High-Efficiency Amplifiers Using AlGaN/GaN HEMTs on SiC

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Abstract

GaN HEMTs on SiC are applied to high-efficiency power amplifier designs. Several class-E hybrid power amplifiers based on the GaN HEMT cell were designed and tested. Around 2 GHz, the first amplifier provides 10 watts CW with associated PAE of 85% and gain of 12 dB. Other higher frequency designs with the same transistor cell provide 10 watts and 80% PAE centered around 2.8 GHz and also 10 watts and 76% PAE centered around 3.4 GHz. Also, a larger-periphery class-E amplifier operating at 2 GHz with a peak power of 63 watts and 75% PAE has been demonstrated using GaN HEMT technology.

INTRODUCTION

Presently, AlGaN/GaN HEMTs on High-Purity Semi-insulating 4H-SiC substrates are being developed to supply a burgeoning market need for high-power, high-efficiency power amplifiers that can improve bandwidth above 3 GHz (e.g, WiMax). Many advantages of wide-bandgap RF transistors, including high-temperature robustness, high output impedance and high power densities, will be leveraged to reduce complexity of architectures in broadband applications and eliminate the current use of more than one PA to cover multiple infrastructure bands [1]. An additonal exciting development in commercialization of GaN HEMTs is that they are ideally suited for switch-mode architectures.

Switch-mode amplifiers, Class-E in particular, offer significant advantages for high-efficiency operation. Although Class-E amplifiers have shown high power and PAE at VHF [2] and also high efficiency at S-band [3], an appropriate transistor technology to achieve both high power and high efficiency over significant bandwidth at microwave frequencies has been heretofore unavailable. The unique combination of high-current and high f_T of a HEMT and also high-breakdown afforded by the wide bandap, enables the GaN/AlGaN HEMT on SiC in high-power switch-mode operation above 2 GHz.

BACKGROUND

Classic switch-mode amplifiers are identified by the use of the active device as a switch rather than as a current source. Efficiency is maximized by synthesizing an output resonant matching network to provide current that is out of phase with the voltage across the switch while also providing sinusoidal output at the load.

One possible implementation of a switch-mode amplifier is shown in Figure 1. An active device is used as a SPST switch with a choke inductor in the drain supply to ensure constant current. The ideal switch is assumed to have good isolation (e.g., high V_{BD}), very low or zero R_{ON} and infinitely high switching speed. This puts very stringent requirements on the transistor technology used in class-E circuits. The capacitance C_1 provides a current path when the switch is open. The resonant circuit parallel to C_1 provides a high-Q that is large enough to suppress harmonics. The simulated current and voltage transients at the ideal switch indicate zero power dissipation and the peak voltage to be roughly 3.5 times V_{DD} of 35 V. The calculated RF power at 2 GHz is about 21 W with 100% efficiency.

The implementation of the amplifier of Figure 1 using a real transistor is shown in Figure 2. Here C_1 is conveniently provided by the c_{ds} of the transistor. It is crucial that the output capacitance be relatively independent of switch voltage since this element is important to the calculation of the LC tank circuit elements. Examining the transients in Figure 2 shows that a non-zero on-resistance and non-zerooutput conductance causes some overlap of current and voltage, and also reduces the peak voltage to about 2.2 times V_{DD}. This results in an expected output power of about 10 W and only 82% efficiency.

SWITCH-MODE DEVICE REQUIREMENTS

In a switch-mode application, requirements other than high breakdown voltage are related in the following expression:

$$f_{\max} \propto \frac{I_{PEAK}}{c_{out} \cdot V_{DD}}$$

Based on this relationship between bias voltage, peak available current, output capacitance and the maximum intended operating frequency, high breakdown voltage can only be utilized at a given frequency if the ratio of I_{PEAK} to output capacitance remains high. High f_T and low on-resistance are also key to increasing efficiency. Considering all active devices available for use in microwave amplifiers, GaN HEMTs offer the best combination of properties for class-E operation above 10 W of peak P_{OUT} at > 2 GHz.

