Gallium Nitride Semiconductors in Power Electronics for Electric Vehicles: Advantages and Challenges

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***Abstract*—Electric and Hybrid Vehicles mostly use Silicon-based IGBTs for driving the motor and controlling DC/DC converters in their powertrain. IGBTs transition times usually limit their switching frequencies in the 10-100 kHz range. Gallium-Nitride semiconductors have been introduced which indicate nano-second range switching times and operating temperatures up to 200°C, with the promise of many advantages in the automotive market. Faster GaN devices will eventually lead to higher switching frequencies and lower switching losses, lower power electronic volume and weight reduction. Faster switching comes with cheaper inductors and capacitors. The silicon (Si) has reached its limits regarding the dynamic performance and conduction losses, which is why several manufacturers and researchers are working on new materials, such as gallium nitride (GaN) for new power devices development. In the paper, a comparison is made between GaN and Si in terms of cost, performance advantages and upcoming improvements. Challenges are highlighted, as driving a high-power device in nanoseconds comes with many unresolved difficulties.**

Keywords—Electric Vehicle; Power Converters; Gallium Nitride Semiconductors;High Electron Mobility Transistor;HEMT

I. INTRODUCTION

Electric and Hybrid Electric Vehicles (EV and HEV) make a significant use of power semiconductors in the drive train, in the battery charging units and in other accessories connected to a common voltage DC-bus. As Li or NiMH batteries do not allow such a high energy density as compared to traditional fuel tanks, using this energy in the best possible way is a key aspect of power conversion devices. Semiconductor components with good performance is demanded in order to have fewer losses and thus a better efficiency. Moreover, size reduction of such power converters is also strongly related to the ability of power switches to commutate rapidly and handle high temperatures. Such power converters and their cooling systems usually take a space (volume and weight) that could be allocated to other functions in the vehicle. Thus, an increase in the semiconductors switching frequency is a topic of interest to develop smaller and cheaper passive components. Actually, most DC/DC and DC/AC converters implemented in the EV field use either IGBTs or power MOSFETs as switching devices, which are predominantly based on silicon semiconductor material. In these applications, silicon technology has nowadays reached its limits [1] in terms of switching speed and on-state resistance. Hence, new power switching components based on different semiconductor material are being looked for; power switches using Gallium-Nitride (GaN) as a replacement for Si are one of them. This development has been initiated in year 2000 for power semiconductors and is continuing at a great pace.

High switching frequency will allow saving substantial space, weight and costs in the EV and HEV powertrains. Tests done with a buck converter confirmed that multiplying the switching frequency 5 times will result by an inductor volume nearly 5 times lower and a reduced capacitor volume as well [2]. A number of automotive manufacturers are actually doing research on the implementation of the GaN material in vehicular applications, such as Toyota [3] and Ford [4].

Four factors make the GaN semiconductor so advantageous: the ability to operate at high temperature, higher breakdown voltage, low on-state resistance (R_{on}) and nanosecond-range (ns-range) switching time leading to high switching frequency. This high frequency is the ultimate result of the high electron mobility. The high voltage breakdown is enabled by the GaN material wide bandgap (WBG), leading to high electrical field capability. Overall, this will result in a chip size reduction for a given power capability and, ultimately, much lower gate capacitance with GaN compared to Si thanks to a diminished size. The operation at high temperature is due to the GaN WBG as well. The low R_{on} is the result of high electron mobility and the two dimensional electron gas (2DEG) created between the GaN and Aluminum Gallium Nitride (AlGaN) thanks to its piezoelectric properties, which allows the current to flow with small resistance.

Two other important arguments for the emergence of GaN material as power devices are: 1) LEDs and radio frequency (RF) transistors are already produced with GaN and 2) most of the Si fabrication process are compatible with the GaN process [5]. This will enable GaN to become available at a low price faster than with silicon carbide (SiC) components. One of the drawbacks of SiC was the high cost of substrate.

