

Channel Temperature Model for Microwave AlGaIn/GaN Power HEMTs on SiC and Sapphire

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Abstract — A key parameter in the design trade-offs made during AlGaIn/GaN HEMTs development for microwave power amplifiers is the channel temperature. An accurate determination can generally only be found using detailed software; however, a quick estimate is always helpful, as it speeds up the design cycle. This paper gives a simple technique to estimate the channel temperature of a generic microwave AlGaIn/GaN HEMT on SiC or Sapphire, while incorporating the temperature dependence of the thermal conductivity. The procedure is validated by comparing its predictions with the experimentally measured temperatures in microwave devices presented in three recently published articles. The model predicts the temperature to within 5 to 10 percent of the true average channel temperature.

Index Terms — AlGaIn/GaN HEMTs, Silicon carbide, Thermal model, Power amplifier

I. INTRODUCTION

At the present time many research groups are studying AlGaIn/GaN HEMTs for high frequency (up to Ka-band), high power microwave applications [1,2]. The large RF power density generated in these amplifiers causes considerable self-heating, and a reasonably accurate estimate of the channel temperature is often desired. Knowledge of the temperature is essential as both the carrier mobility and reliability suffer. The mobility reduces with increasing temperature as $(1/T)^{2.3}$, with resulting decrease in DC and RF performance [3]. Both short and long term reliability are key parameters, which also reflect the need to rapidly calculate the temperature profile in a particular design.

A self-consistent solution for the thermal field in a particular device can be obtained using either 2- or 3-D simulators available in the SILVACO code [4]. Some recent articles [5–7] give techniques to quickly ascertain junction temperatures under certain conditions; two of which neglect the temperature dependence of the thermal conductivity. This article demonstrates a procedure to estimate the channel temperature in microwave AlGaIn/GaN HEMTs on either SiC or Sapphire, using simple analytic expressions which includes the change in thermal conductivity with temperature. The device is modeled using the thermal resistance method, and is applicable to multi-gate, multi-material, structures, and a wide range of power dissipation levels.

II. ANALYSIS PROCEDURE

A generic microwave power AlGaIn/GaN HEMT layout and its cross section is shown in Figs. 1 and 2, respectively. Being a power device, it has multifinger gate structure, and the die is attached to a Cu-W heat sink for efficient thermal management. The thermal conductivities for the many material layers in the cross-section were determined by making rough averages of the values reported in the literature. Figure 3 presents the simple equivalent circuit thermal resistance stack. The heat

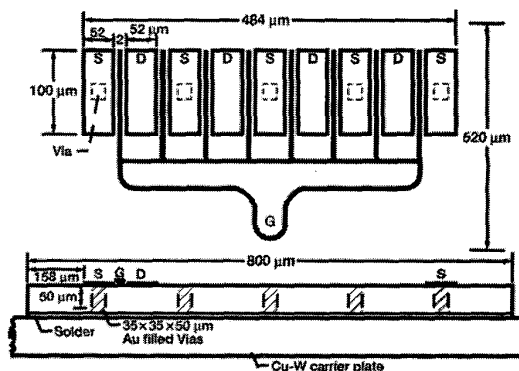


Fig. 1. Schematic of a generic 8-gate AlGaIn/GaN HEMT for a microwave power amplifier.

0.1–175 μm	Si ₃ N ₄ (passivation layer)	K = 0.0096
0.02 μm	GaN (cap layer)	K = 1.6
0.022 μm	Al _{0.2} Ga _{0.8} N (barrier layer)	K = 1.6
0.5 μm	GaN (buffer layer)	K(T ₀) = 1.6 K(T) = calculated
0.015 μm	AlN (nucleation layer)	K = 0.1
100 μm	SiC	K(T ₀) = 3.4 K(T) = calculated
20 μm	AuSn AuGe Epoxy Silver epoxy	K = 2.4 K = 0.9 K = 0.3–0.6 K = 0.018–0.075
1000 μm	Cu-W (carrier)	K = 4

Note: The units for thermal conductivity K are W/(cm-K)
* Two dimensional electron gas

Fig. 2. Cross-section of the HEMT device, showing approximate layers of material with average, or ranges, of thermal conductivities for modeling.

