# *MAXIM*

# Precision, High-Side Current-Sense Amplifiers

*MAX471/MAX472*

## _____General Description

The MAX471/MAX472 are complete, bidirectional, high-side current-sense amplifiers for portable PCs, telephones, and other systems where battery/DC power-line monitoring is critical. High-side power-line monitoring is especially useful in battery-powered systems, since it does not interfere with the ground paths of the battery chargers or monitors often found in "smart" batteries.

The MAX471 has an internal 35mΩ current-sense resistor and measures battery currents up to ±3A. For applications requiring higher current or increased flexibility, the MAX472 functions with external sense and gain-setting resistors. Both devices have a current output that can be converted to a ground-referred voltage with a single resistor, allowing a wide range of battery voltages and currents.

An open-collector SIGN output indicates current-flow direction, so the user can monitor whether a battery is being charged or discharged. Both devices operate from 3V to 36V, draw less than 100µA over temperature, and include a 18µA max shutdown mode.

## _____Applications

Portable PCs:
    Notebooks/Subnotebooks/Palmtops

Smart Battery Packs

Cellular Phones

Portable Phones

Portable Test/Measurement Systems

Battery-Operated Systems

Energy Management Systems
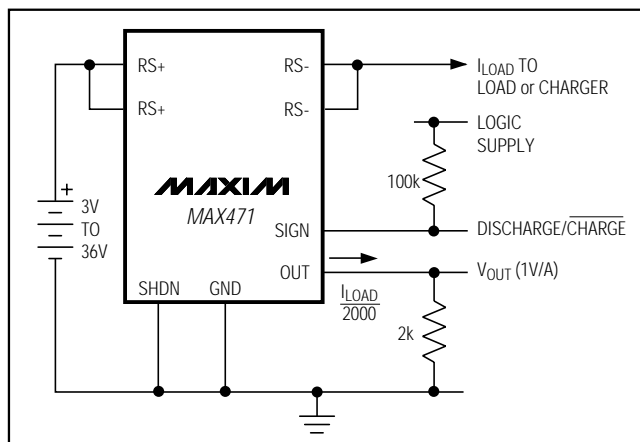
## _____Features

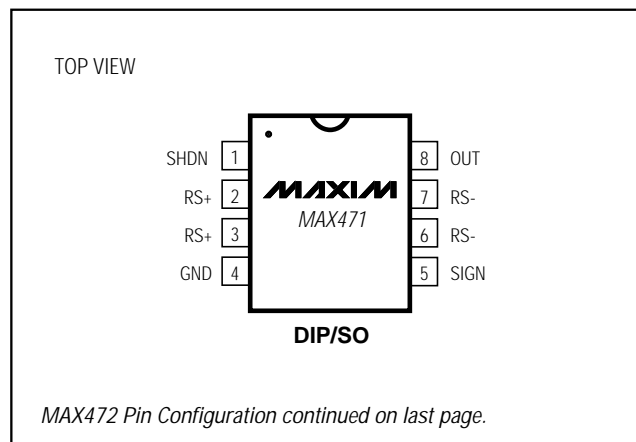♦ **Complete High-Side Current Sensing**

♦ **Precision Internal Sense Resistor (MAX471)**

♦ **2% Accuracy Over Temperature**

♦ **Monitors Both Charge and Discharge**

♦ **3A Sense Capability with Internal Sense Resistor (MAX471)**

♦ **Higher Current-Sense Capability with External Sense Resistor (MAX472)**

♦ **100µA Max Supply Current**

♦ **18µA Max Shutdown Mode**

♦ **3V to 36V Supply Operation**

♦ **8-Pin DIP/SO Packages**

## _____Ordering Information

| PART | TEMP. RANGE | PIN-PACKAGE |
|------|-------------|-------------|
| **MAX471**CPA | 0°C to +70°C | 8 Plastic DIP |
| MAX471CSA | 0°C to +70°C | 8 SO |
| MAX471EPA | -40°C to +85°C | 8 Plastic DIP |
| MAX471ESA | -40°C to +85°C | 8 SO |
| **MAX472**CPA | 0°C to +70°C | 8 Plastic DIP |
| MAX472CSA | 0°C to +70°C | 8 SO |
| MAX472EPA | -40°C to +85°C | 8 Plastic DIP |
| MAX472ESA | -40°C to +85°C | 8 SO |

## _____Typical Operating Circuit



## _____Pin Configurations



TOP VIEW

DIP/SO

*MAX472 Pin Configuration continued on last page.*

*MAXIM* _____ **Maxim Integrated Products   1**

# Precision, High-Side Current-Sense Amplifiers

## ABSOLUTE MAXIMUM RATINGS

Supply Voltage, RS+, RS-, V$_{CC}$ to GND....................-0.3V, +40V
RMS Current, RS+ to RS- (MAX471 only)..........................±3.3A
Peak Current, (RS+ to RS-) ....................................see Figure 5
Differential Input Voltage, RG1 to RG2 (MAX472 only) .....±0.3V
Voltage at Any Pin Except SIGN
   MAX471 only ..........................................-0.3V to (RS+ - 0.3V)
   MAX472 only ..........................................-0.3V to (V$_{CC}$ + 0.3V)
Voltage at SIGN......................................................-0.3V to +40V
Current into SHDN, GND, OUT, RG1, RG2, V$_{CC}$................±50mA
Current into SIGN................................................+10mA, -50mA

Continuous Power Dissipation (T$_A$ = +70°C)
 MAX471 (Note 1):
  Plastic DIP (derate 17.5mW/°C above +70°C) .................1.4W
  SO (derate 9.9mW/°C above +70°C) ............................791mW
 MAX472 :
  Plastic DIP (derate 9.09mW/°C above +70°C) ..............727mW
  SO (derate 5.88mW/°C above +70°C) ..........................471mW
Operating Temperature Ranges
  MAX47_C_A .......................................................0°C to +70°C
  MAX47_E_A .....................................................-40°C to +85°C
Junction Temperature Range ...........................-60°C to +150°C
Storage Temperature Range ............................-60°C to +160°C
Lead Temperature (soldering, 10sec) ............................+300°C

**Note 1:** Due to special packaging considerations, MAX471 (DIP, SO) has a higher power dissipation rating than the MAX472. RS+ and RS- must be soldered to large copper traces to achieve this dissipation rating.