This paper will trace back the quick evolution of the GaN power transistors and provide an overview of the actual state of development. Then a glimpse on the potentials offered by the GaN material over Si will be shown. Also, how the new material will affect the size and efficiency in the EV applications will be fully addressed. Finally, a conclusion will sum up the main points of this paper.

II. GaN Semiconductors State of the Development

Current power chips solutions for EV can be divided along the three different existing technologies. Those are the well-known Si, the new SiC and GaN is a future contender, which specific attributes and history are herein described.

The research on GaN-based power chips started back in 2000, when the very first power GaN FET was produced using RF standards. This component was first built on a SiC substrate and already showed promising performance [6]. A breakdown voltage near 500V, a R_{on} of 75 mΩ.mm² and a 5-ns switching time were obtained.

In 2003, the process was adapted to power transistors, resulting in a 600 V / 2.5 A High Electron Mobility Transistor (HEMT). The first prototype still needed optimizations and long term reliability was identified as an issue [7]. The very first GaN HEMT were “normally-on” devices, meaning that a gate voltage of 0 V will lead to a conductive state and a voltage inferior to 0 is needed to turn off the transistor. The next years, the very first “normally-off” chip is tested by doping the GaN semiconductor with Carbon [8]. Near 2010, a significant step forward was made when the SiC substrate was replaced with a Si substrate. This change has a potential of reducing drastically the fabrication cost. In the same year, the dual gate technology was implemented, with the ability to create a normally-off GaN FET with a low R_{on} resistance [9]. In 2012, a normally-off GaN FET was tested up to 200°C and showed continuous operation without any behavior modification [10]. The high temperature capability associated with the low cost of Si substrate and high dynamical performances is the promise of a game changer in the future of power electronics. In 2013, power demonstrations are done, validating the usefulness of GaN HEMTs in a 2 kW@500 kHz hard-switched converter along with a 430 W@1 MHz converter [11]. The efficiency of these prototypes ranked higher than 95% with a power density near to 11 W/cm^3. With all of these power demonstrations, the feasibility of MHz operation for hard-switched high power converters is starting to emerge.

A new Cascode configuration was introduced in 2014, for transforming a normally-on GaN chip into a normally-off by implementing a low voltage Si MOSFET in series with the high voltage HEMT [12]. Stable R_{on} and gate capacitance were also demonstrated in 2014, with extremely small variations with rising drain-source voltage, allowing the behavior to remain unchanged while in use [13].

Today, the first GaN HEMTs are on sale. The main suppliers are Efficient Power Conversion (EPC), Fujitsu, Transphorm and GaNSystems. A comparison can be made between the standard Si MOSFET products and the new HEMT technology using GaN. An interesting way of comparing power devices together is through Figures of Merit (FOM). Two well-known are the Baliga’s (BFOM) which defines the quality in terms of conduction losses, and the Johnson’s (JFOM) which defines the power-frequency quality of the component [14]. Both are shown in TABLE I. GaN has the potential to have near 16 times less losses than Si at a given frequency and can be 7 times faster for the same power throughput. The result is a faster switching frequency with improved efficiency with less need for cooling (or higher switching frequency for the same efficiency).

Another important fact is that GaN HEMT does not need an anti-parallel reverse diode in order to conduct the current [15]. That is due to the mechanism occurring in the material when reverse conduction happens. In this mechanism, no minority carriers are involved. Hence, the produced GaN HEMTs does not have any recovery charge (Q_{rr}). This advantage toward standard Si MOSFETs will lead to lower losses and lower switching time since extremely small recovery time is needed when reverse current is present.

All of these promising results come with challenges in the use of this new technology. Firstly, most of the tested HEMTs are normally-on devices. Solutions exist and efforts are put in order to obtain a normally-off transistor without performance degradations. The main strategies used are: 1) the above-mentioned cascode configuration, and 2) architecture device engineering, leading to “enhanced GaN” or “e-GaN” technology. In the cascade add-up, the performance remains very good compared to pure Si technology with an efficiency increase up to 5% for the example of a power factor corrector (PFC) converter presented in [12].

