A Review of Gallium Nitride Power Device and Its Applications in Motor Drive

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(Invited)

***Abstract*—Wide band-gap gallium nitride (GaN) device has the advantages of large band-gap, high electron mobility and low dielectric constant. Compared with traditional Si devices, these advantages make it suitable for fast-switching and high-power-density power electronics converters, thus reducing the overall weight, volume and power consumption of power electronic systems. As a review paper, this paper summarizes the characteristics and development of the state-of-art GaN power devices with different structures, analyzes the research status, and forecasts the application prospect of GaN devices. In addition, the problems and challenges of GaN devices were discussed. And thanks to the advantages of GaN devices, both the power density and efficiency of motor drive system are improved, which also have been presented in this paper.**

***Index Terms*—GaN, motor drive, power device.**

I. Introduction

POWER device is an enabling technology to achieve efficient power conversion in power electronic converters. The performance of these power devices can directly affect the efficiency of the power system [1]. The existing Si-based device has reached its performance restriction due to the limitation of its material property, and it is difficult to enhance overall performance through the innovation of device principle, the improvement of structure and the progress of manufacturing process [2]-[3]. To achieve better conversion efficiency, the high-performance power devices are needed which have smaller conduction losses and lower switching losses making them feasible for high-frequency, high-temperature operations. As an example of the third generation of semiconductor materials, the wide band-gap semiconductor material GaN has a wider band gap (band gap width greater than 3.4eV), high critical breakdown electric field, high anti-radiation ability and high electronic saturation velocity [1]-[5]. With all these benefits, the GaN devices can help to compensate the shortages of Si devices and improve the performance of power converters. Fig. 1 compares the key properties of GaN material and Si material. As listed in Table I, GaN material has a broad application prospect, and is one of the effective ways to realize energy saving and consumption reduction in the world. In this paper, the application and research status of GaN power devices are summarized. Especially, the devices were used in motor drive system. Meanwhile, the existing problems and the direction of solution are discussed.

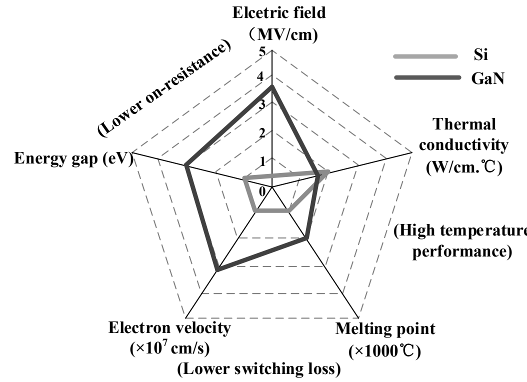

Fig. 1. Comparison of material characteristics between GaN and Si

TABLE I
APPLICATION OF GAN MATERIALS AND ENERGY SAVING (COMPARED WITH SI)

Application areas	Application effect
Electric vehicles	Reducing energy consumption by 20%
High speed railway	Saving energy more than 10%, while reducing the power system volume
Household appliances	Energy saving 50%
Industrial motor	Energy saving 30% ~ 50%
Aerospace	Reducing equipment loss 30% to 50%, Increasing operating frequency by 3 times, Reducing the volume of components 2/3
Smart Grid	Reducing power loss by 50%, while increasing power efficiency by more than 30%
Solar energy generation	Reducing the photoelectric conversion loss by more than 25%
Wind power generation	Increasing the efficiency of 20%
Large capacity communication	Significantly improving signal transmission efficiency, safety and stability

II. GaN Power Device's Advantages and Structure

A. Characteristics and Advantages

After 60 years of development, Si-based power electronics performance has approached the material limits, and are unable

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TABLE II
COMPARISON OF CHARACTERISTIC PARAMETERS FOR DIFFERENT SEMICONDUCTOR MATERIALS

Characteristic parameters	Unit	Si	SiC	GaN
Energy gap	eV	1.1	3.26	3.49
Electron mobility	cm²/Vs	1500	700	2000
Saturated electron velocity	10^7cm/s	1.0	2.0	2.8
Electric breakdown field	MV/cm	0.4	2	3.3
Thermal conductivity	W/cm•K	1.5	4.5	＞1.5
Relative permittivity	ε_r	11.8	10.0	9.0

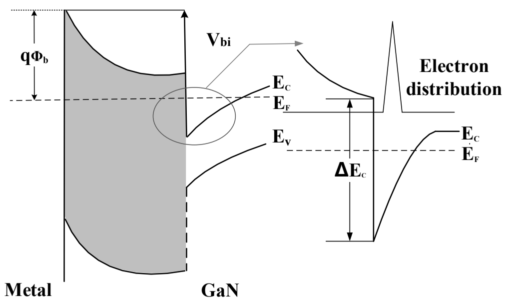

Fig. 2. GaN heterojunction energy band And 2-DEG in quasi - triangular potential well

to satisfy the requirements of high voltage, high frequency, high-efficiency and high-power-density in power electronic converter [6]-[8]. The wide-band-gap semiconductor material has superior performance compared with the traditional Si, such as high critical breakdown electric field, high saturation electron drift velocity and high electron mobility, as summarized in Table II. Therefore, power electronic devices based on GaN materials have excellent electrical properties:

1) Small On-state resistance: GaN devices have a high electron saturation rate (2.8 times than Si material), making GaN devices have a very small on-resistance and low conduction losses.

