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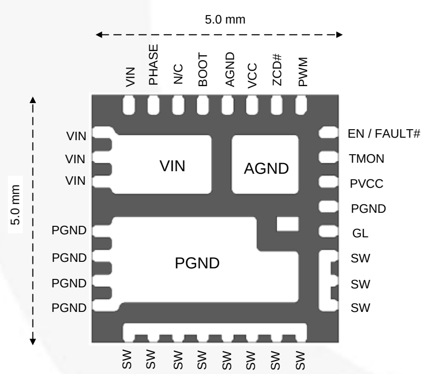
AN-4157
Thermal Analysis of SPS in Multi-Phase Application

Abstract

Thermal performance is one of the key validation items for power devices in most systems, especially in multi-phase power applications. The main factors that impact the thermal performance of power MOSFET device include: power losses, PCB stack-up, airflow, and heat sink. The purpose of this application note is to evaluate the effects of these factors on the Smart Power Stage (SPS) thermal performance.

Introduction

The Smart Power Stage (SPS) is a family of highly efficient synchronous buck power stages. The SPS packages three discrete dies to form a 5 mm x 5 mm power-stage solution using PowerTrench® MOSFETs and a lower impedance, lower dead time, gate driver. The top-side transparent view of SPS is shown in Figure 1.



Top Side Transparent View

Figure 1. Top-Side Transparent View

High-performance PQFN package with “flip–chip” low-side (LS) MOSFET improves thermals and lowers LS source inductance. Flip chip low-side MOSFETs use the PGND plane to pull heat away from LS MOSFET and add a top-side heat slug for dual cooling. The pin configuration of SPS is shown in Figure 2.

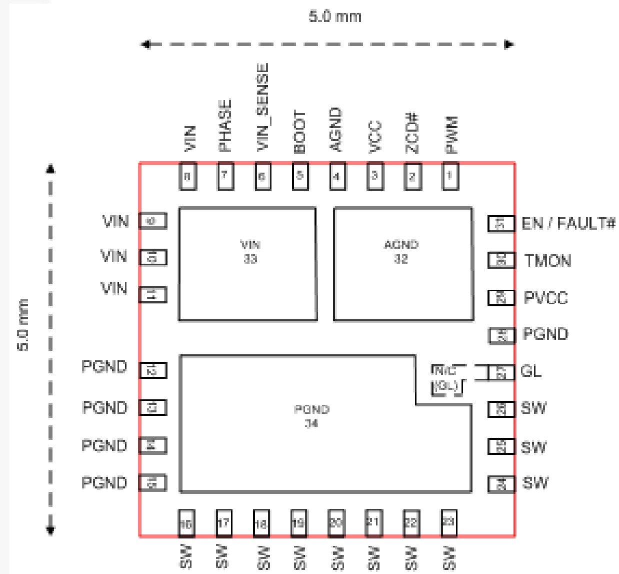


Figure 2. SPS Pin Configuration

Thermal Analysis

Thermal Effect of PCB Stack-up

This section explains the key features of PCB stack-up for thermal performance. The board configuration and test setup for thermal validation are shown in Table 1.

Table 1. Validation Configuration

Smart Power Stage	FDMF5821DC
Switching Frequency	350 kHz
Input Voltage	12.2 V
Output Voltage	1.8 V Output with 1.05mΩ Load Line
Choke	FP1007R3-R17-R (170 nH, 0.29 mΩ)
Number of Phases Active	5 Phases
Soaking Time	20 min. for Each Load
Temperature Sense	K-Type Thermal Couple

6P6367H_SPS_A00 Demo Board

The 6P6367H_SPS_A00 Demo Board is used for SPS multi-phase characterization. The board specifications and structure are shown in Table 2, Figure 3, and Figure 4.

Table 2. Evaluation Board Structure

Dimension	165 mm*162mm
No. of Layers	8 Layers
Total Thickness	1.575 mm
PCB Stack-up	2-2-2-2-2-2-2-2 (oz.)

