# Strong and Weak Inversion Mode of MOS in the Design of Direction Sensitivity Matrix

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## ABSTRACT

In the article there is presented a new arrangement of a temperature sensor system for air velocity and direction measurement. The system utilizes temperature dependence of the current through the channel of MOS structure. The geometric arrangement of temperature sensors allows measurement of temperature gradient. Temperature gradient allows to compute direction of air flow over the chip. Optimal operating modes of weak and strong inversion of MOS structure operation have been selected for the design of integrated temperature matrix. The matrix has been used for the design of a probe for measurement. Various arrangements of MOS sensor structures have been designed. CoventorWare and CADENCE software tools have been used for simulation and modeling of sensor properties. The new circuit design of sensor temperature matrix was used. The new results of sensitivity and resolution of sensor systems was reached. The working efforts are focused on the sensitivity, angle resolution and small power consumption of the gas direction flow systems.

***Keywords***: anemometry, airflow, temperature, microsystem, CMOS sensors

## 1 INTRODUCTION

Modeling and simulation of the properties of the microsystem can be a very difficult problem. There are being developed more and more sophisticated software packages with the aim to improve modeling of properties of the designed microsystem.

For design of a direction sensitive matrix, the anemometric principle may be used. Its operation is based on cooling of temperature sensors of different type. Sensitivity of the sensors is derived from temperature equilibrium in steady state, when electrical energy delivered to the sensor is the same as heat energy lost for cooling of the sensor. The energy loss depends on velocity of flow of the cooling medium. Power delivered for the sensor heating is used for the flow velocity measurement. Sensors using this principle are "hot-wire" sensors (probe is not suitable for integration), thermistors (high sensitivity, not suitable for integration). Another group of sensors using the anemometric principle are p-n junctions (low sensitivity for air velocity), MOS channel (suitable for integration and miniaturization), metal or integrated thermocouples [1] and other types of integrated temperature sensors.

The working principle was introduced in [2]. The analog part contains sensitive temperature sensors $S_1$ thru $S_4$, circuits for signal processing, and differential amplifier - Fig.1. 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.

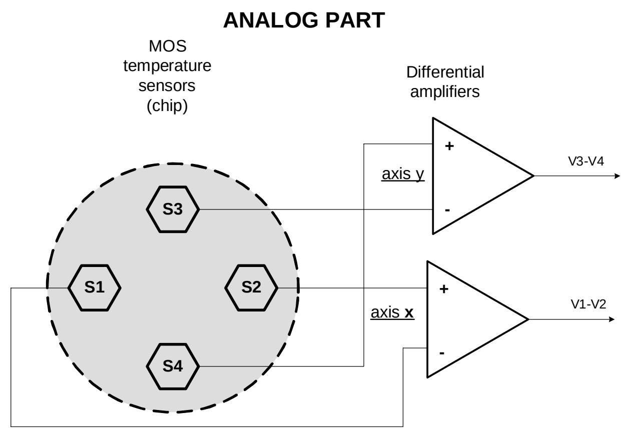


Figure 1: Block diagram of the sensor part for measurement of velocity and flow direction.

## 2 TEMPERATURE MATRIX DESIGN

Simulations of temperature dependence of electric parameters of MOS integrated transistor structures have been performed during the design of the temperature matrix. Optimal operating points (including temperature setup in steady state) have been identified. Maximum values of sensitivity in dependence on operating temperature have been computed from the acquired values. These parameters have been used for the design of operating mode of the temperature matrix as a temperature sensor. The basic principle arrangement for modelling of temperature properties of the structure is shown in Fig. 2. The structure served to identify the region of a strong and week inversion of the transistor and to quantify the sensitivity of the drain current on temperature in those regions for one transistor. Reached results are presented in Fig. 6.

