1. Introduction

Power electronic circuits are required to handle larger power with lighter and smaller package size. Thermal design is important to realize compact packaging. Static thermal resistance is inadequate especially for evaluating the tolerance of power devices in case of fault current and overcurrent. Transient thermal characterization is required for the evaluation of thermal performance of power devices.

Transient thermal testing of a power device clarifies thermal resistance and thermal capacitance of the components used in the heat transfer path such as chip die attach, lead frame, thermal interface material (TIM), heat sink, and contact thermal resistances in between them, etc. Structure functions identified from the transient thermal characterization tests show these heat transfer paths as a 2-D graph with junction as the origin and cumulative thermal resistance in the horizontal axis and cumulative thermal capacitance in the vertical axis quantitatively. Structure functions can be yielded as follows: 1. Execute a transient thermal characterization test, 2. Analyze the measurement result to extract a spectrum of time responses of the Foster-ladder network by deconvolution, 3. Convert Foster RC network into Cauer-ladder network, and 4. Plot summation of thermal resistance in the horizontal axis and thermal capacitance in the vertical axis, in order to show the heat transfer path from the junction to the ambient.[1] The deterioration of die-attach between a chip and a base plate for power cycling stress can be evaluated as the variation of structure functions.[2] Structure function can also identify the differences in heat transfer capability between Al2O3 (Aluminum Oxide) and AlN (Aluminum Nitride) used as insulating substrate of DBC (Direct Bond Copper) in power modules. Evaluation of the TIM, which is used between a lead frame and a cold plate, is a common application of structure function as well.[3, 4]

Acquiring the junction temperature of the device under test (DUT) is required for transient thermal characterization. For Silicon (Si) devices, Electrical Test Method (ETM) is standardized by Joint Electron Device Engineering Council (JEDEC), which is stated in JEDEC Standards JESD51-1.[5] For Gallium Nitride High Electron Mobility Transistors (GaN HEMTs), there have been many research attempts for the measurement of the junction temperature. Optical methods such as infrared thermal imaging and micro Raman spectroscopy,[6, 7] embedding a dedicated temperature sensor on a die,[8] and several electrical methods[9–11] have been introduced. Synchro-
nized sub-microsecond pulsed $I-V$ measurement was used with maximum drain current $I_{\text{dmax}}$ and on-resistance $R_{\text{on}}$ as temperature sensitive parameter (TSP).[9] Another electrical method used the forward junction voltage for a given current as a TSP.[10, 11] This is similar to the method used for measuring the junction temperature of GaAs MESFET (Gallium Arsenide Metal-Semiconductor Field-Effect-Transistor) devices.[12]

It is convenient to use in situ electrical methods for transient thermal characterization, as they do not require direct visual access to the junction of power device. In addition, they do not affect the heat transfer capability of the DUT as additional temperature sensor is not necessary to be implemented inside the DUT.

Transient thermal characterization tests heat up the DUT by self-heating and wait for thermal steady state before the actual measurement of the cooling curve. It is important to obtain correct heating power steps in order to normalize the temperature changes. Oscillation of voltage and current must be avoided during the heating phase, in order to attain thermal steady state and give correct heating power.

It is known that the non-ideal characteristics of the power device have negative effect on the thermal characterization for SiC MOSFET (Silicon Carbide Metal-Oxide-Semiconductor Field-Effect-Transistor) in the early phases right after switching off of the heating power.[13] Countermeasure was developed for this symptom[14] and now the thermal characterization with SiC MOSFETs can be carried out appropriately.

Similar difficulties to the ones experienced with conventional Si based test methods are found for characterizing GaN HEMTs. Charge trapping phenomena are considered to be the cause of the non-ideal characteristics of GaN HEMTs.[15, 16] Due to the difficulties, it was not possible to characterize the heat transfer path from the GaN HEMT junction to the ambient. Comparing the measurement results with different heating power applied is useful to see how well the transient thermal characterization is performed or affected by the electrical transient noise due to the non-ideal characteristics of the power device. Since the characterization results are normalized with power applied to the DUT, they should match well regardless of the heating power applied.

Yang et al. used $V_{gs}$ as TSP with applying sensing current $I_{\text{sense}}$ from drain to source, with $V_{dg}$ set to 0 V.[17] In their experiment, a power step was applied to the sample by a voltage jump of $V_{dg}$.

