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Ultra-wideband GaN Power Amplifiers - From Innovative Technology to Standard Products

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1. Introduction

A number of the modern electronic systems applications require generation, processing, amplification, and emission of signals that have a continuous broadband spectrum or modulated signals with a relatively narrow spectrum whose frequency may change in broad ranges. The first group of applications may include UWB systems of short distance data transmission, radar systems with UWB signals of different kinds (pulse, multi-frequency, or quasi-noise), RFID-systems, and a number of others. The second group includes electronic warfare (EW) systems, EMC-testing systems, as well as universal measuring and testing equipment.

Usually, signals with fractional bandwidth over 20% of band center or more than 500 MHz of absolute bandwidth are referred to UWB signals. As applied to the signal-processing devices, in particular, to amplifiers, the interpretation of the term UWB is somewhat different. Depending on the relative bandwidth the amplifiers are usually divided into the following kinds: narrowband (frequency coverage - relation of the upper working frequency to the lower working frequency (W) is less than 1.2:1); wideband (W from 1.2:1 to 2:1), and ultra-wideband ones (W greater than 2:1). In the present article we shall speak about technologies of microwave ultra-wideband power amplifiers.

The main parameters determining the possibility of using an power amplifier in a definite electronic system are as follows: a working frequency bandwidth (ΔF), the output power with the given criteria of distortion (Po), and the efficiency of transformation DC source power into the output power (DE). With the increase of the frequency coverage W the achieved DE is significantly lowered. Some typical dependence of DE on W, built for typical microwave transistor power amplifiers, is shown in Fig.1.

The highest DE values (up to 70-80%) are realized due to different special circuits, named Harmonic Reaction Amplifiers (Colantonio et al., 2009). In these circuits a special combination of transistor source and load impedances and special biasing allows to achieve the forms of drain current and voltage close to the switching form which results in minimal losses of DC source energy. However, the frequency coverage W, in which these combinations may be realized, is usually limited by 1.1:1 to 1.2:1 values. Amplifiers with the frequency coverage up to 1.5:1 may be built by classical A/AB biasing schemes with multi-contour reactive input and output matching circuits. The forms of currents and voltages in such schemes are close to sinusoidal ones while the DE is limited by the values of 40-50%.

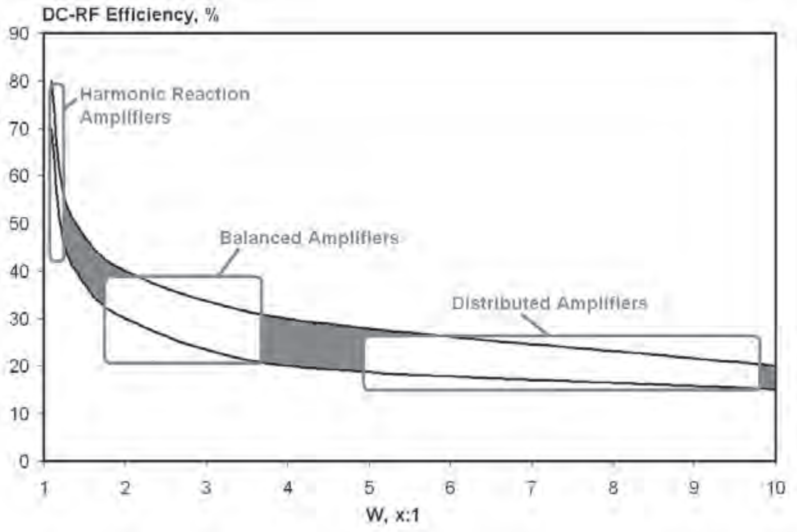


Fig. 1. Typical DC-RF efficiency for power amplifiers with a various bandwidth

For amplifier with W greater than 1.5:1 a high quality input matching and cascading of active elements becomes problematic; here a balance circuit is widely used, in which two identical active elements are connected with the help of 3-dB quadrature directional couplers while the input reflections are fully absorbed by the ballast loads and a close to ideal input and output matching is achieved (Sechi & Bujatti, 2009). In practice the balance amplifiers are used for frequency coverage from 1.4:1 to 4:1 and have efficiency up to 25-45%.

To realize the frequency coverage over 4:1, most often a scheme of a distributed amplifier (DA) is used, in which gates and drains of several transistors are united in artificial transmission lines with a characteristic impendence close to 50 Ohm (Wong, 1993). The lower working frequency of DA is limited only by DC-blocking circuits while the upper frequency is determined by the upper frequencies of the input and output artificial lines and depends on the transistor's own capacitances. The DC-RF efficiency of DA is still lower because of the difference of loads referred to individual transistors and redundancy of the number of transistors used in the circuit. In practice W from 4:1 to over 1000:1 and efficiency of 15-25% are achieved.

The qualitative ratios described above are applicable to amplifiers built on any types of transistors (HBT, MESFET, MOSFET, HEMT). However, we shall go on considering amplifiers on GaN HEMT transistors whose technology is rapidly developing and is taking the first place by the combination of W-Po-DE among the modern semiconductor microwave frequency devices.

2. GaN transistors and MMIC technology

2.1 A short history

The history of invention and development of the GaN microwave transistors and MMICs is rather short – a little less than 20 years from the moment of the first GaN-transistor demonstration to the beginning of industrial devices implementation in electronic systems. Of this period the first 10 to 15 years were devoted to the search for the best transistor constructions and the ways for making them reliable and stable, while during the next five years numerous efforts were directed to the industrial adoption of the technology (Fig.2).