2) Fast switching speed: GaN material has small junction capacitance, and the switching frequency can be as high as the MHz level [9].

3) High voltage performance: GaN material has three times the band gap of Silicon (Si), the critical breakdown electric field up to 3.3 MV/cm, is 10 times than Si material, therefore GaN device has a higher voltage capacity.

Due to the specific polarization characteristics of GaN materials, there is a strong polarization effect between gallium nitride aluminum (AlGaN)/GaN heterojunctions, forming a high concentration of two-dimensional electron gas (2DEG) with a mobility as high as 2000 $cm^2/V•s$ and the surface density is up to $10^{13}cm^{-2}$ [10]-[11] as shown in Fig.2. GaN-based devices utilize 2DEG to achieve small on-resistance, high current density, so it can achieve a greater power density to meet the increasingly severe environmental and performance requirements [12].

B. *Basic structure*

The basic structure of GaN power devices is mainly divided into two categories. One is the planar device, fabricated on Si or Silicon Carbide (SiC) substrates [13]-[14]. The other is the vertical conduction device, which fabricated by homoepitaxial GaN active layer on a GaN self-supporting substrate [15]-[16].

The planar and vertical structures are shown in the Fig. 3. Compared to the planar conduction device, the vertical

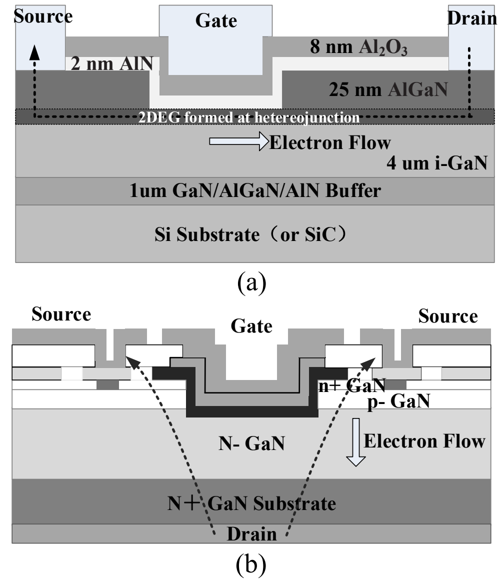

Fig. 3. Schematic of substrate:(a) lateral GaN device on Si substrate; (b) vertical GaN device on GaN substrate

structure has its unique advantages:

Firstly, the breakdown voltage can be higher. Since the drain of the vertical device making on the back of the gate and the source, when the voltage is applied to the drain, the electric field is distributed evenly along the vertical direction without the gate edge spikes of the planar device. Therefore, the vertical device is more conducive to obtain the high breakdown voltage than the planar device [17].

Secondly, it can mitigate the current collapse effect. The high electric field area of the vertical device is inside the material, away from the surface, which can weaken the effect of surface state and slow down the current collapse effect [18]-[19].

Thirdly, it is easier to increase the power density. Since there is no spike electric field, vertical devices do not need to use the field board structure, without increasing the gate leakage spacing to achieve high breakdown voltage, it is easier to improve wafer utilization and improve power density [20].

Although vertical GaN device have various advantages, the existing GaN power devices are still based on planar structure due to the difficulty of material preparation and high cost in fabricating vertical GaN devices [21]. By selecting a substrate with a little lattice mismatch and small thermal mismatch with the GaN material, the heterogeneous epitaxial growth of GaN is realized. With the advantages of large wafer size, low cost and mature technology, Si has become the best substrate for large-scale production of GaN power devices [22]-[23]. At present, the main types of GaN power devices are GaN diodes, GaN high electron mobility transistor (HEMT), Cascode GaN HEMT structure and GaN MOSFET.

III. RESEARCH PROGRESS OF GAN POWER DEVICES

In 2000, GaN-based power devices appeared for the first time, and the GaN FET was fabricated on a SiC substrate using radio frequency standards. Afterwards, with the development of material growth technology, GaN power devices has made a qualitative leap [24].

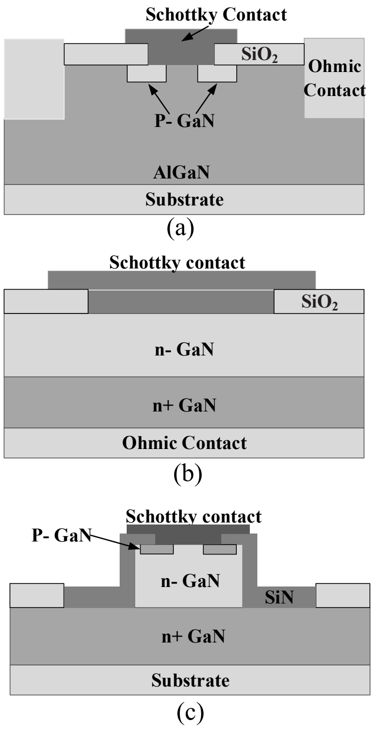

Fig. 4. Cross sections of GaN SBD including: (a) lateral structure; (b) vertical structure;(c) mesa structure

A. GaN power diode

GaN power diodes include two types: GaN Schottky Barrier Diode (SBD) and PN diodes. When the traditional GaN power rectifier is turned on, the electrons must cross the barrier (the pn junction barrier of the PiN tube or the Schottky barrier of the SBD, making the device have a high turn-on voltage that is not conducive to reduce device losses [25].

