Sensors and Materials, Vol. 10, No. 4 (1998) 241–250
MYU Tokyo

S & M 0328

Power Sensor Microsystem Technology and Characterization

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(Received January 31, 1997; accepted March 23, 1998)

Key words: thermoconverter, power sensor, bulk micromachining, reactive ion etching, GaAs MESFET, GaAs heterostructure layer design

A novel concept and technology of a micromachined power sensor microsystem (PSM) are described. In the PSM concept, two power-controlled GaAs MESFETs (as three-terminal heaters) and a GaAs Schottky diode (as a temperature sensor) are monolithically integrated and thermally isolated on two 8-μm-thick GaAs cantilever beams. GaAs MESFET technology is combined by GaAs bulk micromachining to fabricate the PSM. The key PSM transfer characteristics for selected ambient gaseous environments are evaluated to confirm the benefit of the PSM technology developed. Due to a small cantilever thickness, thermal resistance values as high as 6500 K/W, 7300 K/W and 9200 K/W are obtained for air, argon and vacuum environments, respectively. Potential applications of the PSM for precise power measurements are emphasized.

1. Introduction

Recently, thermoconverters are mostly used for standard ac-dc voltage or power transfer measurements. Electrical power is converted into thermal power in a thermally isolated element. The resulting heat is immediately sensed by a high-sensitivity temperature sensor. A major advantage of thermoconverters is that the measurement is independent of the waveform of the ac electrical signal.

The first micromachined power sensor (thermoconverter) was realized by means of industrial CMOS IC technology combined with one subsequent maskless etching step.(1)

The power sensor was based on a polysilicon resistor (as a heater) and a polysilicon/aluminum thermopile (as a temperature sensor) monolithically integrated on a thermally isolated silicon oxide microbridge.

In order to increase the responsivity of the thermal converters based on thin dielectric membranes, bismuth-antimony thermocouples were applied as temperature sensors.(2) The responsivity was improved to 16 V/W in air and 120 V/W in vacuum. By using these converters the ac-dc voltage transfer has been extended into the mV range.

Another approach for improving thermal converter performance by using contactless temperature sensing has also been described.(3) An optical infrared pyrometer was used to sense the temperature of the thin-film resistive heaters. This reduced the diversion of thermal energy from the heaters as well as the time constant and the ac-dc transfer differences due to thermoelectric effects, shunt capacitances and dielectric losses.

A novel method of direct broad-band power measurement based on ac-dc substitution by a three-terminal thermoconverter (TTTC) has been described.(4) The TTTC is principally a thermally isolated heater with three terminals and a dynamically controlled impedance.

The principal diagram of the dual TTTC is shown in Fig. 1. The structure consists of two power-controlled FETs, Q_a and Q_b, and a diode as a temperature sensor, *TS*. The thermal symmetry of Q_a and Q_b relative to the temperature sensor *TS* enables mutual substitution of dissipated powers originating in two independent sources. If the temperature of the substrate is kept constant by controlling the power dissipated in Q_b, then, assuming a constant environmental temperature, we obtain $\Delta P_a = -\Delta P_b$. Controlling the power by means of controlling the voltage U_b at a constant current I_b or by controlling the current I_b at a constant voltage U_b and using the controlled quantity as the output quantity, we can realize a power-to-voltage converter or a power-to-current converter, respectively. A complete power sensor microsystem consists of two thermally isolated dual TTTCs. This enables the creation of a self-balancing thermal bridge that eliminates fluctuations of environmental temperature.

In order to verify the principle of the power measuring method,(4) a new concept of the power sensor microsystem (PSM) based on GaAs cantilever beams was proposed.(5) GaAs

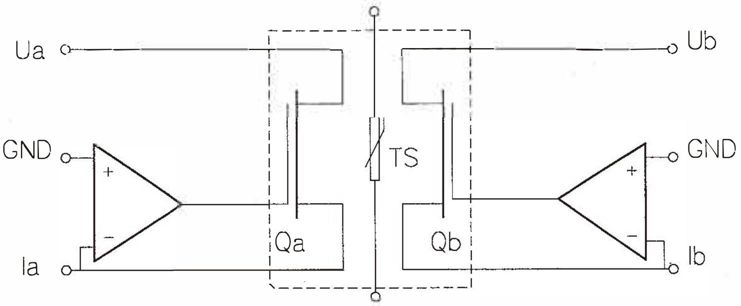

Fig. 1. Principal diagram of the dual TTTC.

chosen was as the basic electronic as well as micromechanical semiconductor material because of its lower thermal conductivity, higher saturation velocity of electrons and higher temperature working conditions as compared with a silicon.

