Application Note

Thermal Analysis of the TMCS1123 Hall-Effect Current Sensor

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ABSTRACT

In-package magnetic current sensors like the TMCS1123 are an invasive style of current measurement, where several amps of current are passed through the device via a non-magnetic lead frame, resulting in thermal losses internal to the package. These losses are typically layout and printed circuit board dependent, as additional copper helps to extract power from the package, and mitigate the overall thermal response of the system. This paper examines a use case over a small sample size of TMCS1123's for both copper thickness, as well as copper area on a PCB to examine how these copper reinforcements may help mitigate thermal response in an application.

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1 Introduction

When designing for invasive current sensing methods, care must be taken to make sure that the thermal problem is well controlled. Whether the thermals persist in the shunt of a traditional current shunt monitor, or are simply the losses seen by the lead frame of a device such as a Hall-effect current sensor, thermal runaway can quickly lead to design issues if not planned for and handled appropriately.

The TMCS11xxEVM is a family of evaluation modules intended to facilitate rapid, convenient evaluation of the TMCS1123, TMCS1126, TMCS1127, and TMCS1133 families of devices. These devices are reinforced isolation-capable Hall-effect current sense monitors with several optional additional features, such as a built in reference output for differential measurement, overcurrent threshold capabilities, and thermal diagnostic options. The EVM is built on a 2-layer, 4 ounce per layer stackup. Like many devices that must optimize internal power losses as part of their normal operating condition, many data sheet parameters are based upon this specific layout and heat dispersion model. This is typical among semiconductor devices such as this, as there are a potential infinite number of use cases the device can be exposed to, based upon the layout of the device, and product makers seek to showcase their device in the best of circumstances, attempting to remove the layout from the equation as much as possible.

Thus, a challenge often exists when designing with such devices: their evaluation modules present an designed for use case for evaluation of the part in a broad sense, and do not often provide information regarding limitations present in a typical design, such as space constraints or power budgets. The following paper briefly examines two such cases for device performance: adjustment of copper weight of the same topology as that of the TMCS1123EVM, and a reduction in copper planar size for the given 4 ounce stackup of the original evaluation module, with the goal of understanding how these decisions can optimize cost and space in the system.

2 Initial Examination of TMCS11xxEVM with CB70-14-CY Copper Lugs

The TMCS11xxEVM comes with a pair of CB70-14-CY 90A rated copper lugs included in the kit to provide a safe transfer of current into the EVM, provided the correct gauge cabling is used for the given signal. These lugs allow the user to move from one sensitivity variant of the chosen product family to another relatively quickly by simply screwing down to the desired variant, and ensuring a secure connection prior to energizing the system. They also allow for re-use, as the user's cabling is also screwed down into the terminal rather than soldering a one-time use design. Figure 2-1 shows a single panel of the EVM in the standard orientation as described in the TMCS1123 User's Guide without cabling attached.

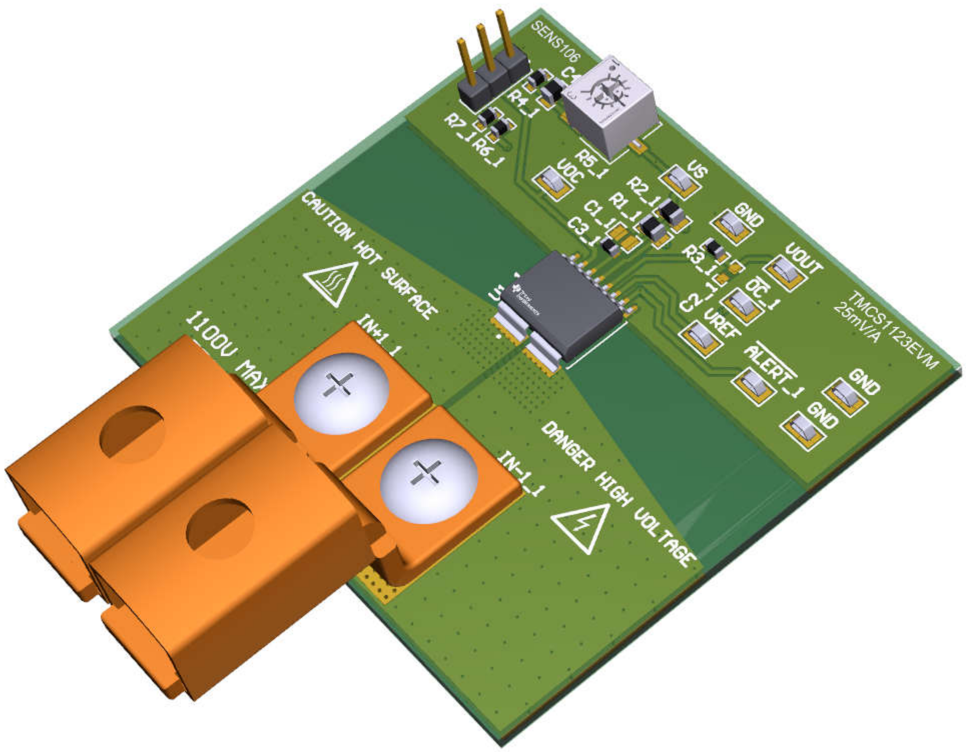

Figure 2-1. TMCS1123EVM Portion, A1 Variant, Standard Configuration, Sensitivity = 25mV/A

When this system was initially developed, varying copper weights were explored on a singular version of the paneled product to ultimately arrive at the 4oz final version available for use today. Figure 2-2 and Figure 2-3 demonstrate measured board performance for 3oz and 4oz pours, respectively, and while performance between these variations is similar, 4oz copper was ultimately chosen for the marginal improvement seen above the 60A mark.

