Application Note

Temperature Sensing using TrenchPLUS devices

AN10137

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Principle of using temperature sensors within Automotive applications.

As the automotive industry moves towards driving higher power motors within (Electronic Powered Assisted Steering) EPAS or (Integrated Starter Alternator) ISA applications, the need for accurate temperature and current sensing becomes paramount.

This application note considers some of the protection strategies available using Philips TrenchPLUS temperature sense devices.

The BUK9107-40ATC is an n-channel power MOSFET with *monolithically integrated* temperature sense and clamping diodes. This allows temperature sensing of the actual MOSFET chip. Designed for high current applications, the device has a typical $R_{DS(ON)}$ of 5.8mΩ at 25°C, 5V gate drive, the market leader in its field.

Application example for Temperature Sensor

It is relatively simple to incorporate temperature sensing into your protection strategy. Traditionally the addition of a comparator and a few passive components would allow a direct measure of the chip temperature and a means by which to protect your system. In this paper we would like to demonstrate that by using a suitable micro-controller, a more accurate method of control can be achieved.

A typical circuit is shown in Figure 1. The MOSFET is shown on the right, being controlled by a micro-controller having an A/D input from the temperature sensor. The resistor values define the current in the sense diode – and hence its Vf - and gate switching time.

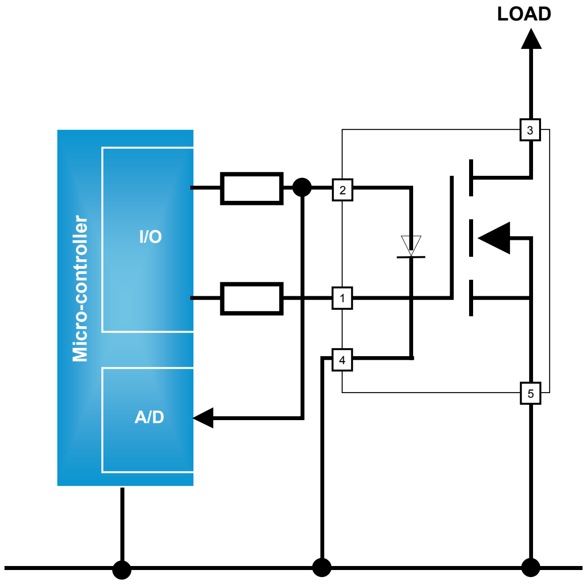

Figure 1 - Typical Temperature Sense Circuit

In normal operation, the Vf of the diode is monitored, and a reference voltage chosen below which the device turns off, $\mathbf{V}_f^{ref}$. The value of $\mathbf{V}_f^{ref}$ chosen depends on Sf - the temperature coefficient of Vf - and the temperature at which the MOSFET should be switched off. The Vf characteristic is linear over the full temperature range – as shown in Figure 2 – thus enabling numerous protection strategies to be implemented. By continually monitoring Vf the micro-controller can provide early warning of over-temperature conditions, as well as determining the rate of change of temperature.

Furthermore, depending on the chosen micro it is possible to respond to the information provided by the temperature sensor in a variety of ways. The signals could be used to trigger a latched shutdown, shutdown and cyclic retries, or simply used as a diagnostic tool for the application.

