High-Efficiency 1.2 kW GaN Based Bridgeless Totem-Pole PFC

Reference Design

DPD1174	**Solantro Semiconductor Corp.**
GS1200BTP-EVB	**GaN Systems**

Solantro Semiconductor Corp®
www.solantro.com
info@solantro.com

GaN Systems, Inc.
www.gansystems.com
Productmarketing@gansystems.com

Table of Contents

1. Introduction

This application note highlights the performance, benefits, and design considerations of a 1.2 kW Bridgeless Totem Pole PFC (BTP PFC) solution controlled by advanced digital control methods coupled with 650 V GaN enhancement mode HEMTs (E-HEMT). This fan-less design solution achieves 80 PLUS® Titanium standards for data centers and computing applications. It has high power density, reliable start-up, high efficiency, reduced heat sinking, low THD and low EMI. The topology is bi-directional and can be easily scaled (~10 kW). This design can be incorporated as a front-end of AC/DC converters for EV on-board chargers and industrial power supply applications.

The latest generation Solantro® SA4041 32-bit, 50 MHz digital power processor facilitates solutions which leverage the performance benefits of GaN Systems' 650 V E-HEMT family. The SA4041 integrates high-speed analog peripherals, hardware accelerators and an event driven timing engine with a 50 MHz micro-processor. This design implements hysteretic current control with adaptive dead-time control and automatic transition between hard and soft-switched operation (ZVS) to provide maximum efficiency with GaN E-HEMTs over a wide operating range. The SA4041 integrated hardware accelerators and event timing engine allow the current control loop to be implemented in hardware and allow CPU resources to be utilized for low frequency bulk voltage control, housekeeping and communications functionality. In this reference design, Solantro's SA4041 uses less than 50% of its available interrupt bandwidth including all control, household, and protection features.

GaN Systems' GS66508B 650 V E-HEMTs are implemented in this design with patented Island Technology® cell layout for reduction of the device size and cost, while delivering substantially higher current and better performance than other GaN devices. GaN*PX*® packaging enables low inductance and thermal resistance in a small package. The GS66508B is a bottom-side cooled transistor that is easy to drive. It has exceptionally low total gate charge, Q_G, and output capacitance, C_{oss}, resulting in low switching losses and therefore providing very high efficiency.

1.1 Solution Overview

This reference design provides the basis for a complete power supply design achieving:

- Universal AC line input voltage (85 V- 264 V)
- 385 V_{DC} regulated bus output voltage. (Adjustable in firmware)
- 1.2 kW continuous output power @ 230 V, 600 W continuous output power @ 115 V.
- Power can be easily scaled by redesigning the magnetic components and providing proper heatsinking and thermal management.
- Full load efficiency > (99%), PF > 0.99 to achieve 80 PLUS® Titanium standards.
- Low THD (< 3%), can be further optimized in product development

Solution Benefits

- Fan-less, Self-powered (from AC input) design with no external DC supplies required
- Minimal external components due to high level of integration with SA4041 controller
- High Efficiency across wide load range is achieved by using GaN E-HEMTs and advanced control techniques.
- Easily scaled to higher power with magnetics and GaN device selection

SA4041 Digital Power Processor

- 32-bit RISC CPU with 64 KB RAM and 256 KB internal flash memory
- On-chip hardware accelerators, low latency comparators, multi-input timing engine and signal conditioning for easy implementation of hysteretic current control in hardware.   Supporting switching frequencies up to ~1 MHz
- Integrated A/D, DACs, anti-alias filtering and configurable digital filtering.
- On-chip digital PLL allowing fast synchronization to AC input waveform and simplifying start-up and operation challenges of BTP PFC implementation.
- Variable frequency control minimizes EMI/RFI vs fixed frequency PWM method
- Adaptive transition between hard-switch and soft-switch operation to minimize losses and maximize efficiency across a wide load range.
- Communication via SPI and UART ports

GS66508B 650V E-HEMTs

- Easy gate drive requirements (0 V- 6 V)
- Transient tolerant gate drive (-20 V / +10 V)
- Very high switching frequency (> 10 MHz)
- Bidirectional power flow
- Zero reverse recovery loss
- GaNPX® packaging enables low inductance & thermal resistance in high power density applications.

Figure 1: BTTP PFC EVB Block Diagram

2. Why GaN-based Bridgeless PFC with Solantro Digital Processor?

A conventional PFC circuit is shown in Figure 2.1. It consists of a full bridge rectifier and a boost pre-regulator. The boost stage can operate with continuous-conduction mode (CCM), or at the border of the discontinuous-conduction mode (DCM) and the critical conduction mode (CrCM) with zero/valley voltage switching for improved efficiency.

Figure 2.1. Conventional boost PFC circuit

However, large power losses occur in the **diode bridge** and cannot be avoided even with zero voltage switching on the boost stage. This inherently limits the peak efficiency of the conventional

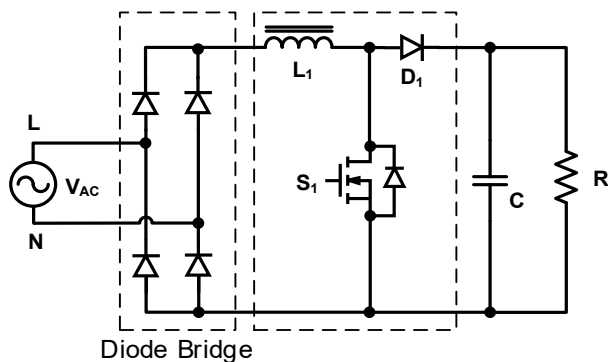PFC stage. A high voltage rectifier diode has higher than 1-V forward voltage drop and with 2 diodes in the current path, this could account at least 2% of the total efficiency loss. A well-designed PFC stage can probably achieve efficiency from 97% to even 98%, but efficiency higher than 98% becomes very challenging due to the fixed diode bridge losses.

For example, the 80PLUS Titanium efficiency standard demands half load efficiency of 94% at 115 V and 96% at 230 V. Considering the typical DC/DC stage efficiency is about 97.5%, in order to meet the 80PLUS Titanium standard, the PFC stage efficiency needs to be higher than 98.5%.

In a bridgeless PFC, the diode losses can be eliminated so efficiencies of 99% or higher are made possible to meet highest efficiency standards. Various bridgeless PFC topologies have been proposed to overcome the high diode bridge losses.

2.2 Bridgeless Totem-Pole PFC

Figure 2.2 a) shows a BTP PFC topology with diodes and GaN HEMT. The diodes D_1 and D_2 form the slow 50 or 60 Hz line frequency leg which can be made with slow AC rectifier diodes. The efficiency is significantly improved since the current path flows only through a diode and a GaN HEMT.

(a) BTP PFC with diodes   (b) BTP PFC with synchronous MOSFETs

Figure 2.2. BTP PFC topologies using GaN HEMT

For efficiency improving, the diodes can be replaced by low-$R_{DS(ON)}$ MOSFETs (S_3 and S_4) as shown in Figure 2.2(b). Also using synchronous rectification with an adaptive dead time control of the GaN HEMTs, the efficiency can be further improved.

The BTP PFC with synchronous GaN HEMTs has the following advantages:

- **Improved efficiency:** main current only flows through two switches at a time. S_1 and S_2 are driven synchronously with complementary signals and the S_3 and S_4 on the slow line frequency legs are low $R_{DS(ON)}$ Si MOSFETs to further reduce the conduction loss.

_____

- **Lower part counts, higher power density and lower BOM cost.** It uses fewer parts and has a simpler circuit.

- **Bi-directional power flow.** BTP PFC is inherently capable of bidirectional operation. This is useful for applications which may require power flow in both directions, such as Energy Storage System (ESS) and on-board bi-directional battery chargers (OBBC).

2.3 Advantages of Solantro SA4041 BTP PFC Implementation

The BTP PFC control can be implemented by a traditional micro-processor and DSP solutions. However, the Solantro SA4041 has the optimum hardware peripherals providing the following benefits to implement this topology:

1. Adaptive Deadtime control during soft-switching to make switching losses virtually zero.

2. Hysteretic current control implementation with the hardware peripherals ensures the switching frequency of the GaN HEMTs is independent of the micro-processor resources. This facilitates high frequency switching which is only limited by the switching losses.

3. SA4041 implementation of hysteretic current control provides cycle-by-cycle current limiting, fast transient response and directly measures the inductor current. This allows the design to be agnostic to the tolerance of the inductor and power train device variations.

2.3 Zero Q_{rr} GaN devices for CCM of BTP PFC

BTP PFC has been proposed before but its application has been very limited until recently. The major challenge is the poor reverse recovery performance and high switching losses of conventional silicon MOSFETs, which makes CCM operation impractical due to the excess Q_{rr} loss at turn-on. To avoid body diode conduction, BTP PFC with silicon MOSFETs must work in CrCM/DCM modes, which only fits for lower power (<500W) and has more complicated control. Usually, multi-phase interleaved configuration is used to get higher power level and improve current ripple, which again adds extra cost and complexity.

The absence of a body diode (zero reverse recovery charge Q_{rr}) and the fast switching nature of GaN HEMTs make them to be a good fit for CCM hard switching. As can be seen in Figure 2. (a), Q_{rr_meas} includes both the high side body diode reverse recovery charge, Q_{rr}, and the MOSFET output charge Q_{oss}. The body diode charge Q_{rr} usually dominates for Si MOSFETs. The two charges contribute to the MOSFETs switching losses. By contrast, GaN HEMTs exhibits significantly lower turn-on loss as there is only losses due to the output charge Q_{oss}. At hard switching, during the turn-on the GaN HEMTs losses are induced due to the output capacitance.

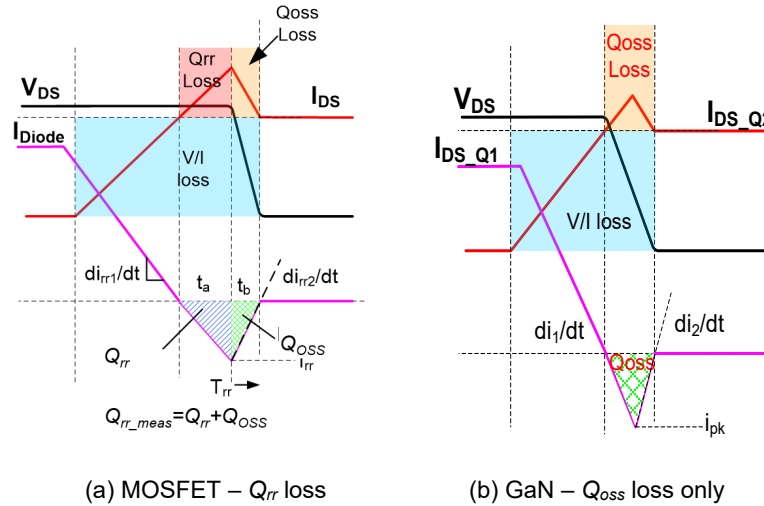(a) MOSFET – Q_{rr} loss   (b) GaN – Q_{oss} loss only

Figure 2.3. Hard turn-on loss breakdown (MOSFET vs GaN)

Table 2.1 compares the switch-on loss caused by Q_{rr_meas} (or Q_{oss} for GaN) between a silicon MOSFET and a GaN Systems E-HEMT. GaN HEMT has zero Q_{rr} and its output capacitance charge is an order of magnitude smaller than 650 V silicon MOSFETs. Even compared to CoolMOS CFD2 with an ultra-fast body diode, GaN shows much superior reverse recovery performance. Assuming a CCM BTP PFC operating at 50 kHz, GaN dissipates 0.75 W switching loss due to the Q_{oss} loss at turn-on, while a similar CoolMOS CFD2 has about 20 W at switch-on because of the Q_{rr} alone! This excellent hard switching performance makes GaN HEMTs the perfect candidate for CCM BTP PFC design.

Table 2.1. Q_{rr}/Q_{oss} Loss Comparison (650 V GaN HEMT vs Si CoolMOS)

	Si CoolMOS CFD2 w/ Fast Body Diode	GaN HEMT	
	IPW65R080CFD	**GS66508B**	Unit
$R_{DS(ON)}$	80	50	mΩ
Q_{rr}	1000	0	nC
Q_{OSS} @ V_{DS} = 400 V	318	57	nC
Turn-on loss due to Q_{rr} + Q_{OSS} @ f_{SW} = 50 kHz	20	0.75	W

2.4 Adaptive Dead-time Control with the SA4041 Digital Power Processor and GaN

The SA4041 digital power processor implements hysteretic current control providing direct inductor current waveform generation, cycle-by-cycle current control, and inherently fast transient response. The SA4041 control method employs low latency hardware peripherals and dedicated timing engine to implement adaptive dead-time control during soft-switching. While

GaN devices have inherently zero Q_{rr}, there is still a need to eliminate the conducted losses associated with reverse operation voltage drop in freewheeling operation. The SA4041 adaptive dead-time control implementation eliminates this type of losses. Integrated hardware peripherals and timing engine monitor the switching node voltage and adaptively control the turn-on of the GaN switches ensuring soft-switching operation for low line voltages and eliminate switching losses for this time.

