ELECTRONICS AND ELECTRICAL ENGINEERING
ISSN 1392 – 1215 2011. No. 6(112)
ELEKTRONIKA IR ELEKTROTECHNIKA

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ELEKTRONIKA

The Approximation Aspects of Characteristics of Semiconductor Temperature Sensors

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http://dx.doi.org/10.5755/j01.eee.112.6.443

Introduction

There are several classes of semiconductor temperature sensors: voltage output sensors; current output sensors; analog output sensors; digital output sensors and resistance output sensors – thermistors.

The contemporary analog and digital semiconductor temperature sensors are made on the base of technology of integrated circuits, where a transistor the collector of which is connected to the base is used as the p-n junction (diode).

The principle of the analog and digital output temperature sensor is that the forward base-emitter voltage U_{BE} of a transistor is temperature and current dependent according to the following equation [1]

$$U_{BE} = U_{BO}\left(1-\frac{T}{T_0)}\right) + U_{BIO}\left(\frac{T}{T_0}\right) + \left(\frac{nkT}{q}\right)\ln\left(\frac{T}{T_0}\right) + \left(\frac{kT}{q}\right)\ln\left(\frac{I_E}{I_{E0}}\right), \quad (1)$$

where U_{B0} – band gap voltage at the absolute zero, U_{BI0} – band gap voltage at the temperature T_0 and currents I_{C0} , I_E and I_{E0} – emitter current values, n – the coefficient the value of which is determined by the sensor material and manufacture technology.

The analog output sensors have an integrated subsystem which linearizes the dependence between the temperature and the output signal; in the same manner the analog-to-digital converter used to convert the temperature signal is integrated into the digital output sensors [2].

Output voltage of the analog sensors is influenced by the temperature of p-n junction, modulation of electrical resistance of the p-n junction, dispersion of coefficient n, self-heating of the sensor, nonlinearity of mathematical relationship and dispersion of the offset voltage.

Calculations and experiments show [3, 4], that the relationship between temperature and p-n junction output voltage is nonlinear.

The equation used for linearization of the sensors readings by

$$T = a_2 \cdot K^2 + a_1 \cdot K + a_0, \quad (2)$$

where T – temperature in grad C, a_i – constants calculated out of the calibration data, K – raw readings of the sensors in grad C.

The operation of the semiconductor temperature sensors on the thermistor basis is based on the non-linear dependence of the thermistor volume resistance on the temperature $R(T)$.

When using thermistors in the temperature monitoring and measurement devices in most cases the thermistor resistance at the respective temperature is measured and by using the approximation equation of the $T(R)$ dependency the temperature value is calculated.

The thermistor resistance dependence on the temperature can be defined as

$$R_T = \alpha e^{\frac{\beta}{T}}, \quad (3)$$

where R_T – the thermistor resistance at the temperature T, α – the thermal coefficient of the thermistor material, β – the parameter of the thermistor material.

The values of coefficients α and β are related to the temperatures at which they were determined; therefore the usage of the equation (3) in practical calculations is complicated. In addition the manufacturers provide only the average values of the coefficient β over some certain temperature range in their catalogs.

Various forms of Steinhart-Hart equations are used to approximate the thermistor $R(T)$ or $T(R)$ characteristics [5, 6].

In order to perform more precise approximation of T(R) characteristics the four-parameter Steinhart-Hart equation is selected most often

$$\frac{1}{T} = A_0 + A_1 \cdot \ln R + A_3 \cdot (\ln R)^3 + A_5 \cdot (\ln R)^5, \quad (4)$$

where A_0, A_1, A_3, A_5 – constants, R – the thermistor resistance, T – the temperature in kelvins.

The task of linearization of the characteristics of semiconductor temperature sensors is one of the more difficult to solve problems.

There are no known methods of linearization of the characteristics of the semiconductor temperature sensors which would be suitable for all kinds of sensors of the respective type [4, 6–9].

