# Micromechanical GaAs Thermal Convertor for Gas Sensors

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## ABSTRACT

This paper discusses design, simulation and fabrication of new Micromechanical Thermal Converters (MTCs) based on GaAs developed for Gas sensors. GaAs MTCs seem to be very attractive for design of thermally based MEMS sensor devices. High thermal isolation of these devices can be done by implementing of free micromechanical hot plates which is designed as thin as possible.

Metal oxide gas sensors generally work in high temperature mode that is required for chemical reactions to be performed between molecules of the specified gas and the surface of sensing material. There is a low power consumption required to obtain the operation temperatures in the range of 200 to 500 $^{o}$C. Mechanical stability and integrity and a fast thermal response are very important parameters that can not be neglected. These above mentioned design rules can be achieved using GaAs based micromachined concept of thermal converter.

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

## 1 INTRODUCTION

The micromachined thermal converters (MTCs) based on GaAs seem to be very attractive for design of thermally based MEMS devices. In general, MTC integrates GaAs microelectronic devices (high-speed transistors or resistors) and temperature sensors on GaAs thermally isolated micromechanical structures (membranes, cantilevers and bridges). The microelectronic devices placed at the end of a cantilever or in the middle of bridge and membrane are designed to work as micro-heaters, and the temperature sensors are proposed to sense the temperature at precisely defined place of the micromechanical structures..

Due to a higher thermal resistance and operation at high temperatures, MTC based on GaAs should be able to perform electro-thermal conversion with higher conversion efficiency than well known Si devices. The most considerable advantages are some intrinsic material properties such as lower thermal conductivity, high temperature performance, heterostructure quantum effects, etc. The HEMT technology creates conditions for MEMS device development fully compatible not only with signal conditioning and drive circuit but also with the monolithic microwave integrated circuits (MMICs). The most of GaAs based MTC devices were developed to be applied for RF and microwave power sensors and infrared thermal sensors [1]. In this work we demonstrate thermal performance of GaAs based MTC device to be applied for gas sensing.

## 2 DEVICE FABRICATION 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. Moreover, optimization of the MTC structure dimensions, in particular the aspect ratio between the MTC structure length which increase the thermal resistance and MTC

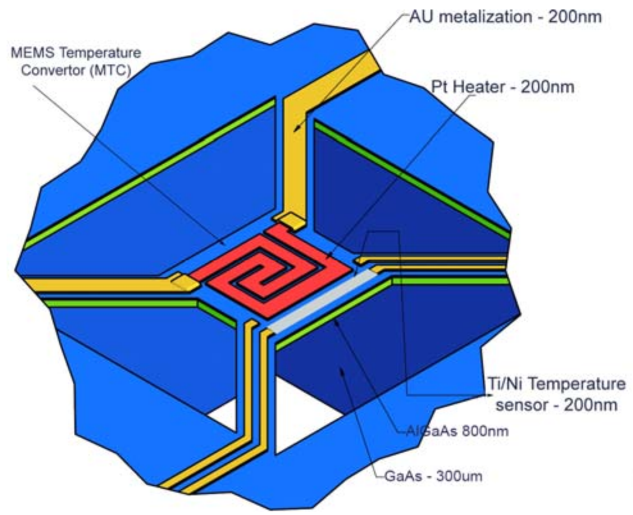


Fig. 1. Model of the gas MTC structure. GaAs island 2 um thick is "floating" in Polyimide layer (not visible). The meander-shaped TS is also shown. *Z*-direction is 20times magnified. The Detail of HEMT heater is on the right.



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thickness, has to be carried out to find the best trade-off between thermal resistance and acceptable mechanical stress.

Figure 1 shows a schematic view of the device. It consists of Ti/Pt resistor as a heater and Ti/Ni meander-like thin film as a temperature sensor. The both devices are integrated on thermally isolated 2 µm-thick AlGaAs/GaAs island structure suspended using the four cross-bridges.

MTC fabrication process starts with the front-side processing technology of the micro-heater and temperature sensor. The process must be combined with surface and bulk micromachining of GaAs. GaAs micromachining technology is fully compatible with the processing technology of integrated microelectronics devices.

The GaAs/AlGaAs heterostructure layer system grown by MBE on GaAs substrate was designed to be used for micromechanical structure fabrication. In first step, double-side aligned photolithography is carried out to define the etching masks on the both sides of the substrate. After this, highly selective reactive ion etching (RIE) of GaAs from the front side was used to define the lateral dimension of the structure. The vertical dimension was defined by deep back side RIE through a 300 µm thick GaAs substrate to the AlGaAs etch-stop layer, hence the structure thickness (vertical dimension) is precisely determined by the thickness of MBE grown GaAs layer over this etch stop layer. The last step is selective etching of the AlGaAs etch stop layer. The details of described micromachining technology can be found in [1].

