

GENERAL OVERVIEW OF GAN DEVICES AND TRANSPORT PROPERTIES OF ALGAN/GAN HEMT STRUCTURES - IMPACT OF DISLOCATION DENSITY AND IMPROVED DESIGN

¹Eduard HULICIUS, ^{1,2}František HÁJEK, ¹Alice HOSPODKOVÁ, ¹Pavel HUBÍK,
¹Zuzana GEDEONOVÁ, ¹Tomáš HUBÁČEK, ¹Jiří PANGRÁC, ¹Karla KULDOVÁ

¹*Institute of Physics CAS, v.v.i., Prague, Czech Republic, EU, hulicius@fzu.cz*

²*Faculty of Nuclear Sciences and Physical Engineering, CTU in Prague, Czech Republic, EU*

<https://doi.org/10.37904/nanocon.2021.4309>

Abstract

GaN-based nanostructures are used for many present semiconductor devices. The main topics are structures for blue LEDs and LDs, but there are also other interesting and important GaN devices namely for power electronics, scintillators and detectors as well as High Electron Mobility Transistors (HEMT). Several of our previous NANOCON contributions were devoted to the scintillator and detector structures; one was a description of optimization of HEMT structures and their growth parameters.

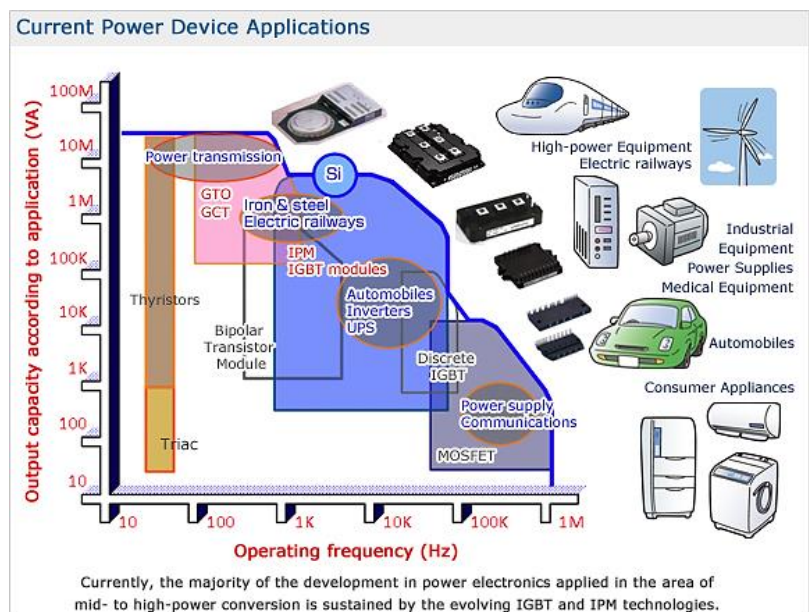
Keywords: GaN devices, HEMT, MOVPE epitaxy, dislocation

1. INTRODUCTION

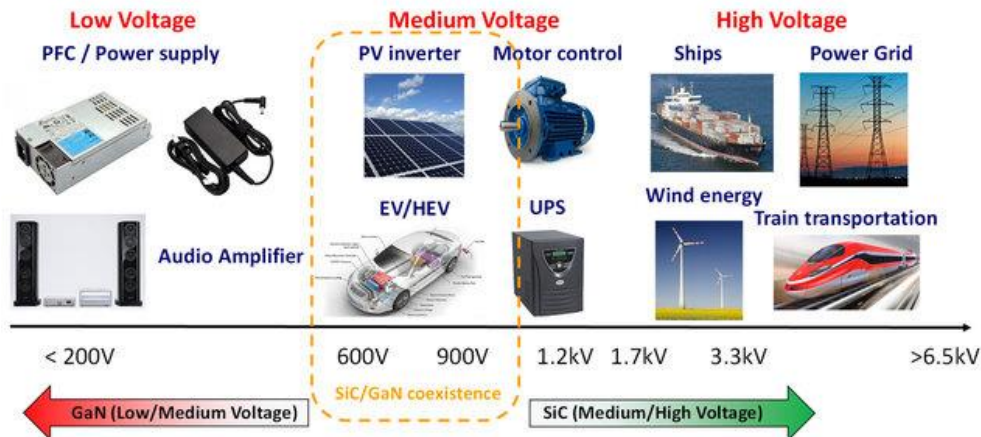
This contribution is devoted to a general review of GaN power electronic devices, a comparison with other materials (mainly Si and SiC), a description of some fields of application and a future forecast.

