Characterization of 650 V GaN Transistors at Cryogenic Temperature in All-electric Aircraft Applications

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***Abstract*—With the growing electrification of aircraft, power electronics is playing an increasingly vital role in driving this transformation. It is expected that some all-electric aircraft to utilizes liquid hydrogen (LH2) as power fuel as well as coolant, which opens the possibility of utilizing cryogenic power electronics which offers higher efficiency and faster switching speeds than its room-temperature counterpart. Literature has shown the most efficient semiconductor switches at cryogenic temperatures is gallium nitride (GaN). Thus this paper focuses on studying the characteristics of 650 V GaN transistor at room temperature and cryogenic temperature at 77 K. Forward and breakdown voltage tests are performed to characterize the device. With the extracted device characteristics, a buck converter is simulated to estimate its efficiency and room and cryogenic temperatures.**

***Index Terms*— Cryogenic propulsion, Cryogenic power electronics, GaN HEMT[1]**

I. INTRODUCTION

NOWADAYS, excessive emissions of carbon dioxide and other greenhouse gases are the major contributor to global warming. According to the research in [1], floods, droughts, heatwaves and hot spells are becoming more frequent, and crop growth duration is affected, as global mean temperature has increased to up more than 2℃ above pre-industrial levels. In response to this trend, major industrialised countries have put forward different timelines for energy saving and emission reduction. "Net Zero 2050" is the carbon neutrality program proposed and implemented by UN [2].

To meet the target of net zero emissions by 2050, Airbus has launched several programmes to accelerate technology breakthroughs and enable zero emission commercial aircraft by 2035 [3]. One of the potential energy sources for all-electric aircraft is liquid hydrogen (LH2). An idea is to use LH2 not only as fuel, but also coolant, whose cryogenic feature will enable the utilization of technologies such as superconducting motors and cryogenic power electronics, both of which are known to have high efficiency and power density [3]. Fig.1 shows a simplified architecture of an all-electric aircraft with temperature zones differentiated. Prior arts have discussed the performance of different devices at cryogenic temperatures, and it was found that Gallium Nitride (GaN) devices have a reduced on-resistance by more than 50%, an increased switching on time, and stable slightly increased breakdown voltage. In contrast, Silicon counterparts have reduced breakdown voltage, while Silicon Carbide ones have increased on-resistance. Therefore, this article will focus on testing commercial off the shelf (COTs) GaN devices [4].

Some literature has already discussed the performance of DC/DC converter at room temperatures (RT) and cryogenic temperatures (CT). In [5] and [6], a bi-directional resonant converter and a DC-DC Boost converter has been tested below 150 K. However, the converter efficiency drops slightly under high input voltage condition [5]. This paper uses the extracted device characteristics to simulate a buck converter at CT and RT.

After this introduce tion, section II reviews different semiconductor switches and makes selection of the devices under test. Section III discusses the methodology of the forward voltage test and the breakdown voltage test. Section IV presents the results of forward voltage voltage tests and breakdown voltage tests at RT and CT. The on-resistance decreases with temperature decreases from room temperature to cryogenic temperature. And the breakdown voltage increases by 10% in the same case as the temperature change. Section V shows the results of buck converter, which have higher efficiency at CT.

II. DEVICES SELECTION

A. Review of semiconductor devices

This section compares different device technologies of silicon (Si), silicon carbide (SiC) and GaN. GaN devices are known to have reduced on resistances with temperature due to the increased electron mobility at low temperature [8][9][10]. For SiC devices, the carbon defects the construction of 4H-SiC and 6H-SiC at low temperature [11]. Therefore, most commercial SiC MOSFETs show monotonically decreasing electron mobility when the temperature decreases from 450 K to less than 150 K [12]. This phenomenon causes monotonically increasing on-resistance When temperature decreases [7]. As a semiconductor device that has been widely used, Si MOSFETs have slightly lower on-resistance. And gate-source threshold voltage increases around 25% at CT, due to the 30 orders of magnitude fall in the intrinsic carrier concentration from 300 K to 77 K [7].

