Temperature Effects of GaN HEMTs on the Design of Power Converters

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Abstract. This paper proposes an experimental study of temperature effects on Gallium Nitride (GaN) High Electron Mobility Transistors (HEMTs). The output and transfer characteristics are monitored at temperatures ranging from 5°C to 105°C. The temperature dependency on static parameters of GaN HEMT is examined, such as: drain current (I_{DS}), on-state resistance ($R_{DS(ON)}$), transconductance (g_m), threshold voltage (V_{TH}) and the gate leakage current (I_{GSS}). The decreases of I_{DS} and g_m accompanied with the increase of $R_{DS(ON)}$ and I_{GSS} when increasing temperature have been observed. Moreover, the decrease in electron mobility with increasing temperatures is considered to be one of the causes of the reduction in the drain current and transconductance. In order to study the impact of temperature on power converters with GaN HEMTs by simulation approach, the thermal characteristics of a 650V, 30A GaN HEMT have been modelled. The used model is a non-segmented Electro-thermal SPICE model of Motorola. The model parameters are extracted using Levenberg-Marquardt Algorithm.

Keywords: characterization; modeling; temperature; GaN; HEMT; Levenberg-Marquardt.

1 Introduction

The global renewable energy consumption is estimated to increase by 78% within 2040 [1]. The use of Gallium Nitride (GaN) power transistors in the renewable energy industry, enable 20% power density increase, 50% power loss reduction, 10% lower system cost, and more efficient energy storage systems, along with bi-directional power flow architectures that are not achievable with silicon (Si) [2].

Furthermore, GaN HEMTs power transistors can operate at higher power levels, frequencies and temperatures, and with an improved energy efficiency with respect to that guaranteed by Si devices [3]. These excellent features are due to the excellent physical properties of GaN semiconductor [4]. In fact, they can allow a reduction of the on-state resistance and parasitic capacitances with respect to Si devices, with an overall reduction of the power losses [5]. The above advantages of the GaN semiconductor make GaN power transistors attractive for renewable energy domain in particular for use in photovoltaic and wind energy systems [6].

In this context, DC-DC power converters are the most inevitable electronic units in power electronic systems, by providing the control and management of the electric power [7]. The investigation of the temperature dependency of GaN HEMT power transistors is vital to the use

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of the GaN HEMTs in power converter applications. Such an investigation is important particularly to understand the cause of deterioration of their electrical performance at elevated temperatures.

In the literature, several studies on the temperature dependency of GaN HEMTs were performed. References [8] and [9] indicate the evolution of GaN HEMTs electrical parameters during thermal stresses depending on the different temperature ranges.

In this paper, current–voltage characteristics of a GaN HEMT power transistor at operating temperatures are studied experimentally. Moreover, the physics underlying various high-temperature operations of current–voltage characteristics is discussed. Finally, the effect of temperature on power converters with GaN HEMT is verified by a simulation approach.

2 Static characterization

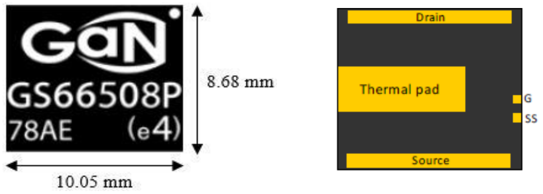
The tested device is a GS66508P from GaN Systems [10]. It is a p-type gate normally-off AlGaN/GaN power transistor which operates in the range of 650V/30A. **Figure 1** provides a bottom and a top view of the tested GaN transistor package. The device package allows to study the temperature dependency of the GaN HEMT characteristics from low temperature (5˚C) to high temperature (105˚C). **Figure 2** illustrates the p-AlGaN gate formed over the undoped AlGaN/GaN heterostructure [11]. The p-AlGaN lifts up the potential at the channel, which enables normally-off operation.

The static characterization is performed using AMCAD pulsed I-V system. The pulses setting is fixed at a pulse frequency of 100 Hz with a gate pulse duty cycle of 0.04%. The pulse width of 4 μs is short enough to ensure iso-thermal measurement of pulsed I-V GaN HEMT characteristics. The used I-V pulsed probes have a high measurement accuracy, which is equal to ±100mA.

The tested GaN HEMT (DUT) is characterized at temperature ranging from 5 ˚C to 105 ˚C in order to study the effect of temperature on GaN power transistors. The temperature is fixed by a Peltier heater plate. The I-V pulsed bench with associated instruments are shown in **Figure 3**.

