# Optimization of GaAs MEMS structures for Microwave Power Sensor

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## ABSTRACT

This report discusses the design of Thermo-mechanical converter that creates heart of the RF power sensor microsystem. The idea 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, over the sensing area, and mechanical stress was optimized by studying different MTC sizes, and layouts of the heater and temperature sensor.

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

## 1 INTRODUCTION

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

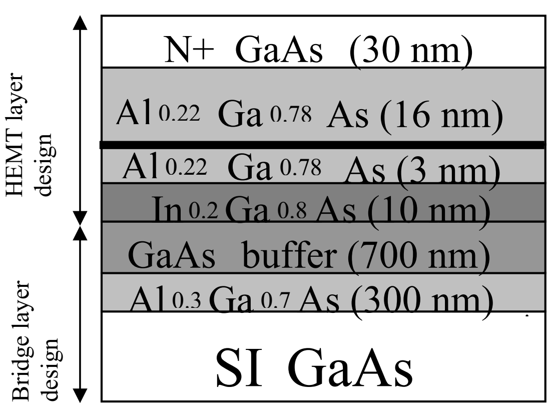


Fig. 1. Heterostructure layer design used for the HEMT and bridge technology

An improved technique 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. 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 optimize the MTC are the temperature distribution over the sensing area, time response, sensitivity analysis and evaluation of the mechanical stresses.

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

The thermoelectric AC power sensor and microwave power sensor were analyzed 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.

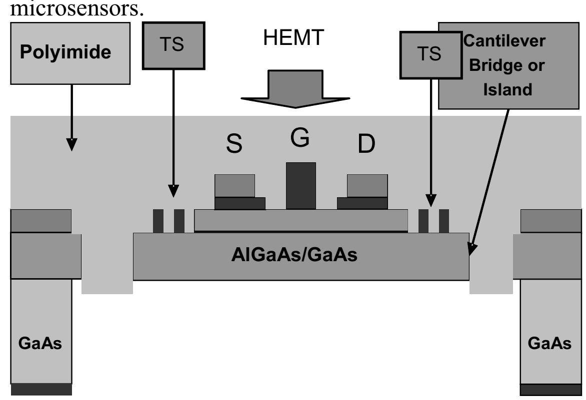


Fig. 2. Schematic cross-section through the polyimide-fixed MTC structure to be integrated with HEMT as heater and poly-Si/Pt thin film resistor as temperature sensor TS

The most considerable 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 μm) 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 MTC TECHNOLOGY AND 3-D MODEL

MTC structures should be designed with the thickness as thin as possible in order to increase the thermal resistance values.

The technology of new GaAs micromechanical island structure begin 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 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.

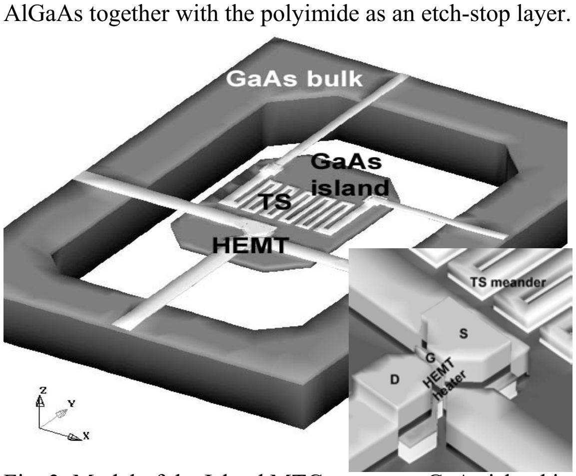


Fig. 3. Model of the Island MTC structure. GaAs island is “floating” in Polyimide 1um thick layer (not visible). The meander-shaped TS is also shown. *Z*-direction is 20times magnified. Detail of HEMT heater is on the right.

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

The layer scheme shown in fig. 1 represents HEMT design. Silicon delta-doped layer is formed in the Al0.22Ga0.78As barrier layer, and it is separated by 3 nm-thick undoped Al0.22Ga0.78As spacer layer 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 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 (225μm x 360μm) mechanically fixes and thermally isolates the GaAs thin plate which is 175μm long and 125μm wide. The GaAs substrate rim has been designed 10 μm thick and 50 μm wide analogous to previous model.

## 3 RESULTS

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

For simulation process the input power dissipation in the heater was defined by heat flux through the HEMT gate area (10 μm x 0.5 μm). We can use this approximation because the heat dissipation in HEMT structure is placed in very thin conduction layer formed under the gate area.

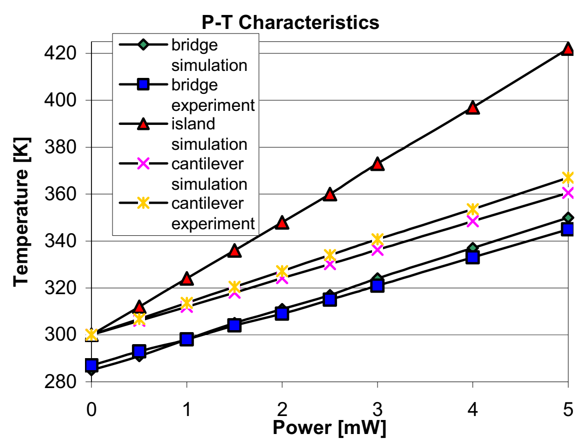


Fig. 4. Simulated island, cantilever and bridge P-T characteristics. Comparison with real micro-machined MTC device. Ambient temperature for bridge MTC was 285 K whereas other two MTCs ambient were 300 K.