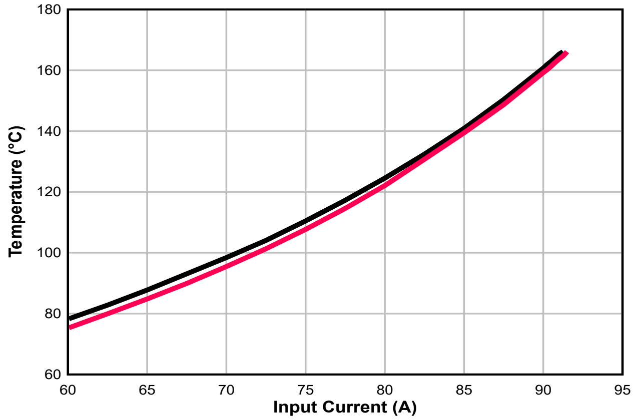

Figure 2-2. TMCS1123EVM Thermal Response Curves for 2 Sample Devices, 3 Oz Copper, >60 Amperes

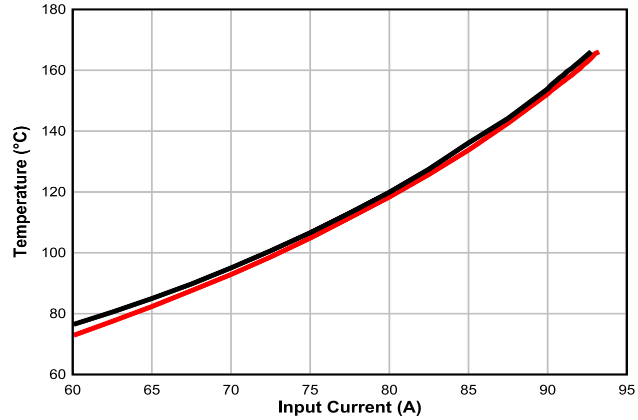

Figure 2-3. TMCS1123EVM Thermal Response Curves for 2 Devices, 4Oz Copper, >60 Amperes

At the 80A maximal point for the device,the observation is that there is roughly a 5°C improvement between the mean points of the measurement between 3oz and 4oz pours. As shown, the EVM, equipped with 4oz planes, is capable of up to approximately 93A of current capacity prior to the junction temperature reaching the absolute maximum rating of 165°C, but copper thickness can vary by lot within the build specification, due to several factors: base copper thickness tolerance, the selected start copper thickness used by the vendor, and the number of cleaning processes used by the vendor to name a few. As such, sufficient headroom is taken to make sure the device operates within the given specification (this is demonstrated in the copper weight section), even for potential worst case scenarios.

3 Experimental Setup and Discussion

The setup for the experiments performed in this application note is comprised of a high-amperage current load in series with the devices under test, and necessary power supplies to drive the load. Figure 3-1 shows a rendering of the board used. From the diagram, note that for each test, all five samples for a given board weight or polygon size were run simultaneously, in series such that all boards can see the same current.

