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Thermal modeling of wide bandgap semiconductor devices for high frequency power converters

S Sharath Sundar Ram [1] and **A Vijayakumari**[2]

[1] Post Graduate Student, [2] Assistant Professor, *Department of Electrical and Electronics Engineering, Amrita School of Engineering, Coimbatore, Amrita Vishwa Vidyapeetham, Amrita University, India.*

Email: mailssr9@gmail.com, a_vijayakumari@cb.amrita.edu (Corresponding Author)

Abstract. The emergence of wide bandgap semiconductors has led to development of new generation semiconductor switches that are highly efficient and scalable. To exploit the advantages of GaNFETs in power converters, in terms of reduction in the size of heat sinks and filters, a thorough understanding of the thermal behavior of the device is essential. This paper aims to establish a thermal model for wideband gap semiconductor GaNFETs commercially available, which will enable power electronic designers to obtain the thermal characteristics of the device more effectively. The model parameters is obtained from the manufacturer's data sheet by adopting an exponential curve fitting technique and the thermal model is validated using PSPICE simulations. The model was developed based on the parametric equivalence that exists between the thermal and electrical components, such that it responds for transient thermal stresses. A suitable power profile has been generated to evaluate the GaNFET model under different power dissipation scenarios. The results were compared with a Silicon MOSFETs to further highlight the advantages of the GaN devices. The proposed modeling approach can be extended for other GaN devices and can provide a platform for the thermal study and heat sink optimization.

1. Introduction

Conventional silicon based devices have dominated the power electronics industry for decades now. The current industry demands for increased efficiency and higher power density have posed a serious challenge for the design of devices based on silicon [1]. The continued search for better materials that can outperform previous materials has led to the discovery of the wide band gap semiconductors [4][5]. Gallium Nitride and Silicon Carbide have emerged as the prime contenders to replace silicon as the chosen material for semiconductor materials in the near future. Wide Band gap semiconductors with typical band-gaps in the range of 2 to 4eV can be used to develop high power, high temperature power electronic devices which can be operated with very high frequencies.

In any power electronic system a significant component of the cost is associated with passives and cooling systems as evident from Figure 1. The future power electronic integration is envisaged for a significant reduction in the cost as well as the required installation space [2].The cost of semiconductors, sensors and control systems are regulated by third party entities. On the other hand, passives and cooling components size and cost are dependent on the system design and hence can be optimised. Various studies have conclusively established that increased switching frequencies lead to reduction in size and cost of the passive components such as inductors and capacitors used in all

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converter designs [2][11]. Further high power applications need large and complex cooling systems that can ensure optimal performance of the switching devices. These particular requirements have paved the way for absorption of wide bandgap semiconductor devices in high frequency high power applications. The latest semiconductor material being offered today is the gallium nitride based Field Effect Transistor or GaNFET[6].

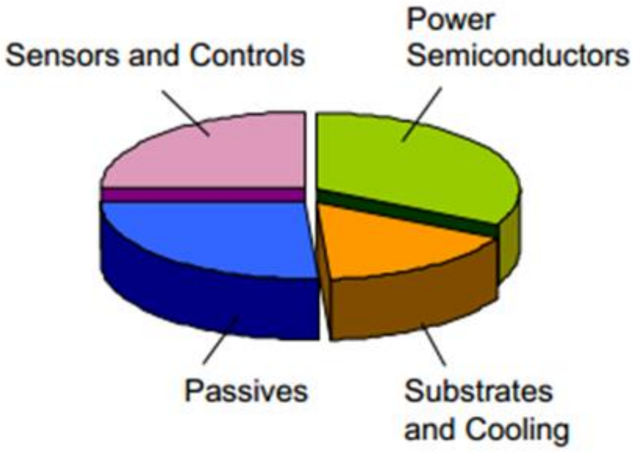

Figure 1: Cost distribution of power electronic converters [2]

With the advent of GaNFETs in the field of power electronics, significant progress can be achieved in terms of efficiency and real estate reduction. Power electronic designs need to optimize the size of heat sinks and filters sizes to accommodate the entire system in the available installation space. The choice of heat sinks has to be evolved from the allowed thermal stress as per the data sheet and the thermal stress expected in the devices during its operation. Thermal modeling of power electronic switches is a standard procedure used during the design stage of the power electronic applications to estimate the thermal stress under typical emulated operating conditions [5]. The results of this modeling procedure can be used to determine the size of the heat sink and other cooling systems that are needed for the particular application. As GaNFETs are relatively new to the market, standard thermal modeling approaches are not explicitly available. The work presented in this paper can be used to rapidly develop a thermal model for commercially available off the shelf GaNFETs.

