Shunt Resistors, High-Performance Op-Amps, Zener Diodes

Low-Side Current Sensing Circuit Design Rev.005

In the areas of automotive and industrial equipment, low-side current sensing circuits are used for functions including current (voltage) control, over current limiting, and remaining battery level detection. The low-side current sensing circuits, which are achieved with a shunt resistor, an op-amp, and external components, can be incorporated most simply at a lower cost compared with other methods. This application note explains the criteria for selecting parts and determining circuit constants for the low-side current sensing circuits.

Low-side current sensing circuit

Figure 1 shows a typical low-side sensing circuit. Load current (I_{LOAD}) from load (LOAD) via the shunt resistor (R_{SHUNT}) causes a voltage drop (ΔV_{SHUNT}). This voltage is differentially amplified by the op-amp (OPAMP), connected to an A/D converter, microcontroller, or other devices in the subsequent stage. Then, the current value is measured and used for system control.

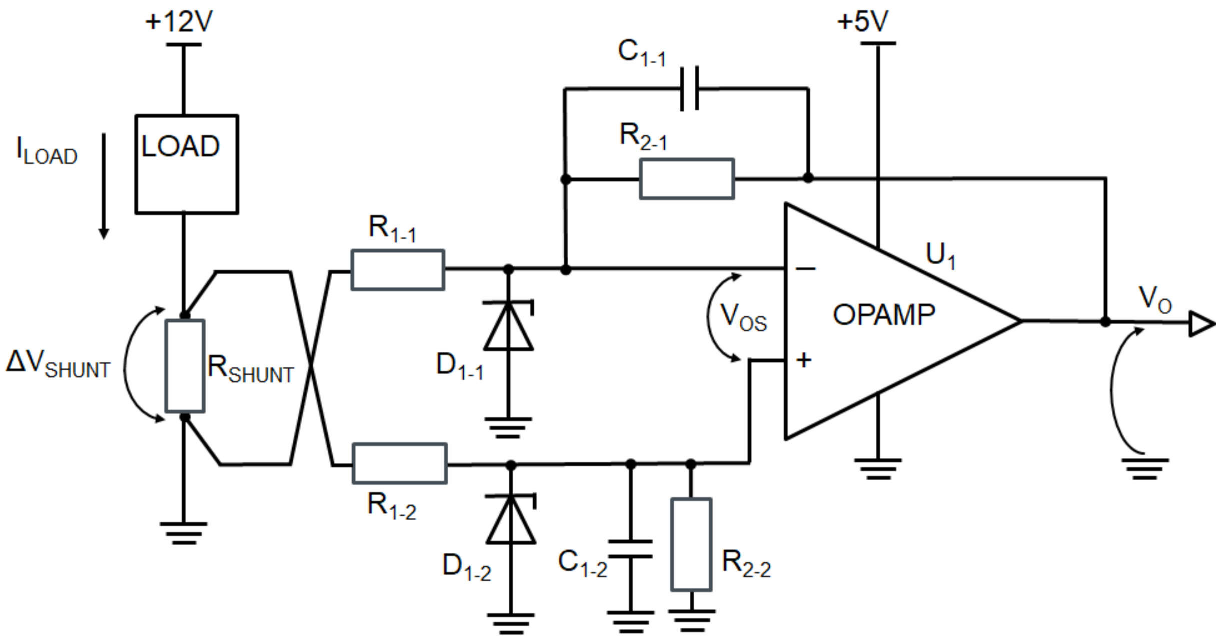


Figure 1. Typical low-side current sensing circuit

The symbols in Figure 1 represent the following:

- OPAMP: Op-amp
- LOAD: Load
- I_{LOAD}: Load current
- R_{SHUNT}: Shunt resistor
- V_{OS}: op-amp offset voltage
- ΔV_{SHUNT}: Shunt voltage
- $R_{1\text{-}1} = R_{1\text{-}2} = R_1$, $R_{2\text{-}1} = R_{2\text{-}2} = R_2$: Gain setting resistors
- $C_{1\text{-}1} = C_{1\text{-}2} = C_1$: Filter capacitor
- $D_{1\text{-}1}$, $D_{1\text{-}2}$: Protection diodes

In an ideal circuit where an op-amp without an input offset voltage is used the following equation with the circuit in Figure 1.

$$V_O = I_{LOAD} \times R_{SHUNT} \times \left(\frac{R_2}{R_1}\right) \quad [V] \quad \cdots (1)$$

In actual circuits, the current sensing error is affected by the input offset voltage of the op-amp, the tolerance of the shunt resistor and the relative tolerance of gain setting resistors R_1 and R_2. The output voltage with these considerations (V_O') can be expressed with the following equation.

$$V_O{}' = \left[I_{LOAD} \times R_{SHUNT}{}' \times \left(\frac{R_2{}'}{R_1{}'}\right) \right] + \left[V_{OS} \times \left(\frac{R_1{}'+R_2{}'}{R_1{}'}\right) \right] \quad [V] \quad \cdots (2)$$

Where R_{SHUNT}', R_1', and R_2' are the values including the respective tolerances. For the input offset voltage for the op-amp (V_{OS}), only the positive direction is described for convenience of calculation.

Furthermore, the current sensing error (E_{rr}) attainable with this circuit can be expressed with the following equation.

$$E_{rr} = \frac{V_O{}'-V_O}{V_O} \times 100 \quad [\%] \quad \cdots (3)$$

How to determine the circuit constants

This section explains how to select the electronic components and determine the circuit constants based on the equations above. First, determine the following items as the required specifications of the current sensing circuit.

