# Micromechanical Sensors Based on GaAs/AlGaAs

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## Abstract

The combination of high temperature stable electronics with micromachining is a powerful means to develop a variety of intelligent sensors. Especially in the GaAs/AlGaAs material system all advantages fit together to realize micromachined sensors with integrated high temperature electronics. The technology includes new ohmic and Schottky contacts with high stability at increased ambient temperature. A thermal sensor is presented that can detect total pressure, gas type as well as gas velocities.

## Introduction

There are several advantages of micromechanically structured sensors with on chip integrated electronics as small size, low power consumption, low cost, and high reproducibility. These advantages do not account only for the case of the commonly applied silicon sensors. There are a number of additional advantages that make the GaAs/AlGaAs-material system capable for intelligent sensors as its high band gap for operation at ambient temperatures up to 300°C [1] and the selective etching against $Al_xGa_{1-x}As$ (x>0.4) [2], so that micromachining is simplified [4]. Another advantage which is utilized here is the thermal resistivity of $Al_xGa_{1-x}As$ which is more than ten times as large (x=0.48) as on Si [3]. The last two features of AlGaAs facilitate the simple fabrication of thin membranes.

These membranes are used to isolate a heating resistor efficiently from the chip so that heat transport appears mainly via the surrounding gas depending on its state. Consequently, the temperature difference between the heater and the chip (heatsink) – measured by a cascade of integrated thermocouples – gives information on the gas velocity, total pressure (T=const.) or even the gas type.

## Technology for high temperature electronics

As mentioned above the large band gap of GaAs and even more that of AlGaAs predestinates these semiconductors to be operated up to 400°C ambient temperature. However, high temperature environments accelerate lifetime processes significantly if conventional technology is used. Most important is therefore the optimization of metallisation and surface passivation to prevent interdiffusion, surface migration and electromigration. Essential technological aspects for the fabrication of high temperature stable MESFET circuits on MOCVD-grown GaAs-wafers are summarized.

### *A. Ohmic contact system*

An ohmic contact system has been established which relies on the reduction of the semiconductor band gap close to the metal contact. Recrystallization of epitaxial InGaAs by reaction from a solid phase was applied in order to obtain optimum surface morphology. The processing is as follows: evaporated $LaB_6$/Pd/In/S(Te)/Pd layers are annealed in $H_2$ at 600°C for 20s. $LaB_6$ acts as diffusion barrier and Si or Te are used as dopants. This system shows excellent surface morphology and contact resistivity of $10^{-5}\Omega/cm^2$. It does not degrade after 100h lifetime test at 400°C. Further details will be published elsewhere.

### *B. Schottky contact system*

Schottky contacts with high stability are realized with $LaB_6$-Au metallisation as it serves as diffusion barrier. They offer a relatively high Schottky barrier of 0.85eV, which does not decrease after 600h exposure to 400°C. Detailed investigations concerning stability and processing have been published by Würfl [5].

### *C. Surface passivation*

Surface passivation of the completed circuits is performed by plasma-enhanced-chemical-vapour deposition of $Si_3N_4$ at 250°C and 30Pa using 3% $SiH_4$ in Ar and $NH_3$. By separating the plasma from the semiconductor surface damage could be minimized. Also best adhesion and diffusion barrier qualities are observed.

DC-characteristics of GaAs MESFETs show reasonable high temperature behaviour. By modelling the characteristics with SPICE the temperature dependant decrease in transconductance can be explained with the decrease in electron mobility. To avoid leakage currents through the substrate at 400°C and higher, additional semiinsulating AlGaAs-buffers are introduced. The behavior of the gate Schottky diode is such that even at highest temperatures gate currents of only some $\mu$A ($I_D$=30mA) are measured which is due to the barrier height of 0.85eV.