Therefore, GaN Schottky diodes have three structures: lateral structure, vertical structure and mesa structure, as shown in the Fig.4. The lateral structure utilizes the AlGaN/GaN structure and the current can be generated without doping, but it increases the area and cost of the device, and the forward current density of the device is generally small [26].

The vertical structure is used in general power electronic devices widely, which can produce a larger current. There are many research organizations using independent GaN chip peeled off from thick epitaxial wafers to achieve Schottky diode with vertical conductive structure. While, such an epitaxial wafer has a high defect that although the current of devices is large, the reverse leakage is also very large, resulting in a huge gap between the breakdown voltage and the level which GaN should be achieved. So the study of the vertical structure GaN Schottky diode is mainly staying in the stage of simulation and improving the material characteristics [27].

The mesa structure, which is also known as the quasi-vertical structure, is epitaxially grown on sapphire or SiC substrates with different doped GaN layers. The low-doped n-layer can increase the breakdown voltage of the device, while the highly doped n+layer is to form a good ohmic contact, this structure

TABLE III
SPECIFICATION FOR GAN RECTIFIER DIODES BY AVOGY

Model	Type	U_{RRM}/V	I_F/A	I_R/μA	Q_C/nC
AVDO2A600A	SBD	600	2	150	4
AVDO5A120A	PN	1200	5	0.1	7
AVDO5A170A	PN	1700	5	0.1	14

Fig. 5. The package of GaN Schottky diode and Gallium nitride HEMT

combines the advantages of lateral and vertical structures, But also has the disadvantages of lateral and vertical structure, its biggest superiority is that it can be compatible with the traditional process, and can be made relatively large size [28].

In 1996, Nathan et al. achieved Pt and Pd Schottky diodes with a barrier height of 1.13 eV and 1.11 eV [29]. In 2000, Dang et al. achieved Au/Pt-GaN Schottky diodes with a breakdown voltage of up to 550V [30]. In 2009, Arslan et al. prepared the Ni/Au-AlGaN/GaN heterojunction Schottky diode by Metal-organic Chemical Vapor Deposition (MOCVD) method and studied its current transport under variable temperature conditions [31]. In 2010, the US International Rectifier introduced the first GaN commercial integrated power products iP2010 and iP2011, using GaN SBD technology platform—GaNpowIR. These devices are mounted in a flip chip packaging platform, can bring higher efficiency and more than 2 times switching frequency than silicon integrated power stage devices, has been applied to large-capacity communications, DC-DC converter, electric vehicles and smart appliances[32]-[33]. In 2010, the German company Micro GaN introduced the 600V series of products for the high power, high voltage applications market, including Schottky diode MGG1TO617. Its turn-on voltage, turn-on resistance and the drain-source voltage is only 0.3V, 329mΩ and 600V respectively, and the leakage current is 1mA, which greatly reduces the switching losses and has been applied in the fields of power conversion, electric vehicles and high-speed trains [34].

At present, American's Avogy, Cree, EPC, Germany's Infineon, Japan's Panasonic, Sanken Electric and other semiconductor companies are developing GaN SBD production with a voltage rating of 600V, but the commercial GaN SBD is still less. EPC Corporation in 2011 launched its own GaN series of products, the maximum voltage reached 300V, and the on-resistance is only 150 mΩ. Japan's Sanken Electric incorporates GaN-based SBD and HEMT solutions in DC/DC converters and puts 600V diodes in 2012. Subsequently, Panasonic and Sharp have introduced 600V GaN-based SBD products. Avogy company is growing rapidly with the support of the ARPA-E (American Energy Advanced Research Projects Agency) and the military, providing not only 600V GaN SBD commercial products, but also 1700V PN-type diodes, which play a role in solar and wind energy inverters, electric and hybrid vehicles, as well as power conversion and aerospace applications [35]. Table III shows Avogy company's commercial gallium nitride diode products.

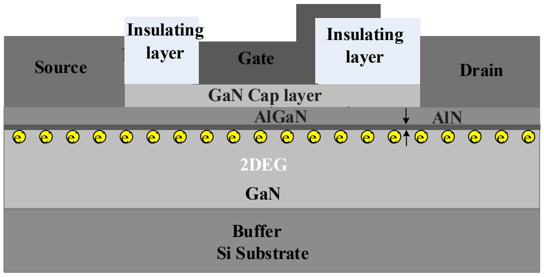

Fig. 6. The structure of normally-open GaN HEMT

In 2017, Cornell University and Qorvo company reported their work on the growth of a vertical barrier Schottky diode (JBSD) on an Independent GaN. By using quasi vertical structure, the good characteristics of Schottky barrier diode and PN diode (PND) are applied to power supply. The conversion efficiency of the original power supply is improved by nearly 20% or more [36]. Fig.5 shows the package of GaN Schottky diode and GaN HEMT.

