MICROMECHANICAL STRUCTURES FOR LOW LEVEL POWER MEASUREMENT IN MEDICAL SYSTEMS

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Abstract: This paper presents the thermal and thermo-mechanical modelling carried on with the aim to find out the optimal temperature distribution of the RF Microwave Power Sensor (RFMPS) microsystem. The sensor can be used in medical wireless data transfer systems to measure and optimise the transmitted power from human body implemented sensors to the data evaluation unit. The main criteria of the RFMPS optimisation are bouth, keep the stable thermal distribution and minimise the thermal stress. 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 Tranzistor) are sensed by the integrated temperature sensor (TS). The temperature distribution over the sensing area and mechanical stress was optimized by studying different MTC sizes, and topologies of the active HEMT heater and temperature sensor.

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.

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 standing micromechanical plate which is technologically realised as thin as possible.

New developed 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 features 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 have been studied.

The thermoelectric AC power sensor and microwave power sensor were first analysed by Jaeggy and Kopystinski [1, 2] 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 (MEMS) 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 [3]. 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 [3].

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However, the presented sensor was principally only another approach to the classical principle of the passive heater design for the measurement of absorbed power.

THEORY

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:

$$div(\lambda gradT) = \rho c \frac{\partial T}{\partial t} - p, \qquad (1)$$

where λ [W m^{-1} K^{-1}] is coefficient of thermal conductivity, ρ mass [kg m^{-3}], c [J kg^{-1} K^{-1}] thermal capacity and p specific heat [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:

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

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

Transcribing above mentioned equation to Cartesian coordinate we get:

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

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

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

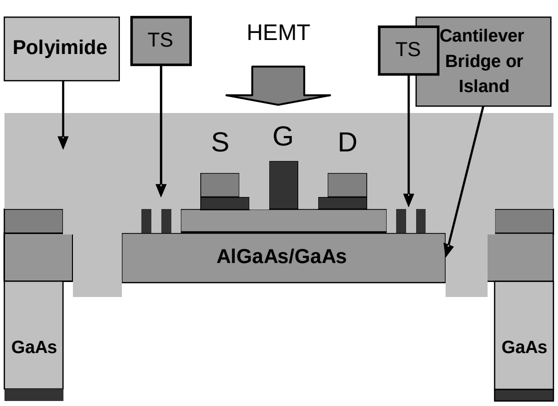

Fig. 1. Schematic cross-section through the polyimide-fixed MTC structure to be integrated with HEMT as heater and poly-Si/Pt thin film resistor as temperature sensor TS

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:

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

For Cartesian coordinate the Laplace operator is given as:

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

α in equation (7) is thermal diffusivity [m^2/s] and mathematically can be expressed as:

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

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]

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

where α[W.m^{-2}.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]:

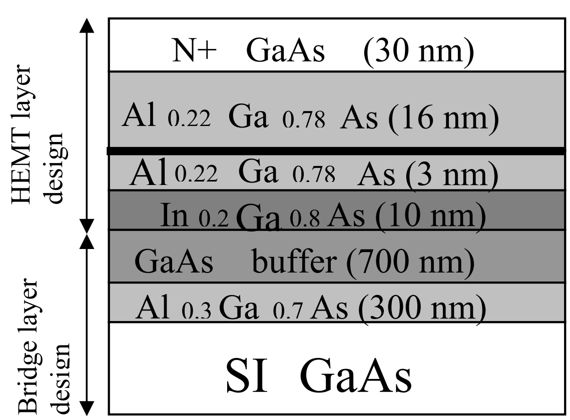

Fig. 2. Heterostructure layer design used for the HEMT and bridge technology

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$Nu = f(Re, Gr, Pr, ...)$, where (11)

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

$$\mathrm{Pr} = \frac{\nu}{a} = \frac{\eta \cdot c_p}{\lambda}, \qquad Gr = \gamma \cdot \Delta t \cdot \frac{gL^3}{\nu^2},$$