*Stresses beyond those listed under "Absolute Maximum Ratings" may cause permanent damage to the device. These are stress ratings only, and functional operation of the device at these or any other conditions beyond those indicated in the operational sections of the specifications is not implied. Exposure to absolute maximum rating conditions for extended periods may affect device reliability.*

## ELECTRICAL CHARACTERISTICS—MAX471

(RS+ = +3V to +36V, T$_A$ = T$_{MIN}$ to T$_{MAX}$, unless otherwise noted. Typical values are at T$_A$ = +25°C.)

| PARAMETER | SYMBOL | CONDITIONS | | MIN | TYP | MAX | UNITS |
|---|---|---|---|---|---|---|---|
| Supply Voltage | V$_{RS+}$ | | | 3 | | 36 | V |
| Supply Current | I$_{RS+}$ | I$_{LOAD}$ = 0A, excludes I$_{SIGN}$ | | | 50 | 113 | µA |
| Sense Current | I$_{LOAD}$ | | | | | ±3 | A$_{RMS}$ |
| Sense Resistor | R$_{SENSE}$ | | | | 35 | 70 | mΩ |
| Current-Sense Ratio | I$_{OUT}$/ I$_{LOAD}$ | I$_{LOAD}$ = 1A, RS+ = 10V | MAX471C | 0.490 | 0.500 | 0.510 | mA/A |
| | | | MAX471E | 0.4875 | 0.500 | 0.5125 | |
| No-Load OUT Error | | I$_{LOAD}$ = 0A, RS+ = 10V | MAX471C | | | 2.5 | µA |
| | | | MAX471E | | | 3.0 | |
| Low-Level OUT Error | | I$_{LOAD}$ = 30mA, RS+ = 10V | MAX471C | | | ±2.5 | µA |
| | | | MAX471E | | | ±3.0 | |
| Power-Supply Rejection Ratio | PSRR | 3V ≤ RS+ ≤ 36V, I$_{LOAD}$ = 1A | | | | 0.1 | %/V |
| SIGN Threshold (I$_{LOAD}$ required to switch SIGN) | | MAX471C | | | ±4.0 | ±6.0 | mA |
| | | MAX471E | | | | ±7.0 | |
| SIGN Output Leakage Current | | V$_{SIGN}$ = 36V | | | | 1.0 | µA |
| SIGN Sink Current | I$_{OL}$ | V$_{SIGN}$ = 0.3V | | 0.1 | | | mA |
| Shutdown Supply Current | I$_{RS+(SHDN)}$ | V$_{SHDN}$ = 2.4V; V$_{CC}$ = 3V to 20V | | | 1.5 | 18.0 | µA |
| SHDN Input Low Voltage | V$_{IL}$ | | | | | 0.3 | V |
| SHDN Input Low Current | I$_{IL}$ | V$_{SHDN}$ = 0V | | | | 1.0 | µA |
| SHDN Input High Voltage | V$_{IH}$ | | | 2.4 | | | V |
| SHDN Input High Current | I$_{IH}$ | V$_{SHDN}$ = 2.4V | | | | 1.0 | µA |
| OUT Output Voltage Range | V$_{OUT}$ | | | 0 | | V$_{RS+}$ - 1.5 | V |
| OUT Output Resistance | R$_{OUT}$ | I$_{LOAD}$ = 3.0A, V$_{OUT}$ = 0V to (V$_{RS+}$ - 1.5V) | | 1 | 3 | | MΩ |
| OUT Rise, Fall Time | t$_R$, t$_F$ | I$_{LOAD}$ = 50mA to 3.0A, R$_{OUT}$ = 2kΩ, C$_{OUT}$ = 50pF, 10% to 90% | | | 4 | | µs |
| OUT Settling Time to 1% of Final Value | t$_S$ | I$_{LOAD}$ = 100mA to 3.0A, R$_{OUT}$ = 2kΩ, C$_{OUT}$ = 50pF | | | 15 | | µs |

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## ELECTRICAL CHARACTERISTICS—MAX472

($V_{CC}$ = +3V to +36V, RG1 = RG2 = 200Ω, $T_A$ = $T_{MIN}$ to $T_{MAX}$, unless otherwise noted. Typical values are at $T_A$ = +25°C.)