In the present study, the technology of the PSM is described in detail. The power-temperature (P-T) conversion efficiency in various gaseous environments is investigated in order to confirm the benefit of the PSM technology developed. The preliminary results of the reliability study of the PSM are also presented.

2. PSM Technology

As mentioned already, the PSM technology is based on GaAs cantilever beam micromechanical structures, which are prerequisite to realizing excellent thermal isolation for the PSM heaters (GaAs MESFETs) and temperature sensors (GaAs Schottky diodes) as well. Therefore, GaAs MESFET technology combined with GaAs bulk micromachining were adopted to fabricate the PSM.

The layered heterostructure shown in Fig. 2 was designed for the PSM technology. An 8-μm-thick GaAs layer grown by MBE on top of an AlGaAs etch-stop layer determines the thickness of the PSM cantilever beams. Three-dimensional patterning of the two independent thin GaAs cantilever beams, as shown in Fig. 3(a), was defined by double-side-aligned selective reactive ion etching (RIE). An Al film was used as a mask material for deep RIE of GaAs, while buried AlGaAs served as an etch-stop layer. Masked GaAs plasma etching from the front side was used to define lateral dimensions of the cantilever beams. Finally, the thickness of the cantilevers was defined by deep back-RIE of the GaAs substrate to the AlGaAs etch-stop layer (Fig. 3(b)).

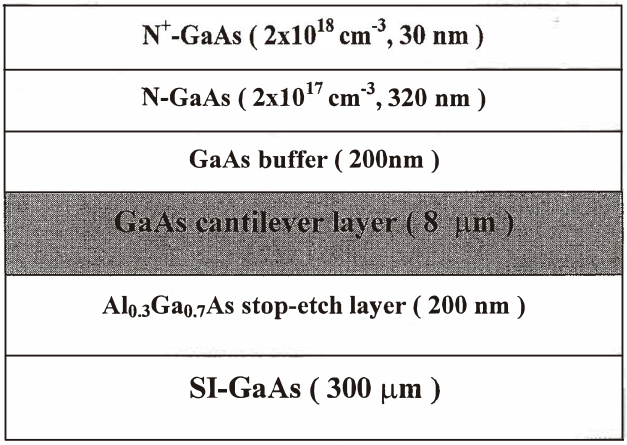

Fig. 2. Heterostructure layer design of PSM.

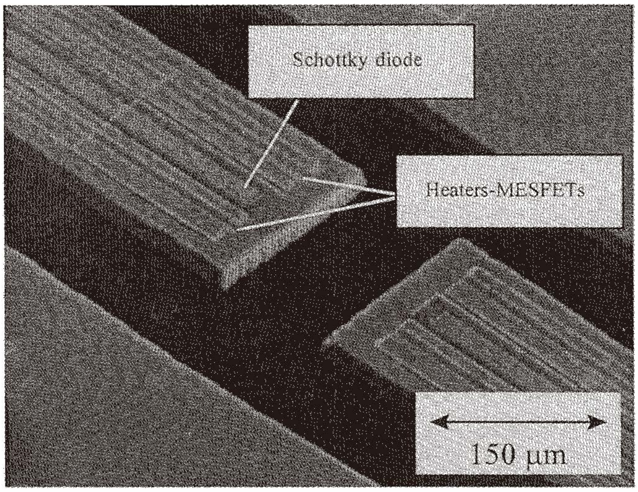

Fig. 3(a). Front of PSM cantilever beams.

