AND9014

Guide to Thermally Enhanced SO8-FL

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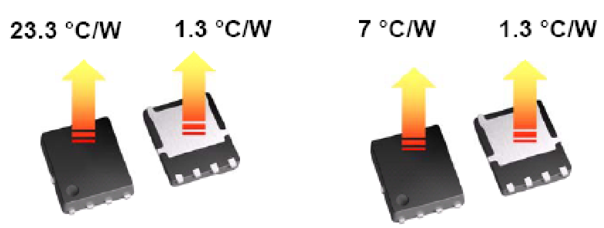
APPLICATION NOTE

Introduction

In today's industry, there is a continuous drive to increase efficiency and power density, and to maximize the performance of power converters. Power MOSFET technology is continually improving, with increased cell density, smaller pitch trench technology, reduced package parasitic properties and smaller footprints. Devices must be able to handle more power and to run cooler in the application. The market is more competitive than ever, with each manufacturer seeking a competitive edge and offering novel solutions to meet the needs of the industry.

The standard 5 mm x 6 mm SO8−FL package is currently one of the most popular power MOSFET packages in the industry, providing better utilization of board space and higher power dissipation. ON Semiconductor has developed a new device called the Thermally Enhanced (TE) SO8−FL that provides lower thermal resistance through the top of the package and therefore provides improved thermal performance, efficiency and power carrying capability. The SO8−FL TE devices have the same footprint and pin−out as the standard 5 mm x 6 mm SO8−FL package, allowing for ease of design−in and manufacturing.



(a) Standard SO8−FL (b) SO8−FL TE

Figure 1. Thermal Resistance through the Top and Bottom of the Package for NTMFS4897NF and NTMFS4825NFE Devices

Figure 1 illustrates the difference in thermal resistance between the standard SO8−FL package and the new SO8−FL TE. The SO8−FL TE mold compound has more than three times the conductivity of the standard mold compound, providing a lower thermal resistance between the die and the top of the package. Adding a heat sink to the top of the SO8−FL TE case allows the heat to dissipate through the top of the package, increasing the power capability of the device.

SO8−FL TE Device Construction

Figure 2 shows the construction of the SO8−FL TE device. As with the standard 5 mm x 6 mm SO8−FL devices, a copper clip is used on the source and the drain pad is directly connected to the Printed Circuit Board (PCB). The new SO8−FL TE utilizes a different mold compound that provides a lower thermal resistance between the die and the top of the package.

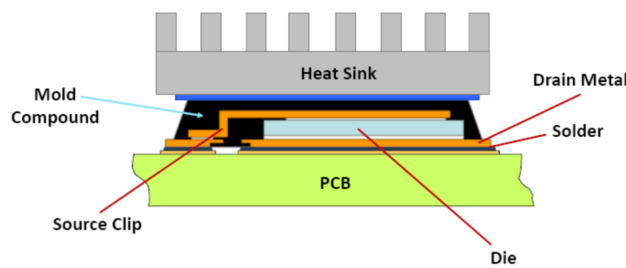


Figure 2. Thermally Enhanced SO8−FL Package Construction

Thermal Resistance

Thermal resistance identifies the effectiveness of heat transfer from one point to another independent of the path taken between the two points, and relates temperature rise and power dissipation (units are °C/W). Thermal resistance is greatly influenced by the materials used in the device construction as well as the size and thickness of any heat sinks or pads that the device is in contact with. For a power MOSFET, materials that influence the thermal resistance include silicon properties, material of the wires or clips connecting the silicon and the lead frame, the mold compound and many other factors. The two most commonly used thermal resistances in Power MOSFET datasheets are the junction−to−ambient thermal resistance, $R_{\theta JA}$ and the junction−to−case thermal resistance, $R_{\theta JC}$. The standard equations for these two thermal resistances are shown below:

$$R_{\theta JA} = \frac{T_J - T_A}{P_d}$$
$$R_{\theta JC} = \frac{T_J - T_C}{P_d} \quad \text{(eq. 1)}$$

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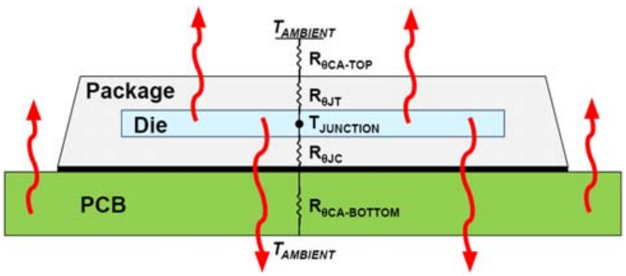
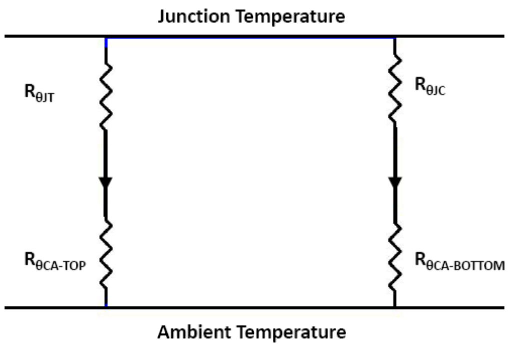
The amount of heat flow between the junction and the ambient is also influenced by the size and thickness of the copper pad that the device package is mounted on, as well as the size and copper thickness and number of layers of the PCB. A simplified thermal resistance model is shown in Figure 3.



