MAX9938

nanoPower, 4-Bump UCSP/SOT23, Precision Current-Sense Amplifier

General Description

The MAX9938 high-side current-sense amplifier offers precision accuracy specifications of V_{OS} less than 500µV (max) and gain error less than 0.5% (max). Quiescent supply current is an ultra-low 1µA. The MAX9938 fits in a tiny, 1mm x 1mm UCSP™ package size or a 5-pin SOT23 package, making the part ideal for applications in notebook computers, cell phones, PDAs, and all battery-operated portable devices where accuracy, low quiescent current, and small size are critical.

The MAX9938 features an input common-mode voltage range from 1.6V to 28V. These current-sense amplifiers have a voltage output and are offered in four gain versions: 25V/V (MAX9938T), 50V/V (MAX9938F), 100V/V (MAX9938H), and 200V/V (MAX9938W).

The four gain selections offer flexibility in the choice of the external current-sense resistor. The very low 500µV (max) input offset voltage allows small 25mV to 50mV full-scale V_{SENSE} voltage for very low voltage drop at full-current measurement.

The MAX9938 is offered in tiny 4-bump, UCSP (1mm x 1mm x 0.6mm footprint), 5-pin SOT23, and 6-pin µDFN (2mm x 2mm x 0.8mm) packages specified for operation over the -40°C to +85°C extended temperature range.

Applications

- Cell Phones
- PDAs
- Power Management Systems
- Portable/Battery-Powered Systems
- Notebook Computers

Features

- Ultra-Low Supply Current of 1µA (max)
- Low 500µV (max) Input Offset Voltage
- Low < 0.5% (max) Gain Error
- Input Common Mode: +1.6V to +28V
- Voltage Output
- Four Gain Versions Available
  - +25V/V (MAX9938T)
  - 50V/V (MAX9938F)
  - 100V/V (MAX9938H)
  - 200V/V (MAX9938W)
- Tiny 1mm x 1mm x 0.6mm, 4-Bump UCSP, 5-Pin SOT23, or 2mm x 2mm x 0.8mm, 6-Pin µDFN Packages

Ordering Information

PART	PIN-PACKAGE	GAIN (V/V)	TOP MARK
MAX9938TEBS+G45	4 UCSP	25	+AGD
MAX9938FEBS+G45	4 UCSP	50	+AGE
MAX9938HEBS+G45	4 UCSP	100	+AGF
MAX9938WEBS+G45	4 UCSP	200	+AGI
MAX9938TEUK+	5 SOT23	25	+AFFB
MAX9938FEUK+	5 SOT23	50	+AFFC
MAX9938HEUK+	5 SOT23	100	+AFFD
MAX9938WEUK+	5 SOT23	200	+AFGZ
MAX9938FELT+	6 µDFN	50	+ACM

+Denotes a lead(Pb)-free/RoHS-compliant package.
G45 indicates protective die coating.

***Note:** All devices are specified over the -40°C to +85°C extended temperature range.*

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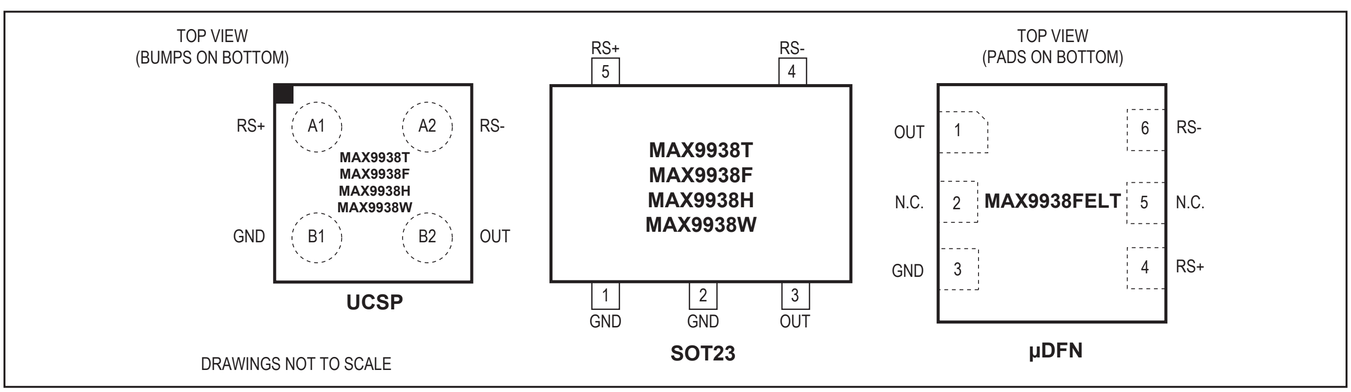
Pin Configurations



Absolute Maximum Ratings

RS+, RS- to GND ....-0.3V to +30V
OUT to GND ....-0.3V to +6V
RS+ to RS- ....±30V
Short-Circuit Duration: OUT to GND ....Continuous
Continuous Input Current (Any Pin) ....±20mA
Continuous Power Dissipation (T_A = +70°C)
  4-Bump UCSP (derate 3.0mW/°C above +70°C)........238mW
  5-Pin SOT23 (derate 3.9mW/°C above +70°C) 312mW
  6-Pin µDFN (derate 4.5mW/°C above +70°C) 358mW

Operating Temperature Range .... -40°C to +85°C
Junction Temperature ....+150°C
Storage Temperature Range .... -65°C to +150°C
Lead Temperature (excluding UCSP, soldering, 10s) .....+300°C
Soldering Temperature (reflow) ....+260°C

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

($V_{RS+} = V_{RS-}$ = 3.6V, $V_{SENSE} = (V_{RS+} - V_{RS-})$ = 0V, T_A = -40°C to +85°C, unless otherwise noted. Typical values are at T_A = +25°C.) (Note 1)

