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Wide Bandgap Semiconductor (SiC & GaN) Power Amplifiers in Different Classes

Sher Azam



Linköping University
INSTITUTE OF TECHNOLOGY

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Material Science Division

Department of Physics, Chemistry and Biology
Linköpings universitet, SE-581 83 Linköping, Sweden

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To my Parents, family and all those who pray for the successful completion of this research work

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ABSTRACT

SiC MESFETs and GaN HEMTs have an enormous potential in high-power amplifiers at microwave frequencies due to their wide bandgap features of high electric breakdown field strength, high electron saturation velocity and high operating temperature. The high power density combined with the comparably high impedance attainable by these devices also offers new possibilities for wideband power microwave systems. In this thesis, Class C switching response of SiC MESFET in TCAD and two different generations of broadband power amplifiers have been designed, fabricated and characterized. Input and output matching networks and shunt feedback topology based on microstrip and lumped components have been designed, to increase the bandwidth and to improve the stability. The first amplifier is a single stage 26-watt using a SiC MESFET covering the frequency from 200-500 MHz is designed and fabricated. Typical results at 50 V drain bias for the whole band are, 22 dB power gain, 43 dBm output power, minimum power added efficiency at P_{1dB} is 47 % at 200 MHz and maximum 60 % at 500 MHz and the IMD3 level at 10 dB back-off from P_{1dB} is below -45 dBc. The results at 60 V drain bias at 500 MHz are, 24.9 dB power gain, 44.15 dBm output power (26 W) and 66 % PAE.

In the second phase, two power amplifiers at 0.7-1.8 GHz without feed back for SiC MESFET and with feedback for GaN HEMT are designed and fabricated (both these transistors were of 10 W). The measured maximum output power for the SiC amplifier at $V_d = 48$ V was 41.3 dBm (~13.7 W), with a PAE of 32 % and a power gain above 10 dB. At a drain bias of $V_d = 66$ V at 700 MHz the P_{max} was 42.2 dBm (~16.6 W) with a PAE of 34.4 %. The measured results for GaN amplifier are; maximum output power at $V_d = 48$ V is 40 dBm (~10 W), with a PAE of 34 % and a power gain above 10 dB. The SiC amplifier gives better results than for GaN amplifier for the same 10 W transistor.

A comparison between the physical simulations and measured device characteristics has also been carried out. A novel and efficient way to extend the physical simulations to large signal high frequency domain was developed in our group, is further extended to study the class-C switching response of the devices. By the extended technique the switching losses, power density and PAE in the dynamics of the SiC MESFET transistor at four different frequencies of 500 MHz, 1, 2 and 3 GHz during large signal operation and the source of switching losses in the device structure was investigated. The results obtained at 500 MHz are, PAE of 78.3%, a power density of 2.5 W/mm with a switching loss of 0.69 W/mm. Typical results at 3 GHz are, PAE of 53.4 %, a power density of 1.7 W/mm with a switching loss of 1.52 W/mm.

Preface

This thesis comprises of two sections. The first section contains introduction, importance and response of wide bandgap (SiC and GaN) transistors in power amplifiers. The second section presents results compiled in three publications. This thesis is presented as partial fulfillment of the requirements for the degree of Licentiate of Philosophy, of Linköping University. The work described in the thesis has been carried out at Materials Science Division at Linköping University and at the department of Microwave Technology, Swedish Defence Research Agency (FOI) between September 2005 and May 2008.

List of appended publications

[1] Single-stage, High Efficiency, 26-Watt power Amplifier using SiC LE-MESFET

S. Azam, R. Jonsson, Q. Wahab; IEEE Asia Pacific Microwave Conf. (APMC), Yokohama (Japan), pp. 441–444, December 2006.

[2] Designing, Fabrication and Characterization of Power Amplifiers Based on 10-Watt SiC MESFET & GaN HEMT at Microwave Frequencies

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[3] Pulse Input Class-C Power Amplifier Response of SiC MESFET using Physical Transistor Structure in TCAD.

S. Azam, C. Svensson and Q. Wahab; J. of Solid-State Electronics, Vol. 52/5, 2008, pp 740-744.

RELATED PAPERS NOT INCLUDED IN THE THESIS

[1] Performance of SiC Microwave Transistors in Power Amplifiers

S. Azam, R. Jonsson, E. Janzen and Q. Wahab; Proceedings of MRS 2008 conference, San Francisco, USA, March 24-28, 2008.

[2] Different Classes (A, AB, C & D) of Power Amplifiers using SiC MESFET

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[3] SINGLE STAGE, 47 W, CLASS-AB POWER AMPLIFIER USING WBG SIC TRANSISTOR

S. Azam, R. Jonsson and Q. Wahab; accepted for oral presentation at 32nd Workshop on Compound Semiconductor Devices and Integrated Circuits, WOCSDICE 2008, Leuven (Belgium) May 18-21, 2008.