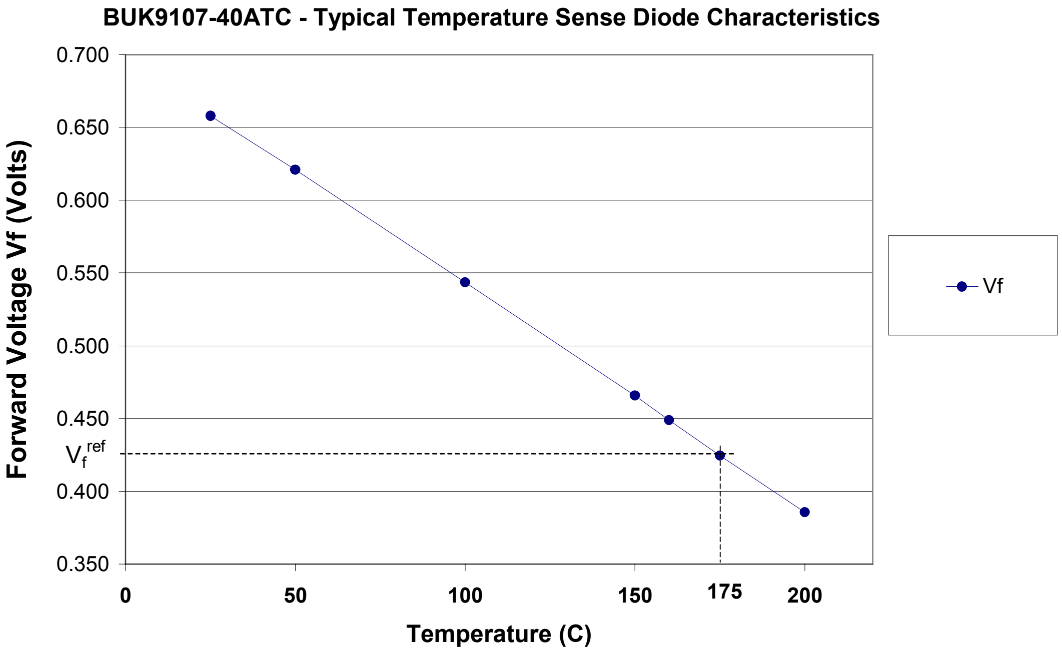

Figure 2 - The variation of Vf with temperature for the temperature sense diode

Theoretical Estimate of device Accuracy

The theoretical accuracy of the temperature sensor is dependent on three factors:-

- The uncertainty in the forward voltage, Vf
- The uncertainty in the value of the temperature coefficient, Sf
- The choice of reference voltage, V_f^{ref}

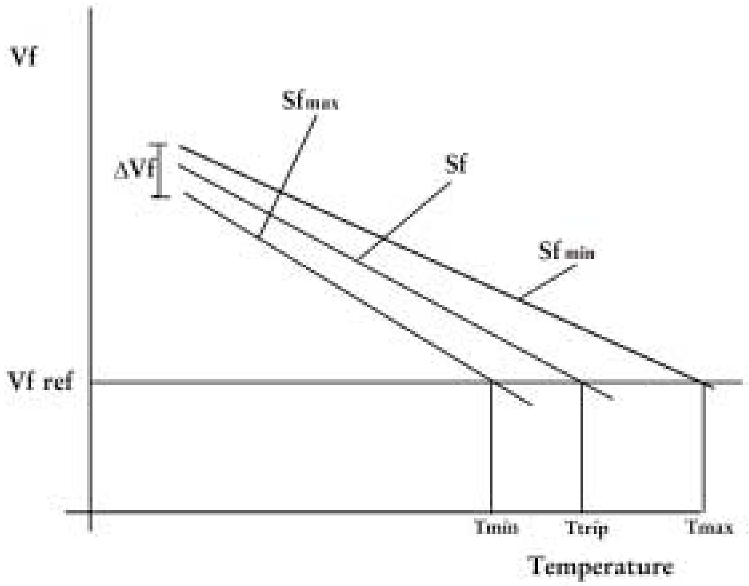

Figure 3: The variation of Ttrip with changes in Vf, Sf.

Figure 3 demonstrates the effect of these factors more clearly. Any inherent variability in Vf will add a fixed offset to T_{trip}. Variations in the temperature coefficient are shown by a change in the gradient. A lower Sf will cause the device to trip at a higher temperature, $T_{\max}$. Depending on the trip temperature this could lead to devices operating above their maximum operating temperature, which would be detrimental to their lifetime. Conversely, a higher temperature coefficient would lead to erroneous nuisance tripping below the desired set point. Both these factors have implications on the protection strategy employed.