(a) Equivalent Thermal Resistance Diagram



(b) Equivalent Thermal Resistance Circuit

Figure 3.

Using the equivalent circuit shown in Figure 3, the total thermal resistance from the junction to the top of the package is $R_{\theta JA-TOP} = R_{\theta JT} + R_{\theta CA-TOP}$. Likewise, the total thermal resistance from the junction to the bottom of the package is $R_{\theta JA-BOTTOM} = R_{\theta JC} + R_{\theta CA-BOTTOM}$. Heat flows in two parallel paths: through the top of the package into ambient air, and through the bottom of the package into the PCB and then into ambient air. The total package thermal resistance, $R_{\theta JA-TOTAL}$, is calculated as the parallel combination of $R_{\theta JA-TOP}$ and $R_{\theta JA-BOTTOM}$:

$$\frac{1}{R_{\theta JA-TOTAL}} = \frac{1}{R_{\theta JA-TOP}} + \frac{1}{R_{\theta JA-BOTTOM}} \qquad \text{(eq. 2)}$$

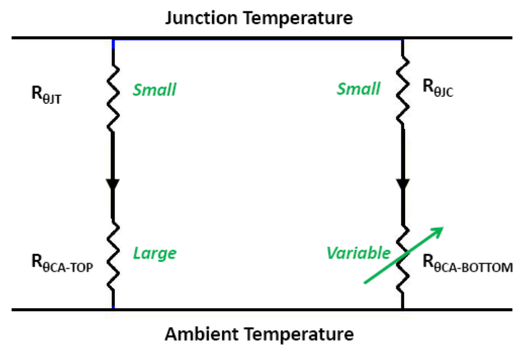
For the standard 5 mm x 6 mm SO8−FL package the thermal resistance $R_{\theta JA-TOP}$ is much higher than $R_{\theta JA-BOTTOM}$. This makes sense when comparing the thermal conductivity of the copper drain and source pads to that of the standard SO8−FL mold compound. The drain and source metal provides a direct connection to the PCB, allowing the majority of the heat to flow through the bottom of the package.

When the $R_{\theta JA-TOP}$ is much larger than the $R_{\theta JA-BOTTOM}$ the term $1 / R_{\theta JA-TOP}$ approaches zero and the majority of the heat is dissipated through the bottom of the package into the PCB and from the PCB into ambient air.

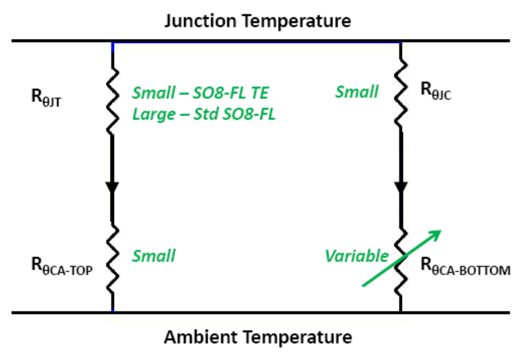
The SO8−FL TE mold compound has 3.5 times higher thermal conductivity compared to the standard SO8−FL mold compound. This greatly reduces the total thermal resistance $R_{\theta JA-TOP}$ providing a usable path for the heat to flow from the die through the top of the package.

SO8−FL TE Guideline for Applications

The following general analysis illustrates when it is beneficial to use the SO8−FL TE rather than the standard SO8−FL.



(a) No Airflow, No Heat Sink



(b) With Heat Sink and Air Flow

Figure 4.

Figure 4(a) shows the equivalent resistance circuit in still air without a heat sink. The total top thermal resistance $R_{\theta JA-TOP}$ is dominated by $R_{\theta CA-TOP}$, as the thermal conductivity of still air is very small. Therefore $R_{\theta JA-TOP} \gg R_{\theta JA-BOTTOM}$, the term $1/(R_{\theta JA-TOP})$ approaches zero (Equation 3) and the majority of the heat dissipates through the bottom of the device (Equation 4). In this case, SO8−FL TE provides little advantage over the standard SO8−FL.

$$\frac{1}{R_{\theta JA-TOTAL}} = \underbrace{\frac{1}{R_{\theta JA-TOP}}}_{\to 0} + \frac{1}{R_{\theta JA-BOTTOM}} \qquad \text{(eq. 3)}$$

$$\frac{1}{R_{\theta JA-TOTAL}} \approx \frac{1}{R_{\theta JA-BOTTOM}} \qquad \text{(eq. 4)}$$

Figure 4(b) shows the equivalent resistance circuit when a heat sink and airflow are both present. In this case $R_{\theta CA-TOP}$ is small and $R_{\theta JA-TOP}$ is comparable to $R_{\theta JA-BOTTOM}$. The SO8−FL TE gives the greatest thermal and efficiency performance benefits when combined with a top−side heat sink and air flow, as the total thermal resistance through the top of the package is greatly reduced compared with the example of Figure 4(a).