2.5 Basic Operating Principle

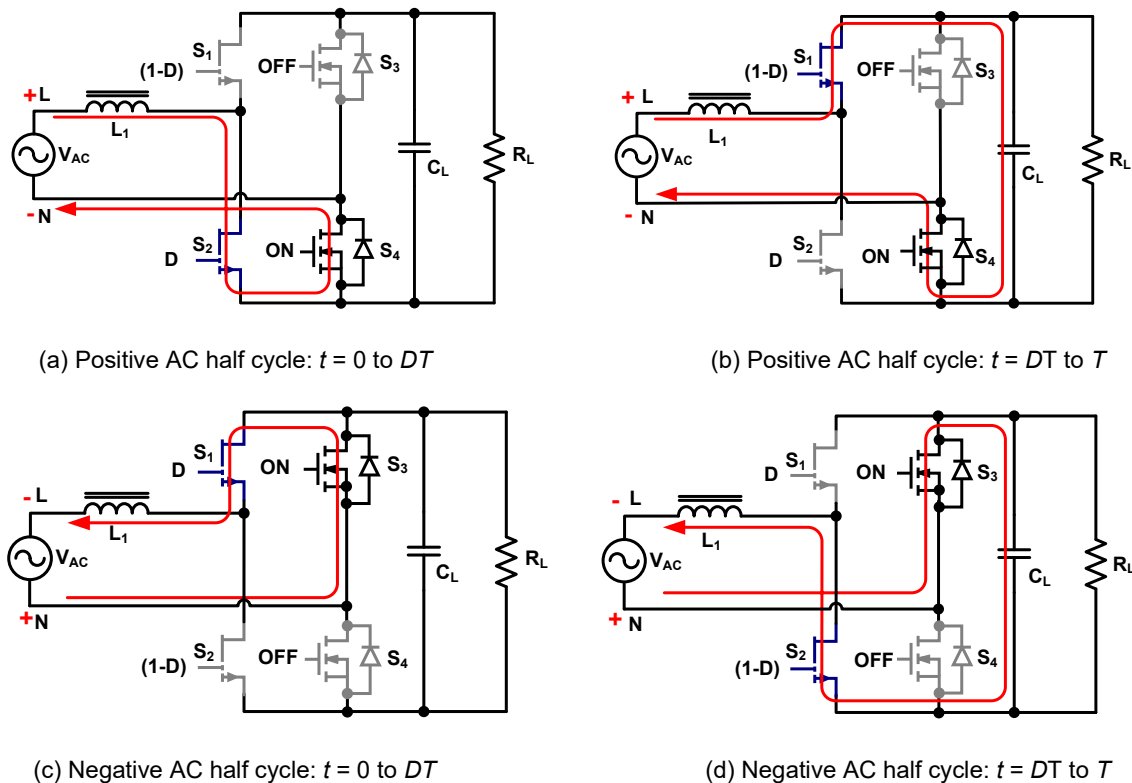The BTP PFC operates in two modes depending on the polarity of the input AC voltage as it shown in the Figure 2.4.

(a) Positive AC half cycle: t = 0 to DT

(b) Positive AC half cycle: t = DT to T

(c) Negative AC half cycle: t = 0 to DT

(d) Negative AC half cycle: t = DT to T

Figure 2.4. Current flows in BTP PFC during positive and negative AC half cycles

1. During the positive half cycle ($V_L > V_N$) S_4 is on and S_3 is off: top switch S_1, bottom switch S_2 and inductor L_1 form a boost DC/DC stage. Where S_2 is the main switch and S_1 is the free-wheeling. The switches S_2 and S_1 are switched with adaptive deadtime control. When the main switch S_2 is on (0 to DT), the current flows from L_1->S_2->S_4 and back to N. When S_2 is off ((1-D) T to T), S_1 is on and the current flows through S_1 and back to N via S_4. The DC bus ground V_{DC}- is tied to N potential as S_4 is conducting all the time.

2. During the negative half cycle ($V_N > V_L$) S_3 is on and S_4 is off: the operation in the negative half cycle is similar except the role of the top and bottom switches are swapped. Now S_1 becomes the main switch and S_2 is free-wheeling.

3. Design Example

The 1.2 kW Bridgeless Totem-Pole PFC (BTP PFC) implemented with two GaN Systems' GS66508B E-HEMTs is controlled by the Solantro advanced digital power processor IC, SA4041. This design meets the 80 PLUS® Titanium performance standards for data centers and computing applications. It has high power density, reliable start-up, reduced heat sinking and low EMI. The topology is typically used as a front-end for AC/DC converters in Electric Vehicle (EV) on-board chargers (OBC) and industrial power supply applications. The 1.2 kW BTP PFC with GaN Systems HEMTs evaluation board and specifications are shown in Figure 3.1 and Table 3.1. Inrush protection and EMI filtering are included on-board - please refer to Figure. 8.1, Mother board schematic for more details.

Table 3.1. 1.2-kW BTPPFC design specification

Parameter		Unit	Min	Nom	Max
Input RMS voltage	V_{in}	V	85	230	264
Line frequency	Hz		50		60
Output DC voltage	V_{out}	V		385	
Continuous Output Power@ 220V Input	P_{out}	W			1200
Switching frequency	f_{sw}	kHz	50	80	400
Input current THD @ Full Power	i_{THD}	%		3	
Efficiency	η	%		99	
Power factor	PF	%		99	

Figure 3.1. 1.2-kW BTP PFC evaluation board

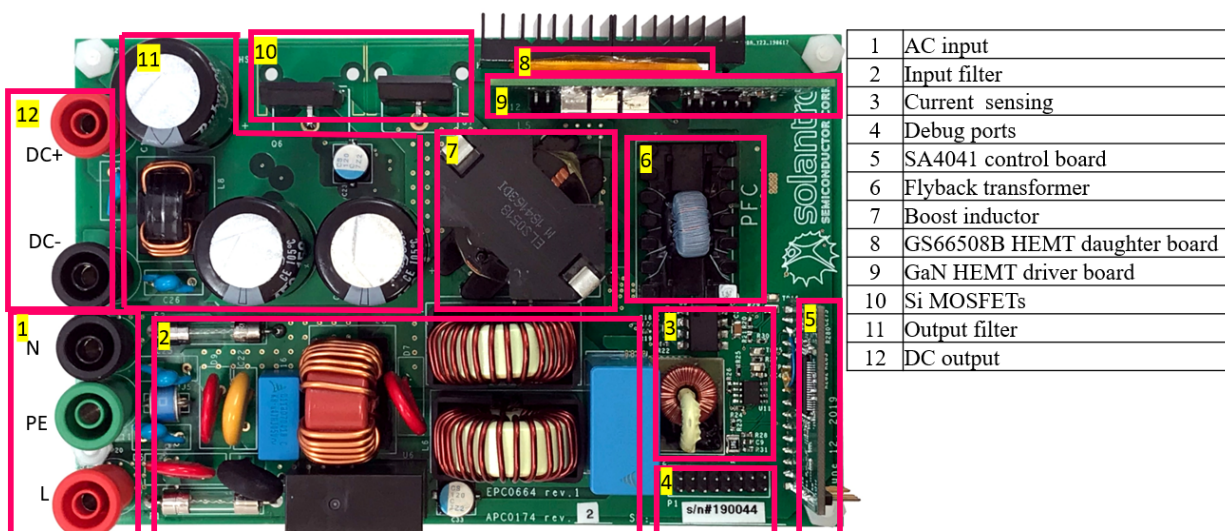| 1 | AC input |
2	Input filter
3	Current sensing
4	Debug ports
5	SA4041 control board
6	Flyback transformer
7	Boost inductor
8	GS66508B HEMT daughter board
9	GaN HEMT driver board
10	Si MOSFETs
11	Output filter
12	DC output

The control circuit is self-powered from the AC input by an on-board fly-back power supply. The PFC control board is shown in Figure 3.2. The board consists of an SA4041 and all necessary

components for its functionality. The communication is done by two isolated UART ports configured as follows (Figure 3.2):

- RS232 for connecting with PuTTY;
- HDLC, labeled as COM on the board, for connecting with Helios.

A digital test connector can be provided for debugging purpose. The SA4041 signals, such as events, gate signals, faults, and debug signals, can be exported and observed on the digital channels of an oscilloscope.
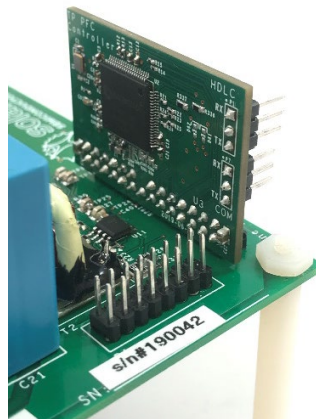

Figure 3.2. PFC control board including an SA4041 digital power processor with two communication ports COM and HDLC

The GS66508B HEMT daughter board is shown in Figure 3.3.

Figure 3.3. GS66508B HEMT daughter board

Note: To avoid risk of damage, digital isolators should be used with the evaluation board used to access communication interface.

Inductor Calculation

The boost inductor is one of the most important PFC components. Its inductance determines the PFC operation mode. A smaller ripple current results in CCM operation over a majority of the operating range, but this means that the boost inductor must have high inductance. For higher inductance, the size of the inductor is bigger. A bigger ripple current results in high conduction losses. To optimize the overall performance of the PFC stage and reach an efficiency balance between low power operation and maximum power operation, the following procedure is proposed for inductor value calculation:

Assume that the minimum switching frequency, f_{min}, is 50 kHz, and the maximum allowed peak-to-peak current, I_{pp_max}, via the inductor is 6 A. This condition allows transition mode operation at 600 W (half of maximum output power). Therefore, the boost inductor inductance is:

$$L = \frac{V_{in\_max}\left(1 - \frac{V_{in\_max}}{V_{out}}\right)}{f_{min}I_{pp\_max}} = \frac{1.41 \cdot 230 \cdot \left(1 - \frac{1.41 \cdot 230}{385}\right)}{50 \cdot 10^3 * 6} = 171(\mu H)$$

A 200 µH inductor was chosen for the this 1.2 kW BTP PFC design. The efficiency and frequency range can be optimized by manipulating the maximum allowed peak-to-peak current via the boost inductor.

The current through the inductor includes the AC 60 Hz sine wave current plus the ripple current. Therefore, the RMS inductor current is:

$$I_L = \sqrt{I_{AC}^2 + I_{Ripple}^2}$$

where I_{AC} is the RMS value of the sine current. For 1.2 kW PFC converter, with the input minimum voltage, $V_{in_{min}} = 195\,V$. I_{AC} is calculated from:

$$I_{AC} = \frac{P_{out}}{V_{min}} = \frac{1200}{195} = 6.15\,A$$

The ripple current can be assumed to have a triangular shape. Then, the RMS of the ripple current, I_{Ripple}, can be approximated by the following equation:

$$I_{Ripple} = \frac{I_{pp\_max}}{2\sqrt{3}}$$

If we assume that the peak-to-peak current is 6 A, then the RMS value of the ripple current I_{Ripple}= 1.73 A. The inductor RMS current I_L is 6.39 A. The inductor wire should be selected to sustain at least 7 A.

For further information on inductor used in this reference design please see contact Solantro (mailto:info@solantro.com).

© 2019 Solantro® The mark "Solantro" is a registered trademark of Solantro Semiconductor Corp. DPD1174 rev. 1
© 2019 GaN Systems Inc GS1200BTP-EVB – rev 190923   12

Please refer to the Evaluation Board/Kit Important Notice on page 41.

PFC Filter Capacitor Design

The filter capacitor should form a pole with the inductor approximately one decade below the minimum switching frequency. Assuming, that the minimum switching frequency, f_{min}, is 50 kHz, the capacitance of the filter capacitor is calculated by the following equation:

$$C = \left(\frac{10}{f_{min}}\right)^2 \frac{1}{4 \cdot \pi^2 \cdot L_{in}} = \left(\frac{10}{50000}\right)^2 \frac{1}{4 \cdot \pi^2 \cdot 200 \cdot 10^{-6}} = 5 \ (\mu F)$$

Since the PFC stage, by design, operates in a frequency range of 50 - 400 kHz, the standard value 3.3 µF capacitor is chosen for the filter capacitor. This value is a compromise between cost and performance and provides good attenuation for the entire frequency operation range. During capacitor selection, a designer should verify that the chosen capacitor is rated to carry the inductor high frequency current component.

PFC Output Capacitor Design

The PFC output capacitor capacitance depends on the maximum output power, the minimum line frequency, the output DC voltage and acceptable output ripple voltage. It can be calculated by the following equation:

$$C_{out} = \frac{P_{max}}{V_{out} 2\pi f_{min} \Delta V_{ripple}}$$

If we assume that the output ripple voltage is ±20 V, then the capacitance of the output capacitor is:

$$C_{out} = \frac{1200}{385 * 2\pi * 50 * 40} = 415 \ \mu F.$$

We can choose the capacitance of the bulk capacitor to be 450 µF.