Fig. 1 demonstrates the MTC model The GaAs island (150 µm x 150 µm) floats in 2 µm thin polyimide membrane (350 µm x 350 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 100 µm wide. A real view of fabricated MTC device is shown in Fig. 2.

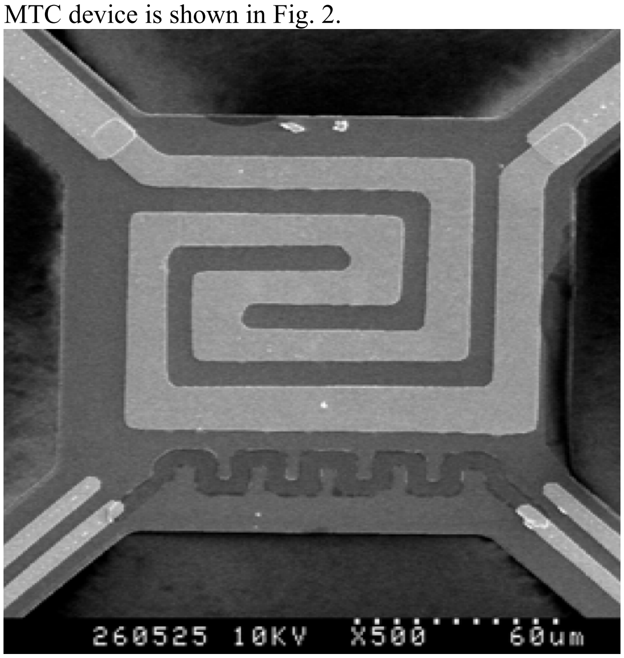


Figure 2. A real view of fabricated MTC device

## 3 DEVICE ELECTRO-THERMAL PERFORMANCE ANALYSIS

The temperature sensitivity of Ti/Ni thin film temperature sensor was investigated in the first stage. I-V characteristic of the temperature sensor at constant current biasing was used to convert the temperature into voltage. Fig. 3 shows the measured voltage response to the temperature at constant current biasing of 1 mA. As expected there is very good linearity in the sensor voltage response observed.

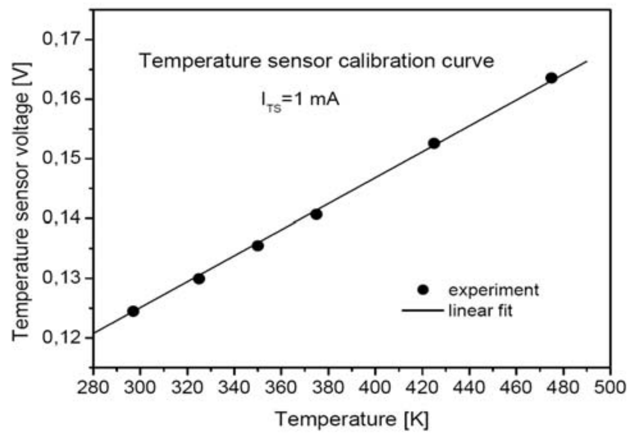


Figure 3. Temperature sensor calibration curve

The linear fit performed on the temperature sensor calibration curve in Fig. 3 allows make transfer of the temperature sensor voltage directly to the temperature. Fig. 4 shows measured power to temperature (P-T) conversion characteristic that can be used to evaluate the conversion efficiency of the MTC structure.

As we can see there is some discrepancy from a straight line observed. After fitting the measured data by a quadratic polynomial regression ( $T = 305.23 + 10.297\ P + 0.262\ P^2$) it is clear that thermal resistance Rth defined as $\partial T/\partial P$ increases with the power dissipation (temperature increase).

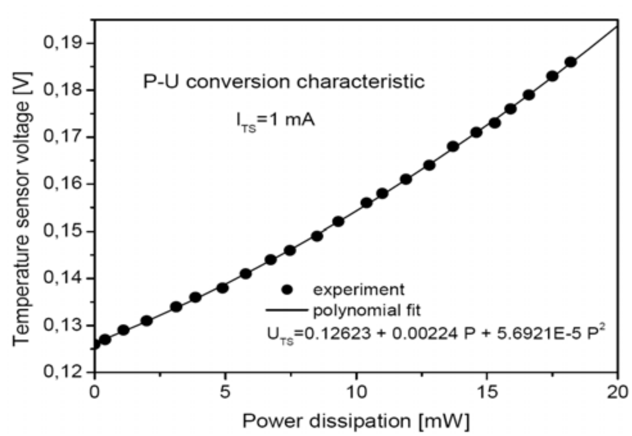


*Figure 4. P-T conversion characteristic of MTC device*

At power dissipation about 20 mW it achieves the value almost 21 K/mW. So, the temperature increase in the sensor active area on the level of 600 K (predicted operating temperature of gas sensor) can be achieved by the power dissipation lower than 20 mW.