PARAMETER	SYMBOL	CONDITIONS	MIN	TYP	MAX	UNITS
Supply Current (Note 2)	I_{CC}	V_{RS+} = 5V, T_A = +25°C		0.5	0.85	µA
		V_{RS+} = 5V, -40°C < T_A < +85°C			1.1	
		V_{RS+} = 28V, T_A = +25°C		1.1	1.8	
		V_{RS+} = 28V, -40°C < T_A < +85°C			2.5	
Common-Mode Input Range	V_{CM}	Guaranteed by CMRR , -40°C < T_A < +85°C	1.6		28	V
Common-Mode Rejection Ratio	CMRR	1.6V < V_{RS+} < 28V, -40°C < T_A < +85°C	94	130		dB
Input Offset Voltage (Note 3)	V_{OS}	T_A = +25°C		±100	±500	µV
		-40°C < T_A < +85°C			±600	
Gain	G	MAX9938T		25		V/V
		MAX9938F		50		
		MAX9938H		100		
		MAX9938W		200		
Gain Error (Note 4)	GE	MAX9938T/MAX9938F/MAX9938H, T_A = +25°C		±0.1	±0.5	%
		MAX9938T/MAX9938F/MAX9938H, -40°C < T_A < +85°C			±0.6	
		MAX9938W, T_A = +25°C		±0.1	±0.7	
		MAX9938W, -40°C < T_A < +85°C			±0.8	
Output Resistance	R_{OUT}	(Note 5), MAX9938T/F/H	7.0	10	13.2	kΩ
		(Note 5), MAX9938W	14.0	20	26.4	
OUT Low Voltage	V_{OL}	Gain = 25		1.5	15	mV
		Gain = 50		3	30	
		Gain = 100		6	60	
		Gain = 200		12	120	
OUT High Voltage	V_{OH}	$V_{OH} = V_{RS-} - V_{OUT}$ (Note 6)		0.1	0.2	V
Small-Signal Bandwidth (Note 5)	BW	V_{SENSE} = 50mV, gain = 25		125		V
		V_{SENSE} = 50mV, gain = 50		60		kHz
		V_{SENSE} = 50mV, gain = 100		30		
		V_{SENSE} = 50mV, gain = 200		15		
Output Settling Time	t_S	1% final value, V_{SENSE} = 50mV		100		µs

Electrical Characteristics (continued)

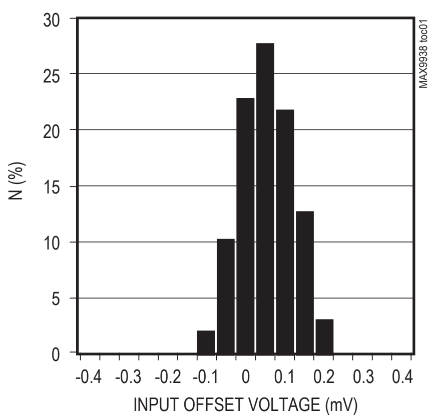
($V_{RS+} = V_{RS-} = 3.6V$, $V_{SENSE} = (V_{RS+} - V_{RS-}) = 0V$, $T_A = -40°C$ to $+85°C$, unless otherwise noted. Typical values are at $T_A = +25°C$.) (Note 1)

Note 1: All devices are 100% production tested at $T_A = +25°C$. All temperature limits are guaranteed by design.
Note 2: $V_{OUT} = 0$. I_{CC} is the total current into RS+ plus RS- pins.
Note 3: V_{OS} is extrapolated from measurements for the gain-error test.
Note 4: Gain error is calculated by applying two values of V_{SENSE} and calculating the error of the slope vs. the ideal:
Gain = 25, V_{SENSE} is 20mV and 120mV.
Gain = 50, V_{SENSE} is 10mV and 60mV.
Gain = 100, V_{SENSE} is 5mV and 30mV.
Gain = 200, V_{SENSE} is 2.5mV and 15mV.
Note 5: The device is stable for any external capacitance value.
Note 6: V_{OH} is the voltage from V_{RS-} to V_{OUT} with V_{SENSE} = 3.6V/gain.

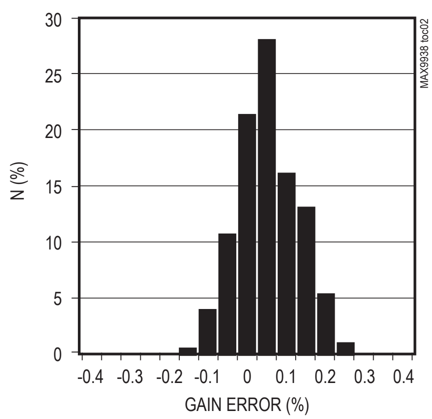
Typical Operating Characteristics

($V_{RS+} = V_{RS-} = 3.6V$, $T_A = +25°C$, unless otherwise noted.)

