LEHIGH UNIVERSITY

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Thermal Impedance Estimation of GaN High Electron Mobility Transistors

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Thermal resistance of GaN High Electron Mobility Transistors (HEMT) is estimated using a simple analytical formula. The thermal resistance is also measured by using the forward characteristics of the gate Schottky diode. The estimated thermal resistance was found to be within *4%* of the experimental value.

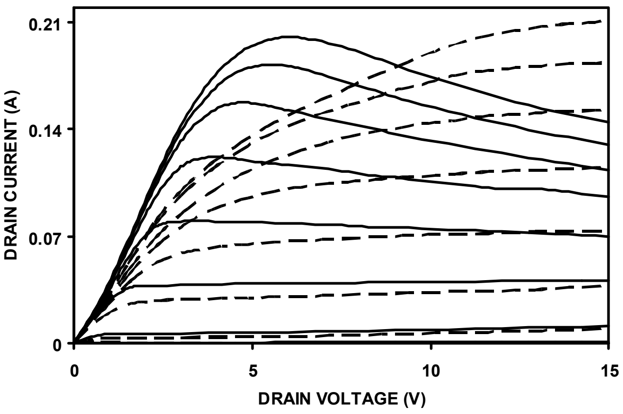
Introduction

Advantages of GaN HEMT devices
- High power
- High temperature
- High Breakdown
- Linearity

Thermal issues with GaN HEMT device
- Self-heating effect due to high power density

Characterization of self-heating
- Thermal time constant
- Thermal impedance

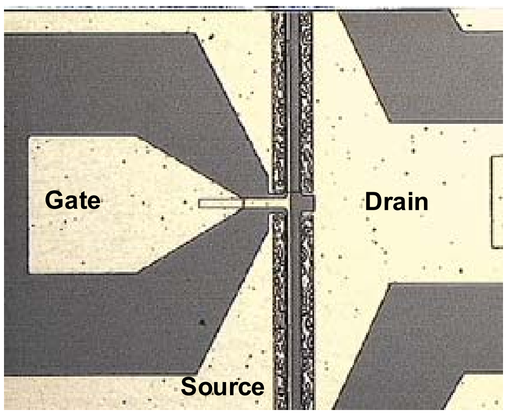
Thermal impedance estimation and measurement
- Analytical estimation using thermal model with specified device structure (sapphire substrate)
- Measurement using forward gate-diode characteristics as temperature sensor



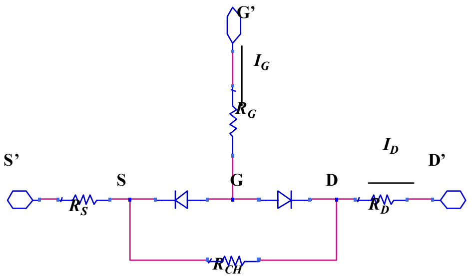
GaN HEMT (—) dc vs. (---) pulsed drain characteristics. V_{GS} = *–6, –5 … 1 V* bottom up. Pulsed characteristics were measured *1 μs* after V_{GS} was pulsed from *–10V* while keeping V_{DS} constant. The difference between dc and pulsed characteristics at high V_{DS} is mainly due to self heating, whereas the difference at low V_{DS} is mainly due to traps.

Device structure

GaN HEMT devices tested were made by SVT Associates, with 0.4mm sapphire substrate, *300 μm* gate width and *1 μm* gate length.



Top view of GaN HEMT device under test



Low-frequency equivalent circuit of a forward-biased GaN HEMT. Primed symbols indicate external terminals.

Analytical estimation of thermal resistance

Thermal model assumptions:
- Semi-infinite sapphire substrate
- Rectangular surface heat source

Thermal resistance can be estimated by [3]:

$$\Theta = \frac{1}{2\pi K}\left[\frac{1}{L}\ln\left(\frac{L+\sqrt{W^2+L^2}}{-L+\sqrt{W^2+L^2}}\right)+\frac{1}{W}\ln\left(\frac{W+\sqrt{W^2+L^2}}{-W+\sqrt{W^2+L^2}}\right)\right]$$

K is the thermal conductivity of the substrate while *L* and *W* are the length and width, respectively, of the heat source.

For the present HEMTs, *L = 1 μm*, *W = 300 μm*, and *K = 0.4 W/cmK*. Therefore, Θ = *196 °C/W*.

