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L.K. KARAPETIAN

CURRENT STATUS AND FUNDAMENTALS OF MICROWAVE INTEGRATED CIRCUIT DESIGN WITH GaN HEMT TRANSISTORS

Gallium nitride (GaN) high electron mobility transistors (HEMTs) are key parts of microwave integrated circuits (MICs) because of their high electron mobility, wide band gap, critical field, permittivity and exceptional thermal conductivity. These options allow GaN HEMTs to work at higher frequencies and power levels than traditional silicon-based transistors. For the RF and microwave systems, this gives them efficiency. The importance of GaN HEMTs in MICs can be listed as follows: higher power density, improved efficiency, wide frequency operation, thermal stability. These benefits make GaN HEMTs a crucial technology for communication systems today, defense and space technologies. Different proposed technologies of recent years on GaN HEMTs have been summarized and compared. The relatively commonly used GaN HEMT types are presented, including their models. 3 main sub-branches of GaN HEMT are discussed: types of transistors, transistor models and characteristics and MICs design. Each of them has its own advantages and disadvantages, depending on the problem, the most suitable one can be chosen. As a result, several important problems are highlighted, such as performance optimization, thermal management solutions, reliability and longevity, signal integrity and noise reduction, future research directions, etc.

Keywords: high electron mobility transistors, microwave integrated circuits, higher power density, improved efficiency, wide frequency operation, thermal stability.

Introduction. HEMTs are now the most used type of transistors for RF and microwave frequency applications, especially when large power outputs are needed [1]. GaN-based HEMTs show great potential for use in power electronics, largely because they offer superior breakdown voltages and power efficiency when compared to silicon-based devices. Key characteristics of HEMTs include factors like contact resistance, current density, capacitance, and breakdown voltage [2] and for these good qualities, GaN HEMTs are used for RF and power Devices [3,4], space applications [5], conventional housing-type power modules [6], etc. This article can be divided into 3 main categories.

- **Types of transistors [7-25]** – The term transistors and their relevance in electronics. Different types of transistors and how they are used in the design of MICs.

▪ **Transistor models and characteristics [26-28]** – The expanded description of each type's characteristic regarding MICs design.

▪ **Microwave integrated circuit design [29,30]** – Definition and a close view of MICs. Modern approaches to the design of the modules, prospects for the development of the GaN HEMTs disadvantages and advantages in MICs.

1. Types of transistors

1.1. Overview of transistors and their significance in electronics

In [7], basic information about transistors, their function of amplifying and switching electrical signals are presented. In radio technology, very faint signals that travel through the air are intensified before being output through speakers. Additionally, a transistor functions as a switch, activating only when it receives a specific signal. An integrated circuit (IC) or large-scale integration (LSI) is essentially a grouping of transistors that perform fundamental transistor functions. Recently, GaN HEMTs have become popular and are used in designing microwave integrated circuits, but their efficiency depends on several factors.

▪ What type of transistor was used?

▪ Which model of transistor was used?

▪ What method was used to design the microwave integrated circuit?

1.2. Variety of transistors and their applications in MICs design

The GaN HEMT devices are available in various forms (Fig. 1), depending on their design, materials, and intended use. Below, we outline the most prevalent types, along with their respective advantages and disadvantages in relation to MICs design.

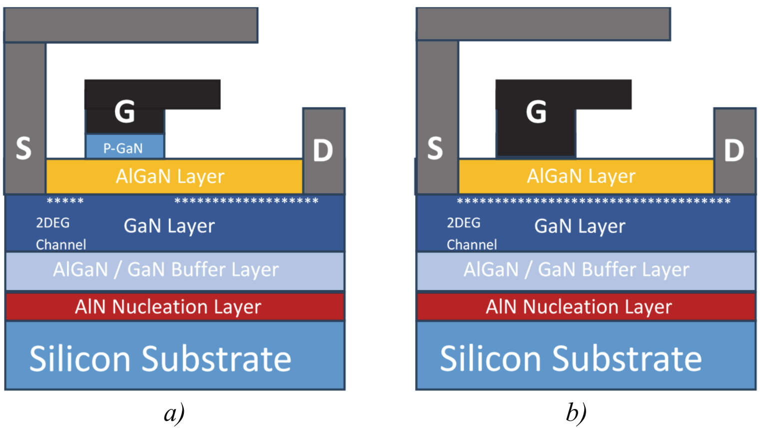

Fig. 1. Simplified device cross-sections of a) E-mode and b) D-mode HEMTs (Source: GaN Power International)

