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Review Article

A High Efficiency Class AB AlGaN/GaN HEMT Power Amplifier for High Frequency Applications

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Abstract

GaN HEMT is chosen for many high frequency applications such as Power Amplifiers because of its desirable properties. Most semiconductors fail at high frequency applications because of their thermal and bias limitations. It's very difficult to operate the amplifier at high frequency and high power ratings. The HEMT transistors can operate at high electric fields and high frequencies. The heterojunction structure provides more no of free electrons without any doping which significantly improves the mobility and the current. The heterostructure also blocks the current flow in unwanted directions. This paper explains about GaN HEMT transistor and its practical application as a Power Amplifier. CREE CGH40010F GaN (10 W) device is chosen and developed at the schematic level. The schematic provides 15.5 dB gain and 66% efficiency.

Keywords: GaN HEMT; Hetero-junction; Power Amplifier

Introduction

In microwave frequency applications, Vacuum Electronic Devices (VED) like Travelling Wave Tube and Klystron modulator but they are heavy and bulky. In comparison, solid-state devices have advantages like (i) Low maintenance. (ii) Instantaneous operation. (iii) Cheaper and less bulky [1].

When it comes to solid-state devices, devices that are made by silicon were used very widely. But there are some limitations that make them unsuitable for Microwave, such as 5G applications [3]. (i) Reduced electron velocity in the semiconductor produces reduced current. (ii) Thermal limitations of the semiconductor. (iii) Bias limitations. (iv) Achieving the required frequency at high power ratings is difficult.

To increase the current, we need to increase the cross-sectional area, which leads to an increase in capacitance. Thus, the speed of the device reduces. High capacitance and low impedance reduce the operating frequency [8].

We are not using silicon made devices in high frequency applications because of the above reasons. The material should withstand the conditions and shoul have some desirable properties to use solid state devices in microwave applications. That is the reason why we are going to use GaN made HEMT structures in High frequency power amplifiers [8].

Desirable properties of GaN

Before GaN HEMT, many structures were proposed, such as MESFET, AlGaAs/GaAs HEMT, to increase mobility and to operate at high frequencies. But later, GaN material came into the discussion, which has many advantages over GaAs/AlGaAs, such as (i) high breakdown field. (ii) Large energy gap. (iii) Low dielectric constant. (iv) Thermal conductivity can be achieved by using SiC as substrate [8].

Material	***Eg (eV)***	***εr***	***K(W/°K-cm)***	***Ec (V/m)***
Si	1.12	11.9	1.5	$3x10^5$
SiC	2.86	10.0	4	$3.8x10^6$
GaN	3.4	9.5	1.3	$2x10^6$
Diamond	5.6	5.5	20-30	$5x10^6$

Table 1: Comparison of parameters in different materials.

High Saturation velocity

The disadvantage of other materials compared to the GaN is they saturate at high electric fields, which means we cannot increase the mobility at the higher electric field. But we can do that in GaN materials. There is no further increase in the velocity after a specified electric field, generally at high electric fields. For GaN, Generally in the order of 100kv/cm.

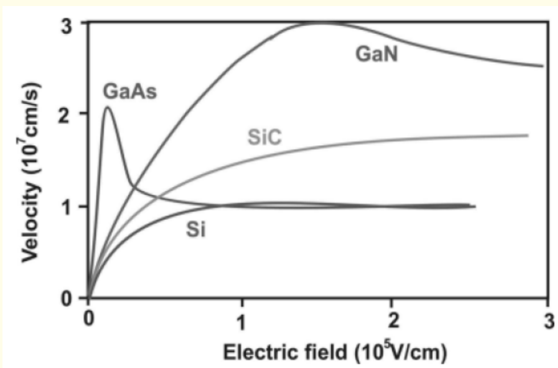


Figure 1: Velocity comparison of different materials.

HEMT Structure and its Working

The High Electron Mobility Transistor (HEMT) is designed on the principle of the Hetero Junction, which gives us a large number of free carriers without any doping. Because of this hetero-structure, there are fewer ionized scatterings, and it significantly improves mobility.

Hetero-structure

When two semiconductors of different bandgaps are attached, a junction called heterojunction forms. The formation itself provides free electrons without any doping.

