

## LM99

# $\pm 1^{\circ}\text{C}$ Accurate, High Temperature, Remote Diode Temperature Sensor with Two-Wire Interface

### General Description

The LM99 is an 11-bit remote diode temperature sensor with a 2-wire System Management Bus (SMBus) serial interface. The LM99 accurately measures: (1) its own temperature and (2) the temperature of a remote diode-connected transistor such as the 2N3904 or a thermal diode commonly found on Graphics Processor Units (GPU), Computer Processor Units (CPU or other ASICs. The LM99 remote diode temperature sensor shifts the temperature from the remote sensor down  $16^{\circ}\text{C}$  and operates on that shifted temperature:

$$T_{\text{ACTUAL DIODE JUNCTION}} = T_{\text{LM99}} + 16^{\circ}\text{C}$$

The local temperature reading requires no offset.

The LM99 has an Offset Register which provides a means for precise matching to various thermal diodes. Contact hardware.monitor@nsc.com for the latest details.

The LM99 and LM99-1 have the same functions but different SMBus slave addresses. This allows for one of each to be on the same bus at the same time.

Activation of the  $\overline{\text{ALERT}}$  output occurs when any temperature goes outside a preprogrammed window set by the HIGH and LOW temperature limit registers or exceeds the  $T_{\text{CRIT}}$  temperature limit. Activation of the  $T_{\text{CRIT\_A}}$  occurs when any temperature exceeds the  $T_{\text{CRIT}}$  programmed limit.

### Features

- Accurately senses the temperature of remote diodes
- Offset register allows use of a variety of thermal diodes

- On-board local temperature sensing
- 10 bit plus sign remote diode temperature data format,  $0.125^{\circ}\text{C}$  resolution
- $T_{\text{CRIT\_A}}$  output useful for system shutdown
- $\overline{\text{ALERT}}$  output supports SMBus 2.0 protocol
- SMBus 2.0 compatible interface, supports TIMEOUT
- 8-pin MSOP package

### Key Specifications

- Supply Voltage 3.0 V to 3.6 V
- Supply Current 0.8 mA (typ)
- Local Temp Accuracy (includes quantization error)
 

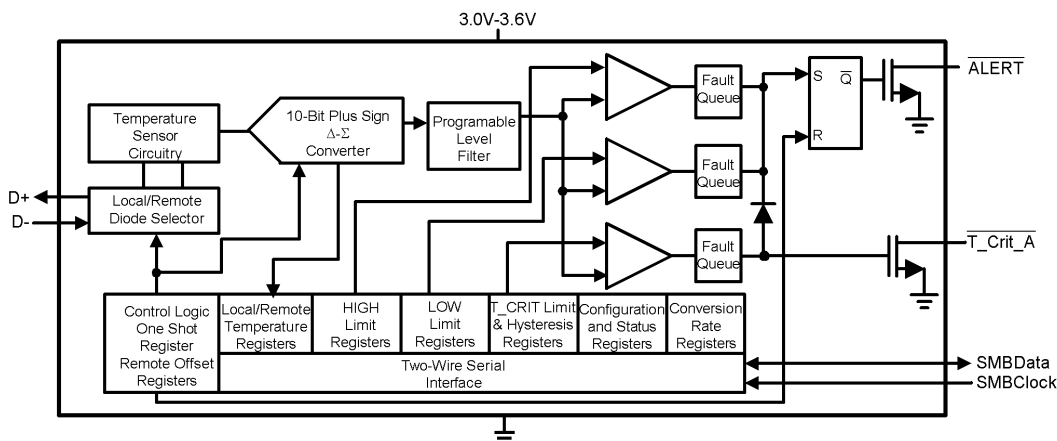
$T_A = 25^{\circ}\text{C}$ to $125^{\circ}\text{C}$	$\pm 3.0^{\circ}\text{C}$ (max)
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- Remote Diode Temp Accuracy (includes quantization error)
 

$T_A = 30^{\circ}\text{C}$ to $50^{\circ}\text{C}$ , $T_D = 120^{\circ}\text{C}$ to $140^{\circ}\text{C}$	$\pm 1.0^{\circ}\text{C}$ (max)
$T_A = 0^{\circ}\text{C}$ to $85^{\circ}\text{C}$ , $T_D = 25^{\circ}\text{C}$ to $140^{\circ}\text{C}$	$\pm 3.0^{\circ}\text{C}$ (max)

### Applications

- Graphics Processor Thermal Management
- Computer Processor Thermal Management
- Electronic Test Equipment
- Office Electronics

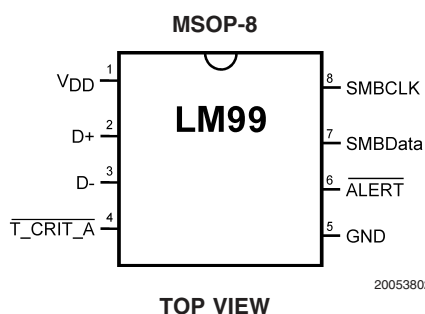
### Simplified Block Diagram



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## Connection Diagram



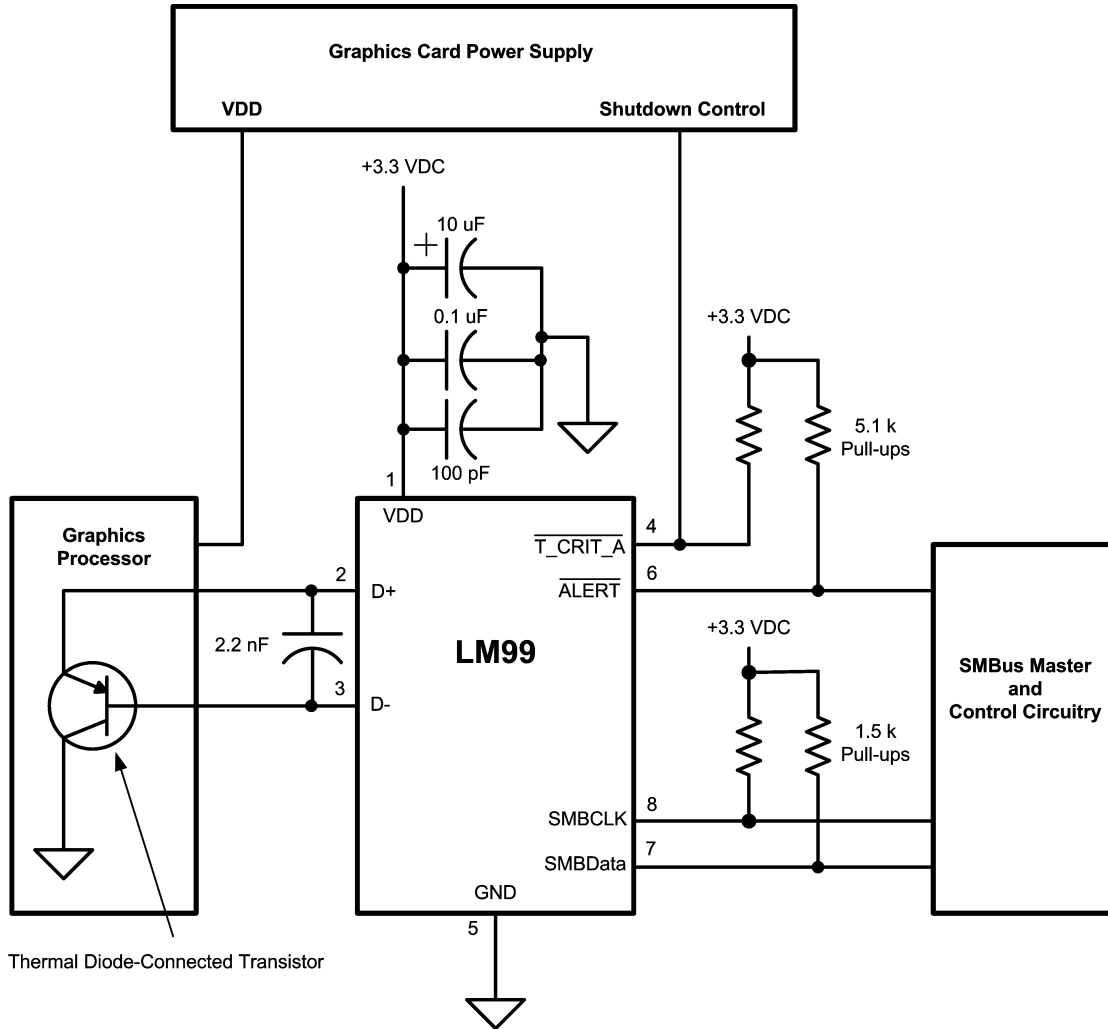
## Ordering Information

Part Number	Package Marking	NS Package Number	Transport Media
LM99C1MM	T17C	MUA08A (MSOP-8)	1000 Units on Tape and Reel
LM99-1C1MM	T20C	MUA08A (MSOP-8)	1000 Units on Tape and Reel
LM99C1MMX	T17C	MUA08A (MSOP-8)	3500 Units on Tape and Reel
LM99-1C1MMX	T20C	MUA08A (MSOP-8)	3500 Units on Tape and Reel

