High-Performance Processor Die Temperature Monitoring

TEXAS INSTRUMENTS

Introduction

Power management in high-performance processors, such as CPUs, GPUs, ASICs, and FPGAs, is typically complex. With thermal monitoring, these systems can not only initiate a safe system shutdown, but also leverage temperature to dynamically adjust performance. To enhance system reliability and maximize performance, it is often desirable to monitor processor temperature. Higher temperatures can activate a cooling fan, modify a system clock, or, should the thermal threshold of the processor be exceeded, quickly shut down the system completely. Applications such as infotainment, ADAS, servers, notebooks, and aerospace and defense systems can take advantage of these thermal monitoring techniques.

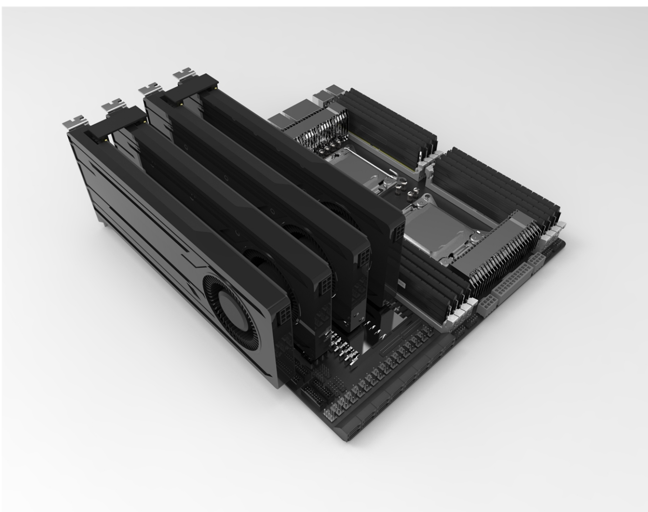

Figure 1. Motherboards With High Performance Processors Typically Need Heak Sinks

Design Considerations in Die Temperature Monitoring

For effective temperature monitoring, there are two design considerations for high-performance processors: (i) Temperature accuracy (ii) Sensor Placement. The temperature accuracy of the processor has a direct correlation to the sensor location.

Processor performance can be maximized to drive the overall system to its thermal design limit through high-accuracy temperature monitoring. While most ICs have built-in temperature sensors due to variations across wafers and other various lots, the accuracy is not consistent. High-performance processors include complex circuitry that impact the accuracy of the integrated sensor. In such systems, the accuracy is at ±5°C. Systems designed with such lower accuracy are not able to maximize their performance their thermal design limit.

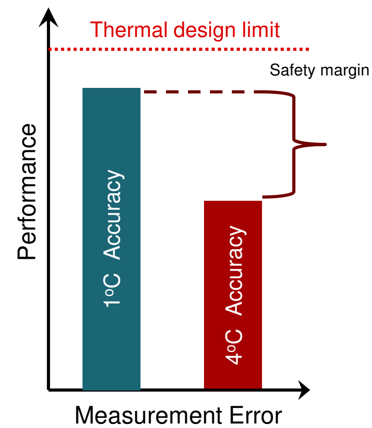

Figure 2. Performance of a System Can be Enhanced Though High-Accuracy Thermal Monitoring

Sensor Placement & Accuracy

The thermal behavior of processors is monitored either through an integrated temperature sensor or thermal diode, or alternatively through an external temperature sensor. In some cases, both are used to maximize performance and boost reliability of the system.

Integrated Temperature Sensor: BJT

Some high-performance processors include a bipolar transistor (BJT) for temperature sensing. This has a very predictable transfer function that is dependent on temperature. Remote temperature sensors use this principle to measure the die temperature. The most common BJT found in CMOS processes is a PNP.

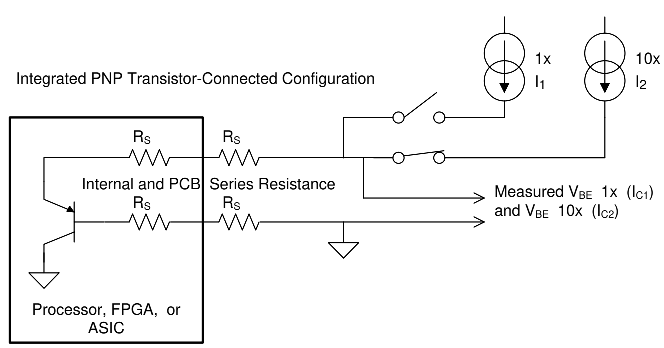

Figure 3. ΔV_{BE} Measurement With Two Currents

The design of such systems can be challenging due to the noise and error caused by BJT process variations. Thermal diode error sources can be from Ideality Factor variation, series resistance, noise injection, and Beta Compensation.