The second part will describe our recent results - the influence of dislocation density on transport properties of HEMT structures is reported. Experimental results, obtained on HEMT structures prepared in the same growth run on templates with different dislocation densities, are compared. We show experimentally that lowering the dislocation density considerably increases the electron mobility in 2DEG. It is shown that the dislocation density has also a significant influence on the Fermi level position in GaN. Presented results suggest that reduction of the dislocation density can improve the performance of high frequency GaN HEMTs applications.

High frequency power electronic devices have many application fields, as it is shown in **Figures 1a** and **b**.



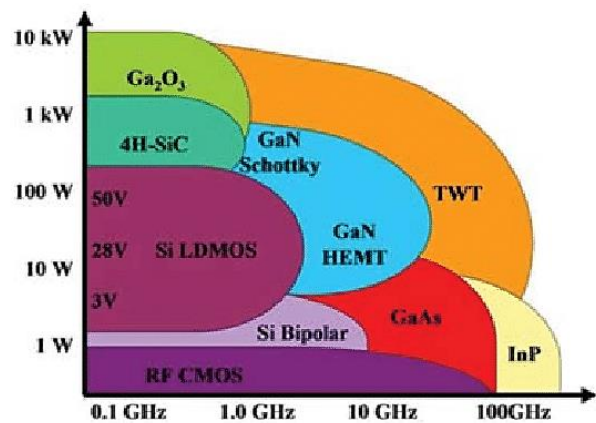
a) Output power (W) versus operating frequencies (Hz) for some current and future devices. The majority of the development in power electronic applied in the area of mid- to high-power conversion is sustained by the evolving IGBT and IPM technologies.



b) Different devices (current and future) according to the maximum applied “Voltages”.

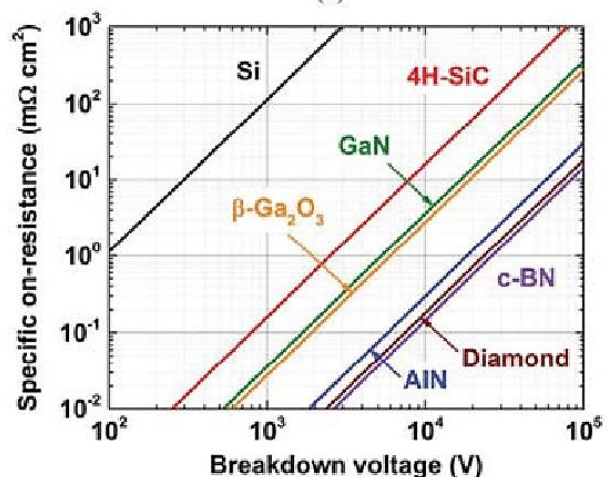
Figure 1a, b Application fields for three the most important semiconductor materials from the output power versus operating frequencies and voltage point of view.

There are three most important and promising materials: Si, SiC and GaN. Devices are based on different structures – see Figure 2, but the material properties are determinative (Figure 2b). Of course, there exist many other interesting materials, as Ga₂O₃, GaAs, InP or old school vacuum tubes – see Figure 2a, at the edge of electric device parameters. However, the main industrial players are only three. They also meet the requirements on temperature and radiation resistance as well as sufficient lifetime.