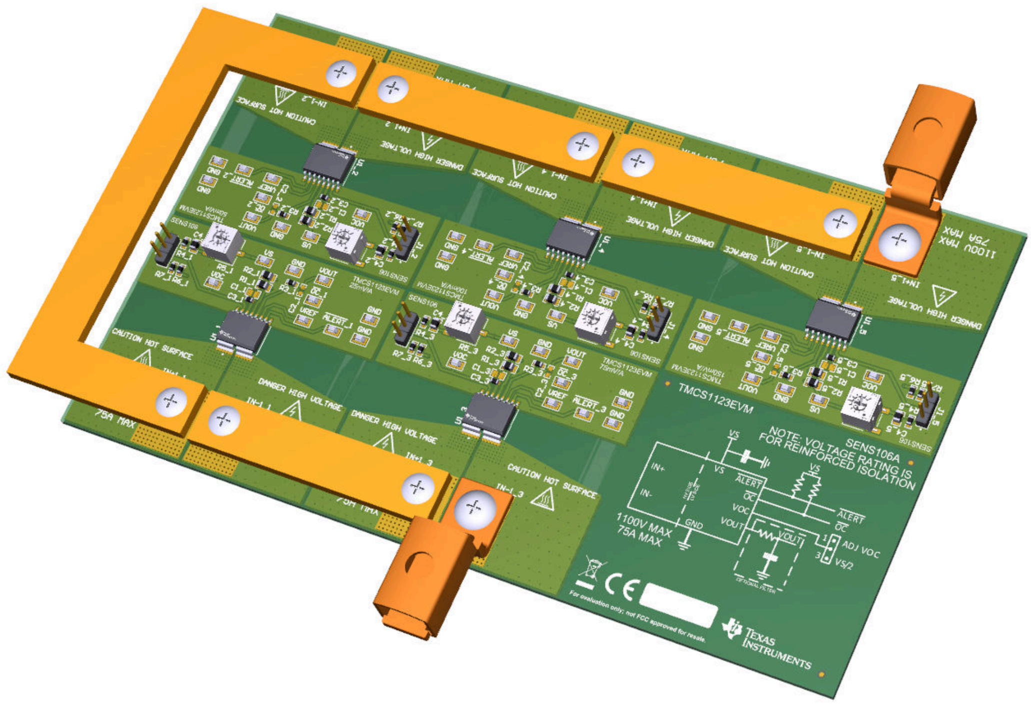

Figure 3-1. TMCS1123EVM, Busbar Configuration

Labview was employed to automate the process, as thermal equilibrium was time consuming to make sure true thermal equilibrium between points. The following steps were performed on each board to capture the below curves:

1. Power on all loads and necessary supplies to energize the test loop.
2. Create a current flow in the DUTs, beginning at 0A, and stepping in increments of 5As per step.
3. Temperature measurements are made in 1 second intervals. Current remains at the given level until residual temperature between measurements is less than 100m°C.
4. Move the next 5A current interval, and repeat steps 2 and 3.
5. Repeat steps 2-4 until one device registers 150°C
6. Reduce the step interval to 250mA per step, building from the largest step achieved in the previous process.
7. Temperature measurements are made in 1 second intervals. Current remains at the given step until residual temperature between measurements is less than 100m°C.
8. Repeat steps 5 and 6 until the first device reaches 165°C
9. Shut down all supplies and deenergize the test loop.

Note that while the same topology of the EVM was used, the addition of series busbars effectively changes the impedance profile of the board, and also creates local heat signatures on the total EVM. This resulted in a reduction of total load each device can manage, but allowed for streamline testing over the full current range. Another observation made during these tests is that thermal efficiency in the connections of the lugs and busbars is paramount, as well as copper plane integrity. Care needs to be taken to make sure that copper is not damaged during assembly, and that connections are tight to make sure as little thermal resistance as possible.

4 Case 1: Copper Weight

The first case examined is device thermal capability with regard to copper weight. For each experimental run, the exact footprint of the TMCS1123 evaluation module was kept intact, and the stack layers were changed to indicated copper weight. Figure 4-1 shows the typical footprint of the TMCS1123EVM. Figure 4-2 through Figure 4-7 show measured data for 1oz through 6oz copper, respectively.