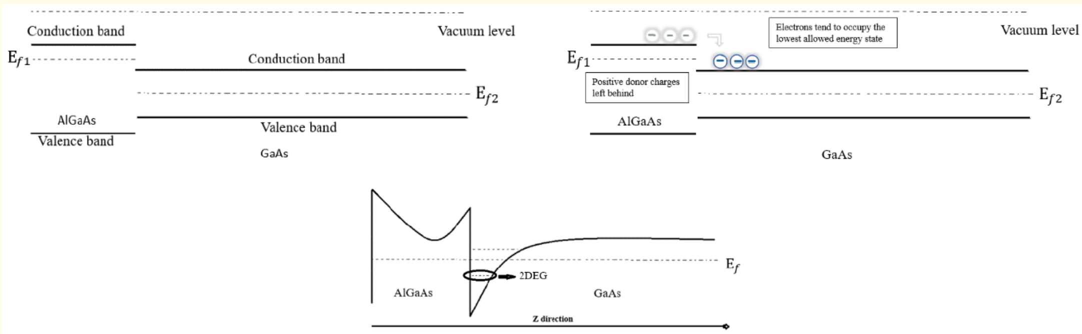


Figure 2: Formation of hetero-structure and 2DEG.

2-Dimensional Electron Gas (2DEG)

The triangular well shown in Fig. 2 is the lowest energy state, it fills with the electrons, and there is no way to move the electrons in the z-direction. The direction through the z-direction is quantized, as shown in Fig. 2. This gives us the advantage of an electron moving in the desired direction. As current through the one direction is quantized, it is named as 2-Dimensional Electron Gas.

Working Principle

In GaN HEMT, the large energy bandgap AlGaN is grown upon a smaller bandgap GaN material to form a heterojunction [7]. Here in the HEMT structure, the free electrons don't face any ions because of less doping which significantly improves mobility. The cross-sectional view of the GaN HEMT is shown in fig. 3 [4].

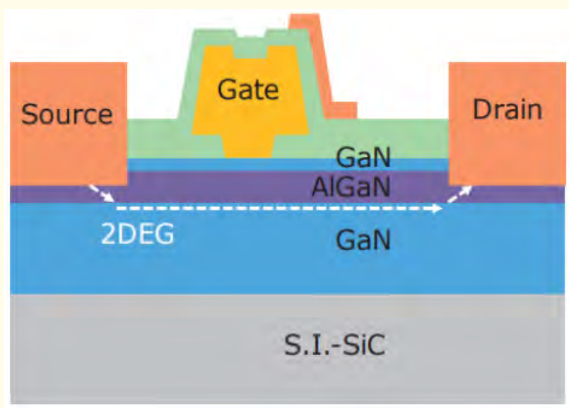


Figure 3: Cross-sectional view of GaN HEMT.

As discussed in 2DEG, the low energy state triangular well fills with the electrons. Those electrons do not have any path to travel across the cross-section, which gives us the advantage of moving the electron in the desired direction. The gate voltage controls the electron flow in 2DEG. Here the Schottky junction is formed between the metal gate and GaN semiconductor. By applying the gate voltage varying the diode barrier, which controls the flow of electrons in the 2DEG channel [5].

HEMT as Power Amplifier

The power amplifier is an electronic device that boosts the input power level to drive the loads, such as speakers and RF transmitters. The signal must have high power levels to travel over long distances in radio frequency transmission. Power amplifiers are classified based on the location of Q – point. Ex. Class – A, Class – B, Class

– C and Class – AB, etc.

When designing a high frequency power amplifier, parameters like efficiency, power dissipation, and harmonic distortion have to be considered.

The power efficiency is nothing but how much of our DC input power is converted into RF output power [3].

$$\eta = \frac{P_{out}}{P_{total}} \qquad (1)$$

The device's power dissipation has to be less because high power dissipation makes the device hot, affecting other semiconductor chips on the board. When designing a power amplifier, certain things like stability, gain, and impedance matching should be considered [6].

There are some stability calculation methods like stability circles, K factor and μ factor, in which μ factor is the most commonly used one. The equation of μ-factor given in the equation (2) and it has to be greater than at our given frequency.

$$\mu = \frac{1-|S_{11}|^2}{|S_{22}-\Delta S_{11}^*|+|S_{12}S_{21}|} > 1 \qquad (2)$$

$$\Delta = S_{11}S_{22} - S_{12}S_{21} \qquad (3)$$

Transducer power gain of the amplifier $G_T = \frac{P_L}{P_{avs}}$. It is nothing but the ratio of the power delivered to the load to the power available from the source [1].

$$G_T = \frac{P_L}{P_{avs}} = \frac{|S_{21}|^2(1-|\Gamma_S|^2)(1-|\Gamma_L|^2)}{|1-\Gamma_S\Gamma_{in}|^2|1-S_{22}\Gamma_L|^2} \qquad (4)$$

Maximum gain can be achieved when $\Gamma_{in} = \Gamma_s^*$ and $\Gamma_{out} = \Gamma_L^*$ [1].

To get the load values for the impedance matching, we will do the load-pull analysis. Load pull analysis is nothing but choosing an optimum load at which the device can deliver more power as well as efficiency. The efficiency is often very low at maximum getable power, and the gain is significantly less at maximum getable efficiency. A designer has to decide the load based on the requirement.