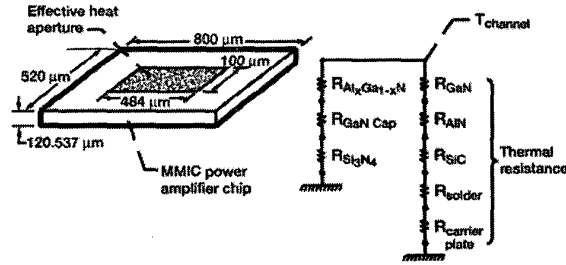


Fig. 3. Device of Fig. 1 on an approximate MMIC chip. The thermal resistance of each layer is calculated separately.

sources are thin strips in the gate-drain channels. The technique consists of determining the thermal footprints of the heat sources at each successive lower layer, and then determining the thermal resistance.

In principle, in any heat transport problem, one solves for the temperature field from the heat flow equation

$$\nabla \cdot \{K_i(T) \nabla T\} = -P \quad (1)$$

Where $K_i(T)$ is the temperature dependent thermal conductivity in the i -th layer, T is the temperature, and P is the dissipated power density. The equation is altered by defining an equivalent artificial temperature via the Kirchhoff transformation

$$T_i^e = T_o + \frac{1}{K_i(T_o)} \int_{T_o}^T K_i(\xi) d\xi \quad (2)$$

where T_o is the reference temperature, T_i^e is the transformed temperature in the i -th layer, and T is the real temperature there. The transform linearizes (1) with the result

$$K_i(T_o) \nabla^2 T_i^e = -P \quad (3)$$

Our first task is to determine analytical expressions for the temperature dependent thermal conductivities of the GaN, SiC, and Sapphire layers. We have not found an analytical expression for the thermal conductivity of GaN, but from [8,9] we may assume it to be

$$K_{\text{GaN}}(T) = 1.6 \left(\frac{300}{T} \right)^{1.4} \frac{\text{W}}{\text{cm} \cdot \text{K}} \quad (4)$$

where we have assumed the behavior of GaN is similar to that of GaP. For SiC we choose [10]

$$K_{\text{SiC}}(T) = 3.4 \left(\frac{300}{T} \right)^{1.5} \frac{\text{W}}{\text{cm} \cdot \text{K}} \quad (5)$$

and for Sapphire we use the result from [11]

$$K(T) = \frac{73.9}{T - 159} \approx \frac{(0.49)(300)}{T} \frac{\text{W}}{\text{cm} \cdot \text{K}} \quad (6)$$

The thermal resistance for a stripe is from [12], see Fig. 4(a).

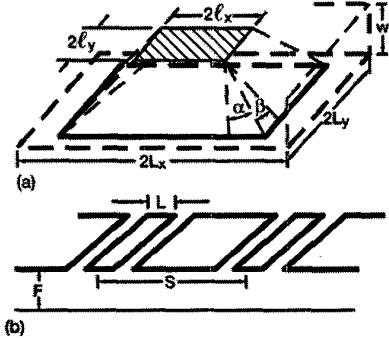


Fig. 4. Geometry for calculating thermal resistance for (a) single stripe. (b) parallel stripes.

$$R_{TH} = \frac{1}{K} \int_0^w \frac{dz}{A(z)} = \frac{1}{4Kl_x} \frac{1}{(\gamma_e \tan \alpha - \tan \beta)} \ln \left[\frac{l_x + w \tan \alpha}{l_x + w \frac{\tan \alpha}{\gamma_e}} \right] \quad (7)$$

where

$$(\tan \alpha)_i = \left(1 - l_{x_n} \right) \frac{w_n + \frac{P_s}{1 + P_s} l_{x_n}}{w_n + \frac{1}{1 + P_s} l_{x_n}} \quad (8)$$

$$(\tan \beta)_i = \left(1 - l_{x_n} \frac{\gamma_e}{\gamma_s} \right) \frac{w_n + \frac{P_s}{1 + P_s} l_{x_n} \gamma_e}{w_n + \frac{1}{1 + P_s} l_{x_n} \gamma_e} \quad (9)$$

$$w_n = \frac{w}{L_x}, \gamma_s = \frac{L_y}{L_x}, \gamma_e = \frac{l_y}{l_x}, l_{x_n} = \frac{l_x}{L_x}, P_s = \frac{K_i}{K_{i+1}}$$

In regions where the thermal fluxes intersect, as in a multi-gate structure as in Fig. 4(b), the formulas from [13] (with typos corrected) for the thermal resistance R_{TH} , are as follows.

