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Junction temperature monitoring for cascode GaN devices using the Si MOSFET's body diode voltage drop

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ABSTRACT

In this paper, a new online junction temperature monitoring method is proposed for cascode GaN devices using the body diode of Si MOSFET. The reverse current during soft-switching mode is utilized to extract the voltage drop of the Si MOSFET's body diode. It is pointed out that, to accurately obtain the voltage drop of Si MOSFET's body diode, the V_{DS} voltage of cascode GaN device should be measured when the reverse current is small during the dead-time period. An experimental platform has been designed to validate the proposed method. The proposed method exhibits an accuracy within 0.6 °C and a $R^2 = 0.99$ goodness of linear fit on a test Buck converter, showing that this method is practical for real applications.

1. Introduction

The application of GaN technology has greatly improved the power density of power converters [1], making portable adapters and phone chargers much lighter than before. There have been several commercial products in GaN roadmaps which can be classified into enhancement-mode devices and cascode devices. GaN devices are intrinsically normally-on devices. To achieve the normally-off operation to meet the safety requirements, there are two ways. One is to dope a p-layer under the gate structure and thus make it into the enhancement-mode device. Another way is to adopt the cascode configuration as shown in Fig. 1, namely use a low-voltage Silicon MOSFET to control the gate of the normally-on GaN high electron mobility transistor (HEMT) device and therefore invert its gate voltage. When a positive voltage is added to the gate of Si MOSFET as shown in Fig. 2, the Si MOSFET is turned on and its drain-source voltage becomes around zero, which means the gate-source voltage of normally-on GaN HEMT is also around zero. Hence, now the normally-on GaN HEMT is turned on (its threshold voltage is around -15 V), and the whole cascode GaN device is turned on. If there is a current, the current will flow through both the normally-on GaN HEMT and Si MOSFET. When a negative voltage is added to the gate of Si MOSFET as shown in Fig. 3, the Si MOSFET is turned off. When the drain-source voltage of the cascode device begins to increase, at the beginning, all the voltage is added to the Si MOSFET, the drain-source voltage of the Si MOSFET will increase, at the same time the gate-source voltage of normally-on GaN HEMT will decrease. When it reaches the threshold voltage, then the normally-on GaN HEMT is turned off, and the whole cascode device is turned off, afterwards, the GaN HEMT device begins to support the extra drain-source voltage.

Compared to enhancement-mode devices, cascode GaN devices have several advantages [2]. Due to the simple structure, the device has a relatively low manufacturing cost. Furthermore, due to the mature production quality of the Si MOSFET, the gate reliability of Si MOSFET is much higher than that of enhancement-mode GaN HEMT devices. The gate of Si MOSFET can easily tolerate voltage overshoot within ±18 V, while that of enhancement-mode GaN HEMT will face a breakdown failure if the gate voltage is larger than 10 V. Besides, the turn-off speed of cascode GaN device is higher than enhancement-mode GaN due to the intrinsic current source acceleration during turn-off transient [3], resulting in a lower turn-off switching loss. Also, driving a cascode GaN device is actually the same as driving a Si MOSFET, hence, there is no other special requirements for the driving circuit. And the products from Transphorm company provides TO-220 and TO-247 packages, which have been widely used in practical designs. This means that a fast application without major modifications to the present design is possible, which is friendly for the performance improvement of the present products. Due to these advantages, cascode GaN devices have already been adopted in some applications [4]. Besides, there have been some commercial products based on cascode GaN devices, for example, Corsair has used it in the 1600 W power supplies and Bel Power Solutions has used it in TET3000 series server power supplies [5,6].

