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Electrothermal power cycling of GaN and SiC cascode devices☆

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ABSTRACT

This study investigates the power cycling tests of the GaN and SiC cascode devices to enable analysis of the alteration of their properties, such as case temperature, transfer characteristics, threshold voltage and leakage current once cycles complete. The highest increase in case temperature is seen in GaN cascode devices and more pronounced changes are seen in the drain current of these devices than that of the SiC devices as well. This is also the case in threshold voltage instability which is seen in the transfer characteristics of GaN devices whereas there is no change in their leakage currents. With respect to SiC cascode devices, the case temperature rise in the devices is around 25 °C and there is little increase in the leakage current after increasing the cycles, although there is a decreasing trend in their threshold voltages that can be linked to the temperature rise of the device while their transfer characteristics are invariant with increasing power cycles.

1. Introduction

The gallium nitride (GaN) and silicon carbide (SiC) power devices have become favourable for power applications [1] due to primary characteristics such as low on-state resistance, higher critical electric field as well as higher saturation velocity that results in the faster switching transients of power devices with higher power density in comparison with the traditional silicon (Si) based power devices [2–4]. These devices can be subjected to difficult working circumstances [5,6] such as elevated temperature and repetitive voltage and current stresses that can lead to failure of the devices. To evaluate the reliability and robustness of these power devices, it is necessary to investigate the results of several reliability experiments, with a key one being power cycling [7].

The power cycling test is generally utilized for accelerated life test technique that exposes the power devices to thermal and electrical stresses to imitate real power application conditions. The aim of the power cycling test is to examine the capability of the power devices to endure these types of stresses and evaluate their lifetime under real-life working circumstances [8].

In the last decades, applying electrothermal stress on the power devices has been well studied, involving thermal stress and electric field stress [9–11]. These stresses can result in phenomena such as current collapse [12], degradation of the drain current, threshold voltage drift and rise of the gate leakage current. To simulate real power applications, some researchers have observed reliability of the power devices after power cycling stress. Regarding GaN devices, the bond wire lift-off and solder delamination are the main reasons for device failure after power stressing tests [13–15]. On the other hand, analysis of the drifts in static parameters during power cycling tests are still absent in literature.

In this paper, detailed investigation on the power cycling test of GaN and SiC power cascode devices has been presented. The paper highlights case temperature changes during power cycling, the transfer characteristics to observe the threshold voltage drift, leakage current as well as drain current after stressing the devices with the current source for various cycles and current levels.

2. Experimental set-up for power cycling test

The power cycling test has been set-up with its schematic view and test rig used in the experimental measurements illustrated in Fig. 1. This test has been performed to investigate any potential degradations or failure that can be observed in 650 V GaN (TPH3212PS) and SiC (UJ3C065080T3S) as well as 900 V GaN (TP90H180PS) and 1200 V SiC (UJ3C120150K3S) cascodes after electrothermal stresses. The voltage level is kept constant at 5 V, and current levels are varied from 6 A to 9 A to analyse the impact of the current level on the device parameters. The periods of heating and cooling cycles are set to 1 s and 5 s, respectively.

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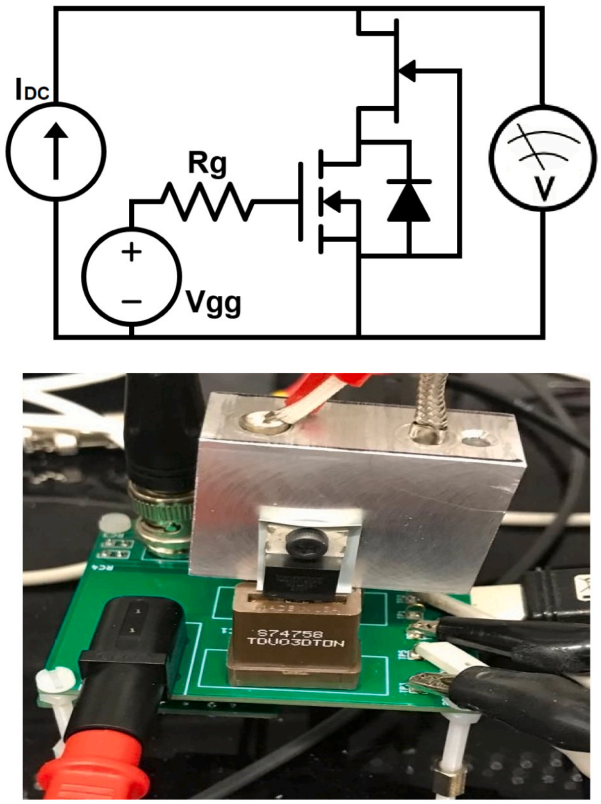

Fig. 1. The schematic view of the power cycling test circuit and the test rig that is used in the experimental measurements.

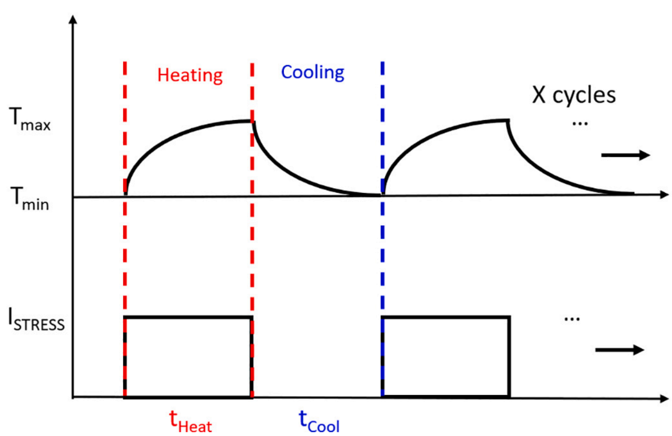

Fig. 2. The current stress period cycles when the device is heated and cooled.

