Application Note

Understanding SOA Curves to Operate at High Output Currents and Temperature

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ABSTRACT

The ongoing trend to smaller solution sizes of power supplies demands an increased understanding of good thermal management. This trend has also raised the popularity of power modules. Typically, a buck power module integrates the main power dissipating elements – the power switches and magnetics – all into one package which enables smaller solution sizes and simplifies the development. Therefore, in addition to the IC losses, the heat generated from the inductor's direct current resistance (DCR) and core losses add to the total power dissipated in the package. Under the same operating conditions as their discrete counterparts (which have an external inductor), the module has the challenge of dissipating more heat through a smaller surface area. Since there are limitations in maximum temperature ratings for both the inductor and IC, there is a constraint on the maximum output current that modules can deliver at higher operating ambient temperatures.

Questions for example, *Can the power solution deliver the desired load current, without exceeding its maximum recommended temperature?* or *How much safety margin does the application have, while operating at its maximum temperature?* are common. Evaluating the thermal performance of the power module by understanding the SOA curves in the data sheet could be a solution to these challenges.

This application note discusses the main thermal metrics $R_{\theta JA}$, Ψ_{JB}, and Ψ_{JT} and introduces SOA curves to understand the thermal performance and output current capability of power modules, to operate them within their recommended temperature limits.

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1 Understanding Different Thermal Metrics

Texas Instruments data sheets provide numerous thermal values to quantify the thermal performance of a particular device. The most commonly used thermal values for power modules are $R_{\theta JA}$, Ψ_{JB}, and Ψ_{JT}. Their basic usage for assessing power modules is described below, while Semiconductor and IC Package Thermal Metrics explains the different thermal metrics in detail.

Equation 1 uses $R_{\theta JA}$ to calculate the rise in the device's temperature (its junction temperature) from a fixed ambient temperature with a given power loss. This equation and thermal value are used when the application's ambient temperature is controlled.

$$T_J = T_A + \left(R_{\theta JA} \times Power\ Loss\right) \tag{1}$$

Equation 2 uses Ψ_{JB} to calculate the rise in the device's temperature from a fixed PCB temperature with a given power loss. This equation and thermal value are used when the application's PCB temperature is controlled. Even though all of the device's power loss does not go into the PCB, the Ψ_{JB} value accounts for this (as opposed to the $R_{\theta JB}$ value) and results in the simple equation.

$$T_J = T_{PCB} + \left(\Psi_{JB} \times Power\ Loss\right) \tag{2}$$

Equation 3 uses Ψ_{JT} to calculate the rise in the device's temperature from the temperature on the top of its case, as measured by a thermal camera for example. This equation and thermal value are used to determine the junction temperature from a measurement of the case temperature. Even though all of the device's power loss does not go up through the top of the case, the Ψ_{JT} value accounts for this (as opposed to the $R_{\theta JC\ (top)}$ value) and results in the simple equation.

$$T_J = T_{case\_top} + \left(\Psi_{JT} \times Power\ Loss\right) \tag{3}$$

The thermal performance not only depends on the device itself, but also on the PCB on which it is routed. The power module's data sheet sometimes gives two sets of thermal values: one for a standard JEDEC PCB and one for the EVM. Unlike the standard JEDEC PCB, the EVM incorporates design techniques to better allow the PCB to work together with the power module to improve the thermal performance. These techniques are discussed in Section 4.

Figure 1-1 shows these three thermal values, from both the JEDEC PCB and the EVM, for a 6-A power module TPSM82866A.

THERMAL METRIC[1]		TPSM8286xA JEDEC 51-5 23 PINS	TPSM8286xA EVM 23 PINS	UNIT
$R_{\theta JA}$	Junction-to-ambient thermal resistance	43.3	25.4	°C/W
$R_{\theta JC(top)}$	Junction-to-case (top) thermal resistance	34.3	n/a[2]	°C/W
$R_{\theta JB}$	Junction-to-board thermal resistance	10.8	n/a[2]	°C/W
Ψ_{JT}	Junction-to-top characterization parameter	3.6	2.4	°C/W
Ψ_{JB}	Junction-to-board characterization parameter	10.7	10.9	°C/W

Figure 1-1. Different Thermal Metrics

2 Understanding SOA Curves

Figure 2-1 shows a Safe Operating Area (SOA) curve for the same TPSM82866A power module. SOA curves show the maximum recommended temperature versus load current, as a quick aid to check if a device is thermally suitable for a given application. This particular curve uses the ambient temperature and the EVM's $R_{\theta JA}$ value to determine the Safe Operating Area. Using these two values, combined with the power loss at each operating point, Equation 1 creates the boundary lines in the SOA curve. The top of the curve at 6 A reflects the recommended maximum output current due to the device's rated current, while the sloped portion of the line reflects the recommended maximum output current due to the power losses, and resulting temperature rise, at that operating point. Operate below the lines to keep the device within its rated junction temperature.

