Digital temperature sensors in the range of 77-300 K

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We investigated the digital sensors of temperature (integrated circuits) manufactured by Analog Devices (AD7416) and National Semiconductor (LM74). We have investigated both lower limits of the operate temperature of digital sensors and measurement accuracy. AD7416 sensors operate as low temperature as −128 °C (145 K). Their measurement error was below ±2 °C. Lower limit for LM74 sensors was different for two investigated sensors: −140 °C and −70 °C. The accuracy is of 5 °C at temperature below −100°C. We have not found any sensor able for a work at the temperature as low as 77 K.

SEMICONDUCTOR TEMPERATURE SENSORS

The operation of integrated temperature sensors is based on the dependence of voltage V_{BE} in the p-n junction on temperature, for a constant value of junction current. For the p-n junction of the diode or the transistor biased for conductance, the current of the junction is a function of voltage bias V_{BE} and temperature T (formula 1).

$$V_{BE} = \frac{k_B T}{e} \ln \frac{I_E}{I_0(T)} + V_G \;, \qquad (1)$$

where: I_E – the current flowing through the junction, e.g. the emitter current,
$I_0(T)$ – the inverse current, k_B – Boltzmann constant,
T – the temperature in the absolute scale,
V_{BE} – the voltage on the p-n junction, e.g. the base-emitter voltage,
V_G – the material constant, a potential difference resulting from the energy gap width of the solid (for Si: V_G = 1.205 V at T = 300 K).

The voltage U_{BE} on the p-n junction of the silicon transistor increases together with its temperature drop from 0.6 V at a temperature of 350 K to 1.3 V at a temperature of 50 K. The sensitivity of the device is therefore equal to −2.3 mV/K. Below the temperature of 50 K the voltage-temperature characteristic of the junction becomes strongly non-linear and in this temperature range the p-n junction is not useful for thermometry.

The semiconductor temperature sensor contains two p-n junctions, usually base-emitter junctions of two transistors, made of one block of semiconductor. Voltage difference V_{BE} for two integrated transistors conducting the emitter current $I_{\mathrm{E1}} \neq I_{\mathrm{E2}}$, is expressed by formula (2):

$$\Delta V_{BE} = V_{BE1} - V_{BE2} = \frac{k_B T}{e} \ln \frac{I_{E1}}{I_0(T)} - \frac{k_B T}{e} \ln \frac{I_{E2}}{I_0(T)} = \left(\frac{k_B}{e} \ln \frac{I_{E1}}{I_{E2}} \right) T. \qquad (2)$$

Integrated thermosensor contains in one structure a couple of transistor-sensor as well as circuits of amplifiers converting the signal ΔV_{BE} to the required level of the voltage V_{out} = f(T) or the output current I_{out} = f(T). Due to a very considerable roll-off in the amplification of internal amplifiers within a temperature range below 200 K, the measuring range of integrated sensors has the lower temperature limit of −50°C (≈ 220 K).

DIGITAL TEMPERATURE SENSORS

Apart from integrated temperature sensors with output analog signal (V_{out} or I_{out}), sensors with output digital signal are also manufactured. An integrated circuit of such sensor is formed of the following elements: a couple of junctions (transistors or diodes), the voltage of which (ΔV_{BE}) is the measuring signal, the signal conditioner (amplifier), the analog-to-digital converter, memory, and the digital interface – Fig. 1.

