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## MAX9611/MAX9612

## High-Side, Current-Sense Amplifiers with 12-Bit ADC and Op Amp/Comparator

### General Description

The MAX9611/MAX9612 are high-side current-sense amplifiers with an integrated 12-bit ADC and a gain block that can be configured either as an op amp or comparator, making these devices ideal for a number of industrial and automotive applications.

The high-side, current-sense amplifiers operate over a wide 0V to 60V input common-mode voltage range. The programmable full-scale voltage (440mV, 110mV, and 55mV) of these amplifiers offers wide dynamic range, accurate current measurement, and application flexibility in choosing sense resistor values. A choice of either an internal op amp or a comparator is provided to the user. The internal amplifier can be used to limit the inrush current or to create a current source in a closed-loop system. The comparator can be used to monitor fault events for fast response.

An I<sup>2</sup>C-controlled 12-bit, 500sps analog-to-digital converter (ADC) can be used to read the voltage across the sense resistor ( $V_{SENSE}$ ), the input common-mode voltage ( $V_{RSCM}$ ), op-amp/comparator output ( $V_{OUT}$ ), op-amp/comparator reference voltage ( $V_{SET}$ ), and internal die temperature. The I<sup>2</sup>C bus is compatible with 1.8V and 3.3V logic, allowing modern microcontrollers to interface to it.

The MAX9611 features a noninverting input-to-output configuration while the MAX9612 features an inverting input-to-output configuration.

The MAX9611/MAX9612 operate with a 2.7V to 5.5V supply voltage range, are fully specified over the -40°C to +125°C automotive temperature range, and are available in a 3mm x 5mm, 10-pin  $\mu$ MAX<sup>®</sup> package.

### Applications

- Hybrid Automotive Power Supplies
- Server Backplanes
- Base-Station PA Control
- Base-Station Feeder Cable Bias-T
- Telecom Cards
- Battery-Operated Equipment

### Features

- 0V to +60V Input Common-Mode Voltage Range
- 2.7V to 5.5V Power-Supply Range, Compatible with 1.8V and 3.3V Logic
- 5 $\mu$ A Software Shutdown Current
- Integrated 12-Bit ADC
- 13 $\mu$ V Current-Sense ADC Resolution
- 500 $\mu$ V (max) Current-Sense ADC Input Offset Voltage
- 0.5% (max) Current-Sense ADC Gain Error
- I<sup>2</sup>C Bus with 16 Addresses
- Small, 3mm x 5mm 10-Pin  $\mu$ MAX Package
- -40°C to +125°C Operating Temperature Range

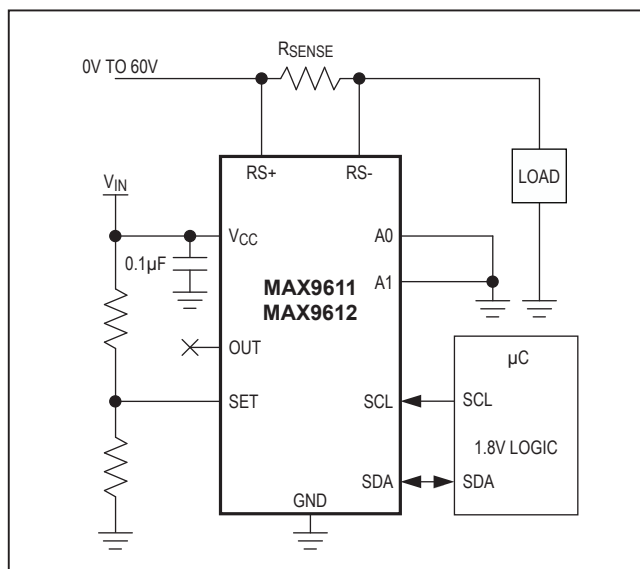
### Ordering Information/Selector Guide

| PART        | OUTPUT       | PIN-PACKAGE  |
|-------------|--------------|--------------|
| MAX9611AUB+ | Noninverting | 10 $\mu$ MAX |
| MAX9612AUB+ | Inverting    | 10 $\mu$ MAX |

**Note:** All devices operate over the -40°C to +125°C temperature range.

+Denotes a lead(Pb)-free/RoHS-compliant package.

### Typical Application Circuit



$\mu$ MAX is a registered trademark of Maxim Integrated Products, Inc.

Functional Diagrams appear at end of data sheet.

## Absolute Maximum Ratings

$V_{CC}$  to GND ..... -0.3V to +6V  
 $RS+$ ,  $RS-$ , OUT to GND ..... -0.3V to +65V  
 Differential Input Voltage,  $RS+$  -  $RS-$  .....  $\pm 65V$   
 All Other Pins to GND ..... -0.3V to +6V  
 OUT Short-Circuit to GND ..... Continuous  
 Continuous Current into Any Pin .....  $\pm 20mA$   
 Continuous Power Dissipation ( $T_A = +70^\circ C$ )  
 10-Pin  $\mu MAX$  (derate 8.8mW/ $^\circ C$  above  $+70^\circ C$ ) ..... 707mW

$\mu MAX$  Package Junction-to-Ambient

Thermal Resistance ( $\theta_{JA}$ ) (Note 1) .....  $13^\circ C/W$   
 Operating Temperature Range .....  $-40^\circ C$  to  $+125^\circ C$   
 Junction Temperature .....  $+150^\circ C$   
 Storage Temperature Range .....  $-65^\circ C$  to  $+150^\circ C$   
 Lead Temperature (soldering, 10s) .....  $+300^\circ C$   
 Soldering Temperature (reflow) .....  $+260^\circ C$

**Note 1:** Package thermal resistances were obtained using the method described in JEDEC specification JESD51-7, using a four-layer board. For detailed information on package thermal considerations, refer to [www.maximintegrated.com/thermal-tutorial](http://www.maximintegrated.com/thermal-tutorial).

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

( $V_{CC} = 3.3V$ ,  $V_{RS+} = V_{RS-} = +12V$ ,  $V_{SENSE} = (V_{RS+} - V_{RS-}) = 0V$ ,  $T_A = -40^\circ C$  to  $+125^\circ C$ , unless otherwise noted. Typical values are at  $T_A = +25^\circ C$ .) (Note 2)

| PARAMETER                                         | SYMBOL                  | CONDITIONS                                        | MIN | TYP   | MAX | UNITS      |
|---------------------------------------------------|-------------------------|---------------------------------------------------|-----|-------|-----|------------|
| <b>CURRENT-SENSE AMPLIFIER DC CHARACTERISTICS</b> |                         |                                                   |     |       |     |            |
| Input Common-Mode Range                           |                         | Guaranteed by CMRR                                | 0   |       | 60  | V          |
| Input Offset Voltage ADC Path (Note 3)            | $V_{OS}$                | $T_A = +25^\circ C$ , gain = 8x                   |     | 0.045 | 0.5 | mV         |
|                                                   |                         | $T_A = -40^\circ C$ to $+125^\circ C$ , gain = 8x |     |       | 2   |            |
|                                                   |                         | $T_A = +25^\circ C$ , gain = 4x                   |     | 0.045 | 0.5 |            |
|                                                   |                         | $T_A = -40^\circ C$ to $+125^\circ C$ , gain = 4x |     |       | 2   |            |
|                                                   |                         | $T_A = +25^\circ C$ , gain = 1x                   |     | 0.1   | 0.8 |            |
|                                                   |                         | $T_A = -40^\circ C$ to $+125^\circ C$ , gain = 1x |     |       | 2.6 |            |
| Gain Error (Note 3)                               | GE                      | $T_A = +25^\circ C$ , gain = 8x                   |     | 0.1   | 0.5 | %          |
|                                                   |                         | $T_A = -40^\circ C$ to $+85^\circ C$ , gain = 8x  |     |       | 1.8 |            |
|                                                   |                         | $T_A = -40^\circ C$ to $+125^\circ C$ , gain = 8x |     |       | 2.5 |            |
|                                                   |                         | $T_A = +25^\circ C$ , gain = 4x                   |     | 0.4   | 1.7 |            |
|                                                   |                         | $T_A = -40^\circ C$ to $+125^\circ C$ , gain = 4x |     |       | 3.1 |            |
|                                                   |                         | $T_A = +25^\circ C$ , gain = 1x                   |     | 1     | 4   |            |
|                                                   |                         | $T_A = -40^\circ C$ to $+125^\circ C$ , gain = 1x |     |       | 4.7 |            |
| Differential Input Resistance                     | $R_{INDM}$              |                                                   |     | 300   |     | k $\Omega$ |
| Common-Mode Input Resistance                      | $R_{INCM}$              |                                                   |     | 12    |     | M $\Omega$ |
| Input Bias Current                                | $I_{RS+}$ , $I_{RS-}$   | $T_A = +25^\circ C$                               |     | 1     | 2   | $\mu A$    |
|                                                   |                         | $T_A = -40^\circ C$ to $+125^\circ C$             |     |       | 5   |            |
| Input Offset Current (Note 4)                     | $(I_{RS+}) - (I_{RS-})$ | $T_A = +25^\circ C$                               |     | 3     | 6   | nA         |
|                                                   |                         | $T_A = -40^\circ C$ to $+125^\circ C$             |     |       | 6   |            |