## Pin Descriptions

Label	Pin #	Function	Typical Connection
V <sub>DD</sub>	1	Positive Supply Voltage Input	DC Voltage from 3.0 V to 3.6 V. V <sub>DD</sub> should be bypassed with a 0.1 $\mu$ F capacitor in parallel with 100 pF to ground. The 100 pF capacitor should be placed as close as possible to the power supply pin. A bulk capacitance of approximately 10 $\mu$ F needs to be in the vicinity of the LM99 V <sub>DD</sub> .
D+	2	Diode Current Source	To Diode Anode. Connected to the collector and base of the remote discrete diode-connected transistor. Connect a 2.2 nF capacitor between pins 2 and 3.
D-	3	Diode Return Current Sink	To Diode Cathode. Connects to the emitter of the remote diode-connected transistor. Connect a 2.2 nF capacitor between pins 2 and 3.
T_CRIT_A	4	T_CRIT Alarm Output, Open-Drain, Active-Low	Pull-Up Resistor, Controller Interrupt or Power Supply Shutdown Control
GND	5	Power Supply Ground	Ground
ALERT	6	Interrupt Output, Open-Drain, Active-Low	Pull-Up Resistor, Controller Interrupt or Alert Line
SMBData	7	SMBus Bi-Directional Data Line, Open-Drain Output	From and to Controller, Pull-Up Resistor
SMBCLK	8	SMBus Input	From Controller, Pull-Up Resistor

# Typical Application



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## Absolute Maximum Ratings (Note 1)

Supply Voltage	–0.3 V to 6.0 V
Voltage at SMBData, SMBCLK, ALERT, T_CRIT_A	–0.5 V to 6.0 V
Voltage at Other Pins	–0.3 V to (V <sub>DD</sub> + 0.3 V)
D– Input Current	±1 mA
Input Current at All Other Pins (Note 2)	±5 mA
Package Input Current (Note 2)	30 mA
SMBData, ALERT, T_CRIT_A Output	
Sink Current	10 mA
Storage Temperature	–65°C to +150°C

Soldering Information, Lead Temperature

## MSOP-8 Packages (Note 3)

Vapor Phase (60 seconds)	215°C
Infrared (15 seconds)	220°C
ESD Susceptibility (Note 4)	
Human Body Model	2000 V
Machine Model	200 V

## Operating Ratings

(Notes 1, 5)

Operating Temperature Range	0°C to +125°C
Electrical Characteristics	
Temperature Range	T <sub>MIN</sub> ≤ T <sub>A</sub> ≤ T <sub>MAX</sub>
LM99	0°C ≤ T <sub>A</sub> ≤ +85°C
Supply Voltage Range (V <sub>DD</sub> )	+3.0 V to +3.6 V

## Temperature-to-Digital Converter Characteristics

Unless otherwise noted, these specifications apply for V<sub>DD</sub> = +3.0 Vdc to +3.6 Vdc. **Boldface limits apply for T<sub>A</sub> = T<sub>J</sub> = T<sub>MIN</sub> ≤ T<sub>A</sub> ≤ T<sub>MAX</sub>**; all other limits T<sub>A</sub> = T<sub>J</sub> = +25°C, unless otherwise noted.

Parameter	Conditions	Typical (Note 6)	Limits (Note 7)	Units (Limit)
Temperature Error Using Local Diode	T <sub>A</sub> = +25°C to +125°C, (Note 8)	±1	<b>±3</b>	°C (max)
Temperature Error Using Remote Diode Connected Transistor (T <sub>D</sub> is the Remote Diode Junction Temperature) T <sub>D</sub> = T <sub>LM99</sub> + 16°C	T <sub>A</sub> = +30°C to +50°C and T <sub>D</sub> = +120°C to +140°C		<b>±1</b>	°C (max)
	T <sub>A</sub> = +0°C to +85°C and T <sub>D</sub> = +25°C to +140°C		<b>±3</b>	°C (max)
Remote Diode Measurement Resolution		11		Bits
		0.125		°C
Local Diode Measurement Resolution		8		Bits
		1		°C
Conversion Time of All Temperatures at the Fastest Setting	(Note 10)	31.25	<b>34.4</b>	ms (max)
Quiescent Current (Note 9)	SMBus Inactive, 16 Hz conversion rate	0.8	<b>1.7</b>	mA (max)
	Shutdown	315		μA
D– Source Voltage		0.7		V
Diode Source Current	(V <sub>D+</sub> – V <sub>D–</sub> ) = + 0.65 V; high level	160	<b>315</b>	μA (max)
			<b>110</b>	μA (min)
	Low level	13	<b>20</b>	μA (max)
			<b>7</b>	μA (min)
ALERT and T_CRIT_A Output Saturation Voltage	I <sub>OUT</sub> = 6.0 mA		<b>0.4</b>	V (max)
Power-On-Reset (POR) Threshold	Measure on V <sub>DD</sub> input, falling edge		<b>2.4</b>	V (max)
			<b>1.8</b>	V (min)
Local and Remote HIGH Default Temperature settings	(Note 11) Add 16°C for true Remote Temperature.	+70		°C
Local and Remote LOW Default Temperature settings	(Note 11) Add 16°C for true Remote Temperature.	0		°C
Local T_CRIT Default Temperature Setting	(Note 11)	+85		°C
Remote T_CRIT Default Temperature Setting	(Note 11) Add 16°C for 126°C true Remote T_CRIT Setting	+110		°C

## Logic Electrical Characteristics

**DIGITAL DC CHARACTERISTICS** Unless otherwise noted, these specifications apply for  $V_{DD} = +3.0$  to  $3.6$  Vdc. **Boldface limits apply for  $T_A = T_J = T_{MIN}$  to  $T_{MAX}$** ; all other limits  $T_A = T_J = +25^\circ\text{C}$ , unless otherwise noted.

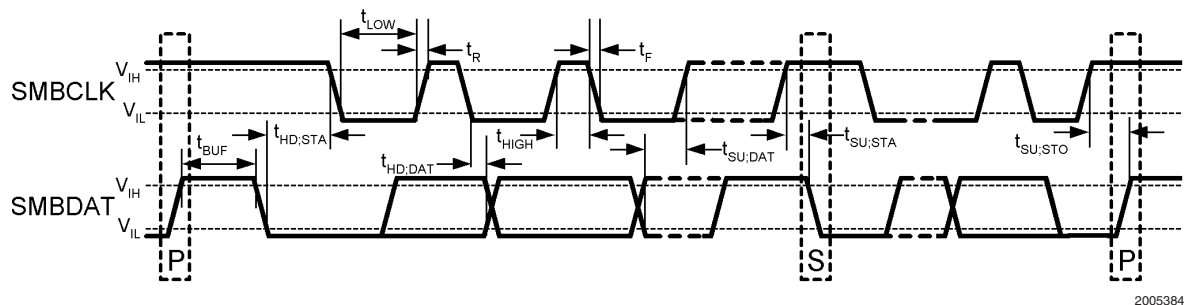
Symbol	Parameter	Conditions	Typical (Note 6)	Limits (Note 7)	Units (Limit)
<b>SMBData, SMBCLK INPUTS</b>					
$V_{IN(1)}$	Logical "1" Input Voltage			<b>2.1</b>	V (min)
$V_{IN(0)}$	Logical "0" Input Voltage			<b>0.8</b>	V (max)
$V_{IN(HYST)}$	SMBData and SMBCLK Digital Input Hysteresis		400		mV
$I_{IN(1)}$	Logical "1" Input Current	$V_{IN} = V_{DD}$	0.005	<b><math>\pm 10</math></b>	$\mu\text{A}$ (max)
$I_{IN(0)}$	Logical "0" Input Current	$V_{IN} = 0$ V	-0.005	<b><math>\pm 10</math></b>	$\mu\text{A}$ (max)
$C_{IN}$	Input Capacitance		5		pF
<b>ALL DIGITAL OUTPUTS</b>					
$I_{OH}$	High Level Output Current	$V_{OH} = V_{DD}$		<b>10</b>	$\mu\text{A}$ (max)
$V_{OL}$	SMBus Low Level Output Voltage	$I_{OL} = 4$ mA $I_{OL} = 6$ mA		<b>0.4</b> <b>0.6</b>	V (max)

## SMBus Digital Switching Characteristics

Unless otherwise noted, these specifications apply for  $V_{DD} = +3.0$  Vdc to  $+3.6$  Vdc,  $C_L$  (load capacitance) on output lines = 80 pF. **Boldface limits apply for  $T_A = T_J = T_{MIN}$  to  $T_{MAX}$** ; all other limits  $T_A = T_J = +25^\circ\text{C}$ , unless otherwise noted. The switching characteristics of the LM99 fully meet or exceed the published specifications of the SMBus version 2.0. The following parameters are the timing relationships between SMBCLK and SMBData signals related to the LM99. They adhere to but are not necessarily the SMBus bus specifications.

