InGaP PHEMTs for 3.5GHz W-CDMA Applications

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Abstract **— In this paper we present DC, small signal, and power characteristics of an InGaP PHEMT device using InGaP as barrier layer material. A comparison of intrinsic Gm, Rds, Cgs, and Cgd with an AlGaAs PHEMT device showed that InGaP PHEMT is a very promising material for microwave and RF linear power amplification. Operating from 12 V supplies, a 15.4 mm InGaP PHEMT device achieved 29.5 dBm output power with 12.1 dB associated gain and 25.6% power-added-efficiency at 3.5 GHz, while meeting the –40 dBc ACPR specification under W-CDMA stimulus.**

I. INTRODUCTION

Power amplifiers with high output power, low distortion and high efficiency are in strong demand for the next generation base station applications. AlGaAs/InGaAs PHEMT devices have entered the market with higher efficiency than Si devices [1-2]. There also has been great interest in replacing AlGaAs with InGaP material in GaAs based InGaAs channel PHEMT device structures for the following reasons. First, InGaP does not have DX centers as in the case of AlGaAs material, which will improve the RF swing at the open channel condition especially for the higher supply voltage operation. Secondly, InGaP material lattice matched to GaAs breaks down at a higher electric field than the AlGaAs material normally used in AlGaAs PHEMTs, which will provide a higher off state breakdown and benefit the high voltage operation. In previous work, InGaP PHEMTs have been used in X band low noise amplifiers and fundamental device studies [3-9]. In this paper, we present the DC and small signal characteristics of our InGaP PHEMT device. RF power performance under 3.5 GHz W-CDMA format for the base station application is also presented, and a comparison to the production AlGaAs PHEMT is made.

II. FABRICATION

The InGaP PHEMT epitaxial wafers are grown by metal organic chemical vapor deposition (MOCVD) on semi-insulating GaAs substrate. The epitaxial structure is a double heterojunction structure with a lattice matched InGaP Schottky barrier layer on top of an undoped InGaAs channel, as illustrated in figure 1. At room temperature, the typical sheet charge and mobility is 2.0E12 cm^{-2} and 6500 cm^2/Vs, respectively. Device fabrication process is similar to the filled gate AlGaAs PHEMT process [10-11], except that H_3PO_4/HCl was used for removing the InGaP etch stop layer. In order to provide good thermal and electrical conduction to the ground, the wafer was thinned to 25 μm from the backside and through via technology was utilized.

GaAs Cap
InGaP Etch Stop
GaAs Recess
InGaP Schottky
Si-δ doping
InGaP Spacer
InGaAs Channel
AlGaAs Spacer
Si-δ doping
AlGaAs Barrier
Buffer Layer
GaAs Substrate

Fig. 1. Double heterojunction structure of the InGaP PHEMT.

III. DC PERFORMANCE

Typical IV characteristics of a 0.6 μm x 200 μm InGaP PHEMT device is shown in figure 2. In Fig. 2, gate source bias voltage ranges from 0 to –1.5 V with –0.25 V voltage step. As can be seen, Idss of 242 mA/mm was obtained on this InGaP PHEMT. Two terminal gate-drain reverse breakdown voltage of 47 V was obtained on this device where breakdown is defined by the gate drain voltage at Igd=-1 mA/mm condition, as illustrated in Fig. 3. This high breakdown is consistent with the theoretical value of InGaP based on its wide bandgap property.

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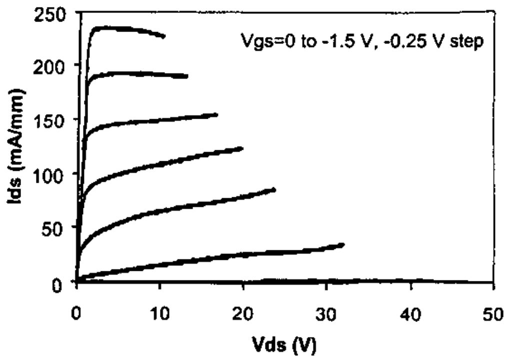


Fig. 2. IV characteristics of a 0.6 μm x 200 μm InGaP PHEMT.

