

Enhancement/Depletion Mode InGaP/AlGaAs PHEMT Process for High Efficiency Power Amplifiers

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ABSTRACT

An integrated enhancement/depletion mode InGaP/AlGaAs power PHEMT process is demonstrated for various single- and dual-supply high efficiency power amplifiers. This technology utilizes excellent etch selectivity and surface charge screening properties of InGaP material. At 900 MHz D-mode PHEMT features output power density of 630 mW/mm with PAE=85% at 7 V, while E-mode PHEMT features PAE>70% from 2 to 7 V and high output power densities, especially at lower voltages.

INTRODUCTION

InGaP material is becoming increasingly popular for both PHEMT and HBT devices for power amplifiers and various other wireless applications (1,2,3,4). Its advantages compared to conventional GaAs or AlGaAs include: i) excellent etch selectivity with respect to GaAs; ii) lower surface potential (0.2 eV, compared to 0.8 eV for AlGaAs); iii) absence of deep levels, such as DX centers; iv) lower surface oxidation rate due to absence of Al; v) higher valence band discontinuity at the InGaP/InGaAs hetero-interface, leading to lower leakage currents and higher breakdown voltages. As a result, InGaP HBT offers improved reliability and manufacturability compared to AlGaAs HBT and InGaP PHEMT has a better breakdown-gate lag trade-off than its AlGaAs counterpart.

We developed an integrated enhancement and depletion mode InGaP/AlGaAs PHEMT process for various types of power amplifiers operating from 2 to 7 V, such as wireless handset, car battery powered or other base station amplifiers.

DEVICE TECHNOLOGY

The E/D-mode InGaP/AlGaAs PHEMT schematic is shown in Figure 1. The process uses a double δ -Si doped epi structure with the InGaP ledge, grown by MOCVD. Hall mobility of 5500 cm²/Vs at room temperature is typically achieved for this structure. The D-mode PHEMT is a single-recess device with the TiPdAu gate placed on InGaP, while E-mode PHEMT is a double-recessed device with the InGaP ledge and TiPdAu gate placed on AlGaAs. Both recesses are done by selective wet chemistry. Devices have 0.8 μ m long gates, NiAuGe ohmic contacts and are passivated with PECVD silicon nitride. This process requires only minor changes compared to our conventional AlGaAs PHEMT process.

IV CHARACTERISTICS

Figure 2 shows the transfer IV characteristics of 2 mm E-PHEMT and D-PHEMT devices measured in the pulsed mode. Figures 3 and 4 show the pulsed output IV characteristics of these devices. The E-PHEMT has $I_{dss} = 1$ mA/mm, $I_{max} = 250$ mA/mm, $V_p = +0.1$ V and peak $G_m = 330$ mS/mm, compared to $I_{dss} = 130$ mA/mm, $I_{max} = 410$ mA/mm, $V_p = -0.5$ V and peak $G_m = 310$ mS/mm for D-PHEMT, as summarized in Table 1.

Breakdown voltages measured at $I_g = 0.1$ mA/mm are 22 and 18 V for E- and D-PHEMT, respectively. These high breakdown levels allow high efficiency operation at voltages as high as 7 V with low gate leakage levels and therefore with adequate safety margins with respect to hot-electron-induced degradation.

RF CHARACTERISTICS

2 mm E- and D-mode InGaP/AlGaAs PHEMT devices are characterized at 900 MHz using the automated on-wafer loadpull system, which allows independent tuning of the fundamental and harmonic impedance presented to the device output. Input and output matching is optimized for best efficiency-output power trade-off.

The new “Inverted Class F” mode of operation is employed for high efficiency operation of E-PHEMT in order to compensate for its low I_{max} compared to the D-PHEMT technology. This recently proposed new class of operation (5) features an open circuit termination for the 2nd harmonic and a near short circuit termination for the 3rd harmonic. This results in clamped I_d current waveform and V_{ds} voltage waveform overshoot. Since E-PHEMT technology features relatively low I_{max} and high breakdown voltage, this arrangement would most efficiently utilize the available space in the output I-V plane.

Figure 5 shows performance of 2 mm E- and D-PHEMT devices at $V_{ds}=3.2$ V. The E-PHEMT delivers 24.5 dBm or 141 mW/mm of output power with associated PAE=70% and small-signal gain of 21.4 dB, compared to 24.8 dBm (151 mW/mm) with associated PAE=73.5% and small-signal gain of 22.6 dB for the D-PHEMT.

