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Short channel GaN FET MMIC technology for high reliability applications

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1 Introduction

1.1 High reliability applications and potential of GaN in this area

Among all application areas of electric circuits, space and military applications are the most demanding in terms of performance and reliability. In order to understand the reason of such high reliability demand, the following definition has to be provided: “Reliability is the probability of operating a product for a given time period under specified conditions without failure” [1]. Analyzing the provided definition, it becomes clear why reliability is so important in these specific application fields. For space applications repair, maintenance or replacing of broken components is almost impossible and in case of failure the whole mission will be completely or partly aborted. As the cost of space mission is much higher as compared to the cost of single component the probability of failure for the device has to be minimized even in cost of device electrical performance. The same situation takes place for military applications. As military equipment mostly operates in unfriendly environment, single component failure can lead to the critical decrease of combat performance and consequent damage or complete destruction of the whole combat unit. Unlike space applications, performance of combat unit components has to be maximized as well in order to outperform enemy’s equipment. Summarizing above mentioned space and military application demands to device reliability and considering the fact that complete system consists of hundreds or thousands of parts one can conclude that probability of failure for the single component has to be close to zero.

Reliability of the single component is defined by many factors. On one hand, aggressive environmental conditions such as humidity, temperature, radiation etc. tend to accelerate failure mechanisms and cause fast device degradation; on the other hand, internal physical and chemical properties of the component can be more or less sensitive to external negative influences. The sensitivity of semiconductor electronic devices is mostly defined by two factors: fundamental properties of semiconductor material (which defines maximum theoretically achievable electrical and reliability performance of the device) and maturity level of device fabrication technology (which goal is to achieve maximum theoretically predicted level of performance). The level of semiconductor material radiation and temperature hardness is mostly defined by bandgap width, therefore, as a wide bandgap semiconductor ($E_g = 3.4$ eV) GaN theoretically outperforms Si and GaAs in these terms. Unfortunately, until recently the maturity level of the GaN technology did not allow achievement of the full theoretical potential of GaN. Therefore, most electrical devices used in high reliability applications were fabricated using more mature Si and GaAs technologies. Nowadays situations are changing significantly, and GaN devices that have better electrical performance and the same level of reliability as compared to the Si and GaAs technologies finally achieved space and military markets [2], [3]. These advances were possible due to the significant improvement of device fabrication technology and allow concluding that further developments in this direction will allow approaching to the theoretical limits of GaN material and replacing conventional Si, GaAs and vacuum devices in high reliability application areas.

1.2 Current state of K- and Ka-band GaN FET technology

Today, conventional AlGaN/GaN HEMT based MMICs of S- and X-band frequency ranges reached technology readiness levels that allow for industrial fabrication and implementation in such demanding application areas as satellites and military radars. A further extension of GaN technology to higher frequency bands (K-, Ka- and above) is in progress. This challenging step requires significant scientific and engineering effort in order to obtain better understanding of physical processes occurring in the devices and to develop device designs that will allow overcoming main limitations due to the short gate dimensions. As a result of the first efforts in this direction, various PA MMICs intended for frequencies from 18 GHz to 40 GHz are already available from different vendors (Table 1). If performance of MMICs available from the shelf does not satisfy customer's demands, various foundry services are also available (Table 2). As depicted in Table 2, the offered operation frequency and output power density of the active elements will allow fabrication of PA MMICs up to Ka-band.

The necessity of the step forward and the replacement of conventional microwave technologies such as vacuum tubes is accompanied by additional advantages offered by the new technology. In contrast to mm-wave tubes GaN MMICs allow for decentralized system architectures and are therefore facilitating grace degradation instead of instantaneous failure as well as novel solutions from system side such as beam steering and phased array approaches. The latter means that a multitude of power amplifiers needs to be combined together in order to ensure targeted antenna directivity and radiation power level. Naturally, this calls for highly reproducible and highly robust GaN MMIC solutions.

The gate lengths of transistors incorporated into K- and Ka-band MMICs range between 100 nm to 250 nm. Naturally, shorter gates yield devices with a higher gain, however there is always a trade-off between the selection of the gate length and performance issues. For example, very short gates might result in short channel effects (weak device pinch-off at higher drain voltages) if the epitaxial layer stack is not adapted properly. On the other hand, a well-adapted material might be instable, for example in AlGaN/GaN material systems if a too high Al-concentration needs to be selected. Therefore, the gate-length selected by different manufacturers can be understood as a "sweet spot" in the trade-off between performance and device stability. Usually for GaN power amplifier MMICs in the 20 GHz range 150 nm gate lengths are favorable.

Table 1: State-of-the-art K- and Ka-band MMICs

Vendor	Freq. (GHz)	Performance	Periphery	P_{out} (W/mm)	L_g (nm)	Year	Ref.
Northrop Grumman	18-23	6 W, PAE > 30 %, V_{ds} = 28 V, Gain = 20 dB	N/A	>3.4	200	2014	[4]
Northrop Grumman	27-31	13 W, PAE = 25.5 % V_{ds} = 28 V, Gain = 19.5 dB	N/A	>3.4	200	2015	[4]
Toshiba	29-31	15 W, PAE = 20 %, Gain = 15 dB	N/A	N/A	N/A	2012	[5]
Qorvo	29-31	8 W, PAE = 23-29 %, V_{ds} = 20 V, Gain = 22-29 dB	14 cells 8×50 μm	>1.4	150	2015	[6]
Qorvo	6-18	10 W, PAE=20 %, V_{ds} = 20 V, Gain = 25 dB	N/A	N/A	150	2016	[7]
IAF	18-20	10 W, PAE = 30 %, Gain = 20 dB	1st stage 2×6×90 μm 2nd stage 4×8×100 μm	>3	250	2016	[8]
OMMIC	30	5.5 W, PAE = 32%, Gain = 20 dB	3 stages	3.3	100	2016	[9]
HRL	40	0.5 W, PAE = 10%, V_{ds} = 14 V, Gain = 7dB	N/A	N/A	20	2016	[10]

Table 2: State-of-the-art foundries

Vendor	Freq. (GHz)	Power density (W/mm)	Lg (nm)
Northrop Grumman	26-30	>4	200
Qorvo	30	3	150
IAF	17-20	4	250
OMMIC	30	3.5	100
FBH	20	>5	150

1.3 Full cycle of GaN MMIC development and testing

The MMIC design strongly depends on application area and performance expected from the circuit. Proper technical specifications and environmental operation conditions are the starting point of the MMIC development routine. Figure 1 shows the flowchart of typical MMIC development cycle. The flowchart is divided in two parts: on the left-hand side is the development sequence from the point of view of the MMIC designer, and on the right-hand side is the point of view of the foundry. As can be seen, the whole development routine contains three main cycles: technology development, design and production.

Technology development starts on the foundry fab and is normally going on during the whole life cycle of technology by releasing new process versions with certain time interval. Fab engineers use feedback from experimental and production processes in order to improve the technology in terms of electrical performance and reliability of final devices. When the stable version of technology comes out of experimental technology development cycle, modeling routines are performed in order to create a model library for the design kit. After this step, the design kit can be provided to the customers and technology can be used in the production cycle.

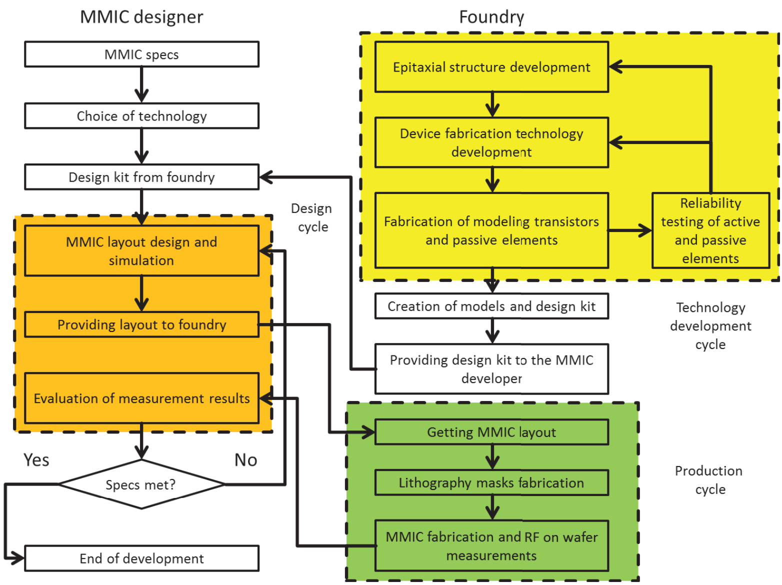

Figure 1: Typical flowchart of MMIC development and testing

The MMIC design cycles are based on the current MMIC technology and the corresponding model implementation. After creation of MMIC layout and subsequent circuit fabrication the feedback from the final measurements may lead to further optimization of layout and electrical performance of the circuit. The design iteration can be performed 2 – 3 times in order to achieve a result close to the optimum.

1.3.1 MMIC specifications

A set of specifications used for MMIC design properly describes the electrical performance expected from the circuit. It is normally provided by system designers that perform RF budget calculations of the whole system. Depending on the MMIC type the specifications can contain demands for different electric properties of MMIC. Table 3 summarizes the typical specifications for some passive and active MMICs.

Table 3: Typical specifications for some passive and active RF circuits

Passive			**Active**	
Switcher	**Attenuator**	**Phase shifter**	**Low noise amplifier**	**Power amplifier**
Frequency range	Frequency range	Frequency range	Frequency range/band width	Frequency range/band width
Isolation	Attenuation range	Phase shift range	Noise figure	Pout 1dB, Pout 3 dB, Pout sat
Insertion loss	Attenuation resolution	Insertion loss	Gain	Gain
Return loss	VSWR	VSWR	Maximum power input/output	PAE
VSWR	Maximum power/voltage	Maximum power/voltage	VSWR	Maximum input power
Switching speed			DC supply voltage/current	VSWR
Maximum power/voltage				IP3
				DC supply voltage/current

As can be seen from the table, some specifications, such as operation frequency, VSWR and maximum power are common for all types of circuits, and the other depend on the circuit type. Based on these specifications the designer decides about technology that will be used for MMIC production. In order to do that, some preliminary calculations can be done in order to translate main specifications into commonly using transistor DC and RF properties such as threshold voltage, breakdown voltage, maximum frequency of oscillation etc. Considering active elements, the important parameters for specifying an amplifier are: gain, PAE and output power at given operation frequency. The basic flowchart for translating device specifications into device properties and consequent technological aspects presented on Figure 2.

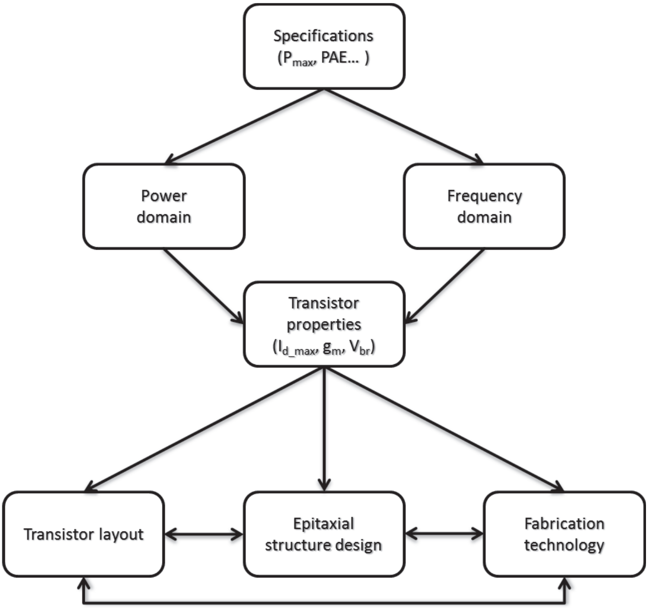

Figure 2: Basic flowchart of MMIC specifications translation into transistor properties and technology aspects

In general, the specifications can be subdivided in two domains: power specifications and frequency specifications. In the power domain, required transistor properties depend on the intended class of operation of the amplifier. For example, considering class B operation Equation 1 can be used [11]:

Equation 1:

$$P_{RF\_max} = \frac{\left(V_{br} - 2 \times |V_{th}| - V_k - V_\varphi\right) \times I_{d\_max}}{8}$$

Where, V_{br} – breakdown voltage, V_{th} – threshold voltage, V_k – knee voltage, V_φ – Schottky barrier height. Considering typical values of V_{th}, V_k and V_φ for GaN transistors the following expression can be obtained:

Equation 2:

$$\boldsymbol{P_{RF\_max} = \frac{(V_{br} - 9) \times I_{d\_max}}{8}}$$

Equation 2 shows that the maximum available output power of the amplifier is proportional to the maximum drain current and breakdown voltage of the transistor. Maximum drain current can be easily increased by increasing transistor size, or number of transistors connected in parallel in the amplifier circuit. However, the application of too big transistors consequently with comparably small output impedances leads to an increase of losses in the transformation chain of the amplifier and consequent reduction of PAE. For this reason, using relatively small transistors with higher breakdown voltages can be a better solution.

In the frequency domain two main figures of merit are normally specified for the transistors: maximum frequency of oscillations f_{max} and maximum cut-off frequency f_t. f_{max} represents the frequency where power gain drops to unity, whereas f_t shows frequency where current gain drops to 0 dB. Equation 3 and Equation 4 show how to calculate f_{max} and f_t, respectively.