Since the DC voltage is 385 V, for reliability purposes, the capacitors should be rated for 450 V.

© 2019 Solantro® The mark "Solantro" is a registered trademark of Solantro Semiconductor Corp. DPD1174 rev. 1
© 2019 GaN Systems Inc GS1200BTP-EVB – rev 190923   13

Please refer to the Evaluation Board/Kit Important Notice on page 41.

The caution box contains the following warnings:

Do not leave the board powered when unattended.

High Voltage! Electric shock is possible when connecting board to live wire. Board must be handled with care by a professional.

For safety, use of isolated test equipment with overvoltage and overcurrent protection is highly recommended.

Hot surface! Contact may cause burns. Do not touch!

4. Test Setup

4.1 Test Equipment

- AC power supply capable of supplying at least 6 A_{rms} at 230 V.
- Load
  - Programmable DC electronic load (capable of 400 V and 3 A).
  - Resistive load (capable of 400 V and 3 A).
- Connection wires with suitable current ratings.
- The following additional equipment is required for observation
  - 4-channel oscilloscope with minimum 200 MHz bandwidth
  - Two high voltage differential probes (at least 600 V differential, 600 common ground and 50 MHz bandwidth) such as the P5200A Tektronix Differential Probe
  - Two current clamp probes (at least 30 Arms and 120 MHz bandwidth) such as the TCP0030 Tektronix Current Probe.
- Power Analyzer - Tektronix PA4000 Power Analyzer or equivalent

4.2 Connecting the Board for Start-up and Transient Response Testing

Refer to Figure 3.1, to make the following connections:
- Set the AC power supply to 230 Vrms. Make sure the AC source is not activated yet.
- Connect N (J6) to the negative terminal of the AC power supply.
- Connect L (J1) to the positive terminal of the AC power supply.
- Connect (RE) (J3) to the protective earth of the AC power supply.
- Set the initial load as follows:

_____

       a. for DC electronic load: set to Constant Current (CC) load and set the current to 0.1

       b. for resistive load: set to 3.8 kΩ (385 V /3.8 kΩ ~ 0.1 A).

- Connect DC- (J4) to the negative terminal of the load.
- Connect DC + (J2) to the positive terminal of the load.
- Connect differential probe 1 to the PFC input, L (J1) and N (J6), and plug it into the oscilloscope CH1. Setup CH1 accordingly.
- Connect differential probe 2 to the PFC output, DC- (J4) and DC + (J2) and plug it into the oscilloscope CH2. Setup CH2 accordingly.
- Clamp current probe 1 on the wire connecting the positive terminal of AC power supply and L (J1). Plug it into the oscilloscope CH3. Setup CH3 accordingly. Press the calibration button on the current probe to calibrate it.
- Clamp current probe 2 on the wire connecting the positive terminal of load and DC + (J2). Plug it into the oscilloscope CH4. Setup CH4 accordingly. Press the calibration button on the current probe to calibrate it.
- Set the trigger source to CH1 and adjust the trigger level accordingly.
- Power up the board by turning ON the AC power supply.

For transient response experiments, the load should be changed according to the test.

5.   Test Results

5.1 Efficiency

To measure the efficiency, power factor, and total harmonic distortion (THD), the circuit shown in Figure 5.1 is used. A Tektronix PA4000 Power Analyzer was used for these measurements. Note: all system bias losses are included in efficiency calculations (see Figure 5.1).

Figure. 5.1. Efficiency and power factor measurements test circuit

Figure 5.2 shows the measured efficiency of the 1.2 kW bridgeless totem-pole PFC reference design.

Figure. 5.2. BTP PFC efficiency vs output power

5.2 Power Factor

The power factor curve is shown in Figure 5.3.

Figure 5.3. BTP PFC power factor vs output power

5.3 Total Harmonic Distortions

Figure 5.4 and 5.5 show the grid voltage and current waveforms for two cases:

1. V_{Grid} = 115 V and P_{out} = 500 W;
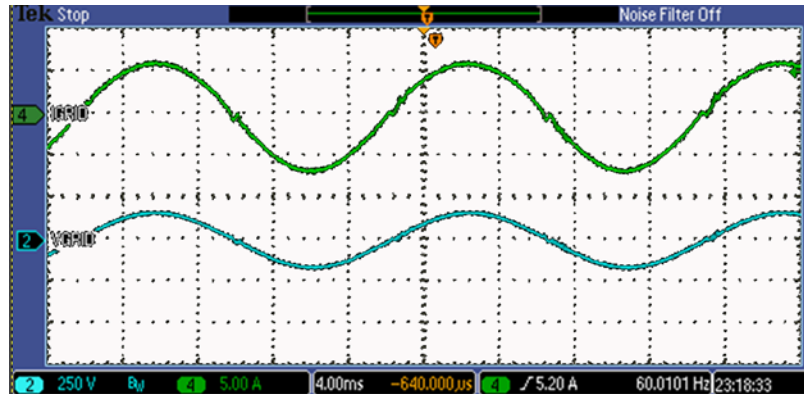2. V_{Grid} = 230 V and P_{out} = 1000 W;

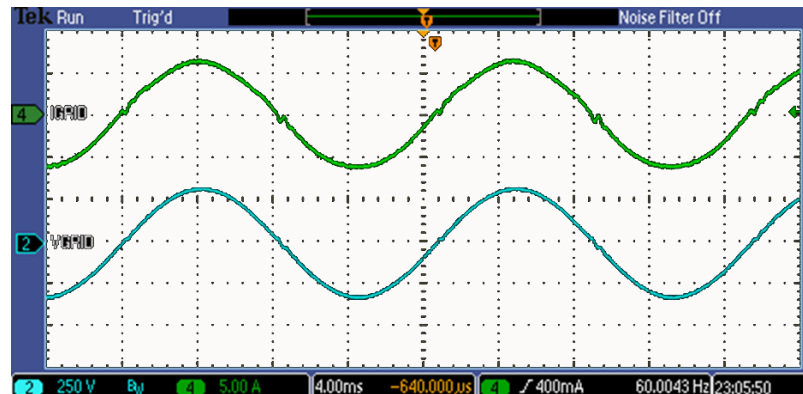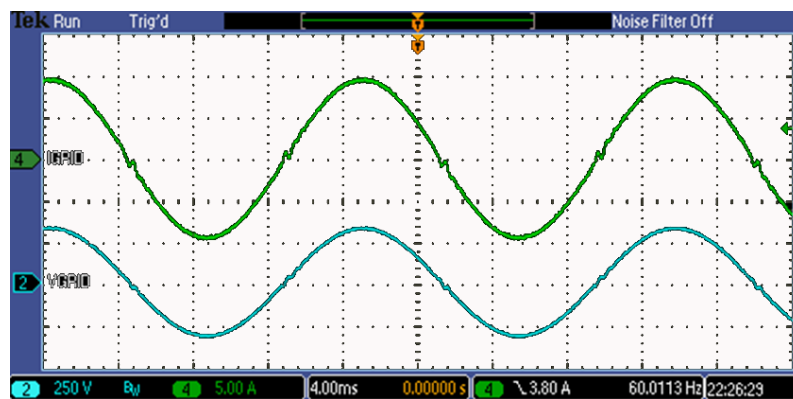Figure 5.4. Grid voltage (115 V) and current at power 500 W: Ch.2 – V_{Grid}; Ch.4 – i_{Grid}

Figure 5.5. Grid voltage (230 V) and current at power 1000 W: Ch.2 – V_{Grid}; Ch.4 – i_{Grid}

Figure 5.6 and 5.7 show the grid voltage and current waveforms for two cases:

3. V_{Grid} = 115 V and P_{out} = 750 W;
4. V_{Grid} = 230 V and P_{out} = 1000 W;

Figure 5.6. Grid voltage (115 V) and current at power 750 W: Ch.2 – V_{Grid}; Ch.4 – i_{Grid}

Figure 5.7. Grid voltage (230 V) and current at power 1000 W: Ch.2 – V_{Grid}; Ch. 4 – i_{Grid}

The THD as measured with a Tektronix PA4000 Power Analyzer was 2.3% for case 3 and 1.7% for case 4.

The THD of the grid current was measured for two input voltage levels (115 and 230 V) and three output power levels. The THD results are presented in Table 4.1.

Table 4.1. THD performance for two input voltage levels

P_{out} (W)	THD%	
	230 V_{AC}	115 V_{AC}
330	4.2	4
660	2.8	2.85
1000	2.2	2.2

5.4 Experimental Results for Start-up and Transient Response

BTP PFC converter is designed to have soft start-up, high efficiency, high power factor, fast transient response, and uniform operation under varying load conditions.

5.4.1 Start-Up

The BTP-PFC implementation is designed to meet soft-start requirements by incrementally increasing the output voltage reference from initial measured voltage to the nominal voltage reference, V_{out_Ref}, with a controlled rate set in the software. This prevents overshoots and excessive input currents. It also reduces the stress on components. No-load start-ups at grid voltage, V_{Grid}, 115 V and 230 V are shown in Figure 5.8 and Figure 5.9. The output voltage rate of change, ΔV_{out_Ref}, equals to 10 V per grid cycle.

Figure 5.8. No-load start-up at V_{Grid}=115 at 60Hz: Ch.2 – i_{out}; Ch.3 – V_{grid}, and Ch.1 – V_{Out}

Figure 5.9. No-load start-up at V_{Grid}=230 V at 60Hz: Ch.2 – i_{out}; Ch. 3 – V_{grid}, and Ch.4 - V_{Out}

Figure 5.10. Full-load start-up at V_{Grid}=115 at 60Hz: Ch.2 – i_{out}; Ch.3 – V_{grid}, and Ch.1 – V_{Out}
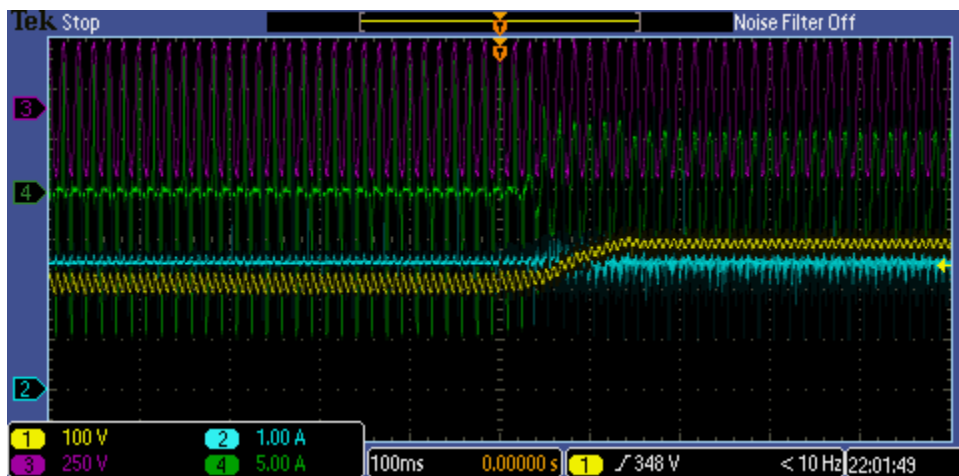

Figure 5.11. Full-load start-up at V_{Grid}=230 at 60Hz: Ch.2 – i_{out}; Ch.3 – V_{grid}, and Ch.1 – V_{Out}

5.4.2 Step Response

The PFC is designed to have fast transient response. The results for the Solantro BTP PFC for input voltages 230 V are shown in Figure 5.10 through Figure 5.13.
The step responses were performed by changing the load from:
- 0 W to 500 W;
- 500 W to 0 W;
- 500 W to 1000 W;
- 1000 W to 500 W.

Figure 5.10. Step response 0 -500 W at V_{Grid}=230 V: Ch.2 - i_{out}; Ch.3 – i_{Grid}, and Ch.4 - V_{Out}

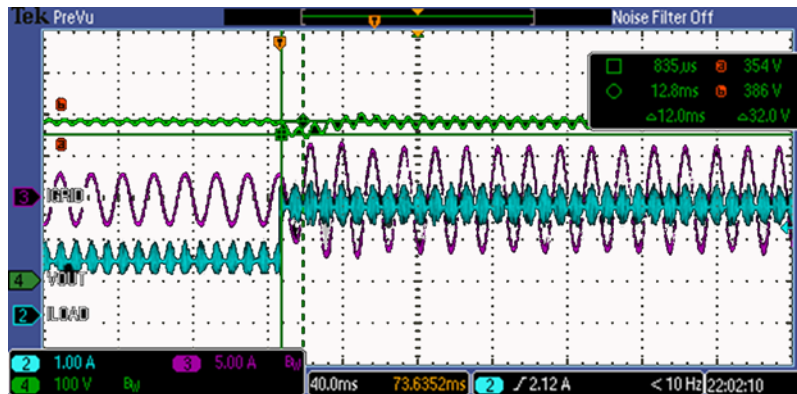Figure 5.11. Step response 500 - 0 W at V_{Grid}=230 V: Ch.2 - i_{out}; Ch.3 – i_{Grid}, and Ch.4 - V_{Out}

Figure 5.12. Step response 500 - 1000 W at V_{Grid}=230 V: Ch.2 - i_{out}; Ch.3 – i_{Grid}, and Ch.4 - V_{Out}

Please refer to the Evaluation Board/Kit Important Notice on page 41.