Symbol	Parameter	Conditions	Typical (Note 6)	Limits (Note 7)	Units (Limit)
$f_{SMB}$	SMBus Clock Frequency			<b>100</b> <b>10</b>	kHz (max) kHz (min)
$t_{LOW}$	SMBus Clock Low Time	from $V_{IN(0),max}$ to $V_{IN(0),max}$		<b>4.7</b> <b>25</b>	$\mu\text{s}$ (min) ms (max)
$t_{HIGH}$	SMBus Clock High Time	from $V_{IN(1),min}$ to $V_{IN(1),min}$		<b>4.0</b>	$\mu\text{s}$ (min)
$t_{R,SMB}$	SMBus Rise Time	(Note 12)	1		$\mu\text{s}$ (max)
$t_{F,SMB}$	SMBus Fall Time	(Note 13)	0.3		$\mu\text{s}$ (max)
$t_{OF}$	Output Fall Time	$C_L = 400$ pF, $I_O = 3$ mA, (Note 13)		<b>250</b>	ns (max)
$t_{TIMEOUT}$	SMBData and SMBCLK Time Low for Reset of Serial Interface (Note 14)			<b>25</b> <b>35</b>	ms (min) ms (max)
$t_{SU,DAT}$	Data In Setup Time to SMBCLK High			<b>250</b>	ns (min)
$t_{HD,DAT}$	Data Out Stable after SMBCLK Low			<b>300</b> <b>900</b>	ns (min) ns (max)
$t_{HD,STA}$	Start Condition SMBData Low to SMBCLK Low (Start condition hold before the first clock falling edge)			<b>100</b>	ns (min)
$t_{SU,STO}$	Stop Condition SMBCLK High to SMBData Low (Stop Condition Setup)			<b>100</b>	ns (min)
$t_{SU,STA}$	SMBus Repeated Start-Condition Setup Time, SMBCLK High to SMBData Low			<b>0.6</b>	$\mu\text{s}$ (min)
$t_{BUF}$	SMBus Free Time Between Stop and Start Conditions			<b>1.3</b>	$\mu\text{s}$ (min)

## SMBus Communication



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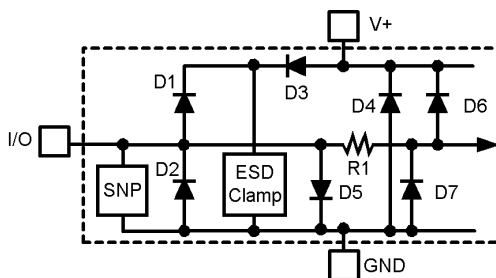
**Note 1:** Absolute Maximum Ratings indicate limits beyond which damage to the device may occur. DC and AC electrical specifications do not apply when operating the device beyond its rated operating conditions.

**Note 2:** When the input voltage ( $V_I$ ) at any pin exceeds the power supplies ( $V_I < \text{GND}$  or  $V_I > V_{DD}$ ), the current at that pin should be limited to 5 mA.

Parasitic components and or ESD protection circuitry are shown in the figure below for the LM99's pins. The nominal breakdown voltage of D3 is 6.5 V. Care should be taken not to forward bias the parasitic diode, D1, present on pins: D+, D-. Doing so by more than 50 mV may corrupt a temperature measurement.

Pin Name	PIN #	D1	D2	D3	D4	D5	D6	D7	R1	SNP	ESD CLAMP
$V_{DD}$	1										X
D+	2	X	X				X	X	X		X
D-	3	X	X			X	X	X			X
$\overline{T\_CRIT\_A}$	4							X	X	X	
$\overline{ALERT}$	6							X	X	X	
SMBData	7							X	X	X	
SMBCLK	8									X	

Note: An "x" indicates that the diode exists.



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**FIGURE 1. ESD Protection Input Structure**

**Note 3:** See the URL "<http://www.national.com/packaging/>" for other recommendations and methods of soldering surface mount devices.

**Note 4:** Human body model, 100 pF discharged through a 1.5 k $\Omega$  resistor. Machine model, 200 pF discharged directly into each pin.

**Note 5:** Thermal resistance junction-to-ambient when attached to a printed circuit board with 2 oz. foil:

– MSOP-8 = 210°C/W

**Note 6:** Typicals are at  $T_A = 25^\circ\text{C}$  and represent most likely parametric norm.

**Note 7:** Limits are guaranteed to National's AOQL (Average Outgoing Quality Level).

**Note 8:** Local temperature accuracy does not include the effects of self-heating. The rise in temperature due to self-heating is the product of the internal power dissipation of the LM99 and the thermal resistance. See (Note 5) for the thermal resistance to be used in the self-heating calculation.

**Note 9:** Quiescent current will not increase substantially with an SMBus.

**Note 10:** This specification is provided only to indicate how often temperature data is updated. The LM99 can be read at any time without regard to conversion state (and will yield last conversion result).

**Note 11:** Default values set at power up.

**Note 12:** The output rise time is measured from ( $V_{IN(0)\text{max}} + 0.15 \text{ V}$ ) to ( $V_{IN(1)\text{min}} - 0.15 \text{ V}$ ).

**Note 13:** The output fall time is measured from ( $V_{IN(1)\text{min}} - 0.15 \text{ V}$ ) to ( $V_{IN(1)\text{min}} + 0.15 \text{ V}$ ).

**Note 14:** Holding the SMBData and/or SMBCLK lines Low for a time interval greater than  $t_{\text{TIMEOUT}}$  will reset the LM99's SMBus state machine, therefore setting SMBData and SMBCLK pins to a high impedance state.

## 1.0 Functional Description

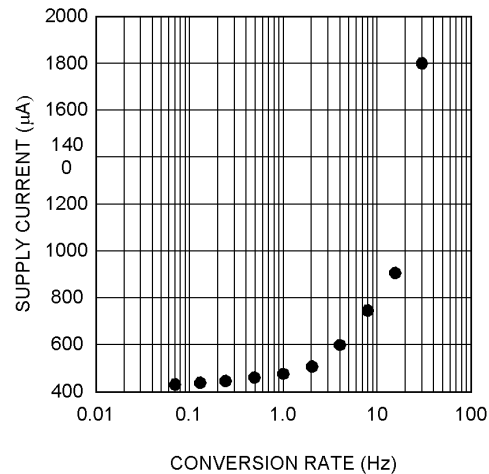
The LM99 temperature sensor incorporates a delta  $V_{BE}$  based temperature sensor using a Local or Remote diode and a 10-bit plus sign  $\Delta\Sigma$  ADC (Delta-Sigma Analog-to-Digital Converter). The LM99 is compatible with the serial SMBus version 2.0 two-wire interface. Digital comparators compare the measured Local Temperature (LT) to the Local High (LHS), Local Low (LLS) and Local T\_CRIT (LCS) user-programmable temperature limit registers. The measured Remote Temperature (RT) is digitally compared to the Remote High (RHS), Remote Low (RLS) and Remote T\_CRIT (RCS) user-programmable temperature limit registers. Activation of the ALERT output indicates that a comparison is greater than the limit preset in a T\_CRIT or HIGH limit register or less than the limit preset in a LOW limit register. The T\_CRIT\_A output responds as a true comparator with built in hysteresis. The hysteresis is set by the value placed in the Hysteresis register (TH). Activation of T\_CRIT\_A occurs when the temperature is above the T\_CRIT setpoint. T\_CRIT\_A remains activated until the temperature goes below the setpoint calculated by T\_CRIT – TH. The hysteresis register impacts both the remote temperature and local temperature readings.

The LM99 may be placed in a low power consumption (Shutdown) mode by setting the RUN/STOP bit found in the Configuration register. In the Shutdown mode, the LM99's SMBus interface remains while all circuitry not required is turned off.

The Local temperature reading and setpoint data registers are 8-bits wide. The format of the 11-bit remote temperature data is a 16-bit left justified word. Two 8-bit registers, high and low bytes, are provided for each setpoint as well as the temperature reading. Two offset registers (RTOLB and RTOHB) can be used to compensate for non-ideality error, discussed further in *Section 4.1 DIODE NON-IDEALITY*. The remote temperature reading reported is adjusted by subtracting from, or adding to, the actual temperature reading the value placed in the offset register.

### 1.1 CONVERSION SEQUENCE

The LM99 takes approximately 31.25 ms to convert the Local Temperature (LT), Remote Temperature (RT), and to update all of its registers. Only during the conversion process the busy bit (D7) in the Status register (02h) is high. These conversions are addressed in a round-robin sequence. The conversion rate may be modified by the Conversion Rate Register (04h). When the conversion rate is modified a delay is inserted between conversions; however, the actual conversion time remains at 31.25 ms. Different conversion rates will cause the LM99 to draw different amounts of supply current as shown in *Figure 2*.



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FIGURE 2. Conversion Rate Effect on Power Supply Current

### 1.2 THE ALERT OUTPUT

The LM99's ALERT pin is an active-low open-drain output that is triggered by a temperature conversion that is outside the limits defined by the temperature setpoint registers. Reset of the ALERT output is dependent upon the selected method of use. The LM99's ALERT pin is versatile and will accommodate three different methods of use to best serve the system designer: as a temperature comparator, as a temperature-based interrupt flag, and as part of an SMBus ALERT system. The three methods of use are further described below. The ALERT and interrupt methods are different only in how the user interacts with the LM99.

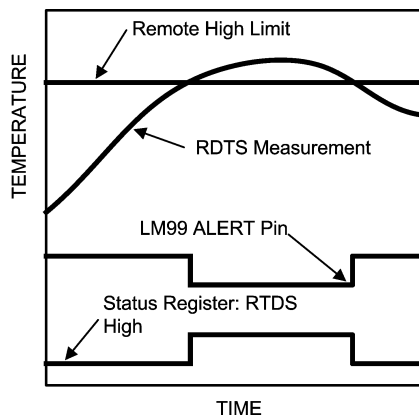
Each temperature reading (LT and RT) is associated with a T\_CRIT setpoint register (LCS, RCS), a HIGH setpoint register (LHS and RHS) and a LOW setpoint register (LLS and RLS). At the end of every temperature reading, a digital comparison determines whether that reading is above its HIGH or T\_CRIT setpoint or below its LOW setpoint. If so, the corresponding bit in the STATUS REGISTER is set. If the ALERT mask bit is not high, any bit set in the STATUS REGISTER, with the exception of Busy (D7) and OPEN (D2), will cause the ALERT output to be pulled low. Any temperature conversion that is out of the limits defined by the temperature setpoint registers will trigger an ALERT. Additionally, the ALERT mask bit in the Configuration register must be cleared to trigger an ALERT in all modes.