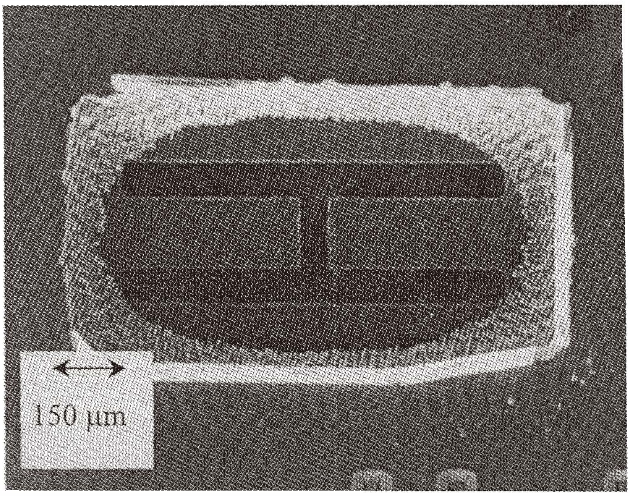

Fig. 3(b). Back of PSM cantilever beams.

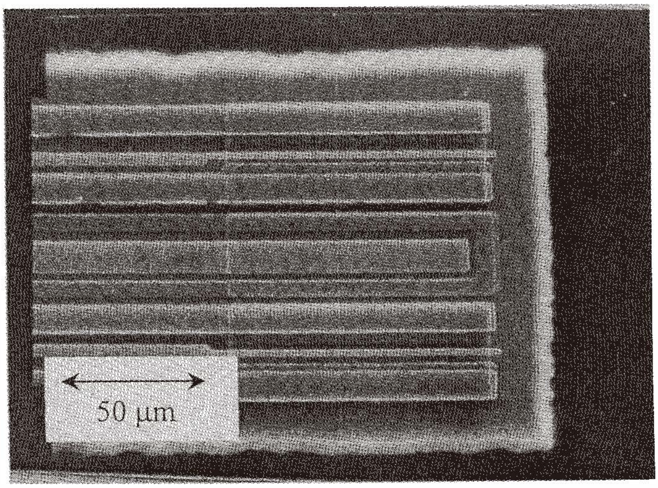

Fig. 3(c). Details of GaAs MESFETs and Schottky diode of PSM.

RIE processing was aimed at establishing the etch conditions which would best meet the following process requirements: (i) a sufficient etch rate of GaAs for deep back-RIE through a GaAs substrate to the stop-etch layer, with the anisotropy needed to minimize lateral undercutting, (ii) selectivity of GaAs etching to the etch masks to achieve overetching of the back of the GaAs substrate to the stop layer, (iii) selectivity of GaAs to AlGaAs etching to plane the bottom of the back of the etched cantilever beams.

CCl_2F_2 was used as the process gas with the chamber pressure of 10, 20 and 30 Pa during etching with a gas flow of 30 sccm. The RF power was varied from 50 to 150 W. The optimum etching conditions for RIE were elucidated from the experiment. The etch rate of GaAs was about 2 μm • min^{-1}, the selectivity of GaAs etching to the electron-beam-evaporated Ni etch mask was better than 2000 and that to the AlGaAs stop-etch layer was better than 1000. These above etching parameters were achieved at the pressure of 18 Pa and RF power of 50 W. A plane smooth bottom of the back of etched cantilevers (Fig. 3(b)) is therefore obtained.

PSM requires first the fabrication of GaAs MESFETs and Schottky diodes. GaAs device processing itself is, therefore, followed by bulk micromachining as a post-processing second step. A recessed gate power MESFET design was applied in the processing, resulting in improved gate-drain breakdown properties. As seen in Fig. 2, a homogeneously doped GaAs layer with the doping concentration of 2×10^{17} cm^{-3} was used for both the channel of the MESFET and the active layer of the Schottky diode.

Details of two symmetrically placed power-controlled GaAs MESFETs and a central temperature-sensor Schottky diode on the active area of the cantilever beam are clearly seen in Fig. 3(c). GaAs MESFETs with a gate length of 2 μm were applied in the processing.