Reliability has become one of the most concerned issues for power

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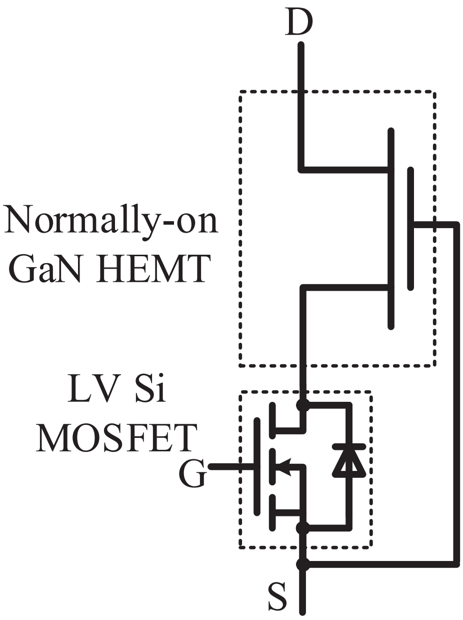


Fig. 1. Interconnection of cascode GaN device.

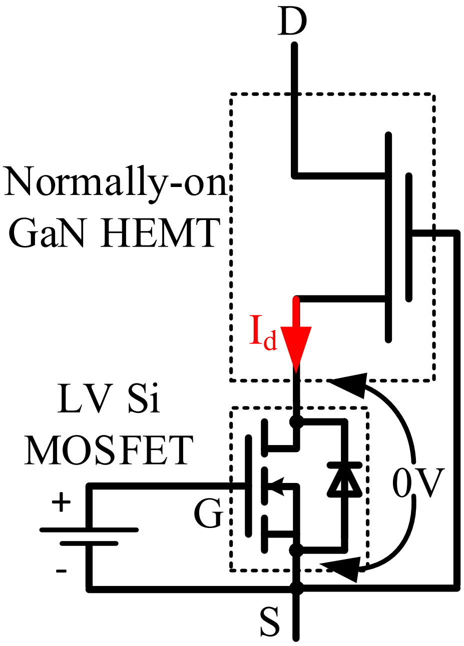


Fig. 2. Cascode GaN device during on-state.

devices. Previous studies have showed that temperatures play a dominant role in device failures [7]. Also, the junction temperature variation is the main factor resulting in package failure [8]. To ensure the safe operation of power devices, it is important to make sure that both the maximum junction temperature and its temperature variation are within acceptable range. Therefore, online junction temperature monitoring is an important technology to assist with better thermal management and lifetime improvement. Due to the difficulty when directly measuring the junction temperature, temperature-sensitive electrical parameters (TSEPs) have become the most practical solutions [9–12]. There have been several studies about extracting the junction temperature on enhancement-mode GaN HEMT devices. An E-field probe is used to monitor the dv/dt to infer the junction temperature [13]. The gate leakage current is measured to infer the junction temperature [14].

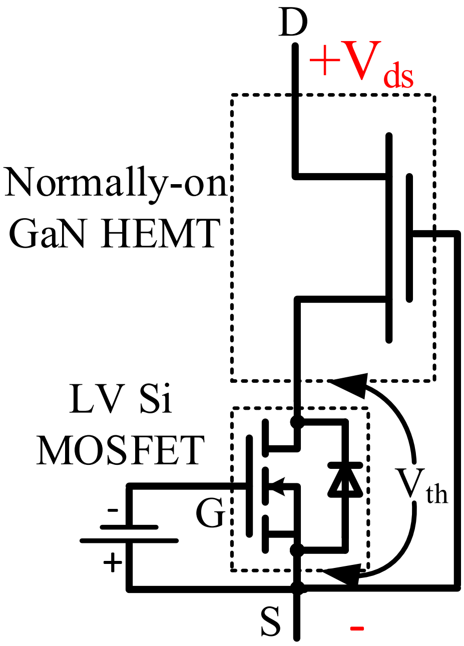


Fig. 3. Cascode GaN device during off-state.

However, these papers are based on the TSEP for e-mode GaN HEMT. Due to the different structure of cascode GaN devices, these methods are no longer suitable, therefore, the junction temperature methods remain to be investigated for cascode GaN devices.