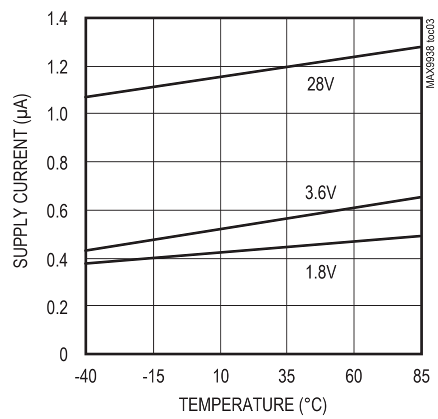
INPUT OFFSET VOLTAGE HISTOGRAM



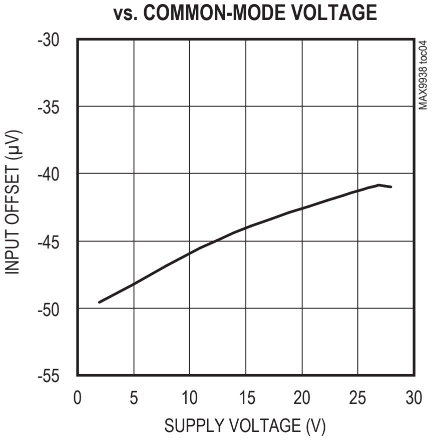
GAIN ERROR HISTOGRAM



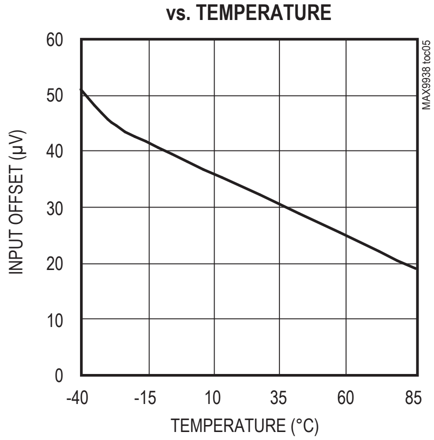
SUPPLY CURRENT
vs. TEMPERATURE



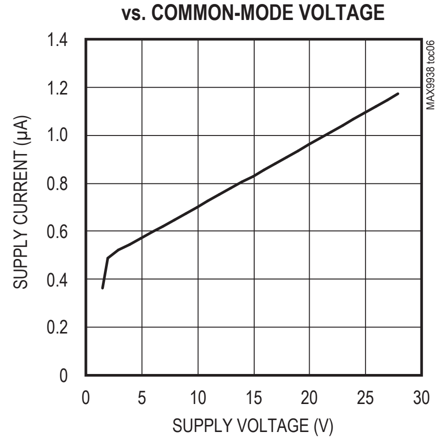
INPUT OFFSET
vs. COMMON-MODE VOLTAGE



INPUT OFFSET
vs. TEMPERATURE



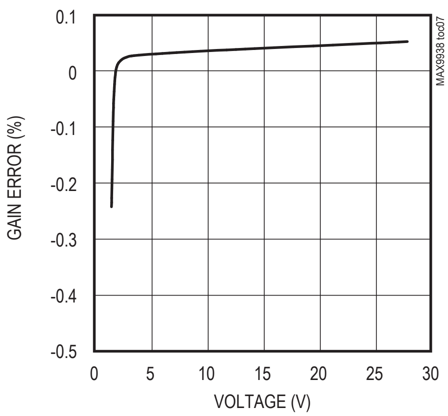
SUPPLY CURRENT
vs. COMMON-MODE VOLTAGE



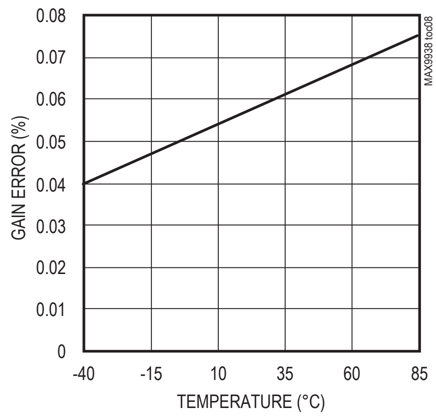
Typical Operating Characteristics (continued)

($V_{RS+} = V_{RS-} = 3.6V$, $T_A = +25°C$, unless otherwise noted.)

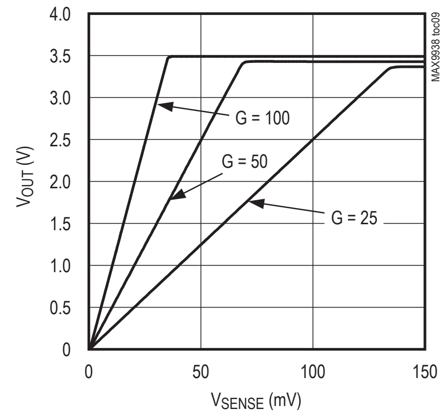
GAIN ERROR vs. COMMON-MODE VOLTAGE



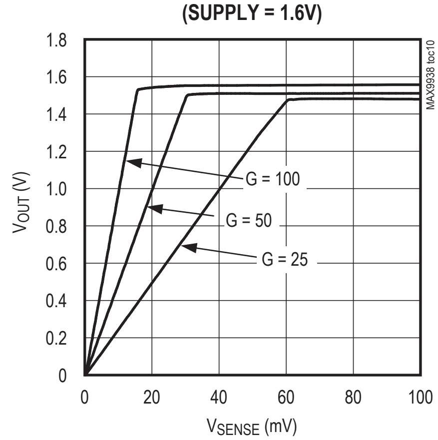
GAIN ERROR vs. TEMPERATURE



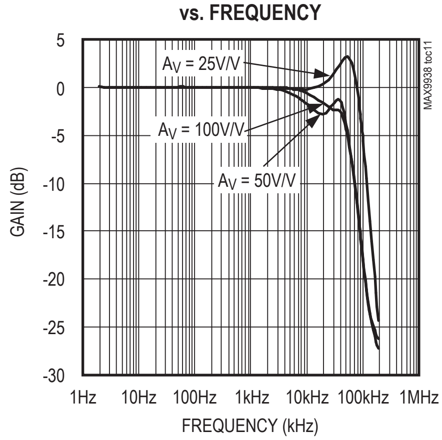
V_{OUT} vs. V_{SENSE} (SUPPLY = 3.6V)



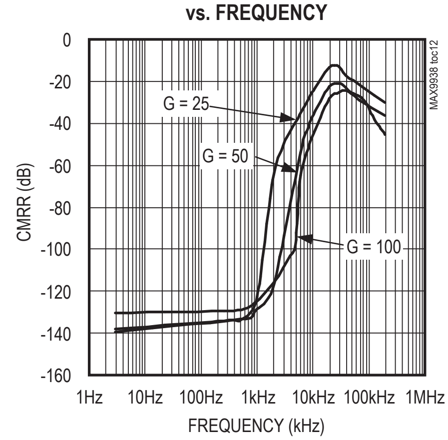
V_{OUT} vs. V_{SENSE} (SUPPLY = 1.6V)



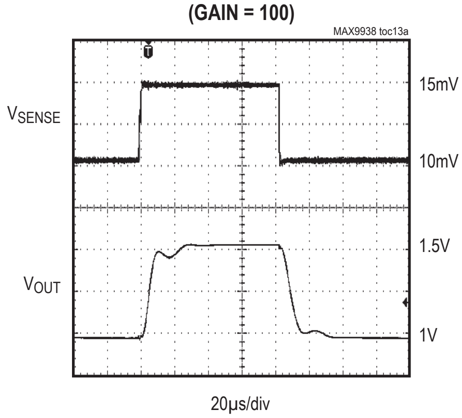
SMALL SIGNAL GAIN vs. FREQUENCY



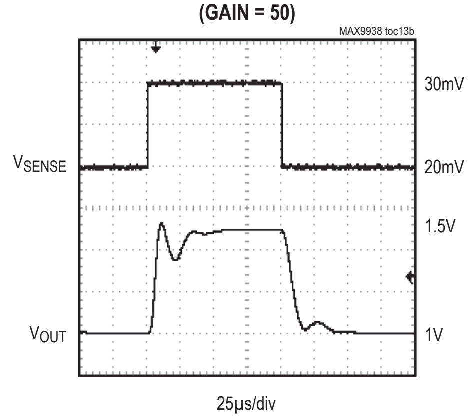
CMRR vs. FREQUENCY



SMALL-SIGNAL PULSE RESPONSE (GAIN = 100)