[4] Influence of interface state charges on RF performance of LDMOS transistor

A. Kashif, T. Johansson, C. Svensson, S. Azam, T. Arnborg and Q. Wahab; In press, J. of Solid-State Electronics.

[5] GaN and SiC Based High Frequency Power Amplifiers

Sher Azam and Q. Wahab; Review article submitted to the book "Micro and Nano Electronics", which will be published by NAM S&T Center, New Dehli.

[6] The Limiting Frontiers of Maximum DC Voltage at the Drain of SiC Microwave Power Transistors in Case of Class-A Power Amplifier.

Sher Azam, R. Jonsson and Q. Wahab; IEEE ISDRS 2007 conference, USA.

[7] Designing of High Efficiency Power Amplifier Based on Physical Model of SiC MESFET in TCAD.

Sher Azam, C. Svensson and Q. Wahab; IEEE International Bhurban Conference on Applied Sciences & Technology Islamabad, Pakistan, 8th-11th January, 2007, pp. 40-43.

[8] A Non-Linear TCAD Large Signal Model to Enhance the Linearity of Transistor

Ahsan-Ullah Kashif, Christer Svensson, Sher Azam, and Qamr-ul Wahab; IEEE ISDRS 2007 conference, USA.

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CHAPTER ONE: Wide bandgap SiC and GaN transistors

1.1 Introduction

The fundamental physical limitations of Si operation at higher temperature and powers are the strongest motivations for switching to wide bandgap semiconductors such as SiC and GaN for these applications. For phase array radars, wireless communication market and other traditional military applications require demanding performance of microwave transistors. In several applications, as well as in radar and military systems, the development of circuits and sub-systems with broadband capabilities is required. From transmitter point of view the bottleneck, and the critical key factor, is the development of high performance PA. The latter, in fact, deeply influence the overall system features in terms of bandwidth, output power, efficiency, working temperature etc. So far, distributed approaches have often been proposed and investigated to design broadband amplifiers also in GaN technology [1]

Next generation cell phones require wider bandwidth and improved efficiency. The development of satellite communications and TV broadcasting requires amplifiers operating both at higher frequencies and higher power to reduce the antenna size of terminal users. The same requirement holds for broadband wireless internet connections as well. This high power and high frequency applications require transistors with high breakdown voltage, high electron velocity and high thermal conductivity. The wide band gap materials, like GaN and SiC are preferable [2]. A summary of the important parameters of Wide band gape materials in comparison to other conventional semiconducting materials Si and GaAs is shown in table 1.1.

The high output power density of WBG transistors allows the fabrication of smaller size devices with the same output power. Higher impedance due to the smaller size allows for easier and lower loss matching in amplifiers. The operation at high voltage due to its high breakdown electric field not only reduces the need for voltage conversion, but also provides the potential to obtain high efficiency, which is a critical parameter for amplifiers. The wide bandgap enables it to operate at elevated temperatures. These attractive features in power amplifier enabled by the superior properties make these devices promising candidates for microwave power applications. Especially military systems such as electrically steered antennas (ESA) could benefit from more compact, broadband and efficient power generation. Another application area is robust front end electronics such as low noise amplifiers (LNAs) and mixers.

Table 1.1 Material parameters of SiC and GaN compared to GaAs and Si [3]

Material	Bandgap [eV]	Critical electric field [MV/cm]	Thermal conductivity [W/cm-K]	Electron mobility [cm ² /Vs]	Saturated electron drift velocity [cm/s]	Relative dielectric constant
4H-SiC	3.26	2	4.5	700	2×10^7	10
GaN	3.49	3.3	1.7	900	1.5×10^7	9
GaAs	1.42	0.4	0.5	8500	1×10^7	12.8
Si	1.1	0.3	1.5	1500	1×10^7	11.8

The critical electric field is the maximum field that the material can sustain before the onset of breakdown and is closely related to bandgap. When the electric field is so high that the carriers can acquire a kinetic energy larger than the band gap, new electron-hole pairs can be created through impact ionization. These newly created carriers are in turn accelerated and, if the electric field is sufficiently high the process is repeated again and again. This causes an increase in the current that will degrade the efficiency and output power and ultimately destroy the device due

to the heat generated. Therefore the critical field limits the supply voltage that can be used for the transistor and hence output power.

The maximum current in the device under high electric field is controlled by the saturated electron velocity (by limiting the flux of electrons). A higher v_{sat} will allow higher current and hence higher power. The saturated electron velocity of SiC and GaN is atleast compared to Si and GaAs. High power per unit gate width is important in the field of microwave devices, because the device needs to be small compared to the wavelength of operation in order to avoid dispersion that would otherwise degrade the gain and efficiency.

The electron mobility of SiC and GaN is inferior to that of Si and GaAs. This reduces the efficiency of the device by increasing the knee voltage especially in the case of SiC MESFET but this effect is reduced by the high breakdown voltage of SiC, which enables a sufficiently high supply voltage that the knee voltage becomes small in comparison. The relatively low mobility of SiC also reduces the high frequency capability of devices. But the impact of the low mobility of SiC on the high frequency performance is partially offset by the high v_{sat} [4]. Working devices have been reported at X-band frequencies [5]. Due to higher mobility and the ability to use high electron mobility transistor (HEMT) structures, GaAs and GaN transistors can be used at substantially higher frequencies than Si or SiC transistors.

