Study of a Fast Over-Current Protection Based on Bus Voltage Drop for Gallium Nitride Power Device

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Abstract. Due to the low threshold voltage, gallium nitride (GaN) high electron mobility transistor (HEMT) is prone to mis-conduction. Meanwhile, compared with silicon (Si) insulated gate bipolar transistors (IGBT) and silicon carbide (SiC) metal-oxide- semiconductor field effect transistor(MOSFET) devices, GaN HEMT have a shorter short-circuit withstand time at highvoltages, only a few hundred nanoseconds, which leads to a serious challenge to overcurrent protection. Traditional inductor detection and desaturation overcurrent detection have a long execution time, which are no longer suitable for over-current protection of GaN. Therefore, this paper proposes a new fast over-current protection method, which is based on the bus voltage drop. Through simulation and experimental verification, the result proves that the proposed protection method can detect the over-current signal within 100ns and turn off the GaN device within 400 ns, achieving fast and reliable over-current protection.

1. Introduction

The third-generation of wide bandgap semiconductor GaN devices have the advantages of large band gaps, high critical breakdown field strength and high electron mobility. It can overcome the shortcomings of current Si materials, such as decreasing the weight of heat sink, reducing the conduction loss, operating in high temperature environment, etc. However, due to the high switching speed, the high change rate will cause severe spike voltages and currents \( u = L \frac{di}{dt} \), \( i = C \frac{du}{dt} \), which induces the gate oscillation of GaN and electromagnetic interference (EMI). Meanwhile, the lower threshold voltage makes GaN is extremely susceptible to EMI, and will mis-conduction. If GaN is applied in a bridge arm of a converter, the mis-conduction will lead to a short-circuit, which will cause serious consequences. Therefore, the ability to survive as short-circuit process is critical, not only in terms of device lifetime, but also critical to the reliability and safety of the entire energy conversion system.

Compared with the Si device, the physical size of GaN device is significantly reduced. During the short-circuit, a large instantaneous current occurs. Then, the thermal stress increases remarkably. Hence, the thermal effect caused by the short circuit is more serious [1]. When the over-current time lasts too long,, the thermal runaway will cause irreversible damage to the power device. Therefore, the key to designing over-current protection is to turn off the device immediately when it enters the high power mode.

At present, the short-circuit protection methods adopted by power devices are mainly divided into two categories [2] one is to measure the drain-source current indirectly, For example, a Rogowski coil or a small series inductor is added to the source of device, but this method will greatly increase the
switching loss at high frequencies, and also affect the switching speed[3]. In addition, by improving the fabrication and packaging of GaN, an integrated current mirror method for high current GaN HEMT is proposed in reference [4]. A parallel FET is added by lithography to detect the drain current and realize over-current protection. However, this integrated protection method requires special device design. Another method is de-saturation detection, which widely used in IGBT and SiC devices [5-6]. It monitors the voltage changes and output characteristics across the device under test (DUT) to determine the faults in the system. However, the blanking capacitor $C_{cap}$ in the desaturation circuit, as shown in Fig.1, will increase the delay of voltage rise during short-circuit pulse, which usually causes 1-3us time to terminate short-circuit current.

![Figure 1. Schematic diagram of desaturation circuit.](image)

In addition, according to the short-circuit robustness test [7], as shown in Fig.2, the short-circuit withstand time of GaN varies greatly under different bus voltages. When the bus voltage is less than 300V, the GaN HEMT can withstand short-circuit pulses of more than 10μs, but when the voltage is higher than 400V, GaN short circuit withstand time is as low as 400 ns [8]. On the contrary, Si and SiC can still withstand a 10us short-circuit pulse at 400V, Therefore, the desaturation method is very suitable for overcurrent protection of IGBT [9].

![Figure 2. Comparison of short-circuit withstand time of 650V power devices[7].](image)

At the same time, Unlike IGBTs, the GaN has a very flat I-V curve, and the transition between the saturated region and the unsaturated region is not obvious,as shown in Fig.3.Therefore, considering the GaN HEMT has a faster switching speed, higher parameter sensitivity, and shorter over-current withstand time,traditional de-saturation detection is no longer suitable for fast switching GaN devices. At present, there are few hundred nanosecond over-current protection circuits that can be used in high voltage GaN HEMTs. A unique gate injection transistor short circuit protection method is proposed in reference [10], which monitors the increase of gate-source voltage to detect over-current fault, but in high frequency, the gate is prone to oscillation, so reliability is not high. In reference [11], a method of over-current protection based on monitoring the drain-source voltage $Vds$ is proposed and verified under
low current. However, the voltage used is very low, only 200 V, and the protection time also only less than 1 us, which is still far from the minimum withstand time of GaN.