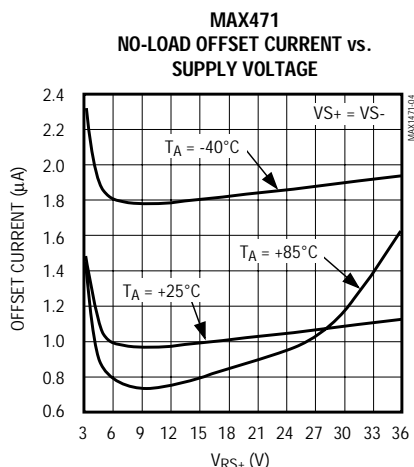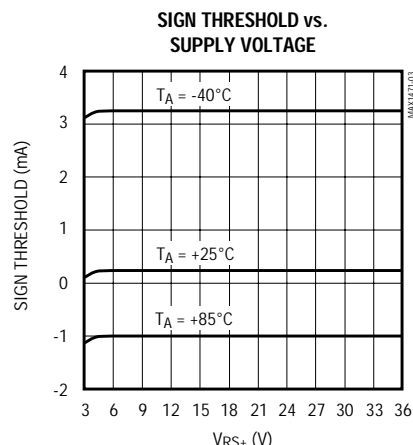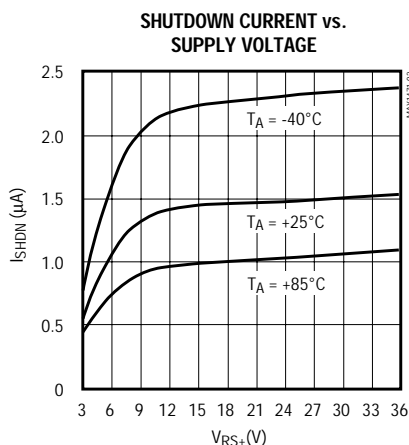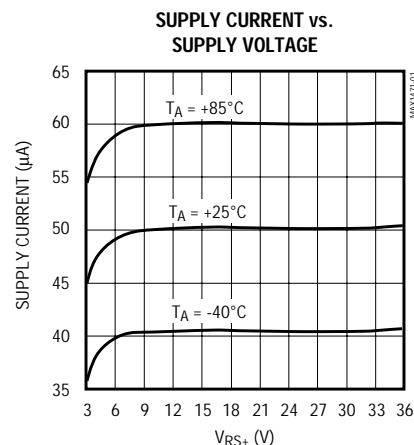| PARAMETER | SYMBOL | CONDITIONS | | MIN | TYP | MAX | UNITS |
|---|---|---|---|---|---|---|---|
| Supply Voltage | $V_{CC}$ | | | 3 | | 36 | V |
| Supply Current | $I_{CC}$ | $I_{LOAD}$ = 0A, excludes $I_{SIGN}$; $V_{CC}$ = 3V to 20V | | | 20 | 48 | µA |
| Input Offset Voltage (Note 2) | $V_{OS}$ | MAX472C | | | | 120 | µV |
| | | MAX472E | | | | 140 | |
| Input Bias Current | $I_{RG1}$, $I_{RG2}$ | | | | 20 | 35 | µA |
| Input Bias-Current Matching | $I_{OS}$ | $I_{RG1}$ - $I_{GR2}$ | | | ±0.4 | ±3.0 | µA |
| OUT Current Accuracy | $I_{RG}/I_{OUT}$ | $V_{SENSE}$ = 100mV, $V_{CC}$ = 10V (Note 3) | MAX472C | | | ±2 | % |
| | | | MAX472E | | | ±2.5 | |
| No-Load OUT Error | | $V_{CC}$ = 10V, $V_{SENSE}$ = 0V | MAX472C | | | 2.5 | µA |
| | | | MAX472E | | | 3 | |
| Low-Level OUT Error | | $V_{CC}$ = 10V, $V_{SENSE}$ = 3mV | MAX472C | | | ±2.5 | µA |
| | | | MAX472E | | | ±3.0 | |
| Power-Supply Rejection Ratio | PSRR | 3V ≤ $V_{CC}$ ≤ 36V, $V_{SENSE}$ = 100mV | | | | 0.1 | %/V |
| SIGN Threshold ($V_{SENSE}$ required to switch SIGN) | | $V_{CC}$ = 10V | MAX472C | | 60 | 120 | µV |
| | | | MAX472E | | 60 | 140 | |
| SIGN Output Leakage Current | | $V_{SIGN}$ = 36V | | | | 1.0 | µA |
| SIGN Output Sink Current | | $V_{SIGN}$ = 0.3V | | 0.1 | | | mA |
| Shutdown Supply Current | $I_{CC(SHDN)}$ | $V_{SHDN}$ = 2.4V; $V_{CC}$ = 3V to 20V | | | 1.5 | 18.0 | µA |
| SHDN Input Low Voltage | $V_{IL}$ | | | | | 0.3 | V |
| SHDN Input Low Current | $I_{IL}$ | $V_{SHDN}$ = 0V | | | | 1.0 | µA |
| SHDN Input High Voltage | $V_{IH}$ | | | 2.4 | | | V |
| SHDN Input High Current | $I_{IH}$ | $V_{SHDN}$ = 2.4V | | | | 1.0 | µA |
| OUT Output Voltage Range | $V_{OUT}$ | | | 0 | | $V_{CC}$ - 1.5 | V |
| OUT Output Resistance | $R_{OUT}$ | $I_{OUT}$ = 1.5mA | | 1 | 3 | | MΩ |
| OUT Rise, Fall Time | $t_R$, $t_F$ | $V_{SENSE}$ = 5mV to 150mV, $R_{OUT}$ = 2kΩ, $C_{OUT}$ = 50pF, 10% to 90% | | | 4 | | µs |
| OUT Settling Time to 1% of Final Value | $t_S$ | $V_{SENSE}$ = 5mV to 150mV, $R_{OUT}$ = 2kΩ, $C_{OUT}$ = 50pF | | | 15 | | µs |
| Maximum Output Current | $I_{OUT}$ | | | 1.5 | | | mA |

**Note 2:** $V_{OS}$ is defined as the input voltage ($V_{SENSE}$) required to give minimum $I_{OUT}$.
**Note 3:** $V_{SENSE}$ is the voltage across the sense resistor.

# Precision, High-Side
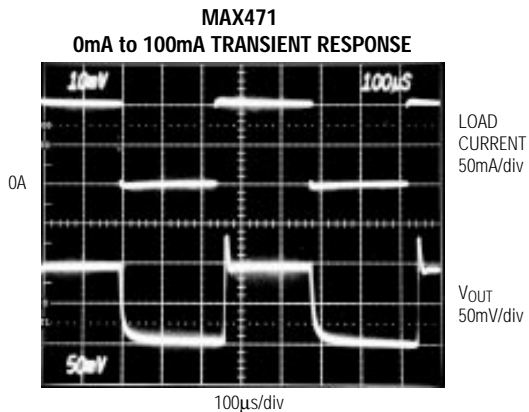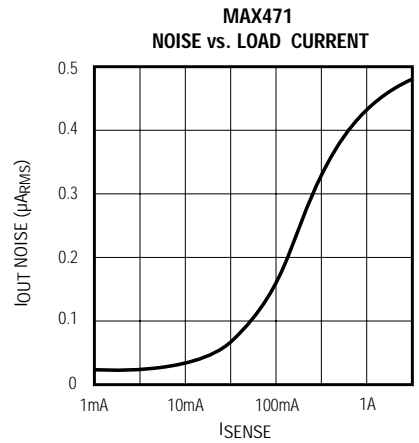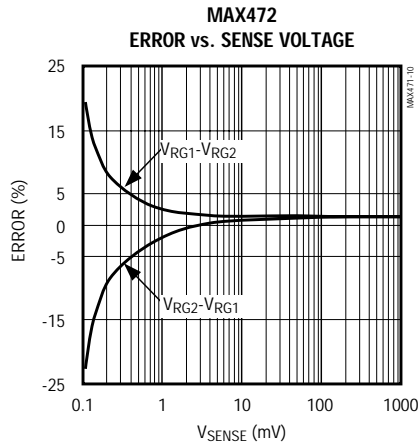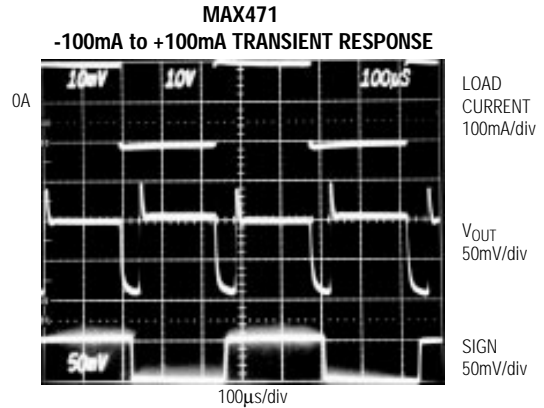# Current-Sense Amplifiers

## _____Typical Operating Characteristics

(Typical Operating Circuit (MAX471) or circuit of Figure 4, RG1 = RG2 = 200Ω, $R_{OUT}$ = 2kΩ (MAX472), $T_A$ = +25°C, unless otherwise noted.)