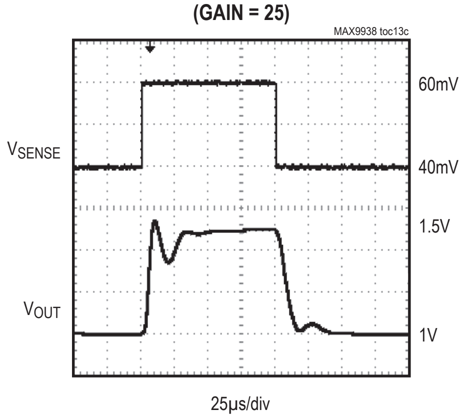
SMALL-SIGNAL PULSE RESPONSE (GAIN = 50)



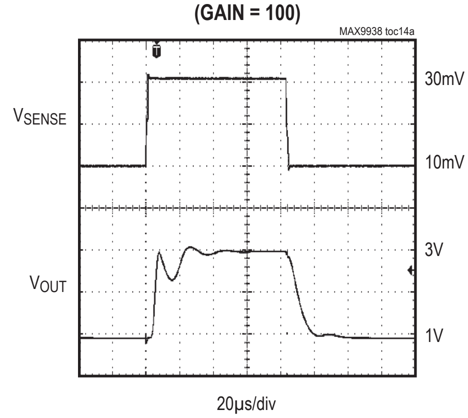
Typical Operating Characteristics (continued)

(V_{RS+} = V_{RS-} = 3.6V, T_A = +25°C, unless otherwise noted.)

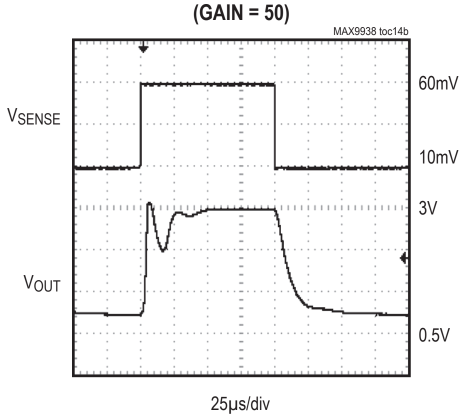
SMALL-SIGNAL PULSE RESPONSE (GAIN = 25)



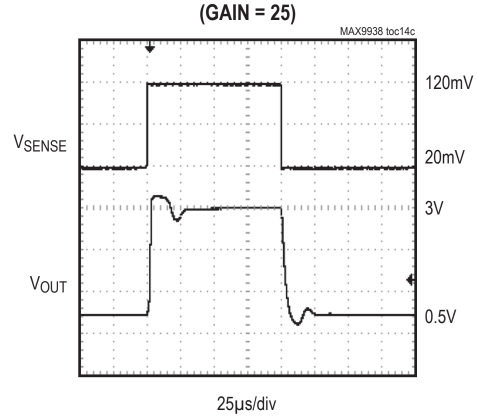
LARGE-SIGNAL PULSE RESPONSE (GAIN = 100)



LARGE-SIGNAL PULSE RESPONSE (GAIN = 50)



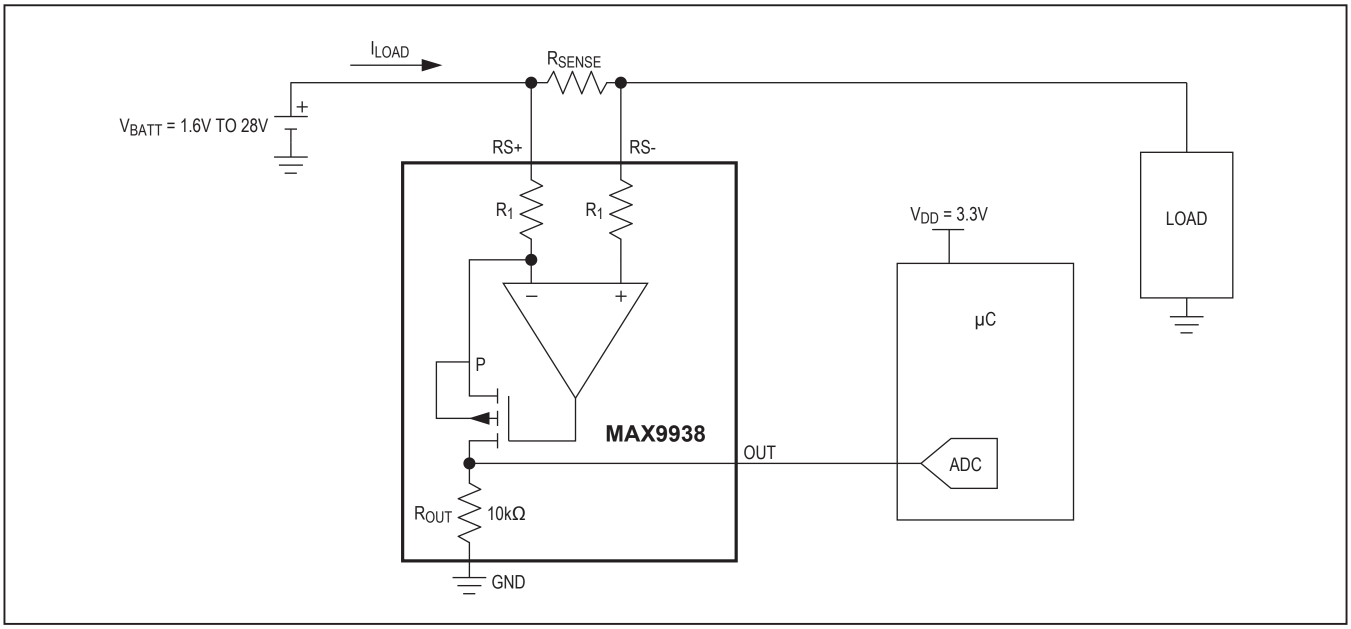
LARGE-SIGNAL PULSE RESPONSE (GAIN = 25)



Pin Description

PIN			NAME	FUNCTION
UCSP	SOT23	µDFN		
A1	5	4	RS+	External Sense Resistor Power-Side Connection
A2	4	6	RS-	External Sense Resistor Load-Side Connection
B1	1, 2	3	GND	Ground
B2	3	1	OUT	Output Voltage. V_{OUT} is proportional to V_{SENSE} = V_{RS+} - V_{RS-}.
—	—	2, 5	N.C.	No Connection. Not internally connected.