During the heating state, the gate terminal is biased to 15 V. These cycles are repeated for 100, 200, 500 and 1000 times for the cascode devices. Under current stress cycles, the max case temperatures of the devices have been captured and presented. After each set of cycles, the transfer characteristics and gate leakage currents of power cascodes have been observed.

The current stress periods for heating and cooling of these devices and the cycles of temperature rise and drop during power cycling test are shown in Fig. 2. Additionally, the transfer characteristic, gate leakage current and drain current of these devices have been recorded after each cycle to examine any impact by the electrothermal stress on properties of cascodes.

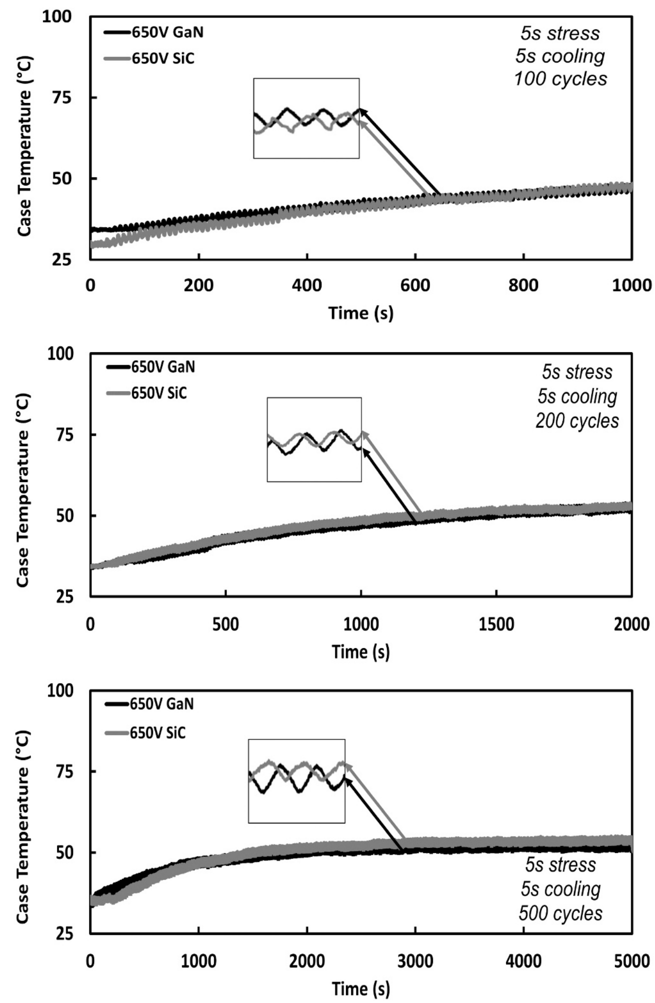

Fig. 3. The case temperature rises during the power cycling test by 6 A current stress with 100, 200 and 500 cycles for low voltage rated GaN and SiC cascode devices.

3. Results and discussion

To investigate the impact of temperature on the power cascode devices, the case temperature of the devices has been captured during power cycling test and the aluminium block has been connected to these devices in order to capture the case temperature swiftly. The current level is kept at 6 A and 9 A to observe the impact of the current stress on the different parameters of the power cascode devices.

3.1. Under 6 A current cycles

The case temperature of low rated GaN and SiC cascode devices under 6 A current stress for 100, 200 and 500 cycles have been demonstrated in Fig. 3. As it is seen in the three graphs, the trend of the case temperature with stress is increasing from room temperature to approximately 50 °C and stabilizes around that temperature. This is due to the power dissipation in heating period that can be extracted during the cooling period resulting in saturation of temperature around that level for both devices.

The thermal conductivity of SiC is much higher than that of the GaN device, while the on-state resistance and switching losses in GaN are lower than that of the SiC case. This can result in close levels of power dissipation in these devices resulting in close temperature rise during power cycling test [16].

Regarding the high voltage rated GaN and SiC cascode devices, their

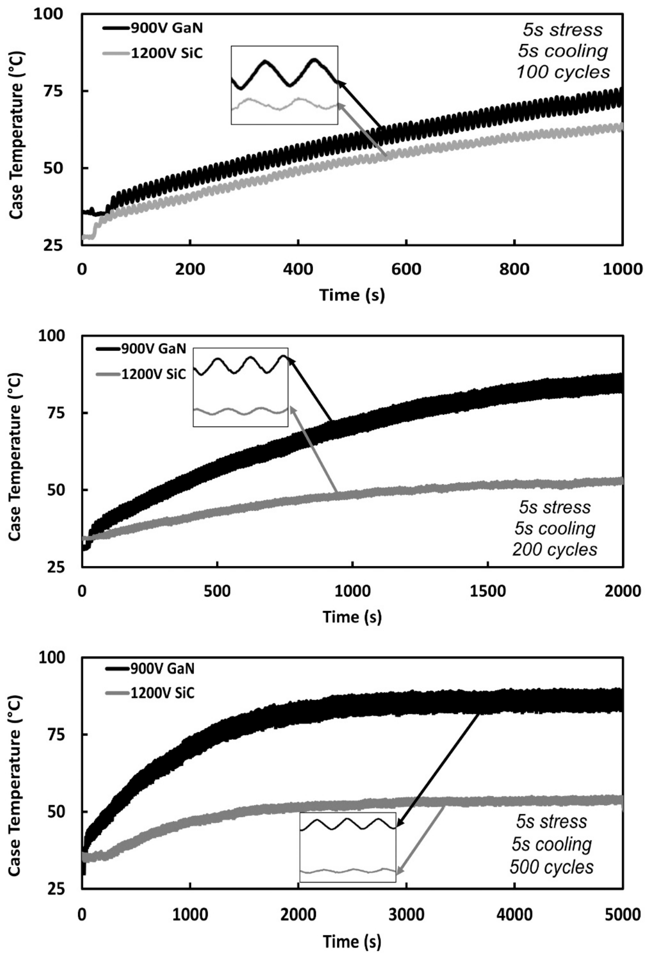

Fig. 4. The case temperature rises during the power cycling test by 6 A current stress with 100, 200 and 500 cycles for high voltage rated GaN and SiC cascode devices.