The drawback of the cascode method is that Q_{rr} does not remain at zero like for standard HEMT and thus more losses will appear when a reverse current occurs. This is a real problem for inverters and bidirectional power converters. A solution has been found with a cascode configuration rated at 600 V with two HEMT in series, one “normally on” and one “normally off”. This solution allows the use of the advantages of both technologies: higher breakdown voltage, positive

TABLE I: SI, SIC AND GAN TABLE OF MERIT

Material	Band -gap (eV)	Hole mobility $cm^2/V_S\varepsilon_s$	Electron mobility μ (cm^2/Vs)	Saturated electron drift velocity V_D(10^7cm/s)	BFOM Norm to Si	JFOM Norm to Si
Si	1.12	11.8	1300	1.0	1	1
SiC	3.26	10	720	2.0	11.5	5.8
GaN	3.44	9.5	900	2.5	16.1	7.7

threshold voltage and no recovery charges [16]. This solution may bring new possibilities if well exploited and drastically raise the voltage and current ratings of commercial GaN HEMTs.

Another solution is to use a specific device, and bandgap engineering to deplete the channel underneath the gate electrode at positive gate voltage. The major challenge of this approach is to keep the R_{on} in the acceptable range. In the literature, such device is presenting 1640 V breakdown voltage on Si, as presented in [17]. The challenge here is to find a way to put this result in a massively produced component and to prove its reliability.

III. Using GaN FET

The HEMT is a valuable component for tomorrow's power converters but its high speed brings other challenges. For a high speed transistor, the gate drive must also have the ability to supply a 1 to 10 A current peak within a few nanoseconds. This gate drive concept is envisioned as a physically embedded gate driver, with the same tolerance to high temperature as the power device itself. More and more manufacturers are seeing interest in the GaN market, and are developing new components to drive them. Examples of this are the AVAGO ACPL-P349 and the Texas Instruments LM5113, both including fast transistors with rising time near 10 ns and current capabilities up to 2.5 A and 5 A, which make them suited to work at high frequencies. In the AVAGO ACPL-P349, a fast GaAs opto-transistor is also included permitting the use of fewer components while having an isolated structure.

Even if for traditional design these components seem suited, research is also needed in the driver circuitry and methods to obtain the maximum efficiency when using HEMT. For a power inverter, the goal of switches drivers is to have the quickest switching to avoid switching losses. The goal may also be to reduce losses meaning lower working temperatures; it leads to lower chip size and a better integration. Four techniques can be found in current literature: 1) The traditional push-pull with a gate resistor 2) The resonant gate driving technique 3) The capacitor type 4) The capacitor-less method.

The first method is the simplest and well known thanks to its current use with IGBTs and Mosfets. It has the disadvantage of producing losses in the driving circuitry and heat the gate resistor. This leads to a bigger chip along with the thermal managing issues. Even though some drawbacks exist the simplicity and the control over the transistor makes it widely used. The second method aim to suppress the losses in the gate resistor by replacing it with an inductor. Then it becomes possible to control the current level thanks to the switching timings [18]. One drawback of this solution is the problem of current oscillation appearing in the gate. The capacitor type driving method uses the transient of a capacitor connected in series with the gate to transmit the current to the gate [19]. Then when both the gate and the capacitor are charged, a current corresponding to the gate leak go through a resistor connected in parallel with the capacitor. The drawback of this method is in the discharge of the capacitor that produces a negative voltage which can damage the transistor or increase its internal resistance. To attain the same performances than the capacitor type driver without the drawbacks, the capacitor-less gate drive has been developed [20] [21]. The principle is to use the internal capacitor of mosfets to control their switching timing. Its theory is based on the diode like HEMT gate behavior. The advantages are to limit the losses inside of the driver while keeping a high switching speed. The drawbacks are the knowledge about the used components whom properties have to be very well known to have the desired output.

While power density rise, it becomes extremely difficult to separate sensitive devices and polluting power ones. Using GaN makes the problem bigger and care must be taken regarding the proximity with other components. Studies have been conducted in order to analyze the effect of components orientation and proximity toward electromagnetic compatibility (EMC) issues [22] [23]. With the same components, and tuning parameters it has been possible to reduce the conducted noise up to 30dB and thus allowing the overall performances to rise. The gained immunity is not only useful to avoid a self-pollution effect but also to emit and receive less electromagnetic (EM) perturbations. Practical rules are defined in order to easily perform a first design optimization and packaging tends to adopt high-speed microelectronic solutions.

With the upcoming performances, the use of specific packaging such as flip-chip tends to be the norm. This is an answer to many issues appearing with the new levels of power and speed. The main issues are 1) The thermal management 2) The packaging inductance. The thermal management becomes even more a key aspect than in standard power conversion. This is due to the small HEMT size and its high power rating. Then different technics have been developed, the ones used in currently for sell HEMT are from EPC and GaN Systems. For the first supplier the transistor is directly mounted on the PCB with solder bumps directly connected to the active regions. Then no resistance is added between the HEMT and the exterior and the inductance of the connection is reduced to a minimum [24]. Another advantage is to not add costs in the fabrication process. GaN Systems choose a very close solution but with the chip enclose between two layers of copper and surrounded by high temperature fiberglass. The obtained result is a very low thermal resistance together with a very low inductance [25]. These packaging will make the standard design rules and habits evolve by adapting technics used for fast low power microelectronic.

IV. ElectricVehicle Improvements Trends

The typical market price for a silicon MOSFET transistor rated 650 V/30 A is roughly 5.52 $ while the cost of a GaN HEMT is currently (2015) around 45 $ for the same rating. The HEMT is still a new product and it is expected that its price will decrease in the next years. A very attractive advantage is the operating temperature that can attain up to 200°C when grown on SiC thanks to the WBG. Thus, less cooling is necessary or harsh environments operations become possible. These devices are well suited in HEV to operate near the combustion engine with possible use of only one cooling liquid for both engine and power electronics.

An important component of an EV is the battery charger, composed of an AC/DC converter followed by a DC/DC converter. The complete architecture is presented in Fig. 1. The two converters together form a Power Factor Controller (PFC) converter. In this element, the operating frequency is directly linked to the inductor and output capacitor values together with current and voltage ripple. The DC/DC converter can be improved by using GaN HEMTs. The increase in frequency results in smaller ripple current with smaller inductor. This leads to a better power factor, smaller and cheaper capacitor. Lower ripple current will also lead to lower stress on the capacitor and thus its reliability will increase. The impact of having smaller passive components will lead to more space for other important parts such as the battery or simply decrease the curb weight of the vehicle. The same approach is also relevant for the DC/DC converter used to convert the battery voltage into a usable one by the onboard electronic even if is a step down converter.

To improve even more space savings and efficiency the two previous AC/DC and DC/DC converters can be merged into one [26]. GaN power devices allow PFC with 99% efficiency. The main factors permitting such improvement are the ultra-low Q_{rr} and R_{on}, as described in [27]. This topology can be reused and adapted to higher power with the next GaN improvements. Then only one converter could perform AC/DC conversion at higher efficiency, using less space and less weight.

Current solutions tend to boost the battery voltage before using it with the DC/AC inverter which feeds the commonly used Permanent Magnet Synchronous Motor. In this kind of converter, energy is stored in an inductor. Faster switching frequency induces a smaller amount of stored energy and reduces the inductor and capacitor size. The result as seen for the PFC is a decrease in final cost and volume. The drawback of this trend is the necessity for the HEMT technology to reach high voltages in order to completely prove its usefulness.