1.2.1. Enhancement-mode (E-mode) GaN HEMT

In [8], a way to improve E-mode GaN HEMTs is described (Fig. 2). The focus is on the p-type GaN layer below the two-dimensional electron gas (2DEG) layer, and the recessed Schottky gate above it. As a result, GaN HEMT is by default a normally-ON transistor. By employing a Schottky gate, such as Ni/Au on AlGaN/GaN, to deplete electrons in 2DEG at the applied negative gate bias V_{gate}, the HEMT can be disabled. This normally-ON HEMT is also known as a depletion-mode (D-mode) HEMT. This work begins with creating a usual OFF HEMT, where electrons in 2DEG are defaulted to be depleted at $V_{gate} = 0\ V$. Because positive threshold voltage (VT) requires positive V_{gate} to activate the HEMT, this device is also known as an E-mode HEMT. For power converters, E-mode is always preferable to D-mode because it requires less static power and functions in a failsafe manner. Under the 2DEG layer, the recessed Schottky gate with a p-type GaN is the main emphasis. Two responses (V_{th}, R_{on}) were obtained from the design of the experiment three factors (AlGaN, L_{gate}, and p-type GaN) at four levels for technology computer-aided design (TCAD) simulation. The list of possible ideal E-mode GaN HEMTs was reduced by feeding 128 sets of observations into the analysis of variance (ANOVA) and artificial neural network (ANN) models. As a result, by analyzing all the variants the best device with AlGaN = 4 *nm*, $L_{gate} = 2\ \mu m$, and p-type GaN = 1.2×10 19 cm^{-3} is predicted $V_{th} = 1.263\ V$ and $R_{ON} = 3.317\ \Omega$. $V_{Th} = 1.224\ V$ and $R_{ON} = 3.235\ \Omega$, which are extremely like the ANOVA-ANN prediction, are obtained via the TCAD verification.

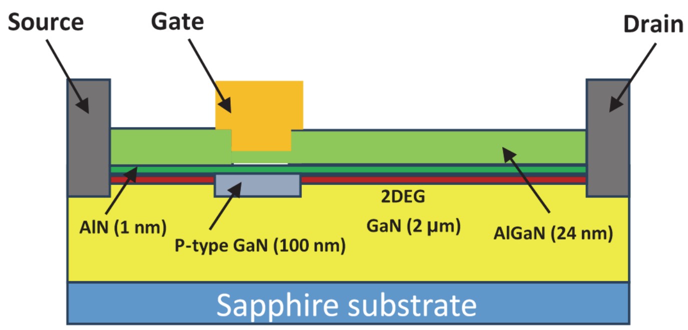

Fig. 2. Scheme of GaN HEMT to indicate the device components and their dimension

[9] presents under gate terminal p-GaN layer doping effect for enhancement-mode (E-mode) GaN HEMT. By simulations, optimal values for the following performance parameters R_{on} and Q_g are found. Once a higher doping method has been used, the device gives lower R_{on}, and can be used in lower switching schemes. For the lower doping method, Q_g is lower, which is the result of the device reaching a certain gate voltage faster.

The method in [10] focuses on switching energy losses determination for 2 types of GaN HEMTs cascode and E-mode. For comparison, 2 models TP65H035WS and GS66508T are used. As a result, for total switching energy losses E-mode HEMTs are preferable, because energy consumption is two - three times lower. The dv/dt value of E-mode HEMT became significantly bigger, specifically when the transistor was turned off (up to 150 *V/ns*).

1.2.2. Depletion-mode (D-mode) GaN HEMT

In [11], for D-mode AlGaN/GaN metal-insulator-semiconductor (MIS)-HEMT model on a Si substrate the temperature sensitivity was studied (Fig. 3). This work reports on the high-temperature (HT) operation around 25°C-400°C and temperature sensing mechanism of a D-mode AlGaN/GaN metal–insulator–semiconductor (MIS) D-mode GaN HEMT on silicon substrate. In the subthreshold functioning region of the transistor, most Si-based CMOS temperature sensors have little currents (*tens of picoamperes/mm*) but HT sensitivity. The conductivity of the 2DEG in the channel region of AlGaN/GaN HEMTs has been found to be influenced by donor-like traps at the GaN-cap/Si_3N_4 interface and acceptor-like traps in the GaN buffer layer. The data analysis presents the effect of these traps on the electron concentration in the 2DEG and the temperature sensitivity of the HEMT drain current. This is achieved by comparing HEMT I_D-V_G measurements with the results of 2-D simulations. When the drain-source current (I_{DS}) is 10 *μA/mm*, the temperature sensitivity of the device under subthreshold operation is close to 8.73*%/K*. This is comparable to the stated values for silicon devices, but at far higher current densities and over a much larger temperature range.