Typical Operating Circuit



Detailed Description

The MAX9938 unidirectional high-side, current-sense amplifier features a 1.6V to 28V input common-mode range. This feature allows the monitoring of current out of a battery with a voltage as low as 1.6V. The MAX9938 monitors current through a current-sense resistor and amplifies the voltage across that resistor.

The MAX9938 is a unidirectional current-sense amplifier that has a well-established history. An op amp is used to force the current through an internal gain resistor at RS+, which has a value of R_1, such that its voltage drop equals the voltage drop across an external sense resistor, R_{SENSE}. There is an internal resistor at RS- with the same value as R_1 to minimize offset voltage. The current through R_1 is sourced by a high-voltage p-channel FET. Its source current is the same as its drain current, which flows through a second gain resistor, R_{OUT}. This produces an output voltage, V_{OUT}, whose magnitude is I_{LOAD} x R_{SENSE} x R_{OUT}/R_1. The gain accuracy is based on the matching of the two gain resistors R_1 and R_{OUT} (see Table 1). Total gain = 25V/V for the MAX9938T, 50V/V for the MAX9938F, 100V/V for the MAX9938H, and 200V/V for the MAX9938W. The output is protected from input overdrive by use of an output current limiting circuit of 7mA (typical) and a 6V clamp protection circuit.

Table 1. Internal Gain Setting Resistors (Typical Values)

GAIN (V/V)	R_1 (Ω)	R_{OUT} (kΩ)
200	100	20
100	100	10
50	200	10
25	400	10

Applications Information

Choosing the Sense Resistor

Choose R_{SENSE} based on the following criteria:

Voltage Loss

A high R_{SENSE} value causes the power-source voltage to drop due to IR loss. For minimal voltage loss, use the lowest R_{SENSE} value.

OUT Swing vs. V_{RS+} and V_{SENSE}

The MAX9938 is unique since the supply voltage is the input common-mode voltage (the average voltage at RS+ and RS-). There is no separate V_{CC} supply voltage pin. Therefore, the OUT voltage swing is limited by the minimum voltage at RS+.

$$V_{OUT}\,(max) = V_{RS+}\,(min) - V_{SENSE}\,(max) - V_{OH}$$

and

$$R_{SENSE} = \frac{V_{OUT}\,(max)}{G \times I_{LOAD}\,(max)}$$

V_{SENSE} full scale should be less than V_{OUT}/gain at the minimum RS+ voltage. For best performance with a 3.6V supply voltage, select R_{SENSE} to provide approximately 120mV (gain of 25V/V), 60mV (gain of 50V/V), 30mV (gain of 100V/V), or 15mV (gain of 200V/V) of sense voltage for the full-scale current in each application. These can be increased by use of a higher minimum input voltage.

Accuracy

In the linear region ($V_{OUT} < V_{OUT}$(max)), there are two components to accuracy: input offset voltage (V_{OS}) and gain error (GE). For the MAX9938, V_{OS} = 500µV (max) and gain error is 0.5% (max). Use the linear equation:

$$V_{OUT} = (gain \pm GE) \times V_{SENSE} \pm (gain \times V_{OS})$$

to calculate total error. A high R_{SENSE} value allows lower currents to be measured more accurately because offsets are less significant when the sense voltage is larger.

Efficiency and Power Dissipation

At high current levels, the I^2R losses in R_{SENSE} can be significant. Take this into consideration when choosing the resistor value and its power dissipation (wattage) rating. Also, the sense resistor's value might drift if it is allowed to heat up excessively. The precision V_{OS} of the MAX9938 allows the use of small sense resistors to reduce power dissipation and reduce hot spots.

Kelvin Connections

Because of the high currents that flow through R_{SENSE}, take care to eliminate parasitic trace resistance from causing errors in the sense voltage. Either use a four-terminal current-sense resistor or use Kelvin (force and sense) PCB layout techniques.

Optional Output Filter Capacitor

When designing a system that uses a sample-and-hold stage in the ADC, the sampling capacitor momentarily loads OUT and causes a drop in the output voltage. If sampling time is very short (less than a microsecond), consider using a ceramic capacitor across OUT and GND to hold V_{OUT} constant during sampling. This also decreases the small-signal bandwidth of the current-sense amplifier and reduces noise at OUT.

Input Filters

Some applications of current-sense amplifiers need to measure currents accurately even in the presence of both differential and common-mode ripple, as well as a wide variety of input transient conditions. For example, high-frequency ripple at the output of a switching buck or boost regulator results in a common-mode voltage at the inputs of the MAX9938. Alternatively, fast load-current transients, when measuring at the input of a switching buck or boost regulator, can cause high-frequency differential sense voltages to occur at the inputs of the MAX9938, although the signal of interest is the average DC value. Such high-frequency differential sense voltages may result in a voltage offset at the MAX9938 output.

The MAX9938 allows two methods of filtering to help improve performance in the presence of input common-mode voltage and input differential voltage transients. Figure 1 shows a differential input filter.

The capacitor C_{IN} between RS+ and RS- along with the resistor R_{IN} between the sense resistor and RS- helps filter against input differential voltages and prevents them from reaching the MAX9938.

The corner frequency of this filter is determined by the choice of R_{IN}, C_{IN}, and the value of the input resistance at RS- (R_1). See Table 1 for R_1 values at the different gain options.

The value of R_{IN} should be chosen to minimize its effect on the input offset voltage due to the bias current at RS-. R_{IN} x I_{BIAS} contributes to the input voltage offset. I_{BIAS} is typically 0.2µA.

Placing R_{IN} at the RS- input does not affect the gain error of the device because the gain is given by the ratio between R_{OUT} and R_1 at RS+.

Figure 2 shows the input common-mode filter.

Again, the corner frequency of the filter is determined by the choice of R_{IN}, C_{IN} and is affected by R_1.

In this case R_{IN} affects both gain error and input offset voltage. R_{IN} should be smaller than R_1 so that it has negligible effect on the device gain. If, for example, a filter with R_{IN} = 10Ω and C_{IN} = 1µF is built, then depending upon the gain selection, the gain error is affected by either 2.5% (G = 25V/V, R_1 = 400Ω) or 5% (G = 50V/V, R_1 = 200Ω) or 10% (G = 100V/V, R_1 = 100Ω) or 10% (G = 200V/V, R_1 = 100Ω).

