Output Phase and Amplitude Analysis of GaN-based HEMT at Cryogenic Temperatures

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Abstract—We report both output phase and amplitude performance for GaN-based HEMT, operating in RF small signal and large signal modes from 270K to cryogenic 70K. Intrinsic elements of the device were extracted employing a small-signal equivalent circuit model. Temperature dependences of maximum available power gain, short circuit current gain, and open circuit voltage gain indicated performance improvement as lowering the ambient temperature. Meanwhile, output phase of small RF signal measurement was found to be decreased linearly with decreasing the temperature. In RF large signal operations, power and phase nonlinearity induced by AM-to-AM and AM-to-PM conversion were characterized via gain and phase compression, respectively. Measured $P_{\text{1dB}}$ was decreased monotonously for $T > 150K$, whereas showed little temperature sensitivity under 150K. Output phase shift was expanded as increasing the input power level, and was all greatly suppressed as dropping the temperature.

Index Terms—Amplitude compression, cryogenic temperature, gallium nitride (GaN), high electron-mobility transistor (HEMT), phase compression.

I. INTRODUCTION

A GaN/GaN based high electron mobility transistors (HEMTs) have emerged as promising candidates for high-frequency applications such as wireless communication, radar sensing, and high-resolution positioning, owing to the large carrier mobility and substantial drain current [1]-[3]. Due to outstanding thermal stability, GaN HEMTs enable operations over a wide temperature range. There have been some investigations studying temperature impact on the frequency performance of GaN HEMTs [4]-[7]. Most of them were devoted to measurements and discussions at or above room temperature. However, there is a lack of data available for cryogenic environments, which is important for applications including space exploration, satellite communications, and so on. When evaluating modulated signal quality, e.g., performing measurements of error vector magnitude (EVM) in high-order modulation transmitter system and signal-to-noise ratio in phased-array receiver, phase analysis is equally important as the amplitude or power degradation study [8], [9]. Currently, there are few reports about temperature-dependent phase shift in either small or large signal operations of GaN HEMTs.

In this letter, temperature impact on RF small and large signal operations were studied for GaN HEMT on Si, which is promising to achieve high performance with much reduced cost. $S_{\text{21}}$ phase in small-signal mode was utilized to analyze the phase behavior as a function of temperature. In addition to linear region study, the nonlinear distortions induced by amplitude-to-amplitude conversion (AM-to-AM) and amplitude-to-phase conversion (AM-to-PM) were revealed via gain and phase compression measurements, respectively [10], [11]. Different from commonly-used two-tone intermodulation method, compression measurement method was employed in this work, due to the fact that it can well characterize both the amplitude and phase performance. However, two-tone intermodulation typically only provides the amplitude information with third-order intercept point (IP3) or intermodulation distortion ( IMD). Study on nonlinear amplitude & phase properties in cryogenic environments as well as their temperature dependence paved a solid pathway for designing reliable MMICs functioning properly in extreme of temperatures and large signal conditions.

II. EXPERIMENTAL METHODS

The HEMT on Si epi layer was provided by NTT-AT, and from bottom to top it consists of a nucleation layer, 4 μm-thick C-doped buffer layer, 300 nm undoped channel layer, and 30 nm undoped A0.25Ga0.75N barrier layer. The device used Ti/Al/Ni/Au (20/160/50/100 nm) as ohmic contact after mesa isolation. A 150 nm thick Si3N4 layer was deposited by PECVD.
at 300°C and then annealed for 10 minutes in N₂ at 400°C. Then RIE gate-opening was implemented for Ni/Au gate metal deposition and interconnection. The gate terminal was fabricated into a rectangular shape with length/width of 1μm and 100 μm, respectively.

Based on the scattering parameters (S-parameters) measurement results with RF small signal, device elements were extracted from 270K to 70K with a temperature step of 10K, employing the equivalent circuit model shown in Figure 1(a) [6], [12]. Parasitic capacitances were de-embedded using an open-circuit pattern. Given fixed quiescent operating point (Vgs = -3.6 V and Vds = 4 V), elements including gmos, gds, Cgs, Cgd, Cgd, Rce, and τm, and their temperature dependences were investigated at 2.1 GHz, a frequency extensively used in wireless communication system. Simulation with Advanced Design System (ADS) [6] was used to verify the representation of extracted elements of the GaN HEMT. The temperature impact on output phase was measured in the linear region with input power (Pin) of -20 dBm.

Compression measurements were performed to characterize the nonlinearity of GaN HEMT under Class-AB bias condition with RF large signal. The amplitude and phase of transmission performances were evaluated using linear-region values as baseline points [13]. Specifically, the reference values of both gain and phase were acquired with Pin of -20 dBm.

III. RESULTS AND DISCUSSIONS

A. Amplitude & Phase Behavior in Small Signal Operations

Figure 1(b) shows the transfer and transconductance characteristics of the GaN HEMT at room temperature, with Vds = 4 V. The threshold voltage Vth was determined to be -4.3 V, which was extracted from the linear extrapolation of Ids-Vgs curve. In this work, Vgs was kept at -3.6 V, around which DC transconductance g_m and the magnitude of S21 reached their maximum values. The output characteristic at Vgs = -3.6 V presents a knee voltage of 1.2 V, and saturation current of 92.4 mA/mm. A breakdown voltage of more than 100 V is achieved in the off-state measurement.

Figure 2 illustrates the extracted elements from small-signal equivalent circuit model and time constant τm (τm = Rce*iCgd) [5]. Temperature-dependent transconductance g_m0 and output conductance g_s are shown in Figure 2(a). As decreasing the temperature, g_m0 was typically increased until 120K and then slightly dropped, whereas g_s was decreased and then saturated. The evolution of g_m0 was highly associated with electron mobility-temperature relationship, that carrier mobility hit its maximum value at around 120K. The small g_s corresponding to the large output resistance, is highly demanded in achieving small power dissipation inside the transistor and higher output microwave power [6]. As shown in Figure 2(b), the input capacitance Cgs is much larger than other two capacitances. From 270K to 70K, the increase of Cgs would play a negative role in achieving high current output cut-off frequency (fI) according to the expression of g_m0/(2π*(Cgs+Cgd)). Meanwhile, a reduction of feedback capacitance Cgd from 24.4 fF to 10.7 fF would lead to a high voltage gain and compensate phase distortion resulted from g_m0 nonlinearity [14]. The increased output capacitance Cgd as lowering the temperature should be considered and compensated by the susceptance when designing HEMT-based circuits, although Cgd has a minor effect on fI. The measured values of input resistance Rce were reduced from 154 ohm/mm to 32 ohm/mm, as decreasing the temperature (Figure 2(c)), a trend in a good agreement with the published work [6]. Due to significant reduction of Rce, the calculated τm shows a negative trend with temperature, as illustrated in figure 2(d). The intrinsic delay time τm was slightly increased, which was attributed to the increase of depletion length toward the drain terminal, as reflected by the reduction of Cgd. Based on linear temperature dependence, as expressed as: P(T)=P(T0) [1+ β(T−T0)], where T0 = 270K, β is the temperature coefficient [6][7]. β of g_m0, g_s, Cgs, Cgd, Cgd, Rce, and τm are extracted to be -0.38%, 0.51%, -0.11%, 0.3%, -0.98%, 0.5%, and -0.25% respectively.