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

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

$$Nu = C \cdot (Gr.\mathrm{Pr})^n, \quad (12)$$

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

Gr.Pr	C	n
$< 1.10^{-3}$	0,45	0,0
$1.10^{-3} \cong 5.10^{2}$	1,18	0,125
$5.10^{2} \cong 2.10^{7}$	0,54	0,25
$2.10^{7} \cong 1.10^{13}$	0,195	0,333

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

Radiation

For MEMS devices operating in room temperature the heat loses 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 loses caused by radiation is given by Stefan-Boltzmann emissive low:

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

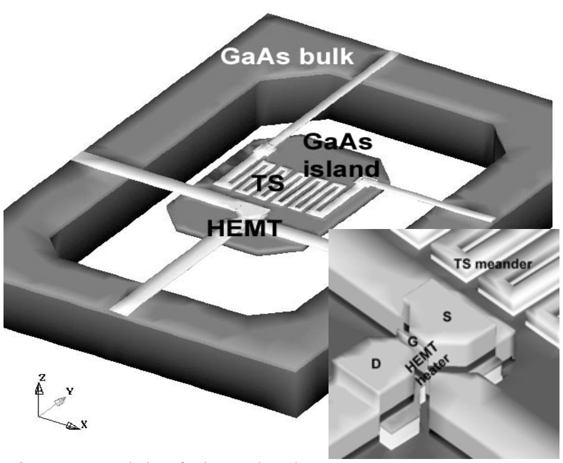

Fig. 3. Model of the Island MTC structure. GaAs island is "floating" in Polyimide 1um thick layer (not visible). *Z*-direction is 20times magnified. Detail of HEMT heater is on the right.

where

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

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

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. 1). 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.

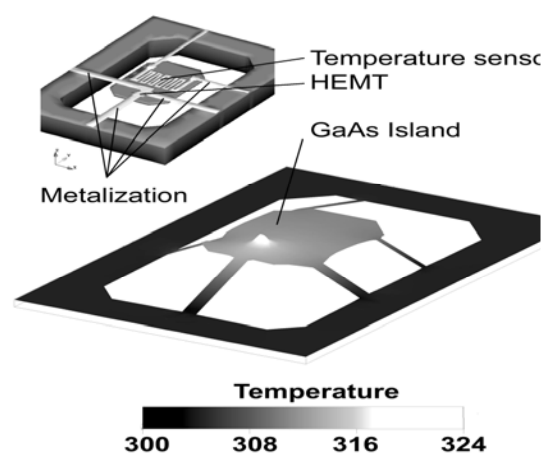

Fig. 4. 3-D plots of temperature distribution of the island MTC structure. The island is "floating" in polyimide layer that mechanically and thermally isolates the MTC structure. Polyimide not shown

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

The layer system shown in fig. 2 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.

RESULTS

P-T Characteristic and Steady state Thermal analysis

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.

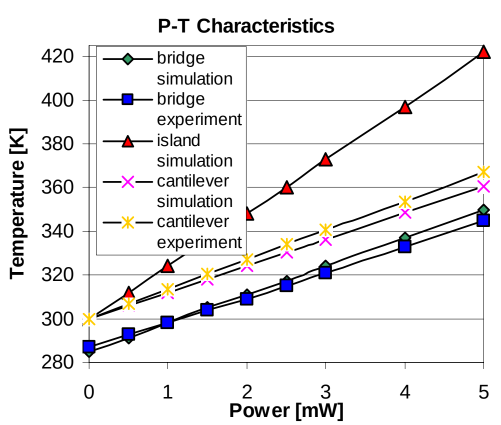

Fig. 5. Simulated island, cantilever and bridge P-T characteristics. Comparison with real micro-machined MTC device. Ambient temperature for bridge MTC was 285 K whereas other two MTCs ambient were 300 K.

3D graph gives good overall visualization of the temperature distribution (fig.4) 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 300 K 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. 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 evaluation

The mechanical stresses can have a great influence on the mechanical as well as electrical properties. The initial residual stress caused by temperature changes during material deposition was evaluated analytically and experimentally [5].

The analytical calculation of the initial stress has been performed by using a simple analytical expression for the 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.

