Introduction

The purpose of this experiment is to test usability of a GreenPAK device in a temperature sensing application, specifically for CPU processors where the temperature domain is 25°C to 100°C.

The temperature sensing system uses a remote temperature sensor 2N3904 (diode connected) and control logic that is implemented in the GreenPAK device. The goal is to achieve a +/- 1°C internal temperature accuracy using an SLG46537 chip.
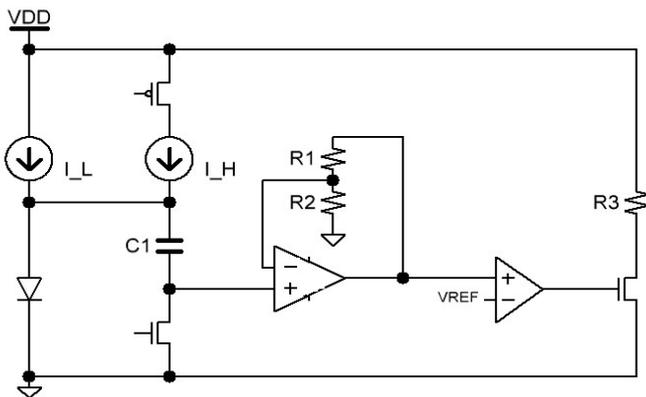

Figure 1 Application circuit for the temperature sensor that implements two-current method

Theory

Two-Current Method

The two-current method is a voltage subtraction method using two current sources, a diode, capacitor, and FET switches. See Figure 1. It is designed to amplify the voltage difference on the diode induced by two different currents I_L and I_H.

The forward voltage of the diode varies based on the current induced e-field across the diode. By subtracting the forward voltage at two known currents, we can eliminate common variables such as offset and saturation current.

The forward bias current, I_D, of a diode is related to the saturation current I_s, and forward voltage V_D by the equation:

$$I_D = I_s e^{V_D/\eta V_T}$$

Where η is the ideality factor of the diode and $V_T = kT/q$. k is the Boltzmann constant and q is the electron charge constant. For this example, I_H will be bias current I_1 and I_L will be bias current I_2. Their forward bias current equations are thus respectively:

$$I_1 = I_s e^{V_1/\eta V_T}$$

$$I_2 = I_s e^{V_2/\eta V_T}$$

By dividing the two-forward bias current equations, we eliminate saturation current and reduce the input current variables to a scalar factor N.

$$\frac{I_1}{I_2} = N = e^{(V_1-V_2)/\eta V_T}$$

If N is known, then by measuring the difference between V1 and V2, we can calculate temperature T.

$$\ln(N) = (V_1 - V_2)q/(\eta kT)$$

$$T = (V_1 - V_2)q/(\eta k ln(N))$$

Ideality Factor η

While k and q are constants and do not vary from part to part, the ideality factor η does vary between the values 1 and 2. The closer this value is to 1, the more that carrier diffusion dominates. The closer this value is to 2, the more recombination dominates. The higher this value, the more erroneous the temperature measurements because

temperature would highly affect recombination but not diffusion. [1]

When picking a remote temp diode, remote diode-connected transistors, BJTs where the base-collector junction is shorted, are better than rectifier diodes because their ideality values are speced.

Almost all BJT transistors have an ideality factor close to 1. Other important parameters include the forward current gain β and series resistance R_s. The forward current gain varies with temperature and collector current and the series resistance presents a constant offset at all temperatures. It is recommended to choose a device whose β doesn't vary between the two currents I_H and I_L.

Experiment Circuit

The purpose of the experiment is to measure the deviation in temperature in general by testing a few points which are 40°C, 60°C and 80°C.

Figure 2 shows a block diagram of the application circuit used in the experiment. Resistor R3 and R4 provide currents I_H and I_L from Figure 1. The switches NMOS and PMOS are internal to GreenPAK (PIN 13 and PIN 15).

Internal GreenPAK design is shown in Figure 3 and gives 10ms Update Time for this sensor.

