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Power added efficiency and linearity tradeoffs in GaN and GaAs microwave power HEMTs

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ABSTRACT

In this paper, power added efficiency (PAE) and linearity characteristics of AlGaN/GaN HEMTs are compared with those of high-voltage GaAs pseudomorphic HEMTs. Devices with different gate widths are characterized for their power output, gain, PAE and linearity performances as a function of bias current and source and load impedance. When compared to the source/load power matched condition, source tuning provides a significant improvement in the linearity without compromising the PAE performance, whereas, load tuning results in a substantial reduction in PAE to gain a marginal improvement in linearity. For the GaN devices, a maximum power added efficiency (PAE) of 58.5% for class AB operation and a maximum third order intercept point (IP3) of 42.7 dBm for class A operation were obtained. When operated at similar dc power dissipation conditions under class AB bias, similar output power and efficiency were measured for the GaN and GaAs devices, but three times higher power density and better linearity were measured for the GaN devices compared to the GaAs devices.

1. Introduction

At present, GaAs pseudomorphic HEMTs (pHEMTs) are widely used for microwave power applications [1,2]. As standard pHEMTs approach their theoretical power limits [3], new device technologies capable of high-voltage and high-power operation are required [4–6]. The GaN based HEMT devices, made on SiC substrates, are an attractive alternative due to a higher breakdown voltage (3 MV/cm vs. 0.4 MV/cm) of GaN and a higher thermal conductivity (4.9 W/cm K vs. 0.5 W/cm K) of the SiC substrate compared to the GaAs pHEMT devices [7–9]. In addition to requirements for high output power and high power efficiency, there is also an increasing demand for highly linear components for multi-tone and digital telecommunication systems [6,10–12]. In this work, we measured and then compared the power efficiency and linearity performance of 0.5 μm GaN/AlGaN HEMTs with 0.3 μm GaAs pHEMTs fabricated with a well matured GaAs technology. As presented later in this paper, even non-optimized GaN HEMT devices not only offer superior power density performance, but also better linearity at high power level with respect to state-of-the-art GaAs devices [13–16]. To our knowledge, there are not many studies where the power added efficiency/linearity performance of GaN HEMTs is compared with that of GaAs pHEMT devices. At this time, there are only a few papers [17–19] on the linearity of AlGaN/GaN HEMTs. Hence, in this work we have thoroughly characterized GaN HEMTs for their linearity under various bias and impedance matching conditions.

In this paper, we present the results of source-pull and load-pull measurements under single-tone and two-tone conditions on GaN and GaAs devices, and discuss the biasing and tuning conditions which maximize linearity and efficiency. The linearity and efficiency of the devices are evaluated by the third order intercept point (IP3) and power added efficiency (PAE), respectively. A comparison of the linearity and PAE performance of GaN and GaAs is made for devices with similar dc power levels. In this paper, performances of HEMTs with different gate widths are compared in terms of power density (W/mm) and linearity figure of merit (LFOM), which is defined as the ratio of IP3 to the dc dissipated power. More detailed definitions on each of the device performance quantities are given in Ref. [20].

2. Experiment

Devices delivered to the US Government under a contract were used in this study. The AlGaN/GaN HEMTs examined in this study were grown by metal organic chemical vapor deposition (MOCVD) on semi-insulating SiC substrates. The gate lengths were 0.5 μm and the gate widths were 300 μm and 500 μm. The gate metal was Ni/Au and the ohmic contact metal was Ti/Al/Ni/Au. The GaAs devices were field plate based pHEMTs with gate lengths of 0.3 μm and total gate widths of 500 μm, 700 μm and 900 μm. The gate

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metal for the GaAs pHEMTs was Ti/Pt/Au and the ohmic contact metal was Au/Ge/Ni.

A "focus microwaves" on-wafer load-pull measurement system capable of CW and two-tone excitation at frequencies between 0.8 GHz and 18 GHz was used for the measurements in this paper. With this system, dc bias control, RF excitation, source and load tuner positioning, and data acquisition were all under computer control. The electro-mechanical tuners were capable of providing reflection coefficients in excess of 0.8 at most of the frequencies, and the power levels attainable were sufficient to drive the devices in this study well into compression under both CW and two-tone excitation.

A series of source- and load-pull measurements and CW and two-tone power measurements were performed at several different DC bias conditions in order to investigate output power and efficiency vs. linearity performance tradeoffs for GaN HEMTs and GaAs pHEMTs as functions of bias class and impedance matching conditions. Linearity was evaluated in terms of IP3 and linearity figure of merit (LFOM). Main focus of the measurements in this work was on class AB bias condition for both types of devices. Measurements were also made for class A bias condition on GaN devices and class B bias condition on both GaN and GaAs devices. Class A bias condition on GaAs devices was not pursued due to excessive power dissipation. For brevity, in this paper, only qualitative results are presented for class B bias condition.

The CW measurements in this study were performed at 4 GHz, and the two-tone measurements performed with tones at 4.000 GHz and 4.001 GHz. Both output power and linearity of the device are known to improve with increasing V_{DS} [13,21]. In this work, all measurements were done keeping V_{DS} at one fixed value. All GaN HEMTs were biased at a fixed V_{DS} of 25 V and GaAs pHEMTs were biased at a fixed V_{DS} of 15 V. The gate voltages (V_{GS}) of the devices were adjusted for drain–source current, $I_{DS} = 0.7I_{DSS}$ (where I_{DSS} is drain–source current with zero applied gate voltage) for class A and $I_{DS} = 0.15\ I_{DSS}$ for class AB, for both GaN and GaAs devices.