An increase in the linearity of approximation *T(R)* characteristics of the sensors of temperature can improve the parameters of the multi-sensory systems of monitoring temperature and increase the effectiveness of dynamic systems [10, 11].

Methods and samples

For all sensors the characteristics temperature – output signal were measured using the mixed hot oil thermostat, the reference FLUKE type 5610 thermistor (serial No. A6B0211, absolute accuracy for temperatures for 0… 100 ^{0}C range not worse than 0,015 ^{0}C), and the thermometer FLUKE type Black Stack 1560 and type 2564 Thermistor readout module. The bath with the reference and the tested sensors was cooled slowly (over more than 24 hours period) from +95 ^{0}C to +25 ^{0}C, thus the characteristics were obtained for several class silicon bandgap temperature sensors of different types: LM35, LM35A, DS620 (declared accuracies of all these sensors were ±0.5^0 C, at 0 – 70^0 C) and five NTC thermistors of type 103JL1A (declared accuracy ±0.5^0 C, 0 – 100^0 C) were measured.

The block diagram of the system for investigation of the thermistor characteristics temperature – output signal is shown in Fig. 1.

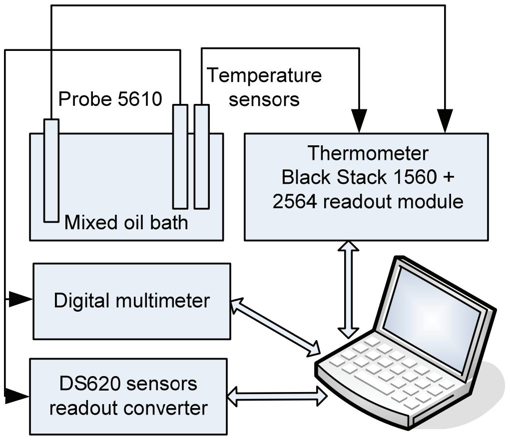

Fig. 1. The block diagram of the system for investigation of the sensor characteristics temperature – output signal

Results of experiments and calculations

The dependencies temperature – output signal obtained experimentally for the analogous (type LM35, LM35A) and digital (DS620) temperature sensors were linearized using the first and the second order polynomials. Errors were calculated as the differences between the reference temperature values and the values determined from the linearized characteristic at the respective points of temperature. Residual plots of the linearization errors for the analogous sensors are shown in Fig. 2 and Fig. 3.

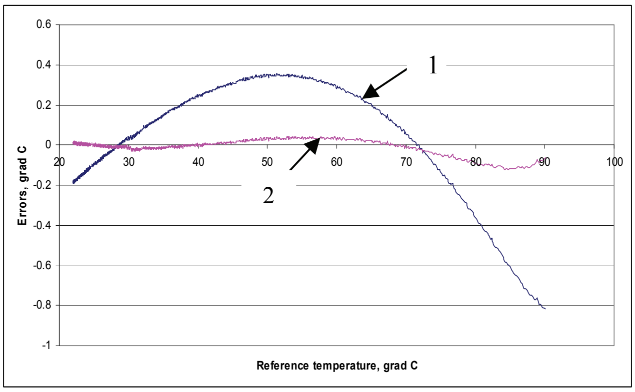

Fig. 2. LM35 sensor 1st (1 – curve) and 2nd (2 – curve) order polynomial linearization

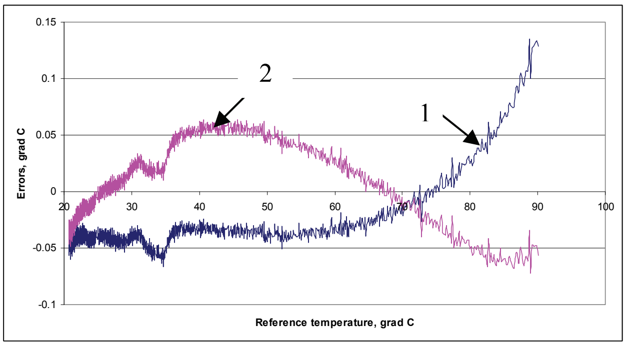

Fig. 3. LM35A sensor 1st (1– curve) and 2nd (2– curve) order polynomial linearization

Thus by using the second order polynomial to linearize the characteristic of the sensor type LM35 it is possible to achieve the decrease of measurement errors: STDEV were respectively 0.210 and 0.0253. In case of sensors type LM35A the linearization using the second order polynomial does not provide the significant reduction of errors: STDEV were respectively 0.0448 and 0.0358.