**SUPPLY CURRENT vs. SUPPLY VOLTAGE**

**SHUTDOWN CURRENT vs. SUPPLY VOLTAGE**

**SIGN THRESHOLD vs. SUPPLY VOLTAGE**

**MAX471 NO-LOAD OFFSET CURRENT vs. SUPPLY VOLTAGE**

**MAX471 ERROR vs. LOAD CURRENT**

**MAX471 POWER-SUPPLY REJECTION RATIO vs. FREQUENCY**

**MAX471 RS+ TO RS- RESISTANCE vs. TEMPERATURE**

**MAX472 NO-LOAD OUTPUT ERROR vs. SUPPLY VOLTAGE**

**MAX472 ERROR vs. SUPPLY VOLTAGE**

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**MAX471/MAX472**

## _____Typical Operating Characteristics (continued)

(Typical Operating Circuit (MAX471) or circuit of Figure 4, RG1 = RG2 = 200Ω, $R_{OUT}$ = 2kΩ (MAX472), $T_A$ = +25°C, unless otherwise noted.)

**MAX472**
**ERROR vs. SENSE VOLTAGE**



**MAX471**
**NOISE vs. LOAD CURRENT**



**MAX471**
**0mA to 100mA TRANSIENT RESPONSE**



$V_{CC}$ = 10V, $R_{OUT}$ = 2kΩ 1%, SIGN PULL-UP = 50kΩ 1%

**MAX471**
**-100mA to +100mA TRANSIENT RESPONSE**



$V_{CC}$ = 10V, $R_{OUT}$ = 2kΩ 1%, SIGN PULL-UP = 50kΩ 1%

**MAX471**
**START-UP DELAY**



$I_{LOAD}$ = 1A, $R_{OUT}$ = 2kΩ 1%

**MAX471**
**0A TO 3A TRANSIENT RESPONSE**



$R_{OUT}$ = 2kΩ 1%

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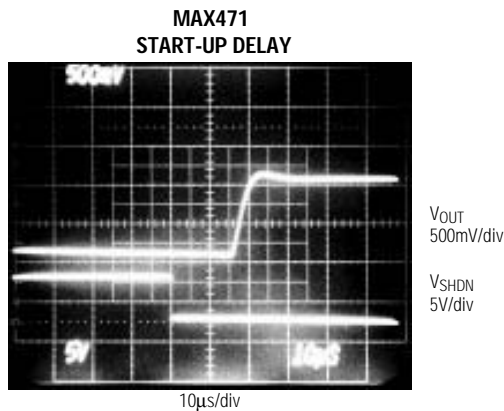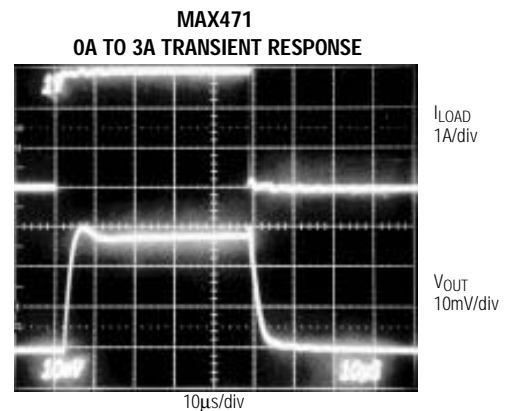
# Precision, High-Side
# Current-Sense Amplifiers

_____**Pin Description**

| PIN | | NAME | FUNCTION |
|---|---|---|---|
| MAX471 | MAX472 | | |
| 1 | 1 | SHDN | Shutdown. Connect to ground for normal operation. When high, supply current is less than 5µA. |
| 2, 3 | — | RS+ | Battery (or power) side of the internal current-sense resistor. The "+" indicates direction of flow for SIGN output only. Connect pins 2 and 3 together at the package. |
| — | 2 | N.C. | No Connect—no internal connection |
| — | 3 | RG1 | Gain Resistor. Connect to battery side of current-sense resistor through the gain resistor. |
| 4 | 4 | GND | Ground or Battery Negative Terminal |
| 5 | 5 | SIGN | An open-collector logic output. For the MAX471, a low level indicates current is flowing from RS- to RS+. For the MAX472, a low level indicates a negative $V_{SENSE}$ (see Figure 2). SIGN is high impedance when SHDN is high. Leave open if SIGN is not needed. |
| 6, 7 | — | RS- | Load side of the internal current-sense resistor. The "-" indicates direction of flow for SIGN output only. Connect pins 6 and 7 together at the package. |
| — | 6 | RG2 | Gain Resistor. Connect to load side of current-sense resistor through the gain resistor. |
| — | 7 | $V_{CC}$ | Power input for MAX472. Connect to sense resistor ($R_{SENSE}$) junction with RG1. |
| 8 | 8 | OUT | Current output that is proportional to the magnitude of the sensed current flowing through $R_{SENSE}$. A 2kΩ resistor from this pin to ground will result in a voltage equal to 1V/Amp of sensed current in the MAX471. |

_____**Detailed Description**

The MAX471 and MAX472 current-sense amplifier's unique topology allows a simple design to accurately monitor current flow. The MAX471/MAX472 contain two amplifiers operating as shown in Figures 1 and 2. The battery/load current flows from RS+ to RS- (or vice versa) through $R_{SENSE}$. Current flows through either RG1 and Q1 or RG2 and Q2, depending on the sense-resistor current direction. Internal circuitry, not shown in Figures 1 and 2, prevents Q1 and Q2 from turning on at the same time. The MAX472 is identical to the MAX471, except that $R_{SENSE}$ and gain-setting resistors RG1 and RG2 are external (Figure 2).

To analyze the circuit of Figure 1, assume that current flows from RS+ to RS- and that OUT is connected to GND through a resistor. In this case, amplifier A1 is active and output current $I_{OUT}$ flows from the emitter of Q1. Since no current flows through RG2 (Q2 is off), the negative input of A1 is equal to $V_{SOURCE}$ - ($I_{LOAD}$ x $R_{SENSE}$). The open-loop gain of A1 forces its positive input to essentially the same level as the negative input. Therefore, the drop across RG1 equals $I_{LOAD}$ x $R_{SENSE}$. Then, since $I_{OUT}$ flows through Q1 and RG (ignoring the extremely low base currents), $I_{OUT}$ x RG1 = $I_{LOAD}$ x $R_{SENSE}$, or:

$$I_{OUT} = (I_{LOAD} \times R_{SENSE}) / RG1$$

### Current Output
The output voltage equation for the MAX471/MAX472 is given below. In the MAX471, the current-gain ratio has been preset to 500µA/A so that an output resistor ($R_{OUT}$) of 2kΩ yields 1V/A for a full-scale value of +3V at ±3A. Other full-scale voltages can be set with different $R_{OUT}$ values, but the output voltage can be no greater than $V_{RS+}$ - 1.5V for the MAX471 or $V_{RG_-}$ - 1.5V for the MAX472.

$$V_{OUT} = (R_{SENSE} \times R_{OUT} \times I_{LOAD}) / RG$$

where $V_{OUT}$ = the desired full-scale output voltage, $I_{LOAD}$ = the full-scale current being sensed, $R_{SENSE}$ = the current-sense resistor, $R_{OUT}$ = the voltage-setting resistor, and RG = the gain-setting resistor (RG = RG1 = RG2).

