International Research Journal of Advanced Engineering and Science
ISSN (Online): 2455-9024

# Electrothermal Performance Analysis of Power Transistor

Babatunde S. Emmanuel
Department of Electrical and Electronic Engineering, Lead City University, Ibadan
Email: sbemmanuel@yahoo.com

***Abstract***— *Power transistors are known for dissipating power in response to current conduction. Therefore, heatsinks are often attached to them for better cooling and to avoid thermal overstress. The power system applications in which high power and frequency performance, as well as, high linearity and reliability are to be achieved require efficient management of electrothermal characteristics of power transistors. Hence, the need to understand and quantify the electrothermal characteristics of power transistors has become very imperative. The design of electronic power systems involves proper management of electric heating which is unfortunately an unwanted consequence of current conduction. In this study, the electrothermal characteristic of power transistor is investigated by measuring and analyzing the operating temperature of power transistor due to joule heating. This was done by determining the relationship between electric heating phenomenon in the transistor and the temperature of the copper connection route with respect to distance of the route. The result showed that due to high thermal conductivity of copper, the thermal energy generated in the transistor is quickly conducted away along the copper route, keeping the thermal stress on the transistor within a tolerable range*.

***Keywords***— *Transistor, power, electrothermal, semiconductor, current*.

## I. Introduction

The design of transistors must be such that it meets the requirements of reduction in size and weight, improve reliability, efficient management of thermal overstress, as well as, electric heating (an unwanted outcome of current conduction). Semiconductors have become the material of choice for power switching and amplification devices known as power transistors. Transistors are broadly divided into three types, namely, bipolar junction transistor (BJT), field-effect transistor (FET), and insulated-gate bipolar transistor (IGBT).

Power transistors are known for dissipating power in response to current conduction. For this reason, heatsinks are often attached for better cooling and to avoid thermal overstress. The power system applications in which high power and frequency performance, as well as, high linearity and reliability of systems are to be achieved, require efficient transistor cooling. Thus, understanding and measuring self-heating effect in transistors is becoming increasingly important as devices are becoming smaller and power densities higher [1]. Usage of power transistors and the operating temperature conditions in which they are employed can cause them to degrade over time, and this gradual process may eventually lead to system's catastrophic failure [2].

Internal heating due to the flow of current is a limiting factor in the operation of power transistors. This adversely affects the characteristics of the transistor, when it is excessive and ultimately its damage. Therefore, in the design of power transistors, which are intended to carry large current loads, the internal heating is an important design consideration [3][4][5]. This paper is aimed at the performance study of power transistor and the copper pathways connected to it to with respect to their electrothermal characteristics.

## II. Literature Review

Several studies on power transistor design and performance have been conducted. As observed from literature, the goals of the studies have revolved around performance analysis of the device under electrical overstress, and electrostatic discharge conditions. Others include performance optimization, switching and amplification performance, dynamic and static operation, linearity and nonlinearity characteristics etc.

Kuzmik, et al. [1] proposed a novel electrical method for measurement of the thermal performance of HEMTs. Several unique studies on the self-heating effects in AlGaN/GaN HEMTs were carried out. This method, in combination with transient interferometric mapping (TIM), provided a fundamental understanding of the heat propagation in a transient state of HEMTs. The AlGaN/GaN/Si HEMT thermal resistance was determined to be 70 K/W after 400 ns from the start of a pulse, and the heating time constant was 200 ns. The experimentation was also conducted on multifinger high-power AlGaN/GaN/sapphire HEMTs. The TIM method indicates that the airbridge structure serves as a cooler, removing approximately 10% of the heat energy.

Gutierrez, et al. [2] carried out a study of the effect of thermal cycling on the degradation of the power module. Using high temperature thermocouples, the thermal performance of the power module was monitored. Device imaging and characterization were performed along with temperature data analysis, to assess failure modes and mechanisms within the power modules. The result showed that wire bond degradation was the life limiting failure mechanism.