For bias current dependent measurements impedance matching was done at both source and load side to obtain maximum output power. For source-pull measurements, the load impedance is fixed for power matching (optimum output power) and the source impedance is varied from the optimum PAE value to the optimum IP3 value; and vice versa for load-pull measurements.

3. Results and discussion

For the 300 μm gate width GaN HEMTs, variation of P_{out}, gain, and PAE with P_{in} for CW operation and variation of $P_{out,f1}$ and $IM3_{2f1-f2}$ (one of the third-order intermodulation distortion product) with $P_{in,f1}$ for two-tone operation are shown in Fig. 1a and b, respectively, at various bias conditions. For each bias condition, both source and load were power matched with input power level at 15 dBm. Though, at low P_{in}, the values of P_{out}, gain, and IM3 are bias current dependent, they become independent at high P_{in}. As the bias current decreased from $0.7I_{DSS}$ (class A) to $0.15I_{DSS}$ (class AB), the maximum PAE increased from 38.7% to 55.2%, where as the IP3 decreased (not directly shown) from 41.0 dBm to 31.8 dBm. The PAE and IP3 values obtained for the $0.5I_{DSS}$ and $0.3I_{DSS}$ bias currents are 45.6%, 40.0 dBm and 51.7%, 36.2 dBm, respectively. The tradeoff observed between efficiency and linearity is expected for a change in bias from class A to class AB [19,22]. The improvement in PAE with decreasing bias current is achieved without compromising the output power and gain of the device.

After studying the effect of bias current on efficiency and linearity, source- and load-pull measurements were performed on 300 μm GaN HEMT for further evaluation of class A and class AB bias conditions. For class A, source tuning to maximize IP3 resulted

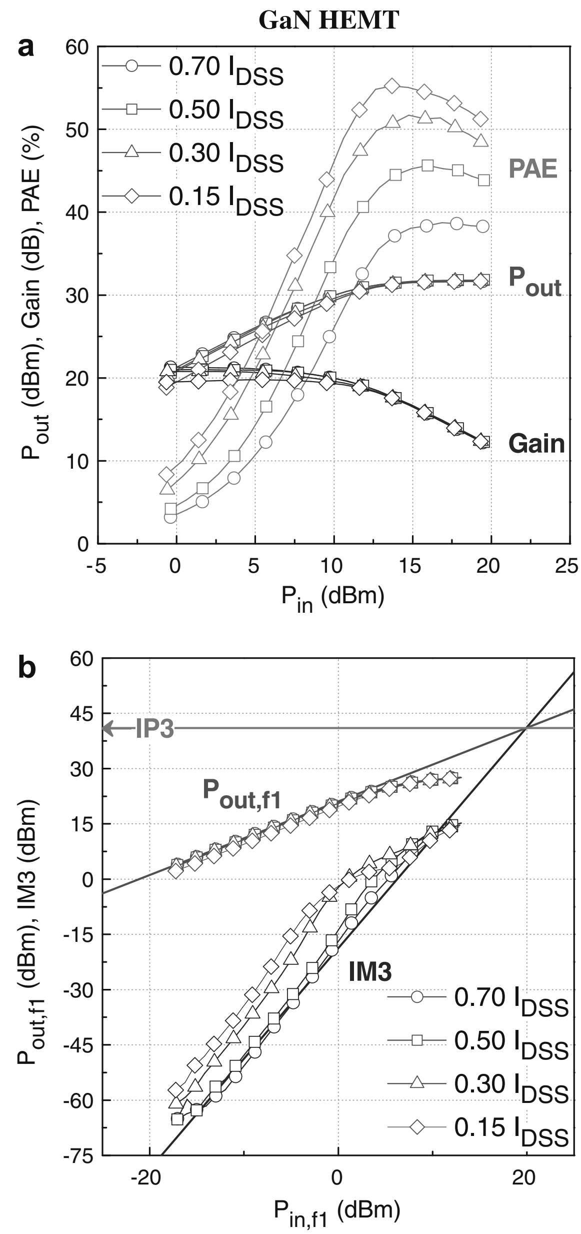

Fig. 1. Bias effect on (a) single-tone and (b) two-tone power performance of 300 μm GaN HEMT.

in an unacceptable reduction in PAE (not shown). To achieve a 11.0 dB increase in IP3 a significant reduction (from 38.4% to 31.4%) in PAE is required. Variation of P_{out}, gain, and PAE with P_{in} for CW operation and variation of $P_{out,f1}$ and IM3 with $P_{in,f1}$ for two-tone operation are shown in Fig. 2a and b, respectively, for class AB bias at three different source impedance values including those corresponding to the optimum PAE and optimum IP3. The third impedance point marked as "midpoint" in Fig. 2 corresponds to the source impedance where contours of intermediate PAE and IP3 values cross each other. For class AB, source tuning improved linearity (IP3) by 5.8 dB, from 32.4 dBm to 38.2 dBm, without any significant changes in maximum P_{out} and maximum PAE. The source tuning from optimum PAE to optimum IP3 resulted in: (1) a decrease in output power and gain at low P_{in} levels, and (2) a shift in the PAE peak towards higher P_{in} values. The maximum PAE observed for optimum PAE match in Fig. 2a is 58.5% which is slightly better than the 55.2% value observed for class AB in Fig. 1a (without source tuning for optimum PAE). As stated before, the source