The distributions of measurement errors for eight digital sensors type DS620 are shown in Fig.4.

After the linearization of characteristics using the first and the second order polynomials was applied the obtained distributions of the measurement errors are illustrated in Fig. 5 and Fig. 6 respectively.

It is obvious that after the characteristic was additionally linearized using the first order polynomial over the temperature range expanded up to 100^0 C the errors (Fig. 5) do not exceed ±0.25^0 C.

After the additional linearization using the second order polynomial the errors are reduced further (down to ±0.15^0 C, Fig.6).

The coefficients of equation (2) calculated from the research data for the eight sensors are given in Table 1.

For the thermistor-based sensors the characteristics were linearized using equation (4), the constants of which A_0,

A_1, A_3, A_4 were estimated using the measurement data of the *R(T)* dependence of the thermistor No. 1 (Fig. 7).

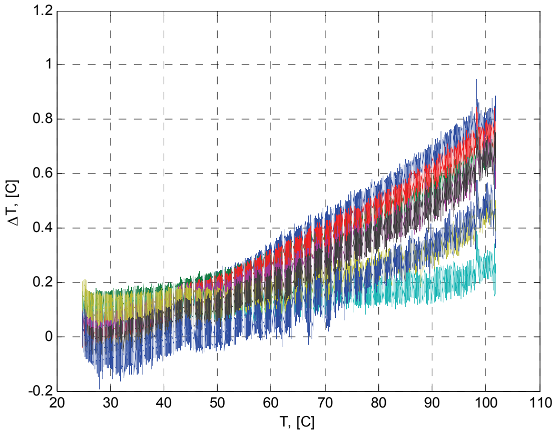

Fig. 4. The measurement errors of the DS620 sensors

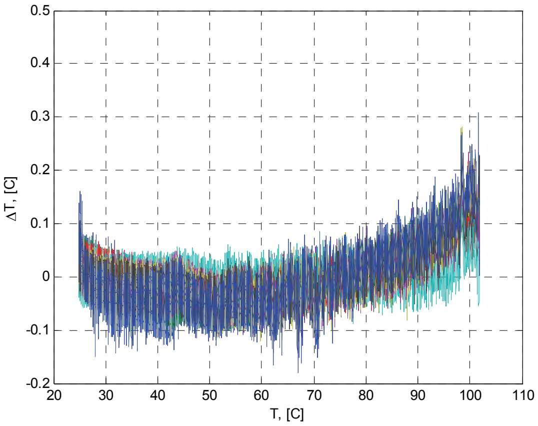

Fig. 5. The measurement errors of the DS620 sensors after 1st order polynomial linearization

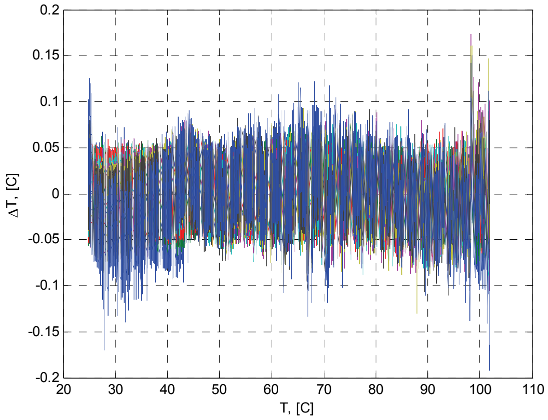

Fig. 6. The measurement errors of the DS620 sensors after 2nd order polynomial linearization

