WHITE PAPER

Transient thermal modeling of gallium nitride devices

Introduction

Gallium nitride offers spectacular performance advantages over silicon when applied to power switching – high voltage breakdown, low on-resistance and unprecedentedly high current densities. GaN Systems in particular has developed a range of devices that fully exploit these attributes. In implementing these devices very considerable thermal and packaging challenges had to be overcome, and innovative solutions devised. This paper describes techniques developed in conjunction with ElectroFlo software for the modeling of thermal transients.

The transient thermal characteristics of a semiconductor device are very important in the prediction of device thermal behavior in different conditions such as switching applications. Knowing the thermal impact of pulse duration for different duty cycles helps to apply the device more efficiently. That is why transient thermal impedance curves appear in many MOSFET data sheets, application notes, and in the literature (see references).

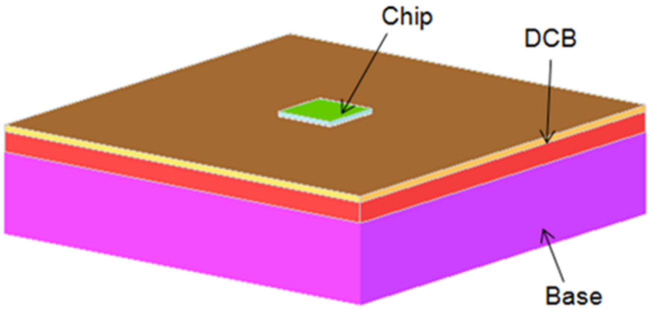
Transient heat transfer is a very complicated process and it is not always easy to obtain results experimentally. Due to the extremely fast response times it is difficult to capture the transient reaction, while the very small device size makes temperature measurement difficult without affecting the behavior. For these reasons thermal simulations assume great importance. The purpose of this paper is to show how this can be done using the thermal analysis software, ElectroFlo.

Thermal Simulation Setup

Geometry

Figure 1 illustrates the model used for the thermal simulation. A 2x2 mm chip, consisting of two layers: gallium nitride (GaN) and silicon carbide (SiC), is attached to a direct copper bond (DCB) substrate. The DCB was modeled as a 0.2mm Cu layer and a 0.635mm aluminum nitride (AlN) layer. Copper tungsten alloy, 13.7x13.7x2.54 mm, was chosen as a base plate.

Figure 1
Thermal model setup



Boundary condition

The GaN layer of the chip was the heat source, with temperature T, and with a power dissipation P = 30 W evenly distributed across the layer. The back surface of the base was kept at a constant temperature of 25°C, which allows the temperature rise in the chip to be easily determined.

Solution

Simulation was done using ElectroFlo, an electronics cooling package from TES International. Radiation and convection were not taken into consideration as their impact is minimal. Conduction was the primary mechanism for taking away heat from the chip. Three types of modeling were conducted:

- Steady state
- Simple transient – the system response for one step change in power dissipation
- Different duty cycles

An adequate mesh was used in order that the thermal variation from the chip to the base could be observed.

Steady state heat transfer

The result for a steady state is shown in Figure 2. The maximum temperature T_{max} = 73.97°C, and thermal resistance was calculated by dividing the maximum temperature difference by the heat dissipation: $R_{j\text{-}a}$ = (73.97-25.0 °C))/(30.0 Watts) = 1.63 °C/W.