Device performance at 7 V is shown in Figure 6. The 2 mm E-PHEMT delivers 28.3 dBm or 340 mW/mm of output power with associated PAE=82%, compared to 31 dBm (630 mW/mm) with associated PAE=85% for the D-PHEMT.

Figure 7 shows the output power, power density and PAE for E- and D-PHEMT at different operating voltages. PAE of 70% or higher is achieved for E-PHEMT for the whole range of voltages from 7 down to 2 V. While the power density of E-PHEMT at lower voltages is not much lower than that of the D-PHEMT, it deviates significantly at higher voltages. This happens primarily due to the low I_{max} limitation of E-PHEMT, whereas D-PHEMT can utilize the full current swing resulting in a very high output power density of 630 mW/mm. At the same time in this condition ($V_{ds} = 7$ V) D-PHEMT draws the maximum average negative gate current of 400 μ A/mm, compared to 10 μ A/mm for the E-PHEMT. The RF gate leakage in E-PHEMT can be further reduced to about 1 μ A/mm by adopting the longer first recess on the drain side of the gate.

These results show big promise for the InGaP/AlGaAs PHEMT technology for E-mode, D-mode or combined E/D mode power amplifier applications at various voltages.

CONCLUSION

An integrated enhancement/depletion mode InGaP/AlGaAs PHEMT process for various power amplifier applications is demonstrated. An E-PHEMT had PAE of 70% or higher for the operating voltage range from 2 to 7 V. To the authors' knowledge, PAE=85% and 630 mW/mm achieved for the D-mode InGaP/AlGaAs PHEMT at 7 V are the highest reported to date, while PAE=82% and 340 mW/mm achieved at 7 V by the E-PHEMT are the best for any single-supply technology.

To achieve high efficiency, the new “Inverse Class F” mode of operation of power transistors was used. It featured an open circuit termination for the 2nd harmonic and approximately a short circuit termination for the 3rd harmonic on the output, which resulted in clamped I_d current waveform and V_{ds} voltage waveform overshoot, an especially effective strategy for the low I_{max} E-PHEMT devices.

Finally, the reported InGaP/AlGaAs process results in improved manufacturing due to employment of selective wet chemical recess processing.

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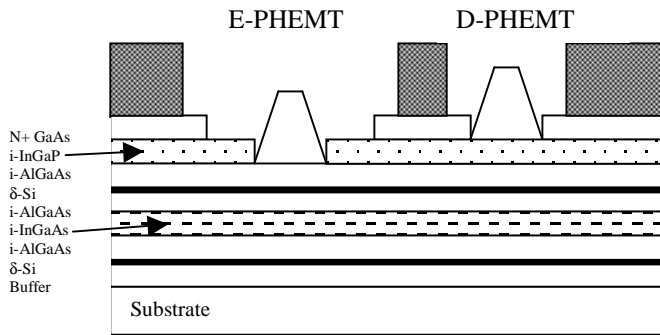


Figure 1. Schematic cross-section of E/D mode InGaP/AlGaAs PHEMT.

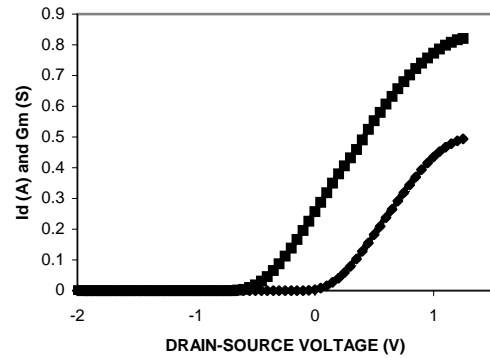


Figure 2. Pulsed transfer IV characteristics of 2 mm InGaP/AlGaAs E-mode and D-mode PHEMT. $V_{ds}=1.5$ V.

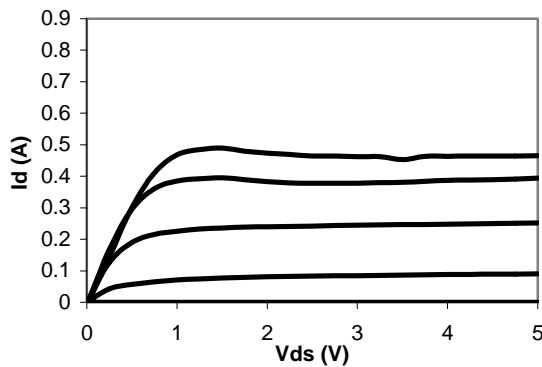


Figure 3. Pulsed IV characteristics of a 2 mm InGaP/AlGaAs E-PHEMT. $V_{gs} = 0.2$ to 1.2 V, step 0.3 V, bottom up.