## Electrical Characteristics (continued)

( $V_{CC} = 3.3V$ ,  $V_{RS+} = V_{RS-} = +12V$ ,  $V_{SENSE} = (V_{RS+} - V_{RS-}) = 0V$ ,  $T_A = -40^{\circ}C$  to  $+125^{\circ}C$ , unless otherwise noted. Typical values are at  $T_A = +25^{\circ}C$ .) (Note 2)

| PARAMETER                               | SYMBOL    | CONDITIONS                                                           |                                   | MIN    | TYP     | MAX     | UNITS |
|-----------------------------------------|-----------|----------------------------------------------------------------------|-----------------------------------|--------|---------|---------|-------|
| Common-Mode Rejection Ratio             | CMRR      | $V_{RS-} = 0V$ to $60V$ ,<br>$T_A = +25^{\circ}C$                    | Gain = 8x,<br>$V_{SENSE} = 50mV$  | 106    | 120     | dB      |       |
|                                         |           |                                                                      | Gain = 4x,<br>$V_{SENSE} = 100mV$ | 106    | 120     |         |       |
|                                         |           |                                                                      | Gain = 1x,<br>$V_{SENSE} = 400mV$ | 100    | 120     |         |       |
|                                         |           | $V_{RS-} = 0V$ to $60V$ ,<br>$T_A = -40^{\circ}C$ to $+125^{\circ}C$ | Gain 8x,<br>$V_{SENSE} = 50mV$    | 94     |         |         |       |
|                                         |           |                                                                      | Gain 4x,<br>$V_{SENSE} = 100mV$   | 94     |         |         |       |
|                                         |           |                                                                      | Gain 1x,<br>$V_{SENSE} = 400mV$   | 84     |         |         |       |
| Power-Supply Rejection Ratio            | PSRR      | $V_{CC} = 2.7V$ to $5.5V$                                            | Gain = 8x,<br>$V_{SENSE} = 50mV$  | 57     | 72      | dB      |       |
|                                         |           |                                                                      | Gain = 4x,<br>$V_{SENSE} = 100mV$ | 56     | 67      |         |       |
|                                         |           |                                                                      | Gain = 1x,<br>$V_{SENSE} = 400mV$ | 48     | 57      |         |       |
| Full-Scale Sense Voltage                | FS        | Used in gain error measurement                                       | Gain = 8x                         |        | 55      | mV      |       |
|                                         |           |                                                                      | Gain = 4x                         |        | 110     |         |       |
|                                         |           |                                                                      | Gain = 1x                         |        | 440     |         |       |
| LSB Step Size                           | LSB       | Gain = 8x                                                            |                                   | 13.44  | $\mu V$ |         |       |
|                                         |           | Gain = 4x                                                            |                                   | 26.88  |         |         |       |
|                                         |           | Gain = 1x                                                            |                                   | 107.50 |         |         |       |
| ANALOG PATH, CSA + AMPLIFIER/COMPARATOR |           |                                                                      |                                   |        |         |         |       |
| Input Offset Voltage                    | $V_{OS}$  | $T_A = +25^{\circ}C$                                                 |                                   | 0.350  | 4       | mV      |       |
|                                         |           | $T_A = -40^{\circ}C$ to $+125^{\circ}C$                              |                                   |        | 10      |         |       |
| SET Input Bias Current                  | $I_B$     |                                                                      |                                   | 1      | 50      | nA      |       |
| Maximum SET Input Voltage Range         |           |                                                                      |                                   | 1.126  |         | V       |       |
| Signal Bandwidth                        | BW        | Gain = 1x, $R_{S-} = 11.6V$                                          |                                   | 4      |         | MHz     |       |
| Gain Bandwidth                          | GBW       |                                                                      |                                   | 2.5    |         | MHz     |       |
| Propagation Delay                       | $t_{PD}$  | In comparator mode, 10mV overdrive                                   |                                   | 1.5    |         | $\mu s$ |       |
| Internal Hysteresis                     | $V_{HYS}$ | In comparator mode, nonlatching                                      |                                   | 8      |         | mV      |       |
| Output Sink Current                     |           | $V_{OUT} = 4V$                                                       |                                   | 15     |         | mA      |       |
| Output Leakage Current                  |           | $V_{OUT} = 36V$                                                      |                                   | 1.7    | 3       | $\mu A$ |       |
| Output Voltage Low                      | $V_{OL}$  | $I_{SINK} = 8mA$ , $T_A = -40^{\circ}C$ to $+85^{\circ}C$            |                                   | 1      |         | V       |       |
|                                         |           | $I_{SINK} = 8mA$ , $T_A = -40^{\circ}C$ to $+125^{\circ}C$           |                                   | 0.5    | 1.5     |         |       |

## Electrical Characteristics (continued)

( $V_{CC} = 3.3V$ ,  $V_{RS+} = V_{RS-} = +12V$ ,  $V_{SENSE} = (V_{RS+} - V_{RS-}) = 0V$ ,  $T_A = -40^{\circ}C$  to  $+125^{\circ}C$ , unless otherwise noted. Typical values are at  $T_A = +25^{\circ}C$ .) (Note 2)

| PARAMETER                                            | SYMBOL             | CONDITIONS                                                                       |                                                            | MIN                       | TYP  | MAX | UNITS |
|------------------------------------------------------|--------------------|----------------------------------------------------------------------------------|------------------------------------------------------------|---------------------------|------|-----|-------|
| OUT VOLTAGE MEASUREMENT (V <sub>OUT</sub> )          |                    |                                                                                  |                                                            |                           |      |     |       |
| Full-Scale Input Voltage                             |                    |                                                                                  |                                                            | 57.3                      |      |     | V     |
| LSB Step Size                                        | LSB                |                                                                                  |                                                            | 14                        |      |     | mV    |
| Gain Error                                           | GE                 | V <sub>RSCM</sub> =<br>(V <sub>RS+</sub> - V <sub>RS-</sub> )/2                  | T <sub>A</sub> = +25°C<br>T <sub>A</sub> = -40°C to +125°C | 0.8                       | 6    |     | %     |
| Input Offset Voltage                                 | V <sub>OSOUT</sub> | T <sub>A</sub> = +25°C<br>T <sub>A</sub> = -40°C to +125°C                       |                                                            | 14                        | 110  |     | mV    |
| COMMON-MODE VOLTAGE MEASUREMENT (V <sub>RSCM</sub> ) |                    |                                                                                  |                                                            |                           |      |     |       |
| Full-Scale Input Voltage                             |                    |                                                                                  |                                                            | 57.3                      |      |     | V     |
| LSB Step Size                                        | LSB                |                                                                                  |                                                            | 14                        |      |     | mV    |
| Gain Error                                           | GE                 | V <sub>RSCM</sub> =<br>(V <sub>RS+</sub> - V <sub>RS-</sub> )/2                  | T <sub>A</sub> = +25°C<br>T <sub>A</sub> = -40°C to +125°C | 0.3                       | 6    |     | %     |
| Input Offset Voltage                                 | V <sub>OSOUT</sub> | T <sub>A</sub> = +25°C<br>T <sub>A</sub> = -40°C to +125°C                       |                                                            | 14                        | 80   |     | mV    |
| SET VOLTAGE MEASUREMENT (V <sub>SET</sub> )          |                    |                                                                                  |                                                            |                           |      |     |       |
| Full-Scale Input Voltage                             |                    |                                                                                  |                                                            | 1.10                      |      |     | V     |
| LSB Step Size                                        |                    |                                                                                  |                                                            | 268                       |      |     | μV    |
| Gain Error                                           | GE                 | V <sub>RSCM</sub> =<br>(V <sub>RS+</sub> - V <sub>RS-</sub> )/2                  | T <sub>A</sub> = +25°C<br>T <sub>A</sub> = -40°C to +125°C | 0.2                       | 5    |     | %     |
| Input Offset Voltage                                 | V <sub>OSOUT</sub> | T <sub>A</sub> = +25°C<br>T <sub>A</sub> = -40°C to +125°C                       |                                                            | 0.3                       | 10   |     | mV    |
| Integral Nonlinearity                                | INL                |                                                                                  |                                                            | 1                         |      |     | LSB   |
| Differential Nonlinearity                            | DNL                |                                                                                  |                                                            | 0.2                       |      |     | LSB   |
| TEMPERATURE MEASUREMENT                              |                    |                                                                                  |                                                            |                           |      |     |       |
| Accuracy                                             |                    |                                                                                  |                                                            | 0.48                      |      |     | °C    |
| Typical Measurement Range                            |                    |                                                                                  |                                                            | -40                       | +125 |     | °C    |
| LSB Step Size                                        | LSB                |                                                                                  |                                                            | 0.48                      |      |     | °C    |
| ANALOG-TO-DIGITAL CONVERTER                          |                    |                                                                                  |                                                            |                           |      |     |       |
| Resolution                                           |                    |                                                                                  |                                                            | 12                        |      |     | Bit   |
| Conversion Time                                      |                    |                                                                                  |                                                            | 2                         |      |     | ms    |
| SCL/SDA LOGIC LEVELS                                 |                    |                                                                                  |                                                            |                           |      |     |       |
| Input Voltage Low                                    | V <sub>IL</sub>    | V <sub>CC</sub> = 2.7V to 5.5V<br>V <sub>CC</sub> = 3.3V, T <sub>A</sub> = +25°C |                                                            | 0.4<br>0.9                |      |     | V     |
| Input Voltage High                                   | V <sub>IH</sub>    | V <sub>CC</sub> = 2.7V to 5.5V                                                   |                                                            | 1.45                      |      |     | V     |
| Input Hysteresis                                     | V <sub>HYS</sub>   |                                                                                  |                                                            | 0.05 x<br>V <sub>CC</sub> |      |     | V     |
| Input Leakage Current                                |                    |                                                                                  |                                                            | 1                         | 200  |     | nA    |
| A1/A0 LOGIC LEVELS                                   |                    |                                                                                  |                                                            |                           |      |     |       |
| Logic State 00-01 Threshold                          |                    |                                                                                  |                                                            | 1/4 x V <sub>CC</sub>     |      |     | V     |
| Logic State 01-10 Threshold                          |                    |                                                                                  |                                                            | 1/2 x V <sub>CC</sub>     |      |     | V     |
| Logic State 10-11 Threshold                          |                    |                                                                                  |                                                            | 3/4 x V <sub>CC</sub>     |      |     | V     |
| Input Leakage Current                                |                    |                                                                                  |                                                            | 1                         | 200  |     | nA    |

**Electrical Characteristics (continued)**

( $V_{CC} = 3.3V$ ,  $V_{RS+} = V_{RS-} = +12V$ ,  $V_{SENSE} = (V_{RS+} - V_{RS-}) = 0V$ ,  $T_A = -40^{\circ}C$  to  $+125^{\circ}C$ , unless otherwise noted. Typical values are at  $T_A = +25^{\circ}C$ .) (Note 2)

