Measuring Die Temperatures with Remote Diode Sensing in Space

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ABSTRACT

High performance systems typically require accurate temperature measurements to ensure robust operation and minimize temperature induced error. Temperature can also be crucial for the health monitoring of a system as operation at temperature extremes can reduce device lifetime. Power dissipation places a limitation on resource allocation for devices like FPGAs and real time temperature monitoring can help maximize device use while remaining within the intended operating limits.

This application note discusses the advantages of monitoring temperature in a dynamically loaded system and how to best use internal temperature diodes found in many modern FPGAs and high speed data converters. The fundamentals of diode temperature monitoring are presented along with the challenges inherent to a discrete solution. An integrated, compact, radiation hardened solution using the TMP461-SP is given as an easy to implement alternative to obtain accurate temperature readings over a wide temperature range.

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1 Introduction

Across industry there is a push for semiconductors that are capable of operating at higher speeds, in smaller packages, with improved performance. This is perhaps best exemplified in the aerospace market where board space is scarce and every gram of extra weight comes at a premium. Emerging communication standards aim to minimize the physical needs of the system while also pushing data rates to unprecedented levels. Faster data rates translate to increased power consumption. Coupled with the desire to minimize solution size, these two trends produce a major concern for manufacturers and users of semiconductor devices: power density.

Power dissipation and the resulting changes in die temperature can impact system performance in a number of ways: operating points may become skewed and additional error can be introduced with temperature drift, or the operational lifetime of a device may be reduced from cumulative temperature stress. In systems where temperature can fluctuate heavily and power consumption is dynamic, such as for FPGAs or High speed data converters, this issue becomes even more pronounced; particularly in space applications where designers do not have the luxury of convection cooling. Many high speed data converters are designed with interleaved architectures that rely on internal calibration to achieve rated performance. As the temperature fluctuates it is often necessary for the device to re-calibrate or suffer a significant performance degradation. For an FPGA, the power limitations of the device place an effective limit on the resources that can be used at any given time. Thus, having reliable temperature measurements of critical devices is imperative for optimizing system performance.

2 Determining Die Temperature

2.1 Current Sensing

Current sensing of supply rails or output lines is often used as a leading indicator of die temperature. This works reasonably well for static conditions where power dissipation is constant and the temperature of the die can be estimated based on the given thermal resistance. However even in these cases, thermal resistances given by manufacturers are typically quite conservative and are intended to provide worst case approximations. Actual die temperature can deviate significantly from that predicted by the thermal resistance. There is also a delay between operating at a given power dissipation level and observing the expected thermal response as it takes time for the junction to heat up. If loads are switching and current demands fluctuate heavily over time, it becomes much more difficult to correlate current to die temperature. Consequently, this method does not produce a very accurate estimation of real time temperature in these kinds of applications.

2.2 Diode Temperature Sensing

To maximize resource allocation, preserve accuracy, and prolong device lifetime by ensuring operation within the specified limits, it is advantageous to have a direct measurement of die temperature. FPGA and high speed data converter manufacturers are aware of this, which is why many have begun to dedicate pins for connection to internal substrate diodes.

So how is the diode temperature measured? From the diode equation (Equation 1), it can be determined that the forward voltage of a diode is directly proportional to its temperature.

$$V_{BE} = \frac{\eta k T}{q} \ln\left(\frac{I_C}{I_S}\right) \tag{1}$$

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3 Diode Sensing Solutions

3.1 Simple Bias Circuit

The simplest approach would be to bias the diode with a voltage source and resistor and measure the voltage drop across the diode. Depending on the diode this voltage changes by 1 mV to 3 mV per degree Celsius. This is a relatively crude implementation though and yields very poor accuracy as the current through the diode changes with voltage. Forcing a fixed current through the diode would be an improvement, but may still not yield very accurate results. From the diode equation (Equation 1), we can see that the forward voltage depends on two diode characteristics, the non-ideality factor (η) and the reverse saturation current (I_S), which are themselves process dependent. The reverse saturation current also has its own temperature dependency. If accuracy is desired, then another approach is required.