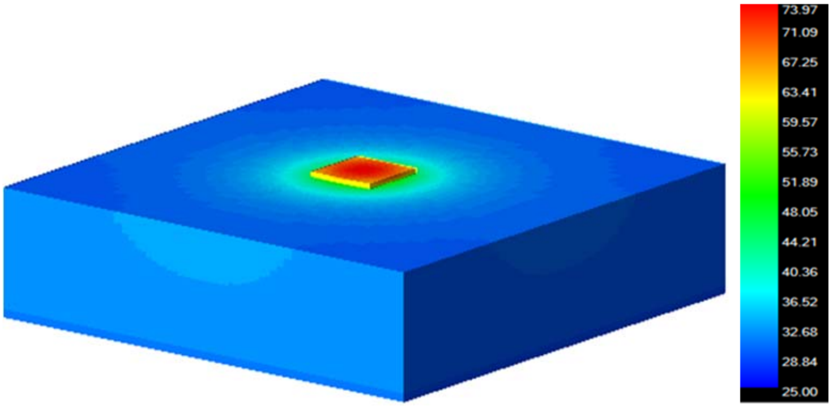


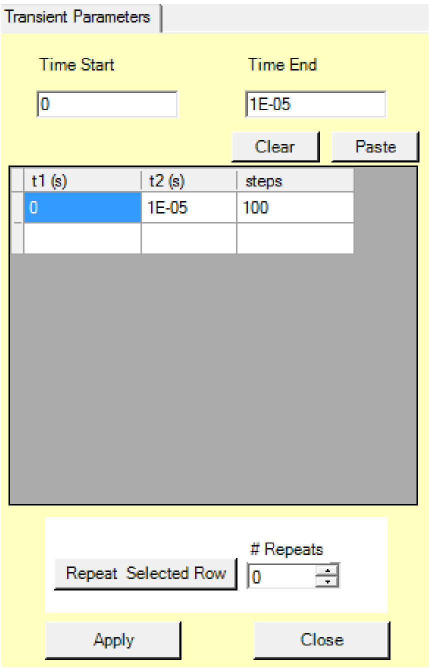
Figure 2
Steady state heat transfer

Single pulse transient response

The single pulse transient thermal response curve was obtained using five simulation runs of different duration (see Table 1). The number of iterations (steps) taken for each simulation was always 100.

Table 1
Transient Parameters for Simple Transient Thermal Modeling

t1(s)	t2(s)	steps
0	1e-4	100
0	1e-3	100
0	1e-2	100
0	1e-1	100



Time Start: 0

Time End: 1E-05

t1 (s)	t2 (s)	steps
0	1E-05	100

Repeats: 0

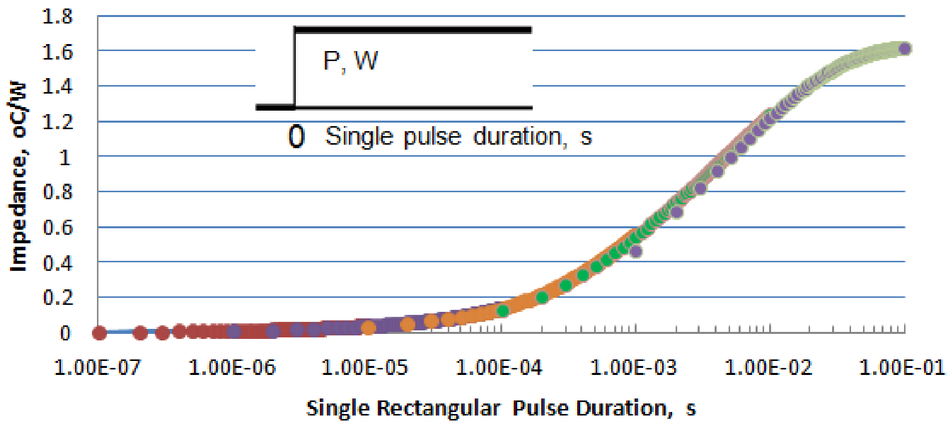


Figure 3
Single pulse transient thermal response curve

Figure 3 shows good correlation between different runs. The result of the single pulse power input versus heating time is shown in Figure 4. It took 100 ms for the system to reach steady state. It can be seen that at 100 ms, the thermal distribution is as would be expected, as the heat has spread not only vertically to the fixed temperature, but also horizontally.

