AN10349

Digital temperature sensor accuracy explained

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Document information

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Keywords	LM75A, SE95, SA56004X, NE1617A, NE1618, NE1619
Abstract	This document explains the various effects on local or remote temperature sensor accuracy.

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Revision history

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1. Introduction

This document explains different factors influencing a digital thermal sensor's accuracy. Although the accuracy of a temperature sensor is guaranteed by design, thorough device characterization and stringent production testing, in order to achieve the best accuracy, the consideration of external factor is equally important. Optimal final system performance, however, depends on several external factors including the characteristics of the remote diode, PCB layout, external noise influence, or choice of sensor placement. The influence of these external effects on local and remote thermal sensors' accuracy is detailed in this document.

Philips Semiconductors offers three classes of digital thermal sensors:

- Local temperature sensor (LM75A and SE95) that monitors its own temperature and is used to measure the temperature hot spot of a system.
- Local and remote temperature sensor (SA56004X, NE1617A and NE1618) which alternately monitors the temperature of itself and that of a remote diode (NPN/PNP transistor) and can be used to measure the temperature hotspot of the system and that of a remote card. The remote diode is a discrete NPN or PNP diode connected transistor such as the 2N3904/2N3906 transistors, or the thermal diode that exists inside an ASIC, FPGA, Graphic Controller, or CPU that has the characteristic similar to a 2N3904/2N3906 transistor.
- Local and remote temperature sensor with voltage monitoring capability (NE1619) which in addition to monitor either the local and/or remote temperature, is capable of monitoring the voltage inputs from multiple power supplies that are in the range between 0 V and 12 V.

2. Effects on remote temperature sensor accuracy

2.1 How a remote temperature sensor works

Before being able to understand the effects of remote temperature sensor accuracy, it is useful to go through a brief summary of how they work.

The remote temperature sensor connects to an external diode that is an NPN/PNP diode connected transistor (see Figure 1). It forces two consecutive well-controlled currents, I_1 and I_2 on D+ and D- pins, measures and averages the change of the base-emitter voltage of the diode. I_1 current is about 10 times that of I_2. As the result of this process, the highly process and temperature dependent parameter of the diode equation, I_S is cancelled out. This leaves the change in base-emitter voltage, which is directly proportional to the temperature.

The forced current is represented by the diode equation, as shown in Equation 1:

$$I = I_S\left(e^{-\left[\left(\frac{V_{BE}}{\eta}\right) \times \left(\frac{kT}{q}\right)\right]} - 1\right) \qquad (1)$$

Since the remote diode operates in the forward bias region, Equation 1 is dominated by the exponential term and is approximated as shown in Equation 2:

$$I = I_S e - \left[\left(\frac{V_{BE}}{\eta}\right) \times \left(\frac{kT}{q}\right)\right] \quad (2)$$

The forced current sources, I_1 and I_2 are represented by Equation 3 and Equation 4, respectively.

$$I_1 = I_S e - \left[\left(\frac{V_{BE1}}{\eta}\right) \times \left(\frac{kT}{q}\right)\right] \quad (3)$$

$$I_2 = I_S e - \left[\left(\frac{V_{BE2}}{\eta}\right) \times \left(\frac{kT}{q}\right)\right] \quad (4)$$

Since $I_1 = N \times I_2$, subtracting Equation 3 from that of Equation 4, and solve for V_{BE1} and V_{BE2}, results in the change of V_{BE} which is proportional to temperature and is as shown by Equation 5:

$$\Delta V_{BE} = V_{BE1} - V_{BE2} = \frac{\eta kT}{q} ln(N) \quad (5)$$

Where,

η **—** non-ideality factor of the remote diode is between 0.95 to 2

I_S — saturation current

k — Boltzman's constant = 1.38×10^{-23} J/°K

T — temperature in Kelvin

q — electronic charge = 1.69 × 10–19 Coulomb

N — forced current ratio = 10 (typically)

V_{BE1} — base-emitter voltage at I_1

V_{BE2} — base-emitter voltage at I_2

V_{BE} — change of emitter-based voltage (proportional to temperature)