#### 1.2.1 ALERT Output as a Temperature Comparator

When the LM99 is implemented in a system in which it is not serviced by an interrupt routine, the ALERT output could be used as a temperature comparator. Under this method of use, once the condition that triggered the ALERT to go low is no longer present, the ALERT is de-asserted (*Figure 3*). For example, if the ALERT output was activated by the comparison of LT > LHS, when this condition is no longer true the ALERT will return HIGH. This mode allows operation without software intervention, once all registers are configured during set-up. In order for the ALERT to be used as a temperature comparator, bit D0 (the ALERT configure bit) in the FILTER and ALERT CONFIGURE REGISTER (xBF) must be set high. This is not the power on default state.



## 1.0 Functional Description (Continued)



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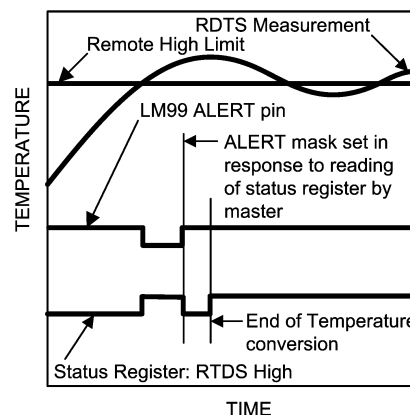
**FIGURE 3.  $\overline{\text{ALERT}}$  Comparator Temperature Response Diagram**

### 1.2.2 $\overline{\text{ALERT}}$ Output as an Interrupt

The LM99's  $\overline{\text{ALERT}}$  output can be implemented as a simple interrupt signal when it is used to trigger an interrupt service routine. In such systems it is undesirable for the interrupt flag to repeatedly trigger during or before the interrupt service routine has been completed. Under this method of operation, during a read of the STATUS REGISTER the LM99 will set the ALERT mask bit (D7 of the Configuration register) if any bit in the STATUS REGISTER is set, with the exception of Busy (D7) and OPEN (D2). This prevents further  $\overline{\text{ALERT}}$  triggering until the master has reset the ALERT mask bit, at the end of the interrupt service routine. The STATUS REGISTER bits are cleared only upon a read command from the master (see Figure 4) and will be re-asserted at the end of the next conversion if the triggering condition(s) persist(s). In order for the  $\overline{\text{ALERT}}$  to be used as a dedicated interrupt signal, bit D0 (the  $\overline{\text{ALERT}}$  configure bit) in the FILTER and ALERT CONFIGURE REGISTER (xBF) must be set low. This is the power-on default state.

The following sequence describes the response of a system that uses the  $\overline{\text{ALERT}}$  output pin as an interrupt flag:

1. Master Senses  $\overline{\text{ALERT}}$  low
2. Master reads the LM99 STATUS REGISTER to determine what caused the  $\overline{\text{ALERT}}$
3. LM99 clears STATUS REGISTER, resets the  $\overline{\text{ALERT}}$  HIGH and sets the ALERT mask bit (D7 in the Configuration register).
4. Master attends to conditions that caused the  $\overline{\text{ALERT}}$  to be triggered. The fan is started, setpoint limits are adjusted, etc.
5. Master resets the  $\overline{\text{ALERT}}$  mask (D7 in the Configuration register).



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**FIGURE 4.  $\overline{\text{ALERT}}$  Output as an Interrupt Temperature Response Diagram**

### 1.2.3 $\overline{\text{ALERT}}$ Output as an SMBus ALERT

When the  $\overline{\text{ALERT}}$  output is connected to one or more  $\overline{\text{ALERT}}$  outputs of other SMBus compatible devices and to a master, an SMBus alert line is created. Under this implementation, the LM99's  $\overline{\text{ALERT}}$  should be operated using the ARA (Alert Response Address) protocol. The SMBus 2.0 ARA protocol, defined in the SMBus specification 2.0, is a procedure designed to assist the master in resolving which part generated an interrupt and service that interrupt while impeding system operation as little as possible.

The SMBus alert line is connected to the open-drain ports of all devices on the bus thereby AND'ing them together. The ARA is a method by which with one command the SMBus master may identify which part is pulling the SMBus alert line LOW and prevent it from pulling it LOW again for the same triggering condition. When an ARA command is received by all devices on the bus, the devices pulling the SMBus alert line LOW, first, send their address to the master and second, release the SMBus alert line after recognizing a successful transmission of their address.

The SMBus 1.1 and 2.0 specification state that in response to an ARA (Alert Response Address) "after acknowledging the slave address the device must disengage its  $\overline{\text{SMBALERT}}$  pulldown". Furthermore, "if the host still sees  $\overline{\text{SMBALERT}}$  low when the message transfer is complete, it knows to read the ARA again". This SMBus "disengaging of  $\overline{\text{SMBALERT}}$ " requirement prevents locking up the SMBus alert line. Competitive parts may address this "disengaging of  $\overline{\text{SMBALERT}}$ " requirement differently than the LM99 or not at all. SMBus systems that implement the ARA protocol as suggested for the LM99 will be fully compatible with all competitive parts.

The LM99 fulfills "disengaging of  $\overline{\text{SMBALERT}}$ " by setting the ALERT mask bit (bit D7 in the Configuration register, at address 09h) after successfully sending out its address in response to an ARA and releasing the  $\overline{\text{ALERT}}$  output pin. Once the ALERT mask bit is activated, the  $\overline{\text{ALERT}}$  output pin will be disabled until enabled by software. In order to enable the  $\overline{\text{ALERT}}$  the master must read the STATUS REGISTER, at address 02h, during the interrupt service routine and then reset the ALERT mask bit in the Configuration register to 0 at the end of the interrupt service routine.

The following sequence describes the ARA response protocol.



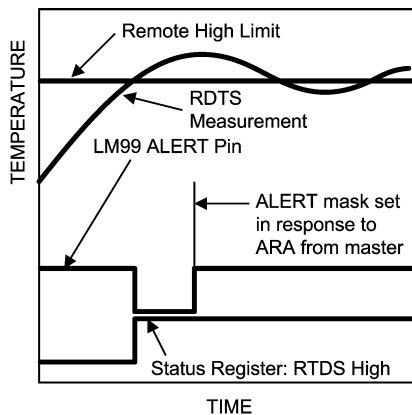
## 1.0 Functional Description (Continued)

1. Master Senses SMBus alert line low
2. Master sends a START followed by the Alert Response Address (ARA) with a Read Command.
3. Alerting Device(s) send ACK.
4. Alerting Device(s) send their Address. While transmitting their address, alerting devices sense whether their address has been transmitted correctly. (The LM99 will reset its ALERT output and set the ALERT mask bit once its complete address has been transmitted successfully.)
5. Master/slave NoACK
6. Master sends STOP
7. Master attends to conditions that caused the  $\overline{\text{ALERT}}$  to be triggered. The STATUS REGISTER is read and fan started, setpoint limits adjusted, etc.
8. Master resets the ALERT mask (D7 in the Configuration register).

The ARA, 000 1100, is a general call address. No device should ever be assigned this address.

Bit D0 (the  $\overline{\text{ALERT}}$  configure bit) in the FILTER and ALERT CONFIGURE REGISTER (xBF) must be set low in order for the LM99 to respond to the ARA command.

The  $\overline{\text{ALERT}}$  output can be disabled by setting the ALERT mask bit, D7, of the Configuration register. The power on default is to have the ALERT mask bit and the  $\overline{\text{ALERT}}$  configure bit low.



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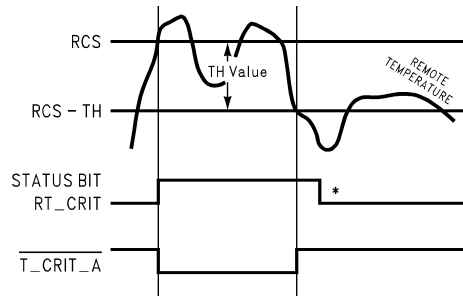
**FIGURE 5.  $\overline{\text{ALERT}}$  Output as an SMBus ALERT Temperature Response Diagram**

### 1.3 $\overline{\text{T\_CRIT\_A}}$ OUTPUT and $\text{T\_CRIT}$ LIMIT

$\overline{\text{T\_CRIT\_A}}$  is activated when any temperature reading is greater than the limit preset in the critical temperature setpoint register ( $\text{T\_CRIT}$ ), as shown in Figure 6. The Status Register can be read to determine which event caused the alarm. A bit in the Status Register is set high to indicate which temperature reading exceeded the  $\text{T\_CRIT}$  setpoint temperature and caused the alarm, see Section 2.3.

Local and remote temperature diodes are sampled in sequence by the A/D converter. The  $\overline{\text{T\_CRIT\_A}}$  output and the Status Register flags are updated after every Local and Remote temperature conversion.  $\overline{\text{T\_CRIT\_A}}$  follows the state of the comparison, it is reset when the temperature falls below the setpoint  $\text{RCS-TH}$ . The Status Register flags are

reset only after the Status Register is read and if a temperature conversion(s) is/are below the  $\text{T\_CRIT}$  setpoint, as shown in Figure 6.



