ACPL-352J

Panasonic X-GaN Transistor

Reference Design

1. Introduction

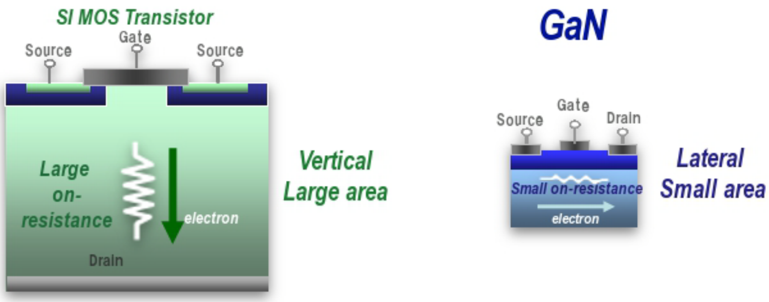
Gallium Nitride (GaN) power semiconductors are rapidly emerging into the commercial market delivering huge benefits over conventional Silicon-based power semiconductors. GaN can improve overall system efficiency with lower on-resistance and the higher switching capability can reduce the overall system size and costs. The technical benefits coupled with lower costs have increased the fast adoption of GaN power semiconductors in applications like industrial power supplies and renewable energy inverters.

Avago Technologies' gate drive optocouplers are used extensively in driving Silicon-based semiconductors like IGBT and Power MOSFETs. Optocouplers are used to provide reinforced galvanic insulation between the control circuits and the high voltages. The ability to reject high common mode noise will prevent erroneous driving of the power semiconductors during high frequency switching. This paper will discuss how the next generation of gate drive optocouplers can be used to protect and drive GaN devices.

2. Advantages of GaN

Gallium Nitride is a wide bandgap (3.4 eV) compound made up of Gallium and Nitrogen. Bandgap is a region formed at the junction of materials where no electron exists. Wide bandgap GaN has high breakdown voltage and low conduction resistance characteristics. Unlike conventional Si transistor that requires bigger chip area to reduce on-resistance, GaN device is smaller in size. This reduces the parasitic capacitance which allows high speed switching and miniaturization with ease. The low conduction resistance is achieved because the on-resistance of the power semiconductor is inversely proportional to the cube of the electrical breakdown. In other words, it is expected that GaN device will have an on-resistance approximately 3 digits lower than the limit of that of Si device. In addition, GaN device has high electron saturation velocity that makes it suitable for high-speed applications.

Figure 1 Silicon vs. GaN Transistor Structure and Size

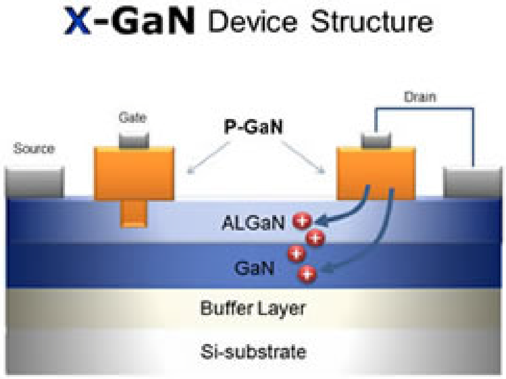


Power semiconductor is the key device and works on tremendous amount of power during electrical energy conversion. It is therefore important to optimize the efficiency of this device to minimize energy loss during their operation. GaN is the next generation power semiconductor able to minimize power loss with the following characteristics: miniaturization, high breakdown voltage and high-speed switching.

Most of the GaN devices are however normally on which means the source and drain are conducting when no voltage is applied at the gate. To stop the conduction, a negative voltage must be used to reverse the conduction channel. A normally on transistor poses danger to the system if the gate is not controlled properly and silicon transistor which is normally off is more suitable for hazardous high voltage application.