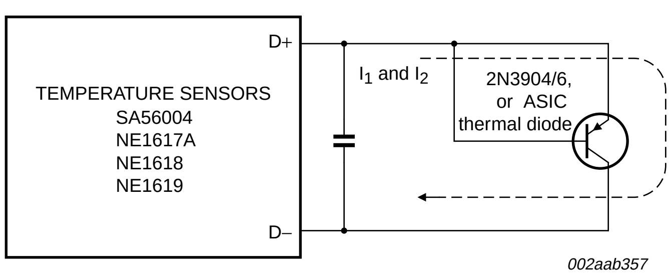


Fig 1. Thermal sensor with remote sensing diode

2.2 Temperature sensor accuracy versus temperature sensor resolution

Temperature sensor resolution refers to the step size of the sensor's temperature measurement. An 11-bit resolution gives a temperature resolution of 0.125 °C. This means the thermal sensor is capable of providing a digital output with a step size of 0.125 °C.

Temperature sensor accuracy refers to how exactly the temperature of the thermal sensor matches that of its targeted measured environment. The design aspect for temperature sensor accuracy is beyond the scope of the document. Most importantly, temperature sensor accuracy is different from temperature sensor resolution. Temperature resolution may affect its accuracy if the accuracy is limited by the resolution. For instance, if the temperature accuracy is ±0.1 °C and its resolution is 11-bit or 0.125 °C, the accuracy is obviously at best the temperature sensor's resolution. In general that is not the case as the resolution is designed to be at least 10 times that of its accuracy. Thus, a ±1 °C accuracy temperature sensor would typically have an 11-bit to 13-bit resolution.

2.3 Remote diode non-ideality factor affecting remote temperature sensor accuracy

The non-ideality factor (denoted) is a parameter of a remote diode that measures the deviation of the diode from its ideal behavior. It is a constant that ranges between 0.9 and 2, and can be found in the diode manufacturer's data sheet. Most remote sensors are pre-trimmed with a fixed non-ideality factor to match the manufacturer's discrete diode or to a particular integrated circuit thermal diode. For example, SA56004X, NE1617A, NE1618 and NE1619 (the remote thermal sensors from Philips) are trimmed to a non-ideality fact of 1.008. If the non-ideality factor of the remote diode does not match that of the thermal sensor, when sensing the temperature, a temperature offset will occur and will result in a measurement error.

To understand how the non-ideality factor affects the remote temperature sensor accuracy, we have to express the forward bias diode equation in terms of V_{BE} (in the form as shown in Equation 5), write two V_{BE} equations by substituting the non-ideality factor and temperature variable of the remote diode and remote thermal sensor. The equations are shown below in Equation 6 and Equation 7. Solving these two equations results in the expression that consists of the non-ideality factors and the remote thermal sensor temperatures shown in Equation 9. The amount of temperature offset will depend on the magnitude of the difference between the two non-ideality factors.

$$\Delta V_{BE} = \frac{\eta_{TS} k T_{TS}}{q} ln(N) \qquad (6)$$

$$\Delta V_{BE} = \frac{\eta_{ACT} k T_{ACT}}{q} ln(N) \qquad (7)$$

$$\frac{\eta_{TS} T_{TS}}{\eta_{ACT} T_{ACT}} = 1 \qquad (8)$$

$$T_{TS} = \frac{\eta_{ACT}}{\eta_{TS}} T_{ACT} \qquad (9)$$

Where:

η_{ACT} = non-ideality factor of remote diode

η_{TS} = non-ideality factor of temperature sensor

T_{ACT} = actual temperature at remote diode in Kelvin

T_{TS} = temperature sensed by the temperature sensor in Kelvin

For example:

Question: If the non-ideality of the temperature sensor (η_{TS}) is 1.008, that of the remote diode (η_{ACT}) is 1.001 and the remote actual temperature (T_{ACT}) is 90 °C, what is the measured temperature (T_{TS})?