Heat removal is a critical issue in microwave power transistors especially for class-A power amplifier operation and continuous wave (CW) applications. The thermal conductivity of SiC is substantially higher than that of GaAs and Si. The large bandgap and high temperature stability of SiC and GaN also makes them possible to operate devices at very high temperatures [6]. At temperatures above 300 °C, SiC and GaN have much lower intrinsic carrier concentrations than Si and GaAs. This implies that devices designed for high temperatures and powers should be fabricated from wide bandgap semiconductors, to avoid effects of thermally generated carriers. When the ambient temperature is high, the thermal management to cool down crucial hot sections introduces additional overhead that can have a negative impact relative to the desired benefits when considering the over all system performance.

The power microwave devices of conventional semiconductors have low impedance, while microwave systems generally use 50 Ω . It is more difficult to build an amplifier from the low impedance device because of the loss and the narrower bandwidth imposed by the matching circuits needed. The higher impedance (higher supply voltage) and lower relative dielectric constant (reduces parasitic capacitances) for both SiC and GaN compared to Si and GaAs simplifies broadband impedance matching. Another important property of amplifiers is their linearity. Excellent linearity has been reported for SiC MESFETs both in power amplifiers [7], and low noise amplifiers [8]. The same is the case for GaN HEMT, because the HEMT structure was announced as the device with lowest noise characteristics in the world [9].

1.2 Performance of SiC transistors in Power Amplifiers

SiC exists in a large number of cubic (C), hexagonal (H) and rhombohedral (R) polytype structures. It varies in the literature between 150 and 250 different. For microwave and high temperature applications the 4H is the most suitable and popular polytype. Its carrier mobility is higher than in the 6H-SiC polytype, which is also commercially available. For microwave, high temperature and power applications 4H-SiC is competing with Si and GaAs up to X- band applications.

The efficiency improvement of power amplifiers decreases power consumption and heat sink requirements, and increases output power because power amplifiers account for the majority of power consumption in wireless communications. Therefore, the switching-mode power amplifiers have recently received attention to improve efficiency. A high efficiency, class-E RF power amplifier in the VHF range is implemented. A maximum drain dc to RF efficiency of 87% was predicted and 86.8 % achieved with 20.5 W output power at 30 V drain voltage [10]. The SiC MESFETs used appear to offer significant advantages, particularly for space applications, over

gallium arsenide (GaAs) transistors, which are inherently low voltage device and more difficult to operate in class-E due to the high drain peak voltage occurring in this class of operation.

Another class-E power amplifier using SiC MESFET is reported with power added efficiency (PAE) of 72.3% and a gain of 10.3 dB at an output power of 40.3 dBm, through significant reduction of harmonic power levels [11]. A new type of pulse input class C power amplifier is reported with a maximum PAE of 80% at 500 MHz, a gain of 36.9 dB and power density of 1.07 W/mm.[12]

A power amplifier (PA) for WiMAX Military Applications in Nato Band I (225 to 400MHz) has been simulated, assembled and tested. Under 802.16 OFDM 64QAM3/4 modulations, the average output power is 25W throughout the bandwidth [13]. A class-E power amplifier using a SiC MESFET is designed and tested at 2.14 GHz. The peak power-added efficiency of 72.3% with a power gain of 10.27 dB is achieved at an output power of 40.27 dBm [14].

Most publications on SiC microwave components concerns L to C-band operation, since these are important radar frequency bands. However, the frequency performance up to the X band has been predicted to be good [15] and SiC MESFETs with power densities of 4.5 W/mm at 10 GHz have been demonstrated [16]. The power amplifier is a narrow-band 3–3.5-GHz design based on a 6-mm SiC MESFET. The amplifier was measured on-wafer and showed a typical power gain of 7 dB, an output power of 2.5 W in continuous wave (CW) operation, and 8W in pulsed mode at 3 GHz. [17]

A single-stage 26 W negative feedback power amplifier is implemented, covering the frequency range 200-500 MHz using a 6 mm gate width SiC Lateral Epitaxy MESFET. The results at 60 V drain bias at 500 MHz are, 24.9 dB power gain, 44.15 dBm output power (26 W) and 66 % PAE [18]. Previous reports on SiC MESFET transistor amplifiers designed for frequencies below 500 MHz showed an output power of 37.5 W and a power density of 1.78 W/mm, the gain was 8 dB, and the efficiency in class A-AB was 55 % at 500 MHz. The IMD3 level at 10 dB back-off from P_{1dB} was -35 dBc for a 1 MHz frequency offset between tones [19].

