Broadband Thermoelectric Microwave Power Sensors using GaAs Foundry Process

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***Abstract* – The paper presents the first demonstration of an integrated MMIC compatible thermoelectric microwave power sensor for frequencies between 1 to 20GHz using a standard GaAs foundry process. Two different types of sensors are described: an insertion sensor for the measurement of transmitted power through a coplanar waveguide and a termination sensor which measures the power dissipated in a 50 Ω load. The transmission sensor has a very low insertion loss of less than 0.3dB and VSWR lower than 1.2. Due to their low time constant of approx. 1μs these sensors are well suited for pulsed applications. The sensor exhibits an inherent linearity for large power levels and does not require any bias.**

I. INTRODUCTION

Power sensors can be applied for applications like power monitoring, gain control or circuit protection. Their operating principle is the measurement of the temperature rise due to the conductor losses when applying a microwave signal. The temperature rise with respect to the temperature of a heat sink is monitored by a cascade of thermopiles. We have presented similar power sensors earlier [1-3], which were fabricated on dedicated substrate material in an in-house fabrication process. Other groups have also presented microwave power sensors on GaAs [4-6] and Si [7-9], but these were not compatible with an MMIC process.

To our knowledge this is the first demonstration of an insertion and termination power sensor fully compatible and fabricated with an MMIC process.

In this publication two different realizations of the microwave power sensor are presented. The first sensor utilizes the losses in the center conductor of a coplanar (CPW) or microstrip waveguide as a measure of the transmitted power through a transmission line. It is intended to be inserted into any MMIC compatible connection in order to measure the rms of the transmitted microwave power. However, it is not possible with this sensor to detect the direction of the power transfer. This sensor is called in the following the insertion power sensor. The second sensor is based on the measurement of the power dissipated in a load resistance (Z_L=50Ω) using a similar technique as for the insertion sensor, where the temperature rise in the load is a measure of microwave power. It can be used for example in the teminated branch of a coupler. This sensor is called in the following a termination power sensor.

Thermoelectric power measurement has many inherent advantages as:

- Passive sensor principle. The thermoelectric sensor generates a signal voltage without the need of biasing,
- Excellent linearity. The only nonlinearity involved is the weak nonlinearity of the thermal resistivity of GaAs,
- High dynamic range. The lowest possible power level which can be measured is given by the thermal noise of the thermopile resistance, while there is virtually no limitation for the maximum microwave power operation
- True rms-measurement,
- Thermal time constants typically are in the 1-10μs range,
- Broadband performance. The measurement can be very broadband since the bandwidth is only limited by the performance of the transmission line. No special coupling structures are needed.

In the past such sensors were using membranes for thermal isolation of the center conductor of a CPW from the bulk GaAs [1-3]. This results in an increased sensitivity. However, the drawbacks of this approach are high insertion loss and poor VSWR, especially in the case of the insertion sensor. Moreover, the membrane process is not a standard technology in GaAs foundry processes.

The high thermal resistivity of GaAs, which is three times that of Silicon, allows a design without membrane. Hence, in this work a new membrane free approach has been implemented. It has the advantages of excellent microwave performance since it results in constant substrate thickness. The required chip area is

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smaller compared with the membrane structure and with structures requiring couplers. The thermal time constant is lower, which is very important for pulsed applications. Additionally, the absence of a membrane results in a very simple fabrication which is compatible with a standard MMIC-foundry process. In the following it is shown, that the sensitivity is still sufficient for the measurement of transmitted microwave powers higher than 10dBm.

II. DESIGN OF THE SENSORS

A cross-sectional drawing of a termination power sensor is shown in Fig. 1. The sensitivity of the sensors is determined by the Seebeck effect of the material. The thermocouples were formed utilizing the implanted channel layer of a power MESFET process for one leg and a Au interconnect for the second leg. The average doping level of the channel is about $N_D=10^{17}cm^{-3}$ resulting in a Seebeck coefficient of typically -350μV/K. The Seebeck coefficient of Au can be neglected.

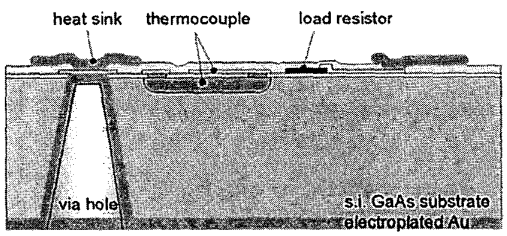

Fig. 1 Cross-section of a termination power sensor with via hole heat sink.

From the point of view of maximum sensitivity GaAs is not the optimum material for thermopiles, since AlGaAs [10] and InGaAs [11] layers result in a much better sensitivity. However, this approach is centered around the compatibility with standard MMIC foundry process.

The insertion power sensor is shown in Fig. 2. A cascade of 10 thermopile measures the temperature rise due to transmitted power in the coplanar transmission line. Air-bridges form the ground conductors in the vicinity of the thermopiles in order to avoid a thermal short-circuit by the ground conductor metal. Via-holes are located at the cold ends of the sensors in order to keep the cold ends of the sensors at base-plate temperature.

