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Overcurrent and Short-circuit Capability Experimental Investigation for GaN HEMT at Cryogenic Temperature

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Abstract — **Recent research reveals that gallium nitride (GaN) devices achieve significantly reduced on-state resistance and faster switching speed operating at cryogenic temperature. These characteristics enable GaN-based power converter to achieve higher efficiency and power density and make GaN device an excellent candidate for cryogenic power electronics applications. However, overcurrent and short-circuit capability of GaN device at cryogenic temperature have not been evaluated. This paper characterizes a 650V-30A enhancement-mode GaN high-electron mobility transistor (HEMT) and experimentally evaluated the overcurrent and short-circuit capability at cryogenic temperature. Testing results show that this GaN HEMT achieves >5X conduction loss reduction and 30% switching loss reduction at cryogenic temperature. Moreover, GaN HEMT is capable of operating at around 4X of rated current at cryogenic temperature. The short-circuit capability at cryogenic temperature is similar to that at room temperature. Both the device failure threshold dc voltage and short-circuit withstand time are almost unchanged at cryogenic temperature.**

Keywords — GaN HEMT, device characterization, overcurrent, short-circuit, cryogenic temperature.

I. INTRODUCTION

High efficiency and high power density are essential for power converters in electrified transportation applications. Superconducting technologies such as motors/generators along with the supportive power system for electric aircraft propulsion applications are growing in importance. Power electronics converters are preferred to be integrated to such a cryogenically cooled system to reduce system complexity as well as achieving high power density. This requires research on operating power device and power converter at cryogenic temperature.

In previous literature, the main candidates of power device for drive system at cryogenic temperature are Si MOSFETS, Si IGBTs, and SiC MOSFETs. Si MOSFETs show reduced on-state resistance and faster switching speed at cryogenic temperature, but the breakdown voltage is only 60%~80% of that at room temperature [1-2]. SiC MOSFETs suffer an obviously increase in on-state resistance and slower switching speed at cryogenic temperature than that at room temperature [3-6]. Si IGBTs show reduced turn-off time at cryogenic temperature. The static characteristics of Si IGBT is like that of Si MOSFET at low temperature.

Recently, GaN devices are also investigated at cryogenic temperature. In [7], a 200V low voltage GaN HEMT from EPC was characterized at cryogenic temperature. Results show significantly reduced on-state resistance and no major changes in the switching characteristics ar. In [8-9], a 650V-60A GaN HEMT from GaN Systems was characterized at cryogenic temperature. Static and dynamic characteristics of this device at cryogenic temperature are demonstrated. Due to the higher dv/dt and di/dt at cryogenic temperature, the dynamic characterization was conducted using the GaN-FET/SiC-diode configuration instead of the GaN-FET/GaN-FET configuration to avoid potential device failure in [8-9]. In [10], a 1kw cryogenically cooled GaN based three-level inverter was reported.

The reduced on-state resistance provides the possibility to operate GaN device at a current level much higher than rated at cryogenic temperature. However, whether the commercial GaN devices are capable of operating at a current level much higher than rated at cryogenic temperature or not has not been explored in literature. GaN HEMT short-circuit characteristic is critical for GaN-based converter protection design but its short-circuit capability at cryogenic temperature has also not been investigated in literature. Furthering previous research, this paper conducts a comprehensive static and dynamic characterization of a 650V-30A GaN HEMT at cryogenic temperature. The overcurrent and short-circuit capability of GaN HEMT are experimentally investigated.

II. STATIC AND DYNAMIC CHARACTERIZATION AT CRYOGENIC TEMPERATURE

A. Test Setup

A cryogenic temperature chamber with liquid nitrogen is usually utilized in the lab to perform device characterization at cryogenic temperature. The temperature inside the chamber can be regulated from room temperature to cryogenic temperature as low as 93 K, and thermal insulation is achieved inside and outside of the chamber. Fig. 1 shows the static characterization test setup. A curve tracer B1505A from Keysight is utilized to test the output and transfer characteristics of GaN device. The Kelvin connection need to be adopted to suppress measurement error introduced by long connected cables. Fig. 2 shows the dynamic characterization test setup. A double pulse test (DPT) circuit is implemented for switching characteristics test. The PCB board including the DUT, gate driver, signal isolator, and auxiliary power supply are put inside the cryogenic chamber while the load inductor and other equipment are located outside. The method details for static and dynamic characterization at cryogenic temperature can be found in [2]. The test is similar to previous work in [9]. The main difference is that, due to the PCB layout optimization to reduce the power loop and gate loop parasitic inductance, the DPT test is able to use GaN-FET/GaN-FET configuration which is more like the real case in a half-bridge based converter.

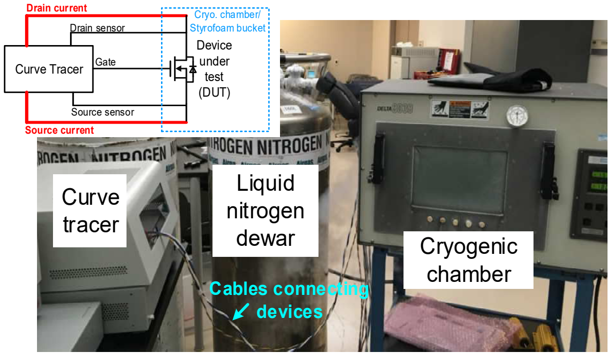
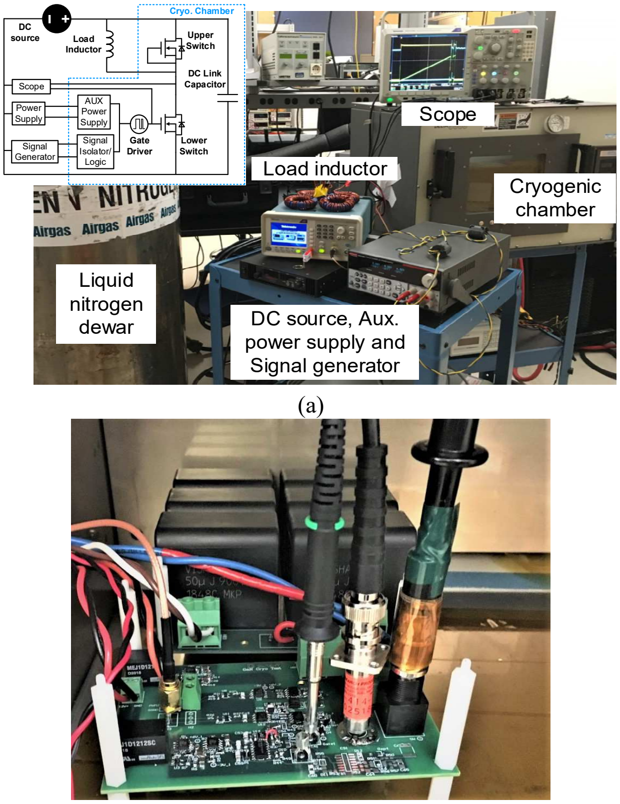


Fig. 1. Test setup for GaN HEMT static characterization at cryogenic temperature.



(a)

(b)

Fig. 2. Test setup for GaN HEMT dynamic characterization at cryogenic temperature, (a) test platform, (b) DPT circuits inside the cryogenic chamber.

B. Static Characterization Results

The output and transfer characteristics of the 650V-30A GaN HEMT are characterized at different temperatures. Fig. 3 summarizes its on-state resistance at different junction temperatures. The on-state resistance gradually decreases when temperature decreases, and it reduces fast at beginning of temperature drop but becomes slow around 140 K. At 93 K, the on-state resistance is 9 mΩ and is a little less than one-fifth of that at room temperature (298 K) which is 48.2 mΩ. The on-state resistance reduction at cryogenic temperature is mainly due to the increased carrier density in the 2DEG of GaN HEMT at cryogenic temperature. Unlike SiC MOSFET, there is no freeze out phenomenon in GaN HEMT down to 93K.

Fig. 4 shows the transconductance of GaN HEMT at different temperatures. The transconductance increases as temperature decreases. At 93 K, the transconductance at 30A is 50 S and is around 2.5 times of that at room temperature which is 19 S. This characteristic enables GaN HEMT to switch much faster at cryogenic temperature. The increase of transconductance at cryogenic temperature is because of the increase in the electron velocity caused by an improvement in 2DEG mobility beneath the gates.

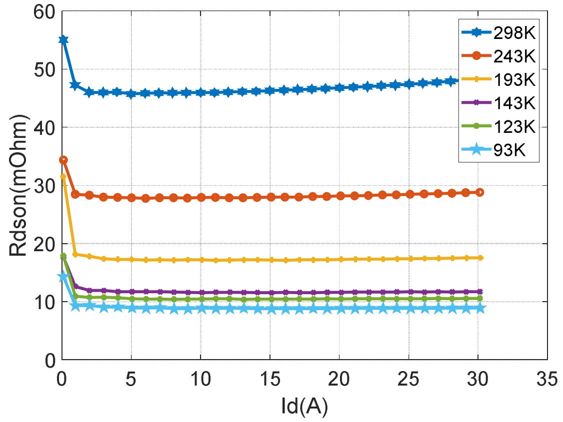


Fig. 3. On-state resistance at different temperatures.

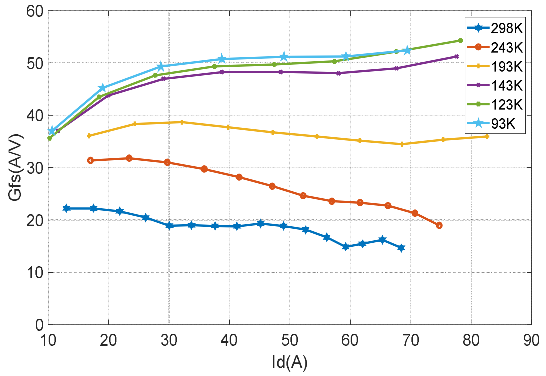


Fig. 4. Transconductance at different temperatures.

Fig. 5 summarizes the output characteristics at different temperatures and different gate voltages. The saturation current increases as temperature decreases. Also, the slope of drain current in ohmic region increases as temperature decreases. This trend is consistent with the conclusion that transconductance increases and on-state resistance decreases at cryogenic temperature.

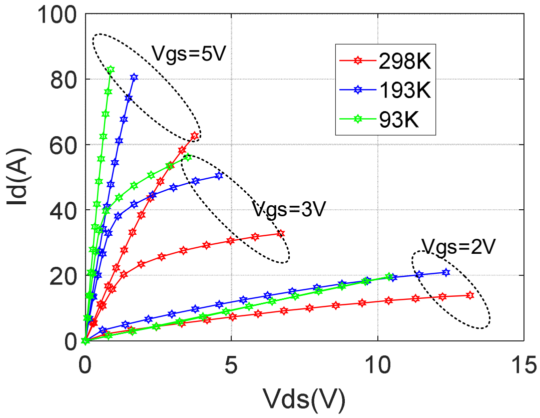


Fig. 5. Output characteristics at different temperatures (Vgs =2, 3, and 5V).

Fig. 6 shows the reverse conduction characteristics of this GaN HEMT. GaN HEMT still has a diode-like behavior although it does not have a real body diode. At different temperatures, the forward voltage of the diode-like behavior has little change, and the equivalent series resistance becomes lower as temperature decreases. This feature helps to reduce freewheeling loss during dead-time in a half bridge GaN circuit configuration.

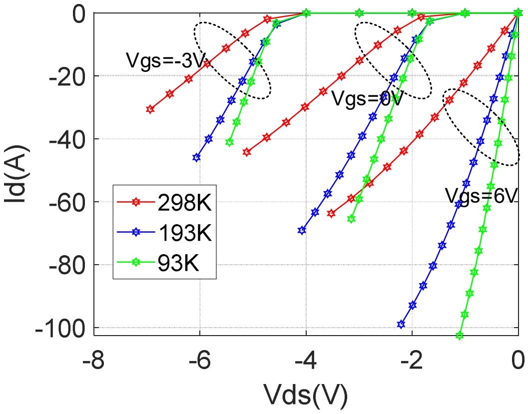


Fig. 6. Reverse conduction characteristics at different temperatures (Vgs =-3, 0, and 6V).

Fig. 7 summarizes the drain leakage current at different temperatures. When drain-source voltage increases up to 700V, the leakage currents are smaller than 0.3uA at all temperatures. Thus, the breakdown voltage almost keeps constant from room temperature to cryogenic temperature.

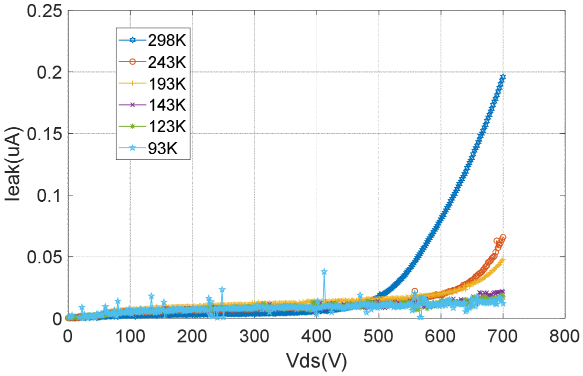
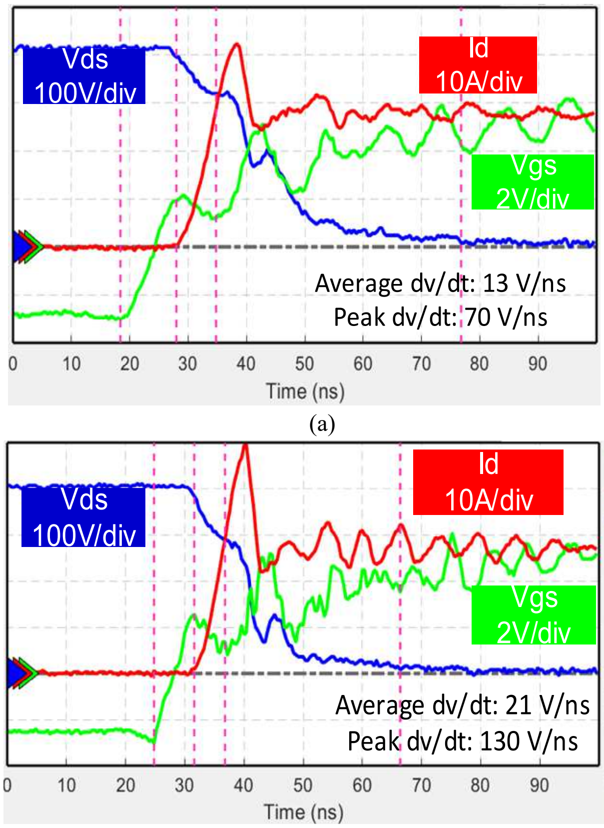


Fig. 7. Leakage drain current at different voltages and temperatures.

C. Dynamic Characterization Results

The switching characteristics of the 650V-30A GaN HEMT are characterized at different temperatures. Turn-on and turn-off voltages are 6V and -3V. Turn-on and turn-off gate resistances are 20 Ω and 2 Ω. Gate driver IC uses Si2871 from Silicon Labs. When temperature decreases to around 130 K, obviously gate voltage drops from output of this gate driver IC is observed. Thus, the dynamic characterization is conducted at temperatures higher than 130 K.



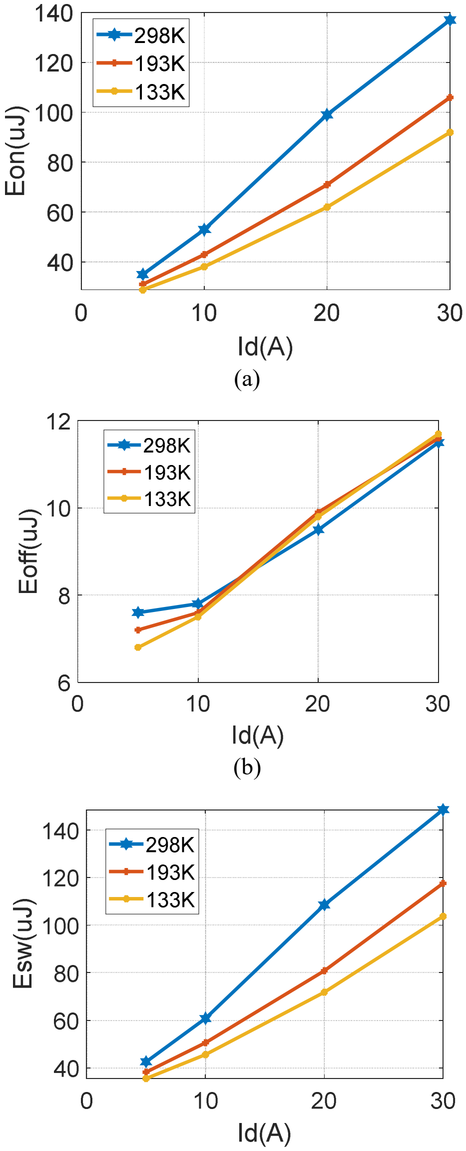
(a)

(b)

Fig. 8. Turn-on waveforms at 400V-30A condition, (a) 298 K, (b) 133 K.

At cryogenic temperature, the switching speed becomes much faster due to the increased transconductance. Fig. 8 shows the turn-on waveforms comparison for 400V-30A operating point at both room temperature and cryogenic temperature. The tested average dv/dt and peak dv/dt are 13 V/ns and 70 V/ns at room temperature while the tested average dv/dt and peak dv/dt are 21 V/ns and 130 V/ns at cryogenic temperature. The dv//dt is almost doubled at cryogenic temperature.

Fig. 9 shows the switching loss comparison at different temperatures and different loads at 400V dc bus voltage. Compared to room temperature case, the turn-on switching loss is reduced by around 30% while turn-off loss is almost kept unchanged at cryogenic temperature.



(a)

(b)

(c)

Fig. 9. Switching loss at different temperatures, (a) turn-on loss, (b) turn-off loss, (c) total switching loss.

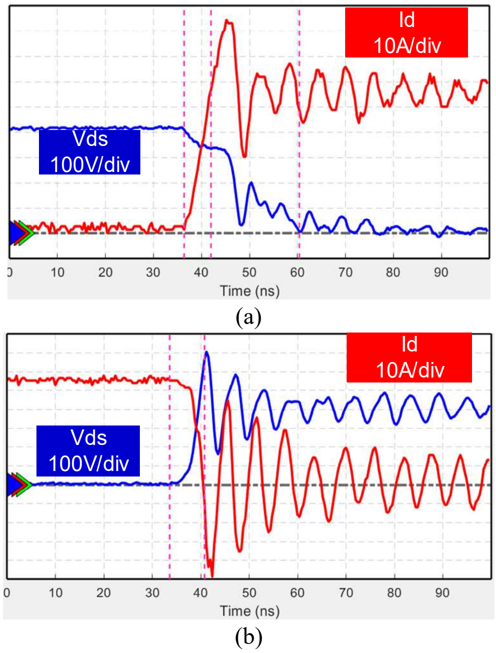
III. OVERCURRENT DYNAMIC CHARACTERIZATION AT CRYOGENIC TEMPERATURE

The significantly reduced on-state resistance provides the possibility to operate GaN device at a current level much higher than rated at cryogenic temperature. Overcurrent dynamic characterization for the 650V-30A GaN HEMT is conducted using the DPT circuit. For this overcurrent test, the load current starts from the rated 30A and keeps increasing until desaturation-based protection triggers or device failure occurs.

As GaN device is more sensitive to gate voltage, the gate measurement probe could introduce extra noise and interfere with gate loop, and result in large oscillation during high dv/dt or high di/dt switching transient. This phenomenon was observed in both overcurrent and short-circuit experiments. Advised by GaN Systems, the gate signal is not measured.

With larger overcurrent, turn-off transient becomes faster and severe turn-off overvoltage occurs. Experiment results show that when load current increases from rated 30A to 60A for 400V dc bus, the turn-off overvoltage exceeds 700V even the turn-off gate resistance is increased from 2Ω to 5.1Ω. To keep the turn-off voltage below 600V for safety operation, the turn-off resistance is selected to be 15Ω. At cryogenic temperature, the load current is able to be increased to 115A, which is nearly 4 times of rated current of this device.

Fig. 10, Fig. 11, and Fig. 12 show the switching waveforms at 60A, 80A, and 115A, respectively. All at 400 V dc bus voltage and 133 K cryogenic temperature.



(a)

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Fig. 10. Overcurrent dynamic characterization at 400V-60A operation point at cryogenic temperature (133 K), (a) turn-on transient, (b) turn-off transient.

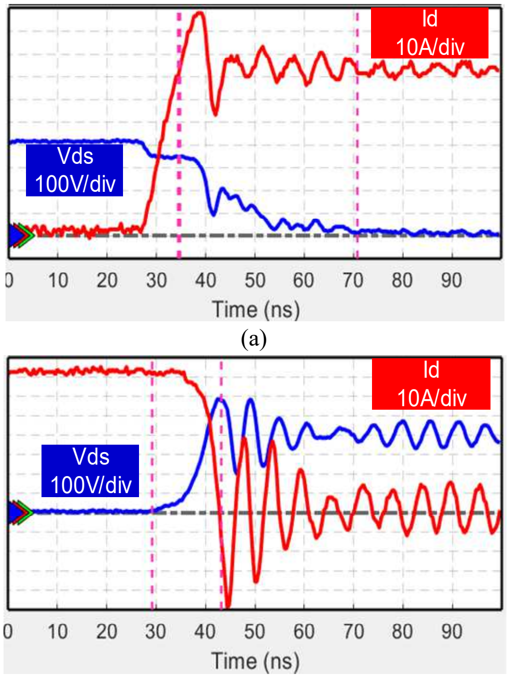


Fig. 11. Overcurrent dynamic characterization at 400V-80A operation point at cryogenic temperature (133 K), (a) turn-on transient, (b) turn-off transient.

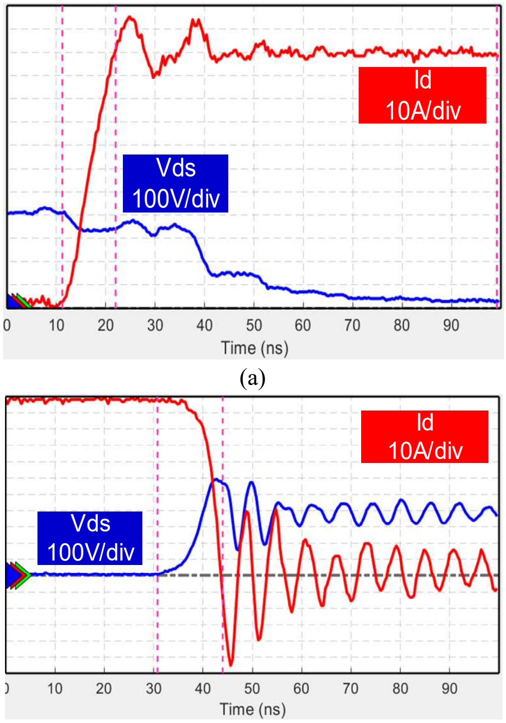


Fig. 12. Overcurrent dynamic characterization at 400V-115A operation point at cryogenic temperature (133 K), (a) turn-on transient, (b) turn-off transient.

In Fig. 12, the tested average dv/dt is 60 V/ns and peak dv/dt is 130 V/ns at 400V-115A operation point. The turn-off voltage is within 600V. Fig. 13 summarizes the switching loss for overcurrent operation from 40A to 115A.

Note that if further increasing the load current, desaturation protection triggers or device failure occurs frequently. The root cause of this phenomenon is still unclear. Possible reasons could be that the device package cannot handle large current or high electric field generated by the large current directly breakdown the device.