3. PSM Characterization

The basic transfer characteristics of the PSM in various gaseous environments were studied in the experiment. Forward I-U characteristics of the sensor Schottky diode for different powers dissipated in the channel of the MESFET were measured using a semiconductor parameter analyzer (HP 4145B). Power-sensor diode voltage (P-U) transfer characteristics under dc diode current biasing of 10 μA were subsequently determined (Fig. 4). As shown in Fig. 4, a nonlinear dependence of diode voltage on power dissipation is observed. It is obvious that the nonlinearity appears to be increased by the decrease of the thermal conductivity of the ambient atmosphere when heat transfer through the GaAs cantilever beam is dominant. Therefore, the nonlinear behavior of the P-U transfer characteristics could be explained by the nonlinear dependence of the GaAs thermal conductance on the local temperature.(6) Numerical two-dimensional thermal simulations of the PSM are currently being developed to confirm this. The average diode response values extracted from the experimental curves in Fig. 4 were determined to be 10.2 V/W, 11.3 V/W and 14.2 V/W for the air, argon and vacuum environments, respectively.

The sensor diode I-U characteristics measured at various calibrated temperatures were used to determine the sensitivity of the diode corresponding to the selected current biases. The sensor diode U-T calibrated curve determined for the current bias of 10 μA is shown in Fig. 5. The sensitivity value of 1.56 mV/K was extracted from the linear curve fitting. Excellent linearity can also be seen here.

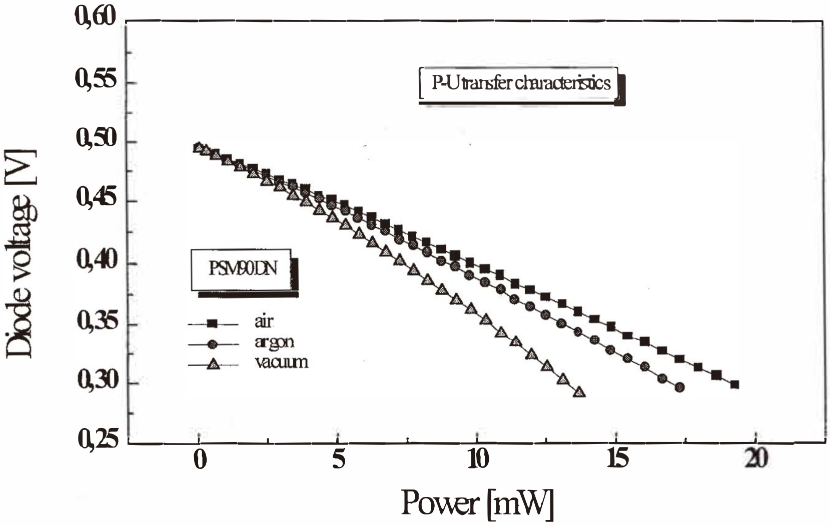

Fig. 4. P-U transfer characteristics of PSM in various atmospheres.

Finally, the calibrated U-T curve (Fig. 5) was used to construct the power-temperature (P-T) transfer characteristics of the PSM (Fig. 6). A nonlinear behavior is also indicated. A derivative (dT/dP) of the P-T curves directly determines the thermal resistance values of the PSM. The thermal resistance value obtained for air at a power dissipation of 11 mW

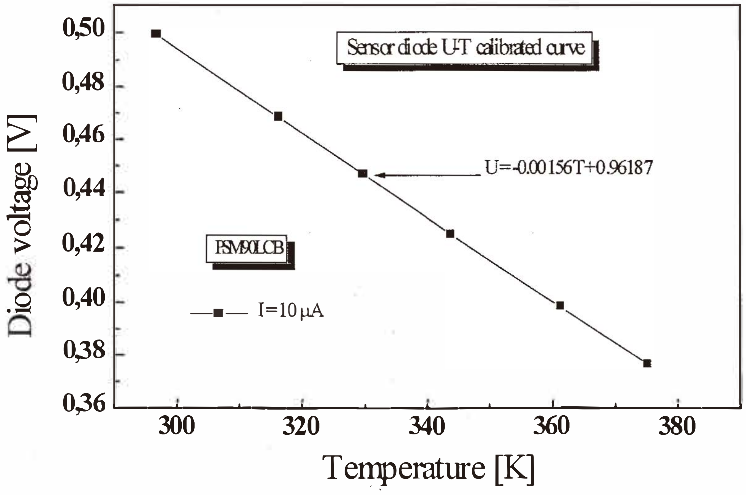

Fig. 5. Temperature sensor diode calibrated curve.

