Current Sensing with Cu Trace

SLG47011

This application note describes how to measure current using a section of PCB copper trace as a sense resistor. The SGL47011 has a flexible, tunable data acquisition and processing system used in conjunction with many configurable logic components. It makes possible the implementation of a current sensing system that includes measuring the voltage drop across a sense resistor, temperature measurement, digitization, temperature compensation, and current calculation.

The application note comes complete with design files which can be found in the Reference section.

Contents

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1. Terms and Definitions

ADC	Analog to digital converter
MCU	Micro controller unit
PCB	Printed circuit board
PGA	Programmable gain amplifier
TCR	Temperature coefficient of resistance

2. References

For related documents and software, please visit:

AnalogPAK™ | Renesas

Download our free Go Configure Software Hub [1] to open the .aap file [2] and view the proposed circuit design. Use the GreenPAK development tools [3] to freeze the design into your own customized IC in a matter of minutes. Renesas Electronics provides a complete library of application notes [4] featuring design examples, as well as explanations of features and blocks within the Renesas IC.

[1] GreenPAK Go Configure Software Hub, Software Download and User Guide, Renesas Electronics
[2] AN-CM-394 Current Sensing with Cu Trace.aap, AnalogPAK Design File, Renesas Electronics
[3] GreenPAK Development Tools, GreenPAK Development Tools Webpage, Renesas Electronics
[4] GreenPAK Application Notes, GreenPAK Application Notes Webpage, Renesas Electronics

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3. Introduction

Measuring current is an important function in electronic circuits. Typically, dedicated sense resistors are used to measure current flow through a load. Such resistors have a high accuracy, low TCR, and long-term stability. And with their help, it is possible to perform high-precision measurements. However, in cases where the high accuracy of measurements is not critical, a section of PCB copper trace can be used as a replacement for the sense resistor and can be used in cost-optimized applications.

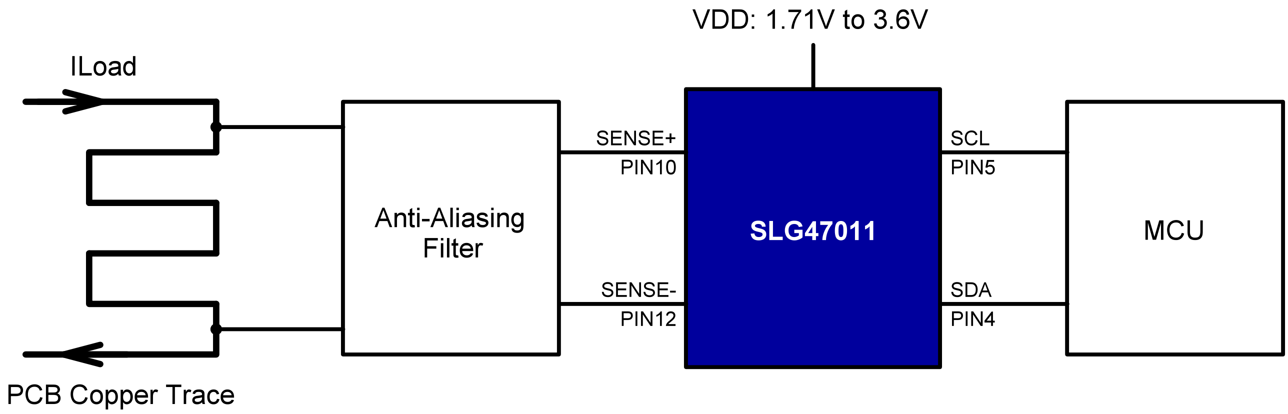

Figure 1. Block Diagram

4. Operating Principle

The sense resistor performs the function of a current-to-voltage converter. The load current flowing through the sense resistor creates a voltage drop proportional to the current value.

$$U_{SENSE} = I_{LOAD} \cdot R_{SENSE}$$

Then, through a anti-aliasing filter, this voltage is fed to the input of the PGA. The PGA provides signal amplification of 1x, 2x, 4x, 8x, 16x, 32x, or 64x, depending on the selected mode and type of amplifier (Buffer, Non-inverting amplifier, Differential amplifier, or Instrumentation amplifier). After amplification, the signal is digitized using an ADC. The SLG47011 has a 14-bit (selectable 14, 12, 10, or 8-bit) successive approximation register analog-to-digital converter macrocell which samples incoming signals.

Since a PCB copper trace is used as the sense resistor, its resistance strongly depends on temperature (temperature coefficient of about 0.393% per °C). That is, it is also necessary to measure the temperature of the sense resistor. In this case, the SLG47011 uses an internal temperature sensor, and the output voltage of the temperature sensor is also digitized using an ADC. Since the SLG47011 is placed above the sense resistor (on both sides of the PCB prototype), it can be assumed that the temperature of the SLG47011 will be equal to the temperature of the sense resistor (PCB copper trace). Of course, an external temperature sensor can be used for better accuracy. However, in this Application Note, we are considering a variant with an internal temperature sensor.

