Design and simulation of the GaAs Micromechanical Thermal Converter for Microwave Transmitted Power Sensor

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ABSTRACT

This paper discusses the thermo mechanical simulations performed with the aim of optimising the temperature distribution of the Micromechanical Thermal Converter (MTC), designed for a Microwave Power Sensor Microsystem. The conception of the absorbed power measurement is based on a thermal conversion, where absorbed RF power is transformed into a thermal power, inside a thermally isolated system. By means of thermal simulations, we propose the Micromechanical Thermal Converter design with the layout and placement of the active heater and the temperature sensor which are integrated within MTC structure. Spatial temperature dependences, thermal time constant power to temperature characteristics, residual stresses and displacements caused as a result of temperature changes in the structure are calculated from the heat distribution and thermo-mechanical simulations. The 3D thermal and thermo-mechanical simulations of the sensor structures were performed, using the Coventor Ware simulator.

Keywords: Micromechanical Thermal Converter, MEMS simulations

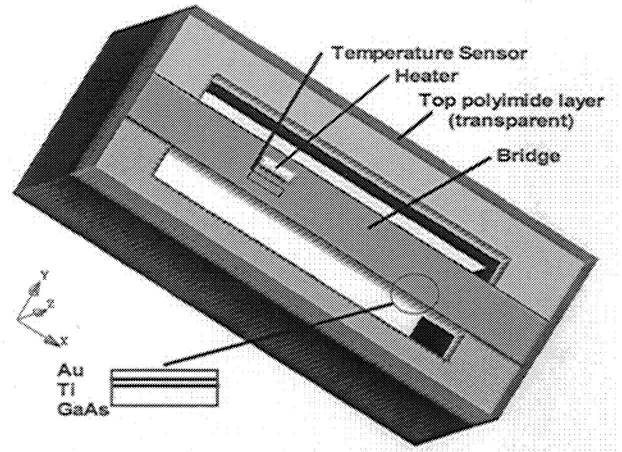

Figure 1: 3D model of fixed bridge MEMS device
Upper Polyimide layer that mechanically fixes a thin bridge structure is also included in simulations, but not visible in this figure. Length of bridge is 880um and width is 270um .

1 MICROMECHANICAL THERMAL CONVERTER

Transmitted radio frequency power (RF) measurements are of a great interest in the field of microwave equipment. The conventional method of transmitted power measurement is based on the measurement of absorbed power waves that requires complex power meter structures and need complicated calibration of the measured data. Prefered approach of the absorbed power measurement is based on thermal conversion principle where, absorbed RF power is transformed into thermal power inside of a thermally isolated system.

Thermo-mechanical numerical modelling has a substantial impact on the optimal MTC topology design. The main characteristics which we use to optimise these devices are the temperature distribution over the sensing area, time response, sensitivity analysis and evaluation of the mechanical stresses in the MTC structure.

The most significant advantages of GaAs based MEMS are some intrinsic properties of the material, 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 e.g. GaAs-InGaAs or GaAs-InGaP. GaAs-based Integrated Circuits can also be

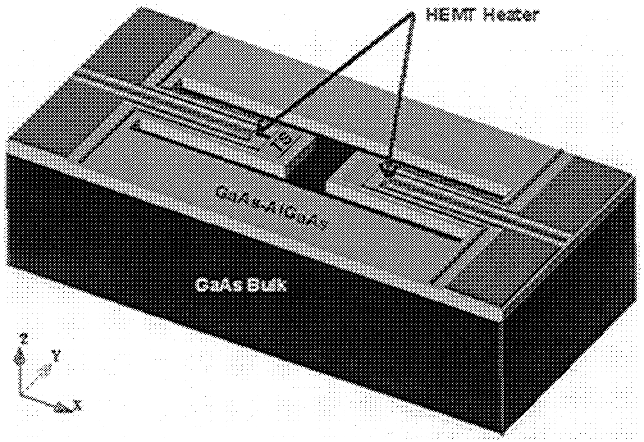

Figure 2: Fixed Cantilever Beam MEMS device
Temperature sensors are placed in the end of beams where we get uniform temperature distribution. Au/Ti metallization lines are implicated in this model. Polyimide is not visible. Length of bridge is 500um.

integrated within the bridge sensor microstructure.

GaAs multilayer MTC creates optimal conditions for the monolithic integration of GaAs based Heterostructure Field Effect Transistors (HFETs) as well as thermal isolation of the microwave sensor elements.

