Characterization of MEMS sensor for RF Transmitted Power Measurement

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Abstract: In this report we introduce the procedure for performing a thermo mechanical design and analysis of thermal GaAs-based MEMS devices. It will provide the procedure how thermal analysis should be made and model equations used to describe conduction, convection, radiation and mechanical effects caused by nonhomogenous temperature distribution. This is demonstrated on the design of Micromechanical thermal converter (MTC) that creates heart of the RF power sensor microsystem. 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. 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.

Key-Words: Thermal Converter, Thermo-mechanical simulations, MEMS, Power sensor, GaAs microsystems

1 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.

A better 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 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 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 was studied.

The thermoelectric AC power sensor and microwave power sensor were analysed 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. 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 [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 Heat Theory

Heat 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:

$$\text{div}(\lambda \nabla T) = \rho c \frac{\partial T}{\partial t} - p,$$

where $\lambda$ [W m$^{-1}$ K$^{-1}$] is coefficient of thermal conductivity, $\rho$ 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:

$$q = -\lambda \cdot \nabla T [W.m^{-2}],$$

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

Transcribing above mentioned equation to Cartesian coordinate we get:

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

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

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

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

For Cartesian coordinate the Laplace operator is given as:

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

\( \alpha \) in equation (7) is thermal diffusivity \([\text{m}^2/\text{s}]\) and mathematically can be expressed as:

\[ \alpha = \frac{\lambda}{\rho c} \]  
(9)

**Heat 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 than in solid body. Individual particles can move mutually.

The density of heat flux under the convection is given \([5]\)

\[ q = \alpha \cdot \Delta t = \alpha (t_{w} - t_{f}) \]  
[W.m\(^{-2}\)],  
(10)

where \( q \) [W.m\(^{-2}\).s\(^{-1}\)] is heat transfer coefficient given by criteria equation (see below), \( t_{w} \) is wall temperature of solid body, \( t_{f} \) is gas or liquid surrounding temperature and \( A \) contact area.

Criteria equation can be found in literature in following form for instance \([5]\):

\[ Nu = f(Re, Gr, Pr, ...), \]  
where  
(11)

\[ Nu = \frac{a L}{\lambda_{w}}, \quad Re = \frac{c \cdot L}{\nu}, \]\n
\[ Pr = \frac{\nu}{\alpha} = \frac{\eta \cdot c_{p}}{\lambda}, \quad Gr = \gamma \cdot \Delta t \cdot \frac{gL^3}{\nu^2}, \]

\[ Pe = \frac{c \cdot L}{\alpha} = Re \cdot Pr \]

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

\[ Nu = C \cdot (Gr \cdot Pr)^n, \]  
(12)

\( C \) and \( n \) constants depends on the value of the product \( Gr \cdot Pr \) according \( \text{tab. 1} \):

<table>
<thead>
<tr>
<th>( Gr \cdot Pr )</th>
<th>( C )</th>
<th>( n )</th>
</tr>
</thead>
<tbody>
<tr>
<td>(&lt; 1 \cdot 10^3 )</td>
<td>0.45</td>
<td>0.0</td>
</tr>
<tr>
<td>( 1.10^3 \approx 5.10^2 )</td>
<td>1.18</td>
<td>0.125</td>
</tr>
<tr>
<td>( 5.10^2 \approx 2.10^1 )</td>
<td>0.54</td>
<td>0.25</td>
</tr>
<tr>
<td>( 2.10^1 \approx 1.10^1 )</td>
<td>0.195</td>
<td>0.333</td>
</tr>
</tbody>
</table>

**Heat 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:

\[ P_{rad} = \varepsilon_{1,2} \cdot C_{0} \cdot A \cdot \sigma T^4 \]  
[W],  
(13)

where

\[ \varepsilon_{1,2} = \frac{1}{\frac{1}{\varepsilon_{1}} + \frac{1}{\varepsilon_{2}} - 1} \]  
(14)

\( \varepsilon \) is emissivity of gray body, \( A \) is the body surface and \( \sigma \) is Stefan-Boltzmann constant = 5.67 \( \cdot \) 10\(^{-8}\) [W.m\(^{-2}\)K\(^{-4}\)].