\* Note: Status Register Bits are reset by a read of Status Register.

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**FIGURE 6.  $\overline{\text{T\_CRIT\_A}}$  Temperature Response Diagram**

### 1.4 POWER ON RESET DEFAULT STATES

LM99 always powers up to these known default states. The LM99 remains in these states until after the first conversion.

1. Command Register set to 00h
2. Local Temperature set to 0°C
3. Remote Diode Temperature set to 0°C until the end of the first conversion.
4. Status Register set to 00h.
5. Configuration register set to 00h;  $\overline{\text{ALERT}}$  enabled, Remote  $\text{T\_CRIT}$  alarm enabled and Local  $\text{T\_CRIT}$  alarm enabled
6. 85°C Local  $\text{T\_CRIT}$  temperature setpoint
7. 110°C Remote  $\text{T\_CRIT}$  temperature setpoint (126°C Remote diode junction temperature)
8. 70°C Local and Remote HIGH temperature setpoints
9. 0°C Local and Remote LOW temperature setpoints
10. Filter and Alert Configure Register set to 00h; filter disabled,  $\overline{\text{ALERT}}$  output set as an SMBus ALERT
11. Conversion Rate Register set to 8h; conversion rate set to 16 conv./sec.

### 1.5 SMBus INTERFACE

The LM99 operates as a slave on the SMBus, so the SMBCLK line is an input and the SMBData line is bi-directional. The LM99 never drives the SMBCLK line and it does not support clock stretching. According to SMBus specifications, the LM99 has a 7-bit slave address. All bits A6 through A0 are internally programmed and can not be changed by software or hardware. The LM99 and LM99-1 have the following slave addresses:

Version	A6	A5	A4	A3	A2	A1	A0
LM99	1	0	0	1	1	0	0
LM99-1	1	0	0	1	1	0	1

### 1.6 TEMPERATURE DATA FORMAT

Temperature data can only be read from the Local and Remote Temperature registers; the setpoint registers ( $\text{T\_CRIT}$ , LOW, HIGH) are read/write.

## 1.0 Functional Description (Continued)

Remote temperature data is represented by an 11-bit, two's complement word with an LSB (Least Significant Bit) equal

to 0.125°C. The data format is a left justified 16-bit word available in two 8-bit registers:

**Actual vs. LM99 Remote Temperature Conversion**

Actual Remote Diode Temperature, °C	LM99 Remote Diode Temperature Register, °C	Binary Results in LM99 Remote Temperature Register	Hex Remote Temperature Register
120	+104	0110 1000 0000 0000	6800h
125	+109	0110 1101 0000 0000	6D00h
126	+110	0110 1110 0000 0000	7100h
130	+114	0111 0010 0010 0000	7200h
135	+119	0111 0111 0000 0000	7700h
140	+124	0111 1100 0000 0000	7200h

Output is 11-bit two's complement word. LSB = 0.125 °C.

**Actual vs. Remote T\_CRIT Setpoint**

Actual Remote Diode T_CRIT Setpoint, °C	Factory-Programmed Remote T_CRIT High Setpoint, °C	Binary Remote T_CRIT High Setpoint Value	Hex Remote T_CRIT High Setpoint Value
126	+110	0110 1110	71h

Local Temperature data is represented by an 8-bit, two's complement byte with an LSB (Least Significant Bit) equal to 1°C:

Local Temperature	Digital Output	
	Binary	Hex
+125°C	0111 1101	7Dh
+25°C	0001 1001	19h
+1°C	0000 0001	01h
0°C	0000 0000	00h
-1°C	1111 1111	FFh
-25°C	1110 0111	E7h
-55°C	1100 1001	C9h

### 1.7 OPEN-DRAIN OUTPUTS

The SMBData,  $\overline{\text{ALERT}}$  and  $\overline{\text{T\_CRIT\_A}}$  outputs are open-drain outputs and do not have internal pull-ups. A "high" level will not be observed on these pins until pull-up current is provided by some external source, typically a pull-up resistor. Choice of resistor value depends on many system factors but, in general, the pull-up resistor should be as large as possible. This will minimize any internal temperature reading errors due to internal heating of the LM99. The maximum resistance of the pull-up to provide a 2.1V high level, based on LM99 specification for High Level Output Current with the supply voltage at 3.0V, is 82 k $\Omega$  (5%) or 88.7 k $\Omega$  (1%).

### 1.8 DIODE FAULT DETECTION

The LM99 is equipped with operational circuitry designed to detect fault conditions concerning the remote diode. In the event that the D+ pin is detected as shorted to  $V_{DD}$  or floating, the Remote Temperature High Byte (RTHB) register is loaded with +127°C, the Remote Temperature Low Byte (RTLb) register is loaded with 0, and the OPEN bit (D2) in the status register is set. As a result, if the Remote T\_CRIT setpoint register (RCS) is set to a value less than +127°C the ALERT and T\_CRIT output pins will be pulled low, if the Alert Mask and T\_CRIT Mask are disabled. If the Remote HIGH Setpoint High Byte Register (RHSHB) is set to a value less than +127°C then ALERT will be pulled low, if the Alert Mask is disabled. The OPEN bit itself will not trigger and ALERT.

In the event that the D+ pin is shorted to ground or D-, the Remote Temperature High Byte (RTHB) register is loaded with -128°C (1000 0000) and the OPEN bit (D2) in the status register will not be set. Since operating the LM99 at -128°C is beyond its operational limits, this temperature reading represents this shorted fault condition. If the value in the Remote Low Setpoint High Byte Register (RLSHB) is more than -128°C and the Alert Mask is disabled, ALERT will be pulled low.

Remote diode temperature sensors that have been previously released and are competitive with the LM99 output a code of 0°C if the external diode is short-circuited. This change is an improvement that allows a reading of 0°C to be truly interpreted as a genuine 0°C reading and not a fault condition.

## 1.0 Functional Description (Continued)

### 1.9 COMMUNICATING WITH THE LM99

The data registers in the LM99 are selected by the Command Register. At power-up the Command Register is set to "00", the location for the Read Local Temperature Register. The Command Register latches the last location it was set to. Each data register in the LM99 falls into one of four types of user accessibility:

1. Read only
2. Write only
3. Read/Write same address
4. Read/Write different address

A **Write** to the LM99 will always include the address byte and the command byte. A write to any register requires one data byte.

**Reading** the LM99 can take place either of two ways:

1. If the location latched in the Command Register is correct (most of the time it is expected that the Command

Register will point to one of the Read Temperature Registers because that will be the data most frequently read from the LM99), then the read can simply consist of an address byte, followed by retrieving the data byte.

2. If the Command Register needs to be set, then an address byte, command byte, repeat start, and another address byte will accomplish a read.

The data byte has the most significant bit first. At the end of a read, the LM99 can accept either Acknowledge or No Acknowledge from the Master (No Acknowledge is typically used as a signal for the slave that the Master has read its last byte). It takes the LM99 31.25 ms to measure the temperature of the remote diode and internal diode. When retrieving all 10 bits from a previous remote diode temperature measurement, the master must insure that all 10 bits are from the same temperature conversion. This may be achieved by using one-shot mode or by setting the conversion rate and monitoring the busy bit such that no conversion occurs in between reading the MSB and LSB of the last temperature conversion.