A Class C mode power amplifier is implemented with a 75 V power supply voltage. The total output power was measured to be 2100 W with a power gain of 6.3 dB, collector efficiency of 45% and power added efficiency of 35%. This is the first time; SiC BJTs have been used to produce an output power of 2 kW at 425 MHz. Although the gain and PAE are not very high, the individual cells are capable of producing 50 W with a gain of 9.3 dB and 51% collector efficiency. [20]. Two SiC MESFET package and prototype power amplifier were demonstrated with P_{1dB} output power of 26 and 35W, respectively. High power and high power gain were maintained through L-band operation across 500 MHz bandwidth (950 MHz to 1500 MHz with 10 dB gain) for the SiC PA module, which will be a critical challenge to other semiconductor devices. [21]

These results show that although SiC based PAs presently can't compete with GaN and other conventional devices like GaAs in terms of frequency but in terms of power and efficiency, they could be the strong competitors and future devices for, RADAR, Electronic Warfare (EW), Wireless Communications and base stations applications.

1.3 SiC MESFET

The hole mobility of SiC is low, so majority carrier devices, such as MESFETs are preferred, which do not rely on holes for their operation. The 4H-SiC has been the material of choice for high frequency SiC MESFETs because of the higher electron mobility in 4H-SiC (approximately twice that of 6H-SiC). The first SiC MESFETs were fabricated on conducting substrates, which limits the frequency performance by creating large parasitic capacitances in the device. The solution is to process devices on highly resistive or semi-insulating (SI) substrates. In 1996 S. Siriam et al. published the development of 4H-SiC MESFETs on SI substrates [22]. The devices had a gate length of 0.5 μm and exhibited f_{max} of 42 GHz. The output power density has since climbed to the levels predicted by Trew et al. in [23]; a power density of 5.6 W/mm at 3 GHz

has been reported by Cree [24]. A schematic of MESFET structure is shown in Figure 1.1. Similar structure was optimized in our group [25]. This structure was further optimized and studied in some part of this research work.

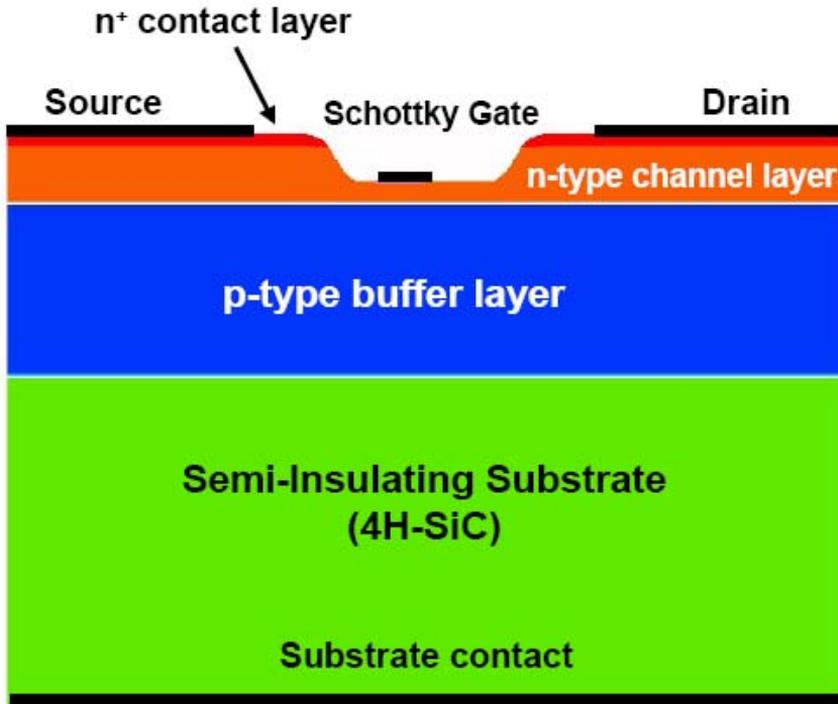


Fig. 1.1: Schematic of MESFET structure. In large transistors (for high Power), multiple gates are combined to increase gate width (wg).

1.4 Performance of GaN transistors in Power Amplifiers

In the last decade, AlGaIn/GaN HEMT technology has established itself as a strong contender for the applications of phase array radars, wireless communication market and other traditional military applications because of its large electron velocity ($>10^7$ cm/s), wide band gap (3.4 eV), high breakdown voltage (> 50 V for $f_T = 50$ GHz) and sheet carrier concentration ($>10^{13}$ cm $^{-2}$). Due to the superior electronic properties of the GaN material and the possibility to use SiC substrate demonstrating high thermal conductivity (3.5 W/cm.K), power densities as high as 30 W/mm @ 4 GHz [26] as well as output power of 500 W @ 1.5 GHz [27] have already been achieved. An output power of 75 W of a packaged single-ended GaN-FET has been reported under pulsed conditions for L/S band applications [28].

The GaN technology is currently widely used for power amplifier applications. In mobile base station applications a number of manufacturers and researchers have reported high efficiencies, output powers and power densities [29]–[50]. A class-E amplifier at 13.56 MHz with a high-voltage GaN HEMT as the main switching device is demonstrated to show the possibility of using GaN HEMTs in high frequency switching power applications such as RF power-supply. The 380 V/1.9 A GaN power HEMT was designed and fabricated for high voltage power electronics applications. The circuit demonstrated has achieved the output power of 13.4 W and the power efficiency of 91 % under a drain-peak voltage as high as 330 V. This result shows that high-

voltage GaN devices are suitable for high-frequency switching applications under high dc input voltages of over 100 V. [29]. The Eudyna GaN hybrid power amplifier is capable of efficiently delivering 200 W at 2.1 GHz for W-CDMA applications [30].