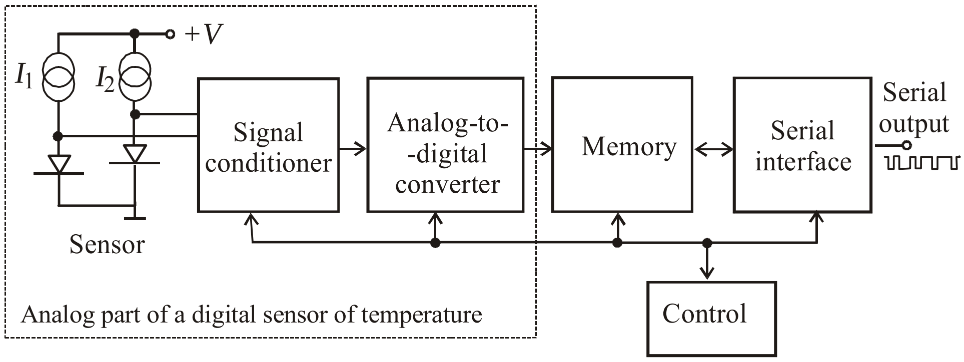

Figure 1. Block diagram of a digital sensor of temperature

The analog part of the sensor is sensitive to temperature change. The digital part should be insensitive to the influence of temperature in a wide range, especially when digital circuits are manufactured in the CMOS technology. Usually integrated digital sensors are allowed to be connected to various types of digital interface systems. Integrated digital sensors are offered by such manufactures as Analog Devices, National Semiconductor or Maxim. A review of digital temperature sensors is tabulated in Table 1.

Table 1. Digital integrated sensors of temperature (AD – Analog Devices, LM – National Semiconductor, MAX – Maxim, DS – Dallas Semiconductor)

Type	Measuring range	Accuracy (narrow range)	Accuracy (wide range)	Resolution	Output signal	Interface type
AD7416	–40°C to +125°C	±2°C	±3°C	0.25°C	10-bit	I^2C
AD7818	–40°C to +125°C	±2°C	±3°C	0.25°C	10-bit	I^2C
LM74	–55°C to +150°C	±1.25°C	±5°C	0.0625°C	12-bit + sign	SPI
LM92	–55°C to +150°C	±0.5°C	±1.5°C	0.0625°C	12-bit + sign	SPI
MAX6635	–55°C to +150°C	±1°C	±2.5°C	0.0625°C	12-bit + sign	2-Wire, SMB
MAX6662	–55°C to +150°C	±1°C	±2.5°C	0.0625°C	12-bit + sign	3-Wire, SPI
DS1624	–55°C to +125°C	±0.5°C	+3°C/–2°C	0.0625°C	12-bit + sign	2-Wire, SMB
DS18B20	–55°C to +125°C	±0.5°C	±2°C	0.0625°C	8 to 12-bit	1-Wire, SPI

Semiconductor temperature sensors – both analog and digital – are characterised with big conversion error, usually not less than ±1°C (without calibration), and with relatively narrow measuring range, at best included between −55 °C and +150 °C. For this regard, the area of their applications comprises watchdogs and monitoring systems as well as temperature indicators; they are quite rarely applied to industrial control systems. Though the manufacturers determine the lower limit of the measuring range as –40 °C or –55 °C, for most types of digital sensors the measuring range may be much wider in lower values. Our testing of digital sensors was done for AD7416 integrated sensors (Analog Devices) and LM74 digital sensors (National Semiconductor).

The AD7416 digital sensor has its measuring range from −40°C to +125°C, the measuring resolution 0.25°C and the output signal in the form of a 10-bit word. Analog-digital converter of SAR type (successive approximation register) was applied in the circuit. In a temperature range of −25°C to +100°C the measuring error is equal to ±2°C and in the range of −40°C to +125°C the error is equal to ±3°C (catalogue data). The digital 10-bit output word enables to record 2^{10} combinations. For the AD7416 sensor, for the measuring resolution of 0.25°C it gives the measuring range from −128°C (to this temperature corresponds the output word Y_{min} = 10 0000 0000) to +127°C (the output word Y_{max} = 01 1111 1100). The sensor may be connected to a microprocessor system with a 2-wire line of the I^2C serial interface.