The measured output characteristic curves for a gate-to-source voltage (V_{GS}) equals to 6V under operating temperatures equal to 5°C, 25°C, 75°C and 105 °C are shown in **Figure 4 (a)**. As observed, the drain current I_D is modulated by the voltage V_{GS}. The transfer characteristic is obtained for a drain-source voltage (V_{DS}) equals to 2V and for various temperatures equal to 5°C, 25°C, 75°C and 105 °C see **Figure 4 (b)**. The tested device has the advantage of safe normally-off operation for temperature up to 105˚C.

According to the output characteristic in **Figure 4 (a)**, the evolution of the following electrical parameters are extracted: the on-state resistance, the threshold voltage. From the transfer characteristic in **Figure 4 (b)**, the evolution of the transconductance g_m versus temperature is determined.



(a) (b)

Fig. 1. GS66508P package [10]: (a) Top view; (b) bottom view

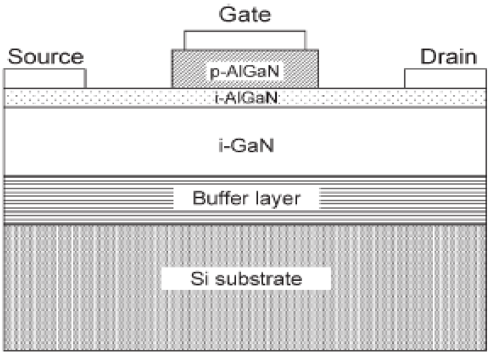


Fig. 2. Schematic illustration of the tested GaN HEMT power transistor structure [11]

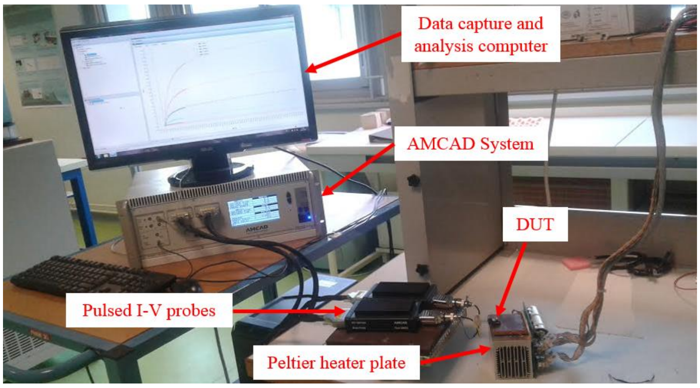
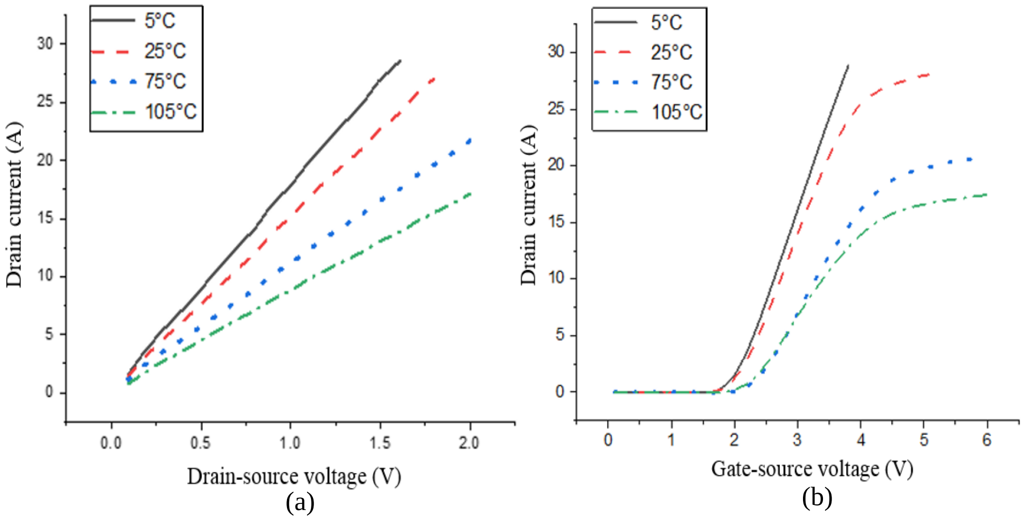


Fig. 3. I-V pulsed bench with associated instruments

2.1 On-state resistance ($R_{DS(ON)}$)

The R_{DSON} is defined as the inverse of the slope of output characteristics in the linear region and it calculated by the following equation:

$$R_{DS(ON)} = \left.\frac{\Delta I_D}{\Delta V_{DS}}\right)^{-1}_{V_{GS}=6V,\,V_{DS}\to 0V} . \qquad (1)$$



(a) (b)

Fig. 4. (a) Output characteristic of GaN HEMT at V_{GS} = 6V; (b) Transfer characteristic of GaN HEMT at V_{DS} = 2V for various temperatures: 5°C, 25°C, 75°C and 105 °C.