3.2 Switched Current Circuit

An alternative method that has gained popularity involves switching between two precision current sources, where one source is a precise multiple of the other. By using multiple current sources and taking the difference of the two diode voltage measurements, the dependency on the reverse saturation current can be eliminated and only the ratio of the current sources needs to be known. The following equations demonstrate this approach:

$$\Delta V_{BE} = V_{BE1} - V_{BE2} \tag{2}$$

$$\Delta V_{BE} = \frac{\eta k T}{q} \ln\left(\frac{I_{C1}}{I_S}\right) - \frac{\eta k T}{q} \ln\left(\frac{I_{C2}}{I_S}\right) \tag{3}$$

$$\Delta V_{BE} = \frac{\eta k T}{q} \ln(r) \tag{4}$$

where:

$$r = \frac{I_{C1}}{I_{C2}} \tag{5}$$

This simplifies the calibration process and yields more accurate measurements than a single current source can.

For the best accuracy, the non-ideality factor of the diode must also be known, as any deviation in the actual value from the assumed value results in a gain error. This information is generally available from the manufacturer, but if not then diode characterization can yield the appropriate values for offset and gain adjustment.

3.2.1 Discrete Solution

There are a variety of ways to implement this solution discretely but in general the following devices are required:

1. a precision op amp or transistor based current source
2. a switch to cycle between the different current levels
3. another op amp to condition the diode voltage
4. an analog to digital converter to feed the signal to a microcontroller to perform the calculation
5. Clocking is also needed to control the transition between current levels

An example circuit might look like Figure 1. Note the clocking circuitry and controller are not included and it is assumed that the clocking for the switches would be provided by the controller.

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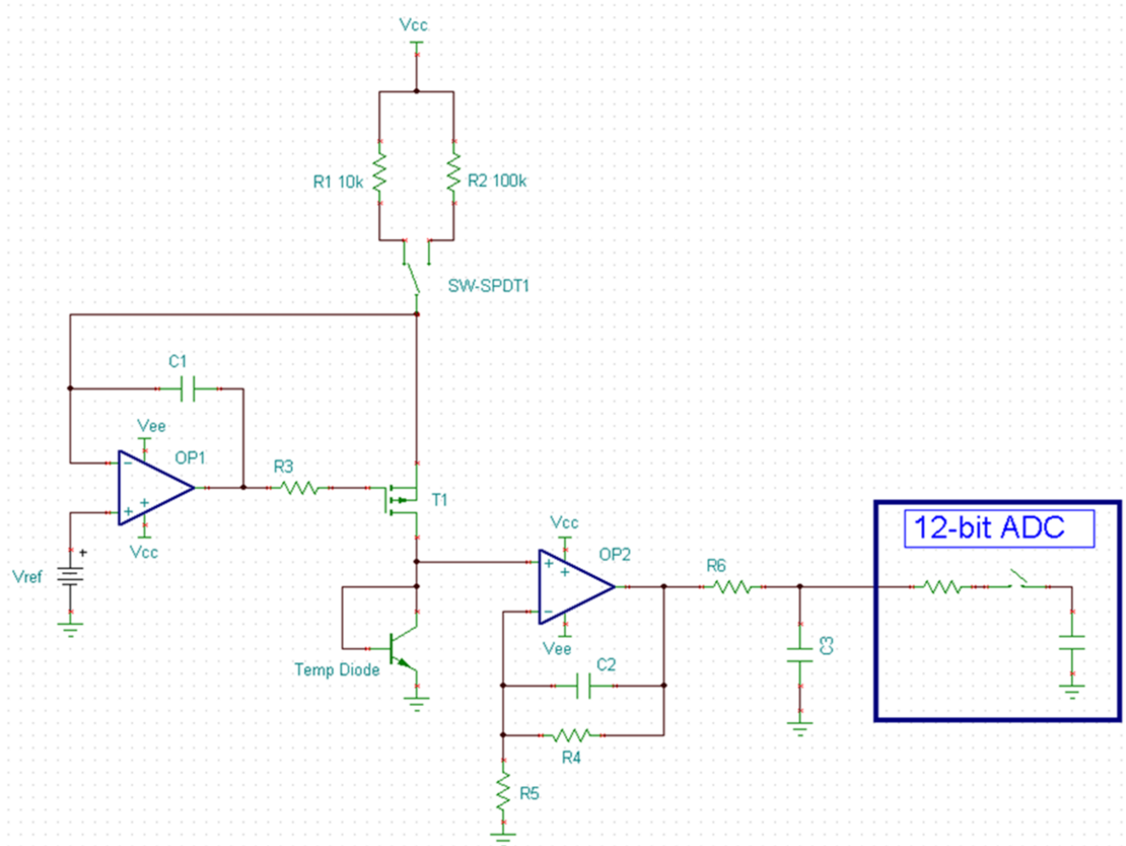