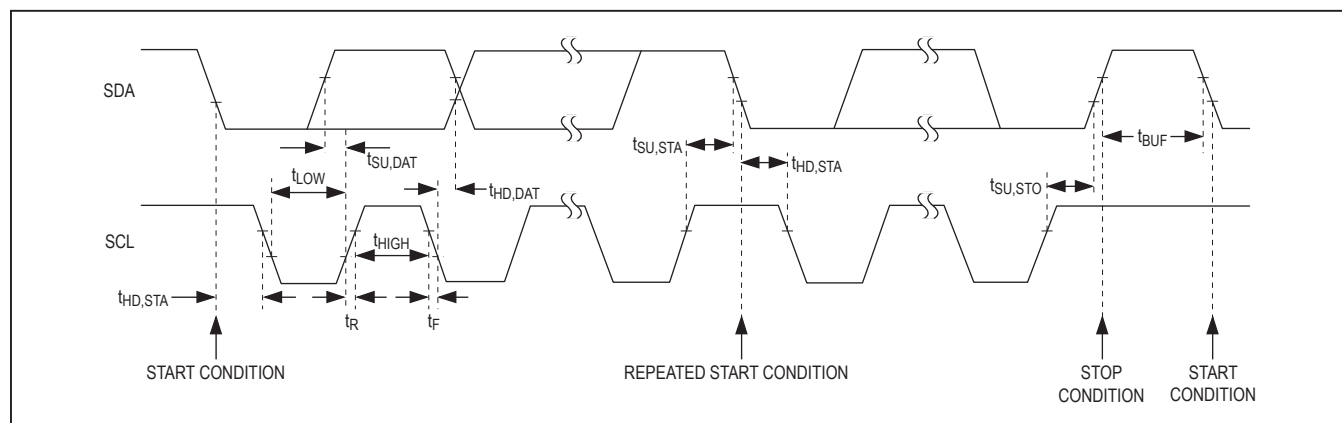
| PARAMETER                                                            | SYMBOL       | CONDITIONS         | MIN           | TYP | MAX | UNITS   |
|----------------------------------------------------------------------|--------------|--------------------|---------------|-----|-----|---------|
| <b>POWER-SUPPLY CHARACTERISTICS</b>                                  |              |                    |               |     |     |         |
| Power-Supply Input Range                                             | $V_{CC}$     | Guaranteed by PSRR | 2.7           |     | 5.5 | V       |
| Quiescent Current                                                    | $I_{CC}$     |                    |               | 1.6 | 2.6 | mA      |
| Shutdown Current                                                     | $I_{SHDN}$   | No activity on SCL |               | 5   | 10  | $\mu A$ |
| <b>I<sup>2</sup>C TIMING CHARACTERISTICS (COMPATIBLE WITH SMBus)</b> |              |                    |               |     |     |         |
| Serial-Clock Frequency                                               | $f_{SCL}$    |                    | 0             |     | 400 | kHz     |
| Bus Free Time Between a STOP and a START Condition                   | $t_{BUF}$    |                    | 1.3           |     |     | $\mu s$ |
| Hold Time, (Repeated) START Condition                                | $t_{DH,STA}$ |                    | 0.6           |     |     | $\mu s$ |
| SCL Clock Low Period                                                 | $t_{LOW}$    |                    | 1.3           |     |     | $\mu s$ |
| SCL Clock High Period                                                | $t_{HIGH}$   |                    | 0.6           |     |     | $\mu s$ |
| Setup Time for a Repeated START Condition                            | $t_{SU,STA}$ |                    | 0.6           |     |     | $\mu s$ |
| Data Hold Time                                                       | $t_{DH,DAT}$ |                    | 0             |     | 900 | $\mu s$ |
| Data Setup Time                                                      | $t_{SU,DAT}$ |                    | 100           |     |     | ns      |
| SDA/SCL Receiving Rise Time                                          | $t_R$        | (Note 5)           | $20 + 0.1C_B$ |     | 300 | ns      |
| SDA/SCL Receiving Fall Time                                          | $t_F$        | (Note 5)           | $20 + 0.1C_B$ |     | 300 |         |
| SDA Transmitting Fall Time                                           | $t_F$        | (Note 5)           | $20 + 0.1C_B$ |     | 250 |         |
| STOP Condition Setup Time                                            | $t_{SU,STO}$ |                    | 0.6           |     |     | $\mu s$ |
| Bus Capacitance                                                      | $C_B$        |                    |               |     | 400 | pF      |
| Pulse Width of Spike Suppressed                                      | $t_{SP}$     |                    |               | 50  |     | ns      |

**Note 2:** All devices are 100% production tested at  $T_A = +25^{\circ}C$ . Temperature limits are guaranteed by design.

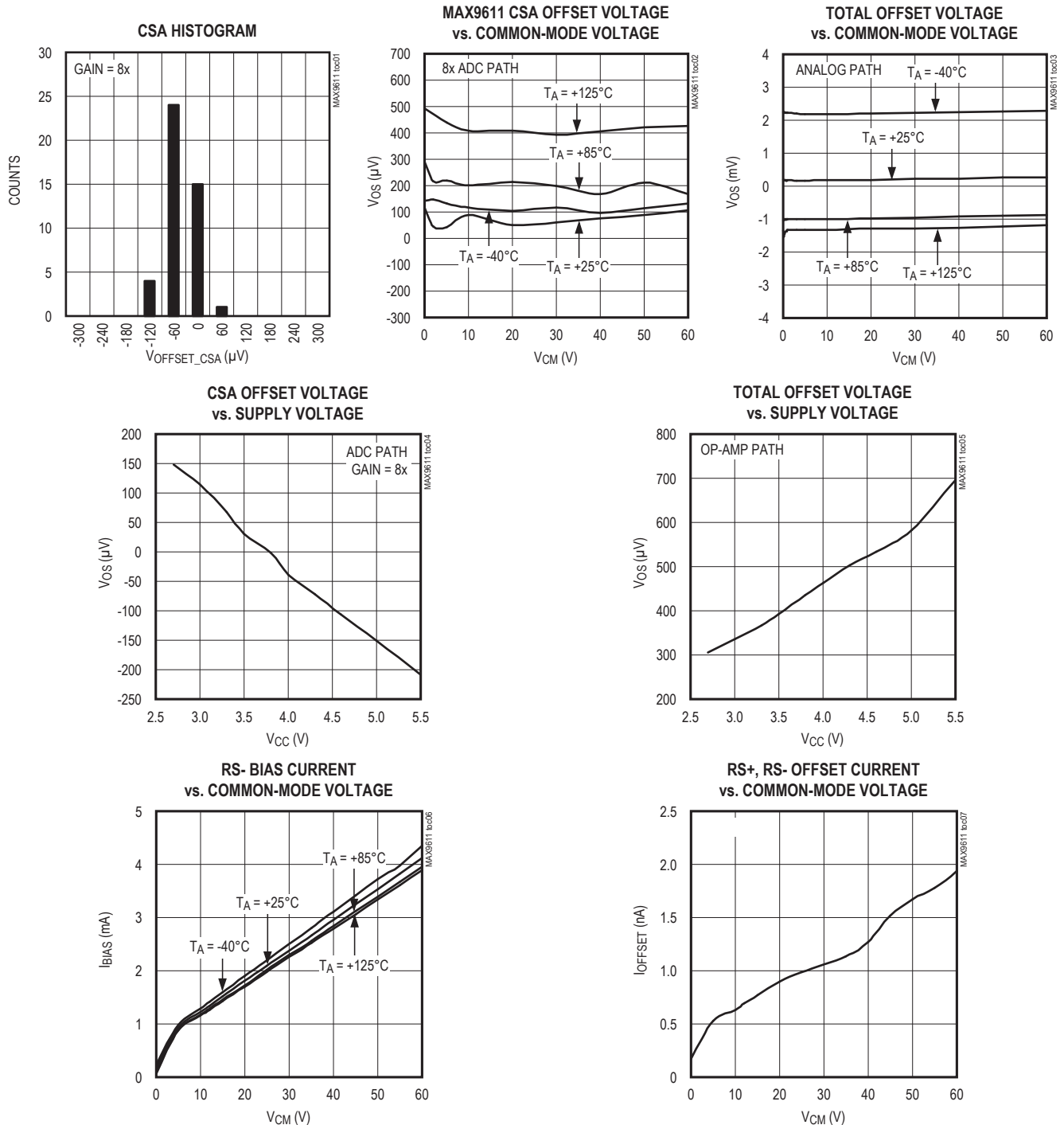
**Note 3:**  $V_{OS}$  and gain error of current-sense amplifier extrapolated from a two-point measurement made at  $V_{SENSE} = (V_{RS+} - V_{RS-}) = 5mV$  to  $50mV$  in gain of 8x,  $5mV$  to  $100mV$  in gain of 4x, and  $10mV$  to  $400mV$  in gain of 1x.

**Note 4:** Guaranteed by design.

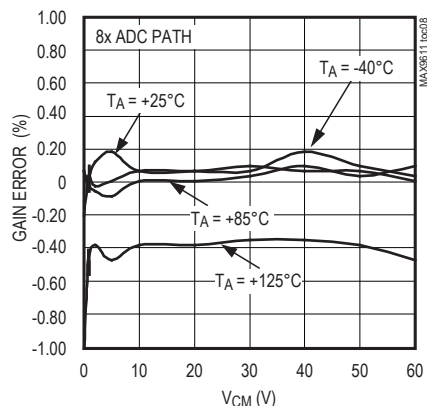
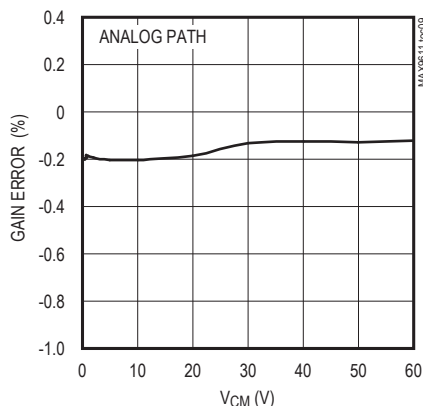
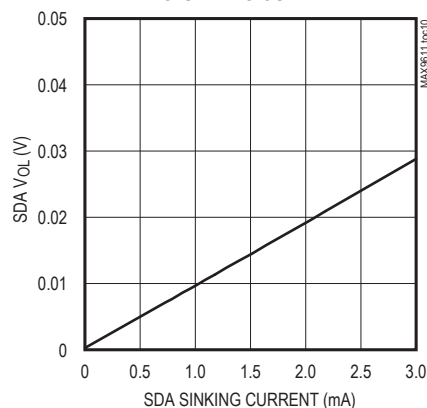
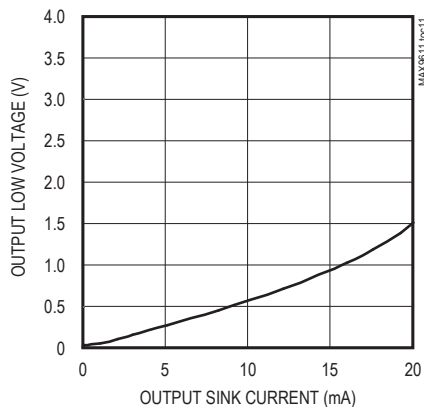
**Note 5:**  $C_B$  is in pF.