The above equation can be modified to determine the $R_{OUT}$ required for a particular full-scale range:

$$R_{OUT} = (V_{OUT} \times RG) / (I_{LOAD} \times R_{SENSE})$$

For the MAX471, this reduces to:

$$R_{OUT} = V_{OUT} / (I_{LOAD} \times 500µA/A)$$

OUT is a high-impedance current-source output that can be connected to other MAX471/MAX472 OUT pins

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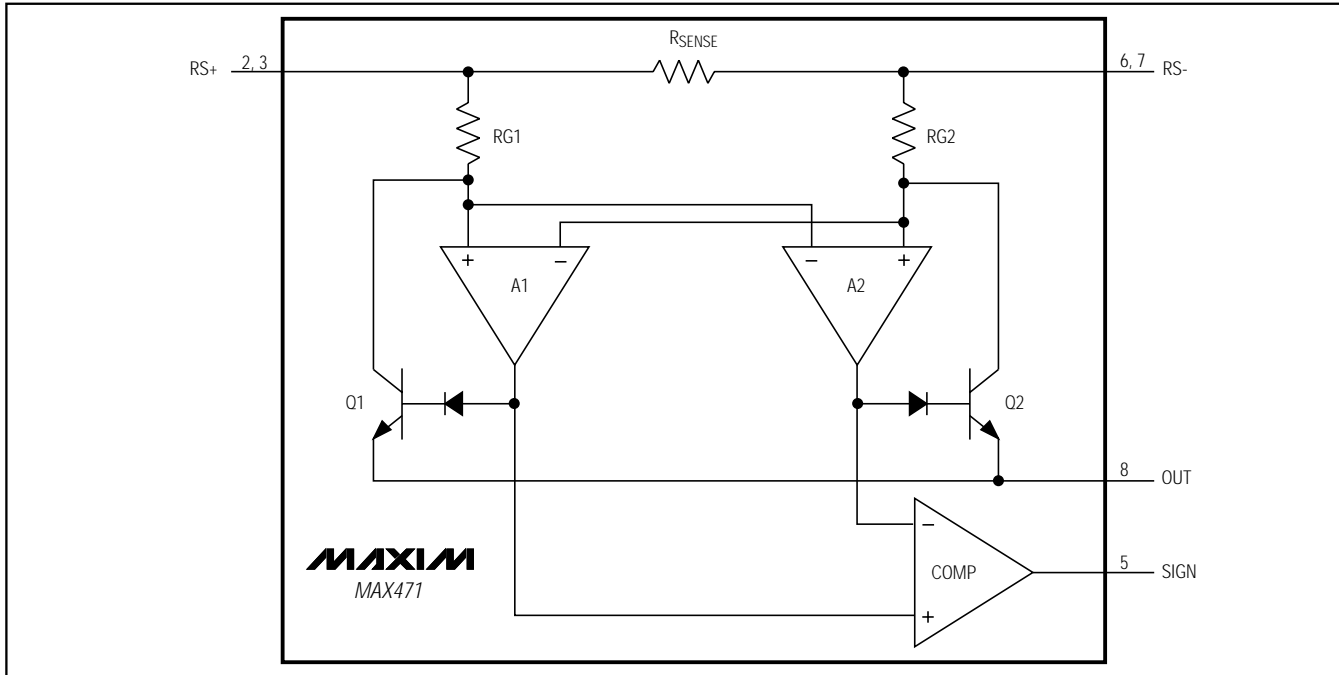
**MAX471/MAX472**