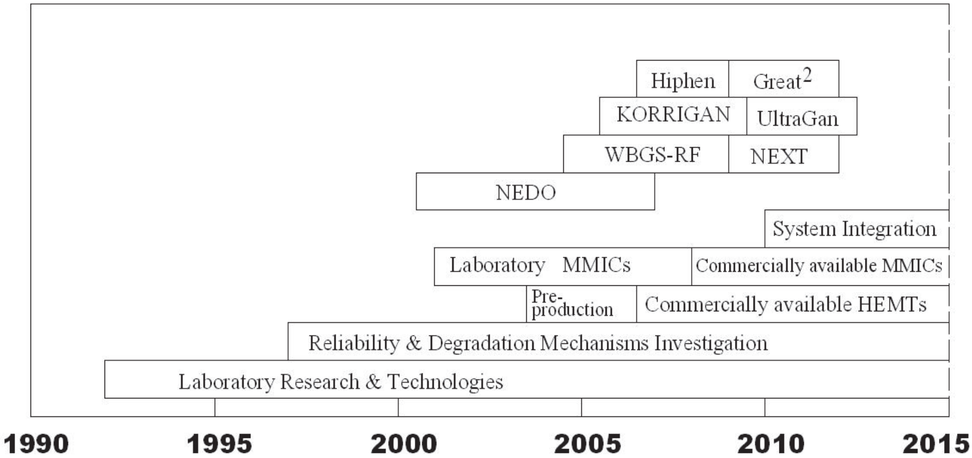


Fig. 2. The steps of GaN technology development history

This later stage was greatly promoted by a number of research programs financed by military, governmental and corporate bodies of the USA, Japan and Europe. Among the one should mention the Japanese program NEDO (Nanishi et al., 2006), the American DARPA programs, called WBGS-RF and NEXT (Rosker et al., 2010), as well as the European programs KORRIGAN, UltraGan, Hyphen, Great2 (Quay & Mikulla, 2010).
Early in the 2000s practically all the leading world electronic companies somewhat connected with the production of GaAs-components begin making their own investments in the GaN technology. These investments have given results and in the years 2006 and 2007 one watches announcing and then real appearance in the market of the first commercial GaN-products: universal wideband transistors in the range of frequencies up to 2-4 ГГц with the output CW power from 5 to 50 Watt (and somewhat later from 120 to 180 Watt). The following companies have become the pioneers of the commercial market: Eudyna (now Sumitomo Electric Devices Innovation, SEDI), Nitronex, Cree, and RFHIC. A little later Toshiba, RF Microdevices (RFMD), TriQuint Semiconductor (TQ), and a number of other companies have joined this first team.
In 2009 TriQuint began producing ultra-wideband MMIC amplifiers with the band of 2 to 17 GHz. By the end of 2010 GaN-based transistors and MMICs were already present in catalogs of more than 15 companies – producers of semiconductor components from the USA, Europe, Japan, South Korea, China and Russia.

2.2 Advantages

The interest of developers in GaN-transistors (or to be more precise in transistors on the basis of heterostructures AlGaN/GaN) was due to combination of a number of important material properties (Table 1).

Properties	Si	AlGaAs /InGaAs	SiC	AlGaN /GaN
Bandgap (E_g), eV	1.1	1.4	3.2	3.4
Electron mobility (μ_n), $cm^2 V^{-1}s^{-1}$	1350	8500	700	1200-2000
Saturation field electron velocity (υ_{sat}), $*10^7$ cm/s	1.0	2.0	2.0	2.5
2D sheet electron density (n_s), cm^{-2}	--	$3 * 10^{12}$	--	$(1-2) * 10^{13}$
Critical breakdown field (E_c), MV/cm	0.3	0.4	2.0	3.3
Thermal conductivity (K), $Wcm^{-1}K^{-1}$	1.5	0.5	4.5	1.3

Table 1. Basic properties of semiconductor materials for microwave power transistors

The maximum band-gap is determines the possibility of a transistor's work at high levels of activating influences (temperature and radiation). Very high electron density in the area of two-dimentional electronic gas and a high saturation field electron velocity make possible high channel current density and high transistor's gain. The maximum critical breakdown field allows realizing breakdown voltages of 100 to 300 V and increasing the working DC voltage up to 50-100 V, which together with a high current density provides for power density of industrial GaN transistors 4 to 8 W/mm (and up to 30 Watt/mm in laboratory samples), which is ten times greater than the output power density of GaAs transistors. The quality relations given in Fig.3 (Okumura, 2006) illustrate well the connection of the material physical properties with the possible device output power density.

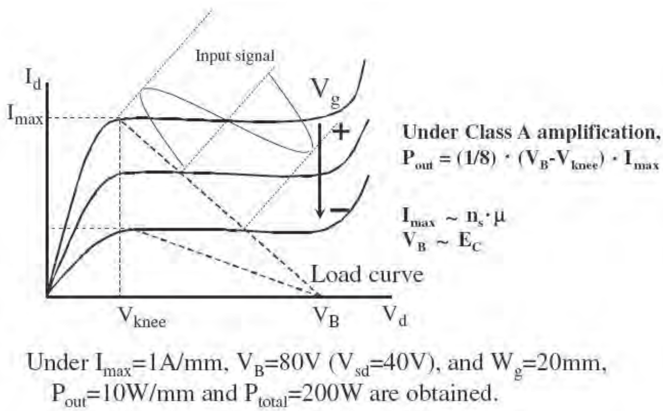


Fig. 3. Relations between the material physical properties and transistor power density (Okumura, 2006)

The main power microwave transistors and MMIC technology well developed in the mass production – the GaAs pseudomorphic HEMT technology (pHEMT) – is the main competitor of the rapidly developing GaN technology. That is why further on we shall compare parameters of transistors and MMICs having in mind these two technologies. For estimating and comparing the application possibilities of GaN and GaAs transistors in the wideband power amplifiers, as well as possible „migration" of technical solutions from one material to the other, let us make a simple analysis of their specific (i.e.related to 1 mm of the gate width) parameters. Here was shall use the known (Cripps, 1999) estimations for the A class amplifier with maximum output power P_{max} and optimal (for reaching such power) transistor's load resistance R_{opt} :

$$P_{max} = V_{ds} * I_{max} / 8 \quad (1)$$

$$R_{opt} = 2 * V_{ds} / I_{max} \quad (2)$$

where V_{ds} is DC drain supply voltage, I_{max} is maximum open channel current.
From the presented expressions one can easily receive a formula for a new parameter – specific optimal load resistance (R_x):

$$R_x = V_{ds}{}^2 / (4 * P_x) \quad (3)$$

where P_x is a transistor's output power density, which is the parameter that is widely used in literature. The typical specific parameters of GaN HEMT and GaAs pHEMT transistors received from the analysis of their linear equivalent circuits given in literature and in datasheets, as well as the above parameter R_x are presented in Table 2.

Parameters	**GaAs** pHEMT		**GaN** HEMT	
	typical	TQ **TGF2022-12** (1.2 mm)	typical	TQ **TGF2023-01** (1.25 mm)
Specific gate-source capacitance (C_{gsx}), pF/mm	1.8 - 3	2.77	1.1 - 2	1.43
Specific transconductance (G_{mx}), mS/mm	200-400	313	150-300	216
Specific drain-source capacitance (C_{dsx}), pF/mm	0.15-0.3	0.19	0.2-0.4	0.246
Output power dencity (P_x), W/mm	0.7	1.0	5	4.5
Drain-source DC voltage (V_{ds}), V	9	10	28	28
Specific optimal load (R_x), Ohm*mm	29	25	39	43.5
Power gain @ 10 GHz, dB	--	12.9	--	10.4
PAE @ 10 GHz, %	--	52.4	--	52
Output CW power @ 10 GHz, Watt	--	1.2	--	5.5

Table 2. Absolute and specific transistor parameters comparison for GaAs and GaN technologies

For comparison in this Table to as correct as possible we give specific parameters of two industrial transistors produced by same company (TriQuint Semiconductor) and having similar topologies, gate width and the equal gate length (0,25 µm).
The following conclusions can be drawn from the analysis of presented data:

- specific gate-surce capacitance and transconductance of GaN transistors (simultaneously) are from 1.5 to 2 times as low as in GaAs transistors, which is more likely the advantage of the former from the point of view of wideband input matching, because it requires smaller transformation coefficients in matching circuits. The achieved gain with the same gate-length may be considered to be sufficiently close.
- specific drain-source capacitance, that is shunting the optimal load of transistor and making difficult the building of wideband output matching circuit at frequences that are higher some cutt-off frequency, is in both classes of transistors almost the same.
- specific optimal loads of transistor (R_x) also turn out to be close (somewhat higher for GaN-transistors).

2.3 “Technical solution migration”

The above considerations allow making a subtantiated assumption that many projects and technical solutions as matching circuits or topology, worked out for GaAs-transistors and MMICs, may with minimal changes be applied for GaN-transistors with the same or from 20% to 50% greater gate width. And if the gate length of booth types of active structures are close, one can receive the same bandwidth, gain, and size of circuit, but with a several times greater output power.

In the work (Fanning et al., 2005) there is description of rather a successful experiment on „migration“ of standard GaAs pHEMT wideband power MMIC amplifier project (TGA9083 MMIC amplifier that have been manufactured for over 10 years by TriQuint Semiconductor) to the GaN-on-Si technology, worked out by Nitronex Company. Frequency characteristics of the saturated CW output power of two MMIC samples (GaAs pHEMT and GaN-on-Si HEMT), assembled in a test circuit are shown in Fig.4, while the comparison of their parameters is made in Table 3.

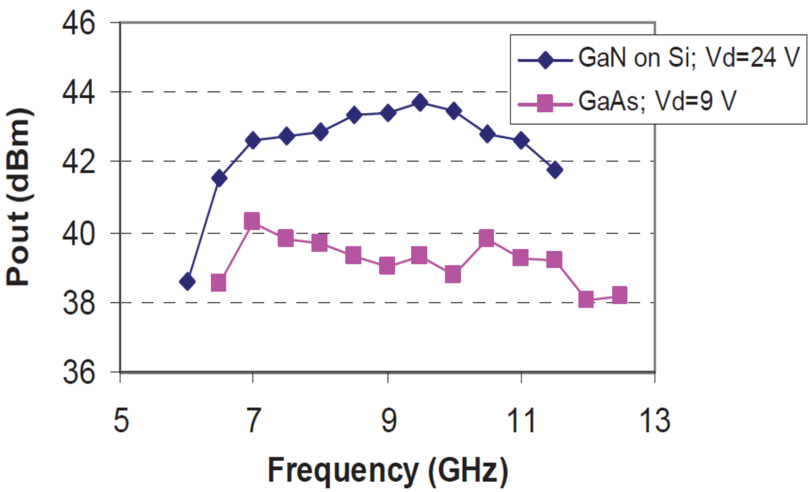


Fig. 4. Saturated output power of two MMIC amplifiers, manufactured according same topology project on GaAs and on GaN-on-Si (Fanning et al., 2005)

Parameters	TGA9083 (GaAs pHEMT)	New (GaN-on-Si HEMT)	Comments
Frequency range, GHz	6.5 - 11	7 – 10.5	=
Linear gain, dB (typ.)	19	20.9	=
Output CW power @ 3-dB gain compression, W	8	20	x 2.5
PAE, %	35	27	=
Vd, V	9	24	x 2.7
Chip size, мм^2	4.5 x 3		=

Table 3. Comparison of parameters of two MMIC amplifiers, manufactured according same topology project on GaAs and on GaN-on-Si (Fanning et al., 2005)

As one can see from the presented data a simple transfer of the complicated wideband MMIC amplifier project onto a new technology gives considerable increase of the device output power while the rest of the parameters remain preserved. A modification of this project with a correct GaN transistor's nonlinear model should further improve PAE and output power of amplifier.

2.4 The ways for further improvement

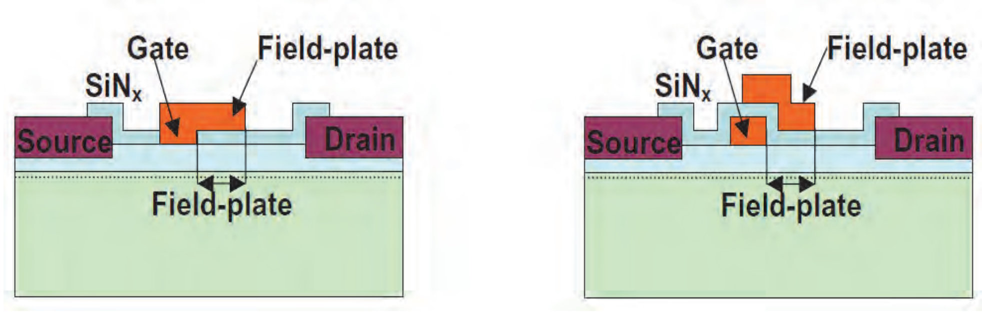
The further improvement of the GaN transistor constructions is done in several directions. First, it is the increase of the power density by raising break-down voltage, improving heat removal, and increasing of efficiency. Second, is the frequency range extending into the millimeter-wave frequencies with preservation of the power density and efficiency. Third, is the lowering of production cost.

The increase of the transistor's power density depends on the following:

- by increasing the breakdown voltage (V_B);
- by lowering of transistor's heat resistance by improvement thermal conductivity of the substrate and optimization of transistor's construction;
- by increasing the maximum channel current (I_{max});

FP (Field Plate) electrode has become an effective way for increasing the breakdown voltage that is successfully used in manufactured GaN transistors. This term is applied to a number of transistor constructions. An additional electrode is located along the gate and it is connected either with gate, or with source, or it is not connected with transistor electrodes at all. This electrode allows changing the distribution of electric field in the channel, "moving away" the peak of the field from the gate's edge and "smoothing" it. This lows down the gate leakage and increases the drain-source voltage when an avalanche ionization begins. The constructions of FP electrodes used in GaN transistors are quite diverse. Two most widespread ones are shown in Fig.5.

It is evident that the presence of an additional electrode, besides the increase of breakdown voltage and output power density, causes other changes in the transistor characteristics as well. In particular, there are significant changes in the cut-off frequencies F_t и F_{max}, and parasitic capacitances of the active structure. Fig.6 shows relative changes of parameters of GaN transistors with a FP electrode depending on the length of FP electrode L_f. investigated in the works (Kumar et al., 2006) and (Wu et al., 2004).



(a) (b)

Fig. 5. Field-plated AlGaN/GaN HEMTs: (a) integrated field plate; (b) separated field plate (Mishra, 2005)

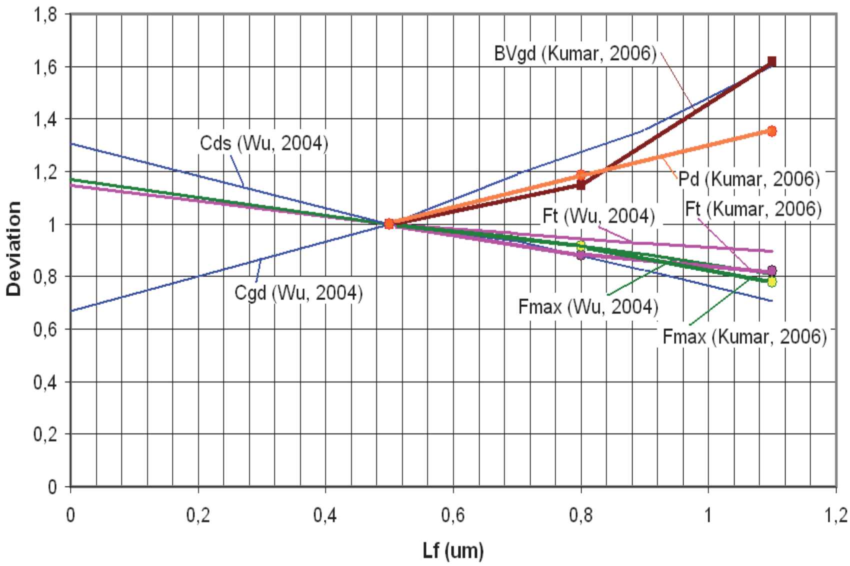


Fig. 6. Deviations of basic transistor parameters with FP-electrode length (L_f) variation

Inserting of the gate-connected FP electrode with L_f = 1,1 um allowed increasing the breakdown voltage from 68 to 110 volt and raising the output power density by 35%, from 5,4 to 7,3 Watt/mm. At the same time the current gain cut-off frequency decreased by 18% to 20% (Kumar et al., 2006). This is probably conditioned by a considerable (two times) increase of the parasitic capacitance Cgd (Wu et al., 2004). Transconductance and gate-source capacitance of transistor after FP inserting have practically no any changes. The use of a field electrode connected with the source of transistor, on the contrary, cuts down the parasitic capacity Cgd and somewhat increases the cut-off frequencies and maximum available (or stable) gain of transistor. The construction of such FP electrode is shown in Fig.7 (Therrien et al., 2005).

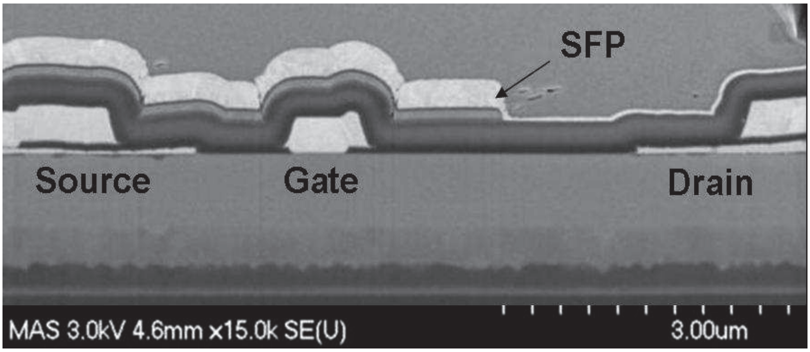


Fig. 7. Cross section of AlGaN/GaN HEMT with source field plate (Therrien et al., 2005)

When such electrode was inserted (Therrien et al., 2005) transistor's Cgd was decreased by 30%, while maximum stable gain (MSG) increased by 1,5 dB. Breakdown voltage also increased significantly and there was also 1,5 times growth of output pulse power density at Vd = 48 V. In the same way the insertion of a field electrode, connected with the source, affected the parameters of transistor produced with the use of other technologies. In particular, in GaAs MESFET transistor (Balzan et al., 2008) the capacity Cgd decreased by 43%, while the F_t increased by 16%. In the SiC MESFET (Sriram et al., 2009) Cgd decreased by 45% and MSG increased by 2, 7 dB.
The growth of output power density also leads to an increase of the heat dissipation on the unit of the area of transistor's active structure. If additional effortes are not taken, the growth of channel temperature will limit the growth of transistor's parameters and will lead to the lowering of reliability. In modern GaN transistors the following materials and composites are used (Table 4) as substrates on which the epitaxial layer of GaN is formed.

Substrate	Thermal conductivity, W/ cm * K
Mono-crystalline SiC	4,9
High Resistive Si $_{(111)}$	1,5
Silicon on poly-crystalline SiC (SopSiC)	3
Silicon on Diamond (SoD)	10-18

Table 4. Substrates for power GaN transistors

The mono-crystalline SiC substrate is the most often used material for industrial growing epitaxial structures for GaN transistors. It is used by TriQuint Semicionductor, RFMD, Toshiba, SEDI, Cree and a number of others. The production on substrates up to 100 mm diameter was developed (Palmour et al., 2010). The technology using inexpensive substrates of high-resistance silicon with intermediate buffer layers (GaN-on-Si) was developed by Nitronex. TriQuint Semiconductor also plans to use this technology in future. Substrates of SopSiC type, manufactured by method of transfer of the thin layer of high-resistance silicon onto the poly-crystalline SiC substrate, are proposed for approbation by PicoGiga (PicoGiga

International, 2011). In commercial production of transistors they are not used yet. Such substrate must be cost-effective as compared to those from mono-crystalline SiC although they are close to them in heat conductivity. A considerable progress in heat conductivity may be expected from the use of composite substrates on the basis of poly-crystalline CVD diamond developed by sp^3 Diamond Technologies (Zimmer & Chandler, 2007). The proposed GaN transistor on SOD substrate cross-section is shown on Fig.8.

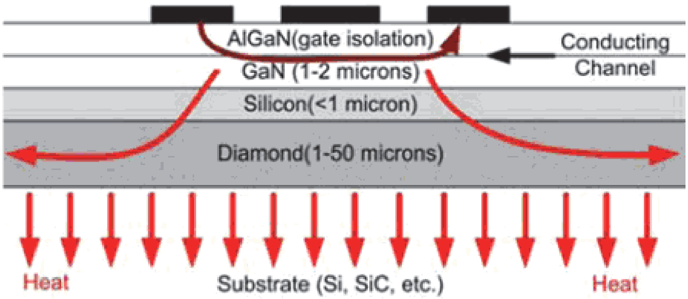


Fig. 8. Proposed GaN on SOD technology (Zimmer & Chandler, 2007)

Authors estimate that this technology will allow increasing the dissipated power of GaN transistor by 50% as related to the mono-crystalline SiC.
The improvement of GaN transistor's gain and extending of working frequencies into the area of millimeter-waves are related with a search for new effective heterostructures that would allow increasing electrons mobility, 2D sheet electron density, and, as a consequence, increasing device's transconductance, maximal open channel current, and cut-off frequencies. These efforts are carried out in different fields. The achieved parameters of some types of heterostructures (Wang et al., 2010, Sun et al., 2010, Jardel et al., 2010) in comparison with the standard AlGaN/GaN structure are given in Table 5.
If the development of the above technologies are successful in industrial production, parameters of GaN transistors and MMICs may be greatly improved already in the current decade and will be characterized by the following figures (Table 6).

Parameters	Heterostructures	
	Industry standard: AlGaN/GaN	Innovative: AlGaN/AlN/GaN, AlInN/GaN, InAlN/GaN …
Electron mobility ($cm^2 V^{-1}s^{-1}$)	1000 - 1200	1400 - 2000
2D sheet electron density (cm^{-2})	$1 * 10^{13}$	$(1.4 – 2.0) * 10^{13}$
Idss (mA/mm)	500 - 1000	1300 - 2300
Gm (mS/mm)	150 - 300	400 - 550

Table 5. Available GaN heterostructures parameters

Parameters	Industry standard 2010	Industry standard 2015 - 2020
Power density (W/mm)	4 - 8	8 - 15
Gate length (um)	0.25 – 0.5	0.05 – 0.5
Frequency Range (GHz)	0 - 20	0 - 100
Output power (W/die)	5 - 100	5 - 200

Table 6. Available vs. today industry standard GaN transistors parameters

3. Manufacturing status

3.1 GaN discrete transistors

Discrete GaN transistors with the working frequencies up to S-band were historically first in the microwave semiconductor market. Today they are produced with output CW power from 5 to 200 Watt in different package types or in die form. The main parameters of the commercially available devices is given in Table 7. There are data on three groups of devices that are of interest as active elements for building UWB power amplifiers. The first group («Low End») includes transistors with the output power of 5 to 12 Watt (this is the minimal power level of the transistors produced today). They are supplied in die form or in miniature SMD packages. On the basis of these transistors on can realize UWB amplifiers with frequency coverage W from 3:1 to more than 100:1, because the maximum output power is provided for with load impedance close to 50 Ohm (see Table 2) and the possibilities for optimal output matching are limited in fact only by the construction of the

Parameters	«Low End» (5W)	“High End Die” (100W)	“High End Flange” (200W)
Output CW Power (W)	5 - 12	100-120	180 - 220
Usable Upper Frequency (GHz)	6 - 20	3-10	1.5 – 2.5
Available UWB ranges (GHz)	0.1 - 3 1 – 6 3 – 10.5 4 - 12	0.8 – 2.5 1 – 3 2 - 4	0.5 – 1 1.0 – 1.5
Linear gain @ UF (dB)	12 - 15		
Power gain @ UF (dB)	8 - 10		
Drain Efficiency (%)	55-65		
Packages	SMD (4x4), Die	Die	Dual Flange
Some models	TQ TGF2023-01 TQ T1G6000528Q3 Cree CGH40006P Cree CGH60008D RFMD RF3930D	TQ TGF2023-20 Cree CGH60120D RFMD RF3934D	Cree CGH40180PP Nitronex NPT1007 SEDI EGNB180M1A

Table 7. Discrete GaN HEMT main parameters

drain DC bias circuit, which can be performed as a very wideband one. The maximum working frequency for the amplifier based on discrete transistor with W greater than 3:1 may be estimated by the value of 12 GHz.
The maximum amplifier's bandwidth may be realized by using transistors in die form that have minimal parasitic gate and drain inductances. In our days there are GaN transistors in die form with the gate width up to 28 mm and output CW power up to 120 Watt ("High End Die"). On the basis of these devices one can realize UWB amplifiers with frequency coverage more than 3:1 on frequencies up to 4 GHz. Here the bandwidth is limited by the difficulties of high-ratio impedance transformers realization to providing for an optimal load at 3 or 4 Ohm with the parallel parasitic capacitance Cds being about 7 to 10 pF. The most powerful CW transistors ("High End Flange") are produced in a double flange ceramic packages, in which two separate transistors are located. They are used in the amplifier either in accordance with the push-pull circuits, or in balanced chains. The first one has an advantage that allows a 4 times increase of impedance of the input and output matching circuits and provides for matching in a larger bandwidth. The second circuits allows providing low input and output reflection coefficients and a good matching with the driver and load. The most powerful industrial transistors of this class have output CW power of up to 220 W. Because of significant package parasitic reactances of such transistors the upper frequency of the wideband amplifier is seldom greater than 1.5 – 2 GHz.

3.2 UWB MMIC GaN amplifiers

Product mix of GaN MMIC power amplifiers is not yet great, but it is growing rapidly. UWB microwave MMIC amplifiers are built in accordance with two main principals which we have already mentioned above. This is a two- or three-stage circuit with reactive/dissipative matching (RMA) and a distributed amplifier (DA). The balance circuits in GaN MMIC devices is not widespread since the SiC substrate is cost-expensive, so using of quadrature couplers on MMIC chip is not considered rational.

3.2.1 Distributed MMIC amplifiers

The greatest frequency coverage is provided for by the amplifier built on the principle of distributed amplification, which is also called traveling-wave amplifier. The principle of distributed amplification (Wong, 1993) has been used in electronics since the middle of the last century and the epoch of vacuum-tube amplifiers. GaAs MMIC DA's are manufactured by dozens of companies. However, the output power and PAE of such devices have already reached their full capacity. The appearance of GaN MMIC technology has allowed making a considerable jump in the parameters of DA amplifiers. In Table 8 we give parameters of the most powerful MMIC DA, realized by GaAs and GaN technologies in the 2-18 GHz frequency range which is standard for such amplifiers (and widely used for EW systems). Image of 2-18 GHz GaN MMIC DA with the output CW power greater than 11 W, developed by specialists of TriQuint Semiconductor (Reese et al., 2010) in the framework of stage III of WBGS-RF program is shown in Fig.9. As compared to the most powerful commercially available GaAs DA this amplifier has 10 times as great output power, higher efficiency and 3,4 times greater die size. As a commercially available only one type of GaN MMIC is so far known (TriQuint TGA2570) with 8 W output power and 15-25% PAE. Improvement of parameters of heterostructure and development of diamond-based substrates will allow increasing the 2-18 GHz MMIC DA's output power to the level of 20 to 30 W.

Parameters	MMIC DA 2 – 18 GHz	
	GaAs	GaN
Output CW Power (W)	1.0 – 1.2	11.0
PAE (%)	20	28
Linear gain (dB)	14	12
Vd (V)	10	35
Die size (mm^2)	2.89 x 1.55	5.54 x 2.71
Model	Hittite Microwave HMC797	(Reese et al., 2010)

Table 8. GaN vs. GaAs MMIC distributed amplifier's main parameters

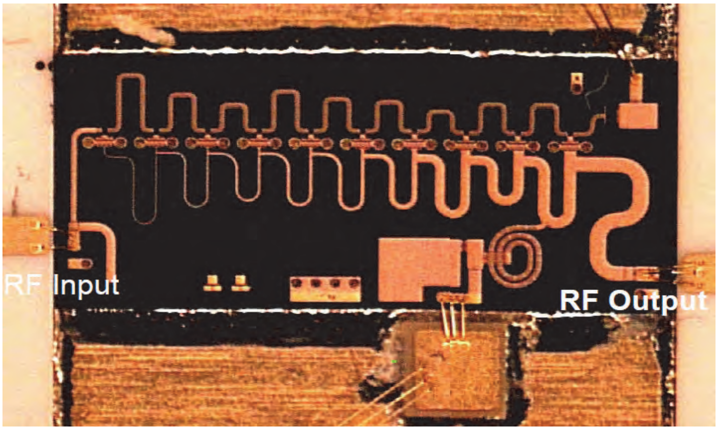


Fig. 9. Photograph of the 2-18 GHz 11 Watt MMIC amplifier (Reese et al., 2010)

3.2.2 Reactive matched multistage MMIC amplifiers

The second solution that is often used for building MMIC amplifiers with frequency coverage from 1.4:1 to 3:1 is a two- or three-stage circuit with a corporate reactive output matching circuit and reactive/dissipative inter-stage and input matching circuits (RMA). Today the majority of GaAs MMIC power amplifiers with the output power of over 1 or 2 W have been built in accordance with this principle. This scheme has a better efficiency, however it does not provide for a good input and inter-stage matching and, as a rule, it has large gain ripple. And here also the appearance of GaN MMIC technology has allowed making a considerable jump in parameters. In Table 9 we give main parameters of RMA-amplifiers realized on GaAs and GaN technologies in the frequency ranges of 2-6 GHz and 6-18 GHz having frequency coverage of 3:1.

Parameters	MMIC RMA 2-6 GHz		MMIC RMA 6 - 18 GHz	
	GaAs	GaN	GaAs	GaN
Output CW Power (W)	10-12	22 - 35	2.5 - 3	6 - 10
PAE (%)	25 - 32	42 - 44	18 - 30	15 - 20
Linear gain (dB)	16 - 21	21 - 28	23 - 27	18 - 20
Vd (V)	10	28	8	25
Die size (mm^2)	5.0 x 6.34	3.6 x 3.6	4.3 x 2.9	6.43 x 3.08
Model	M/A Com MAAPGM 0078-Die	Cree CMPA20600 25D	TriQuint TGA2501	(Mouginot et al., 2010)

Table 9. GaN vs. GaAs MMIC reactively matched amplifier's main parameters

On frequencies up to 6 GHz the advantages of GaN MMICs are considerably in all parameters: the output power is 2.5-3 times higher, the efficiency is 1.5 times higher, and the die size is 2.5 times smaller. In the range from 6 to 18 GHz GaN MMIC has the output power 3 times as great, but in the PAE and dimensions it is still inferior to GaAs amplifier. It should be noted that GaN amplifier is one of the first models in the given class of MMIC, while the GaAs amplifier has already been manufactured for 10 years. With improvement of technology, nonlinear models of GaN transistors, and design methods GaN MMICs in this range will show advantages in the efficiency as well. Image of the 2,5-6 GHz 30 W GaN MMIC amplifiers, developed by the specialists of TriQuint Semiconductor (TGA2576) is shown in Fig.10.