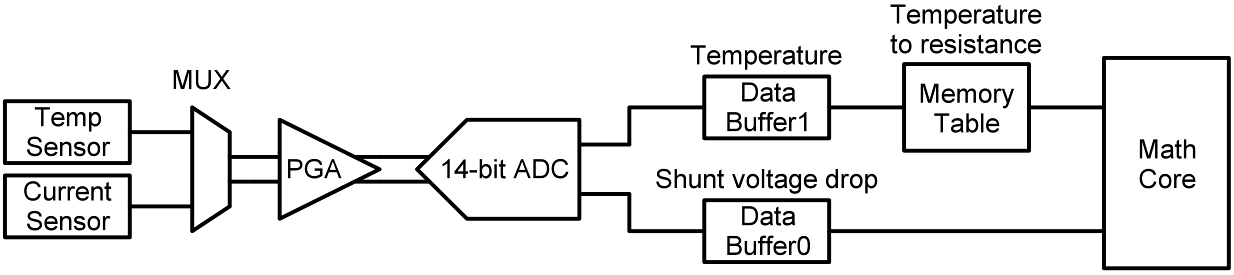

Figure 2. Data Processing Scheme

After the current sense voltage and temperature sensor voltage is sampled by the ADC, the data is written into the Data Buffers (see Figure 2. Data Processing Scheme). Data Buffers consist of up to eight 16-bit words. The user can select a Data Buffer length of 1, 2, 4, or 8 words, and can select the Data Buffer mode: Storage, Moving Average, or Oversampling. In this Application Note, the averaging function is used to filter noise.

The Memory Table is used to implement the temperature compensation function. The Memory Table macrocell is a memory block that consists of 4096 12-bit words. It has a 12-bit address and a 12-bit data port. The address of each particular word comes from the address input. The input source for the Memory Table address is selected from Data Buffer1 (temperature sensor). This means that for each temperature value (ADC code averaged by the Data Buffers and truncated to 12 bits), the Memory Table can store the corresponding actual resistance value of the current sense resistor (the resistance of the PCB copper trace). That is, for each load current calculation, we will have the voltage across the sense resistor and the actual resistance value of this sense resistor.

The SLG47011 also has a Mathematical core (MathCore) macrocell which allows to perform four mathematical operations: addition, subtraction, multiplication, division (cyclic shift), as well as their combinations. The MathCore macrocell calculates the load current value based on the voltage and resistance values (see Figure 2. Data Processing Scheme) using the formula:

$$I_{LOAD} = \frac{U_{SENSE}}{R_{SENSE}} = U_{SENSE} \cdot \frac{1}{R_{SENSE}}$$

where:

U_{SENSE} – voltage drop across the sense resistor (digital value)

$\frac{1}{R_{SENSE}}$ – sense resistor conductivity values (1/R) preprogrammed into the Memory Table

The multiplication function will be used since the MathCore cannot divide by any arbitrary number. Accordingly, the Memory table is filled with sense resistor conductivity values (1/R).

The calculation result can be read by the MCU through I²C or SPI and/or used by internal macrocells such as DAC or DCMP.