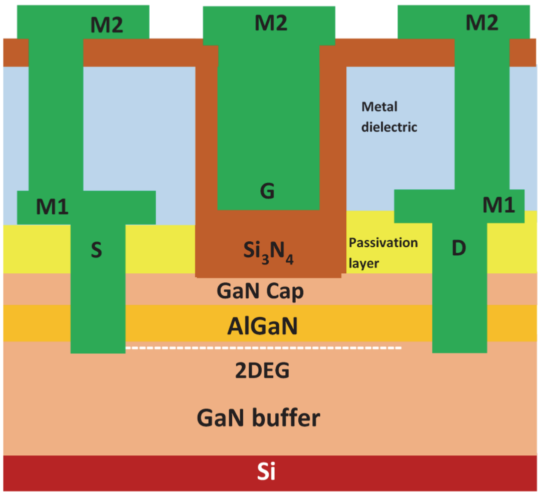

Fig. 3. Scheme of GaN HEMT to indicate the device components and their dimension

In [12], Si based D-mode GaN HEMT device for the high voltage operations is presented. The device worked over 200 *V* with an isolation resistance of 4.68×10^{10} *Ohms/sq* and shows a peak trans-conductance of 110 *mS/mm*. For device fabrication 650 μm thick silicon substrate, was used for forming 2DEG in GaN HEMT device a GaN buffer layer of 3.9 μm and AlGaN barrier layer (20 *nm*) over buffer layer was used. For fixing leakage currents a GaN cap layer of 2 *nm* thickness is grown over the barrier layer.

As mentioned in [13], the D-mode GaN HEMTs has been used for design monolithic high-efficiency buck converter. D-mode GaN HEMTs provide greater frequency and current density, making them suitable for Monolithic Microwave Integrated Circuits (MMICs) Power amplifier (PA) design. A monolithic GaN buck converter with integrated drive circuits and GaN switches is the most efficient strategy for minimizing parasitic and area in the envelope-tracking supply modulator (ETSM) systems. This buck reaches a peak efficiency of 90.7%, with a peak output power of 11.6 *W* at a 112.5-*MHz* switching frequency. PA efficiency was increased by 14.3% compared with the PA with fixed supply voltage.

1.2.3. GaN-on-Si HEMT

In [14], GaN HEMTs processed on a silicon substrate is used in this type (Fig. 4). It offers a cost advantage and is compatible with conventional silicon processing techniques. Source and drain (S/D) ohmic connections were made using Au-free Ta/Al metals that had recessed etching. The ohmic contact resistance may be decreased because of GaN or InGaN regeneration [15-17]. After establishing a rectangular gate with a L_G of 80 *nm* using electron beam lithography (EBL), Ti/Al (20 *nm*/60 *nm*) metallization was carried out. In the final stage, the devices' surface was passivated using 10-*nm* Al_2O_3. A Keysight B1505A semiconductor device analyzer was used for DC characteristics analysis, and a Keysight N5244A PNA-X network analyzer was used for RF small signal characteristics analysis. Large signal RF power characteristics were measured using the Maury load-pull technique. Ultimately, a metallization process compatible with CMOS was used to construct GaN-on-Si HEMTs with 80-*nm* rectangular gates. An exceptional f_{MAX} of 74 *GHz*, and I_{dmax} of 1.95 *A/mm* were received. With a mobile SoC-compatible supply voltage of 5 *V*, the device obtained P_{out}>1 *W/mm* and the gain of 16 *dB* at 2.5, 3.5, and 5 *GHz*. The outcomes show that GaN-on-Si HEMTs have the potential to be highly performing and reasonably priced RF in 5 *G* sub-6 *GHz* mobile SoC applications. As a result, it is figured out that the device is perfect for cost sensitive applications. GaN-on-Si HEMTs offer a balance of performance and cost, making them ideal for commercial microwave applications. However, there are a couple of issues with:

▪ *Lower thermal conductivity* - Silicon has a lower thermal conductivity than SiC, which may restrict its capacity to disperse heat and impact high-power microwave circuit performance;

▪ *Substrate-related losses* - The material characteristics of silicon can result in parasitic losses at high frequencies, which lowers the effectiveness of MICs that operate in the microwave spectrum.

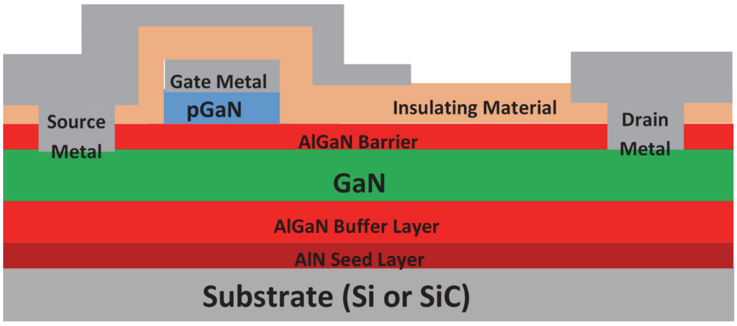

Fig. 4. By growing a p-type E-Mode GaN layer on top of the AlGaN the 2DEG is depleted at zero volts on the gate on Si or SiC substrate

[18] presents 200 *mm* Si substrate E-mode GaN-on-Si HEMTs working on up to 100 *V* V_{DS} voltage for power electronics industry. The device presents an ultralow drain leakage current at maximum V_{DS} voltage. The dynamic $R_{ds\text{-}on}$ behavior of the manufactured devices is measured using a resistive load test equipment. The 150 *uF* capacitors and 5 *Ω* to 100 *Ω* load resistors were employed, with a stress V_{DS} range of 5 *V* to 100 *V*. As a result, a high reliability device based on Si substrate is presented.