$R_{\theta CA-BOTTOM}$ can vary greatly depending on the copper weight, the size of the PCB and the number of layers. When a multi−layer board is used, heat dissipation through the PCB becomes much easier, and $R_{\theta JA-BOTTOM}$ is much lower than $R_{\theta JA-TOP}$. Under these conditions, the primary heat dissipation path is through the bottom of the device, and SO8−FL TE will provide little advantage over the standard SO8−FL (refer to Equations 3 and 4). However, when the PCB has limited copper it becomes much more difficult for heat to dissipate through the PCB. In this case $R_{\theta CA-BOTTOM}$ is relatively large and the $R_{\theta CA-TOP}$ has a significant influence in the total heat dissipation of the device. Therefore, SO8−FL TE has an advantage over the standard SO8−FL in applications where the amount of heat dissipated through the PCB is limited due to the PCB design and the size of the drain and source pads on the PCB.

Figure 5 below shows the equivalent resistance circuit of the SO8−FL TE device when used with a heat sink. $R_{\theta CA-TOP}$ now includes the thermal resistance of the interface material used between the device package and the heat sink. An interface material is necessary because the two surfaces are not perfectly smooth. Surface roughness creates small air gaps between the two surfaces, impeding heat flow from the package to the heat sink. The interface material fills in the air gaps. The two most common interface materials used are thermal pads and thermal grease.

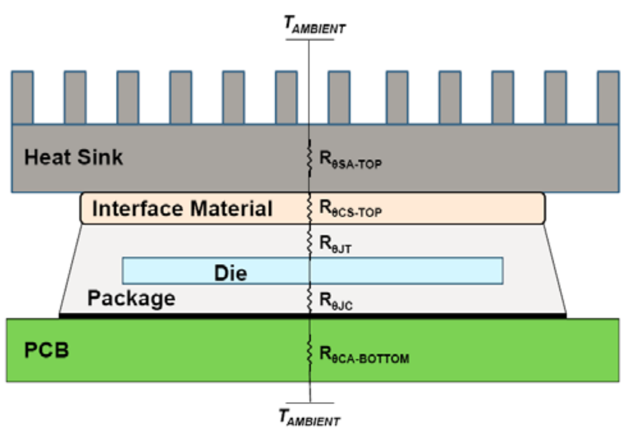


Figure 5. SO8−FL TE Equivalent Resistance Diagram with Heat Sink

With the addition of the heat sink , $R_{\theta JA-TOP}$ is now the sum of the resistances $R_{\theta JT} + R_{\theta CS-TOP} + R_{\theta SA-TOP}$, as shown in Equation 5 below. The junction−to−case thermal resistance $R_{\theta JT}$ is a property of the MOSFET. The case−to−heat−sink thermal resistance $R_{\theta CS-TOP}$ is the resistance of the interface material (thermal grease, thermal pad, isolation pad). $R_{\theta SA-TOP}$ is the thermal resistance between the heat sink and the ambient air. Equation 2 is restated here as Equation 6.

$$R_{\theta JA,TOP} = R_{\theta JT} + R_{\theta CS-TOP} + R_{\theta SA-TOP} \ (°C/W) \quad \text{(eq. 5)}$$

$$\frac{1}{R_{\theta JA-TOTAL}} = \frac{1}{R_{\theta JA-TOP}} + \frac{1}{R_{\theta JA-BOTTOM}} \quad \text{(eq. 6)}$$

Device Construction: SO8−FL TE vs. Metal Top Design

How does the Thermally Enhanced SO8−FL differ from other products in the market? The SO8−FL TE device uses a mold compound with greater thermal conductivity in order to lower the thermal resistance from junction to ambient through the top of the package. An alternative solution uses a metal slug attached directly to the source of the MOSFET that is an exposed pad on the top of the device. The metal slug allows the device to have lower $R_{\theta JT}$ than the TE SO8−FL. However, there are some disadvantages to this approach.

Because the metal slug on the top of the case is electrically connected to the die source, there is no electrical isolation between the top of the package and the die. For switching applications and applications in which a heat sink is used, manufacturers of the metal top devices recommend using an isolation interface material that is placed between the top of the package and the heat sink. One example is the GP1500 isolation pad, which has a thickness of 20 mils and an $R_{\theta JA}$ of approximately 11 °C/W for a 30 mm^2 pad area.

