Monolithic Integrated Direction-Sensitive Flow Sensor

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***Abstract*—A monolithic integrated direction-sensitive flow sensor for measuring the velocity of gas or liquid flow is described. Its operation is based on the transfer of heat from a heated chip to a flowing fluid. Temperature differences on the chip are a measure for the flow velocity and flow direction in a plane parallel with the chip's surface. The sensor can be embedded in a wall, for example, in a wall of a tube conducting a fluid flow, and can be shielded from a direct contact with the fluid. Measurements are stated for velocities in a range below 3 m/s for air at room temperature.**

I. INTRODUCTION

THE ADVANTAGE of a monolithic (flow) sensor over other types of (flow) sensors is that it can be combined with an integrated circuit (IC) for signal processing on one chip. Such a combination can lead to a high-quality (flow) transducer capable of being mass-produced at low cost.

The flow velocity of gasses and liquid can be measured by a chip if there is a physical effect present to provide an interaction between the flow velocity and an electrical signal inside the chip. For sensors we particularly make use of the IC's sensitivity to those external influences, normally undesirable in signal processing, such as: mechanical pressure, temperature, radiation, magnetic field, electric field, and chemical parameters. Basically, each of these parameters can be applied to realize monolithic flow sensors.

Out of these possibilities, temperature sensing is selected for several reasons: 1) the absolute and relative temperatures can be measured very accurately by electronic circuits on the chip, 2) the thermal contact between the fluid and heated chip provides a well-defined square-root-like relation between flow velocity and a temperature difference on the chip, 3) the temperature difference is direction-sensitive, 4) the method is suitable for nearly all kinds of liquids and gasses, 5) the chip can be fabricated in a standard IC process without additional technological steps, and 6) the thermal interaction does not require a direct contact between the flowing medium and the active side of the chip but can be acquired, for instance, via the back side of the chip or via a shielding layer.

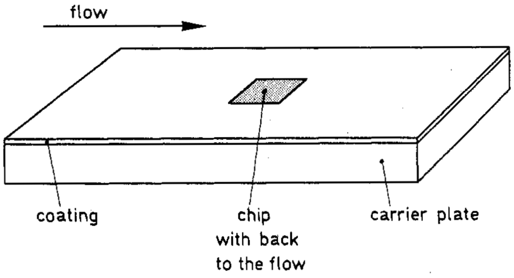

Fig. 1. A chip mounted with a beam-lead technique on a carrier plate and placed in a fluid.

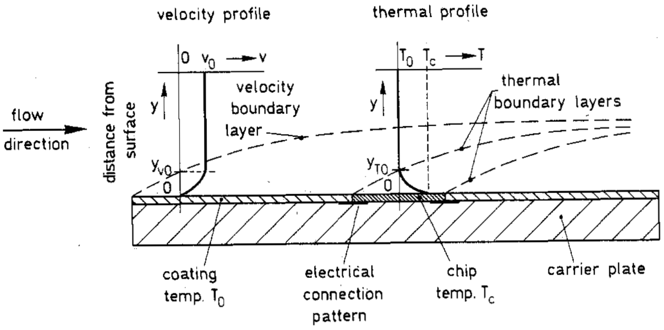

Fig. 2. Cross section of the chip and carrier plate with velocity and thermal profiles.

Other realizations of flow sensors which use IC components have been described in [1] and [2]. Their principle of operation is close to the conventional anemometer principle, which is not direction-sensitive. The idea of using an integrated resistance bridge for a flow sensor described in [3] has inspired the authors to develop the sensor presented here. Preliminary results have briefly been reported in [4].

The present paper deals with: the principle of operation of the direction-sensitive flow sensor in Section II, a practical realization of a three-transistor sensor chip in Section III, measurement results in Section IV, and a conclusion in Section V.

II. PRINCIPLE OF OPERATION

The thermal coupling between a fluid and a chip is depicted in Figs. 1 and 2. The chip is mounted with its component side on a carrier plate and is embedded in a coating layer so as to provide a smooth surface. Electrical connections between the chip and the plate can be made, for example, by beam-lead contacts. The flow is supposed to run parallel to the chip and the carrier plate. From the point where the flow strikes the leading edge of the carrier-plate going in the downstream direction a laminar boundary layer with increasing thickness builds up in the fluid.

