Direct On-Wafer Non-Invasive Thermal Monitoring of AlGaN/GaN Power HFETs Under Microwave Large Signal Conditions

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Abstract - **For the first time, we report direct on-wafer non-invasive temperature distribution measurements of AlGaN/GaN HFETs grown on Si substrates under microwave large-signal conditions. An infrared camera and a load-pull measurement system coupled to a probe station enable us to produce surface temperature maps with micronic resolution. Results include the impact of the RF drive, differences between RF and DC drive, as well as impact of reduced power added efficiency on the surface temperature of the device.**

Index Terms - **GaN, HFETs, infra-red spectroscopy, reliability, temperature, thermal effects.**

I. INTRODUCTION

In the wireless communication technology area, the requirements placed upon power amplifiers are becoming more and more stringent, and the technologies currently used such as Si-LDMOS are reaching their limits [1]. On the other hand, due to the intrinsic properties of GaN, AlGaN/GaN HFETs offer important advantages for many applications in the microwave domain, including low noise, high power and high temperature applications [2,3]. High power microwave circuits have already been proposed showing the great potential of this technology [4-6]. However, the reliability of this technology is still a concern that limits its presence in today's electronic systems [7-10].

The total power present in GaN-based power FETs is large and results in large amounts of power dissipated as heat. As a consequence, AlGaN/GaN HFETs may exhibit high channel temperature and suffer from self-heating effects that reduce the device performance if not designed for proper thermal dissipation [11]. In addition, high temperatures accelerate many failure mechanisms affecting the device lifetime. Accurately determining the channel temperature of a device is critical in gauging its reliability. Knowledge of the temperature in the active area of a transistor is essential in optimizing the device design for reliability and performance [12].

In this paper, we present a novel test system that enables one to perform on-wafer measurements of the surface temperature distribution of devices under microwave large-signal condition. This system is used to investigate the impact of the RF drive, any differences between RF and DC power, as well as the impact of the device size and the power added efficiency on the surface temperature of AlGaN/GaN HFETs grown on 100mm Si substrates.

Section II introduces this unique measurement system and the device technology, while Section III discusses the measurement results: Section III-A, III-B, and III-C deal with the effects of the RF drive, the origin of the dissipated power, and the relationship between PAE and temperature, respectively.

II. DEVICE TECHNOLOGY AND MEASUREMENT SYSTEM

The devices studied in this work use a conservative AlGaN/GaN HFET structure. The devices are built on 100mm FZ Si (111) substrates [1]. The growth consists of the deposition of a transition layer, which is used to mitigate the thermal expansion and lattice mismatch between GaN and Si. The transition layer is followed by 0.5-1μm of undoped GaN. Finally, a 200Å undoped AlGaN based device structure is deposited with an Al content of 20%. The device is processed through a typical GaN device process flow [2] Following all processing, the wafers are thinned to 150μm in order to improve thermal performance. From a geometrical perspective, the device gate length (L_G), the gate-drain, (L_{GD}), source-gate (L_{SG}), and source-drain (L_{SD}) are 0.7μm, 3μm, 1μm, and 4.7μm, respectively. Fig. 1 illustrates the device layer structure.

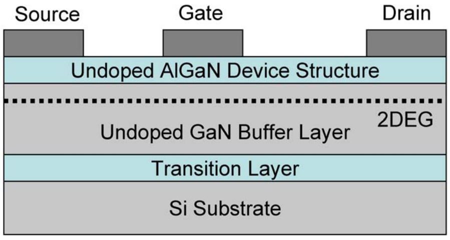

Fig. 1 Device cross-section of a AlGaN/GaN HFET on Si substrate.

The unique measurement setup used in this work enables direct on-wafer non-invasive thermal monitoring of AlGaN/GaN power HFETs under large signal microwave conditions. It consists of a probe station, a load-pull characterization system, and an infrared microscope. The probe station enables on-wafer testing of the devices. It is equipped with a hot chuck that allows variation of the base temperature from room temperature up to 150°C. The load-pull measurement system is capable of driving the transistor under test into the non-linear operating regime at various load and source impedances. The infrared microscope enables us to produce surface temperature maps of a powered transistor running at elevated temperature with a resolution as good as a few microns when using a high power IR objective lens. The true temperature of the transistor is determined by measuring the infrared radiant energy leaving the device at a fixed surface temperature. This known temperature and radiant energy are then used to determine the emissivity for the various materials on the surface, and pixel-by-pixel emissivity correction is applied [13]. Fig.2 illustrates the surface temperature map, collected by the infrared microscope, from a 10-finger 2mm transistor biased at a drain-to-source voltage (V_{DS}) of 15V and a gate-to-source voltage (V_{GS}) of –1.2V. The load and source impedance were tuned for maximum power added efficiency (PAE) at the 1dB compression point. For this image, the RF input power was set at 15dBm driving the AlGaN/GaN HFET near the peak PAE condition. The base temperature was set to 70°C. The temperature scale ranges from 70°C to 136°C. We can distinctly observe the probe tips (pitch of 150μm) from the temperature map. We observe that except at the tips, the probe temperature is close to the base temperature. Also, from this surface temperature distribution, we clearly observe that the temperature is higher at the center-fingers than at the edge fingers. In an HFET, the heat spreads from the device channel, vertically in the different layers, and horizontally through the layers. Due to the presence of the neighboring heat sources, the lateral heat diffusion from the center fingers is more difficult than at the edge-fingers, resulting in higher channel temperature and thermal effects.

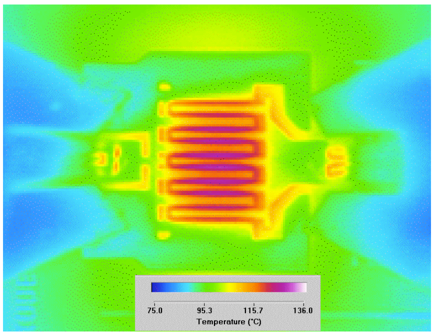

Fig. 2 Temperature distribution of an AlGaN/GaN HFET under microwave large signal condition, running at a base temperature of 70°C.

III. MEASUREMENT RESULTS AND ANALYSIS

A. *EFFECT OF AN RF DRIVE*

In this section, we report the effect of RF drive on the peak surface temperature of a powered AlGaN/GaN HFET running with a base temperature of 70°C. The device under test is a 10-finger transistor with a total gate width of 2mm. It is biased at a drain-to-source voltage (V_{DS}) of 15V and a gate-to-source voltage (V_{GS}) of –1.2V. Fig. 3 shows the power performance of the device at 2.14GHz with the load and source impedances optimized for maximum output power at the 1-dB compression point (P_{OUT}^{1dB}). The absolute saturated output power (P_{SAT}) and the peak power added efficiency (Peak-PAE) are 35dBm, and 50%, respectively, while the linear gain is as high as 20dB.

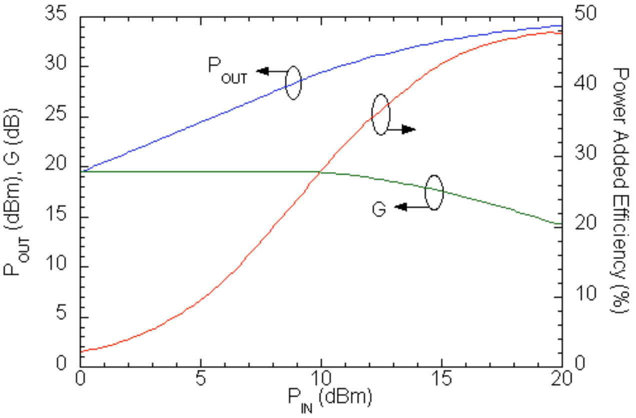

Fig. 3 Power performance at 2.14GHz of the 2mm AlGaN/GaN HFET.

By expressing a simple energy balance, it is possible to calculate the total power dissipated in the device (P_{DISS}) from the power sweep data:

$$P_{DISS} = P_{IN} - P_{OUT} + P_{DC} \qquad (1)$$

where P_{DC} is the supplied dc power dominated by the product V_{DS} x I_{DS}. Fig.4 shows the evolution of the peak surface temperature (T_{PEAK}) with the RF input power level (P_{IN}). The tuning conditions were selected such that the test setup can drive the device into saturation while achieving maximum PAE. We observe that, as previously reported in [12], P_{DISS} varies with the RF input power level. In this example, P_{DISS} varies between 2.8W and 2.3W leading to a relative variation of around 20%. As expected, the peak surface temperature strictly follows the trend of variation of the parameter P_{DISS}, and varies from 134°C to 124°C resulting in a relative variation of the device surface peak temperature on the order of 10%. At low P_{IN}, the total dissipated power in the device is dominated by the dc power, P_{DC}. When moving toward higher RF input power level and into the device nonlinear regime, the device efficiency increases resulting in a significant decrease in P_{DISS} and T_{PEAK}. Further increase in the RF input power level drives the transistor into saturation, and any increment of P_{IN} increases P_{DISS} and T_{PEAK}.

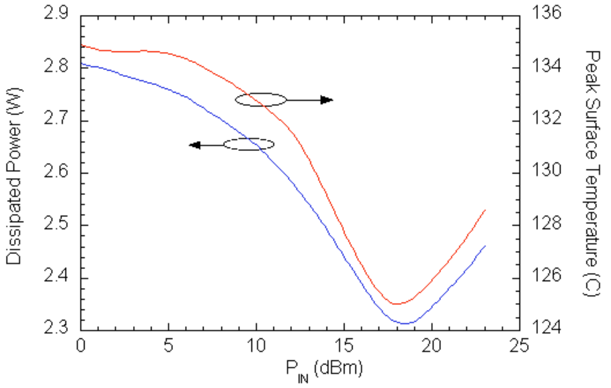

Fig. 4 Evolution of the peak surface temperature with the RF input power level.

B. *DIFFERENCE BETWEEN RF AND DC DRIVE*

In this section, we study the effect of the source of dissipated power in the device on the peak surface temperature. The two conditions considered are “dc-only”, and “dc+RF”. The device under test (DUT), the base temperature, the bias, and the impedance conditions, used are the same as in Section III-A. Fig. 5 shows the measured T_{PEAK} for different P_{DISS}. In the case of “dc+RF”, P_{DISS} is calculated using Eq.1. In the “dc-only” case, P_{DISS} is approximated by the product V_{DS} x I_{DS}, and is varied by changing the parameter V_{GS}, V_{DS} being kept constant at 15V. We observe that on the entire P_{DISS} range considered, the variation of the parameter T_{PEAK} is similar in both “dc-only” and “dc+RF” case. This proves that the peak surface temperature is related only to the total power dissipated in the device, disregarding the origin of that power. The multi-valued behavior observed in the “dc+RF” case in Fig.5 is associated to the fact that P_{DISS} increases again when P_{IN} goes above 18dBm (see Fig.4), and to the error margin of the temperature measurement system (<1ºC).

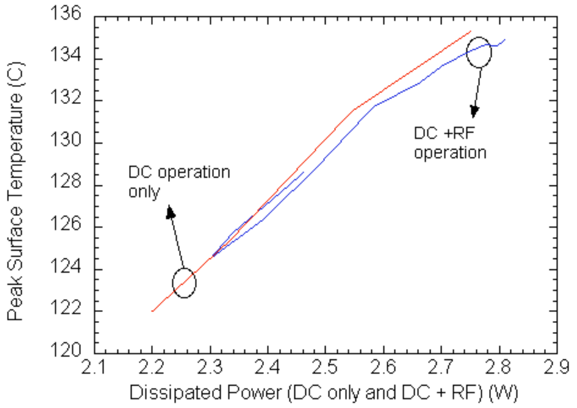

Fig. 5 Device peak surface temperature for different power to be dissipated (dc-only, and dc+RF).

C. *EFFECT OF PAE ON TEMPERATURE*

In this section, we highlight the strong relation between the device PAE and the peak surface temperature. In order to do so we measure devices of different sizes operating under large-signal condition at different load and source impedances. The gate pitch for each device was adopted to keep the peak surface temperature equivalent [11]. Table 1 summarizes the geometrical parameters of the studied devices.