Current sensing range: $I_{LOADmin}$ to $I_{LOADmax}$ [A]

Current sensing error: E_{rr} [%]

Current sensing frequency: f_{sense} [Hz]

The current sensing frequency represents how fast the current can be measured relative to the current variation. If the current sensing speed is too slow, the sensing cannot follow the variation in the load current, leading to incorrect measurement. If the current sensing speed is too fast, noise and other irregularities may be detected, also leading to incorrect measurement. Therefore, it is necessary to define the sensing frequency that matches the time transient of the current to be measured.

Maximum voltage drops at the shunt resistor: $\Delta V_{SHUNTmax}$ [V]

The current sensing error is falling with increasing voltage drop (ΔV_{SHUNT}) at shunt resistor (R_{SHUNT}). (see Footnote 1). Since voltage drop (ΔV_{SHUNT}) of is between load and ground in low -side current sense circuit setup, ground voltage level seems to be raised. This can lead to instability of load circuit.

Maximum output voltage of the op-amp: V_{Omax} [V]

Determine the specification based on a balance between the maximum voltage which can provided at output of op-amp and the input voltage range that can be accepted by an A/D converter or other devices in the subsequent stage.

After determining the specifications, select the electric components and calculate the constants according to the procedures described in the following pages.

Step 1: Selection of the shunt resistor

The shunt resistor value is calculated with Equation (4) based on the required specifications determined above. In addition, since a large current flows through the shunt resistor, it is necessary to pay attention to the power rating. Along with, of course, using the shunt resistor within its own rating, it is recommended that a shunt resistor with a sufficient margin for the power capacity rating should be selected, considering the effect of heat generation by the shunt resistor on the surrounding area. The power rating is calculated with Equation (5). Select a shunt resistor satisfying these conditions.

Shunt resistor value
$$R_{SHUNT} = \frac{\Delta V_{SHUNTmax}}{I_{LOADmax}} \quad [\Omega] \quad \cdots (4)$$

Shunt resistor power rating
$$P_{SHUNT} \geq \Delta V_{SHUNT} \times I_{LOADmax} \quad [W] \quad \cdots (5)$$

Step 2: Design of the gain setting resistors

The signal gain is expressed with Equation (6). If either of R_1 or R_2 is determined, the resistor value of the other can be calculated.

$$\text{Gain} = \frac{V_{Omax}}{\Delta V_{SHUNTmax}} \quad [V/V] \quad \cdots (6)$$

$$= \frac{R_2}{R_1} \quad [V/V] \quad \cdots (7)$$

Step 3: Selection of the op-amp

When selecting the op-amp, it is necessary to pay attention to the following items.

- Offset voltage. Using Equations (1), (2), and (3), calculate the input offset voltage for the op-amp required to achieve current sensing error E_{rr}.
- The input voltage range of the op-amp must have a margin for ΔV_{SHUNT}.
- The output voltage range of the op-amp must be wider than the input voltage range of the system in the subsequent stage (for example, an A/D converter or microcontroller).
- The op-amp must be operable with the given system supply voltage.
- The frequency characteristics of the op-amp must be at least approximately 10 times higher than f_{sense}.

Step 4: Design of the frequency characteristics

Value of capacitor C_1 can calculated with Equation (8).

$$C_1 = \frac{1}{2\pi \times f_{sense} \times 10 \times R_2} \quad [F] \quad \cdots (8)$$

Step 5: Other peripheral circuits

• Protection circuit

In Figure 1, Zener diodes are used for over voltage protection on the input terminal of the op-amp in case of an open failure of the shunt resistor. If the shunt resistor opens, a voltage of +12 V at maximum may be applied to the input terminal of the op-amp [+12 V is the same voltage applied to the load (LOAD)]. Therefore, it is necessary to insert protective elements so that the voltage rating of the input terminal of the op-amp is not exceeded.

Depending on the circuit protection requirements, it is necessary to design the circuit protection including the protection circuit method and the type of protection diode.

How to determine the circuit constants (design example)

Within next chapter, according to the procedures for selecting the electronic components and setting the constants described in the previous section, select the electronic components and determine the circuit constants.

Assume that the required specifications of the low-side current detection circuit are as follows.

Current sensing range: $I_{LOADmin}$ to $I_{LOADmax}$ = 30 A to 50 A

Current sensing error: E_{rr} = 7%

Current sensing frequency: f_{sense} = 1 kHz

Voltage drop at shunt resistor: $\Delta V_{SHUNTmax}$ = 50 mV

Maximum output voltage of the op-amp: V_{Omax} = 3.3 V

Step 1: Selection of the shunt resistor

Value of shunt resistor is determined by substituting the values into Equations (4) and (5) above.

Shunt resistor value $$R_{SHUNT} = \frac{\Delta V_{SHUNTmax}}{I_{LOADmax}} = \frac{50m}{50} = 1 \quad [\mathrm{m\Omega}]$$

Shunt resistor power rating $$P_{SHUNT} \geq \Delta V_{SHUNT} \times I_{LOADmax} = 50m \times 50 = 2.5 \quad [\mathrm{W}]$$

In this example, the smallest type is selected from ROHM's shunt resistors.