To clearly show the internal layout, a photo of a decapsulated cascode GaN device (TP65H050G4WS) is shown in Fig. 4. To minimize the parasitic inductance, the LV Si MOSFET is soldered directly onto the normally-on GaN HEMT, therefore, there is a tight thermal coupling between the two devices. Although it will take some time to reach a thermal balance, which means the temperature behaviour of the Si MOSFET will lag a little behind than that of normally-on GaN HEMT. Considering that the chip area of Si MOSFET is much smaller than that of normally-on GaN HEMT and the thickness of solder layer in between is usually very thin. Besides, junction temperature variation in real

Fig. 4. Photo of a decapsulated cascode GaN device.

application is resulted from the load variation, whose time scale is usually larger than the time constant of reaching a thermal balance between the two devices. Therefore, it is feasible to utilize the TSEP of Si MOSFET to estimate the temperature of normally-on GaN HEMT device.

Several TSEPs of Si MOSFET have been verified to be good indicators of junction temperature, among which the voltage drop of body diode has a high linearity and long-term stability [15]. Therefore, in this paper the voltage drop of the Si MOSFET's body diode is proposed as a TSEP for cascode GaN devices.

To measure the voltage drop of the Si MOSFET's body diode during operation, soft-switching turn-on is required for the converter. Nowadays, soft-switching turn-on is adopted in many practical applications. For instance, in the half-bridge configuration, a zero-voltage-switching (ZVS) utilizes the turn-on of the MOSFET switch no earlier than the start of body diode conduction to avoid turn-on switching losses [16]. Remarkably, the voltage drop of the Si MOSFET's body diode can be measured right before this happens and be utilized to infer junction temperatures. However, for cascode GaN devices, the normally-on GaN HEMT device is conducting too when the current is flowing inversely. Therefore, a more detailed analysis needs to be carried out in this case. In the remainder of this paper, the working principle of proposed method will first be analyzed. Its application in practical situations will be then introduced. The adopted experimental platform is presented, and experimental results are shown and discussed in the end.

2. Proposed method

To obtain the voltage drop of the Si MOSFET's body diode when there is inverse current flowing through it, the Si MOSFET channel needs to be turned on later, otherwise the reverse current will be bypassed by the Si MOSFET channel.

Assume a reverse current $I_{d,r}$ is flowing through the device as shown in Fig. 5. For the convenience of the explanation following, the middle point between Si MOSFET and normally-on GaN HEMT is marked as I, the drain of cascode GaN is marked as D, and the source of the cascode GaN is marked as S. Then the voltage between the source and drain terminals of cascode GaN device can be expressed as Eq. (1), where V_{SI} is source-drain voltage of Si MOSFET and V_{ID} is the source-drain voltage of normally-on GaN HEMT.

$$V_{SD} = V_{SI} + V_{ID} \tag{1}$$

To ensure the reverse current flows through the body diode rather than the channel of Si MOSFET, a negative voltage is applied to its gate to turn it off, hence V_{SI} is the voltage of Si MOSFET's body diode as shown in Eq. (2).

$$V_{SI} = V_{diode} \tag{2}$$

At the same time, the gate-source voltage of normally-on GaN HEMT equals to V_{SI}, which is slightly positive. Therefore, the normally-on GaN HEMT is totally turned on and works in its linear region. Therefore, the V_{ID} can be expressed as Eq. (3).

$$V_{ID} = I_{d,r} \times R_{ds,GaN} \tag{3}$$

According to [15], the voltage drop of Si MOSFET's body diode V_{SI} has a negative relationship with temperature, and according to the device datasheet, $R_{ds,GaN}$ of normally-on GaN HEMT has a positive relationship with temperature. Hence, with a given current $I_{d,r}$, when the junction temperature T_j changes, Eq. (1) can be expressed as Eq. (4), where the expression $k_1(I_{d,r})T_j + b_1(I_{d,r})$ represents V_{SI} and $k_2(I_{d,r})T_j + b_2(I_{d,r})$ represents V_{ID}.

$$\begin{aligned} V_{SD} = {} & k_1\left(I_{d,r}\right)T_j + b_1\left(I_{d,r}\right) \\ & + k_2\left(I_{d,r}\right)T_j + b_2\left(I_{d,r}\right) \end{aligned} \tag{4}$$

In expression (4), coefficients k_1, $b_1$and k_2, b_2 are all dependent on the current $I_{d,r}$. However, k_1 is negative (negative temperature coefficient), whereas k_2 is positive (positive temperature coefficient). Besides, considering that the body diode has a minimum conduction voltage around 0.7 V, when the current is small, the V_{SI} is always around 0.7 V, but the V_{ID} can be much smaller than V_{SI}. Namely, when the current is small enough, k_2 will be smaller than k_1 (its absolute value), which means that the V_{SD} is mainly composed of V_{SI}, not V_{ID}, therefore, the V_{SD} will show negative coefficient with temperature. And vice versa, when the current is large enough, the V_{ID} can be larger than V_{SI}, and k_2 will be larger than k_1 (its absolute value), which means the V_{SD} is mainly composed of V_{ID}, not V_{SI}, and the V_{SD} will show positive coefficient with temperature. Moreover, according to [17], the on-resistance of the normally-on GaN HEMT will increase with the device degradation under aging, and it is commonly shared that the voltage drop of Si MOSFET's body diode will not be affected under aging. Putting the two concepts above together, in order to ensure measurement stability and exclude the effect brought by aging, the current needs to be kept small enough to make sure that the V_{SD} is mainly composed of the Si MOSFET's part.

To investigate the validity of the above assumptions, we added an electrical connection to the midpoint (which is the point I in Fig. 5) of a commercial cascode GaN device (TPH3208PS), and the Voltage-Temperature curves under different reverse currents from 25 °C to 125 °C were acquired separately for the Si MOSFET, the normally-on GaN HEMT, and the total voltage for cascode GaN device. The results are shown from Fig. 6(a) to (c).

From Fig. 6(a) it is seen that k_1 changes slightly under different currents, however, from Fig. 6(b) it is seen that k_2 changes significantly with currents. When the current is small enough, k_2 can be very small, and therefore the global V_{SD} shows a negative coefficient with temperature, which is validated through Fig. 6(c). From Fig. 6(c), it is seen that when the current is 0.1A, the V_{SD} shows a negative coefficient with temperature. When the current is 2.6A, the V_{SD} shows no relation with temperature. When the current is 12A, the V_{SD} shows a positive coefficient with temperature. It can be concluded that when the current is smaller than 2.6A, k_2 is smaller than k_1 (its absolute value); when the current is 2.6A, k_2 equals to k_1 (its absolute value); when the current is larger than 2.6A, k_2 is larger than k_1 (its absolute value).

To show more clearly, the voltage proportions of Si MOSFET in cascode GaN device (which is V_{SI}/V_{SD}) under different currents and temperatures are shown in Fig. 7, which shows that when the current is small V_{SD} is mainly composed of V_{SI}.

These experimental test results validate the analysis. To conclude, to accurately extract the junction temperature through the voltage drop of Si MOSFET's body diode, its voltage needs to be measured when the current is small enough.

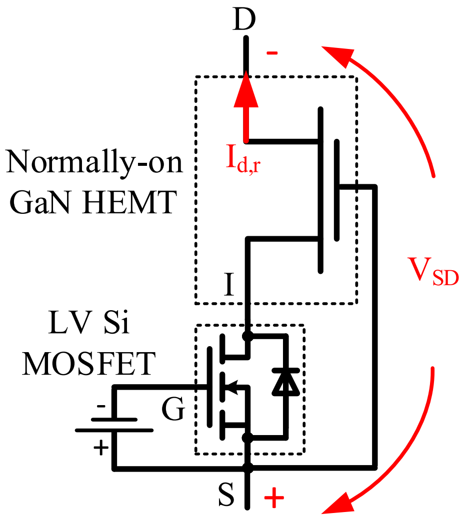
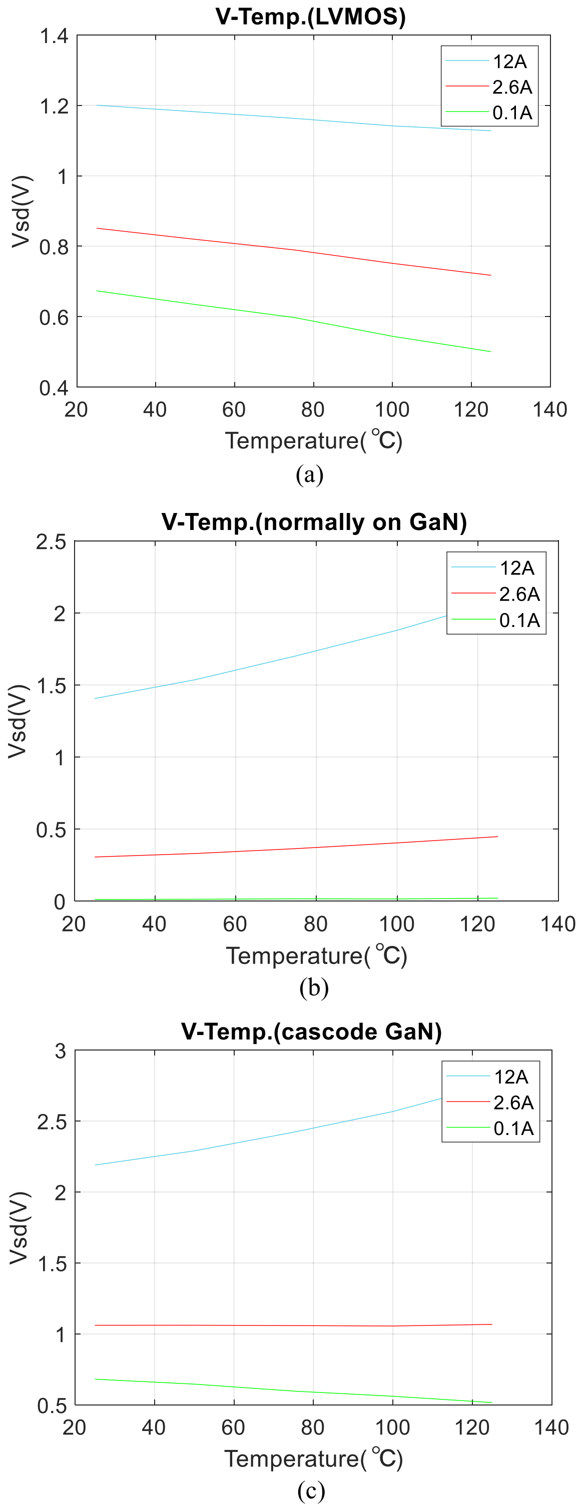


Fig. 5. Diagram of a cascode GaN when a reverse current flows through it.



(a)

(b)

(c)

Fig. 6. Relationship between voltage drop and temperature (V-Temp. curve) under different currents (a) LV Si MOSFET (b) normally-on GaN HEMT (c) cascode GaN.

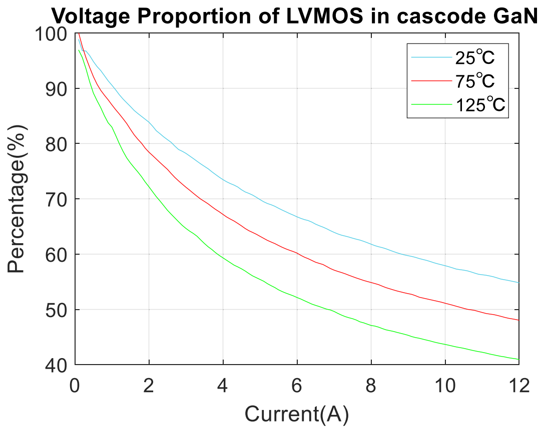


Fig. 7. Voltage proportion of Si MOSFET in cascode GaN.

In order to measure the voltage drop of the body diode when the reverse current is small, the soft-switching turn-on needs to be guaranteed for the converter. A proper parameter design is required depending on different converter topologies. The inductor current should be flowing reversely before the main switch turns on, then during the dead-time period the reverse current will flow through the body diode, and the voltage measurement can be carried out at this moment when the current is small. In the following experimental tests, a Buck converter is developed. For the Buck converter, to achieve a soft-switching turn-on, synchronous rectification and a small inductor is required, so that the inductor current will flow reversely before the main switch turns on, detailed waveforms will be shown in the following part.