(a)

Figure 2 Comparison of some semiconductor materials and structures for different Output power versus Operating frequencies – upper part (a), and key physical parameters, which are responsible for device and structure limits – lower part (b). (*TWT is Traveling-wave tube amplifier, a specialized vacuum tube that is used in electronics to amplify radio frequency (RF) signals in the microwave range.*)

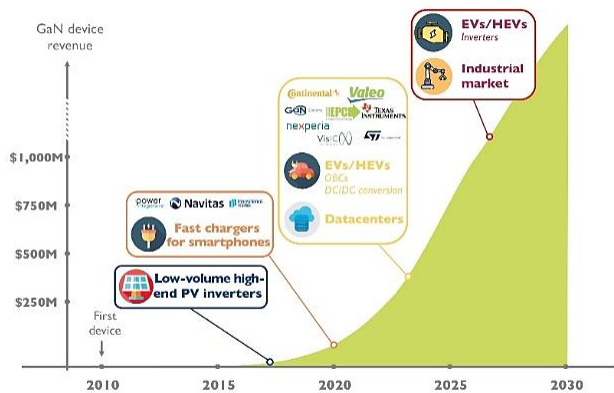


(b)

We prepare and study InGaN/GaN and AlGaIn/GaN scintillator and HEMT structures not only for scientific research, but also for industrial applications for the last 8 years, thus we will put here stress on GaN. In Figure 3, there are shown development and predictions of GaN power devices market.

Roadmap for GaN power devices

(Source: GaN Power 2021: Epitaxy, Devices, Applications and Technology Trends report, Yole Développement, 2021)

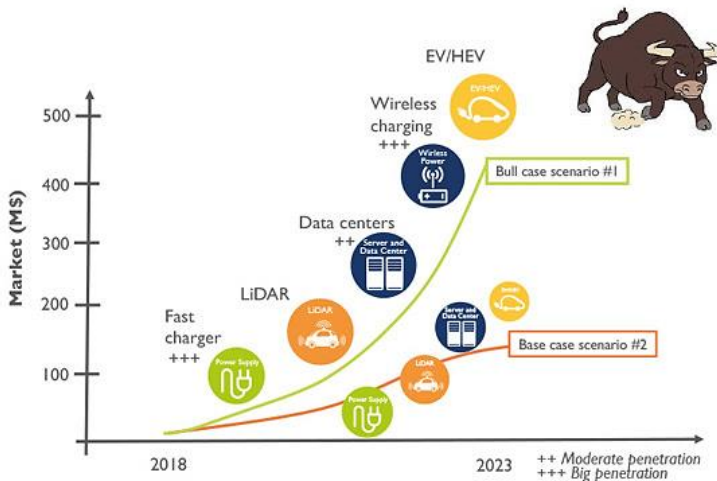


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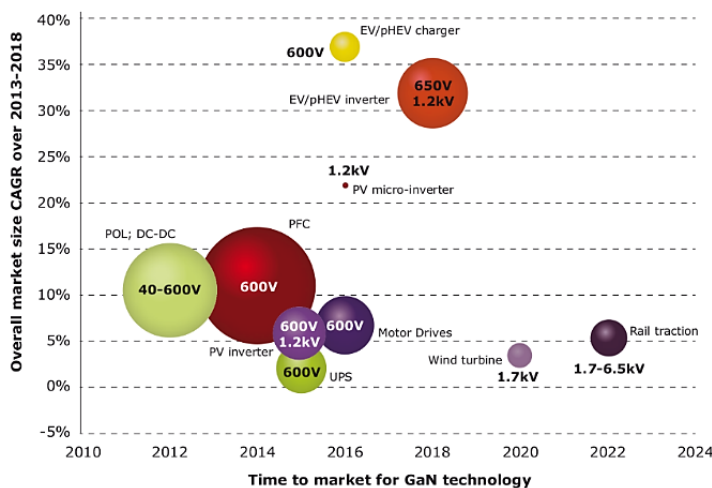
a) Rather optimistic YOLE prediction (2021), starting from the “Low-volume high-end PV inverters (2017)” over the “Fast chargers for smartphones (2020)”, “E-cars, and Datacenters (2023)” to the “EVs/HVs Inverters and Industrial market (2027)”.