Figure 5.13. Step response 1000 -500 W at V_{Grid}=230 V: Ch.2 - i_{out}; Ch.3 – i_{Grid}, and Ch.4 - V_{Out}

Figure 5.14 and Figure 5.15 show the results of AC voltage transient response tests: from 115 V to 230 V and 230 V to 115 V, respectively.
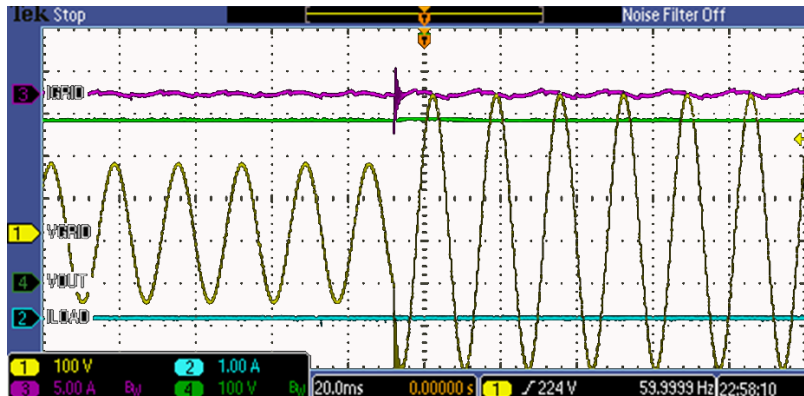

Figure 5.14. AC voltage transient response: from 115 V to 230 V.Ch.1 – V_{Grid}; Ch.2 – i_{out}; Ch.3 – i_{Grid}, and Ch.4 - V_{Out}
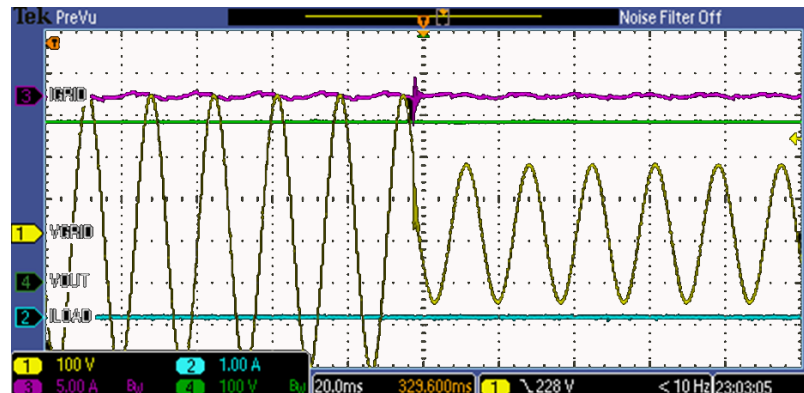

Figure 5.15. AC voltage transient response: from 230 V to 115 V.Ch.1 – V_{Grid}; Ch.2 – i_{out}; Ch.3 – i_{Grid}, and Ch.4 - V_{Out}

6.   Applications

The application scope of this 1.2-kW GaN E-HEMT-based BTP PFC includes, but is not limited to following:

1. Data Center and Telecom applications. The BTP PFC can also be applied to the telecom applications to increase efficiency, reduce systems size and reduce system BOM cost.
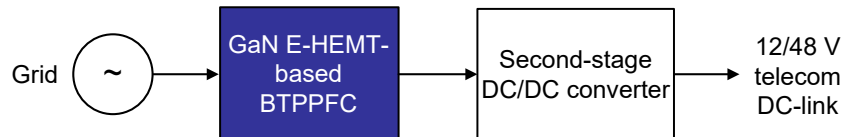

Figure 6.3. Data Center and Telecom power supply application

2. Unidirectional or bi-directional onboard battery charger in electrified vehicle application. The BTP PFC is a promising bidirectional PFC candidate to achieve the bidirectional power flow from grid to vehicle (G2V) and from vehicle to grid (V2G).
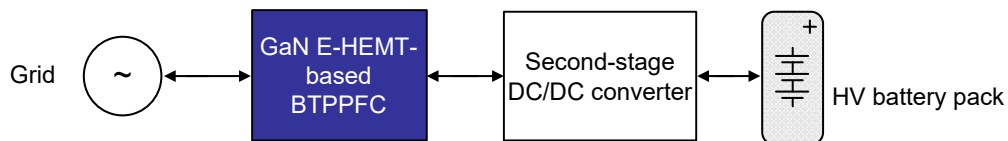

Figure 6.1. Electrified vehicle onboard bidirectional battery charger system

3. Energy storage systems. The BTP PFC can realize the bi-directional interconnection between the grid and an energy storage system to better utilize the harvested energy and optimize the overall system.
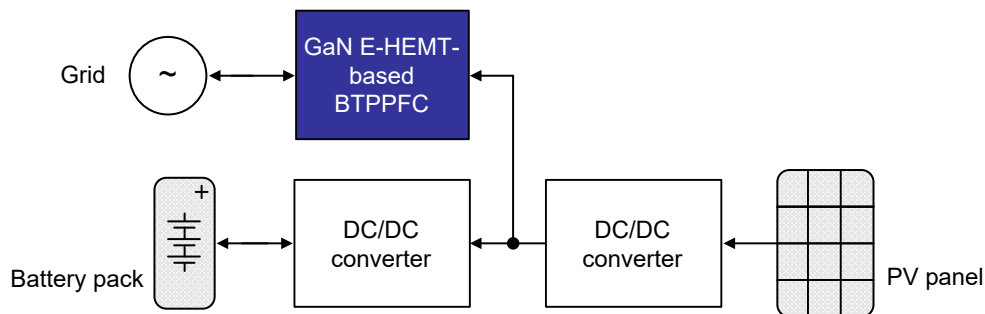

Figure 6.2. Energy storage system

Please refer to the Evaluation Board/Kit Important Notice on page 41.

7. Conclusion

In summary, the BTP PFC controlled by Solantro's SA4041 digital power processor coupled with 650 V GaN Systems enhancement mode HEMTs demonstrates superior performance and high-power density. This design can be scaled easily for applications requiring a front-end AC/DC converter for EV on-board chargers, data centers, performance computing, motor drive, and industrial power supplies.

The simplicity of implementing this architecture, by using Solantro's on-chip hardware accelerators and timing engine, further allows for power system designers to get solutions to market quickly with less complexity in firmware development then the conventional DSP-based control solutions.

GaN Systems' 650 V E-HEMTs (GS66508B) facilitate optimum balance of conduction and switching losses while supporting high frequency switching which is critical for reducing the size of the passive components and therefore obtaining high power density.

This Reference design provides the basis for customers to quickly develop a complete power supply design including heatsinking, thermal management and appropriate operating points.

_____

8.   Appendix

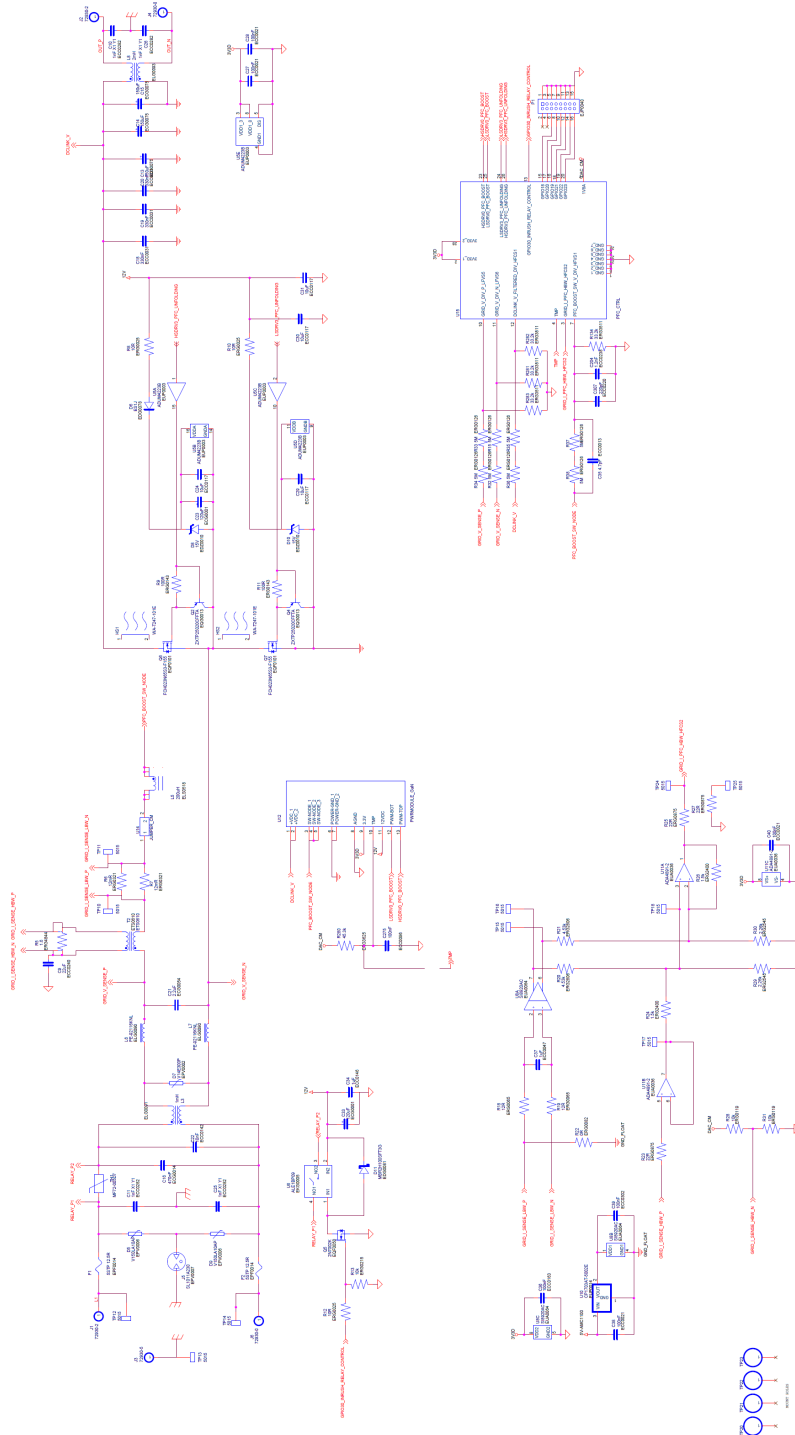## 8.1 Evaluation Board Schematics
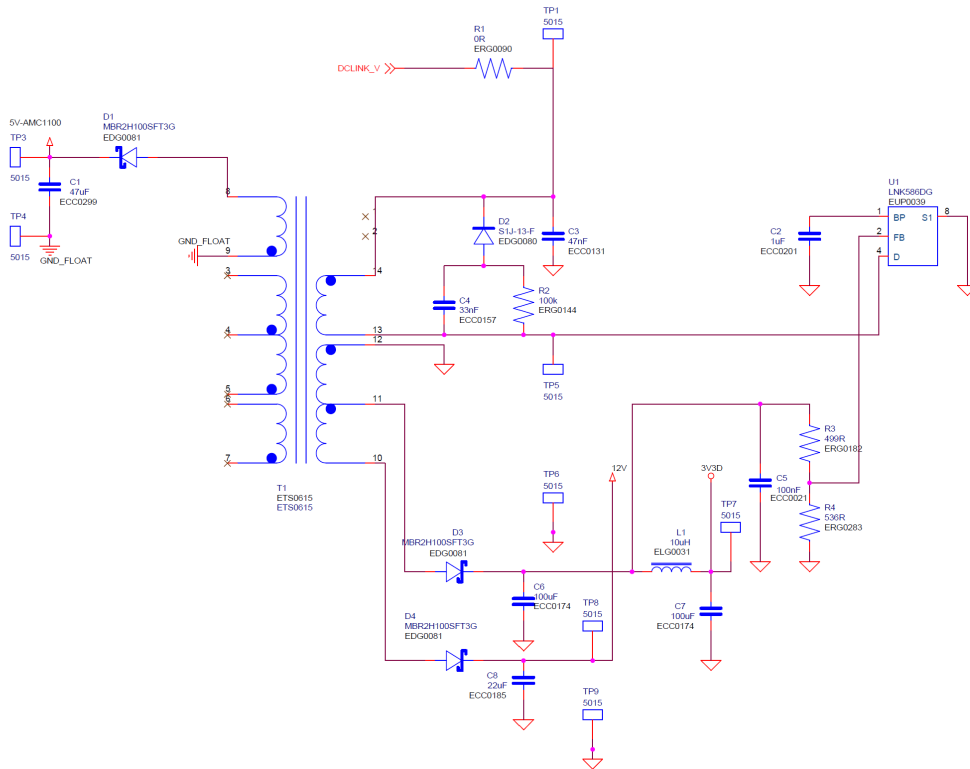