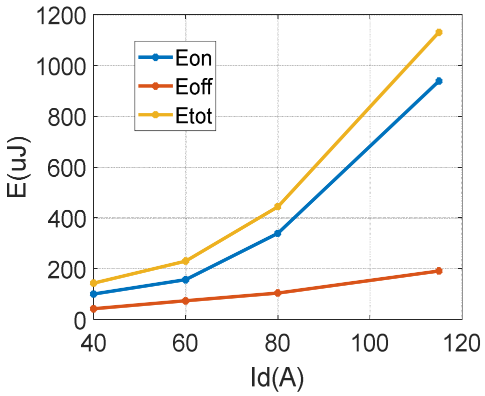


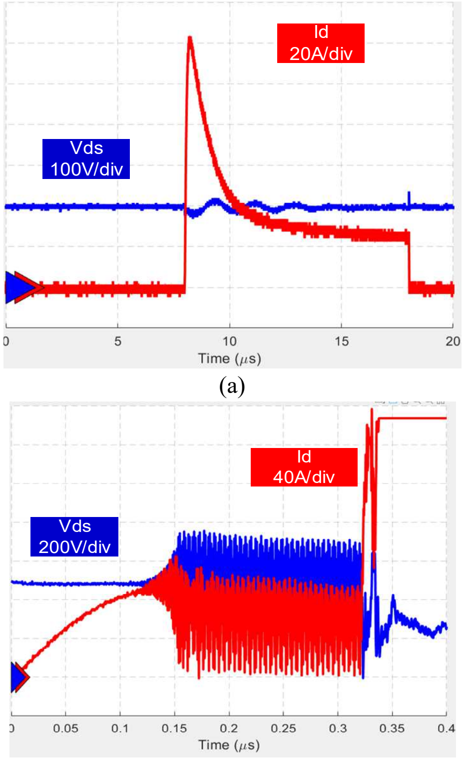
Fig. 13. Switching loss of overcurrent (> rated 30A) characterization at cryogenic temperature (133 K).

IV. SHORT-CIRCUIT CHACRACTERIZATION AT CRYOGENIC TEMPERATURE

Short-circuit test is conducted using the same DPT circuit. The upper device is shorted, and the hard switching fault (HSF) is tested for lower device. A 10 us pulse is applied to the DUT (lower device) under varies dc bus voltages from 50V to 500V at different temperatures.

Fig. 14 (a) and Fig. 14 (b) show the room temperature short-circuit test waveforms at 200V and 500V dc bus voltage, respectively. At 200V dc bus, the DUT pass the 10 us short-circuit pulse test. From Fig. 14(a), the short-circuit current first increases quickly to a peak value and then decreases. This is because the DUT generates large loss due to both high voltage and high current and thus temperature increases fast during the short-circuit transient. As a result, transconductance decreases and channel saturation current decreases. The on-state gate leakage current also increases and thus the gate voltage drops. This further reduces transconductance and channel saturation current. The strong negative temperature feedback realizes the short circuit current self-regulation. At 500V dc bus voltage, device failure occurs during the 10 us short-circuit pulse. Oscillation occurs before the device is fully damaged as can be observed in Fig. 14(b). The short circuit withstand time is 240 ns for 500V dc bus.

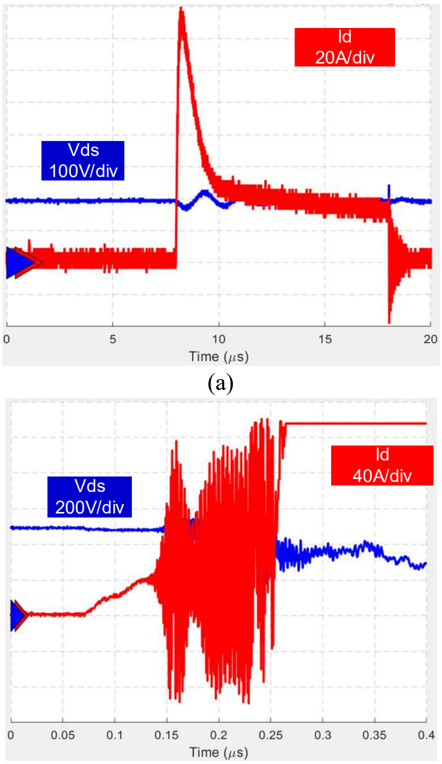
Fig. 15 (a) and Fig. 15 (b) show the cryogenic temperature short-circuit test waveforms at 200V and 500V dc bus voltage, respectively. The waveforms are similar to that at room temperature.



(a)

(b)

Fig. 14. Short-circuit test at room temperature (298K), (a) Vdc=200V, (b) Vdc=500V.