Figure 3(a) reports maximum available power gain (MAG), short circuit current gain (hβ21)2, and open circuit voltage gain (A_v). MAG and |hβ21|2 are derived directly from the measured S-parameters, whereas A_v is derived by g_m0/g_s. Owing to the small value of g_s, A_v reached its peak value of 124.8 at 130K, more than doubled than the value obtained at room temperature and those reported in the literature [5]. Both MAG and |hβ21|2 were typically increased as cooling the environment, and the values were slightly decreased after hitting the peaks at 120K, 11.4 dB and 8.5 dB, respectively. The slight drop of MAG, |hβ21|2, and A_v was also attributed to reduction of electron mobility in the corresponding temperature range, from 120K to 70K. As shown in Figure 3(b), both current gain cut-off frequency f_I and maximum work frequency f_mw were improved, from 3.6 GHz to 4.7 GHz (30.5% improvement), and from 7.1 GHz to 8.6 GHz (21.1% improvement) respectively, although Cgd was expanded with decreasing temperature (Figure 2(b)). It is attributed to the fact that g_m0 dictates the variations of f_I and...
RF power at a low or cryogenic temperature. The occurrence, which indicates a smaller dynamic range of input associated to the lowering of 1/3/5-dB gain compression decreasing the temperature. The increment of harmonics is harmonics climb from -27.5/-43.2 dBm to -16.8/-31 dBm as $V_{ds} = 4$ V). As shown in the inset of Figure 4(c), 2nd/3rd order points, in a line with the results that higher gain and larger $g_{m0}$ was achieved as decreasing the temperature. Single-tone nonlinearity (AM-to-AM conversion) is characterized by 1/3/5-dB power compression point ($P_{1dB}$), referring to the input power at which the gain shifts from linearity by 1/3/5-dB. All of the measured $P_{1dB}$ was decreased monotonously for $T > 150$K, at which the measured $P_{1dB}$ was deviated from its 270K-point by 1.36 dB, however, shows little sensitivity to temperatures below 150K. The assumption [7] that power compression requires a pre-set output power to reach certain amplitude degradation could explain the lowering of 1-dB points, in a line with the results that higher gain and larger $g_{m0}$ was achieved as decreasing the temperature. Single-tone harmonics were measured at frequency of 4.2 / 6.3 GHz with input power of 8 dBm, and the device is biased at the same DC point as the gain and phase compression test ($V_{gs} = -3.6$ V, $V_{ds} = 4$ V). As shown in the inset of Figure 4(c), 2nd/3rd order harmonics climb from -27.5/-43.2 dBm to -16.8/-31 dBm as decreasing the temperature. The increment of harmonics is associated to the lowering of the 1/3/5 dB gain compression occurrence, which indicates a smaller dynamic range of input RF power at a low or cryogenic temperature.

Figure 4(d) illustrated the phase deviations from the reference value, for four different $P_m$ (-5/0/5/10 dBm). The output phase was typically unchanged as the device was fed with small input power no larger than 0 dBm. However, with a relatively large input power of 10 dBm, the phase compression was decreased from 4.3° at 270K to 1.6° at 140K, a temperature dependence which should be taken into account when designing high performance millimeter-wave modulators demanding low-EVM. The narrowed and stabilized output phase shift under 150K was attributed to the reduction of $C_{gs}$ at cryogenic temperatures that phase distortion was reportedly mitigated as suppression of feedback capacitance $C_{gs}$ [14].

**IV. CONCLUSION**

Output phase and amplitude of GaN HEMT was investigated from 270K to 70K, for both RF small signal and large signal operations. Based on small signal measurements, temperature dependent amplitude analysis showed that output gains including MAG, $j_{3dB}$, and $A_v$ were all increased until 120K and then slightly compromised; while output phase exhibited a linear decrease for the whole temperature range. Meanwhile, nonlinearity of large signal performance was investigated employing gain and phase compression measurements. 1/3/5-dB compressions were found to be occurred at a relatively smaller input power as dropping the temperature until 150K and showed little sensitivity below 150K. The phase compression at the input power of 5 dBm or above was typically narrowed down as cooling the environment into cryogenic range. The compression measurement method and results paved a way for characterizations of power and phase nonlinearity of HEMT devices and utilization of GaN-HEMTs for cryogenic RF applications.
REFERENCES