PSR100 1mΩ, power rating 4 W (at 140°C), size 6.4 mm × 3.2 mm

Step 2: Design of the gain setting resistors

Values of resistors R1 and R2 for setting gain is determined with Equations (6) (7). Set R_1 = 2kΩ and calculate R_2.

$$\text{Gain} = \frac{V_{Omax}}{\Delta V_{SHUNTmax}} = \frac{R_2}{R_1}$$

$$R_2 = R_1 \times \left(\frac{V_{Omax}}{\Delta V_{SHUNTmax}}\right) = 2k \times \frac{3.3}{50m} = 132k \quad [\Omega]$$

For circuits where the gain is set with external resistors, it is necessary to consider the relative tolerance of R_1 and R_2 to determine the gain. Furthermore, to reduce the number of electronic components, select 120kΩ from the E24 series. Chip resistors from ROHM's series MCR01, MCR03, MCR10, or MCR18 can be selected. For these resistors, the tolerance of the resistor value is Class D ±0.5%, and the temperature characteristics are ±50 ppm/°C (between 100Ω and 1MΩ).

Step 3: Selection of the op-amp

The offset voltage of the op-amp required to achieve a current sensing error E_{rr} of 7% or less is derived from Equations (1), (2), and (3). Substitute Equations (1) and (2) into Equation (3), and rearrange it into an equation for calculating V_{OS}. For R_1', R_2', and R_{SHUNT}', the calculation includes the tolerance of the resistor values and the temperature characteristics of the resistor values. Current sensing error E_{rr} reaches its maximum under the following conditions. Substitute them into the equation to calculate V_{OS}.

R_1' = (Tolerance) × (Temperature characteristics) × R_1 = (-0.5%) × (-50 ppm/°C) × R_1

R_2' = (Tolerance) × (Temperature characteristics) × R_2 = (+0.5%) × (+50 ppm/°C) × R_2

R_{SHUNT}' = (Tolerance) × (Temperature characteristics) × R_{SHUNT} = (+1%) × (+100 ppm/°C) × R_{SHUNT}

$V_{OS} \leq 847\mu$ (at T_A = 125°C) [V]

Considering the other characteristics required for the op-amp, in this example ROHM's LMR1802G-LB is selected.

(Why ROHM's op-am LMR1802G-LB has been selected is described within Footnote 2.)

Step 4: Design of the frequency characteristics

Equation (8) is used to calculate filter capacitor C_1. 150pF is selected from E6 series.

$$C_1 = \frac{1}{2\pi \times f_{sense} \times 10 \times R_2} = \frac{1}{2\pi \times 1k \times 10 \times 120k} = 133 \qquad \text{[pF]}$$

Step 5: Other peripheral circuits

For the selected op-amp, LM1802G-LB, the rating of the input terminal voltage is 7 V. Furthermore, Zener Voltage (V_Z) is set to +5V, the supply voltage of the op-amp. If it is assumed that the shunt resistor is open Current flow through the Zener diodes (I_{ZD}) is calculated with below equation.

$$I_{ZD} = \frac{V_{in} - V_Z}{R_1} = \frac{12-5}{2k} = 3.5m \qquad \text{[A]}$$

If a zener diode with 5V Zener voltage and 3.5mA Zener current is required, ROHM's products can be selected such as TDZV5.1, UDZV4.7B, EDZV4.7B, and CDZV4.7B.

Following example circuit can now set up with calculated and selected electronic components.

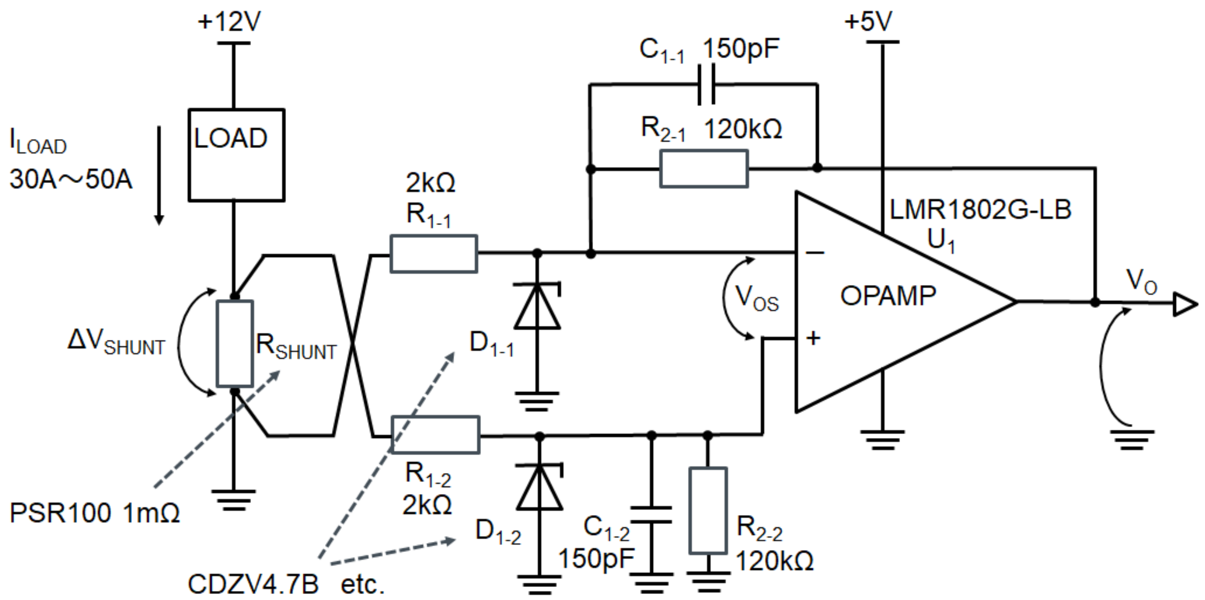


Figure 2. Circuit satisfying the required specifications of the Current Sensing Circuit

Bill of materials for the designed circuit.