Yang et al. [6] investigated the characteristics of Tunnel field-effect transistors (TFETs) under power-on electrical overstress and electrostatic discharge conditions by numerical simulation. The impact of an elevated ambient temperature, variations in current rise time and discharge duration, as well as, the device structure on the triggering voltage and failure current are evaluated. The results showed that TFETs exhibited better performance than isolation diodes in whole-chip protection networks

Zhang et al. [7] conducted a simulation study of the electrothermal performance of GaN vertical metal-oxide-semiconductor field-effect transistors (MOSFETs) and lateral AlGaN/GaN high-electron-mobility transistors (HEMTs). In the models, a comparison with the dc characteristics, and the study of the maximum achievable power density of the device was carried out at peak temperature not exceeding 150 °C. The results showed that the vertical MOSFETs have the potential to achieve a higher electrothermal performance than the lateral HEMTs,

Zelnik et al. [8] presented the simulation analysis of the switching performance of a GaN power transistor connected in high voltage configuration. The analysis employed the use of high-accurate simulation models of selected GaN transistors and performance in a wide range of operational conditions of transistors such as drain current and switching frequency were analyzed. Parametric evaluation of switching losses under each operational condition was carried out. The results obtained are applicable for optimization of the electrothermal performance of target power semiconductor converter.

Amarnath et al. [9] presented an electrothermal comparative analysis of vertical power transistors with gallium-oxide such as FinFET and MOSFET under dynamic and static operating conditions. From the results of the study, it was observed that there was an agreement between the threshold-voltage and current gain in the vertical MOSFET structure. Enhanced FinFET design in donor concentration was achieved for normally-off condition. The results of the study indicated that the fabrication of efficient gallium-oxide ($Ga_2O_3$) based power transistor is viable.

Gorecki, et al. [10] investigated the electrothermal characteristics of Insulated gate bipolar transistors (IGBTs) often used in modern power electronic circuits as electronic switches. It was observed that the problem of modelling thermal properties of the IGBT using a non-linear compact thermal model is the influence of internal temperature of this transistor on efficiency of heat dissipation. The validity of the proposed model is verified experimentally for different cooling conditions and different values of ambient temperature.

Lumbreras et al. [11] presented the comparative study of models of different heat dissipation systems suitable for high power density GaN-based power converters. The effectiveness of bottom-side dissipation using thermal vias and top-side dissipation using different thermal interface were analyzed. The results of the study showed the effectiveness of the analysed heat dissipation systems and how top-side cooled converters have the lowest parasitic inductance among the studied power converters. Additionally, it was observed that the design of a cooling system is critical in power converters based on wide-bandgap (WBG) semiconductors.

Gerrer, et al. [12] presented finite element simulations of the design rules for high power amplifier device structures for GaN-on-diamond amplifiers, benchmarked against GaN-on-SiC. At 8 W/mm power density, a 13 $\mu$m gate pitch GaN-on-diamond design compared to a commonly employed 40 $\mu$m gate pitch GaN on-SiC design results in cooler peak channel temperature. The simulations were validated with 1.25 mm wide, 10-finger GaN-on-diamond high electron-mobility transistors (HEMT) devices of 13 and 40 $\mu$m gate pitch, with good electrical performance in pulsed I–V measurements and Raman thermography measurements.

Ismail, et al. [13] proposed a new method for failure prognosis of power electronic converters, specifically, insulated gate bipolar transistor (IGBT) failures. It was noted that when power converters are subjected to a high frequency rate beyond their limits, it often lead to energy systems failures as a result of thermal overstress. The proposed prognosis approach is based on the computation of the time-domain features to extract the degradation behavior of the IGBT device and the performance was reportedly satisfactory.

Chen et al. [14] analyzed the thermal characteristics of silicon carbide (SiC) power MOSFET module with special concerns on high-temperature operating conditions, and with particular focus on SiC MOSFET dies. Cauer-type thermal model of the SiC MOSFET was proposed and extracted based on finite element simulations. The Cauer model-based analysis revealed the temperature-dependence of the thermal property of the module's layers and suitable for high-temperature thermal-profile prediction.

