Research and Application of Temperature-sensitive Characteristics of Gate Parameters in GaN high electron mobility transistors

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Abstract. A gallium nitride (GaN) high-electron-mobility transistors (HEMTs) operates in a high-frequency switching state, and its usage reliability is reduced when the temperature increases as a result of the increase of power density and size reduction. To measure the HEMT temperature increase based on the characteristics of the gate-source structure of the HEMT device, this paper proposes the use of reverse gate current as a thermo-sensitive parameter to measure the temperature and improve the temperature characteristics of the parameter by reasonably changing the gate voltage. A theoretical analysis of the reverse gate current components was carried out, and the trends and changes in its temperature characteristics were investigated. The influencing factors affecting the reverse gate current were discussed, and the phenomenon of the current’s sudden change with temperature was explained.

1. Introduction
Gallium nitride (GaN) high-electron-mobility transistors (HEMTs) devices occupy an important position in the semiconductor industry owing to their unique high-frequency power switching characteristics [1] [2]. Because HEMT devices were commonly used in high-frequency switching processes, the temperature sensitivity of the conventional time-series and peak-type temperature parameters is not high. Therefore, their acquisition and extraction is difficult, and it is not easy to use them in engineering applications. The use of the Schottky gate-diode forward characteristics to measure the channel temperature is a widely used electrical method of measuring the current temperature of HEMT devices[3]. However, this method obtains the cooling process of the channel directly after the device is heated. Therefore, the transient temperature increase of the device is not obtained in real time. Using the channel parameters (VDS and IDS) as TSEPs in the actual operation of the HEMT device can effectively avoid the influence exerted by the introduction of a test signal[4]. However, the matching circuits and loads introduce effects such as resistance and inductance. The actual measured electrical parameters cannot avoid the effects of the load and spurious factors. To the extent possible, the extraction of the temperature-sensitive parameters should not affect the normal operation of the device.

For this reason, and in accordance with the structural characteristics of the HEMT and the actual working conditions of the device, this paper proposes the use of reverse gate current as a thermo-sensitive parameter (TSEP). Moreover, this study aimed to develop a method of improving the temperature sensitivity and a new high temperature early warning mechanism by investigating the device’s temperature characteristics and relevant influencing factors and components.
2. Gate-source reverse bias current composition and temperature characteristics

By analyzing the structure of the HEMT device, the gate and source of the device were found to be similar to the Schottky structure. Since the threshold voltage of the HEMT device is negative, the gate-source control voltage is always negative during switching, the Schottky junction is in a reverse bias state, and there exists a reverse bias current between the gate and the source. Several researchers have conducted various useful investigations with regard to the composition and influencing factors of the gate-source reverse bias current. A proportion of the current component has a certain dependence on temperature. The gate-source voltage makes a certain contribution to the current size, and the doping condition exerts a certain influence on the configuration of the current.

In the highly doped low temperature range, the gate-source reverse bias current is dominated by the tunneling current, as follows:

\[ J_{g\rightarrow s} = \frac{A^{**}T^2}{kT} \int_{E_m} F_m T(E) (1 - F_n) dE \]  

where \( F_m \) and \( F_s \) are the Fermi-Dirac distribution functions for metals and semiconductors, and \( T(E) \) is the tunneling probability depending on a certain barrier width.

The composition of the tunneling current can be roughly divided into three parts: the thermionic emission current across the barrier, the field emission current (FE) near the Fermi level, and a certain amount of thermionic-field emission current (TFE) between the thermionic emission and the field emission.

For HEMT device with a negative gate-source voltage operating state, the reverse gate current consists mainly of FE and TFE:

\[ J_{FE} = A^{**} \left( \frac{E_{00}}{k} \right)^2 \left( \frac{\phi_{BN} + V_R}{\phi_{BN}} \right) \exp \left( -\frac{2q\phi_{BN}^{3/2}}{3E_{00}\sqrt{\phi_{BN} + V_R}} \right) \]  

\[ J_{TFE} = \frac{A^{**T}}{k} \sqrt{\pi E_{00} q \left[ V_R + \frac{\phi_{BN}}{\cos h(E_{00}/kT)} \right] \exp \left( -\frac{q\phi_{BN}}{E_{00}} \right) \exp \left( \frac{qV_R}{e^T} \right)} \]

where \( A^* \) is the effective Richardson constant, and \( A^{**} \) is the attenuation result after considering the influence of the quantum mechanical reflection and tunneling during the particle transport. Relevant studies have reported that the tunneling current induced by FE has almost no dependence on temperature[5]. From Equation (3), the following conclusion can be drawn: the tunneling current caused by TFE has an approximately linear one-to-one correspondence with the temperature. Through the above analysis, it can be seen that the reverse gate current of the HEMT device occupies a large proportion, and that the reverse gate current was approximately linearly related to the temperature (the exponent term was ignored) [5].

