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<td>Keywords</td>
<td>Accurate temperature sensing, temperature control, sensor theoretical accuracy, forward voltage, temperature coefficient, trip temperature, trip temperature error</td>
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<td>Abstract</td>
<td>As the automotive industry moves towards driving higher powered motors in Electronic Power-Assisted Steering (EPAS) and Integrated Starter Alternator (ISA) applications, the need for accurate sensing of temperature and current becomes paramount. This document considers some of the protection strategies available using NXP TrenchPLUS temperature sensing devices.</td>
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1. Introduction

The market-leader in the field of temperature sensing devices is the BUK9107-40ATC. An N-channel power MOSFET with monolithically-integrated temperature sensing and clamping diodes that internally monitor the temperature of the MOSFET chip. Designed for high current applications, the device has a typical $R_{DS(ON)}$ of 5.8 mΩ at 25 °C with a gate drive of 5 V.

It is relatively simple to incorporate temperature sensing into your temperature protection strategy. Traditionally, a system can be protected against overtemperature using a comparator and a few passive components which directly measure the chip temperature. This application note demonstrates that a more accurate method of temperature control can be achieved using a suitable microcontroller.

2. Example of a temperature sensing device application

A typical temperature sensing circuit is shown in Figure 1 which shows the MOSFET controlled by a microcontroller. The output from the MOSFET temperature sensor is connected to the analog-to-digital input of the microcontroller. The resistor values of $R_A$ and $R_G$ define the current in the sense diode and hence its forward voltage ($V_F$) and gate switching time.

![Fig 1. Typical temperature sensing circuit](image)

During normal operation, the $V_F$ of the diode is monitored and a reference level ($V_{F(ref)}$) is chosen, below which the device switches off. The value that is chosen for $V_{F(ref)}$ depends on the $V_F$ temperature coefficient ($S_F$) and the temperature at which the MOSFET should be switched off.

The $V_F$ characteristic is linear over the full temperature range, which enables numerous overtemperature protection strategies to be implemented; see Figure 2. By continually monitoring $V_F$, the microcontroller can provide an early warning of overtemperature conditions, and can also determine the rate-of-change of temperature.

Depending on the microcontroller used, there are various possible ways to respond to the information provided by the temperature sensor. The information could be used to trigger a latched shutdown, shutdown and cyclic retries, or simply used as a diagnostic tool for the application.
2.1 Theoretical estimation of temperature sensor accuracy

The theoretical accuracy of the temperature sensor depends on three factors:

- Uncertainty of \( V_F \)
- Uncertainty of \( S_F \)
- Chosen value of \( V_F(\text{ref}) \)

The effect of the above factors is shown more clearly in Figure 3. Any inherent variability in \( V_F \) adds a fixed offset to the trip temperature \( T_{\text{trip}} \). Any variation in \( S_F \) is shown by a change in the gradient. A lower value of \( S_F \) causes the device to trip at a higher temperature \( T_{\text{trip}(u)} \). Depending on the value of \( T_{\text{trip}} \) this may lead to devices operating above their maximum operating temperature which may reduce their life expectancy. Conversely, a higher value of \( S_F \) causes erroneous nuisance tripping below the desired set point. Both these factors have implications for the overtemperature protection strategy employed.
The total error in temperature sensor accuracy is the sum of all contributions from the uncertainty of both $V_F$ and $S_F$.

The values for $V_F$ and $S_F$ of the temperature sensing diode given in the data sheet for the BUK9107-40ATC are shown in Table 1.

### Table 1. Temperature sense diode characteristics for BUK9107-40ATC

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter</th>
<th>Min</th>
<th>Typ</th>
<th>Max</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_F$</td>
<td>forward voltage</td>
<td>648</td>
<td>658</td>
<td>668</td>
<td>mV</td>
</tr>
<tr>
<td>$S_F$</td>
<td>temperature coefficient</td>
<td>$-1.4$</td>
<td>$-1.54$</td>
<td>$-1.68$</td>
<td>mV/K</td>
</tr>
</tbody>
</table>

The BUK9107-40ATC has a very tight $V_F$ tolerance of 10 mV, and the variation in $S_F$ is also correspondingly tight. However, if the device is used in the circuit shown in Figure 1 without calibration, then the total error in $T_{\text{trip}}$ due to errors in both $V_F$ and $S_F$ becomes significant. The maximum error will occur if the $V_F$, at $T_j=25 \degree C$, is at its highest value and $S_F$ is at its lowest value.