Designator	Electronic component	Product item number
U1	Op-amp	LMR1802G-LB
R_{SHUNT}	Shunt resistor for current sensing	PSR100 1mΩ
D_{1-1}, D_{1-2}	Zener diodes for op-amp input terminal protection	TDZV5.1, UDZV4.7B, EDZV4.7B, CDZV4.7B, etc.
R_{1-1}, R_{1-2}	Gain setting resistors	MCR01/03/10/18 series 2kΩ, Class D (±0.5%)
R_{2-1}, R_{2-2}	Gain setting resistors	MCR01/03/10/18 series 120kΩ, Class D (±0.5%)
C_{1-1}, C_{1-2}	Capacitors for frequency characteristics	150 pF

Note: For the detailed specifications of each electronic component, refer to the data sheet on the ROHM website.

Table 1. Bill of material

Current sensing error and other characteristics of the designed circuit

At first, current sensing error is to verify. A current sensing error E_{rr} of 7% is to ensure in respect to input offset voltage, tolerance of each electronic component and temperature characteristics. Under the conditions for the input offset voltage for the op-amp, tolerance of the resistor value, and temperature characteristics as described in Table 2, current sensing error E_{rr} is to check.

Conditions	Input offset voltage V_{OS} (LMR1802G-LB)	Shunt resistor value R_{SHUNT} (PSR100)	Gain setting resistors R_1 and R_2
(1) Typ condition	Typ = 5 μV	Typ value	Typ value
(2) Only the offset voltage is at maximum (T_A = 25°C)	Max. 450 μV (T_A = 25°C)	Typ value	Typ value
(3) The offset voltage is at maximum and the tolerance of the resistor value is included (T_A = 25°C)	Max. 450 μV (T_A = 25°C)	Class F (±1%)	Class D (±0.5%)
(4) The offset voltage is at maximum and the tolerance of the resistor value is included (T_A = 125°C)	Max. 500 μV (T_A = 125°C)	Class F (±1%) +100 ppm/°C	Class D (±0.5%) ±50 ppm/°C

Note: For the temperature characteristics, increase in temperature due to self-heating is not considered.
Care must be taken if the parts may generate heat in actual equipment.

Table 2. Calculation conditions for plots in Figure 3

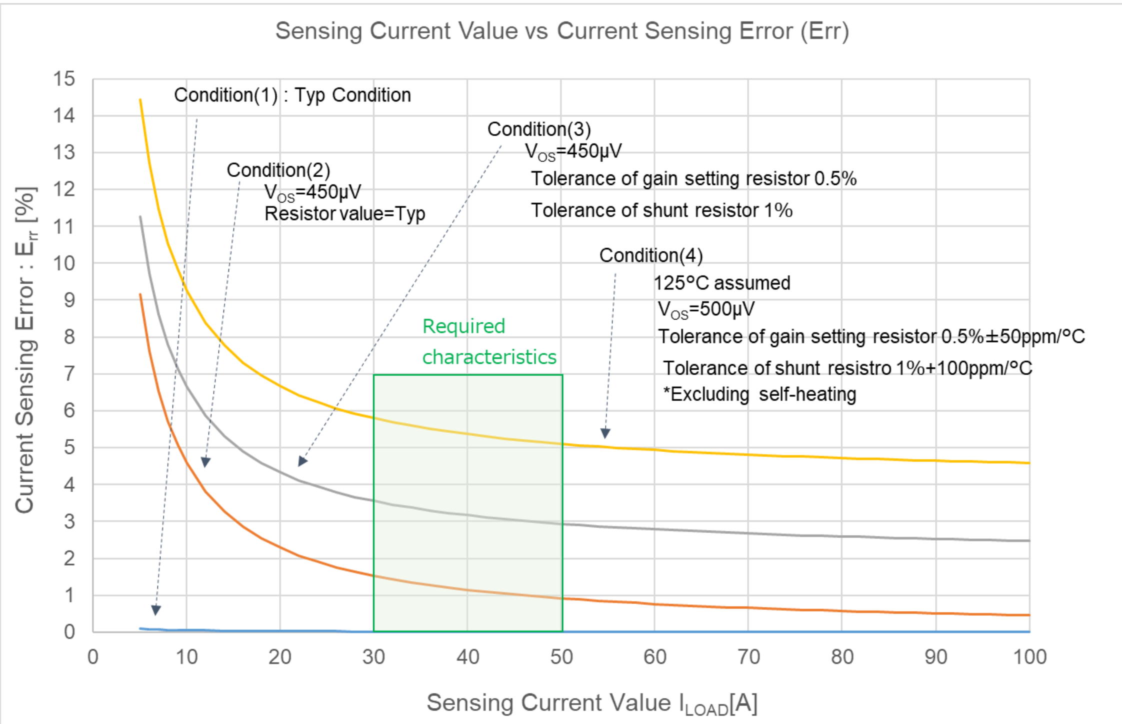


Figure 3. Current sensing error vs. sensing current value for the designed circuit

In the range I_{LOAD} = 30 A to 50 A as set in the specification, the current sensing error is below 7%.

Other characteristics are calculated as follows. It is confirmed that the circuit design can satisfy the required specifications.

Output maximum voltage V_{Omax} = 3.153 V [under Condition (4)] ≤ 3.3 V

Frequency characteristics f_{sense} = 8.85 kHz (Secured 8.85 times the actual operation frequency of 1 kHz.)

Verify with "ROHM Solution Simulator" (free web simulation tool)

Circuit simulation can be done with a free web simulator called "ROHM Solution Simulator". Since circuit constants can be changed, it is easy to design and verify the optimal circuit for the application.