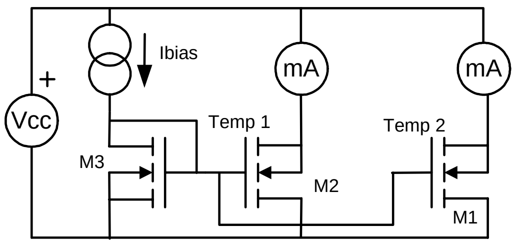


Figure 2: Principle circuit connection for simulation of the temperature dependence of the MOS structure.

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 (see Fig. 3). The temperature dependence of mobility of the charge carrier is dominant in strong inversion. In the week inversion mode the temperature drift of the Fermi potential is dominant which evoke the drift of the threshold voltage of the transistor. In the strong inversion the temperature coefficient of the drain current is negative, in the week inversion region is positive.

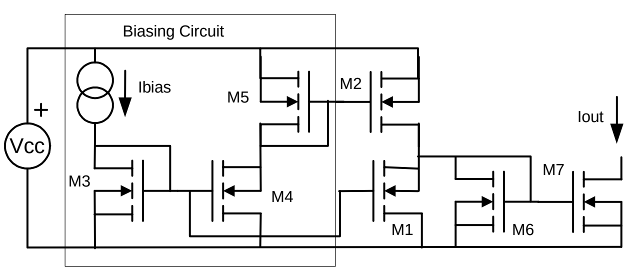


Figure 3: One MOS temperature sensor.

Serial connection of the transistors with different temperature dependence of the drain current improves the sensitivity of the structure.

Transistors M3, M4 and M5 serve as a biasing circuit for the sensing transistors M1 and M2 (Fig. 3). In the ideal case the drain current of M1 and M2 is same but the different temperature coefficients of the transistors causes divergence of this current which is mirrored by M6 and M7 to the output and consequently transformed to the voltage.

There are 4 temperature matrices on the chip. They constitute of 2 pairs with mutually orthogonal geometrical layout. Differential amplifiers process the output signals. The differential output signals are sent to the digital computational part. It serves for computation of the direction of airflow using goniometric functions. The connection allows compensating influence of the environment temperature and responses to fast dynamic changes.

# 3 PHASE-LOCKED-LOOP CIRCUIT FOR PROCESSING OF A TEMPERATURE SENSOR SIGNAL

Principle of operation of the Phase-Locked-Loop 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.

Processing of a sensor signal in a PLL is very advantageous from the point of view of compatibility with other electronic circuits, small temperature dependence of the PLL digital circuits, linearity of the transfer characteristic and small hysteresis.

The transducer can be used to process signals of the different sensors, e.g. temperature sensors, optoelectronic sensors, sensors for pressure measurement etc. The article treats processing of the signals from temperature CMOS sensors operating in the weak and strong inversion region (in the sub-threshold and above-threshold region). Block diagram of the transducer designed is in Fig.4.

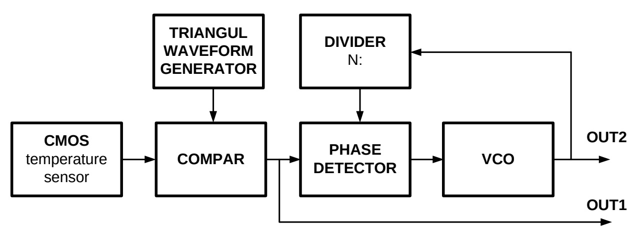


Figure 4: Temperature transducer with PLL sensor signals processing.

## 3.1 Matching of the sensors outputs to the comparators inputs

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. The generator signals have amplitude in the range from 2.24 V to 3.14 V. The output signals of the sensor operating in the strong inversion mode must be inverted to suppress influence of the temperature on the PWM output pulses width. The number of the pulses counted is proportional to the temperature measured. The circuits designed are in Fig. 5.