TABLE II: GAN AND SI SOLUTION COMPARISON

	MOSFET Si[1]	**HEMT GaN[2]**
V_{DSmax} (V)	650	650
I_{ds} (A)	30	30
Q_g (nc)	96	6.5
C_{oss} (pf)	125 @100V	70 @400V
Q_{rr} (µc)	10	0
R_{DSon} (mOhm)	125	52
Size (mm)	14.81x9.7x4.3	10x8.63x0.45

[1] Part IPA60R125C6

[2] Part GS66508P-E03 from GaNSystems

Another important way to improve overall efficiency is to include GaN chips in the power inverter. This allows the inverter to operate at higher frequency. Then new topologies appear. One often mentioned consists in adding an inductor at each phase output before feeding the electrical motor. Then a comparison between classic 15 kHz insulated gate bipolar transistor (IGBT) solution and 100 kHz GaN HEMT solution is done in [28]. The result is a significant improvement in current waveform and overall efficiency increased up to 8%, mainly due to reduced motor losses. Another structure often used is the Z source inverter (ZSI). This topology aims to use one structure to boost and make pure sinus waveform while reducing the stress on the components [29] [30]. Since its theory is based on the transistors cross conduction, the use of WBG semiconductors with very low R_{on} might greatly reduce the losses when high current flows. Whereas the efficiency only appears slightly better than with a traditional boost and inverter configuration, the reduced stress allows an increase in the electronic lifespan.

V. RATINGS AND USES

The GaN is a material permitting a very high current density with very low capacitances and recovery charges. Thus a key aspect in the development of HEMTs is the possibility to attain high voltages. The higher the voltage the higher the spreading in many architectures. Currently if we exclude the cascode configuration because it does not purely uses GaN as a semi-conductor, the higher recorded breakdown voltage available for sold is 350 V. It allows many applications as DC/DC converters and motor driving. Even though many applications can be found, it is not enough to take the lead on high power motor driving such as electrical vehicles. It can still be improved since the technology is at its beginning but the lateral structure is limiting by itself. Creating an artificial vertical structure may be a solution but is only reported on sapphire [31].

Then comes the cascode configuration, as mentioned earlier, the available products need to use two kind of technologies. Current research shows the possibility to create a cascode component with a high voltage “normally on” HEMT

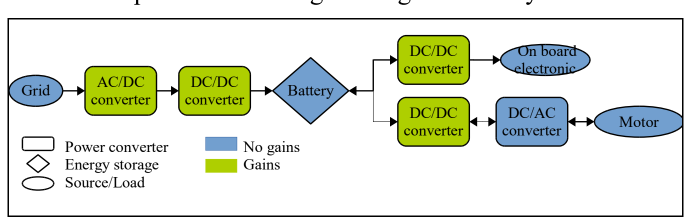

Fig 1. Usual power topology for EV applications

in series with a low voltage “normally off” HEMT. The drawback of adding a Qrr value would be removed and the capabilities of the high voltages “normally on” HEMT could be used in classic power converters.

VI. FUTUR CHALLENGES

Even though the GaN already shows good dynamic and losses properties, the technology is only at its beginning and only few suppliers exist. To have a better market share, some aspects still need improvements.

One of most important is the cost reduction. These chips will have the capacity to be massively produced since the fabrication process is well known, due to the GaN based led industry and all the research put into it as discussed in the paper. The process on how to use the Si wafers is already mature and will lead to 200 mm wafers. One great benefit is that many Si tools used for traditional Si MOSFETs can be reused [5] for GaN technology fabrication, the investment is low, the wafers size will keep expanding leading to lower components prices in the next years.

A great challenge for the mass production is the production defaults since it can lead to reduced performances [32]. The current lack in GaN substrates leads the manufacturers to use SiC, Sapphire or Si instead. Using another material implies lattice mismatches, that can lead to defects in the active layers of the device [33]. Sapphire got poor thermal qualities and high mismatches. SiC is currently the best material. It has a very low mismatch, a good thermal conduction but is still expensive. Its production is limited to small 100 mm wafers and cannot lead to cheap GaN components. Its future use can still focus on high end products. The Si is intensively studied due to its high quality for large wafers. GaN can be grown on such a wafer with a multi-layer technology in order to limit mismatches of the structure.