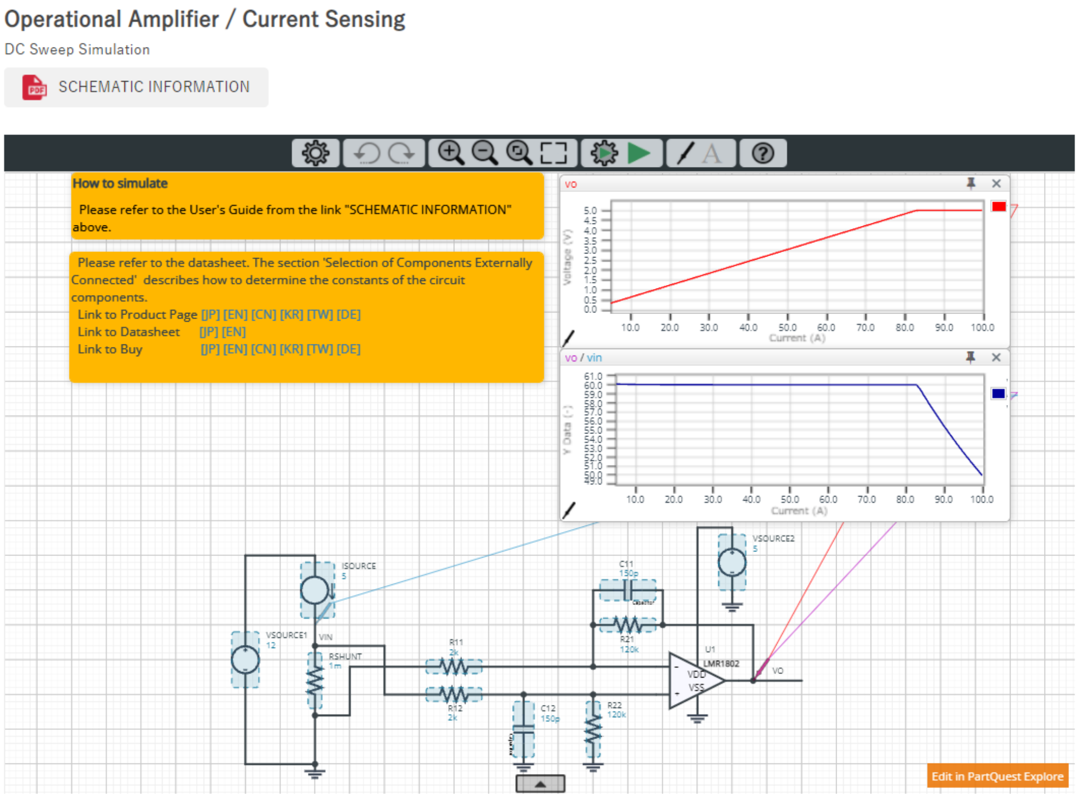


Figure 4. Simulation circuit example on ROHM Solution Simulator

The following circuits are prepared as low-side current sensing circuits, depending on the simulation parameters.

DC Sweep	: DC sweep of the current to be detected, output voltage and gain can be monitored.
DC Sweep with offset	: Add offset to check the effect to a current sensing error.
Transient Response	: The response of output voltage when current is applied in pulses.
Frequency Response	: Frequency characteristics of input terminal to output voltage.

*For more information about the simulation, please refer to the Schematic Information of each simulation circuit page.

*To access the ROHM Solution Simulator, you must be logged in with your MY ROHM account.

Please register for a MY ROHM account.

Thermal Evaluation Result of an actual board

In low-side current sensing circuits that use shunt resistors, operational amplifiers, and external components, the shunt resistors generate heat, so board design is also important. The results of thermal evaluation and simulation of an actual board are shown below. Please refer to the reference design [REFSENS002] for details of the circuit, board pattern, and evaluation data.

Conditions : 100A Current Sense
Shunt Resistor PSR400 2mΩ 4-parallel (0.5mΩ)

PCB Layout : Please refer to Reference Design [REFSENE002] for detail PCB layout.