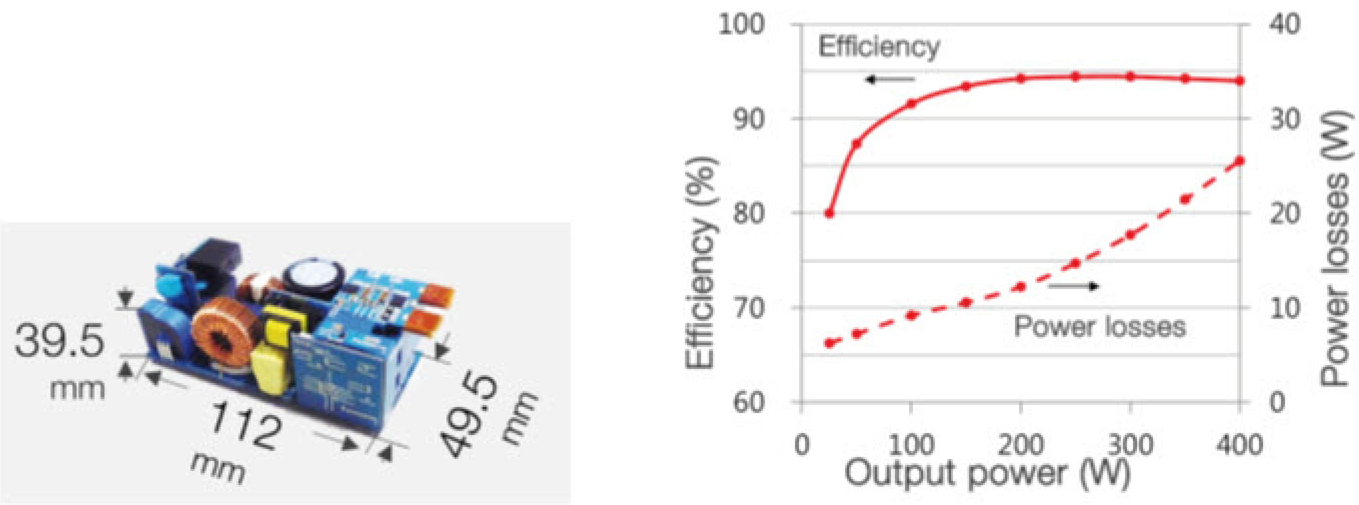
To speed up GaN adoption, Panasonic's X-GaN™ employed a normally off Gate Injection Transistor (GIT) structure by using P type GaN gate and diffuse AlGaN channel under the gate. At the same time, the P type GaN add holes near the drain which recombines with the electrons at high voltage. This method solves current collapse problem whereby electrons trapped near the channel during high voltage increases the transistor on-resistance. If the increase of on-resistance is not controlled, the GaN device will overheat and destroy over time. Panasonic GaN transistors are capable of no current collapse for up to 850V.

Figure 2 Panasonic X-GaN™ Transistor Structure



Panasonic has done a concept demo of the world's smallest 400W class All-In-One power supply. The power conversion stages, PFC and LLC operate at 100 kHz and 280 kHz respectively. The high frequencies reduce the cost and size of the power supply by more than 30%. The miniaturized power supply is measured 11.2cm × 4.95cm × 3.95cm and with effective power density of 1.83W/cm^3. It also achieved a high conversion efficiency of 94% with the low switching and conduction losses.

Figure 3 Panasonic World’s Most Compact 400W Power Supply with 94% Conversion Efficiency



3. GaN Market and Adoption

GaN technology is now widely recognized as a reliable alternative to silicon. Recent financial investments into GaN startups like GaN Systems and Transphorm and corporate partnership between Infineon and Panasonic indicate market confidence in GaN devices. GaN has huge Total Accessible Market (TAM) like PF, EV/HEV and PV inverter is one of the earliest adopters of GaN. In 2014, Yaskawa Electric Corp launched the world's first PV inverter using a GaN-based power semiconductor. The PV inverter has the ability to operate without cooling fans, is 60% the volume of competing devices and with an overall peak efficiency above 98%.

Avago gate drive optocouplers have been used extensively in driving Silicon-based semiconductors like IGBT. This paper will discuss how the improvements in the next generation of gate drive optocouplers can also be used to drive and protect GaN devices.

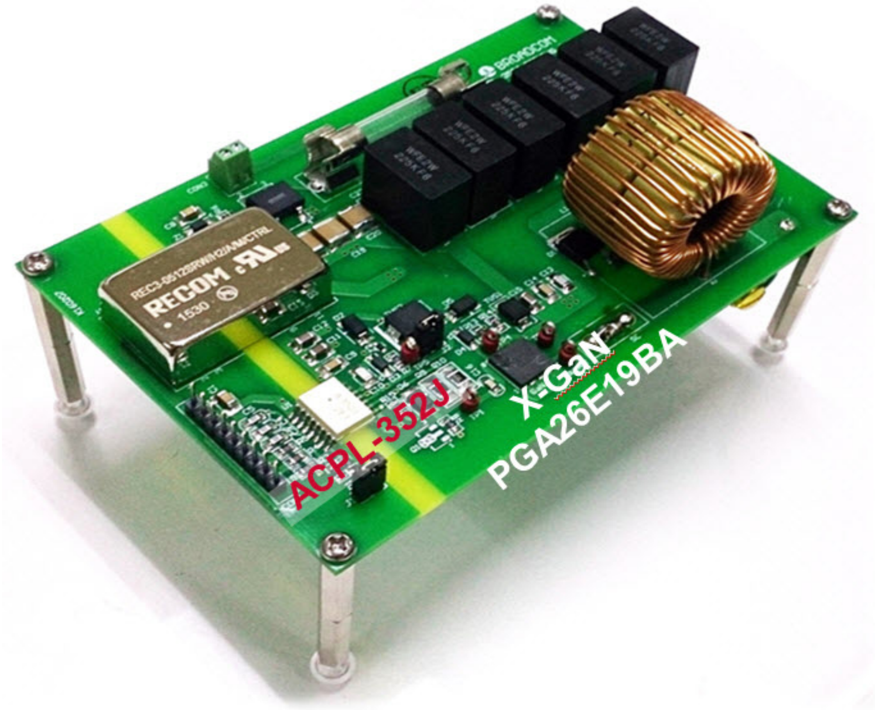
4. GaN Transistor and Gate Drive Optocouplers

To determine suitable gate driver for GaN operation, Broadcom evaluated gate drive optocoupler ACPL-352J with Panasonic GaN transistor, PGA26E19BA using a 100-150V, 5A chopper board at 100 kHz.

The ACPL-352J is industry's highest output current, 5A smart gate drive optocoupler. The high peak output current, together with wide operating voltage make it ideal for driving GaN transistor directly. The device features fast propagation delay of 100ns with excellent timing skew performance and has very high common mode transient immunity (CMTI) of more than 50kV/µs. It can provide GaN with over current protection and fail-safe functional safety reporting. This full-featured gate drive optocoupler comes in a compact, surface-mountable SO-16 package. It provides the reinforced insulation certified by safety regulatory IEC/EN/DIN, UL and CSA.

The PGA26E19BA is a 600V, 10A GaN enhancement mode transistor. It uses Panasonic's proprietary Gate Injection Transistor (GIT) technology to achieve normally off operation with single GaN device. This extremely high switching speed X-GaN is capable of no current collapse for up to 850V and has zero recovery loss characteristic.

Figure 4 100–150V, 5A Chopper Bard with ACPL-352J and PGA26E19BA



5. Driving GaN Transistor

Figure 5 ACPL-352J Driving Circuit for GaN Transistor

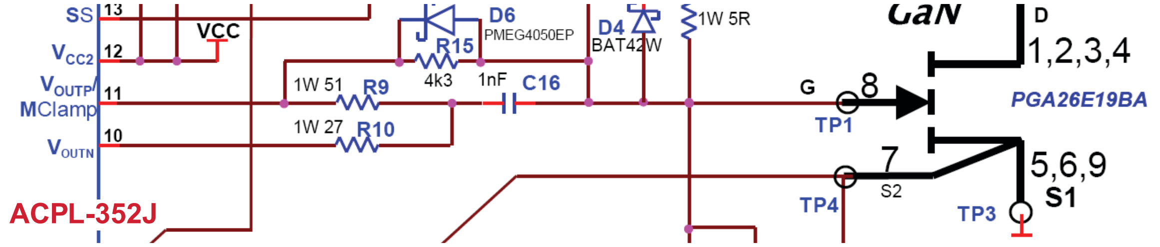
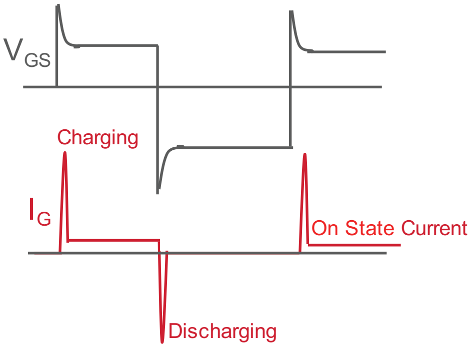


Figure 5 shows the ACPL-352J gate drive outputs, V_{OUTP}/MClamp and V_{OUTN} and external resistors and capacitor for switching the GaN transistor. The full chopper board schematic can be found in Figure 11.