Answer: Temperature is in Kelvin, so we begin by converting: 90 °C is 363.13 K (that is, 90 + 273.13 = 363.13 K). Temperature measured by the thermal sensor using Equation 9 is:

$$T_{TS} = \frac{1.001}{1.008} 363.13 = 360.61\ K$$

Converting the result from Kelvin to Celsius, the temperature measured by the thermal sensor becomes:

$$T_{TS} = 360.61\ K - 273.13\ K = 87.48\ °C$$

The temperature error, denoted as TempError, incurred by the difference in the two non-ideality factors is:

$$TempError = 87.48\ °C - 90.0\ °C = -2.52\ °C$$

2.3.1 How to compensate for the temperature offset using the SA56004X thermal sensor from Philips

The SA56004X has an 11-bit offset register comprised of two 8-bit registers (11h and 12h) with five reserved bits that are ‘Don’t Care’. This offset register is used to compensate for temperature offset caused by external factors. When there is temperature offset in the measurement, the offset value should be written to the offset register. After each temperature conversion, the SA56004X automatically adds the measured temperature value with that of the offset register, and latches the data into the temperature value register. As in the above example, the TempError is –2.52 °C, in order to cancel this offset value, a +2.52 °C must written to the offset registers. This is shown in Figure 2.

Remark: According to Equation 9, the offset value caused by the non-ideality factor goes up the increase in temperature. For example, temperature offset when the measured temperature is 90 °C and 120 °C, is 2.5 °C and 2.7 °C, respectively.

reserved bits (bit 4 – bit 0)

bit 15	bit 14	bit 13	bit 12	bit 11	bit 10	bit 9	bit 8	bit 7	bit 6	bit 5	bit 4	bit 3	bit 2	bit 1	bit 0
0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0

11h (bit 15 – bit 8)   12h (bit 7 – bit 0)

002aab360

The content of the offset register is +2.5 °C and is as close as possible to the desired +2.52 °C limited by the 11-bit resolution (0.125 °C).

Fig 2. Compensating for temperature offset using SA56004X

2.4 Series resistance on D+ and D– affecting remote thermal sensor accuracy

The series resistance on D+ and D– contributes to temperature error. In general, the series resistance exists because of cold soldered joints or poor contacts on D+ or D–. Improper PCB layout such as long skinny traces is another example. This effect on temperature error is additive to other temperature offset error and could be stored in the offset register.

Figure 3 depicts the diagram of a remote diode connected to the remote temperature sensor's D+ and D– pins. The series resistance is represented by R_{S1} and R_{S2}. The temperature sensor forces two currents I_1 and I_2 and measure change of voltage drop across the base and emitter. The series resistance causes additional voltage drop in the path of measurement and results in a temperature error. Consequently, if the error is not addressed by compensation, it affects the temperature accuracy. Writing a loop equation, the series resistance is the unwanted offset denoted as ηV_M in Equation 10.

$$\Delta V'_{BE} = \underbrace{(R_{S1} + R_{S2}) \times (I_2 - I_1)}_{\Delta V_M} + \underbrace{\frac{\eta kT}{q} ln(N)}_{\Delta V_{BE}} \qquad (10)$$

Where:

$\Delta V'_{BE}$ is the change of voltage as measured by the temperature sensor

ΔV_M is the undesired offset voltage caused by the series resistance

ΔV_{BE} is the desired measured voltage.

The change of 1 °C corresponds to (nk/q)*ln(N) or approximately equal to 198.6 µV (for a forced current ratio of 10 : 1) or 240 µV (for a forced current ratio of 16 : 1). The contribution of temperature error is realized by dividing ΔV_M by the quantity (nk/q)*ln(N) or 198.6 µV/°C or 240 µV and the result is expressed as Equation 11.

In general, if the consecutive forced currents are 10 µA and 100 µA, the effect of series resistance is about 0.45 °C/Ω.

$$Let\ R_{ST} = R_{S2} + R_{S2} \rightarrow \Delta V_M = R_{ST} \times (I_2 - I_1) \quad (11)$$

$$TempError = \frac{R_{ST} \times (I_2 - I_1)}{\frac{nk}{q} ln(N)}$$

For example:

If I_2 = 100 µA, and I_1 = 10 µA, R_{ST} = 1 Ω,

then: (nk/q)ln(N) = 198.6 µV/°C

Temperature error = 1 Ω × (100 µA – 10 µA) / 198.6 µV/°C = 0.45 °C

Series resistance increases the temperature error by +0.45 °C.