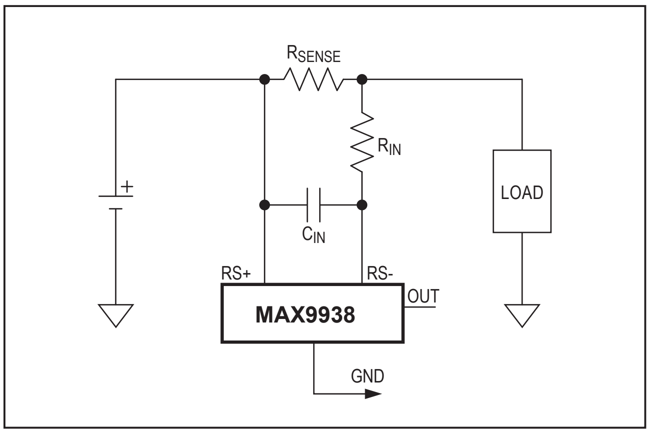


Figure 1. Differential Input Filter

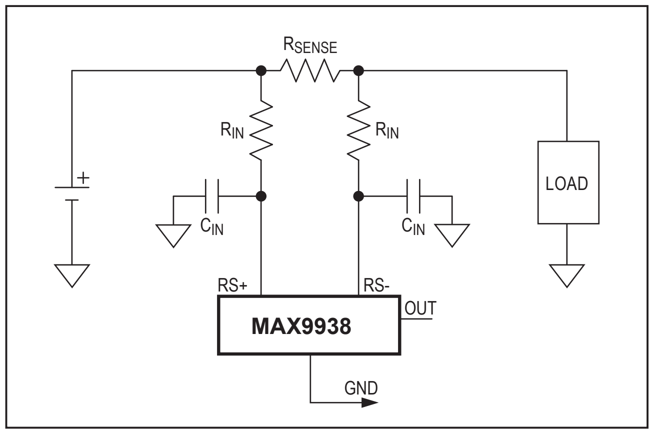


Figure 2. Input Common-Mode Filter

Bidirectional Application

Battery-powered systems may require a precise bidirectional current-sense amplifier to accurately monitor the battery's charge and discharge currents. Measurements of the two separate outputs with respect to GND yields an accurate measure of the charge and discharge currents respectively (Figure 3).

UCSP Applications Information

For the latest application details on UCSP construction, dimensions, tape carrier information, PCB techniques, bump-pad layout, and recommended reflow temperature profile, as well as the latest information on reliability testing results, refer to the Application Note 1891: *Wafer-Level Packaging (WLP) and Its Applications* available on Maxim's website at **www.maximintegrated.com/ucsp**.