2. Thermal Modeling

Thermal modeling of devices needs extensive details from the manufacturer like the internal and external dimensions, the material properties and the complete internal structure of the device [4][7]. Such material and device structure information are neither readily available nor made public for designers. Rather the thermal models were made available by the manufacturer themselves in the form of application notes [8]. Development of an accurate model representing heat flow paths are yet another significant task in thermal modeling. The concepts of heat flow paths which when added makes the model highly complex and numerous sub circuits are to be established to completely represent the thermal model of a particular power device.

The thermal modeling approach followed in this paper exploits the R-C network based thermal equivalent model for GaNFET semiconductor devices. To develop an accurate thermal model of any semiconductor device, the thermal impedance data from the manufacturer's data sheet is essential. The thermal impedance available in the data sheet is confined to regular single pulses or fixed duty ratio pulses [11]. But the power electronic design will require a complete thermal model which is expected to represent and respond to rigorous transient conditions commonly occurring during the course of operation of the actual device in any power electronic converter. The thermal impedance for transient operation should be modelled based on the standard thermal impedance data available in the datasheet [11]. The thermal impedance details in the datasheet represent the combined values of the thermal resistance and thermal capacitance at different measurement points in the junction. In order to develop a realistic thermal modeling approach, a commercial GaNFET TPH3206 has been considered in this paper. The graphs in Figure 2 represent the thermal impedance curves for TPH3602 GaNFET. The curves represent the variation of the thermal impedance with respect to time. The thermal impedance curves for different conditions such as single pulse, 25% duty ratio, 10% duty ratio and 50% duty ratio are shown. The curves represent continuous variation of thermal impedance with respect to time.

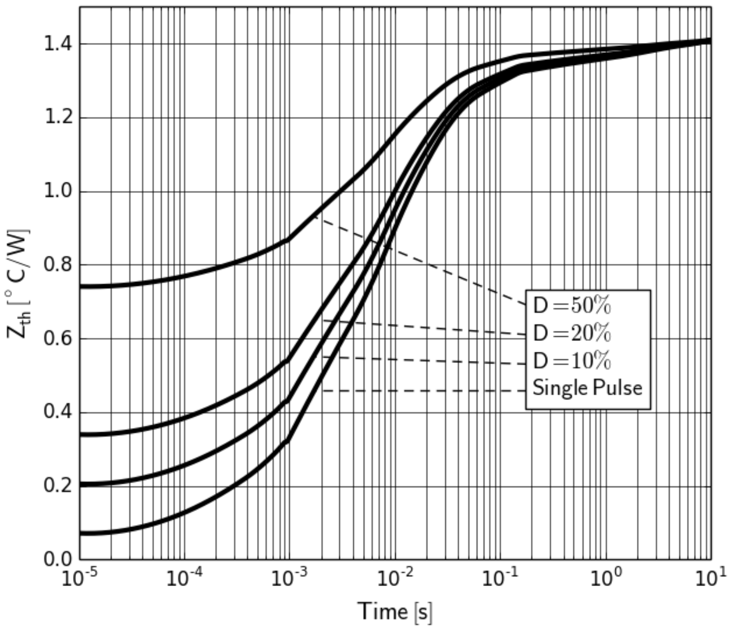

Figure 2: Thermal impedance curves of TPH3602[11]

3.Methodology

Thermal analysis of the GaNFET can be broadly divided into three tasks: (1) Develop the thermal characterization of the GaNFET; (2) Developing the thermal model; and (3) Running a thermal circuit using P-SPICE or an equivalent platform.

Two R-C models are commonly used for thermal modeling of devices namely Foster model and Cauer models. The Cauer model represents the continued fractional model which is a representation of the physical semiconductor structure of the device. This model utilizes individual R-C elements that are assigned to each of the layers within the device. This method of modeling allows determination of temperature at each of the junctions in the device. Figure 3 shows the typical electrical equivalent network for Cauer model.

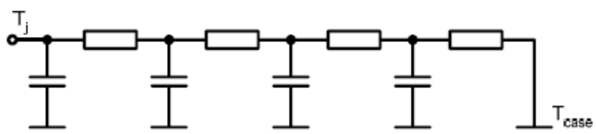

Figure 3: Cauer model electrical equivalent representation

The other model considered is the Foster tank model, also known as the partial fraction model. In this model the R-C parameters are no longer associated with the individual layers inside the actual device. This model is more suitable to obtain the thermal characteristics from the available datasheet provided by the manufacturer. Fig 4 shows typical Foster R-C model network.

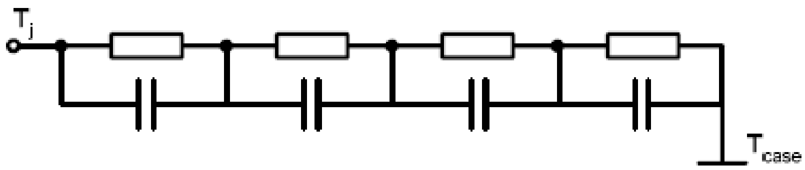

Figure 4: Foster model electrical equivalent representation

From the preceding discussions on Foster and Cauer models, it is evident that the R-C pairs are used to model the behaviour of the GaNFET. The values of these R-C pairs must be such that the thermal impedance response resulting from the Foster model or the Cauer model should match the thermal impedance curves shown in Figure 2. In order to determine the R-C pair values in a Cauer model, the complete details regarding the material properties and the physical dimensions of the device are essential. Typically the substrate material details, the physical structure and dimensions of the device are not provided to the end user. Therefore designing an effective Cauer model cannot be rapidly performed and validated. On the other hand, the Foster model can be developed from the thermal impedance curves, which are provided in datasheets by all major semiconductor device manufacturers. Therefore, the Foster model was selected to develop the thermal model for the GaNFET. Equation 1 shows the mathematical representation of the response of the Foster R-C pairs. The values of the R-C pairs should be such that, the response of the Foster model should match the thermal impedance curve of TPH3202 shown in Figure 2. Equation 2 can be used to determine the thermal capacitance for the four R-C pairs used in the Foster modeling technique

$$RT(t) = R_1(t) * \left(1 - e^{\left(-\frac{t}{\tau_1}\right)}\right) + R_2(t) * \left(1 - e^{\left(-\frac{t}{\tau_2}\right)}\right) + R_3(t) * \left(1 - e^{\left(-\frac{t}{\tau_3}\right)}\right) + R_4(t) * \left(1 - e^{\left(-\frac{t}{\tau_4}\right)}\right) \qquad (1)$$

$$C_x = \frac{\tau_x}{R_x} \qquad (2)$$

To correctly adapt the thermal model for a given GaNFET the thermal impedance data for a single pulse has been used. This is because for a given power dissipation pattern across the junction in the semiconductor , the resultant power dissipation pattern can be expressed as the sum of the effects due to individual pulses applied sequentially. Fifty five data points from the thermal impedance curve for TPH3206 GaNFET shown in Figure 2 were used as the base data to reproduce the thermal impedance curve of TPH3202. The curve fitting tool available with the MATLAB was used to calculate the individual R-C values of the Foster model. The thermal impedance expression in Equation 1 was provided as the base equation to fit the curve developed from the base data obtained earlier from the datasheet .

The upper and lower bounds for the parameters were determined by the values provided in the datasheet. Based on the constraints of the device, the parameters of the R-C model were determined. Figure 5 shows the final curve that has been fit into the existing dataset.