Figure 1. Discrete Temperature Sensing Circuit

The accuracy of this solution is influenced by a number of factors. First, there is the resolution of the converter. As previously mentioned the voltage across a typical p-n junction tends to change by approximately 1 mV to 2 mV per degree Celsius, but most of this actually stems from the temperature dependency of the reverse saturation current. By eliminating the influence of this current, the actual delta depends on the non-ideality factor and the ratio of currents used. Typically, this voltage will be in the range of 100 to 300 microvolts per degree Celsius. With signal levels in this range a low-noise design is required for accurate measurements and additional filtering may be necessary. If for example a 12-bit converter is used with a 5V supply, then the size of the least significant bit is approximately 1.22 mV. There is only so much gain that can be applied to the diode signal before violating the full scale input of the converter and increasing gain also increases the error contributed by the amplifier along with any noise in the system. Thus the converter resolution places a limitation on the accuracy. For accuracy down to 1°C, a 14-bit converter or better is generally needed.

Gain error also has a significant impact on the accuracy of the measurement. There are 3 major sources of gain error for this circuit: The mismatch between the assumed and the actual non-ideality factor of the diode, the matching of the current setting resistors and how close they come to the intended ratio (including the switch resistance), and the gain setting resistors for the amplifier that drives the converter. In order to determine this gain, it is necessary to know what the full scale range of the diode voltage will be with the chosen current sources, and this typically requires characterization of the diode at the temperature extremes. Furthermore, the amplifier and passive components exhibit temperature drift themselves, and if the temperature of the measurement circuit also fluctuates then the accuracy of the reading will also drift.

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There are other error sources that may also factor in depending on the signal levels and desired sensitivity. The resistance between the diode and the measurement point such as that which might develop from a long trace length can introduce additional error and requires a third current source for calibration. In systems where high currents are present it may also be necessary to measure the diode voltage differentially to ensure any potential developed between the amplifier ground and diode ground does not show up in the measurement.

3.2.2 Integrated Solution with TMP461-SP

Designing a circuit for accurate temperature measurements is not a trivial task, and finding components that are suitable for space applications can be difficult given the limited selection. The design also requires resources from the host microcontroller or FPGA to control the switching, take the readings, and process the data to determine the temperature. To simplify the process of obtaining a high accuracy temperature reading, Texas Instruments offers the TMP461-SP. The TMP461-SP integrates the functionality described above and performs the temperature calculation itself, freeing up resources in the host controller and providing accuracy across temperature to 1.5°C with a resolution of 0.0625°C. The device is also qualified to QMLV RHA standards and is tested to a Total Ionizing Dose of 100 kRad. It also includes registers for the non-ideality factor and offset correction with an internal programmable digital filter and input series resistance cancellation. If values for the non-ideality factor and offset can be determined by an initial characterization, then accuracy within fractions of a degree Celsius can be achieved. The TMP461-SP also includes a local integrated temperature diode for board measurements wherever the device is placed, eliminating the need for an additional thermistor.

