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TEMPERATURE-DEPENDENT TRANSFER CHARACTERISTICS AND THERMAL MODEL OF 200V SCHOTTKY P-GaN HEMTs

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ABSTRACT

In this paper, Gallium Nitride (GaN) High Electron Mobility Transistors (HEMTs) are introduced as emerging wide bandgap power devices, with both semiconducting properties and device structures. A GaN testing circuit designed for DC-DC power conversion applications that includes the capability for dynamic channel resistance measurement is presented. An experimental design for investigating the temperature-dependent transfer characteristics of these devices, alongside concepts for transistor thermal modelling, is detailed, employing a systematic methodology. Findings encompass the device transfer characteristics, gate leakage current, and thermal equivalent circuit simulations of the Schottky p-GaN HEMT under conditions both with and without a heat sink. The results underscore the significant impact of thermal effects on GaN HEMTs power circuit applications.

KEYWORD

GaN HEMT, Wide Bandgap Semiconductor, Thermal Model, Transfer Characteristics, Heat Sink, Circuit Simulation

INTRODUCTION

Amidst the push for renewable energy and power electronic advancements, the quest for efficient and reliable power conversion has highlighted the limitations of traditional silicon-based semiconductors like MOSFETs in power density, thermal endurance, and switching speeds. Wide-bandgap semiconductors, especially GaN, offer a superior alternative, boasting higher electric field tolerance, larger energy bandgaps, and improved electron mobility (Roccaforte et al., 2018). These properties enable them to excel in high-efficiency, high-power applications. GaN HEMTs, with their unique AlGaN/GaN structures, are emerging as a leading choice for medium voltage applications due to their exceptional semiconductor properties, shown in Figure 1.

Figure 1(c) showcases an experimental GaN converter circuit utilizing a half-bridge topology for step-down DC-DC power conversion. GaN HEMTs are versatile, finding applications in renewable energy, fast electronic charging, electric vehicle (EV) charging, and RF communications, with their wider bandgap making them excellent candidates for space applications (Chow, 2015). Despite the exceptional performance of GaN transistors, thermal management is a critical issue due to the material's relatively poor thermal conductivity (Chen et al., 2017). This paper aims to characterize GaN HEMTs at both the device and circuit levels, including a time-dependent analysis of device transfer properties. Through thermal model equivalent and SPICE circuit simulations, we investigate the junction and case temperatures with and without a heatsink. Results indicate a significant reduction in temperature, with a GaN HEMT operating in a 100V input power circuit within a heatsink achieving 46.1°C, which is 3.24 times cooler than the initial condition of 149.5°C at the junction. These findings highlight the critical role of thermal management in GaN circuits and offer a predictive solution for the GaN circuit community.

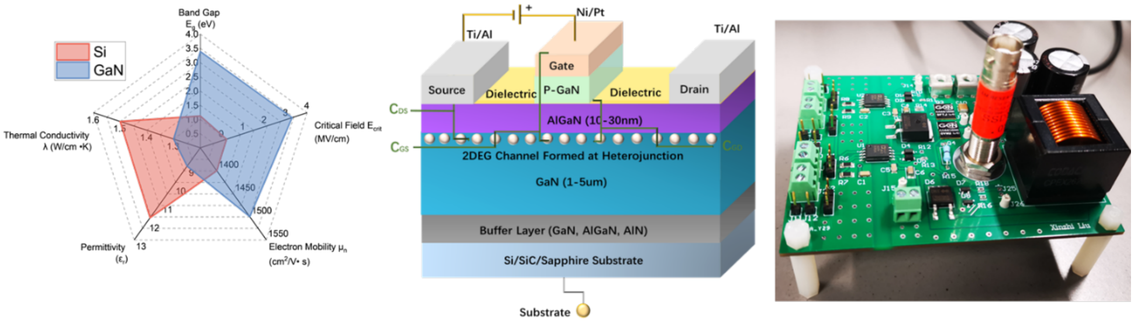

Figure 1: Introduction of GaN HEMT (a) Radar plot of semiconducting properties comparison with silicon. (b) Typical normally off device structures. (c) GaN power converter testing circuit.

METHODOLOGY

Figure 2 illustrates the experimental setup configured to measure the transistor transfer characteristics across a temperature range from 25°C to 125°C. For this purpose, a digital signal analyser was utilized in conjunction with a probe station, where the substrate was thermally regulated using a thermostat for controlled heating. To enhance safety and minimize the risk of damage to the device, the drain current compliance was limited to 1A. Additionally, the analyser was operated in pulse mode rather than DC mode, a strategic choice aimed at reducing thermal load on the device and mitigating the effects of self-heating during measurements.