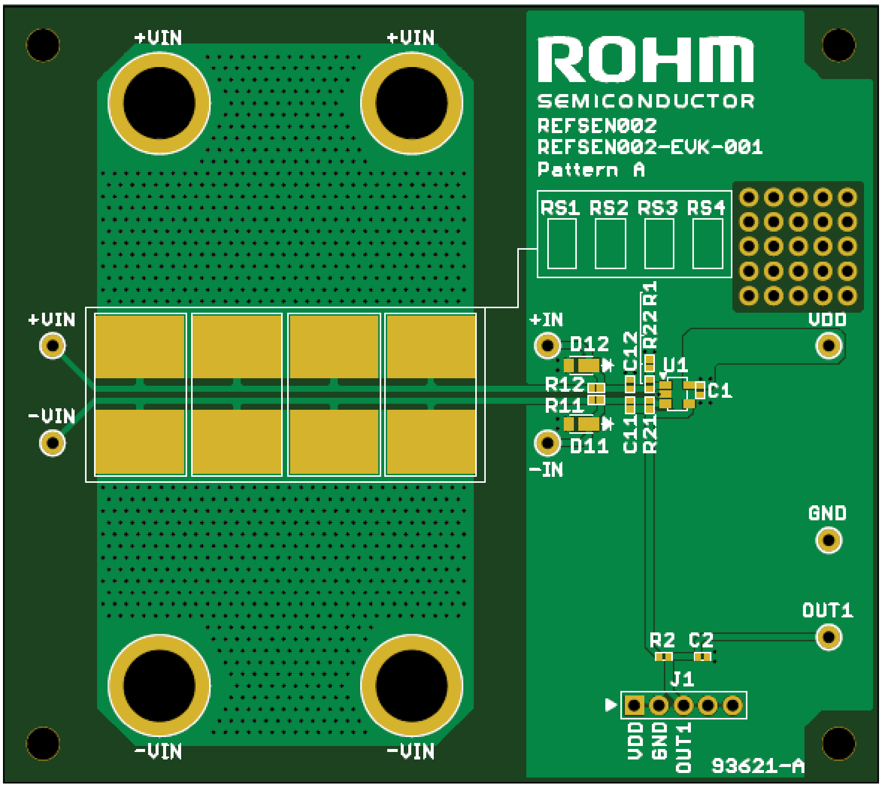
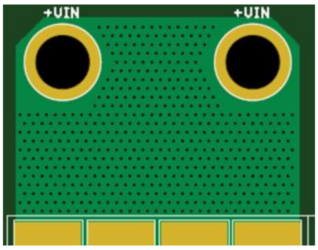
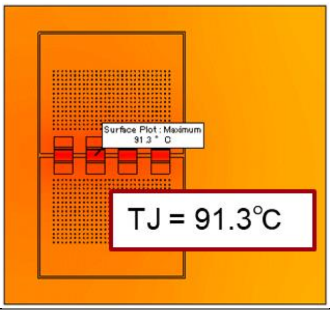
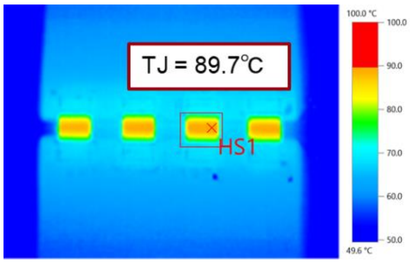
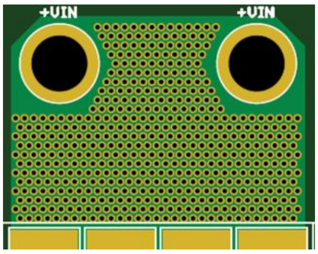
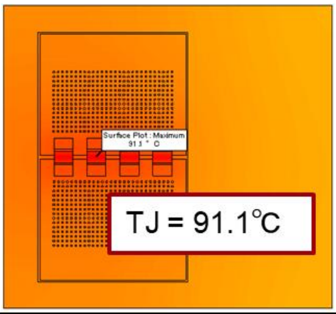
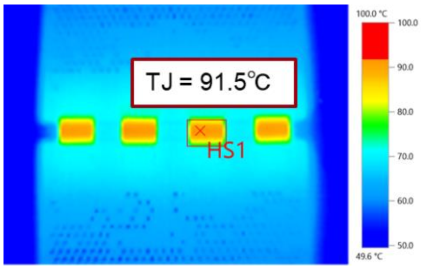
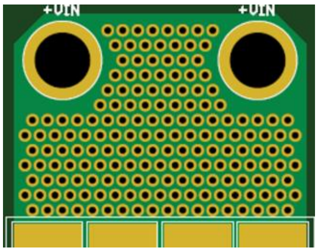
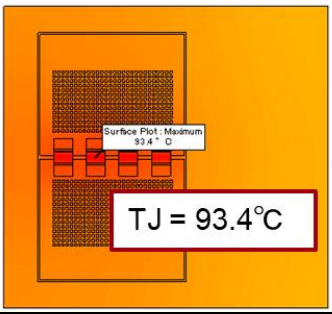
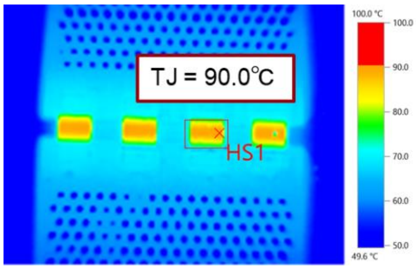
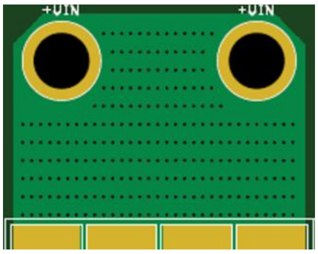
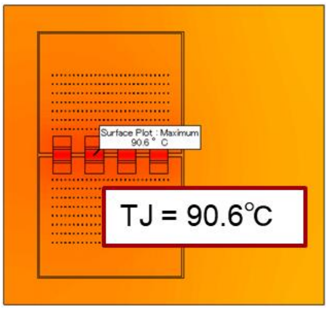
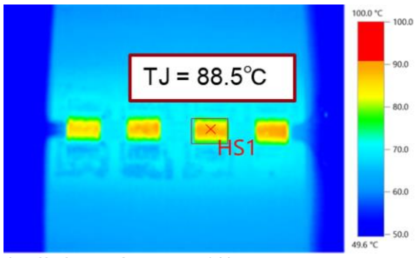
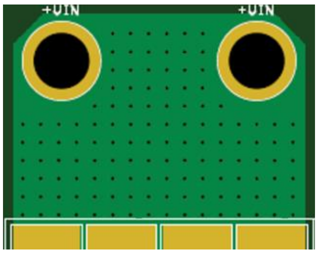
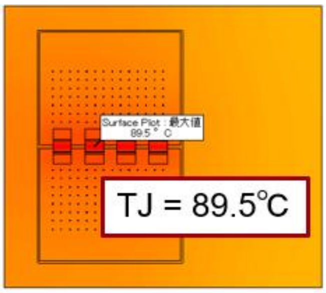


Figure 5. PCB Layout of Reference Design [REFSENS002]

Experiment content : It fixed the placement of the shunt resistor and the width and length of the pattern, and compared the heat generation by the thermal VIA diameter and placement.