1.1 Cantilever Beam Processing and Model Topology

For Coventor Ware simulation tools 3D models of GaAs MTC has been designed and their structures are depicted in fig.1. The first model represents a two symmetrical cantilever beams structure fixed, by a polyimide layer in a rigid GaAs substrate. For the purpose of the thermal and thermo-mechanical simulations the layer has been designed 10μm. Second structure is GaAs island "floating" in a polyimide layer which also mechanically fix MTC structure. Both MTC devices consist of a heater (the MBE-grown MESA isolated type of AlGaAs/InGaAs/GaAs pHEMT transistor monolithically integrated on the micromechanical structure) and the temperature sensor. The temperature changes, induced in the cantilever beam by electrical power dissipated in the HFET, are sensed using the temperature sensor. The MTC GaAs MEMS structure (1μm) is completed by Ti (50nm)/ Au (150nm) metallization, which is connecting the heater and temperature sensor. Free micromechanical structure is fixed by 1μm polyimide layer (not depicted on Fig.1).

The fabrication of the MEMS device is provided by front-side surface processing of HFET structures, temperature sensor and metallization lines. The surface processing is combined with a back-side bulk GaAs micromachining of a cavity of MEMS structure.

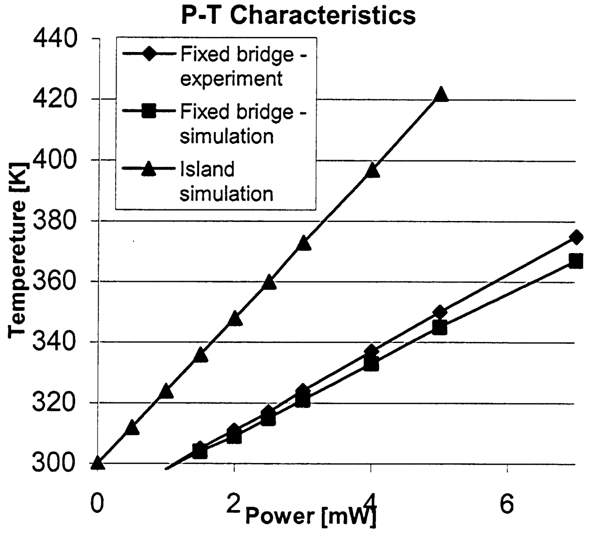

Figure 3: Simulated island and cantilever bridge P-T characteristics. Comparison with real micromachined MTC device.

2 SIMULATION

The temperature distribution over the sensing area and device mechanical stresses were optimized by studying different MTC formations and layouts of the heater and temperature sensor. We have investigated three basic adjustments to be able to compare their thermal and mechanical behavior:

- *Fixed Cantilever Beam MEMS devices*
- *Fixed Island MEMS device*
- *Fixed bridge*

Main characteristics to be optimized for such devices are the temperature distribution over the sensing area caused by power dissipation in a heater, thermal time response as a result of power changes, evaluation of the mechanical stresses, displacement and deformation in the MTC structure.

The thermo-mechanical modules MemTherm and MemMech ware used to simulate the thermal and mechanical behaviour of the micromechanical thermal converter.

The input power dissipation in the heater was defined as a heat flux through the gate area patch of HEMT.

3. RESULTS

3.1 Steady state simulations and P-T characteristic

The calculation of the membrane bridge spatial temperature distribution and steady state heat flux has taken into the account the heat transfers to infinity.

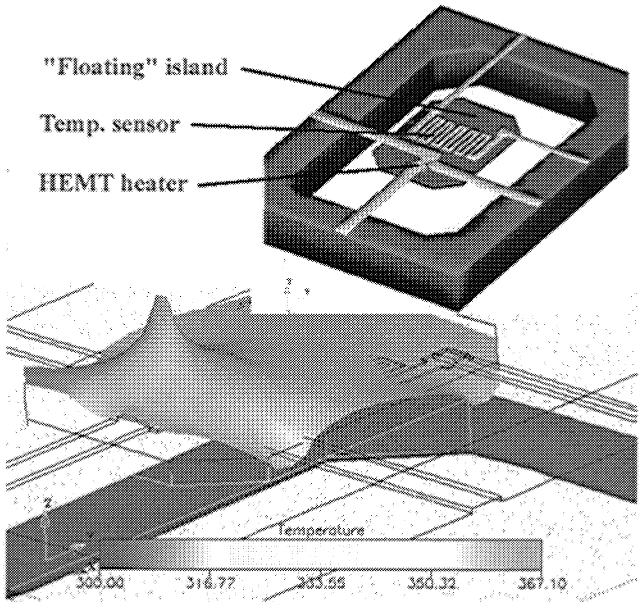

Figure 4: 3D temperature [K] distribution graph of island MTC structure. The island is "floating" in polyimide layer that mechanically fixes and thermally isolates the MTC structure. Polyimide not shown.