This paper proposes a suitable transient thermal characterization method for GaN HEMTs with p-Type Gate, which uses $V_{gs}$ as TSP as well, but a different heating and measuring method is proposed for the transient thermal characterization test of GaN HEMT. It has repeatability and robustness regardless of the measurement conditions. The theoretical background of the TSP, measurement procedures of the proposed method, and discussion for the measurement results with this method will be shown.

The rest of this paper is organized as follows. Section 2 introduces the static characteristics of the GaN HEMT used in this paper. These characteristics are used by transient thermal characterization test methods shown in the following section. Section 3 introduces the conventional transient thermal characterization test measurement methods and the proposed method. Section 4 covers experimental results for both the conventional methods and the proposed method, which were described in Section 3. The problems of the conventional methods and the benefits of the proposed method are shown here. The concluding remarks are presented in Section 5.

2. Static Characteristics of GaN HEMT Used in This Paper

The thermal characteristics of a normally-off type GaN HEMT, Panasonic PGA26C09DV are evaluated in this paper. It has Gate Injection Transistor (GIT) structure[18] as shown in Fig. 1. High-density 2DEG (2-Dimensional Electron Gas) is formed by the polarization-induced charges in the undoped AlGaN/GaN heterojunction. The p-AlGaN gate is formed over the undoped AlGaN/GaN heterostructure to enable normally-off operation.

Wiring diagrams of the static characteristic measurements are shown in Fig. 2 – Fig. 4. The measured results of the device are shown in Fig. 5 – Fig. 7. Figure 5 shows the forward and reverse $I_d-V_{ds}$ characteristics with $V_{gs}$ as a parameter at room temperature (25°C), measured by the

![Fig. 1 Schematic cross section of the GIT structure.](image-url)
Figure 6 shows the $I_d - V_{ds}$ characteristics for $V_{ds} = 10$ V and $I_g - V_{gs}$ characteristics for drain open with temperature as a parameter, measured by the circuit shown in Fig. 3. Figure 7 shows the $I_d - V_{gs}$ characteristics for gate – drain shorted with temperature as a parameter, measured by the circuit shown in Fig. 4. These characteristics were measured by the Power Device Analyzer/Curve Tracer B1505A[19] and the temperature was regulated by placing the DUT on a hot plate. The detailed settings are shown in Table 1.

Normally-Off characteristics can be seen from the first quadrant of Fig. 5. The studied GaN HEMT does not have a body diode structure. However, it conducts reverse drain current as shown in the third quadrant of Fig. 5. This is called SCRC (Self-Commutated Reverse Conduction).[20, 21] Temperature dependences are shown in Fig. 6 and Fig. 7. These characteristics indicate that they could be used as TSP. They will be explained in Section 2.1 – 2.3.

![Measurement wiring diagram of forward and reverse $I_d - V_{ds}$ characteristics.](image1)

(a) Measurement wiring diagrams of $I_d - V_{gs}$ characteristics at gate – drain shorted at small current range.

(b) Measurement wiring diagrams of $I_d - V_{gs}$ characteristics at gate – drain shorted at wider range.

![Measurement wiring diagrams of $I_d - V_{ds}$ characteristics at 25°C.](image2)

![Forward and reverse $I_d - V_{ds}$ characteristics at 25°C.](image3)
Fig. 6  $I_d - V_{gs}$ characteristics.

Fig. 7  $I_d - V_{gs}$ characteristics at gate – drain shorted with temperature as a parameter at wider range.

Table 1  Test conditions of curve tracer.

| Parameters | Value | Notes |
|------------|-------|-------|
| $V_d$ limit | $-10 \text{ V.. } 15 \text{ V}$ | $V_g$ and $V_d$ sweep |
| $I_d$ limit | $-10 \text{ A.. } 15 \text{ A}$ |
| $P_d$ limit | 50 W |
| $V_g$ range | $-4 \text{ V.. } 2 \text{ V}$ | For reverse $I$ - $V$ |
| | 1.6 V.. 2.4 V | For forward $I$ - $V$ |
| $V_d$ | 10 V | $V_g$ sweep |
| $I_d$ limit | 8 mA |
| $V_g$ range | 0 V.. 3 V |
| $I_d$ limit | 8 mA | $V_g$ sweep with drain opened |
| $V_g$ range | 0 V.. 4.5 V |
| $I$ limit | 8 mA | Voltage sweep with gate - drain shorted |
| $V$ range | 0 V.. 1.6 V |
| $V$ limit | 5 V | Current sweep with gate - drain shorted |
| $I$ range | 0 A.. 15 A |
2.1 Temperature characteristics of gate threshold voltage $V_{th}$