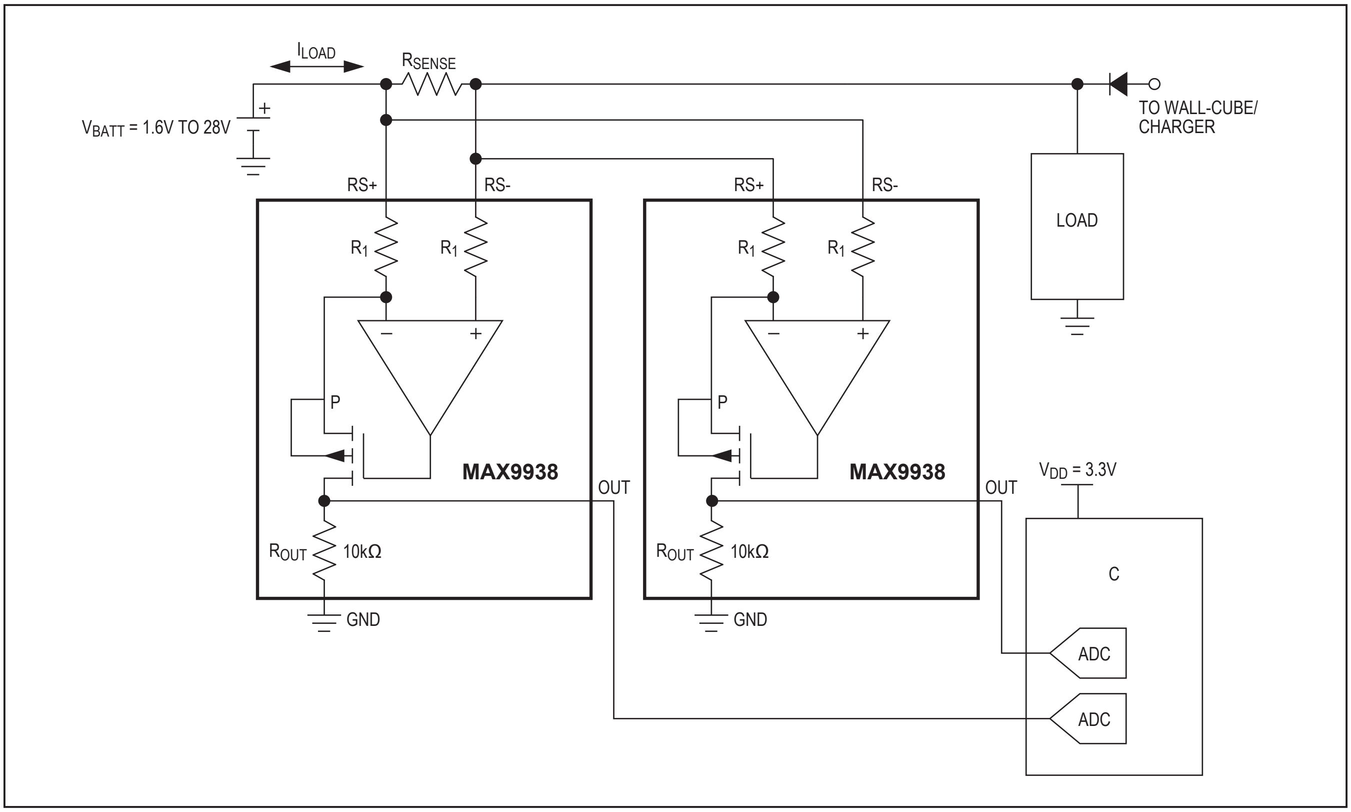


Figure 3. Bidirectional Application

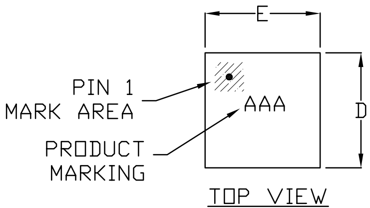
Chip Information

PROCESS: BiCMOS

Package Information

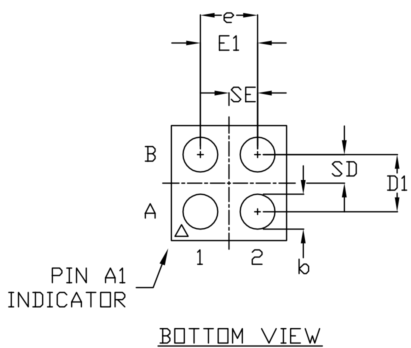
For the latest package outline information and land patterns (footprints), go to **www.maximintegrated.com/packages**. Note that a "+", "#", or "-" in the package code indicates RoHS status only. Package drawings may show a different suffix character, but the drawing pertains to the package regardless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

PACKAGE TYPE	PACKAGE CODE	OUTLINE NO.	LAND PATTERN NO.
2 x 2 UCSP	B4+1	21-0117	—
5 SOT23	U5-2	21-0057	90-0174
6 µDFN	L622+1	21-0164	90-0004

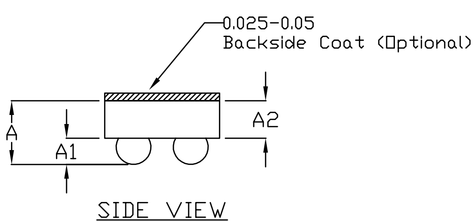


COMMON DIMENSIONS	
A	0.62+0.05−0.08
A1	0.29±0.02
A2	0.33 REF.
b	ø0.35±0.03
D1	0.50 BASIC
E1	0.50 BASIC
e	0.50 BASIC
SD	0.25 BASIC
SE	0.25 BASIC

PKG. CODE	VARIABLE DIMENSIONS		DEPOPULATED SOLDER BALLS
	D	E	
B4-1	1.00±0.05	1.00±0.05	NONE
B4-2	1.05±0.05	1.05±0.05	NONE
B4-3	1.10±0.05	1.10±0.05	NONE



NOTES:
1. ALL DIMENSIONS ARE IN MILLIMETERS UNLESS OTHERWISE SPECIFIED.
2. MATERIAL MUST COMPLY WITH BANNED AND RESTRICTED SUBSTANCES SPEC #10-0131.
3. OUTER DIMENSION (D & E) IS DEFINES BY CENTER LINES BETWEEN SCRIBE LINES.
4. MARKING SHOWN IS FOR PACKAGE ORIENTATION REFERENCE ONLY. NUMBER OF CHARACTERS AND LINES VARY PER PRODUCT.
5. ALL DIMENSIONS APPLY BOTH TO LEAD FREE (+) & LEADED (−) PKG. CODES.
6. PACKAGE CODE: B4-1, B4-2, B4-3



−DRAWING NOT TO SCALE−

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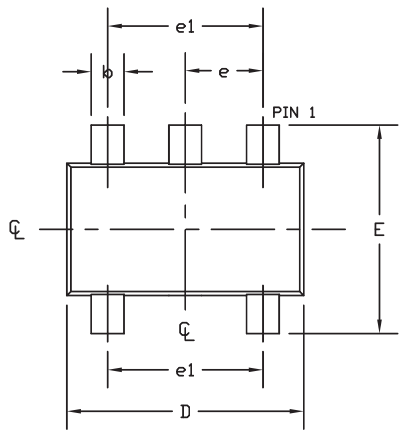
TITLE: PACKAGE OUTLINE, 4 BUMPS UCSP (B), 2X2 ARRAY

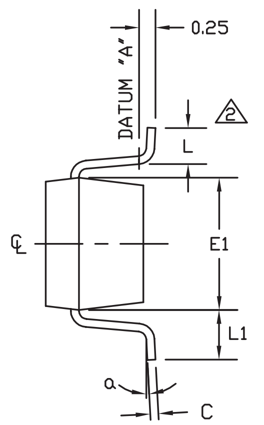
APPROVAL	DOCUMENT CONTROL NO.	REV.	
	21-0117	I	1/1

Package Information (continued)

For the latest package outline information and land patterns (footprints), go to **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.

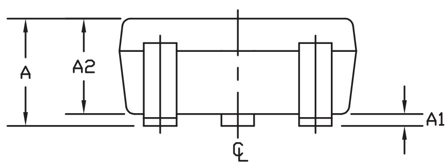


TOP VIEW



SIDE VIEW

SYMBOL	MIN	NOM	MAX
A	0.90	1.25	1.45
A1	0.00	0.05	0.15
A2	0.90	1.10	1.30
b	0.35	0.40	0.50
C	0.08	0.15	0.20
D	2.80	2.90	3.00
E	2.60	2.80	3.00
E1	1.50	1.625	1.75
L	0.35	0.45	0.60
L1	0.60 REF		
e	0.95 BSC.		
e1	1.90 BSC.		
a	0°	2.5°	8°
PKG CODES: U5-1, U5-2			



FRONT VIEW

NOTES:
1. ALL DIMENSIONS ARE IN MILLIMETERS.
2. FOOT LENGTH MEASURED AT INTERCEPT POINT BETWEEN DATUM A & LEAD SURFACE.
3. PACKAGE OUTLINE EXCLUSIVE OF MOLD FLASH & METAL BURR. MOLD FLASH, PROTRUSION OR METAL BURR SHOULD NOT EXCEED 0.25 MM.
4. PACKAGE OUTLINE INCLUSIVE OF SOLDER PLATING.
5. MEETS JEDEC MO178, VARIATION AA.
6. LEADS TO BE COPLANAR WITHIN 0.10 mm.
7. SOLDER THICKNESS MEASURED AT FLAT SECTION OF LEAD BETWEEN 0.08mm AND 0.15mm FROM LEAD TIP.