Figure 6 GaN Transistor Gate Current and Voltage Switching Waveform



The initial in-rush charging current to turn on the GaN quickly is provided by ACPL-352J V_{OUTP} and the peak current limited by R9. C16 is used to turn on the GaN faster by increase the charging current momentarily. The required I_{G_CHARGE} can be calculated by the GaN's Qgd and turn on time Δt, for example 10ns.

Equation 1

$$I_{G\_CHARGE} = Qgd / \Delta t = 4.5nC / 10ns = 450mA$$

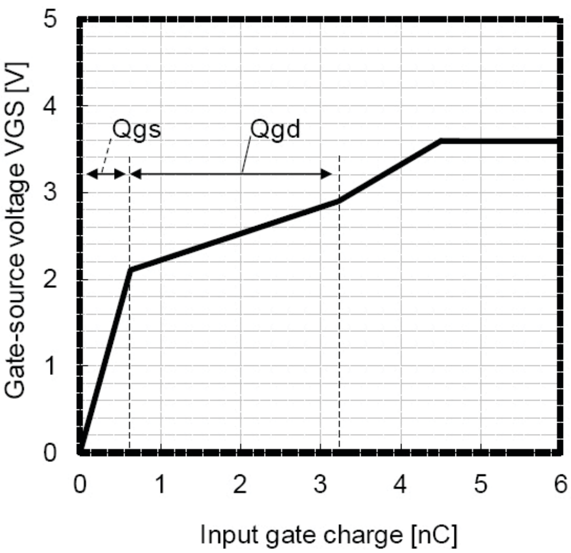
The value of R9 can then be calculated by the gate drive supply, V_{CC}, GaN gate plateau voltage, $V_{plateau}$ and I_{G_CHARGE}:

Equation 2

$$R9 = (V_{CC} - V_{plateau}) / I_{G\_CHARGE} = (24V - 2.9V) / 450mA = 46\Omega$$

51Ω is selected for R9.

Figure 7 GaN Transistor V_{GS} vs. Q_g Characteristic



The "speed-up" capacitor, C16 can be calculated using the Qg characteristic graph which shows the gate charge needed to turn on the GaN is 4.5nC.

Equation 3

$$C16 > Qg / (V_{CC} - V_{GS} - \Delta V(neg)) = 4.5nC / (24V - 3.6V - 5V) = 292pF$$

A higher C16, 1nF is chosen to ensure more accumulation charge for faster turn on.

The GaN transistor would require 4.75mA on state current to continuously bias the V_{GS} diode at 3.6V to maintain the transistor in on state. This is provided V_{OUTP} and the value of R15 can be calculated:

Equation 4

$$R15 = (V_{CC} - V_{GSF}) / I_{G\_ONSTATE} = (24V - 3.6V) / 4.75mA = 4.3k\Omega$$

$4.3k\Omega$ is selected for R15.