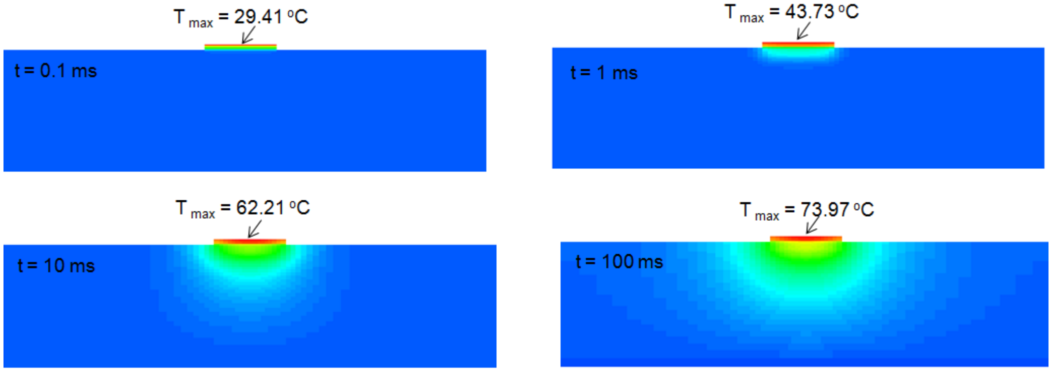


Figure 4
Temperature change during the single pulse power input

Thermal duty cycle

When modeling the thermal duty cycle the following parameters should be considered:

- Pulse duration or pulse width (The length of time the power is "on”)
- Pulse shape (Square, saw tooth, etc.)
- Duty cycle period (Total time for one complete cycle, power both "on" and "off")

- Total analysis time (How long should the simulation run?)
- A typical cycle is shown in Figure 5

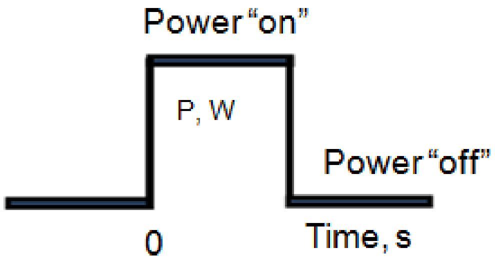
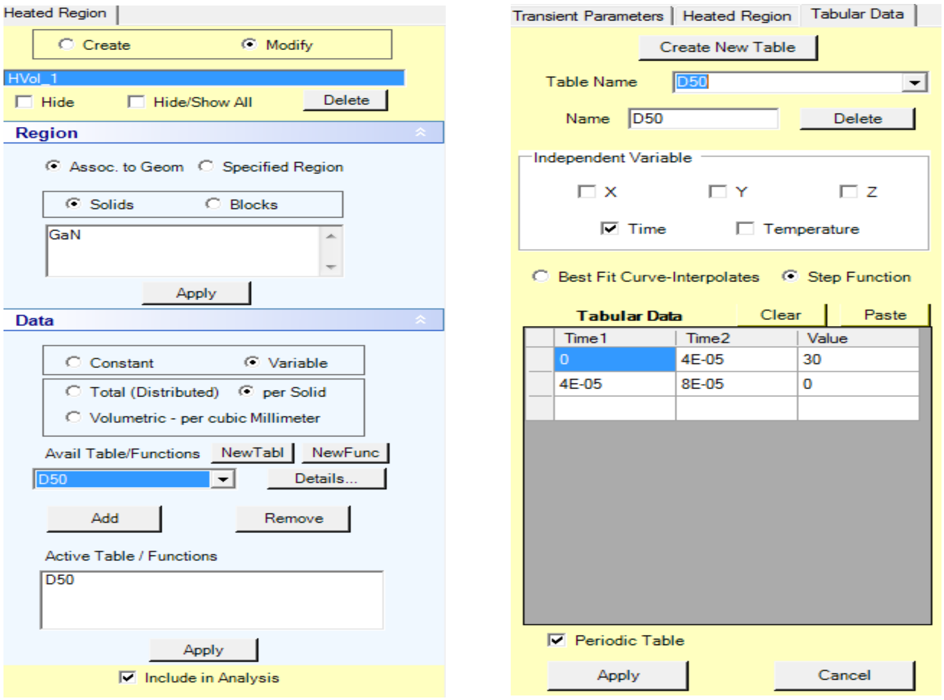