The saturated Doherty power amplifier implemented using two Eudyna EGN010MK GaN HEMTs with a 10 W peak envelope power for 2.14 GHz forward-link W-CDMA signal. The amplifier delivers an excellent efficiency of 52.4% with an acceptable linearity of 28.3 dBc at an average output power of 36 dBm. Moreover, the amplifier can provide the high linearity performance of 50 dBc using the digital feedback pre-distortion technique [31]. A wideband envelope tracking Doherty amplifier, implemented using Eudyna 10 W GaN high electron mobility transistor for world interoperability for microwave access (WiMAX) signals of the 802.16 d and 802.16 e, the Doherty amplifier covers the 90 MHz bandwidth. The envelope tracking amplifier delivers a significantly improved relative constellation error (RCE) performance of 35.3 dB, which is an enhancement of about 4.3 dB, maintaining the high PAE of about 30 % for the 802.16 d signal at an average output power of 35 dBm [32].

An ultra wide-band high efficiency power amplifier (PA) is implemented in GaN technology as shown in Fig. 3. A HEMT device with 1 mm of gate periphery at 0.8-4 GHz, showing drain efficiency greater than 40% with an output power higher than 32 dBm in the overall bandwidth [33]. CREE Inc. has also demonstrated compact, high-power microwave amplifiers taking advantage of the high-voltage and high power density of GaN HEMTs [39]. A peak power of 550 W (57.40 dBm) is achieved at 3.45 GHz with 66% DE and 12.5 dB associated gain. An outstanding power-efficiency combination of 521 W and 72.4% is obtained at 3.55 GHz. Such power levels, accompanied by the high efficiencies, are believed to be the highest at around 3.5 GHz for a fully-matched, single-package solid-state power amplifier, attesting the great potential of the GaN HEMT technology.

The state-of-the-art efficiency over 50% drain efficiency (over 45 % PAE) of GaN HEMT high power amplifier with over 50 W output power at C-band is proposed and implemented in [40]. A 16 mm gate periphery will be enough for 60 W output power for this power density. Considering that GaAs demands 75.6 mm gate-width for 20 W output [41], a 230 mm total gate width would be needed to realize 60 W. Therefore, GaN HEMT devices are desirable to realize broadband high power amplifier.

A 2-stage amplifier up with the 30 W driver stage amplifier, 42 % efficiency (including 30 W driver amplifier) and -50 dBc ACLR at the average power of 49 dBm (80 W) with saturation power of 56.5 dBm and Gain of 32 dB is obtained for WCDMA applications [42]. A 0.4 mm wide GaN device with 0.15-gm gate and 0.25-gm field plate operated up to 60 V achieved 13.7 W/mm power densities at 30 GHz, the highest for a FET at millimeter-wave frequencies. [43]

A highly efficient, wide band power amplifier designed in GaN technology and utilizing a non-uniform distributed topology is reported. Measured results demonstrate very high efficiency across the multi-octave bandwidth. Average CW output power and PAE across 2-15 GHz was 5.5 W and 25 %, respectively. Maximum output power reached 6.9 W with 32 % PAE at 7 GHz. [44]. The results obtained for class-E power amplifier using GaN HEMT are; the power added efficiency (PAE) of 70 % with a gain of 13.0 dB at an output power of 43.0 dBm, through significant reduction of harmonic power levels [11].

A class F mode PA using Eudyna's GaN HEMT has been biased at class C and adopted a new output matching topology that improved the overall transmitter efficiency. For the WiMAX OFDM signal, the calculated overall drain efficiencies of the optimized EER amplifier, which are based on the measured bias dependent efficiencies, are about 73 % at an average power of 31 dBm at 2.14 GHz. The proposed highly efficient bias modulation PA for the EER transmitter provides a superior overall efficiency than that of any conventional switching or saturation mode PAs.[45]

A 2-chip amplifier has recorded 220 W output power at C-band, which is the highest output power ever reported for GaN HEMT amplifiers at C-band and higher bands [46]. A highly efficient broadband monolithic class-E power amplifier is implemented utilizing a single

0.25 μm x 800 μm AlGaIn/GaN field-plated HEMT producing 8 W/mm of power at 10.0 GHz. The HPA utilizes a novel distributed broadband class-E load topology to maintain a simultaneous high PAE and output Power over (6-12 GHz). The HPA's peak PAE and output power performance measured under three pulsed drain voltages at 7.5 GHz are: (67 %, 36.8 dBm @ 20 V), (64 %, 37.8 dBm @ 25 V) and (58 %, 38.3 dBm @ 30 V) [47].