The total error is the sum of the contributions from the uncertainty in both Vf and Sf.

Table 1 shows the datasheet values for the temperature sense diode.

	MIN	TYPICAL	MAX
Vf (mV)	648	658	668
Sf (mV/K)	1.40	1.54	1.68

Table 1 - Temp Sense Diode Characteristics

The BUK9107-40ATC has a very tight Vf tolerance of ±10mV and the variation in Sf is correspondingly tight too. However, if the device were used in the circuit of Figure 1 without calibration then the total error in the trip temperature due to the errors in both Vf and Sf becomes significant.

The maximum error will occur if the Vf (25°C) is at its highest and Sf is low.

If the trip temperature were set to 150°C, then the error in T_{trip} is given by

$$T_{Trip} = \frac{\left(Vf - \overline{V_f^{ref}}\right)}{Sf} - \left(T_{Trip} - 25\right)$$

Equation 1 - Trip temperature if neither Vf, nor Sf are measured

where the average reference voltage, $\overline{V_f^{ref}} = \overline{Vf} - (T_{Trip} - 25) \times \overline{Sf} = 465.5mV$.

Substituting the datasheet values into the above equations yields

$$T_{Max} = 150 + 19.6°C$$

$$T_{Min} = 150 - 16.4°C$$

In practice the results are much better than this.

A number of devices have been measured across the temperature range and the actual trip temperature determined for each using a reference voltage of 465.5mV. A plot of trip temperature versus V_f measured at 25°C is shown below.

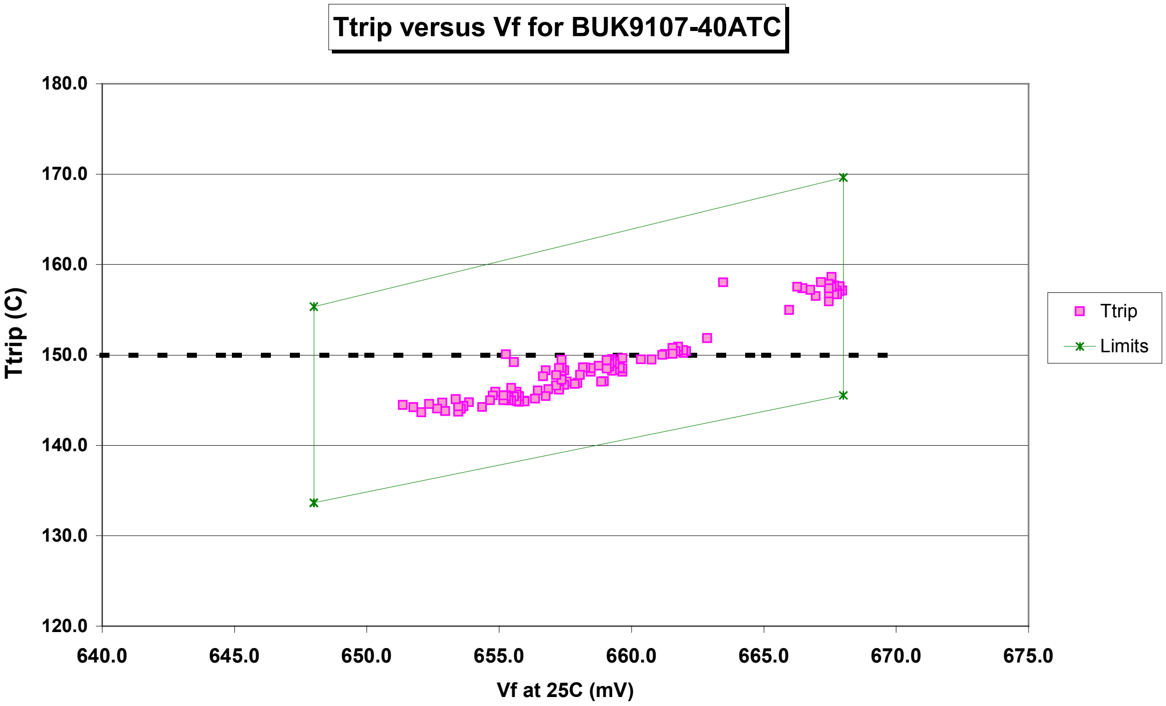

Figure 4 - Measured Trip temperature as a function of Vf without making any corrections.