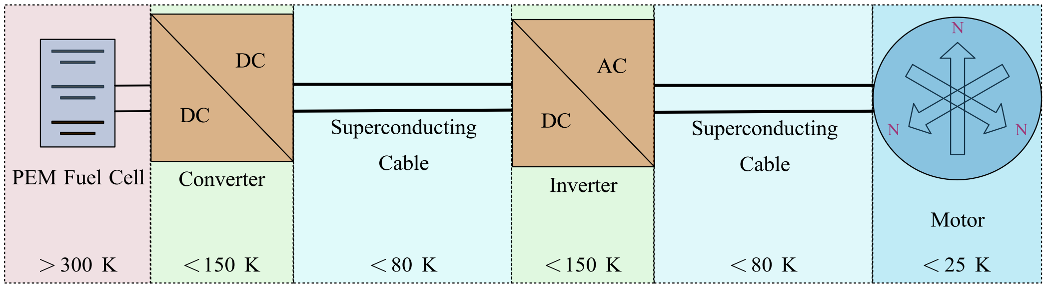


Fig. 1. A typical architecture of the propulsion system on-board all-electric aircraft with different temperature zones highlighted

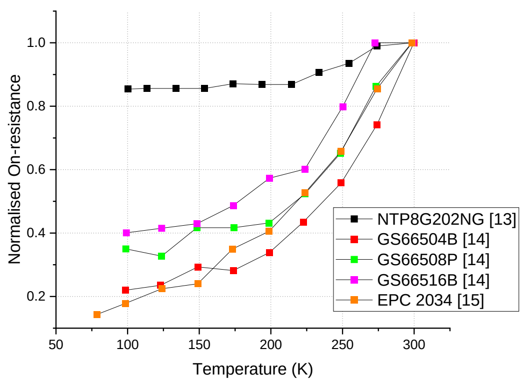


Fig. 2. Normalised on-resistance of GaN transistors

Compared with Si and SiC MOSFETs, GaN transistors show the largest reduction of on-resistance at temperature down to 77K. As shown in Fig. 2, the on resistance of GaN transistors from GaN systems (GS66504B, GS66508P and GS66516B) and EPC (EPC 2034) at CT decrease to less than 40% of that at 300 K [13][14][15] Si and SiC transistors have decreased breakdown voltage at low temperature. In contrast, as shown in Fig. 3, GaN transistors have higher breakdown voltage at CT than RT. Considering the reduced on-resistance and the increased breakdown voltage of GaN transistors.

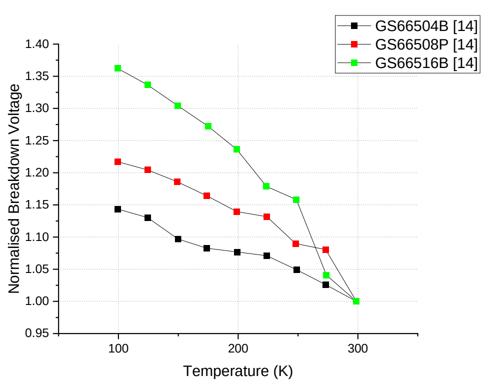


Fig. 3. Normalised breakdown voltage of GaN transistors

B. Device selecion

Two cascaded GaN HEMTs are tested in this paper. A cascaded GaN HEMT combines a high voltage GaN HEMT with a low voltage Si MOSFET, which can withstand higher gate voltage. In contrast to some of GaN HEMT, the natural operating state of the GaN HEMT Cascode is the off state, which is the same as what we are used to with Si MOSFETs [16]. Moreover, the built-in low voltage Si MOSFETs have little increase in Rds(on).

III. Methodology of Characteristic Tests

To assess the performance of cascaded GaN HEMT at CT, this paper presents the static characteristic results for this semiconductor device. In the following tests, the devices are fully submerged in liquid nitrogen. Therefore, the CT environment here means 77 K, which is the temperature of the liquid nitrogen. All the results at cryogenic temperatures are recoded after 10 minutes of immerging the devices in liquid nitrogen.

Two different cascoded GaN HEMTs are assessed by the forward voltage test and breakdown voltage test. Three samples were tested for each type of the devices to guarantee the results are repeatable. In the following figures and tables, device under test is abbreviated with DUT. 'A' and 'B' refer to the two cascaded GaN HEMTs with different part numbers. '1', '2' and '3' are used to note the different samples under the same part number.

A. Forward voltage test

Fig. 4 illustrates the setup of the forward voltage test. The DUT is kept on supplied by a DC source (Lambda GSP10-1000).The output current of the DC source is gradually increased. Measurement module cDAQ 9185 with NI 9229 records the drain-source voltage and the drain-source current of DUT. All the test sequences are defined through LabVIEW. Normally, The diode in the following result is from the sum of Si MOSFETs part inside the GaN HEMT Cascode and the channel of the depletion GaN.

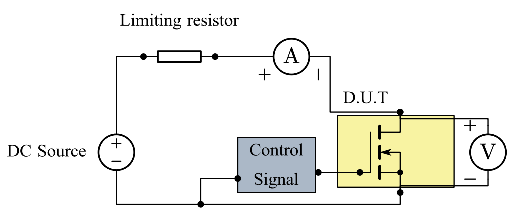


Fig. 4. Setup of the forward voltage test

B. Breakdown voltage test

To find out the drain-source breakdown of the device, Glassman-High-Voltage-Source EJ (3 kV – 200 mA) is used to bias the drain-source of the DUTs with high voltage. Fig.5 shows the setup of the breakdown voltage test. Shunt resistor is used for current measurement. To prevent overvoltage on the analog inputs of NI9229, a voltage divider is formed to scale down the drain-source voltage.

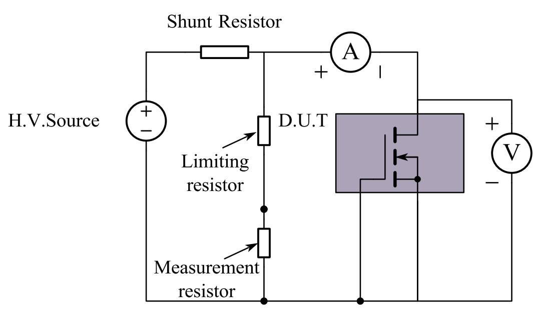


Fig. 5. Setup of the breakdown voltage test

IV. Test Results

A. Output and third quadrant characteristic

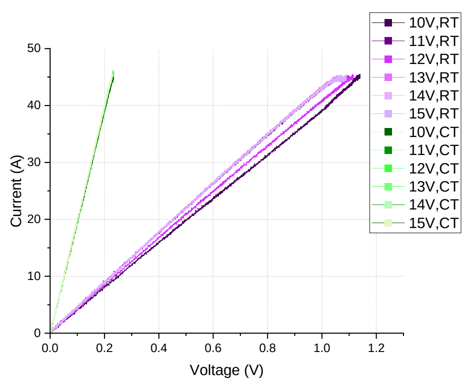


Fig. 6. I-V curve at forward voltage test for DUT A1

Fig.6 and Table 1 shows the performance of DUT A1 with rated drain-source voltage of 650 V and rated drain-source current of 95 A The purple curves in Fig.5 have smaller slope than the green curves. The on resistance of DUT A1 at cryogenic temperature is smaller than that at room temperature. Table I lists the extracted on-resistance of DUT A1 at various gate voltage under RT and CT. As shown, compared to RT, the on-resistance of DUT A1 at CT decreases around 77%.

Fig.7 shows the third quadrant characteristic of DUT A1. As shown, the reverse diode curves for both temperatures cross at around 18 A, which is close to the trends in the datasheet.

TABLE I
ON RESISTANCE AT DIFFERENT TEMPERATURE FOR DUT A1

Gate voltage (V)	10	11	12	13	14	15
R_{on} in datasheet (mΩ)	27	-	-	-	-	-
R_{on} at RT (mΩ)	26	23	25	23	23	23
R_{on} at CT (mΩ)	6	5	5	5	5	5

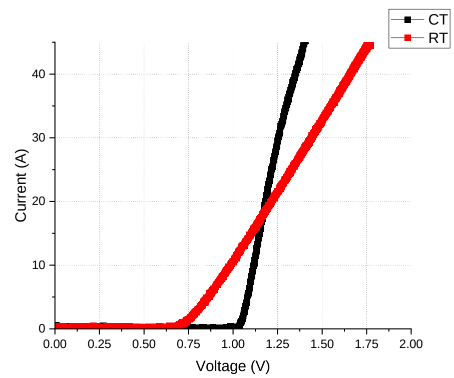


Fig. 7. Third quadrant Characteristics of reverse diode for DUT A1

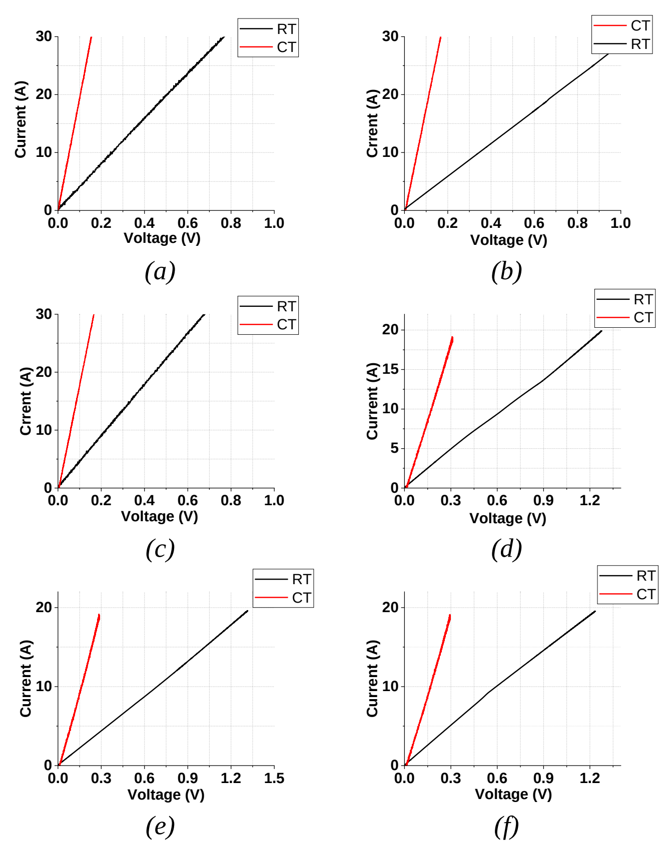


Fig. 8. I-V curve of forward voltage test for (a)-(c) DUT A1-A3 and (d)-(e) DUT B1-B3

Fig. 8 demonstrates repeatability of the forward voltage test on DUT A and B. DUT B has drain-source voltage rating of 650V and drain-source current rating of 35A. According to the result in Fig.8 and Fig.9, the on-resistance of DUT A decreases to around 6 mΩ, while the on-resistance of DUT B decreases from more than 60 mΩ to around 15 mΩ, which show the same trends as in other reference [17]-[19].

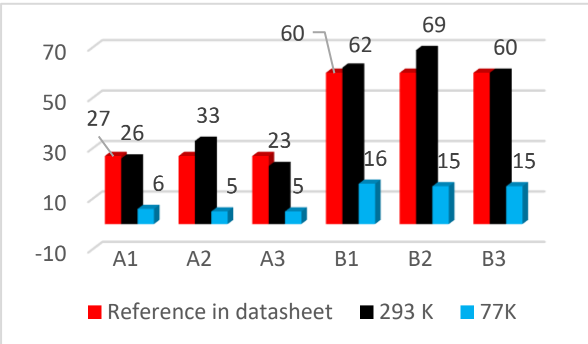
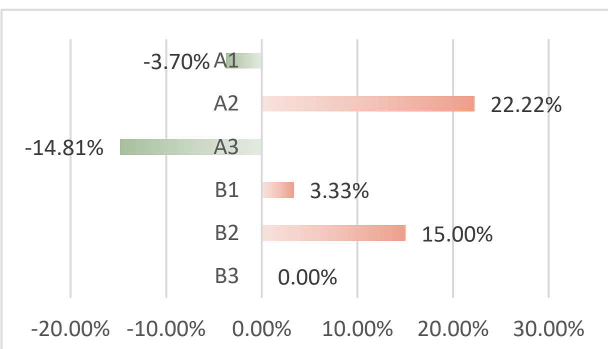
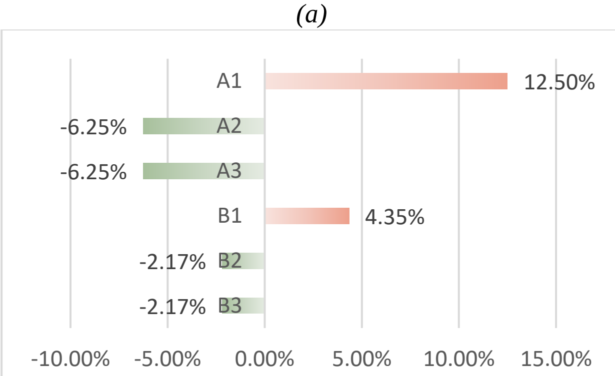


Fig. 9. Resistance comparison for DUT A and B

Fig. 9 shows the comparison of on-resistance at different temperature. The on-resistance of all the DUTs reduce by more than 75% when temperature is decreased from room temperature to cryogenic temperature.



(a)



(b)

Fig. 10. Analyse for nomalised on-resistance compared to the reference value at (a) room temperature and (b) cryogenic temperature

To visualize the difference in on-resistance of the same device, Fig. 10 (a) compares the measured on-resistance at room temperature with the reference value of the datasheet. And for the numerical analysis in low temperature environment, the reference on-resistance of Fig.10 (b) is set as the average on-resistance of the three samples at 77K. At room temperature, the difference between measured on-resistance and reference value are less than 23%, while the difference is less than 15% at cryogenic temperature.

B. Breakdown voltage test

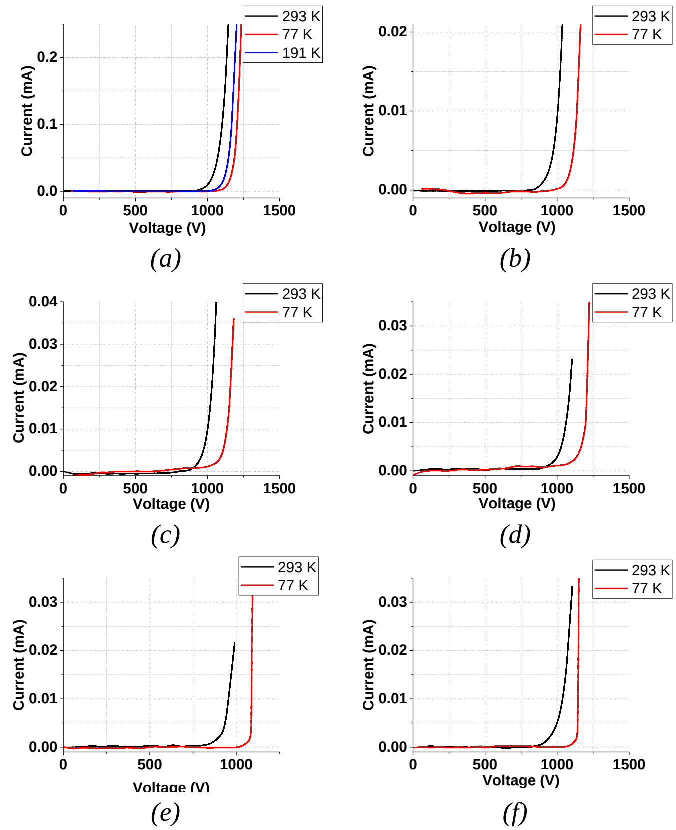


Fig. 11. I-V curve of breakdown voltage test for (a)-(c) DUT A1-A3 and (d)-(f) DUT B1-B3