3. Experimental validation

To prove that proposed method is applicable for practical applications, an experimental platform is developed, the schematic is shown in Fig. 8. The DUT used in this experiment is a commercial product from Transphorm company (TP65H050G4WS) whose internal layout is shown in Fig. 4. The Buck topology is adopted in the platform, unlike the most common Buck converter, the main switch sits in the lower arm in our test platform, which is more friendly for signal measurements, but the working principle of this Buck converter is not changed. To achieve the synchronous rectification for the soft-switching turn-on, the free-wheeling diode is replaced by a SiC MOSFET. To accurately measure the V_{DS} voltage, a simple and commonly adopted on-state voltage measurement circuit is connected to the drain terminal of DUT. This circuit is composed of a high-voltage diode, a Zener diode, and a current-limiting resistor. When the drain voltage of DUT is below the breakdown voltage

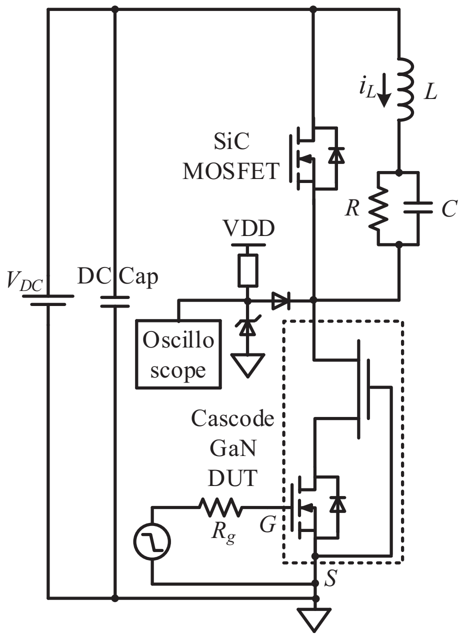


Fig. 8. Schematic of experimental platform.

of Zener diode, the high-voltage diode is in on-state, and the output of this circuit will follow the change of DUT's drain voltage. When DUT's drain voltage is higher than the breakdown voltage of Zener diode, the output of this circuit will be clamped at the breakdown voltage of Zener diode, and the high-voltage diode is in off-state to block the high voltage from drain terminal of the DUT. Therefore, this circuit can monitor and output the on-state voltage of the DUT. For the convenience of experimental validation, an oscilloscope is connected to the output of this circuit to measure its voltage, in practical applications, the oscilloscope can be replaced by an ADC converter and DSP controller to achieve the online monitoring during operation.

The photo of the experimental platform is shown in Fig. 9 and the zoom-in detail of the DUT part is shown in Fig. 10. The DUT and SiC MOSFET sit on a half-bridge test board with optimized power loop. The cascode GaN device is partially decapsulated so that its real junction temperature can be easily measured by the infrared camera. To emulate the working conditions under different temperatures, a heating resistor is attached to the bottom side of the DUT, by adding extra heating power through the heating resistor, different target temperature can be reached.

Due to the safety concern brought by the decapsulation process to the DUT, the working voltage in the experiments is lowered to 50 V. To achieve the soft-switching turn-on, the complementary PWM signals are given to the DUT and SiC MOSFET for a synchronous operation. A small inductor of 270uH is used, the switching frequency is set to 20 kHz, then the load resistor is adjusted until the inductor current can flow reversely within a switching period, and the working waveforms are shown in Fig. 11.

It is worth mention that the setting of dead time is vital to achieve the soft-switching turn-on, the dead time should be set at a value to make sure that the DUT will turn on when the inductor current is still flowing reversely, so that its body diode is still conducting and the V_{DS} keeps around zero. Apart from this, there is another concern, to adopt the proposed T_j method, the V_{DS} should be measured when there is a small reverse current flowing through the body diode. Therefore, the dead time should be set to make sure that the switch will turn on when the reverse current is small enough. A simple and practical way is to set the dead time to make sure that the switch turns on when the inductor current equals to zero. In our design case, the dead time is set to 5us and the switch turns on when the inductor current is zero, then both the soft-switching turn-on and a proper timing for V_{DS} measurement can be guaranteed. In this experiment, the V_{DS} is measured when the reverse inductor current is 0.1A during the dead time.