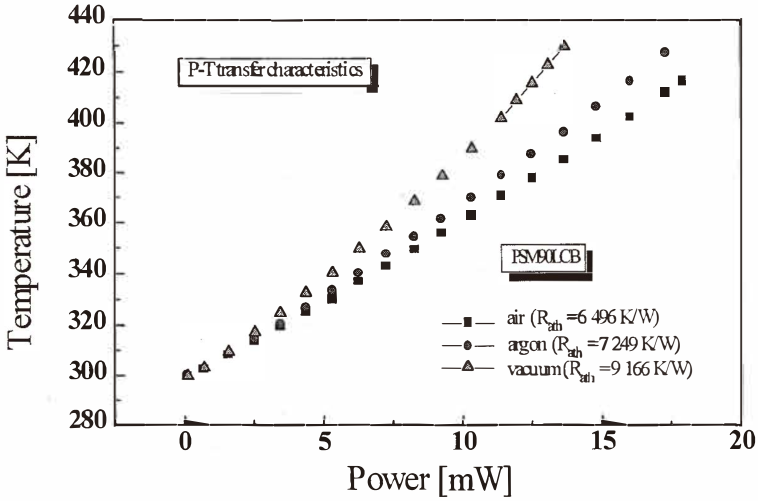

Fig. 6. P-T transfer characteristics of PSM in various atmospheres.

exceeded 6500 K/W, so this working temperature is approximately 70 K above the environmental temperature. As seen in Fig. 6, the power-temperature conversion efficiency (thermal resistance value) can be increased by decreasing the thermal conductivity of the surrounding atmosphere. Extracted average thermal resistance values (R_{ath}) as high as 7250 K/W and 9200 K/W were found for the argon and vacuum environments, respectively.

A contactless infrared laser interferometric method was used to study the temperature dynamics in the PSM.(7) The thermal time constant of about 2.4 ms was obtained from the transient optical study. The results were found to be consistent with the electrical measurements and the thermal simulation.

4. Reliability Study of PSM

A considerable number of reliability tests of GaAs MESFETs have been conducted in some laboratories,(8) with the aim of extracting the dominant failure mechanisms. The main failure mechanisms identified are related to gate metallization and Schottky contacts (metal/GaAs interdiffusion, gate electromigration), ohmic contact degradation (increase of contact resistance, drain/source electromigration), surface effects and high humidity effects.

Because the PSM is designed to operate at high temperatures (T = 60 –100°C), the preliminary tests of its reliability should also be conducted. The reliability of the PSM was investigated using a high-temperature storage test in an argon atmosphere at 200°C. Figure 7 shows the P-U transfer characteristics of PSM after subsequent storage time. A shift of the transfer characteristics towards lower sensor diode voltages was observed. We have found that the main failure mechanisms identified are related to the Schottky gate contacts (metal/GaAs interdiffusion) and transistor bias leads (intermetalic reactions). The first one lowered the Schottky barrier height of the temperature sensor diode (the shift of the transfer characteristics). The second one led to the increase in the transistor bias lead sheet resistance values (the increase in the source and drain resistance), as seen in Fig. 8. Consequently, the increase of $R_S + R_D$ parasitic resistance was accompanied by the decrease of the PSM responsivity, as shown also in Fig. 8. It should be noted that the dominant failure mechanisms identified are in good agreement with those found by Christou.(8)

A novel high-temperature stable metallic system for the Schottky gate contacts, as well as transistor bias leads, are currently being developed to improve the PSM reliability.