Figure 1.  MAX471 Functional Diagram
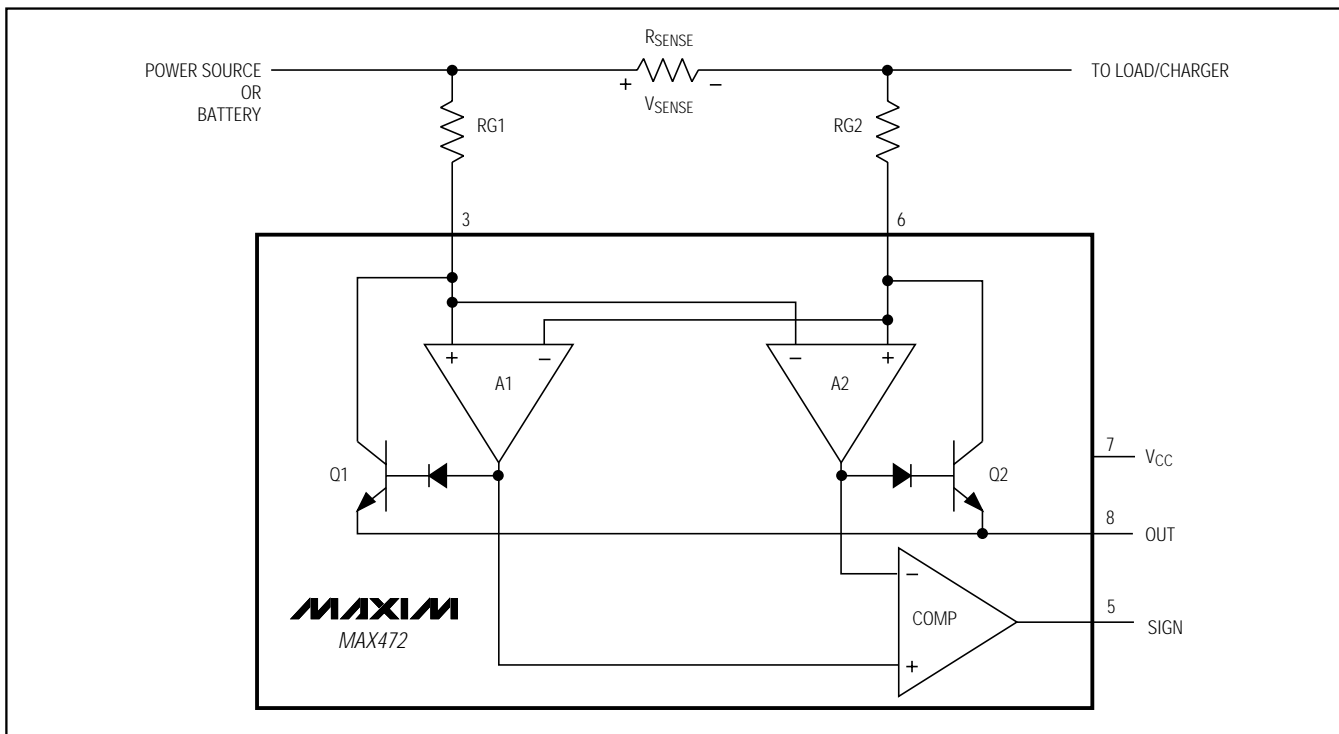


Figure 2.  MAX472 Functional Diagram

**MAX471/MAX472**
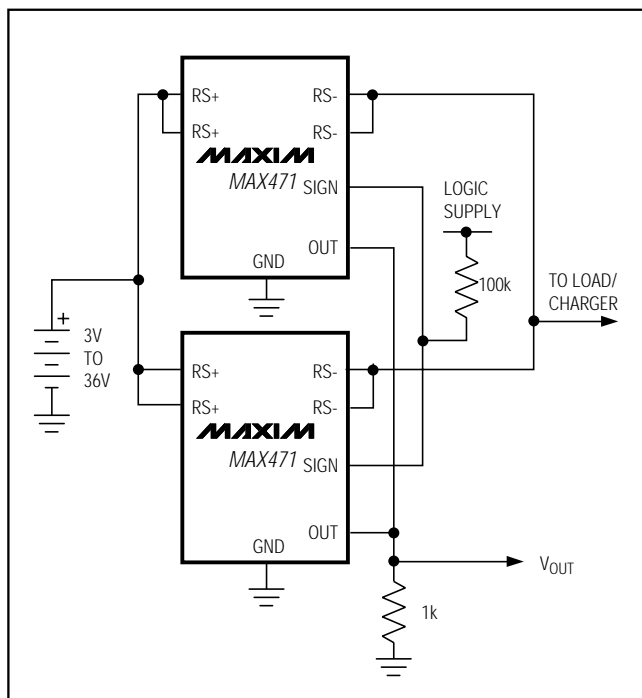


Figure 3. Paralleling MAX471s to Sense Higher Load Current



Figure 4. MAX472 Standard Application Circuit

for current summing. A single scaling resistor is required when summing OUT currents from multiple devices (Figure 3). Current can be integrated by connecting OUT to a capacitive load.

### SIGN Output

The current at OUT indicates magnitude. The SIGN output indicates the current's direction. Operation of the SIGN comparator is straightforward. When Q1 (Figures 1 and 2) conducts, the output of A1 is high while A2's output is zero. Under this condition, a high SIGN output indicates positive current flow (from RS+ to RS-). In battery-operated systems, this is useful for determining whether the battery is charging or discharging. The SIGN output may not correctly indicate if the load current is such that $I_{OUT}$ is less than 3.5µA. The MAX471's SIGN output accurately indicates the direction of current flow for load currents greater than 7mA.

SIGN is an open-collector output (sinks current only), allowing easy interface with logic circuits powered from any voltage. Connect a 100kΩ pull-up resistor from SIGN to the logic supply. The convention chosen for the polarity of the SIGN output ensures that it draws no current when the battery is being discharged. If current direction is not needed, float the SIGN pin.
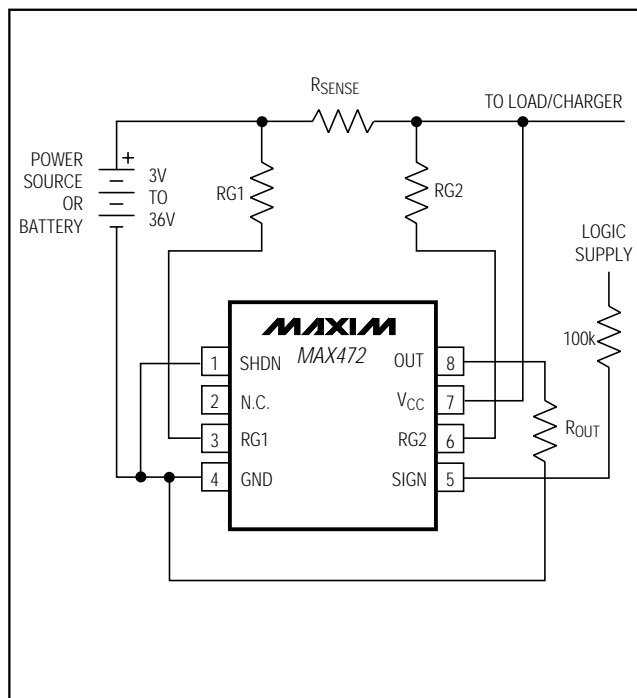
### Shutdown

When SHDN is high, the MAX471/MAX472 are shut down and consume less than 18µA. In shutdown mode, SIGN is high impedance and OUT turns off.

## _____Applications Information

### MAX471

The MAX471 obtains its power from the RS- pin. This includes MAX471 current consumption in the total system current measured by the MAX471. The small drop across $R_{SENSE}$ does not affect the MAX471's performance.

### Resistor Selection

Since OUT delivers a current, an external voltage gain-setting resistor ($R_{OUT}$ to ground) is required at the OUT pin in order to get a voltage. $R_{SENSE}$ is internal to the MAX471. RG1 and RG2 are factory trimmed for an output current ratio (output current to load current) of 500µA/A. Since they are manufactured of the same material and in very close proximity on the chip, they provide a high degree of temperature stability. Choose $R_{OUT}$ for the desired full-scale output voltage up to RS- - 1.5V (see the *Current Output* section).