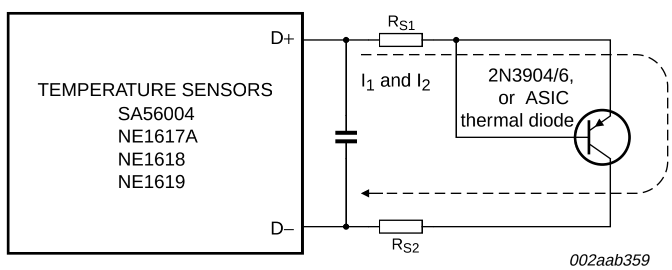
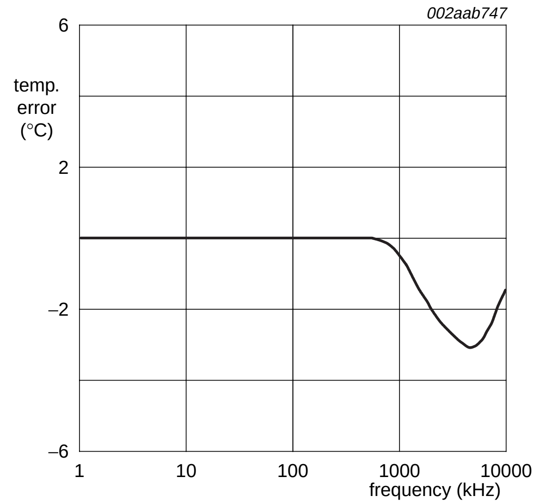


Fig 3. Effect of series resistance on remote sensor

2.5 Common mode noise at D+ and D– affecting remote sensor accuracy

Common mode noise at D+ and D– induces temperature error. High frequency interference or D+/D– trace length mismatches are the possible sources of common mode noise. Figure 4 shows the effect on a Philips remote temperature sensor. A 100 mV peak-to-peak oscillating signal is AC-coupled the D+ and D–. This illustrates the contribution of common mode noise to temperature error. Errors begin to occur above approximately 1 MHz.

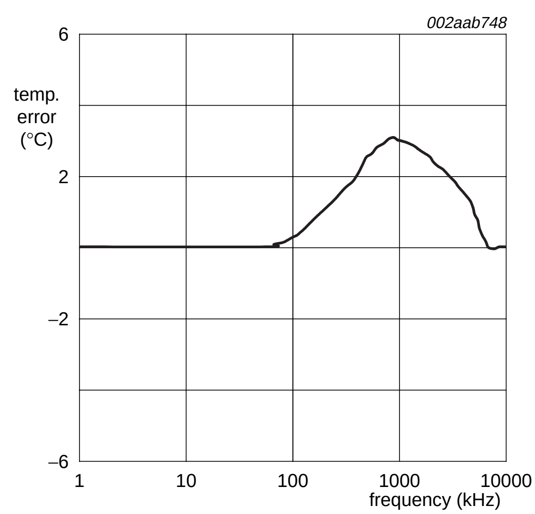


V_{IN} = 100 $mV_{p\text{-}p}$ and AC coupled to D–

Fig 4. Temperature sensor error versus Common mode noise

2.6 Differential noise at D+ and D– affecting remote sensor accuracy

Differential noise at D+ and D– contributes to temperature error. High frequency interference and poorly isolated differential pairs are possible sources of noise. Figure 5 shows the error induced on one of Philips' remote temperature sensor. A 100 mV peak-to-peak oscillating signal is AC-coupled the D+ and D–. This illustrates the impact of differential noise to temperature error. Error begins to occur above approximately 100 kHz.



V_{IN} = 100 $mV_{p\text{-}p}$ and AC coupled to D– and D+

Fig 5. Temperature error versus differential noise

2.7 PCB trace leakage at D+ and D– affecting remote sensor accuracy

Leakage on PCB track should not occur unless the PCB is defective. Figure 6 shows the error induced on one of Philips' temperature sensor. A 10 MΩ leakage on either D+ or D– caused by a defective PCB could result in as much as 1 °C in temperature error.