A C-band high-power amplifier with two GaN-based FET chips exhibits record output powers under continuous-wave (CW) and pulsed operation conditions. At 5.0 GHz, the developed GaN-FET amplifier delivers a CW 208 W output power with 11.9 dB linear gain and 34 % power-added efficiency. It also shows a pulsed 232 W output power with 8.3 dB linear gain [48]. A class D-1 amplifier is implemented with GaN MESFETs and working around 900 MHz, delivering 51.1 W output power with 78 % peak drain-efficiency [49].

A highly efficient class-F power amplifier (PA) using a GaN HEMT designed at W-CDMA band of 2.14 GHz has the drain efficiency and power-added efficiency of 75.4 % and 70.9 % with a gain of 12.2 dB at an output power of 40.2 dBm [50]. The GaN HEMTs have also proven to be very attractive and viable as a power source for millimeter wave applications [51]– [55]. Similar to microwave frequencies, microstrip and CPW MMICs have been demonstrated, a microstrip Ka band GaN MMIC power amplifier capable of delivering 11 W of output power [51]. Wu et al. announced an amplifier with an 1.5-mm-wide device produced 8.05 W output power at 30 GHz with 31 % PAE and 4.1 dB associated gain. The output power matches that of a GaAs-based MMIC with a 14.7 m wide output device but with a 10 times smaller size. Recently, GaN MMIC performance has been demonstrated at W-band as well [55].

The demonstrated high power amplifiers and MMICs with high power densities, efficiencies and suitable gain will enable the proliferation of solid state solutions at millimeter wave frequencies.

1.5 GaN HEMT

The High Electron Mobility Transistor (HEMT) is a commonly used transistor for microwave and high power amplifiers applications. The idea of world's first High electron mobility transistor was presented in the late seventies [9]. Conventional HEMTs on today's market has material limitations and scientists have pushed the GaAs material to its theoretical limit during the last 50 years. New techniques and materials are required for the development of today's technology. The GaN is the material of choice for the next generation of HEMT technology because of its strong physical and electronics properties.

The HEMT is one type of FET family of transistors with excellent high frequency characteristics. It consists of epi layers grown on top of each other with three contacts attached to the surface. These contacts are called drain, source and gate. When a source-drain voltage is applied, the current through the device is amplified and also can be controlled by the gate voltage. An AlGaIn HEMT usually works in depletion mode i.e. current flows through the device even without an external gate-voltage [56]. The gate voltage necessary to stop the current flow between the source and drain is defined as the pinch-off voltage. The operation principle of a MESFET is more or less identical to a HEMT with the use of a Schottky gate contact to deplete a channel [57]. When the gate voltage is zero there is a potential well present at the AlGaIn/GaN hetero interface. Inside this well a two-dimensional electron gas will be formed. The 2DEG is usually a couple of nanometers thick. It is in this thin layer all electrons are gathered to minimize their energy. This thin channel is also known as a conducting channel where electrons travel from source to drain. Since the well is very thin, electrons prefer to move sideways in two dimensions instead of up and down because otherwise they would have to move out of the well into a less preferable energy state [58]. The AlGaIn-GaN hetero junction requires some special attention due to its polarization fields. The potential profile and amount of charges induced at the interface in an AlGaIn/GaN interface are strongly dependent of the polarization fields that GaN and AlGaIn materials pose [59]. The AlGaIn HEMT does not require an n+ doped top layer (like in AlGaAs HEMT for

electrons in 2DEG). In fact, the polarization fields are so strong that it alone can provide high amount of electrons to the junction [60]. A schematic of GaN/AlGaN HEMT structure is shown in Figure 1.2.

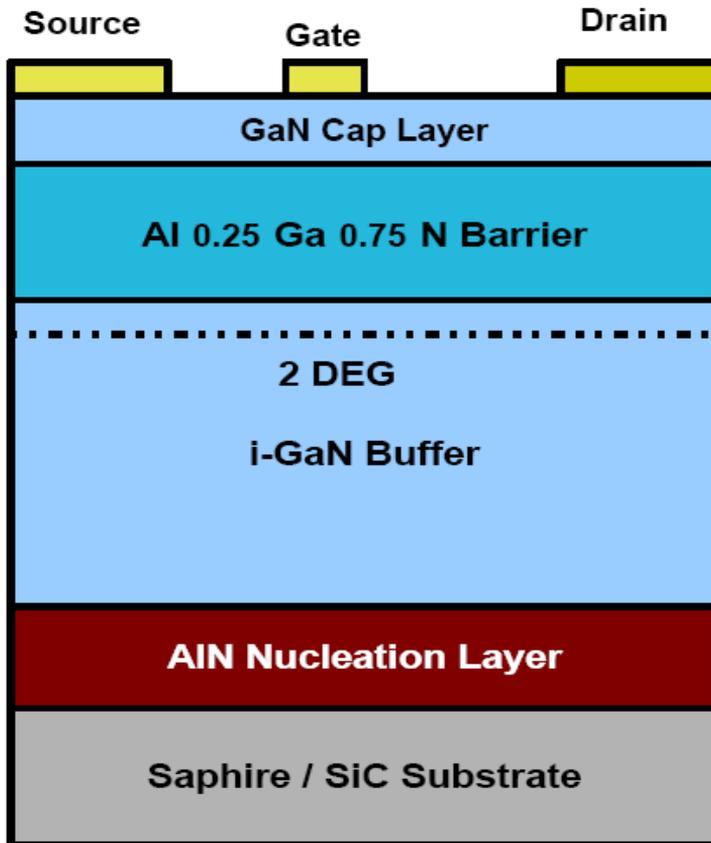


Figure 1.2: Schematic of GaN/AlGaN HEMT structure.

