Dynamic Models for Predicting the Thermal Behavior of Vertical MOSFET Transistors under Pulsed Conditions

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***Abstract* — This paper describes a method for calculating the thermal resistance of a vertical MOSFET power amplifier. The method for measuring the thermal resistance under a given set of input conditions is given. From this data a thermal transient model with the thermal resistance and capacitance parameters is created. This model can be utilized to determine the thermal resistance of any input signal condition. This model compares well to a physical based, finite element model that is used to investigate physical changes to the device structure.**

***Index Terms* — power transistors, power amplifiers.**

I. Introduction

Traditional methods of measuring thermal resistance for high power semiconductor devices involve expensive equipment such as IR scan equipment. In a traditional MOSFET device the package lid is removed and the IR camera measures the temperature at the top of the die where the junction is located and the heat is generated. In vertical MOSFET technologies like the HVVFET™ the wafer is mounted in a flip-chip package. The source terminal and the junction reside on the bottom of the die close to the heatsink for optimal thermal performance. The thermal image at the top of the vertical die only captures the average temperature of the junction after propagating through the thickness of the wafer and will not measure the hot spots that predict device failure in semiconductor devices. A method of determining the transient and steady-state thermal behavior of power amplifiers constructed with vertical technology is presented below.

II. Determining Thermal Resistance

A simple procedure has been used to determine the thermal resistance of an active device. The strong relationship between voltage, current and temperature of a diode is used to model heating effects within the device [1]. The initial voltage across the diode is measured at ambient temperature as the reference value. A known amount of power is dissipated within the device which will cause a rise in junction temperature of the device. The heating power is removed and the measuring current is again applied to the body diode and the forward voltage is re-measured. The difference in voltage between the measurements can be converted to a rise in temperature if the k-factor of the diode is known [2]. Therefore the first step in determining the thermal resistance is to characterize the drain-source body diode voltage change over temperature.

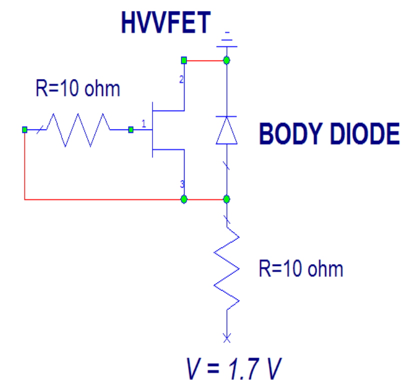

Fig. 1. Test circuit schematic used to characterize the drain-source body diode inherent to HVVFET technology. A constant current was forced through the diode as the forward voltage drop across the diode was monitored.

The drain-source body diode intrinsic to many MOSFET devices is shown in Figure 1. The strong relationship between voltage, current and temperature of a diode is used to model heating effects within the device [3]. A packaged HVVFET device is mounted on a 1" thick block of copper and placed in a controlled temperature environment. A resistance temperature detector (RTD) is attached to the copper block in close proximity to the package of the device to measure the case temperature. The drain terminal of the HVVFET device is the cathode of the diode and is held to zero volts. The gate voltage potential should be equal or less than the source terminal potential in order to prevent the device from turning on during the testing cycle.

A power supply wired as a constant current source is connected to the diode. A constant current is forced through the body diode at various temperatures as the forward voltage drop across the diode is recorded. It is necessary to force a large enough current through the diode to ensure a stable measurement. It is also important to not force too high a current which will lead to self heating and artificially inflate the results. The measuring current through the diode for the thermal resistance data was chosen such that both conditions were met. Figure 2 shows the body diode characterization of a vertical power device at two different forcing currents 50mA and 100mA. A linear fit is performed on the data which shows 1.8mV/°C slope in both cases.

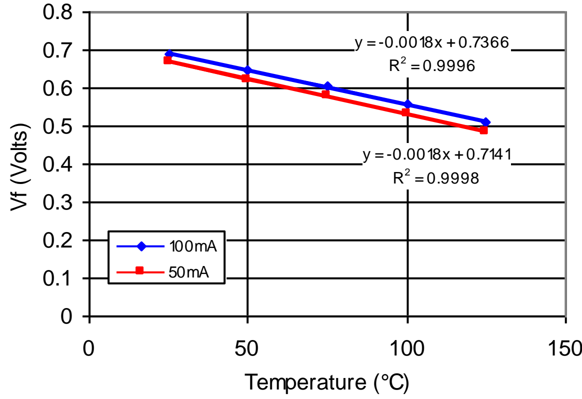

Fig. 2. Relationship between the forward voltage drop across the body diode and temperature. A linear best fit interpolation shows the value of the k-factor is 1.8mV/°C for both values of current.

A vertical device with a rated output power of 300W was tested with a TESEC model 9424-KT ΔVF tester. An amount of power is dissipated in the device to cause heating. A dissipated power of 250W was applied with a 25V supply and 10A of current. This amount of heating mimics the actual device in operation as the device is more than 50% efficient. After the heating power is removed a measuring current is forced through the body diode. The forward voltage is measured after the heating is stopped. This voltage data is recorded at a series of points of time and is shown below in Figure 3.

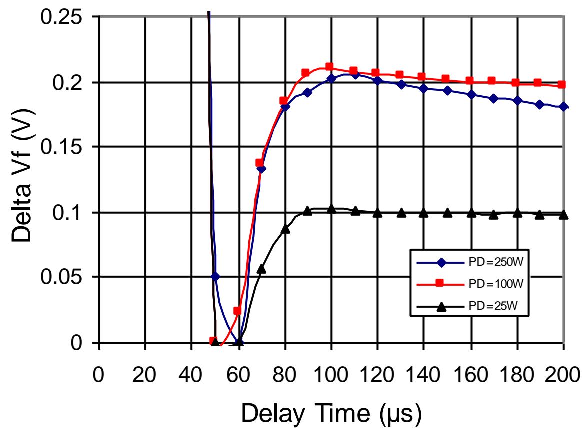

Fig. 3. Measured forward voltage drop across the body diode at various time delays. Stable measurements are achieved after 100µs.

The transistor immediately begins to cool after the heating power is removed. Measuring the voltage across the diode captures the cooling curve of the device. The values of voltage should decrease monotonically over time as the devices cools. Figure 3 shows that for different amounts of dissipated power used to heat the device the measurements do not stabilize until after a 100µs delay. As an added safety measure the values of voltage were all measured with a 120µs delay to ensure a stable measurement.

II. Transient RC Network Thermal Model

Figure 4 shows the theoretical transient thermal model consisting of a number of rungs of a RC ladder network. The accuracy of the model is increased with the number of RC rungs in the ladder network. The number of RC rungs required for the model is dependent on how well the model fits the measured data. In this case the thermal behavior of the device junction to the case can be modeled with as little as four stages of the RC network to a high degree of precision.

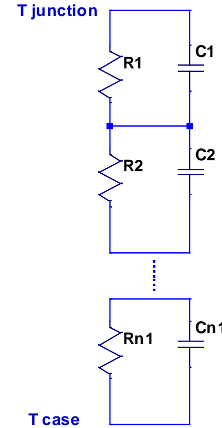

Fig. 4. Schematic of a multi-stage RC network .

The thermal data was collected using the method described above. The values of the resistors and capacitors for the model were calculated using the solver function in Excel. The least-squared error between the measured data and the RC network model was minimized to 1E-6. It can be seen in Figure 5 that the modeled data with the delay very closely matches the data collected during measurement.

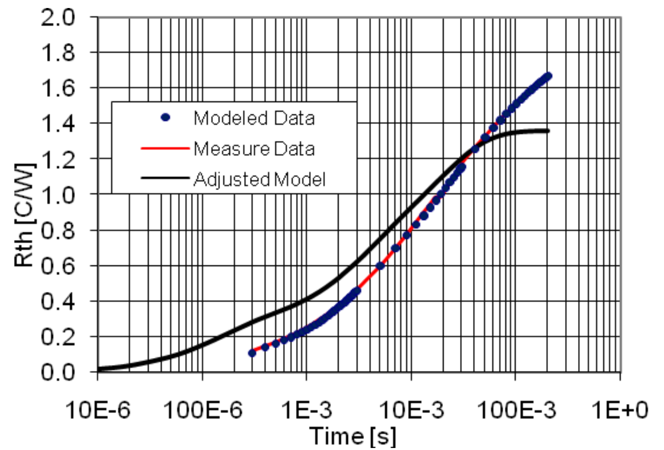

Fig. 5. Thermal resistance versus time. The measured data matches the RC network model very accurately. The RC network model is mathematically adjusted to remove the 120µs delay which describes the temperature at the device junction immediately after the heating source is removed.

