One-chip MOS Structure for Temperature Flow Sensor

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ABSTRACT

There is described a MOS structure in the use of flow sensor system in the paper. MOS structure as a temperature sensor allows measurement of temperature gradient. One allows computation of direction of air flow over the structure chip. Four MOS structure of temperature sensors has been used for the design of sensitivity flow sensor. Different arrangements of MOS structure have been designed. Software standard tools have been used for simulation and modeling of structure properties. Maximum values of structure sensitivity in dependence on operating temperature have been computed. The parameters have been used for the design. Suitable structure temperature was found during simulations. Circuit connection of sensor temperature matrix was designed. New results of sensitivity and resolution of MOS sensor systems were obtained. The working efforts were focused on the sensitivity, angle resolution and small power consumption.

Keywords: MOS, structure, flow, direction, sensors, sensitivity, design

1 INTRODUCTION

The new types of microelectronic structures are used in the flow measurement technology, new type of materials and structure design can be used. Typical structures use anemometric principle for flow measurement as small structures with very small power consumption. For design of a direction sensitive flow sensor structures, the anemometric principle can be used. The principle uses cooling of temperature sensor structure, different type of sensor structures can be used. Power delivered for the sensor structure heating is used for the flow velocity measurement. Measure sensitivity of the sensor structures is derived from temperature equilibrium in steady state, when electrical power delivered to the sensor structure is the same as heat energy lost for cooling of the sensor structure. The power loss depends on velocity of flow of the cooling fluid. Sensor structures using this principle are resistive heated sensors, thermistors, calorimetric structures, Thomas flowmeter, Hasting temperature profilometer, different resonance structures using micromembranes or microbridges. Another group of sensors using the anemometric principle are p-n junctions (low sensitivity for air velocity) or special integrated structures on chip, as one-chip working with constant temperature of silicon chip. Other types of structures can be used for temperature measurement, as MOS channel (suitable for integration and miniaturization), metal or integrated thermocouples [1] and other types of integrated temperature sensors for example. The basic working principles and rules were described in [2].

2 PRINCIPLES

The designed structure serves to identify the region of a week and strong inversion (operating mode) of the transistor and to quantify the drain current versus temperature in those regions for one transistor structure. The arrangement for modelling of temperature properties of the structure (basic principle) is shown in Fig. 1.

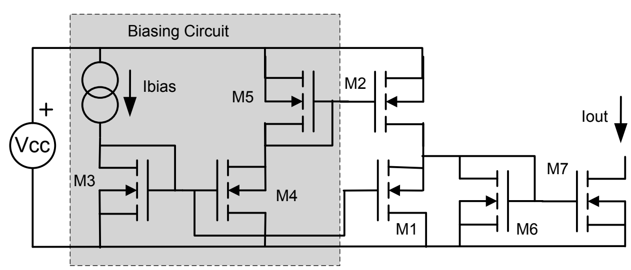

Figure 1: One MOS transistor temperature sensor structure.

Simulations of temperature dependence of electric parameters of MOS integrated transistor structures have been performed during the design of the temperature matrix (reached results are presented in Fig. 5).

The temperature sensors S1 thru S4 are designed as the matrices of NMOS and PMOS transistors. The operating points are set in the area of strong inversion for NMOS transistor M1 and week inversion for the PMOS transistor M2. The temperature dependence of mobility of the charge carrier is dominant in strong inversion. In the strong inversion the temperature coefficient of the drain current is negative, in the week inversion region is positive.

The analog part contains sensitive temperature sensors S_1 thru S_4, circuits for signal processing, and differential amplifier - Fig. 2. The differential output signals are sent to the digital computational part. It serves for computation of the direction of airflow using goniometric functions. According to sensor arrangement, it is possible to measure flow direction up to 360^o using two couples of temperature sensors in perpendicular arrangement.

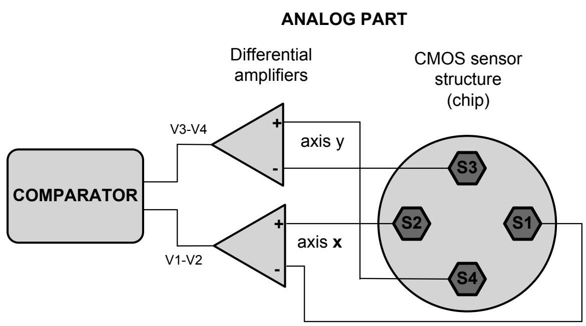

Figure 2: Block diagram of the sensor structure part.