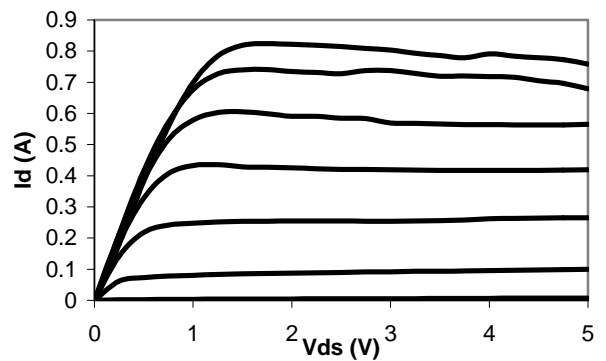


Figure 4. DC transfer characteristics of E-PHEMT at $V_{ds}=2$ V. I_{dss} is approximately equal to $1 \mu\text{A}/\text{mm}$.

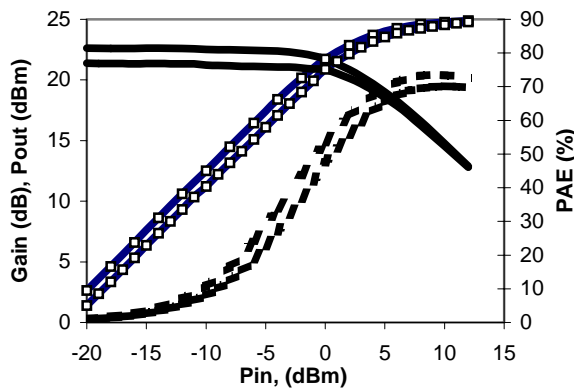


Figure 5. Loadpull characteristics of 2 mm D-mode and E-mode InGaP/AlGaAs PHEMTs at 900 MHz, $V_{ds}=3.2$ V, $I_{d0}=50$ mA. (—) gain, (□) output power, (---) power-added efficiency.

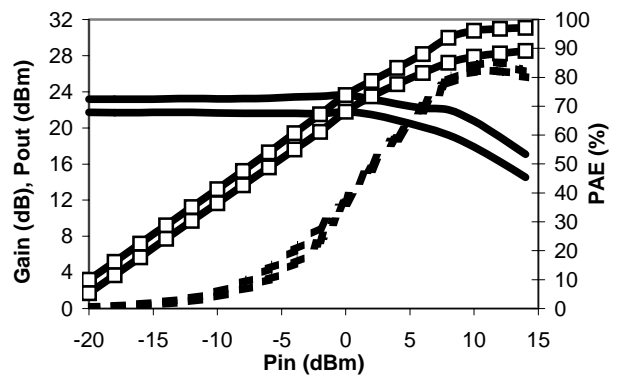


Figure 6. Loadpull characteristics of 2 mm D-mode and E-mode InGaP/AlGaAs PHEMTs at 900 MHz, $V_{ds}=7$ V, $I_{d0}=50$ mA. (—) gain, (□) output power, (---) power-added efficiency.

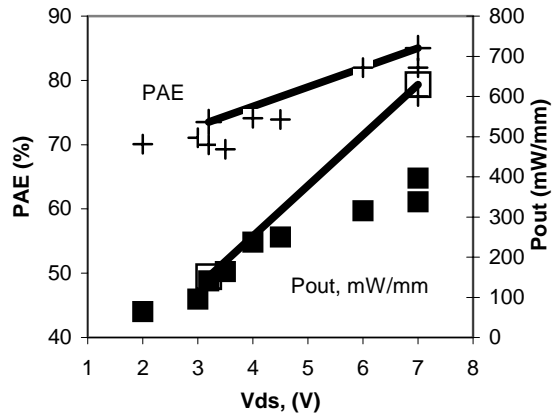


Figure 7. On-wafer loadpull measurements of 2 mm E-PHEMT (symbols) and 2 mm D-PHEMT (lines+symbols): PAE (crosses) and Pout (squares) at 900 MHz.

	E-PHEMT	D-PHEMT
Idss, mA/mm	1	130
Vds=1.5 V		
Imax, mA/mm	250	410
Vds=1.5 V		
Vpo, V	+0.1	-0.5
Vds=1.5 V		
Gm.peak, mS/mm	330	310
Vbd, V	22	18
Ig=0.1 mA/mm		

Table 1. Pulsed IV characteristics of the 2 mm Enhancement mode and Depletion mode InGaP/AlGaAs PHEMT.