Since the formation of PN junction technology on GaN materials is not yet mature, relatively speaking, there are few reports on GaN PN diodes. At present, there are a few reports of GaN PN power rectifiers based on GaN bulk materials or SiC substrates [37]. However, the forward turn-on voltage of the GaN power rectifier is gradually approaching the theoretical value, the working mechanism of the traditional device structure has become the shackles of its development, and it is urgent to propose a new device structure to break through this limitation. Professor Chen from University of Electronic Science and technology of China broke through the limitation of traditional GaN power rectifier, and proposed an AlGaN/GaN lateral field controlled power rectifier structure. Through the Schottky-ohm composite anode, this structure realizes the Schottky grid controlled 2DEG channel, greatly reducing the on-resistance, reducing power consumption by 20% [38]-[39].

B. GaN high electron mobility transistor

In the heterojunction formed by GaN, the polarization electric field significantly modulates the distribution of energy bands and charges. Even if the entire heterojunction structure is not doped, a 2DEG having a high density and a high mobility can be formed at the GaN interface. The 2DEG channel is more advantageous than the bulk electron channel to obtain a strong current drive capability. Therefore, GaN transistor is dominated by GaN heterojunction field effect transistor. The device structure is also called HEMT [40].

1) Enhanced GaN HEMT

Due to the polarization characteristics of the conventional GaN HEMT, there is a high concentration of 2DEG in the channel, even without any gate voltage, which makes the device in a normally-on state, that is, depletion of the device, as shown in Fig.6. In order to achieve the shutdown function, a negative gate voltage must be applied. In the most commonly used voltage-type power converter, power switches are required to be in a normally-off state from the perspective of safety and energy saving, so a lot of research work is now focused on implementing enhanced GaN HEMT devices. At present, the enhanced GaN HEMT has been prepared by injecting fluorine ion into the gate, metal oxide semiconductor (MOS) channel HEMT and p-type GaN gate, all above methods have obtained a higher breakdown voltage [41]-[45].

Fig. 7. GaN devices products and application of different companies

TABLE IV
SPECIFICATION FOR NORMALLY-OFF GAN HEMT

Tpye	U_{DS}/V	R_{ON}/mΩ	I_{Dmax}/A	U_{GS}/V	C_{iss}/PF	C_{oss}/PF
EPC2100	30	8	9.5	-4~6	380	290
EPC2033	150	7	31	-4~6	1140	580
EPC2025	300	120	6.3	-4~6	200	46
GS66502B	650	220	7	-10~7	64	16
GS66504B	650	220	15	-10~7	64	16

As the enhanced-GaN HEMT is normally-off state, eliminating the potential danger of short circuit through, so widely used [46]-[47], and depletion-type power converter is not common, only micro-GaN company has some products, its normally-open GaN HEMT is MGG1TO617.

The world's first GaN HEMT device was manufactured by Khan from APA Optics company of America， then the enhanced HEMT technology has been developed rapidly [48]-[49]. In 2000, the University of California, Santa Barbara U.K.Mishra team developed a high-voltage AlGaN/GaN HEMT power switching devices for the first time [50]. At present, the international large semiconductor companies, such as American's MicroGaN, Transphorm, EPC, Germany's Infineon, Japan's Panasonic, Canada's GaN systems have introduced GaN HEMT power devices, the highest voltage reached 1200V.

Among them, Transphorm, GaN Systems, EPC companies are in the forefront of the industry, their latest products include a series of normally-off products with a withstand voltage of 600V and integrated power module. EPC supplies from 30V/10A to 300V /6.5A GaN HEMT, its consumption and efficiency than the same level Si-based devices have greatly improved. In July 2014, Transphorm demonstrated a 1kW single-phase inverter built with its 600V-thick GaN HEMT device, which can be widely used in solar photovoltaic inverter and motor drives with peak efficiency of over 98.6%.In 2015, Canada's GaN Systems continues to make progress in the development of GaN-based power devices. In March, GaN Systems announced the development of the world's smallest 650V/15A GaN HEMT, model GS66504B, it is only $5.0\text{mm}\times 6.5\text{mm}$, compared with similar products reduced by 50%. Fig.7 is a partial comparison of the gallium nitride products with the Si products.

In the same year, at the PCIM Asia Forum held in Shanghai, GaN Systems demonstrates its new member of the GaN high power transistor family, a 60A enhancement device that extends the rated current of 8A to 250A power switching device product line. The typical product model and parameters of normally-off GaN HEMT are shown in TABLE IV. In recent years, with the increase of energy crisis, the need of energy saving and emission reduction, and some high efficiency electrical energy conversion requirements, enhanced GaN HEMT has been widely used in smart grid, automotive, high-speed railway, aerospace and solar power generation and other fields.

2) High voltage Cascode GaN HEMT

As the GaN power device voltage is mainly below 600V, thus limiting the application of the device. The emergence of high voltage cascade GaN HEMT makes GaN devices also play a role in high voltage applications.

The cascade structure combines a high-voltage normally-on GaN HFET and a low-voltage normally-off type Si MOSFET into a completely new mixing tube, and through this method to achieve normally-off, as shown in Fig.8. It is a voltage-controlled device, when the negative voltage between the gate and the source is greater than the threshold voltage, the gate is activated, 2DEG will be formed and the transistor is turned on. When the voltage between the gate and the source is less than the threshold voltage, the transistor turns off. Because Cascode GaN HEMT on-state losses and switching losses are very small, and its body diode has better reverse recovery characteristics compared with the Si MOSFET, which can significantly improve the efficiency of the power system [51].

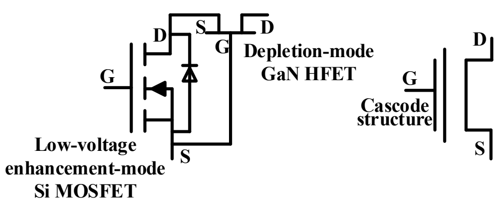

Fig. 8. Device structure of cascode GaN HEMT

Because of excellent characteristics of Cascode GaN HEMT, it has been favored by major semiconductor manufacturers all over the world. In 2012, Transphorm introduced the first 600 V voltage level of GaN power device products, through cooperation with Fujitsu company, launched a mass production of products, and its device structure is cascade structure. In half of 2014, Yasukawa Electric used cascode GaN power electronic devices in its mass production 4.5 kW power regulator, the product is characterized by a maximum conversion efficiency of 98%, switching frequency of 40kHz~50kHz, and the volume is reduced by about 40%. The power losses can be reduced by half [52]. GaN Systems utilizes the cascode GaN HEMT developed by its "Island Technology" patent, enabling the device to have a fast switching speed of 100V/ns and ultra-low heat loss. At the same time, a great deal of research and experimental work on the suitability of the device for electric vehicles and hybrid vehicles has proved that cascode GaN devices have excellent performance in applications suitable for hybrid/electric vehicle applications. The latest development is that in 2016, On Semiconductor and Transphorm worked together to develop and promote GaN-based products and power system solutions, the introduction of 600V GaN cascade structure transistors NTP8G202N and NTP8G206N, aimed at industrial control, high-capacity communications, clean lighting and smart grid and other high-voltage applications.

TABLE V
SPECIFICATION FOR CASCODE GAN HEMT

Tpye	U_{DS}/V	R_{ON}/mΩ	I_{Dmax}/A	U_{GS}/V	C_{iss}/PF	C_{oss}/PF
TPH3002LD	600	290	9	±18	785	26
TPH3205WS	600	52	36	±18	2150	119
NTP8G202N	600	290	9	±18	760	26
NTP8G206N	600	220	15	±18	760	26

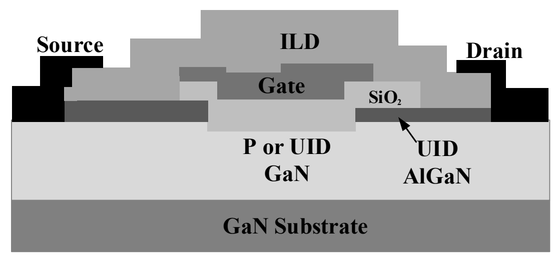

Fig. 9. Cross section of GaN transversely MOSFET

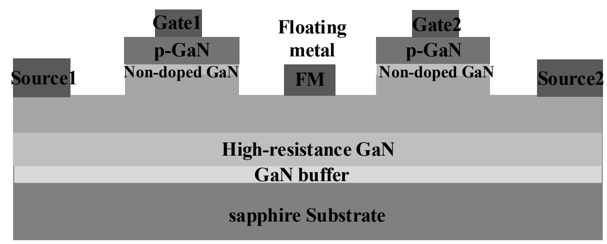

Fig. 10. Cross section of bidirectional heterogeneous GaN FET

C. *GaN MOSFET*

At the same time, in the case of high voltage power switching, lateral GaN MOSFET exhibit the advantages of constant and large conduction band migration, making them less susceptible to hot electron injection and other reliability problems such as the effect of surface state and current collapse, and become a good alternative to replacing SiC MOSFETs and GaN HEMTs. The channel mobility of the SiO_2/GaN interface in the lateral GaN MOSFET is only 170 $cm^2/V{\bullet}s$, but the cut-off voltage is as high as 2.5kV [53]-[54]. Due to the influence of interface states, surface roughness and scattering phenomena, low channel mobility of lateral GaN MOSFETs is a big problem. To solve this trouble, the AlGaN/GaN heterostructure is introduced into the RESURF region of the GaN MOSFET, as shown in Fig.9. The hybrid MOS-HEMT manufactured by this method contains the advantages of both. Not only has the high mobility of 2DEG in AlGaN/GaN heterojunction, but also to achieve the characteristics of small on-resistance in normally-off state and high cut-off voltage [55]-[56].