3. Increased temperature sensitivity of gate-source reverse bias currents

Although the gate-source reverse bias current itself has a linear relationship with temperature. However, the gate voltage was low during the operation of the HEMT device, and the gate-source reverse bias current was small when the gate voltage was too low, which increases the difficulty of acquisition and causes the temperature sensitivity of the temperature sensitive parameter to be too low, which was not favorable for engineering applications. For this reason, increasing the gate bias voltage of the negative electrode under the condition that the HEMT device was turned off, and increasing the negative gate voltage under the condition of the device helps to increase the gate source current and improve the temperature sensitivity. The appropriate change of the gate voltage proposed here was only applicable to the OFF mode of the HEMT device, and reducing the gate voltage in the on-state will cause the device power consumption to increase and the transconductance decreases, which affects the normal operation of the device and was not applicable. However, this does not affect the application of this method: HEMTs operating in high-frequency switching states have extremely high on-state and off-state switching frequencies, and can use switch-off states to directly characterize the temperature of a
switching cycle. Figure 1 shows the gate-source reverse bias current variation under different gate voltage conditions.

![Figure 1. Influence of gate voltage on temperature sensitivity of reverse gate current.](image1)

An appropriate increase in the negative gate voltage can increase the reverse gate current. For a high-speed switching HEMT device, the method that negative-state negative-going gate-up voltage does not affect its operating conditions is reasonable and effective to improve the temperature characteristics of the reverse gate current. However, it should be noted that only the vertical tunneling current between the gate and the source was considered in the above discussion, while the tunneling current of the vertical gate source was disregarded. Various scholars have reported that the lateral tunneling current affects the transport process of the gate-source current; that is, the source-drain voltage has a certain influence on the reverse gate current[6]. Figure 2 shows the variation of the reverse gate current under different source-drain voltage conditions with the same gate voltage ($V_{GS}$).

![Figure 2. Source and drain voltages affecting reverse gate currents($V_{GS}=10V$)](image2)

In the actual operation of the HEMT device, the source-drain voltage $V_{DS}$ was generally kept constant, and the gate-source voltage continuously increased or decreased to switch the control channel on and off and control the device. Let us consider the HEMT device of the Cree Model CGH40010 as an example: under the operating conditions, the source-drain voltage ($V_{DS}$) was kept constant at 2 V or 5 V, the gate bias was -2.2 V in the on state. In order to increase the temperature sensitivity of the parameters, the gate voltage was raised to -5V and -10V in the off state. Figure 3 shows a view of experimental setup, and Figure 4 shows a schematic diagram of a calibration temperature curve under different gate voltage ($V_{GS}$) and source-drain voltage ($V_{DS}$).

![Figure 3. View of experimental setup.](image3)
When the thermionic electron emission and diffusion current have a dominant role, the corresponding relationship between $I_{GS}$ and the temperature will gradually deviate from linearity and the value will increase rapidly as the temperature increases.

4. CONCLUSION
This paper proposed the temperature characteristics of the reverse gate current on the basis of the gate structure of the HEMT device. In combination with the actual working conditions of the device, the temperature sensitivity of the reverse gate current is enhanced by reasonable changes to the gate-source voltage in the shutdown condition. Additionally, the temperature characteristics of the parameter were improved to facilitate its accurate acquisition and practical implementation in engineering applications. By increasing the gate-source voltage, the temperature sensitivity of the reverse gate current increases by an order of magnitude, which is advantageous in enhancing the temperature characterization capability of the parameter. In actual applications, the reverse gate current of the HEMT device can be accurately extracted, and according to the unique of the reverse gate current’s temperature characteristics, the temperature of the device can be characterized. The composition and influencing factors of the reverse gate current were discussed and verified. It was proven that there exists a monotonic relationship between the different components of the reverse gate current and the temperature. Additionally, the proportion of parameters changes as the temperature increases.

References
[1] Malik, A., Sharma, C., Laishram, R., et al. (2018) Role of AlGaN/GaN interface traps on negative threshold voltage shift in AlGaN/GaN HEMT. Solid-State Electronics., 142: 8-13.
[2] Maafri, D., Saadi, A., Slimane, A., et al. (2018) An efficient and reliable small signal intrinsic parameters extraction for HEMT GaN devices. Microwave & Optical Technology Letters., 60(2):455-458.
[3] Darwish, A. M., Bayba, A. J., & Hung, H. A. (2008) Utilizing diode characteristics for gan hemt channel temperature prediction. IEEE Transactions on Microwave Theory & Techniques., 56(12):3188-3192.
[4] Menozzi, R., Umana-Membreno, G. A., Nener, B. D., Parish, G., Sozzi, G., & Faraone, L., et al. (2008) Temperature-dependent characterization of algan/gan hems: thermal and source/drain resistances. IEEE Transactions on Device & Materials Reliability., 8(2):255-264.
[5] Sze, B. S. M. (1969) Physics of semiconductor devices. Wiley-Interscience
[6] Miller, E. J., Dang, X. Z., & Yu, E. T. (2000) Gate leakage current mechanisms in algan/gan heterostructure field-effect transistors. Journal of Applied Physics., 88(10):5951-5958.