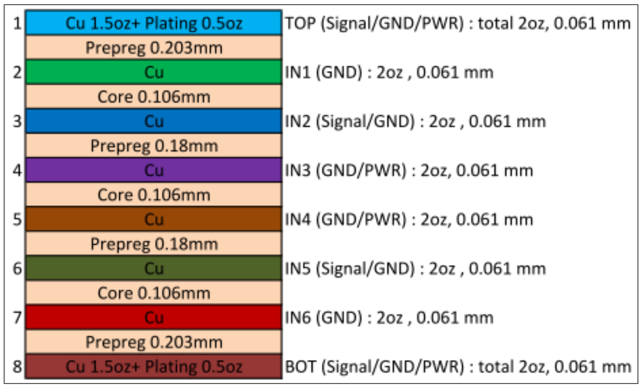


Figure 3. Evaluation Board Stack-up

The 5-phase placement area marked in Figure 4 is 45 mm x 11.5 mm.

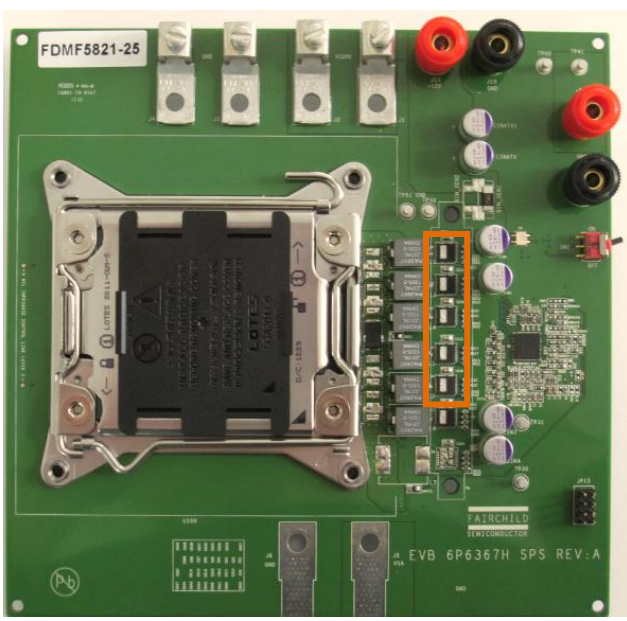


Figure 4. Board Photograph (A00 and A01)

Thermal Validation Results

The 6P6367H_SPS_A00 Demo Board thermal test results are shown in Table 3. The total loss includes 5-phase choke, SPS, and PCB power loss. The module loss per phase is without choke loss.

Table 3. Thermal without Airflow or Heat Sink

Output Load (A)	85	120	150
Total Loss (W)	8.525	13.054	18.267
Module Loss per Phase (W)	1.505	2.328	3.276
Temp. (°C) at Phase 1	57.08	78.21	102.89
Temp. (°C) at Phase 2	58.07	79.80	105.13
Temp. (°C) at Phase 3	54.12	73.17	95.23
Temp. (°C) at Phase 4	58.94	80.86	106.57
Temp. (°C) at Phase 5	53.83	73.49	96.01

6P6367H_SPS _A01 Demo Board

The 6P6367H_SPS_A01 Demo Board is used for SPS multi-phase characterization validation. The board specifications and structure are shown in Table 4 and Figure 5. The board photograph is the same with 6P6367H_SPS_A00 board as Figure 4.

Table 4. Evaluation Board Structure

Dimension	165 mm*162 mm
No. of Layers	8 Layers
Total Thickness	1.531 mm
PCB Stack-up	2-1-1-2-2-1-1-2 (oz.)

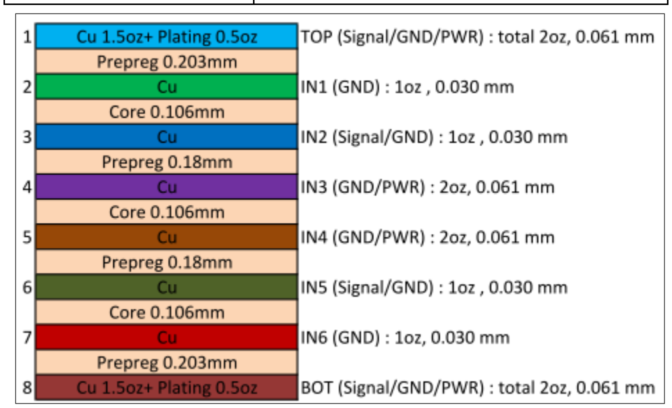


Figure 5. Evaluation Board Stack-up

Thermal Validation Results

The 6P6367H_SPS_A01 Demo Board thermal test results are shown in Table 5. The total loss includes 5-phase choke, SPS, and PCB power loss. The module loss per phase is without choke loss.