Load pull analysis significantly improves the power amplifiers' gain and efficiency, which reduces the reflections and losses due to the RF signal. It is suggested that the optimum load that we are choosing should be near to the 50 Ohm real point on the smith chart so that the matching network requires a smaller number of RF traces.

For the reduced power losses and reflections, impedance matching should be done. Impedance matching is one of the essential parts of a power amplifier design. As we operate the device at high frequencies, lumped elements cannot perform as they are supposed to. This is where the transmission lines comes into the picture. In a lossless transmission line, the input impedance is given by

$$Z_{in}(l) = Z_0 \left[\frac{Z_L + jZ_0 tan\beta l}{Z_o + jZ_L tan\beta l}\right] \qquad (5)$$

Z_L and Z_o are load impedance and characteristic impedance, respectively.

Design and Simulation Results

Any power amplifier that we design should under go the fallowing steps, they are (i) Biasing (Class of operation and operating DC current). (ii) Stability (µ-factor > 1). (iii) Load-pull Analysis (Finding out the load value which can deliver desirable power as well as the efficiency shown in Fig 5.a). (iv) Impedance matching (between the load from the loadpull and the actual load the power amplifier is designing for). (v) Converting the Schematic into the Layout with the peoper substrate defined.

Thanks to the advancement in simulation tools, Load pull is complete tool-based analysis where it imposes the different load values on the smith-chart and gives us the power and efficiency of those particular load points (usually called as power and efficiency contours). Which makes easy for us to know where the selected device (Transistor PDK) can be at its best.

In this paper, we chose CREE CGH40010F as our power amplifier. The selected device is operated at 2.4 GHz, and its biasing is done at V_{GS} = -2.7 V and V_{DS} = 28 V. This is biased to operate in the Class AB mode [2].

The device is unstable at the operating frequency when stability and gain analysis is done on the raw transistor (µ = 0.725). It is observed that the stability modifications show a negative impact on the gain of the raw transistor. It is suggested to the designers to take care of the gain while doing stability modifications. The designed schematic maintains stability over high frequencies (from 1 GHz).

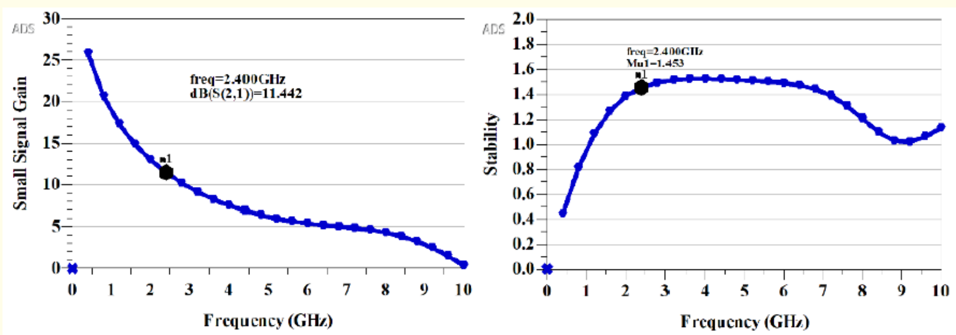
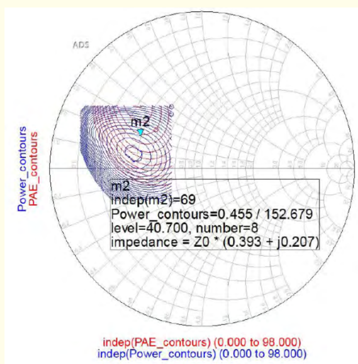
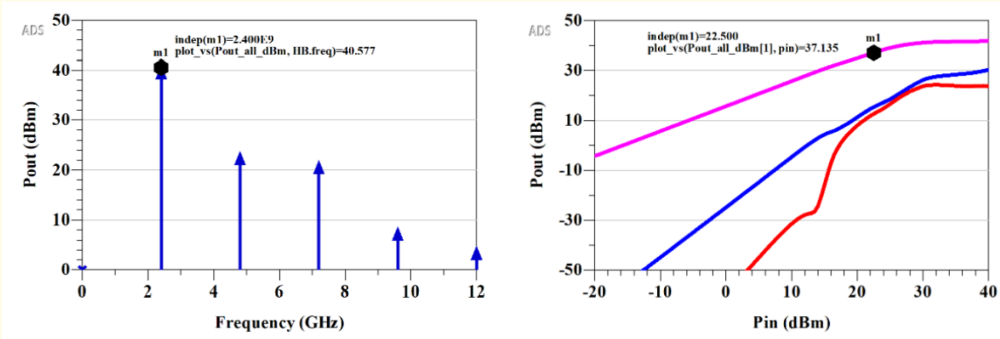


Figure 4: µ-factor and gain (after stability modifications).