2.1 Principle of Anemometric Measurement

The system is created of four warming up elements (sensors) together with 4 temperature sensors for temperature measurement of the heated and cooled points [3]. The warming up elements are heated over the level of ambient temperature ϑ_o. The air flows over the surface of the chip with velocity **v.** The flow direction created the angle **φ** with the **x**-axis**.**

The principle for 1D space, i.e. the **x**-axis. The flowing air cools the first heated point by $\Delta\vartheta_1$ and at the same time it itself is heated by $\Delta\vartheta$. Then the heated point has the temperature

$$\vartheta_1=\vartheta_H-\Delta\vartheta_1 \quad (1)$$

where ϑ_H is the temperature of the heated point without airflow. The heated air flows over the chip points to the second heated point. The second heated points is cooled less, i.e. it has the temperature

$$\vartheta_2=\vartheta_H-\Delta\vartheta_2 \quad (2)$$

Then it holds for the temperature of the heated points $\vartheta_2>\vartheta_1$. The slower the airflow created the higher the temperature gradient $\Delta\vartheta$. If airflow has the opposite direction then the heated points are cooled in the reversed order. Then it holds $\vartheta_2<\vartheta_1$ for the temperature of the heated points. When the airflow has the range up to 360^o it is necessary to design 2D orthogonal system. The principle of measurement is based on decomposing of flow velocity vector into x and y components and their measurement by means of several identical sensors.

The measurement of flow direction can be done by four identical temperature sensors and heated elements. We can measure v_x and v_y components of the flow. For the measurement we can use the temperature gradient implemented using two temperature sensors S_1 (temperature υ_1) and S_2 (temperature υ_2) – see Fig. 3.

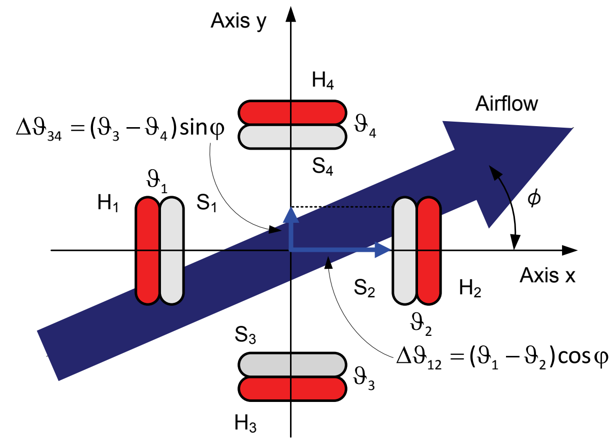

Figure 3: The principle of two-dimensional direction measurement.

Heated point H_1 is cooled more than heated point H_2, because the air is heated by the heat of H_1 and cooling of H_2 is reduced. Different surface cooling by the airflow created the temperature gradient on the chip surface. Sign of the temperature difference changes when direction of the flow is changed by 180^o. A simple direction sensitive sensor can be designed using two heated points and sensors placed symmetrically. The temperature difference $\Delta\vartheta_{12}=\vartheta_1-\vartheta_2$ is measured. For the flow vector having angle φ (see Fig. 3), the direction sensitivity in x-axis may be expressed as

$$\Delta\vartheta_{12} = (\vartheta_1 - \vartheta_2) \cos \varphi \quad (3)$$

According to sensor arrangement showed in Fig. 3, it is possible to measure flow direction up to 180^o. The range of measurement can be increased up to 360^o using two orthogonal couples of heated points and temperature sensors - see Fig. 3. Sensitivity of the sensors in the axes y is

$$\Delta\vartheta_{34} = (\vartheta_3 - \vartheta_4) \sin \varphi \quad (4)$$

We can obtain table of signs for single-valued determination of angle φ according to the presented relations. Sensors S_1 thru S_4 measure temperature of the heated points ϑ_1 thru ϑ_4. Output sensor voltages V_1 thru V_4 correspond to measured temperatures. Voltage difference $V_{12}=V_1-V_2$ corresponds to temperature difference $\vartheta_{12}=\vartheta_1-\vartheta_2$. The velocity of airflow over the chip can be computed from the equation