**3 MTC 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 micromachining 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. 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 system 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. 2 demonstrates model of GaAs island structure which has been proposed to increase a sensor thermal resistance. The GaAs island floats in 1 μm thick polyimide layer. The polyimide membrane (225 μm x 360 μm) mechanically fixes and thermally isolates the GaAs thin plate which is 175 μm long and 125 μm wide. The GaAs substrate rim has been designed 10 μm thick and 50 μm wide analogous to previous model.

4 Simulation and measurement results

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. High electro-thermal conversion efficiency defined by extracted thermal resistance values (Rth) 24 K/mW was obtained for island MTC (figure 3). The 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. Mechanical displacement is also demonstrated on the fig. 4. 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 fix 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. 2. Model of the Island MTC structure. GaAs island is “floating” in Polyimide 1μm thick layer (not visible). The meander-shaped TS is also shown. Z-direction is 20times magnified.

Fig. 3. 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.
Transient on/off power characteristics for island structure are depicted on fig. 5. 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 three transients on the fig. 5. Upper is the max. temperature of the heater and the bottom dependence reflect average temperature of TS. Stress and displacement magnitude evaluation were simulated using MemMech simulator. Outer substrate rim was set as rigid (non moveable). The most extreme mechanical stresses were found in meander shaped PolySi temperature sensor.

Optimization of the MTC design

The design criteria to assess the general performance and considerations of the sensor are given below:

- Reduced maximum stress in both GaAs substrate and Ti/Au metallization layers, in particular in the heated active area of the MTC device.
- Uniform temperature distribution over the sensing element (meander-like tem. sensor).
- Increase sensitivity (dissipating power to temperature conversion, \( R_{th} \)).
- Quick time response (change of the temperature as a result of change of input power)

According to the above criteria extensive 3-D models of the MTC structure have been designed and numerical simulations have been carried out to evaluate the performance of the sensor. New optimized island structure design reduces the maximal stress caused by temperature changes; minimize the temperature losses that were caused by too short supplying metallization to HEMT transistor. The 3-D model is depicted on fig. 6. 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 [1].

5 Conclusion

Power to temperature (P-T) conversion characteristics of the MTC devices was determined to compare the sensitivity of the three forenamed structures. The highest electro-thermal conversion efficiency defined by extracted thermal resistance values \( R_{th} \) 24 K/mW was achieved for the island structure, which is more then twice as high as in comparison with the cantilever bridge (11.5 K/mW) and the cantilever beam structure (13.4 K/mW). As compared with the experiment, the thermal resistance values are congruent. Time responses of the island structure (0.9 ms) and the cantilever beam (2.1 ms) are nearly consistent. On the other hand the island structure has the biggest mechanical

Figure 4. Plots of temperature distribution of the island MTC structure for power dissipation of 2mW. The island is “floating” in polyimide layer that mechanically and thermally isolates the MTC structure. Polyimide not shown.

Fig. 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 5ms the power was switched OFF.
displacement (6.1 μm for 3 mW power generation) and local mechanical stress reaches up to 890 MPa. However, this value of the displacement is rather small in the comparison with the other device proportions and does not have significant influences with the regard to the micromechanical integrity.

For the MPS application the island structure seems to have the best performance. To increase the sensibility and the thermal time constant of the MPS, the volume and the dimensions of the MTC should be reduced.

Using GaAs new active HEMT heater MTC approach, the MPS is expecting to work in the range of up to 10 GHz. The MPS are expected to become a heart of a new generation of the power meters. The simplicity may result in a significant reduction of measuring parts of RF systems e.g. cost reductions and increase of the device reliability.

Photograph of “floating” Island MTC structure is on figure 7. Top polyimide layer was removed in order to see the surface of island.

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Fig. 7. Photograph of “floating” Island MTC structure. The polyimide was removed in order to see the surface of island.

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

References:


