350 W LLC EVALUATION BOARD WITH ICeGaN™

User Guide

CGD-UG2204

Cambridge GaN Devices Limited	Property of Cambridge GaN Devices Ltd
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Safety Warning

DANGER: Do not touch the board when high voltages are applied. There are exposed locations of high voltage on the board when connected to a power source. Brief contact may result in serious injury or death. Allow all components to fully discharge before handling the board. This evaluation kit is designed for use by qualified, experienced engineers only. Appropriate safety measures must be put in place before use and the board should never be left unattended.

WARNING: Some components may become hot during operation and remain so afterwards. There is no built in electrical or thermal protection. Operating voltages, currents and temperatures should be monitored closely throughout operation to prevent damage to the board.

CAUTION: This product contains parts susceptible to ESD (electrostatic discharge). ESD prevention procedures must be used while handling the board.

Operating Limits and Recommendations

Operating outside this window is not recommended and may cause damage.

Voltage Limits

CGD has a recommended maximum operation of 400 V on the LLC board.
Low voltage inputs should not exceed 22 V

Heat Dissipation

Heatsinking the GaN switch devices has been provided through bottom side cooling of the devices. Heatsinking of the synchronous rectifiers has been provided through drain pads of the MOSFETs. CGD makes no guarantees as to the thermal performance of the heatsinking solution provided.

User Guide Overview

This user guide will outline the capabilities and operation of the CGD Half Bridge LLC Evaluation Board, and detail how the customer can use the board to rapidly design their own magnetics. It will explain the operation of the included design, with 4 separate PCBs and detail how each board can be adapted to match the user's needs. This guide, along with the board itself is targeted at experienced engineers with a prior understanding of the LLC topology. It will assume the competence of the engineer to safely operate the design with exposed high voltages.

Target Audience

This guide, along with the board itself, is aimed at experienced engineers and assumes a knowledge of necessary equipment to analyse the performance of the board. It is designed to enable SMPS engineers, Design Engineers and Technicians involved in the development of a system to rapidly assess the performance of CGD ICeGaN™ within the LLC topology.

Technical Support

CGD is happy to provide expert help with any questions or problems. For support, please contact CGD at techsupport@camgandevices.com.

Revision History

Revision Number	Comments	Engineer(s)	Date
1.0	Initial Release	JF	09/03/2022

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FIGURE LIST 38

1 Board Overview

Assembly Name	CGD Devices Utilised	$R_{DS(on)}$	Capabilities	Device Package
CGD-ASYEVB00501-01	CGD65A055S2	55 mΩ	ICeGaN™	DFN8x8

Table 1 - Part Numbers of CGD Hardware Covered by this User Guide

The Cambridge GaN Devices (CGD) LLC Evaluation Board highlights the performance advantages of CGD GaN over its competitors through ICeGaN™ Technology in the half bridge LLC topology. This board allows users to evaluate CGD GaN 650V transistors in this topology with their own resonant tank design. CGD ICeGaN™ Gate enables the driving of GaN HEMTs through an extremely large range of 9 to 20 V, allowing for easy and affordable drive through readily available silicon drivers, without having a detrimental impact on GaN's excellent switching performance. This is highlighted with the included UCC256402 LLC controller, conventionally used with silicon MOSFETs. In addition, CGD's ICeGaN™ increases the threshold voltage of the GaN to around 3 V, preventing unwanted turn-on events, eliminating the need for negative driving voltages, as required for other discrete enhancement mode HEMTs currently available on the market.

Figure 1 - Photograph of Half Bridge LLC Evaluation Board

1.1 Feature List

Basic featured of the board.

- 2 x 650 V CGD Devices
- ICeGaN™ Gate with 9-20 V Drive
- UCC256402 LLC controller
- SRK2001 Synchronous Rectifier Controller on Output with 2x80 V MOSFETs
- Example resonant tank design (Series Inductor + Transformer + Resonant Capacitor)

1.2 Minimum Required Equipment

List of the equipment the customer will need in order to operate the board.

- High Voltage DC supply
- Optional Low Voltage DC Supply
- Suitable load

1.3 Inputs and Outputs

The LLC evaluation board has been designed to be as simple as possible for the customer to operate. Using the included magnetics, the LLC has been configured to operate with a 20 V output and it optimised around a 380 V input voltage.

A shrouded header is included for the input of the LLC. The screw terminal has connections, one high voltage input, one low voltage input and two grounds. The two grounds are both referenced to the primary side of the LLC, although the one intended for use as HV return connects to 0 V via the common mode choke.

A pair of 3 mm screw holes have been included on the output to enable connection to a load with minimal additional resistance. Given the high current on the output the efficiency achieved is very sensitive to output resistance.

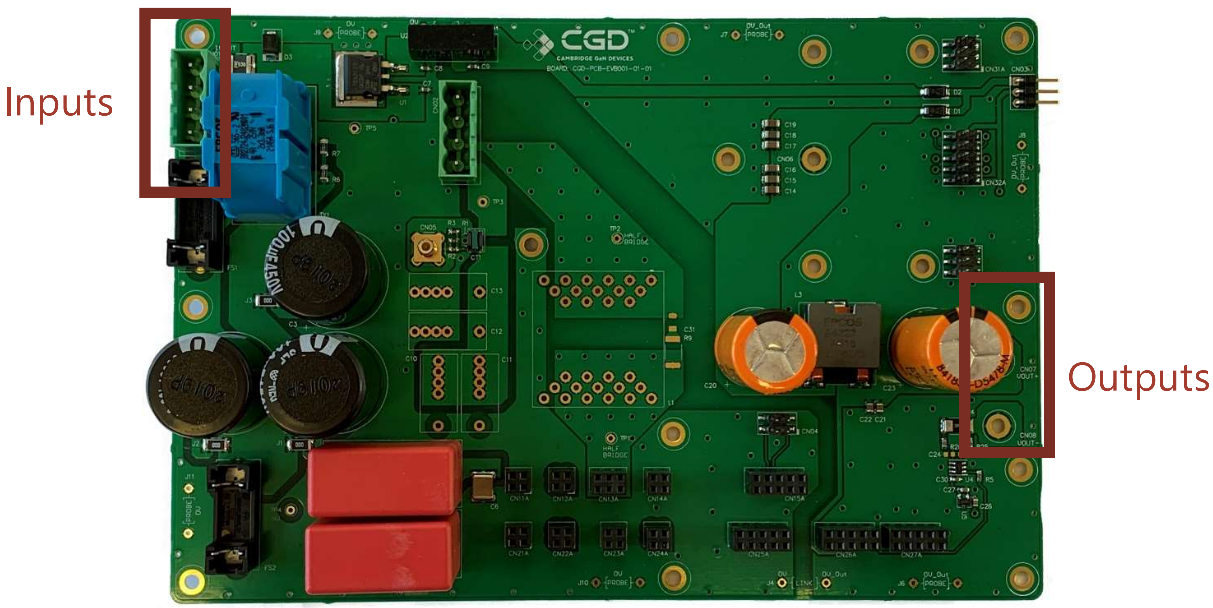

Figure 2 – Top View of Main Power Board with Inputs and Outputs

A full table of all input and output connections have been given below. Note this is the inputs and outputs to external equipment and does not include connections between different LLC Evaluation Board PCBs.

Signal	Ports	Connector Name	Comments
HV +	Shrouded Header	CN01 (Pin 1)	DC Input, Max 420 V_{DC}.
HV -	Shrouded Header	CN01 (Pin 2)	
LV +	Shrouded Header	CN01 (Pin 3)	DC Low Voltage, Max 22 V.
LV -	Shrouded Header	CN01 (Pin 4)	
V_{OUT+}	3mm Screw	CN07	
V_{OUT-}	3mm Screw	CN08	

Table 2 - Inputs and Outputs List

1.4 Board Overview

To enable maximum flexibility the LLC evaluation board has been designed as 4 different PCBs detailing 4 different building blocks for rapid development. Such a design allows the user to change a single building block and form a direct comparison without needing 2 full sets of hardware. The 4 PCBs are as follows.

- Main Power Board.

  This board carries the power from primary through to secondary. All the connections to external supplies and loads are made on this board. The resonant tank also sits on this board. The board can be split with two separate grounds and if chosen by the test engineer, there can be galvanic isolation between input and output.

- GaN Board

  This board houses the CGD GaN. This is the simplest of the 4 PCBs and along with the two CGD devices it holds a pair of headers intended for fans. There is also a small amount of decoupling for the high voltage on this PCB.

- LLC Controller Board

  The LLC Controller Board has the main LLC controller located upon it. It interfaces with both the Main Power Board as well as the GaN Board. Gate signals are passed directly from the LLC Controller Board to the GaN board to minimise gate loop inductance. Connections to the Main Power Board can be split into two sections, input side and output side. The input side is used for the controller operation including pins to enable start-up and sense the resonant tank. The output side connector is used for a feedback loop through an optocoupler.

- Synchronous Rectifier Board

  Included within the design is a Synchronous Rectifier Board that uses a pair of 80 V Infineon MOSFETs with a ST SRK2001 synchronous rectification controller. This board is configured to run in isolation from the primary side control.

Connectors on the boards have all been named based on their location, or by between which boards they connect. Any connector that interfaces between two boards will have the same number on both and an 'A' and a 'B' variant. This should make it clear how all the boards fit together and allow for easy signal tracing across the multiple schematic sheets. A table outlining this is shown below.

Board A	Board B	Connector Name
Main	N/A	CN0*
Main	GaN	CN1*A & CN1*B
Main	Controller	CN2*A & CN2*B
Main	Sync Rec	CN3*A & CN3*B
GaN	N/A	CN6*
GaN	Controller	CN5*A & CN5*B
Controller	N/A	CN7*
Sync Rec	N/A	CN8*

Table 3 - Table Showing Board Connector Names by Location

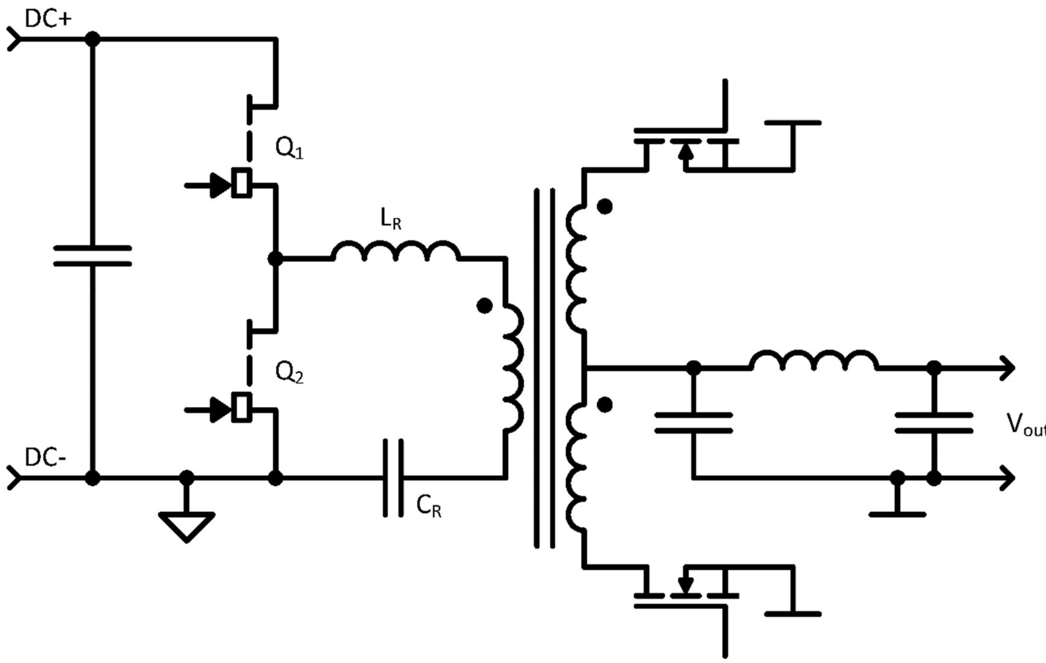

Figure 3 – Simplified LLC Schematic

1.5 Probe Locations

CGD has provided several different probe locations to allow the user to view all aspects of the evaluation board. Probe locations have been given names indicating their location on the schematic. It is advised the user cross references these against the schematic.

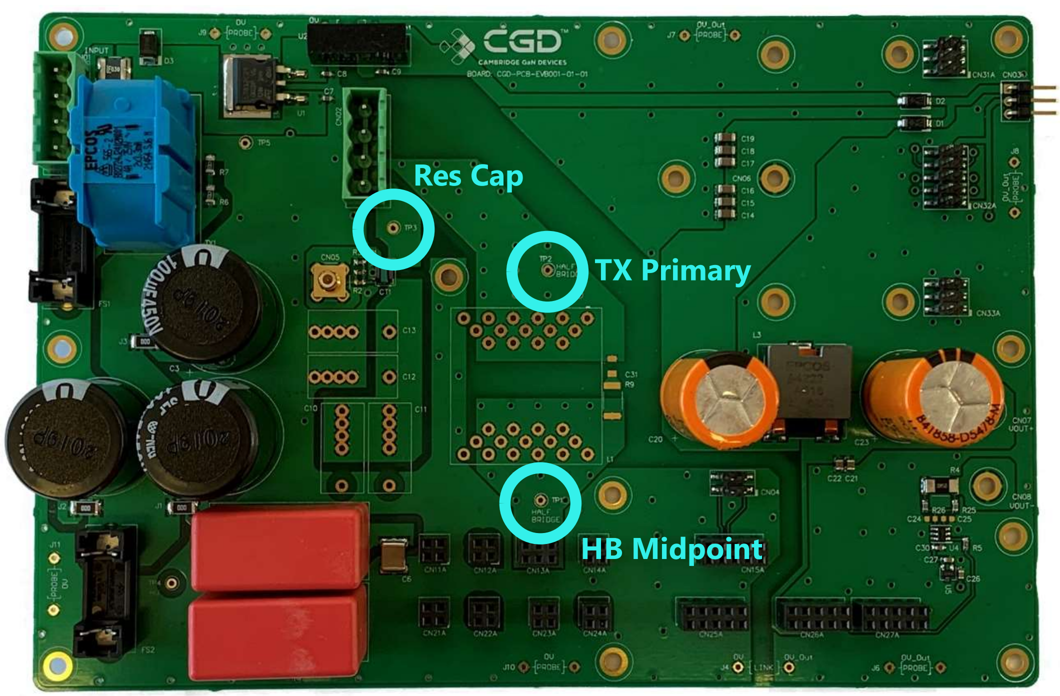

Figure 4 - Probe Locations on Main Power Board

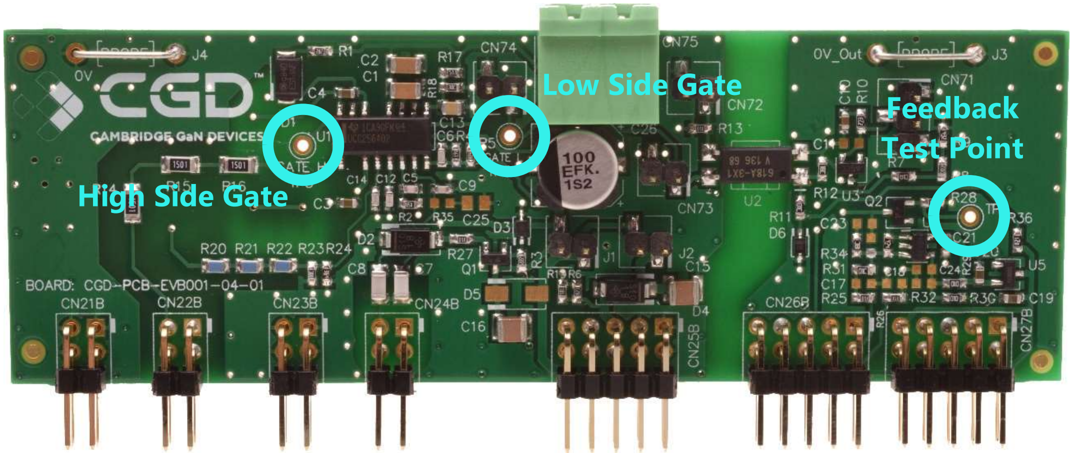

Figure 5 - Probe Locations on LLC Controller Board

2 Main Power Board

As mentioned, the Main Power Board is the primary board in the LLC Half Bridge Evaluation Board. It handles connections to loads and sources and interfaces with each of the three other boards. It is worth noting that galvanic isolation from primary and secondary is provided as an option throughout this PCB. There are however several link points where the user could choose to clamp the two grounds together should the user wish. This could be useful if the user wishes to be able to observe signals on both the primary and secondary of the PCB without using an isolated probe.

Find a labelled photograph of the Main Power Board below in Figure 6.

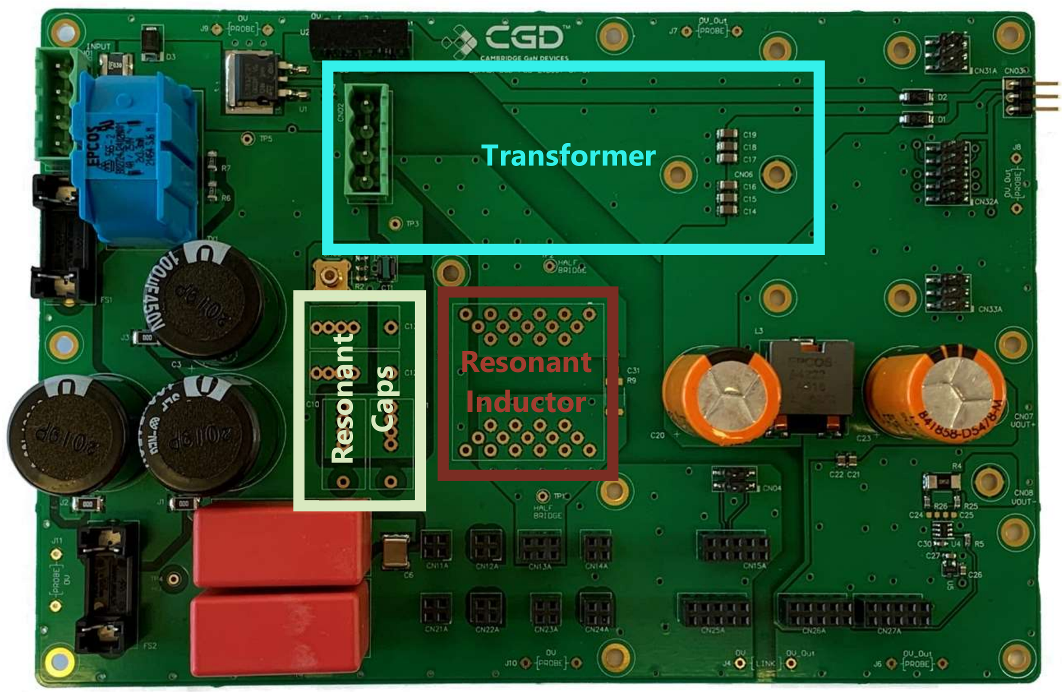

Figure 6 - Photograph of Main Power Board

2.1 Resonant Inductor

As can be seen in Figure 6 this board also houses the resonant inductor. Several provisions have been made to try and accommodate as large a range of designs as possible. Footprints for EFD20, EFD25 and EFD30 coil formers have been included on the PCB. Using a series inductor with a different footprint will require the engineer to use their judgement on the best way to solder it down. Should the user not require any additional series resonant inductance as they intend to use the stray inductance of the transformer this node will need to be shorted together.

2.2 Transformer

Space has been allocated for the transformer to allow for either a conventional or a planar design. On the primary side a screw terminal port (CN02) has been included as it is expected to carry relatively low current. Two of the pins are dedicated to the transformer primary while two are dedicated to the bias winding required to power the LLC controller. Providing power to the controller board via the bias winding is not mandatory, however the presence of the bias winding is required for the included controller to operate correctly. The secondary side is connected to both the Main Power Board and the Synchronous Rectifier Board through M3 studs. Given the high current of the output, the design is sensitive to just a few mΩ of parasitic resistance. The M3 studs are used to reduce this as much as possible. Note, the studs are not shown on this photograph, only the holes in which they are placed.

2.3 Resonant Capacitor

Included on the PCB is space for up to 4 resonant capacitors. Two run between net "Cres" and "0V" and two between "Cres" and the positive DC rail. Multiple spacings have been included within each capacitor footprint for use of differently spaced capacitors.

3 GaN Board

The GaN Board interfaces with both the Main Power Board as well as having a direct connection with the controller board. The connectors with the controller board carry the gate signals as well as the V_{DD} required for the ICeGaN™. The connectors with the main PCB carry the current for the main switching path of the half bridge. There is 440 nF of decoupling capacitance for the half bridge.

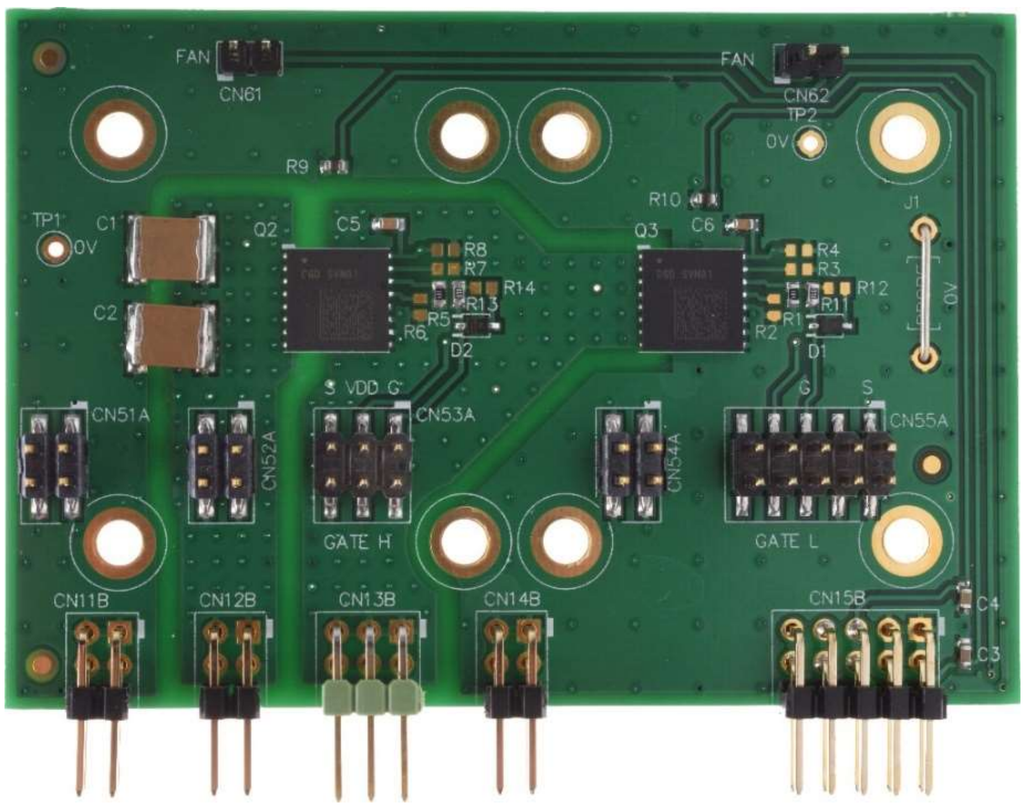

Figure 7 - Photograph of GaN Board

4 LLC Controller Board

The LLC Controller Board houses the TI UCC256402 controller. This half bridge LLC controller is designed to be used with Silicon MOSFETs and the UCC25640X line is widely accepted within the marketplace. For a detailed document describing the exact mechanisms of the UCC256402 CGD would recommend reading the datasheet for this part. For reference however some of the key parts that directly impact how the circuit operates have been outlined below.

4.1 Start Up

UCC256402 has two main pins important for start-up. The first is “HV”. This pin is used to draw power out of the HV bulk rail and charge the local low voltage supply. It is thought unlikely the user will require adjusting anything on this pin. The V_{CC} pin requires sufficient capacitance on it to hold up the voltage until power begins to arrive from the bias winding. CGD found that 100uF was required to achieve this. Secondly the BLK pin is used to sense the voltage on the bulk rail and set the voltage at which the controller should begin operation. Since UCC256402 is used in this example, the controller will begin switching when the BLK pin reached ~3 V. CGD has set this through the resistor chain R20, R21, R22, R23 and R24 to occur at around 325 V_{DC}. UCC256402 has no over-voltage protection on this pin. Once start up begins the controller will hold the low side device on for a period to charge the high side V_{DD} labelled “HB”. The voltage on HB is used to power the V_{DD} of the high side ICeGaN™ device and net R_{Vcc} is used to power the V_{DD} of the low side ICeGaN™ device. It is important to consider this when sizing capacitors on these nodes.

4.2 Control Loop

To control the LLC, the UCC256402 uses a combination of a representation of the primary side voltage and current as well as a FB pin representative of the voltage on the output of the converter. The signal to the FB pin is provided through an optocoupler to ensure galvanic isolation through the PCB.

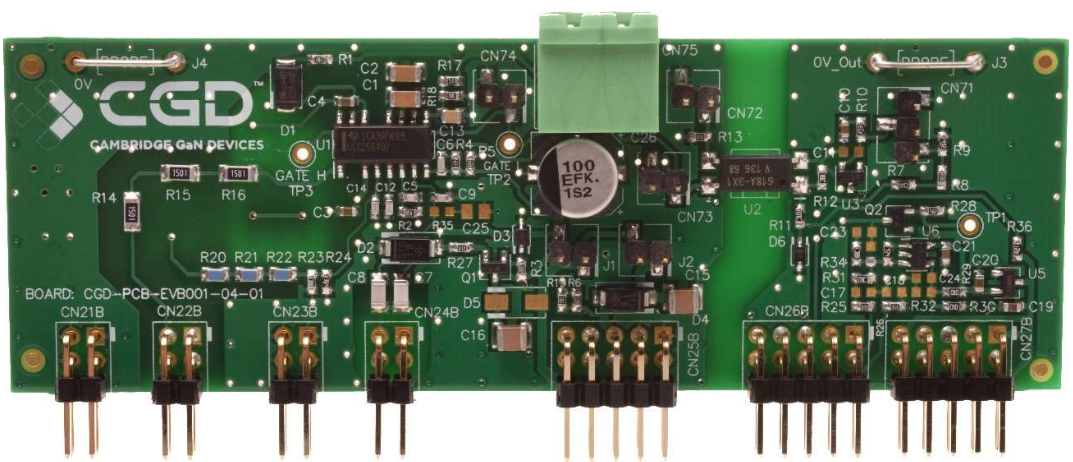

Figure 8 - Photograph of LLC Controller Board

5 Synchronous Rectifier Board

The Synchronous Rectifier Board contains two 1.9 mΩ 80 V Infineon MOSFETs and an SRK2001 controller. As photographed and labelled, at the top, there are the three screw holes used for the transformer connections. Two connect directly to the drain of the synchronous rectifier MOSFETs and the central hole passes through to the Main Power Board as the common central leg of the transformer. There are four provided 0 V connections (labelled on the PCB) that provide a low resistance path off the Synchronous Rectifier Board back to 0 V output on the Main Power Board.

This PCB has been designed to be able to run in isolation from the rest of the control network. It powers itself from the output voltage and regulates this to 12V to limit power dissipation from switching the MOSFETs. The jumpers on CN03 and CN84 must be set correctly to allow this.

For maximum flexibility with options for control, CGD has included a blank connector with 3 pairs of signals that run from the sync rec board along the Main Power PCB and to the Controller Board. CGD would expect these may be required should the user opt to swap the LLC Controller Board for one containing an MCU.

The Synchronous Rectifier Board has been designed such that the user can select its orientation. This means the probe points can be available in one orientation for the user to assess electrical performance while in the other orientation the board can be heatsinked to assess the thermal performance of the design.

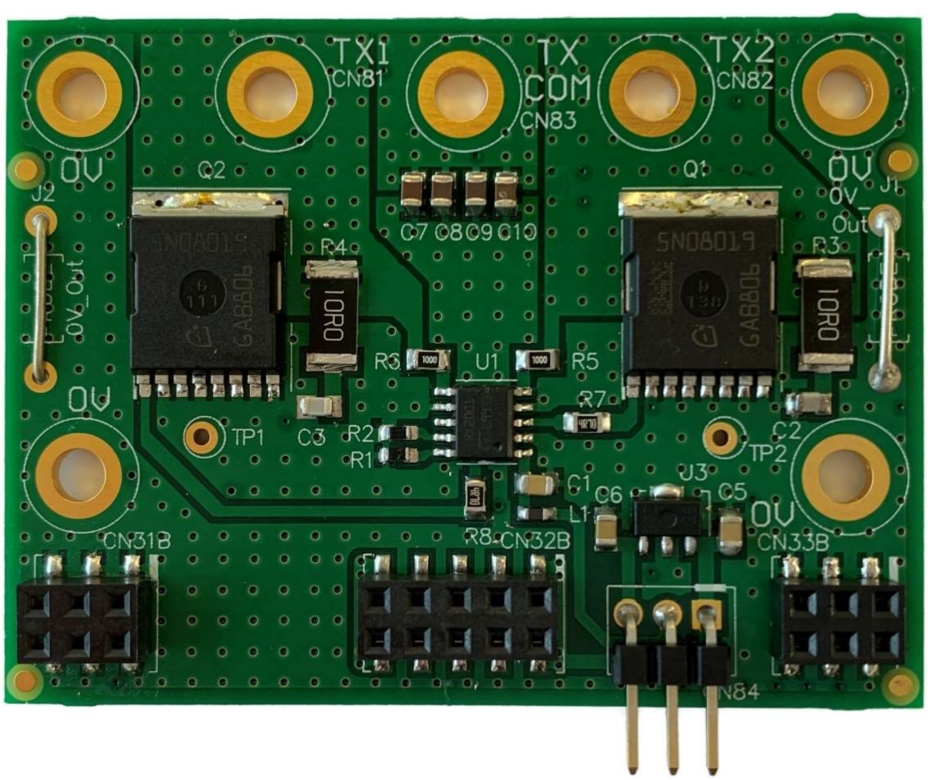

Figure 9 - Photograph of Synchronous Rectifier Board

6 Example Waveforms

CGD has included example magnetics to enable the evaluation board to be operational upon its delivery. For more information on component value selection and why said values have been selected please consult the CGD Application Note ICeGaN™ in LLC.

Figure 10 - LLC Eval Operating at 350 W. 2 µs/div.

LS Gate – Yellow (3 V/div), V_{mid} – Blue (100 V/div), Sync Rec Gate – Purple (4 V/div), I_{tank} – Green (3 A/div)

See the LLC Eval operating at full 350 W output power in Figure 10. V_{in} = 380 V_{DC}, V_{out} = 20 V. Probes are low side gate (yellow), half bridge switching node (blue), synchronous rectifier gate (purple) and primary side current (green). As expected, under nominal input voltage conditions the LLC is operating very close to resonance as tank gain $M_g \approx 1$. This can be observed by the near sinusoidal tank current. It can be seen frequency is at 238 kHz under this test condition. The original calculation estimated that f_0 would be at 237 kHz.

See below in Figure 11 a capture of the LLC operational at 100 W. Here secondary current has been captured rather than primary to show the synchronous rectifier operation.

Figure 11 - LLC Eval Operating at 100 W. 1 µs/div.

LS Gate – Yellow (10 V/div), V_{mid} – Blue (200 V/div), Sync Rec Gate – Purple (4 V/div), I_{sec1} – Green (3 A/div)

Features of SRK2001 can be observed. There is a blanking period included by the controller that ignores the initial spike causes by parasitic capacitance on the secondary side. Turning the device on during this condition would worsen system efficiency. Secondly the adaptive turn off can be seen by how close to the end of the conduction period the driver turns off. Adaptive turn off is required to compensate for stray inductance in series with the MOSFETs $R_{DS(on)}$.

Start up into 100 W has been shown in Figure 12. Note the features of UCC256402 where it turns on the low side device for a long period at the start of the first cycle to charge the high side V_{CC} through the bootstrap circuit. Once this fixed period is complete the normal start-up operation of the controller begins. CGD recommends that customers read the UCC25640x datasheet to understand the start-up sequence fully.

Please note the irregularly shaped current waveform is an artefact of scope aliasing due to the zoomed-out view taken to capture the full start up event.

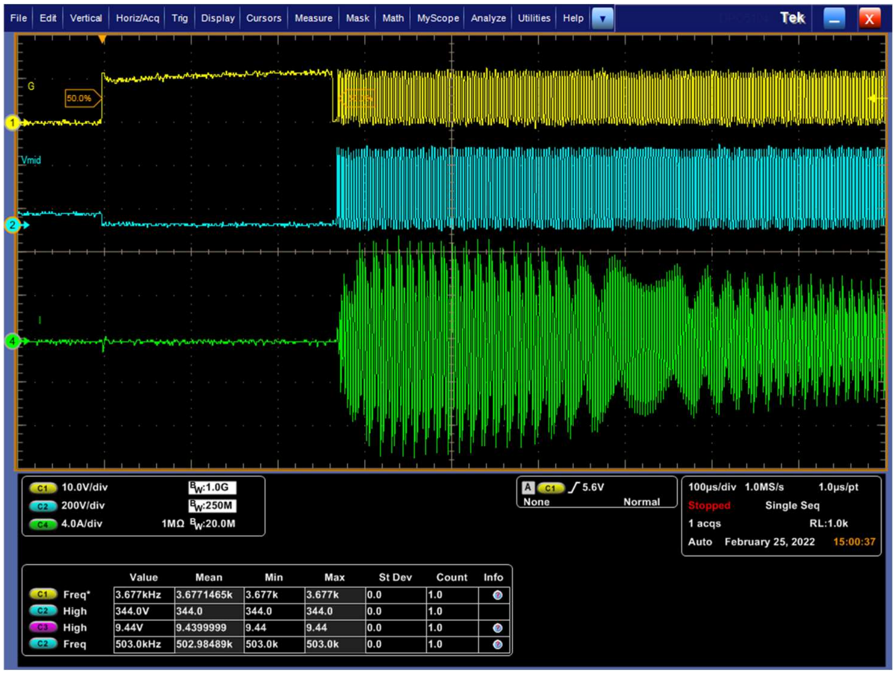

Figure 12 - LLC Start Up into 100 W. 200 µs/div.

LS Gate – Yellow (3 V/div), V_{mid} – Blue (100 V/div), I_{tank} – Green (3 A/div)

To highlight the stability of the loop and the stability of the output voltage a dynamic load test is shown below in Figure 13. Here load is stepped from 0% to 100% with 4 ms on and 6 ms off.

Figure 13 - LLC 0-100% Dynamic Load Steps

V_{out} – Purple (700 mV/div with 20 V offset), I_{out} – Green (4 A/div)