Ideality Factor Variation— BJT-thermal-diode characteristics are dependent on process geometry and other process variables. If the Ideality Factor n is known, the n-factor register can be used to correct the n-factor error. Alternatively, software calibration methods can be used to correct this in the desired temperature range.

Series Resistance— Due to the current source, any resistance in the signal path appears as a voltage offset. Modern remote temperature sensors employ a series resistance cancellation algorithm that removes temperature error due to resistance up to 1–2 kΩ. This enables robust, accurate measurements, even when coupled with RC Filters.

Noise Injection— EMI or inductive coupling into the remote junction PCB traces can cause error when diode traces run in parallel with high-frequency signal lines carrying high currents. Tracing remote temperature sensors need to consider this during board design.

Beta Compensation— Thermal Transistors integrated into an FPGA or processor may have Beta < 1. A remote temperature sensor with Beta Compensation is specifically designed to work with these transistors, and to correct temperature measurement errors associated with them. The Beta Compensation feature provides no benefit when used with a typical discrete transistor.

Device Recommendation

TMP46x devices offer high-accuracy temperature measurements to monitor up to eight remote BJTs, as well as the local temperature. Many commercial applications can benefit from such multi-channel remote sensors. The TMP451-Q1 offers an automotive qualified high-accuracy remote and local temperature sensor for automotive applications.

External Temperature Sensor

Some processors have built-in temperature sensor. While the location is ideal, the built-in sensors make them less accurate due to variations across the wafers and different lots. Additionally, it is essential to trim the processor based on a reference; this reference is compared with die temperature to adjust the coefficients. Given the complex circuitry, the processors incur self-heating that builds an error. This error increases with increases in temperature.

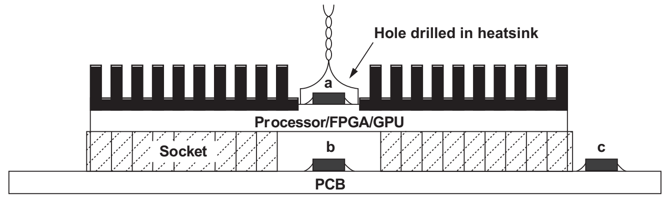

Figure 4. Sensor Placement for High-Performance Processor Temperature Monitoring

i. **Location a:** Sensor located in a hole drilled into the center of the heat sink of the microprocessor provides close proximity. The heat sink can be clipped to the processor or attached with epoxy, and generally sits on top of the processor. These typically require long leads, and as the heat sink-to-microprocessor thermal connection degrades, the sensor data becomes incorrect.

ii. **Location b:** Another potential location is in the cavity beneath a socketed processor, with which assembly is straightforward. Given the sensor is isolated from the airflow, ambient temperature has minimal impact on the sensor reading. Additionally, if the heat sink gets detached from the processor, the sensor indicates an increase in processor temperature. That said, given the sensor placement, the temperature differences between the sensor and the processor case are 5°C to 10°C.

iii. **Location c:** The sensor can be mounted on the circuit board next to the MPU. While this is simple to implement, the correlation between sensor temperature and MPU temperature is much weaker.

Device Recommendation

Footprint size is a factor in selecting a local temperature sensor. The TMP112 with a 1.6 x 1.6 mm can be used in close proximity of the processor and gain a good accuracy of 0.5°C. This can maximize performance when compared to a 5°C to 20°C that is typically observed in temperature sensors integrated within processors.

Table 1. Key Collaterals

COLLATERAL	DESCRIPTION
Remote Temperature Sensor	*Optimizing Remote Diode Temperature Sensor Design*
Local Temperature Sensor	*Temperature Sensors: PCB Guidelines for Surface Mount Devices*
Board Temperature Monitoring	*Monitoring Board Temperature*