With the continued warming of GaN device research， the two-way heterojunction GaN field effect transistor with bipolar junction concept has been published. Fig.10 shows the cross section of bidi-rectional heterogeneous GaN-FET. In this device, the gate structure of the Schottky and p-n junction in the GaN-FET is arranged on a sapphire insulating substrate, isolation voltage between devices is greater than 2kV, the forward on-resistance and the reverse on-resistance are respectively 24mΩ and 22mΩ [57].

Compared with GaN HEMT device structure, GaN MOSFET devices are more suitable for high-voltage power conversion applications through the use of insulating dielectric gate structure to make the gate leakage current greatly reduced. In 2008, W.Huang of the United States Rensselaer Polytechnic Institute obtained a GaN MOSFET device with a breakdown voltage of 2.5 kV by using a lateral implant to reduce the surface electric field on a sapphire substrate [56]. In 2014, Toyota's 600 V GaN power converters made with GaN MOSFETs, with a switching frequency of 2.5 MHz and efficiencies of 97%, are used in the fields of electric vehicles and aerospace, while using the same level of silicon Power electronics, switching frequency up to 150 kHz, the efficiency is 20% lower than the GaN device [58].

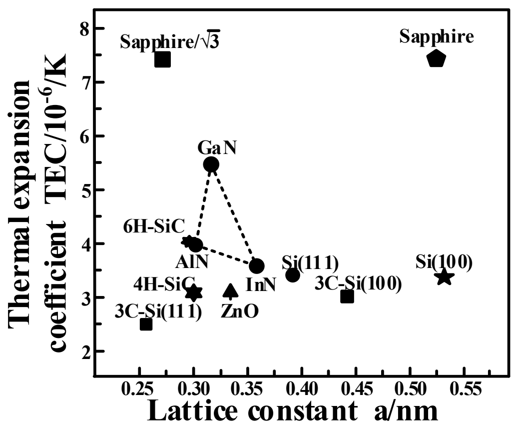

Fig. 11. Thermal expansion coefficient of GaN and common substrates as a function of lattice constant.

In 2016, Boeing and General Motors Corporation owned research and development laboratories-HRL Labs announced the realization of GaN complementary metal oxide semiconductor (CMOS) [59], which will further promote the GaN MOSFET power device maturity and comprehensive industrialization.

IV. CHALLENGES OF GAN POWER DEVICE DEVELOPMENT

Although the current GaN devices have made great progress and gradually enter the market, but it still exists many problems cannot be ignored. To replace the silicon technology and become main-stream, there are still several challenges as followed.

A. Material growth

High-quality epitaxial material is the core of GaN-based power devices. Compared with Si, the lattice mismatch of SiC and sapphire is smaller and thermal conductivity is higher, which are indispensable advantages for high-power devices [60]. However, the high cost limits its practicality, although the lattice mismatch between Si and GaN is large, its cost is low and the lattice mismatch can be attenuated with the introduction of buffer layer for stress management. Therefore, the Si substrate is still the mainstream technology of GaN based power devices. Fig.11 shows the function of lattice constant between thermal expansion coefficient of GaN and common substrates. In addition, due to the heterogeneous structure, GaN power devices are mainly lateral structure. Although this makes it been favored in the field of high frequency, but also limits its high-power characteristics. At present, the industry consensus is that GaN is more suitable for low voltage and high speed switch (<1.2kV), such as power factor correction, green energy and others [61].

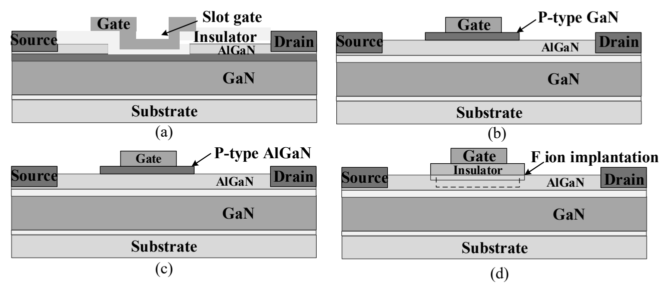

Fig. 12. Gate techniques for e-mode GaN HFETs: (a) slot gate; (b) P-GaN gate; (c) P-AlGaN gate; (d) fluorine ion implantation.

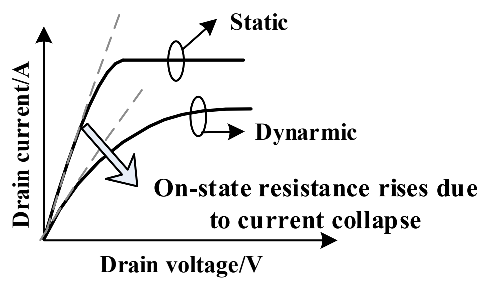

Fig. 13. The current collapse effect.

B. Device technology

In the aspect of device technology, there are two main problems: the first is to improve high voltage capability, and the other is to make the production of normally-off (enhanced) devices.