The model is mathematically adjusted by removing the 120µs measurement delay which gives the accurate junction temperature immediately following the removal of the heat source. The transient elements of the model are removed after several thermal time constants which occurs after 100ms and the steady-state value of the thermal resistance of 1.36°C/W is reached.

The value of the RC network model is the predictive ability for the thermal resistance at values of time that were not directly measured. The use of the model enables the determination of thermal resistance at points in time that were not obtainable with measured data, such as at 1µs as shown in Figure 5. It is therefore possible to understand the thermal behavior at any time during the operation of the device under the given set of input conditions.

Now the values of the RC network can be implemented in spice simulation software at any given case temperature and power dissipation [4]. Figure 6 is an electrical representation of the device thermal model. The values used in the model are shown in Table 1. The current source sets both the amount of power and the time that the power is dissipated in the device. The voltage source sets the device case temperature.

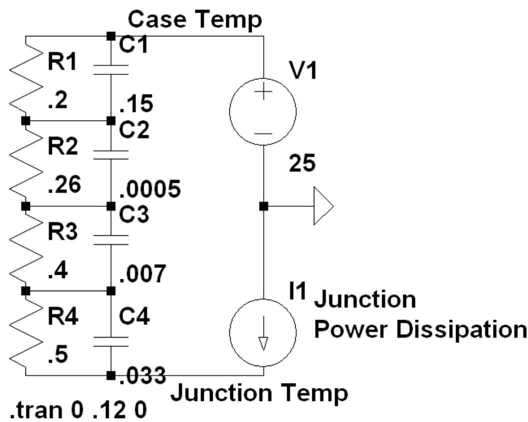

Fig. 6. Four Rung Ladder Network Device Spice Model

The spice model is used to calculate the thermal resistance of the active device under any input signal conditions [5]. The case temperature is typically set to the ambient temperature of

TABLE I
VALUES OF RC LADDER MODEL

Model Parameter	Value	Unit
R1	0.2	ohm
C1	150	mF
R2	0.26	ohm
C2	0.50	mF
R3	0.40	ohm
C3	7.0	mF
R4	0.50	ohm
C4	33.0	mF

25°C. Under pulsed input signal conditions the amount of power dissipated in the device is different within the pulse width and over the entire period of the pulse. Therefore the thermal resistance is dependent on the input pulse values.

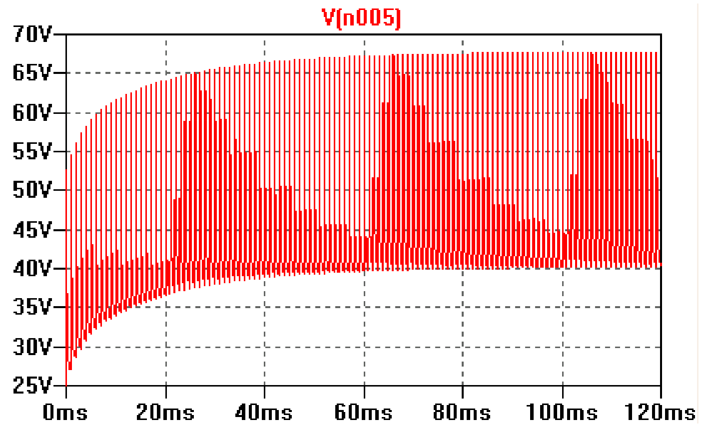

Fig. 7. Voltage (temperature) versus time for pulsed conditions: pulse width = 50µs and duty cycle = 5%.

The waveform shown in Figure 7 depicts the junction temperature of the device as a function of time for a given test condition. The input pulse waveform in this case has a pulse width of 50µs and a pulse period of 1ms which has an overall duty cycle of 5%. The vertical axis represents the junction temperature in degrees C. The thermal resistance of the device is computed by dividing the temperature rise by the known dissipated power. The rise in the junction temperature is calculated as the difference between the maximum and the initial temperatures. For this example, the case temperature is set to 25°C and from Figure 7 the maximum temperature is 68°C. The amount of dissipated power is set to 300W in the model. Therefore, Rth is (68-25) °C/300W or 0.14C/W for the 50us test condition. A summary of thermal resistance values for various test conditions is shown in Table 2.

