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Control of the Temperature in the Fluid Flow by Semiconductor Sensors

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Introduction

The semiconductor temperature sensor can be manufactured as one integral on-chip crystal, together with signal conditioning circuitry [1–4]. Analog [1], [2] or digital [3], [4] signal is received at the output. Accuracy of analog temperature sensors reaches ±0.5^0 C, and nonlinearity reaches ±0.2^0 C [1], [2]. Accuracy of digital temperature sensors reaches ±0.5^0 C [3], and resolution reaches 0.016^0 C [4]. Semiconductor sensors typically have lesser accuracy than platinum sensors, but are considerably cheaper to manufacture.

Relationship between temperature and sensor output voltage

Operation of semiconductor temperature sensors is based on relationship between temperature and voltage between p-n junction areas, when forward current is flowing through it. This relationship considering only diffusion of charge carriers is characterized by (1) equation [5].

$$I = I_s\left(\exp\frac{U_f}{\frac{kT}{q}} - 1\right), \qquad (1)$$

here I_s – the saturation current; U_f – the forward voltage; k – the Boltzmann's constant; T – temperature, ^{0}K; q – the electron charge.

Therefore any diode can be used as a temperature sensor. However the saturation current *Is* is related with physical and technological parameters of the diode and its material. Modern technologies can not ensure the repeatability of parameters in manufacture, which would be suitable for accurate sensors, furthermore, only the diffusive current flowing through the junction is evaluated in the equation (1).

Transistor in which collector is connected to the base is used in semiconductor temperature sensors due to its technological peculiarities. The relationship between forward current I and base-emitter voltage U_{be}, as a function of absolute temperature T, for such transistor is supplemented with non-ideality constant ŋ and equation can be rewritten as (2) [2; 6].

$$I = I_s\left(\exp\frac{U_f}{\frac{\eta kT}{q}} - 1\right), \qquad (2)$$

here η – non-ideality constant.

For the forward current values in equation (2) 1 can be omitted; then equation (2) can be written as

$$I = I_s\left(\exp\frac{U_f}{\frac{\eta kT}{q}}\right). \qquad (3)$$

Influence of the saturation current can be avoided partially by measuring diode voltage under two values of the forward current I_1 and I_2.

Then

$$I_{f1} = I_s\left(\exp\frac{U_{f1}}{\frac{\eta kT}{q}}\right); \qquad (4)$$

$$U_{f1} = \frac{\eta kT}{q}\ln\left(\frac{I_1}{I_s}\right); \qquad (5)$$

$$I_{f2} = I_s \left(\exp \frac{U_{f2}}{\frac{\eta kT}{q}} \right); \qquad (6)$$

$$U_{f2} = \frac{\eta kT}{q} \ln\left(\frac{I_2}{I_s}\right). \qquad (7)$$

Assume that $I_2 > I_1$, then difference of voltage drops on the diode is

$$\Delta U = U_{f2} - U_{f1} = \frac{\eta kT}{q} \ln\left(\frac{I_2}{I_1}\right). \qquad (8)$$

In the equation (8) the saturation current I_s is eliminated. Although this equation is valid only when electrical resistance of the structure base-emitter is not modulated when current flowing through the diode is increased from I_1 to I_2, and additionally the voltage drop on the resistance of the base-emitter structure is not evaluated in this equation.

After reconstructing equation (8), temperature is calculated as

$$T = \frac{q}{\eta k \ln\left(\frac{I_2}{I_1}\right)} \cdot \Delta U. \qquad (9)$$

For technological purposes bipolar transistors with its collector connected to the base are used in temperature sensors instead of diodes.

By applying equation (7) the relationship between temperature and sensor output voltage should be linear.

The value of non-ideality constant n is usually from 0.95 to 2 [8]. In [9] it is mentioned, that n = 0.008 for temperature sensors, and n = 0.0021 for sensors manufactured directly in CPU.

Nevertheless, the typical nonlinearity of real sensors can be in the range ± (0.15 – 1) ^{0}C [1].

Thus not fully defined factors remain in the relationship between measured voltage values and temperature: these are non-ideality constant n, electrical resistance of the structure base-emitter, which is related with magnitude of the current, temperature and self-heating of the sensor.

On the grounds of equation (9) we can write

$T = a + b\Delta U,$

here a – diode bandgap voltage, when temperature of p-n junction is equal 0 ^{0}C, is calculated by approximating the measurement results

$$b = \frac{q}{\eta k \ln\left(\frac{I_2}{I_1}\right)}. \qquad (10)$$

Calculations and experiments show [7], that relationship between temperature and diode voltage is nonlinear.