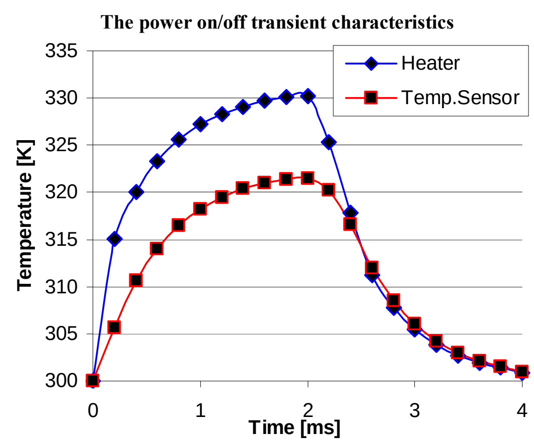

Fig. 6. The simulated power on/off transient characteristics for island MTC structure for power ON of 1 mW. At the beginning there was power of 1mW switched ON. In the time of 4 ms the power was switched OFF.

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ΔT is the temperature difference at the deposition technology process. The initial stress in metallization (before MTC etching) for the temperature deposition difference $\Delta T = 170$ K is 81.6 MPa for Ti layer and 51.3 MPa for Au layer respectively. The "averaged" stress to the whole bridge structure is 25 MPa. The measurement method used to evaluate bridge stress is based on the measurement of the membrane deflection amplitudes, as a response to acoustic pressure [5]. The experimental result for the bridge MTC (150 μm x 880 μm) which was fully covered by Ti/Au metallization is 21.6 MPa. This result is consistent with analytical calculation.

In order to model the MTC devices, where thermal gradients in a material induce mechanical stresses, we must combine the heat conduction equations with the linear elasticity theories.

The mechanical and thermal boundary conditions were defined for side walls of GaAs substrate. These sides were kept at the room temperature of 300 K while other sides were adiabatic and were set as rigid e.g. non moveable. The initial stress was set in each material according the analytical calculation.

The stress and displacement magnitude evaluation were simulated using MemMech simulator.

The biggest stresses (520 MPa) are located in the place of the meander-shaped PolySi temperature sensor. The MTC structure is fixed by polyimide layer which was taken into account during the simulation. Maximal stress in the island MTC structure has been located in Si/Pt meander-shaped TS. For the power dissipation of 3 mW the TS temperature is 375 K and the mechanical stress reaches up to 900 MPa. However these values of residual MTC stresses have no significant influences with regard to the micromechanical integrity of the MEMS device.

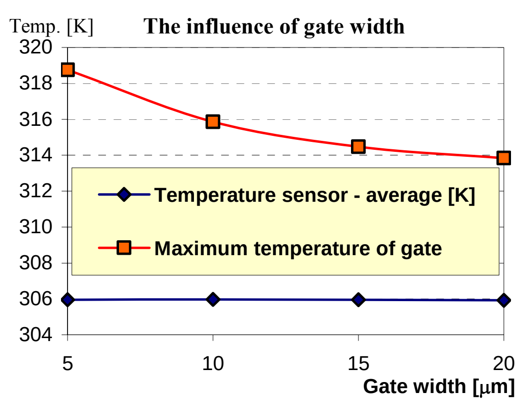

Fig. 7 – Maximal and average temperature – HEMT gate width dependence. Dissipated power was 0.5 mW.

For the displacement analysis the mechanical boundary conditions have been set hereinbefore. Fig. 9 shows the most extreme island structure displacement dependence on the power dissipation in the z-axe direction. The value represents the difference between the substrate surface and the displaced island.

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 remained 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.