temperature rises during the 5 sec heating and 5 sec cooling cycles as illustrated in Fig. 4. The temperature rise with heating period in the 900 V GaN cascode device is much larger than in the 1200 V SiC cascode device when they are seen in the close views on the graphs which concludes that the case temperature of the GaN reaches 75 °C while that temperature of SiC device reaches up to 50 °C which can be related to the fact that the heat extraction mechanisms in 1200 V SiC device are more efficient than in the 900 V GaN device.

The thermal view of all cascode devices after 500 cycles at 6 A current stress is exhibited in Fig. 5. Compared to other cascode devices, the temperature rise in 900 V GaN cascode device is the highest after each

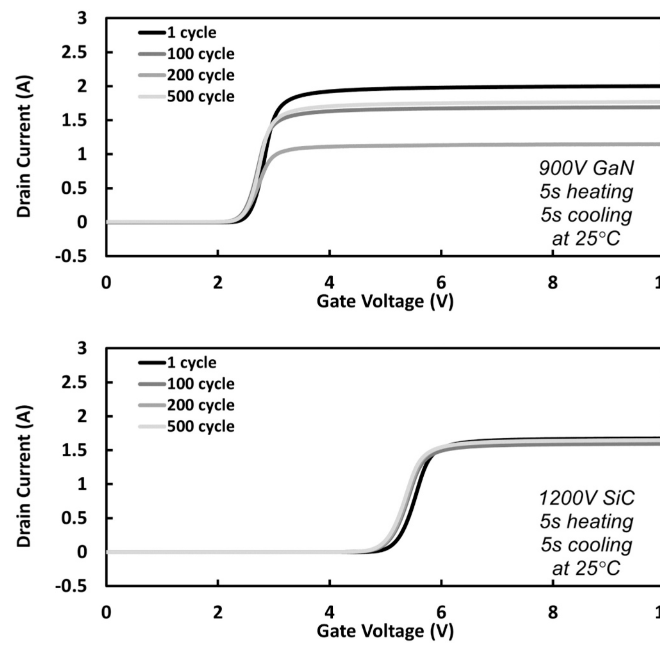

Fig. 6. The transfer characteristics for high voltage power cascode devices after each set of power cycles.

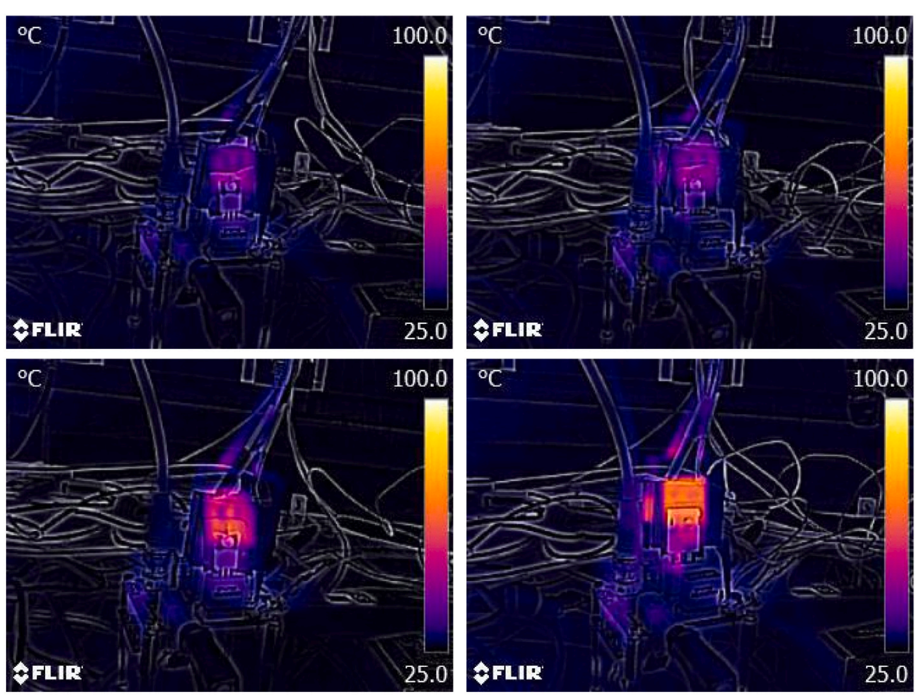

Fig. 5. The thermal views of 650 V GaN (top-left) and SiC (top-right) as well as 900 V GaN (bottom-left) and 1200 V SiC (bottom-right), after 6 A 500 power cycles.

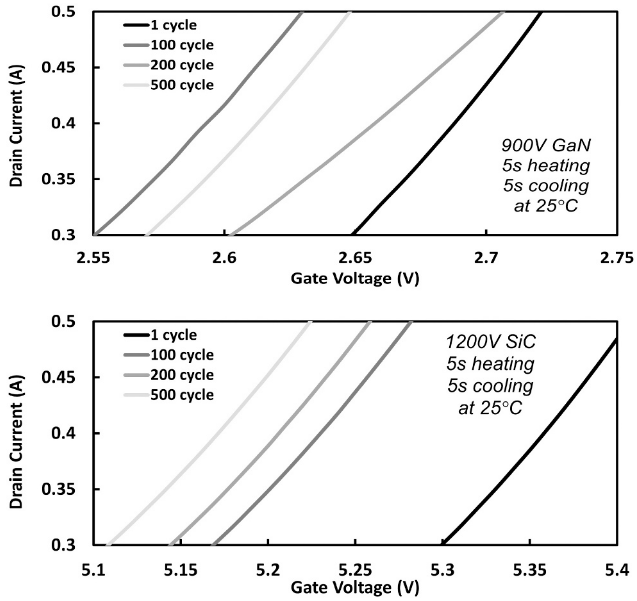

Fig. 7. The close views of transfer characteristics for high voltage cascode devices after each set of power cycles.

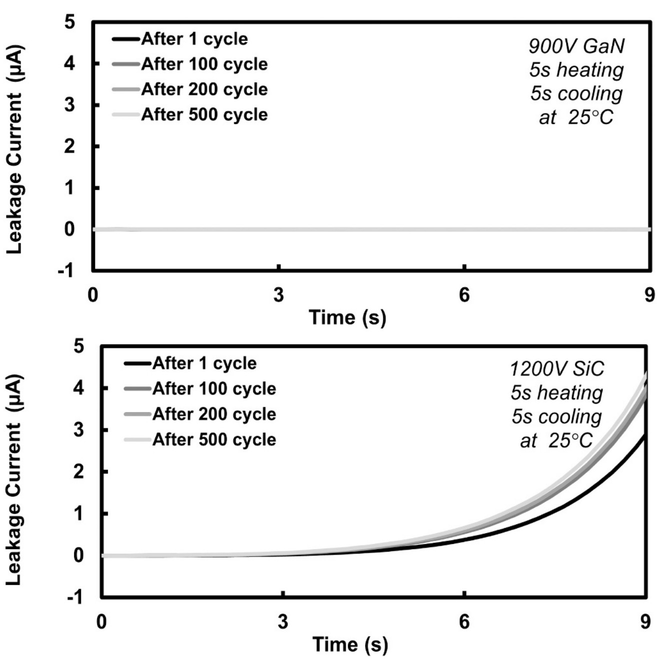

Fig. 8. The close views of transfer characteristics for high voltage cascode devices after each set of power cycles.

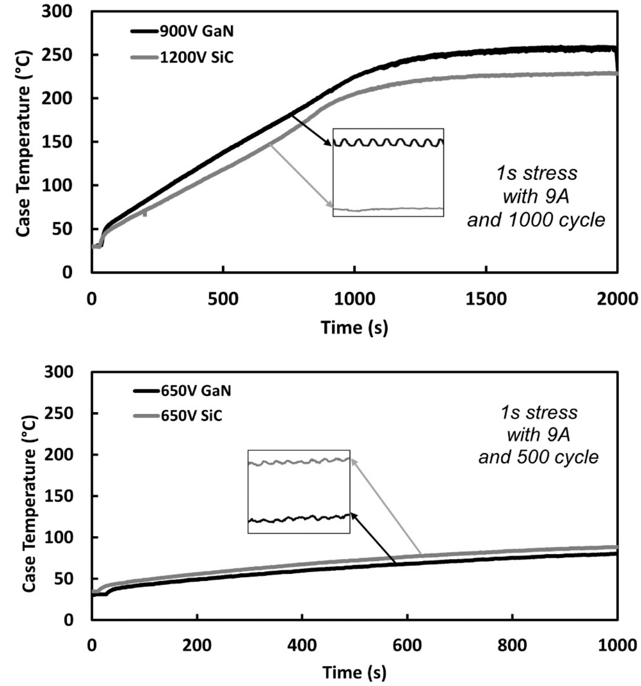

Fig. 9. The case temperature rises during the power cycling test by 9 A current stress for 1 sec heating and 500 cycles for all cascode devices.

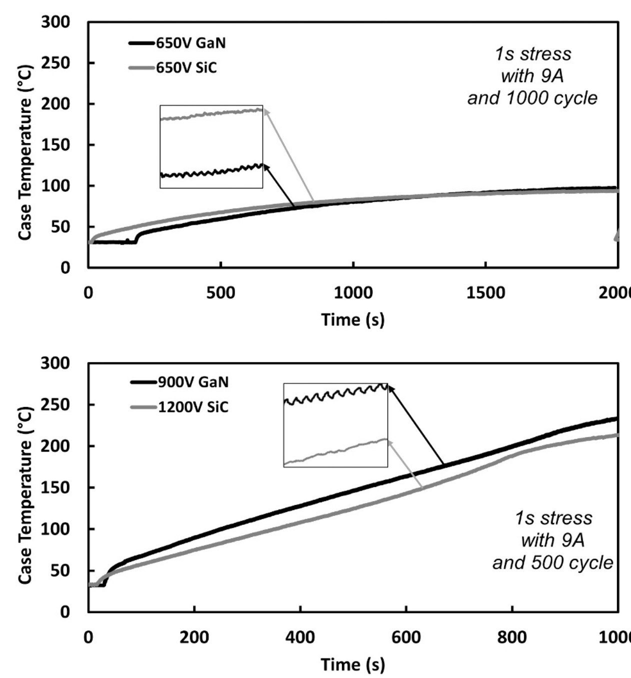

Fig. 10. The case temperature rises during the power cycling test by 9 A current stress for 1 sec heating and 1000 cycles for all cascode devices.

set of cycles. This larger increase is related to power dissipation as well as thermal sensitivity of the GaN, which is higher than the SiC devices. Moreover, the thermal conductivity of the GaN device is lower than SiC that leads to higher increase of temperature during power cycling tests. The transfer characteristics of the high voltage cascode devices are shown in Fig. 6. As it is seen, the drain currents of the GaN cascode devices are remarkably decreasing with increased number of cycles in comparison with the SiC counterparts.

Regarding SiC power cascode devices, there are only slightly changes in their transfer characteristics. This is given that GaN cascode device have lower thermal resistance and the lower thermal conductivity results in presence of higher thermal stress in the device structure. The decrease of the drain current can be related to accumulation of defects or traps during the power cycling process. When the device is subjected to the electrothermal stresses, the number of defects can be increased that are used as recombination centres which increases the trapping of the carriers causing the decrease of the drain current in the semiconductor [17]. Regarding the increasing of the number of cycles, the device might recover itself through annealing. During annealing, the trapped charges can be released from the defects which decreases the recombination rates and results in the increase of the drain current after 500 cycles

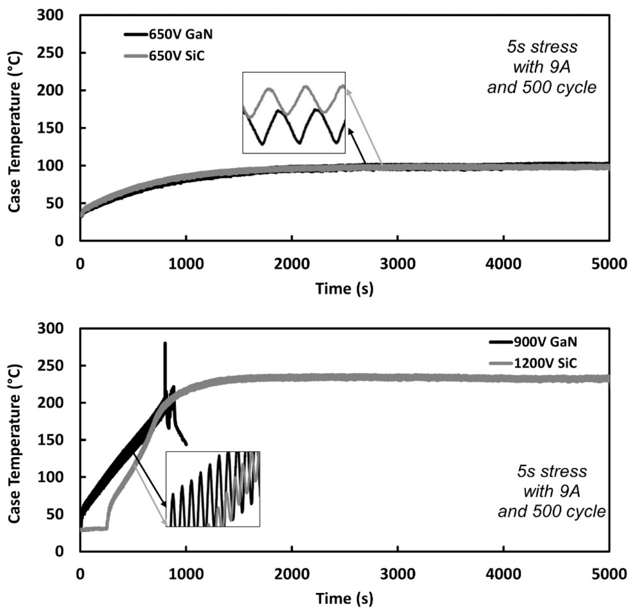

Fig. 11. The case temperature rises during the power cycling test by 9 A current stress for 5 sec heating and 500 cycles for all cascode devices.

[18].

The threshold voltage drift in the high voltage cascode devices is shown in Fig. 7. As it appears, the threshold voltage of the SiC cascode devices follows a decreasing trend while the threshold voltage of GaN cascode devices exhibits instability with increase and decrease cycles. Concerning the SiC cascode device, the threshold voltage is decreasing with increase of the cycles of the current stress, since threshold voltage decreases with temperature. Furthermore, the power cycling test causes thermal and mechanical stress, and these stresses cause damage to the gate oxide layer, and this results in the decreasing of the threshold voltage of the device by additional traps. The stresses can also have impact on defect state and dislocations in device structure that leads to decrease of the threshold voltage.

The gate leakage currents of the high voltage power cascode devices after each set of current cycles are demonstrated in Fig. 8. As it is shown, the GaN cascode devices exhibits no fluctuations in their leakage current after current cycles, which indicates that the leakage current cannot be used as a lifespan prediction parameter for these devices [19]. On the other hand, the gate leakage currents slightly increase for the SiC cascode devices. These changes can be correlated with temperature rise after power cycling test that can change the thermal properties and result in the slight changes in the gate leakage current [20,21]. In addition, the current stress cycles may affect the diffusion of the impurities and gather them near gate oxide layer that increase this parameter as well.

3.2. Under 9 A current cycles

To accelerate the stress, the current level is increased to 9 A to investigate the impact of the power cycling on the power cascode devices more clearly. This current level causes a clear increase in the case temperature related to junction temperature of all power cascode devices. The case temperature rises to up to nearly 80 °C for low rated cascode devices while it reaches above 200 °C for the high rated cascode devices after 1 sec heating and 1 sec cooling with 500 and 1000 cycles as shown in Figs. 9 and 10. Especially, the case temperature of the 900 V GaN cascode device reaches almost 250 °C that shows the heat extraction mechanism of the 1200 V SiC cascode device is more efficient than the GaN cascode device.

Regarding longer periods of heating and cooling with 5 s, the case temperature in low rated cascode devices reaches the thermal equilibrium around 100 °C whereas in the high rated cascode devices it exceeds 200 °C which is close to the previous test. On the other hand, with this longer period, the 900 V GaN device fails before reaching equilibrium temperature. The device is depredated and loses its ability to conduct as highlighted in Fig. 11. It is important to highlight that these experiments have often led to failure and are not reversible.

As for the thermal views of all cascode devices, the highest temperature can be seen in 900 V GaN cascode device followed by the 1200 V

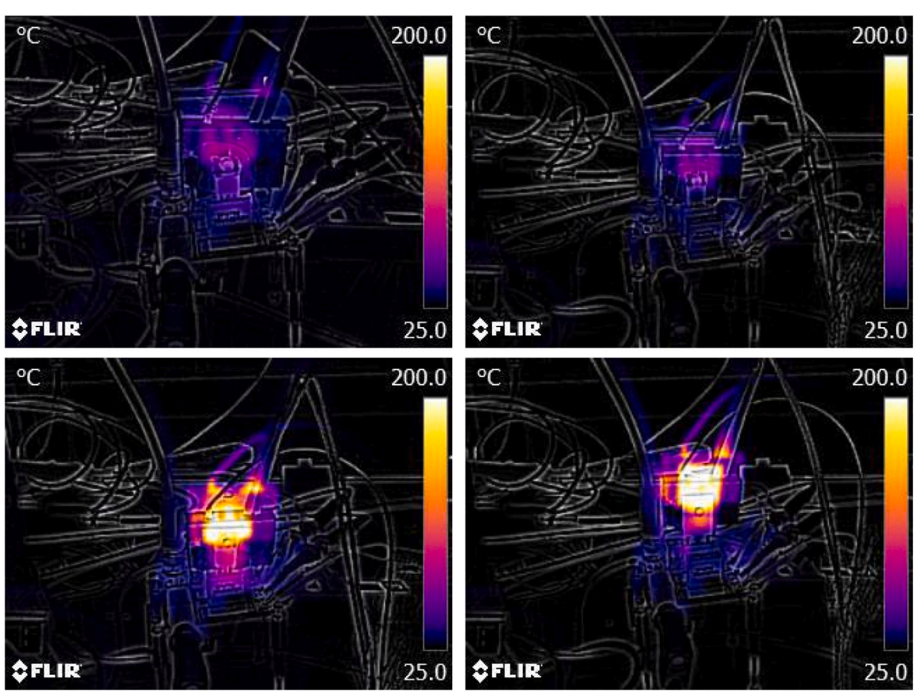

Fig. 12. The thermal views of 650 V GaN and SiC at the top as well as 900 V GaN and 1200 V SiC at the bottom, respectively after 9 A current stress for 1 sec heating with 1000 cycles.

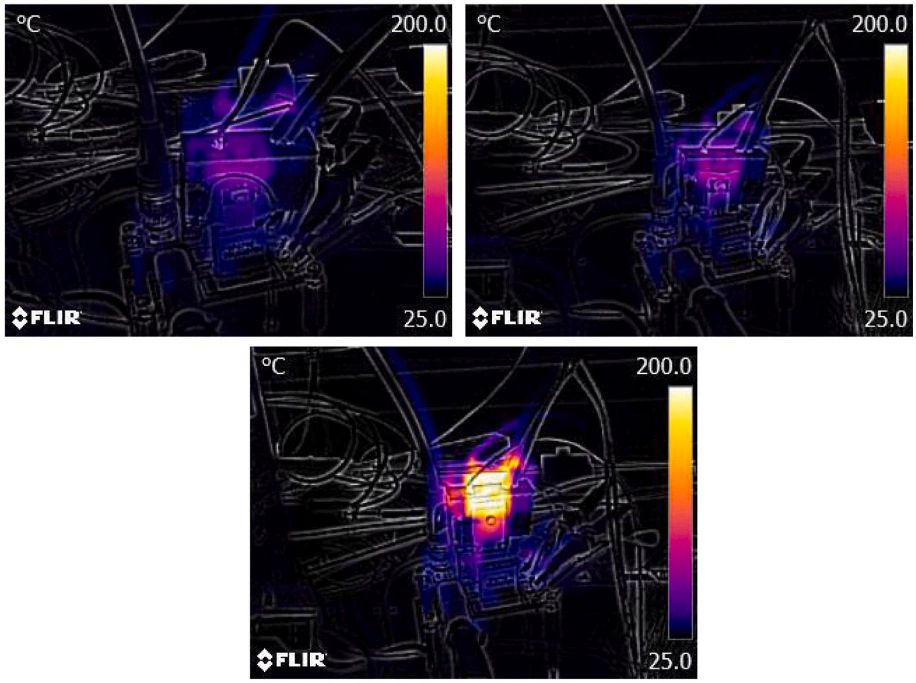

Fig. 13. The thermal views of 650 V GaN (top-left) and the SiC (top-right) as well as 1200 V SiC at the bottom, after 9 A current stress for 5 sec heating with 500 cycles. The 900 V GaN device failed in-between cycling.

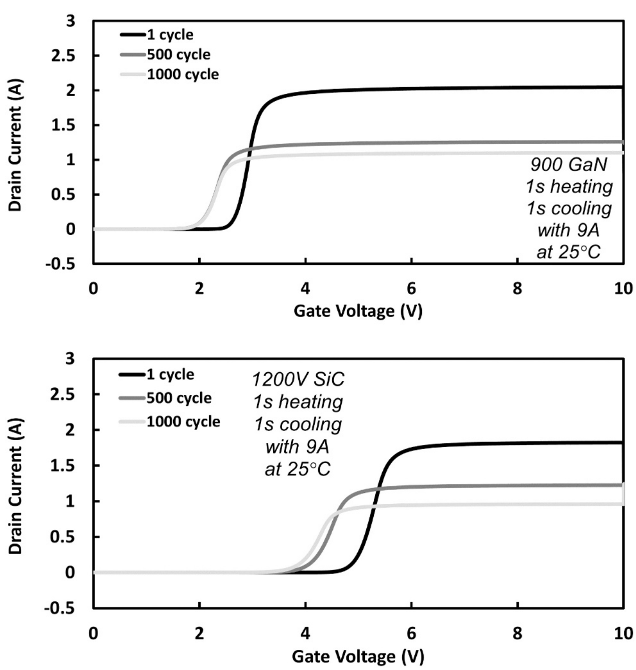

Fig. 14. The transfer characteristics for high voltage power cascode devices after 1000 cycles of 9 A current stress for 1 sec heating and 1 sec cooling.

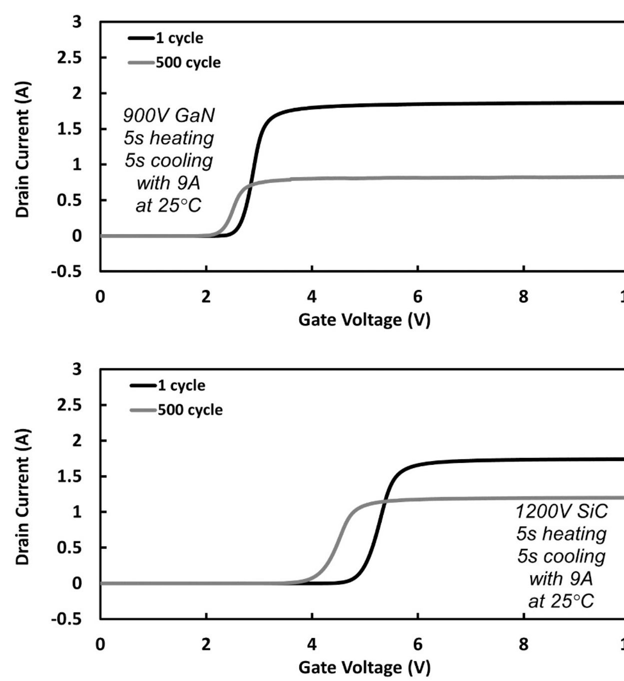

Fig. 15. The transfer characteristics for high voltage power cascode devices after 500 cycles of 9 A current stress for 5 sec heating and 5 sec cooling.

SiC cascode device as shown in Figs. 12 and 13. As it is seen in these figures, the heat extraction is effective in the backside (tab) of the TO-220 & TO-247 packages for all devices.

In Fig. 14, the impact of the number cycles on the transfer characteristics of the high voltage power cascode devices are compared with each other. The greater degradation in drain current can be seen for the 900 V GaN and 1200 V SiC cascode device, while there is less decrease in the drain current for the low rated cascode devices.

The aging of the power cascode devices can be accelerated by the power cycling test with higher current levels that results in the decrease of the drain current.

After longer power cycling tests with 5 sec heating and cooling periods, the degradation of the power cascode devices is clearer, especially for the high rated cascode devices as shown in Fig. 15. The 900 V GaN cascode device shows very small drain current in its transfer characteristics, and it even loses its conduction ability as shown in the case temperature graph.

The threshold voltage changes can be clearly seen after increasing

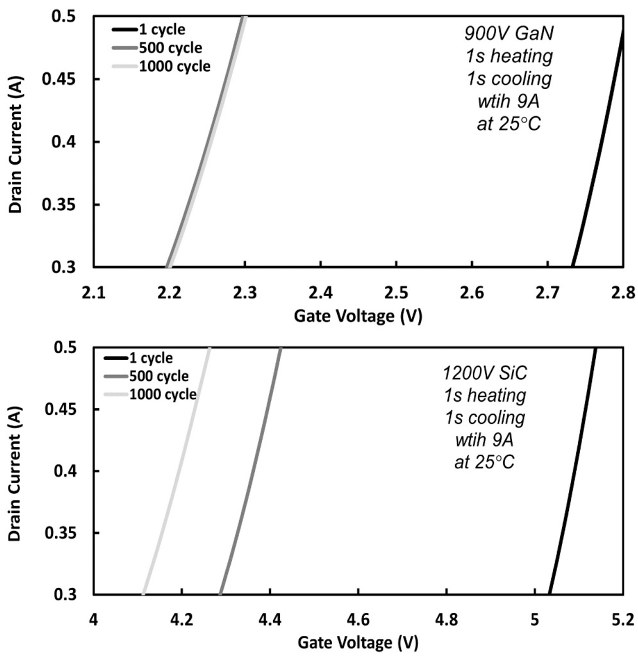

Fig. 16. The close views of transfer characteristics for high voltage cascode devices after 500 and 1000 cycles of 9 A current stress for 1 sec heating and 1 sec cooling.

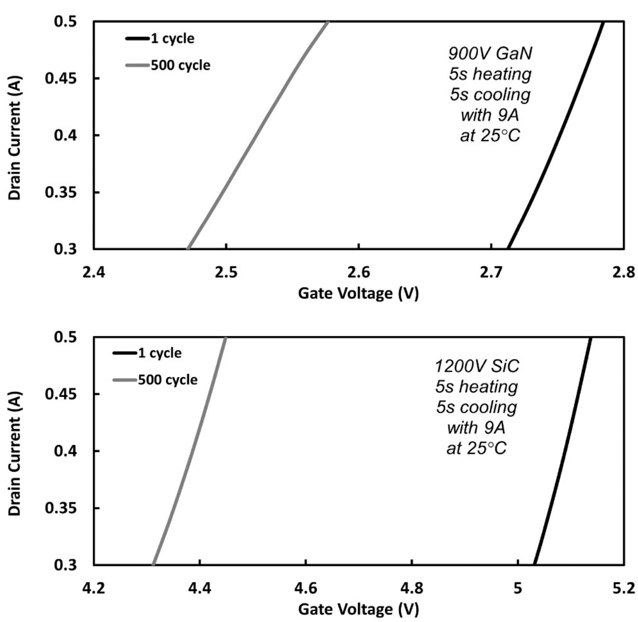

Fig. 17. The close views of transfer characteristics for high voltage power cascode devices after 500 cycles of 9 A current stress for 5 sec heating and 5 sec cooling.

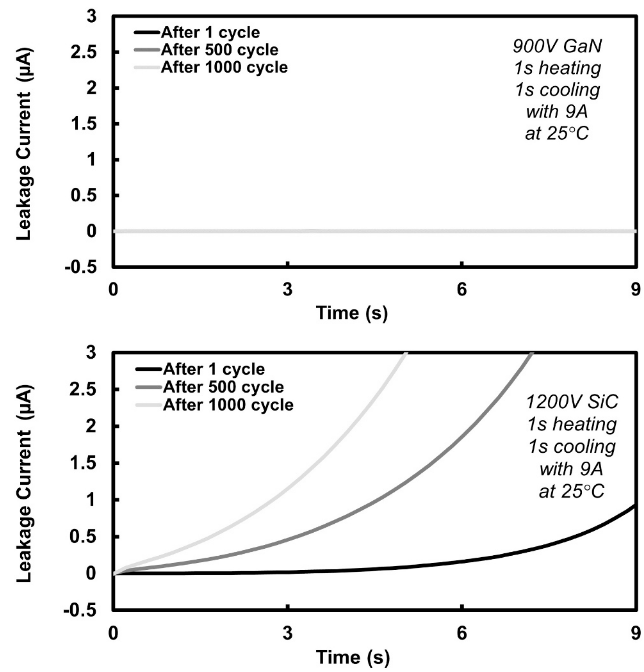

Fig. 18. The leakage current for high voltage power cascodes after 500 cycles of 9 A stress for 1 sec heating and 1 sec cooling.