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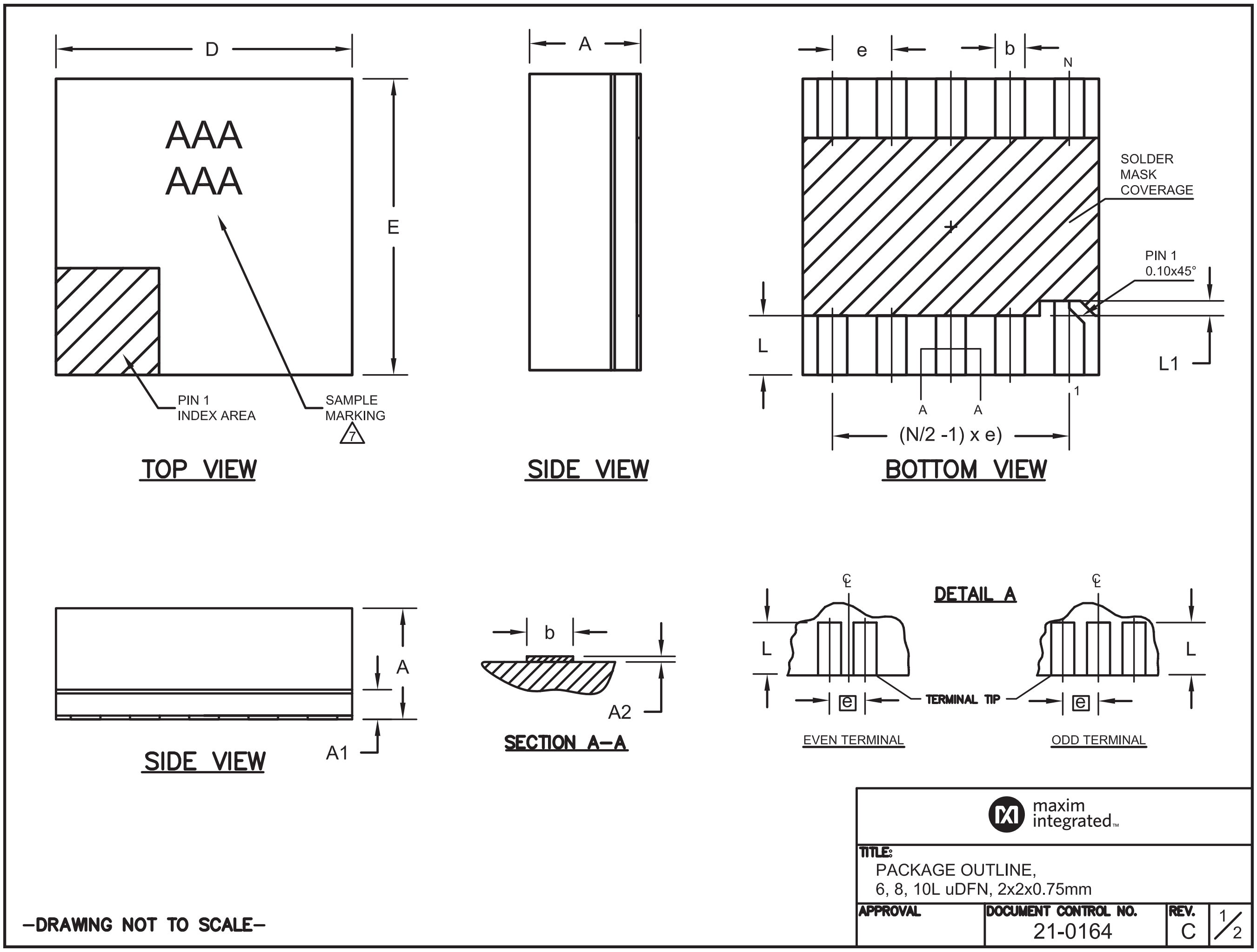
TITLE: PACKAGE OUTLINE, SOT-23, 5L

APPROVAL	DOCUMENT CONTROL NO.	REV.	
	21-0057	F	1/1

SOT-23 5L .EPS

Package Information (continued)

For the latest package outline information and land patterns (footprints), go to 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 Information (continued)

For the latest package outline information and land patterns (footprints), go to 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.

COMMON DIMENSIONS			
SYMBOL	MIN.	NOM.	MAX.
A	0.70	0.75	0.80
A1	0.15	0.20	0.25
A2	0.020	0.025	0.035
D	1.95	2.00	2.05
E	1.95	2.00	2.05
L	0.30	0.40	0.50
L1	0.10 REF.		

PACKAGE VARIATIONS				
PKG. CODE	N	e	b	(N/2 -1) x e
L622-1	6	0.65 BSC	0.30±0.05	1.30 REF.
L822-1	8	0.50 BSC	0.25±0.05	1.50 REF.
L1022-1	10	0.40 BSC	0.20±0.03	1.60 REF.

NOTES:
1. ALL DIMENSIONS ARE IN mm. ANGLES IN DEGREES.
2. COPLANARITY SHALL NOT EXCEED 0.08mm.
3. WARPAGE SHALL NOT EXCEED 0.10mm.
4. PACKAGE LENGTH/PACKAGE WIDTH ARE CONSIDERED AS SPECIAL CHARACTERISTIC(S).
5. "N" IS THE TOTAL NUMBER OF LEADS.
6. NUMBER OF LEADS SHOWN ARE FOR REFERENCE ONLY.
7. MARKING IS FOR PACKAGE ORIENTATION REFERENCE ONLY.
8. ONLY 8L PACKAGE COMPLIES TO JEDEC MO252.
9. ALL DIMENSIONS APPLY TO BOTH LEADED (–) AND PbFREE (+) PACKAGE CODES.
10. LEAD PLATING MATERIAL: GOLD, 0.5 MICROMETER MINIMUM THICKNESS.

–DRAWING NOT TO SCALE–

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TITLE: PACKAGE OUTLINE, 6, 8, 10L uDFN, 2x2x0.75mm

APPROVAL	DOCUMENT CONTROL NO.	REV.	
	21-0164	C	2/2

Revision History

REVISION NUMBER	REVISION DATE	DESCRIPTION	PAGES CHANGED
0	4/08	Initial release	—
1	9/08	Added µDFN package information	1, 2, 4, 5, 9
2	2/09	Added G45 designation to part number	1
3	10/09	Added *Input Filters* section and MAX9938W to the data sheet	1, 2, 6–9
4	2/10	Updated EC table and *Input Filters* section	2, 8
5	8/10	Removed Power-Up Time parameter	2
6	1/11	Corrected error on Figure 2	8
7	4/17	Updated title of data sheet to include “nanoPower”	1–14

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