The 3D graph gives good overall visualization of the temperature distribution (fig.4) in the island MTC structure for the power dissipation of 2 mW generated by the HFET heater. The island is "floating" in the polyimide layer that mechanically and thermally isolates the MTC structure. HEMT heater and zig-zag temperature sensor is integrated within the island structure. Polyimide layer is not shown, but was considered in simulation. The island structure floating in polyimide is well thermally isolated and the heat flux goes only through the metallization lines.

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.

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 (Fig. 3). High electro-thermal conversion efficiency defined by extracted thermal resistance values (R_{th}) 11 K/mW (experimental measurement) and 11.5 K/mW (CoventorWare simulation), respectively, was achieved for a fixed bridge structure. The highest temperature resistance of 24 K/mW was obtained for island MTC. When compared with the experiment, the thermal resistance values are congruent.

3.2 Temperature transient analysis results

It is essential to evaluate the transient response characteristic to calculate temperature time constant of the designed MTC structures. The transient temperature characteristics were simulated as a response on power ON or power OFF in the given time. The power on/off transients for island MTC structure is depicted on figure 5. We can see that power ON and power OFF temperature time constant is almost equal. Temperature time constant of cantilever beam adjustment is 0.5 ms.

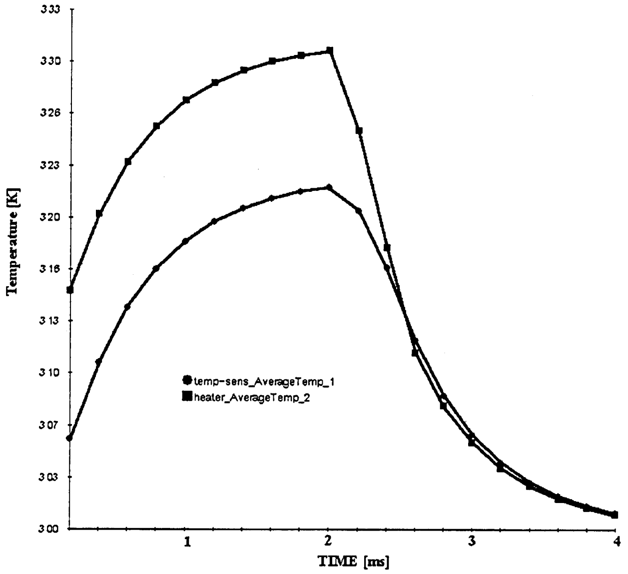

Figure 5: The power on/off transient characteristics for island MTC structure for power ON of 2mW. At the beginning there was power of 2mW switched ON. In the time of 2ms the power was switched OFF.

3.3 Stress and displacement evaluation

Mechanical stresses can have a great influence on mechanical as well as electrical properties of MTC structures. The initial residual stress caused by the temperature changes during deposition was evaluated analytically as well as experimentally [2].

Analytical calculation of the initial stress has been performed by using a simple analytical expression for thermal expansion $\sigma = E\Delta\alpha\Delta T$, where E is Young's modulus, $\Delta\alpha$ is the difference between the thermal expansion coefficients of GaAs, Ti and Au layers, ΔT is the temperature difference at the deposition technology process. The initial stress in metallization (before bridge etching) for temperature deposition difference $\Delta T = 170$K is 81.6 MPa for Ti layer and 51.3 MPa for Au layer respectively.

Stress magnitude dependences over the cantilever bridge and evaluation of the displacement magnitude, caused by initial stress in the bridge were simulated using MemMech simulator. Figure 6 shows residual stresses and a deformation of the island structure caused by heating up. The power dissipation in the heater was 1mW. The biggest stresses are in the place of the temperature sensor. The MTC structure is fixed by polyimide layer that is not shown in the figure.