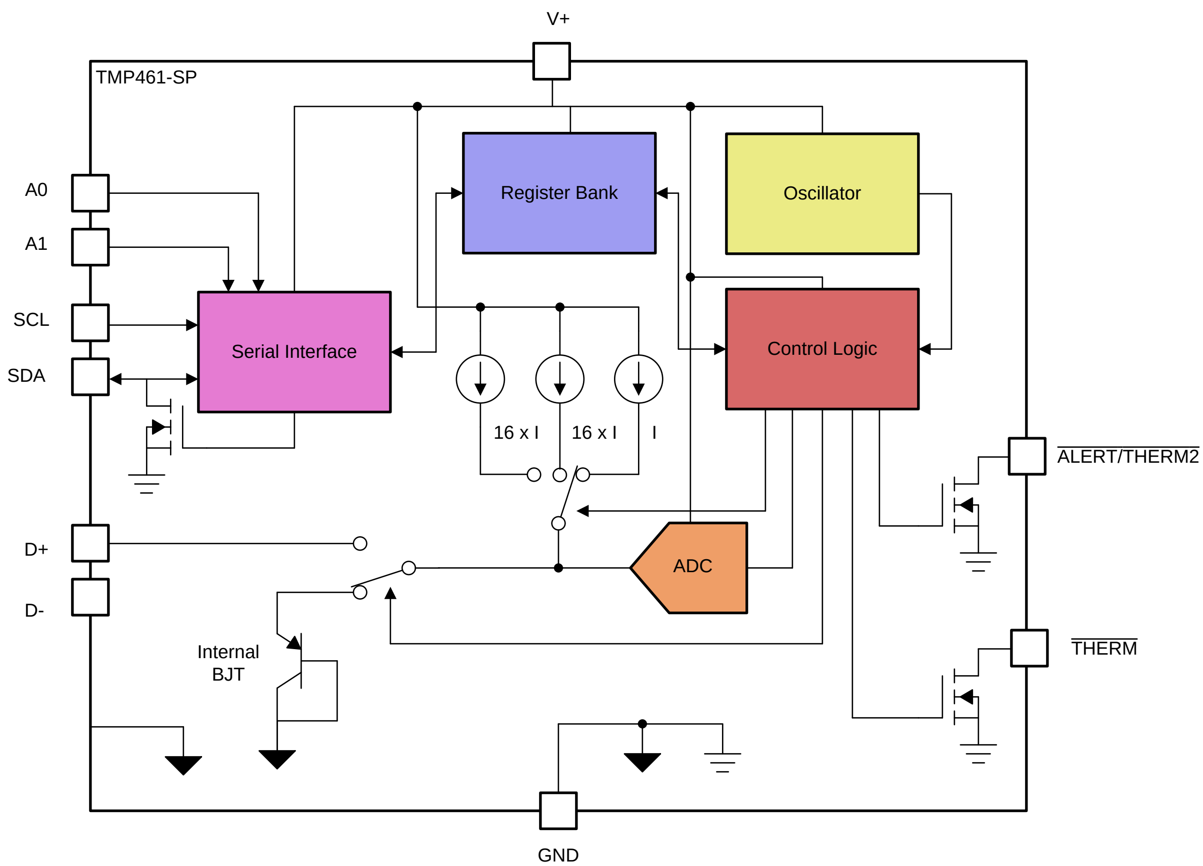

Figure 2. TMP461-SP Integrated Solution

The TMP461-SP not only simplifies the overhead for accurate measurements, but also requires approximately 3x less board space than a simple discrete solution. An example board layout is shown in Figure 3.