7 Schematics and Layout

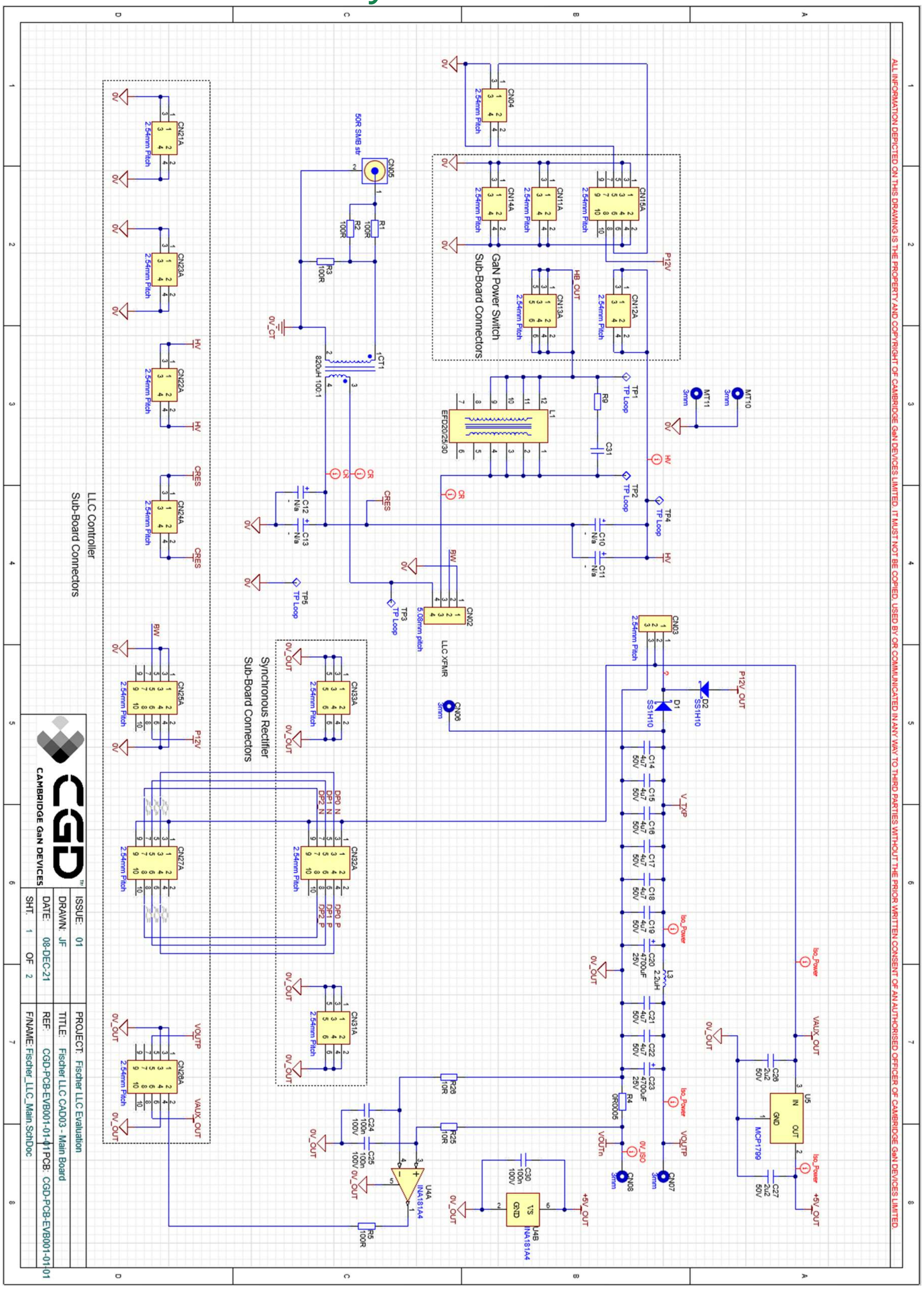

Figure 14 - Main Power Board Schematic Page 1

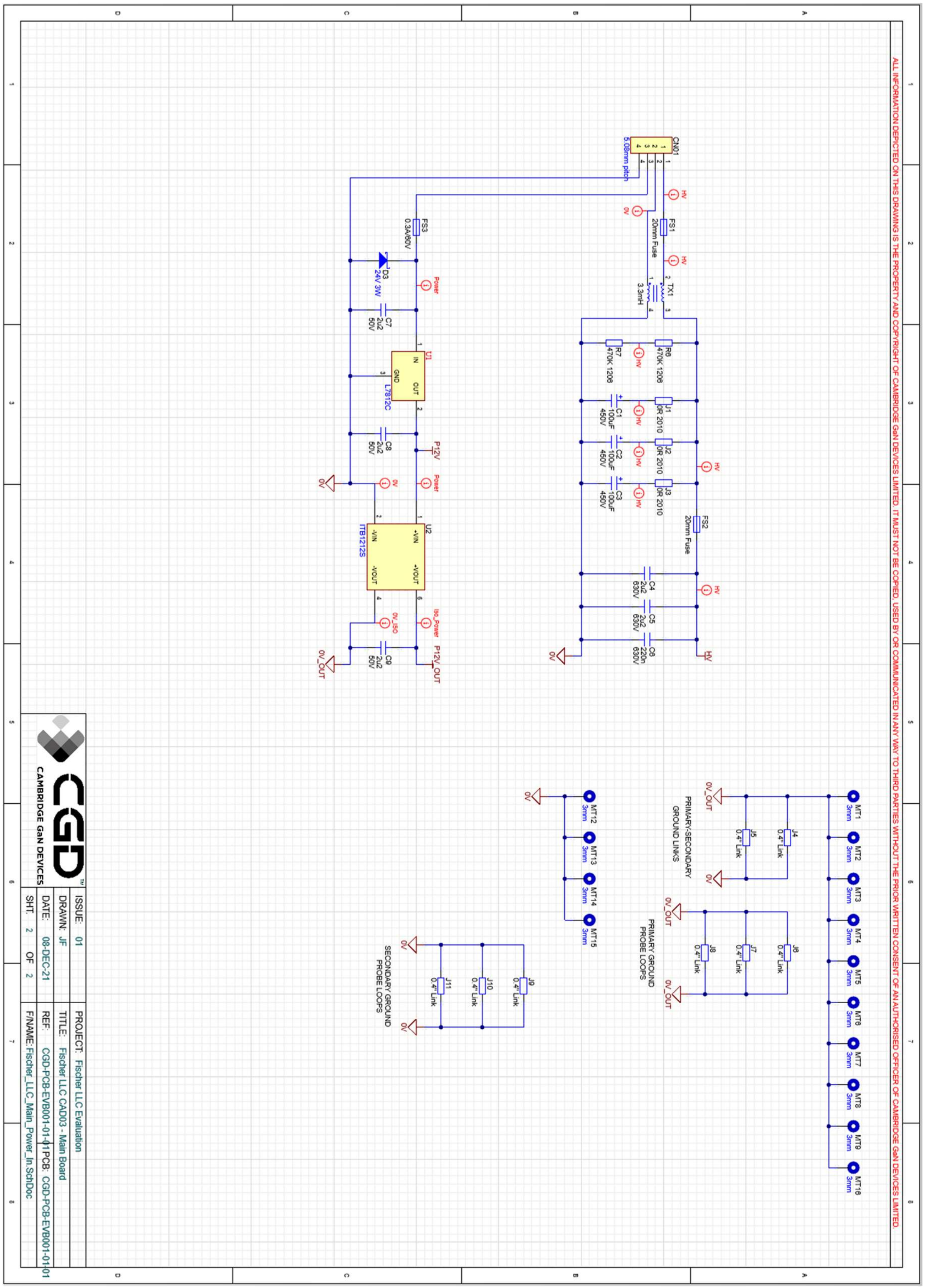

Figure 15 - Main Power Board Schematic Page 2

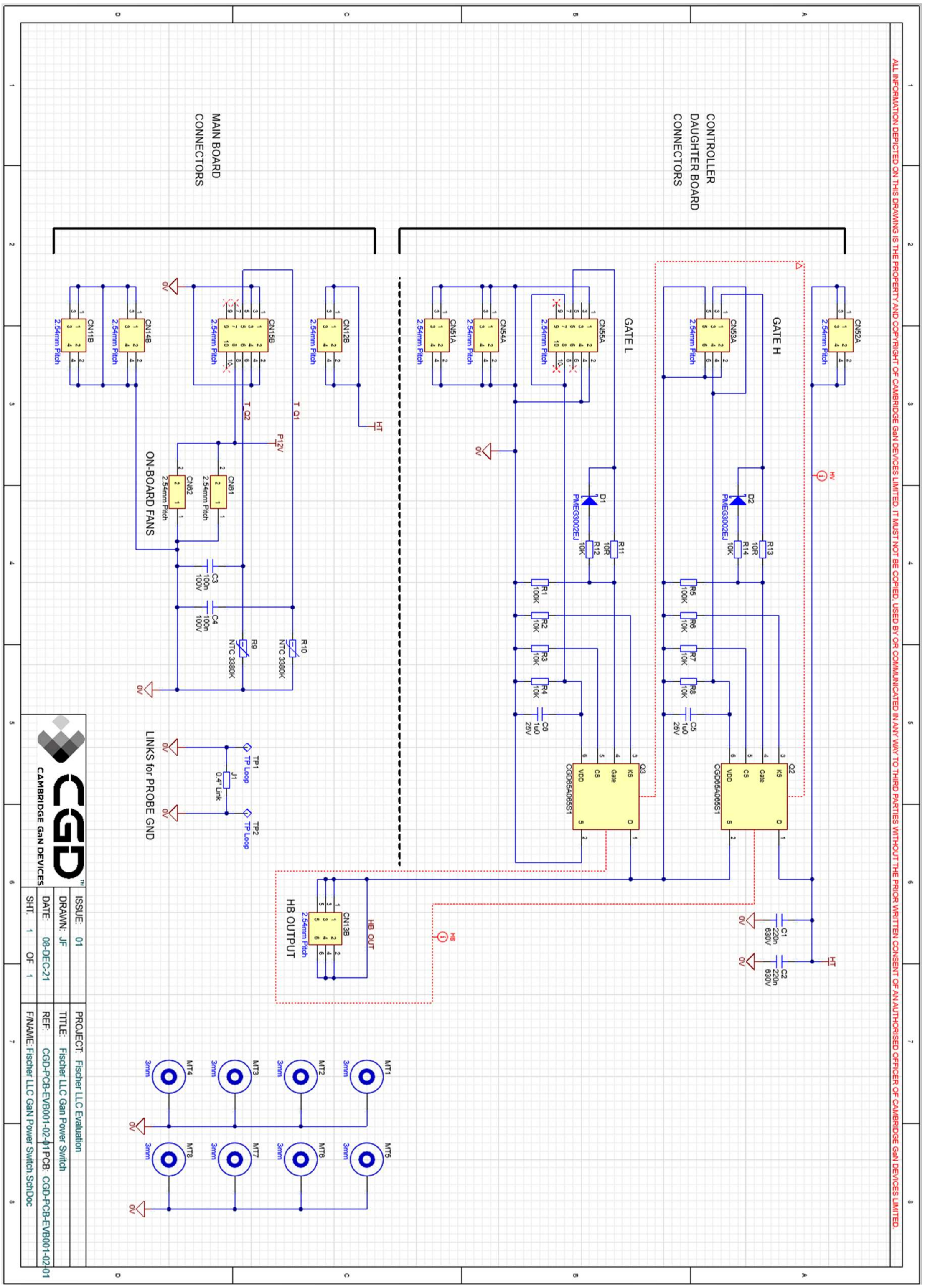

Figure 16 - GaN Board Schematic

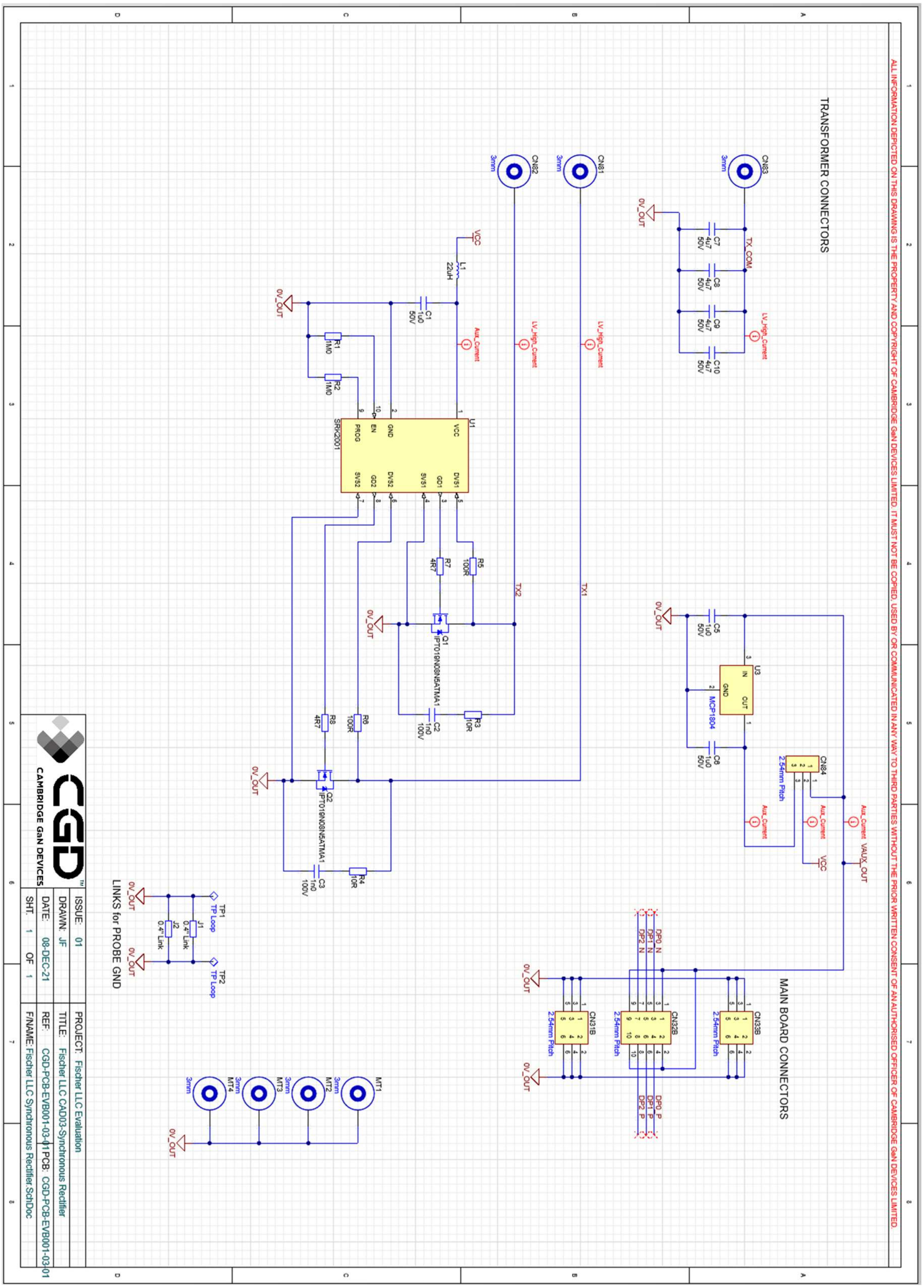

Figure 17 - Synchronous Rectifier Board Schematic

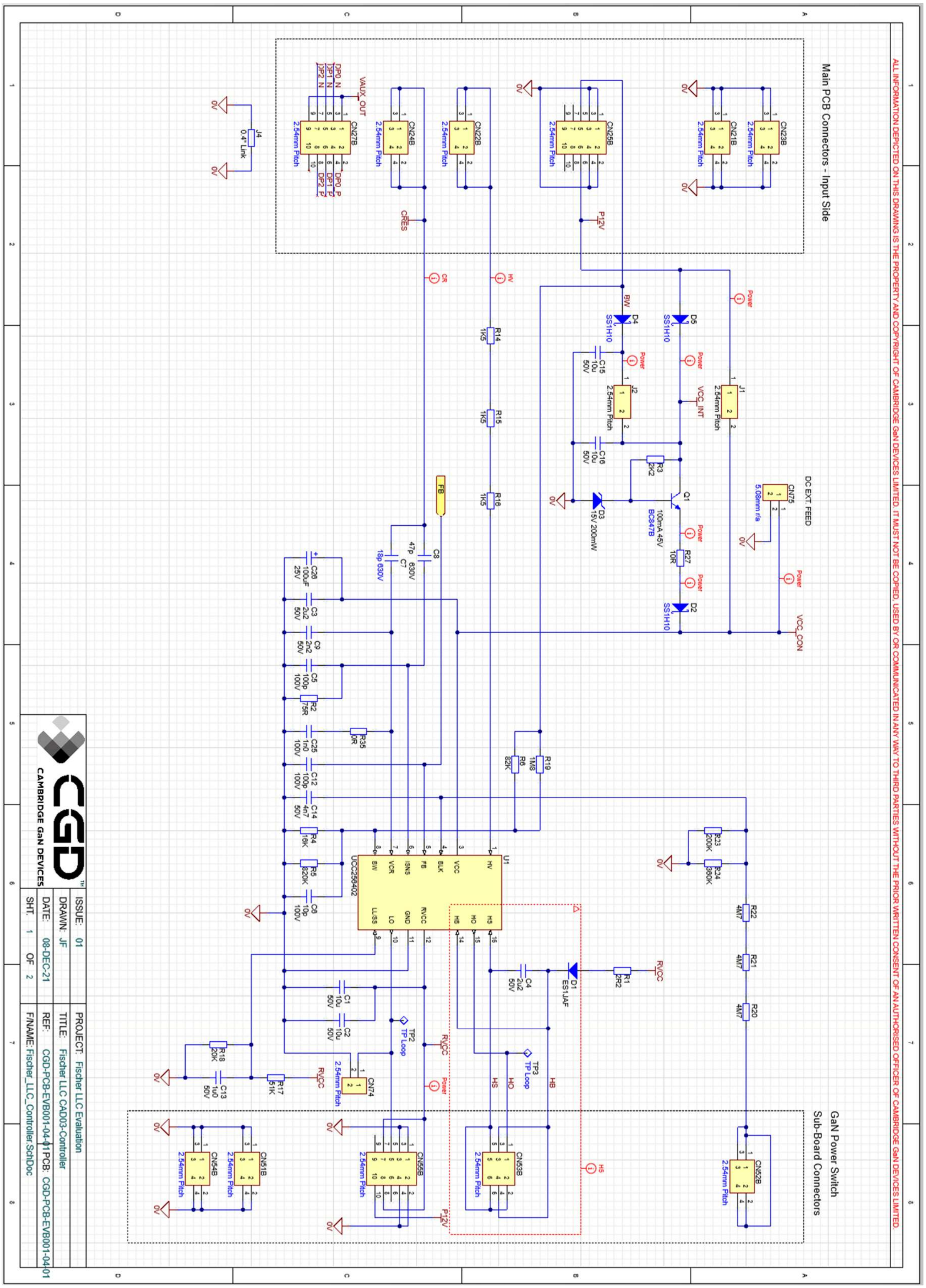

Figure 18 – LLC Controller Board Schematic Page 1

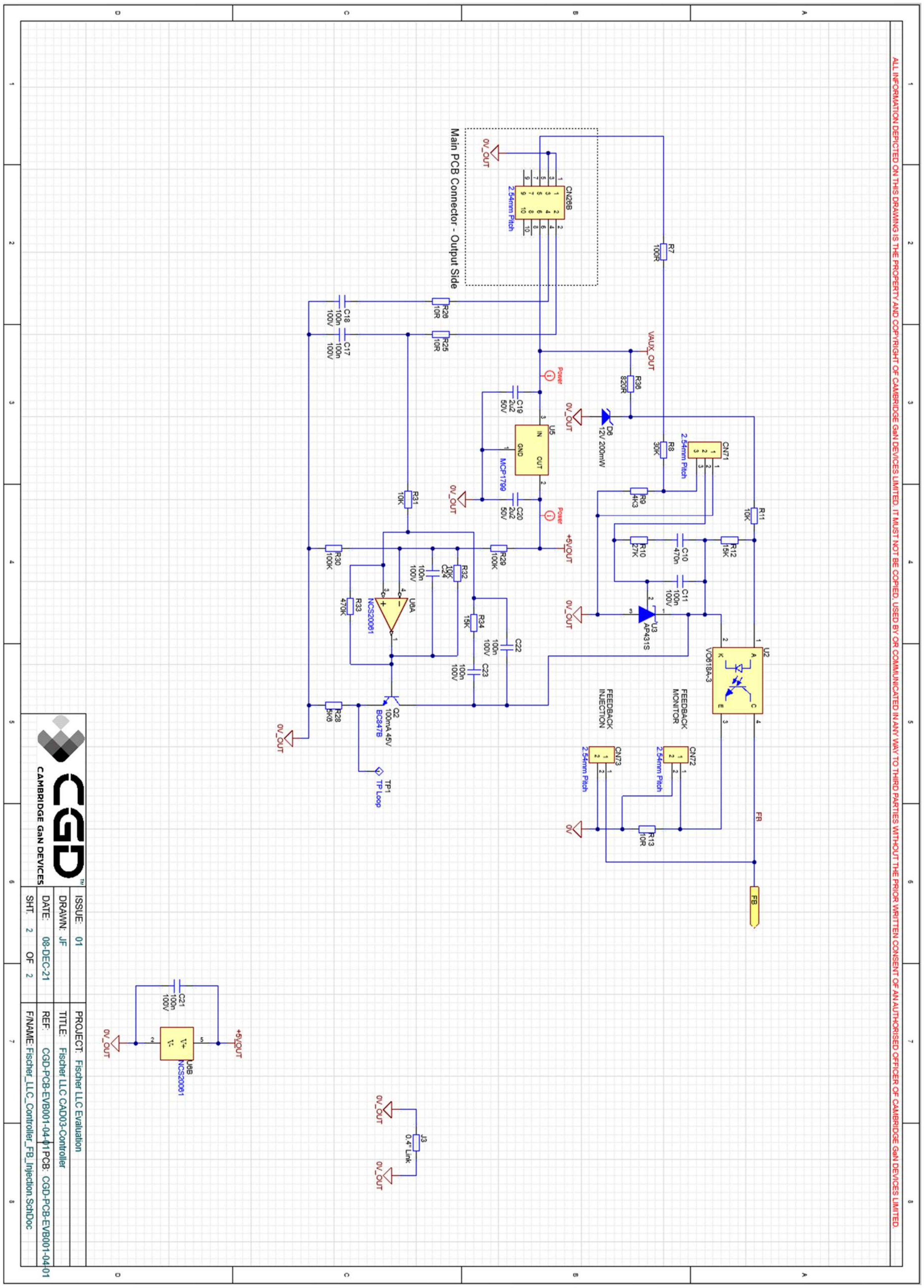

Figure 19 – LLC Controller Board Schematic Page 2

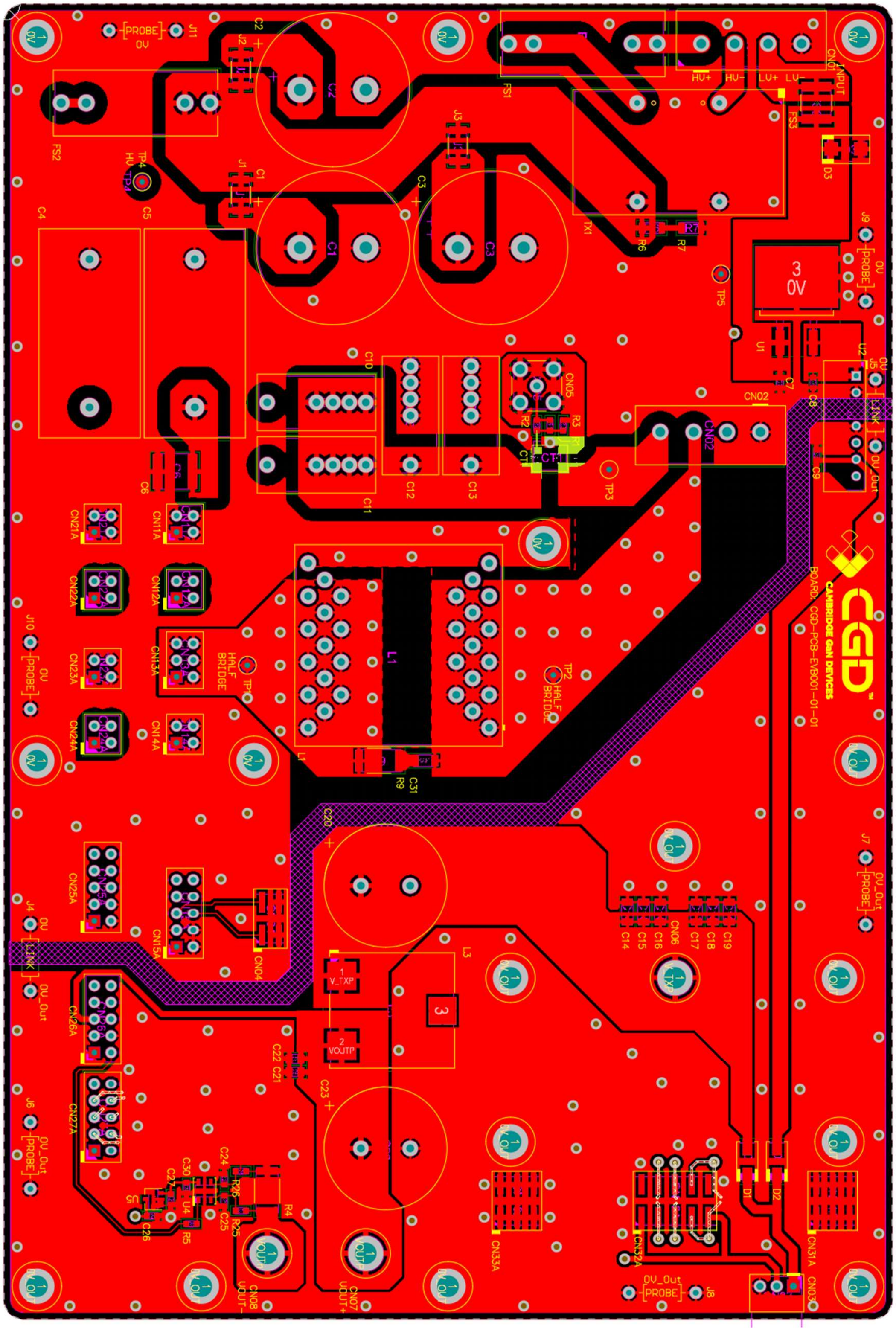

Figure 20 - Main Power Board Layer 1

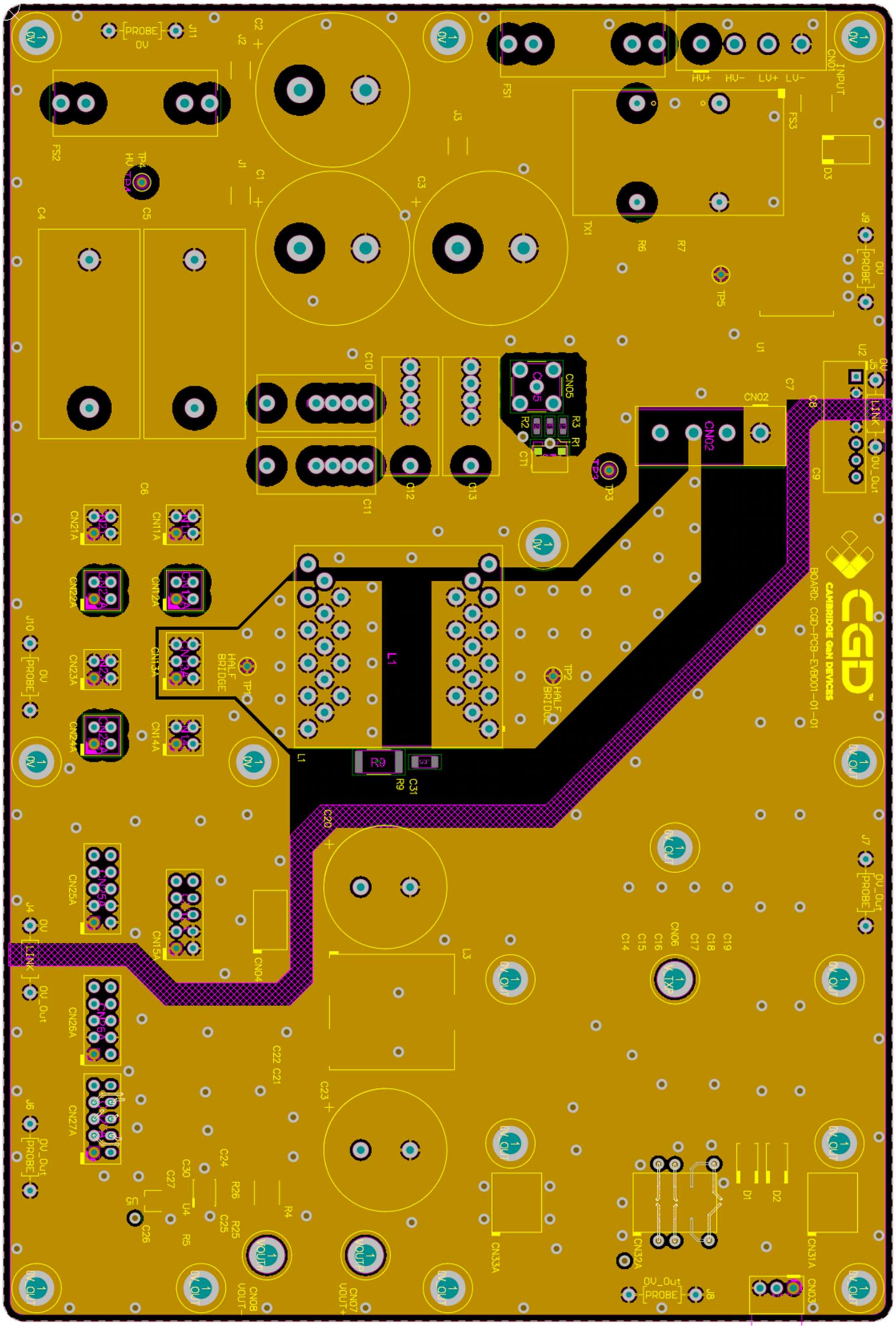

Figure 21 - Main Power Board Layer 2

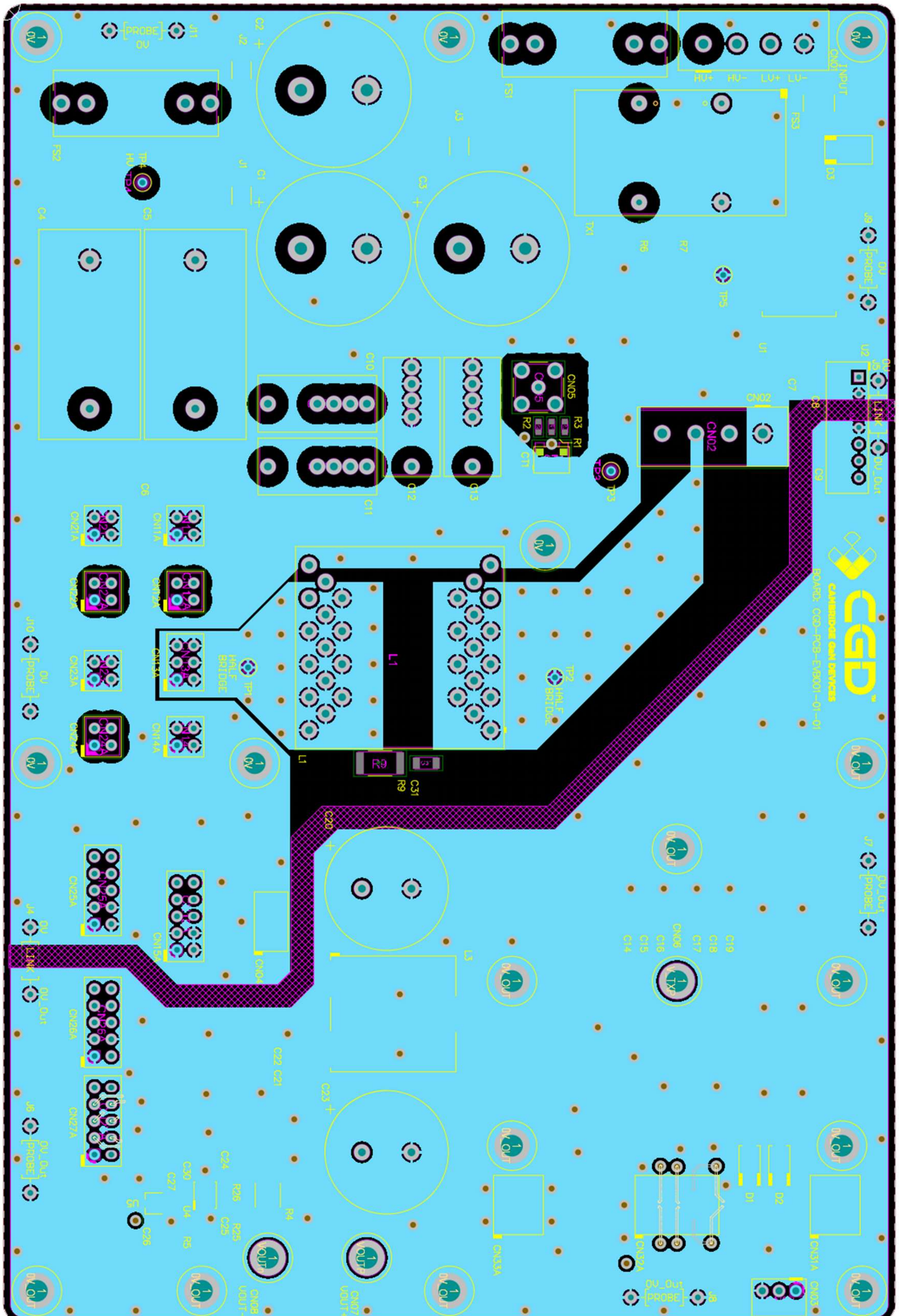

Figure 22 - Main Power Board Layer 3

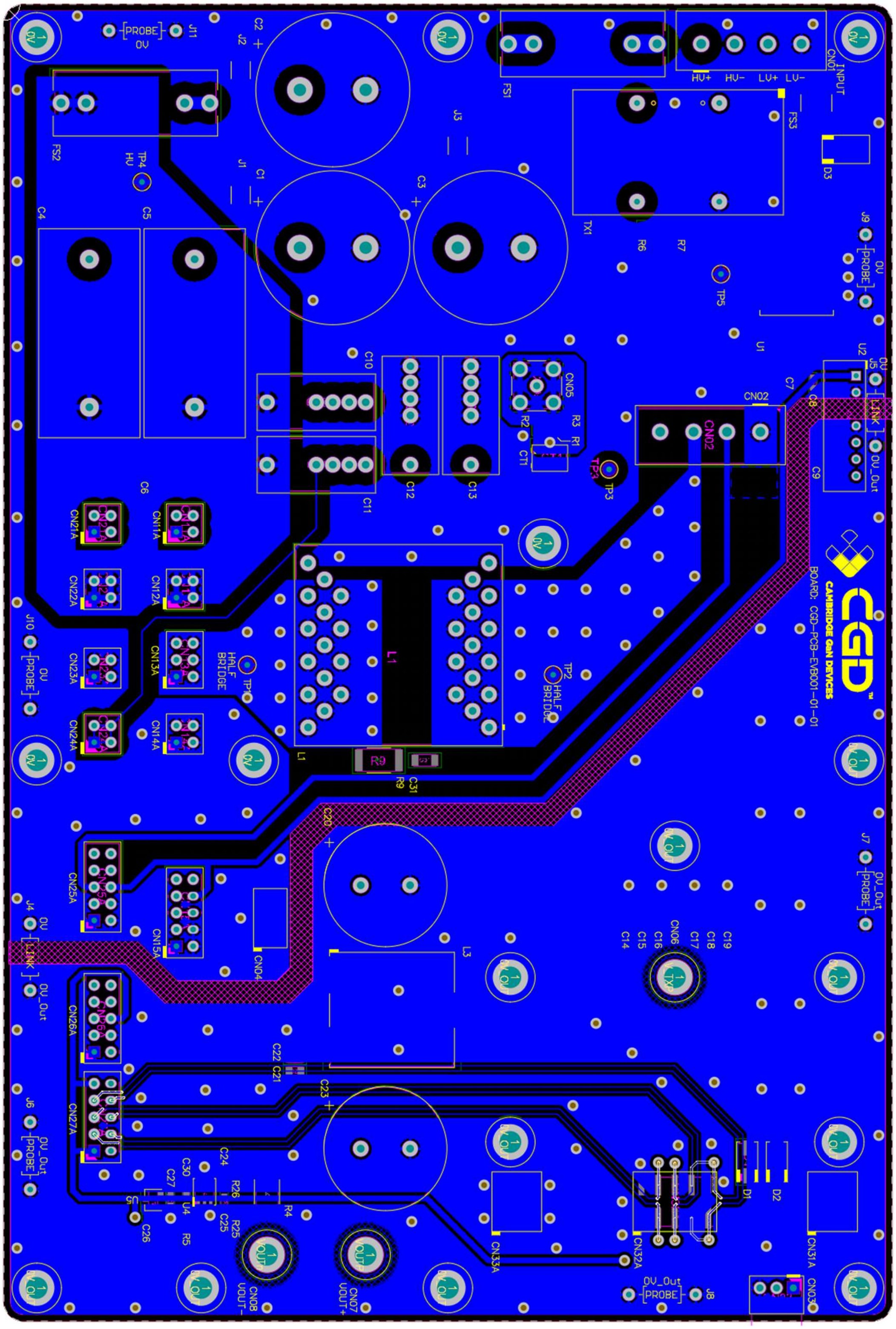

Figure 23 - Main Power Board Layer 4

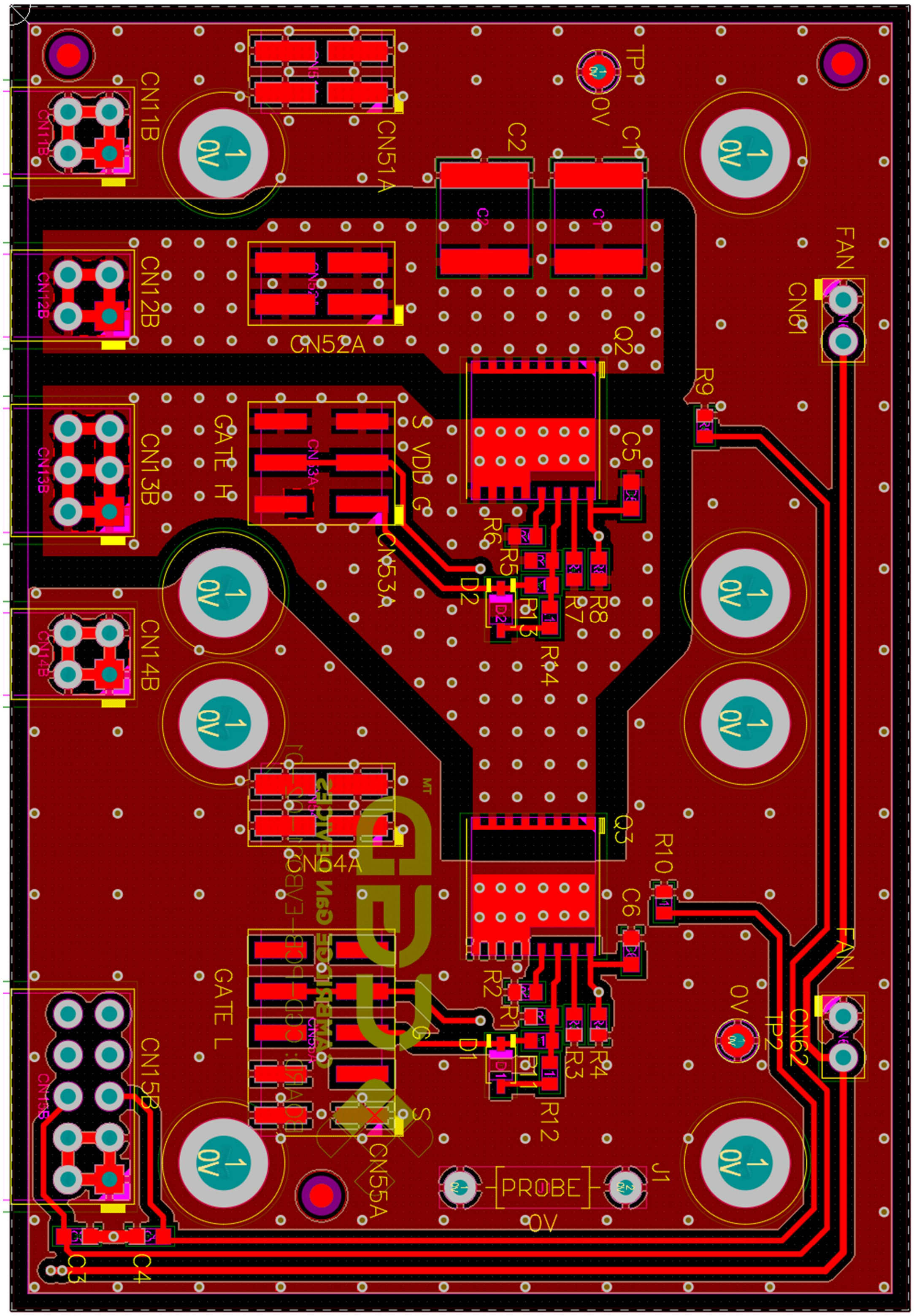

Figure 24 - GaN Board Layer 1

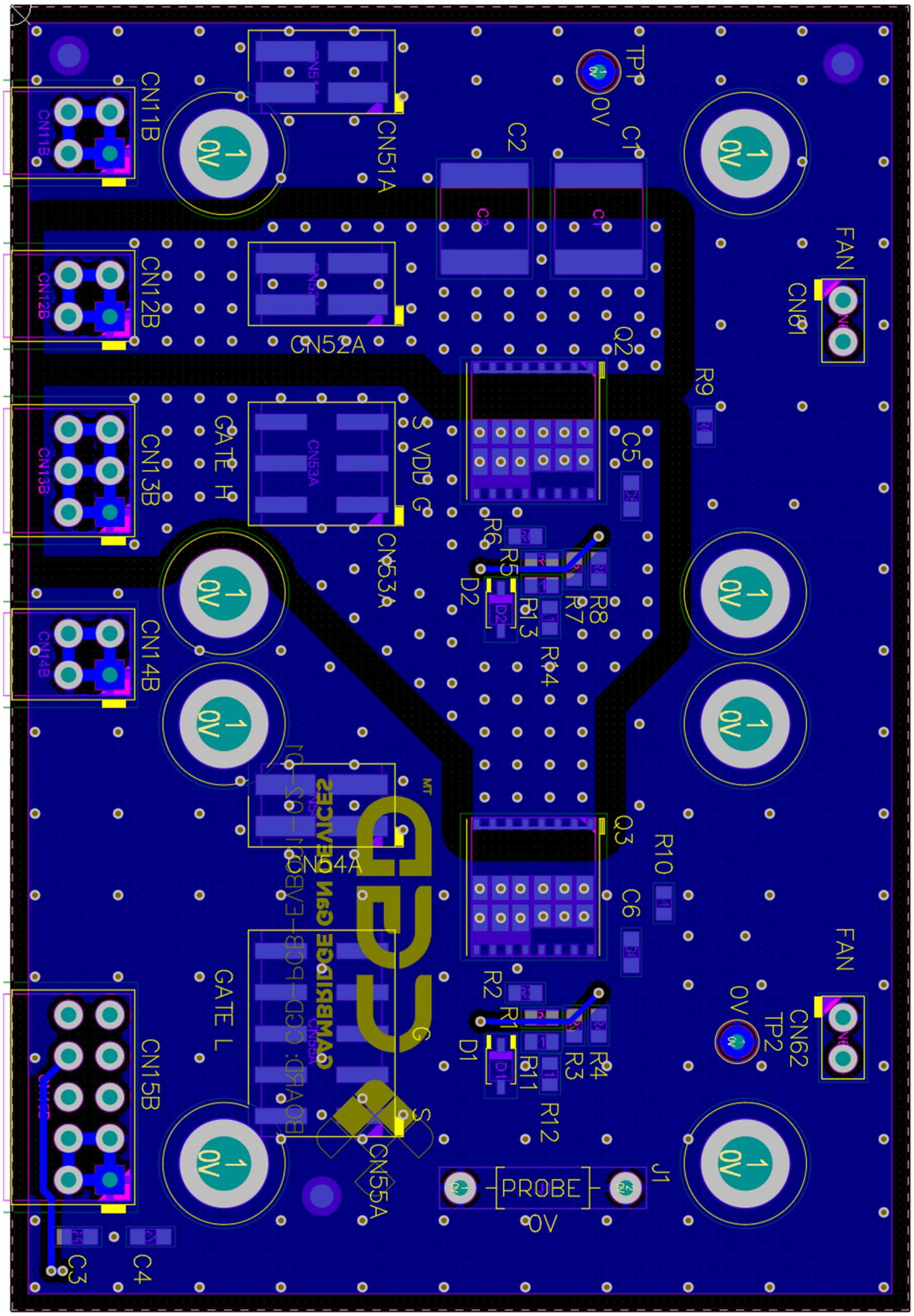

Figure 25 - GaN Board Layer 2

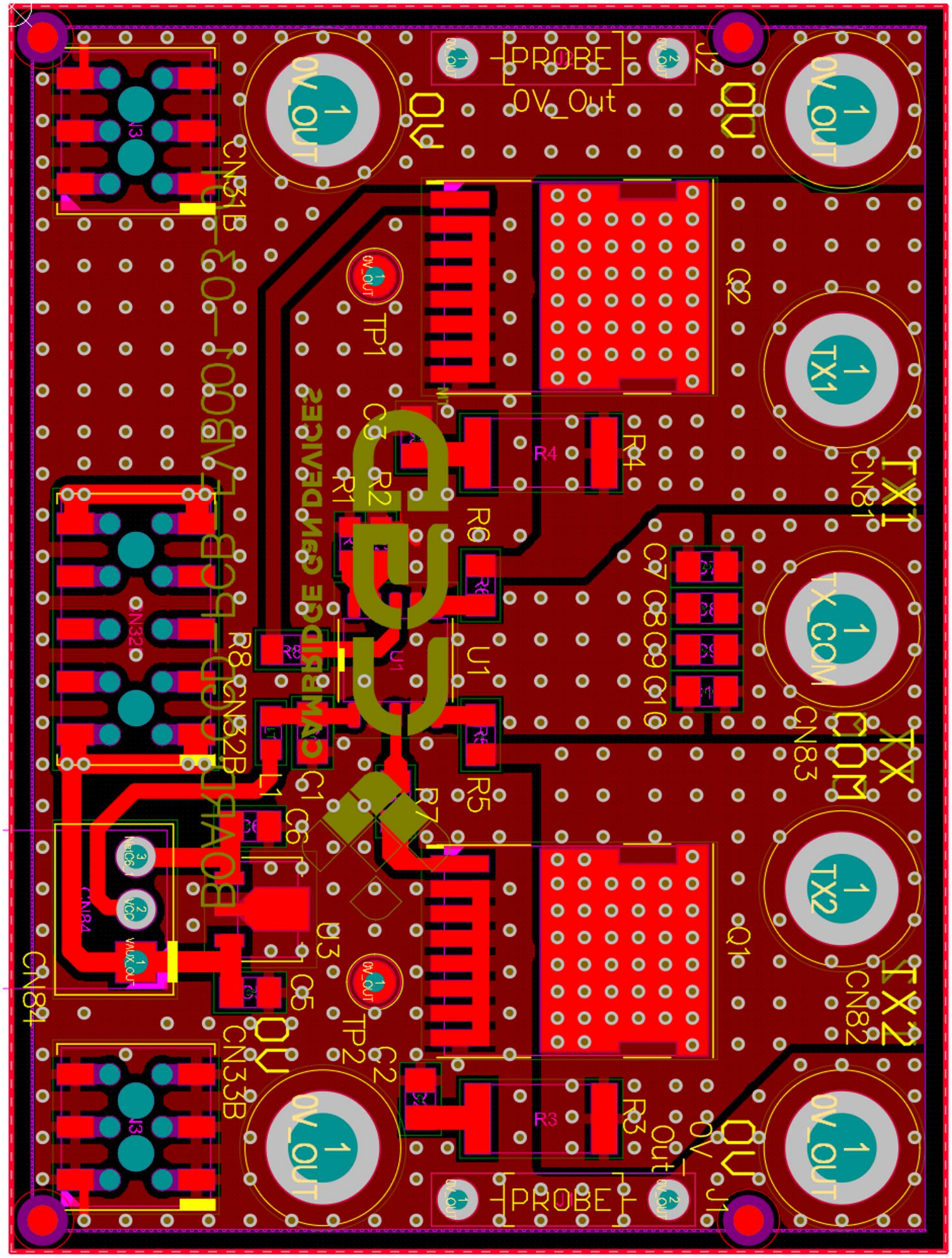

Figure 26 - Synchronous Rectifier Board Layer 1

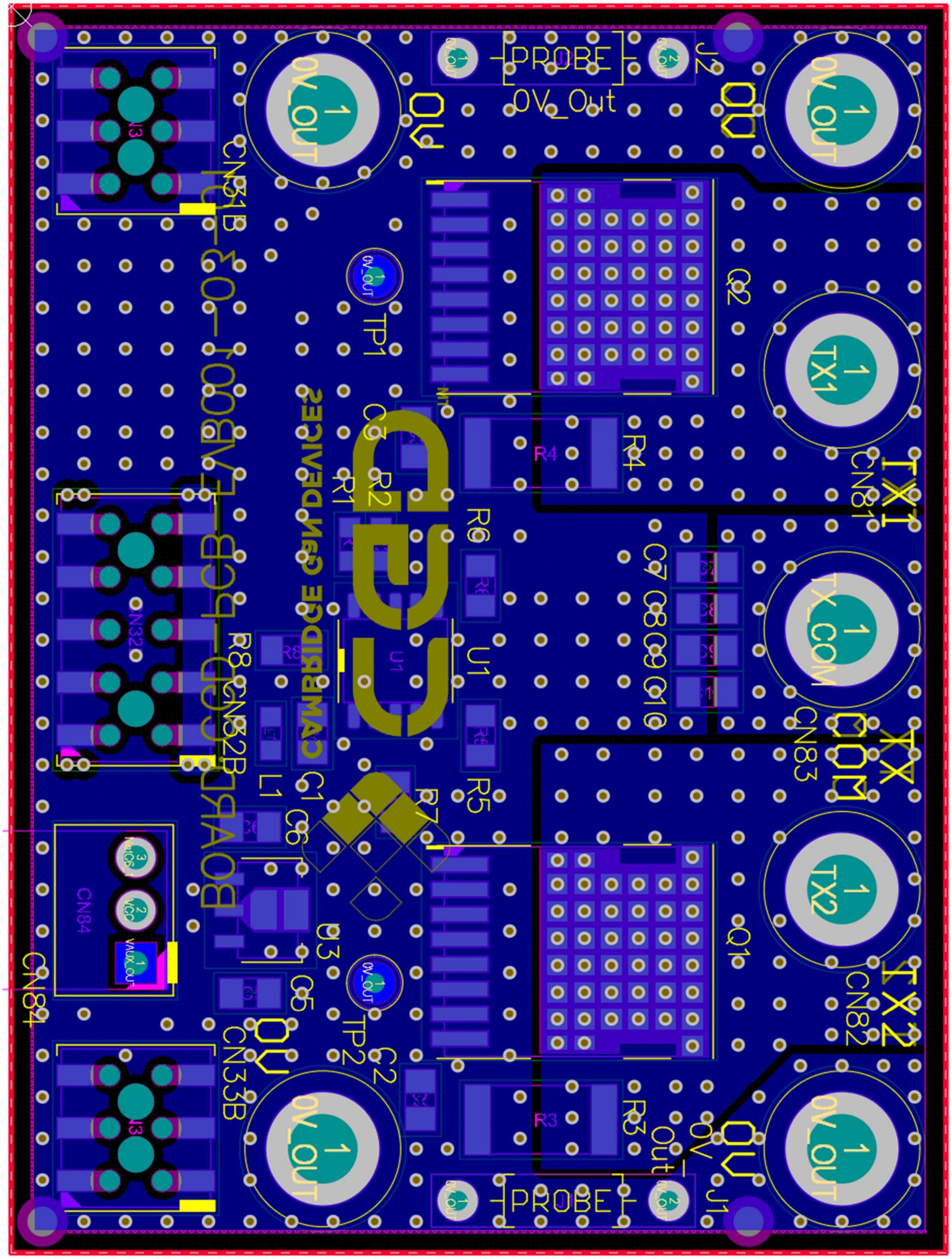

Figure 27 - Synchronous Rectifier Board Layer 2

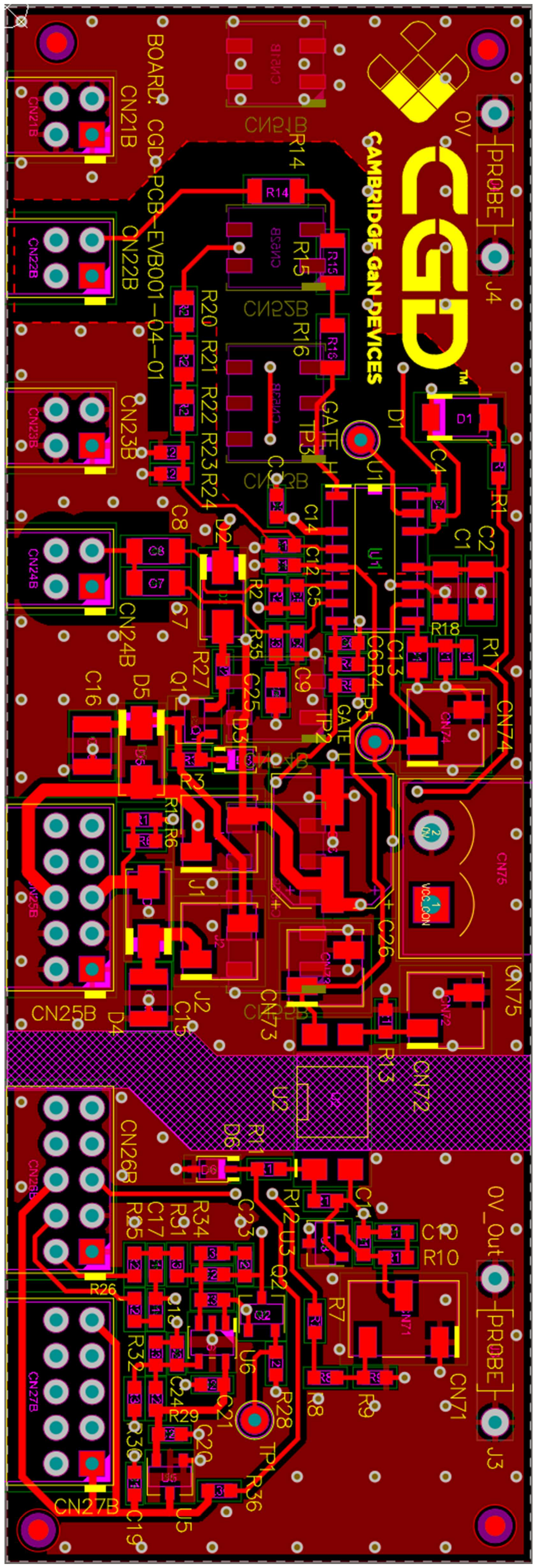

Figure 28 – LLC Controller Board Layer 1

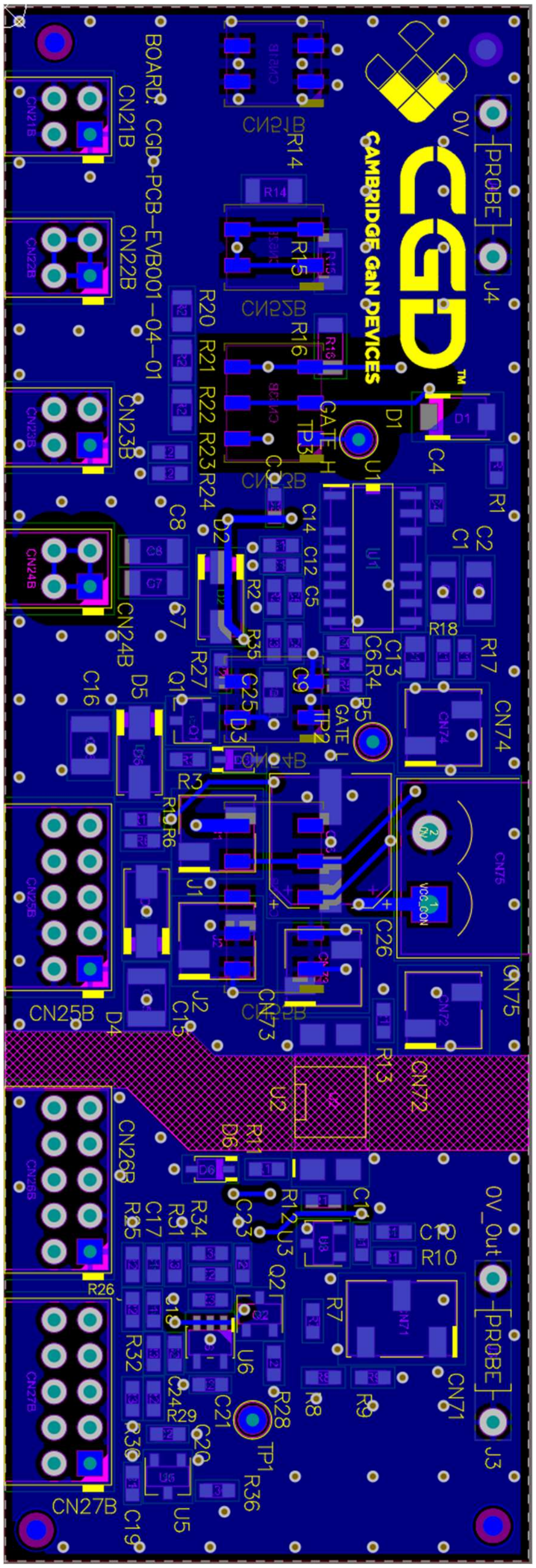

Figure 29 – LLC Controller Board Layer 2

8 BOM

Part	Value	Manufacturer	MPN
C1, C2, C3	100uF	Rubycon	450VXH100MEFCSN22X25
C4, C5	2.2uF	TDK/Epcos	B32674D6225K
C6	200nF	TDK	C5750X7R2J224K230KA
C7, C8, C9, C26, C27	2.2uF	Murata	GRM21BR61H225KA73L
C10, C11, C12, C13			
C14, C15, C16, C17, C18, C19	4.7uF	Murata	GRM31CR71H475KA12L
C20, C23	4700uF	Rubycon	25YXG4700MEFC18X35.5
C21, C22	4.7uF	Murata	GRM21BZ71H475KE15
C24, C25	100nF	Murata	GRM188R72A104KA35
C30	100nF	Murata	GRM188R72A104KA35
C31	10uF	TDK	CGA5L1X7R1E106K160AE
CN01, CN02		Camdenboss	CTBP9308/4
CN03		Harwin	M20-9750342
CN04		Harwin	M20-8760242
CN05	50Ω Coax	Multicomp	24-14-2-TGG
CN11A, CN12A, CN14A, CN21A, CN22A, CN23A, CN24A		Harwin	M20-7830246
CN13A		Harwin	M20-7830346
CN15A, CN25A, CN26A, CN27A		Harwin	M20-7830546
CN31A, CN33A		Harwin	M20-8760342
CN32A		Harwin	M20-8760542
CT1	100:1	TDK/Epcos	B82801A1824A100
D1, D2	1A, 100V	Vishay	SS1H10-E3/61T
D3	24V	On Semi	1SMB5934BT3G