The capacitor C4 is charged with I_L when NMOS is pulled low and PMOS is floating. And charged with I_H when PMOS is pulled high and NMOS is floating. The control logic of the system is programmed to provide a dead band time, between the NMOS and PMOS turn-on time to get the voltage difference on

C4. This difference enters IN+ input of the op amp (SLG88103). A waveform of voltage across C4 is shown in Figure 4.
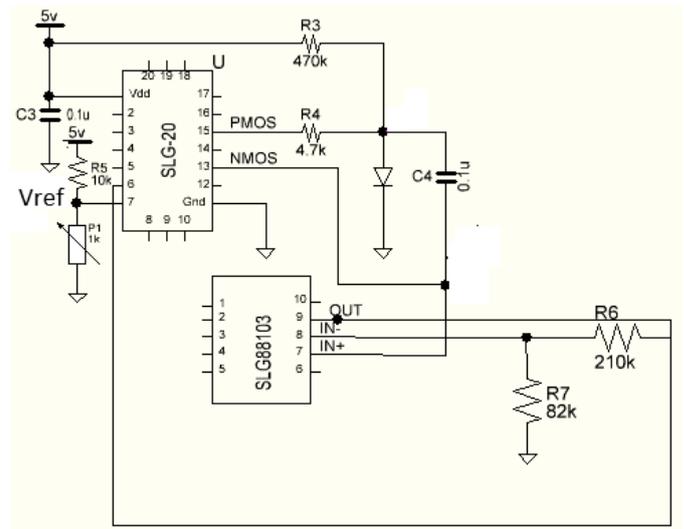

Figure 2 GreenPAK block diagram for the temperature sensing application circuit
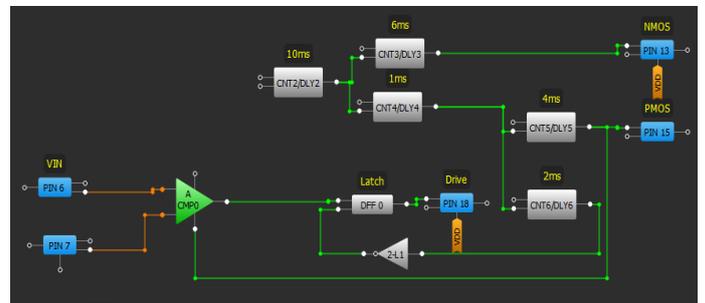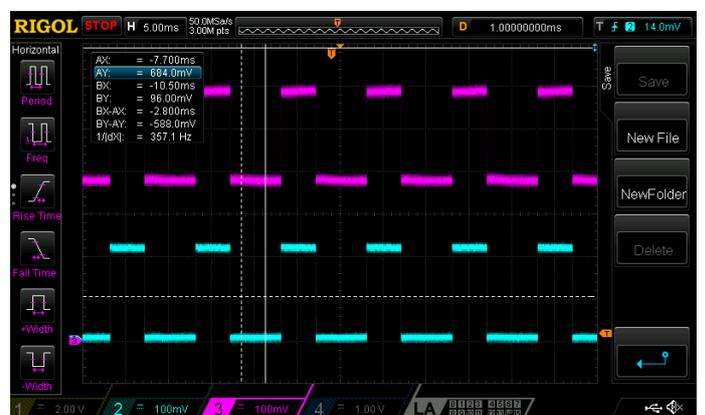

Figure 3 Internal GreenPAK Design

Figure 4 Waveform of voltage across C4

PIN 7 of the GreenPAK device is connected to a voltage divider with a variable resistance (a trimpot potentiometer) which is used for adjusting the switching voltage of the analog comparator ACMP0 in the internal GreenPAK design. The switching voltage is the moment when the voltage on PIN 7 reaches the voltage on PIN 6 (the op-amp output voltage). The output voltage of the op-amp (and, consequently, the switching voltage of ACMP0) is different for different temperatures. Therefore, in the experiment the resistance of P1 is tuned until the switching moment occurs. Based on the measured resistance of the potentiometer P1, the ACMP0 switching voltage (Vref) can be calculated.

Results

The error induced by GreenPAK (the temperature measurement accuracy) is measured by testing the output across multiple devices (3 GreenPAK devices).

Test result for three sensor circuits with only one different component (GreenPAK5 device) is shown in Figure 2.1. Where:

- The temperature in the oven is measured with a thermocouple.

- The resistance of P1 is measured with a fluke multimeter.

- Vref values are calculated based on the resistance value of P1.

The results are summarized with graphs in the Figure 2.2.