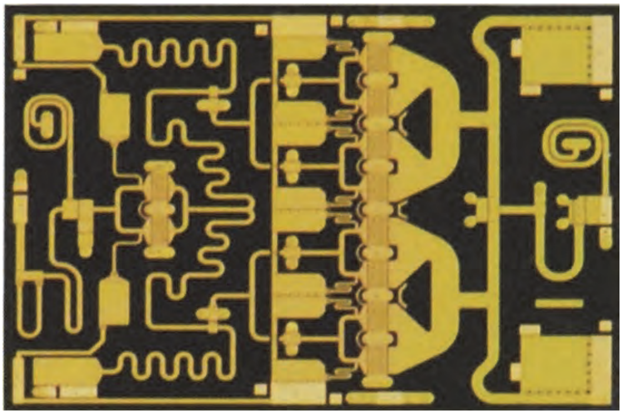


Fig. 10. Photograph of the 2.5-6 GHz 30 Watt MMIC amplifier (www.triquint.com)

Improvement of hetero-structures parameters and mastering of diamond-based substrates will allow increasing further the output power of MMIC RMA in the range from 2 to 6 GHz up to the level of 50 to 60 W.

3.3 Commercially available GaN MMIC amplifiers

Parameters of some types of UWB MMIC amplifiers produced nowadays are given in Table 10. These MMICs cover the range of frequencies from 20 MHz to 17 GHz with the output saturated power from 2 to 25-30 W. Among the manufactured MMICs only two types are DA amplifiers, while in all the others the principle of reactive/dissipative matching is used. All the UWB ranges with the output CW power from 10 to 30 Watt and DC-RF efficiency from 20% to 50% are being overlapped by GaN MMIC amplifiers already in the third year of manufacturing. Promotion of these devices in the market in future will depend on the successes in the increase of production yield and lowering of prices as well as on the "second jump" of the power density from 4-8 Watt/mm to 10-15 Watt/mm due to the implementation of diamond-based substrates and improvement of transistor heterostructures. The laboratory results of recent years (Micovic, 2008), that have demonstrated the possibility of realizing MMIC amplifiers in the ranges up to 95 GHz with the output power up to 0.5 Watt, will also be realized in commercially available MMICs.

Model	Manu-facturer	ΔF, GHz	P_{-3dB}, W	G_{ss}, dB	ΔG, ±dB	PAE, %	RL_{in}, dB	RL_{out}, dB
RFHA1000	RFMD	0,03-1,0	12-20	15 - 18	±1.5	60	-13	-5
RF3833	RFMD	0,03-2,1	25	10-13	±1.5	40-50	-9	-5
RF3826	RFMD	0,02-2,5	9	13	±1.0	35-45	-10	--
TGA2540-FL	TQ	0,03-3	9	19	--	40	--	--
CMPA0060002D	Cree	0,02 – 6,0	2-4	17	±1.0	28-43	-9	-11
CMPA0060025F	Cree	0,02 – 6,0	25	16 - 21	±3.0	26-40	-4	-7
CMPA2060025D	Cree	2.0-6.0	25	21 - 28	±3.5	42-44	-7	-7
CMPA2560025F	Cree	2.5-6.0	25-37	22 - 28	±3.0	> 30	-6	-5
TGA2576	TQ	2.5-6.0	35-45	20 - 23	±1.5	> 35	-15	-6
CMPA801B025D	Cree	8 - 11	32-47	27-30	±1.5	37-44	-5	-12
TGA2570	TQ	2 - 17	8-12	10-12	±2.0	20	-10	-10

Table 10. Some GaN power MMIC amplifiers parameters

4. High power GaN amplifier modules

Successes in the industrial development of GaN transistors and MMIC have immediately found response in the efforts and results of the work of the developers of high power UWB amplifier modules and systems. In 2009 through 2011 new devices appeared in the catalogues of the majority of companies producing power amplifiers, which in their overall mass parameters and the levels of CW output power surpass the earlier amplifiers on GaAs components. The attraction of the discrete GaN transistors is conditioned by the following considerations.

First. The scheme of the amplifier's output stage, which provides for the main energy consumption and dimensions, has been greatly simplified. To receive the required output power one needs from 4 to 10 times less of the discrete or MMIC devices, power combiners, and passive components. This cuts down the cost of the module construction and allows making it much smaller in size. To illustrate the above we present in Fig.11 in the same scale photographs of output stages of MIC broadband amplifiers with the output power of 10-15 Watt and the frequency range 4-11 GHz manufactured by Microwave Systems JSC on the basis of GaAs p-HEMT transistors (by combining the power of four balance quasi-monolithic MIC amplifying chains) and on the basis of GaN HEMT transistors (one balance MIC chain). The width of a module with GaN-based output stage has decreased three times as compared with the variant on GaAs transistors with the same level of the output power.

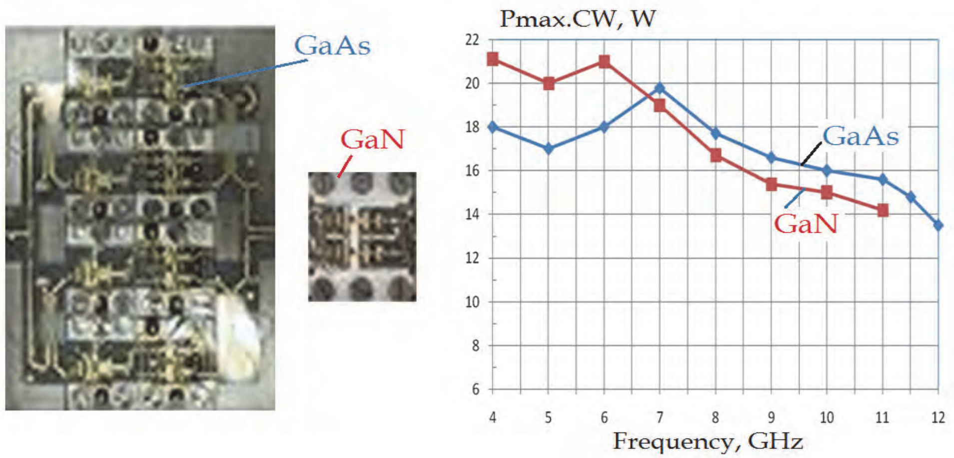


Fig. 11. Output stages of 4-11 GHz 15 Watt MIC amplifiers based on GaAs and GaN commercially available transistors – sizes and output CW power (Microwave Systems JSC)

The advantage in the size of the GaN modules may be estimated looking at Fig.12, where photographs of two amplifiers produced by Empower RF Systems (www.empowerrf.com) are given in the same scale. Both pictured models have the 50 W saturated output power in the 1 to 3 GHz frequency range. GaAs-based model (BBM4A6AH5) have the volume of 71.8 inch^3 and weight of 5 lb, while the volume and the weight of the GaN-based model (BBM4A6AHM) are correspondingly 23.9 inch^3 and 1.5 lb (the ratio here is 3:1).