Load pull analysis has been performed, and the power device (CREE CGH40010F) is giving desirable gain and efficiency at the load value 19.15+j11.95 Ohms.



(a)



(b) (c)

Figure 5: (a) Load pull contours, (b) power distribution over the harmonics, and (c) P1 dB compression point.

For the input power (Pavs) of 28 dBm, before doing the load pull analysis, the transistor provides a fundamental output power of 37.522 dBm and a drain efficiency of 37.26%.

Load pull analysis was performed (Pavs = 28 dBm) and the load we choose (19.15+j11.95 Ohms) producing 40.577 dBm of output fundamental power and 66.09% drain efficiency. It is observed that at the P1 dB compression point (The point where the large signal gain dropped by 1 dB), the output power is shifted from 32.96 dBm to 37.135 dBm which means the linearity of the amplifier is increased. The complete load pull data is given in Tables 2 and 3.

Stage	*Pin (Pavs)*	*Pout*	*Drain efficiency*
Before Load pull	28 dBm	37.522 dBm	37.26 %
After Load pull	28 dBm	40.58 dBm	66.09%

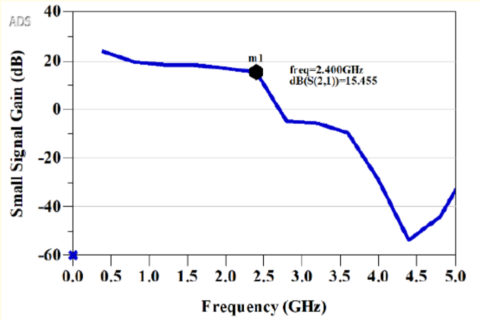
Table 2: Improvement in Pout and Drain efficiency after load pull.

They are the load values that gives maximum power but not the effecence or maximum efficiency but not the power. We should tacke care when we are choosing the load value, it should give the desirable power as well as the efficiency. For this design, the below table provides the load-pull data.

Source and load imped-ance (Ohms)	*P1dB pow-er (dBm)*	*Pin at p1dB (dBm)*	*Maxi-mum gain*	*Efficien-cy at maxi-mum gain (%)*	*Pout at maxi-mum gain (dBm)*	*Pin at maxi-mum gain (dBm)*	*Efficien-cy at max-imum PAE (%)*	*Gain at maxi-mum efficien-cy*	*P out at maxi-mum ef-ficien-cy (dBm)*	*Pin at maxi-mum ef-ficien-cy (dBm)*
Z_S = 50 Z_L = 50	32.962	22.5	11.442	0.118	8.442	-3	47.448	6.32	40.32	34
Z_S = 50,Z_L 19.15+j11.95	36.136	25	12.135	9.362	27.635	15.5	65.819	7.061	41.061	34
Zs = 3.19-j4.7, Z_L=19.15+j11.95	37.135	22.5	15.72	11.815	28.22	12.5	65.851	10.754	41.254	30.5

Table 3: Load pull data.

It is observed that the load we chose gives desirable results. The impedance matching has been done to the 50 Ohm termination on both sides for the chosen impedances.



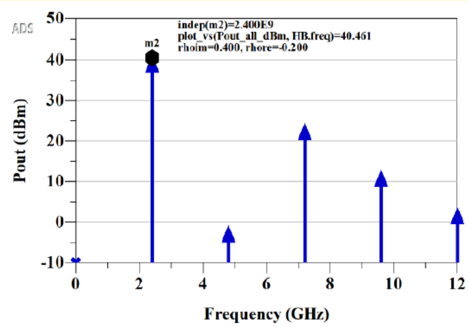


Figure 6: Gain after impedance match. ***Figure 7:*** Power distribution over the Harmonics

After doing the impedance matching, the simulated results passed our requirements. Essential parameters like gain and power distribution over the harmonics have shown below in Fig. 6 and 7. The schematic level design of the selected device gives the desired results.

Conclusion

This paper explains the importance and working of GaN HEMT transistor in high frequency applications. The CREE CGH 40010F (GaN HEMT) transistor is selected and biased in such a way that it will operate in ClassAB mode. It is producing 40.461 dBm output power for the input of 28 dBm. The schematic provides 15.5 dB gain and 63% PAE efficiency (66% Drain efficiency). The layout design and EM simulation have to be performed. With this design the achieved results are significantly more compared to the results given in the datasheet of the chosen transistor. Complete simulations are performed in Advanced Design System (ADS). It is observed that the developed schematic is providing the best results than the data given by the manufacturer. There is still some scope to improve the efficiency without affecting the gain.

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