Table 1. Sensors type DS620 linearization equation constants

Sensor No.	a_2	a_1	a_0
0	-9.5723e-5	1.0016	-2.3672e-2
1	-8.3619e-5	1.0030e	-1.3378e-1
2	-6.0222e-5	9.9798	7.5596e-2
3	-2.2173e-5	1.0009	-1.0480e-1
4	-7.4462e-5	1.0018	-5.1492e-2
5	-8.5011e-5	1.0067	-2.4923e-1
6	-8.4045e-5	1.0021	2.3430e-4
7	-1.1468e-4	1.0076	-1.0047e-1

The error distributions after the linearization are shown in Fig. 7. The errors do not exceed ±0.17 ^{0}C in the range from 20 ^{0}C to 100 ^{0}C.

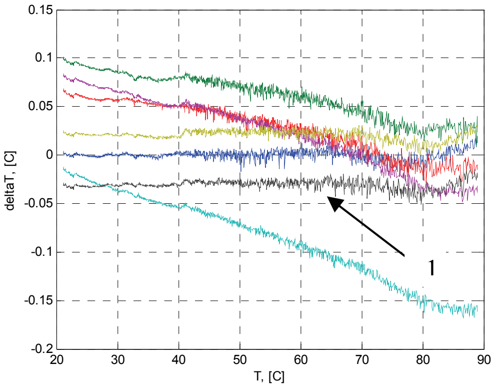

Fig. 7. The residual plots of errors of the temperature measurement using thermistors after the linearization of the characteristics

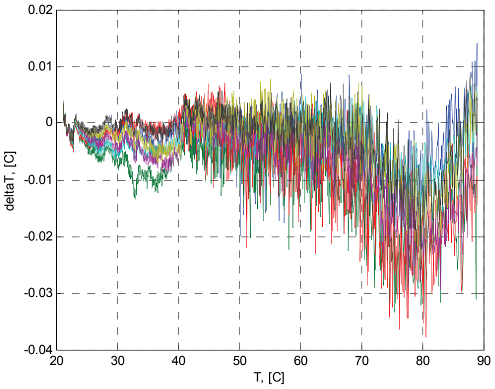

Fig. 8. The residual plots of errors of the temperature measurement using thermistors after the linearization of characteristics and after the additional correction

Bias and gain correction was applied to the measurement data using the measurement data at the two reference temperature points. The data after the correction is given in Fig. 8. After the addition correction the errors did not exceed ±0.04^0 C.

It follows that when using the R(T) dependence measurement data of one thermistor and Steinhart-Hart equation and by using the two point data for the additional correction it is possible to reduce the error of the temperature measurement using type 103JL1A thermistors and also it is possible to implement this procedure for the same batch (series) of sensors.

The approximation of the semiconductor sensor temperature characteristics using experimental data is advisable also when using sensors of the other types [4].

Conclusions

1. In order to linearize the characteristics of the analogous semiconductor temperature sensors type

LM it is advisable to use the second order polynomials the constants of which are calculated from the measurement data.
2. In order to expand the measurement temperature range using digital sensors type DS620 it is advisable to linearize the dependencies temperature – output signal using the second order polynomial.
3. In order to reduce the measurement errors using thermistor-based temperature sensors it is purposeful to use the Steinhart-Hart equation (provided by the manufacturer) with four constants and additional correction performed by using the data of the two measurement points.