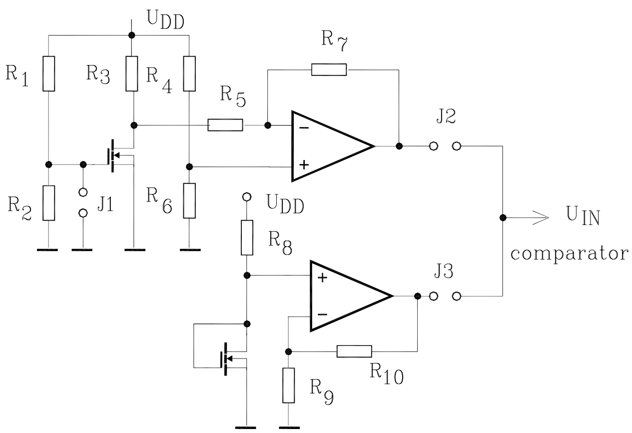


Figure 5: The principle connection of the sensors in weak and strong inversion mode.

## 4 REACHED RESULTS

There are evident the week and strong inversion regions for one NMOS transistor in Fig. 6.

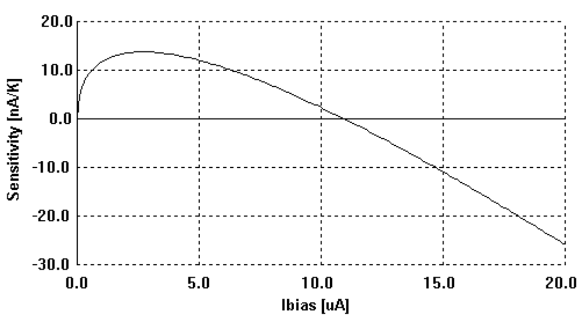


Figure 6: Dependence of the temperature sensitivity of the drain current of the NMOS transistor on the biasing drain current.

The same simulation was presented for PMOS structure. Optimal heating temperature was found during simulations in CoventorWare program. 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. 7 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. 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 [3].

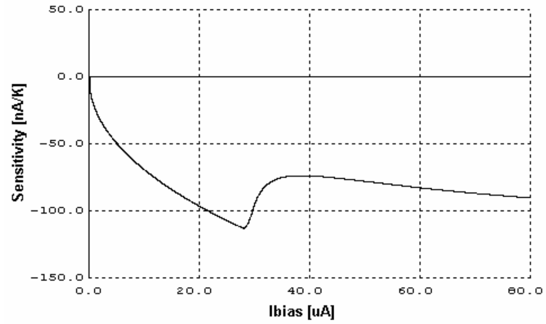


Fig. 7. Dependence of the temperature sensitivity of the output current from the temperature sensor on the biasing current at 60 $^{o}$C.

Transfer characteristic of the transducer have been measured for constant temperature =25 $^{o}$C. Input voltage signal $U_{IN}$ simulating the output signal of the CMOS temperature sensors was applied to the comparator noninverting input. The output signal of the comparator is a pulse signal and is measured by a counter. The transfer characteristic is presented in Fig. 8 and shows good linearity. Temperature dependence of the transducer output signals $U_{OUT1}$ and $U_{OUT2}$ was measured for the transducer temperatures in the range from 25$^{o}$ C to 125$^{o}$ C.

In the course of measurement constant voltage 2.7 V was applied to the noninverting input. Output pulses frequency corresponding to the input voltage was 490 Hz.

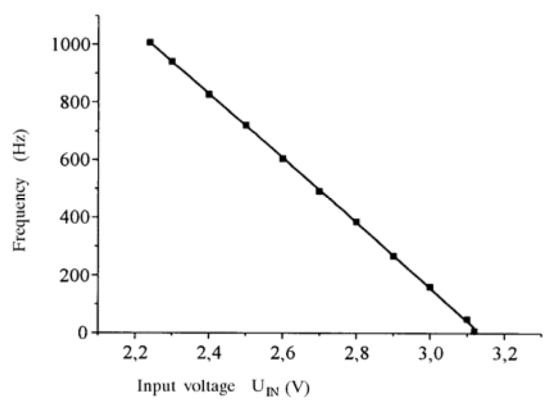


Figure 8: Transfer characteristic for temperature=25 $^{o}$C.