Due to the necessity of obtaining isolation through the interface material, the total thermal resistance from junction to the heat sink, $R_{\theta JS-TOP}$, of the metal top device is the sum of the device thermal resistance $R_{\theta JT}$ and the isolation pad thermal resistance $R_{\theta CS-TOP}$ (refer to Equation 5). For a metal top device with $R_{\theta JT}$ = 4.4 °C/W, the thermal resistance $R_{\theta JS-TOP}$ = 4.4 °C/W + 11 °C/W = 15.4 °C/W when using the GP1500 isolation pad. Even if isolation is not required for the application, a thermal pad should be placed between the heat sink and the exposed pad of the metal top device in order to alleviate mechanical stress on the die caused by the heat sink attachment and to reduce the transmission of the switching noise from the heat sink.

The SO8−FL TE does not require an isolation pad, as the die is electrically isolated from the top of the package. As a result, alternative interface materials can be used. Thermal grease offers the best thermal performance of the thermal interface materials available, as the grease fills in all the air gaps and creates an extremely thin surface between the package and the heat sink, resulting in a negligibly low thermal resistance. Therefore, for SO8−FL TE, the total thermal resistance $R_{\theta JS-TOP}$ is simply the device thermal resistance $R_{\theta JT}$. For the NTMFS4923NE device, the thermal resistance $R_{\theta JS-TOP}$ = 8.3 °C/W. The results of Experiment 2 illustrate the performance of SO8−FL TE with thermal grease.

When selecting heat sinks, additional factors must be considered for metal top devices that can be disregarded for SO8−FL TE. Since the SO8−FL TE is electrically isolated, a single heat sink can be used for both the high side and low side MOSFETs in a single−phase DC−DC application; furthermore a single heat sink can be used for all phases in a multi−phase DC−DC application. Due to the direct connection between the metal slug and the source in the metal top devices, separate heat sinks must be used for the high side and low side MOSFETs unless an isolation interface material is used when connecting the heat sink to the top of the case. As illustrated in the above example, however, this will reduce the effectiveness of cooling.

Experiment 1: Standard SO8−FL vs. Thermally Enhanced S08FL

The ON Semiconductor standard SO8−FL and SO8−FL TE devices were tested on a 61 mm x 55 mm single−layer 1 oz PCB using a minimum size drain pad. Each device was tested under four different conditions in a wind tunnel in order to measure the impact to the junction temperature and total power dissipation. The NTMFS4935N and NTMFS4923NE devices were selected for this experiment, as they have the same die. Table 1 shows the device parameters of the standard SO8−FL and the SO8−FL TE.

Table 1. DATASHEET PARAMETERS OF NTMFS4935N AND NTMFS4923NE

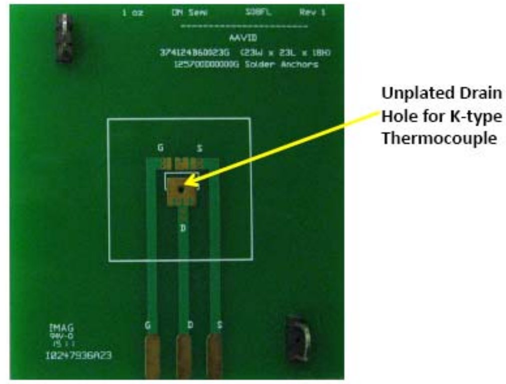
Device	$R_{\theta JC,TOP}$ (°C/W)	Typical	
		$R_{DS(ON)}$ at 4.5 V (mΩ)	$R_{DS(ON)}$ at 10 V (mΩ)
NTMFS4935N (Standard SO8−FL)	27.8	3.7	2.7
NTMFS4923NE (SO8−FL TE)	8.3	3.7	2.7

The 23 mm x 23 mm x 18 mm Aavid Thermalloy #374124B60023G heat sink was used in this experiment. The Chomerics T766 Phase Change Pad was removed, and each device was tested using Wakefield Engineering thermal grease #120−5. The four test conditions used for this experiment are shown in Table 2.

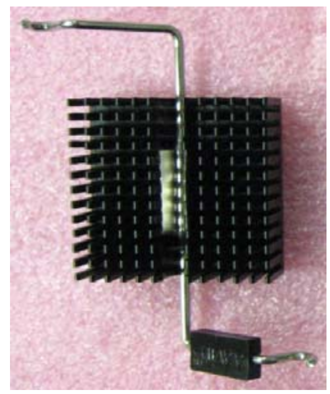
A 36−gauge K−Type thermocouple was attached to the center of the drain pad of the device through an unplated via in order to measure the device temperature. Figure 6 shows the board and the thermocouple placement.

Table 2. EXPERIMENT CONDITIONS TESTED FOR STANDARD VS. SO8−FL TE

Test Case	Air Flow	Heat Sink
1	None	None
2	None	Aavid Part # 374124B60023G
3	200 LFM	None
4	200 LFM	Aavid Part # 374124B60023G



(a) Single−Layer 1 oz Cu Board



(b): Aavid Thermalloy Heat Sink #374124B60023G

Figure 6.

The MOSFET body diode was used to heat up the die. A constant current load was applied for 10 minutes before the thermocouple reading and forward diode voltage were recorded (see Figure 7). The total power dissipation was calculated using the forward drop of the diode and the current applied.