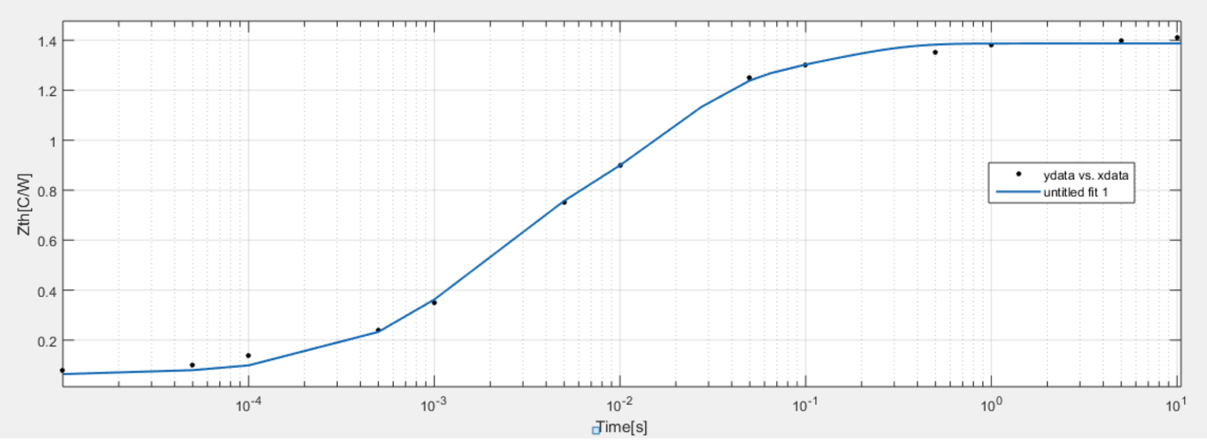

Figure 5: Output of cfTool in MATLAB

Table 1. Final thermal resistance values obtained after curve fitting process

Parameter	Thermal Resistance(C/W)
R1	0.087402
R2	0.01
R3	0.06498
R4	0.632

Table 2. Final thermal capacitance values obtained after curve fitting process

Parameter	Thermal Capacitance(Joules/C)
C1	0.087402
C2	0.01
C3	2
C4	27.9

Values in Table1 and Table 2 represent the thermal resistance and thermal capacitance values obtained from curve fitting techniques performed in MATLAB. These values were provided as the input for the circuit that was developed to simulate the thermal behaviour [9]. Figure 6 shows the circuit that was used to simulate the thermal characteristics in P-SPICE. The current source I1 represents the power being dissipated at the junction of the device. The DC voltage source has been set to a value of 25V. This corresponds to the ambient temperature, as thermal equivalent of voltage is temperature. The ambient temperate is assumed to be 25 degrees Celsius, as all measurements are typically carried out at this temperature. The power dissipation profile for the simulation has been created manually by varying the power in the form of pulses for set duration of times. As the initial expression for the thermal model has been developed for a single curve, the same expression can be used to determine the temperature of the junction for various power dissipation patterns as the pulses are essentially single pulse trains. The junction temperature was measured across the C1 capacitor. The maximum value of applied power dissipation is 560W for a duration of 7.5ms and the corresponding temperature is 192 degrees Celcius.

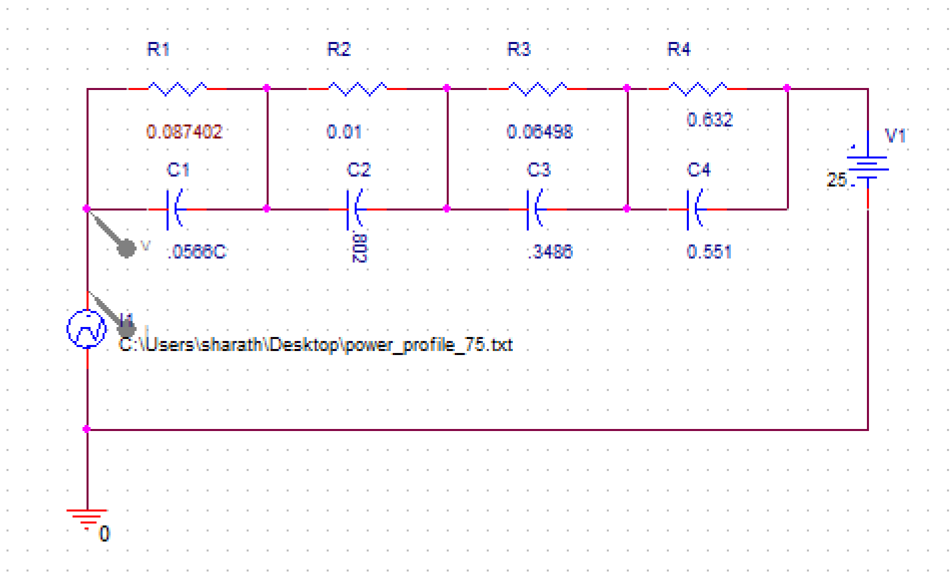

Figure 6: Thermal equivalent simulation in P-SPICE[8]

4. Results

The graphs of estimated junction temperatures and the applied power profiles are shown in Figure 7.