In the course of the transfer characteristic measurement for sensor operating in the strong inversion mode the output signal was amplified and via jumper J2 applied to the comparator noninverting input. Jumper J1 is on. The measurements were performed for two gains $A_{INV}$. The measured characteristics are in Fig. 9. 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.

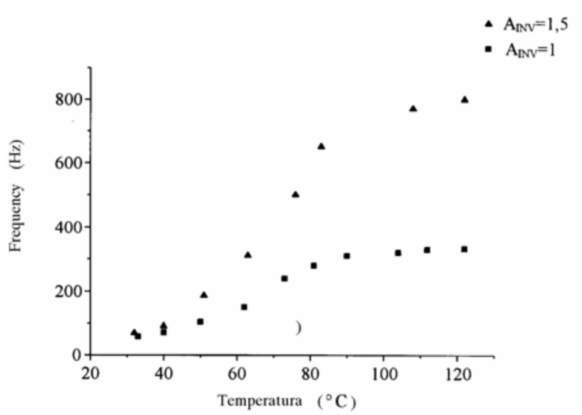


Figure 9: Transfer characteristic of the transducer with the CMOS temperature sensor connected in the strong inversion mode.

During the transfer characteristic measurement for the sensor operating in the weak inversion mode the jumper J1 is on and jumper J3 is off. Amplified temperature dependent voltage signal from the sensor is applied to the comparator input. The transfer characteristic is in Fig. 10.

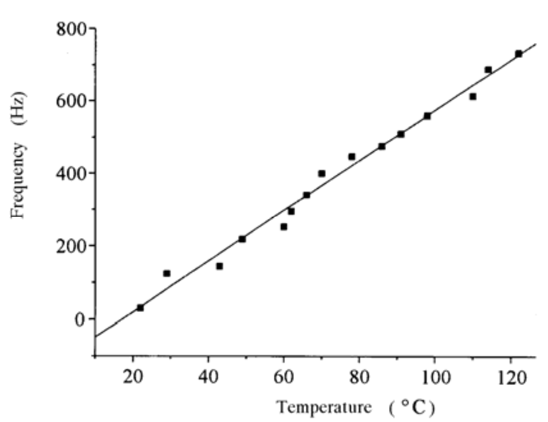


Figure 10: Transfer characteristic of the transducer with the CMOS temperature sensor connected in the weak inversion mode.

## 5 CONCLUSIONS

The new circuit design of sensor temperature matrix was used. The new results of sensitivity and resolution of sensor systems was reached. The working efforts were focused on the sensitivity, angle resolution and small power consumption of the gas direction flow systems.

Anemometric system with integrated temperature probe has been designed. Each sensor contains MOS transistors which work in the area of strong and week inversion. Axes of 2 sensor pairs are perpendicular. From the emerging temperature gradients of both sensor pairs, the airflow velocity and direction are computed.

The temperature dependence $I_D$=f(temp) of the CMOS gates of IC in the weak and strong inversion operation mode have been measured. The transfer characteristics f=g(temp) of the CMOS temperature sensors and PLL transducer have been measured too. onnection of PLL transducer for CMOS temperature sensor signal processing has been designed and realized. The transfer characteristic of the transducer measured for constant temperature is linear. Temperature dependence of the transducer output signals $U_{OUT1}$ and $U_{OUT2}$ in the temperature range from 25$^o$ C to 85$^o$ C is linear, the difference is about 0.5%.

The real circuit model of intelligent structure has been realized and tested. With the appropriate setup the system is able to measure with resolution of 1°. The accuracy and reproducibility of the flow velocity measurement has been evaluated to be 4 per cent and has been the same as accuracy and reproducibility of measurement of airflow direction. Reached results show that it is possible to use MOS temperature sensors for realization of an integrated probe for measurement of velocity and direction of gas flow. Measured results correspond with simulated results very well.

## 6 ACKNOWLEDGEMENTS


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