Enhancing the ability of withstanding high voltage is the first problem to be considered. On one hand, this is related to the material properties of GaN itself. On the other hand, it is also closely related to the device structure and substrate quality, Therefore, the current scheme to improve the breakdown voltage of the device is mainly concentrated in the following three aspects: improving the substrate structure, improving the buffer layer structure, and improving the device structure [62].

Secondly, the production of normally-off (enhanced) devices are needed in real applications. Unlike the depletion-mode devices, the enhanced devices can realize the normally-off state without adding bias voltage on the gate, which ensures the safe operation of the system. The industry generally uses the slot gate, P-GaN gate or P-AlGaN gate and fluorine ion implantation method to achieve enhanced devices [63]-[66].

Fig. 12 shows some of these published techniques.

C. Suppression of current collapse effect

The current collapse effect of AlGaN/GaN HEMT devices is a serious challenge to the practical success of GaN power devices. It is also one of the main problems faced by current GaN power devices. The phenomenon is as follows: when a large bias is applied to the drain, the leakage current will degrade [67]-[68], as shown in Fig. 13.

At present, the mechanism of the current collapse effect of GaN devices mainly includes the following types:

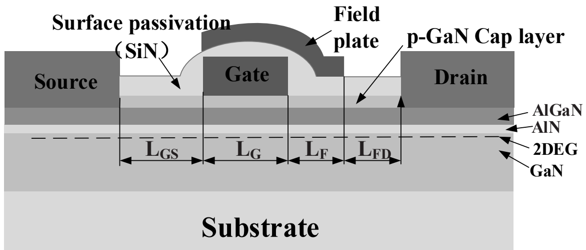

Fig. 14. Three important methods of suppressing the current collapse.

(1) The carrier traps caused by the deep level centers in the material creates the current collapse;

(2) The change of the polarization charge caused by the surface state and the surface effect causes the 2DEG concentration in the AlGaN/GaN conductive channel to decrease, resulting in current collapse;

(3) Material structure and the energy band structure boundary are too critical, a slight disturbance will affect the 2DEG, leading to current collapse [69]-[70].

The method of suppressing the current collapse is mainly as follows:

(1) Surface passivation treatment [71]: Passivation can suppress current collapse. However, it also has some negative effects such as both the device's gate leakage current and cut-off frequency, Md.Tanvir Hasan team studied the effect of SiN passivation layer on current collapse in HEMT devices, the results show that the current collapse effect is improved with the increase of SiN deposition temperature and the annealing temperature, which indicates that the SiN/AlGaN surface trap density decreases with the increase of SiN temperature and annealing temperature.

(2) Field plate structure [72]. Field plate is a metal plate connected with metal, the introduction of field plate structure can improve the distribution of the electric field under the electrode to inhibit the current collapse. The WataruSaito has studied the effect of four different field plate structures (single source field plate, dual source field plate, single gate field plate and source gate field plate) on the AlGaN/GaN HEMT current collapse effect. By analyzing the influence of the field plate on the electric field distribution, the influence of the field plate on the current collapse effect is deduced. Experiments show that the rise of the on-resistance caused by the current collapse effect can be effectively suppressed by the single gate field plate and the source gate field plate, because the gate field plate can reduce the electric field at the gate edge and the source gate field plate can more effectively suppress the current collapse effect.

(3) Growth of P-type cap layer [73].The cap layer refers to the growth of a thin P-GaN layer on the AlGaN layer, and then the electrode was fabricated on the cap layer. Experiments show that the cap layer can improve the current collapse effect. By using this method, the material growth process is relatively simple and easy to control, but it increases the difficulty of the manufacturing process. For example, the gate fabrication process is complicated. Fig. 14 shows the main methods of suppressing the current collapse.

D. Thermal dissipation and Thermal design

Thermal dissipation and thermal design are still an important issue that constrains the performance of GaN power devices.

High power density advantage of GaN is difficult to realize in real high power devices, and the performance is that the output power density of the device decreases rapidly with the increase of the gate temperature. The gate of the high-power device is mostly multi-gate structure. In the working state, the dense channel exhibits significant self-heating effect, resulting in a rapid increase in junction temperature. Even the SiC substrate is difficult to meet the demand of heat dissipation, which severely limits the device's output power. In particular, with the increase of the operating frequency, the breakdown voltage and efficiency also decrease. Since the carrier transport characteristics are significantly degraded at high junction temperature, the high power density advantage of GaN is also lost [74]-[75].

The problem of heat dissipation can be sloved by increasing the thermal conductivity of the substrate. An important technical trend is to use a diamond substrate instead of a SiC substrate. The thermal conductivity of monocrystalline diamond is as high as 2200W/(mK) and thermal conductivity of polycrystalline diamond prepared by Chemical Vapor Deposition (CVD) method can also reach 1200 ~ 1500 W/(mK). Both of them can greatly improve the heat dissipation capacity of the substrate (4H-SiC thermal- conductivity is 490W/(mK)).The mainstream technology is chip bonding, using GaN heterojunction epitaxial wafers bonded on CVD diamond substrates. Compared with the strong heat dissipation of the SiC substrate, the power per unit area can reach more than 3 times [76]. In addition, another measure to improve the heat dissipation problem is to enhance the surface heat dissipation of the device by changing the SiN passivation layer to the AlN passivation layer, which has a higher thermal conductivity.