$$R_{TH} ZK = \frac{n}{\pi \left[\frac{2(n-1)}{\ln M} - \frac{(n-2)}{\ln P} \right]} \quad (10)$$

where n = the number of fingers
 Z = total gate width

and

$$M = \frac{2\sqrt{u} + 1}{\sqrt{u} - 1}, \quad u = \frac{\cosh \left[\frac{\pi}{4} \left(\frac{S+L}{F} \right) \right]}{\cosh \left[\frac{\pi}{4} \left(\frac{S-L}{F} \right) \right]} \quad (11)$$

TABLE I
For a typical chip with 8 gate fingers, $L_g = 0.15 \mu\text{m}$, $W_g = 100 \mu\text{m}$,
gate centered in the source drain gap of $2 \mu\text{m}$ and PAE = 30 percent

Power density, W/mm	Carrier plate temperature, K (°C)	Channel temperature, K (°C)	Thermal resistance (°C/W)				
			$R_{\text{carrier plate}}$	R_{solder}	R_{SiC}	R_{AlN}	R_{GaN}
2	300 (27)	366 (93)	0.02	0.525	7.67	10.7	56.5

$$P = 2 \sqrt{\frac{\cosh\left(\frac{\pi L}{4F}\right) + 1}{\cosh\left(\frac{\pi L}{4F}\right) - 1}} \quad (12)$$

The step-by-step procedure starts with the heat sources on the top surface; which are strips with the short side dimension being that of the gate, or the gate-drain spacing. Using (8) and (9), to determine the flow pattern; the footprint on the next lower surface is determined. The thermal resistances may be obtained from (10) which is applicable for either a single strip, or multiple ones; whereas (7) is restricted to single ones. With the flow patterns and resistances of each layer determined, the calculation continues by starting at the assumed sink temperature and working upward through the layers. The change in temperature across a layer is given by

$$\Delta T_i = R_{TH_i} P_{DISS} \quad (13)$$

where ΔT_i = the temperature rise
 R_{TH_i} = the thermal resistance
 P_{DISS} = the power dissipated

The actual temperatures are used in the layers with constant thermal conductivity, and the artificial ones are used in the GaN, SiC, and Sapphire layers. For the GaN, SiC, and Sapphire layers, the actual temperature is determined from the transformed temperature by

$$T_A(\text{GaN}) = \left\{ \frac{[T^e - T_o(3.5)](-0.4)}{T_o^{1.4}} \right\}^{-2.5} \quad (14)$$

$$T_A(\text{SiC}) = \left\{ \frac{[T^e - T_o(3)](-0.5)}{T_o^{1.5}} \right\}^{-2} \quad (15)$$

$$T_A(\text{Sapphire}) = T_o \exp\left[\frac{T^e - T_o}{T_o}\right] \quad (16)$$

While the Kirchhoff transform gives a linear equation, the nonlinearity inherent in (1) is now pushed into the boundary conditions. For a layered structure such as a HEMT, this can be troublesome when attempting to write simple code [14]. In layered structures, the artificial temperature will generally have jumps across interfaces.

However, as stated in [14], these jumps can be eliminated by choosing the analytical forms for the conductivities of the layers $K_i(T)$ in such a way that their ratio is independent of temperature. This lead us to assume the forms given above. For GaN and SiC, the ratio of the conductivities is

$$\frac{K_{\text{GaN}}(T)}{K_{\text{SiC}}(T)} = 0.266T^{0.1} \approx \text{constant} \quad (17)$$

or a 6 percent change over a 200 °C range. As an example for the device in Fig. 1, the calculated thermal resistances are shown in Table I.