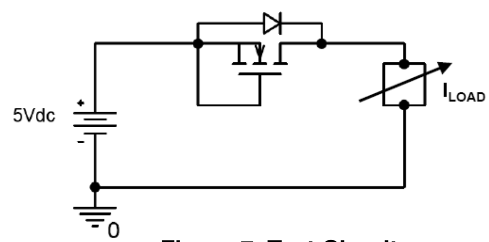


Figure 7. Test Circuit

The device temperature was measured in each test, and the power dissipation was calculated. As seen in Figure 8, the SO8−FL TE had a lower junction temperature at a given power. This advantage became more prevalent as air flow and heat sink were added.

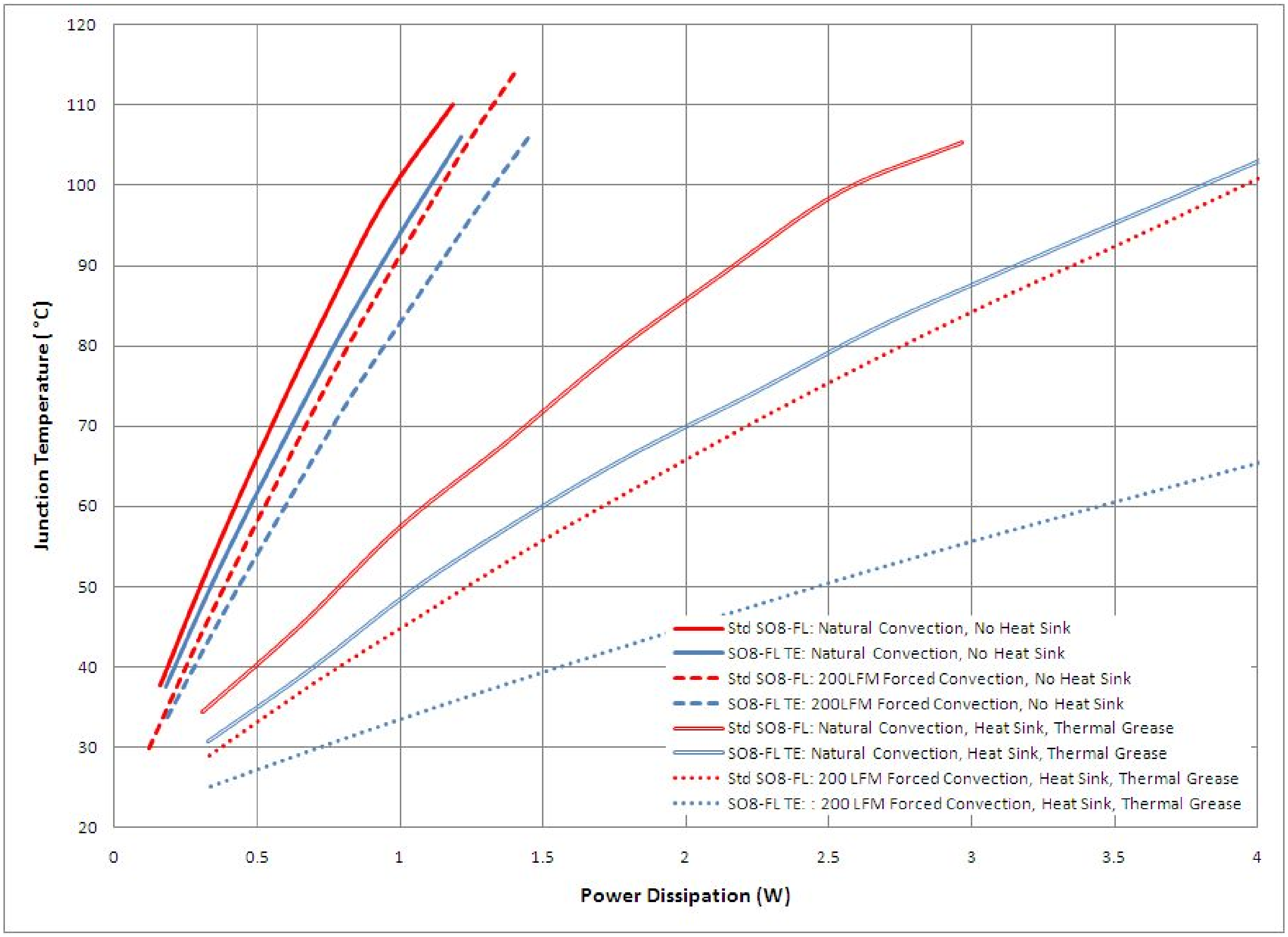
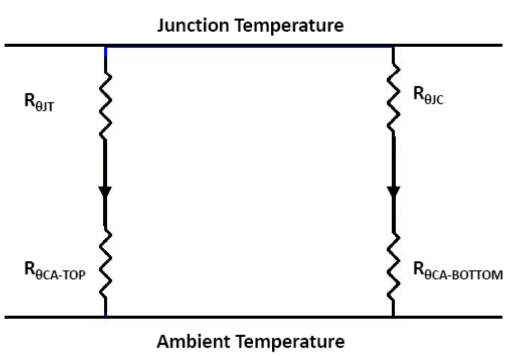