The method in [19] focuses on developing E-mode GaN HEMT in GaN-on-Si material for 150 *mm* wafer. The final device structure characterized the breakdown behavior. V_{BR} values of up to 1000 *V* were reached through growth optimization of the GaN layer. As mentioned by the author for next research of the electrical characterization of the developed device will be presented.

1.2.4. GaN-on-SiC HEMT

In [20], GaN-on-SiC HEMT technology examined in microwave oscillators implementation, instead of gallium arsenide (GaAs), indium phosphide (InP), or silicon germanium (SiGe) technology. By using GaN-on-SiC technology they avoid the use of additional power amplifiers for the correction of relatively low output power level. Depending on the field of use of the integrated oscillator, it can be divided into a voltage-controlled oscillator (VCO) or a fixed-frequency oscillator (FFO). In [21], the first VCO made with GaN HEMT technology is unveiled. It features a 10% frequency tuning range, an output power of more than

28 *dBm*, a phase noise (PN) of -92 *dBc/Hz* at an offset frequency of 100 *kHz*, and the ability to operate at 6 *GHz*. Other GaN VCOs which also operate at the C-band or X-band, as demonstrated in [22 - 24], have limited applications because of their comparatively low PN. The ultra-low PN integrated FFO described in this study was made using Cree's 0.25 μm GaN-on-SiC HEMT technology, and the die was connected to the PCB and heat sink for measurement. According to the measurements, the proposed FFO had an 8.6% DC-RF efficiency, 21 *dBm* power, and ran at 7.9 *GHz*. Additionally, PN is 113 *dBc/Hz* at 100 *kHz* and 135 *dBc/Hz* at 1 *MHz* offset frequency. In conclusion, that device is ideal for managing heat and high power, because of its excellent thermal characteristics and high-power handling, GaN-on-SiC HEMTs are typically the best option for high-power microwave applications, nevertheless, there are additional issues related to:

▪ *More costly* - SiC substrates are more costly than silicon, which raises the total cost of the device and circuit.

▪ *Complex processing* - GaN-on-SiC devices are more difficult to fabricate, which can restrict supply and make microwave circuit design more complicated.

As mentioned in [25], the GaN-on-SiC-based device has been presented with a high doped buffer layer. By the following options like a highly doped buffer region, AlN nucleation layer and SiC substrate under gate terminal a better 2DEG layer is formed. Compared with other varioants on substrate materials SiC provides a better lattice mismatch, thermal resistance, etc. (*Table*).

Table

Some key properties of Al_2O_3, SiC, and Si

Substrate	Crystal plane	Lattice spacing *Å*	Lattice mismatch *%*	Relative thermal expansion $10^{-5}\ K^{-1}$	Thermal conductivity *W/cm*K*	Relative Cost
Al_2O_3	(0001)	4.758	16.1	-1.9	0.42	Middle
SiC	(0001)	3.08	3.5	1.4	3.8	Highest
Si	(111)	3.84	-17	3	1.5	Lowest

It is necessary to evaluate certain trade-offs for each kind of GaN HEMT keeping in mind the specific needs of your microwave integrated circuit design; For example, how well-balanced are the designs for drivers and ICs, including power and control?

2. Transistor models and characteristics

Several manufacturers have produced GaN HEMT transistors and therefore several successful models aimed at different applications that are all available on the market. Such models are different in key parameters, such as power output; frequency band; applicable area, such as RF/microwave technology, power electronics, etc. This is a comparative evaluation of the advantages and disadvantages of the different models of GaN HEMT from different manufacturers for their use in microwave integrated circuits.

2.1. Cree (Wolfspeed) GaN HEMT Model CCGH40045

The model presented in paper [26] is a GaN HEMT model which is classified as −48V RF IC for microwave applications focused on bandwidth up to 4 *GHz*. This device employs GaN technology, which is superior to silicon technology in terms of dielectric breakdown due to high electrical mobility enhancing electron density, rectifying and improving power efficiency. Special attention, regarding thermal management, is paid in the construction of CCGH40045 allowing it to remain functional at high operating conditions and ensuring a high degree of reliability against failure in harsh environments. Its compact design facilitates integration into smaller microwave systems, an essential attribute for applications with size limitations, such as radar and advanced communication systems, while maintaining performance integrity. Targeted for radar and communication applications, this device delivers high power output. Operating at 28 volts, the CGH40045 offers a broad solution that is suitable for microwave and RF applications. GaN HEMTs are highly efficient and provide a lot of gain and have a lot of bandwidth making this device CGH40045 useful noise blocks/linear and compressed amplifier circuits. For high-power, lower frequency MICs, models like the CGH40045 are ideal because they have a large power output, and good heat dissipation as a model type, this model also has some disadvantages such as:

- High degree of thermal power means there will be a requirement of more advanced cooling solutions whatsoever.
- In compact microwave integrated circuit designs a few models have relatively larger pack sizes, which can result in larger circuit size.