FS1, FS2		Multicomp	MC000830
FS3		Littelfuse	2016L030DR
J1, J2, J3	0Ω	Generic	R2010 0R
J4, J5, J6, J7, J8, J9, J10, J11		Generic	22AWG Tinned Wire
L1	EFD20/25/30		
L3	2.2uH	TDK	B82559A4222A016
R1, R2, R3, R5	100Ω	Generic	R0603 100R
R4	5uΩ	TE	TLR3A10DR0005FTDG
R6, R7	470kΩ	Generic	R1206 470K
R9	5uΩ	TE	TLR3A10DR0005FTDG
R25, R26	10Ω	Generic	R0603 10R
TX1	3.3mH	TDK/Epcos	B82724J2402N001
U1	12V	ST	L7812CD2T-TR
U2	12V	XP Power	ITB1212SA
U4		TI	INA181A4IDBVT
U5	5V	Microchip	MCP1799T-5002H/TT

Table 4 – Main Power Board BOM

Part	Value	Manufacturer	MPN
C1, C2	200nF	TDK	C5750X7R2J224K230KA
C3, C4	100nF	Murata	GRM188R72A104KA35
C5, C6	1uF	Murata	GCJ188R71E105KA01D
CN11B, CN12B, CN14B		Wurth	61300421021
CN13B		Wurth	61300621021
CN15B		Wurth	61301021021
CN51A, CN52A, CN54A		Molex	15-91-0040
CN53A		Harwin	M20-8760342
CN55A		Harwin	M20-8760542
CN61, CN62		Harwin	M20-9990245
D1, D2	200mA, 30V	Nexperia	PMEG3002EJ
J1		Generic	
Q2, Q3	55mΩ ICeGaN™	CGD	CGD65A065S1
R1, R5	100kΩ	Generic	
R2, R3, R4, R6, R7, R8, R12, R14	10kΩ	Generic	
R9, R10	10kΩ	Murata	NCU18XH103F60RB
R11, R13	10Ω	Generic	

Table 5 - GaN Board BOM

Part	Value	Manufacturer	MPN