Experimental results: According to the board actual measurement results in Table 3., the layout of heat dissipation vias "via diameter: φ0.3mm, left-right 1.2mm pitch, up-down 2.4mm pitch" results in the least heat generation. In addition, although actual measurements have not been performed, thermal simulation results show that "via diameter: φ0.3 mm, up-down and left-right 2.4 mm pitch" has the lowest heat generation. It can be seen that the design of thermal via diameter and placement is important. The trends of thermal simulation and actual measurement match relatively accurately, and it can be said that the use of thermal simulation is a design method that leads to a reduction in board design man-hours for applications that are sensitive to heat generation.

Table 3. Simulation and Evaluation result by Thermal VIA diameter and placement

Pattern and VIA	Thermal Simulation (100A)	Thermal Evaluation (100A)
 VIA diameter:φ0.3mm Up-down, Left-right :1.2mm pitch		 (Diff. from Sim -1.8%)
 VIA diameter:φ0.5mm Up-down, Left-right 1.2mm pitch		 (Diff. from Sim +0.44%)
 VIA diameter:φ0.8mm Up-down, Left-right 1.2mm pitch		 (Diff. from Sim -3.6%)
 VIA diameter:φ0.3mm Up-down 1.2mm pitch, Left-right 2.4mm pitch		 (Diff. from Sim -2.3%)
 VIA diameter:φ0.3mm Up-down, Left-right 2.4mm pitch		— （not measured）

Summary

How to determine circuit constants, calculating and selecting electronic components for a low side-current sensing circuit is explained within this application note.
ROHM manufactures both shunt resistors and high-performance op-amps that can meet the required specifications of various applications. For the products and product lineups listed in this application note, and for related application notes, refer to the following resources.

The calculation of the current detection accuracy in this application note does not include errors due to the noise characteristics and CMRR characteristics of the operational amplifier. If you need to calculate the accuracy more accurately, please take these factors into account.

<Added in Rev.005>
It conducted a heat generation evaluation on an actual board and showed that it is possible to reduce heat generation depending on the diameter and placement of thermal VIA. It also shows the possibility of using thermal simulation to reduce board design man-hours.
This application note uses an operational amplifier for the current sensing circuit, but ROHM has a lineup of Current Sense Amplifier (CSA) products with built-in gain resistors. The options will expand depending on the required current sensing accuracy, board size, price, etc.

References

Shunt Resistor Press Release: Expanding Lineup of Shunt Resistors Contributes to Miniaturization In High Power Applications
Application Note: Op-Amp/Comparator Tutorial

Related application notes

Shunt resistor : Method of Suppressing Increase in Surface Temperature of Shunt Resistors
Effect of PCB Design on Temperature Coefficient of Resistance
Thermal design : Effect of PCB Design on Temperature Coefficient of Resistance
Basics of Thermal Resistance and Heat Dissipation

Related products

Shunt resistor	Lineup of shunt resistors
High-performance op-amp	Lineup of high-performance op-amps
Diode	Lineup of Zener diodes
Current Sens Amplifier	Lineup of Current Sense Amplifier

Related Reference Design

REFSENS002 Up to 100A Current Sensing with Shunt Resistor and OpAmp Reference Design
REFSENS003 Up to 30A Current Sensing with Shunt Resistor and Current Sense Amp Reference Design

History

Jun. '21 : Rev.001 Draft
Jul. '21 :Rev.002, 003 typo correction
Oct. '21 :Rev.004 Add links of ROHM Solution Simulator
Jan, '23 :Rev.005 Add thermal simulation and evaluation on actual board

Footnote1

Why is current sensing error falling with increasing voltage drop (ΔVSHUNT) at shunt resistor (RSHUNT)? As can also be seen from Equation (2), the current sensing error depends on the voltage drop at the shunt resistor (ΔV_{SHUNT}) and the input offset voltage for the op-amp (V_{OS}).

The sensing error can be improved by selecting an op-amp with a smaller input offset voltage. A balance between the sensing error and the cost or characteristics should be considered.