Figure. 8.1. Mother board schematic
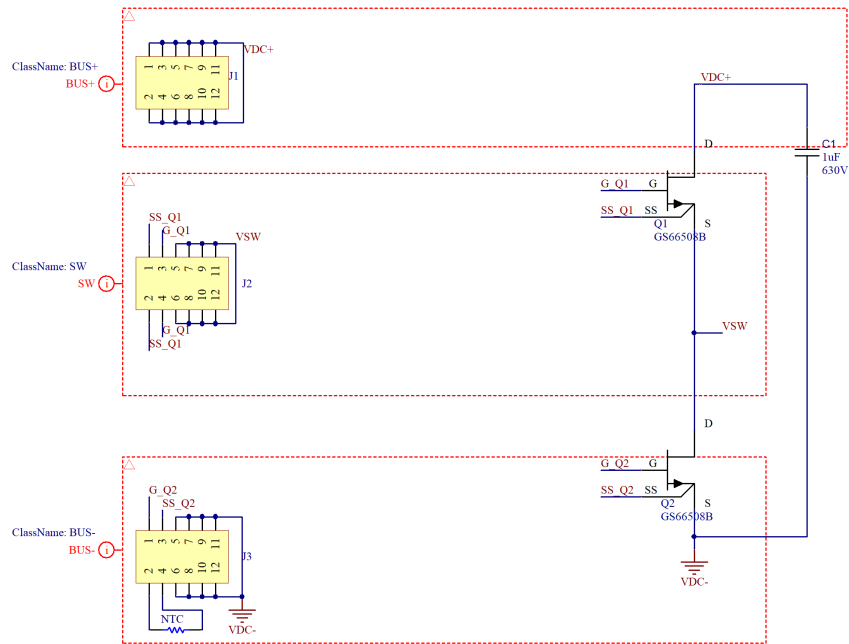
Figure. 8.1. Mother board schematic (Continued)

Figure. 8.2. GaN IMS board schematic

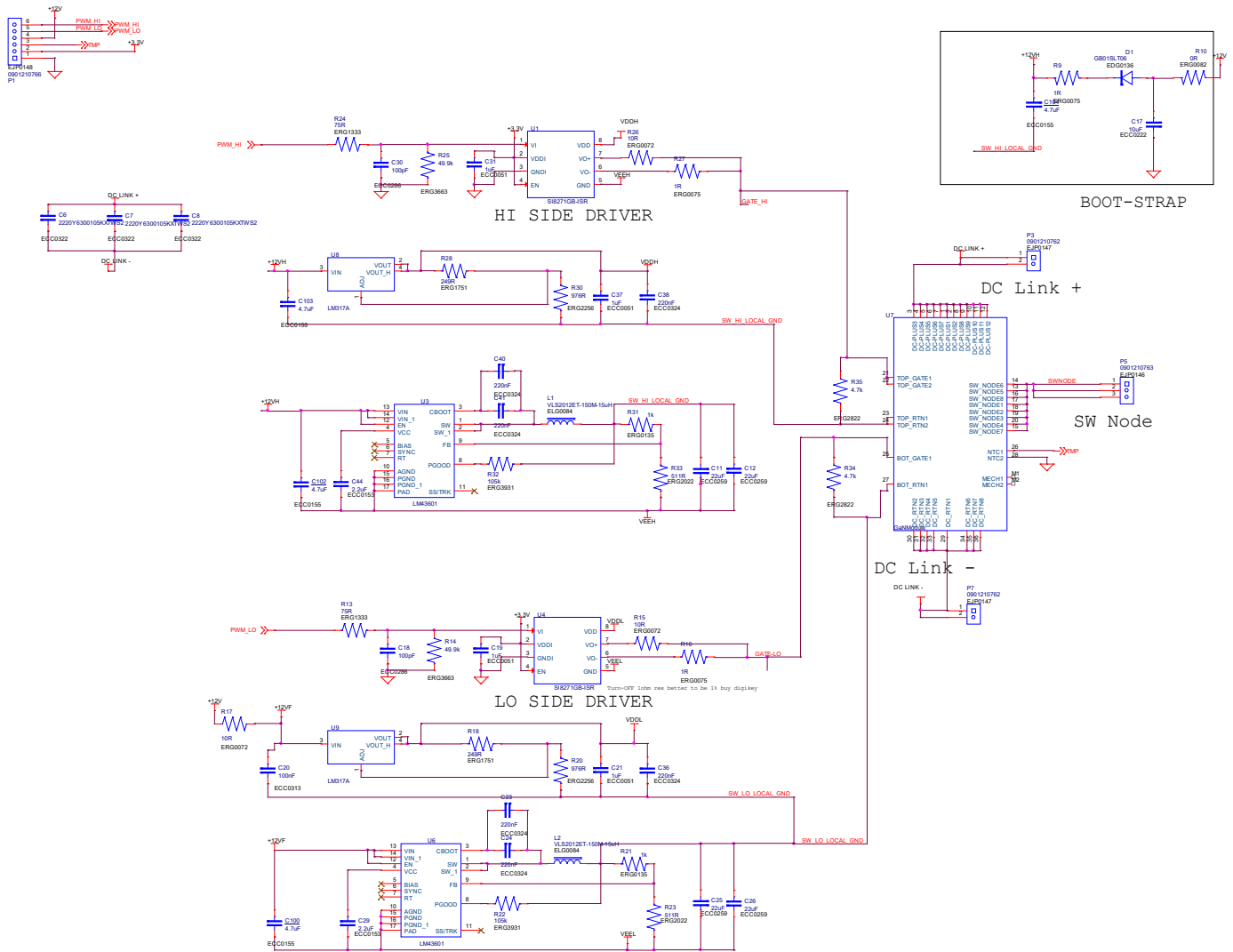**Please refer to the Evaluation Board/Kit Important Notice on page 41.**

Figure. 8.3. GaN driver board schematic

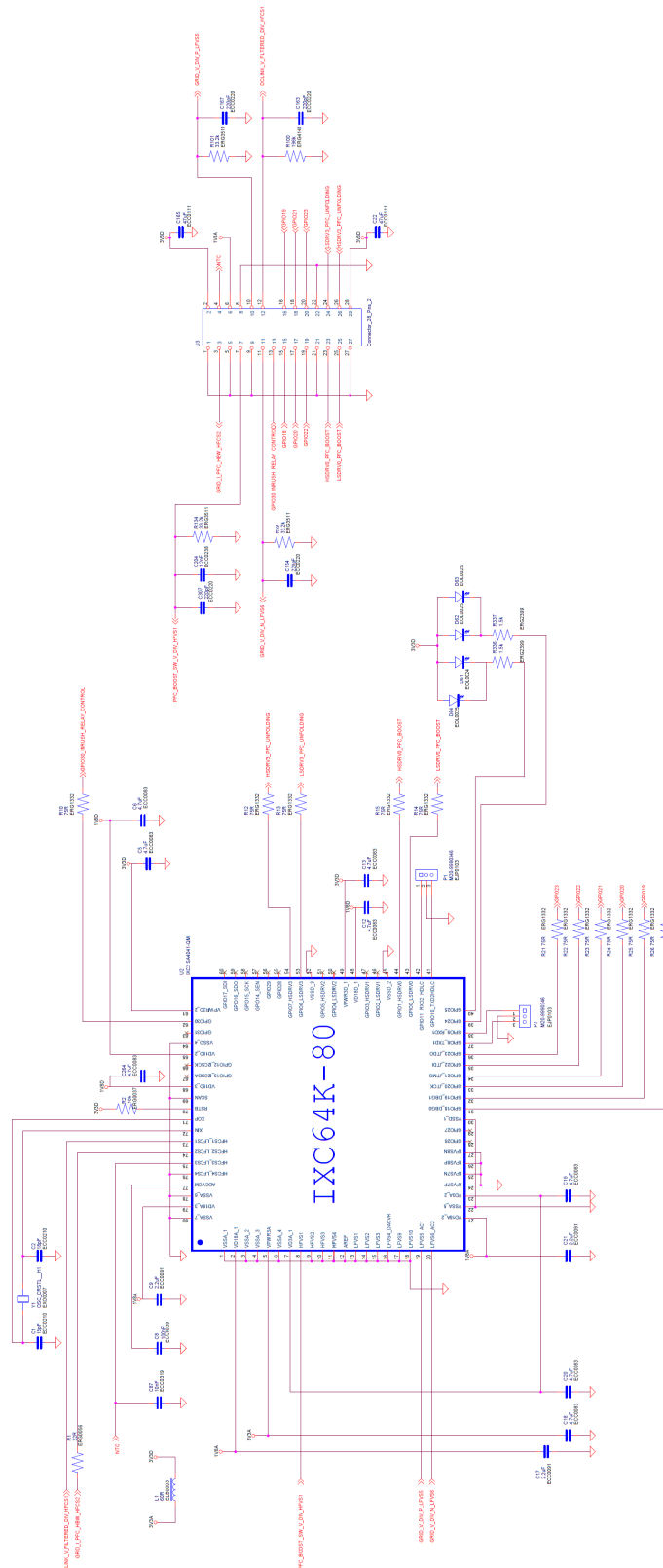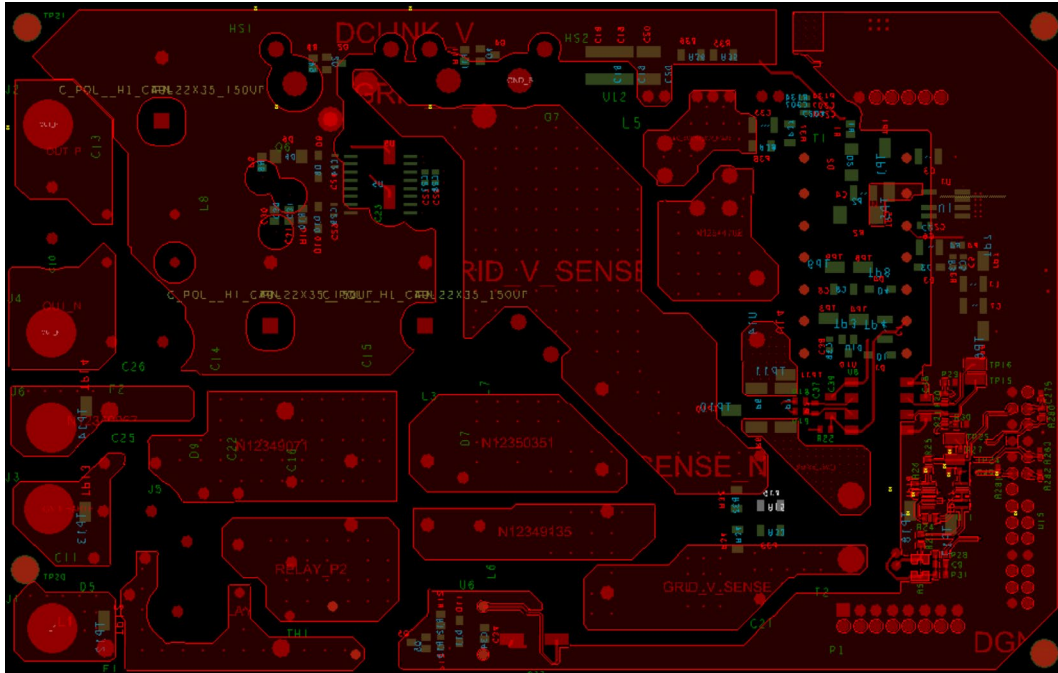Please refer to the Evaluation Board/Kit Important Notice on page 41.

Figure. 8.4. SA4041 PFC controller board schematic

8.2 PCB Layout

(a)

(b)

(c)

(d)

Figure. 8.5. Mother board PCB layout, (a) top layer, (b) mid layer 1, (c) mid layer 2, (d) bottom layer

(a)

(b)

(c)

(d)

Figure. 8.6. GaN driver board PCB layout, (a) top layer, (b) mid layer 1, (c) mid layer 2, (d) bottom layer

(a)

(b)

Please refer to the Evaluation Board/Kit Important Notice on page 41.