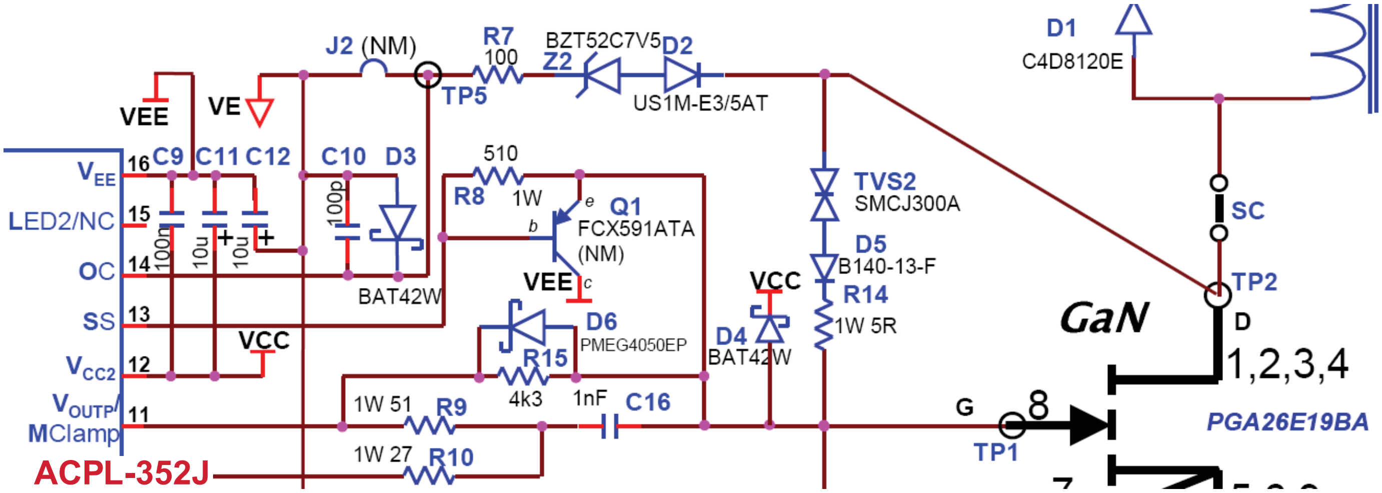
Switching off or discharging the gate of the GaN is done by ACPL-352J's V_{OUTN} and R10. ACPL-352J is connected to a bi-directional power supply and gate is discharge through V_{OUTN} to –9V. At the same time, the active Miller clamp (Mclamp) will turn on when the gate discharge to –7V. GaN transistor has very low typical gate threshold voltage of 1.2V. The negative gate voltage and active Miller clamp help to hold the transistor in off state and shunt parasitic Miller current to prevent false turn on. The peak discharging gate current can be calculated:

Equation 5

$I_{G\_DISCHARGE} = (V_{GSF} - V_{EE2}) / R10 = (3.6V - (-9V)) / 27\Omega = 0.467A$

6. Protecting GaN Transistor

Figure 8 ACPL-352J Over Current Protection Circuit for GaN Transistor



The drain-source voltage of the GaN is monitored by ACPL-352J's OC pin through high voltage blocking diode D2. The chopper is designed to operate at 5A and over current threshold is set at 7A. When over current occurs, the V_{DS} of the GaN increases to about 0.8V. ACPL-352J has an internal over current threshold voltage, V_{OC} of 9V. The threshold of the over current detection can then be set by Zener diode, Z2.

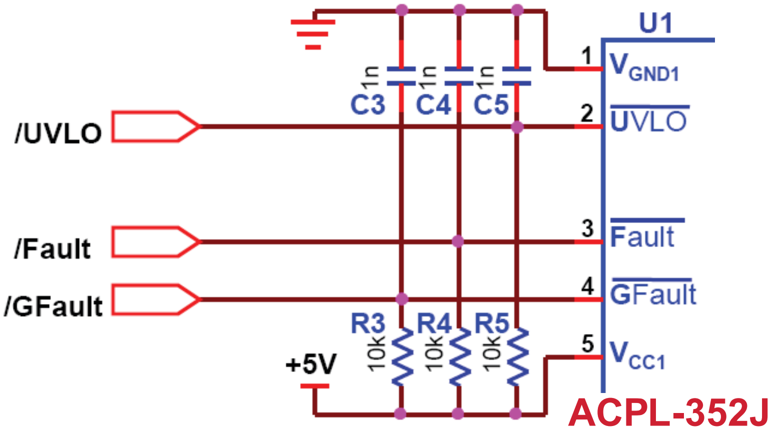
Equation 6

$Z2 = V_{OC} - V_{D2} - V_{DS\_OVERCURRENT} = 9 - 0.7 - 0.8 = 7.5V$

During over current, if the GaN is shutdown abruptly, high overshoot voltage induced by the load or any parasitic inductance can develop across the drain and source of the GaN. The overshoot will damage the GaN if it exceeds the breakdown voltage. To minimize such damaging overshoot voltage, ACPL-352J's pin 13, SS does a soft shutdown when over current is detected. GaN gate voltage is slowly reduced to low level off-state. The rate of soft shutdown can be adjusted through external transistor Q1 and resistor R8 to reduce the overshoot voltage.