Table 5. Thermal without Airflow or Heat Sink

Output Load (A)	85	120	150
Total Loss (W)	8.415	12.850	18.325
Module Loss per Phase (W)	1.483	2.287	3.288
Temp. (°C) at Phase 1	61.70	86.04	112.85

Temp. (°C) at Phase 2	61.49	86.17	114.09
Temp. (°C) at Phase 3	58.19	79.76	104.25
Temp. (°C) at Phase 4	62.66	88.19	116.69
Temp. (°C) at Phase 5	57.87	79.97	104.91

The thermal curve of PCB stack-up impact is shown in Figure 6. The phase 4 SPS is the hotspot and phase 3 SPS temperature is the lowest of five phases.

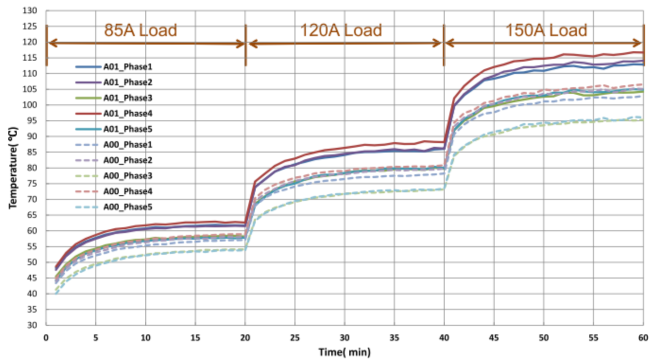


Figure 6. Temperature Curve of PCB impact

Effect of PCB Stack-up

The main factor between Table 3 and Table 5 thermal test results is PCB stack-up. PCB stack-up impacts the thermal performance as shown in Table 6. All eight layers of 6P6367H_SPS_A00 Demo Board are 2-oz copper, the thermal performance of it is better. The hotspot temperature gaps of PCB stack-up effect are 3.72°C at 1.505 W power loss condition, 7.33°C at 2.328 W power loss condition, and 10.12°C at 3.276 W power loss condition.

Table 6. Temperature Gap of PCB Stack-up

Output Load (A)	85	120	150
T_{GAP} (°C) at Phase1	4.62	7.83	9.96
T_{GAP} (°C) at Phase2	3.42	6.37	8.96
T_{GAP} (°C) at Phase3	4.07	6.59	9.02
T_{GAP} (°C) at Phase4	3.72	7.33	10.12
T_{GAP} (°C) atPhase5	4.04	6.48	8.90

Effect of Airflow without Heat Sink

This section explains the effects of airflow on the thermal performance, without heat sink. The board configuration and test setup for thermal validation are shown in Table 7.

Table 7. Validation Configuration

Evaluation Board	6P6367H_SPS Demo Board_A01
Smart Power Stage	FDMF5821DC
Switching Frequency	350 kHz
Input Voltage	12.2 V
Output Voltage	1.8 V Output with 1.05 mΩ Load Line
Choke	FP1007R3-R17-R (170 nH, 0.29 mΩ)
Active Phases	5 Phases
Soaking Time	20 min for Each Load
Temperature Sense	K-Type Thermal Couple

Thermal Validation Results

The thermal test results of without airflow and without heat sink are shown in Table 8. The total loss is including 5-phase choke, SPS, and PCB power loss. Based on 120 A output load results, SPS can handle 2.287 W power loss per phase under 90°C at 5-phase applications. The module loss per phase is without choke loss.