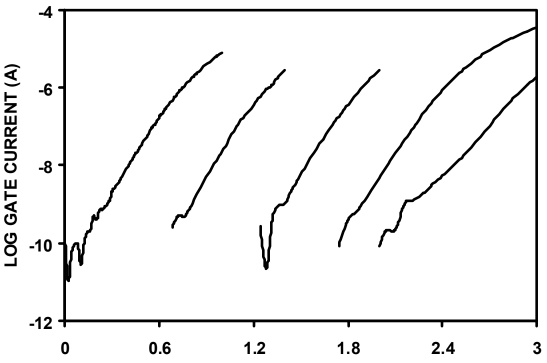
Experimental Verification

Forward Schottky characteristics of HEMT gate-diode can be used as thermal sensor to detect the channel temperature inside the device. Forward gate current can be expressed by:

$$I_G \propto T^2 \exp(-q\Phi_B/kT)\,[\exp(qV_{GS}/nkT) - 1]$$

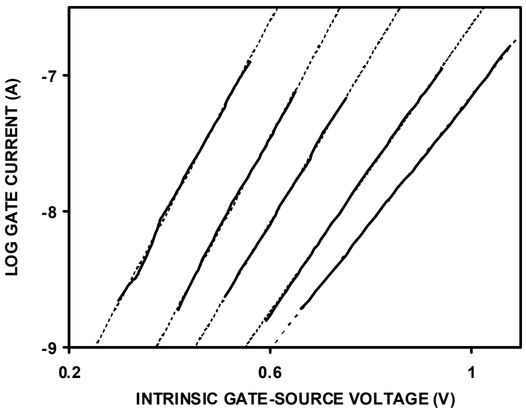
where *T* is the channel temperature, *q* is the electron charge, V_{GS} is the gate-source voltage, Φ_B is the Schottky barrier height, *n* is the ideality factor and *k* is the Boltzmann constant.

The slope of *log* I_G *(*V_{GS}*)* is proportional to *q/nkT*, from which channel temperature can be derived experimentally from the forward gate characteristics measurement results.



Forward gate current as a function of extrinsic gate-source voltage ($V_{G'S'}$).

Intrinsic gate-source voltage is extracted from extrinsic gate-source voltage by subtracting the voltage drop over series resistances.



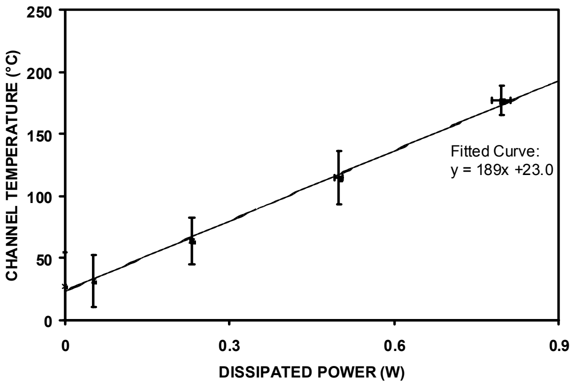
Forward gate current as a function of intrinsic gate-source voltage (V_{GS}). Dotted lines are fitted curves from which slopes are extracted.

Knowing the channel temperature extracted from forward gate-diode characteristics, the thermal resistance *Θ* can be calculated from:

$$T - T_0 = \Theta \cdot P$$

where T_0 *is the ambient temperature, P is the dissipated power*

The slope of right plot represents a thermal resistance of *189 °C/W*, which is within *4%* difference from the value calculated according to analytical estimation.



Channel temperature extracted from the dependence of forward gate current on intrinsic gate-source voltage. V_{DS} = *0, 1 … 4 V* left to right . The dissipated power horizontal error bar is obtained from error caused by slight change of drain current with the gate-source voltage sweep (causing some deviation in dissipated power). The channel temperature vertical error bar is obtained from the error introduced by slope value extraction.

Discussion

- Here channel temperature is assumed to be uniform across the device. In fact, it would be different over different position. But to our research on device electrical characteristics, a simple analytical estimation of channel temperature is enough.

- For other devices with different structure and different materials, the analytical estimation assumption used here might not be valid. Different assumption should be re-established accordingly and different formula should be derived and used.

- For total thermal effect characterization, thermal time constant should be extracted and modeled in order to complete the full model for thermal effect. Research on this issue is being performed presently.