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A micromachined mass-flow sensor with integrated electronics on GaAs

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Abstract

An integrated mass-flow sensor on GaAs based on the principle of convective heat transfer has been developed. An AlGaAs etch-stop layer is used for the fabrication of the membrane for thermal isolation of the heater. The temperature of the mesa-type heating resistor is measured by cascaded thermopiles. A differential MESFET amplifier is integrated for on-chip amplification and impedance transformation. Measurements show that the mass-flow sensor can be used up to an ambient temperature of 300 °C.

Keywords: Gallium arsenide; Integrated electronics; Mass-flow sensor; Micromachining

1. Introduction

Integrated sensors have a number of advantages, such as small size, the possibility to integrate electronics, on-chip temperature compensation [1,4], detection of the direction of the flow [2,6,3], fast response [5] and low current consumption. All these publications present micromachined anemometers on silicon. However, the III–V semiconductor GaAs has some additional advantages:

(a) Because of its high band gap of 1.4 eV, GaAs allows operation at ambient temperatures up to 400 °C, provided the device technology is optimized for this temperature [7,8]. The possibility of growing semi-insulating GaAs material facilitates easy electrical separation of the individual devices of a circuit. This high-temperature technology for FETs and bipolar devices is fully compatible with the sensor micromachining technology presented here.

(b) Micromachining is extremely simple with GaAs because of its large etch selectivity with respect to $Al_{(1-x)}Ga_xAs$, provided the Al mole fraction x is larger than 0.4.

(c) The thermal resistivity of $Al_{(1-x)}Ga_xAs$ is $(2.27+28.83x-30x^2)$ K cm W^{-1}. From this it can be inferred that the thermal resistivity of $Al_{0.52}Ga_{0.48}As$ is more than 10 times larger than that of silicon. Therefore the heater can be isolated much more efficiently, resulting in a lower power consumption of the chip. This is especially important for the heat flow through the thermopiles.

In addition to previous work [9], the incorporation of a high-temperature-stable active circuit on the GaAs anemometer chip is presented here for the first time. This circuit allows the safe transfer of the output signal to control electronics.

The etching was performed in this case from the backside of the wafer. This simplifies the technology compared to the previous work [9], where the membrane was etched from the frontside through access holes. For this process windows for the bonding pads were opened after etching the membrane. The procedure employed in this paper has the advantage that the etching of the membrane can be performed after having completed the frontside process. There is no longer a critical photolithographical step needed after completion of the membrane. Additionally, the surface of the sensor is not interrupted by the access holes previously needed.

Measurements of the sensitivity and the temperature dependence in a wind tunnel are presented here.

2. Design and fabrication

The principle of the mass-flow sensor is based on the convective heat transfer from a heater kept at a

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constant temperature T_h. For laminar flow the transferred heat P can be approximated by the well-known semi-empirical formula:

$$P=(R_0+\mathrm{const.}(Pr)^{1/3}(Re)^{1/2})(T_h-T_0) \qquad (1)$$

In this formula R_0, Pr and T_0 are the thermal resistance of the heater without flow, the dimensionless Prandtl number and the ambient temperature, respectively. The Reynold's number $Re=uL/\nu$ is proportional to the air velocity u and the characteristic length L of the device. ν is the viscosity of the medium.

The additional power, P_t, which is required to maintain the temperature T_h at a non-zero flow ($Re>0$) is given by

$$P_t=P-P_0=\mathrm{const.}(Pr)^{1/3}(Re)^{1/2}(T_h-T_0) \qquad (2)$$

Therefore the additional power P_t required to maintain the temperature constant is a measure of the velocity of the medium. In order to keep the power consumption of the chip low, the heater is thermally isolated from the heat sink (e.g., the backside of the chip) by a membrane, as indicated in the layout of the chip in Fig. 1.

The measurement of the temperature difference between the heater and the ambient temperature is performed with a cascade of 16 GaAs/AlGaAs thermopiles. The output voltage of the thermopiles is amplified by the differential amplifier. The output signal can therefore be transferred without interference problems to a second electronic circuit located at a convenient place outside the hot environment. The second electronic circuit contains the control for the heating voltage.