The box defines the theoretical limits of the trip temperature. It is clear that the data lies within ±10°C of the target temperature.

Improving the accuracy

The accuracy of the device can be vastly improved if a measure is made of the room temperature value of Vf. Using this value, V_f^{ref} can be reset to eliminate the error in Vf. This situation is visualised in Figure 5:

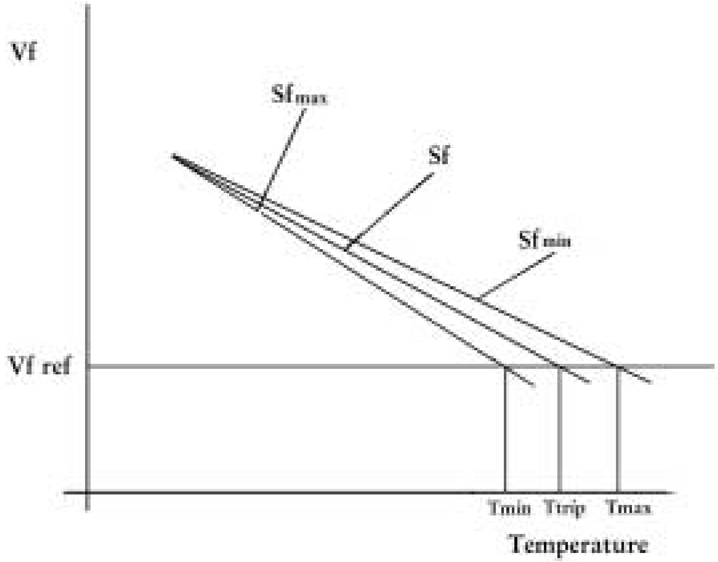

Figure 5 - If Vf is measured, the error in Ttrip will decrease.

In this case there is still an error associated with Sf, shown by the variation in gradient. As before the max/min values of Sf are taken from the datasheet (Table 1).

The error is now given by the expression,

$$d(\Delta T) = -\Delta Vf \frac{dSf}{(Sf)^2} + \frac{1}{Sf} d(\Delta Vf)$$

Equation 2 – Total error in trip point

where ΔVf is the voltage drop required to trip at 150°C from 25°C, and dSf is the variation in the temperature coefficient given in the datasheet (1.68-1.54 = 0.14). By adjusting the reference voltage the term on the right hand side of Equation 2 becomes zero. Substituting the remaining values yields,

$$T_{trip} = 150 \pm 11°C$$

Again actual results are better than this.

An estimate of the actual trip temperature was made for the same devices using an adjusted reference voltage, V_f^{ref}, the results of which are shown in Figure 3.