The software package ANSYS was used for the thermal design of the sensor. The simulations show, that it is essential to locate the hot ends of the thermopiles as close as possible to the center conductor of the coplanar waveguide. A trade-off has to be made between the microwave performance of the waveguide and the thermal performance of the sensor. Special test structures were investigated with different distances between the hot ends of the thermopiles and the center conductor of the CPW in order to verify the thermal simulations.

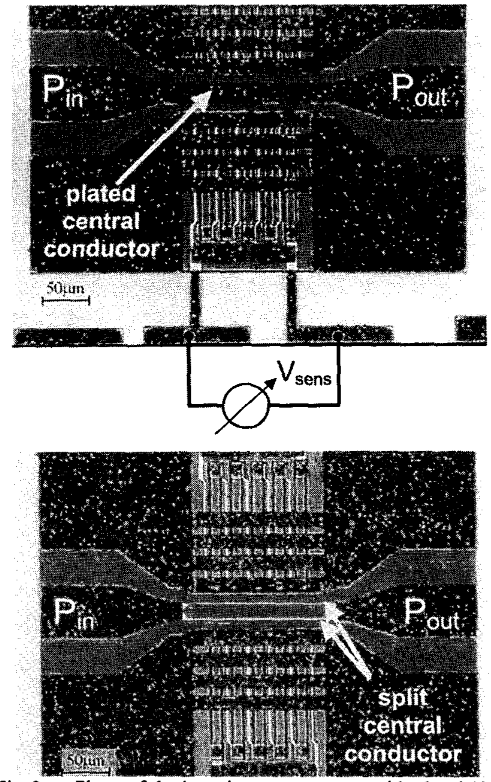

Fig. 2 Photo of the insertion power sensor with plated (design I) and split metal evaporated (design III) central conductor, respectively. The sensor dimensions are 100x300μm^2.

Different designs for the center conductor have been investigated:

1. Design I for low insertion loss with plated center conductor as shown in Fig. 2,
2. The same geometrical layout as shown in Fig. 2 but with evaporated metal only, design II.
3. Design III for high sensitivity with a center conductor split into two 5 μm transmission lines and evaporated metal only.

An important issue in the design is to keep the ohmic resistance of the thermopiles as low as possible since it determines the signal to noise ratio and the dynamic range of the sensor. Therefore the area of the ohmic contact should be sufficiently large. Additionally, the length of the thermopiles plays an important role. Longer thermopiles give a better sensitivity since their cold ends are located in a colder area of the chip but result in a higher resistance. Simulations with ANSYS as well as investigations with special test structures show that the optimum length is between 50μm and 100μm Termination sensors having different lengths are illustrated in Fig. 3.

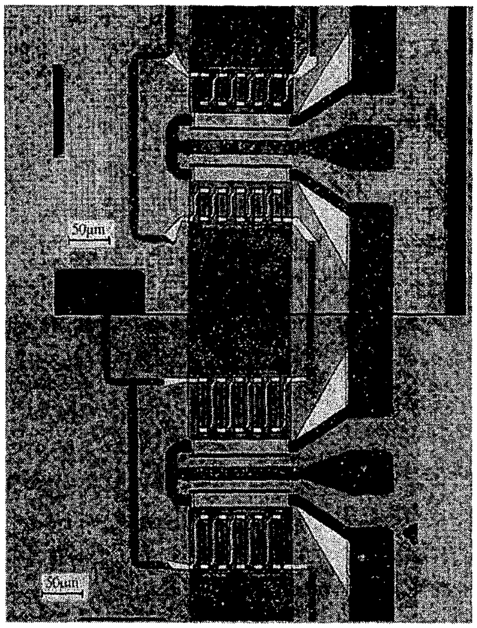

Fig. 3 Photograph of two termination power sensors with different thermopile lengths.

III. MEASUREMENT RESULTS

The insertion loss and VSWR of the sensors were measured in the range between 0.45 MHz and 26 GHz using a HP 8510B network analyzer using PicoProbe wafer probes. The results for the transmission power sensor are shown in

Fig. 4. The results demonstrate, that the sensor exhibits an excellent microwave performance, especially an insertion loss less than 0.3 dB and a VSWR lower than 1.2 in the whole frequency range.

The sensitivity S of the insertion power sensor is defined by the DC output voltage of the thermopile cascade divided by the input microwave power. A value of S = 10mV/W was measured for the insertion sensor based on design III. The theoretical resolution is 1.3μV provided the bandwidth is limited to 1MHz. This corresponds to a noise equivalent power of NEP=0.13mW.