# 1.0 Functional Description (Continued)

## 1.9.1 SMBus Timing Diagrams

### LM99 Timing Diagram

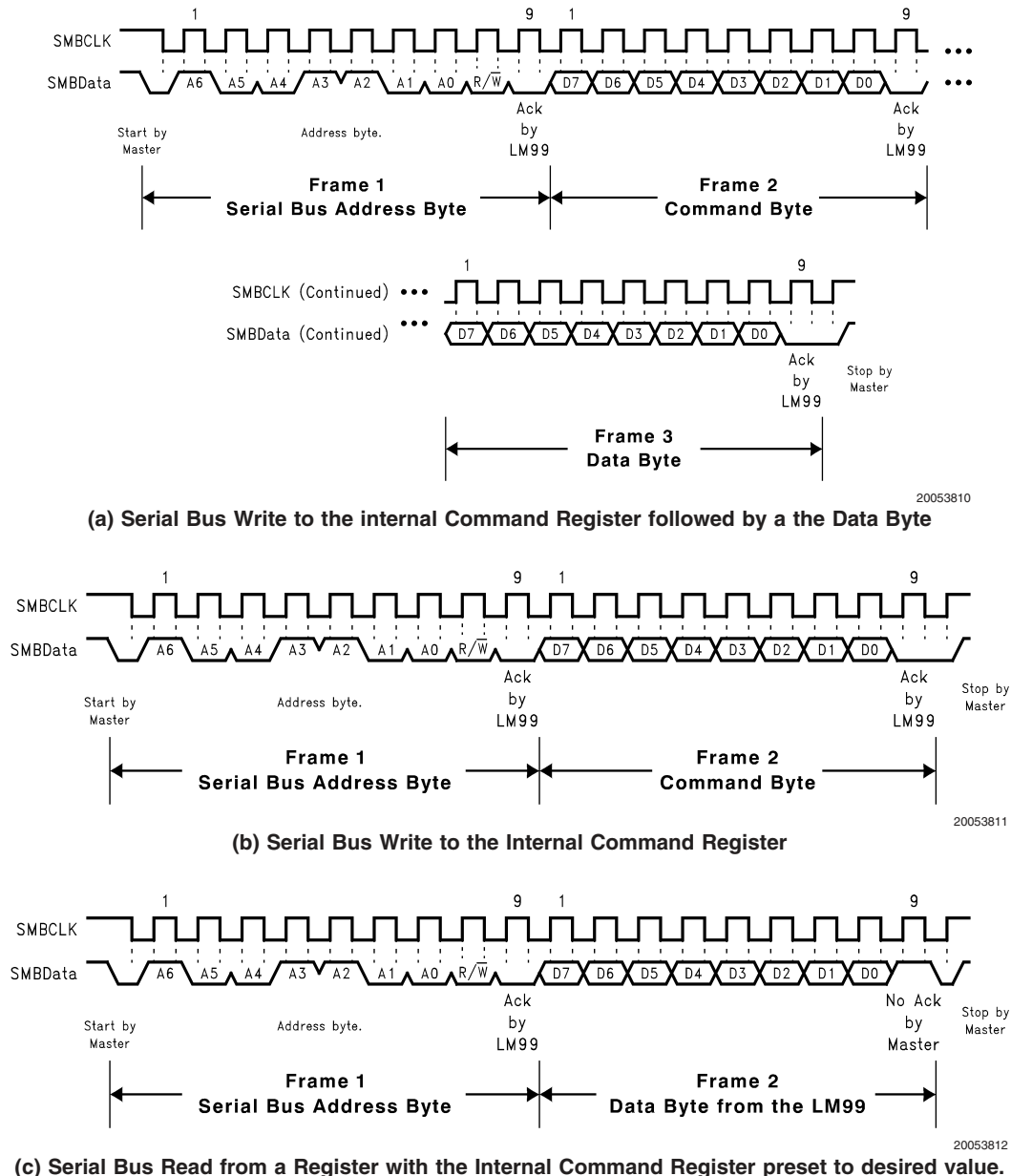


FIGURE 7. SMBus Timing Diagrams

### 1.10 SERIAL INTERFACE RESET

In the event that the SMBus Master is RESET while the LM99 is transmitting on the SMBData line, the LM99 must be returned to a known state in the communication protocol. This may be done in one of two ways:

1. When SMBData is LOW, the LM99 SMBus state machine resets to the SMBus idle state if either SMBData or SMBCLK are held low for more than 35 ms ( $t_{TIMEOUT}$ ). Note that according to SMBus specification 2.0 all

devices are to timeout when either the SMBCLK or SMBData lines are held low for 25-35 ms. Therefore, to insure a timeout of all devices on the bus the SMBCLK or SMBData lines must be held low for at least 35 ms.

2. When SMBData is HIGH, have the master initiate an SMBus start. The LM99 will respond properly to an SMBus start condition at any point during the communication. After the start the LM99 will expect an SMBus Address address byte.

## 1.0 Functional Description (Continued)

### 1.11 DIGITAL FILTER

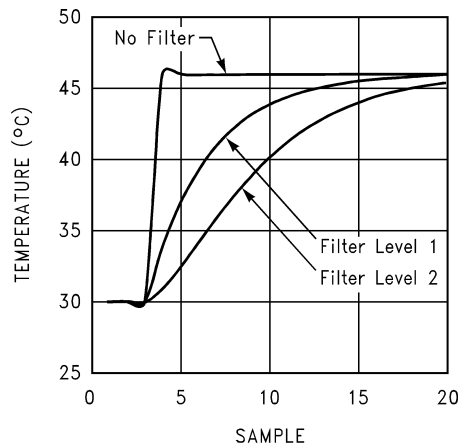
D2	D1	Filter
0	0	No Filter
0	1	Level 1
1	0	Level 1
1	1	Level 2

In order to suppress erroneous remote temperature readings due to noise, the LM99 incorporates a user-configured digital filter.

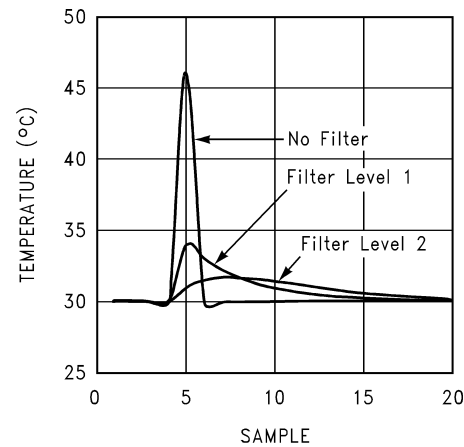
The filter is accessed in the FILTER and ALERT CONFIGURE REGISTER at BFh. The filter can be set according to the table shown.

Level 2 sets maximum filtering.

Figure 8 depicts the filter output to in response to a step input and an impulse input. Figure 9 depicts the digital filter in use in a Pentium 4 processor system. Note that the two curves, with filter and without, have been purposely offset so that both responses can be clearly seen. Inserting the filter does not induce an offset as shown.

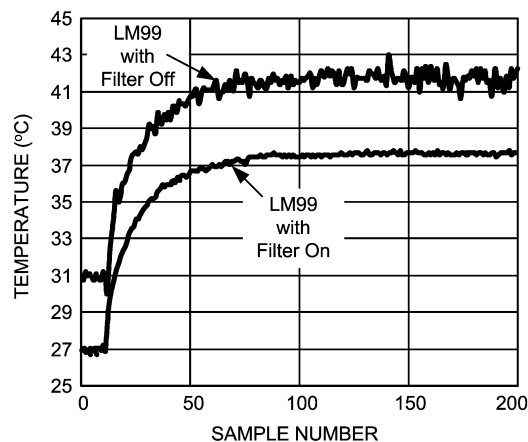


a) Step Response



b) Impulse Response

FIGURE 8. Filter Output Response to a Step Input



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FIGURE 9. Digital Filter Response in a Pentium 4 processor System. The filter on and off curves were purposely offset to better show noise performance.

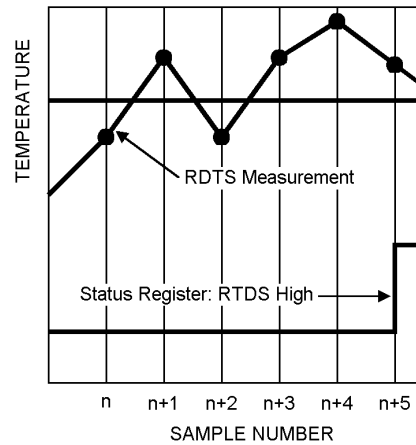
## 1.0 Functional Description (Continued)

### 1.12 FAULT QUEUE

In order to suppress erroneous ALERT or T\_CRIT triggering the LM99 incorporates a Fault Queue. The Fault Queue acts to insure a remote temperature measurement is genuinely beyond a HIGH, LOW or T\_CRIT setpoint by not triggering until three consecutive out of limit measurements have been made, see *Figure 10*. The fault queue defaults off upon power-on and may be activated by setting bit D0 in the Configuration register (09h) to "1".

### 1.13 ONE-SHOT REGISTER

The One-Shot register is used to initiate a single conversion and comparison cycle when the device is in standby mode, after which the device returns to standby. This is not a data register and it is the write operation that causes the one-shot conversion. The data written to this address is irrelevant and is not stored. A zero will always be read from this register.



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FIGURE 10. Fault Queue Temperature Response Diagram

## 2.0 LM99 Registers

### 2.1 COMMAND REGISTER

Selects which registers will be read from or written to. Data for this register should be transmitted during the Command Byte of the SMBus write communication.

P7	P6	P5	P4	P3	P2	P1	P0
Command Select							

P0-P7: Command Select

Command Select Address		Power On Default State		Register Name	Register Function
Read Address <P7:P0> hex	Write Address <P7:P0> hex	<D7:D0> binary	<D7:D0> decimal		
00h	NA	0000 0000	0	LT	Local Temperature
01h	NA	0000 0000	0	RTHB	Remote Temperature High Byte
02h	NA	0000 0000	0	SR	Status Register
03h	09h	0000 0000	0	C	Configuration
04h	0Ah	0000 1000	8 (16 conv./sec)	CR	Conversion Rate
05h	0Bh	0100 0110	70	LHS	Local HIGH Setpoint
06h	0Ch	0000 0000	0	LLS	Local LOW Setpoint
07h	0Dh	0100 0110	70	RHSB	Remote HIGH Setpoint High Byte
08h	0Eh	0000 0000	0	RLSB	Remote LOW Setpoint High Byte
NA	0Fh			One Shot	Writing to this register will initiate a one shot conversion

## 2.0 LM99 Registers (Continued)

Command Select Address		Power On Default State		Register Name	Register Function
Read Address <P7:P0> hex	Write Address <P7:P0> hex	<D7:D0> binary	<D7:D0> decimal		
10h	NA	0000 0000	0	RTLB	Remote Temperature Low Byte
11h	11h	0000 0000	0	RTOHB	Remote Temperature Offset High Byte
12h	12h	0000 0000	0	RTOLB	Remote Temperature Offset Low Byte
13h	13h	0000 0000	0	RHSLB	Remote HIGH Setpoint Low Byte
14h	14h	0000 0000	0	RLSLB	Remote LOW Setpoint Low Byte
19h	19h	0110 1110	110	RCS	Remote T_CRIT Setpoint
20h	20h	0101 0101	85	LCS	Local T_CRIT Setpoint
21h	21h	0000 1010	10	TH	T_CRIT Hysteresis
B0h-BEh	B0h-BEh				Manufacturers Test Registers
BFh	BFh	0000 0000	0	RDTF	Remote Diode Temperature Filter
FEh	NA	0000 0001	1	RMID	Read Manufacturer's ID
FFh	NA	LM99 0011 0001 LM99-1 0011 0100	49 52	RDR	Read Stepping or Die Revision Code

### 2.2 LOCAL and REMOTE TEMPERATURE REGISTERS (LT, RTHB, RTLB)

(Read Only Address 00h, 01h):

BIT	D7	D6	D5	D4	D3	D2	D1	D0
Value	SIGN	64	32	16	8	4	2	1

For LT and RTHB D7–D0: Temperature Data. LSB = 1°C. Two's complement format.

