High Temperature Performances of AlGaN/GaN Power HFETs

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Abstract - **We report the variation with temperature of key parameters extracted from dc, small-signal, large-signal, and noise measurements, of AlGaN/GaN HFETs. The rates obtained are lower than that of GaAs pHEMTs confirming the potential of GaN for high temperature applications.**

I. INTRODUCTION

Microwave transistors that can operate at high temperatures without external cooling are required for applications in the following domains: aerospace, automotive, mineral exploration, and energy production [1]. The materials usually considered for providing ICs that operate in such severe environments are GaAs and Si due to their technological maturity. Optimum device designs for high temperatures operation have already been presented for these technologies [2]. However, the advent of wide-bandgap GaN-based electronic devices have received much attention due to their inherent ability to operate under high-power and high-temperature conditions [3,4]. Because of its higher bandgap (3.4eV), as compared to Si (1.1eV) and GaAs (1.4eV), GaN does not run into intrinsic carrier conductivity difficulties until temperatures beyond 900K [1]. In addition, such a wide bandgap results in high breakdown fields beneficial for high power operation. In order to provide a reliable GaN technology at high temperatures, it is necessary to evaluate the high temperature performances of the devices from dc to microwave frequencies.

In this work we present the degradation of AlGaN/GaN power HFETs performances when increasing the temperature of operation up to 540K. Section II reports the dc current-voltage characteristics, section III reports the high-frequency small-signal performances, section IV reports the microwave large-signal behavior, section V reports the high frequency noise, section VI presents the impact of the temperature on the matching networks, and finally section VII compares the various measured rates with the one reported for GaAs pHEMT technology.

II. CURRENT-VOLTAGE CHARACTERISTICS

The transfer characteristics of a transistor lead to the knowledge of the threshold voltage (V_{TH}), the saturated drain current (I_{DSS}), and the peak transconductance (peak-G_M). These parameters allow one to compare devices, they are critical to select the optimum bias point for a specific application (low noise, high gain, high output power, high power added efficiency), and they dominate the large signal behavior of a transistor for operation below the cutoff frequency (f_T). Fig.1 shows the evolution of the transfer characteristics of an AlGaN/GaN HFET (W_G=250μm, L_G=0.35μm) when increasing the temperature from 380K to 540K. While V_{TH} increases with temperature, I_{DSS} decreases at a rate of –3.7mA/10°C when increasing the temperature. It results in a reduction of the RF swing under large signal operation, participating to the reduction of the saturated RF output power at high temperatures. Also, the peak-G_M decreases with a rate of –0.25mS/10°C that results in a reduction of the cutoff frequency.

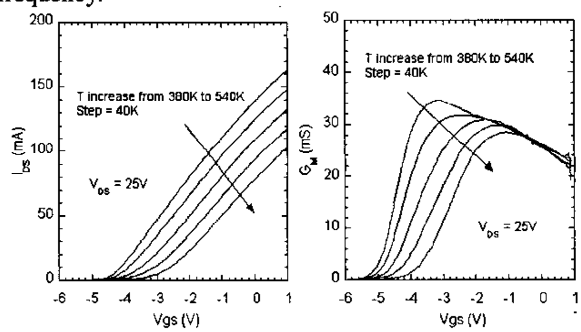

Fig. 1 Transfer characteristics of an AlGaN/GaN HFET (W_G=250μm, L_G=0.35μm) from 380K to 540K.

III. SMALL-SIGNAL CHARACTERISTICS

In addition to the stability circle and initial matching condition for maximum output power under large signal operation, the small-signal characteristics lead to the determination of the cutoff frequency (f_T) and maximum frequency of oscillation (f_{MAX}). The extrinsic f_T of the studied devices (L_G = 0.35μm) is in the 30GHz range at 295K. The products f_T x L_G and f_{MAX} x L_G allow the comparison of the frequency performances with other devices regardless of the transistor dimensions. As shown in Fig.2, when increasing the temperature of operation from 380K to 540K, f_T x L_G and f_{MAX} x L_G decreases with a rate of –0.084GHz.μm/10°C, and –0.29GHz.μm/10°C, respectively. For the studied devices, this rate results in a decrease of the cutoff frequency by –0.24GHz/10°C. This reduction of f_T predicted from the dc-transconductance, is associated to a decrease of the carrier mobility when increasing the temperature.

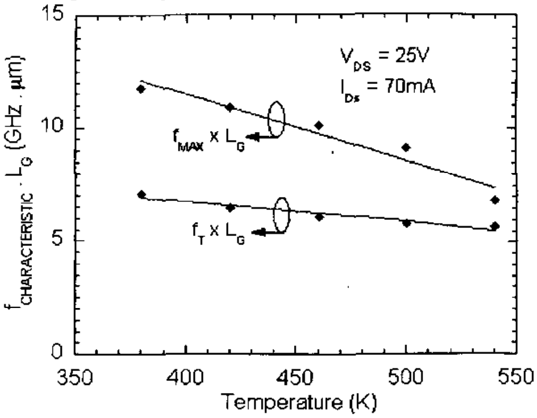

Fig. 2 Small-signal performances of an AlGaN/GaN HFET (W_G=250µm, L_G=0.35µm) from 380K to 540K.

IV. LARGE-SIGNAL CHARACTERISTICS

The high output power capabilities of GaN-based electronic devices make them very attractive for commercial and military applications such as base stations and active phased array radars. Power densities in X-band above 10W/mm have already been reported [5]. Fig.3 shows the degradation of the output power of an AlGaN/GaN device (gate width = 1.5mm) at 4GHz when increasing the temperature of operation up to 540K. At each temperature the load and source impedance are tuned for maximum output power at the 1dB compression point. A relatively constant degradation of –0.138dB/10°C of the saturated output power is reported between 295K and 540K.