(c)

(d)

Figure. 8.7. SA4041 PFC controller board PCB layout, (a) top layer, (b) mid layer 1, (c) mid layer 2, (d) bottom layer
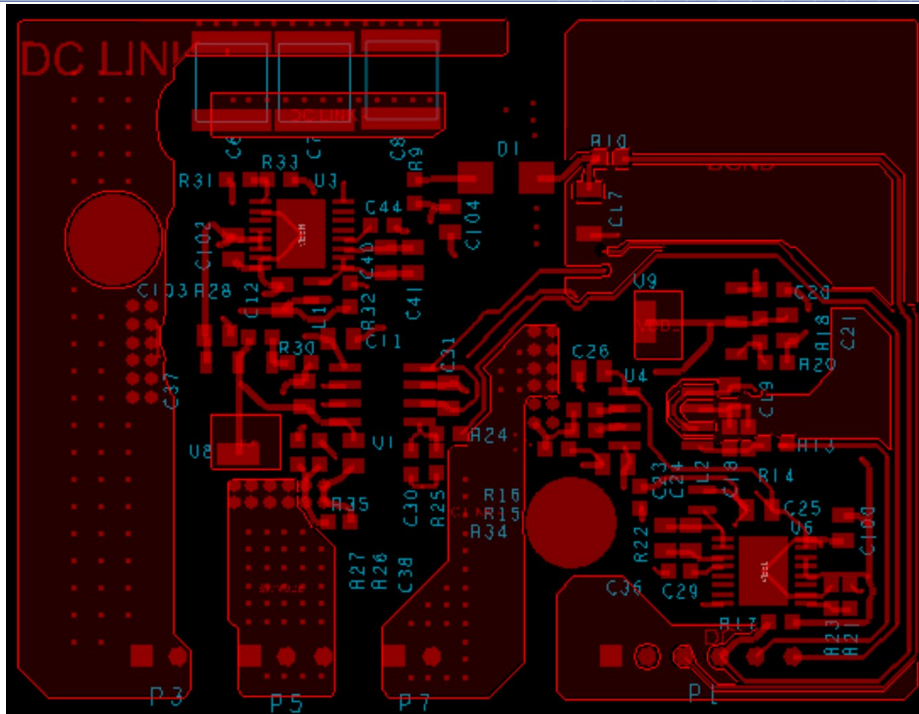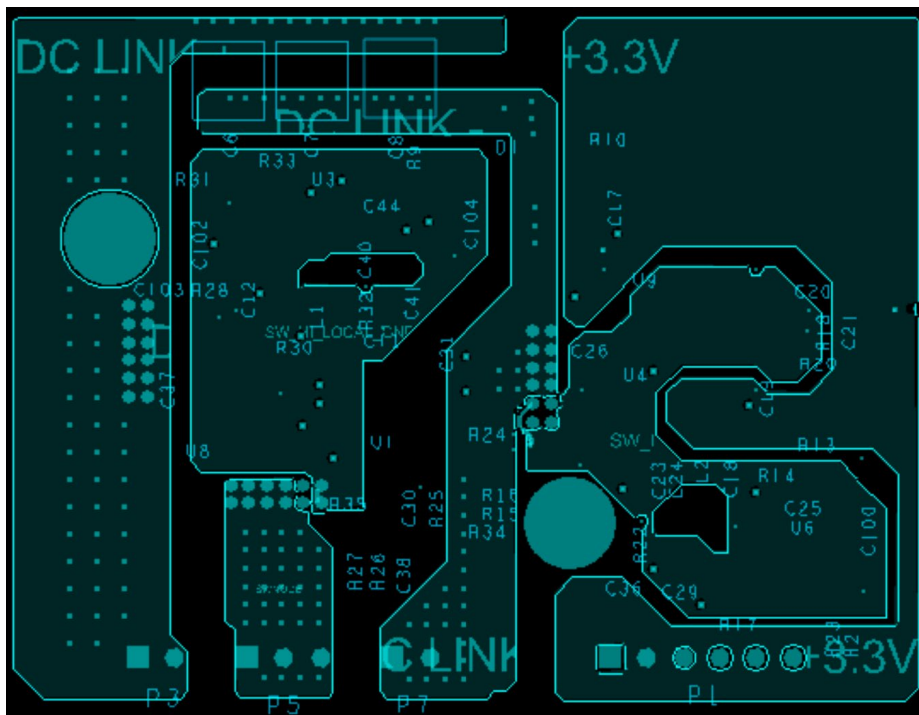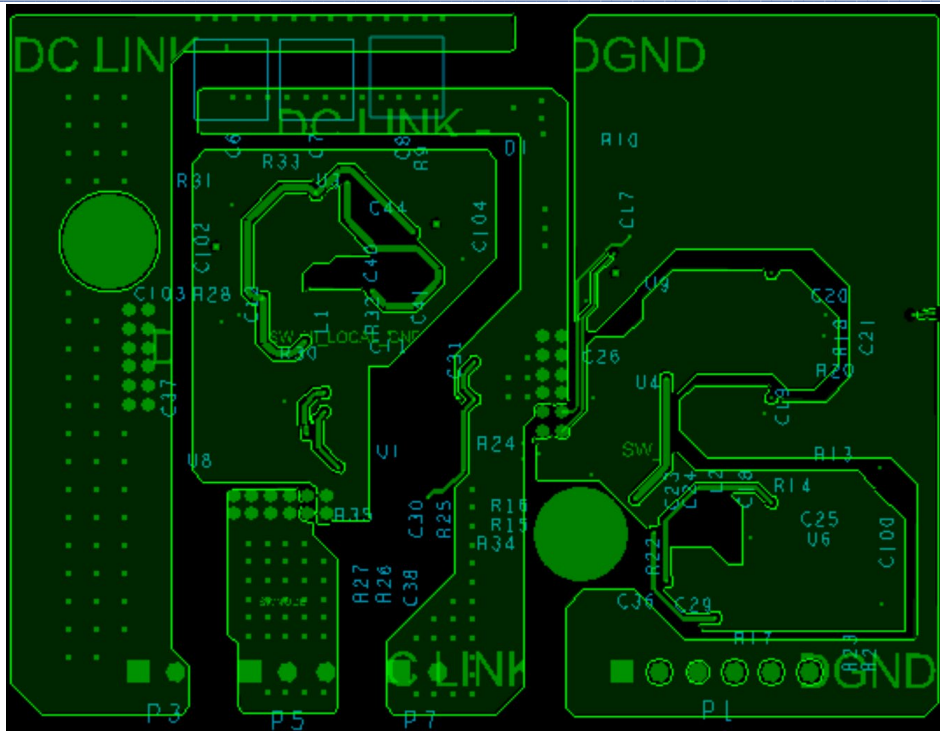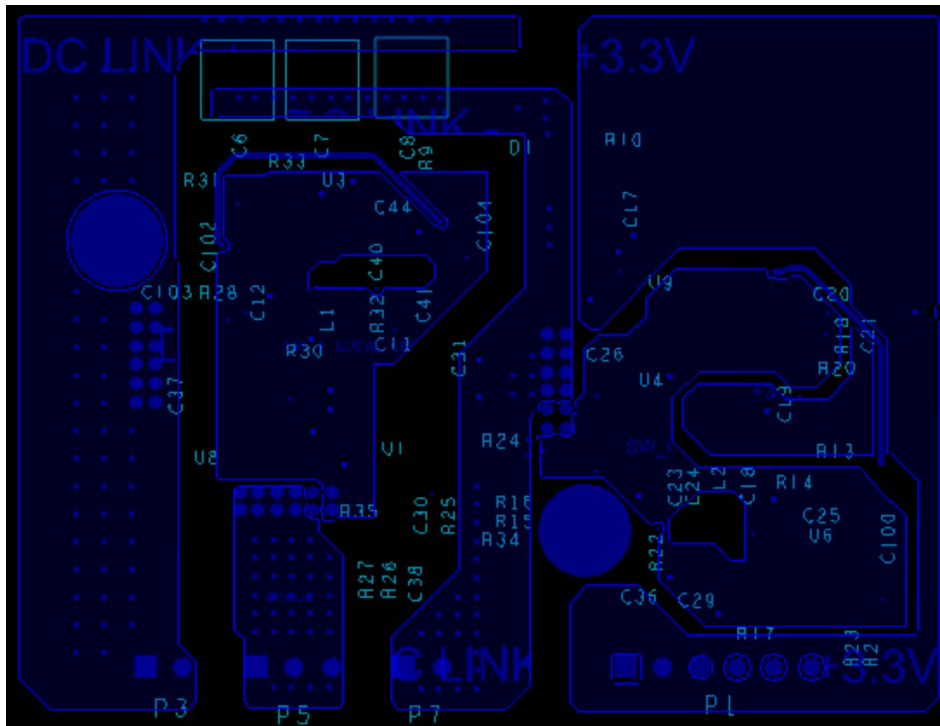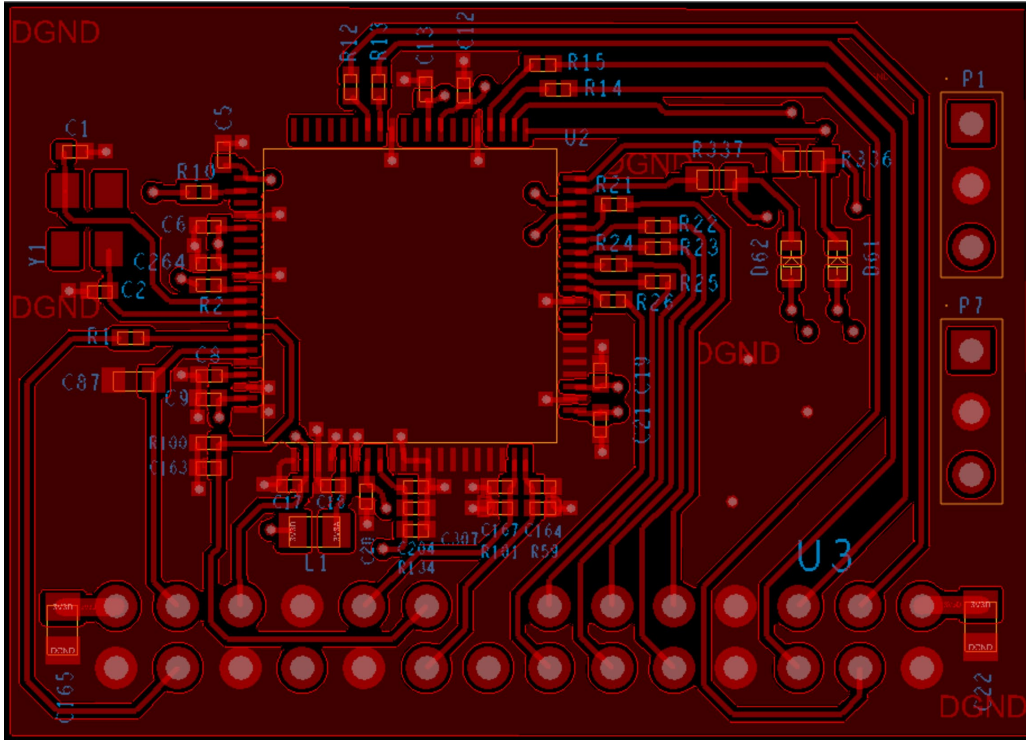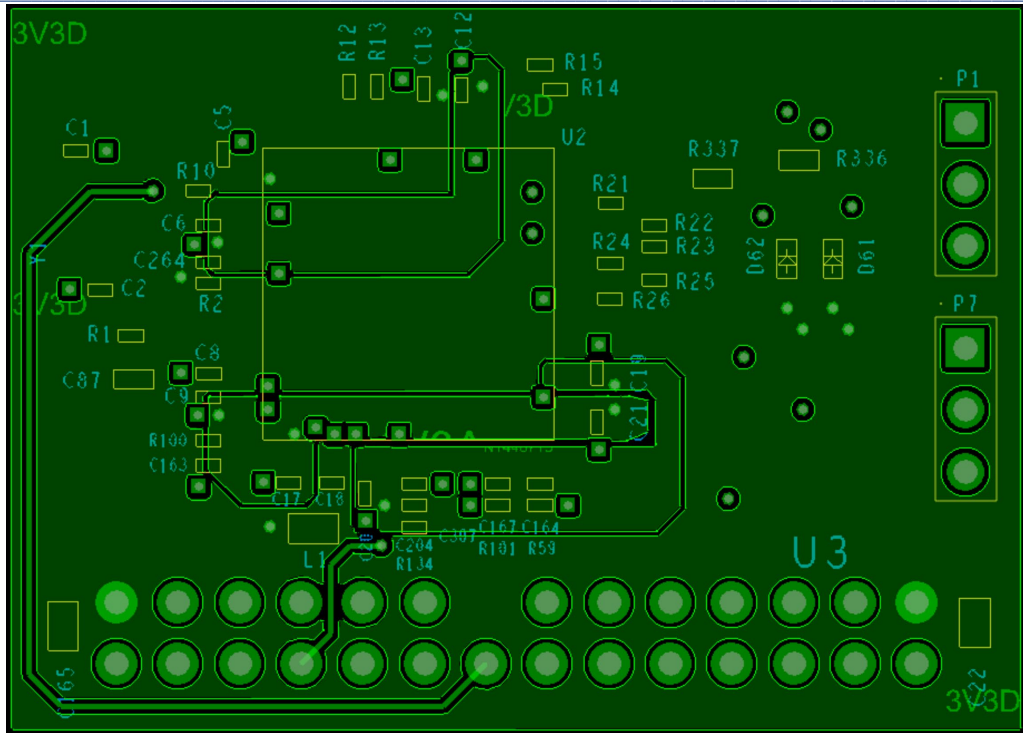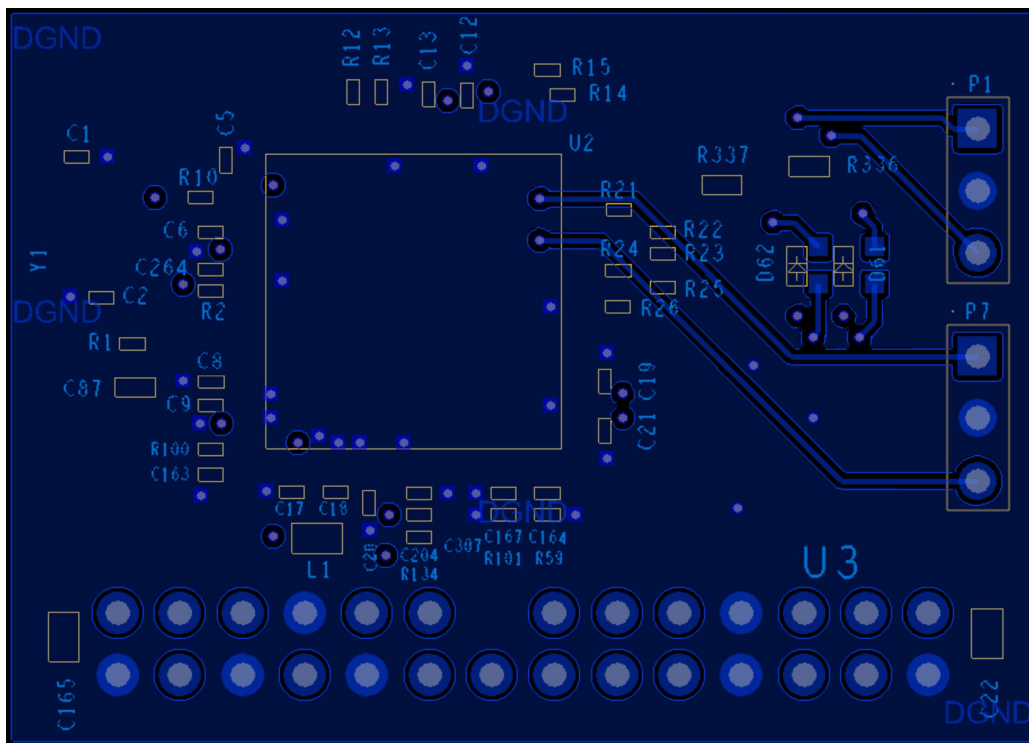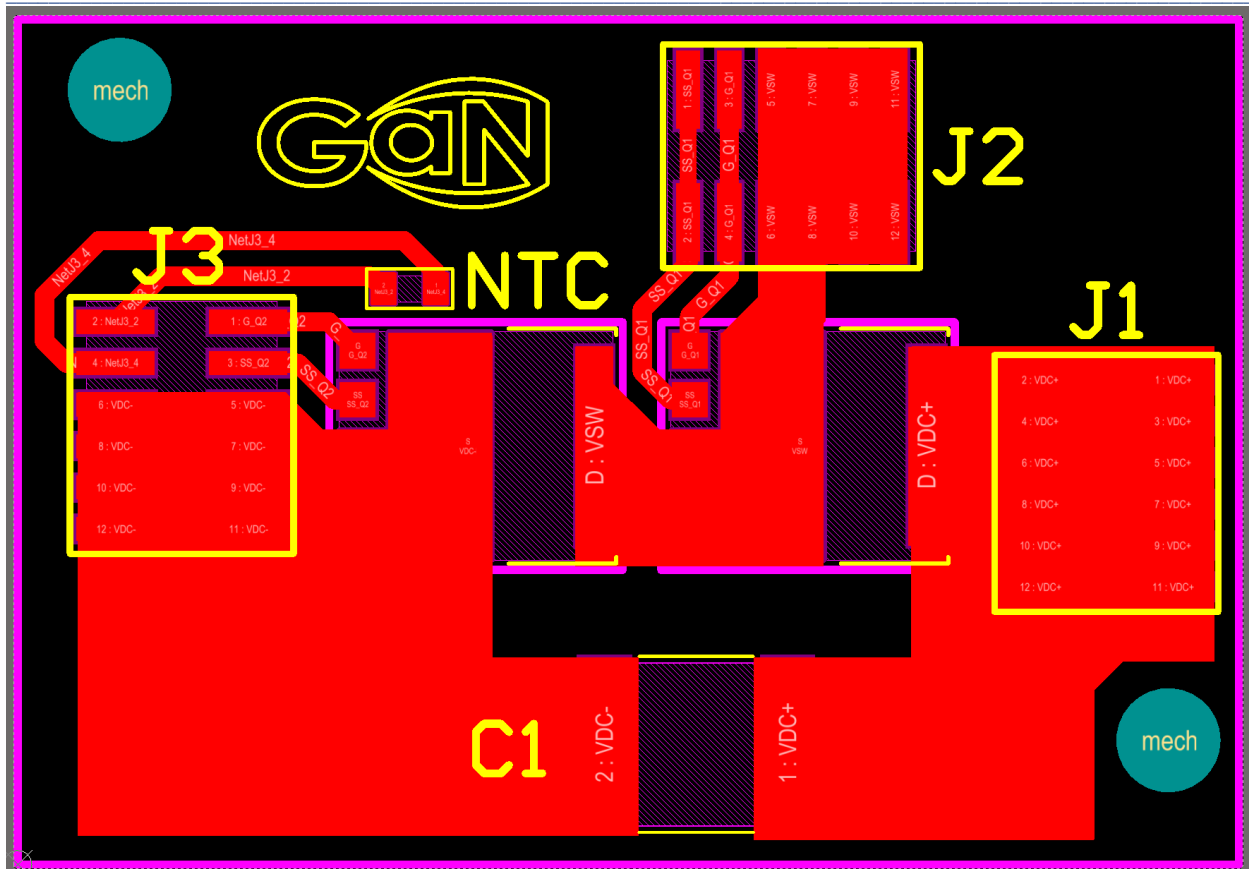
Please refer to the Evaluation Board/Kit Important Notice on page 41.