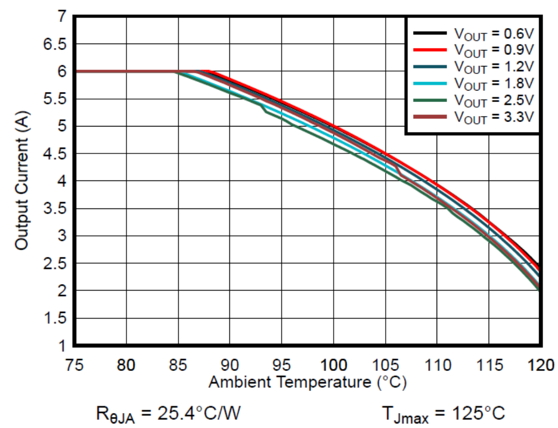

Figure 2-1. Safe Operating Area (SOA) Curve

Table 2-1 shows two operating conditions for powering an SoC with an input voltage of 5 V and output voltage of 1.2 V. Figure 2-2 demonstrates that the first operating condition (red dot) is outside of the SOA curve, at the elevated ambient temperature. The second operating condition (blue dot) shows one solution to operate within the SOA curve: lower the output current.

Table 2-1. Operating Conditions Example

Operating Condition 1	Operating Condition 2
Ambient temperature: 95°C	Ambient temperature: 95°C
Output current: 6 A	Output current: 5 A
Not recommended	Recommended

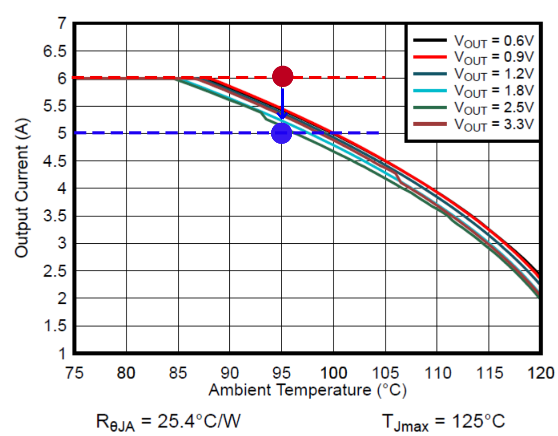

Figure 2-2. SOA Curve Showing Different Operating Conditions

One way to reduce the output current is to reduce the processing speed of the SoC. Another solution to operate within the SOA curve would be to reduce the maximum ambient temperature or to reduce the $R_{\theta JA}$ by adding airflow to the system.

3 How to Create the SOA Curve

The SOA curves are usually created from measured efficiency data on the EVM. From Equation 1, the power loss at various ambient temperatures creates the temperature rise required to reach the power module's maximum operating temperature of 125°C.

Equation 4 calculates the power loss from the data sheet's efficiency curves:

$$Power\ Loss = (Vout * Iout)*(1/\eta - 1) \quad (4)$$

Because efficiency at high loads decreases with increasing temperature, the efficiency values at an elevated temperature (such as 85°C) are used. As an example, Figure 3-1 shows the efficiency curve at 85°C for the same 5 V_{in} and 1.2 V_{out} condition. At 5.5 A load with nearly 84% efficiency, Equation 4 calculates the power loss as 1.25 W. Multiplying by the 25.4 °C/W $R_{\theta JA}$ value gives a temperature rise of 32°C. Subtracting this from the 125°C maximum temperature results in a maximum ambient temperature of 93°C. Thus, the SOA curve in Figure 2-1 crosses 5.5 A near 93°C.