## Micromachining of GaAs/AlGaAs

The main advantage of GaAs/AlGaAs micromachining is that heterostructures can be grown epitaxially with abrupt interfaces of high lateral smoothness. A thin AlGaAs layer (down to 1$\mu$m) of high Al content is used as etch stop layer. (This layer is equivalent with the

AlGaAs-buffer mentioned in the former section.) GaAs is etched isotropically with $H_2O_2$ (30%) + $NH_4OH$ (25%) (pH=7.6-8.4) while $Al_xGa_{1-x}As$ ($x \geq 0.4$) is attacked hardly.

Two ways of constructing thin membranes have been applied. The first starts from the front side of the chip. By using a $Si_3N_4$-etch mask holes through the active GaAs and the AlGaAs stop layer are etched unselectively. Consequently the selective etchant can underetch the AlGaAs which is now freestanding. This method has been used to fabricate first anemometers [6] but it suffers from undesired underetching through pinholes in the mask, so that circuits might be damaged. Additionally, this method requires excellent edge coverage of the passivation. The second method avoids this complication. After mechanical thinning the chip down to 100$\mu$m a $Si_3N_4$-etch mask is defined on the back side. Now the GaAs can be etched from the back side selectively against the AlGaAs layer and an uninterrupted membrane is worked out. As the front side of the chip is glued to a glass suspender when the membrane is etched the completed electronics will not be damaged. One disadvantage of this process is given by the relatively poor back side alignment of the etch mask provided by our mask aligner that results in a misalignment of approximately $\pm 10\mu$m.

## Design of the sensor

Three basic conditions have to be considered in the design of the epitaxial layers of the MOCVD grown wafer.

1. A thin membrane was necessary for thermal isolation of a heating resistor. This layer has to be about 1$\mu$m thick in order to assure mechanical stability.
2. One layer, which acts as the temperature sensitive thermopile, must have an sufficient Seebeck coefficient to ensure high sensitivity and low resistivity. A tradeoff between the last two items has to be made by optimizing Al mole fraction and doping of this layer. Of course, additionally the thermal resistance of this layer contributes significantly to the overall thermal resistance of the device.
3. MESFETs should be integrated to the sensor.

A heterobuffer MESFET wafer was chosen for this application. The 1$\mu$m thick $Al_{0.45}Ga_{0.55}As$ buffer serves as membrane with excellent etchstop quality and maximum available thermal resistivity. The $Al_{0.15}Ga_{0.85}As$ channel ($n = 1.0\times10^{17}cm^{-3}$) is suitable for MESFETs and has a Seebeck coefficient of approx. 300$\mu$V/K [7].

A large mesa type heating resistor ($100\times1000\mu m^2$) is located in the middle of a membrane ($1700\times585\times1\mu m^3$) which contains holes to enshure pressure equilibrium between front and back side and to increase the thermal resistivity of the structure. We measured the thermal resistance of the heating element to be $(7.28\pm0.12)\times{}^3K/W$ at normal conditions in air. A cascade of 20 thermocouples is structured out of the channel material. For the interconnect Cr/Au lines have been used. The thermopile has a sensitivity of 3.23mV/K. The sensors time constant of 3.8ms (63% max. value) was measured by applying a chopped voltage to the resistor and observing the time step response of the thermopile.

### *A. Vacuum and gas detection*

The heating resistor transferres heat to the ambient mainly via two effects. Heat conduction takes place through the membrane, thermoelements and metallic interconnectors. This effect was minimized by design and the choice of materials so that the second important loss of heat dominates. That is the heat transferred via the gas to the heat sink which is the ceramic substrate of the chip. At atmospheric pressure the heat conduction depends on the thermal conductivity of the gas. This value varies strongly with the gas type. Measurements with the sensor show its high sensitivity to the gas type (fig. 1). Even between air and nitrogen it is possible to distinguish.