$$|v| \approx (V_{12}^2 + V_{34}^2)^{1/2} \quad (5)$$

3 PROCESSING OF A SENSOR TEMPERATURE DATA

Principle of operation of PLL circuit for processing of a temperature sensor signal is based on comparison of the voltage sensor signal with a triangular waveform signal in a comparator. The triangular waveform signal has a constant and temperature independent frequency. At the output of the comparator is a PWM signal. Width of the signal pulses is a function of the temperature. Constant frequency of the PWM signal is N-times multiplied in the PLL circuit. At the output of the voltage-controlled oscillator VCO there is an N-time multiple of the PWM signal and its duty cycle is 50%. Output signals are processed by a counter. Number of pulses counted by the counter in the course of the PWM pulse duration is proportional to the temperature measured. Block diagram of the transducer designed is in Fig. 4. The output signals of the sensors operating in the weak and strong inversion mode must be amplified to a level corresponding to the level of the signal at the output of the generator.

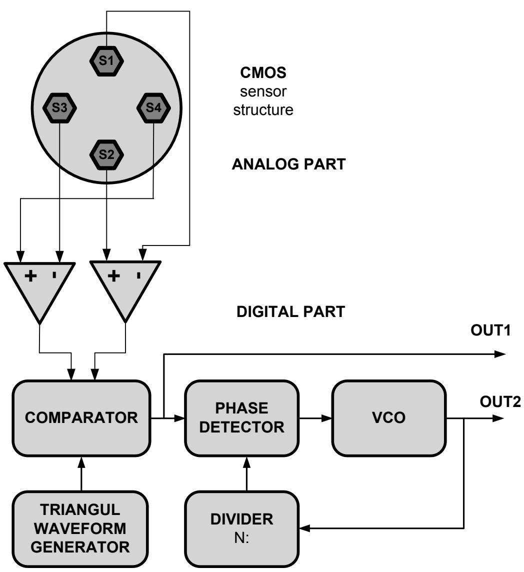

Figure 4: Temperature transducer with PLL sensor signals processing.

4 RESULTS

There are evident the week and strong inversion regions for one NMOS transistor on Fig. 5. The same simulation was presented for PMOS structure. There exists optimal biasing current, where the sensitivity of the MOS temperature sensor is maximal but these current changes with the temperature. On the Fig. 6 there is presented the dependence of the sensitivity of the temperature sensor on the biasing current at 60 ^{o}C. Optimal current in that case is about 29 μA.

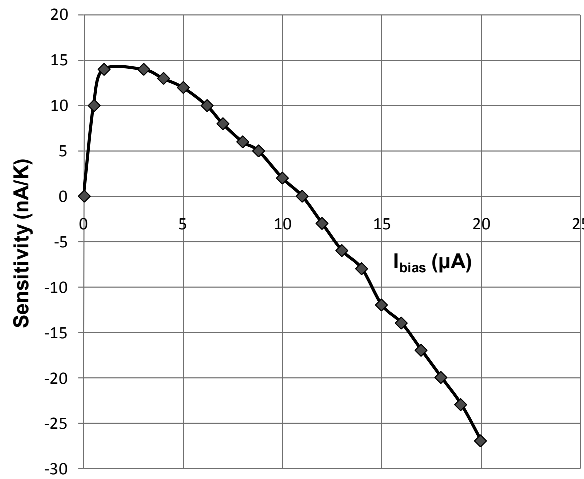

Figure 4: Temperature sensitivity of the drain current of the NMOS transistor versus biasing drain current.

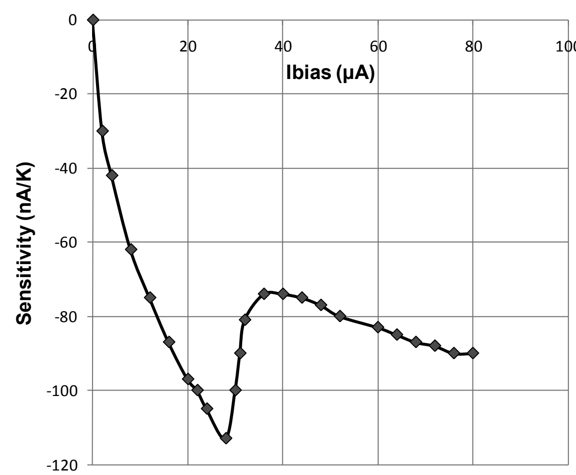

Figure 6: Temperature sensitivity of the output current from the temperature sensor versus biasing current at 60 ^{o}C.