To validate proposed method, firstly the DUT is heated up to target temperature, after the temperature becomes stable, the result of V_{DS} measurement is recorded. This process is repeated under different temperatures from 50 °C to 125 °C as shown in Fig. 12.

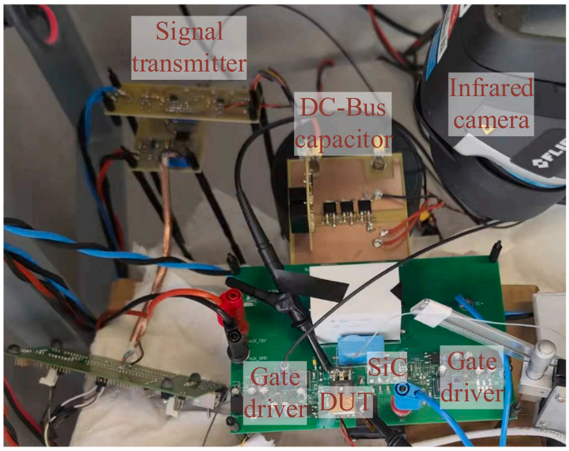


Fig. 9. Photo of the experimental platform.

Fig. 10. Zoom-in detail of the DUT.

It is seen from the results that based on proposed method, the measured V_{DS} shows a high linearity with junction temperatures from 50 °C to 125 °C. And the one-order fitting method is used to obtain its relationship. The expression is written in Fig. 12 which shows a $R^2 = 0.99$ goodness of linear fit. In practical applications, this test is also a calibration process to obtain the relationship between junction temperature and V_{DS}. The obtained expression can be stored in a DSP controller for the online T_j monitoring.

To verify the static accuracy of proposed method, the DUT is heated up to another two temperature points, 60 °C and 110 °C, which did not appear in the calibration process in Fig. 12. Then the V_{DS} is recorded and the estimated T_j is calculated according to the expression obtained in Fig. 12. The thermal image under 60 °C is shown in Fig. 13, and the test results are concluded in Table 1. From the results it is seen that proposed method shows a good measurement accuracy within 0.6 °C, proving its applicability in practical applications.

4. Conclusions

This paper proposes a new junction temperature monitoring method for cascode GaN devices, which uses the voltage drop of its Si MOSFET's body diode. It is pointed out that when a reverse current flows through the cascode GaN device when it is turned off, the voltage drop V_{SD} is composed of the Si MOSFET's part V_{SI} and the normally-on GaN HEMT part V_{ID}. Under a given current, the Si MOSFET's part V_{SI} shows a negative relationship with temperature, while the normally-on GaN HEMT part V_{ID} shows a positive relationship with temperature. Due to minimum conduction voltage around 0.7 V of Si MOSFET's body diode, when the reverse current is small enough, the global V_{SD} is mainly composed of Si MOSFET part and shows negative relationship with temperature, besides, the on-resistance increase brought by aging can also be excluded. To measure the voltage drop of Si MOSFET's body diode during a practical operation, the soft-switching turn-on needs to be guaranteed. To validate proposed method, a Buck converter is developed with soft-switching turn-on, and the voltage drop of Si MOSFET's body diode is measured during the dead time. Both the linearity and accuracy of proposed method are tested, which shows a $R^2 = 0.99$ goodness of linear fit and static accuracy of 0.6 °C. The experimental results prove that proposed method is applicable for a practical application.

CRediT authorship contribution statement

Zhebie Lu: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing – original draft, Visualization. **Francesco Iannuzzo:** Writing – review & editing, Supervision, Project administration.