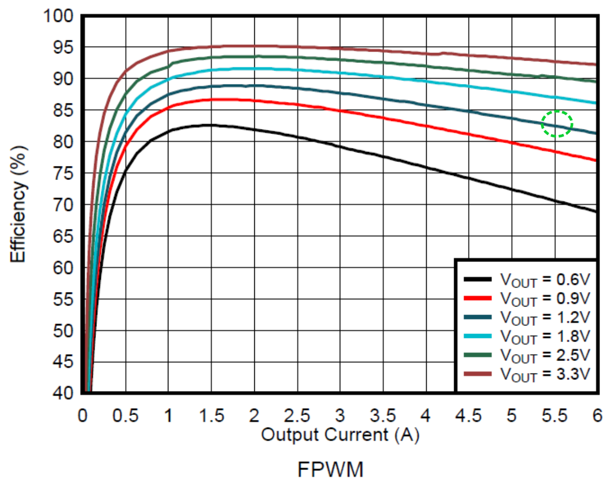

Figure 3-1. Efficiency at V_{in} = 5 V and T_A = 85°C

4 Designing for Optimal Thermal Performance

The $R_{\theta JA}$ value is one metric to quantify a device's thermal performance. The $R_{\theta JA}$ value depends on the power module's design, as well as the PCB's design. Having external thermal pads under the package allows good thermal performance by allowing multiple GND vias to heat sink the device to the PCB's multiple GND layers. Also, having a pin-out that allows large copper planes to connect to the device's power pins (VIN, GND, VOUT) reduces the $R_{\theta JA}$ value. Figure 4-1 shows that the TPSM82866A provides a large thermal pad, while Figure 4-2 shows that the pin-out allows an easy plane connection to the power pins.

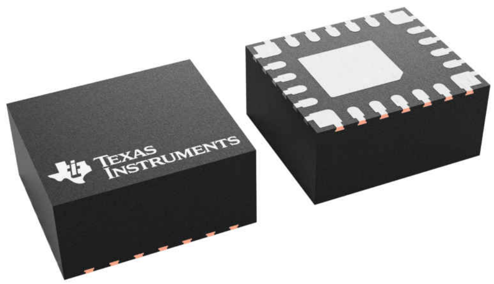

Figure 4-1. TPSM82866A Package with Exposed Thermal Pad

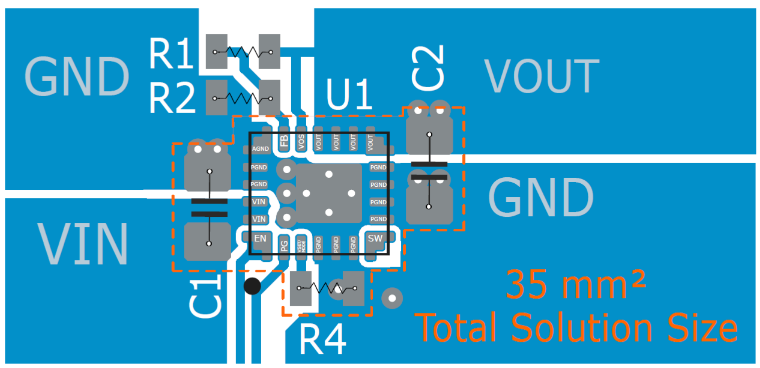

Figure 4-2. TPSM82866A Layout Example

Once the power module is designed for good thermal performance, the PCB must be designed to work effectively with the power module to remove the power loss. Thermal vias should be placed beneath the thermal pad to transfer the heat from the power module to the layers within the PCB. Placing multiple vias closely spaced to each other reduces the $R_{\theta JA}$ value. However, once a few vias are placed on the thermal pad, the point of diminishing returns is reached and adding more vias does not usually reduce the value significantly. The number of vias shown in the data sheet's layout example or in the package drawing is a good starting point for achieving good thermal performance. Thermal Performance Optimization of High-Power Density Buck Converters discusses the impact of vias on thermal performance in detail.

In addition to thermal vias, having ground planes on multiple PCB layers and increasing the copper area connected to the power pins of the device helps improve the thermal performance. Adding airflow greatly reduces the $R_{\theta JA}$ value. Improving the Thermal Performance of a MicroSiP™ Power Module provides more details on improving thermal performance through thermal vias and additional PCB layers.

5 Summary

Due to the increased power loss in a power module, operation within their thermal limits must be considered. Power module data sheets provide SOA graphs to easily evaluate the thermal performance. A good power module design coupled with a good PCB design enables operation at high output currents and high temperatures.