CHAPTER TWO: POWER AMPLIFIER CLASSES

2.1 Power Amplifier Classes

There are different classes of power amplifiers but a power transistor performance can be conveniently evaluated using a class-A or class-AB. The design comprises of several blocks like biasing network, input matching network, output matching network for the input and output ports to be matched with 50 Ohm which is the requirement of the system.

The class of operation of a power amplifier depends upon the choice of gate and drain DC voltages called quiescent point (Q-point). The choice of q-point greatly influences linearity, power and efficiency of the amplifier. Also for the PA the primary objective is to provide the required amount of power to antenna. The typical classes of power amplifiers on the basis of gate biasing are shown in Fig. 2.1. The most common classes are briefly described below.

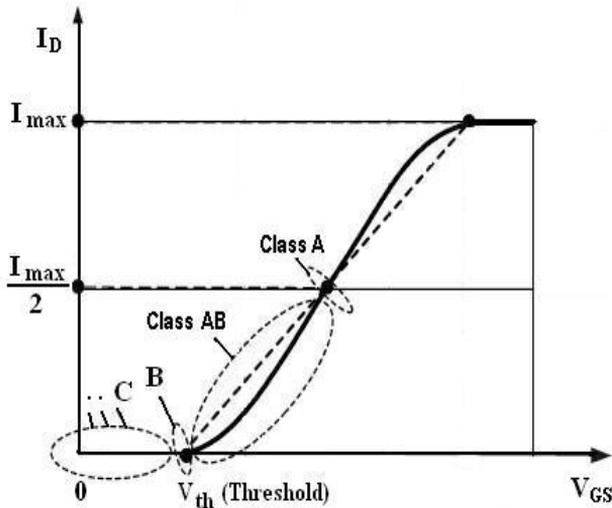


Fig. 2.1: The typical classes of power amplifiers on the basis of gate biasing.

2.1.1 Class A

Class-A are the most linear amplifiers with the q-point biased close to half of the maximum drain current. They have low DC power efficiency (theoretically equal to 50 %). Figure 2.1 shows biased q-point for class-A operation. The strongly non-linear effect (overdrive) occurs only when the drain current exceeds its saturation point (pinch-off) and/or gets into sub threshold region (cut-off).

2.1.2 Class B

For a class-B amplifier the operation point has to be selected at the threshold voltage to achieve high power efficiency (theoretically equal to 78 %). In a given case the linear characteristics drastically decrease due to the fact that the conduction angle is half as that for class-A. There will be current through the device only during half of the input waveform

(the positive part for the N-channel transistor). Hence, the input power capability of such a mode is almost twice as high.

2.1.3 Class AB

The class-AB amplifier shows a flexible solution for a trade-off between linearity and efficiency of the previous classes. In this mode the q-point has to be chosen in between A and B points with its exact place being a matter of application requirements. Therefore, the conduction angle is typically chosen closer to the threshold voltage as shown in Fig. 2.1. Thus, the transistor response of class-AB is wider than for class-B due to the operation point. Also, the power efficiency is higher than for class-A. Many telecommunication applications utilize this mode.

2.1.4 Class C

In the application where linearity is not an issue, and efficiency is critical, non-linear amplifier classes (C, D, E, or F) are used. Class C is an amplifier with a conduction angle of less than 180 degrees. In Class C, the amplifying device is deliberately operated non-linearly as a switch, in order to reduce resistance losses. In effect, the tank circuit makes the RF output sine wave. The theoretical efficiency of a typical Class C amplifier approaches 100 %.

2.1.5 Class D

A class-D amplifier, which may also be known as a switching amplifier or a digital amplifier, utilizes output transistors which are either completely turned on or completely turned off (switch mode operation). This means that when the transistors are conducting (switched on) there is virtually no voltage across the transistor and when there is a significant voltage across the transistor (switched off), there is no current flowing through the transistor. When we have simultaneous voltage across and current flow through the device, there will be power dissipation in the form of heat. This heat is wasted power. Class D PA use two or more transistors as switches to generate square drain-current or voltage waveform.

2.1.6 Class E

Like class-D it also has switch mode operation with some design modification. Class E PA use single transistor operated as switch. In the ideal situation, the efficiency of a class-E amplifier is 100%. However, in practice, the switch has a finite on-resistance, and the transition times from the off-state to the on-state and vice-versa are not negligible. Both of these factors result in power dissipation in the switch and reduce the efficiency.