(Read Only Address 10h):

BIT	D7	D6	D5	D4	D3	D2	D1	D0
Value	0.5	0.25	0.125	0	0	0	0	0

For RTLB D7–D5: Temperature Data. LSB = 0.125°C. Two's complement format.

The maximum value available from the Local Temperature register is 127; the minimum value available from the Local Temperature register is -128. The maximum value available from the Remote Temperature register is 127.875; the minimum value available from the Remote Temperature registers is -128.875.

Note that the remote diode junction temperature is actually 16°C higher than the Remote Temperature Register value.

### 2.3 STATUS REGISTER (SR)

(Read Only Address 02h):

D7	D6	D5	D4	D3	D2	D1	D0
Busy	LHIGH	LLOW	RHIGH	RLOW	OPEN	RCRIT	LCRIT

Power up default is with all bits "0" (zero).

D0: LCRIT: When set to "1" indicates a Local Critical Temperature alarm.

D1: RCRIT: When set to "1" indicates a Remote Diode Critical Temperature alarm.

D2: OPEN: When set to "1" indicates a Remote Diode disconnect.

D3: RLOW: When set to "1" indicates a Remote Diode LOW Temperature alarm

D4: RHIGH: When set to "1" indicates a Remote Diode HIGH Temperature alarm.

D5: LLOW: When set to "1" indicates a Local LOW Temperature alarm.

D6: LHIGH: When set to "1" indicates a Local HIGH Temperature alarm.

D7: Busy: When set to "1" ADC is busy converting.



## 2.0 LM99 Registers (Continued)

### 2.4 CONFIGURATION REGISTER

(Read Address 03h / Write Address 09h):

D7	D6	D5	D4	D3	D2	D1	D0
$\overline{\text{ALERT}}$ mask	$\overline{\text{RUN/STOP}}$	0	Remote $\overline{\text{T\_CRIT\_A}}$ mask	0	Local $\overline{\text{T\_CRIT\_A}}$ mask	0	Fault Queue

Power up default is with all bits "0" (zero)

D7:  $\overline{\text{ALERT}}$  mask: When set to "1"  $\overline{\text{ALERT}}$  interrupts are masked.

D6:  $\overline{\text{RUN/STOP}}$ : When set to "1" SHUTDOWN is enabled.

D5: is not defined and defaults to "0".

D4: Remote  $\overline{\text{T\_CRIT\_A}}$  mask: When set to "1" a diode temperature reading that exceeds  $\overline{\text{T\_CRIT\_A}}$  setpoint will not activate the  $\overline{\text{T\_CRIT\_A}}$  pin.

D3: is not defined and defaults to "0".

D2: Local  $\overline{\text{T\_CRIT\_A}}$  mask: When set to "1" a Local temperature reading that exceeds  $\overline{\text{T\_CRIT\_A}}$  setpoint will not activate the  $\overline{\text{T\_CRIT\_A}}$  pin.

D1: is not defined and defaults to "0".

D0: Fault Queue: when set to "1" three consecutive remote temperature measurements outside the HIGH, LOW, or  $\text{T\_CRIT}$  setpoints will trigger an "Outside Limit" condition resulting in setting of status bits and associated output pins..

### 2.5 CONVERSION RATE REGISTER

(Read Address 04h / Write Address 0Ah)

Value	Conversion Rate
00	62.5 mHz
01	125 mHz
02	250 mHz
03	500 mHz
04	1 Hz
05	2 Hz

(Read Address 04h / Write Address 0Ah)

Value	Conversion Rate
06	4 Hz
07	8 Hz
08	16 Hz
09	32 Hz
10-255	Undefined

### 2.6 LOCAL and REMOTE HIGH SETPOINT REGISTERS (LHS, RSHSB, and RLSLB)

(Read Address 05h, 07h / Write Address 0Bh, 0Dh):

BIT	D7	D6	D5	D4	D3	D2	D1	D0
Value	SIGN	64	32	16	8	4	2	1

For LHS and RSHSB: HIGH setpoint temperature data. Power-on default is  $\text{LHIGH} = \text{RHIGH} = 70^{\circ}\text{C}$ . 1 LSB =  $1^{\circ}\text{C}$ . Two's complement format.

(Read / Write Address 13h):

BIT	D7	D6	D5	D4	D3	D2	D1	D0
Value	0.5	0.25	0.125	0	0	0	0	0

For RLSLB: Remote HIGH Setpoint Low Byte temperature data. Power-on default is  $0^{\circ}\text{C}$ . 1 LSB =  $0.125^{\circ}\text{C}$ . Two's complement format.

### 2.7 LOCAL and REMOTE LOW SETPOINT REGISTERS (LLS, RLSHB, and RLSLB)

(Read Address 06h, 08h, / Write Address 0Ch, 0Eh):

BIT	D7	D6	D5	D4	D3	D2	D1	D0
Value	SIGN	64	32	16	8	4	2	1

For LLS and RLSHB: HIGH setpoint temperature data. Power-on default is  $\text{LHIGH} = \text{RHIGH} = 0^{\circ}\text{C}$ . 1 LSB =  $1^{\circ}\text{C}$ . Two's complement format.

(Read / Write Address 14h):

BIT	D7	D6	D5	D4	D3	D2	D1	D0
Value	0.5	0.25	0.125	0	0	0	0	0

For RLSLB: Remote HIGH Setpoint Low Byte temperature data. Power-on default is  $0^{\circ}\text{C}$ . 1 LSB =  $0.125^{\circ}\text{C}$ . Two's complement format.

## 2.0 LM99 Registers (Continued)

### 2.8 REMOTE TEMPERATURE OFFSET REGISTERS (RTOHB and RTOLB)

(Read / Write Address 11h):

BIT	D7	D6	D5	D4	D3	D2	D1	D0
Value	SIGN	64	32	16	8	4	2	1

For RTOHB: Remote Temperature Offset High Byte. Power-on default is LHIGH = RHIGH = 0°C. 1 LSB = 1°C. Two's complement format.

(Read / Write Address 12h):

BIT	D7	D6	D5	D4	D3	D2	D1	D0
Value	0.5	0.25	0.125	0	0	0	0	0

For RTOLB: Remote Temperature Offset High Byte. Power-on default is 0°C. 1 LSB = 0.125°C. Two's complement format.

The offset value written to these registers will automatically be added to or subtracted from the remote temperature measurement that will be reported in the Remote Temperature registers.

### 2.9 LOCAL and REMOTE T\_CRIT REGISTERS (RCS and LCS)

(Read / Write Address 20h, 19h):

BIT	D7	D6	D5	D4	D3	D2	D1	D0
Value	SIGN	64	32	16	8	4	2	1

D7–D0: T\_CRIT setpoint temperature data. Local power-on default is T\_CRIT = 85°C. Remote power-on default is T\_CRIT = 110°C (+126°C actual remote diode temperature). 1 LSB = 1°C, two's complement format.

### 2.10 T\_CRIT HYSTERESIS REGISTER (TH)

(Read and Write Address 21h):

BIT	D7	D6	D5	D4	D3	D2	D1	D0
Value				16	8	4	2	1

D7–D0: T\_CRIT Hysteresis temperature. Power-on default is TH = 10°C. 1 LSB = 1°C, maximum value = 31.

### 2.11 FILTER and ALERT CONFIGURE REGISTER

(Read and Write Address BFh):

BIT	D7	D6	D5	D4	D3	D2	D1	D0
Value	0	0	0	0	0	Filter Level		ALERT Configure

D7-D3: is not defined defaults to "0".

D2-D1: input filter setting as defined the table below:

D2	D1	Filter Level
0	0	No Filter
0	1	Level 1
1	0	Level 1
1	1	Level 2

Level 2 sets maximum filtering.

D0: when set to "1" comparator mode is enabled.

### 2.12 MANUFACTURERS ID REGISTER

(Read Address FEh) Default value 01h.

### 2.13 DIE REVISION CODE REGISTER

(Read Address FFh) The LM99 version has a default value 31h or 49 decimal. The LM99-1 version has a default value of 34h or 52 decimal. This register will increment by 1 every time there is a revision to the die by National Semiconductor.

### 3.0 Application Hints

The LM99 can be applied easily in the same way as other integrated-circuit temperature sensors, and its remote diode sensing capability allows it to be used in new ways as well. It can be soldered to a printed circuit board, and because the path of best thermal conductivity is between the die and the pins, its temperature will effectively be that of the printed circuit board lands and traces soldered to the LM99's pins. This presumes that the ambient air temperature is almost the same as the surface temperature of the printed circuit board; if the air temperature is much higher or lower than the surface temperature, the actual temperature of the of the LM99 die will be at an intermediate temperature between the surface and air temperatures. Again, the primary thermal conduction path is through the leads, so the circuit board temperature will contribute to the die temperature much more strongly than will the air temperature.