Influence of non-ideality constant and of alternations of measurement currents can be evaluated by equation (8).

Let‘s consider, that the real temperature of p-n junction is T_r = 100 ^{0}C.

Influence of non-ideality constant. If the real value of non-ideality constant η_r is higher than the nominal value η_n = 1.008 by 1 % then the temperature measured by the sensor will be T_m = 99.01 ^{0}C.

Influence of instability of measurement currents. Assume that electric current I_2 = 100 µA and current I_1 = 10 µA (ratio equals 10); when current I_2 increases and current I_1 decreases by 1%, the measured temperature will be 99.14 ^{0}C.

The offset voltage U_{offset} is required for Centigrade temperature sensors. Value of the offset voltage should be such that under temperature 0 ^{0}C the sensor output voltage would be 0 V. When sensor is produced, the selected value of the voltage U_{offset} will define the magnitude of the sensor output voltage U_{out}.

Typical structure of analog temperature sensor is shown in Fig. 1.

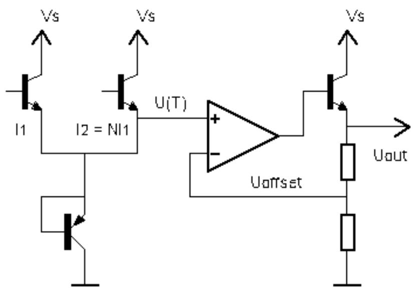

Fig. 1. The structure of typical analog temperature sensor

As it follows, output voltage of the analog sensor is influenced by the temperature of p-n junction, modulation of electrical resistance of the p-n junction, uncertainty of non-ideality constant, self-heating of the sensor, nonlinearity of mathematical relationship and uncertainty of the voltage U_{offset}.

For accurate temperature sensors U_{out} = 0V under 0 ^{0}C, and the scale factor is 10 mV/ ^{0}C [1].

Temperature field of the sensor body

When sensor is not immersed into liquid flow directly or while being in the pocket, and is fastened, for example, on the surface of the tube, the inner temperature field of the sensor is related with the quality of its thermo-isolation.

If heat is transferred by conductivity, then heat transfer is described by the equation (11)

$$\rho C \frac{\delta T}{\delta t} + \nabla \cdot (-k \nabla T) = Q, \qquad (11)$$

the variables and quantities in this equation: Q – the heat source; T – the temperature; k – thermal conductivity; C – the heat capacity; ρ – the density; t – the time.

For a steady-state model temperature does not change with time. If the heat transfer is by conduction only, the boundary conditions are: $-\mathbf{n}\cdot(-k\nabla T)=0$ insulation or symmetry; $-\mathbf{n}-$ is the normal vector of the boundary; $T=T_0$ – the defined temperature.

The interior boundary condition

$$-\mathbf{n}_l\cdot(-k_l\nabla T_l)-\mathbf{n}_r\cdot(-k_r\nabla T_r)=0 \qquad (12)$$

is the condition of continuity, indexes *l* and *r* – condition on the right and on the left of boundary.

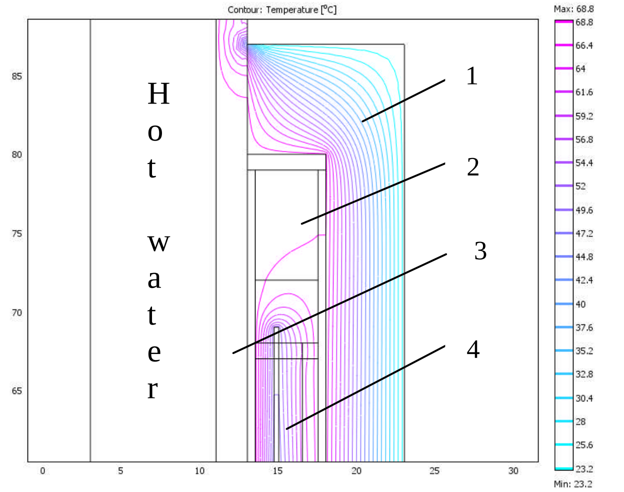

Fig. 2. The temperature field in the area of the sensor body. Thickness of the thermo-isolation 1 layer is 10 mm. Here 1 – thermo-isolation; 2 – sensor; 3 – pipe wall; 4 – cable.

