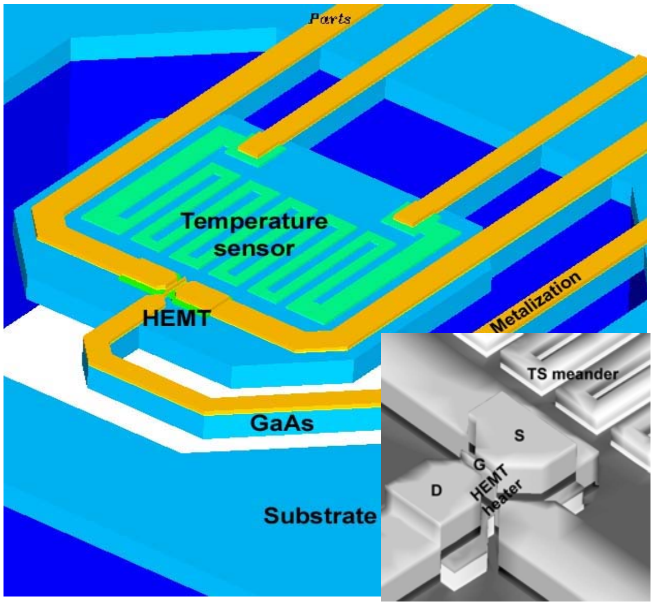

Fig. 2. Model of the Island MTC structure. GaAs island is “floating” in Polyimide 1 um thick layer (not visible). The meander-shaped TS is also shown. *Z*-direction is 20times magnified. The Detail of HEMT heater is on the right.

Thin polyimide layer is deposited after the bulk GaAs micromachining and enables the micromechanical structures to be mechanically fixed and thermally isolated in a fee space.

Schematic cross-section is shown on fig. 1. Silicon delta-doped layer is formed for HEMT design in the Al0.22Ga0.78As barrier layer. This layer is separated by 3 nm thick undoped Al0.22Ga0.78As spacer from the In0.2Ga0.8As channel. GaAs/Al0.3Ga0.7As (700 / 300 nm) heterostructure buffer layer under channel was designed to define the thickness of the MEMS structure.

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

Fig. 2 demonstrates the model of GaAs island structure which has been proposed to increase a sensor thermal resistance. The GaAs island (175 μm x 125 μm) floats in 1 μm thin polyimide membrane (225 μm x 360 μm) that mechanically fixes and thermally isolates the GaAs MTC plate. For numerical simulation purposes GaAs substrate rim has been designed 10 μm thick and 50 μm wide.

3 RESULTS

Main characteristics for the thermal converters optimization are the temperature distribution over the sensing area, the time response, the sensitivity and the mechanical stresses in the multilayer structure.

The input power dissipation in the heater was defined as heat flux coming through the HEMT gate area (10 μm x 0.5 μm). We can use this approximation because the heat dissipation in HEMT structure is generated in very thin conduction layer which formed under the gate area.

3.1 P-T Characteristic and Steady state Thermal analysis

For an isotropic homogenous material the steady state heat equation can be written [4]:

$$\nabla^2 T \equiv \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} = -\frac{1}{k} Q(x, y, z)$$

where Q represents generated internal heat, k denotes the thermal conductivity, c_p its specific heat and T its temperature. For the thermal analysis problem, the essential boundary conditions are prescribed temperatures.

The spatial temperature distribution of the MTCs and steady state heat flux were calculated taking into the account the heat transfers to infinity. In the current analysis, according to the application requirement, the fixed thermal boundary is defined for the all side walls of GaAs substrate. These sides were kept at the room temperature of 300 K while other sides were adiabatic.

3-D diagram gives good overall visualization of the temperature distribution (fig.5) in the island MTC structure