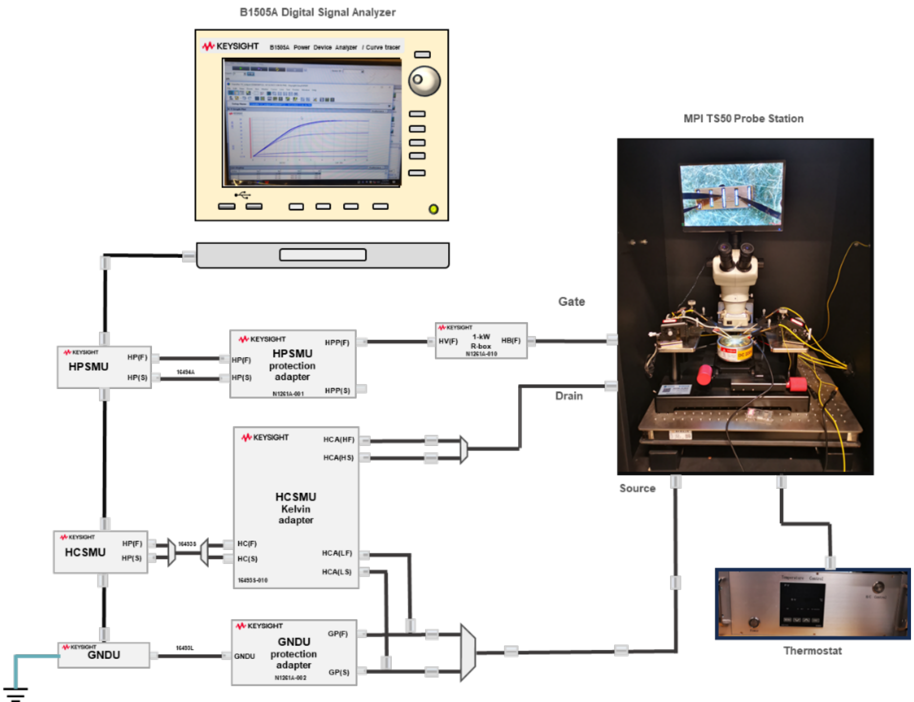

Figure 2: Experimental setup for temperature-dependant GaN HEMT device characterization.

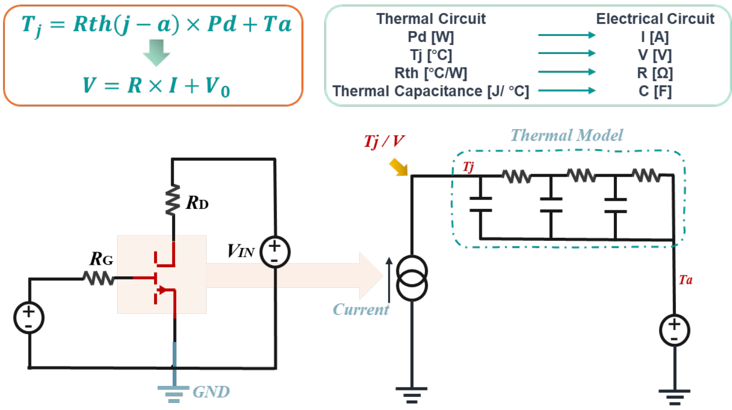

Figure 3: illustration of GaN transistor thermal circuit model.

GaN transistor thermal model represents an electrical circuit's transient thermal resistances, facilitating the analysis of the thermal circuit associated with its electrical counterpart. In this model, thermal resistances are denoted by R, and thermal capacities by C. This model allows for the correlation between thermal and electrical circuits, as depicted in Figure 3, enabling a comprehensive understanding of the thermal behaviour in GaN transistors through electrical circuit analogies.

RESULT AND DISCUSSION

Figure 4 illustrates the temperature-sensitive transfer characteristics of a 200V commercial GaN HEMT. As temperature rises, a notable negative shift in threshold voltage is observed (Panel a), typical for GaN HEMTs due to variations in carrier dynamics. This shift may impact device activation thresholds, affecting operational performance. Concurrently, an escalation in gate leakage current with temperature is evident (Panel b), signalling potential reliability and efficiency concerns in the device's off-state.