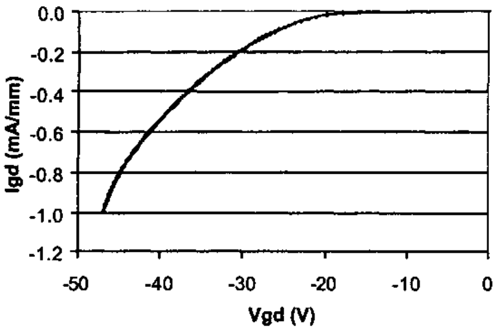
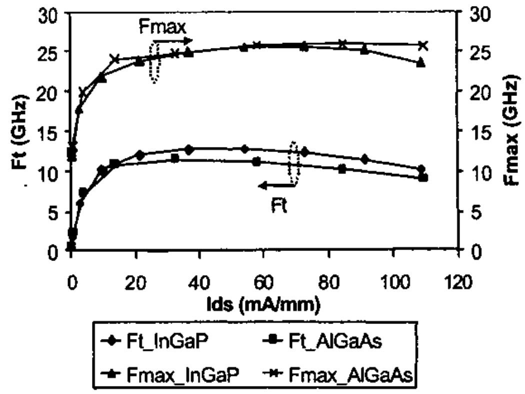


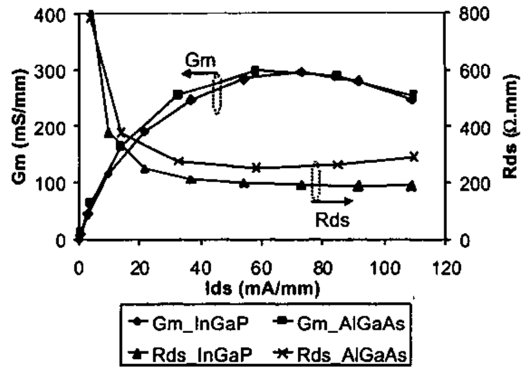
Fig. 3. Gate-drain reverse breakdown curve of a 0.6 μm x 200 μm InGaP PHEMT.

IV. SMALL SIGNAL PERFORMANCE

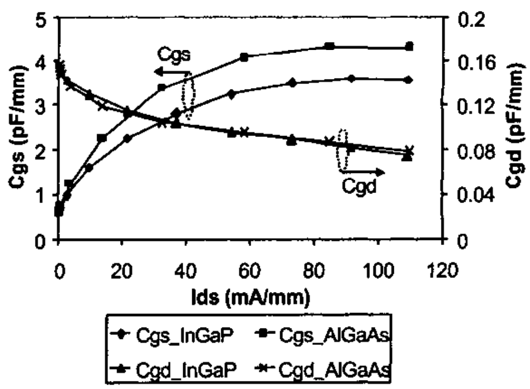
Small signal S-parameter measurements were conducted on a 1.9 mm RF probeable device using an HP8510C network analyzer in the ICCAP framework. Equivalent circuit parameters at 12 V were then extracted from S-parameters in the frequency range of 45 MHz to 26.5 GHz. Device Ft, Fmax, and the major nonlinear parameters Gm, Rds, Cgs, and Cgd are displayed in Fig. 4 (a) through 4 (c) as a function of drain source current. The same parameters from a production AlGaAs PHEMT device are included in these figures for comparison purposes. During W-CDMA operation, device will be DC biased at around Idq=12 mA/mm, and the average drain current will not exceed Ids=25 mA/mm under RF signal swing considering self-biasing effect. Comparing the data within the 25 mA/mm range in figure 4, it is evident that the intrinsic InGaP PHEMT device has very similar Ft, Fmax, Gm, and Cgd parameters as the AlGaAs device. The smaller Rds and Cgs in the InGaP device (Fig. 4 (b) and 4 (c)) may come from the differences in the detailed design of epitaxial structures.