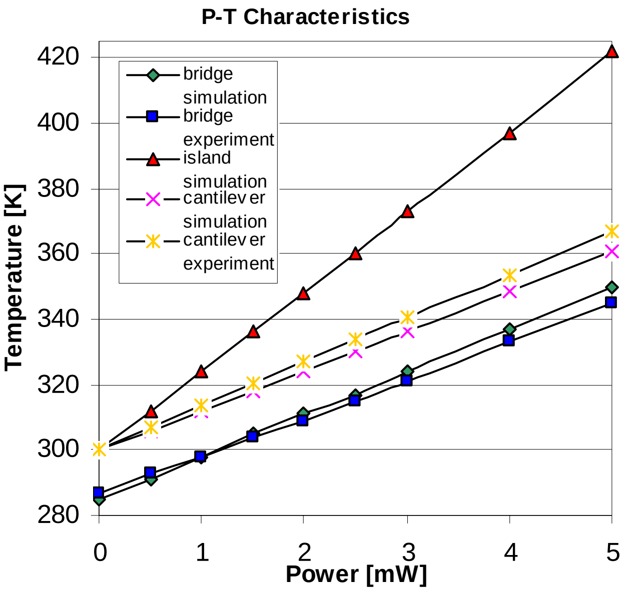

Fig. 3. Simulated island, cantilever and bridge Power to Temperature characteristics. Comparison with real micro-machined MTC device. Ambient temperature for bridge MTC was 285 K whereas other two MTCs ambient were 300 K.

caused by the power dissipation generated by the HEMT heater. 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 fixes 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. 4. At the beginning there was power of 2mW switched ON. In the time of 5 ms the power was switched OFF. Thermal time constant of the island structure arrangement is 1.9 ms. There are three transients on the fig. 4. Upper is the maximal temperature of the heater and the bottom dependence reflect average temperature of TS.

Stress and displacement magnitude evaluation were simulated for BC where outer substrate rim was set as rigid (non moveable). Fig 5 shows mechanical deflection of the island MTC structure for power dissipation of 2 mW.

3.2 Optimization of MTC structures

New optimized island structure design reduces the maximal stress caused by temperature changes; minimize the temperature losses that were caused by short supplying metallization to HEMT transistor.

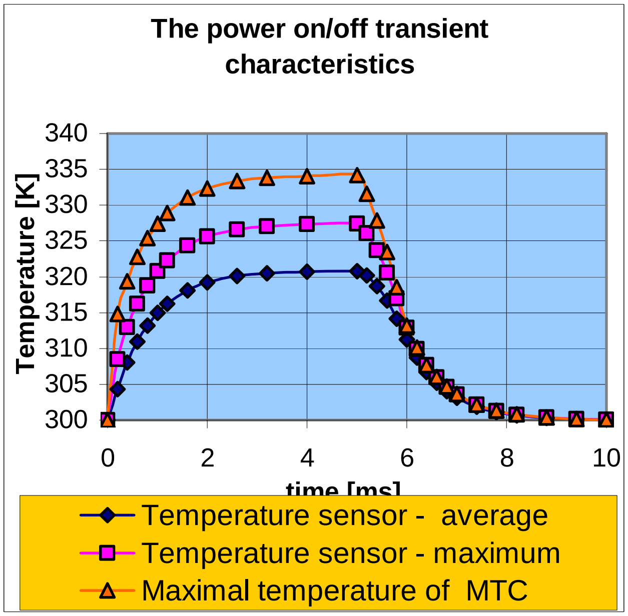

Fig. 4. The power on/off transient characteristics for island MTC structure for power ON of 2mW. At the beginning there was power of 2mW switched ON. In the time of 5ms the power was switched OFF

Gate supplying metallization was led around the island in order to lengthen it as much as possible (Fig 5.). The temperature losses are minimized by this solution. Another advantage is that all metallization are entering the substrate surface in the same side. Mechanical compressions and stresses are minimized by this solution.

The influence of the gate width on maximal temperature of MTC structure has been simulated. Temperature distribution in the HEMT and in the MTC structure for different gate widths (5 µm, 10 µm, 15 µm,

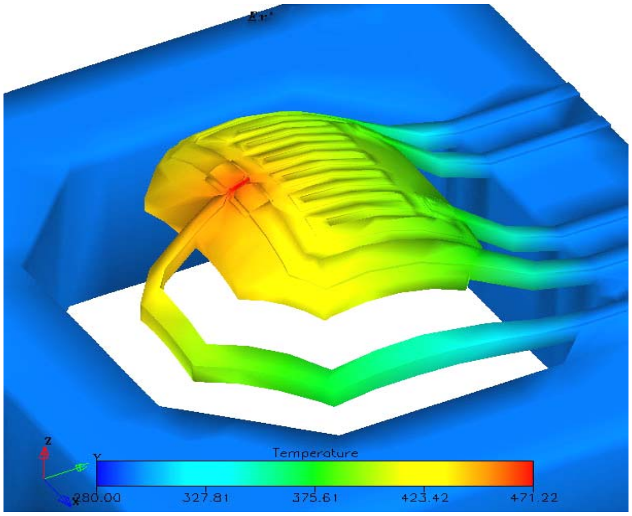

Fig. 5. 3-D Plots of temperature distribution of the island MTC structure for power dissipation of 2 mW. The island is "floating" in polyimide layer that mechanically and thermally isolates the MTC structure. Polyimide not shown.