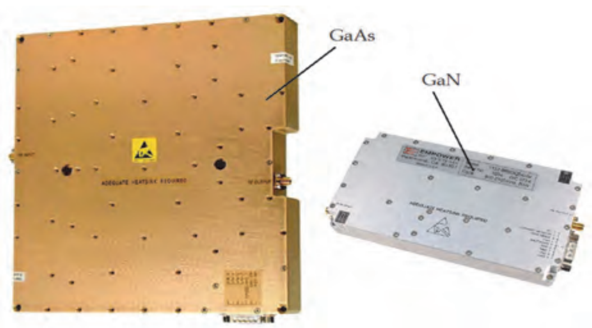


Fig. 12. Comparison of sizes of 1-3 GHz 50W GaAs vs. GaN amplifier modules (Empower RF Systems).

Second. With the appearance of GaN transistors the design methodology of the broadband power amplifiers has been considerably simplified. High supply voltage and high impedance of the optimal transistor load necessary for obtaining the maximum output power and power-added efficiency make much simpler the construction of the output matching circuits and improve the quality of matching in a much wider band of frequencies.

Third. The use of GaN transistors allows increasing DC-RF efficiency of amplifiers. The drain efficiency of GaN transistor itself biased in class AB without the use of special circuits with harmonic reflections comprises from 60% to 65%, while in GaAs p-HEMT transistors it is rarely over 55%. Due to this, as well as because here is a considerable decrease of losses in the output combiners, DC-RF efficiency of GaN-amplifiers is as a rule from 1.2 to 1.8 times greater than that in GaAs-amplifiers with the same power.

At the same time GaN amplifiers have specific features affecting their application in the some systems. Primarily these are specificities of the dynamic characteristic having a lengthy part of a monotonous gain compression with the growth of the input power, which is not typical for GaAs amplifiers. The maximum output power and DE in GaN amplifiers is realized with the gain compression from 3 to 7 or 8 dB and more, while in most GaAs amplifiers the value of compression is not greater than 1 or 2 dB. Different characters have also dependences of the harmonic level and intermodulation distortions from the input power. Fig.13 gives dependences of the 2-tone output power and third order combination components for two models of amplifiers having the same frequency range (from 2 to 4 GHz), the same maximum output CW power (25 W), and the same linear gain (43 dB), but built on different types of transistors.

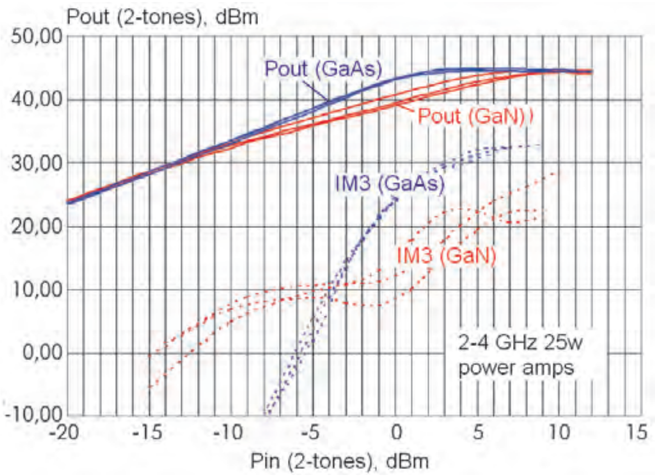


Fig. 13. Dynamic transfer characteristics and third-order intermodulation products of GaN vs. GaAs 2-4 GHz 25W power amplifiers (Microwave Systems JSC)

The active introduction of GaN transistors and MMICs in the industry and the advantages described above have led to the situation that during three years (from 2008 through 2010) tens of UWB high power GaN amplifier modules have been put out into the market, while a considerable part of the earlier GaAs amplifiers up to 3 GHz disappeared from the catalogs of manufacturers due to harsh competition. The main characteristics of the most powerful UWB GaN amplifiers that are being produced in 2011 are described in Table 11.

Model	Manufacturer	ΔF, GHz	P_{sat}, W	G_{ss}, dB	ΔG, ±dB	PAE, %	Vdc, V
BME2719-150	Comtech PST	0,02-1,0	150-200	70	-	35	18-36
BBM3T6AMQ	Empower RF	0,96-3,0	160	56	±2	30	28
BME19258-150	Comtech PST	1,0-2,5	250	70	--	25	18-36
SSPA-1,5-3,0-200	Aethercomm	1,5-3,0	200	67	±2,5	25	36
BME25869-150	Comtech PST	2,5-6,0	150-200	65	--	18	18-36
BBM5A8CGM	Empower RF	2,0-6,0	40	55	±1,5	15	28
PA020180-3932	Aeroflex	2,0-16,0	8	22	±3,5	24	28

Table 11. UWB high power amplifiers parameters.

Thus, the area of radio frequencies from 20MHz to 6 GHz is occupied by module UWB amplifiers on GaN transistors and MMICs with drain efficiency from 20% to 35% and the output CW power up to 200 Watt. On the frequencies of over 6 GHz the level of the output power of GaN amplifiers has so far been somewhat more modest; however there is no doubt that in the nearest future in these ranges up to millimeter waves the models on GaAs will partially be forced out from the market by devices on GaN.

5. Conclusion

This Chapter is devoted to consideration of the development process in the technology of GaN microwave power transistors and MMICs and to demonstration of the prospects for the development of this technology as an industrial standard in the nearest future. Electric and exploitation parameters of GaAs and GaN technologies were compared with the consideration of possible migration of power amplifier technical solutions from one to the other. Considered and analyzed were also parameters and specific features of commercially available GaN discrete transistors and MMICs, features of their application in constructions of high power UWB amplifiers, and the parameters of industrial models of such amplifiers.

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