## III. FUNDAMENTALS CONCEPTS

In the modeling of power transistor to study its electrothermal characteristic, thermal resistance of components in the device is crucial. Thermal resistance can be defined as a quantification of resistance changes to heat conduction. In order words, it is the ratio of the temperature difference between two given points to the heat flowing between the points measured in [°C/W]. Put simply, thermal resistance measures the difficulty with which heat flows through a component. The value should be as low as possible for efficient power dissipation [11].

$$R_{th} = \frac{T_1 - T_2}{P} \quad (1)$$

Where:

$R_{th}$ = Thermal resistance

$T_1 - T_2$ = Temperature difference

$P$ = Heat flow or power dissipated

The junction temperature $T_J$ can be calculated by Equation (2).

$$T_j = R_{th-jA} x P_c x T_A \quad (2)$$

Where:

$R_{th\text{-}JA}$ = $Thermal\ resistance\ between\ junction\ and\ ambient\ temperature$ $[°C/W]$

$P_C$ = $Power\ consumption\ of\ device$ $[W]$

$T_A$ = $Ambient\ temperature$ $[°C]$

## IV. METHODOLOGY

The electrothermal simulation study of power transistor described in this paper was performed using COMSOL Multiphysics. The methodological workflow employed is depicted in Figure 1.


Figure 1: Methodological Workflow for Electrothermal Simulation Study of Power Transistor

International Research Journal of Advanced Engineering and Science
ISSN (Online): 2455-9024

The simulation study of electrothermal characteristics of power transistor was carried out to create, analyze, and visualize the Joule heating effect on the behaviour of the semiconductor device. The system parameters defined for the device include the model parameters, material properties and boundary conditions.

As shown in Figure 2, the transistor structure is modeled as an internal surface. The pin connections are assumed to have negligible heat transfer effect. The front and the rear parts of the transistor chip is made of ceramics and copper respectively. Typically, heat sink is clamped to the copper part to regulate electrothermal properties.

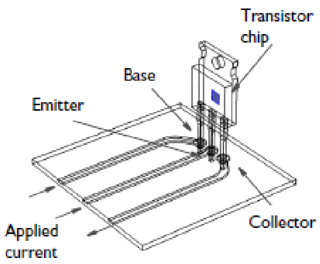


Figure 2: Model geometry of power transistor

The solder material 60Sn-40Pb, that is, 60 % tin and 40 % lead, is used to solder the transistor pins to the circuit board. The fabrication of the circuit board is based on FR4 standard. Flame Resistant 4 (FR4) laminates refer to flame-retardant materials from glass reinforced with epoxy-like resin, commonly used in the fabrication of printed circuit board (PBC) for their resistance to heat, mechanical shock, solvents, and chemicals [15]. The FR 4 based circuit board guarantees the non-propagation of fire when the material burns. The material properties were defined from COMSOL materials library as shown in Tables 1 to 4.

Table 1: Material Properties for Copper

| Material Property | Value |
|---|---|
| Electrical conductivity | 5.998e7[S/m] |
| Heat capacity at constant pressure | 385[J/(kg*K)] |
| Relative permittivity | 1 |
| Density | 8960[kg/m$^3$] |

Table 2: Material Properties for FR4

| Material Property | Value |
|---|---|
| Heat capacity at constant pressure | 1369 [J/(kg*K)] |
| Density | 1900 [kg/m$^3$] |
| Thermal conductivity | 0.3 [W/(m*K)] |

Table 3: Material Properties for Silica Glass

| Material Property | Value |
|---|---|
| Heat capacity at constant pressure | 703 [J/(kg*K)] |
| Density | 2203 [kg/m$^3$] |
| Thermal conductivity | 1.38 [W/(m*K)] |

Table 4: Material Properties for Solder – 60Sn-40Pb

| Material Property | Value |
|---|---|
| Electrical conductivity | 6.67e6 [S/m] |
| Heat capacity at constant pressure | 150 [J/(kg*K)] |
| Density | 9000 [kg/m$^3$] |
| Thermal conductivity | 50 [W/(m*K)] |
| Relative permittivity | 1 |

Due to current flow, electrical heating occurs in the copper pathways, pin connections and soldered points. Therefore, the physics of heat transfer and heat production due to Joule heating are coupled to the current conduction in the in the copper pathways, pin connections and soldered points.