### 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 300K while other sides were adiabatic.

3D graph gives good overall visualization of the temperature distribution (fig.5) in the island MTC structure caused by the power 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 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.

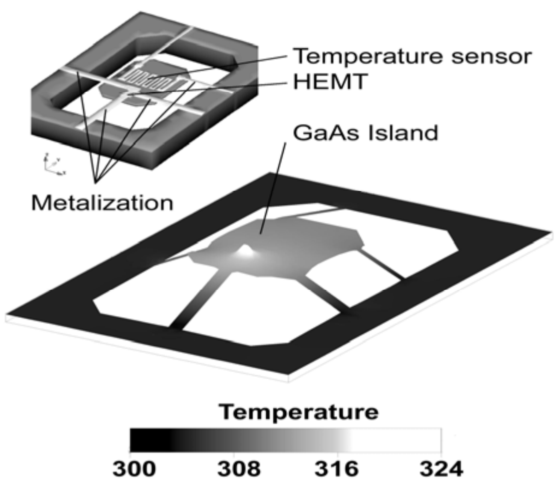


Fig. 5. 3-D plots of temperature distribution of the island MTC structure. The island is “floating” in polyimide layer that mechanically and thermally isolates the MTC structure. Polyimide not shown

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 for BC where outer substrate rim was set as rigid (non moveable).

### 3.2 Optimization of MTC structures

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, 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. 7 and.

The analysis also proved that the temperature sensed by temperature sensor remained the same. It can be concluded that the HEMT gate width does not have any influence to the resulted sensitivity, only maximal temperature changes. In order to minimize maximal temperature of the sensor it is desirable to increase the HEMT gate width as soon as possible. The dissipated power is then generated in greater volume. Due to maximal temperature reduction the sensor structure could be used for wider field of measured power while the sensitivity remains the same.

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. The 3-D model is depicted on fig. 8.

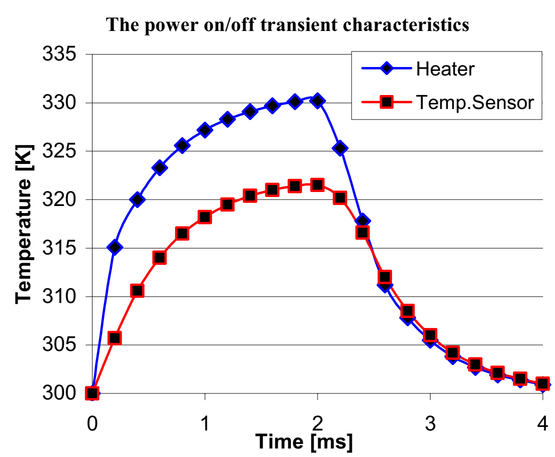


Fig. 6. The simulated power on/off transient characteristics for island MTC structure for power ON of 1 mW. At the beginning there was power of 1 mW switched ON. In the time of 4 ms the power was switched OFF.

Gate supplying metallization was led around the island order to lengthen it as much as possible. The temperature losses are minimized by this solution.

Another advantage is that all metallization are entering the substrate surface in the same location and there are no other metallization on the opposite site. Mechanical compressions are minimized by this solution. 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* |

## 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.

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.

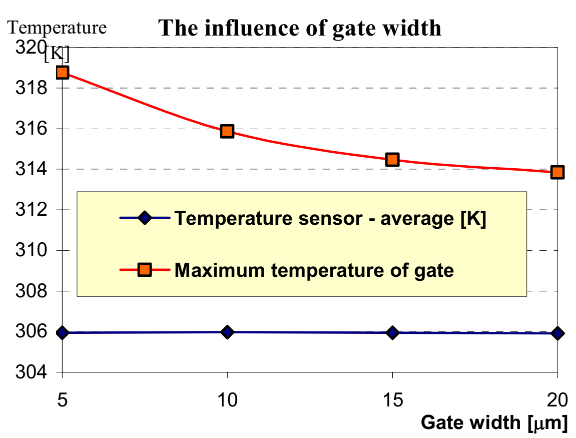


Fig. 7 – Maximal and average temperature – HEMT gate width dependence. Dissipated power was 0.5 mW.

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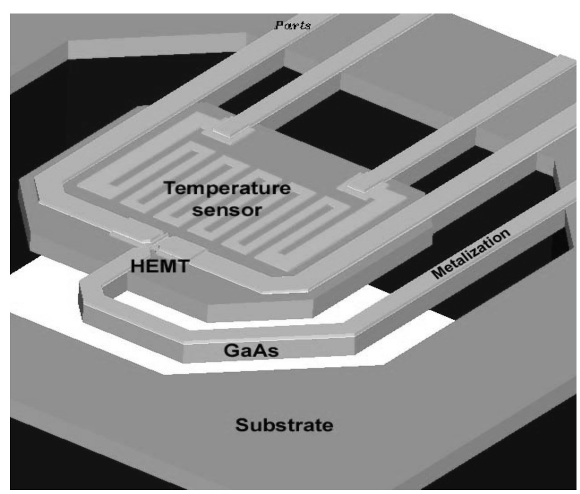


Fig. 8 – 3-D model of the optimized island MTC structure