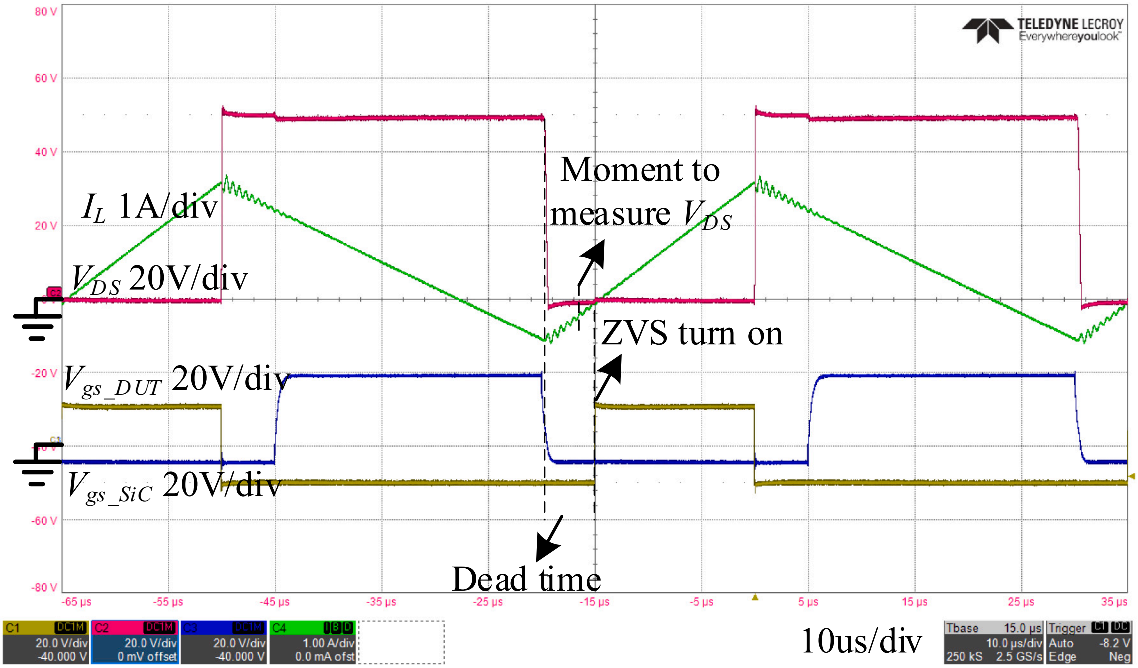


Fig. 11. Working waveforms of the Buck converter.

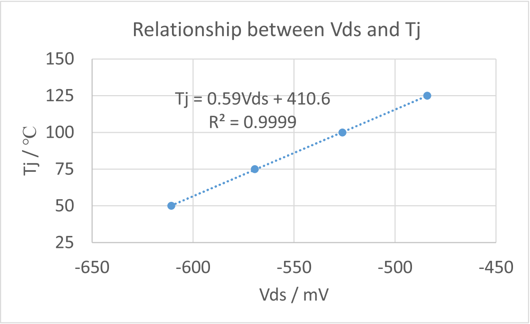


Fig. 12. Experimental results of proposed T_j method.

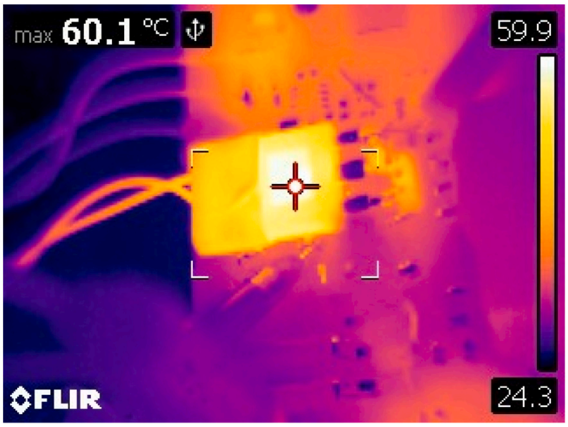


Fig. 13. Thermal image obtained through infrared camera.

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.

Table 1
Static error test for proposed method.

Real T_j	V_{DS}/mV	Estimated T_j
60.1 °C	−594	60.1 °C
110.3 °C	−508	110.9 °C

Data availability

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

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