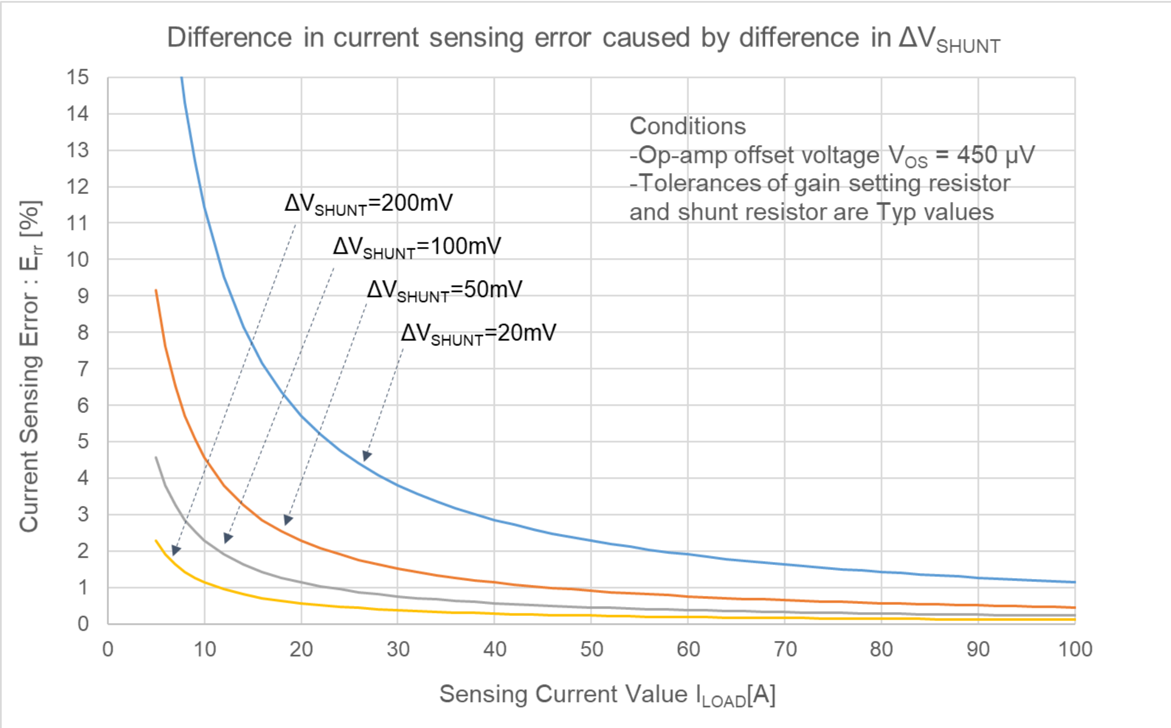


Figure 6. Effect of difference in ΔV_{SHUNT} on the current sensing error

Footnote2

This footnote explains characteristics of LMR1802G-LB and why this op-amp has been selected. The main characteristics of LMR1802G-LB and the result of their examination against the required specifications are shown below.

Parameter	Electrical characteristic	reason for choosing LMR1802G-LG
Supply voltage range	2.5 V to 5.5 V	Operable in the 3.3 V and 5 V systems.
Output voltage range	$V_{OH} = V_{DD} - V_{OUT}$: Max. 50 mV V_{OL}: Max. 50 mV	If the input voltage range of an A/D converter or other devices in the subsequent stage is set to approximately 4 V and the op-amp is operated in the 5 V system, the circuit can be designed so that V_O < 4 V.
Input voltage range	Input common-mode voltage range: V_{SS} to V_{DD} - 1.0 V	When the op-amp is operated normally, the input voltage will be increased only to the ΔV_{SHUNT} level at the highest, causing no issues.
Input offset voltage	T_A = 25°C, Typ = 5 μV Max. 500 μV over the entire temperature range	Satisfies the offset voltage specification required for the op-amp.

Note: For the detailed specifications of LMR1802G-LB, refer to the data sheet.

Table 4. Summary of the LMR1802G-LB op-amp and result of examination

The required input offset voltage range is ensured over the entire temperature range. Op-amp LMR1802G-LB was selected because of: small temperature drift of the offset voltage (0.4 μV/°C). In power applications, heat may be generated not only by the shunt resistor but also by peripheral circuits (for example, by a switching transistor). Therefore, it can be anticipated that the surrounding temperature environment is undesirable. In addition, if the gain setting is relatively high, the input referred noise voltage also emerges as an error. LMR1802G-LB has achieved an industry-leading low noise with excellent usability.

Notes

1) The information contained herein is subject to change without notice.

2) Before you use our Products, please contact our sales representative and verify the latest specifications :

3) Although ROHM is continuously working to improve product reliability and quality, semiconductors can break down and malfunction due to various factors.
Therefore, in order to prevent personal injury or fire arising from failure, please take safety measures such as complying with the derating characteristics, implementing redundant and fire prevention designs, and utilizing backups and fail-safe procedures. ROHM shall have no responsibility for any damages arising out of the use of our Poducts beyond the rating specified by ROHM.

4) Examples of application circuits, circuit constants and any other information contained herein are provided only to illustrate the standard usage and operations of the Products. The peripheral conditions must be taken into account when designing circuits for mass production.

5) The technical information specified herein is intended only to show the typical functions of and examples of application circuits for the Products. ROHM does not grant you, explicitly or implicitly, any license to use or exercise intellectual property or other rights held by ROHM or any other parties. ROHM shall have no responsibility whatsoever for any dispute arising out of the use of such technical information.

6) The Products specified in this document are not designed to be radiation tolerant.

7) For use of our Products in applications requiring a high degree of reliability (as exemplified below), please contact and consult with a ROHM representative : transportation equipment (i.e. cars, ships, trains), primary communication equipment, traffic lights, fire/crime prevention, safety equipment, medical systems, servers, solar cells, and power transmission systems.

8) Do not use our Products in applications requiring extremely high reliability, such as aerospace equipment, nuclear power control systems, and submarine repeaters.

9) ROHM shall have no responsibility for any damages or injury arising from non-compliance with the recommended usage conditions and specifications contained herein.

10) ROHM has used reasonable care to ensure the accuracy of the information contained in this document. However, ROHM does not warrants that such information is error-free, and ROHM shall have no responsibility for any damages arising from any inaccuracy or misprint of such information.

11) Please use the Products in accordance with any applicable environmental laws and regulations, such as the RoHS Directive. For more details, including RoHS compatibility, please contact a ROHM sales office. ROHM shall have no responsibility for any damages or losses resulting non-compliance with any applicable laws or regulations.

12) When providing our Products and technologies contained in this document to other countries, you must abide by the procedures and provisions stipulated in all applicable export laws and regulations, including without limitation the US Export Administration Regulations and the Foreign Exchange and Foreign Trade Act.

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ROHM SEMICONDUCTOR

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