To measure temperature external to the LM99's die, use a remote diode. This diode can be located on the die of a target IC, allowing measurement of the IC's temperature, independent of the LM99's temperature. The LM99 has been optimized to measure the NVIDIA® GeForce™FX family thermal diode. Remember that a discrete diode's temperature will be affected, and often dominated, by the temperature of its leads.

#### 3.1 DIODE NON-IDEALITY

##### 3.1.1 Diode Non-Ideality Factor Effect on Accuracy

When a transistor is connected as a diode, the following relationship holds for variables  $V_{BE}$ ,  $T$  and  $I_F$ :

$$I_F = I_S \left[ e^{\frac{V_{BE}}{\eta V_t}} - 1 \right]$$

where:

$$V_t = \frac{kT}{q}$$

- $q = 1.6 \times 10^{-19}$  Coulombs (the electron charge),
- $T$  = Absolute Temperature in Kelvin
- $k = 1.38 \times 10^{-23}$  joules/K (Boltzmann's constant),
- $\eta$  is the non-ideality factor of the process the diode is manufactured on,
- $I_S$  = Saturation Current and is process dependent,
- $I_F$  = Forward Current through the base-emitter junction
- $V_{BE}$  = Base-Emitter Voltage drop

In the active region, the -1 term is negligible and may be eliminated, yielding the following equation

$$I_F = I_S \left[ e^{\frac{V_{BE}}{\eta V_t}} \right]$$

In the above equation,  $\eta$  and  $I_S$  are dependant upon the process that was used in the fabrication of the particular diode. By forcing two currents with a very controlled ratio ( $N$ ) and measuring the resulting voltage difference, it is possible to eliminate the  $I_S$  term. Solving for the forward voltage difference yields the relationship:

$$V_{be} = \eta \frac{kT}{q} \ln(N)$$

The voltage seen by the LM99 also includes the  $I_F R_S$  voltage drop of the series resistance. The non-ideality factor,  $\eta$ , is the only other parameter not accounted for and depends on the diode that is used for measurement. Since  $\Delta V_{BE}$  is proportional to both  $\eta$  and  $T$ , the variations in  $\eta$  cannot be distinguished from variations in temperature. Since the non-ideality factor is not controlled by the temperature sensor, it will directly add to the inaccuracy of the sensor. As an example, assume a temperature sensor has an accuracy specification of  $\pm 1^\circ\text{C}$  at room temperature of  $25^\circ\text{C}$  and the process used to manufacture the diode has a non-ideality variation of  $\pm 0.1\%$ . The resulting accuracy of the temperature sensor at room temperature will be:

$$T_{ACC} = \pm 1^\circ\text{C} + (\pm 0.1\% \text{ of } 298^\circ\text{K}) = \pm 1.4^\circ\text{C}$$

The additional inaccuracy in the temperature measurement caused by  $\eta$ , can be eliminated if each temperature sensor is calibrated with the remote diode that it will be paired with.

##### 3.1.2 Compensating for Diode Non-Ideality

In order to compensate for the errors introduced by non-ideality, the temperature sensor is calibrated for a particular processor. National Semiconductor temperature sensors are always calibrated to the typical non-ideality of a given processor type. The LM99 is calibrated for the non-ideality of the NVIDIA GeForceFX family thermal diode. When a temperature sensor calibrated for a particular processor type is used with a different processor type or a given processor type has a non-ideality that strays from the typical, errors are introduced.

Temperature errors associated with non-ideality may be reduced in a specific temperature range of concern through use of the offset registers (11h and 12h). See Offset Register table below.

Please send an email to [hardware.monitor.team@nsc.com](mailto:hardware.monitor.team@nsc.com) requesting further information on our recommended setting of the offset register for different processor types.

Offset Register Settings for Specific Devices

Processor Family	Offset Register Settings		
	$\Delta T, ^\circ\text{C}$	Register 11h	Register 12h
NVIDIA GeForceFX Graphics Processor	default	default	default
Intel® Pentium® 4 Processor	+2.625	0000 0010	1010 0000
Intel Pentium 3 Processor	+2.375	0000 0010	0110 0000

### 3.0 Application Hints (Continued)

#### 3.2 PCB LAYOUT FOR MINIMIZING NOISE



FIGURE 11. Ideal Diode Trace Layout

In a noisy environment, such as a processor mother board, layout considerations are very critical. Noise induced on traces running between the remote temperature diode sensor and the LM99 can cause temperature conversion errors. Keep in mind that the signal level the LM99 is trying to measure is in microvolts. The following guidelines should be followed:

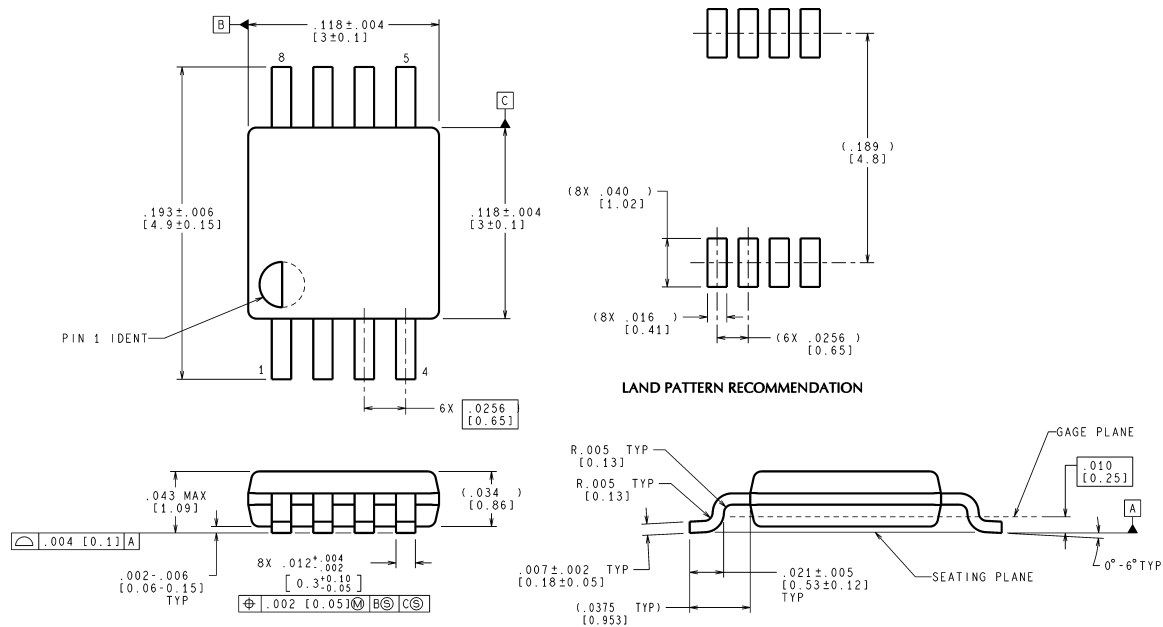
1. Place a 0.1  $\mu$ F power supply bypass capacitor as close as possible to the  $V_{DD}$  pin and the recommended 2.2 nF capacitor as close as possible to the LM99's D+ and D- pins. Make sure the traces to the 2.2 nF capacitor are matched.
2. Ideally, the LM99 should be placed within 10 cm of the Processor diode pins with the traces being as straight, short and identical as possible. Trace resistance of 1  $\Omega$  can cause as much as 1°C of error. This error can be compensated by using the Remote Temperature Offset Registers, since the value placed in these registers will automatically be subtracted from or added to the remote temperature reading.
3. Diode traces should be surrounded by a GND guard ring to either side, above and below if possible. This GND

guard should not be between the D+ and D- lines. In the event that noise does couple to the diode lines it would be ideal if it is coupled common mode. That is equally to the D+ and D- lines.

4. Avoid routing diode traces in close proximity to power supply switching or filtering inductors.
5. Avoid running diode traces close to or parallel to high speed digital and bus lines. Diode traces should be kept at least 2 cm apart from the high speed digital traces.
6. If it is necessary to cross high speed digital traces, the diode traces and the high speed digital traces should cross at a 90 degree angle.
7. The ideal place to connect the LM99's GND pin is as close as possible to the Processors GND associated with the sense diode.
8. Leakage current between D+ and GND should be kept to a minimum. One nano-ampere of leakage can cause as much as 1°C of error in the diode temperature reading. Keeping the printed circuit board as clean as possible will minimize leakage current.

Noise coupling into the digital lines greater than 400 mVp-p (typical hysteresis) and undershoot less than 500 mV below GND, may prevent successful SMBus communication with the LM99. SMBus no acknowledge is the most common symptom, causing unnecessary traffic on the bus. Although the SMBus maximum frequency of communication is rather low (100 kHz max), care still needs to be taken to ensure proper termination within a system with multiple parts on the bus and long printed circuit board traces. An RC lowpass filter with a 3 dB corner frequency of about 40 MHz is included on the LM99's SMBCLK input. Additional resistance can be added in series with the SMBData and SMBCLK lines to further help filter noise and ringing. Minimize noise coupling by keeping digital traces out of switching power supply areas as well as ensuring that digital lines containing high speed data communications cross at right angles to the SMBData and SMBCLK lines.

## Physical Dimensions inches (millimeters) unless otherwise noted



MUA08A (Rev E)

**8-Lead Molded Mini-Small-Outline Package (MSOP),  
JEDEC Registration Number MO-187  
Order Number LM99C1MM or LM99C1MMX  
NS Package Number MUA08A**

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