Figure 8. Junction Temperature vs. Power Dissipation for the NTMFS4935N Standard SO8−FL and NTMFS4923NE SO8−FL TE Devices

In the case of natural convection and no heat sink, the total top thermal resistance $R_{\theta JA-TOP}$ is much larger than $R_{\theta JA-BOTTOM}$, causing the heat to flow primarily through the bottom of the package to the PCB and ambient. Under these conditions, the SO8−FL TE performance is only slightly better than the Standard SO8−FL because its $R_{\theta JT}$ is lower than the Standard SO8−FL $R_{\theta JT}$.



$$\frac{1}{R_{\theta JA-TOTAL}} = \frac{1}{R_{\theta JA-TOP}} + \frac{1}{R_{\theta JA-BOTTOM}}$$

Figure 9. Equivalent Thermal Resistance Circuit

In the case of 200 LFM of forced convection and no heat sink, the thermal resistance $R_{\theta CA-TOP}$ is reduced, giving more influence of the heat dissipation path to the $R_{\theta JT}$. This means that when the SO8−FL TE is used (much smaller $R_{\theta JT}$) more heat will flow through the top of the package than with the standard SO8−FL.

In the case of heat sink in natural convection, the $R_{\theta CA-TOP}$ is reduced even further. The Aavid Thermalloy # 374124B60023G heat sink has a thermal resistance of 23.4 °C/W in natural convection. As seen in Figure 8, the difference between the standard and TE SO8−FL curves is even larger than for the previous two cases.

Finally, when a heat sink and 200 LFM of forced convection are both present, the $R_{\theta CA-TOP}$ becomes very small, and $R_{\theta JT}$ (parameter of the MOSFET) has a significant effect. The Aavid Thermalloy # 374124B60023G heat sink has a thermal resistance of 7.39 °C/W for 200 LFM air flow. The performance improvement of the SO8−FL TE is the most pronounced for this case.

Experiment 2: Thermally Enhanced S08FL vs. Metal Top Device

The ON Semiconductor SO8−FL TE and a metal top device were tested on a 61 mm x 55 mm single−layer 1 oz PCB using a minimum size drain pad. Each device was tested under four different conditions in a wind tunnel in order to measure the impact to the junction temperature and total power dissipation. The NTMFS4923NE and a metal top device with similar $R_{DS(ON)}$ datasheet specifications were selected for this experiment. Table 3 shows the device parameters of the SO8−FL TE and the metal top devices.

Table 3. DATASHEET PARAMETERS OF NTMFS4923NE AND A METAL TOP DEVICE

Device	$R_{\theta JC,TOP}$ (°C/W)	Typical	
		$R_{DS(ON)}$ at 4.5 V (mΩ)	$R_{DS(ON)}$ at 10 V (mΩ)
NTMFS4923NE	8.3	3.7	2.7
Metal Top Device	4.4	3.4	2.4

The 23 mm x 23 mm x 18 mm Aavid Thermalloy #374124B60023G heat sink was used in this experiment. The Chomerics T766 Phase Change Pad was used as the interface material between the heat sink and the device package. An additional test was then run for the SO8−FL TE using Wakefield Engineering thermal grease #120−5 instead of the Phase Change Pad. The four test conditions used for this experiment are shown in Table 4.

Table 4. EXPERIMENT CONDITIONS TESTED FOR SO8−FL TE VS. METAL TOP DEVICE

Test Case	Air Flow	Heat Sink
1	None	None
2	None	Aavid Part # 374124B60023G
3	200 LFM	None
4	200 LFM	Aavid Part # 374124B60023G

The device temperature was measured in each test, and the power dissipation was calculated. As seen in Figure 10, the SO8−FL TE combined with thermal grease had a lower junction temperature at a given power than the metal top design. This advantage became more prevalent as air flow and heat sink were added.