The measurement conditions of normalized $R_{DS(ON)}$ are: V_{GS} = 6V and varying temperature from 5°C to 105°C. **Figure 5** shows the variation of the normalized $R_{DS(ON)}$ versus temperature. An increasing of 180% in on-state resistance at 105°C can be observed compared to its value at 5°C.

The temperature dependency of $R_{DS(ON)}$ is due to the impact of temperature on the channel between the source and gate contacts [12]. In fact, if the device temperature is raised, the low-field electron mobility in the channel is decreased [13], and a proportional increase of the channel resistance related to the drain-source resistance (R_{DS}) can be expected. This result is also confirmed in [14] which is suggested to use GaN HEMT transistors with higher 2-D electron gas (2DEG) channel density for enhanced performances.

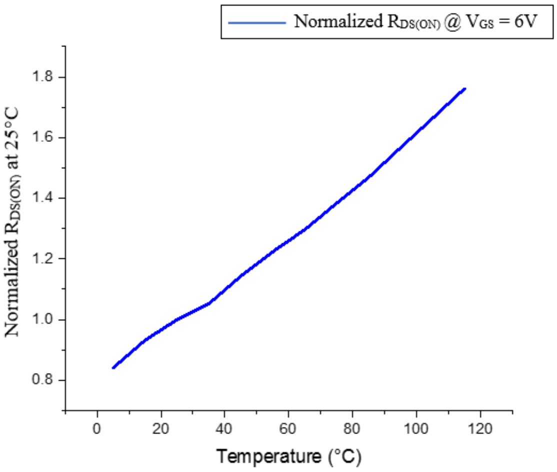


Fig. 5. Normalized $R_{DS(ON)}$ as a function of temperature at V_{GS} = 6V

2.2 Threshold voltage (V_{TH})

The V_{TH} is extracted using Extrapolation in the Linear Region (ELR) method [15]. The temperature dependency of the extracted threshold voltage is given in **Figure 6 (a)**. As shown in this figure, the threshold voltage of GaN HEMT at 105 °C decreases about 12% compared to their values at 5°C.

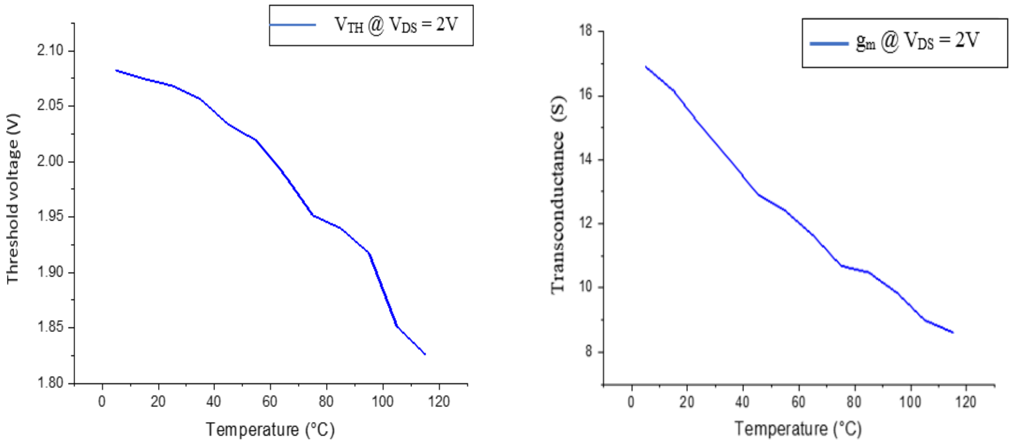
The dependency of V_{TH} on temperature is due to holes injected from the metal to the p-GaN layer. The injected holes are accumulated at the p-GaN/AlGaN interface. This lead to a negative shift in threshold voltage, which can also be observed in [16]. Recent studies [17] shows that using hydrogen plasma treatment instead of etching technology may compensate holes in the p-GaN layer above the two dimensional electron gas (2DEG) channel to release electrons in the 2DEG channel and form high resistivity area to reduce leakage current and increase threshold voltage stability.