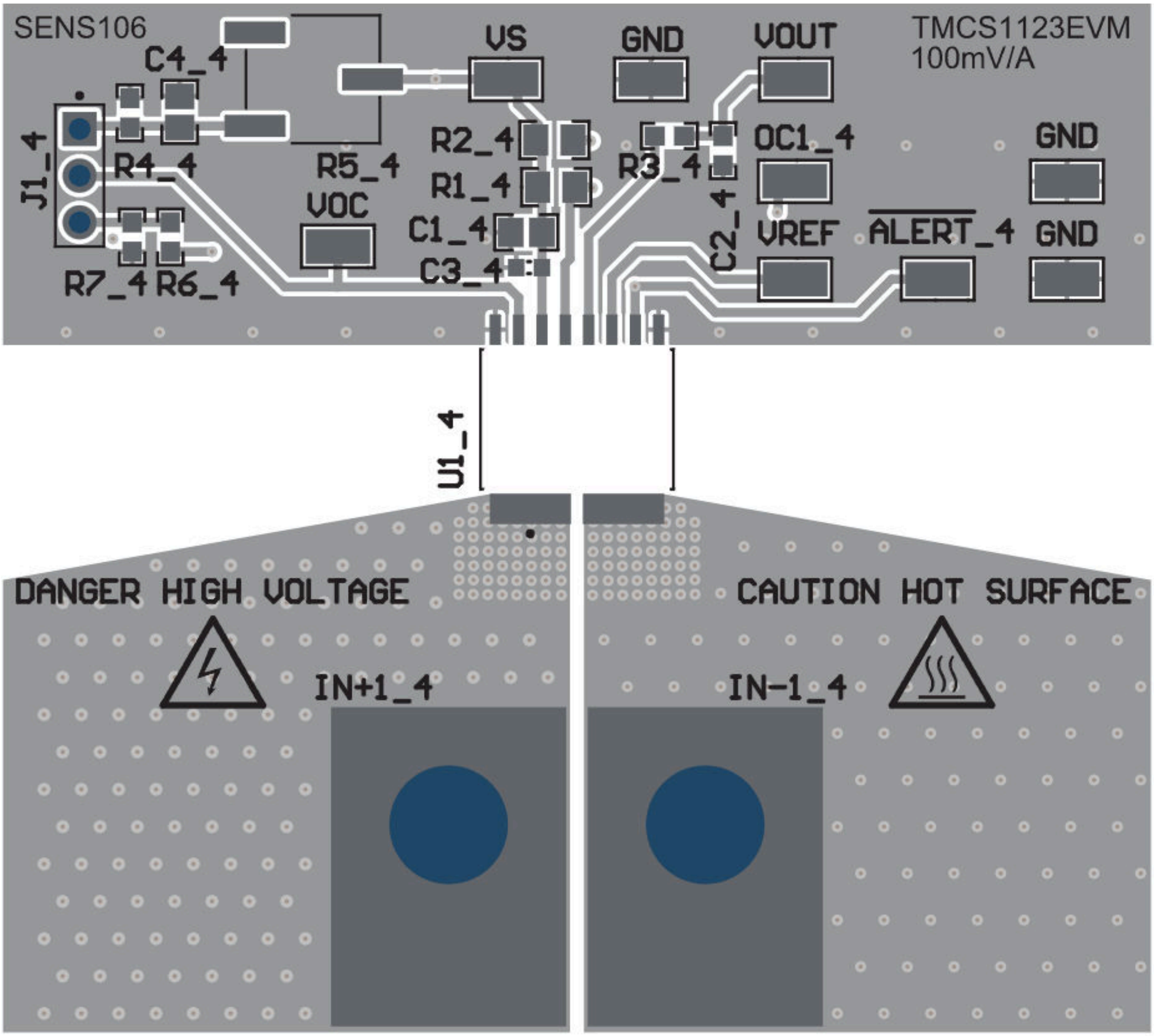

Figure 4-1. TMCS1123EVM Portion, A4 Variant, Sensitivity = 100mV/A

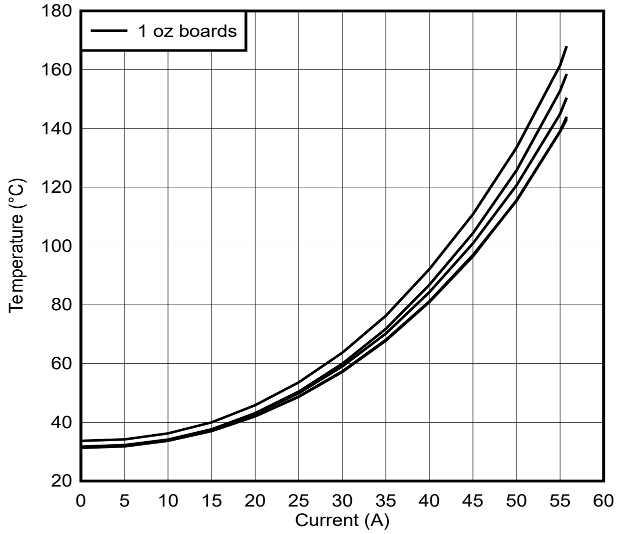

Figure 4-2. TMCS1123EVM Thermal Response Curves for 5 Devices, 1 Oz Copper

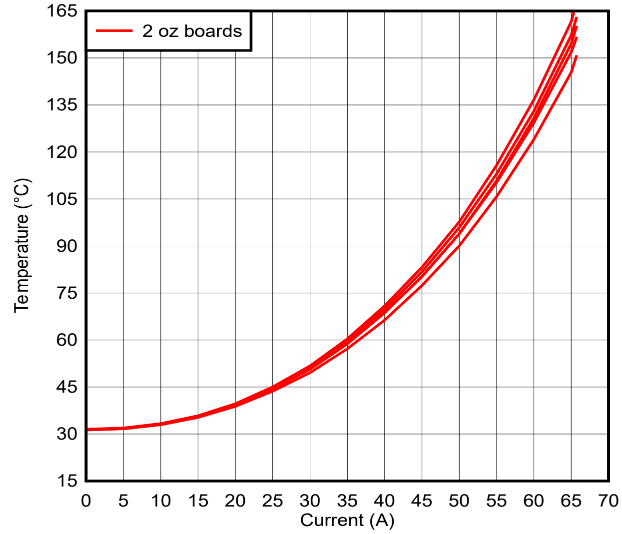

Figure 4-3. TMCS1123EVM Thermal Response Curves for 5 Devices, 2 Oz Copper

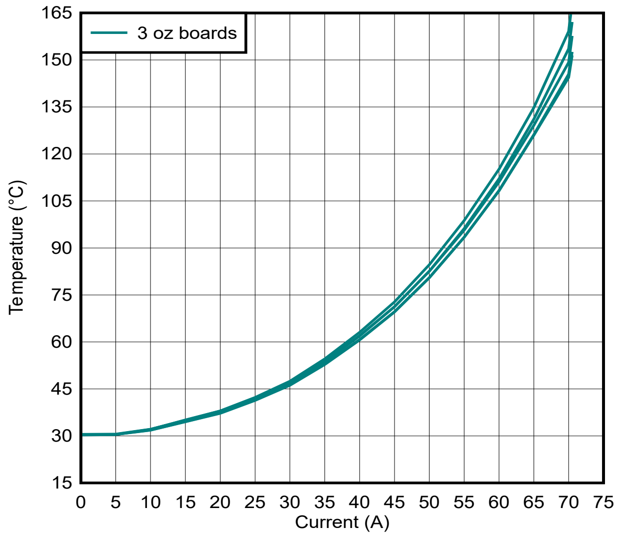

Figure 4-4. TMCS1123EVM Thermal Response Curves for 5 Devices, 3Oz Copper