Table 8. Thermal without Airflow or Heat Sink

Output Load (A)	85	120	150
Total Loss (W)	8.415	12.850	18.325
Module Loss per Phase (W)	1.483	2.287	3.288
Temp. (°C) at Phase 1	61.70	86.04	112.85
Temp. (°C) at Phase 2	61.49	86.17	114.09
Temp. (°C) at Phase 3	58.19	79.76	104.25
Temp. (°C) at Phase 4	62.66	88.19	116.69
Temp. (°C) at Phase 5	57.87	79.97	104.91

The thermal test results with 200 LFM airflow and without heat sink are shown in Table 9. The total loss is including 5-phase choke, SPS, and PCB power loss. Based on 150 A output load results, SPS can handle 3.07 W power loss per phase under 90°C at 5-phase applications with 200 LFM airflow. The module loss per phase is without choke loss.

Table 9. Thermal with 200 LFM Airflow, without Heat Sink

Output Load (A)	85	120	150
Total Loss (W)	8.256	12.261	17.233
Module Loss per Phase (W)	1.451	2.169	3.070
Temp. (°C) at Phase 1	48.84	65.56	85.76
Temp. (°C) at Phase 2	48.69	65.44	86.62
Temp. (°C) at Phase 3	45.46	60.40	77.93
Temp. (°C) at Phase 4	49.67	66.77	88.46
Temp. (°C) at Phase 5	45.44	60.65	79.16

The thermal curve of 200LFM airflow impact is shown in Figure 7. The phase-4 SPS is the hotspot and phase-3 SPS temperature is the lowest of five phases.

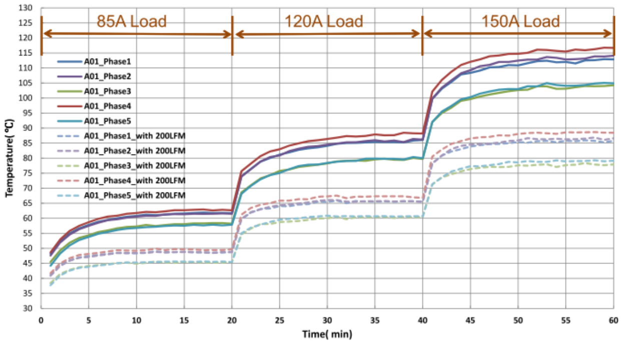


Figure 7. Temperature Curve of Air Flow Impact

The main factor difference between Table 8 and Table 9 thermal test results is airflow. The airflow setup is 200 LFM for Table 9 validation results. Airflow impacts the thermal performance, as shown in Table 10. The hotspot temperature gaps of airflow effect are 12.99°C with 0.032 W power loss gap, 21.42°C with 0.118 W power loss gap, and 28.23°C with 0.218 W power loss gap.

Table 10. Temperature Gap of 200LFM Airflow

Output Load (A)	85	120	150
P_{GAP} (W) per Phase	0.032	0.118	0.218
T_{GAP} (°C) at Phase 1	12.86	20.48	27.09
T_{GAP} (°C) at Phase 2	12.80	20.73	27.47
T_{GAP} (°C) at Phase 3	12.73	19.36	26.32
T_{GAP} (°C) at Phase 4	12.99	21.42	28.23
T_{GAP} (°C) at Phase 5	12.43	19.32	25.75

Effect of Heat Sink without Airflow

The thermal test results of without airflow and with heat sink are shown in Table 11. The total loss includes 5-phase choke, SPS, and PCB power loss. Based on 150 A output load results, SPS can handle 3.211 W power loss per phase under 100°C at 5-phase applications with heat sink. The module loss per phase is without choke loss.