Equation 3:

$$\boldsymbol{f_{max} = \frac{f_t}{2 \times \sqrt{\frac{R_g + R_i + R_s}{R_{ds}} + 2\pi f_t R_g C_{gd}}}}$$

Equation 4:

$$\boldsymbol{f_t = \frac{g_{m-ext}}{2\pi C_g}}$$

Depending on the specific transistor design f_{max} can be either higher or lower than f_t. Knowing f_{max} and using rule of thumb which says that small signal gain decays 20 dB per decade (8 dB per octave, first order low pass behavior), one can calculate the transistor gain at a given frequency. As can be seen from the equations above, f_{max} depends on f_t, which, at the same time depends on transconductance $g_{m\text{-}ext}$. Equation 5 and Equation 6 show the expressions for transconductance calculation. As can be seen from these expressions, transconductance, and consequently f_{max} is proportional to the effective electron velocity, which is a physical property of semiconductor material.

Equation 5:

$$\boldsymbol{g_{m-ext} = \frac{g_{m-int}}{1 + g_{m-int} R_s}}$$

Equation 6:

$$g_{m-int} = \frac{\varepsilon_0 \varepsilon_{bar} v_{eff}}{t_{bar}}$$

Once the connection between the MMIC specifications and transistor performance is clear, the appropriate technology for the MMIC fabrication can be chosen.

1.3.2 Choice of technology

The specific properties of each technology strongly relate to semiconductor material properties. Current technologies available on the RF market are represented on the Figure 3. In order to choose the optimal technology for MMIC realization, developers have to be aware not only of the output power available at certain frequency, but also another advantages and disadvantages of selected technology. Based on this knowledge a proper tradeoff between electrical performance expected from specifications and production and development cost of MMIC has to be found. The importance of economical aspect is application dependent: for the space and military applications the MMIC performance and reliability are the major factors, at the same time for civil applications and large production volumes, performance can be partly sacrificed in favor of production and development cost reduction. Among the technologies available today, silicon and GaAs are more matured and present on the market for dozens of years for now; at the same time GaN technology is relatively new, but performance offered by this technology attracts a lot of attention despite. As it was explained in [8], GaN technology is the best candidate for the fabrication of efficient power amplifiers with high output power density, as well as for fabrication of robust low-noise amplifiers not sensitive to the large signal levels on the input.

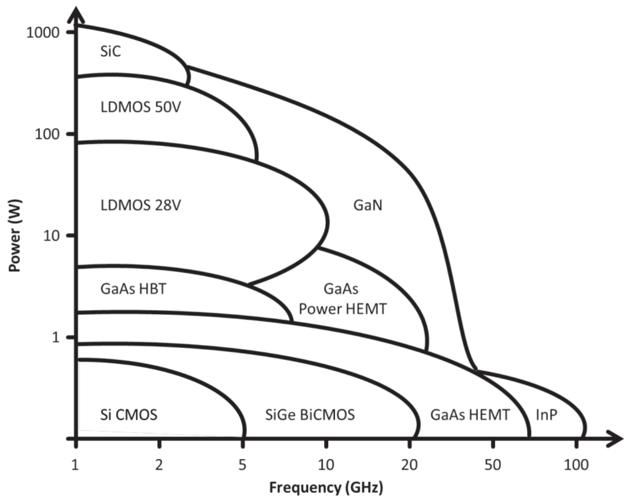

Figure 3: Output power at different frequencies for various transistor technologies

1.3.3 MMIC design, simulation and layout creation

As the decision about the technology has been made, the MMIC designer needs a design kit provided by a foundry in order to start the design routine. The design kit contains the rules that have to be followed during the layout design, as well as a library of active and passive elements available for fabrication in the foundry fab. The simulation of RF circuits is normally performed in harmonic balance and electromagnetic simulation software packages such as “Microwave office”, “Advanced design system” and so on [12]. By performing such a simulation, MMIC designers can predict the expected level of circuit performance with a certain level of precision. The accuracy of performance calculations depends on many factors, such as number of effects considered during the simulation, accuracy of the models provided in the design kit and process stability on the foundry fab (how consistent are the models with the really fabricated devices). If any of the earlier mentioned factors are violated, the performance of fabricated MMIC will be different from simulator prediction. In order to achieve the desired performance, additional design and fabrication iterations have to be done after finding of the noncompliance reason.

1.3.4 Development of epitaxial structure design and MMIC fabrication technology

Each foundry fab has a portfolio of technologies available for the customers. Usually, only one or two different technologies are available on the same fab. Normally foundries