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## Peak Sense Current

The MAX471's maximum sense current is 3A$_{RMS}$. For power-up, fault conditions, or other infrequent events, larger peak currents are allowed, provided they are short—that is, within a safe operating region, as shown in Figure 5.
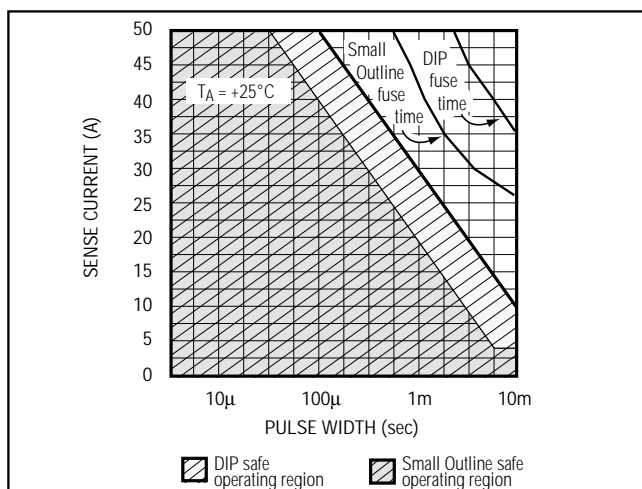


*Figure 5. MAX471 Pulse Current Safe Operation for 10,000 Pulses and Fuse Time for Continuous Current. Pulse tests done with 250mW average power dissipation.*

## MAX472

R$_{SENSE}$, RG1, and RG2 are externally connected on the MAX472. V$_{CC}$ can be connected to either the load/charge or power-source/battery side of the sense resistor. Connect V$_{CC}$ to the load/charge side of R$_{SENSE}$ if you want to include the MAX472 current drain in the measured current.

## Suggested Component Values for Various Applications

The general circuit of Figure 4 is useful in a wide variety of applications. It can be used for high-current applications (greater than 3A), and also for those where the full-scale load current is less than the 3A of the MAX471.

Table 1 shows suggested component values and indicates the resulting scale factors for various applications required to sense currents from 100mA to 10A.

Higher or lower sense-current circuits can also be built. Select components and calculate circuit errors using the guidelines and formulas in the following section.

## R$_{SENSE}$

Choose R$_{SENSE}$ based on the following criteria:

a) **Voltage Loss:** A high R$_{SENSE}$ value will cause the power-source voltage to degrade through IR loss. For least voltage loss, use the lowest R$_{SENSE}$ value.

b) **Accuracy:** A high R$_{SENSE}$ value allows lower currents to be measured more accurately. This is because offsets become less significant when the sense voltage is larger.

c) **Efficiency and Power Dissipation:** At high current levels, the I$^2$R losses in R$_{SENSE}$ may be significant. Take this into consideration when choosing the resistor value and power dissipation (wattage) rating. Also, if the sense resistor is allowed to heat up excessively, its value may drift.

d) **Inductance:** If there is a large high-frequency component to I$_{SENSE}$, you will want to keep inductance low. Wire-wound resistors have the highest inductance, while metal film is somewhat better. Low-inductance metal-film resistors are available. Instead of being spiral wrapped around a core, as in metal-film or wire-wound resistors, these are a straight band of metal. They are made in values under 1$\Omega$.

e) **Cost:** If the cost of R$_{SENSE}$ becomes an issue, you may want to use an alternative solution, as shown in Figure 6. This solution uses the PC board traces to create a sense resistor. Because of the inaccuracies of the copper "resistor," you will need to adjust the full-scale current value with a potentiometer. Also, the resistance temperature coefficient of copper is fairly high (approximately 0.4%/°C), so systems that experience a wide temperature variance should take this into account.

## Table 1. Suggested Component Values for the MAX472

| FULL-SCALE LOAD CURRENT, I$_{SENSE}$ (A) | CURRENT-SENSE RESISTOR, R$_{SENSE}$ (m$\Omega$) | GAIN-SETTING RESISTORS, RG1 = RG2 ($\Omega$) | OUTPUT RESISTOR, R$_{OUT}$ (k$\Omega$) | FULL-SCALE OUTPUT VOLTAGE, V$_{OUT}$ (V) | SCALE FACTOR, V$_{OUT}$/I$_{SENSE}$ (V/A) | TYPICAL ERROR AT X% OF FULL LOAD (%) | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | **1%** | **10%** | **100%** |
| 0.1 | 500 | 200 | 10 | 2.5 | 25 | 14 | 2.5 | 0.9 |
| 1 | 50 | 200 | 10 | 2.5 | 2.5 | 14 | 2.5 | 0.9 |
| 5 | 10 | 100 | 5 | 2.5 | 0.5 | 13 | 2.0 | 1.1 |
| 10 | 5 | 50 | 2 | 2 | 0.2 | 12 | 2.0 | 1.6 |

**MAX471/MAX472**

In Figure 6, assume the load current to be measured is 10A and that you have determined a 0.3 inch wide, 2 ounce copper to be appropriate. The resistivity of 0.1 inch wide, 2 ounce copper is 30m$\Omega$/ft (see Note 4). For 10A you may want $R_{SENSE}$ = 5m$\Omega$ for a 50mV drop at full scale. This resistor will require about 2 inches of 0.1 inch wide copper trace.

### RG1 and RG2

Once $R_{SENSE}$ is chosen, RG1 and RG2 can be chosen to define the current-gain ratio ($R_{SENSE}$/RG). Choose RG = RG1 = RG2 based on the following criteria:

a) **1$\Omega$ Input Resistance.** The minimum RG value is limited by the 1$\Omega$ input resistance, and also by the output current limitation (see below). As RG is reduced, the input resistance becomes a larger portion of the total gain-setting resistance. With RG = 50$\Omega$, the input resistance produces a 2% difference between the expected and actual current-gain ratio. This is a gain error that does not affect linearity and can be removed by adjusting RG or $R_{OUT}$.

b) **Efficiency.** As RG is reduced, $I_{OUT}$ gets larger for a given load current. Power dissipated in $R_{OUT}$ is not going to the load, and therefore reduces overall efficiency. This is significant only when the sense current is small.

c) **Maximum Output Current Limitation.** $I_{OUT}$ is limited to 1.5mA, requiring RG $\geq$ $V_{SENSE}$ / 1.5mA. For $V_{SENSE}$ = 60mV, RG must be $\geq$ 40$\Omega$.

d) **Headroom.** The MAX472 requires a minimum of 1.5V between the lower of the voltage at RG1 or RG2 ($V_{RG\_}$) and $V_{OUT}$. As RG becomes larger, the voltage drop across RG also becomes larger for a given $I_{OUT}$. This voltage drop further limits the maximum full-scale $V_{OUT}$. Assuming the drop across $R_{SENSE}$ is small and $V_{CC}$ is connected to either side of $R_{SENSE}$, $V_{OUT}$ (max) = $V_{CC}$ - (1.5V + $I_{OUT}$ (max) x RG).

e) **Output Offset Error at Low Load Currents.** Large RG values reduce $I_{OUT}$ for a given load current. As $I_{OUT}$ gets smaller, the 2.5µA max output offset-error current becomes a larger part of the overall output current. Keeping the gain high by choosing a low value for RG minimizes this offset error.