GaN for power electronics application: evolution of the market with two scenarios

(Source: Power GaN 2018: Epitaxy, Devices, Applications and Technology Trends, Yole Développement, November 2018)



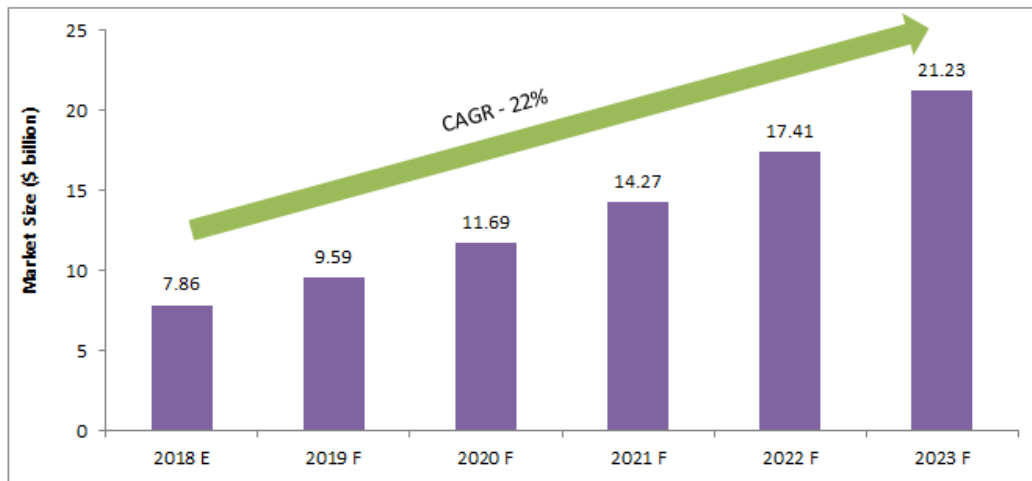
b) GaN power devices market forecasts. **Bull case scenario** = higher or moderate penetration and earlier realizations and as new: “Wireless charging (2022)” It is about 1/4 of all GaN possible applications.



c) GaN devices development versus voltage. **Dark red 600 V** Power Factor Correction (PFC) single-phase AC/DC; **Green 40-600 V** DC/DC converters and UPS; **Red 650 – 1 200 V** – EV/pHEV inverter; **Violet 600 – 1 200 V** – PV inverter, Motor drivers and Rail traction.

Figure 3a, b, c GaN power devices market forecast for different application fields and producer companies

Global Smart Lighting Market Size (2018–2023)



Source: Beroe Analysis

Figure 4 GaN LED market predictions are more than order of magnitude higher than GaN power devices

In comparison with GaN blue/white LED huge market – see **Figure 4**, the GaN power devices market is only 10 % of the LED market, but absolute value of the GaN power devices market is currently about 2 billion USD with estimated strong growth, as it is shown in **Figure 3**.

2. RESULTS OF OUR RESEARCH ON ALGAN/GAN HEMT STRUCTURE

2.1. Regular AlGaIn/GaN HEMT structure (without AlGaIn back barrier)

In our laboratory were prepared different HEMT structures [1]. The scheme are depicted in **Figure 5**. Structures were prepared on three types of GaN templates differing in dislocation density: GaN substrate with a very low dislocation density of approximately 10^6 cm^{-2} , and two templates on sapphire differing by the GaN buffer technology leading to lower (LDD) and higher dislocation density (HDD). For comparison of transport properties of these structures, see **Table 1**.