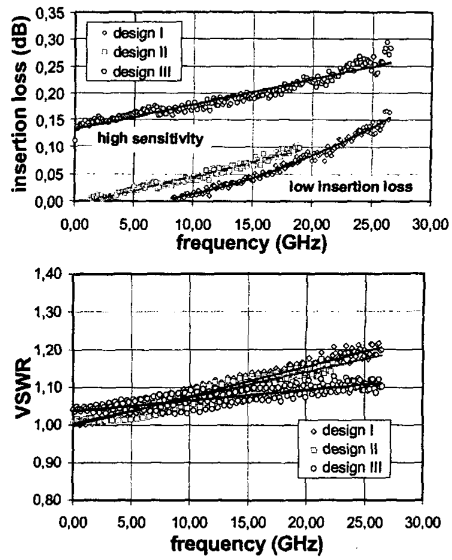

Fig. 4 Measured insertion loss and VSWR versus frequency of the insertion power sensor.

The time constant was measured by observing the response of a square-wave input signal at the input of the transmission line. The measured time constants are in the range of around 1μs. This result is clearly dominated by the surrounding air. We expect that the time constants of the sensors are lower when operated in hermetic environment.

The termination power sensor exhibits a much higher resolution of about 0.55V/W due to the fact that all the incident microwave power is dissipated in the sensor The output voltage versus the dissipated microwave power is provided in Fig. 5. The thermopile resistance is around 13kΩ. The VSWR of the termination power sensor is comparable to that of the transmission power sensor and depends strongly on the accuracy of the terminating load resistor, which has a value of Z_L=50Ω in our design. In order to realize the 50Ω resistance values two 100Ω resistors are connected in parallel.

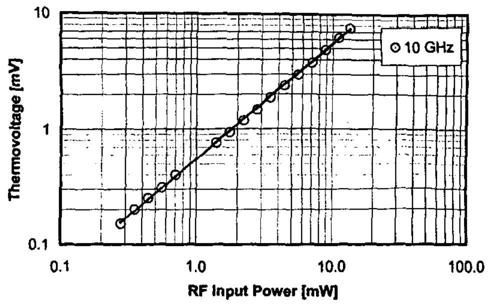

Fig. 5 Output voltage versus the microwave input power for the termination power sensor. The sensitivity of this sensor is approx. 0.55V/W at 10GHz.

IV. CONCLUSION

We have presented the first GaAs MMIC compatible microwave power sensor for insertion and load measurements. The sensor is realized in coplanar waveguide using a commercial GaAs power MESFET process.

It can be concluded that microwave power sensors without membrane have sufficient sensitivity for most power applications and excellent microwave properties as e.g. a low insertion loss of less than 0.3dB and low VSWR of less than 1.2 up to 26.5 GHz, respectively. The sensors presented have a short time constant of about 1µs, which makes them suitable for measurements in communication systems.

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REFERENCES

[1] A. Dehé, V. Krozer, K. Fricke, H. Klingbeil, K. Beilenhoff, and H. L. Hartnagel: Integrated microwave power sensor, Electron. Lett. Vol. 31, No. 25, pp. 2187-8, 1995.

[2] A. Dehé, H. Klingbeil, V. Krozer, K. Fricke, K. Beilenhoff, and H.L. Hartnagel: GaAs Monolithic Integrated Microwave Power Sensor in Coplanar Waveguide Technology. Proc. IEEE MTT-S Symposium, San Francisco, CA, USA, June 16-21, 1996. pp. 161-164.

[3] A. Dehé, V. Krozer, B. Chen, and H. L. Hartnagel: High-sensitivity microwave power sensor for GaAs-MMIC implementation, Electron. Lett. Vol. 32, No. 20, pp. 2149-50, 1996.

[4] T. Lalinský. J. Kuzmik, et. al.: Monolithic GaAs MESFET power sensor microsystem. Electron. Lett. Vol. 31, No. 22, pp. 1914-5, 1995.

[5] Xavier, P. Rauly, D. Daulle, A.: A principle of a hybrid microwave power sensor based on thermometric measurements, Microelectronics Intern., 1997

[6] Chong, N. Ahmed, H.: Polysilicon air-bridge thermal sensor coupled to log-periodic antenna for infrared detection, Microelectronic Eng., 1998

[7] P. Kopystynski, E. Obermayer, et. al.: Silicon power sensor from dc to microwave, Micro System Technologies 90, pp. 605-610, Berlin, 1990, Springer.

[8] A. Jaeggi, H. Baltes and D. Moser: Thermoelectric ac power sensor by CMOS technoloy. IEEE Electron Dev. Lett. Vol. 13, No. 7, pp. 366-8, 1992.

[9] S. Kadao, T. Wakabaysashi, et. al.: New structure for. dc-60GHz thermal power sensor. Proc. IEEE MTT-S Symposium, San Francisco, CA, USA, June 16-21, 1996. pp. 871-4.

[10] A. Dehé and H.L. Hartnagel: Free-standing AlGaAs thermopiles for infrared sensor design. IEEE Trans. Electron Dev. Vol. 43, No. 8, pp. 1193-9, 1996.

[11] A. Dehé, D. Pavlidis et al.: InGaAs/InP thermoelectric infrared sensor utilizing surface bulk micromachining technology. IEEE Trans. Electron Dev. Vol. 44, No. 7, pp. 1052-9, 1997.