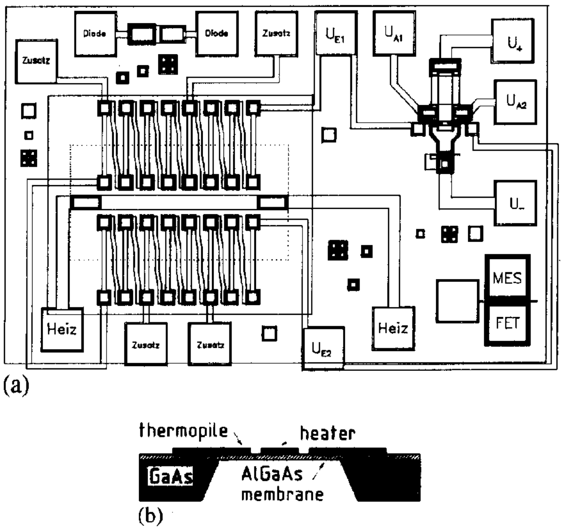

Fig. 1. (a) Layout of the mass-flow sensor on GaAs. The membrane is located under the rectangular area indicated by a dotted line. Chip size is 2 mm×1.28 mm. (b) Schematic cross section of the flow sensor.

Table 1
MOCVD material used for the mass-flow sensor

No.	Thickness	Doping	Al concentration	Purpose
1	200 nm	$n=5.5\times10^{17}$ cm^{-3}	0	cap
2	150 nm	$n=1.0\times10^{17}$ cm^{-3}	0–0.15	grading
3	400 nm	$n=1.0\times10^{17}$ cm^{-3}	0.15	active layer
4	1000 nm	undoped	0.45	etch stop
5	600 μm	Cr-compensated	0	substrate

Thus the active circuit on the chip allows the sensor to operate in a hot environment, being separated from the electronics.

Additionally, the ambient temperature can be measured by the temperature dependence of the current–voltage characteristic of a Schottky diode.

In order to incorporate active devices into the chip design, MOCVD material according to the specifications of Table 1 is used with an $Al_{0.15}Ga_{85}As$ active layer. MESFET devices with 5 μm gate length are fabricated on this material using the technology reported earlier [7]. This technology is capable of long-term operation at ambient temperatures up to 400 °C because of the introduction of ohmic contacts and an Si_3N_4 passivation, both optimized for high-temperature operation. For this purpose the thickness of the Au layer of the conventional Au Ge Ni ohmic contact was reduced and a WSi diffusion barrier was introduced [7]. Cr/Au metallization was used for the interconnect.

Before the etching of the membrane was performed, the wafer was thinned to a thickness of 100 μm. The membrane was etched with an H_2O_2: NH_4OH solution [10], adjusted to a pH of 8.4, from the backside of the wafer. This etching solution etches isotropically with an etch rate of approximately 5 μm min^{-1}. A PECVD Si_3N_4 etch mask was used. The membranes obtained with this method are completely flat. This indicates that there is only marginal compressive stress in the membrane, as one may expect because of the slightly increased lattice constant of the AlGaAs with respect to that of GaAs. Because of the high selectivity of the etchant used, the thickness of the membrane is equivalent to the thickness of the $Al_{0.45}Ga_{0.55}As$ layer (1 μm).

3. Results

The measurement of the thermal resistance of the membrane was performed by heating the complete chip and monitoring the resistance of the heater as a function of the temperature. Subsequently the thermal resistance was determined by operating the sensor at room temperature and heating the centre of the membrane with the heater. Comparison with the measured temperature dependence of the heater resistance yields a thermal resistance of the membrane of 2700 K W^{-1} at room temperature. At increased ambient temperatures, this value increases further because of the positive temperature coefficient of the AlGaAs thermal resistance. The sensitivity of the 16 thermopiles was measured to be 2.8 mV K^{-1}.

The integrated differential amplifier showed about 10 dB gain at room temperature. At 300 °C the gain dropped to about 8 dB. The following measurements are performed in a wind tunnel without the output of the thermopiles beeing connected to the amplifier. A brass rod (150 mm long, 4 mm diameter) was used to support the flow sensor. The flow meter was mounted onto a flat area that was machined at one end of the rod. Bond wires were used for the electrical connection. In order to ensure an undisturbed flow over the sensor, the bond wires were located outside the direction of flow over the membrane. Additionally the bond wires were kept as low as possible.

In Fig. 2 the thermovoltage as a function of the air velocity is depicted for different but constant heating powers. The thermovoltage at zero air velocity is subtracted in this Figure. Despite the relatively low heating power, a reasonable sensitivity was obtained. The resistance of the heater is 3 kΩ. Therefore 10 V are required to achieve 33 mW heating power.