The digital thermosensor LM74 has its measuring range from−55°C to +150°C, the measuring resolution 0.0625°C and the output signal in the form of a 12-bit word plus bit of a sign (+ or −), 13 bits altogether. Analog-digital converter of Δ-Σ type was applied in the circuit. The maximum measuring error for the LM74 sensor depends on the measuring range:

- range: −10°C to +65°C, error ±1,25°C
- range: −25°C to +110°C, error ±2.1°C
- range: −40°C to +110°C, error +2.65°C/−2.0°C
- range: −55°C to +125°C, error ±3°C.

The format of the digital output word allows to send the information on temperature of even −255°C, if the sensor could work in such low temperature.

MEASUREMENTS OF DIGITAL TEMPERATURE SENSORS

We conducted research of selected types of digital temperature sensors in the range of +10°C to −196°C (77 K). The lower limit of temperature range, in which the sensor was still operating, was verified. The measurement error of the ΔT digital sensor was also measured in the function of temperature of the T_{Dig} digital sensor. For reference temperature measurement the Pt100 thermometer was used.

$$\Delta T = T_{Dig} - T_{Pt100} \tag{3}$$

The measurements were carried out on a group of 4 sensors of AD7416 type (Analog Devices) and 2 sensors of LM74 type (National Semicon.). The Pt100 sensor and each digital temperature sensor tested (AD7416 or LM74) were mechanically connected to ensure good thermal contact between them.

All the AD7416 sensors tested preserved their working ability in a temperature reduced to −128°C. Further temperature reduction did not change the defined output word Y_{min} = 10 0000 0000, but the heating of the sensor to a temperature higher than −128°C restored its proper working. The sensors tested were exposed to repeated cooling-heating cycles (up to 10 cycles), which did not change the proper working of the sensors.

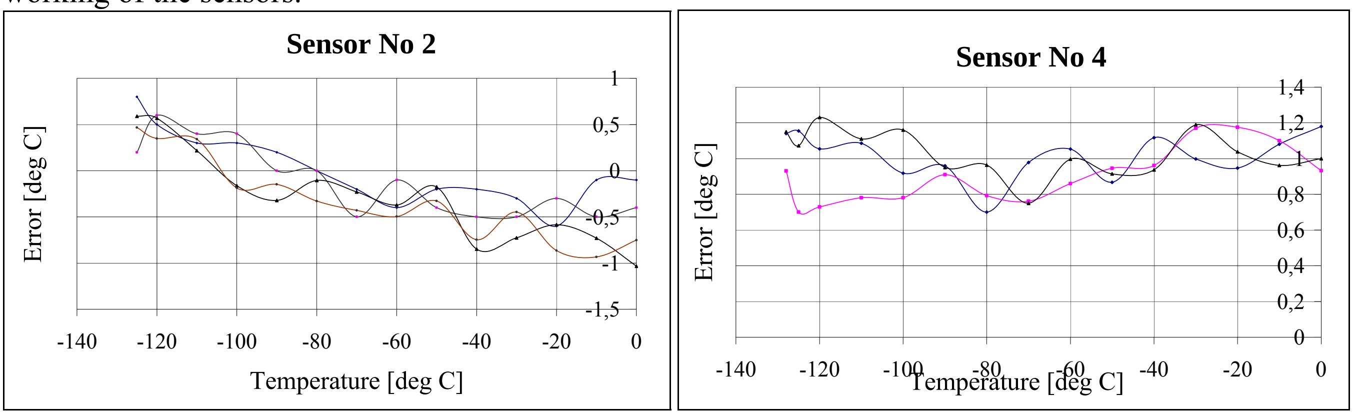

Figure 2. The error ΔT for temperature measurement with AD7416 digital sensors: No 2 (4 cycles) and No 4 (3 cycles)

Figure 2 shows an exemplary diagram of the difference between the temperature measurement using AD7416 sensors (No 2 and No 4) and the Pt100 thermometer in the temperature function T_{Dig} for 4 measuring cycles. The testing revealed a surprisingly good coincidence of temperature measuring with a digital sensor and the Pt100 thermometer. The error ΔT in measurement realised by means of a digital sensor was less than ±1.5°C in the whole range from −125°C to +10°C. The measurement error was not greater than ±2°C for the remaining AD7416 sensors tested. In the measuring range given by the manufacturer up to −40°C the measurement error was less than the limit value ±3°C for all 4 sensors tested.