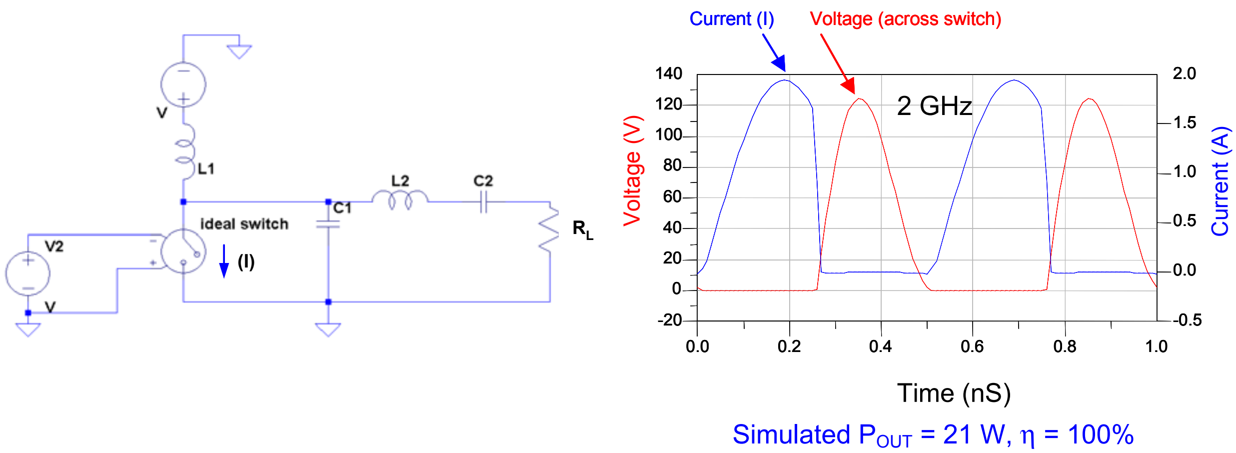


Figure 1. Schematic of an idealized Class-E switched-mode amplifier design and representation of instantaneous voltage and current waveforms showing very low power dissipation through an idealized RF switch (i.e., $R_{ON} = 0$). VDD = 35 V, $R_L = 26\ \Omega$, $C_1 = 0.64$ pF, $L_1 = 50\ \mu$H, $L_2 = 13$ nH, $C_2 = 0.61$ pF.

GaN-on-SiC HEMT Description

The epilayers in our HEMTs are grown by metal-organic chemical vapor deposition (MOCVD) in a high-volume reactor on 3-inch semi-insulating 4H silicon carbide (SI 4H-SiC) substrates that are cut on-axis. The epitaxial growth process is highly reproducible and has been transferred to 4-inch substrates, as well [4]. The typical structure comprises an AlN nucleation layer, 2 µm of Fe-doped insulating GaN, approximately 0.6 nm AlN barrier layer, and a 27 nm cap layer of undoped $Al_{0.24}Ga_{0.76}N$. This nominal layer thickness and mole fraction yields electron mobilities near 2000 cm^2/V-s and sheet electron concentrations of 8-10x10^{12}/cm^2 at room temperature.

The HEMTs are fabricated in the same production facility that is utilized for commercial SiC MESFET discretes and MMIC foundry products [5] with SPC implemented on all processes in congruence with Cree's ISO-9000 certified process. The high-resistivity of the underlying insulating GaN layer provides excellent device isolation. A standard contact alloy of Ti/Al/Ni/Au layers annealed at 850 °C yields an ohmic contact with very repeatable contact resistivity below <0.4 Ω-mm. In the baseline devices, 0.45-µm Schottky T-gates are formed directly on the top AlGaN layer. An offset gate configuration is used to reduce source resistance and increase gate-drain breakdown voltage. In order to accommodate the high peak voltages in a class-E circuit, the breakdown voltage is typically greater than 100 volts. Cree's baseline 10-watt GaN HEMT cell nominally provides a P_{1dB} of 10 watts with associated gain of 17 dB and 60% DE at 2 GHz when operated in class-AB mode at 28 V. These transistors have extremely good linearity, as evidenced by a third-order intermodulation product measured at P_{1dB} that is greater than -31 dBc.