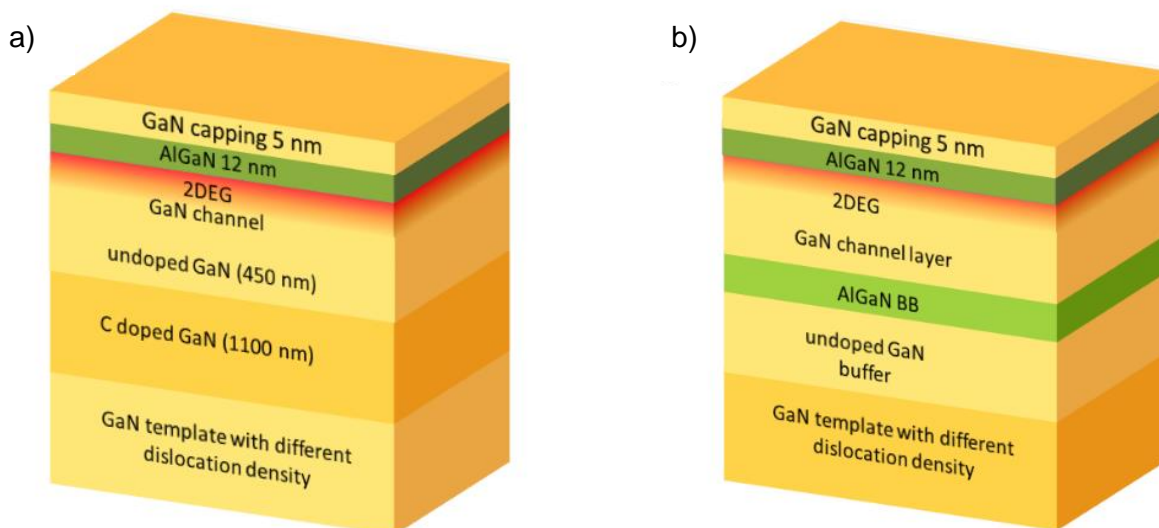


Figure 5 Scheme of (a) conventional HEMT structure and (b) HEMT structure with AlGaIn back-barrier

Table 1 Dislocation density according to XRD, concentration and mobility of samples on different templates

Sample	Type of template and substrate	Dislocation densities (cm ⁻²)	Apparent 2DEG concentration from CV (cm ⁻²)	Sheet Hall concentration (cm ⁻²)	Mobility (cm ² /Vs)
HDD template	HDD on sapphire	2.79×10 ¹⁰	1.20×10 ¹³	8.77×10 ¹²	1187
LDD template	LDD on sapphire	9.36×10 ⁸	1.18×10 ¹³	1.56×10 ¹³	1360
PLDD	LDD on patterned sapphire	6.81×10 ⁸	1.17×10 ¹³	1.09×10 ¹⁴	539
GaN substrate	GaN substrate	3×10 ⁶	9.78×10 ¹²	3.18×10 ¹⁵	798

Surprisingly, poor mobility results were obtained on samples prepared on patterned sapphire or GaN substrates with lower dislocation densities. According to Hall measurements, these samples also revealed very high sheet carrier concentrations. Capacity measurements giving carrier profiles revealed that this unexpectedly high carrier concentration is not caused by carriers in the 2DEG channel, but by carriers from a deeper layer in the heterostructure. In structures prepared on LDD substrate, deeper layers have low resistivity, and conductive channels parallel to 2DEG are dominant in Hall measurement. Parallel currents in nitride structures grown on sapphire substrates were also previously reported [2]. These parasitic channels not only influence Hall measurement results, but they are also detrimental for HEMT applications. In the case of HDD structures, undoped GaN and C-doped GaN regions become highly resistive and they insulate the channel region from the deeper layer of the structure. Thus, only for the HDD structures was the 2DEG active region measured by Hall measurement. For the same reason, it is not a problem to grow industrial HEMT structures on Si substrates, where a high density of dislocations is formed.

In order to study the influence of dislocation density on transport properties of HEMT structures a method for improved localization of electrons in the channel region is required. Such a solution could also be useful for the application of HEMT structures with a low dislocation density. We have found that the widely used carbon doping of buffer layers (see conventional HEMT structure in **Figure 5a**) is not reliable and does not provide sufficient isolation, especially for structures with a much lower dislocation density. The lower resistance of C-doped layers causes this, when the dislocation density is low. Fe doping creating a semi-insulating buffer may help to solve this problem [3]. AlN/GaN superlattice can also be used [4]. Another possible solution, which has been recently published [5,6], and which we have decided to follow and investigate in more detail, is the introduction of a so called “back barrier” (BB) layer below the channel region, see **Figure 5b**.