**I<sup>2</sup>C Timing Diagram**

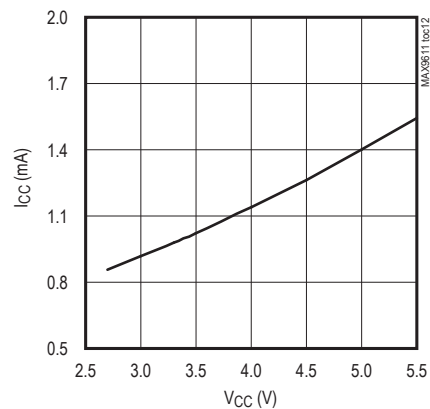
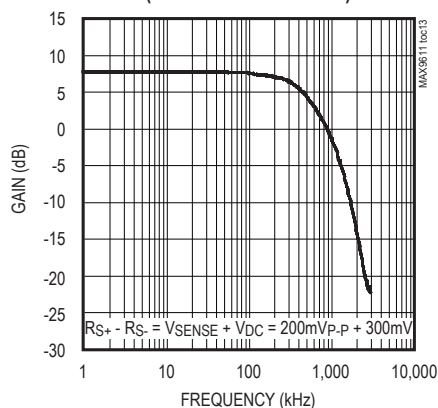
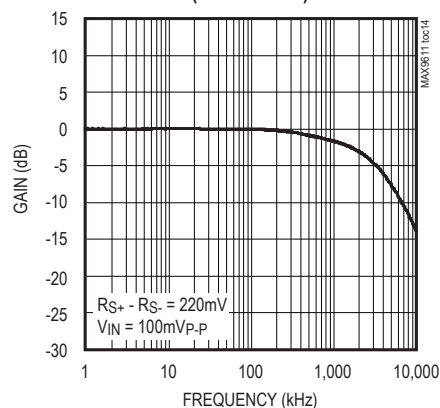
## Typical Operating Characteristics

(V<sub>CC</sub> = 3.3V, V<sub>CM</sub> = 12V, T<sub>A</sub> = +25°C, unless otherwise noted.)

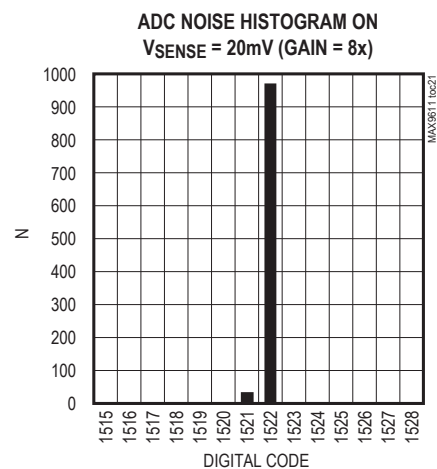
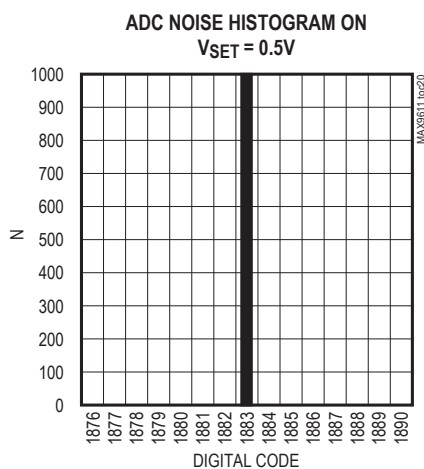
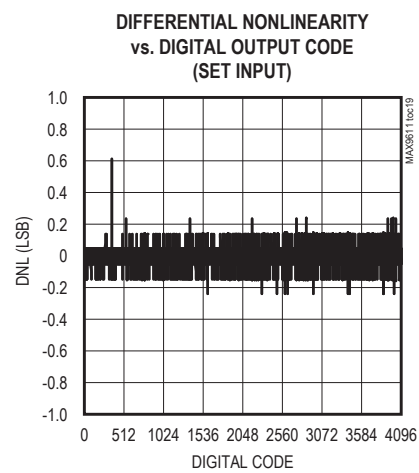
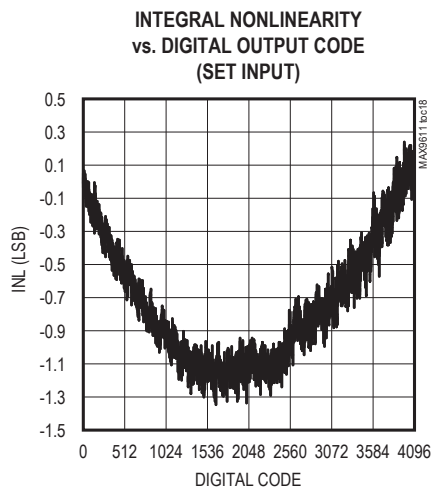
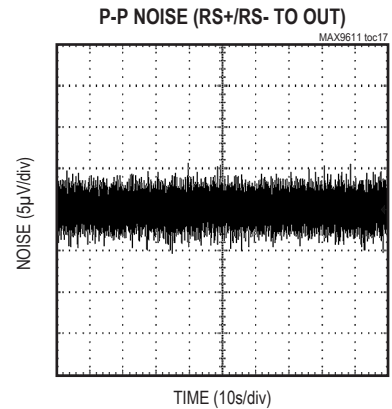
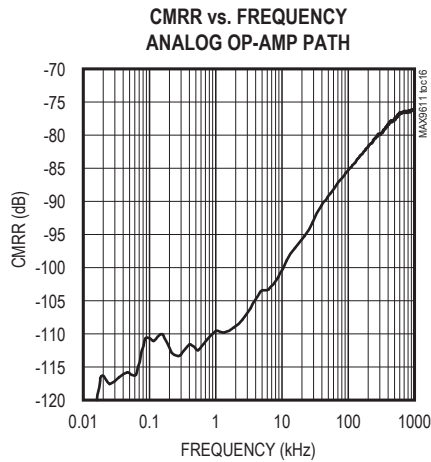
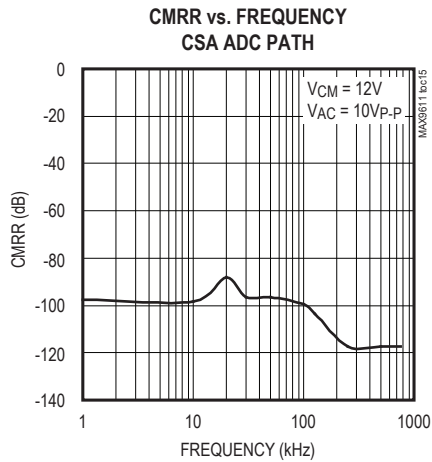
## Typical Operating Characteristics (continued)

(V<sub>CC</sub> = 3.3V, V<sub>CM</sub> = 12V, T<sub>A</sub> = +25°C, unless otherwise noted.)MAX9611 CSA GAIN ERROR  
vs. COMMON-MODE VOLTAGETOTAL GAIN ERROR  
vs. COMMON-MODE VOLTAGESDA/SCL V<sub>OL</sub>  
vs. SINKING CURRENTOUTPUT LOW VOLTAGE  
vs. OUTPUT SINK CURRENT

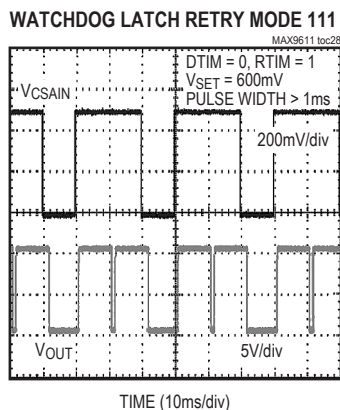
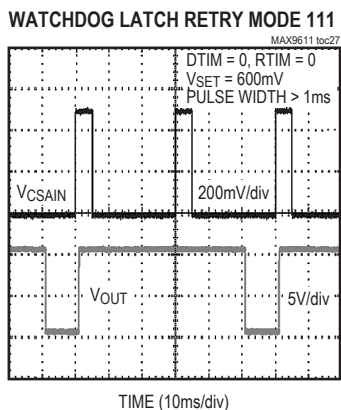
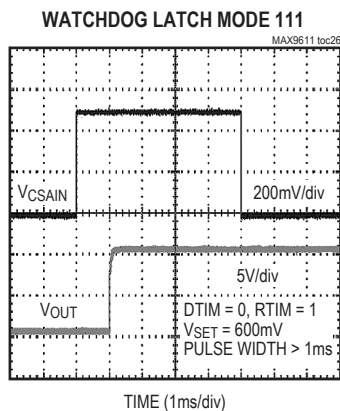
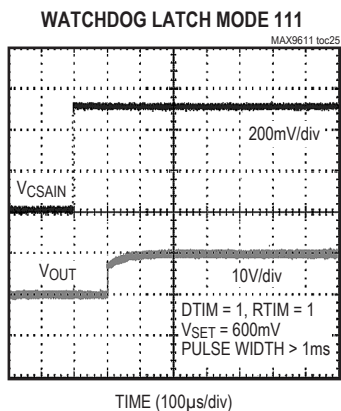
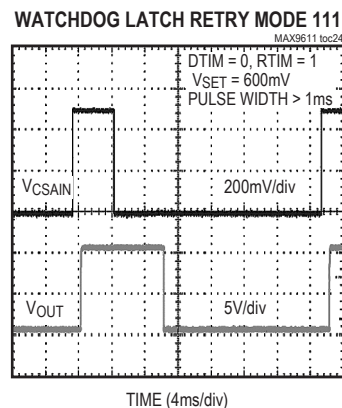
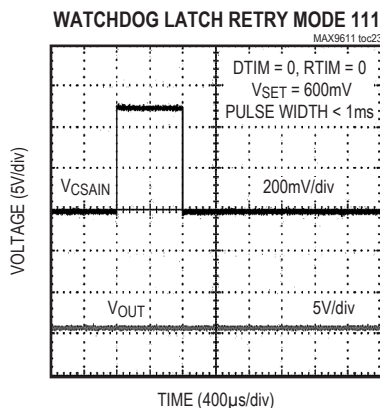
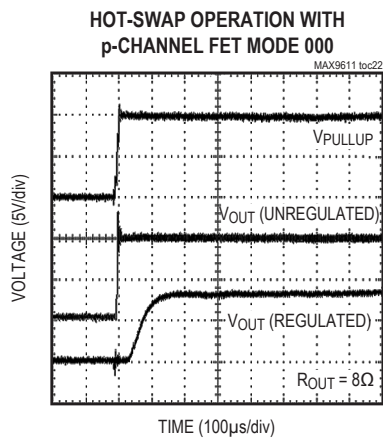
SUPPLY CURRENT vs. SUPPLY VOLTAGE