The gate threshold voltage $V_{th}$ has temperature dependence. The temperature dependence can be yielded from the threshold voltage equation shown in Eq. (1):

$$V_{th} = \phi_{ms} - \frac{Q_D}{C_D} + 2\psi_R + \frac{4\epsilon_0\epsilon_0 N_A\psi_R}{C_D},$$  

where $\phi_{ms}$ is the work-function difference [V], $Q_D$ is the space-charge density in depletion region [C/m$^2$], $C_D$ is the depletion-layer capacitance per area [F/m$^2$], $\psi_R$ is the Fermi level from intrinsic Fermi level [V], $\epsilon_0$ is the permittivity of semiconductor [F/m], $q$ is the unit electron charge [C], and $N_A$ is the Acceptor impurity concentration [m$^{-3}$].

Since $\phi_{ms}$ and $Q_D$ are essentially independent of temperature, the differential coefficient of $V_{th}$ with respect to temperature $T$ yields:

$$\alpha = \frac{dV_{th}}{dT} = 1 \left( \psi_R - \frac{E_{g0}}{kT} \right) \left( 2 + \frac{1}{C_D} \right) \left( \frac{\epsilon_0 N_A}{\psi_R} \right),$$

by applying:

$$\frac{d\psi_R}{dT} = \frac{1}{T} \left( \psi_R - \frac{E_{g0}}{kT} \right),$$

where $k$ is the Boltzmann Constant [J/K], and $E_{g0}$ is the energy gap [eV] at $T = 0$ [K].

Due to this temperature dependence, $V_{gs}$ in the sub-threshold region which can be observed by applying constant small sensing current $I_{sense}$ from drain to source, can be used as TSP. The $I_d - V_{gs}$ characteristics with temperature as a parameter is shown in Fig. 6 (a).

2.2 Temperature characteristics of forward voltage drop in $V_{f-gs}$

The GaN HEMT used in this paper has a PN junction between the gate and source, especially between p-AlGaN and i-AlGaN, as shown in Fig. 1. The $I - V$ characteristics of the PN junction is expressed as a function of the junction temperature [5] as Eq. (4):

$$I_f = I_0(T) \left[ \exp\left( \frac{qV_{f-gs}}{nkT} \right) - 1 \right],$$

$$I_0(T) = MT^m \exp\left( - \frac{E_g}{nkT} \right),$$

where $I_f$ is the forward current [A] of the PN junction, which serves as the gate current $I_g$ to the applied forward gate voltage $V_{f-gs}$, $I_0$ ($T$) is the saturation current [A], $E_g$ is the energy gap [eV], and $M$ and $m$ are constants. $V_{f-gs}$ can be yielded from Eq. (4) as:

$$V_{f-gs} = \frac{nkT}{q} \left( \ln I_f - \ln I_0(T) \right),$$

where the approximation of $\exp\left( \frac{qV_{f-gs}}{nkT} \right) \approx 1$ is used. This approximation holds for $(V_{f-gs} > 0.3 \text{ V}) \cap (T < 600 \text{ K})$, for example. Then the differential coefficient of $V_{f-gs}$ with respect to temperature can be yielded from Eq. (5) and Eq. (4) as:

$$\alpha = \frac{dV_{f-gs}}{dT} = \frac{n\epsilon_0}{q} \ln I_f - \ln I_0(T) - \frac{nkT}{q} \frac{d}{dT} \left( \ln I_0(T) \right),$$

where the temperature dependence of $E_g$ can be neglected. Strictly speaking, the relationship between voltage and temperature is not exactly linear due to the second term in the Eq. (6) and the non-ideal characteristics of the devices. However, in most cases the effects are quite small and could be ignored. In this paper, quadratic curve fitting is used to approximate this term. The $I_d - V_{gs}$ characteristic for drain kept open with the temperature as a parameter is shown in Fig. 6 (b).

Eq. (2) and Eq. (6) are called Sensitivity, and the reciprocals of them are called K-factor. However, it is commonly used for expressing the relationship of temperature and TSP as “K-factor”. In this paper, Eq. (2), Eq. (6), and the data plots of temperature vs TSP are called K-factor.

2.3 Temperature characteristics of $I_d - V_{gs}$ at gate – drain shorted

The $I - V$ characteristic with the gate – drain shorted is shown in Fig. 7 (a). It has similar temperature dependence to $V_{gs}$ as shown in Fig. 6 (a). However, it does not have a unique operating point for the same current as shown in Fig. 7 (b). This will be discussed in Section 4.1.2.

3. Transient Thermal Characterization Test

Transient thermal characterization test has been elaborated for Si devices. The test is done by the following steps:[23] First, the tested device is heated up to the thermal steady state, the heating is terminated with current jump or voltage jump.[24] This paper uses current jump. The current used for the self-heating is called “heating current ($I_{heat}$).” Then the time response of junction temperature is recorded from hot steady state until it reaches the cold steady state.

3.1 Conventional transient thermal characterization test methods

Four conventional test methods which are used for Si devices[24] are shown in this section.

3.1.1 MOS-SAT mode

MOS-SAT mode was devised to characterize MOSFETs. MOSFET is heated up by applying forward current ($I_{heat}$) from drain to source with specified gate voltage. The gate
voltage is switched to 0 V or negative in cooling operation. This mode uses the knee voltage of the body diode as TSP. Eq. (6) can be used as the coefficient. $I_{\text{sense}}$ is applied in reverse direction, from source to drain through body diode. MOS-SAT mode can be used for RC-IGBT (Reverse Conducting Insulated Gate Bipolar Transistor) as well. A circuit diagram for this measurement mode is shown in Fig. 8.

### 3.1.2 MOS-Diode mode

MOS-Diode mode was formulated to characterize normally-off MOSFETs. The gate and drain are shorted and $I_{\text{sense}}$ and $I_{\text{heat}}$ flow from drain to source. The gate threshold voltage is used as TSP. Eq. (2) can be used as the coefficient. In this setup, drain-source acts as a two-terminal device, or a diode due to MOSFET $I-V$ characteristics. Therefore, it is called MOS-Diode mode. It can be used for IGBTs as well. A circuit diagram for this measurement mode is shown in Fig. 9.

### 3.1.3 RDS-ON mode

RDS-ON mode was first invented to characterize Bipolar Junction Transistors (BJT), and then expanded to other 3-terminal devices such as MOSFETs and IGBTs. $I_{\text{heat}}$ and $I_{\text{sense}}$ are applied from drain to source. This mode regulates $V_{gs}$ to keep the drain voltage constant for the applied constant drain current and temperature change caused by the current, to achieve constant heating power. $V_{gs}$ is kept regulated not only during the heating, but also after $I_{\text{heat}}$ is switched off, till the end of the cooling phase. $V_{gs}$ is used as TSP. Eq. (2) can be used as the coefficient. A circuit diagram for this measurement mode is shown in Fig. 10.

### 3.1.4 Body-Diode mode

The body-Diode mode uses built-in diode in MOSFETs for the measurement. Gate is connected to source or negative bias to put it into forward blocking mode. The forward voltage of the body diode $V_{sd}$ is used as TSP. Eq. (6) can be used as the coefficient. The heating and measurement are done by applying reverse current to the body diode. A circuit diagram for this measurement mode is shown in Fig. 11.

### 3.2 Proposed test method

The target DUT of GaN HEMT in this paper has a gate, which has a PN junction above the channel. Current will flow through the gate when forward bias voltage is applied between gate and source or drain. The knee voltage of PN junction in gate and source ($= V_{f-gs}$) is used as TSP as described in 2.2 in the proposed test method. The sensing current $I_{\text{sense}}$ applied from the gate to source is kept constant during the entire sequence. The heating current $I_{\text{heat}}$ is applied to the DUT from drain to source, due to channel conduction with the gate current ($= I_{\text{sense}}$). Using $V_{f-gs}$ as TSP is intended to separate TSP from a flow path of $I_{\text{heat}}$. In this paper, this test method is called “Gate $V_f$ mode” (Fig. 12). [25]
4. Results and Discussion

First, the difficulties in characterizing the thermal performance of GaN HEMTs using conventional transient thermal characterization methods are reviewed. Then the measurement results with the proposed method are shown later. The tests were carried out by using the T3Ster thermal transient tester.[26] The test environment of the transient thermal characterization test is shown in Fig. 13. The DUT is attached to a cold plate inside the Peltier Thermostat with thermal grease applied.