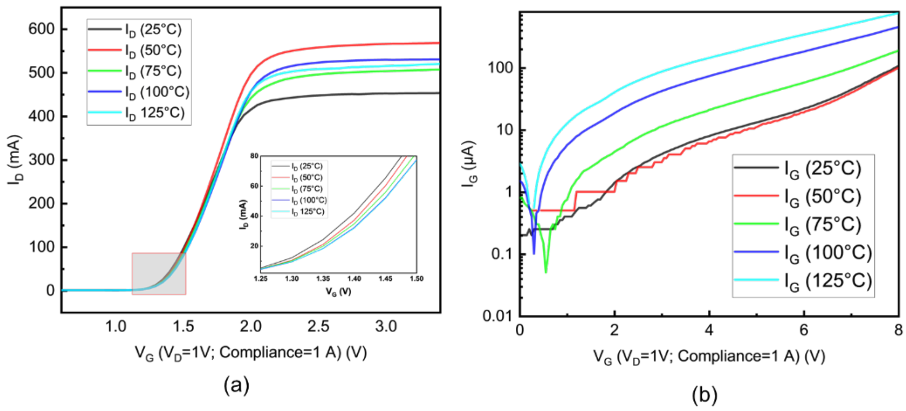

Figure 4: Temperature-dependent transfer characteristics of GaN HEMT. (a) voltage threshold (b) gate leakage current.

The SPICE circuit simulation was conducted to explore the effect of a heatsink on the junction temperature. This comprehensive analysis, highlighted in Figure 5, examines a GaN transistor operating within a power circuit at an input voltage of 100V. The gate signal was maintained at a 100% duty cycle, ensuring that the device continuously remained in the switching-on state. In a no-load condition, the junction temperature reached 149.5°C. Conversely, Figure 6 introduces an aluminium heatsink characterized by a contact area of 100 mm² and a volume of 1000 mm³. The results demonstrated a significant reduction in temperature to 46.1°C, indicating that the heatsink made the junction temperature 3.24 times cooler compared to the initial state without a heatsink.

These discoveries underscore the importance of effective thermal management in GaN HEMTs, as temperature fluctuations markedly influence key performance metrics. Accurate knowledge of these thermal effects is vital for the engineering of dependable and efficient power electronics that integrate GaN technology.

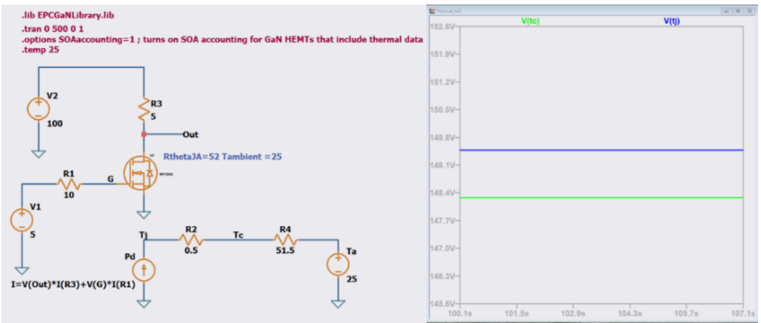

Figure 5: Thermal modelling SPICE simulation of Schottky p-GaN HEMT $R_{theta,JA}$=52, $T_{ambient}$ =25 Celsius, without Heat Sink.

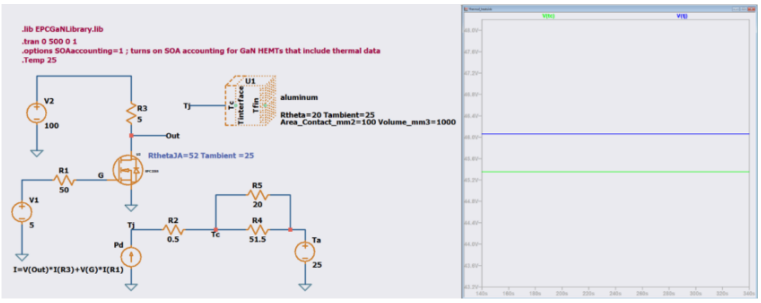

Figure 6: Thermal modelling SPICE simulation of Schottky p-GaN HEMT $R_{theta,JA}$=52, $T_{ambient}$ =25 Celsius, within Heat Sink.

CONCLUSION

This study highlights the significant influence of thermal effects on the performance of GaN HEMTs in power circuit applications. Through a comprehensive experimental setup, it examines the temperature-dependent transfer characteristics, gate leakage currents, and thermal behaviours of Schottky p-GaN HEMTs. The findings, which compare scenarios with and without a heat sink, underscore the critical role of thermal management in optimizing the operational efficiency and reliability of GaN HEMTs in advanced power systems.

ACKNOWLEDGEMENT

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