5. AnalogPAK Design

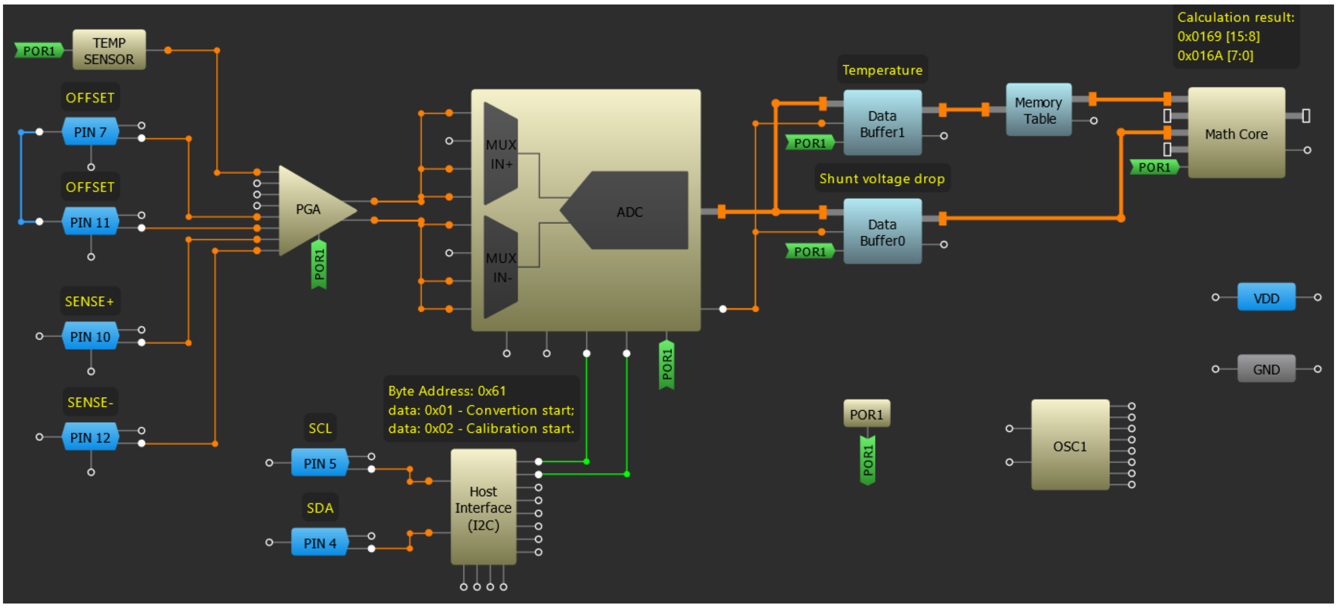

Figure 3. AnalogPAK Design

As can be seen, the design is very simple and requires only a few I²C commands for control. Two inputs are used to control the ADC.

The first – Conversion start. A high level on this input triggers the ADC conversion.

The second – Calibration start.

In general, system offset calibration considers the whole chain of external sources or devices and internal blocks inputs (MUX and PGA).

To start the system offset calibration, the external device or sensor must be in its zero magnitude. However, a special feature of this design is that a separate shorted channel, CH2, is used for calibration. Therefore, system calibration can be started at any time. The only condition is that the ADC conversion must be stopped for a calibration period.

In this configuration, system calibration only cancels the PGA offset and noise error. The result of system calibration will be saved as a system offset error compensation value in special calibration registers. After the system calibration is complete, the system offset calibration value will be subtracted from each data of the ADC output. Please note that the PGA has four channels, but there are only two calibration registers: the first register calibrates CH0 and CH1 and the second calibrates CH2 and CH3. In system calibration, calibration register #0 is measured for CH0 but applied to both CH0 and CH1, and calibration register #2 is measured for CH2 but applied to both CH2 and CH3. System calibration only makes sense if both channels of the same pair are configured to function in differential mode.

In the considered design, PGA CH0 is configured as a single-ended input (mode 6: Buffer) and is used for temperature sensing. CH1 is disabled. CH2 is configured as a differential input (mode 5a: Differential input, single-ended output) and is used for system calibration. CH3 has the same settings as CH2 and is used for current sensing. System calibration is enabled only for the pair of channels CH2 and CH3. The default gain is set to 64x for CH2 and CH3, but it can easily be changed via I²C.

Gain settings for CH2 and CH3:

Byte address: 0x14D

- Gain 1x: data 0x09;
- Gain 2x: data 0x12;
- Gain 4x: data 0x1B;
- Gain 8x: data 0x24;

- Gain 16x: data 0x2D;
- Gain 32x: data 0x36;
- Gain 64x: data 0x3F (default in this design).

After changing the gain, it is recommended to run the system calibration procedure.

The ADC is configured with 14-bit resolution and eight samples per channel. This means that once conversion starts, the ADC takes at least eight samples per channel, and accordingly, Data Buffers with a length of 8 words will be filled out with ADC data. Data Buffers function in Moving Average mode, which is good for noise canceling.

As mentioned, the Data Buffer1 output (temperature sensor) is an address input source for the Memory Table. And the Memory Table stores the actual resistance (actually 1/R) of the sense resistor for each temperature value inside the temperature range -40 °C to +85 °C. See the data calculations for the Memory Table below.

First of all, let's calculate the output voltage range of the temperature sensor for the temperature range -40 °C to +85 °C according to the datasheet formula.

$$\mathrm{V_{TS}} = 753.8 - 1.83 \cdot \mathrm{T}$$

where:
V_{TS} (mV) – temperature sensor output voltage;
T (°C) – temperature.

Thus, for the extreme points of the temperature range, $V_{TS(-40)}$ = 827 mV; $V_{TS(+85)}$ = 598.25 mV.

After ADC conversion it will be: $V_{TS(-40\ ADC\ 14\text{-}bit)}$ = 8364; $V_{TS(+85\ ADC\ 14\text{-}bit)}$ = 6050.

$$\mathrm{V_{TS(ADC\ 14-bit)}} = \frac{16383}{\mathrm{V_{ref}}} \cdot \mathrm{V_{TS}}$$

where:
16383 – max code of 14-bit ADC;
V_{ref} – reference voltage of ADC (1.62 V).

The Memory Table has a data truncation feature which means the ADC 14-bit values will be converted to 12-bit values. Truncated data: $V_{TS(-40\ 12\text{-}bit)}$ = 2091; $V_{TS(+85}$ 12-bit) = 1512. Therefore, the values between 1512 and 2091 correspond to the sense resistor temperature in the temperature range from -40 °C to +85 °C, 580 Memory Table addresses in total. All that remains is to calculate the data for the Memory Table.