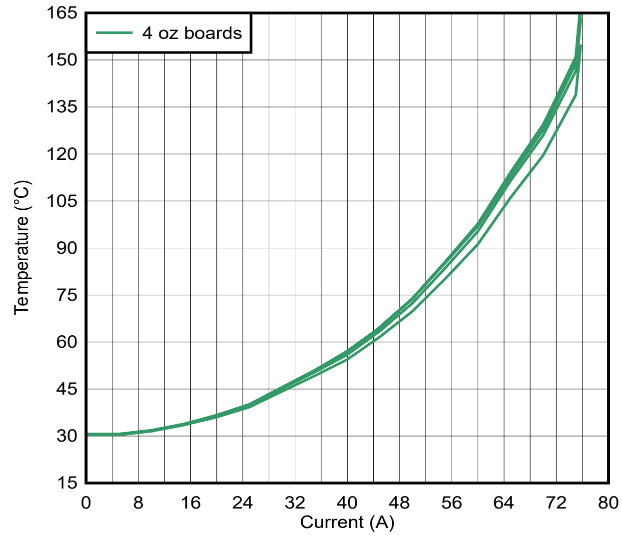

Figure 4-5. TMCS1123EVM Thermal Response Curves for 5 Devices, 4Oz Copper

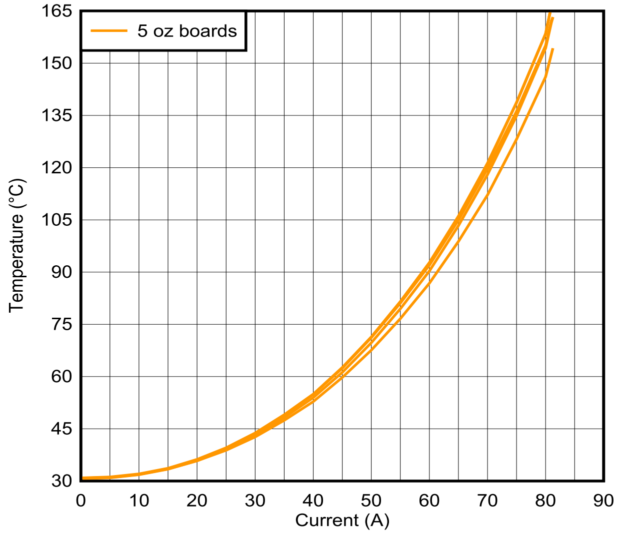

Figure 4-6. TMCS1123EVM Thermal Response Curves for 5 Devices, 5 Oz Copper

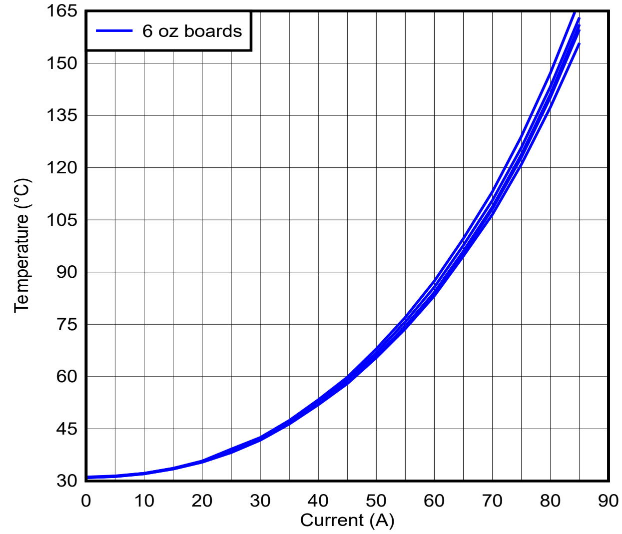

Figure 4-7. TMCS1123EVM Thermal Response Curves for 5 Devices, 6 Oz Copper

Figure 4-8 examines the same curves captured above, and overlays all data on top of one another to examine improvements by weight as current grows.