The average power in a given pulse period increases as the pulse width or duty cycle increases. The thermal resistance increases in both of these cases. It can be seen that the thermal resistance will approach the value of 1.36°C/W as the pulse conditions continue to increase towards a 100% duty cycle.

TABLE II
VALUES OF RC LADDER MODEL

Dissipated Power	Signal Conditions		Thermal Resistance (°C/W)
	Pulse Width (µsec)	Duty Cycle (%)	
300W	10	1	0.03
300W	50	5	0.14
300W	200	10	0.33
300W	2000	1	0.53

This value can also be calculated by adding only the R values of the RC network (R1+R2+R3+R4 = 1.36).

III. PHYSICAL BASED TRANSIENT THERMAL MODEL

In addition to the RC network model, thermal performance can be evaluated using Finite Element Analysis (FEA). Figure 8 shows an example of a model which is used to determine transient and steady state thermal resistance. This physically based model includes all geometry – die, die attach, flange, etc – relevant to correctly simulating heat flow within the structure.

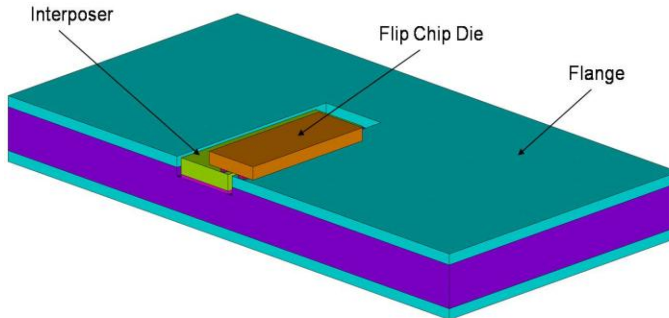

Fig. 8. Diagram of half symmetry finite element model which includes all physical geometry for accurately predicting thermal behavior.

Similar to the RC model, the finite element model is validated by comparison to delta Vf data measured using TESEC as described previously. Excellent correlation between FEA and measured data has been obtained. Additionally, whatever method is used to model the actual system, the models should demonstrate similar results to any given input. Figure 9 shows

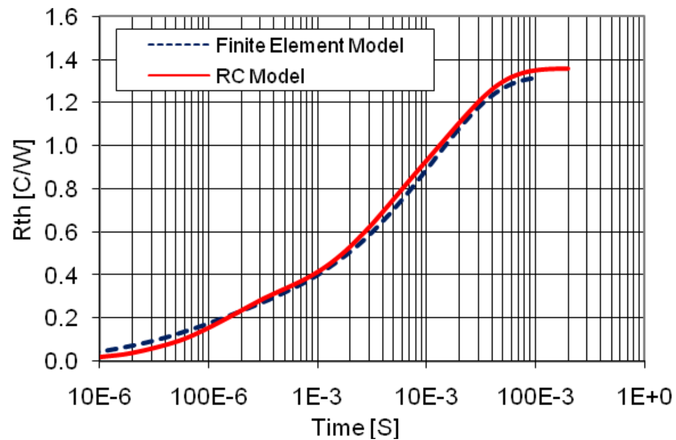

Fig. 9. Comparison of RC network and finite element models to a step function input showing good agreement between the two approaches.

the thermal resistance response to a step function input for the two models. As can be seen, the RC model and finite element model agree quite well.

IV. THERMAL BEHAVIOR FLEXIBILITY

We now have two independent, validated approaches to modeling thermal performance of a device. The RC network model is fit to a specific device and can be used to obtain thermal resistance results for any given input to that device as indicated above. This can also be done using the finite element model but the simulation run times make it less convenient. However, FEA can be used to quickly investigate physical design changes which the RC network model cannot.

The value of the finite element model is that it can be used to predict the thermal behavior not only to changes in pulse conditions but also to any dimensional material or layout variations one may want to investigate. This allows for quick design analysis without the need for costly and time consuming assembly of multiple design options.

V. Conclusion

Two methods of calculating thermal resistance models were verified to the measured data. These models can be used to predict the thermal resistance of the device under multiple input signal conditions and even physical changes in the device itself. The RC network model can be used for very quick thermal resistance calculations once the parameters of a device are known and the finite element model is used to efficiently investigate potential design changes in the internal construction of the device.

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