GaN-on-SiC Amplifier Results

A non-linear model has been established for the GaN HEMTs and used to design the class-E hybrid amplifiers that operate in various microwave frequency bands. Typically the output match integrates the entire drain-source capacitance, c_{ds}, into the output matching network design. The input match is designed to provide a reasonable match at approximately 25% I_{PEAK}, which is the full power operating point. It pro-

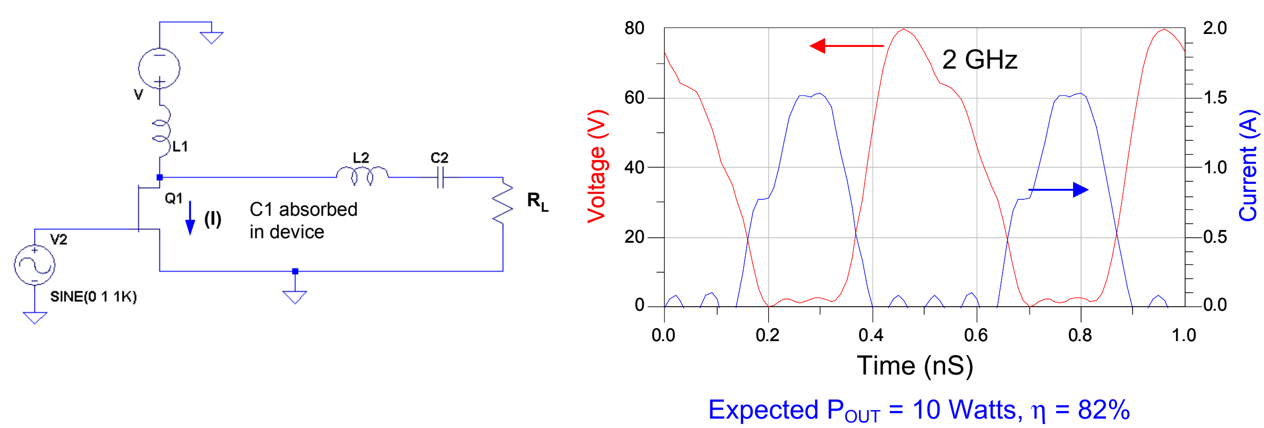


Figure 2. Schematic of a Class-E switched-mode amplifier design and representation of instantaneous voltage and current waveforms showing very low power dissipation through a realistic RF switch (i.e., GaN HEMT w/ $R_{ON} = 6.1\ \Omega$-mm).

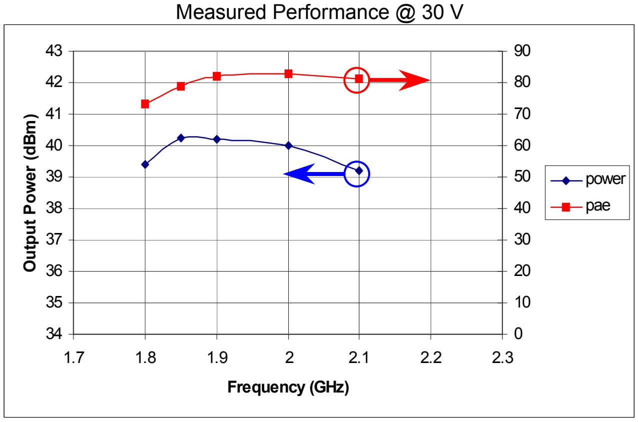
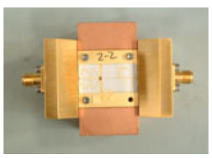


Figure 3. Hybrid design fabricated using advanced GaN device structure and the novel amplifier topology: V_{DD} = 30 volts, 50 Ω input/output, 10 W P_{OUT}, 84% PAE, 1.9 – 2.1 GHz.

vides peak gain under full RF drive. The hybrid amplifiers are constructed using alumina substrates on which the input and output distributed networks are fabricated.



The first demonstration of the high-efficiency design technique with a GaN HEMT was designed around 2 GHz. The measured saturated output power and PAE from 1.8-2.1 GHz are shown in Figure 3. The PAE is greater than 82% with output power above 10 watts in the center of the band. A photograph of the fixturized amplifier is shown in the inset. This combination of power level, efficiency and bandwidth is not known to have been demonstrated with any other semiconductor transistor technology.