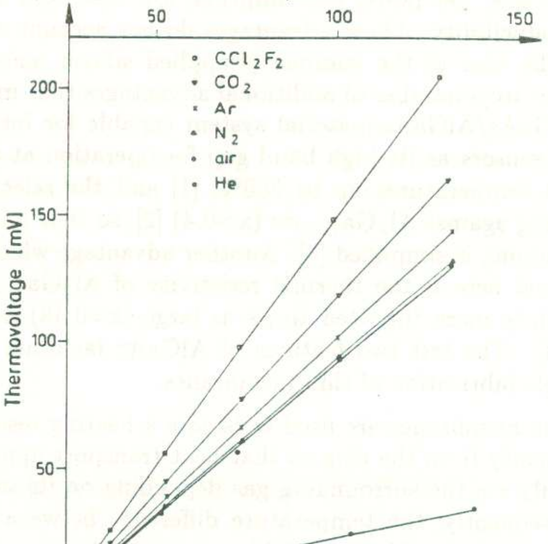

Figure 1: Heat conductivity measurements for different gases at atmospheric pressure and room temperature.

When the total pressure of the gas is reduced the heat conductivity decreases due to the increasing mean free path of the molecules [8]. If the mean free path gets larger than the sensor dimensions (especially the gap distance between resistor and ceramic: approx. 150-200$\mu$m) the sensor becomes insensitive and heat dissipation is only possible via radiation and conduction through the solid.

The measurements show the high pressure sensitivity of the sensor which reaches over more than four decades (fig. 2). Near atmospheric pressure an increasing resolution of the gas type is possible as explained above. The average sensitivity at 80Pa is about $2.4\times10^{-3}\mathrm{Pa}^{-1}$. At pressures below 1Pa it is impossible to distinguish between the different gases. In first approximation the thermal resistance of the heater changes from $7.28\times^{3}\mathrm{K/W}$ at normal pressure to $20\times^{3}\mathrm{K/W}$ at vacuum condition.

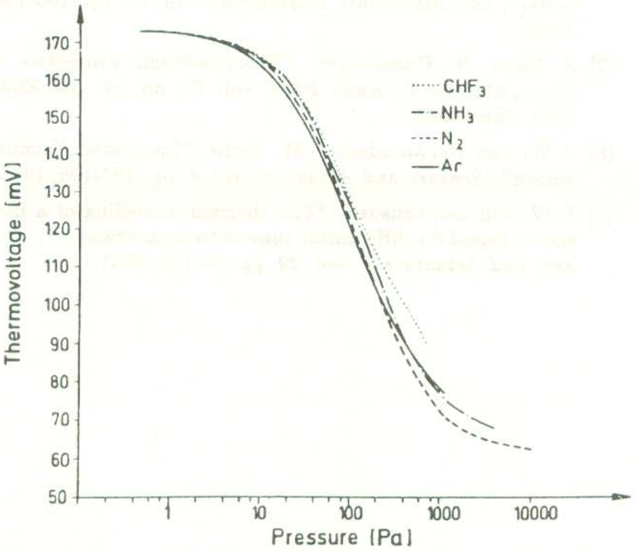

Figure 2: Total pressure measurement with different gases at room temperature. The heating power is 6.4mW.

*B. Anemometer operation*

The same sensor can be used as an gas velocity sensor. Two operation modes are possible.

A passive detection mode is to keep the heating power at a constant value and then measuring the thermovoltage changing with the velocity of the gas. The gas flows parallel to the surface and the heat transfer is increased with increasing velocity (fig. 3). The sensitivity does not change significantly with the heating power and is $0.024(\mathrm{m/s})^{-1}$.

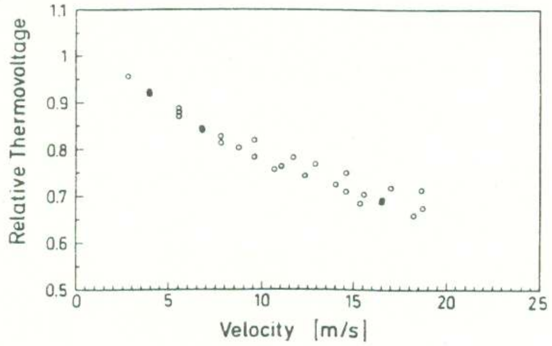

Figure 3: Relative change of the thermovoltage for three different heating powers (0.17, 6.7 and 24.3mW).