Heat Sink Dimension

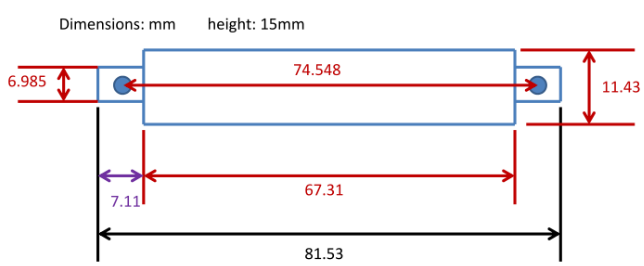


Figure 8. Heat Sink Dimensions

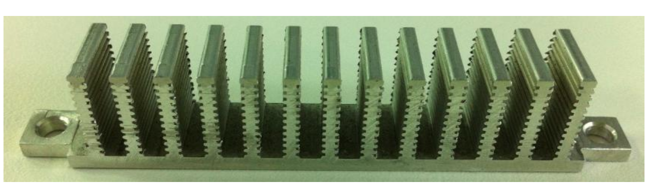


Figure 9. Heat Sink Photograph

Table 11. Thermal without Airflow, with Heat Sink

Output Load (A)	85	120	150
Total Loss (W)	8.437	12.533	17.938
Module Loss per Phase (W)	1.487	2.224	3.2110
Temp. (°C) at Phase 1	55.50	74.77	96.61
Temp. (°C) at Phase 2	54.68	73.65	94.94
Temp. (°C) at Phase 3	53.22	71.00	90.81
Temp. (°C) at Phase 4	55.47	74.96	96.93
Temp. (°C) at Phase 5	53.77	72.14	92.63

The thermal curve of heat sink impact is shown in Figure 10. The phase-4 SPS is the hotspot and phase-3 SPS temperature is the lowest of five phases.

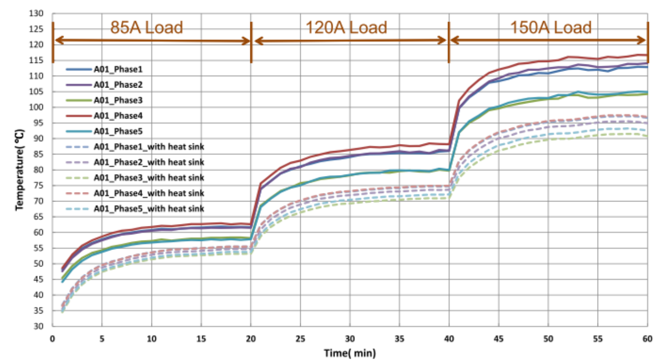


Figure 10. Temperature Curve of Heat Sink Impact

The main difference between Table 8 and Table 11 thermal test results is the heat sink. The heat sink dimension is described as Figure 8. Heat sink impacts the thermal performance as shown in Table 12. The hotspot temperature gaps of heat sink effect are 7.19°C with 0.004 W power loss gap, 13.23°C with 0.063 W power loss gap, and 28.23°C with 0.078 W power loss gap.

Table 12. Temperature Gap of Heat Sink

Output Load (A)	85	120	150
P_{GAP} (W) per Phase	0.004	0.063	0.078
T_{GAP} (°C) at Phase 1	6.20	11.27	16.24
T_{GAP} (°C) at Phase 2	6.81	12.52	19.15
T_{GAP} (°C) at Phase 3	4.97	8.76	13.44
T_{GAP} (°C) at Phase 4	7.19	13.23	19.76
T_{GAP} (°C) at Phase 5	4.10	7.83	12.28

Effects of Airflow with Heat Sink

The thermal test results with 200 LFM airflow and heat sink are shown in Table 13. The total loss includes 5-phase choke, SPS, and PCB power loss. Based on 150 A output load results, SPS can handle 2.957 W power loss per phase under 70°C at 5-phase applications with 200LFM airflow and heat sink. The module loss per phase is without choke loss.

Table 13. Thermal with 200 LFM Airflow, Heat Sink

Output Load (A)	85	120	150
Total Loss (W)	8.308	12.028	16.669
Module Loss per Phase (W)	1.462	2.123	2.957
Temp. (°C) at Phase 1	40.88	52.27	66.52
Temp. (°C) at Phase 2	39.97	51.01	64.82
Temp. (°C) at Phase 3	38.38	48.25	60.74
Temp. (°C) at Phase 4	40.74	52.26	66.65
Temp. (°C) at Phase 5	39.28	49.90	63.13

The thermal curve of 200 LFM airflow with heat sink impacts is shown in Figure 11. The phase-4 SPS is the hotspot and phase-3 SPS temperature is the lowest of five phases.