4.1 Measurement results of conventional test methods

4.1.1 MOS-SAT mode

The dynamical electric response of a GaN HEMT due to the non-ideal characteristics of the power device disturbed the thermal response characterization. It was clearly observed when a measurement was carried out without a heating current. The result for $I_{\text{sense}} = 100$ mA is shown in Fig. 14. The junction temperature doesn’t change in steady state unless the device is heated up. However, switching the gate voltage from 3 V to −3 V, which is not causing any self-heating, induced disturbance in the selected TSP. Since it is difficult to separate thermal transient response from the disturbing electrical response due to non-ideal characteristics of power device, this measurement mode is not appropriate for transient thermal characterization of the GaN HEMT device.

4.1.2 MOS-Diode mode

Usually, oscillation doesn’t occur in the measurements of normally-off type Si MOSFETs with MOS-Diode mode. However, the GaN HEMT used in this paper oscillated while applying the heating current. The result with $I_{\text{heat}} = 1$ A is shown in Fig. 15 (a). Constant power cannot be applied to the DUT. Furthermore, the oscillation could damage the device.

It was the gate parasitic oscillation,[27, 28] which was confirmed with the $I-V$ static electrical characteristics of the GaN HEMT device.
the device in a MOS-Diode mode connection as shown in Fig. 9. The oscillation can be avoided by adding a gate resistor. The result is shown in Fig. 15 (b). However, the transient thermal measurement results didn’t match well when varying the applied heating power (Fig. 16). The electrical transient disturbed the thermal transient response.

4.1.3 RDS-ON mode

In our experiment, \( V_{gs} \) was controlled for \( V_{ds} = 2 \text{ V} \). \( I_{\text{sense}} = 100 \text{ mA} \) and \( I_{\text{heat}} = 2 \text{ A}, 4 \text{ A}, \text{ and } 6 \text{ A} \) were tested to compare different heating power applied to the DUT. Extracted structure functions yielded by different heating power didn’t correspond to each other at all as shown in Fig. 17. There was no consistency to the results. Just like MOS-SAT mode and MOS-Diode mode, electrical transient disturbed the thermal transient response.

4.1.4 Body-Diode mode

Characterization results with \( V_{gs} = -1.62 \text{ V} \), \( I_{\text{sense}} = 20 \text{ mA} \), \( I_{\text{heat}} = 1 \text{ A}, 2 \text{ A}, 3 \text{ A}, \text{ and } 4 \text{ A} \) are shown in Fig. 18. \( I_{\text{heat}} \) varied to see the difference of heating power applied to the DUT. Unfortunately, structure functions yielded by different heating power didn’t match neither. As other conventional measurement modes were disturbed by electrical transient, the thermal transient response in case of using Body-Diode mode was also disturbed.

Usually, thermal resistance could become slightly larger in the following conditions when larger heating power is applied: 1, if the applied power makes differences in the thermal conductive path due to higher power density, 2, if the applied power makes the temperature significantly higher and thermal dependencies of the thermal conductivity becomes not negligible. Interestingly, all three graphs shown in Fig. 16 – Fig. 18 show that the more heating power is applied, the less thermal resistance becomes. This symptom is difficult to explain thermally. It also indicates that the results are disturbed by electrical transient. [29]

4.2 Measurement results of the proposed gate \( V_f \) mode

The test conditions are shown in Table 2. The K-factor was identified with \( I_{\text{sense}} = 1 \text{ mA} \), as shown in Fig. 19. It showed monotonically decreasing characteristic with respect to temperature. Quadratic curve fitting was used.

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**Table 2  Test conditions of gate \( V_f \) mode.**

| Parameters             | Value             | Notes |
|------------------------|-------------------|-------|
| Heating current        | 7 A, 10 A, and 12 A | Applied as \( I_{\text{ds}} \) |
| Sensing current        | 1 mA              | Applied as \( I_{\text{gs}} \) |
| Heating time           | 30 s              |       |
| Measurement time       | 30 s              |       |
| Square Root fitting    | 317–1,112 \( \mu \text{s} \) | JESD51-14[23] |
and $V_{F-G}$ [V] could be represented by $T$ [$^\circ$C] as shown in Eq. (7).

$$V_{F-G} = -4.964 \times 10^{-6} \cdot T^2 - 2.385 \times 10^{-3} \cdot T + 2.887. \quad (7)$$

This data was used for the proposed measurement method described in this section.