Figure 5
One square pulse cycle

A time step function and the periodic table from the ElectroFlo menu, "Boundary Condition, Heated Volume" were used to create the duty cycle and the pulse width. In this analysis only a square pulse was used, but it is possible to create any shape of pulse.

Table 2 shows how the pulse duration of 0.04 ms and 50% duty cycle, (power should be "On" from 0 to 0.04 ms and "Off" from 0.04 ms to 0.08 ms,) was created. To ensure that this pulse was repeated, a periodic table was used, allowing the table to be repeated for the duration of the analysis.



○ Create ● Modify
HVol_1
☐ Hide ☐ Hide/Show All
● Assoc. to Geom ○ Specified Region
● Solids ○ Blocks
GaN
○ Constant ● Variable
○ Total (Distributed) ● per Solid
○ Volumetric - per cubic Millimeter
Avail Table/Functions: D50
Active Table / Functions: D50
☑ Include in Analysis

Table Name: D50
Name: D50
Independent Variable
☐ X ☐ Y ☐ Z
☑ Time ☐ Temperature
○ Best Fit Curve-Interpolates ● Step Function

Time1	Time2	Value
0	4E-05	30
4E-05	8E-05	0

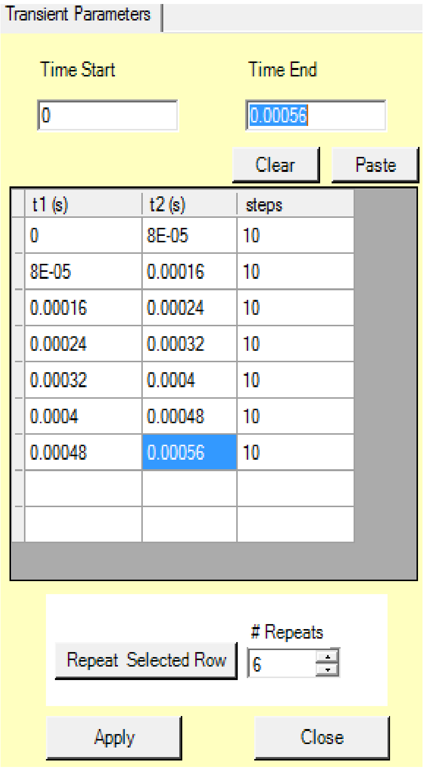
☑ Periodic Table

Table 2
Boundary condition-Heated volume

There are two different ways to set up the transient parameters for one cycle:

1. Break the time of one full cycle (power "on" and "off") into a number of subintervals and repeat this cycle as many times as necessary to get the actual temperature rise :

   $\Delta T = T_{max} - T_a$, (Table 3a).
2. Divide the cycle into two parts: power "On" and power "Off" (Table 3b). This allows a different number of steps for the heating and cooling parts of the cycle to be chosen. This is very important when modeling low duty cycles. This table can be created in Excel and then pasted into ElectroFlo.

