Silicon Based Temperature Sensors with Extended Temperature Range and Simple One-Point Calibration

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Abstract— **Temperature is the most important parameter to be measured in industry, automation, environment and many other fields. Almost any silicon diode can be used as a temperature transducer. Its main advantages are the high precision and the high long-term stability while the drawbacks are the limited operation temperature and the parameter spread due to fabrication uncertainties. We propose a dedicated fabrication technology for silicon-based temperature diodes, specifically designed and optimized to overcome these limitations. It is designed for higher temperature sensing applications where simple calibration, high accuracy and high long-term stability are most important. We demonstrate test results to evaluate the obtained process stability and discuss potential application fields in hybrid multi-sensor systems and more complex feedback-based sensor-actor systems.**

Keywords-silicon temperature sensor; one-point calibration; platforms; building blocks; pressure sensor; dew point sensor.

I. INTRODUCTION

The demand for high performance sensors in the field of process and environmental control, automation and security is obvious. Here, sensors for pressure, humidity, concentration [1], play the most important role. But high accuracy and long term stability of those sensors must been seen in context with the performing of temperature. Another trend goes conform to the accuracy: the spatial distance between the main sensor (e.g. pressure) and the temperature sensor or the distance between the temperature sensor and the measuring substance (air, liquid, solid matter) must be as small as possible. From another perspective, [2] classifies this fact regarding the invasive, semi-invasive and non-invasive principle. Miniaturization and integration are the strategy in the future. Therefore, in the last years the sensing of temperature has played an ever increasing role in different fields of smart sensor systems and system integration. With the silicon-diode based temperature sensor described in [3] a common denominator has been found for all these challenges. In following we describe three typical designs and technologies of silicon temperature sensors.

First of all the design and technology of single-chip temperature sensors including proposals for a higher temperature range will be described. Advantages regarding stability, working range, size, cost, ease of use, are compared to the well established thermocouple, resistive and thermistor based temperature sensors. To enter this market with single-chip silicon temperature sensors is more difficult but possible. Decisive advantages should be the compatibility of the electrical interfaces and signal processing [2] and the potential for an easy-to-integrate assembly process in chip-on-board or flip-chip technologies.

Secondly the silicon diode as temperature sensor is described forwarding full or hybrid integration close to the signal processing. The main advantages should be the technology compatibility from the process point of view and the assembly as close as possible to other devices. Sensors measuring environmental parameters such as humidity, pressure, force, gas and liquid concentration have typically strong temperature dependencies. This temperature cross sensitivity has in most cases the effect, that the higher the working temperature is, the lower the resulting accuracy for the primary quantity under investigation. Temperature measurements at the point of primary detection system (for the purpose of temperature compensation) are absolutely necessary.

The third case is of increasing importance for sensor-actor-systems where integrated temperature sensors decide about accuracy and expense for calibration. One predestined system is the dew point sensor system [4]-[6]. Such a sensor system consists of two different transducers (temperature and condensation) and a heating-cooling system. The temperature sensor has to measure the water temperature as the result of a closed-loop conducted by the cooling element.

For all these applications an integrated silicon temperature sensor can have the same dominator and enough potential for extended temperature applications. Trends in application fields like smart mobility, smart health, smart security, and smart manufacturing [7] go conform to the progressive trends of microelectronic, micro system technique [8] and key enabling technologies [9].

In Section II, the technology strategy is described under the point of view of possible kinds of silicon integration. Basis for this integration is the typical current-voltage characteristic of a silicon p-n junction (see Section III). Section IV covers different temperature sensors and applications. Section V concludes the paper.

II. TECHNOLOGY STRATEGY

Already in [4][10], the monolithic integration of temperature sensors in a CMOS- process had been described. Up to now, some of these concepts have been realized by products on the market.

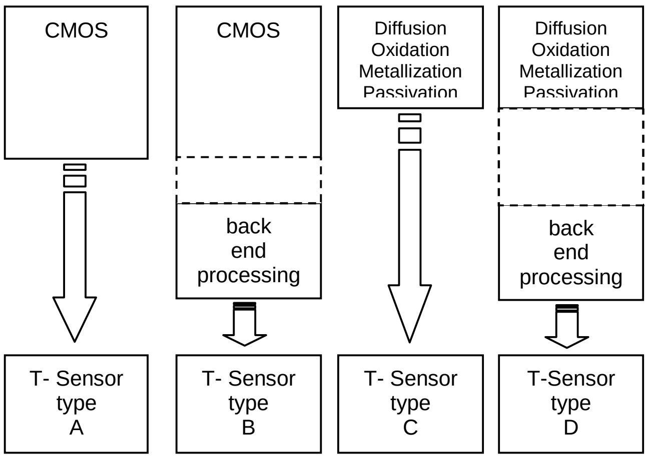

Figure 1. Selection of different sensor integration

Fig. 1 presents an overview of different integration concepts for temperature sensors into systems. Type A is part of a complete CMOS process realized e.g. in [11]-[13]. After the CMOS process, no further back end technology steps are necessary. The CMOS electronics can be used for signal processing of the temperature signal [14].