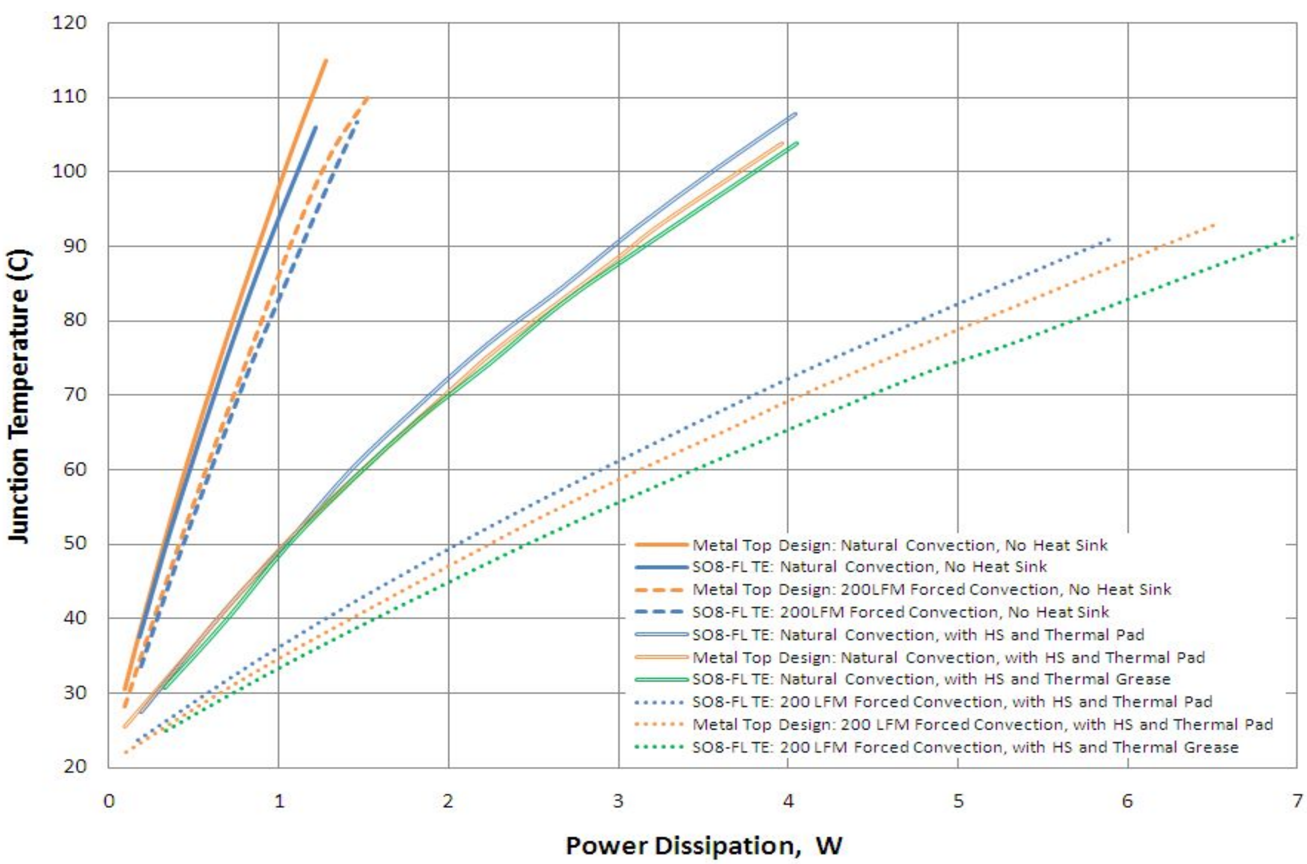


Figure 10. Junction Temperature vs. Power Dissipation for the SO8−FL TE and Metal Top Devices

When a heat sink was not used, the SO8−FL TE performed similarly to the metal top device. In this case, the total top thermal resistance $R_{\theta JA-TOP}$ is much larger than $R_{\theta JA-BOTTOM}$ and has a very small effect on the total thermal resistance $R_{\theta JA-TOTAL}$.

In the case of heat sink in natural convection, the $R_{\theta CA-TOP}$ is significantly reduced. The Aavid Thermalloy # 374124B60023G heat sink has a thermal resistance of 23.4 °C/W in natural convection. The SO8−FL TE combined with thermal grease performed better than the metal top device under these conditions. Referring back to Equation 5, the thermal resistance $R_{\theta JA-TOP}$ is the sum of the resistances $R_{\theta JT} + R_{\theta CS-TOP} + R_{\theta SA-TOP}$. As was shown in the section "Device Construction: SO8−FL TE vs. Metal Top Design" the thermal resistance of the interface material plays a significant role. Thermal grease offers the best thermal performance of the thermal interface materials available, as the grease fills in all the air gaps and creates an extremely thin surface between the package and the heat sink, resulting in a very low thermal resistance. As a result the $R_{\theta CS-TOP}$ is greatly reduced by using thermal grease instead of a thermal pad as the interface material.

Finally, when a heat sink and 200 LFM of forced convection are both present, the $R_{\theta CA,TOP}$ becomes very small, and has a significant effect. The Aavid Thermalloy # 374124B60023G heat sink has a thermal resistance of 7.39 °C/W in 200 LFM air flow. For this case, the performance improvement of the SO8−FL TE combined with thermal grease is the most pronounced.

Experiment 3: SO8−FL TE in a Synchronous Buck Converter

The previous experiments provided insights into the influences of air flow, heat sinks and a reduced junction−to−case thermal resistance through the top of the MOSFET package. The on resistance $R_{DS(ON)}$ is a function of temperature. As the device heats up its $R_{DS(ON)}$ increases, causing a decrease in efficiency. The results of the previous experiments illustrated that the SO8−FL TE runs cooler than the standard SO8−FL when air flow, a heat sink or both are present. In the practical application of a synchronous buck converter, this translates to lower $R_{DS(ON)}$, and therefore an efficiency improvement.