The entire over current protection is completed by reporting the /Fault through the insolated feedback path to the controller. Beside over current fault, the ACPL-352J also reports high side under voltage lockout fault (/UVLO) and GaN gate status fault (/Gfault).

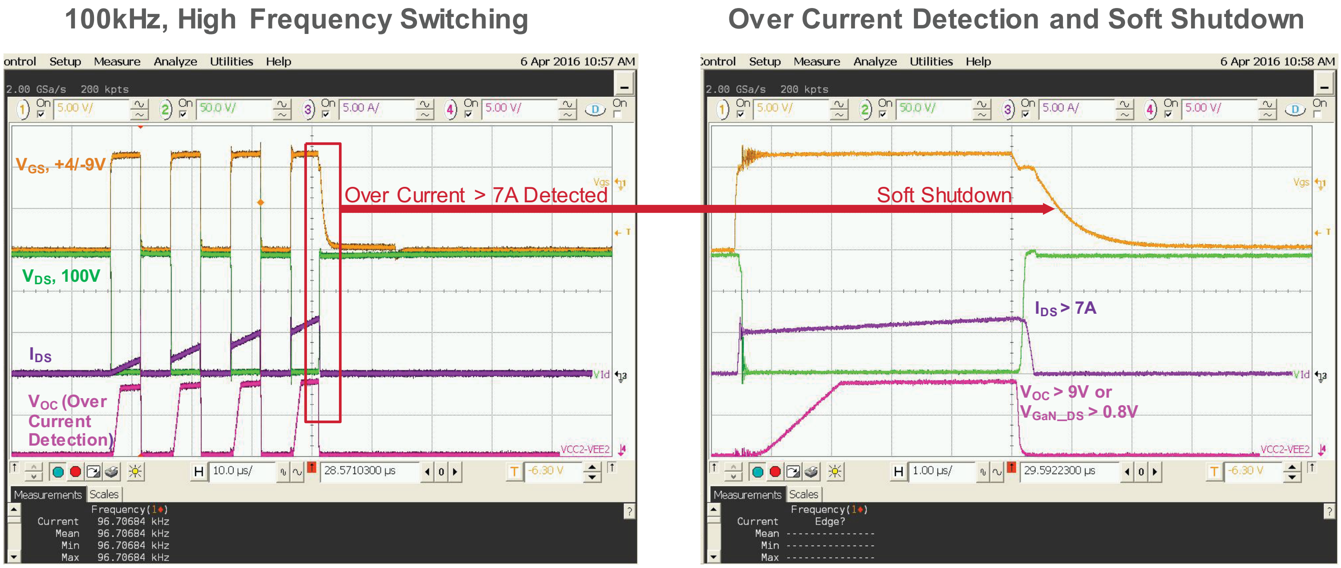
Figure 9 ACPL-352J Functional Safety Fault Reporting



7. Chopper Board Switching Performance

The chopper board is designed to switch the X-GaN transistor at 100kHz with DC bus voltage from 100-150V. The GaN nominal working drain current is 5A and over current threshold is set at 7A. Figure 10 shows the switching waveforms of the GaN V_{GS}, V_{DS}, and I_{DS}. As the chopper board is not connected to any load to dissipate the energy, I_{DS} increases on very switching pulse and eventually triggers the ACPL-352J's V_{OC}, over current detection threshold. The waveform on the right zooms into the soft shutdown process once over current is detected.

Figure 10 Chopper Board Switching Performance, Over Current Detection and Soft Shutdown