2.2. Ampleon GaN HEMT model CLF1G0035-50

In [27], a study that explores the characteristics of a GaN HEMT model with particular focus on RF applications in the 0.5 to 3.5 *GHz* range has been found. The model has compatibility with broadband wireless communication systems. The CLF1G0035-50 GaN HEMT is designed for instrumentation and base station applications which require high radio frequency ranging from 0.5 to 3.5 *GHz* frequency band making it ideal for broadband wireless communication systems. This device makes use of GaN technology which has excellent thermal management properties and high breakdown voltage, so the choice depends on your specific MIC design requirements (frequency range, power output, cost, and thermal considerations).

▪ Limited to lower microwave frequencies, which can restrict its use in high-frequency MICs.

▪ These levels may be regarded as moderate, which rules out their use in cases requiring high power levels.

2.3. Qorvo GaN HEMT model TGF2935

In [28], a general-purpose GaN HEMT for high-frequency applications is presented, which is up to 18 *GHz*. It is often employed in RF amplifiers for communications and defensive applications. The Qorvo TGF2935 model of *GHz* HEMT can be described as a wide-band high-power amplifier covering up to 18 *GHz* frequency range, a typical example being Qorvo's GaN HEMT TGF2935 model or Qorvo's GaN technology. This device has a wide bandwidth with good efficiency and is suitable for RF amplification in communication and defense systems. High power density and efficient thermal management which is inherent in GaN technology are necessary for reliable performance in harsh environmental conditions. Besides, the TGF2935 is built in such a way as to meet high linearity expectations, thus being beneficial in preventing signal losses across a large frequency range in multi usage broadband and broadband pulsed applications. For high-frequency MICs, models like TGF2935 are suitable for high-frequency microwave circuits loads such as radar and the communication of satellites, but this model has also some bad points like:

▪ It's more costly than other models which can be a problem in high power microwave circuits.

▪ At these power levels, thermal management becomes a major headache and requires the use of advanced cooling approaches.

3. Microwave integrated circuit design

3.1. Basics of MICs

In [29], foundational information is provided regarding the theoretical principles of MIC design, including the aspects related to transmission lines, modeling of linear networks, the definition of S parameters, and elements pertinent to microwave metrology and network design.

3.2. MICs design key methods

3.2.1. Monolithic and Hybrid Microwave Integrated Circuits

In [30], MMICs and HMICs methods are proposed, which are based on single or multiple semiconductor dies, to provide standard RF capabilities in standardized packages. These two MMICs and HMICs for design methods for microwave integrated circuits are key methods in RF systems, but they provide different capabilities and functionalities. HMICs and MMICs are the two chief and integrated circuits used in microwave systems. Apparently, almost all new microwave components are touted to be MMICs. Their main differences tend to rest in the construction methods:

▪ MMICs consist of 1 single semiconductor die. A single base material is used to fabricate all circuits and components on the chip. This is done with standard planar processes, although future MMICs will be designed as 3D circuits using heterogeneous integration.

▪ HMICs consist of discrete, semiconductor or integrated circuit blocks. Devices are then connected with metalized wires and contacts, forming a modularized structure.

Both types of circuit are then encapsulated in epoxy or similar material. Such packages are generally standard IPC form factors such as QFN and SOT. Since these components function at microwave range frequencies, they are not normally through hole parts, through hole leads tend to cause high frequency signal integrity problems associated with stubs. When MMIC or HMIC devices do not come in custom packages they may look close to a Si integration.

3.2.2. GaN HEMTs in MICs design

The GaN HEMT devices are considered a precious resource in MIC design because of their extremely high electron mobility, allowing these devices to amplify power efficiently at high frequencies. Thus, their application can be expanded to MMIC and distributed circuit designs. Still, there are challenges with regards to managing heat dissipation and integration costs, as these devices are quite costly to manufacture and dissipate a lot of heat when operated at high power levels. It remains important to deal with the above issues since this will enable the devices to be more effectively used in advanced microwave applications.

4. Results

During the analysis, the following measures were indicated concerning the functioning of microwave integrated circuits with GaN HEMT transistors:

▪ Performance optimization – Tackling the limitations in the power efficiency and the frequency response of the microwave integrated circuits utilizing GaN HEMT transistors.

▪ Thermal management solutions - Presenting methods of achieving minimization of heat production and improvement of cooling techniques in GaN HEMT based circuits.

▪ Reliability and longevity – Discussing the subject of the increased tolerance and operational life of the microwave circuits populated with GaN HEMT transistors under high stress conditions.

