

# Using Forward Voltage to Measure Semiconductor Junction Temperature

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**S**EMICONDUCTOR junctions, from the millions of transistors used in integrated circuits to the large-area compound junctions that make high brightness LED's possible, are all susceptible to early failure due to increased heat. This becomes an even larger issue when feature size shrinks and current requirements increase. Even normal operation can cause heat build up, raising the junction temperature. These elevated temperatures can cause an increase in defects within the junction, which can lead to decreased performance, as well as a shortened lifespan. An accurate temperature-measurement method for the semiconductor device is needed to ensure that critically high temperatures are avoided. In this article, we will show how a simple junction-temperature measurement can be performed using common test and measurement instruments and how this information can then be used to monitor operating conditions for a given device.

## Background

The ideal measurement of junction temperature is to monitor the device temperature as close as possible to the heat source. Current flowing through a semiconductor junction produces heat, which then flows through the junction material to the outside world. One method that could be employed is to place a temperature sensor very close to the semiconductor junction and measure the sensor output signal. As the heat flows to the outside area, it would cause a rise in temperature of the area and the sensor. This

is straightforward, but there are physical limitations to this technique due to the finite size of the sensor. In many cases, the sensor itself would be larger than the junction to be measured. This would add a large thermal mass to the system, and additional error to the measurement which would lessen the accuracy of the measurement. Therefore, this technique would not be very useful in most applications.

A better technique is to employ the junction itself as a temperature sensor. With most materials, there is a strong correlation between the forward voltage drop of a junction and the temperature of that junction. The point at which a junction becomes nonlinear with respect to junction temperature is dependent on the material of the junction as well as its design. It is safe to assume linearity for most materials in normal operating environments up to 80-100°C. Nonlinearity can be determined experimentally by measuring the voltage at higher and higher ambient temperatures, until a deviation from linearity occurs.

This relationship is nearly linear for most devices and can be expressed mathematically as:

$$T_j = m \cdot V_f + T_o \quad (\text{Equation 1})$$

where

$T_j$  = junction temperature in°C

$m$  = slope\* in°C/Volt

$V_f$  = forward voltage drop

$T_o$  = intercept\* in°C

\*Device specific parameters

So, at a given temperature,  $T_j$ , the semiconductor junction, will have a specific forward voltage drop,  $V_f$ . If we measure the  $V_f$  at two different temperatures, we can calculate the slope,  $m$ , as well as the intercept,  $T_o$ , for a particular junction. And, because this relationship is linear, we can then use equa-

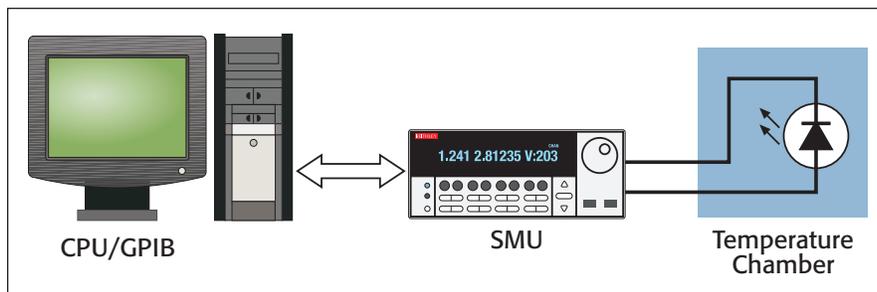


Figure 1. SMU setup.

tion 1 to find the junction temperature under different conditions simply by measuring the  $V_f$ . Knowing  $T_j$  for different operating conditions and packages allows us to calculate thermal parameters such as thermal resistance for differing package types and designs. This is important when designing for a particular operating condition by ensuring maximum lifetime for the device, because thermal effects are a major contributor to early device failure.

### Test Technique

In this test technique, the device-under-test (DUT) is placed in a temperature chamber and connected to the drive and measurement equipment. This can be a programmable current source and voltmeter, but there are also instruments capable of sourcing a current and measuring a voltage simultaneously. They are commonly referred to as Source Measure Units (SMU's) and can simplify the instrumentation considerably. (See *Figure 1*.)

Next, connect the SMU to the device using a four-wire, or Kelvin, measurement technique. Four-wire voltage measurements decrease the error caused by lead resistance in a voltage measurement by sensing the voltage around the DUT, not in sensing it at the input to the SMU (see *Figure 3* for a close-up of four-wire measurement).

Place the DUT into an environmental chamber and set the chamber to an initial temperature. The initial point is commonly measured at 25°C, with the DUT then allowed to reach thermal equilibrium. A dwell time can be determined experimentally, but, for most packages, a soak of 10 minutes should be sufficient.

After the junction has come to thermal equilibrium, a short duration current is sourced into the DUT and the voltage drop is measured. The time duration of the pulse as well as the amplitude are very important. Delivering a larger amount of power (too much current or too long a pulse) may skew the results by heating the junction. Many times, the junction under test is a silicon or compound diode. For these device types, a good starting point for experimentation is 1ms of sourced current at a few mA of drive current. If you are unsure, the self-heating of the junction can also be determined experimentally by using a source capable of very short pulses (<1ms). You can then experiment by varying pulse widths and compare the voltages of each pulse duration. Voltage differences on the order of 1–2mV commonly indicate a 1°C change in junction temperature.