CSA GAIN vs. FREQUENCY  
(R<sub>S+</sub>/R<sub>S-</sub> TO OUT PATH)OP-AMP GAIN vs. FREQUENCY  
(SET TO OUT)

## Typical Operating Characteristics (continued)

(V<sub>CC</sub> = 3.3V, V<sub>CM</sub> = 12V, T<sub>A</sub> = +25°C, unless otherwise noted.)

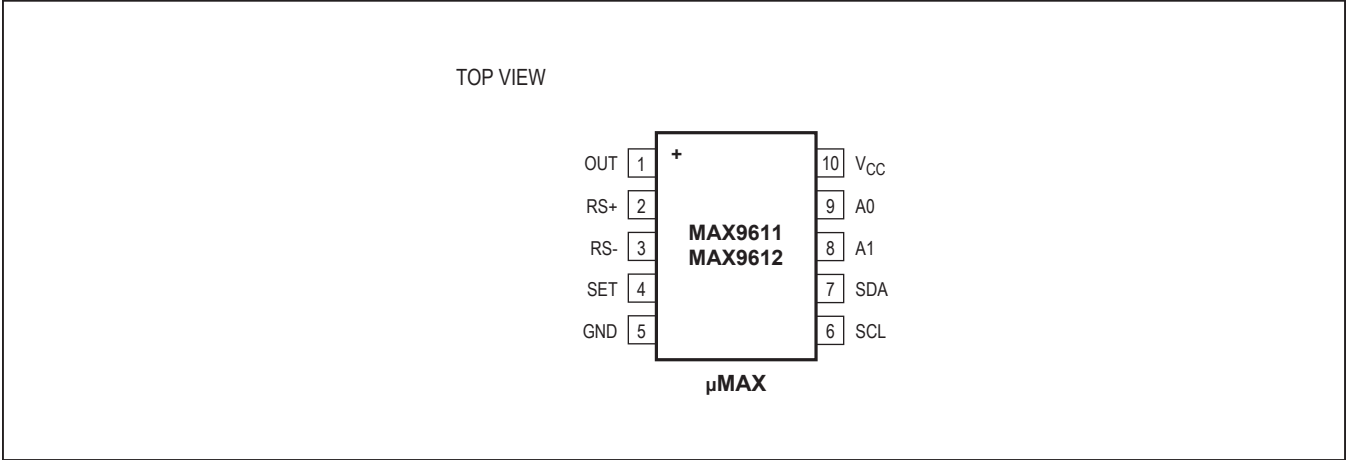
## Typical Operating Characteristics (continued)

(V<sub>CC</sub> = 3.3V, V<sub>CM</sub> = 12V, T<sub>A</sub> = +25°C, unless otherwise noted.)

MAX9611/MAX9612

High-Side, Current-Sense Amplifiers with  
12-Bit ADC and Op Amp/Comparator

Pin Configuration



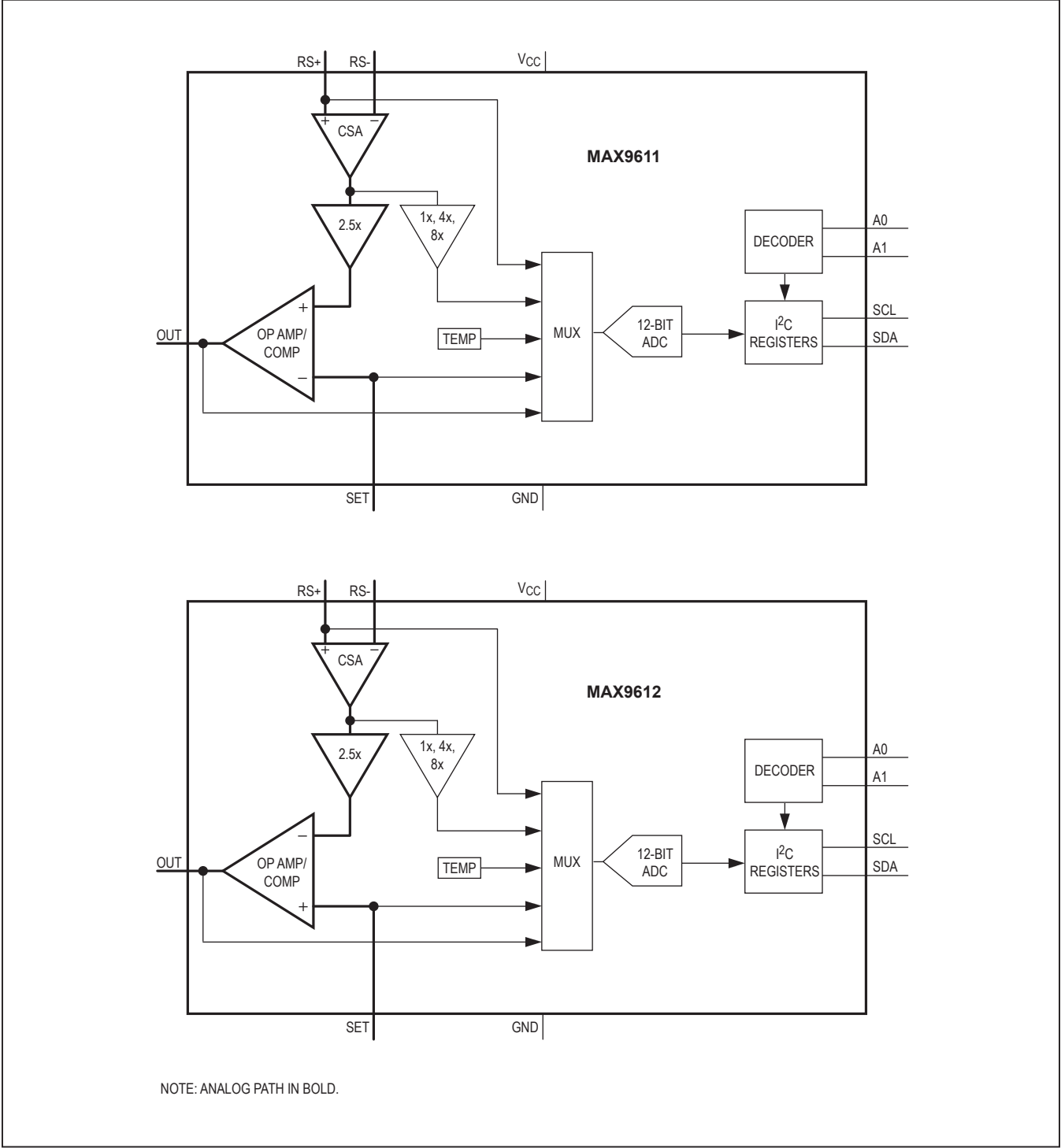
Pin Description

| PIN | NAME            | FUNCTION                                                                                            |
|-----|-----------------|-----------------------------------------------------------------------------------------------------|
| 1   | OUT             | Internal Amplifier/Comparator Output                                                                |
| 2   | RS+             | Positive Current-Sensing Input. Power side connects to external sense resistor.                     |
| 3   | RS-             | Negative Current-Sensing Input. Load side connects to external sense resistor.                      |
| 4   | SET             | External Set-Point Voltage                                                                          |
| 5   | GND             | Ground                                                                                              |
| 6   | SCL             | I <sup>2</sup> C Interface Clock Input                                                              |
| 7   | SDA             | I <sup>2</sup> C Interface Data Input/Output                                                        |
| 8   | A1              | Address Input 1                                                                                     |
| 9   | A0              | Address Input 0                                                                                     |
| 10  | V <sub>CC</sub> | Supply Voltage Input. Bypass V <sub>CC</sub> to GND with a 0.1μF and a 4.7μF capacitor in parallel. |

MAX9611/MAX9612

High-Side, Current-Sense Amplifiers with  
12-Bit ADC and Op Amp/Comparator

Functional Diagrams



Detailed Description

The MAX9611/MAX9612 are high-side, current-sense amplifiers with an integrated 12-bit ADC and an internal selectable op amp/comparator. These devices are ideal for a variety of industrial and automotive applications.

The MAX9611/MAX9612's high-side, current-sense amplifiers operate over a wide 0V to 60V input common-mode voltage range. The programmable full-scale voltage (440mV, 110mV, and 55mV) allows for a wide dynamic range current measurement and application flexibility in choosing sense resistor values.