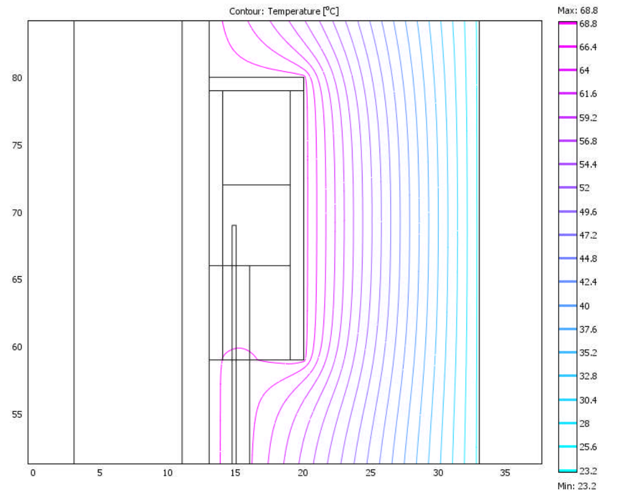

Fig. 3. Temperature field in the area of the sensor body. Thickness of the thermo-isolation layer is 20 mm

It was assumed during modeling that temperature sensor is placed in the protective sheath, is fastened to the surface of the tube and is covered by thermo-isolating cover. Finite element method was used for the modeling, and finite element analysis program "COMSOL Multiphysics" was selected.

For the model the temperature of the fluid flow T_f = 70 ^{0}C was defined and the temperature of the ambient medium (air) was defined equal to 22 ^{0}C.

To illustrate the results of the modeling are given for two cases - when thermal isolation is poor and acceptable (results are shown in Fig. 2 and Fig. 3).

When the thickness of the thermo-isolation layer was 10 mm, temperature across the sensor varied from 69.906 ^{0}C to 69.013 ^{0}C, and from from 69.588 ^{0}C to 67.566 ^{0}C along the sensor. When the thickness of the thermo-isolation layer was increased up to 20 mm, temperature across the sensor varied from 69.993 ^{0}C to 69.895 ^{0}C, and from 69.934 ^{0}C to 69.946 ^{0}C along the sensor. Therefore by optimizing the parameters of the thermo-isolating cover it is possible to form such environment conditions for the sensor, that it would be located in the temperature field, which is analogous to the temperature field of the liquid flow.

The results of the experiment

Characteristics U_{out} *(T)* of 10 units of the analog temperature sensors of the type LM35 was investigated. Temperature measurement was performed with uncertainty of ±0.02 ^{0}C, and the output voltage was measured with uncertainty of ±0.001 V. Output voltage dependence on the temperature of one sensor is shown in Fig. 4. Linear relationship was received in the temperature range from 24 ^{0}C to 92 ^{0}C (correlation factor R = 0.9999).

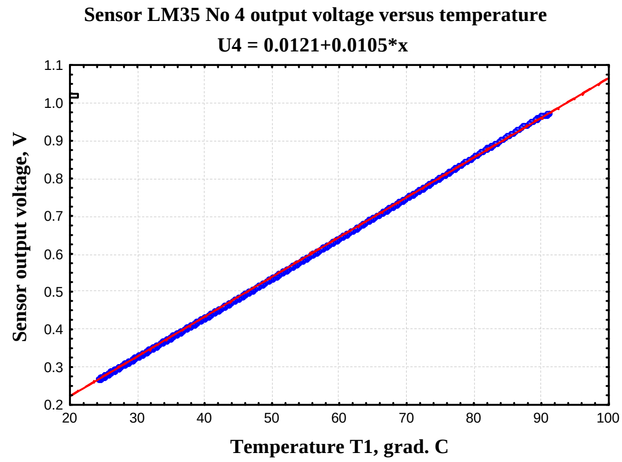

Fig. 4. The dependence of the sensor output voltage on the temperature

Means and standard deviations (STDEV) of the regression line calculated from the measurement results are given in Fig. 5.

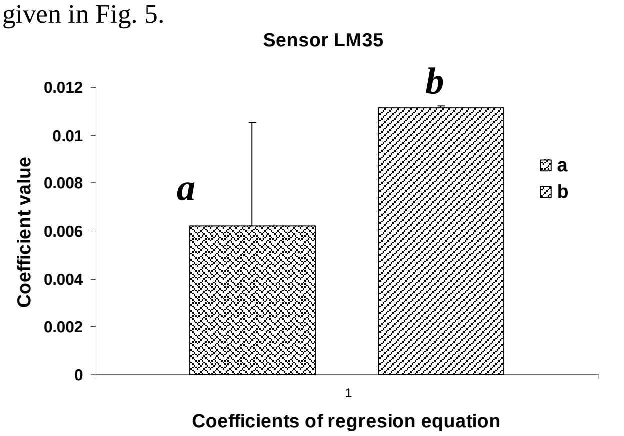

Fig. 5. Average values of the coefficients *a* and *b* of the regression equation and their STDEV (*n* = 10)

General form of the regression equation according to the results of the measurements

$$Uout = 0.00621 + 0.0106 * T, \qquad (13)$$

here $Uout$ – sensor output voltage, V; T – temperature, ^{0}C.