References

1. **Bakker A., Beijing J.** High–accuracy CMOS smart temperature sensors. – Kluwer Academic Publishers, Boston, 2000.
2. **Bakker A., Huijsing J. H.** A CMOS Smart Temperature Sensor With a 3σ Inaccuracy of $\pm 0.5^0$C from 50^0C to 120^0C // IEEE Journal of solid–state circuits, 2005. – Vol. 40. – No. 2. – P. 454–461.
3. **Dumčius A., Augutis V., Gailius D.** Control of the temperature in the fluid flow by semiconductor sensors // Electronics and Electrical Engineering. – Kaunas: Technologija. 2008. – No. 7(87). – P. 27–30.
4. **Dumčius A. Žizniakovas T.** Approximation T–U characteristics of analog semiconductors temperature sensors // Electronics and Electrical Engineering. – Kaunas: Technologija. 2009. – No. 1(89). – P. 105–108.
5. **Steinhart I. S., Hart S.R.** Calibration curves for thermistors // Deep Sea Research, 1968. – Vol. 15(3). – P. 497–503.
6. **Hoge H. J.** Useful procedure in least squares, and test of some equations for thermistors // Review of Scientific Instruments, 1988. – Vol. 59. – P. 975–979.
7. **Alexander M. D., MacQuare** K. T. B. Toward standard thermistor calibration method and data correction spreadsheets // Ground Water, Monitoring, Remediation, 2005. – Vol. 25. – P. 75–81.
8. **Ilić D., Butorac J., Fercović L.** Temperature measurements by means of NTC resistors and a two–parameter approximation curve // Measurement, 2008. – Vol. 41(3). – P. 294–299.
9. **Chiachung Chen**. Evaluation of resistance–temperature calibration equations for NTC thermistors // Measurement, 2009. – Vol. 42(7). – P. 1103–1111.
10. **Dimitrov D. Tz.** Wireless Module for Distance Measurement of Patient's Temperature in Hospitals // Electronics and Electrical Engineering. – Kaunas: Technologija, 2008. – No. 2(82). – P. 53–56.
11. **Balaišis P., Eidukas D., Gužauskas R., Valinevičius, A.** Modeling of Efficiency of Dynamic Electronic Systems // Electronics and Electrical Engineering. – Kaunas: Technologija, 2008. – No. 6(86). – P. 55–59.

Received 2011 01 15

A. Dumcius, V. Augutis, D. Gailius. The Approximation Aspects of Characteristics of Semiconductor Temperature Sensors // Electronics and Electrical Engineering. – Kaunas: Technologija, 2011. – No. 6(112). – P. 47–50.

The aim of the work is to analyze the possibilities to reduce the temperature measurement errors which emerge when using semiconductor analogous and digital sensors and thermistor-based sensors. The dependence of the output signal of the semiconductor temperature sensors in respect of the temperature is non-linear. By using the additional calibration at the several reference temperature points the sensor output signal dependencies on the temperature can be linearized better. In this way it is possible to reduce the temperature measurement errors several times and/or expand the range of the measured temperatures without the use of the expensive and precise temperature sensors. It was shown that for the sensors type DS620 the errors after the additional linearization and correction in the range (20-90) ^{0}C did not exceed ± 0.035 ^{0}C. The experimental and calculation results are provided. Ill. 8, bibl. 11, tabl. 1 (in English; abstracts in English and Lithuanian).

A. Dumčius, V. Augutis, D. Gailius. Puslaidininkinių temperatūros sensorių charakteristikų aproksimavimo aspektai // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2011. – Nr. 6(112). – P. 47–50.

Darbo tikslas – naudojant puslaidininkinius analoginius, skaitmeninius sensorius bei sensorius termistorius, išanalizuoti galimybes sumažinti temperatūros matavimo temperatūros sensoriais paklaidas. Puslaidininkinių temperatūros sensorių išėjimo signalo priklausomybė nuo temperatūros yra netiesinė. Papildomas kalibravimas keliuose atraminės temperatūros taškuose padeda geriau linearizuoti sensorių išėjimo signalo priklausomybes nuo temperatūros. Taip galima keletą kartų sumažinti temperatūros matavimo paklaidas ir/ar praplėsti matuojamų temperatūrų ruožą, nenaudojant brangių tikslių temperatūros sensorių. Parodyta, kad po papildomo linearizavimo ir korekcijos sensorių DS620 paklaidos (20–90) °C neviršijo ±0,035 °C. Pateikti eksperimentų ir skaičiavimų rezultatai. Il. 8, bibl. 11, lent. 1 (anglų kalba; santraukos anglų ir lietuvių k.).