Table 1. GreenPAK5_1

T(°C)	Resistance of P1(KΩ)	Vref (V)
40	1.18	0.531
58	1.254	0.561
59.5	1.259	0.563
79.6	1.353	0.600

Table 2. GreenPAK5_2

T(°C)	Resistance of P1(KΩ)	Vref (V)
40	1.183	0.532
40.3	1.186	0.533
60	1.268	0.566
79.7	1.352	0.599
80	1.355	0.600

Table3. GreenPAK5_3

T(°C)	Resistance of P1(KΩ)	Vref (V)
40	1.185	0.533
40.3	1.186	0.533
60	1.269	0.567
80	1.356	0.601
80.7	1.36	0.602

Figure 2.1 Test results for three sensors with different GreenPAK device
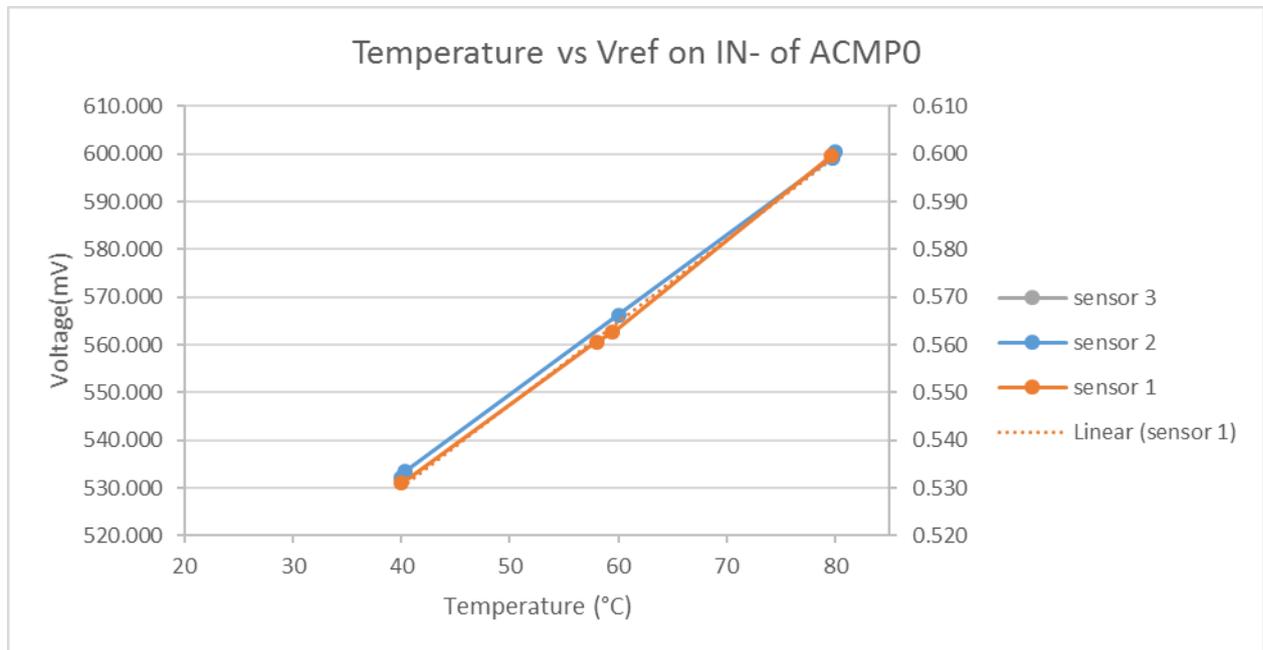
Figure 2.2 Graphs based on the measurements of three sensors with different GPAK device

Figure 2.2 shows that the sensors 2 and 3 give linear graphs that overlap while the sensor 1 gives the line that is very close to the presented linear Trendline for sensor 1.

The slope of the graphs for sensor 2 and 3, as well as the Trendline for sensor 1, is 1.7mV per 1°C (between T=40°C and T=80 °C).

The maximum difference among the measurements of the three GreenPAK devices is 2mV, which means GreenPAK introduces a part-to-part error around 1°C.

Error sources

Analog Comparator

The GreenPAK design suggests that the part to part variation would most likely occur from the analog comparator component (ACMP0).

ACMP0 setting in the design for this application:

IN+ source: pin6, IN- : Ext. Vref (pin7) , IN+ gain=1, Hysteresis: disable.

The offset voltage of ACMP (and, consequently, the switching voltage) changes with temperature and supply voltage.

The conclusion of the experiment is based upon the measurements of the GreenPAK sample of three, too few for statistical analysis. As a typical representation, we can use ACMP Offset Voltage char data, which is based a set 35 components tested over temperature and voltage. The component ACMP offset results for Ext.Vref=600mV and 5V Supply voltage, measured at room temperature are shown in Table 4.