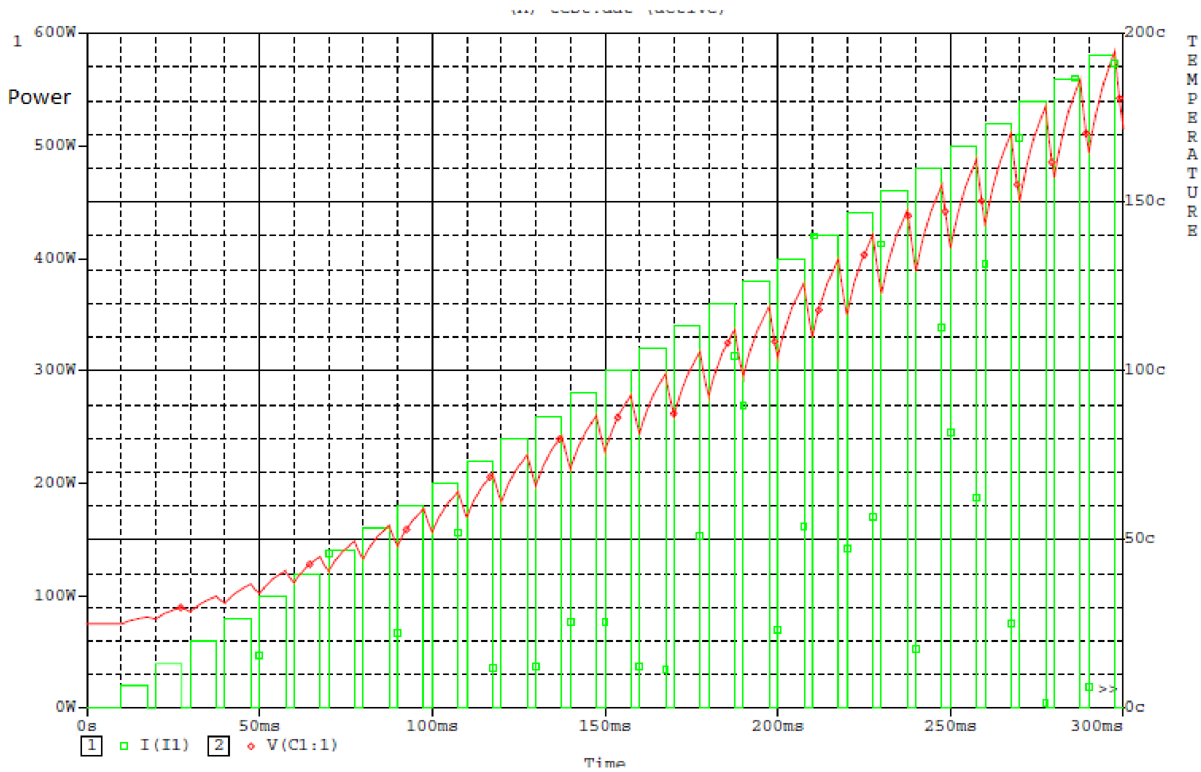

Figure 7: Temperature vs Power dissipation plot for increasing power pulse profile at 75% duty ratio

Therefore based on the graphs shown, this modeling approach can be used for commercially available GaNFETs to determine the temperature characteristics. Further this approach can be used to determine temperature characteristics for different operating conditions of the device. By changing the values of the DC voltage source, the variation of ambient temperature can also be simulated.

The temperature model of the GaNFET is governed by the fourth order R-C tank circuit. It is essential to note that the graph in Figure 7 does not represent the actual variation of power dissipation at the device junction. Equation 1 determines the actual power dissipation across the junction. The temperature characteristics of the FET are displayed for specific power dissipation patterns. A similar plot for MOSFETs of the same rating is shown in the Figure 7. The maximum junction temperature of the device is rated at 150 degrees. From the plot for the GaNFET and the MOSFETs it can be seen that for a given power dissipation rating, the temperature of the GaNFET is significantly lower than the MOSFETs. This has major implication on the sizing of the heat sinks to be used in the power converters. The reduced temperature of the GaNFET implies smaller heat sink dimensions. This has direct reduction of cost and size of the converter. Further, the GaNFETs can operate at switching frequencies exceeding 2MHz while the conventional MOSFETs are restricted to operate at 20kHz. Switching in excess of 1MHz leads to drastic reduction of passive components, as the harmonic filters needed for the power converter are smaller.

5. Conclusion

The thermal model for the GaNFET was developed using the Foster model. The parameters for the Foster model were developed using curve fitting techniques. The final model was successfully implemented in P-SPICE and the temperature characteristics of the device were plotted. The model developed can be used as a tool to determine the cooling requirements of the power converter at the initial design stages itself. To put matters into perspective, thermal characteristics of a conventional MOSFET were also established and compared with the characteristics obtained for the GaNFET.

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