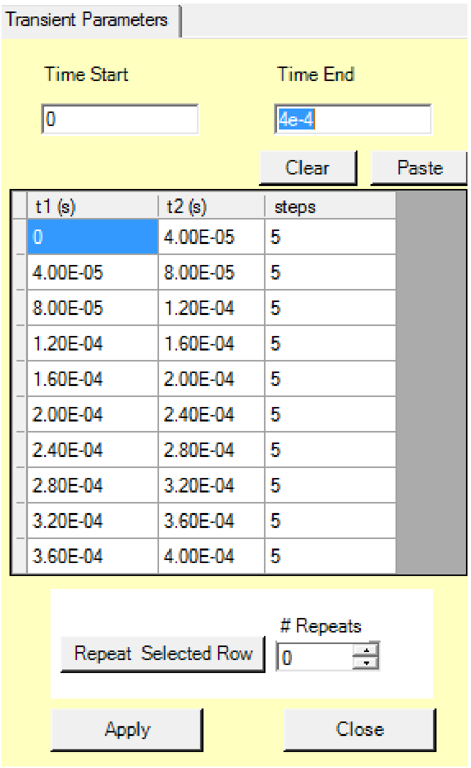


Time Start: 0

Time End: 0.00056

t1 (s)	t2 (s)	steps
0	8E-05	10
8E-05	0.00016	10
0.00016	0.00024	10
0.00024	0.00032	10
0.00032	0.0004	10
0.0004	0.00048	10
0.00048	0.00056	10

Repeats: 6



Time Start: 0

Time End: 4e-4

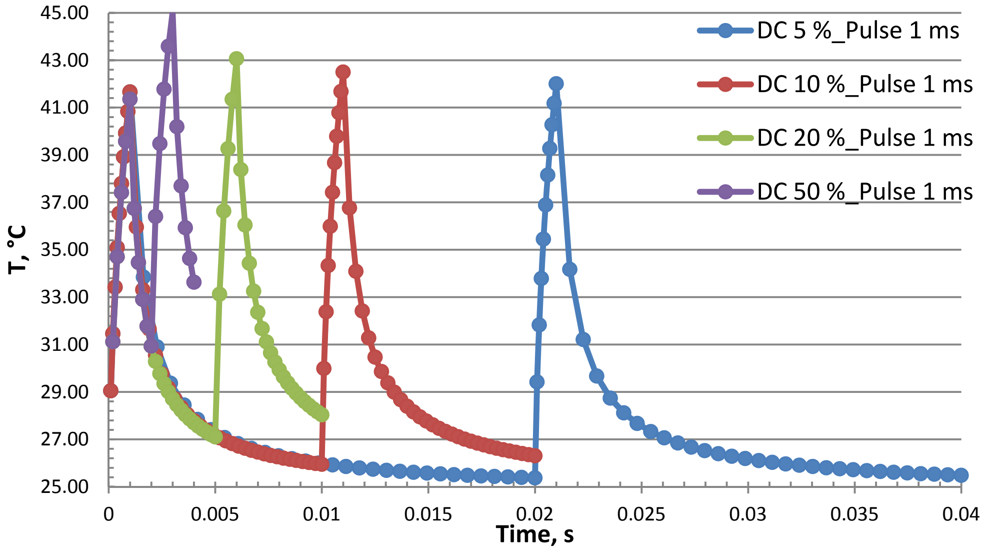
t1 (s)	t2 (s)	steps
0	4.00E-05	5
4.00E-05	8.00E-05	5
8.00E-05	1.20E-04	5
1.20E-04	1.60E-04	5
1.60E-04	2.00E-04	5
2.00E-04	2.40E-04	5
2.40E-04	2.80E-04	5
2.80E-04	3.20E-04	5
3.20E-04	3.60E-04	5
3.60E-04	4.00E-04	5