▪ Cost-effective manufacturing - Investigating techniques which will lead to a decrease in the production cost of these circuits while at the same time improving the effectiveness of GaN HEMT transistors in these circuits.

▪ Signal integrity and noise reduction – Discussing methods designed for the reduction of signal loss and noise in microwave integrated circuits by using GaN HEMT transistor configuration.

▪ Future research directions – Recommending areas for further investigation such as advancing the materials or scaling techniques to further improve the capabilities of GaN HEMT transistors for microwave use.

Conclusion. GaN HEMTs have become a pivotal technology in the development of integrated circuits, especially in applications that demand high power and high-frequency capabilities. While offering improved electron mobility, a greater breakdown voltage and exceptionally good thermal conductivity, these devices have many more advantages over the traditional silicon-based transistors. Such capabilities help to transfer power effectively, reduce switching losses, and permit high frequency operation, making the GaN HEMTs ideally suited for RF amplifiers, power supplies of high efficiency and many other sophisticated electron systems. However, there are several other problems the GaN HEMT industry is facing. First and foremost is the high cost of the production that comes with GaN materials. GaN device production requires expensive substrates such as silicon carbide or sapphire as opposed to the silicon substrate which pushes up production costs. Additionally, GaN HEMTs inherently suffer from equipment thermal management problems because of their high-power density. Proper heat removal is critical for the designed basic reliability of the device particularly in the cases of high-power density and for the tightly packed integrated circuitry.

REFERENCES

1. **Leuzzi G., Stornelli V., Ellinghaus P.** Simulation of GaN/AlGaN heterostructures for a HEMT simulator // UNIVERSITY of L'AQUILA, Faculty of Engineering Department of Pure and Applied Mathematics, Master Thesis in Mathematical Engineering. - 2011. -P. 1 - 7.
2. **Liang X.** Characterization of GaN based HEMTs for power electronics // Degree project in engineering physics, second cycle, 30 credits.- Stockholm, Sweden, 2020. -P. 4.
3. ASM GaN: Industry Standard Model for GaN RF and Power Devices—Part 1: DC, CV, and RF Model / **Sourabh Khandelwal, Yogesh Singh Chauhan, Tor A. Fjeldly, Sudip Ghosh, et al** // IEEE Transactions on Electron Devices.- January, 2019. - Vol. 66, issue 1.-P. 80–86.
4. **Wu H., Fu X. and Hu S.** A 650V Enhancement Mode GaN HEMT Device with Field Plate for Power Electronic Applications// 2021 International Conference on Electrical, Communication, and Computer Engineering (ICECCE).- Kuala Lumpur, Malaysia, 2021. -P. 1-5.
5. Broadband GaN HEMT Microwave Integrated Circuit for Space Applications / **Ken Osawa, Hiroyuki Yoshikoshi, Akitada Kodama, Tsuneyuki Tanaka, et al** // SEI TECHNICAL REVIEW.- OCTOBER 2018. -N87.