C1, C5, C6	1uF	Kemet	C0805C105K5RACTU
C2, C3	1nF	AVX	08055A102FAT2A
C7, C8, C9, C10	4.7uF	Murata	GRM21BZ71H475KE15
CN31B, CN33B		Harwin	M20-7810345
CN32B		Harwin	M20-7810545
CN84		Harwin	M20-9750342
J1, J2		Generic	
L1	22uF	TDK	MLF1608C220KTA00
Q1, Q2	80V, 1.9mΩ	Infineon	IPT019N08N5ATMA1
R1, R2	1MΩ	Generic	
R3, R4	10Ω	Generic	
R5, R6	100Ω	Generic	
R7, R8	4.7Ω	Generic	
U1		ST	SRK2001
U3	12V	Microchip	MCP1804T-C002I/MB

Table 6 - Synchronous Rectifier Board BOM

Part	Value	Manufacturer	MPN
C1, C2	10uF	Murata	GRT31CR61H106KE01
C3, C4, C19, C20	2.2uF	Murata	GRM21BR61H225KA73L
C5, C12	100pF	Murata	GCM1885C2A101FA16
C6	10pF	Murata	GCM1885C2A100FA16
C7	18pF	Murata	GRM31A5C2J180JW01D
C8	47pF	Murata	GRM31A5C2J470JW01D

C9	2.2nF	Murata	GCM1885C1H222JA16D
C10	470nF	Taiyo Yuden	UMK107B7474KA-TR
C11, C17, C18, C22, C23, C24	NF	Murata	GRM188R72A104KA35
C13	1uF	Kemet	C0805C105K5RACTU
C14	4.7nF	Murata	GCM1885C1H472JA16
C15, C16	10uF	Murata	GRM32ER71H106KA2L
C21	100nF	Murata	GRM188R72A104KA35
C25	NF	AVX	08055A102FAT2A
C26	100uF	Panasonic	EEE-FK1E101AP
CN21B, CN22B, CN23B, CN24B		Wurth	61300421021
CN25B, CN26B, CN27B		Wurth	61301021021