5. Conclusions

In conclusion, we have presented a novel concept and technology of a GaAs micromachined power sensor microsystem. In the PSM concept, two power-controlled GaAs MESFETs (as three-terminal heaters) and a central Schottky diode (as a temperature sensor) are monolithically integrated and thermally isolated on two GaAs cantilever beams

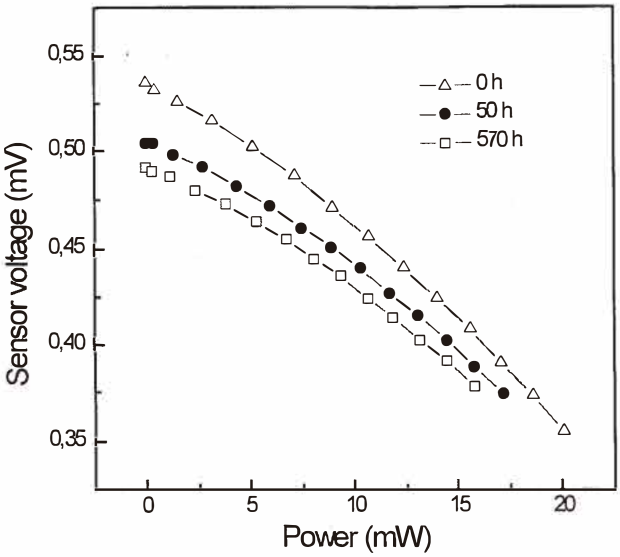

Fig. 7. P-U transfer characteristics of PSM after subsequent storage time.

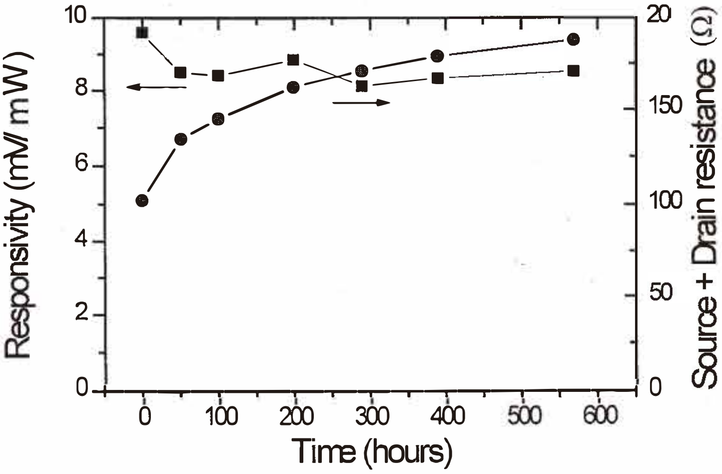

Fig. 8. PSM response and parasitic resistance vs time.

with the thickness of 8 μm. In the PSM technology developed, GaAs MESFET processing is combined with GaAs bulk micromachining. The technology permitted precise control of the thickness and uniformity of the cantilever beams directly via the thickness of the MBE-grown material over an AlGaAs etch-stop layer. It should be emphasized that the GaAs bulk micromachining technology described can, in principle, to be used for cantilever thickness patterning in the submicrometer or even nanometer range.

The benefit of the PSM technology developed was confirmed by investigating the basic microsystem transfer characteristics in various gaseous environments. Due to the use of thin GaAs cantilevers, a high power-temperature conversion efficiency was achieved. Average thermal resistance values as high as 6500 K/W, 7250 K/W and 9200 K/W were determined for air, argon and vacuum environments, respectively. Further improvement in the power-temperature conversion efficiency is expected on decreasing the cantilever thickness.

Preliminary results of the PSM reliability investigation were presented. An increase in the transistor bias lead resistance was observed as a dominant gradual degradation mechanism.

The presented results of the GaAs PSM technology and characterization are highly significant for further technological modifications and scaling design rules. The results are useful for any III-V semiconductor based cantilever proposal for sensors where extremely high thermal resistance values are required.

Finally, it should be noted that ac-dc power transfer measurements are currently being performed to verify the accuracy of the power measurement expected.

Acknowledgments

This work was supported by the CEC COPERNICUS programme, Contract No. CIPA-CT94-0197 and both the Slovak Grant Agency for Science, VEGA-Commission, Grant No. 2/4060/97 and GAT-Commission, Grant No. 95/5305/104.

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