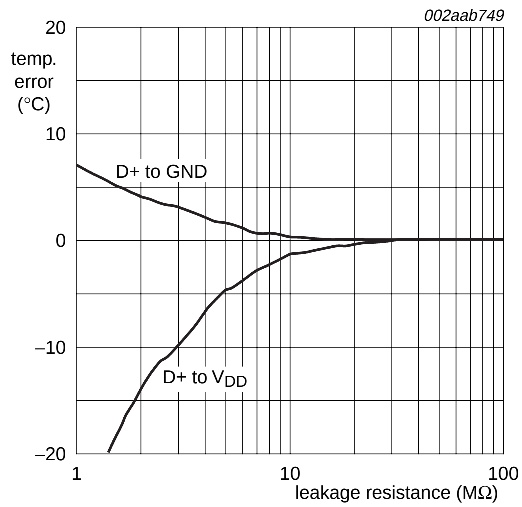


Fig 6. PCB leakage on D+ and D–

2.8 External D+ to D– capacitance affecting remote sensor accuracy

The capacitor on D+ and D– acts like a low-pass filter that helps to suppress high frequency noise and improve EMI. Figure 7 shows the effect of a D+ to D– capacitance on one of Philips' temperature sensors. It illustrates the impact of larger external capacitance on temperature error. Capacitance value larger than 3 nF or 3000 pF begins to affect temperature accuracy.

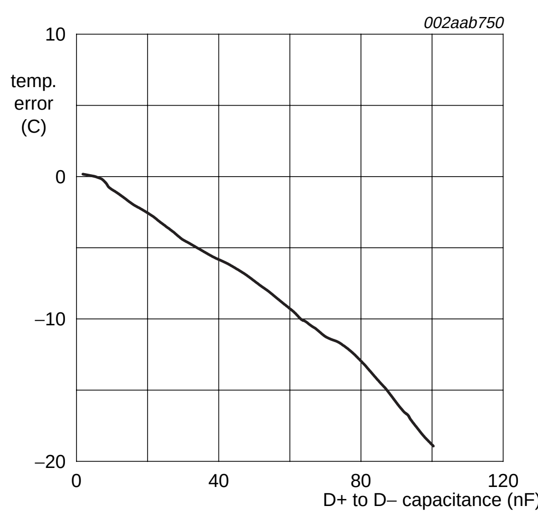


Fig 7. D+ to D– capacitance versus temperature error

3. Effects on local temperature accuracy

Factors affecting a local thermal sensor accuracy are different from those of a remote sensor. For a local thermal sensor, the sensing diode is on the same die as the sensor. Therefore, there is no need to worry about the remote diode's characteristics or any factors discussed above. Also, a remote thermal sensor measures the temperature of a remote diode or that of the integrated circuit's thermal diode, therefore it has a faster response time to change of temperature and measures the temperature more accurately at any point in time.

Unlike a remote thermal sensor, a local thermal sensor can only be placed adjacent to a hotspot, and only monitors the general ambient temperature of the environment. Its response time and accuracy will be diminished compared to a remote thermal sensor in the same application. In general, the ambient temperature may vary. Depending on the airflow, at any instant in time, the ambient temperature may be different from the actual die temperature of the local thermal sensor. Because the primary thermal path is through the leads of the sensor, careful placement of the local sensor and good contact between the PCB and the sensor's leads are key to achieve optimum accuracy.

4. PCB layout guideline

The following guidelines on PCB layout should be considered when designing with local or remote temperature sensors.

1. For local thermal sensors, since the primary thermal path is through the leads of the sensor, make sure the sensor leads are well connected to the PCB plane.
2. A 0.1 μF bypass capacitor should be placed as close to the supply pin as possible.
3. The external capacitor across the D+ to D– traces should be placed as close the remote sensor's input D+ and D– pins as possible.
4. Place the remote thermal sensor as close to the remote sensing diode as possible.
5. Avoid routing clock, high frequency switching bus the remote sensor. Where possible, do not use near CRTs.
6. D+ and D– traces should be closed coupled with matched trace length, and provide guard ground traces on each side. If possible include a ground trace below the pair.
7. Wide traces of approximately 10 mil for D+ and D– would minimize inductance and reduce noise sensitivity.
8. Avoid soldered joints wherever possible.
9. If remote sensing diodes located several feet away from the sensor, use shielded twisted-pair cable instead of PCB traces.

5. Abbreviations

Table 1. Abbreviations

Acronym	Description
ASIC	Application Specific Integrated Circuit
CPU	Central Processing Unit
CRT	Cathode Ray Tube
EMI	ElectroMagnetic Interference
FPGA	Field Programmable Gate Array
NPN	Negative-Positive-Negative
PCB	Printed-Circuit Board
PNP	Positive-Negative-Positive

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7. Contents

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