Metal oxide gas sensors generally work in high temperature mode that is required for chemical reactions to be performed between molecules of the specified gas and the surface of sensing material. There is a low power consumption required to obtain the operation temperatures in the range of 500 to 700 K. Likewise, uniform temperature distribution in the active sensing area is needed to ensure equal sensing properties of the whole surface. Thermo-mechanical stability and integrity and a fast thermal response belong to very important parameters that can not also be neglected.

## 4 DEVICE THERMAL SIMULATION

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. The steady state temperature analysis has been performed to determine the temperature distributions and thermal resistance of the MTC device. The temperature distributions caused by power dissipation in the heater were evaluated by the Coventor Ware three-dimensional (3D) simulation tools.

For the thermal analysis problem, the essential boundary conditions are prescribed temperatures. The spatial temperature distribution 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 MTC 3-D model. These walls were kept at the room temperature of 300 K while other sides were adiabatic. The CoventorWare simulation manager (SimMan) was used to investigate the influence of the power dissipation in the heater.

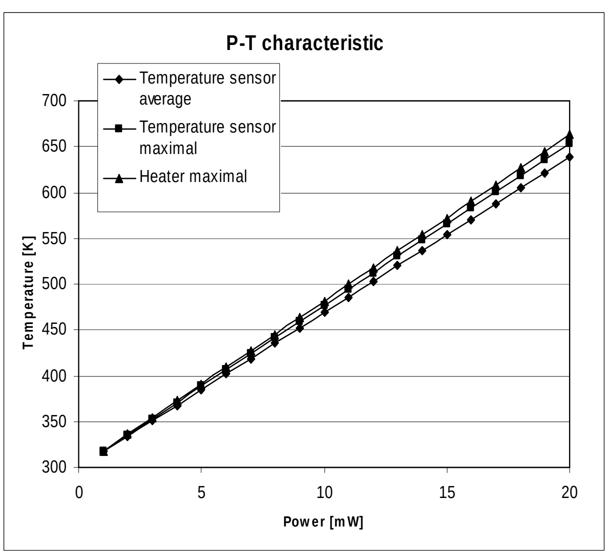


Figure 5. Simulated P-T conversion characteristics

3D graph as shown in Figure 8 gives good overall visualization of the temperature distribution in the suspended island structure of the MTC device, which is caused by the power dissipation generated in the thin film resistive meander-like heater. The thermal analyses were performed for both vacuum ambient and non-convective gaseous air around the MTC structure. The heat losses, due to radiation, were viewed as negligible.

The power to temperature (P-T) conversion characteristics of the MTC device were also investigated by the simulation (Figure 5). High electro-thermal conversion efficiency defined by the extracted thermal resistance value (Rth=17.3 K/mW (CoventorWare simulation) was achieved. This value corresponds to the average value obtained from the experiment (see Figure 4). Transient power characteristics are depicted on fig. 6. At the beginning there was dissipated power of 1 mW switched ON. There are three transients on the fig. 6. Upper is the maximal temperature of the heater and the bottom dependence reflect average temperature of TS.

## 5 DEVICE THERMO-MECHANICAL CHARACTERIZATION

In order to evaluate the temperature time constant of the MTC device an optical method as presented in [2] can be used. It is based on measurement of deformation changes of the island membrane structure induced by the temperature changes. Temperature changes in most of such micromechanical structures can induce structure

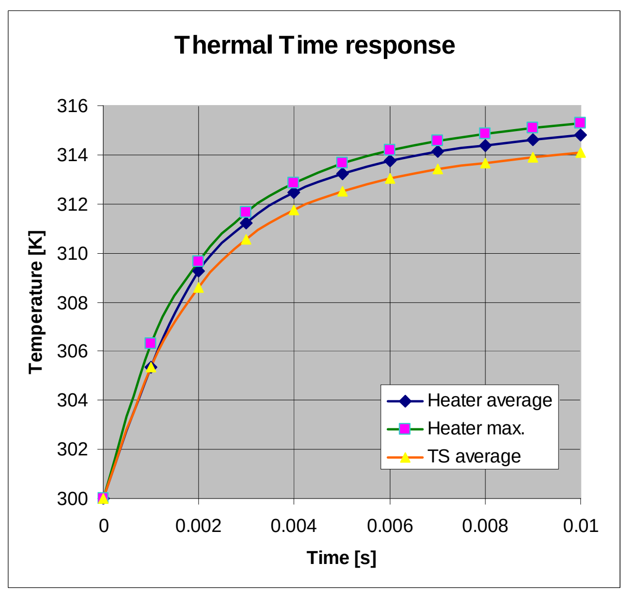


Figure 6. The simulated thermal time response for 1 mW power dissipation in the heater. At the beginning there was power of 1 mW switched ON



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deformations due to different thermo-mechanical properties of the multilayer material system. The non-stationary dynamic process of transient heat flow creates also time dependent mechanical movements. To observe these deformation changes the optical method such as Laser Doppler Vibrometer (LDV) can be applied. The heterodyne interferometrical system of Polytec OFV-303 vibrometer is capable to detect the vibrational amplitudes in units of some nanometers.