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

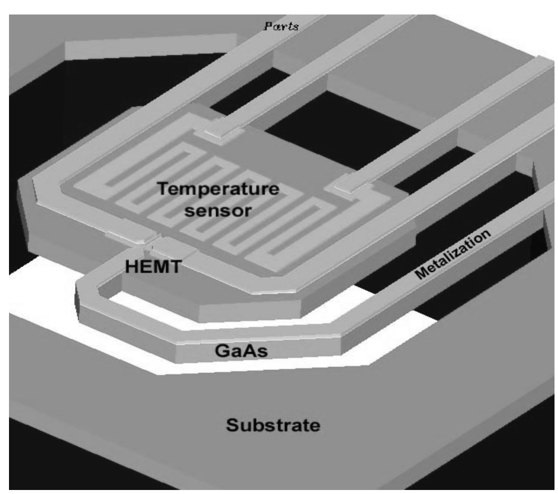

Fig. 8 – 3-D model of the optimized island MTC structure

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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. 2.

Table 2 - Comparison of the designed island MTC structures

	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*

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.

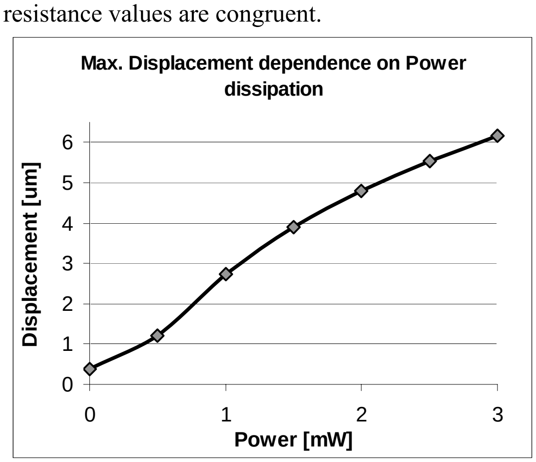

Fig. 9. Maximal Displacement dependence on Power dissipation simulated for Island structure in Z direction.

Photograph of "floating" Island MTC structure is on figure 10. Top polyimide layer was removed in order to see the surface of island.

REFERENCES

[1] JAEGGY, BALTES H. and MOSER D. (1992): 'Thermoelectric AC Power Sensor by CMOS Technology', IEEE Electron Device Letters, 13, p. 366

[2] KOPYSTINSKI P., OBERMAYER H., DELFTS H., HOHENESTER W., and LOSER A. (1990): 'Silicon RF Power Sensor from DC to Microwave', Microsystem Technologies, p. 605

[3] DEHE A., KROZER V., CHEN B. and HARTNAGEL H. (1996): 'High-sensitivity microwave Power Sensor for GaAs-MMIC implementation', Electronics Letters, *32*, pp. 2149-2150

[4] LALINSKÝ T., KUZMÍK J., PORGES M., HASCÍK S., MOZOLOVÁ Z., GRNO L. (1995): 'Monolitic GaAs MESFET power sensor microsystem', Electronics Letters, 31, pp. 1914-1920

[5] SENTURIA S.D. (2001): 'Microsystem Design, Kluwer Academic Publisher book'

[6] ELWENSOEKK M., WIEGERINK R. (2000): 'Mechanical Mikrosensors, Springer'

[7] TAI-RAN H. (2001): 'MEMS and Microsystems Design and Manufacture', Mc Graw Hill

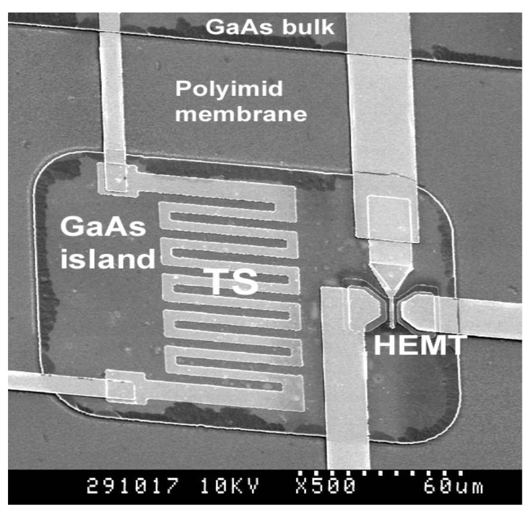

Fig. 10. Photograph of "floating" Island MTC structure. The polyimide was removed in order to see the surface of island.

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