For example, a sense resistor made of a PCB Copper trace should have a value of 10 mΩ. Its dimensions can be calculated according to the formula below.

$$\mathrm{R} = \frac{\rho \cdot \mathrm{L}}{\mathrm{w} \cdot \mathrm{t}}$$

where
ρ – resistivity at 20°C ($1.72 \cdot 10^{-6}\ \mathrm{Ohm} \cdot \mathrm{cm}$);
L (cm) – trace length;
w (cm) – trace width;
t (cm) – trace thickness (usually $35 \cdot 10^{-4}\ \mathrm{cm}$).

For the PCB prototype, a copper trace with a width of 5 mm and a thickness of 35 µm is used. So, according to the formula the required length of copper trace is roughly 10.2 cm. Based on these dimensions, five prototype PCBs were made, and the real resistance values of the sense resistors were measured at 20 °C. These values are: RPCB1 = 10.04 mΩ; RPCB2 = 9.91 mΩ; RPCB3 = 10.34 mΩ; RPCB4 = 9.93 mΩ; RPCB5 = 10.21 mΩ. Further calculations and tests were performed for the PCB1 prototype.

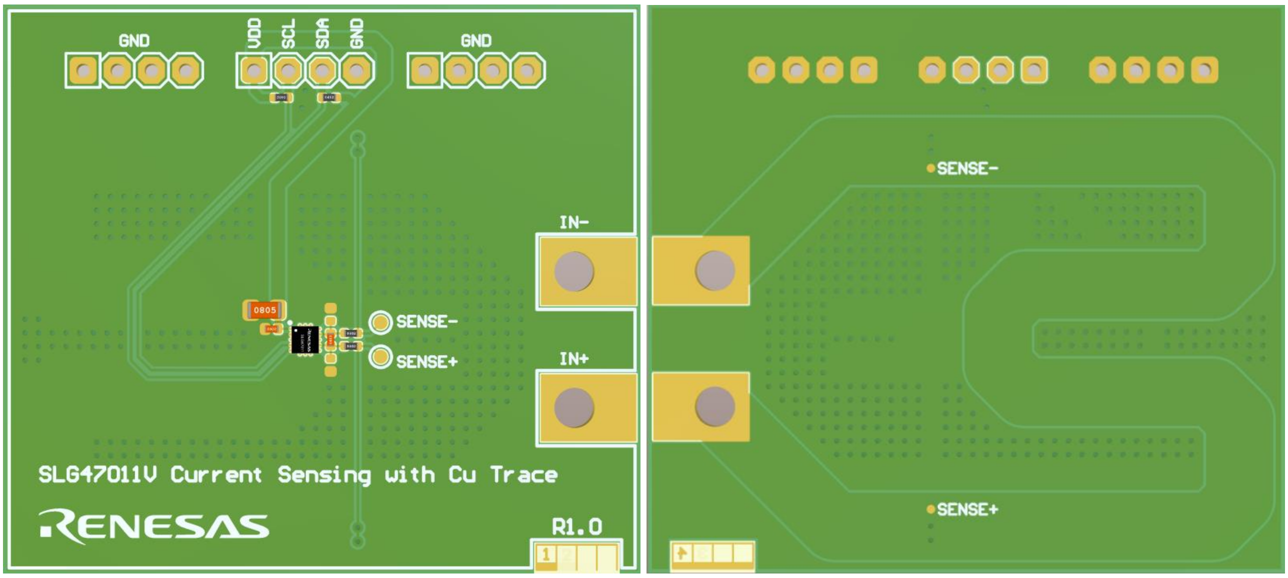

Figure 4. PCB Prototype Design

The following formula is used for the sense resistor resistance calculations, which depend on the temperature.

$$R = R_0 + R_0 \cdot \alpha \cdot (T - T_0)$$

where:

R (Ω) – conductor resistance at temperature T;

R_0 (Ω) – conductor resistance at reference temperature;

α – temperature coefficient of resistance for copper (0.393% per °C);

T_0 – reference temperature at which α is specified for the conductor material (20 °C).

The resistance calculations for PCB1 at -40 °C and +85 °C result in $R_{(-40)}$ = 7.67 mΩ; $R_{(+85)}$ = 12.60 mΩ.

As mentioned earlier, the Math Core can't divide by the data from the Memory Table. Therefore, the Memory Table is filled with 1/R values, and the multiplication operation of the Math Core is used. So, we have:

$$\frac{1}{R_{(-40)}} = 130.378\ S;\ \frac{1}{R_{(+85)}} = 79.365\ S.$$

Since the Memory Table can store 12-bit words (numbers up to 4095), the calculation results are multiplied by 10 and rounded to get more significant numbers. This improves transformation accuracy.

So, the Memory Table is filled with the following data:

- Min temperature -40 °C: address: $V_{TS(-40\ 12\text{-bit})}$ = 2091, data: $\frac{10}{R_{(-40)}}$ = 1304.
- Max temperature +85 °C: address: $V_{TS(+85\ 12\text{-bit})}$ = 1512, data: $\frac{10}{R_{(+85)}}$ = 794.

The data for the rest of the points (Memory Table addresses from 1513 to 2090) are calculated in the same way.