In a similar manner, to exploit the frequency capability of the GaN HEMT, two more amplifiers with the 3.6-mm cell were demonstrated at higher frequencies. Measured results shown in Figure 4 show impressive performance of near 10 watts and 80% PAE centered around 2.8 GHz. Furthermore, a hybrid amplifier designed around a center frequency of 3.4 GHz exhibits almost 10 watts and 76% PAE as shown in Figure 5. Note for these three 10-W amplifiers that are fabricated with the same generation device, it is more difficult to maintain bandwidth, power and PAE as the center frequency increases. Next generation devices with improved f_T will improve class-E amplifier performance above 3 GHz.

A much larger periphery amplifier was also designed, fabricated and assembled into a demonstration module as shown in Figure 6. Measured saturated power and PAE for this amplifier are shown in Figure 7. Greater than 60 W is achieved at 2 GHz even while maintaining a very high efficiency of 75% in the large circuit. Refinement of this circuit can flatten the response over a 1.9-2.1 GHz bandwidth. Innovative uses of the class-E amplifier include modulation through the drain supply, which requires a flat PAE response over a wide range of V_{DD}. This behavior is demonstrated in the 60-W HPA as shown a plot of power and PAE vs. drain voltage in Figure 8.

SUMMARY

The utilization of GaN HEMT technology in switch-mode architectures, such as class-E, provides the vehicle to achieve high total power and efficiency at microwave frequencies. With the promise of ultra-high-efficiency operation in the 10's of watts, new architectures and pre-distortion techniques are being developed to utilize GaN HEMT amplifiers in commercial basestation applications [6]. Furthermore, Cree is currently participating in the DARPA WBGS program that is dedicated to making GaN HEMT technology ready for reliable X-band power amplifiers [7].

Cree is also currently driving the diameter of SI 4H-SiC substrates to 4-inches on a Title-III Technology Investment Agreement from the U.S. Air Force. On this program, Cree will accelerate the transition of MMIC technology from 3-inch to 4-inch production. Realization of the high-efficiency

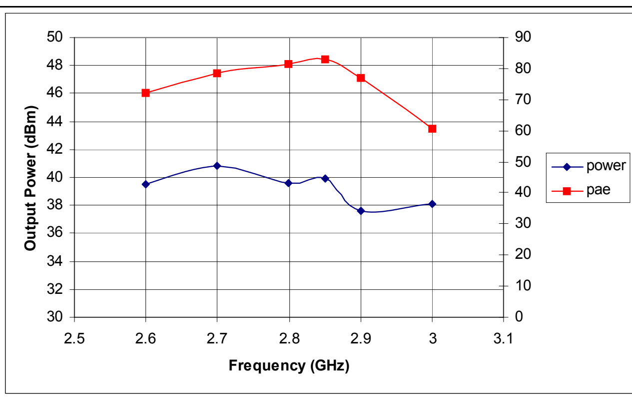


Figure 4. Hybrid design fabricated using advanced GaN device structure and the novel amplifier topology: V_{DD} = 30 volts, 50 Ω input/output, ~10 W P_{OUT}, 12 dB Power Gain, 76-82% PAE, 2.7-2.9 GHz.

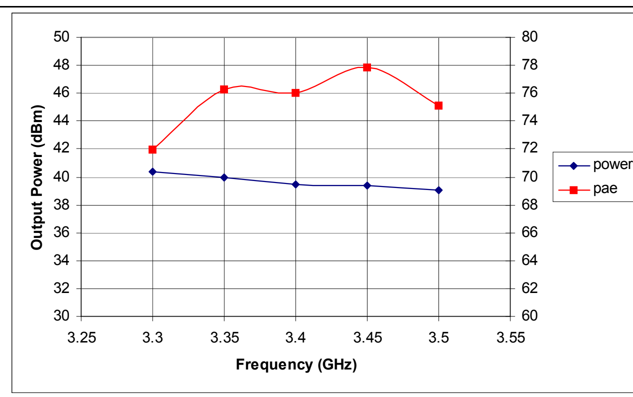


Figure 5. Hybrid design fabricated using advanced GaN device structure and the novel amplifier topology: V_{DD} = 30 volts, 50 Ω input/output, P_{OUT} ~10 W, 11 dB Power gain, 72-78% PAE, 3.3-3.5 GHz.

architecture in MMIC format should be possible.