STDEV = ±0.00433 for the coefficient a from the general regression equation, and STDEV= ±0.0000943 for the coefficient b. Using equation (10) the temperature can be calculated as

$$T = 94.3396\ Uout - 0.585859, \qquad (14)$$

here T – temperature, ^{0}C, $Uout$ – sensor output voltage, V.

Second experiment was performed when temperature in the liquid flow T_{ST} was measured using measurement device "1560 Black Stack". Its measurement uncertainty is ±0.02 ^{0}C, and the secondary thermistor probe type is 5610 with the basic accuracy of ±0.015 ^{0}C. Probe was immersed into the liquid. Temperature T_M was measured by calibrated sensor of the type LM35, which was attached to the surface of the tube and covered with thermal isolation type Thermaflex cover thickness 20 mm. Yield of the liquid flow was 0.115 m^3/h, temperature of the delivered liquid was maintained at the 75±2^{0}C and 19±0.5^{0}C. The duration of the measurement was 8 h. Measurement results are listed in the Table 1.

Table 1. Results of the temperature control in fluid flow

No	Parameter	Average value, ^{0}C
1	Temperature T_{ST}	75.116±0.104
2	Temperature T_M	75.063±0.063
3	Temperature T_{ST}	19.271 ± 0.470
4	Temperature T_M	19.258 ± 0.474

Temperature mean values measured in the liquid flow using both methods differed by 0.053 ^{0}C and 0.013 ^{0}C. When sensor is attached to the surface of the tube, measurement results are considerably influenced by the quality of thermal insulation of the cover placed on the sensor and on the part of the tube.

Conclusions

1. It is purposeful to use analog semiconductor temperature sensors for temperature control in the liquid flow.
2. By optimizing the parameters of the thermo-isolating cover it is possible to form such environment conditions for the sensor, that it would be located in the temperature field, which is analogous to the temperature field of the liquid flow.
3. Standard deviation of the bandgap voltage values for the investigated sensors amounts 0.697 of the average value of the bandgap voltage.
4. For temperature control in the fluid flow using analog sensors of the type LM35 it is necessary to calibrate them additionally in order to reach higher accuracy than declared by manufacturer.

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Application possibilities of the semiconductor temperature sensors for measurement of the temperature in the fluid flow are analyzed. Possible causes for scattering of the sensor parameters during manufacture were investigated. It was shown, that by additional calibration of the analog temperature sensors it is possible to increase the accuracy of the measurements. The simulation and experiment results are introduced. Ill. 5, bibl. 9 (in English; summaries in English, Russian and Lithuanian).

А. Думчюс, В. Аугутис, Д. Гайлюс. Контроль температуры в потоке жидкости полупроводниковыми сенсорами // Электроника и электротехника. – Каунас: Технология, 2008. – № 7(87). – С. 27–30.

Рассматривается возможность применить для контроля температуры в потоке жидкости полупроводниковые сенсоры температуры. Анализируется влияние разброса в процессе производства некоторых параметров сенсоров на выходной параметр. Показано, что дополнительной калибровкой можно увеличить точность контроля. Приведены результаты моделирования и экспреримента. Ил. 5, библ. 9 (на английском языке; рефераты на английском, русском и литовском яз.).

A. Dumčius, V. Augutis, D. Gailius. Skysčio srauto temperatūros kontrolė puslaidininkiniais jutikliais // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2008. – Nr. 7(87). – P. 27–30.

Nagrinėjamos galimybės puslaidininkinius temperatūros sensorius panaudoti skysčių srauto temperatūros kontrolei. Nagrinėta sensorių kai kurių parametrų reikšmių sklaidos gamybos procese įtaka išėjimo parametrui. Parodyta, kad papildomai kalibruojant analoginius temperatūros sensorius galima padidinti temperatūros skysčio sraute kontrolės tikslumą. Pateikti modeliavimo ir eksperimento rezultatai. Il. 5, bibl. 9 (anglų kalba; santraukos anglų, rusų ir lietuvių k.).