CN51B, CN52B, CN54B		Wurth	61000421821
CN53B		Wurth	61000621821
CN55B		Wurth	61001021821
CN71		Harwin	M20-8770342
CN72, CN73, CN74		Harwin	M20-8770242
CN75		Phoenix Contact	1757242
D1	1A, 600V	On Semi	ES1JAF
D2, D4	1A, 100V	Vishay	SS1H10-E3/61T
D3	15V	Diodes Inc.	DDZ9702S-7
D5	NF	Vishay	SS1H10-E3/61T
D6	12V	Nexperia	BZX384-C12,115
J1, J2		Harwin	M20-8770242
J3, J4		Generic	
Q1, Q2	40V	Multicomp Pro	BC847B
R1	2.2Ω	Generic	
R2	75Ω	Generic	
R3	2.2kΩ	Generic	
R4	16kΩ	Generic	
R5	820kΩ	Generic	
R6	82kΩ	Generic	
R7	100Ω	Generic	
R8	30kΩ	Generic	
R9	4.3kΩ	Generic	
R10	27kΩ	Generic	
R11, R31	10kΩ	Generic	
R12, R34	15kΩ	Generic	
R13, R25, R26, R27	10Ω	Generic	
R14, R15, R16	1.5kΩ	Generic	
R17	51kΩ	Generic	
R18	20kΩ	Generic	
R19	1.8MΩ	Generic	
R20, R21, R22	4.7MΩ	Generic	
R23	200kΩ	Generic	
R24	360kΩ	Generic	
R28	5.6kΩ	Generic	

R29, R30	100kΩ	Generic	
R32	NF	Generic	
R33	470kΩ	Generic	
R35	NF	Generic	
R36	820Ω	Generic	
U1		TI	UCC256402DDBR
U2		Vishay	VO618A-3X017T
U3		Diodes Incorporated	AP431SAN1TR-G1
U5	5V	Microchip	MCP1799T-5002H/TT
U6		On Semi	NCS20061SN2T1G

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