In case of type B temperature sensor the CMOS process is added by back end processing steps. Typically, Micro-electro-mechanical systems (MEMS) technology steps like membrane etching or realization of electrodes including deposition of functional layers are described by this technology chain. Both realizations have limitations due to the temperature range of CMOS electronics.

Type C is similar to A, except that the temperature sensor fabrication is based on selected CMOS steps only (diffusion, metallization and passivation). Substrates, diffusion parameters and metallization can be selected to obtain a higher operation temperature of the sensor [15]-[16]. In the same matter, Type D is the most commonly used technology in micro sensor systems. From the main sensor point of view, the temperature sensor stands for front end processing followed by the sensor specific MEMS steps.

III. SILICON P-N JUNCTION TEMPERATURE SENSORS

The electrical potential difference (at a given current) at p-n junctions shows pronounced temperature dependence. With increasing temperature the current-voltage characteristics shifts to lower voltages. This relationship is shown in Fig. 2. This correlation between current, voltage and temperature is the base for the use of p-n-junctions in temperature measurements.

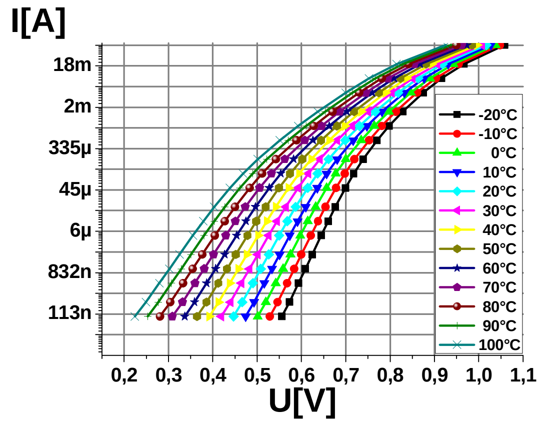

Figure 2. Current-voltage characteristic of a temperature diode at different temperatures

IV. DESIGN AND RESULTS

A. *Single p-n junction Temperature Sensor*

In Fig. 3 a typical layout is shown. In order to minimize the voltage deviation by using higher currents, a four-wire measurement is possible. Since n-substrate is used, the effective diode is formed by the p-type implantation in the middle of the structure.

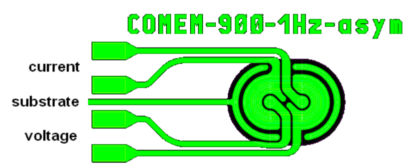

Figure 3. Typical sensor layout for four-wire measurement

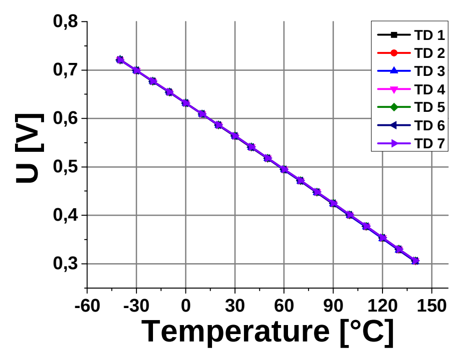

Figure 4. Voltage-temperature characteristics of seven different temperature diodes of one type

Fig. 4 shows the voltage versus temperature for seven diodes fabricated in the same process. A constant supply is used in this case. The slope of these characteristics is almost identical within a certain margin.

This allows a single-point calibration. By modifying the preparation using silicon-in-insulator (SOI) technology, the measuring range can be extended up to 250 °C. In this case, the manufacturing tolerance, i.e. the deviation of the characteristic curve of a sensor from the mean value, is minimal. The biggest differential illustrated in Fig. 5 at 140 ° C corresponds to a relative error of 0.5 %.