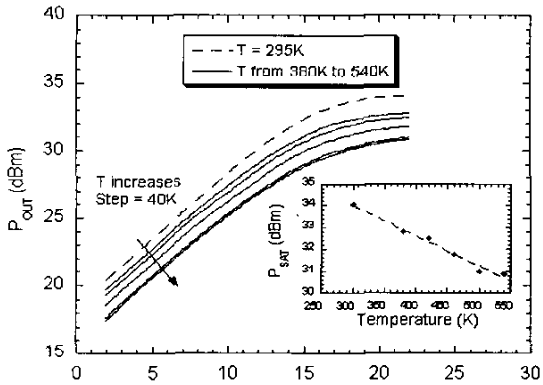

Fig. 3 Power characteristics of an AlGaN/GaN HFET (W_G=1.5mm, L_G=0.35µm) at 4GHz from 295K to 540K.

V. NOISE CHARACTERISTICS

One of the primary uses of GaN-based transistors is to replace actual GaAs-based and vacuum-tube-based microwave power amplifiers modules in high power applications [6,7]. However, AlGaN/GaN HFETs can also be used for low noise amplifiers (LNA). Due to the inherent high breakdown voltage of GaN-based transistors, such low noise devices could operate reliably without limiter devices, which would significantly decrease system noise figure and further enhance system performance. Fig.4 presents the degradation of the noise parameters measured at 3GHz using the multiple source impedance technique from 380K to 540K. The minimum noise figure (F_{MIN}), and the noise resistance (R_N) increase with a rate of +0.068dB/10°C, and +2.57Ω/10°C, respectively, while the associated gain decreases by –0.114dB/10°C. The increase of R_N when increasing the temperature of operation will result in faster degradation of the noise figure when the source impedance is moved away from the optimum termination for minimum noise figure.

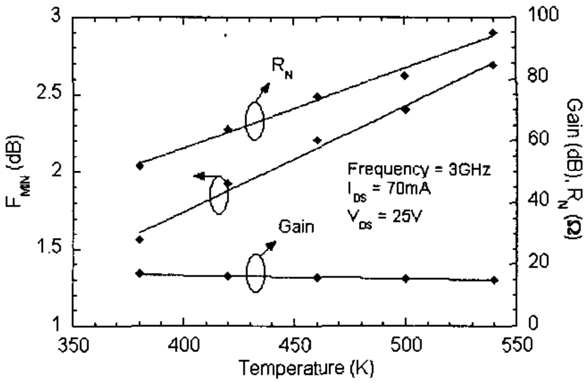

Fig. 4 Minimum noise figure, noise resistance, and associated gain at 3GHz of an AlGaN/GaN HFET (W_G=250µm, L_G=0.35µm) from 380K to 540K.

VI. MATCHING NETWORKS

The knowledge of the modification of the load and source impedance that corresponds to a specific situation (minimum noise, maximum output power, or power added efficiency) with the temperature of operation is as critical as the degradation of the device performances themselves, since matching networks greatly impact circuit performances. Fig.5 illustrates the evolution of the optimum source reflection coefficient for minimum noise figure, as well as the optimum load and source reflection coefficient for maximum output power at the 1dB compression point, of an AlGaN/GaN HFET at 4GHz from 380K to 540K. It is noteworthy that these measured optimum reflection coefficients are almost constant over the whole temperature range, which is beneficial to minimize the degradation of circuit performances over temperature.

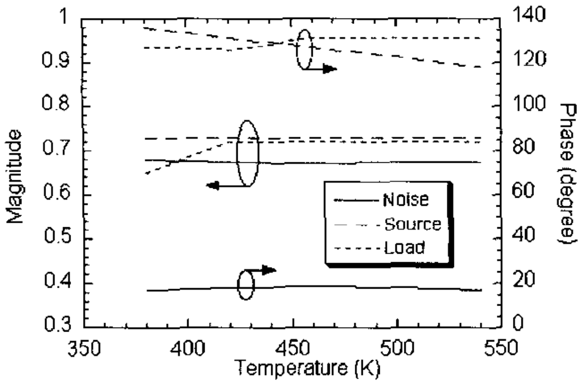

Fig. 5 Optimum load and/or source coefficients for minimum noise figure and maximum output power the 1dB compression point, at 4GHz, of AlGaN/GaN HFETs from 380K to 540K.

VII. Discussion

The decrease in device performances when increasing the environmental temperature is larger for GaAs pHEMTs than for AlGaN/GaN HFETs. For instance, f_T and P_{SAT} of GaAs devices change with a rate of −0.5GHz/10°C and −0.25dB/10°C [8], respectively, which is twice as large as the one reported in this work for GaN devices. Also, it is noteworthy that the GaN devices exhibit irreversible degradation of the current-voltage characteristics after thermal cycling up to 540K. This is associated with the presence of irreversible mechanisms that occur in the devices at high temperatures. If only the bandgap is considered, GaN-based electronic devices could operate up to 900K, however, operating at high temperatures enhances all the degradation processes, and special technological processes are necessary to achieve a reliable GaN technology for high temperatures. An in depth investigation of the metal/semiconductor contacts at high temperatures is critical, to provide stability of Schottky and Ohmic contacts.

VIII. Conclusion

The degradation rates with respect to the temperature of operation of key parameters, extracted from dc, small-signal, large-signal and noise measurements, are reported for AlGaN/GaN HFETs. GaN-based transistors exhibit lower degradation rates compared to devices fabricated using conventional semiconductors, confirming the potential of wide-bandgap semiconductors for high-temperatures applications. Also, improvements in the device structure and fabrication must be achieved to ensure thermodynamic stability, necessary to provide a reliable high-temperature GaN technology.

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