f) **Input Bias Current and Input Bias Current Mismatching.** The size of RG also affects the errors introduced by the input bias and input bias mismatching currents. After selecting the ratio, check to
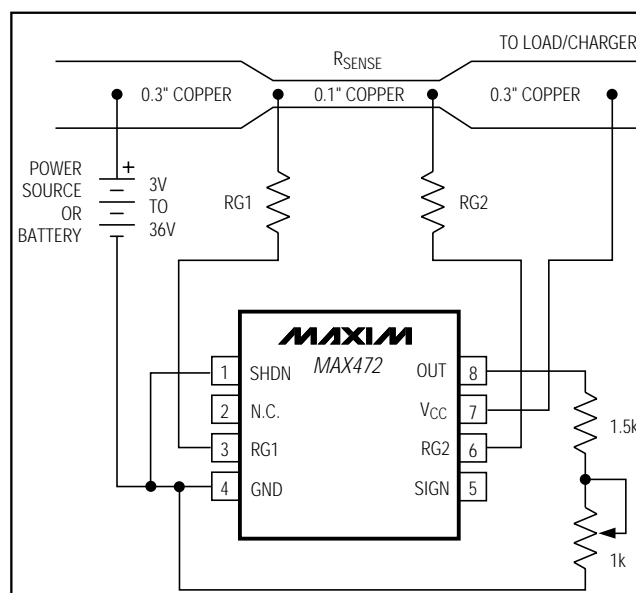


Figure 6.  MAX472 Connections Showing Use of PC Board Trace

make sure RG is small enough that $I_B$ and $I_{OS}$ do not add any appreciable errors. The full-scale error is given by:

$$\% \text{ Error} = \frac{(RG1 - RG2) \times I_B + I_{OS} \times RG}{I_{FS} \times R_{SENSE}} \times 100$$

where RG1 and RG2 are the gain resistors, $I_B$ is the bias current, $I_{OS}$ is the bias-current mismatch, $I_{FS}$ is the full-scale current, and $R_{SENSE}$ is the sense resistor.

Assuming a 5A load current, 10m$\Omega$ $R_{SENSE}$, and 100$\Omega$ RG, the current-gain ratio is 100µA/A, yielding a full-scale $I_{OUT}$ of 500µA. Using the maximum values for $I_B$ (20µA) and $I_{OS}$ (2µA), and 1% resistors for RG1 and RG2 (RG1 - RG2 = 2$\Omega$), the worst-case error at full scale calculates to:

$$\frac{2\Omega \times 20µA + 100\Omega \times 2µA}{5m\Omega \times 5A} = 0.48\%$$

The error may be reduced by: a) better matching of RG1 and RG2, b) increasing $R_{SENSE}$, or c) decreasing RG.

### Current-Sense Adjustment (Resistor Range, Output Adjust)

Choose $R_{OUT}$ after selecting $R_{SENSE}$, RG1, and RG2. Choose $R_{OUT}$ to obtain the full-scale voltage you

**Note 4:**  Printed Circuit Design, by Gerald L. Ginsberg; McGraw-Hill, Inc.; page 185.

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require, given the full-scale $I_{OUT}$ determined by $R_{SENSE}$, RG1, and RG2. The high compliance of OUT permits using $R_{OUT}$ values up to 10kΩ with minimal error. Values above 10kΩ are not usually recommended. The impedance of OUT's load (e.g., the input of an op amp or ADC) must be much greater than $R_{OUT}$ (e.g., 100 x $R_{OUT}$) to avoid degrading the measurement accuracy.

### High-Current Measurement
The MAX472 can achieve higher current measurements than the MAX471 can. Low-value sense resistors may be paralleled to obtain even lower values, or the PC board trace may be adjusted for any value.

An alternative method is to connect several MAX471s in parallel and connect the high-impedance current-source OUT pins together to indicate the total system current (Figure 3). Pay attention to layout to ensure equal IR drops in the paralleled connection. This is necessary to achieve equal current sharing.

### Power-Supply Bypassing and Grounding
The MAX471 has been designed as a "high side" (positive terminal) current monitor to ease the task of grounding any battery charger, thermistor, etc. that may be a part of the battery pack. Grounding the MAX471 requires no special precautions; follow the same cautionary steps that apply to the system as a whole. High-current systems can experience large voltage drops across a ground plane, and this drop may add to or subtract from $V_{OUT}$. For highest current-measurement accuracy, use a single-point "star" ground.

The MAX471/MAX472 require no special bypassing, and respond quickly to transient changes in line current. If the noise at OUT caused by these transients is a problem, you may want to place a 1μF capacitor at the OUT pin to ground. You can also place a large capacitor at the RS- terminal (or "load" side of the MAX472) to decouple the load and, thereby, reduce the current transients. These capacitors are not required for MAX471/MAX472 operation or stability, and their use will not degrade performance.

For the MAX472, the RG1 and RG2 inputs can be filtered by placing a capacitor (e.g., 1μF) between them to average the sensed current.
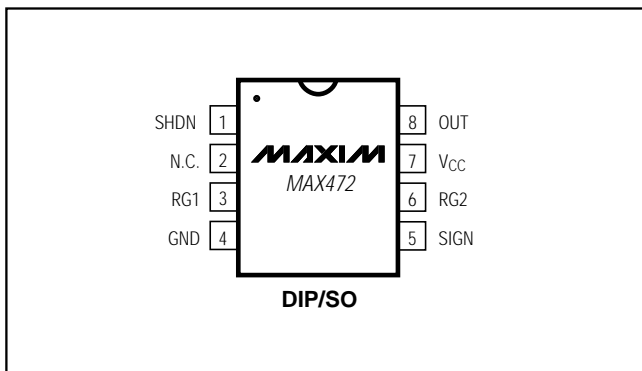
### MAX471 Layout
The MAX471 must be soldered in place, since sockets can cause uneven current sharing between the RS+ pins (pins 2 and 3) and the RS- pins (pins 6 and 7), resulting in typical errors of 0.5%.

In order to dissipate sense-resistor heat from large sense currents, solder the RS+ pins and the RS- pins to large copper traces. Keep the part away from other heat-generating devices. This procedure will ensure continuous power dissipation rating.

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## ___Pin Configurations (continued)

```
         ┌──────────────┐
 SHDN ─┤1│ ·            │8├─ OUT
        │   MAXIM       │
 N.C. ─┤2│              │7├─ Vcc
        │   MAX472      │
 RG1  ─┤3│              │6├─ RG2
        │              │
 GND  ─┤4│              │5├─ SIGN
         └──────────────┘
             DIP/SO
```