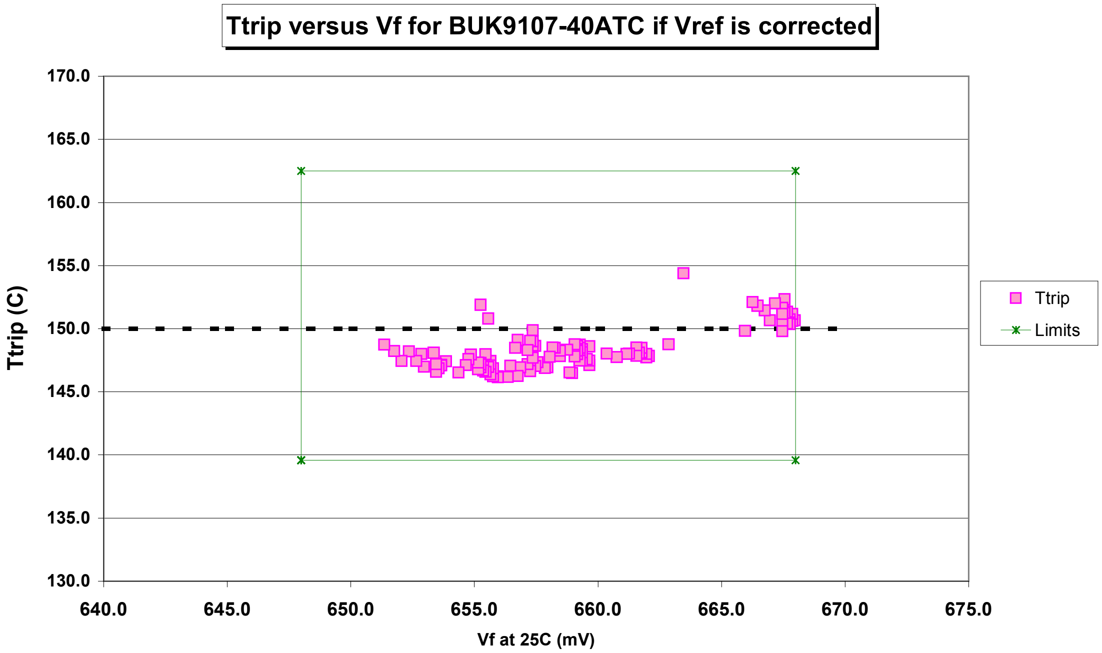

Figure 3 - Measured trip temperature if reference voltage adjusted

As before the outer box defines the theoretical limit, which has now become $T_{trip} = 150 \pm 11°C$. The measured values now lie within ±5°C of the target. It is clear that significant improvements in accuracy are possible from a simple measure of the room temperature Vf.

A further theoretical improvement can be made because a relationship exists between Sf and Vf measured at 25°C. The accuracy will be increased if Vf (25°C) is measured, and Sf calculated using the expression given in Equation 3.

Using the graph, if Vf (25°C) is measured the value of Sf will lie in the range

$$Sf_{Calc} = \{[-0.0041 \times Vf(25C)] + 4.2387\} \pm 0.099$$

Equation 3 – Empirical definition of Sf from Vf measured at 25°C.

The 0.099 error in Sf represents 5 standard deviations from the mean. If we again assume that the trip temperature, T_{trip}, is set to 150°C, the accuracy now becomes

$$T_{trip} = 150 \pm 8°C$$

Of course, the greatest accuracy is achieved if both Vf and Sf are measured for each device. In this case Vf (25°C) and Vf (150°C) are measured, and Sf is calculated and stored using

$$Sf = \frac{Vf(25) - Vf(150)}{150 - 25}.$$

Again, V_f^{ref} must be redefined as in method two. In this way the trip temperature will be limited only by the accuracy of the voltmeter used, and an accuracy of ±1°C can be readily achieved. This could be integrated in to the module build to provide excellent temperature control in your system.

Summary

There are 4 methods of using the temperature sense diode each with increasing theoretical accuracy. The 2 simplest methods have been measured and compared with theory. A summary of results is shown here

	Theory	Experiment
No Measure of Vf	$T_{trip} = 150 \pm 19°C$	$T_{trip} = 150 \pm 10°C$
Measure Vf (25C), and use Sf = 1.40 – 1.68	$T_{trip} = 150 \pm 11°C$	$T_{trip} = 150 \pm 5°C$
Measure Vf (25C), and calculate Sf	$T_{trip} = 150 \pm 8C$	
Measure Vf and Sf	$T_{trip} = 150 \pm 1°C$	