Influence of polyimide layer fixation on residual

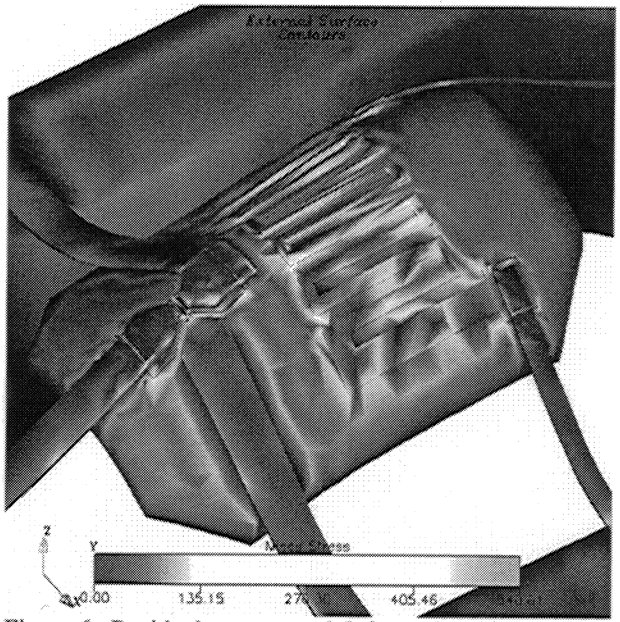

Figure 6: Residual stresses and deformation of the island structure caused by heating up with power dissipation of 1mW in the heater. Polyimide layer was investigated in simulation (not visible). Values of stress are in MPa.

stresses and deformation was also simulated in the given models.

Displacement dependences along the length of the cantilever bridge are depicted in fig. 7. The comparison between bridge fixed by polyimide layer and bridge where polyimide layer was removed is shown. GaAs base bulk frame was set as rigid e.g. non moveable.

The residual cantilever bridge stresses are admissible and there are no significant influences with the regard to the micromechanical integrity of the MEMS device.

4 CONCLUSION

The cantilever bridge and island micromechanical thermal converter structure P-T characteristic, like temperature distribution, mechanical stresses and displacement of GaAs MEMS device for power sensor microsystem have been simulated using CoventorWare. We have optimized their thermal conversion properties. Using FEM simulations, the layout of HFET transistor, temperature sensor and MTC shapes and dimensions were also optimized.

Simulation results were compared with the experiment. he high electro-thermal conversion efficiency defined by extracted thermal resistance values (R_{th}) 24 K/mW (island structure) and 11.5 K/mW (cantilever bridge), respectively, was achieved. As compared with the experiment, the thermal resistance values are congruent. Real view of micromachined Cantilever Beam MEMS device is in fig. 8.

ACKNOWLEDGMENTS

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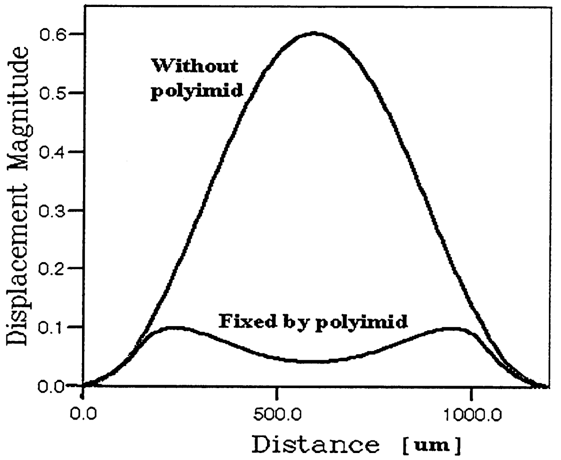

Figure 7 shows displacement magnitude along the length of the bridge caused by initial stress in metallization. Comparison between bridge fixed by polyimide layer and bridge where polyimide layer was removed is shown. A cross section was made in the middle of the beam in x-axes direction.

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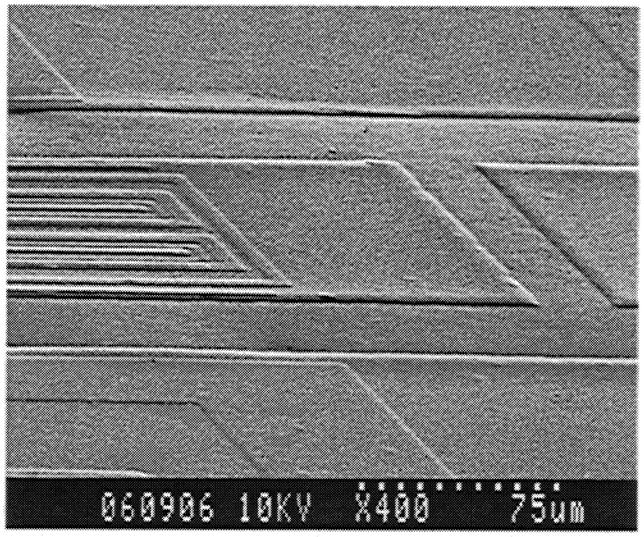

Figure. 8: Real view of micromachined Cantilever Beam MEMS device