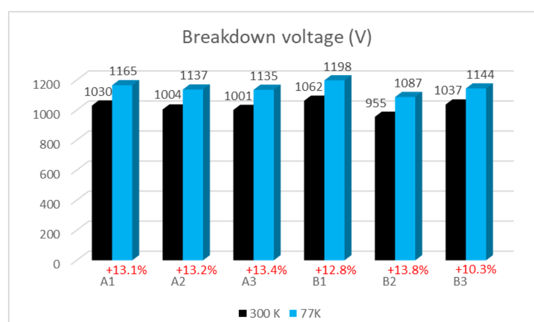
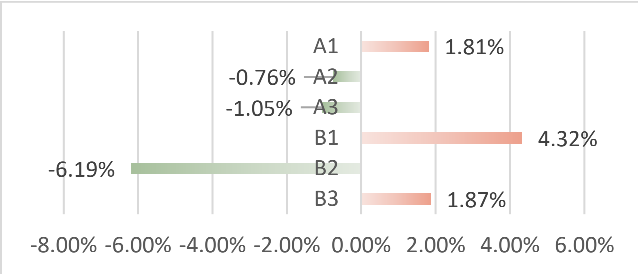
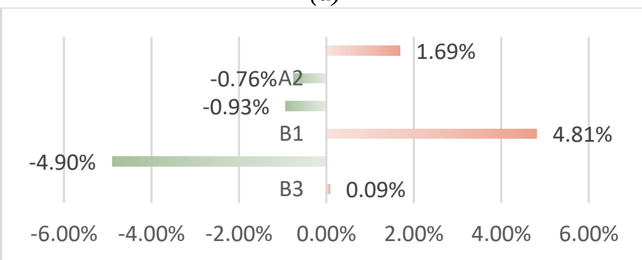


Fig. 12. Breakdown voltage comparison for DUT A and B

In contrast to Si MOSFETs and SiC MOSFETs, GaN HEMTs have a slightly higher breakdown voltage at lower temperature, as shown in Fig.11. This negative temperature coefficient is the same as some other papers and manufacture clarified [7].



(a)



(b)

Fig. 13. Analyse for nomalised breakdown voltage compared to the reference value at (a) room temperature and (b) cryogenic temperature

The breakdown voltage for GaN transistor DUT A in this test can increase by around 13%, from around 1000 V at room temperature (black curve) to more than 1130 V in liquid nitrogen (red curve). The breakdown voltage for DUT B increase by more than 10%, as the result shown in Fig.12.

To visualize the difference in breakdown voltage of the same device, Fig. 13 compares the measured breakdown voltage of the device at different temperature with the average value. At room temperature, the difference between measured breakdown voltage and the datasheet specification is less than 7%, while the difference is less than 5% at cryogenic temperature.

C. Summary of results

Table II shows the summary of the forward voltage tests and the breakdown voltage tests. All the DUT show a positive correlation coefficient for on-resistance. When temperature decreases from 300 K to 77 K, the on-resistance decrease by more than 70%, while the breakdown voltage increases by more than 10%.

TABLE II

ON RESISTANCE AND BREAKDOWN VOLTAGE COMPARISON

Device	**On-resistance**				**Breakdown voltage**		
	Datasheet value (Ω)	Measured value (Ω)		Difference	Measured value (V)		Difference
		RT	CT		RT	CT	
A1	27	26	6	- 76.92%	1030	1165	+ 13.11%
A2		33	5	- 84.85%	1004	1137	+ 13.25%
A3		23	5	- 78.26%	1001	1135	+ 13.39%
B1	60	62	16	- 74.19%	1062	1198	+ 12.81%
B2		69	15	- 78.26%	955	1087	+ 13.82%
B3		60	15	- 75.00%	1037	1144	+ 10.32%