The I<sup>2</sup>C bus is 1.8V and 3.3V logic compatible and can interface with modern microcontrollers. An internal 12-bit, 500sps integrating analog-to-digital converter (ADC) allows the user to read analog signals such as die temperature, V<sub>OUT</sub>, V<sub>SET</sub>, V<sub>RSCM</sub>, and V<sub>SENSE</sub>.

At power-up, the selectable op-amp/comparator block is configured in the op-amp mode. The op amp has an effective 60V Class A-type output stage and can be used to limit inrush currents and create a current source when used in a closed-loop system. When the internal comparator is selected, the MAX9611/MAX9612 can be configured to have a latched and retry functionality, allowing a 60V open-drain transistor output, ideal to operate high-side relay-disconnect FETs. The MAX9611 has a noninverting input-to-output configuration while the MAX9612 has an inverting input-to-output configuration.

Current-Sense Amplifier

The MAX9611/MAX9612 feature a precision current-sense amplifier with a 0V to 60V input common-mode voltage range. An internal negative charge pump elimi-

nates input stage crossover distortion, typical in most rail-to-rail input current-sense amplifiers. Low input bias currents and low input offset currents allow a wide selection of input filters to be designed without degrading the accuracy of the current-sense amplifier.

The current-sense amplifier inputs feature both a -0.3V/+65V common-mode absolute maximum rating as well as a ±65V differential absolute maximum rating, allowing a wide variety of fault conditions to be withstood easily by the device without damage.

The current-sense amplifier has a gain of 2.5V/V and connects directly to the output op-amp/comparator inputs. The ADC path features a 1x, 4x, and 8x programmable gain providing for 440mV, 110mV, and 55mV full-scale sense voltage.

Analog-to-Digital Converter (ADC)

The MAX9611/MAX9612 feature an internal dual-slope integrating 12-bit ADC that has a 2ms conversion time and a 1.8V and 3.3V logic-compatible I<sup>2</sup>C bus. An internal mux allows the following on-chip variables to be read: input sense voltage, input common-mode voltage, SET voltage, OUT voltage, and die temperature.

Temperature Measurement

Die temperature can be read by the ADC over the entire operating range (-40°C to +125°C) with 0.5°C resolution. Die temperature can be used for application calibration and thermal monitoring and is available in a 9-bit, two's complement format. Readings outside of normal operating temperature range (-40°C to +125°C) are inaccurate and should be considered invalid. See Table 1 for binary and hex values.

Table 1. Binary and Hex Digital Output Values for Temperature Measurements

| TEMPERATURE (°C) | DIGITAL OUTPUT      |      |
|------------------|---------------------|------|
|                  | BINARY              | HEX  |
| +122.4           | 0111 1111 1xxx xxxx | 7F8x |
| +24              | 0001 1001 0xxx xxxx | 190x |
| +0.48            | 0000 0000 1xxx xxxx | 008x |
| 0                | 0000 0000 0xxx xxxx | 000x |
| -0.48            | 1111 1111 1xxx xxxx | FF8x |
| -24              | 1110 0111 0xxx xxxx | E70x |
| -40              | 1101 1001 1xxx xxxx | D98x |

### SET Voltage Measurement

The SET voltage serves as a reference voltage for the internal op amp or comparator around which a control loop can be designed. The low bias current for SET allows high-impedance resistor-dividers and current output DACs to be used, making it easy to interface without introducing additional errors.

The SET input can also serve as an auxiliary input port to the ADC if the op amp or comparator is not utilized in the application. Its full-scale input range extends from 0V to 1.10V.

### OUT Voltage Measurement

The internal amplifier/comparator output voltage can be monitored over the entire 0V to 57.3V range by the ADC. An internal high-value resistor-divider on OUT reduces leakage current effects.

### Common-Mode Voltage Measurement

The input common-mode voltage is defined as the average of the voltage at RS+ and RS-. A high-value resistor-divider allows measurement of the input common-mode voltage over the 0V to 57.3V range.

### Sense Voltage Measurement

Three programmable gains allow for a wide range of currents to be read by the ADC. The current-sense amplifier gain can be set to 1x, 4x, or 8x. The full-scale sense voltages are then 440mV, 110mV, and 55mV, respectively.

### Output Amplifier/Comparator

The MAX9611/MAX9612 feature an internally selectable op amp and comparator where one of the inputs is connected to the 2.5x current-sense amplifier, and the other input is connected to the SET input. The op amp or the comparator output can be selected and connected to OUT. The output stage is an open-drain 60V nFET, that requires a suitable pullup resistor for proper operation. The op amp then behaves like a Class-A output stage. Select op amp or comparator function in Control Register 1 (0x0A) bit 7 (see Tables 4 and 5).

### Watchdog/Latch/Retry Functionality

Internal digital circuitry is used to implement a watchdog feature that can be useful to handle normal application transients that are not true fault conditions. This feature applies both to the op amp and comparator modes of part operation. A watchdog delay time is internally set to 1ms by default but can be changed to 100μs. The retry delay time is internally set to 50ms by default, but can be changed to 10ms (see Tables 6 and 7).

In normal operation mode, (Control Register 1 (0x0A) 000x xxxx), the amplifier output responds to the difference between its inputs, i.e., the CSA output voltage and the SET voltage. In open-loop configuration, the op amp can be used as a comparator.

In a watchdog-latch-retry mode (Control Register 1 (0x0A) 111x xxxx), the output of the comparator waits for a watchdog delay time (to ensure the CSA output continues to stay above the SET voltage for this duration) before responding, and then latches onto this state. After a retry delay time, it resets the comparator state and the cycle repeats.

Similar functionality is implemented for the op-amp mode as well (Control Register 1 (0x0A) 000x xxxx to 011x xxxx).

A RESET bit is defined in Control Register 1 (0x0A) to reset a latched state when commanded by the user.

### I<sup>2</sup>C Interface

The MAX9611/MAX9612 I<sup>2</sup>C interface consists of a serial-data line (SDA) and serial-clock line (SCL). SDA and SCL facilitate bidirectional communication between the MAX9611/MAX9612 and the master at rates up to 400kHz. The MAX9611/MAX9612 are slave devices that transfer and receive data. The master (typically a microcontroller) initiates data transfer on the bus and generates the SCL signal to permit that transfer.

## Slave Address

A bus master initiates communication with a slave device by issuing a START (S) condition followed by a slave address. When idle, the MAX9611/MAX9612 continuously wait for a START condition followed by their slave address. When the MAX9611/MAX9612 recognize a slave address, it is ready to accept or send data. The MAX9611/MAX9612 offer 16 different slave addresses using two address inputs, A1 and A0. See Table 2 for different slave address options. The least significant bit (LSB) of the address byte (R/W) determines whether the master is writing to or reading from the MAX9611/MAX9612 (R/W = 0 selects a write condition, R/W = 1 selects a read condition). After receiving the address, the MAX9611/MAX9612 (slave) issue an acknowledge by pulling SDA low for one clock cycle.

## I<sup>2</sup>C Write Operation

A write operation (Figure 1) begins with the bus master issuing a START condition followed by seven address bits and a write bit (R/W = 0). If the address byte is successfully received, the MAX9611/MAX9612 (slave) issue an acknowledge (A). The master then writes to the slave and the sequence is terminated by a STOP (P) condition for a single write operation.

For a burst write operation, more data bytes are sent after the register address before the transaction is terminated.

**Table 2. MAX9611/MAX9612 Address Description**

| A1                    | A0                    | DEVICE WRITE ADDRESS (hex) | DEVICE READ ADDRESS (hex) |
|-----------------------|-----------------------|----------------------------|---------------------------|
| 0                     | 0                     | 0xE0                       | 0xE1                      |
| 0                     | 1/3 x V <sub>CC</sub> | 0xE2                       | 0xE3                      |
| 0                     | 2/3 x V <sub>CC</sub> | 0xE4                       | 0xE5                      |
| 0                     | V <sub>CC</sub>       | 0xE6                       | 0xE7                      |
| 1/3 x V <sub>CC</sub> | 0                     | 0xE8                       | 0xE9                      |
| 1/3 x V <sub>CC</sub> | 1/3 x V <sub>CC</sub> | 0xEA                       | 0xEB                      |
| 1/3 x V <sub>CC</sub> | 2/3 x V <sub>CC</sub> | 0xEC                       | 0xED                      |
| 1/3 x V <sub>CC</sub> | V <sub>CC</sub>       | 0xEE                       | 0xEF                      |
| 2/3 x V <sub>CC</sub> | 0                     | 0xF0                       | 0xF1                      |
| 2/3 x V <sub>CC</sub> | 1/3 x V <sub>CC</sub> | 0xF2                       | 0xF3                      |
| 2/3 x V <sub>CC</sub> | 2/3 x V <sub>CC</sub> | 0xF4                       | 0xF5                      |
| 2/3 x V <sub>CC</sub> | V <sub>CC</sub>       | 0xF6                       | 0xF7                      |
| V <sub>CC</sub>       | 0                     | 0xF8                       | 0xF9                      |
| V <sub>CC</sub>       | 1/3 x V <sub>CC</sub> | 0xFA                       | 0xFB                      |
| V <sub>CC</sub>       | 2/3 x V <sub>CC</sub> | 0xFC                       | 0xFD                      |
| V <sub>CC</sub>       | V <sub>CC</sub>       | 0xFE                       | 0xFF                      |

## I<sup>2</sup>C Read Operation

In an I<sup>2</sup>C read operation (Figure 2), the bus master issues a write command first by initiating a START condition followed by seven address bits, a write bit (R/W = 0) and the 8-bit register address. The master then issues a Repeated START (Sr) condition, followed by seven address bits, a read bit (R/W = 1). If the address byte is successfully received, the MAX9611/MAX9612 (slave) issue an acknowledge (A). The master then reads from the slave. For continuous read, the master issues an acknowledge bit (AM) after each received byte. The master terminates the read operation by sending a not acknowledge (NA) bit. The MAX9611/MAX9612 then release the data line SDA allowing the master to generate a STOP condition.