Repeats: 0

Table 3a &
Table 3b
Transient parameters for
50 % DC and 0.04 ms
pulse duration

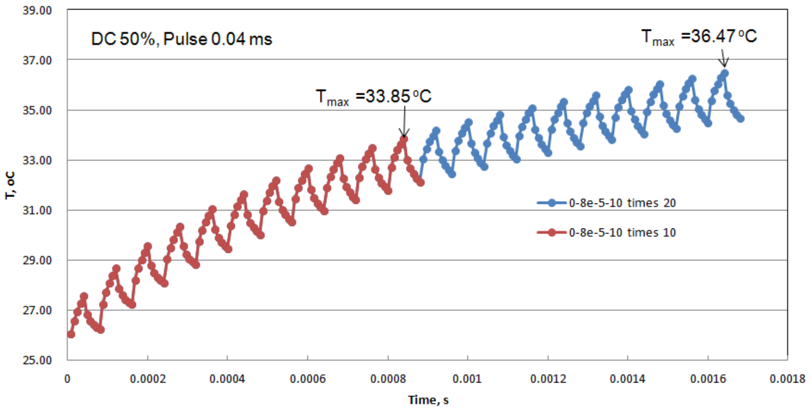
Ten steps were chosen for the pulse duration of 0.04 ms and 50% duty cycle (full cycle = 0.08ms). In this case the subinterval was 0.008 ms and there were five steps when power was "On" and five steps when power was "Off" (Table 3a). The same cycle is shown in Table 3b, but created differently. Both tables provide the same result, but Table 3b gives more flexibility and accuracy, as any number of steps can be chosen. As mentioned above, when creating a different pulse width for low duty cycle it is better to use Table 3b and chose at least five steps to describe the cycle. While modeling a 2% and 5% duty cycle, ten and thirty steps were used; for a 10% duty cycle ten and twenty steps as seen in Figure 6. At times when there is a dramatic increase in temperature it is better to have a smaller time step. This becomes more important for a lower duty cycle.

Figure 6
Pulse width modeling for different duty cycles



Another very important transient parameter is total analysis time. Figure 7a and Figure 7b show the temperature rise during a 50% duty cycle and 0.04 ms pulse width, but for a different total analysis time. If the total analysis time were 0.88 ms (11 cycles) the temperature rise would be $\Delta T = T_{max} - T_a = 8.85°$ C, whereas for 1.68 ms (21 cycles) $\Delta T = 11.47$ °C (Figure 7a).

Figure 7a
Temperature rise during 50 % duty cycle and 0.04 ms pulse width for different total analysis time



The temperature rise depends on the total analysis time. The optimal total analysis time should be chosen to get the right value of the temperature rise in order to calculate the thermal impedance. Though there is no issue with increasing the time, it means that each analysis takes longer to solve.

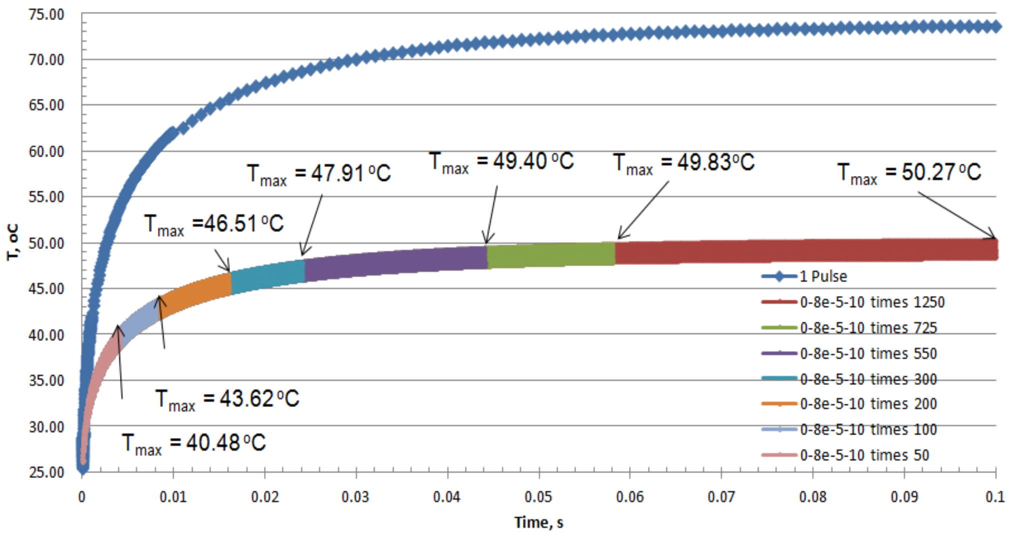


Figure 7b
Temperature rise during 50 % DC and 0.04 ms pulse width for different total analysis time

As can be seen from Figure 7b, between 60 ms and 100 ms the maximum temperature shows only a 0.9% difference, but due to the very small iterative time steps used during the simulation the extra 40 ms is time consuming. However the results are of questionable accuracy with a total time analysis of less than 60 ms, with a possible discrepancy of 30%, so the additional time is necessary, and 100 ms was chosen as the “steady state” point.