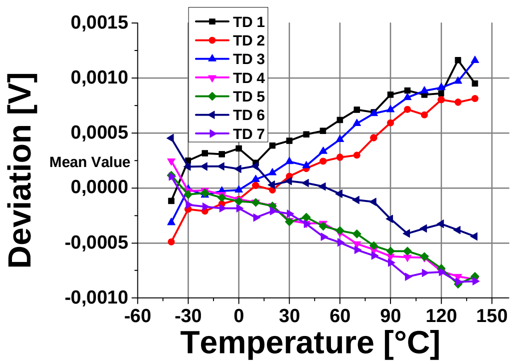

Figure 5. Deviations from the mean voltage in the temperature range from -40 °C to 140 °C

B. p-n junction temperature sensor for error compensation (using the example of a pressure sensor)

A silicon based piezoresistive pressure sensor is a good example for a monolithic integration of a MEMS component with a temperature sensor. Temperature variations influence parameters like linearity, sensitivity and accuracy. The on-chip temperature measurement is essential for a compensation of these cross sensitivities. An integrated silicon temperature sensor realized as p-n junction does not need further technology steps, but its integration has further advantages.

Firstly the sensor can be placed close to the piezoresistors and measures the temperature direct without artefacts, secondly the p-n junction does not need additional layers such as metal depositions which could cause mechanical effects and affect the performance of the piezoresistors. Fig. 6 shows a typical design where the Wheatstone bridge and the temperature sensors (left hand corner) are integrated on one chip. The integration of several diodes at different places does not cause additional cost but does e.g. not provide further improvements of this concept.

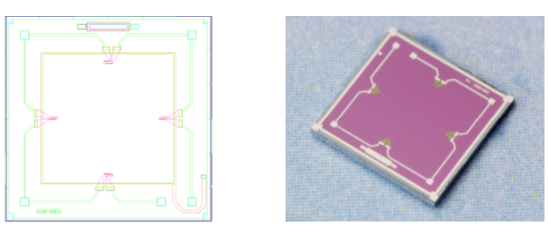

Figure 6. Design of a piezoresistive pressure sensor with integrated p-n junction as temperature sensor [17]

C. p-n junction temperature sensor as part of a sensor-actor-system (using the example of a dew point sensor)

Temperature sensors are of central importance in the realization of a thermal detecting dew point sensor [5][18]. On the one hand temperature sensors are used to determine the state of condensation on a sensitive sensor membrane, on the other hand to detect the temperature of the sensing spot.

Water has a high heat capacity and a high enthalpy of vaporization. Thus, it makes up a high energy conversion in the evaporation even of smallest water droplets. The heat capacity of a micro mechanic membrane with heating and temperature sensing elements, however, is extremely small. Comparing the heat capacity of a dewy and not dewy spot on the membrane can determine condensation qualitatively. For this task it is ideal to use Seebeck elements. These allow the determination of a temperature profile in response to a transient heating pulse.

In a balance of condensation and evaporation, located on a water-surface, the surface temperature is corresponding to the dew point temperature. To determine the temperature of the condensing surface of the thermal dew point sensor, two measurements are required. By means of a diode, implanted in the silicon bulk, is the bulk-temperature determined. The temperature dependence of the diode forward voltage (approximately 2.3 mV/K) is calibrated at several points in order to achieve a high accuracy. Furthermore, the temperature difference between the silicon bulk and the sensitive condensation spot on the membrane is determined by using Seebeck elements. The two determined temperature values are added and result in the absolute temperature of the sensitive condensation spot. In Fig. 7 the design of the dew point sensor is presented and both temperature sensors are marked.

Further technology modules e.g. thinfilm peltier modules [19] increase the value chain and the potential of further miniaturization.

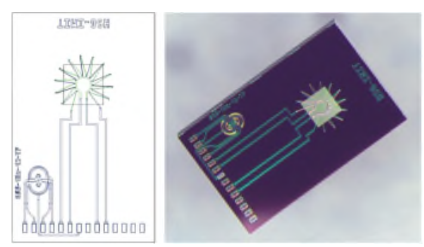

Figure 7. Design (left) and photograph (right) of the silicon sensor chip including sensor for absolute (left hand corner) and condensed water (in the middle) temperature measurement [20]

V. CONCLUSION

Silicon based temperature sensors are of increasing importance for the actual and next generation of smart sensor systems. Single temperature devices as well as integrated device for process automation and environmental conditions are not possible without temperature sensing. Current development in this field addresses the extension of the working range to higher temperatures. Next generation of

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process sensors are focused more and more on in-situ and on in-line applications and are exposed harsh environments and higher temperatures. To keep pace with the advantages of cost effective microelectronic technology the implementation of silicon temperature sensor as front end or backend process is still the most promising way.

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