III. COMPARISON WITH EXPERIMENTAL DATA

A. First Example

Temperature measurements on microwave AlGaN/GaN HEMTs on both SiC or Sapphire were made using Raman spectroscopy [15, 16]. For the single gate device on SiC discussed in [15], we model the heat source as a $1 \mu\text{m}$ wide stripe (gate length). The GaN thickness was $F = 1.2 \mu\text{m}$. Using (10) for $n = 1$ gives $R_{THZK} = 0.587$. Assume $K(T) = 1.6$ (the 300 K value) as we don't know the actual temperature at the interface. This will underestimate the final channel temperature. We find $R_{TH}(\text{GaN}) = 18.35 \text{ K/W}$. Using (7) and (8) we find the footprint on the SiC layer is $3.086 \mu\text{m}$ by $200.2 \mu\text{m}$. Use (10) again for this layer and obtain $R_{THZK} = 2.02$ and $R_{TH}(\text{SiC}) = 29.73 \text{ K/W}$. The dissipated power is 1.754 W, which yields $\Delta T(\text{SiC}) = 52 \text{ K}$, $\Delta T(\text{GaN}) = 32.2 \text{ K}$. Using (15) gives $T(\text{SiC, actual}) = 86.6 \text{ °C}$. Then in the GaN layer, $T^e = 359.6 + 32.2 = 391.8 \text{ K}$, or $T(\text{GaN, actual}) = 121 \text{ °C}$. We can make a correction for $R_{TH}(\text{GaN})$ by using $K(359.6\text{K}) = 1.24$. Then $R_{TH}(\text{GaN}) = 23.7 \text{ K/W}$ and the temperature predicted by our model becomes 132 °C . The measured value was $124 \text{ °C} \pm 5 \text{ °C}$. Thus the uncorrected and corrected temperatures bracket the measured value. The 3-D model used in [15] assumed constant K and predicted $T = 99 \text{ °C}$. For the sapphire substrate case we choose $L = 4 \mu\text{m}$, (gate length), $K(\text{sapphire, 300 K}) = 0.49$; then $R_{TH}(\text{GaN}) = 8.35 \text{ K/W}$, $R_{TH}(\text{SiC}) = 180.5 \text{ K/W}$, $\Delta T(\text{sapphire}) = 117.3 \text{ K}$, and $\Delta T(\text{GaN}) = 5.4 \text{ K}$. Then the calculated temperature using our model on the top surface becomes 176 °C . The measured value was 180 °C and the 3-D model predicted 140 °C .

B. Second Example

An 8-gate device on SiC (Fig. 1) (for 2–4 GHz amplifier applications) was measured in [16], and the thermal profile is shown in Fig. 5(a). Using the outlined procedure one obtains $T = 183^\circ\text{C}$ (shown dotted); which agrees favorably with the average of the measurement.

C. Third Example

Measurements using nematic liquid crystal thermography on a 2-gate device on sapphire were performed in [17]; see Fig. 5(b). Our computations yielded 59 and 76.5°C for the two input power levels, respectively.

Our modeling procedure can estimate the channel temperature to within 5 to 10 percent and in some cases, much better than that.

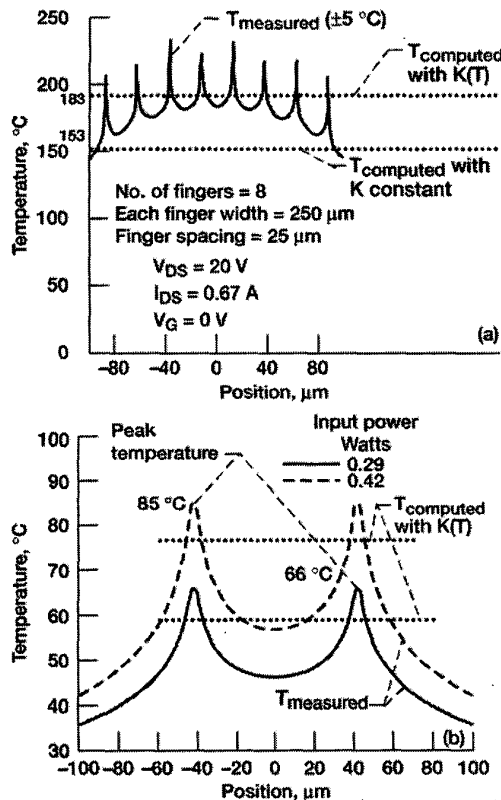


Fig. 5. Comparison with Kuball [16] and Park [17]. (a) measured (solid) [16] and calculated this paper (dotted). (b) measured (solid and dashed) [17] and calculated this paper (dotted) for two input power levels.

IV. CONCLUSION

We have demonstrated a simple analytical method to estimate the channel temperature in an AlGaIn/GaN HEMT for microwave power amplifiers. It is applicable for multi-gate, multi-layer structures on SiC or Sapphire substrates, and for wide ranges of dissipated power. With accurate expressions for the temperature dependent thermal conductivity and using previously published equations for the thermal resistance of parallel stripes, one calculates a temperature that is within 5 to 10 percent of the true average channel temperature.

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