6. **Kou L. and Lu J.** Applying GaN HEMTs in Conventional Housing-Type Power Modules // 2020 IEEE Energy Conversion Congress and Exposition (ECCE).- Detroit, MI, USA, 2020. –P. 4006-4011.
7. **Transistors Functions | Electronics Basics | ROHM**, Accessed: 10/16/2024.
8. Methodology to Optimize E-Mode GaN HEMT with P-Type Doping under 2DEG Layer / **M.F. Abdullah, N.A. Aziz and H.W. Lee, et al** // 2024 IEEE International Conference on Semiconductor Electronics (ICSE). - Kuala Lumpur, Malaysia, 2024. -P. 9-12.
9. **Mahajan D.** and **Khandelwal S.** Impact of p-GaN layer Doping on Switching Performance of Enhancement Mode GaN Devices // 2018 IEEE 19th Workshop on Control and Modeling for Power Electronics (COMPEL). - Padua, Italy, 2018. -P. 1-4.
10. **Vukić V.D.**, **Mrvić J.** and **Katić V.A.** Comparison of the Switching Energy Losses in Cascode and Enhancement-Mode GaN HEMTs// 2019 20th International Symposium on Power Electronics (Ee). - Novi Sad, Serbia, 2019. -P. 1-5.
11. High-Temperature Sensitivity of a Depletion-Mode AlGaN/GaN MIS-HEMT / **Z. Mutsafi, K. Shimanovich, V. Kairys, R. Shima-Edelstein, et al** // In IEEE Transactions on Electron Devices.- Nov. 2021.- Vol. 68, no. 11. -P. 5695-5700.
12. 200 V-Depletion mode GaN HEMT on Si / **P. Kachhawa**, **S. Mishra**, **A.K. Jain**, **et al** // 2020 5th IEEE International Conference on Emerging Electronics (ICEE). - New Delhi, India, 2020. -P. 1-4.
13. A Monolithic D-Mode GaN-Based Buck Converter With Novel Resistor–Capacitor-Multiplexing Dead-Time Adjustment Structure for Envelope-Tracking Power Amplifier Application / **C. Bo, et al** // In IEEE Microwave and Wireless Technology Letters.- July 2025.- Vol. 35, no. 7. -P. 1065-1068.
14. GaN-on-Si HEMTs Fabricated with Si CMOS-Compatible Metallization for Power Amplifiers in Low-Power Mobile SoCs / **H. Xie, et al** // In IEEE Microwave and Wireless Components Letters.- Feb. 2021.- Vol. 31, no. 2. -P. 141-144.
15. GaN HEMTs on Si with regrown contacts and cutoff/maximum oscillation frequencies of 250/204 GHz / **L. Li, et al** // IEEE Electron Device Lett.- May 2020.- Vol. 41, no. 5. -P. 689-692.
16. 3D heterogeneous integration of high performance high-K metal gate GaN NMOS and Si PMOS transistors on 300 mm high-resistivity Si substrate for energy-efficient and compact power delivery RF (5G and beyond) and SoC applications / **H.W. Then, et al** // IEDM Tech. Dig.- Dec. 2019. -P. 17-1-17-3.
17. MBE-regrown ohmics in InAlN HEMTs with a regrowth interface resistance of \$0.05~Omegacdothbox{mm}\$ / **J. Guo, et al** // IEEE Electron Device Lett.- Apr. 2012.- Vol. 33, no. 4.- P. 525-527.
18. Reliability of 200mm E-mode GaN-on-Si Power HEMTs / **D.C. Zhou et al** // 2020 IEEE International Reliability Physics Symposium (IRPS).- Dallas, TX, USA, 2020. -P. 1-3.
19. HEMT test structure technology for fast on-wafer characterization of epitaxial GaN-on-Si material / **M. Schuster, et al //** 2013 International Semiconductor Conference Dresden - Grenoble (ISCDG).-Dresden, Germany, 2013.-P. 1-3.
20. Design of Ultra-Low Phase Noise and High-Power Integrated Oscillator in 0.25 μm GaN-on-SiC HEMT Technology / **H. Liu, X. Zhu, C.C. Boon, X. Yi, et al** // In IEEE Microwave and Wireless Components Letters.- Feb. 2014.- Vol. 24, no. 2. -P. 120-122.

21. **Shealy J.B., Smart J.A., and Shealy J.R.** Low-phase noise AlGaN/GaN FET-basedvoltage-controlled oscillators (VCOs)// IEEE Microw. Wireless Compon. Lett.- Jun. 2001.- Vol. 11, no. 6. -P. 244-245.
22. **Kaper V.S., Thompson R.M., Prunty T.R., and Shealy J.R.** Signal generation controland frequency conversion AlGaN/GaN HEMT MMICs// IEEE Trans. Microw. Theory Tech.- Jan. 2005.- Vol. 53, no. 1. -P. 55-65.
23. Alow phase-noise X-band MMIC VCO using high-linearity and low-noise composite-channel HEMTs / **Z.Q. Cheng, Y. Cai, J. Liu, Y. Zhou, et al** // IEEE Trans. Microw. Theory Tech.- Jan. 2007.- Vol. 55, no. 1. -P. 23-29.
24. A monolithic AlGaN/GaN HEMTVCO using BST thin-film varactor / **C. Kong, H. Li, X. Chen, S. Jiang, et al** // IEEE Trans. Microw. Theory Tech.- Nov. 2012.- Vol. 60, no. 11. -P. 3413-3419.
25. Investigation of Single Event Transients in Buffer-Free GaN-on-SiC HEMT / **S. Raut**, **K. Sehra**, **M. Mishra**, **D.S. Rawal**, **et al** // 2020 5th IEEE International Conference on Emerging Electronics (ICEE).- New Delhi, India, 2020. -P. 1-4.
26. Cree, Wolfspeed, CGH40045, 45 W, DC - 4 GHz, GaN HEMT **-** Accessed: 06/08/2025.
27. **CLF1G0035-50_1G0035S-50.fm -** Accessed: 06/08/2025.
28. **Important Notice - Qorvo -** Accessed: 06/08/2025.
29. **L'vov A.A., Semezhev N., Solopekina A.A., and Meschanov V.P.** A theoretical basics of microwave networks for software defined radio systems// 2016 International Conference on Actual Problems of Electron Devices Engineering (APEDE).- Saratov, Russia, 2016. -P. 1-5.
30. **Monolithic and Hybrid Microwave Integrated Circuits: What's the Difference? -** Accessed: 06/08/2025.

Yerevan State University. The material is received on 06.09.2025.