2.2. HEMT structures with AlGaN back barrier – experimental results

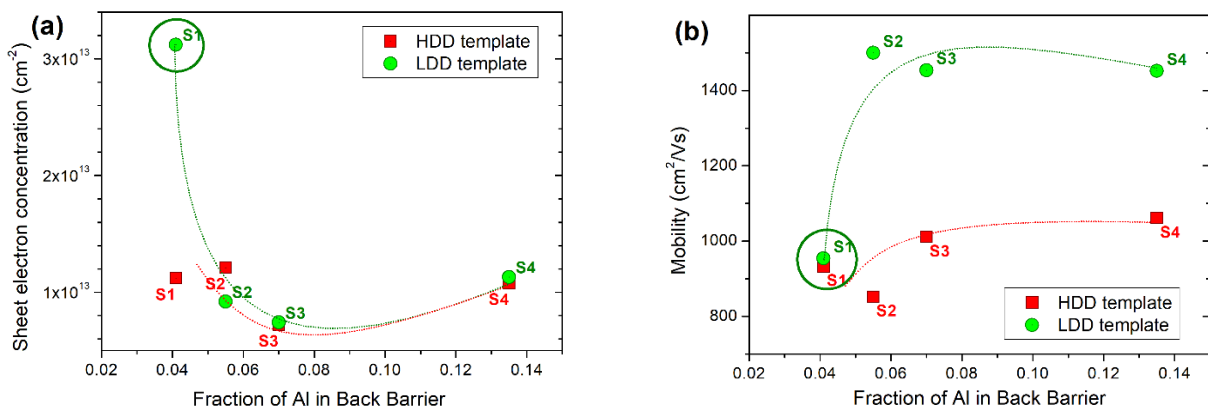


Figure 6 (a) Measured sheet carrier concentration and **(b)** mobility as a function of Al concentration in AlGaN BB for HDD (red squares) and LDD (green circles) samples. The results marked by circle suggest leaking AlGaN BB for LDD sample S1, [1].

Three sets of structures were prepared to identify optimal parameters for a structure with an AlGa_xN BB and to compare experimental and simulated results. Particular sets of structures used to study the influence of BB composition, thickness of BB and GaN channel layer thickness are color-coded in the table. All structures were prepared on LDD and HDD templates during the same procedure to study the influence of dislocation density on transport properties in 2DEG.

Results of transport measurements are shown in **Figure 6**. The most obvious result is that, in the case of structures prepared on HDD templates, structure parameters do not significantly influence electron mobility in the 2DEG channel.

3. CONCLUSION

We have shown that reduction of dislocation density considerably increases electron mobility in 2DEG. All presented results support our expectation that a suitably designed AlGa_xN back barrier can help to prevent this phenomenon. The best results were obtained for an Al_xGa_{1-x}N BB composition, with x in the range 0.07-0.15, a BB thickness of 17 nm and a GaN channel layer thickness > 140 nm. For structures prepared on HDD buffer, parallel currents through deeper parts of the heterostructure were not detected, even in the case where no BB or other isolation layer was used. We did not observe any influence of BB parameters on transport properties of samples prepared on HDD templates.

The exact mechanism of how the dislocation density significantly influences 2DEG transport will be the subject of further investigation. Since scattering on dislocations was excluded as a significant scattering mechanism in 2DEG, other mechanisms, such as scattering on ionized impurities surrounding dislocations or the influence of the interface morphology, may be responsible for lowering the electron mobility in structures with a high dislocation density. Finally, the presented results suggest that reduction of dislocation density increases electron mobility in 2DEG, which is beneficial for GaN HEMTs high frequency applications.

ACKNOWLEDGEMENTS

The authors acknowledge support from MEYS project LTAIN19163; from CzechNanoLab project LM2018110 at LNSM Res. Infrastructure and from the Operational Programme RDE financed by EU Structural and Invest. Funds and by MEYS (Project No. SOLID21 CZ.02.1.01/0.0/0.0/16_019/0000760).

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