An active mode of measuring the velocity is to keep the heater at constant temperature $T_h$, which is controlled by the thermopile. The additional power $P_{ad}$, that has to be mustered up to keep the heater at constant temperature, is a measure for the velocity $v_0$ of the laminar gas stream [9]:

$$P_{total} = P_0 + P_{ad} = (R_t + const.\sqrt{v_0})(T_h - T_0)$$

with $T_0$ being the temperature of the chip and the ambient gas. In this mode the sensor has a sensitivity of $0.027(\mathrm{m/s})^{-1}$ but the measurements do not show the theoretical square root behavior (fig. 4).

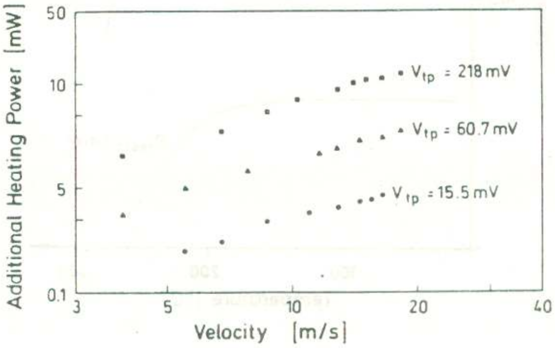

Figure 4: Additional heating power that was necessary to keep the heater at constant temperature.

In a future design the resulting thermovoltage can be supplied to an integrated MESFET operational amplifier, that should be used to regulate the additional heating power.

*C. High temperature operation*

To run the sensor at elevated temperatures, the absolute temperature of the gas has to be known, what is easily maintained by the temperature dependant current characteristic of an integrated Schottky diode.

The sensor has been tested up to 280°C air temperature at low velocity (v=0.6m/s) (fig. 5). At medium heating powers the thermovoltage changes only little (-12%) up to 200°C air temperature so that no calibration is necessary in this range of temperature. With high heating power and calibration the sensor may be used till 300°C or even higher temperatures. The drop in thermovoltage at high temperatures may be due to imperfect surface passivation resulting in leakage currents.

## Conclusion

A new technology for the realization of GaAs sensors has been developed. In detail the following results have been obtained:

- A technology for the fabrication of thin membranes has been presented.
- The technology is fully compatible with the MES-

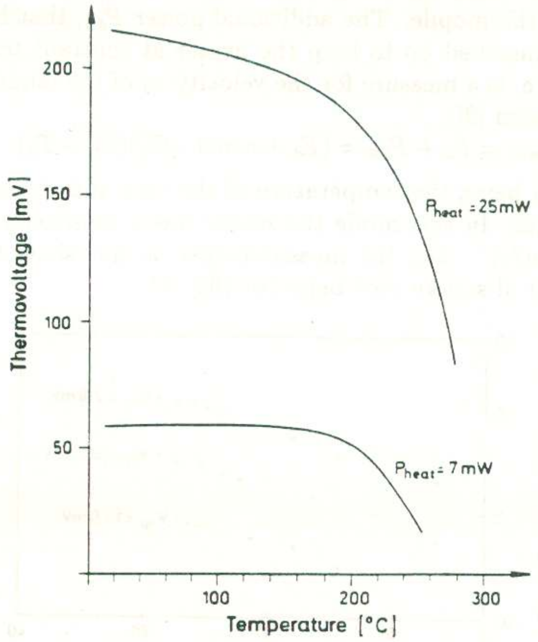

Figure 5: High temperature operation of the anemometer at an air velocity of approximately 0.6m/s.

FET high temperature process developed in Darmstadt.

- As an example for thermal based sensors utilizing the Seebeck effect and the low thermal conductivity of AlGaAs two sensors have been demonstrated: a sensor for measurement of low gas pressures and/or gas type detection and a mass flow sensor (anemometer).

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