2.1.7 Class F

The class-F amplifier is one of the highest efficiency amplifiers. It uses harmonic resonators to achieve high efficiency, which resulted from a low dc voltage current product. In other words, the drain voltage and current are shaped to minimize their overlap region. The inductor L and capacitor C are used to implement a third harmonic resonator that makes it possible to have a third harmonic component in the collector voltage. The output resonator is used to filter out the harmonic, keeping only the fundamental frequency at the output. The magnitude and the phase of the third harmonic control the flatness of the collector voltage and the power of amplifier.

2.2 Power Amplifier Design Considerations

The descriptions of power amplifiers in the previous section have dealt with ideal devices. In reality, transistor amplifiers suffer from a number of limitations that influence amplifier operation and ultimately reduce their efficiency and output power. In practical FET, there are four fun-

damental effects that force the operation of FET to deviate from the ideal case: the drain source resistance, the maximum channel current I_D , the open channel avalanche breakdown voltage, and the drain-source break down voltage [Robert, 1988]. The following are the major properties of amplifiers, which a designer has to consider in designing.

2.2.1 Output Power

It is the actual amount of power (in watts) of radio frequency (RF) energy that a power amplifier produces at its output. Power transistors are the most expensive components in power amplifiers. In cost driven designs, designers are constrained to use the lowest cost transistors. The larger power output capability of the circuit design, the cheaper its practical implementation.

2.2.2 Power Gain

The gain of an amplifier is the ratio of an output power to its input power. There are three important power gains are average power gain, transducer power gain and available power gain.

2.2.3 Stability

It is a major concern in RF and microwave amplifiers. The degree of an amplifiers stability can be quantified by a stability factor. The transistor is stable when embedded between 50- Ω source and load, and it will not oscillate. However, this is not considered unconditional stability, because with different source and load impedances the amplifier might break into oscillation. A properly designed (stabilized) amplifier will not oscillate no matter what passive source and load impedances are presented to it, including short or open circuits of any phase.

2.2.4 Power-Added Efficiency

Efficiency is output power versus input power, while PAE includes the effect of the drive power used frequently at microwave frequencies. It is a crucial parameter for RF power amplifiers. It is important when the available input power is limited, like mobile etc. It is also important for high power equipment, when the cooling system cost is significant compared to actual equipment.

2.2.5 Linearity

Real amplifiers (not ideal) are only linear within certain practical limits. When the signal drive to the amplifier is increased, the output also increases until a point is reached where some part of the amplifier becomes saturated and cannot produce any more output; this is called clipping, and results in non linearity. Class A is the most linear lowest efficiency PA and linearity decreases and efficiency increases when we go to class AB, B and all switching PAs are the most non linear and most efficient amplifiers.

CHAPTER THREE: CONCLUSIONS

Three power amplifiers are presented using SiC MESFET and GaN HEMT at 200-500 MHz and 0.7-1.8 GHz. Typical results for single stage 26-watt power amplifier using a SiC MESFET covering the frequency range from 200-500 MHz at 50 V drain bias for the whole band are, around 22 dB power gain, around 43 dBm output power, minimum power added efficiency at P_{1dB} is 47 % at 200 MHz and maximum 60 % at 500 MHz and the IMD3 level at 10 dB back-off from P_{1dB} is below -45 dBc. The results at 60 V drain bias at 500 MHz are, 24.9 dB power gain, 44.15 dBm output power (26 W) and 66 % PAE.

In the second generation, two power amplifiers at 0.7-1.8 GHz without feed back for SiC MESFET and with feedback for GaN HEMT are designed and fabricated (both these transistors were of 10 W). The measured maximum output power for the SiC amplifier at $V_d = 48$ V was 41.3 dBm (~13.7 W), with a PAE of 32 % and a power gain above 10 dB. At a drain bias of $V_d = 66$ V at 700 MHz the P_{max} was 42.2 dBm (~16.6 W) with a PAE of 34.4 %. The measured results for GaN amplifier are; maximum output power at $V_d = 48$ V is 40 dBm (~10 W), with a PAE of 34 % and a power gain above 10 dB. The SiC amplifier gives better results than for GaN amplifier for the same 10 W transistor.

A comparison between the physical simulations and measured device characteristics has also been carried out in this work. A novel and efficient physical device large signal simulation technique is further developed to study the class-C switching response of the devices. The method was used to investigate the switching losses, power density and PAE in the dynamics of the SiC MESFET transistor at four different frequencies of 500 MHz, 1, 2 and 3 GHz during large signal operation and to find the source of switching losses in the device structure. The results obtained at 500 MHz are, PAE of 78.3 %, a power density of 2.5 W/mm with a switching loss of 0.69 W/mm. Typical results at 3 GHz are, PAE of 53.4 %, a power density of 1.7 W/mm with a switching loss of 1.52 W/mm.

These results show that although SiC based PAs presently can not compete with GaN and other conventional devices like GaAs in terms of frequency but in terms of power and efficiency, they could be the strong competitors and future devices for, RADAR, Electronic Warfare (EW), Wireless Communications and base stations applications. In terms of power and efficiency GaN devices are and will be superior above 10 GHz.

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