Figure. 8.8. GaN IMS board PCB layout

Please refer to the Evaluation Board/Kit Important Notice on page 41.

8.3 List of Materials

Table 8.1. GaN driver board list of materials

QTY	Ref-Des	Manufacturer	Part Number	Description
3	C6,C7,C8	Knowles Syfer	2220Y6300105KXTWS2	CAP CER 1UF 630V X7R 2220
4	C11,C12,C25, C26	Taiyo Yuden	EMK212BBJ226MG-T	CAP CER 22uF 16V 20% X5R 0805
1	C17	TDK Corporation	C3216X7R1V106K160AC	CAP CER 10uF 35V 10% X7R 1206
2	C18,C30	Kemet	C0603C101K5RACTU	CAP CER 100pF 50V 10% X7R 0603
4	C19,C21,C31, C37	Samsung Electro-Mechanics America, Inc	CL21B105KAFNNNE	CAP CER 1uF 25V 10% X7R 0805
1	C20	AVX Corporation	MM033C104KCZ2A	CAP CER 100nF 25V X7R 0603
6	C23,C24,C36, C38,C40,C41	Taiyo Yuden	UMK212F224ZD-T	CAP CER 220nF 50V -20%/+80% Y5V 0805
2	C29,C44	TDK Corporation	C1608X5R1C225K080AB	CAP CER 2.2uF 16V 10% X5R 0603
4	C100,C102,C103,C104	Taiyo Yuden	TMK212AB7475KG-T	CAP CER 4.7uF 25V 10% X7R 0805
1	D1	GeneSiC Semiconductor	GB01SLT06-214	DIODE SCHOTTKY 650V 1A DO214AA
2	L1,L2	TDK Corporation	VLS2012ET-150M	FIXED IND 15uH 400mA 1.062ohm
1	P1	Molex	901210766	CONN HEADER R/A 6POS 2.54MM
2	P3,P7	Molex	901210762	CONN HEADER R/A 2POS 2.54MM
1	P5	Molex	901210763	CONN HEADER R/A 3POS 2.54MM
3	R9,R16,R27	Stackpole Electronics Inc	RMCF0603JT1R00	RES 1R 1/10W 5% 0603
4	R10,R15,R17, R26	Stackpole Electronics Inc	RMCF0603JT10R0	RES 10R 1/10W 5% 0603
2	R13,R24	Panasonic Electronic Components	ERJ-PA3F75R0V	RES 75R 1% 1/4W 0603 100ppm/C Pulse-withstanding
2	R14,R25	Panasonic Electronic Components	ERJ-3EKF4992V	RES 49.9k 1% 1/10W 0603 100ppm/C
2	R18,R28	Panasonic Electronic Components	ERJ-3EKF2490V	RES 249R 1% 1/10W 0603 100ppm/C
2	R20,R30	Panasonic Electronic Components	ERJ-3EKF9760V	RES 976R 1% 1/10W 0603 100ppm/C
2	R21,R31	Yageo	RC0603FR-071KL	RES 1k 1/10W 1% 0603
2	R22,R32	Panasonic Electronic Components	ERJ-3EKF1053V	RES 105k 1% 1/10W 0603 100ppm/C
2	R23,R33	Panasonic Electronic Components	ERJ-3EKF5110V	RES 511R 1% 1/10W 0603 100ppm/C
2	R34,R35	Panasonic Electronic Components	ERJ-3EKF1003V	RES 100k 1% 1/10W 0603 100ppm/C
2	U1,U4	Silicon Labs	SI8271GB-ISR	DGTL ISO 2.5KV GATE DRVR 8SOIC
2	U3,U6	Texas Instruments	LM43601PWPR	IC REG BUCK ADJ 1A SYNC 16SSOP
2	U8,U9	Texas Instruments	LM317AEMPX/NOPB	IC REG LIN POS ADJ 1.5A SOT223-4

Table 8.2. Mother board list of materials

QTY	Ref-Des	Manufacturer	Part Number	Description
1	C1	Taiyo Yuden	EMK325AC6476MM-P	CAP CER 47uF 16V 20% X6S 1210
1	C2	Taiyo Yuden	UMK107AB7105KA-T	CAP CER 1uF 50V 10% X7R 0603
1	C3	TDK Corporation	C3225X7R2J473K200AM	CAP CER 47nF 630V 10% X7R 1210
1	C4	TDK Corporation	CGA6M2C0G2A333J200AA	CAP CER 33nF 100V 5% NP0 1210
5	C5,C27,C28,C38,C40	Kemet	C0603C104K4RACTU	CAP CER 100nF 16V 10% X7R 0603
2	C6,C7	Taiyo Yuden	EMK325ABJ107MM	CAP CER 100uF 16V 20% X5R 1210
1	C8	Samsung Electro-Mechanics America, Inc	CL31X226KAHN3NE	CAP CER 22uF 25V 10% X6S 1206
1	C9	TDK Corporation	C1608X5R0J226M080AC	CAP CER 22uF 6.3V 20% X5R 0603
4	C10,C11,C25,C26	Murata Electronics North America	DE1E3KX102MA4BP01F	CAP CER 1nF 300VAC 20% E Radial Disc X1 Y1 10mm Lead Spacing
3	C13,C14,C15	Rubycon	450VXH150MEFCSN22X35	CAP ALUM 150UF 20% 450V SNAP
1	C16	Wurth Electronics Inc	890334024005CS	CAP FILM 470nF 310VAC RADIAL 10% X2
3	C18,C19,C20	Kemet	C1812V334KCRACTU	CAP CER 330nF 500V 10% X7R 1812
1	C21	EPCOS (TDK)	B32923C3225M	CAP FILM 2.2uF 305Vac RADIAL 20% X2 22.5mm Lead Spacing
1	C22	Vishay BC Components	VY2103M63Y5US63V7	CAP CER 10nF X1-440Vac Y2-300Vac 20% RADIAL X1Y2 7.5mm Lead Space
2	C23,C33	Nichicon	PCS1C121MCL1GS	CAP ALUM 120uF 16V 20% SMD
4	C24,C29,C30,C31	TDK Corporation	C2012X6S1C106K085AC	CAP CER 10uF 16V 10% X6S 0805
1	C34	Yageo	CC0805KKX7R7BB105	CAP CER 1uF 16V 10% X7R 0805
1	C35	AVX Corporation	SQCB7M4R7CAJME	CAP CER 4.7pF 500V +-0.25pF Microwave 1111
1	C36	Kemet	C1206C104K4RACTU	CAP CER 100nF 16V 10% X7R 1206
1	C37	Samsung Electro-Mechanics America, Inc	CL10B105KQ8NNNC	CAP CER 1uF 6.3V 10% X7R 0603
1	C39	Kemet	C1206Y104K9RAC7800	CAP CER 100nF 6.3V 10% X7R 1206
1	C204	Kemet	C0402C122J5GACTU	CAP CER 1.2nF 50V 5% NP0 0402
1	C275	TDK Corporation	C1005X7R1C104K050BC	CAP CER 100nF 16V 10% X7R 0402
1	C307	Murata Electronics North America	GRM1555C1H221JA01D	CAP CER 220pF 50V 5% NP0 0402