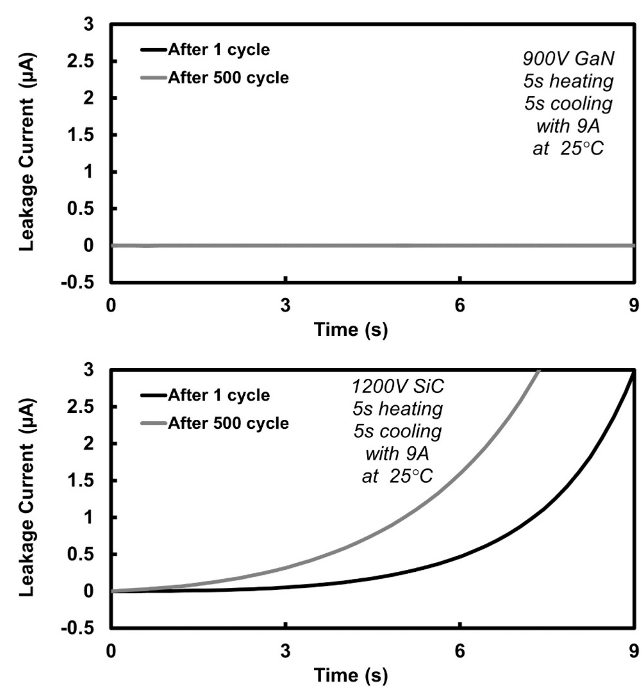

Fig. 19. The leakage current for high voltage power cascodes after 500 cycles of 9 A stress for 5 sec heating and 5 sec cooling.

the number of cycles from 500 to 1000 cycles as the cascode devices are stressed more, leading to more observable degradation patterns. The threshold voltage drift can be clearly seen in Fig. 16 after 9 A current stress cycles. The decrease of threshold voltage for low rated cascode devices is around 0.3 V whereas this reaches nearly 1 V for high rated cascode devices. When the cycle periods are increased from 1 s to 5 s, the threshold voltage drift is close to the trend observed in the previous test as shown in Fig. 17.

The leakage current changes are observed in Figs. 18 & 19 for the high voltage cascode devices after the power cycling tests and the results indicate that the leakage current of the GaN cascode devices are invariant with the power cycling test while it is increasing for the SiC cascode devices. The rate of increase is more dominated by the shorter heating and cooling cycles.

The threshold voltages divided by on-state resistances of the power cascode devices against the number of cycles are calculated across the devices after 1 sec heating power cycling tests with 500 and 1000 cycles as indicated in Fig. 20. The results show that the rise of the junction temperature in the device causes an increase of the on-state resistance

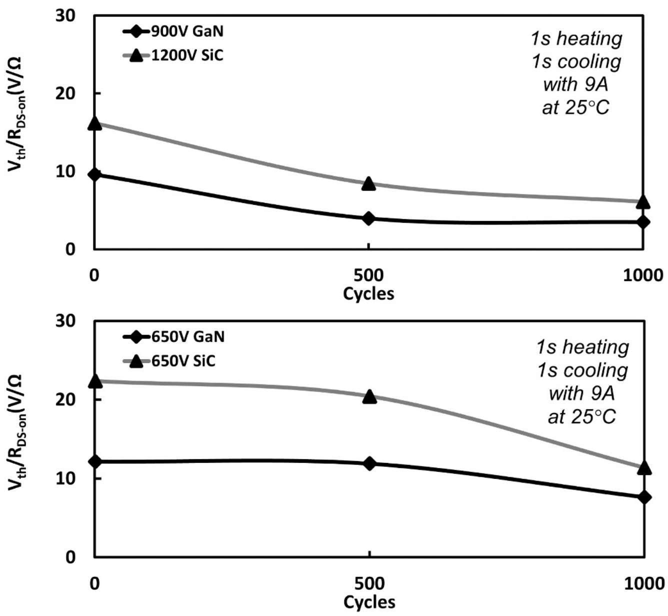

Fig. 20. The threshold voltage over on-state resistance for all power cascode devices after each set cycles of 9 A stress for 1 sec heating and 1 sec cooling.

for all cascode devices. The on-state resistance rise is doubled after cycling tests for the high rated cascode devices, whereas it is slightly increased for the low rated cascodes.

4. Conclusion

In this paper, power cycling tests have been carried out for GaN and SiC power cascode devices to investigate the impact of the electro-thermal stress on their parameters such as case temperature, transfer characteristics, threshold voltage and leakage current. The higher temperature rise, large drain current change and threshold voltage instability are seen in GaN devices while there are no changes in their leakage currents after stressing with 6 A and 9 A current cycles and with varying periods and cycles. As for SiC cascode devices, their case temperature rise is smaller than GaN cascode device and there have been a decrease in their threshold voltage and rise in leakage current following the cycling.

CRediT authorship contribution statement

Y. Gunaydin: Conceptualization, Investigation, Writing – original draft. **S. Jahdi:** Conceptualization, Methodology, Writing – review & editing. **R. Yu:** Investigation. **Xibo Yuan:** Investigation. **Olayiwola Alatise:** Methodology, Writing – review & editing. **Jose Ortiz Gonzalez:** Methodology, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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