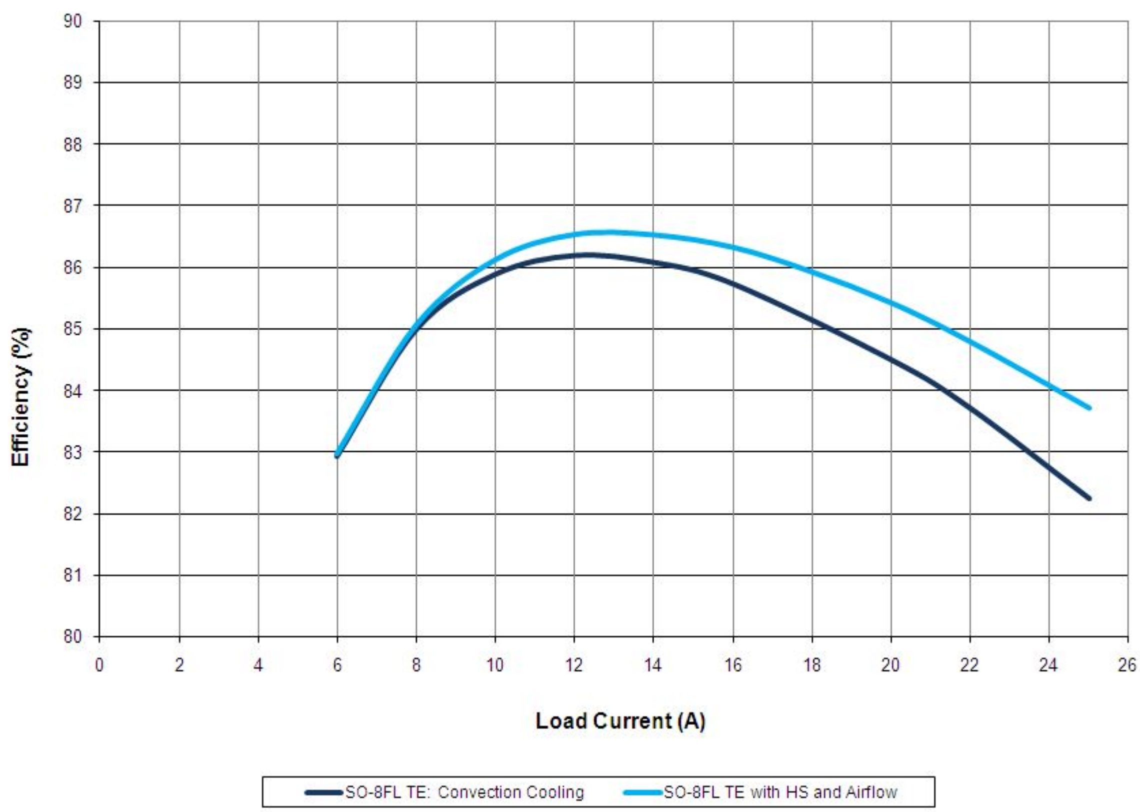


Figure 11. NTMFS4923NE x NTMFS4825NFE Efficiency in a Synchronous Buck Converter for 12 V Input Voltage, 1.2 V Output Voltage, 600 kHz Switching Frequency

Thermally Enhanced SO8−FL performance was tested in a single phase synchronous buck converter. The NTMFS4923NE was selected for the high side MOSFET and the NTMFS4825NFE was selected for the low side MOSFET. Figure 11 shows the efficiency performance of a Thermally Enhanced SO8−FL combination in a practical application. As expected, the efficiency increases when a heat sink and air flow are applied.

Conclusion

The Thermally Enhanced (TE) SO8−FL has improved the thermal resistance through the top of the package providing a parallel path for heat to flow. Experiments were conducted to examine the impact of the improved thermal resistance on the junction temperature and total power dissipation of the device under various air flow and heat sink conditions. The results confirmed the reduction of junction temperature and increase of power dissipation for the SO8−FL TE over the standard SO8−FL. This can be translated into practical applications, providing increased efficiency and reliability.

The SO8−FL TE has the greatest performance advantage when combined with a heat sink and air flow. In applications where the amount of heat dissipated through the PCB is limited by the PCB design (number of layers, copper thickness, size of the device foot print) the SO8−FL TE can provide a significant performance improvement over the standard SO8−FL.

The SO8−FL TE was compared with the metal top device. The SO8−FL TE die is electrically isolated from the top of the package, while the metal top device is not. Therefore, a metal top device must use an isolation pad between the package and the heat sink in order to create isolation between the die and the heat sink and to reduce the transmission of switching noise through the heat sink. The SO8−FL TE does not require an isolation pad. For this reason, thermal grease can be used as the interface material between the package and the heat sink. The SO8−FL TE outperformed the metal top device when it was combined with a heat sink and thermal grease.

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