If $T_{\text{trip}}$ is set to 150 $\degree C$ and $V_F$ and $S_F$ are not measured, then the $T_{\text{trip}}$ error is given by Equation 1:

$$T_{\text{trip}} = \frac{(V_F - V_{F\text{ref}})}{S_F} - (T_{\text{trip}} - 25)$$

(1)

where the average reference forward voltage $V_{F\text{ref}}$ is given by Equation 2:

$$V_{F\text{ref}} = V_F - (T_{\text{trip}} - 25) \times S_F = 465 \text{ mV}$$

(2)

Substituting the values given in the data sheet into Equation 2 gives the following results:

$T_{\text{trip(u)}} = 150 + 19.6 \degree C$

$T_{\text{trip(l)}} = 150 - 16.4 \degree C$

In practice, the results are much better than that shown.
Figure 4 shows $T_{trip}$ as a function of $V_F$ for where a number of devices have been measured across the temperature range, and the actual $T_{trip}$ value has been determined for each using a reference voltage of 465.5 mV.

The box in Figure 4 defines the theoretical limits of $T_{trip}$. The data clearly lies within ±10 °C of the target temperature.

### 2.2 Improving accuracy

The accuracy of the device can be vastly improved if its $V_F$ is measured at room temperature. Using this value, $V_{F(ref)}$ can be reset to eliminate the error in $V_F$. This situation is shown in Figure 5.
In this case there is still an error associated with $S_F$ shown by the variation in gradient. As before, the upper values of $S_F$ are taken from the maximum values given in the data sheet shown in Table 1.

The total error at $T_{\text{trip}}$ is now given by Equation 3:

$$d(\Delta T) = -\Delta V_F \frac{dS_F}{(S_F)^2} + \frac{1}{S_F} d(\Delta V_F)$$

Equation 3

where $\Delta V_F$ is the voltage drop required to trip at 150 °C from 25 °C, and $dS_F$ is the variation in $S_F$ given in the data sheet (1.68 − 1.54 = 0.14). By adjusting $V_{F(\text{ref})}$, the term on the right-hand side of Equation 3 becomes zero. Substituting the remaining values gives the following results:

$T_{\text{trip}} = 150 \pm 11^\circ C$

Again, in practice, the results are better than this.

Figure 6 shows the effect when an estimate of $T_{\text{trip}}$ is made for the same device using a corrected $V_{F(\text{ref})}$. 
As in Figure 4, the outer box defines the theoretical limit which now gives the following results: \( T_{\text{trip}} = 150 \pm 11^\circ C \)

The measured values now lie within \( \pm 5^\circ C \) of the target. It is clear that significant improvements in accuracy are possible by measuring the value of \( V_F \) at room temperature.

A further theoretical improvement can be made because a relationship exists between \( S_F \) and \( V_F \) measured at 25 \(^\circ C\). The accuracy will be increased if \( V_F \) (at 25 \(^\circ C\)) is measured, and \( S_F \) is calculated using the expression given in Equation 4.

Using the graph, if \( V_F \) (at 25 \(^\circ C\)) is measured, the value of \( S_F \) will lie in the range given in Equation 4:

\[
S_F(\text{calc}) = \left[\frac{-0.0041 \times V_F(25^\circ C) + 4.2387}{0.099}\right] \pm 0.099
\]  

(4)

The error in \( S_F \) of 0.099 represents 5 standard deviations from the mean. If we again assume that \( T_{\text{trip}} \) is set to 150 \(^\circ C\), the accuracy now becomes: \( T_{\text{trip}} = 150 \pm 8^\circ C \).

The greatest accuracy can be achieved if both \( V_F \) and \( S_F \) are measured for every device. In this case, \( V_F \) (at 25 \(^\circ C\)) and \( V_F \) (at 150 \(^\circ C\)) are measured, and \( S_F \) is calculated and stored using Equation 5.

\[
S_F = \frac{V_F(25) - V_F(150)}{150 - 25}
\]  

(5)

Again, \( V_F(\text{ref}) \) must be redefined as in Equation 3. In this way, \( T_{\text{trip}} \) will be limited only by the accuracy of the voltmeter used, and an accuracy of \( \pm 1^\circ C \) can be readily achieved. This could be integrated into the module build to provide excellent temperature control in your system.
3. Summary

There are four methods of using the temperature sensing diode with increasing theoretical accuracy for each subsequent method. The two simplest methods have been measured and compared with theory. A summary of all the results is given in Table 2.

Table 2. Summary of results

<table>
<thead>
<tr>
<th>Accuracy method</th>
<th>Result</th>
<th>Theory</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_F$ not measured</td>
<td>$T_{trip} = 150\pm 19 , ^\circ \text{C}$</td>
<td>$T_{trip} = 150\pm 10 , ^\circ \text{C}$</td>
<td></td>
</tr>
<tr>
<td>$V_F$ measured (at 25 °C) and use $S_F = 1.40 - 1.68$</td>
<td>$T_{trip} = 150\pm 11 , ^\circ \text{C}$</td>
<td>$T_{trip} = 150\pm 5 , ^\circ \text{C}$</td>
<td></td>
</tr>
<tr>
<td>$V_F$ measured (at 25 °C) and calculate $S_F$</td>
<td>$T_{trip} = 150\pm 8 , ^\circ \text{C}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Measure $V_F$ and $S_F$</td>
<td>$T_{trip} = 150\pm 1 , ^\circ \text{C}$</td>
<td></td>
<td></td>
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