**Figure 3.** Comparison of I-V curves between IGBT and GaN devices.

Based on the analysis of over-current protection mechanism, this paper proposes a new fast protection method for half-bridge circuit, through the instantaneous drop of bus voltage, the over-current signal is detected, and then the fast and reliable protection is achieved by signal latching and soft-shutdown. The second section details this new overcurrent protection method, and gives the specific circuit and its design principle. The third section builds a short-circuit experimental platform for GaN devices, and verifies the rapidity and reliability of the protection solution. Finally, the article was discussed and concluded.

2. **Principle and design of half-bridge over-current protection circuit**

This section presents a fast and efficient over-current detection method. By detecting the voltage of half-bridge phase-leg, the voltage noise caused by switching is avoided, as shown in Fig. 4. When the circuit operates normally, the detection voltage equals to the phase-leg Vdc. Once the short circuit occurs, the current flowing through the half-bridge circuit suddenly increases, and Vdc first experiences a significant voltage drop, then oscillates and attenuates. This voltage drop is a high frequency signal that occurs immediately after a short-circuit fault happened, compared to the device saturation voltage. Therefore, this voltage drop can be used as a fast short-circuit indication signal.

**Figure 4.** Fast drop detection and protection circuit.
Different from the de-saturation detection, the new protection circuit detects the phase voltage of the half-bridge, not the drain-source voltage of the GaN device, avoiding the voltage fluctuation caused by normal switching of power transistor. And when the over-current occurs, the protection is realized by quickly detecting the instantaneous drop of the bus voltage, instead of waiting for the blanking time to enter the saturation zone for detection. The comparison of the two detection methods is shown in Fig.5.

![Detection circuit comparison](image)

**Figure 5.** New detection position and signals.

The bandpass filter is used to detect the voltage drop signal while blocking the DC voltage and higher frequency switching noise. The equivalent frequency of the voltage drop is about 5MHz, which is determined by the $\frac{di}{dt}$ and phase-leg decoupling capacitors and the GaN loop inductance. The schematic diagram of the proposed bandpass filter is shown in Fig. 6(a). It consists of $C_1$, $R_1$, $R_2$ and $C_2$. The transfer function of the detection circuit is:

$$H(S) = \frac{sR_1C_1}{s^2R_1R_2C_1C_2+S(R_1C_1+R_2C_2)+1} \quad (1)$$

According to the approximate voltage drop during short-circuit, it is assumed that the input is a step change with an amplitude of 400V-390V, and the output waveform under different filter parameters is as shown in Fig. 6 (b). It can be seen from the scanning waveform, that changing the parameter value to increase the bandwidth of the filter can better detect the voltage drop signal. The final bandpass filter parameters are determined as follows:

$C_1 = 200\text{pF}$, $C_2 = 1\mu\text{F}$, $R_1 = 100\Omega$, $R_2 = 1k\Omega$.
Fast voltage drop detection

As shown in Fig.7(a), in converter normal operation, $C1$ is charged by the bus voltage, $C2$ is charged by the power supply $V2$, and finally the voltage on $C1$ reaches the bus voltage level of 400V, and the voltage on $C2$ reaches 5V. Thereafter, the voltage of capacitors $C1$ and $C2$ remains stable, and no current flows through the detection circuit. Once a over-current fault occurs, as shown in Fig.7(b), the phase-leg voltage drops rapidly and $C1$ starts to discharge. At the same time, the voltage of $C2$ drops rapidly due to the change of $C1$. Power $V2$ charges capacitor $C1$ through resistor $R2$. The current relationship is $I_{C1} = I_{C2} + I_{R2}$. Subsequently, after the voltage drop signal is successfully collected, it is sent to the comparator to compare with the threshold voltage of the judging circuit.

According to the definition of the over-current of GaN device: when the drain-source conduction voltage increases to 1.5 times at the maximum drain-source current, it was determined that the device had an over-current. From Current-voltage relationship in the data sheet, current is 28A when the drain-source voltage is 2.7V, and the device has a short-circuit fault. At this point, the sampled signal voltage drops more than 4V. Therefore, the negative terminal of the voltage comparator is set to 4V. Once the sampled voltage is lower than this value, it is considered that a short-circuit fault occurs, and at this time, the output of comparator is high level.

Since the over-current signal is an instantaneous value, it must be latched by a logic control circuit such as a high-speed SR latch [12]. When an over-current fault occurs, the output of the latch becomes a high voltage, which in turn triggers the execution circuit, becomes a high voltage, as shown in Fig.8.
When the device is turned off, in order to avoid the instantaneous overshoot of the current on parasitic inductance caused by too fast switch, a capacitor C and a Zener diode D are added between the gate and source to achieve a low voltage clamping of the gate. In addition, the "soft turn-off" reduces the rate of \( \frac{di}{dt} \) and voltage overshoot. First, the execution signal first turns on M1 and M3 to drive down the driving voltage., and then turns on M2 after RC charging delay, By connecting a large resistor in series, the gate voltage change rate is reduced, and gate overshoot and oscillation are avoided, as shown in Fig.9. This delayed switching mode can effectively reduce the loss of over-current.

According to the above analysis, the detection of over-current signal is indirectly realized by measuring the phase voltage VDC of the half-bridge circuit. The change of \( V_P \) is essentially caused by the charge and discharge of the capacitor C. This process requires short-term energy accumulation, so the circuit has strong anti-interference abilities and rapidity, meeting the requirements of GaN withstand time. The final protection circuit is shown in Fig.4.

3. Simulation and experimental verification
In order to verify the feasibility of the fast over-current protection method. The simulation is first performed using the LTspice. The device model used for the simulation is a 650V/15A GaN from GaN System. Because the bus voltage change is caused by parasitic parameters in power circuit, in order to make the simulation waveform closer to the actual waveform, it is necessary to use ANSYS Q3D to extract the parasitic parameter values in the circuit,. The extraction process is shown in Fig.10, and the final extracted power loop parasitics are shown in Fig.11.
Figure 10. Schematic diagram of Q3D extraction PCB parasitic parameters.

Figure 11. Power loop parasitic inductance extraction results.

The simulation circuit is built according to the extracted parasitic parameters and the final simulation waveform is shown in Fig.12. The key voltage and current waveforms, such as bus voltage drop Vdc, over-current detection circuit output Vt, logic control circuit output Vc-out, turn-off execution circuit out Vs-out, GaN gate voltage Vgs the drain-source current are listed.

Figure 12. Overcurrent protectionsimulation waveform.

It can be seen from the simulation results that the GaN over-current state can be effectively detected by the detection circuit. Assuming that the half-bridge circuit is short-circuited at 100ns, the current of
GaN rises instantaneously, and the drain-source voltage drops rapidly from 400V, thereby manufacturing an overcurrent fault, and finally turning off the GaN transistor takes only 300ns, which is much shorter than the desaturation circuit.

At the same time, in order to further verify the feasibility of the proposed circuit, a half-bridge overcurrent test platform is built as shown in Fig.13. The device used for the experimental test was a chip-type device 650V/15A 66504B from GaN System, and a short circuit fault is created by keeping the upper device open and the lower device gate applying a short-circuit pulse.

![Figure 13. Overcurrent protection experimental platform.](image)

The final experimental waveform is shown in Fig.14. As can be seen from the figure, the over-current protection is mainly composed of three stages: a short circuit fault is detected after the GaN device is turned on for 150 ns. Then, turn on the soft-shutdown circuit and disable the gate driver chip. Since there is a time delay before the drive chip is disabled, so the gate voltage is first clamped to a low voltage state. Finally, chip enable port is closed and the drive voltage is equal to 0V. When the gate voltage is clamped at a lower voltage, the drain-source current of GaN devices reduced, so the short-circuit energy is limited. The gate drive chip has a turn-off delay of 100 ns, and the GaN device is finally turned off for about 120 ns. Finally, it takes about 370ns to complete the over-current protection, achieves fast and reliable over-current protection function.

![Figure 14. Experimental waveform of voltage drop over-current protection.](image)

4. Conclusion
This paper presents a fast over-current protection circuit for high-speed switching GaN devices. Different from the traditional desaturation protection circuit, the fast protection circuit realizes over-current detection by monitoring the phase voltage drop of half-bridge circuit, and then triggers the execution circuit to slowly turn off the power device, thereby avoiding overshoot and misconnection of the gate. At the same time, the over-current protection time is greatly shortened. The feasibility of the proposed protection circuit is verified by LTspice simulation and experiment.. The test results show that
the proposed protection circuit can respond to GaN over-current condition within 150 ns. And start soft-shutdown within 200ns. Ultimately, the over-current of the GaN HEMT is limited to 45A while ensuring that the device is completely turned off within 400ns. Therefore the proposed over-current protection circuit has the characteristics of short protection time and strong anti-interference ability, which can effectively improve the short-circuit overcurrent problem in high-frequency GaN applications.

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