4	D1,D3,D4,D11	ON Semiconductor	MBR2H100SFT3G	DIODE SCHOTTKY 100V 2A SOD123FL
1	D2	Diodes Incorporated	S1J-13-F	DIODE GEN PURPOSE 600V 1A DO-214AC (SMA)
2	D5,D9	Littelfuse Inc	V150LA10AP	VARISTOR MOV 150Vac 200Vdc 216Vclmin DISC 14mm 7.5mm spacing
1	D6	Fairchild Semiconductor	ES1J	DIODE FAST REC 600V 1A DO-214AC (SMA)
1	D7	Littelfuse Inc	V14E300P	VARISTOR MOV 300Vac 385Vdc 423Vclmin DISC 14mm 7.5mm spacing
2	D8,D10	ON Semiconductor	MMSZ4702T1G	DIODE ZENER 15V 500mW SOD123
2	F1,F2	Bel Fuse Inc.	5STP 12.5-R	FUSE 12.5A 250Vac SLOW 5X20mm GLASS TH AXIAL
2	J1,J2	Pomona Electronics	72930-2	CONN BANANA F PANEL MOUNT RED 36A for Sheathed Plugs
1	J3	Pomona Electronics	72930-5	CONN BANANA F PANEL MOUNT GREEN 36A for Sheathed Plugs
2	J4,J6	Pomona Electronics	72930-0	CONN BANANA F PANEL MOUNT BLACK 36A for Sheathed Plugs
1	J5	Littelfuse Inc	SL1011A230A	GAS TUBE 230V MED DUTY 5kA Axial
1	L1	Taiyo Yuden	CBC3225T100MR	IND 10uH 20% 900mA 172.9mR SMD 1210
1	L3	Wurth Electronics Inc.	744824101	COMMON MODE CHOKE 1MH 10A 2LN TH
1	L5	Minntronix	MTX4816110R	200uH output Inductor
2	L6,L7	Pulse Electronics Power	PE-92116KNL	FIXED IND 55UH 7A 17 MOHM TH
1	L8	Wurth Electronics	7448031002	7448031002
1	P1	Harwin Inc	M20-9980846	CONN HEADER M .100 2x8 16POS VERT TIN PC TAIL PIN
2	Q2,Q4	Diodes Incorporated	ZXTP25020CFFTA	TRANSISTOR PNP MED PWR 20V SOT-23F-3
1	Q5	Fairchild Semiconductor	2N7002K	MOSFET N-CH 60V 300mA SOT-23-3
2	Q6,Q7	ON Semiconductor	FCH023N65S3-F155	MOSFET N-CH 650V 75A TO247
1	R1	Stackpole Electronics Inc	RMCF0805ZT0R00	RES 0R 1/8W JUMP 0805
1	R2	Rohm Semiconductor	MCR50JZHJ104	RES 100k 1/2W 5% 2010
1	R3	Vishay	CRCW0603499RFKEA	RES 499R 1/10W 5% 0603
1	R4	Panasonic Electronic Components	ERA-3AEB5360V	RES 536R 1/10W 0.1% 0603
1	R5	Panasonic Electronic Components	ERJ-14BQF1R6U	RES 1.6R 1% 1/2W 1210 100ppm/C Current Sense

2	R6,R7	Panasonic Electronic Components	ERJ-M1WSF12MU	RES 12mR 1% 1W 2512 100ppm/C Current Sense
3	R8,R10,R12	Rohm Semiconductor	ESR10EZPJ100	RES 10R 0.4W 5% 0805
2	R9,R11	Yageo	RC0805FR-07100RL	RES 100R 1/8W 1% 0805
1	R13	Stackpole Electronics Inc	RMCF0603FT10K0	RES 10k 1/10W 1% 0603
8	R15,R32,R33,R34,R35,R36,R37,R38	Ohmite	HVC1206T5004JET	RES 5M 1/4W 5% 1206
2	R18,R19	Yageo	RC0603FR-0712RL	RES 12R 1/10W 1% 0603
2	R20,R21	Panasonic Electronic Components	ERJ-3EKF4531V	RES 4.53k 1% 1/10W 0603 100ppm/C
1	R22	Stackpole Electronics Inc	RMCF0603ZT0R00	RES 0R 1/10W JUMP 0603
3	R23,R25,R27	Panasonic Electronic Components	ERJ-3EKF22R0V	RES 22R 1% 1/10W 0603 100ppm/C
2	R24,R26	Panasonic Electronic Components	ERJ-3EKF1501V	RES 1.5k 1% 1/10W 0603 100ppm/C
2	R28,R31	Yageo	RC0603FR-0710KL	RES 10k 1/10W 1% 0603
2	R29,R30	Panasonic Electronic Components	ERJ-3EKF2261V	RES 2.26k 1% 1/10W 0603 100ppm/C
4	R134,R281,R282,R283	Panasonic Electronic Components	ERJ-2RKF3322X	RES 33.2k 1% 1/10W 0402 100ppm/C
1	R280	Panasonic Electronic Components	ERJ-3EKF4532V	RES 45.3k 1% 1/10W 0603 100ppm/C
1	T1	Transtek	TMS63966CT	Dual primary flyback
1	T2	Minntronix	MTX4815220R	High Frequency CS transformer
1	TH1	Ametherm	SL15 22101	CURRENT LIMITER INRUSH 220R 1A
19	TP1,TP3,TP4,TP5,TP6,TP7,TP8,TP9,TP10,TP11,TP12,TP13,TP14,TP15,TP16,TP17,TP18,TP24,TP25	Keystone Electronics	5015	CONN PCB TEST POINT SMT 0.25mm
1	U1	Power Integrations	LNK586DG	IC Offline Switcher Zero Standby Pwr SO8C
1	U10	Microchip Technology	MCP1703AT-5002E/CB	IC REG LDO 5V 250mA SOT-23A-3
1	U11	Analog Devices Inc	ADA4891-2ARZ-R7	IC OPAMP GP 240MHZ RRO 8SOIC
1	U5	Analog Devices Inc	ADUM4223BRWZ	IC DGTL ISO 2CH LOGIC 16SOIC-W 7.5V MIN OUTPUT
1	U6	Panasonic Electric Works	ALE1PB09	RELAY GEN PURPOSE SPST-NO 16A 9V
20	U14	Alpha Wire	295 SV005	WIRE BUS BAR 16AWG 100' TINNED
1	U8	Silicon Labs	SI8920AC-IP	IC OP AMP ISOLATION 8DIP-GW 16xGain

Please refer to the Evaluation Board/Kit Important Notice on page 41.

Table 8.3. PFC controller board list of materials

QTY	Ref-Des	Manufacturer	Part Number	Description
2	C1,C2	Murata Electronics North America	GRM1555C1E180JA01D	CAP CER 18pF 25V 5% NP0 0402
8	C5,C6,C12,C13, C18,C19,C20, C264	TDK Corporation	C1005X5R0J475M050BC	CAP CER 4.7uF 6.3V 20% X5R 0402
1	C8	Murata Electronics North America	GRM155R71C104KA88D	CAP CER 100nF 16V 10% X7R 0402
3	C9,C17,C21	TDK Corporation	C1005X6S0J225K050BC	CAP CER 2.2uF 6.3V 10% X6S 0402
2	C22,C165	TDK Corporation	C2012X5R0J476M125AC	CAP CER 47uF 6.3V 20% X5R 0805
1	C87	Kemet	C0603C103K4RACTU	CAP CER 10000PF 16V X7R 0603
3	C163,C164,C167	Murata Electronics North America	GRM1555C1H221JA01D	CAP CER 220pF 50V 5% NP0 0402
1	D63	Kingbright	APTD1608LSURCK	LED RED CLEAR SMD
1	D64	Kingbright	APTD1608LZGCK	LED GREEN CLEAR 0603 SMD
1	L1	Wurth Electronics Inc	742792063	FERRITE BEAD 60 OHM 3.0A 0805
2	P1,P7	Harwin Inc	M20-9990346	CONN HEADER M .100 1x3 3POS VERT TIN
1	R1	Stackpole Electronics Inc	RMCF0402JT22R0	RES 22R 1/16W 5% 0402
1	R2	Stackpole Electronics Inc	RMCF0402FT10K0	RES 10k 1/16W 1% 0402
11	R10,R12,R13,R14, R15,R21,R22,R23, R24,R25,R26	Panasonic Electronic Components	ERJ-2RKF75R0X	RES 75R 1% 1/10W 0402 100ppm/C
2	R336,R337	Panasonic Electronic Components	ERJ-PA3F1501V	RES 1.5k 1% 1/4W 0603 100ppm/C Pulse-withstanding
1	U2	Solantro Semiconductor	SA4041-QM	SOL IC SA4041 SA4041-QM 64kB RAM 256kB FLASH 80-pin LQFP 12x12 mm 0.5 mm pitch
1	U3	Sullins Connector Solutions	PRPC014DBAN-M71RC	CONN HEADER M .100 2x14 28POS RA GOLD
1	Y1	ECS Inc	ECS-250-18-33Q-DS	CRYSTAL 25MHz 18pF SMD 4-SMD, No Lead (DFN, LCC) - 40Cto125C

Please refer to the Evaluation Board/Kit Important Notice on page 41.

Evaluation Board/kit Important Notice

GaN Systems Inc. (GaN Systems) and Solantro Semiconductor Corp. (Solantro) provide the enclosed product(s) under the following **AS IS** conditions:

This evaluation board/kit being sold or provided by GaN Systems and Solantro is intended for use for **ENGINEERING DEVELOPMENT, DEMONSTRATION, and OR EVALUATION PURPOSES ONLY** and is not considered by GaN Systems nor Solantro to be a finished end-product fit for general consumer use. As such, the goods being sold or provided are not intended to be complete in terms of required design-, marketing-, and/or manufacturing-related protective considerations, including but not limited to product safety and environmental measures typically found in end products that incorporate such semiconductor components or circuit boards. This evaluation board/kit does not fall within the scope of the European Union directives regarding electromagnetic compatibility, restricted substances (RoHS), recycling (WEEE), FCC, CE or UL, and therefore may not meet the technical requirements of these directives, or other related regulations.

If this evaluation board/kit does not meet the specifications indicated in the User's Guide, the board/kit may be returned within 30 days from the date of delivery for a full refund. THE FOREGOING WARRANTY IS THE EXCLUSIVE WARRANTY MADE BY THE SELLER TO BUYER AND IS IN LIEU OF ALL OTHER WARRANTIES, EXPRESSED, IMPLIED, OR STATUTORY, INCLUDING ANY WARRANTY OF MERCHANTABILITY OR FITNESS FOR ANY PARTICULAR PURPOSE. EXCEPT TO THE EXTENT OF THIS INDEMNITY, NEITHER PARTY SHALL BE LIABLE TO THE OTHER FOR ANY INDIRECT, SPECIAL, INCIDENTAL, OR CONSEQUENTIAL DAMAGES.

The user assumes all responsibility and liability for proper and safe handling of the goods. Further, the user indemnifies GaN Systems and Solantro from all claims arising from the handling or use of the goods. Due to the open construction of the product, it is the user's responsibility to take any and all appropriate precautions with regard to electrostatic discharge.

No License is granted under any patent right or other intellectual property right of GaN Systems and Solantro whatsoever. **GaN Systems nor Solantro assume liability for applications assistance, customer product design, software performance, or infringement of patents or any other intellectual property rights of any kind.**

GaN Systems and Solantro currently service a variety of customers for products around the world, and therefore this transaction **is not exclusive**.

Please read the User's Guide and, specifically, the Warnings and Restrictions notice in the User's Guide prior to handling the product. Persons handling the product(s) must have electronics training and observe good engineering practice standards.

This notice contains important safety information about temperatures and voltages. For further safety concerns, please contact a GaN Systems' or Solantro application engineer.

© 2019 Solantro® The mark "Solantro" is a registered trademark of Solantro Semiconductor Corp. DPD1174 rev. 1
© 2019 GaN Systems Inc GS1200BTP-EVB – rev 190923   41

Please refer to the Evaluation Board/Kit Important Notice on page 41.

GaN Systems

Canada:

GaN Systems Inc.
1145 Innovation Drive Suite 101
Ottawa, Ontario, Canada K2K 3G8
T +1 613-686-1996

In Europe:

GaN Systems Ltd., German Branch
Terminalstrasse Mitte 18,
85356 München, Germany
T +49 (0) 8165 9822 7260

In the United States:

GaN Systems Corp.
2723 South State Street, Suite 150,
Ann Arbor, MI. USA 48104
T +1 248-609-7643

solantro®
SEMICONDUCTOR CORP.

In Canada:

Solantro Semiconductor Corp. Inc.
146 Colonnade Rd, Suite 200,
Ottawa ON, K2E7Y1
T +1 613-274-0440

In China:

Solantro (Shanghai Belling) Branch
810, Yishan Road
Shanghai, China, 200233
T +86-21-24261000

© 2019 Solantro® The mark "Solantro" is a registered trademark of Solantro Semiconductor Corp. DPD1174 rev. 1
© 2019 GaN Systems Inc   GS1200BTP-EVB – rev 190923   42

Please refer to the Evaluation Board/Kit Important Notice on page 41.