Լ.Կ. ԿԱՐԱՊԵՏՅԱՆ

GaN HEMT ՏՐԱՆԶԻՍՏՈՐՆԵՐՈՎ ՄԻԿՐՈԱԼԻՔԱՅԻՆ ԻՆՏԵԳՐԱԼ ՍԽԵՄԱՆԵՐԻ ՆԱԽԱԳԾՄԱՆ ԱՌԿԱ ՎԻՃԱԿԸ ԵՎ ՀԻՄՆԱՀԱՐՑԵՐԸ

Գալիումի նիտրիդի (GaN) բարձր էլեկտրոնային շարժունակությամբ տրանզիստոր-ները (HEMT) միկրոալիքային ինտեգրալ սխեմաների (MIC) հիմնական մասերն են՝ իրենց բարձր էլեկտրոնային շարժունակության, լայն արգելման գոտու, կրիտիկական դաշտի, թափանցելիության և բացառիկ ջերմահաղորդականության շնորհիվ: Այս տարբերակները թույլ են տալիս GaN HEMT-ներին՝ աշխատել ու ավելի բարձր հաճախականություններով և հզորության մակարդակներով, քան ավանդական սիլիցիումային տրանզիստորները: Ռադիոհաճախականության և միկրոալիքային համակարգերի դեպքում դա նրանց ապա-հովում է արդյունավետություն: GaN HEMT-ների կարևորությունը MIC-ներում կարելի է թվարկել հետևյալ կերպ՝ ավելի բարձր հզորությամբ խտություն, բարելավված արդյունա-վետություն, լայն հաճախականությամբ աշխատանք, ջերմային կայունություն: Այս առավելությունները GaN HEMT-ները դարձնում են կարևորագույն տեխնոլոգիա այսօրվա կապի համակարգերի, պաշտպանական և տիեզերական տեխնոլոգիաների ոլորտներում: Վերջին տարիներին GaN HEMT-ների վերաբերյալ առաջարկվող տարբեր տեխնոլոգիաներ ամփոփվել և համեմատվել են: Ներկայացվում են համեմատաբար հաճախ օգտագործվող GaN HEMT-ների տեսակները, ներառյալ դրանց մոդելները: Քննարկվում են GaN HEMT-ի 3 հիմնական ենթաճյուղեր՝ տրանզիստորների տեսակները, տրանզիստորների մոդելներն ու բնութագրերը և MIC-ների նախագծումը: Դրանցից յուրաքանչյուրն ունի իր առավելություններն ու թերությունները, և կախված խնդրից՝ կարելի է ընտրել ամենահարմարը: Արդյունքում, ընդգծվում են մի քանի կարևոր խնդիրներ, ինչպիսիք են՝ աշխատանքի օպտիմալացումը, ջերմային կառավարման լուծումները, հուսալիությունը և երկարակեցությունը, ազդանշանի ամբողջականությունը և աղմուկի նվազեցումը, ապագա հետազոտությունների ուղղությունները և այլն:

Առանցքային բառեր. բարձր էլեկտրոնային շարժունակությամբ տրանզիստորներ, միկրոալիքային ինտեգրալ սխեմաներ, ավելի մեծ հզորությամբ խտություն, բարելավված արդյունավետություն, լայն հաճախականության գործարկում, ջերմային կայունություն:

Л.К. КАРАПЕТЯН

СОВРЕМЕННОЕ СОСТОЯНИЕ И ОСНОВЫ ПРОЕКТИРОВАНИЯ СВЕРХВЫСОКОЧАСТОТНЫХ ИНТЕГРАЛЬНЫХ СХЕМ С ТРАНЗИСТОРАМИ GaN HEMT

Транзисторы с высокой подвижностью электронов (HEMT) на основе нитрида галлия (GaN) являются ключевыми частями микроволновых интегральных схем (MIC) из-за их высокой подвижности электронов, широкой запрещенной зоны, критического поля, диэлектрической проницаемости и исключительной теплопроводности. Эти опции позволяют GaN HEMT работать на более высоких частотах и уровнях мощности, чем традиционные кремниевые транзисторы. Для радиочастотных и микроволновых систем это обеспечивает им эффективность. Важность GaN HEMT в MIC заключается в следующем: более высокая плотность мощности, улучшенная эффективность, работа в широком диапазоне частот, термостабильность. Эти преимущества делают GaN HEMT важнейшей технологией для современных систем связи, оборонных и космических технологий. В работе обобщены и сравнены различные предлагаемые в последние годы технологии GaN HEMT. Представлены относительно часто используемые типы GaN HEMT, включая их модели. Обсуждаются три основные подветви GaN HEMT: типы транзисторов, модели и характеристики транзисторов и конструкция MIC. Каждая из них имеет свои преимущества и недостатки, в зависимости от проблемы можно выбрать наиболее подходящую подветвь. В результате было выделено несколько важных проблем, таких как оптимизация производительности, решения по управлению температурным режимом, надежность и долговечность, целостность сигнала и снижение шума, будущие направления исследований и т.д.

Ключевые слова: транзисторы с высокой подвижностью электронов, микроволновые интегральные схемы, более высокая плотность мощности, улучшенная эффективность, работа в широком диапазоне частот, термостабильность.