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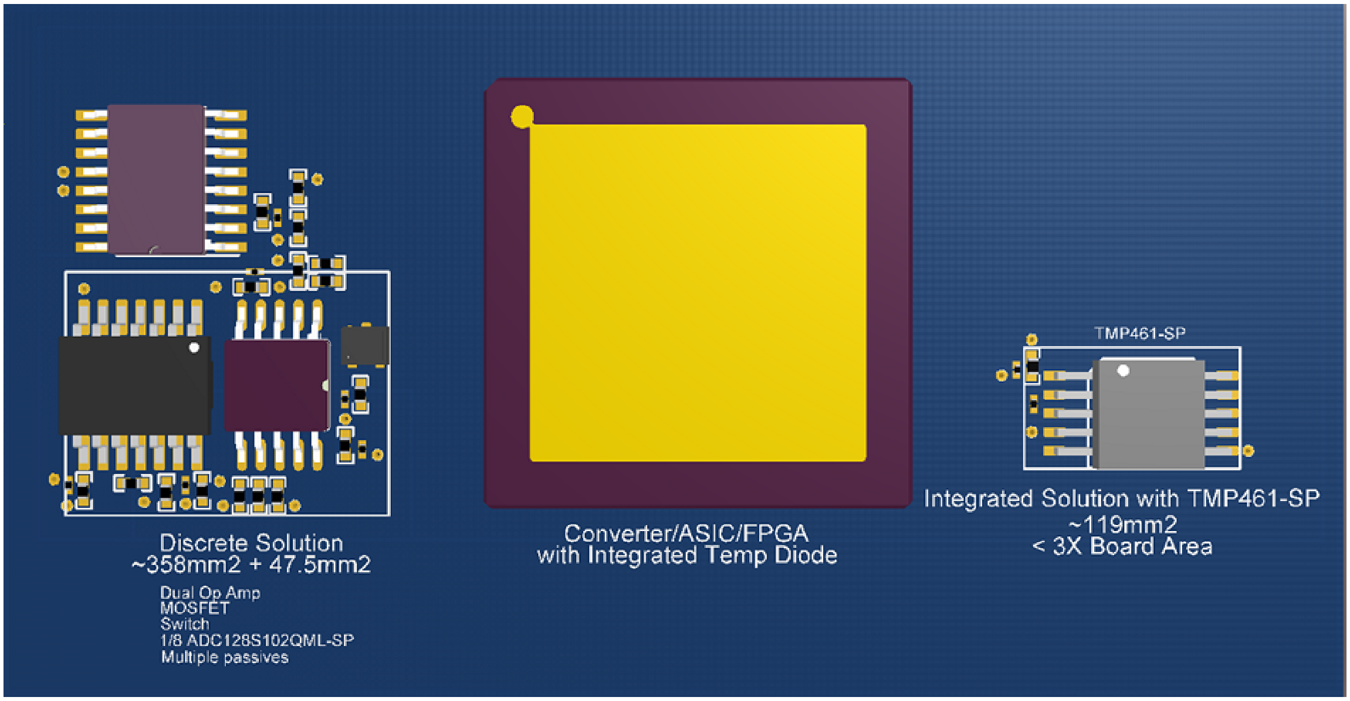

Figure 3. Discrete Solution vs. TMP461-SP Layout

4 Summary

Monitoring the real time temperature of a device that is loaded dynamically has many advantages and can help with resource optimization and on the fly response if the intended operating range is exceeded. It is possible to implement a discrete solution, but it can be challenging to achieve the desired accuracy and board real estate must be sacrificed. There are relatively few components qualified for space, and finding suitable devices can be difficult and may require additional design complexity or tradeoffs. The TMP461-SP provides a space qualified integrated solution to this problem that significantly simplifies the design process while achieving high accuracy and minimizing the board area and weight required to realize this function. For more information on how to optimize the design with an integrated temperature sensor like the TMP461-SP, see *Optimizing Remote Diode Temperature Sensor Design, SBOA173*.

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