20 μm) has been obtained. From the simulation results follows that the maximal temperature of the MTC which is located in the gate of the HEMT is inversely proportional to the gate width, fig. 6.

These analyses have demonstrated that the temperature sensed by temperature sensor remained the same. It can be concluded the HEMT gate width does not have any influence to the sensitivity of MTC, only maximal system temperature changes. In order to minimize maximal temperature of the sensor it is desirable to increase the HEMT gate width. Due to maximal temperature reduction the sensor could be used for wider field of measured power while the sensitivity remains the same.

Comparison of the designed island MTC structures is summarized in Tab. 1.

	Island without GaAs	Island with GaAs	Optimized island with GaAs
R_{th} simulation [K/mW]	*24*	*13*	*26*
R_{th} measurement [K/mW]	-	*14*	-
τ simulation [ms]	*0.9*	*0.9*	*0.8*
τ measurement [ms]	-	*0.8*	-
Max. temperature [K] (1mW)	*332*	*320*	*336*
Max. displacement [μm] (1mW)	*2.74*	*0.26*	*5.28*
Max. mechanical stress [MPa] (1mW)	*540*	*434*	*284*

Tab. 1 – MTC simulation results summary

4 CONSLUSION

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.

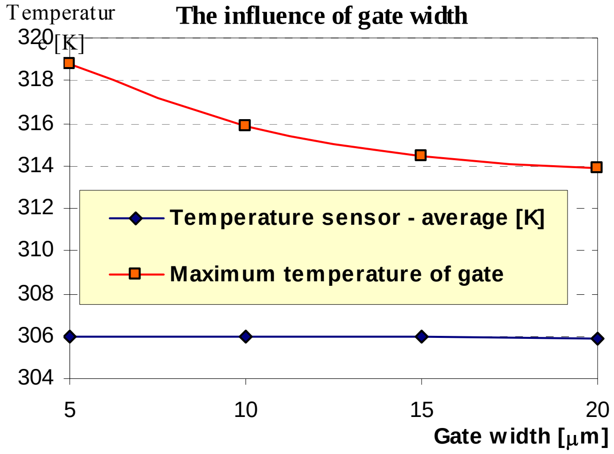

Fig. 6 – Maximal and average temperature – HEMT gate width dependence. Dissipated power was 0.5 mW.

Power to temperature (P-T) conversion characteristics of the MTC devices was simulated and compared with measurement of real micromachined structures. 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.

REFERENCES

[1] T. Lalinský, M. Držík, J. Jakovenko, M. Husák, MEMS/NEMS handbook: techniques and applications, Chapter 3, Ed. C. T. Leondes, (2006), pp. 49-109

[2] J. Jakovenko, M. Husak, T. Lalinsky, "Design and simulation of micromechanical thermal converter for RF power sensor microsystem", Microelectronics Reliability, Elsevier, ISSN 0026-2714, Vol. 44, pp. 141 – 148, 2004.

[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.

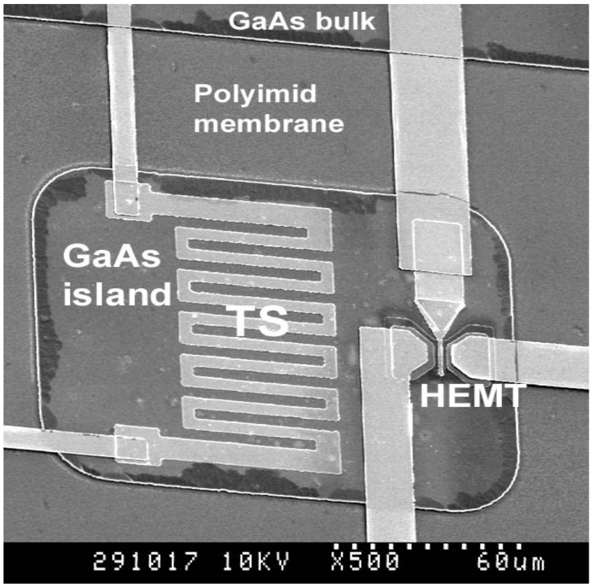

Fig. 7 – Real micromachined island MTC structure