For the Math Core, its function is goes from Adder/Subtractor -> Multiplier mode. This means that subtraction will be performed first, and then multiplication. Since mode 5a (differential input) of the PGA is used for CH3 (current sense), this channel has an offset of ADC_Vref/2 (8191). So, the Subtractor should be used to correct the zero point. After multiplying Data Buffer0's 14-bit data (voltage) by the Memory table's 12-bit data (conductance) in the Math Core, we may get a value greater than 16-bit. Therefore, the Right shifting function (2^8 in this design) of the Math Core is used. After that, the 16-bit result can be read via I²C. Byte address 0x0169 [15:8]; 0x016A [7:0].

So, the Math Core operates according to the formula:

$$\text{MathCore\_Result} = ((\text{Current\_Sense\_Data} - \frac{\text{ADC\_Vref}}{2}) \cdot \text{Memory\_Table\_Data}) >> 8$$

where:

Current_Sense_Data – 14-bit data of Data Buffer0 (sense resistor voltage drop);

Memory_Table_Data – 12-bit data of Memory table (sense resistor conductance);

ADC_Vref/2 – 8191 (ADC resolution is 14-bit).

The equation of the inverse transformation is:

$$I_{LOAD} = \frac{\text{MathCore\_Result} \cdot V_{ref} \cdot 2^8}{16383 \cdot \text{Gain} \cdot 10} \text{ [A]}$$

where:
MathCore_Result – calculation result read via I^2C;
V_{REF} – ADC reference voltage 1.62 V;
Gain – PGA gain (can be changed on the fly via I^2C);
2^8 – left shifting (can be changed on the fly via I^2C).

Depending on the specific case and the customer's preferences, some of the coefficients can be considered when filling out the Memory Table. This will simplify the formula.

6. Testing the Design

The application schematic is shown in Figure 5. This design consumes about 0.9 mA at V_{DD} = 3.3 V. If the design measures the load current periodically, then the design can be slightly changed, and the Power Controller macrocell can be used to activate the SLG47011's Sleep Mode during idle time. In Sleep Mode, the design consumes less than 2 μA.

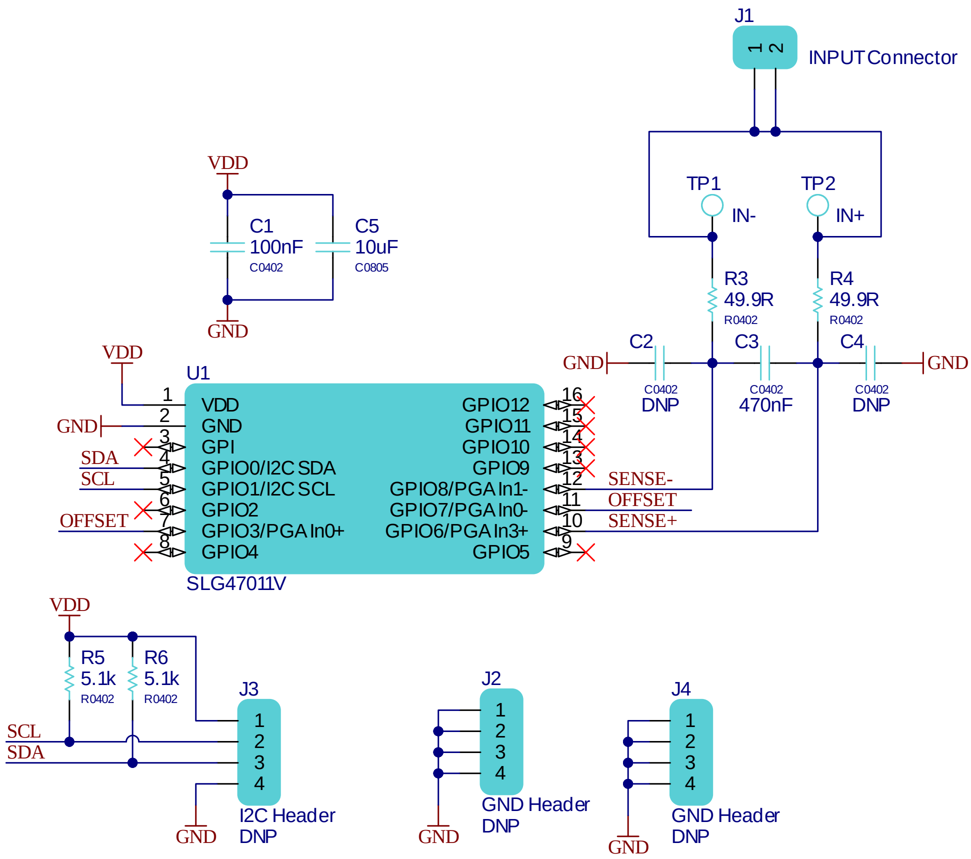

Figure 5. Application Schematic

This design is tested for different load current values at a temperature range of -40 °C to +85 °C. The test results are below:

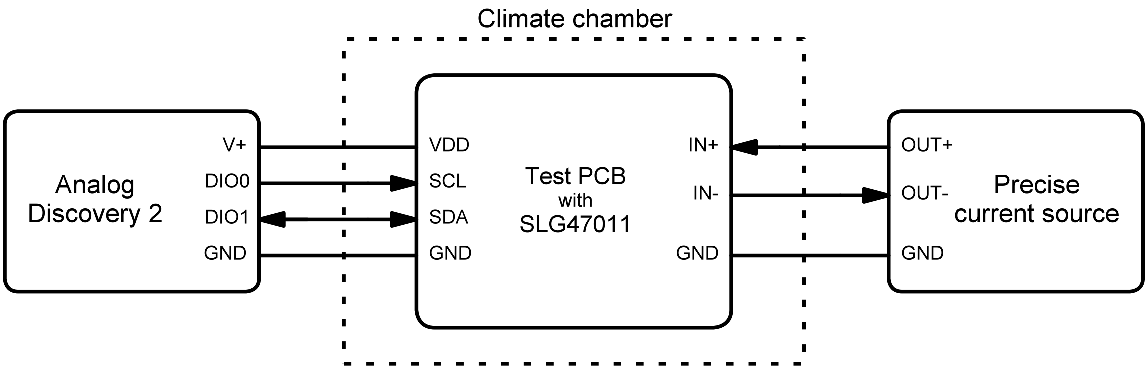

Figure 6. Testing Scheme

Table 1. Load current: 1 A, PGA Gain: 64x

Temperature (calculated), [°C]	Shunt Voltage (Data Buffer0) 0x2212 [15:8] 0x2213 [7:0]	Shunt Temperature (Data Buffer1) 0x2224 [15:8] 0x2225 [7:0]	Current (Math Core) 0x0169 [15:8] 0x016A [7:0]	Shunt Voltage (calculated), [mV]	Current (calculated), [A]	Error, [%]
-39.4	5034	8352	25550	8.02	1.0418	4.18
-34.1	5152	8254	25460	8.21	1.0382	3.82
-23.8	5401	8064	25381	8.60	1.035	3.50
-13.3	5656	7869	25322	9.01	1.0325	3.25
-2.8	5914	7675	25279	9.42	1.0308	3.08
7.5	6152	7485	25179	9.80	1.0267	2.67
18.0	6411	7290	25147	10.21	1.0254	2.54
23.2	6537	7194	25125	10.41	1.0245	2.45
28.7	6645	7092	24999	10.58	1.0193	1.93
39.0	6898	6901	24977	10.99	1.0185	1.85
49.3	7135	6711	24894	11.36	1.0151	1.51
59.7	7378	6518	24822	11.75	1.0122	1.22
69.9	7624	6329	24803	12.14	1.0114	1.14
80.6	7860	6131	24694	12.52	1.0069	0.69
86.7	7997	6018	24649	12.74	1.0051	0.51