(a)

(b)

Fig. 15. Short-circuit test at cryogenic temperature (133 K), (a) Vdc=200V, (b) Vdc=500V.

Comparing Fig. 14 and Fig. 15, the short-circuit peak current is larger at cryogenic temperature due to the lower initial temperature. Fig. 16 summarizes the short circuit peak current value as a function of device drain-source voltage at different temperatures. Generally, short circuit peak current increases as temperature decreases and voltage decreases.

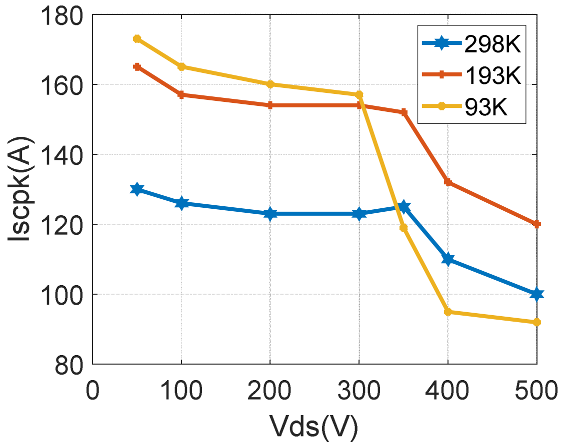


Fig. 16. Short-circuit peak current at different voltages and temperatures.

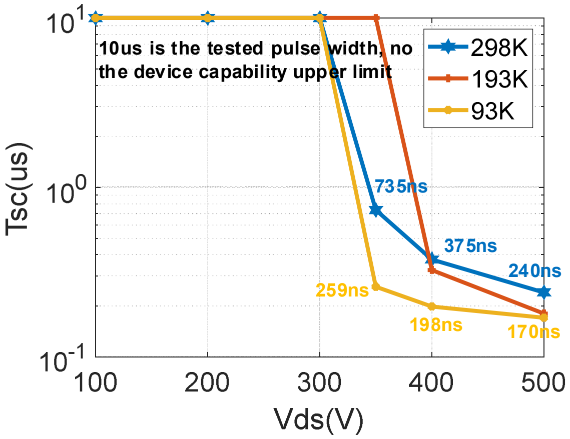


Fig. 17. Short-circuit withstand time at different voltages and temperatures.

The short-circuit test results from 50V to 500V indicate that the short circuit failure threshold dc voltage of this GaN HEMT is around 350 V – which means that the device can pass 10 us short-circuit pulse when dc voltage is below 350V.

Fig. 17 summarizes the short circuit withstand time as a function of drain-source voltage at different temperatures. From Fig. 17, both the device failure threshold dc voltage and short circuit withstand time do not have obviously change at cryogenic temperature. The short circuit withstand time actually decrease a little bit although initial temperature is lower. Cryogenic temperature allows higher temperature rise for the DUT, which is beneficial to short circuit withstand time. On the other hand, due to the lower initial temperature, DUT current increases faster and short-circuit current peak is also higher. Thus, energy accumulates faster which is detrimental to short circuit withstand time. The benefit of lower initial temperature may be canceled out and thus no improvement of the short-circuit capability is observed in the test. In addition to thermal related failure, the high localized electric filed generated by the high voltage and current during short-circuit transient may also break down the device.

Note that this conclusion is only verified for the condition that the device has a relatively large thermal impedance from junction to ambient as no heatsink is applied in this test. Consequently, the device junction temperature rises fast during short-circuit transient. If the device has a relatively small thermal impedance (i.e., heatsink is applied), how short circuit withstand time varies at cryogenic temperature compared to that at room temperature needs further investigation.

V. CONCLUSION

This paper presents the characterization of a 650V-30A GaN HEMT at cryogenic temperature. The GaN HEMT achieves >5X conduction loss reduction and around 30% switching loss reduction at cryogenic temperature. The overcurrent and short circuit capability of GaN HEMT at cryogenic temperature are experimentally evaluate. The GaN HEMT is capable of operating at nearly 4X of rated current at cryogenic temperature. The short-circuit capability of GaN HEMT at cryogenic temperature is similar to that at room temperature. Both the short-circuit withstand time and device failure threshold dc voltage are almost unchanged at cryogenic temperature.

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