100kHz, High Frequency Switching

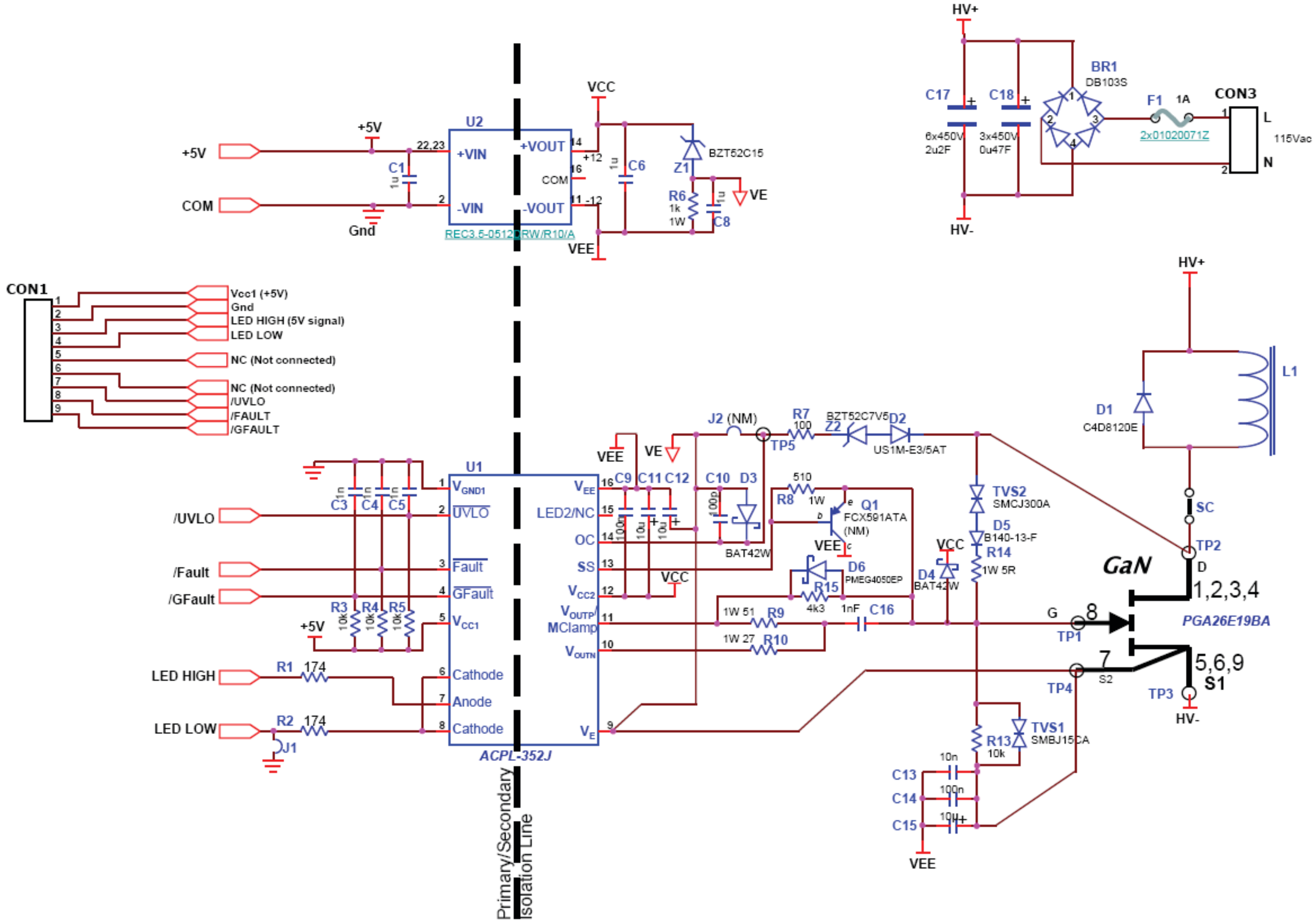
Over Current Detection and Soft Shutdown

```
         Frequency(1♦)
Current   96.70684 kHz
   Mean   96.70684 kHz
    Min   96.70684 kHz
    Max   96.70684 kHz
```

```
         Frequency(1♦)
Current      Edge?
   Mean ---------------
    Min ---------------
    Max ---------------
```

8. Other Design Considerations

Figure 11 Chopper Board Schematic



The ACPL-352J is powered by a RECOM Econoline DC/DC converter REC3.5-0512DRW. It is a 3.5W regulated converter and provides up to 10kVDC of reinforced isolation. The 24V dual output is split by a 15V Zener diode Z1 to provide bi-directional gate voltage of +15 for turning on and –9V for turning off.

Active clamping is provided by TVS diode TVS2, D5 and R14 to clamp the V_{DS} of the GaN from exceeding 300V. 15V Bi-directional TVS diode TVS1is used to protect the gate of the GaN transistor. Schottky diode D3 is used to clamp negative transient at ACPL-352J's V_{OC} to prevent any false fault triggering.