For the LM74 sensors their working ability in low temperatures was confirmed as well. According to the manufacturer, the lower limit of the measuring range was different. For the first investigated sensor LM74 the limit was −140 °C instead of −55 °C. The lower limit was only −70 °C for the second sensor LM74. In the temperature range given by the manufacturer (up to −55°C) the measurement error amounted to +2°C and was less than the limit error ±3°C. A diagram of the measurement error in temperature function for two LM74 sensors tested was shown in Fig. 3. In the range of low temperatures the measurement error amounted to +5°C. The sensor placed in a temperature below −140°C generated a constant output word corresponding to temperature −140°C. It means that the digital part of the sensor does not work in this temperature range.

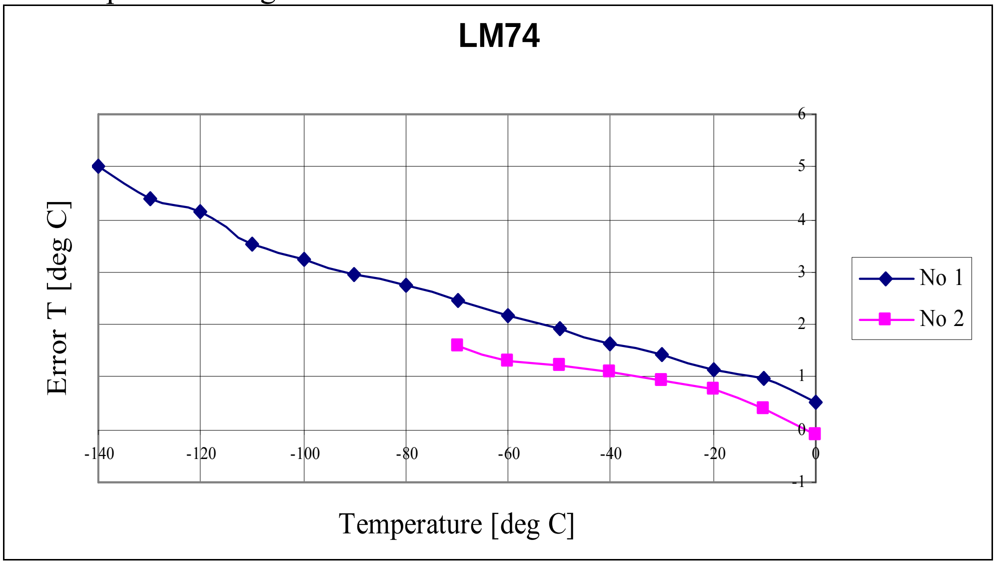

Figure 3. The measuring error ΔT for temperature measurement with the LM74 digital sensors No 1 and No 2 (sensor No 2 does not operate below −70 °C)

CONCLUSIONS

The testing of sensors realised on a sample of AD7416 and LM74 integrated circuits showed that digital temperature sensors preserve their working ability in temperature much lower than that defined by the manufacturers. For the group of AD7416 sensors the lower limit of working temperature was equal to −128°C. For one LM74 sensor the limit was still lower: −140°C. The reduction of lower limit of the measuring range is impossible for the AD7416 sensors. The reduction of this lower limit for the LM74 sensors would be useful because of changes in parameters of the analog part of the sensor in temperature function. For some devices of the sensors tested the measuring error did not exceed ±1.5 °C, for others it amounted to +5 °C. Single devices of digital temperature sensors may be therefore used to construct cryogenic thermometers of less accuracy. It is useful especially in such measurements in which a signal from analog sensor is notably distorted, for example by a strong electromagnetic field.

REFERENCES

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2. Analog Devices, National Semiconductor, Maxim, Dallas Semiconductor – Catalogues 2004