We assume that the surface of the carrier plate is at the tem-

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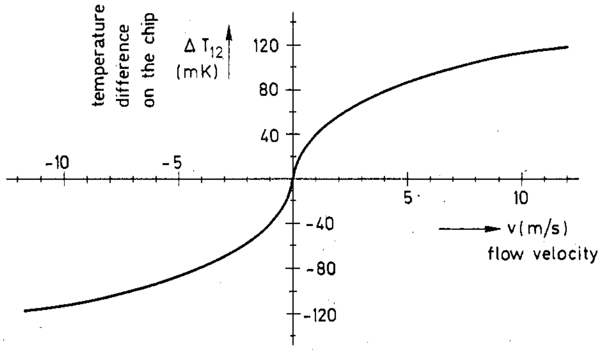

Fig. 3. Temperature difference on the chip as a function of the flow velocity.

perature T_0 of the fluid. In contrast, the chip is heated to a temperature T_c kept at a constant value $\Delta T_{c0} = T_c - T_0$. A suitable value for the temperature step ΔT_{c0} is 40 K. When the flow in the boundary layer reaches the chip, the flow undergoes a temperature shock. This results in a thermal boundary layer with the shape shown in Fig. 2. The most important aspect of this shape is that the thermal boundary layer is thinner at the front end, where the flow first hits the chip, than at the rear end. This means that the front end of the chip convects more heat into the flow than the rear end does. Consequently, the front end cools more than the rear end, so that a temperature difference ΔT_{12} can be measured across the chip in the flow direction. It can be derived that the temperature difference ΔT_{12} is proportional to the square root of the flow velocity v_0, at low velocities ($v_0 < 1$ m/s), and to the temperature step ΔT_{c0} [5]

$$\Delta T_{12} \simeq C \Delta T_{c0} \sqrt{v_0}.$$

The proportionality factor C depends on the size of the chip and of several flow parameters, such as thermal conductivity, dynamic viscosity, the state of turbulence, etc. With a chip of 2 × 2 mm in contact with dry air, the value of C is of the order of 10^{-3} $(\mathrm{s/m})^{1/2}$ at room temperature ($T = 293$ K).

The relation between the flow velocity v_0 and the temperature difference ΔT_{12} on the chip is shown in Fig. 3. If the flow direction is inverted, the difference ΔT_{12} also becomes inverted.

When temperature differences are measured in two directions perpendicular to each other, the amplitude and direction of a velocity vector in a plane parallel to the chip can be determined. In this way, it is possible to realize a fully electronic weather vane, to cite an example.

The transfer function of Fig. 3 naturally starts at zero without the artificial means for the compensation of a large zero-velocity output signal, required by most other sensors based on the anemometer principle. For that reason, a good zero-point stability can be expected.

The square-root characteristic offers a high sensitivity in the lower velocity region whereas the output signal is being compressed at the high velocity end. So, the sensor can be expected to be useful in a wide velocity range.

If we were to keep the power dissipation P_1 in the chip at a constant value instead of the temperature step ΔT_{c0}, the chip would be cooled too much at higher flow velocities and the farthest parts of the characteristic of Fig. 3 would curve backwards. This would result in a nonsingular interpretable characteristic, which is not desirable. In order to keep the temperature step ΔT_{c0} at a constant value, the flow temperature T_0 must be measured separately from the chip temperature T_c.

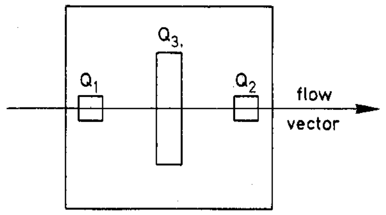

Fig. 4. Basic chip layout.

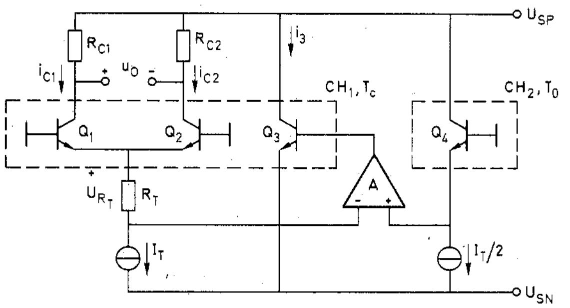

Fig. 5. Circuit of the direction-sensitive flow transducer.

The fact that the temperature step is spread out by the thermal conductivity of the carrier plate and coating layer and that the sensing elements underneath the chip are only indirectly coupled with the flow causes, to a certain extent, a decrease in the sensitivity, although the principle remains unchanged. Moreover, it is allowable to attach a shielding layer on the top of the carrier plate and chip in order to protect the chip against damaging chemicals in the fluid.

III. Realization

The integrated circuit on the chip has the task of accurately measuring the small temperature difference ΔT_{12} (of the order of 0.1 K) and further of maintaining the chip temperature at a constant value ΔT_{c0} above the flow temperature.

Two equally shaped bipolar transistors Q_1 and Q_2 have been chosen for measuring ΔT_{12}. The chip layout of Fig. 4 shows the symmetrical position of these transistors, placed near the front and rear ends of the chip, with the heating transistor Q_3 located in the center.

When the transistors Q_1 and Q_2 are connected in a long-tailed-pair circuit (Fig. 5), the differential output current of this configuration $i_o = i_{c1} - i_{c2}$ is highly sensitive to the temperature difference ΔT_{12} between Q_1 and Q_2 [6]

$$i_o \simeq \frac{q(U_{BE} - U_G)}{kT_c} \frac{\Delta T_{12}}{T_c} \frac{I_T}{2} \simeq -0.04\, \Delta T_{12} I_T$$