The gate resistance, input voltage, power rating, load resistor and inductance used in the Simulink model are listed in table III, which are set to be the same as its datasheet of DUT A. In the simulation, the power rating of the converter should be more than 20 kW with output current around 134 A. As shown in Table IV, the efficiency of the buck converter increases from 98.72% at RTto 99.62% at CT with 20 kHz switching frequency. At other frequencies, the efficiencies show similar trends, increasing by around 2% when temperature decreases. $P_{conduction}$ is the conduction loss of the converter, $P_{switching}$ is the switching loss of the GaN HEMTs and $P_{inductor}$ is the energy losses of the inductor.According to (1) and (2), the total power losses is around 69 W. Because the duty rate here is set to 50%, the conduction loss is calculated to 45 W as (3). So, the sum of switching loss and inductor losses is around 24 W at that case.

$$P_{conduction} + P_{switching} + P_{inductor} = P_{loss}. \quad (2)$$

$$I^2 \cdot R = P_{conduction}. \quad (3)$$

TABLE III

PARAMETERS FOR PHASE LEG

Input voltage (V)	270
Power rating (kW)	20
Load resistor (Ω)	1
Inductor (µH)	570
Gate resistance (Ω)	15

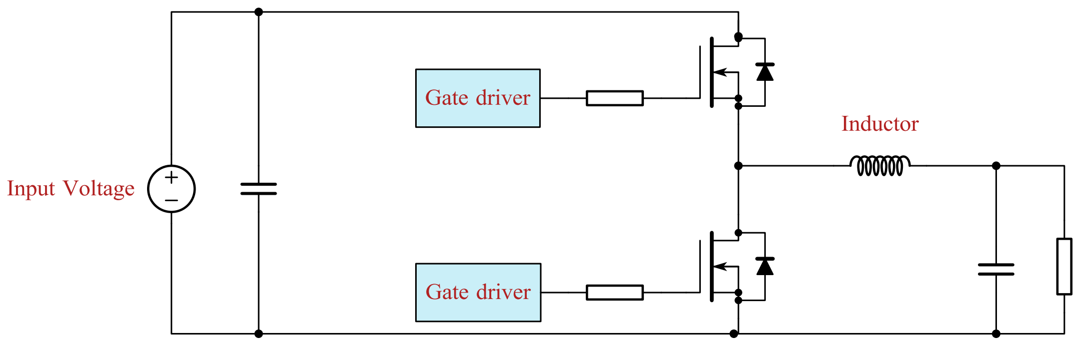


Fig. 14. Topology in MATLAB/SIMULINK with the experiments data at cryogenic temperature

TABLE IV
EFFICIENCY WITH DIFFERENT SWITCHING FREQUENCY

Frequency (kHz)	Efficiency (%)	
	RT	CT
20	98.72	99.62
30	98.72	99.63
40	98.71	99.63
50	97.11	99.63

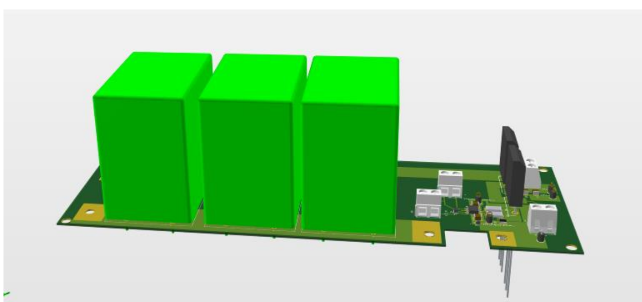


Fig. 15. PCB design for the double pulse test

V. CONCLUSION

Forward voltage test and breakdown voltage test are performed on six cascaded GaN HEMTs under room temperature and cryogenic temperature (77K). Test results show 75% reduction of forward voltage and 10% increment of breakdown voltage at cryogenic temperature compared to room conditions. to the extracted device characteristics are used to estimate the efficiency of a buck converter at room and cryogenic temperature. It was shown that the efficiency increases by more than 2% when temperature decreases from RT to CT, with operating frequency at 20 kHz, 30 kHz, 40 kHz and 50 kHz. To further evaluate the performance of the device at cryogenic temperatures, additional tests, such as the double pulse test which is shown in Fig. 15, are required to analyze the switching losses at cryogenic conditions. The circuit for this test is currently under construction and will be the future work.

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