To be fully utilized on high power converters, breakdown voltage needs to be improved. Currently sold products break around 650 V. The main problem resides in the difficulty to have a vertical structure like for Si and SiC components. In GaN HEMTs, to increase the voltage, two parameters are to be taken into account. One is the distance between drain and gate and the second, is the distance to the substrate. For a Si wafer, electrical field penetration in the substrate will damage the Si wafer permanently. Solutions have been reported to create very high voltage HEMTs, up to 8300 V [31]. In this work, vias are machined in the sapphire substrate, to recreate a vertical structure through the different layers. This promising result leads to new possibilities, heat transfer remains an important issue even though the vias permit to evacuate some of the heat.

The reliability of the HEMTs is one of the most important aspects for industrial use. However the very first components could not maintain their performances for long periods, the recent works demonstrated a good reliability over time with GaN on diamond technology with more than 3000 hours at 350°C [34]. Studies show that GaN on Si has the potential to last during 10^7 hours at 150°C [35]. This study presents an important improvement through the years. However most of the studies are focused on RF applications, care should be taken when considering high power HEMTs.

Finally, all of these improvements will only be useful, if great care is taken when designing the power circuitry. With high frequencies, the need to limit parasitic inductances and capacitances become a real need. Without doing so, ringing and unexpected losses could lead to damage the component. Then, considerations from high speed and low voltage designs must be included and taken into account. The current evolution of power conversion leads to the fusion of numerous domains such as power electronics, high frequency electronics and electromagnetic compatibility. Power designers will have to shorten even more their tracks and include more rules in their design. Ensuring electromagnetic compatibility will also need a lot of work since extremely short rising and falling time may conduct to more EMC issues and less reliability for sensitive devices. The augmented switching frequency impact many components, capacitors can show an inductive behavior and inductances a capacitive one when used at very high frequency.

VII. CONCLUSIONS

The main objective of this paper is to show the clear advantages and challenges of the GaN as a semiconductor material for embarked power converters as the used in EVs and HEVs. All the reported studies show a great potential for high power and high speed power conversion. The main points are:

- High switching speed;
- Low conductivity losses;
- Low switching losses;
- High operating temperature;
- Small packaging size;
- Low cost to be expected;

These changes brought by the GaN material have the potential of leading to a new era of power electronics. Its characteristics in term of electrical and thermal properties allow high speeds with low losses power converters. That will lead to higher power density and efficiency. Even if the technology is not fully mature yet, the rapid improvements done over the years and the intense research will rapidly bring great changes. These changes will impact most of the converters topologies. For EVs the main gains will be cost, weight and size reduction with higher overall efficiency.

Some manufacturers already sell GaN HEMTs even at high costs in order to help this new technology to be taken into account in future developments by publishing design guides and tools. The first components available already exceed the best Si CoolMos and IGBT regarding their switching speed and R_{on} losses. Solutions are still being developed in order to produce cheaper and higher quality chips to spread the technology and ensure technological advance toward the competitors.

With always higher voltages and current specifications, the market share of the GaN should reach more and more applications, starting with low frequencies and low power applications, commonly used in small power sources to high power high voltage applications as electrical propulsion. Moreover their high operating temperature and their long lifespan may change the conventional designs.

Despite many research and promises, challenges still have to be faced. The most important one being to improve the voltage ratings. The high speed will lead to problems regarding passive components behavior and how to have the desired ratings at the desired frequencies. EMC may be a huge question of interest in order to not perturb other electronic parts. Another point in the use of today transistors is how to put them in parallel or series in order to attain the desired power capacity. This issue comes from the question on how to drive efficiently such a high speed component with standard or GaN based drivers. These issues are essentials to design a converter meeting current needs in modern power converters.

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