Vdd=5.0V	min, mV	average, mV	max, mV
Vih, mV	599.743	1.244	603.442
Vil, mV	600.053	1.244	604.366
max offset	0.257	1.244	4.366

Table 4. ACMP offset testing for Ext.Vref=600mV_AutoPWR, 35 components, Room Temperature

Voffset calculations are based on the equation below:

$$Voffset = \max(abs(Ext.Vref - Vih), abs(Ext.Vref - Vil))$$
Data accuracy +/- 0.2mV

The test results based on 35 components suggests that the ACMP offset can be up to 4.366 mV which can introduce the error up to 2.5°C.

2N3904 Component

Transistors parameters that affect temperature measurements accuracy (remote accuracy) are the forward current gain β (I) and series resistance Rs. Based on the Microchip lab data for 2N3904 those parameters have a small effect on temperature measurement accuracy over the entire sensor's sourced current range (4.5-920uA). [1] Figure 3.1 shows the typical beta values of transistors tested by Microchip and can be used as a typical representation for the limited quantity of 2N3904 transistors. [1]

Equation 3 gives the temperature error due to illustrated beta variation around 0.02°C at 80 °C.

Similarly, using Microchip's data for Rs of the set of 2N3904 (around 0.7 Ohm) with equation 4 gives a temperature error due to Rs of around 0.8°C. [1]
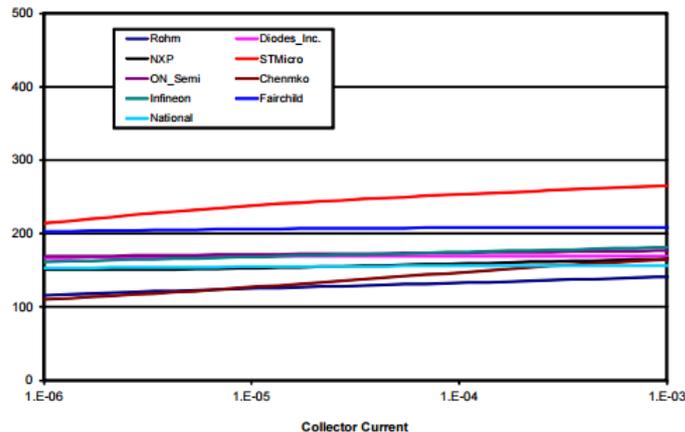

Figure 3.1 Typical Beta Values for 2N3904 Transistors at 23°C (the Microchip lab data)

EQUATION 3: **TEMPERATURE ERROR DUE TO BETA VARIATION**

$$\Delta T_{ERROR} = T_{REAL} \times \left[\frac{In\left(\frac{\beta_{F2} \times (1 + \beta_{F1})}{\beta_{F1} \times (1 + \beta_{F2})}\right)}{In(N)} \right]$$

EQUATION 4: **TEMPERATURE OFFSET ERROR DUE TO SERIES RESISTANCE**

$$T_{offset} = \left(\frac{q}{\eta k}\right) \frac{(I_{F2} - I_{F1})R_S}{In\left(\frac{I_{F2}}{I_{F1}}\right)}$$

Op-amp consideration

SLG88103 Voltage Offset is typically 0.35mV (up to 2.4mV for VCM close to VSS (ground)), plus typically 0.16mV (T=80°C) for adding offset drift with temperature. Typical values introduce a small error coming from the op-amp for this application. However, having in mind the maximum offset value the SLG88103 op-amp can introduce more than 1 °C error.

Conclusion

The temperature sensing system that is used in the experiment gives the output gain of 1.7 (mV/°C).

The test results based on sample of three GreenPAK devices suggest that the implementation of GreenPAK in a temperature sensing system alone introduces an error around 1°C.

Key Features of the sensor are based on the experiment's results where the temperature domain is for the remote sensor while the internal temperature system with GreenPAK was kept at room temperatures during the experiment.

Key Features

- Temperature domain (25°C - 100°C)
- Accuracy
  - ±1°C Remote Temperature Accuracy (accuracy of 2N3904 sensor)
  - ±1.5°C Internal Temperature Accuracy
- 1.7V-5.5V Supply Voltage
- 10ms Update Time
- 1.7 (mV/°C) Output Gain
- 29μA Quiescent Current

Sources

[1] Remote Thermal Sensing Diode Selection Guide, SMSC AN12.14

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