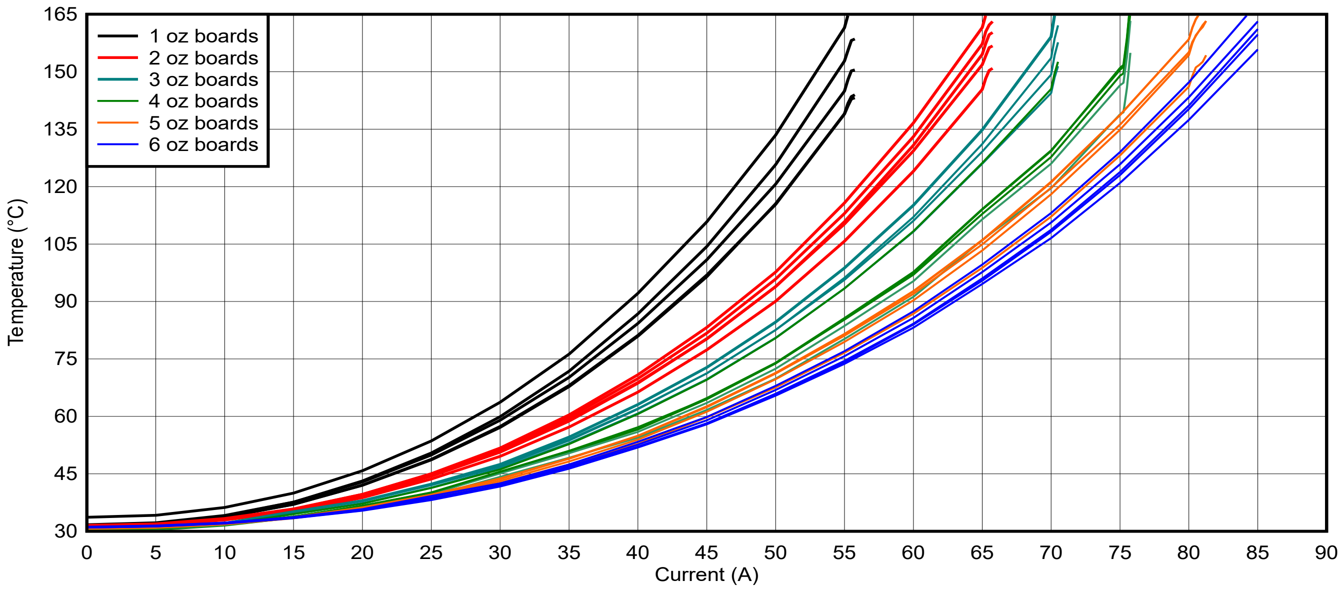

Figure 4-8. TMCS1123EVM Thermal Response Curves for all Copper Weights

From the chart, the following observations can be made:

- A doubling of copper results in roughly the same magnitude improvement, at least at lower thickness levels. From 1oz to 2oz, an approximate 10A improvement from 55A to 65A. At the 4oz mark, move to 75A capability, which is again a 10A improvement, for a doubling from 2oz to 4oz. However, also, the 6oz copper was capable of 85A, which by the same relationship can be expected of 8oz copper.
- At higher copper levels, for example, beyond 4oz, we begin to see diminishing returns in capability. While 6oz is still an improvement over 5oz, and 5oz is an improvement over 4, these curves are much tighter in distribution, with some worst case devices matching best case performance of the next copper weight.
- As stated previously, board manufacturing tolerances and capabilities can change the thermal profile from board to board. As an example, examining the 1oz data shows that at the point the worst performing device reaches 165°C, the best performing device is only at 145°C. As such, it is imperative that sufficient headroom be made in the design to make sure of success in the face of lot to lot variation

5 Case 2: Polygon Sizing

The second case analyzed is a reduction in the polygon size for the same current sweep. From the above, the 4oz copper weight profile serves as the starting point for this experiment, as this is the full 100% of plane topology. Each polygon leading into the EVM is approximately 900mm^2 in terms of PCB area, equating to 1800mm^2 of two 2-layer, 4oz via-stitched planes. From this base calculation, ratios of 40%, 60%, and 80% of this area were calculated, and removed from the PCB while keeping the designed for shape of the PCB polygon pours. Figure 5-1, Figure 5-3, and Figure 5-5 show the topology post copper removal, while Figure 5-2, Figure 5-4, and Figure 5-6 show device performance for the respective ratio.