2.3 Transconductance (g_m)

The g_m quantifies the drain current variation with a gate-source voltage variation while keeping the drain-source voltage constant (bias voltage). It is defined by the following equation, while V_{DS} is the bias voltage.

$$g_m = \left.\frac{\partial I_D}{\partial V_{GS}}\right)_{V_{DS}=2V} . \qquad (2)$$

Figure 6 (b) shows the variations of the transconductance g_m as a function of temperature. As shown in this figure, the transconductance g_m at 105 °C decreases about 58.38% compared to their values at 5°C. The decreasing of g_m with the increase of temperature is due to the decrease of both the electron mobility in the channel and the electron velocity [18]. The decrease of the transconductance when increasing temperature is observed in [19] which is confirmed that the channel mobility decreases with the increase of temperature [20].



(a) (b)

Fig. 6. (a) Threshold voltage; (b) Transconductance as a function of temperature at V_{DS} = 2V

2.4 Gate leakage current

The gate leakage current is defined as the leakage that occurs when the specified voltage is applied across the gate and source with drain and source short-circuited. The leakage current measurements were performed by using Keithly 2636B SourceMeter.

Figure 7 shows the evolution of the gate leakage current as a function of temperature. As observed, the current I_{GSS} is increased by 77.77% when varying temperature from 5°C to 105°C. It was demonstrated in reference [21] that increasing temperature may reduce the schottky barrier height at the metal/p-GaN contact and, consequently, increase the gate leakage current. Moreover, in p-GaN/AlGaN/ GaN heterostructure, the reduction of the Schottky barrier height at the metal/p-GaN gate enhances the tunneling of holes through the barrier [22]. Then, as highlighted by Hwang et al. [23], the enhancement of holes injection leads not only to a negative shift of the V_{TH} but also to an increase in the leakage current in p-GaN HEMT. The increase in the leakage gate current when increasing temperature is also observed in [24], which is attributed to the lowering of the Schottky barrier height of the metal/p-GaN gate.

3 Modeling temperature dependency

The purpose of this part is to model the temperature dependency of the GaN HEMT in order to evaluate the effects of GaN HEMT on the power efficiency of the DC-DC converters by a SPICE simulation approach. **Figure 8** shows the studied DC-DC boost converter, which is a 12/24 V boost converter with an output power equals to 180 W. The tested device (DUT) is the SPICE Electro-thermal model of the GaN HEMT.

The proposed drain current model of the DUT is a non-segmented, smooth and continuous equation inspired from the Motorola Electro-thermal Model (MET) developed by Curtice et al. [25] and described in [26].

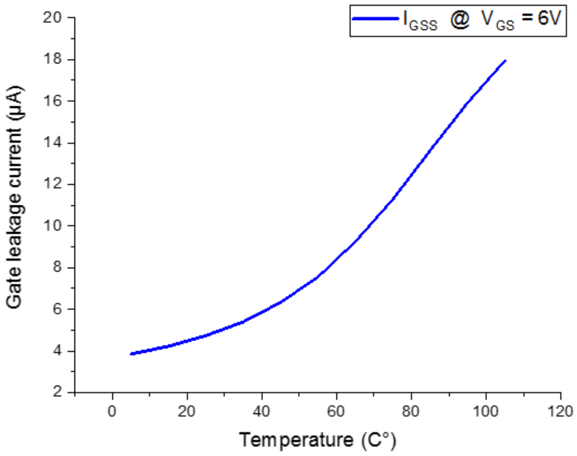


Fig. 7. Gate leakage current as a function of temperature at V_{GS} = 6V

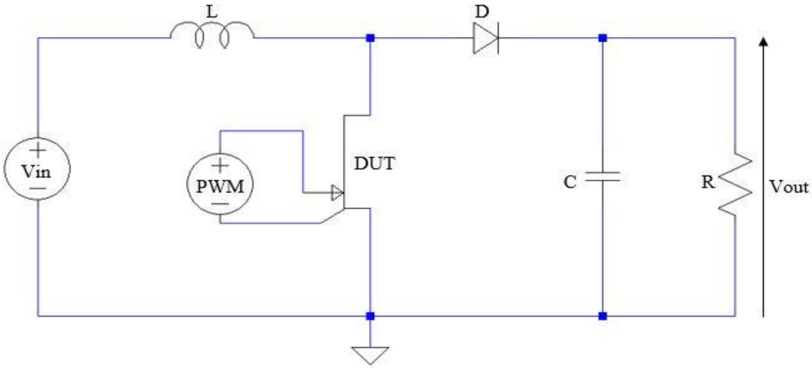


Fig. 8. DC-DC boost converter with L = 21.41 µH, Vin = 12V, Vout = 24V, C = 90.9 µF and R = 1.71 Ω. The switching conditions of the DUT transistor are: f = 50 kHz and duty-cycle = 50 %.