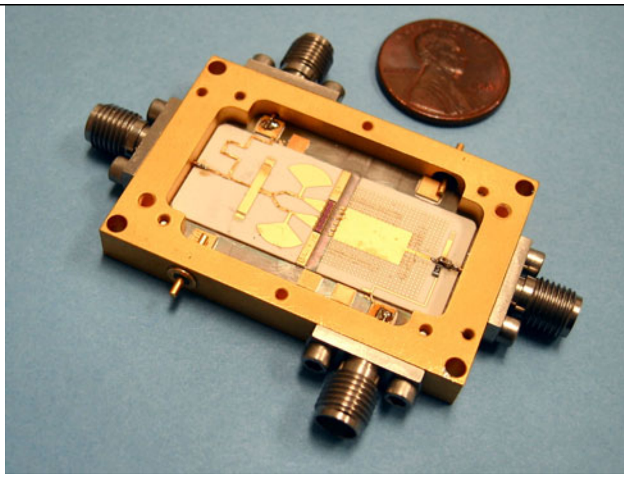


Figure 6. Hybrid Class-E GaN Amplifier Module.

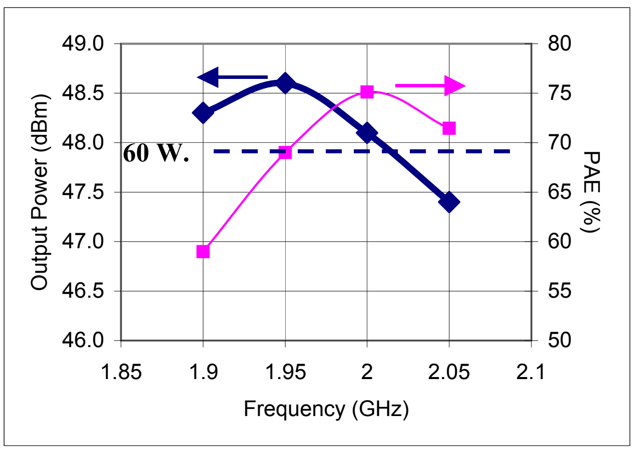


Figure 7. Hybrid design fabricated using advanced GaN device structure and the novel amplifier topology: V_{DD} = 30 volts, 50 Ω input/output, P_{OUT} ~63 W, 18 dB power gain, 75% PAE @ 2 GHz.

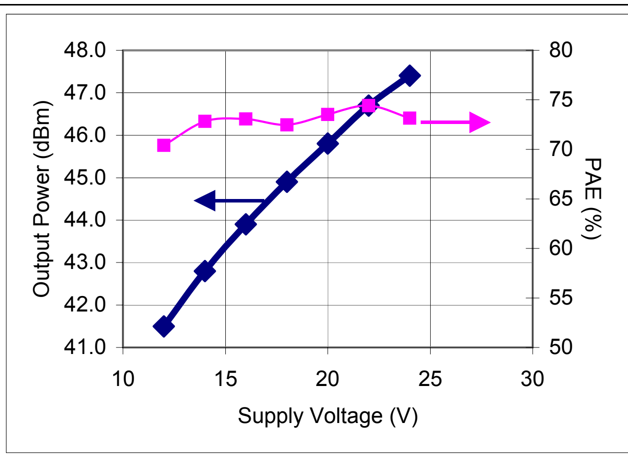


Figure 8. Drain Modulation for the 60-W Class-E Amplifier.

Acronyms

SiC: Silicon Carbide
HPSI: High Purity Semi-insulating
MESFET: Metal Semiconductor Field Effect Transistor
GaN: Gallium Nitride
HEMT: High Electron Mobility Transistor
PA: Power Amplifier
SPST: Single Pole Single Throw
SPC: Statistical Process Control

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