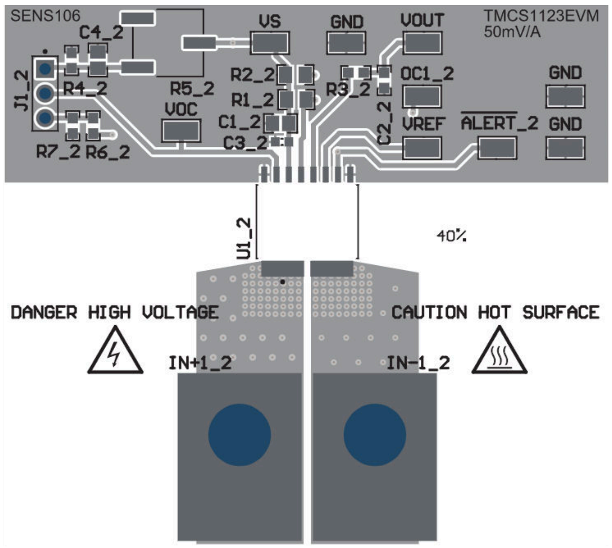

Figure 5-1. TMCS1123EVM, 40 Percent of EVM Plane

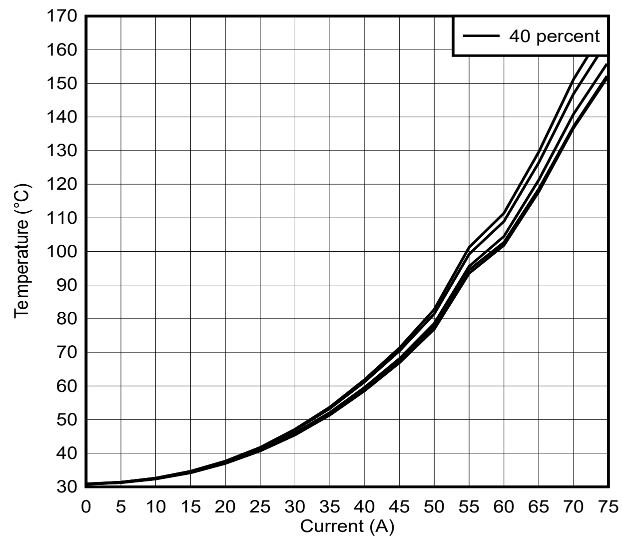

Figure 5-2. TMCS1123EVM Thermal Response Curves for 5 Devices, 40 Percent of EVM Plane

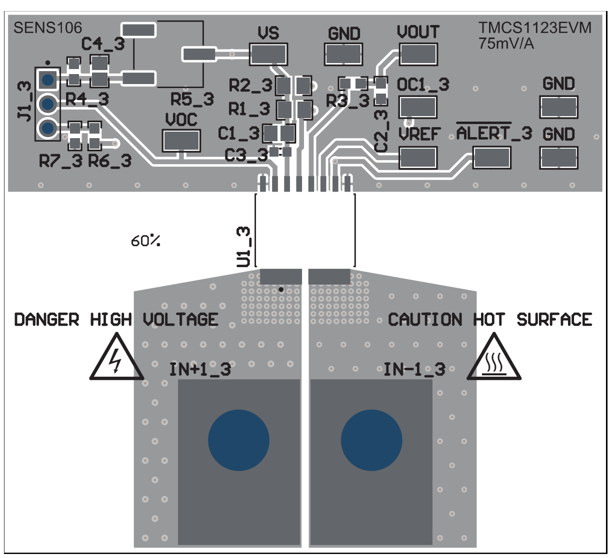

Figure 5-3. TMCS1123EVM, 60 Percent of EVM Plane

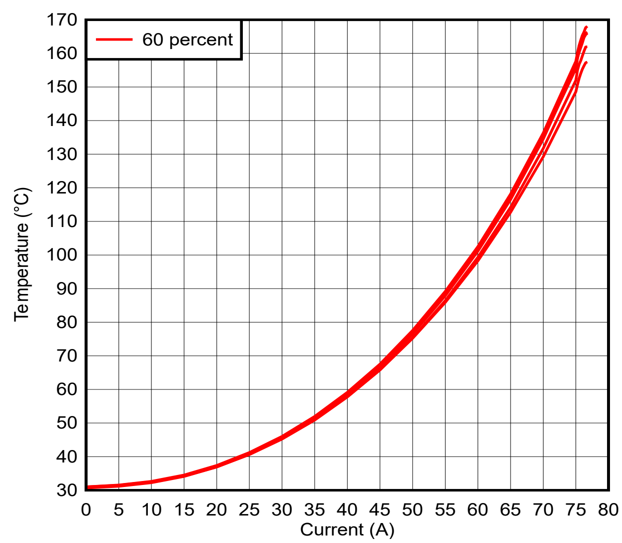

Figure 5-4. TMCS1123EVM Thermal Response Curves for 5 Devices, 60 Percent of EVM Plane