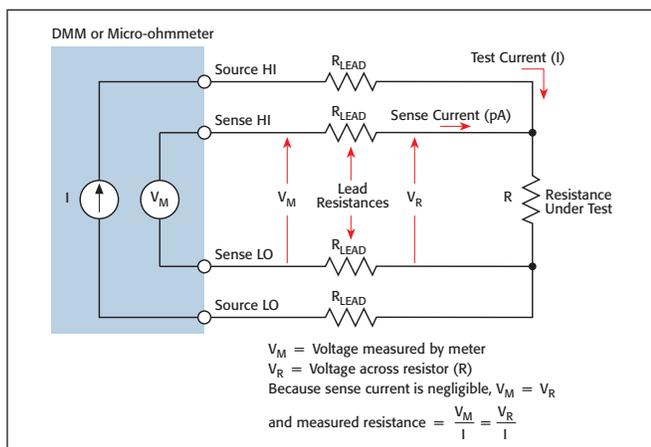


Figure 3. Close-up of four-wire measurement technique.

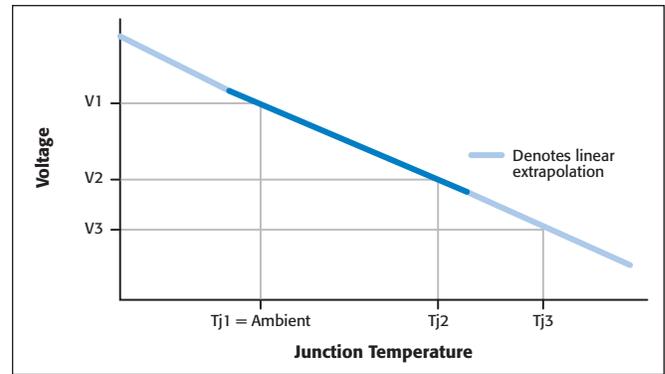


Figure 2. A graph depicting the linearity of junction temperature.

This measured voltage is the  $V_{f1}$  @  $T_{j1}$  (25°C).

The temperature is then elevated to a higher value (50°C for example), the DUT is allowed to reach thermal equilibrium, and the current pulse is again delivered. Voltages recorded at this temperature are labeled the  $V_{f2}$  @  $T_{j2}$  (50°C in this example).

These steps can be repeated over a number of values and then plotted as Voltage vs. Junction Temperature (*Figure 2*). It is best to use at least three temperatures in the analysis to check for any discrepancies in the approximation.

You can now calculate the slope,  $m$ , of the line as well as the intercept.

Equation 2: Calculating  $m$  (Point-Slope form of equation 1)

$$T_j = m \cdot V_f + T_0 \quad (\text{Equation 1})$$

$$T_{j2} - T_{j1} = m(V_{f2} - V_{f1})$$

(Point-Slope form of equation 1)

$$m = (T_{j2} - T_{j1}) / (V_{f2} - V_{f1})$$

and you can then calculate  $T_0$  by extrapolation.

$$T_{j2} - T_{j1} = m(V_{f2} - V_{f1})$$

(Point-Slope form of equation 1)

By setting  $V_{f2}$  to 0, equation 2 becomes

$$T_{j2} = T_{j1} - mV_{f1}$$

$T_{j2}$  in this case is equal to the intercept, or  $T_0$ .

$$T_0 = T_{j2} = T_{j1} - mV_{f1}$$

### Real World Example: High Brightness LED

In this example, a new high brightness LED die is being developed. This new device is designed to carry more current than previous units, and we need to be sure that we can keep the heat flux high in order to minimize the junction temperature. This will ensure that we have adequate device lifetime for some of our more rigorous applications. A common LED failure occurs when the bond wire connecting the Anode or Cathode to the LED Die is broken. The common cause of breakage is temperature cycling of the bondwire. This is a direct result of elevated junction temperatures due to inadequate heat removal.

We place the LED die in an oven and follow the above prescribed test plan. We measure the following results:

$$V_{f1} @ T_{j1} (25^{\circ}\text{C}) = 1.01 \text{ V}$$

$$V_{f2} @ T_{j2} (50^{\circ}\text{C}) = 0.78 \text{ V}$$

$$m = (50 - 25^{\circ}\text{C}) / (0.78 - 1.01)\text{V} \\ = -108.70^{\circ}\text{C}/\text{V}$$

$$T_0 = T_{j1} - mV_{f1} \\ = 25^{\circ}\text{C} - (-108.70^{\circ}\text{C}/\text{V}) \cdot (1.01\text{V}) \\ = 134.79^{\circ}\text{C}$$

So, the first order equation describing the Junction Temperature vs. Forward Voltage for this device is:

$$T_j = -108.70^{\circ}\text{C}/\text{V} \cdot V_f + 134.79^{\circ}\text{C}$$

We can now vary other aspects of the evaluation such as operating current, environmental/case temperature, and packaging, and simply measure the  $V_f$  to measure the actual junction temperature.

## Sources of Error

The largest source of measurement error comes from the uncertainty of measurement of temperature in the environmental chamber. This measurement is typically made using a thermocouple, which can have errors of  $\pm 2^{\circ}$  or more. Additional accuracy can be obtained by placing a more accurate thermal measurement sensor, such as a thermistor or RTD, near the DUT and using a separate DMM to measure the temperature.

Uncertainty in the voltage measurement also adds to the error in the calculation of junction temperature. Selecting an instrument with a high degree of accuracy and resolution on voltage measurements is the key to minimizing this error.

Errors in the junction temperature measurement can propagate to other thermal cal-

culations, such as thermal impedance and resistance as well. Therefore, minimizing these errors is critical to obtaining accurate measurement results.

## Conclusion

A simple electrical technique for measuring the junction temperature of a semiconductor junction was shown. The data can then be used to analyze the effects of heat sinking, environmental, and source conditions on the junction in question. 

## About the Author

Jason Chonko is a senior applications engineer with Keithley Instruments in Cleveland, OH. He has a B.S. in Physics from Kent State University and has over five years experience working with optoelectronics devices.

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