To produce the transient impedance curves, shown in Figure 8, thermal simulations were conducted for pulse durations of 0.01, 0.04, 0.1, 0.4, 1.0, 4.0 ms and 2%, 5%, 10%, 20%, 50% duty cycle. As a result of these simulations, the maximum temperature was obtained and used to calculate the transient thermal impedance:

$$Z_{\theta j-a} = {}^{(T_{MAX} - T_a)}\!/_{P}.$$

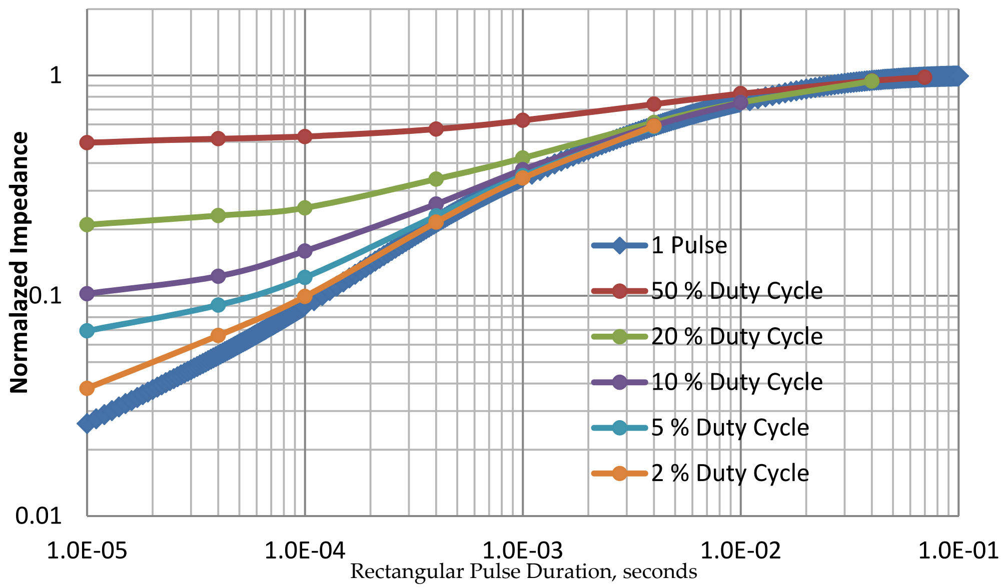


Figure 8
Transient thermal impedance curves for different pulse duration and duty cycle

Conclusion

1. GaN Systems was able to successfully use ElectroFlo thermal software from TES International to perform thermal transient and thermal duty cycle simulations.
2. Normalized thermal transient impedance curves for different duty cycles and pulse width were generated.
3. The results show ElectroFlo's good capability in performing steady state, transient and duty cycle thermal simulations.

References

1. Application Note AN-949, *"Current Rating of Power Semiconductors, International Rectifier"*, www.irf.com

2. Roger Paul Stout, *"How to Generate Square Wave, Constant Duty Cycle, Transient Response Curves"*, AND8219/D, Semiconductor Component Industries, LLC, 2006, *http://onsemi.com*

3. A. Lidow, J. Strydom, M.de Rooij, Y. Ma, *"GaN Transistors for Efficient Power Conversion"*, Power Conversion Publications, El Segundo MMXII, 2012

4. R. Tiziani, Application Note AN257/0189, *"Thermal Characteristics of the Multiwatt Package"*, SGS-Thomson Microelectronics

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