4 (a)



4 (b)



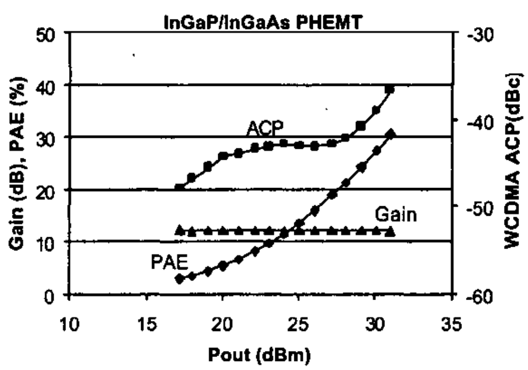
4 (c)

Fig. 4. Intrinsic small signal equivalent circuit parameters of a 1.9 mm InGaP and a 1.9 mm AlGaAs PHEMT device biased at 12 V. (a) Ft and Fmax, (b) Gm and Rds, (c) Cgs and Cgd.

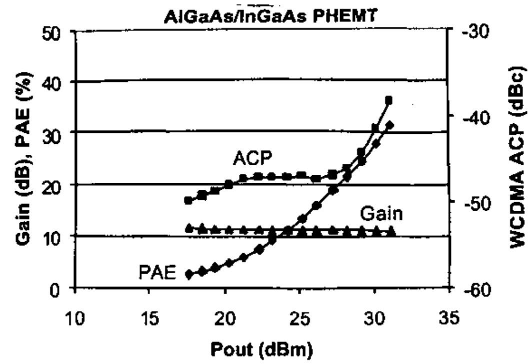
V. POWER PERFORMANCE

As the real demand for the base station application lies in the linear characteristics of the device, W-CDMA power performance of a 15.4 mm InGaP PHEMT was acquired using a Maury load pull system. The W-CDMA modulation signal used in the measurement has an 11.2 dB peak-to-average ratio at 0.01% probability. Figure 5 displays the W-CDMA gain, adjacent channel power ratio (ACPR), and power added efficiency (PAE) versus output power at 3.5 GHz, Vds=12 V, Idq=180 mA. ACPR of −40 dBc is normally specified as the linearity requirement for the device because linear RF power amplifier manufacturers can design to this level. It is seen from Fig. 5 (a) that the InGaP/InGaAs device can produce 29.5 dBm output power with 25.6% efficiency and 12.1 dB associated gain, while meeting the ACPR specification of −40 dBc. This performance is not as comparable to the production AlGaAs/InGaAs device (Fig. 5(b)), which produces 30.6 dBm output power with 29.7% PAE and 11.2 dB gain, when satisfying −40 dBc ACPR. This performance hit is believed to be due to the extrinsic source and drain resistances of the InGaP device. We have observed higher ohmic contact resistance in the InGaP/InGaAs epitaxial structure than in the AlGaAs/InGaAs device. Large On-resistance has suppressed the RF signal swing, and consequently, limited the output power, efficiency, and linearity.

Even though the InGaP PHEMT device RF performance reported in this paper is poorer than the production AlGaAs PHEMT [2], it is still very good considering neither the epitaxial structure nor the device process is optimized. Further optimization is on-going to improve the RF performance.



5 (a)



5 (b)

Fig. 5. Gain, power-added-efficiency, and ACP of the 15.4 mm (a) InGaP and (b) AlGaAs PHEMTs biased at 12 V and 180 mA operated under W-CDMA stimulus at 3.5 GHz.

VI. CONCLUSION

InGaP PHEMTs have been fabricated in Motorola's CS1 production fab. DC, small signal, and large signal power performance were presented in this paper. In summary, intrinsic small signal characteristics of this InGaP PHEMT are as good as the AlGaAs PHEMT, indicating a great potential for the microwave and RF power amplification. For 3.5 GHz W-CDMA application, a 15.4 mm InGaP PHEMT device has achieved 29.5 dBm output power with 25.6% PAE and 12.1 dB associated gain under 12 V operation, while satisfying the −40 dBc ACPR specification. Currently, the limiting factor for the large signal performance is the high extrinsic source and drain resistances. We believe that with improvements in the device fabrication process and optimization in the epitaxial structure, the intrinsic material promise of InGaP will be confirmed.

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