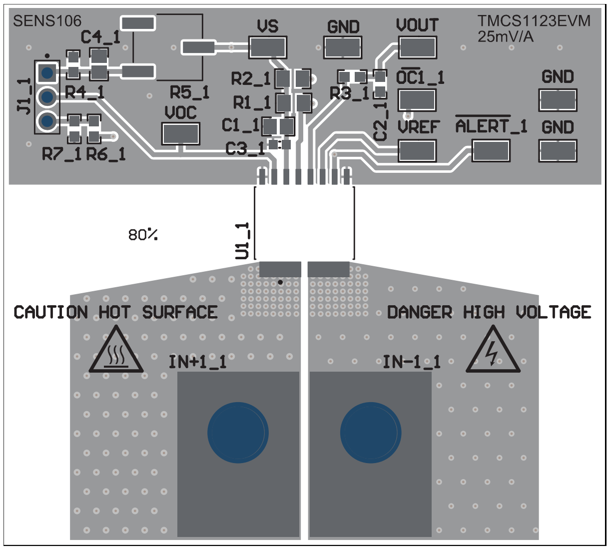

Figure 5-5. TMCS1123EVM, 80 Percent of EVM Plane

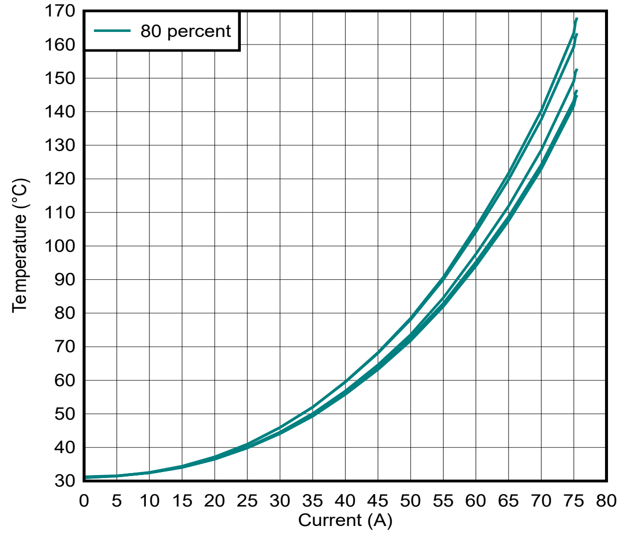

Figure 5-6. TMCS1123EVM Thermal Response Curves for 5 Devices, 80 Percent of EVM Plane

The responses were then once again overlaid to examine behavioral performance over the various percentages in Figure 5-7.

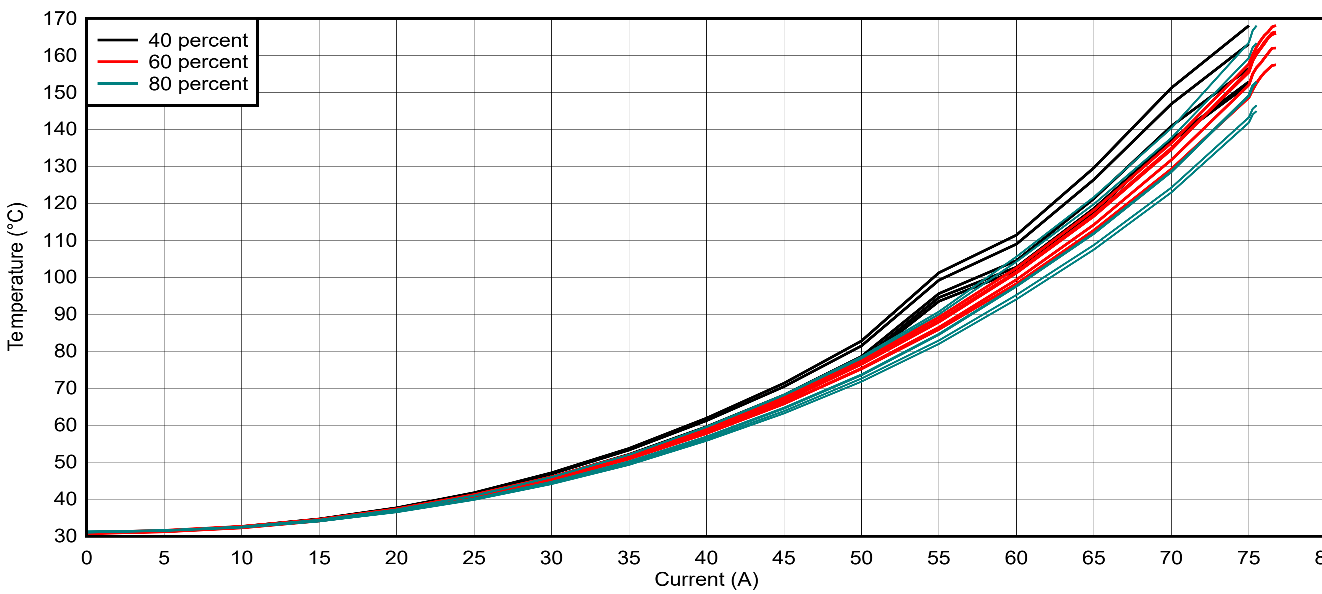

Figure 5-7. TMCS1123EVM Thermal Response Curves for all Copper Sizes

From the chart, draw the following observations:

- While there is marginal improvement due to the polygon sizing, current carrying capability remains roughly equal across all of the polygons
- The 60% polygons were capable of slightly higher current capacity, but this was concluded to be an artifact of the board to board distribution. The expectation is that over additional samples, the true mean of performance does not demonstrate this advantage.
- Again, board manufacturing tolerances and capabilities altered the spread of devices from board.

The final observation here is that while the current capacity is roughly similar in this distribution, thermal response can most likely reach equilibrium more quickly for the smaller polygons over the larger polygons, due to the additional copper and therefore additional time for the total thermal mass to reach an equilibrium point. This effect, however, was not examined during data gathering.

6 Summary

This application note shows a method for assessing thermal performance of in-package magnetic current sensors. Current carrying capability is shown to be enhanced, as expected, by copper weight placed on a PCB. However, polygon sizing was shown to play a much a smaller role in thermal mitigation. Overall, the curves presented in this document can help designers to make informed decisions about the total amount of copper needed for an in-package current sensor for proper steady state operation.

7 References

- Texas Instruments, *TMCS1123 Precision 250kHz Hall-Effect Current Sensor With Reinforced Isolation Working Voltage, Overcurrent Detection and Ambient Field Rejection*, data sheet.