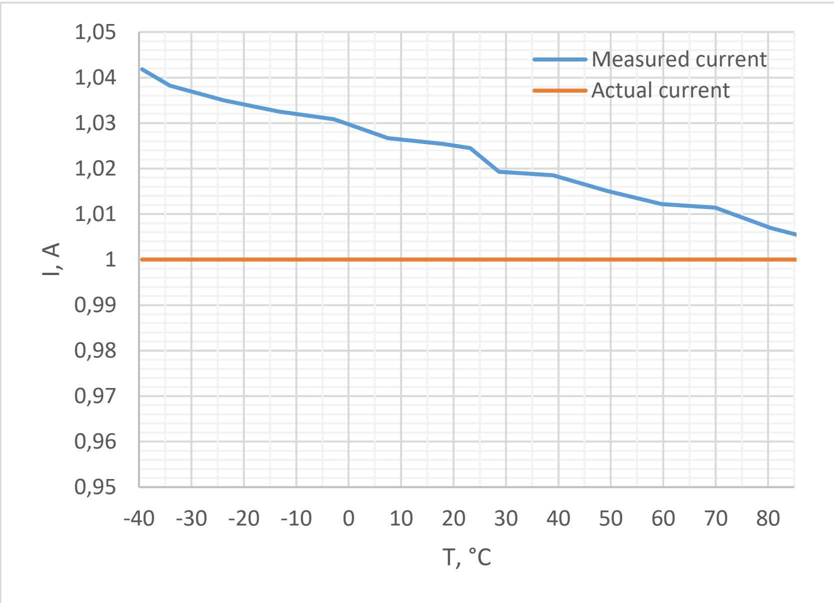

Figure 7. Measured current vs Temperature, 1 A, Gain 64x

Table 2. Load Current: 2 A, PGA Gain: 32x

Temperature (calculated), [°C]	Shunt Voltage (Data Buffer0) 0x2212 [15:8] 0x2213 [7:0]	Shunt Temperature (Data Buffer1) 0x2224 [15:8] 0x2225 [7:0]	Current (Math Core) 0x0169 [15:8] 0x016A [7:0]	Shunt Voltage (calculated), [mV]	Current (calculated), [A]	Error, [%]
-39.1	5077	8346	25725	15.98	2.0732	3.66
-34.0	5200	8252	25695	16.37	2.0708	3.54
-23.7	5451	8062	25595	17.16	2.0628	3.14
-13.4	5709	7871	25565	17.97	2.0603	3.01
-2.5	5970	7670	25491	18.79	2.0544	2.72
7.5	6211	7484	25424	19.55	2.049	2.45
17.9	6464	7291	25355	20.35	2.0434	2.17
23.1	6587	7196	25319	20.74	2.0405	2.03
28.3	6717	7099	25300	21.15	2.039	1.95
38.4	6970	6913	25287	21.94	2.0379	1.90
48.8	7216	6719	25210	22.72	2.0317	1.58
59.1	7460	6529	25152	23.48	2.0271	1.36
69.6	7708	6335	25090	24.27	2.0221	1.11
80.6	7965	6131	25022	25.07	2.0166	0.83
86.0	8074	6032	24949	25.42	2.0107	0.53

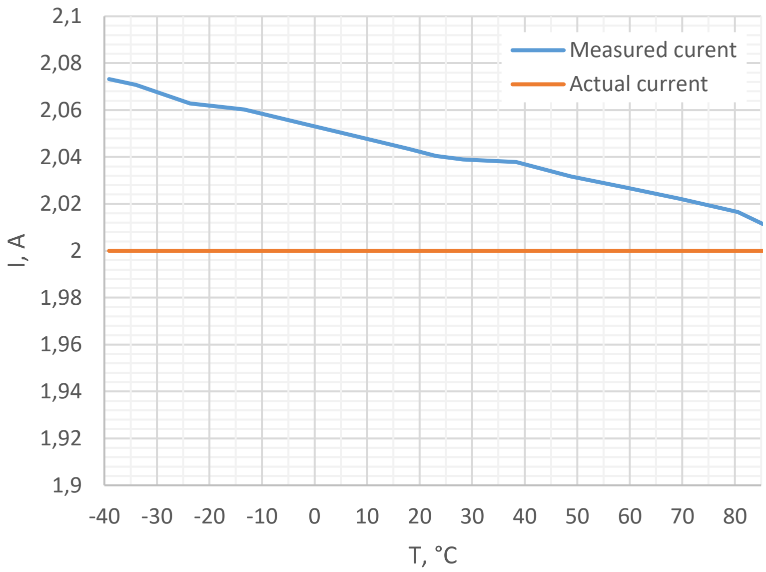

Figure 8. Measured current vs Temperature, 2 A, Gain 32x

Table 3. Load current: 4 A, PGA Gain: 16x

Temperature (calculated), [°C]	Shunt Voltage (Data Buffer0) 0x2212 [15:8] 0x2213 [7:0]	Shunt Temperature (Data Buffer1) 0x2224 [15:8] 0x2225 [7:0]	Current (Math Core) 0x0169 [15:8] 0x016A [7:0]	Shunt Voltage (calculated), [mV]	Current (calculated), [A]	Error, [%]
-39.3	5085	8351	25795	31.71	4.1172	2.93
-33.7	5235	8246	25811	32.64	4.1196	2.99
-23.6	5477	8061	25709	34.14	4.1034	2.58
-13.2	5739	7867	25684	35.78	4.0994	2.49
-2.3	6004	7665	25605	37.43	4.0868	2.17
7.6	6265	7483	25623	39.06	4.0897	2.24
18.2	6517	7287	25542	40.63	4.0767	1.92
23.4	6638	7190	25491	41.39	4.0686	1.72
28.6	6767	7095	25457	42.19	4.0632	1.58
38.7	7015	6906	25427	43.73	4.0583	1.46
49.2	7279	6713	25413	45.39	4.0561	1.40
59.7	7537	6518	25347	46.99	4.0456	1.14
70.0	7777	6328	25282	48.49	4.0352	0.88
81.1	8037	6123	25221	50.11	4.0255	0.64
86.8	8178	6016	25192	50.99	4.0208	0.52