9. Bill of Material

Designator	Descriptions	Manufacture Name	Manufacturer Part Number
C1, C6, C8	CAPACITOR, X7R, 1206, 50V, 1µF	MULTICOMP	MCSH31B105K500CT
C3, C4,C5	CAPACITOR, 0805, 1nF, 25V	TDK Corporation	C2012C0G1E103J060AA
C9, C14	Capacitor F X7R 100nF 50V 10%	KEMET	C1206C104K5RACTU
C10	CAPACITOR, X7R, 1206, 50V, 100pF	Samsung-Electro	CL31C101JBCNNNC
C11, C12, C15	Capacitor MLCC X7R 10µF 25V 10%	TAIYO YUDEN	TMK316B7106KL-TD
C13	Capacitor F X7R 10nF 50V 10%	Murata Electronics	GRM3195C1H113JA01D
C16	Capacitor X7R 1nF 50V 10%	YAGEO (PHYCOMP)	CC0805KRX7R9BB152
C17a,b,c	Capacitor Metal Film 450VDC 2.2µF	Panasonic	ECW-FE2W225K
C18a,b,c	Capacitor X7T, 630V, 0.47µF	TDK Corporation	C5750X7T2J474K
D1	DIODE, Schottky, 1200V	Cree Inc.	C4D08120E
D2	Diode, FRD, 1000V	VISHAY	US1M-E3/5AT
D3, D4	DIODE, SCKY RECTI	MULTICOMP	BAT42W
D5	DIODE, SCKY RECTI	DIODES INC.	B140-13-F
D6	DIODE, SCKY RECTI	NXP	PMEG4050EP
Z1	Diode, Zener 15V	DIODES INC.	BZT52C15V
Z2	Diode, Zener 7V5	DIODES INC.	BZT52C7V5
BR1	Diode, Bridge AC230V	MULTICOMP	DB103S
TVS1	TVS 15V bidirectional	Fairchild	SMBJ15CA
TVS2	TVS 300V unidirectional	Littelfuse Inc.	SMCJ300A
R1, R2	RESISTOR, 0805, 330 OHM, 5%	Stackpole	RMCF0805JT330R
R3, R4, R5, R13	RESISTOR, 0805, 10k OHM, 5%	Stackpole	RMCF0805JT10K0
R6	RESISTOR, 0805, 1k OHM, 5%	Yageo	RC0805JR-071KL
R7	RESISTOR, 0805, 100 OHM, 5%	Panasonic	ERJ-6GEYJ101V
R8	RESISTOR, 0805, 510 OHM, 5%	Yageo	RC0805JR-071KL
R10	RESISTOR, 1210, 27 Ohm, 1W	Rohm	MCR25JZHJ270
R14	RESISTOR, 2512, 5R1 Ohm, 1W	Stackpole	RMCF2512JT5R10
R15	RESISTOR, 0805, 4k3 OHM, 5%	Stackpole	RMCF0805JG4K30
R9	RESISTOR, 2512, 51 OHM, 1W	Stackpole	RMCF2512JT51R0
J1~J2	HEADER, 2.54MM, 2WAY	MOLEX	22-27-2021
CON1	HEADER, 2.54MM, 9WAY	Amphenol FCI	68000-103HLF
CON2	HEADER, 2.54MM, 3WAY	MOLEX	WM4112-ND
CON3	Terminal Block 125Vac 2Way	Phoenix Contact	1725656
CNT1,2,3	Connector, Agilent Probe	Oxley	Consign
CNT4a,b	Fuse Holder	Littelfuse Inc.	01020071Z
U1	Isolated Gate Driver Optocoupler	Broadcom	ACPL-352J
F1	Fuse, Bussman (FNM-1)	Bussman	FNM-1
GaN	Transistor, GaN	Panasonic	PGA26E19BA
SW1	Switch Toggle, SPST	Eaton	8444k4

Designator	Descriptions	Manufacture Name	Manufacturer Part Number
L1	Inductor	Transmore	Consign
U2	Dc-Dc converter	RECOM ECONOLINE	REC3-0512DRW
Q1	TRANS PNP 40V 1A SOT-89	Diodes Incorporated	FCX591ATA

10. Acknowledgment

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