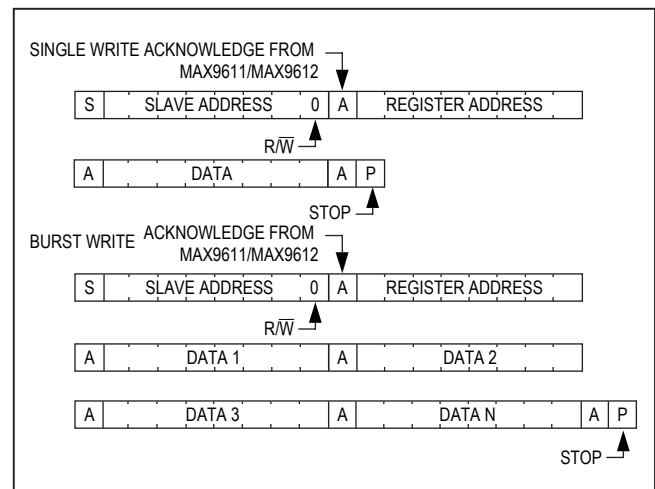


Figure 1. I<sup>2</sup>C Write Operation

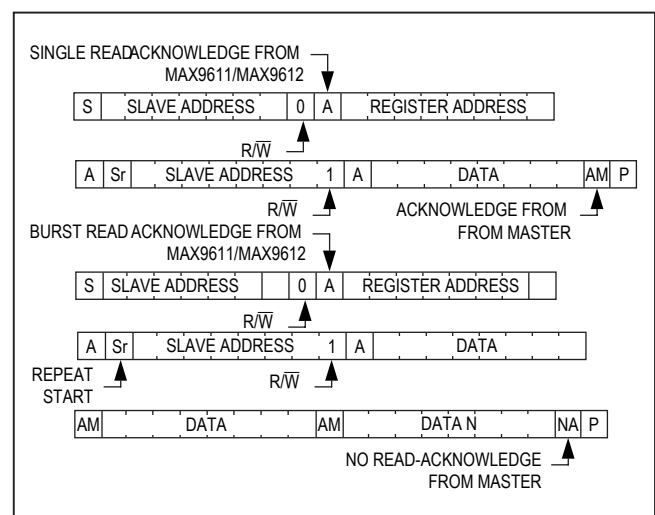


Figure 2. I<sup>2</sup>C Read Operation

## Registers

The MAX9611/MAX9612 include five 12-bit data register banks and two 8-bit control registers.

The two control registers are read/write registers used to configure the ADC for different modes of operation.

Table 3 lists all the registers, their corresponding POR values and their addresses.

**Table 3. Internal Register/Addresses**

| REGISTERS               | POR VALUES (hex) | REGISTER ADDRESS (hex) |
|-------------------------|------------------|------------------------|
| CSA DATA BYTE 1 (MSBs)  | 0x000            | 0x00                   |
| CSA DATA BYTE 1 (LSBs)  | 0x000            | 0x01                   |
| RS+ DATA BYTE 1 (MSBs)  | 0x000            | 0x02                   |
| RS+ DATA BYTE 1 (LSBs)  | 0x000            | 0x03                   |
| OUT DATA BYTE 1 (MSBs)  | 0x000            | 0x04                   |
| OUT DATA BYTE 1 (LSBs)  | 0x000            | 0x05                   |
| SET DATA BYTE 1 (MSBs)  | 0x000            | 0x06                   |
| SET DATA BYTE 1 (LSBs)  | 0x000            | 0x07                   |
| TEMP DATA BYTE 1 (MSBs) | 0x800            | 0x08                   |
| TEMP DATA BYTE 1 (LSBs) | 0x000            | 0x09                   |
| CONTROL REGISTER 1      | 0x000            | 0x0A                   |
| CONTROL REGISTER 2      | 0x000            | 0x0B                   |

## Data Registers

The five 12-bit data registers banks comprise two 8-bit registers for 8 MSBs and 4 LSBs. The 12-bit data is split between the two 8-bit data bytes as seen in Figure 1. They are read-only registers that hold the converted data. Do not issue a STOP command until both bytes are read. Instead use a Repeated START command to read the second byte.

### Byte 1

| BIT 7 | BIT 6 | BIT 5 | BIT 4 | BIT 3 | BIT 2 | BIT 1 | BIT 0 |
|-------|-------|-------|-------|-------|-------|-------|-------|
| MSB12 | MSB11 | MSB10 | MSB09 | MSB08 | MSB07 | MSB06 | MSB05 |

### Byte 2

| BIT 7 | BIT 6 | BIT 5 | BIT 4 | BIT 3 | BIT 2 | BIT 1 | BIT 0 |
|-------|-------|-------|-------|-------|-------|-------|-------|
| LSB05 | LSB03 | LSB02 | LSB01 | 0     | 0     | 0     | 0     |

## Control Register 1

Control Register 1 is an 8-bit write/read register that configures the MAX9611/MAX9612 for different modes of operation. Tables 4 and 5 show the bit location and function for Control Register 1.

**Table 4. Control Register 1 Bit Location**

| BIT NUMBER | 7     | 6     | 5     | 4  | 3    | 2    | 1    | 0    |
|------------|-------|-------|-------|----|------|------|------|------|
| BIT NAME   | MODE2 | MODE1 | MODE0 | LR | SHDN | MUX2 | MUX1 | MUX0 |
| POR VALUE  | 0     | 0     | 0     | 0  | 0    | 0    | 0    | 0    |

**Table 5. Control Register 1 Bit Description**

| BIT     | BIT NAME            | FUNCTION                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |
|---------|---------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 2, 1, 0 | MUX2, MUX1, MUX0    | 000 Channel A: Read current-sense amplifier output from ADC, gain = 1x<br>001 Channel A: Read current-sense amplifier output from ADC, gain = 4x<br>010 Channel A: Read current-sense amplifier output from ADC, gain = 8x<br>011 Channel B: Read average voltage of RS+ (input common-mode voltage) from ADC<br>100 Channel C: Read voltage of OUT from ADC<br>101 Channel D: Read voltage of SET from ADC<br>110 Channel E: Read internal die temperature from ADC<br>111 Read all channels in fast-read mode, sequentially every 2ms. Uses last gain setting. |
| 3       | SHDN                | Power-on state = 0<br>0 = Normal operation<br>1 = Shutdown mode                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |
| 4       | LR                  | 0 = Normal operation<br>1 = Reset if comparator is latched due to MODE = 111. This bit is automatically reset after a 1 is written.                                                                                                                                                                                                                                                                                                                                                                                                                              |
| 7, 6, 5 | MODE2, MODE1, MODE0 | 000 = Normal operation for op amp/comparator<br>111 = Comparator mode. OUT remains low until CSA output > $V_{SET}$ for 1ms, OUT latches high for 50ms, then OUT autoretries by going low. The comparator has an internal $\pm 10\text{mV}$ hysteresis voltage to help with noise immunity. For MAX9612, the polarity is reversed.<br>011 = Op-amp mode. OUT regulates pFET for 1ms at $V_{SET}$ . OUT latches high for 50ms, then OUT autoretries by going low. For MAX9612, the polarity is reversed.                                                          |

**Control Register 2**

Control Register 2 is an 8-bit write/read register that provides the different time delay options for asserting the comparator output when monitoring fault events. Tables 6 and 7 show the bit location and function for Control Register 2.

**Table 6. Control Register 2**

| BIT NUMBER | 7 | 6 | 5 | 4 | 3    | 2    | 1 | 0 |
|------------|---|---|---|---|------|------|---|---|
| BIT NAME   | X | X | X | X | DTIM | RTIM | X | X |
| POR VALUE  | 0 | 0 | 0 | 0 | 0    | 0    | 0 | 0 |

**Table 7. Control Register 2 Bit Descriptions**

| BIT        | BIT NAME | FUNCTION                                          |
|------------|----------|---------------------------------------------------|
| 7, 6, 5, 4 | X        | Set to 0                                          |
| 3          | DTIM     | Watchdog delay time<br>0 = 1ms<br>1 = 100 $\mu$ s |
| 2          | RTIM     | Watchdog retry delay time<br>0 = 50ms<br>1 = 10ms |
| 1, 0       | X        | Set to 0                                          |

### Power-On Reset

The MAX9611/MAX9612 include power-on reset circuitry that ensures all registers reset to a known state on power-up. Once  $V_{CC}$  goes above 2.4V, the POR circuit releases the registers for normal operation.

## Applications Information

### Inrush Current Limiter

The MAX9611 can be used as an inrush current limiter for a number of applications as shown in Figure 3. Note that the sense resistor can be placed on either side of the pFET. Since the input common-mode voltage of the MAX9611 extends to ground, the sense resistor can be placed at the load side as well, allowing current to be sensed even when there is a dead-short on the load.

The inrush current limiting circuit reads and measures the load current during normal operation and can limit the load current to a user-set value. In normal operation, the load current is below the set threshold. The pFET is fully turned on because the op-amp output is at 0V. In the event of an overcurrent situation at the load, the op-amp controls the pFET's gate-voltage so it transitions to a linear region, thus limiting the load current. In this case, the op-amp output voltage is between 0V and  $V_{BAT}$ , as required for current-limiting.

Choose a suitable sense resistor and a low  $R_{DS-ON}$  pFET to ensure the best efficiency during normal operation. Choose a pFET with large power dissipation to ensure compliance with safe operating area of the pFET. The MAX9611 comes equipped with a variety of watchdog options to help with this design (see Control Register 2, Table 7).

Choose resistor values  $R_1$  and  $R_2$  to ensure that the pFET is fully on in normal operating conditions and to ensure that the  $V_{GS}$  maximum rating is not exceeded. Also,  $R_1$  and  $R_2$  help limit the current in the open-drain output stage of the internal op amp.  $R_{COMP}$  and  $C_{COMP}$  help rolloff high-frequency gain of the feedback control system.  $R_2$  and  $C_{COMP}$  set a pole, for which 10kHz is a good choice.  $R_{COMP}$  and  $C_{COMP}$  set a zero, for which 100kHz is a good choice.

With the internal gain of the current-sense amplifier (2.5V/V), the inrush current-limit threshold can be set using resistor-divider  $R_3$  and  $R_4$  as follows:

$$\frac{V_{CC} \times R_3}{(R_4 + R_3)(2.5 \times R_{SENSE})} = I_{LIMIT}$$

**Note:** The inrush current limiter can be changed to a high-side relay-disconnect circuit by using the MAX9611 set to comparator mode (MODE 111).