Transfer characteristic have been primarily measured of sensor part with output signal V_2-V_1 and V_4-V_3. Temperature gradient is function of flow velocity. Based on the results, it is possible to derive a model for simulation of output voltage from the differential amplifier in dependence on flow velocity [4].

Transfer characteristic of the measure sensor system have been measured at constant temperature 26 ^{o}C. The output voltage signal of the CMOS temperature structure in the simulation shape was applied to the comparator. The output signal of the comparator has a pulse character and is measured by a counter. Temperature dependence of the sensor output signals V_{OUT1} and V_{OUT2} was measured for the sensor temperature range from 26 ^{o}C to 120 ^{o}C.

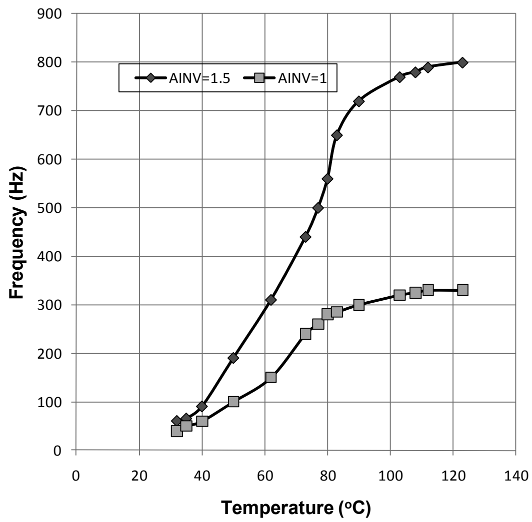

Figure 7: Transfer characteristic of the structure with the CMOS temperature sensor operating in the strong inversion mode.

Transfer characteristics of sensor structure operating in the strong inversion mode are in Fig. 7. Two gains A_{INV} were used for the measurements. The characteristics are nonlinear, increasing temperature causes the higher nonlinearity. This is caused by nonlinearities of the sensor circuit and by the gate voltage temperature dependence. Transfer characteristic of sensor structure operating in the weak inversion mode are in Fig. 8. Signal from the sensor is applied to the comparator input.

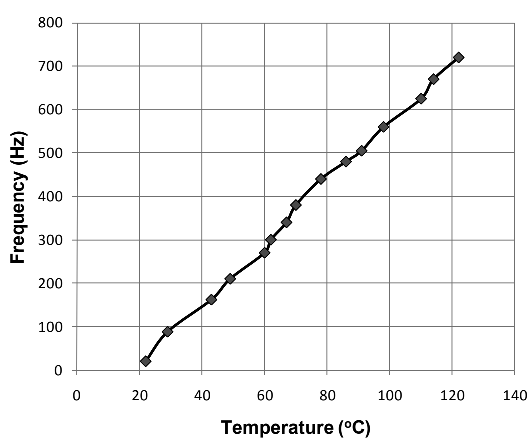

Figure 8: Transfer characteristic of the structure with the CMOS temperature sensor operating in the weak inversion mode.

5 CONCLUSIONS

An electronic circuit was designed, taking care of the mathematical functions including compensation functions. The transient analysis of the electronic circuit connection was used for vertical velocity simulation.

The designed simple sensor system is capable to measure a vertical velocity from 2 $m \cdot s^{-1}$, the altitude measurement is auxiliary information for the vertical velocity calculation, and the measurement accuracy is 2 m. The system is necessary to calibrate, one also contains a calibration section. The system includes distortion compensation. The calibration of the sensor system is performed by the simulation software SPICE.

The pressure sensor MPX4115 was used in the design and realization of sensor system. Problem of nonlinearity due to the exponential function of barometric pressure versus altitude was solved in the work. The altitude was calculated from the measured value using a linear interpolation.

6 ACKNOWLEDGEMENT

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