The proposed drain current equation is shown as follows:

$$\begin{cases} I_{DS} = K(T)\cdot\log\left[1+\exp\left(\dfrac{V_{GS}-b}{c}\right)\right]\cdot\dfrac{(m+n\cdot V_{GS})V_{DS}}{1+P(T)\cdot(d+e\cdot V_{GS})V_{DS}} \text{ , } V_{DS}\geq 0 \\ K(T)=K.\left[1+T_{C1}.(T-25)+T_{C2}\cdot(T-25)^2\right] \\ P(T)=P.\left[1+T_{C3}.(T-25)+T_{C4}\cdot(T-25)^2\right] \end{cases} . \quad (3)$$

Where K is the device forward transconductance (A.V^{-1}) parameter at 25°C, P is the output conductance (V^{-1}) at 25°C, b and c are related parameters of the transfer characteristic, while m, n, d and e are related parameters of the output characteristic. Tc1, T_{C2}, T_{C3} and Tc4 are temperature coefficients. These parameters are extracted by using the Levenberg-Marquardt algorithm [27] as shown in Table 1.

The conduction power loss (P_C) is defined by:

$$P_c = \frac{1}{T_{on}}\int_0^{T_{ON}} i_{ds}\cdot v_{ds}\cdot dt \ . \quad (4)$$

Where, i_{ds} is instantaneous drain current, v_{ds} is the instantaneous drain voltage and T_{on} is the conduction time which is given by:

$$T_{on} = \frac{d_c}{f} \ . \quad (5)$$

Where, d_c is the duty cycle and f is the frequency.

Figure 9 shows the conduction power losses of the DUT used in the DC-DC converter of **Figure 8** at various junction temperatures: 25°C, 70°C and 105°C. From **Figure 9**, an increase in conduction power losses is observed, which is mainly due to the increase of the dynamic on-state resistance of the DUT when increasing temperature.

Table 1. Extracted Electrothermal SPICE model parameters

Parameter	K	b	c	m	n	P
Value	1.42	1.65	0.14	8.12	-1.15	0.75
Parameter	d	e	T_{C1}	T_{C2}	T_{C3}	T_{C4}
Value	1.94	-0.35	-8.02E-3	3.22E-5	-3.75E-3	4.01E-6

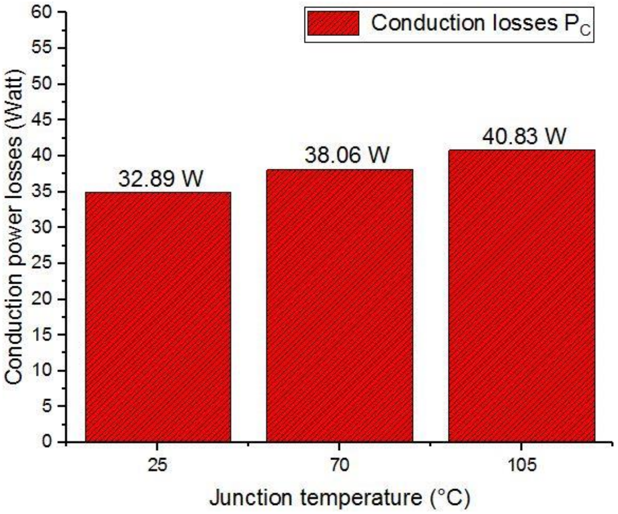


Fig. 9. Conduction power losses of GaN HEMT at T_J = 25°C, 70°C and 105°C

4 Conclusion

In conclusion, the temperature dependency of GaN HEMT static characteristics has been studied based on experimental measurements. The decreases in $R_{DS(ON)}$, I_{DS} and g_m with the increase of temperature are due to the decrease in electron mobility. The increase in I_{GSS} and the negative shift of V_{TH} when increasing temperature is attributed to the lowering of the Schottky barrier height of the metal/p-GaN gate and to hole injection at the metal/p-GaN. It is suggested to use GaN HEMT transistors with hydrogen plasma treatment instead of etching technology to reduce leakage current and increase threshold voltage stability. Upon cooling after high temperature characterization at 105 °C, GaN HEMT transistors showed recovered output and transfer characteristics. The effect of increasing the operational temperature of the GaN HEMT transistors on a DC power converter is verified by modeling the thermal characteristics of the GaN HEMT. Such an investigation is important particularly to understand the cause of deterioration of GaN HEMT electrical performances at high temperatures. The temperature dependency of GaN HEMT dynamic characteristics will be studied in the next work in order to take into account the switching losses. This enable an accurate design of power converters with GaN HEMTs for renewable energy applications by a simulation approach.

Acknowledgments

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