Figure 7 shows the mechanical time response (time dependence of deflection) of the membrane suspended island structure obtained by the optical measurement. The time constant value about 1.5 ms can be determined from the exponential fit. It corresponds to the thermal time constant.

## 6 CONCLUSIONS

The micromachined concept of GaAs based thermal converter device to be designed for metal oxide gas sensors, to our knowledge, has been presented. It is fully compatible with the GaAs MESFET or HEMT based signalprocessing and controlling electronics to be monolithically integrated with the gas sensors.

A comprehensive electro-thermo-mechanical performance analysis of the device was performed. The MTC device introduced exhibits very good mechanical integrity and thermal stability. Due to very high electro-thermal conversion efficiency, defined by the extracted thermal resistance values (Rth~15-21 K/mW), the power consumption can be kept very low ($P < 20$ mW) to obtain the temperature of gas sensitive area on the level of 600-650 K.

3D thermo-mechanical simulation of the device was performed. We optimized MTC structure to obtain uniform temperature distribution in the active gas sensitive area of the device. We achieve high conversion efficiency. Simulated values were compared to evaluated values performed by the experiment.

The thermal time constant ($\tau$~1.44 ms) of the MTC device was also estimated by simulation and calculated from the mechanical time response measurements using LDV method. The processing technology of described gas sensor based on the MTC device have been in progress. The process flow is now focused to define gas sensitive area based on polycrystalline NiO thin films with a dense fine-grained microstructure.

**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.


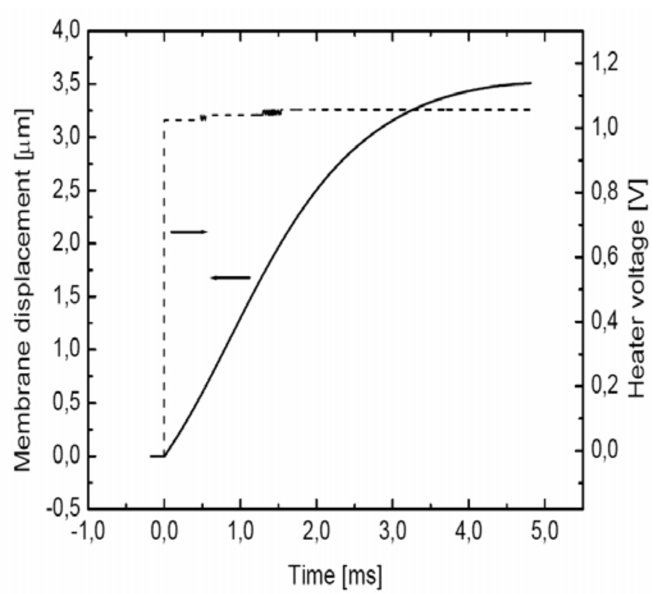


Figure 7. Mechanical time response to the input step-wise heater voltage (temperature increase of 482 K)

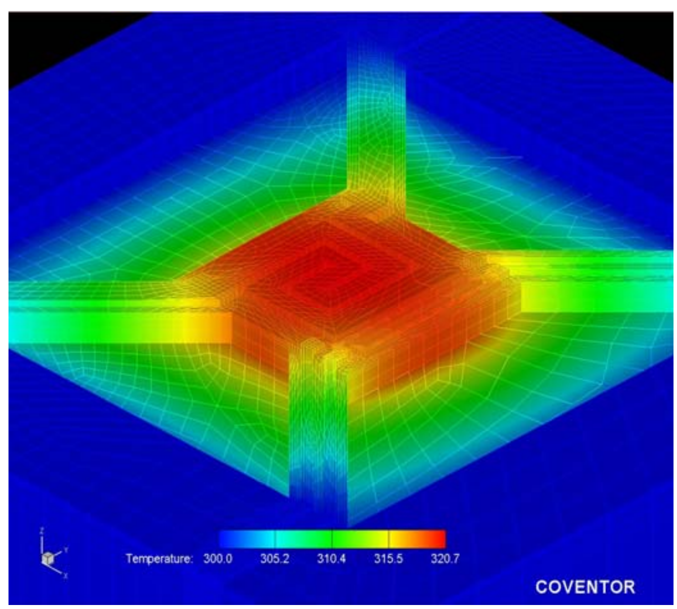


Figure 8. Device spatial temperature distribution (Dissipated power in the heater was 1 mW) Uniform temperature distribution was obtained by this implementation.