The transistor model is represented by an interior boundary with an internal production of heat corresponding to 0.9 W. Cooling through convection takes place at all external boundaries with a heat transfer coefficient of 5.0 W/(m$^2$·K). This value of the heat transfer coefficient corresponds to the worst possible case scenario where there is no cooling system. The ambient temperature is 293.15 K. The current values at the copper pathways connected to the emitter and the collector are 0.2 A and 0.1998 A respectively. The difference in absolute current between the emitter and collector currents corresponds to the current at the copper route connected to the base, which is 0.2 mA.

## V. Results and Discussions

The temperature distribution in the modeled power transistor produced a peak temperature value of 354 K which is within the operating temperature range of the transistor. Furthermore, there is a relationship between the Joule heating phenomenon in the transistor and the temperature of the copper route with respect to distance of the route. This is as a result of the high thermal conductivity of copper as some of the thermal energy generated in the transistor is quickly conducted away along the copper route. The temperature profile of the copper pathways connected to transistor's base and collector is illustrated in Figure 3.

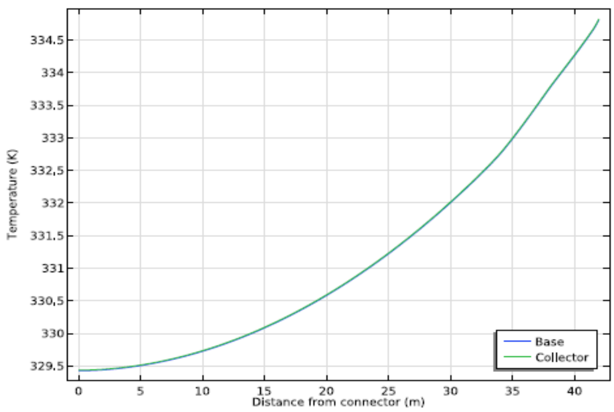


Figure 3: Temperature profiles copper pathways connected to the base and collector.

From the results obtained, it was observed that even though the current density in the collector is 1000 times higher than the current density in the base, the temperature profiles of the two transistor pins are identical. This is as a result of the high conductivity of copper.

## VI. Conclusion

In conclusion, the need to understand and quantify the electrothermal characteristics of power transistors has become increasingly imperative. Considering the requirements for miniaturized power devices and improved power density, the



Babatunde S. Emmanuel, "Electrothermal Performance Analysis of Power Transistor," *International Research Journal of Advanced Engineering and Science*, Volume 7, Issue 4, pp. 223-226, 2022.

employment of power transistors and the environmental conditions in which these devices operate can cause them to degrade over time, and this gradual process may eventually lead to catastrophic system failure. Design of electronic power systems involves proper management of electric heating which is essentially an unwanted consequence of current conduction. In this study, the electrothermal characteristic of power transistor is analyzed. The performance of the semiconductor device was investigated based on the measurement and analysis of its operating temperature due to joule heating. This was done by determining the relationship between electric heating phenomenon in the transistor and the temperature of the copper connection route with respect to distance of the route. The result showed that due to the high thermal conductivity of copper, the thermal energy generated in the transistor is quickly conducted away along the copper route, keeping the thermal stress on the transistor within a tolerable range.

## REFERENCES

[1] J. Kuzmik, S. Bychikhin, E. Pichonat, C. Gaquière, E. Morvan, E. Kohn, and D. Pogany. Self-heating phenomena in high-power III-N transistors and new thermal characterization methods developed within EU project TARGET. International Journal of Microwave and Wireless Technologies. 2009, 1(02), 153. doi:10.1017/s1759078709990444

[2] E. Gutierrez, K. Lin, P. McCluskey, and D. DeVoto. Thermal Assessment and In-Situ Monitoring of Insulated Gate Bipolar Transistors in Power Electronic Modules: Preprint. Golden, CO: National Renewable Energy Laboratory. 2020. NREL/CP-5400-73583 https://www.nrel.gov/docs/fy20osti/73583.pdf

[3] E. R. Heller and A. Crespo. Electro-thermal modeling of multifinger AlGaN/GaN HMET device operation including thermal substrate effects," Microelectron. Rel. 2008. vol. 48, no. 1, pp. 45–50, Jan. 2008.