In Fig. 3 the additional power P_t, which is required to maintain the heater temperature above ambient $T_o = T_h - T_0$ is given as a function of the air velocity u. The thermopile voltage was kept constant in this measurement by varying the heater voltage. The parameters were the heating power for zero flow, P_0, and the corresponding temperature above ambient, T_o. The output power P_t did not show the predicted square-root behaviour, but the sensitivity decreases at about 20 m s^{-1}.

In order to determine the temperature dependence of the thermopile voltage, air with a constant velocity

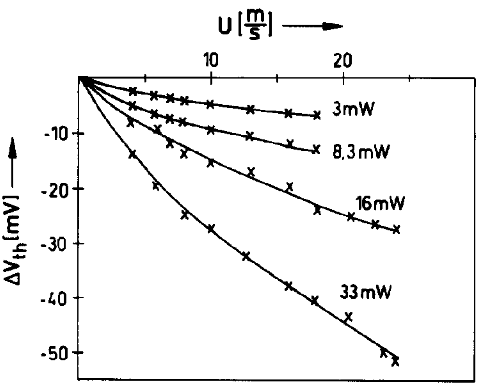

Fig. 2. Change of the thermovoltage with respect to the thermovoltage at zero flow, ΔV_{th}, as a function of the air velocity. Parameter is the heating power P_0.

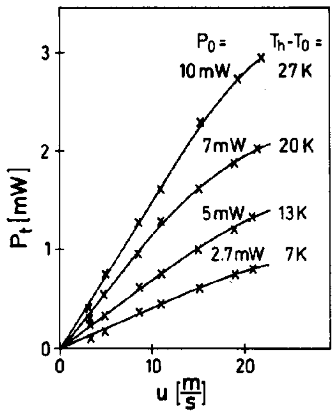

Fig. 3. Additional power P_t needed for constant temperature of the heater, $T_h - T_0$, as a function of the air velocity. Parameters are the heating power P_0 and the heater temperature above ambient $T_h - T_0$.

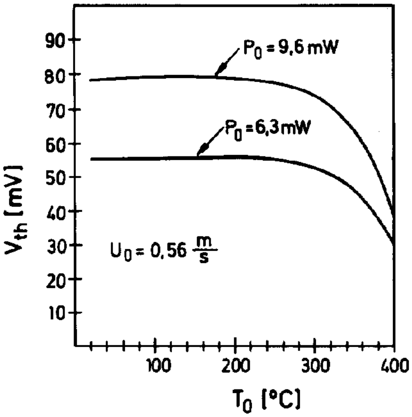

Fig. 4. Thermopile voltage as a function of the ambient temperature at an air velocity of 0.56 m s^{-1}. Parameter is the heating power P_0.

of 0.56 m s^{-1} and temperatures between room temperature and 400 °C were used. The thermopile voltage V_{th} for two different heating powers P_0 is depicted in Fig. 4. It can be seen clearly that the thermovoltage only changes marginally up to temperatures of 240 °C. The decrease at higher temperatures is most probably because of the thermal generation of carriers in the semi-insulating GaAs, which becomes significant at temperatures above 300 °C. The measurement shows clearly that operation of the mass-flow sensor is possible up to temperatures of 240 °C without any problems.

4. Conclusions

A simple technology has been presented for the fabrication of a mass-flow sensor on GaAs, which may be operated up to ambient temperatures of about 240 °C. The membrane for the thermal isolation of the heater was fabricated by selective etching. Measurements of the mass-flow meter in a wind tunnel demonstrated a reasonable sensitivity despite a low heating power in the mW range.

By the integration of an integrated MESFET differential amplifier, compatibility with the micromechanical structuring was demonstrated. Also the differential amplifier is capable of operation up to 300 °C.

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Biography

Klaus Fricke was born in Munich, Germany, in 1957. He recieved the Dipl.-Ing. degree in electrical engineering from the Technical University of Darmstadt, West Germany, in 1983. Since October 1983, he has been employed at the Institute of High-Frequency Electronics at the Technical University of Darmstadt, where he is engaged in studies of technological improvements of GaAs power MESFETs. Since receiving the Ph.D. degree in 1989, he has been involved in the design of high-temperature GaAs circuits and sensors.