Device	Total Gate Width	Fingers Width (μm)	Gate Pitch (μm)
A	1 mm	100	20
B	2 mm	200	30
C	3 mm	300	40
D	4 mm	400	50

Table. 1 Device geometry of the studied AlGaN/GaN HFETs.

Fig.6 shows the evolution of the absolute output power and the PAE at the 3-dB compression point (base temperature of 25°C) when the device is tuned for maximum output power. The power density at 3dB is relatively constant around 1.0W/mm with the PAE at 48%. This results in constant power dissipated and junction temperature. Running at the 3-dB compression point results into high efficiency and consequently into a reduced peak device temperature and reduce magnitude of the self-heating.

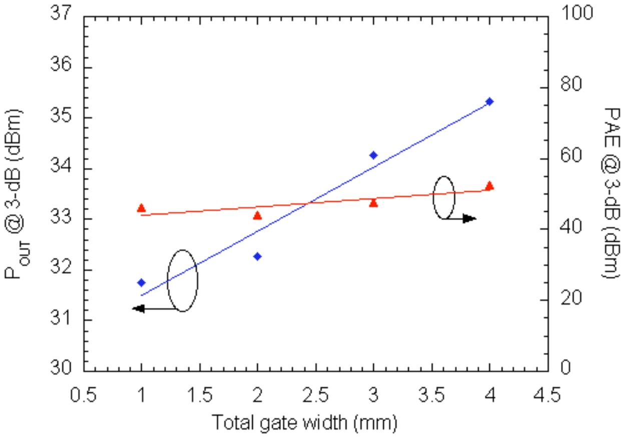

Fig. 6 Evolution of parameter PAE P_{OUT} with the total gate width of the device at the 3-dB compression point.

Operating the devices at non-optimal load and source impedances of devices with different sizes allows one to measure the device characteristics when operating under different dissipated power condition and different PAE. Fig.7 shows the evolution of the device PAE and the peak surface temperature versus the dissipated power. The operating frequency and the base temperature were 2.14GHz, and 70ºC, respectively. We observe that when the parameter PAE decreases, T_{PEAK} increases. The correlation between these two parameters reflects the strong link between the magnitude of the thermal effects and the device efficiency. Therefore, when operating under large signal conditions resulting in maximum PAE the peak surface temperature is minimum (see Fig.4), and consequently the magnitude of the self-heating is reduced. The relation between parameters PAE and T_{PEAK} highlights the importance of large signal RF effects in thermal analysis and of the proper tuning of the device for the target operating condition. Having the ability to directly measure self-heating as a function of RF drive is essential in understanding these effects.

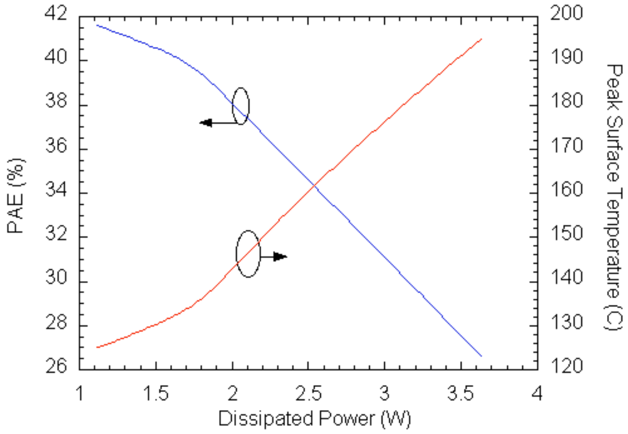

Fig. 7 Evolution of the parameters PAE, and T_{PEAK} versus P_{DISS}.

IV. CONCLUSION

We have presented direct non-invasive on-wafer temperature distribution measurement of AlGaN/GaN HFETs grown on Si substrates under microwave large-signal condition. The RF drive is reported to have a significant impact on the device peak temperature. We report that the device peak temperature follows the evolution of the total power to be dissipated in the transistor. We have also demonstrated that the difference of origin of the power applied to the device (dc or RF+dc) does not affect the temperature distribution in the transistors. And finally, the impact of reduced PAE on the peak temperature of the device is demonstrated.

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