### 4.2.1 Repeatability of transient thermal measurement

First, repeatability of the measurement results was evaluated by comparing two consecutive measurement results. $I_{heat}$ was 10 A. Measured time response of $V_{F-G}$ in cooling operation are shown in Fig. 20. Both results agreed and gave good repeatability.

Square Root Fitting [23] was used to extrapolate the temperature vs. $\sqrt{t}$ curve for estimating initial junction temperature at $t = 0$ [sec], as shown in Fig. 21. The acquired structure functions are shown in Fig. 22. The two consecutive measurement results matched, and the repeatability was confirmed. A minor temperature offset (approx. 0.3°C) can be seen in Fig. 21. This is due to the difference at the Peltier Thermostat area (> 10 J/K), shown in the upper right corner of Fig. 22.

### 4.2.2 Transient thermal measurement tests with different heating power application

Next, measurement robustness was checked. Measurements were performed with three different heating power applied to the DUT by varying $I_{heat}$. The measurement results of $V_{gs}$ are shown in Fig. 23. The data was converted
from TSP to $T_J$ by using the K-factor shown in Eq. (7). The results are shown in Fig. 24. Structure functions identified from the measurement results are shown in Fig. 25. The structure functions almost correspond to the ones with different power applied. The consistency has been significantly improved compared with the conventional measurement methods. A minor difference was observed at around 0.5 K/W. This stems from the differences in the heat flow paths caused by the significantly different power applied to the sample. As it is shown in Fig. 24, hot steady state temperatures of $T_J$ at the instant of switching off $I_{heat} = 7$ A, 10 A, and 12 A are approx. 37°C, 65°C, and 109°C respectively. Temperature dependencies of the thermal conductivity will be also considered to be the cause of the difference. The difference was analyzed by shifting the curves along X axis as shown in Fig. 26 (a). Curves of Fig. 25 pulled together along X axis to the lead frame area, around 0.003.. 0.3 J/K, is shown in Fig. 26 (a). This graph indicates that the differences can be separated into two areas: die attach area and the area between lead frame and cold plate.

Curves of Fig. 25 pulled together along X axis to the cold plate area, right end of the graph, is shown in Fig. 26 (b). This shows that the heat flow paths are identical at cold plate area, or outside of the DUT. The heat flow paths at the cold plate area, characterized by measuring a GaN HEMT with Gate $V_f$ mode by varying heating power applied, have matched perfectly. This could be possible only when the measurements are not disturbed by electrical transient. This result holds the theory that the minor differences seen in Fig. 25 is independent from electrical transient and is due to the changes of the heat flow areas on both die attach area and the area between lead frame and cold plate, which is shown in Fig. 26 (a).

4.3 Discussion

In Gate $V_f$ mode, heating power is applied to the DUT by injecting heating current from drain to source. On the other hand, TSP is measured by the voltage between gate and source while applying sensing current from gate to source. This paper shows that the strategy to separate the heating current path and TSP measurement ports worked
well. The results indicate that charge trapping phenomena exist mainly in the channel region. The Gate $V_f$ mode has successfully captured the transient temperature of the junction without being disturbed by the electrical transients.

The Gate $V_f$ mode is not limited to GaN HEMT with p-type gate, but also applicable with normally-on type Schottky-gated HEMTs. Furthermore, it can be used to measure BJT.

5. Conclusion

Four conventional Si based methods of transient thermal characterization test (MOS-SAT mode, MOS-Diode mode, RDS-ON mode, and Body-Diode mode) were evaluated. They were not applicable for GaN HEMT due to the non-ideal characteristics of the GaN HEMT. This paper proposed a thermal characterization method “Gate $V_f$ mode” for GaN HEMT with p-type gate and validated the proposing method. The K-factor for the proposed method showed monotonically decreasing characteristic with respect to temperature, which is suitable for being used as TSP. Measurement results with the proposed method are immune to the disturbance induced by the electrical transient due to the non-ideal characteristics of the GaN HEMT and measurement repeatability was confirmed. The proposing Gate $V_f$ mode is suitable for measuring GaN HEMT with p-type gate.

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