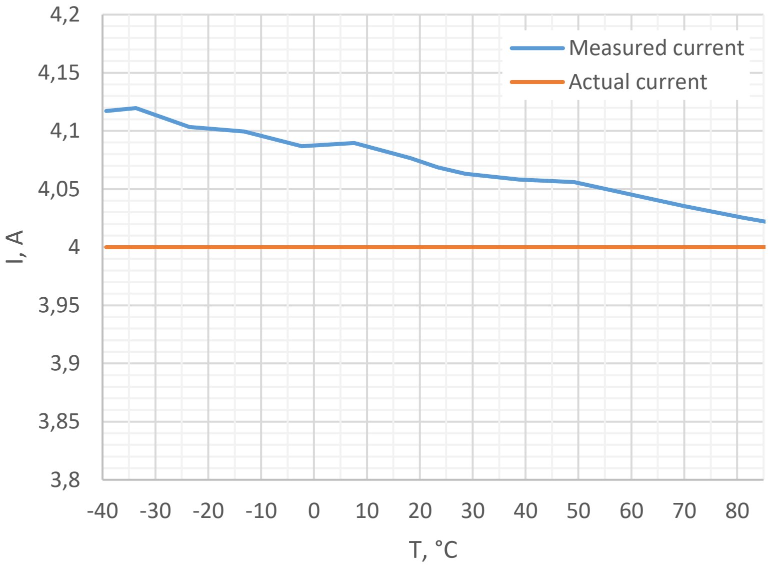

Figure 9. Measured Current vs Temperature, 4 A, Gain 16x

Table 4. Load Current: 5 A, PGA Gain: 8x

Temperature (calculated), [°C]	Shunt Voltage (Data Buffer0) 0x2212 [15:8] 0x2213 [7:0]	Shunt Temperature (Data Buffer1) 0x2224 [15:8] 0x2225 [7:0]	Current (Math Core) 0x0169 [15:8] 0x016A [7:0]	Shunt Voltage (calculated), [mV]	Current (calculated), [A]	Error, [%]
-39.9	3197	8362	16272	39.56	5.1553	3.11
-33.8	3294	8249	16258	40.76	5.1508	3.02
-23.6	3462	8059	16246	42.84	5.1469	2.94
-13.3	3611	7870	16174	44.69	5.1244	2.49
-2.7	3783	7673	16165	46.82	5.1214	2.43
7.4	3946	7485	16144	48.83	5.1148	2.30
18.6	4106	7279	16048	50.81	5.0845	1.69
23.0	4180	7197	16082	51.74	5.0951	1.90
28.9	4267	7089	16047	52.81	5.0840	1.68
38.6	4420	6909	16027	54.70	5.0776	1.55
49.0	4569	6716	15961	56.55	5.0569	1.14
59.5	4751	6522	16001	58.80	5.0694	1.39
69.9	4902	6330	15947	60.66	5.0524	1.05
80.6	5059	6132	15906	62.61	5.0394	0.79
86.4	5141	6025	15866	63.63	5.0266	0.53

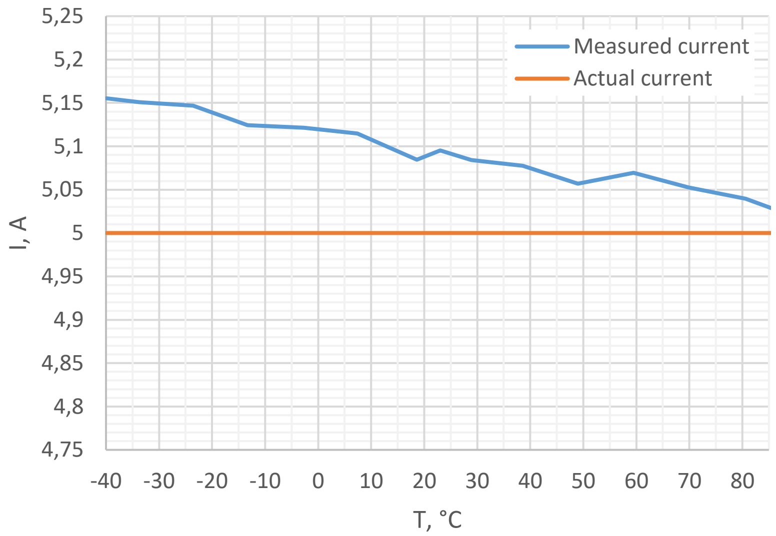

Figure 10. Measured Current vs Temperature, 5 A, Gain 8x

The main problem with using a Cu trace as a sense resistor is the significant temperature coefficient of copper of 0.393% per °C. For example, let's analyze the test results in Table 1. At a current of 1 A, the voltage across the sense resistor changes from about 8 mV to 12.7 mV when the temperature changes from -40 °C to +85 °C. It means the resistance changes from 8 mΩ to 12.7 mΩ. So, without temperature compensation, we would get an error of ~27%. Implementing temperature compensation reduces the error by a factor of six times, and now it does not exceed 4.18% over the entire temperature range (-40 °C to +85 °C).

One of the sources of error is that the temperature of the SLG47011 and the sense resistor are slightly different since copper traces heat up as current passes through, and the chip and sense resistor are placed on opposite sides of the used PCB. So, an external temperature sensor can be used to improve accuracy.

The main disadvantages of using copper traces as sense resistors are that they take up a lot of space on the PCB, and during mass production, it is impossible to precisely control their dimensions, especially their thickness and width. As a result, such resistors will have a significant resistance deviation from the expected.

7. Conclusion

This application note describes how to measure current using a PCB copper trace as a sense resistor and solve the temperature coefficient problem. The main advantages of using the SLG47011 are the availability of the Math Core, Memory Table, and Data Buffers macrocells. These macrocells make it possible to easily implement a measurement and data processing system with temperature compensation.

8. Revision History

Revision	Date	Description
1.00	Sep 24, 2024	Initial release.

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