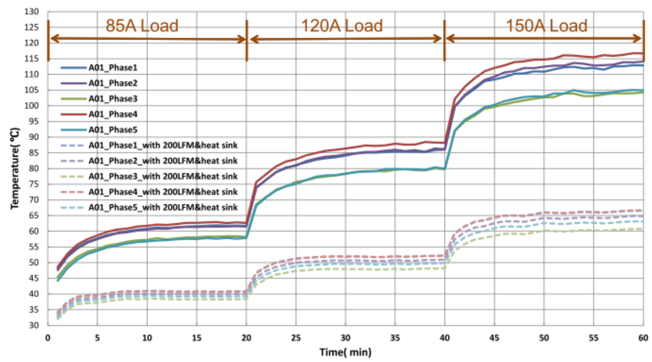


Figure 11. Temperature Curve of heat sink impact

Factors between Table 8 and Table 13 thermal test results are airflow and heat sink. The airflow setup is 200 LFM and the heat sink dimension is described in Figure 8. Airflow and heat sink impact on thermal performance are shown in Table 14. The hotspot temperature gaps of 200 LFM airflow and heat sink effect are 21.92°C with 0.021 W power loss gap, 35.93°C with 0.164 W power loss gap, and 50.04°C with 0.331 W power loss gap.

Table 14. Temperature Gap of 200 LFM Airflow and Heat Sink

Output Load (A)	85	120	150
P_{GAP} (W) per Phase	0.021	0.164	0.331
T_{GAP} (°C) at Phase 1	20.82	33.77	46.33
T_{GAP} (°C) at Phase 2	21.52	35.16	49.27
T_{GAP} (°C) at Phase 3	19.81	31.51	43.51
T_{GAP} (°C) at Phase 4	21.92	35.93	50.04
T_{GAP} (°C) at Phase 5	18.59	30.07	41.78

Summary

The phase-4 burn-in 20-minute temperature curves of 85 A, 120 A, and 150 A output load are shown in Figure 12. According to the curve, the temperature is thermal balanced after 15 minutes of burn-in.

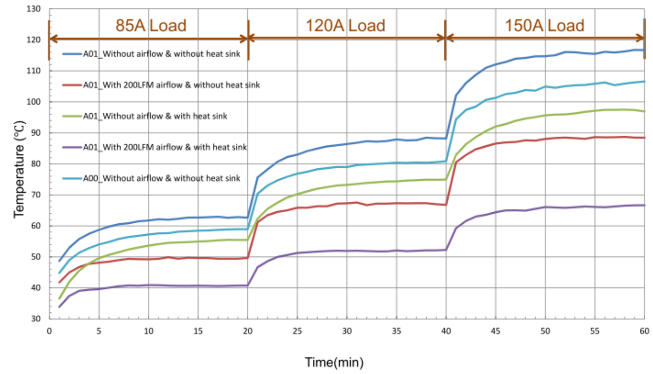


Figure 12. Burn-in Temperature Curve

Figure 13 is phase-4 thermal and power loss results based on different conditions. It is helpful to anticipate the temperature of power loss under different conditions. According to this curve, SPS can handle 2.75 W power loss around 102°C without airflow and without heat sink, 87°C with heat sink, 81°C with 200 LFM airflow, and 63°C with heat sink and 200 LFM airflow based on A01 PCB stack up.

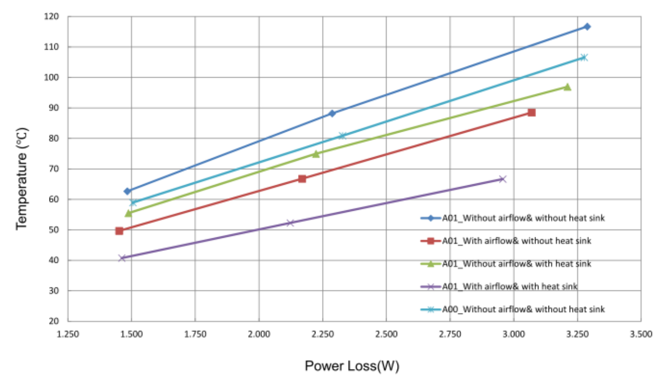


Figure 13. Temperature Curve of Power Loss

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