[4] G. Sozzi and R. Menozzi. A review of the use of electro-thermal simulations for the analysis of heterostructure FETs," Microelectron. Rel. 2007. vol. 47, no. 1, pp. 65–73, Jan. 2007.

[5] J. Zarębski and K. Górecki. The electrothermal large-signal model of power MOS transistors for SPICE, IEEE Transactions on Power Electronics. 2010. Vol. 25 , No. 5-6, pp. 1265 – 1274, 2010.

[6] Z. Yang, P. Mao, Y. Zhang, N. Yu and J. J. Liou. Characteristics of Tunnel Field-effect Transistors under Power-on Electrostatic Discharge and Electrical Overstress Conditions, Sens. Mater. 2020. Vol. 32, No. 5, p. 1889-1897.

[7] Y. Zhang, M. Sun, Z. Liu, D. Piedra, H. S. Lee, F. Gao and T. Palacios. Electrothermal Simulation and Thermal Performance Study of GaN Vertical and Lateral Power Transistors. IEEE Transactions on Electron Devices. 2013. 60(7), 2224–2230. doi:10.1109/ted.2013.2261072

[8] R. Zelnik and M. Pipiska. Simulation analysis of switching performance of GaN power transistors in a high-voltage configuration. 2020 21st International Scientific Conference on Electric Power Engineering (EPE). doi:10.1109/epe51172.2020.9269164

[9] G. Amarnath, D. Krishna and A. Vinod. TCAD-based Comparative Study of Gallium-Oxide based FinFET and MOSFET. 2020 IEEE International Conference on Advent Trends in Multidisciplinary Research and Innovation (ICATMRI). 2020. doi:10.1109/icatmri51801.2020.9398440

[10] K. Gorecki and P. Gorecki. Nonlinear Compact Thermal Model of the IGBT Dedicated to SPICE. IEEE Transactions on Power Electronics, 35(12), 13420–13428. 2020. doi:10.1109/tpel.2020.2995414

[11] D. Lumbreras, M. Vilella, J. Zaragoza, N. Berbel, J. Jordà, A. Collado. Effect of the Heat Dissipation System on Hard-Switching GaN-Based Power Converters for Energy Conversion. Energies. 2021; 14(19):6287. https://doi.org/10.3390/en14196287

[12] T. Gerrer, J. Pomeroy, F. Yang, D. Francis, J. Carroll, B. Loran, M. Kuball. Thermal Design Rules of AlGaN/GaN-Based Microwave Transistors on Diamond. IEEE Transactions on Electron Devices. 2021. 68(4), 1530–1536. doi:10.1109/ted.2021.3061319

[13] A. Ismail, L. Saidi, M. Sayadi and M. Benbouzid. Remaining useful lifetime prediction of thermally aged power insulated gate bipolar transistor based on Gaussian process regression. Transactions of the Institute of Measurement and Control. 2020. 014233122092047. doi:10.1177/0142331220920470

[14] M. Chen, H. Wang, D. Pan, X. Wang and F. Blaabjerg. Thermal Characterization of Silicon Carbide MOSFET Module Suitable for High-Temperature Computationally-Efficient Thermal-Profile Prediction. IEEE Journal of Emerging and Selected Topics in Power Electronics. 2020. 1-12. https://doi.org/10.1109/JESTPE.2020.2984586

[15] J. Goergen and M. Hernandez. Flame retardants in printed circuit board; United States Environmental Protection Agency. Technical Report; August 2015. Accessed from https://www.epa.gov/sites/default/files/2015-08/documents/pcb_ch2.pdf on May 30, 2022



Babatunde S. Emmanuel, "Electrothermal Performance Analysis of Power Transistor," *International Research Journal of Advanced Engineering and Science*, Volume 7, Issue 4, pp. 223-226, 2022.