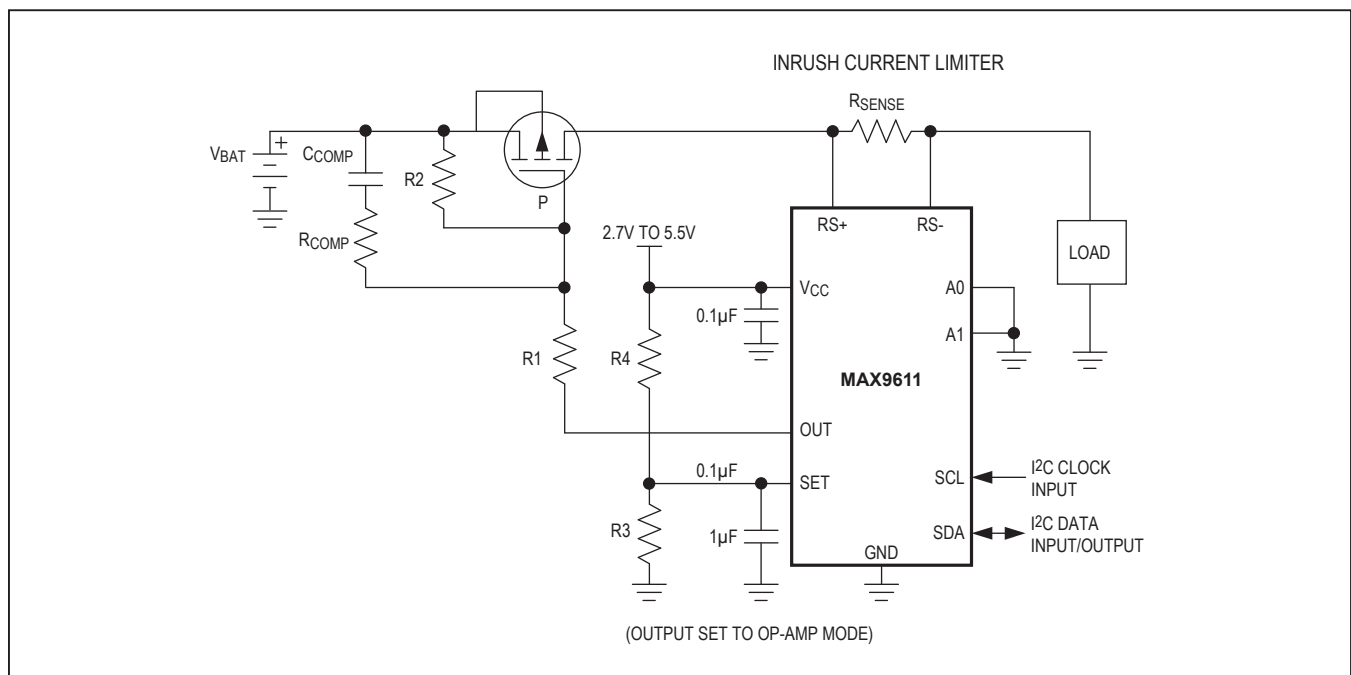


Figure 3. Inrush Current Limiter

### Base-Station PA Gain Control

While the MAX9611 is designed to control high-side pFETs, the MAX9612 can be similarly used to control low-side nFETs. For example, the MAX9612 can be used to control the DC bias point of power amplifier LDMOS or GaN nFETs in base-station applications. The circuit shown in Figure 4 also allows the option to apply negative bias voltages to the PA FET, which is required for certain types of transistors for proper operation.

In the circuit shown, the nFET is in a linear mode of operation to allow it to amplify high-frequency RF signals, while the MAX9612 sets the DC operating point. The gain of the FET can be varied by changing its drain current. This operating point can be varied by an external DAC voltage that feeds the SET pin.

$V_{NEG}$  and  $V_{CLAMP}$  together with  $R1$ ,  $R2$ , and  $R3$  set the DC bias point limits for the PA transistor.  $V_{CLAMP}$  is a suitable positive voltage and  $V_{NEG}$  is a suitable negative voltage. When  $V_{OUT} = 0V$ , the gate voltage of the PA FET is:

$$\frac{V_{NEG} \times R2}{(R1 + R2)} = V_{OUT}$$

When the OUT open-drain transistor is off, the gate voltage of the PA FET is:

$$V_{GATE} = \frac{V_{CLAMP}R1}{R1 + R2 + R3} + \frac{V_{NEG}(R2 + R3)}{R1 + R2 + R3}$$

$R_{COMP}$  and  $C_{COMP}$  connected to the OUT pin compensate the internal amplifier. Choose a corner frequency of 100kHz.

Choose suitable  $R_{SENSE}$  as required for the application. The inductor isolates the DC measuring point of current from the high-frequency AC signals through the PA FET, as well as helping with the high-frequency gain.

### Power-Supply Bypassing and Grounding

The MAX9611/MAX9612 share a common ground pin for both the analog and digital on-chip circuitry. It is therefore very important to properly bypass the  $V_{CC}$  to GND, and to have a solid low-noise ground plane on the circuit board so as to minimize ground bounce. Bypass  $V_{CC}$  to GND with low ESR 0.1μF in parallel with a 4.7μF ceramic capacitor to GND placed as close as possible to the device.

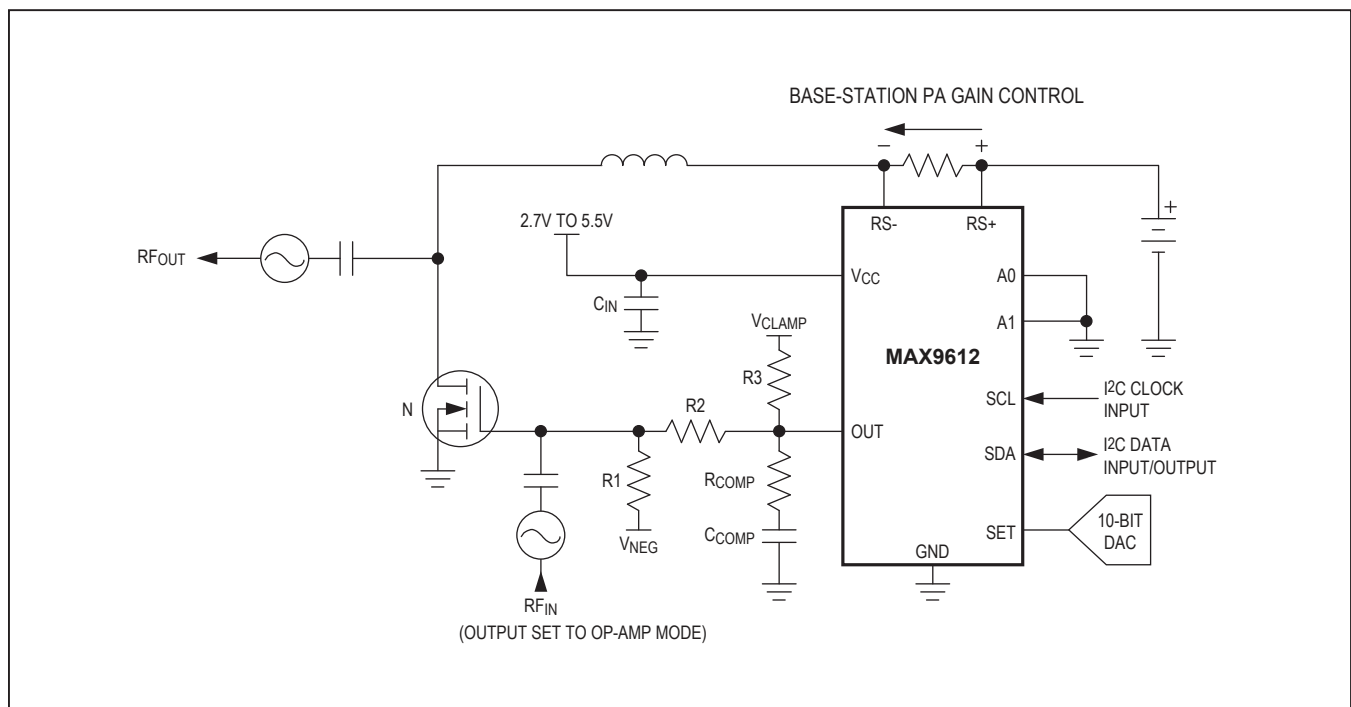


Figure 4. Base-Station PA Gain Control

### Chip Information

PROCESS: BiCMOS

### Package Information

For the latest package outline information and land patterns (footprints), go to [www.maximintegrated.com/packages](http://www.maximintegrated.com/packages). Note that a "+", "#", or "-" in the package code indicates RoHS status only. Package drawings may show a different suffix character, but the drawing pertains to the package regardless of RoHS status.

| PACKAGE TYPE | PACKAGE CODE | OUTLINE NO.             | LAND PATTERN NO.        |
|--------------|--------------|-------------------------|-------------------------|
| 10 $\mu$ MAX | U10+2        | <a href="#">21-0061</a> | <a href="#">90-0330</a> |

## Revision History

| REVISION<br>NUMBER | REVISION<br>DATE | DESCRIPTION                                                                                  | PAGES<br>CHANGED |
|--------------------|------------------|----------------------------------------------------------------------------------------------|------------------|
| 0                  | 9/10             | Initial release                                                                              | —                |
| 1                  | 11/10            | Updated text in Table 5 to add “comparator” to mode 000 for bits 7, 6, 5                     | 16               |
| 2                  | 1/11             | Relaxed room temperature limits for 4x and 8x gains from 0.3mV to 0.5mv                      | 1, 2             |
| 3                  | 6/11             | Updated TYP spec for output current sink in the <i>Electrical Characteristics</i> and TOC 11 | 3, 7             |
| 4                  | 6/14             | Update equation in <i>Inrush Current Limiter</i> section                                     | 17               |
| 5                  | 12/19            | Updated <i>Electrical Characteristics</i>                                                    | 4                |

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