E. Reliability

The reliability of GaN devices is still not high enough, and there are many constraints. The two-dimensional electron gas in the GaN heterojunction is very sensitive to the piezoelectric polarization strength (determined by the strain state) and the surface state (cleanliness, oxidation degree, trap state, etc.) Therefore, the strain and the instability of the surface state are the intrinsic factors that restrict the reliability of GaN devices [77]. Meanwhile, the degradation of GaN power devices in the working state is mainly caused by two important external factors, namely, electric field and junction temperature. Nitride material appears in the reverse piezoelectric effect under strong electric field [78]. It is shown that the electric field causes the additional tensile strain of AlGaN, which overlaps with the original tensile strain of itself, so that when the voltage increases to a certain critical voltage, the high-voltage field region of gate near the drain will produce cracks and other defects. A large number of hot electrons in the strong electric field can cause the space transfer and reduce the electron density of the channel, leading to a decrease in saturation current and transconductance. The hot electrons also collide with the lattice to create new defects and exacerbate the aging of the device.

Under high power operating condition, the junction temperature of GaN HEMT devices (especially large gate devices) rises, severely limiting the device's output power density and reliability. The seriousness of this problem is that the high junction temperature reduces the thermal conductivity of the substrate, thereby further increasing the junction temperature and seriously deteriorating the reliability of the device.

Furthermore, high density dislocation defects and large residual stresses in the material are also parasitic factors that affect the reliability of GaN devices. Therefore, it is a daunting task to improve the reliability of GaN devices. A variety of aspects need to consider, i.e. reducing the material defect density, elevating manufacturing process stability and repeatability, optimizing electric field distribution and improving heat dissipation.

V. Applications of GaN in motor drive

With the development of GaN power devices, scholars have done some research in application of GaN power devices in motor drive.

In paper [79], the operating characteristics of a normally on GaN HEMT device with a normally off low voltage Sibased MOSFET in cascode have been discussed, and the test results showed that it has the advantage of low switching and conduction losses, and operation without any external freewheeling diode. Further, the switching and conduction loss in the 6-in-1 GaN HEMT device operating at 100 kHz is seen to be much lower than Si-based IGBT inverter operating at 15 kHz. The size of the output sine wave filter is very small and the loss in the sine wave filter is much lower than the extra losses in the motor without filter.

Scholars in University of Wisconsin–Madison proposed the modular converters based on GaN FETs and eliminated heat sinks. With the superior switching performance of GaN FETs, the size and height of capacitors are reduced, and all the capacitors can be integrated into an integrated modular motor drive (IMMD) at a high switching frequency. They evaluated the capacitor size and found the optimal point in the capacitor selection. In addition, the experimental results prove that the IMMD has a superior running performance with small current ripple and reasonable heat dissipation design [80].

Paper [81] proposed a BLDC Motor speed control system using a100 kHz GaN-based Half-Bridge Resonant Converter and its electrical and thermal performance was verified by both simulation and experimental setup. Simulation and experimental results have proven that the GaN-based switches are not only compact but also more efficient compared to their Si-based counterpart. GaN switches are more reliable in terms of temperature and it is observed that efficiency goes up by almost 20 percent compared to its Silicon counterpart. Also it operates at higher switching frequency and have lower power losses and higher accuracy in speed control applications when compared to conventional converters.

Paper [82] designed a three phase motor drive system based on lateral enhance mode GaN switches with vertical power loop structure and CM noise current propagation control. The experiments verified that the motor drive system can operate with no issues for a long time at a switching frequency of 100 kHz.

In paper [83], the effect of the reverse voltage drop of the GaN HEMT in the operation of a diode-free GaN HEMT based high-speed single-phase BLDC motor drive was discussed. They found that the overall system efficiency of unipolar PWM with active freewheeling is higher than that of bipolar PWM with passive freewheeling by 13%. Experiments have shown that the additional antiparallel diodes in GaN HEMT based motor drive can be an effective and simple solution for both reverse conduction and switching losses reduction.

In summary, the power devices based on GaN material can be applied to motor drive control with the advantages of fast switching speed, small on-resistance and high junction temperature. On the one hand, extremely high switching frequency can effectively reduce current harmonics, which can greatly reduce the volume of the support capacitor and the filter inductor. On the other hand, the on-resistance is small and the loss is low, and the efficiency of the controller is effectively improved. Considering the high temperature operation ability of the GaN material itself, the heatsink can be greatly reduced. Therefore, both the degree of integration of the driver and the power density are greatly improved. In addition, the high-frequency switching modulation combined with the low-pass filter can effectively remove the harmonics of the inverter output current, hence, the torque ripple of the motor is small under the light load and the losses of motor is reduced, which improve the operating efficiency of the overall motor-inverter system.

VI. Conclusions

GaN power electronic device will play an important role in future power electronics applications due to its excellent performance. With the continuous progress of manufacture technology, GaN power devices with high breakdown voltage, high temperature resistance, low conduction losses, high output power, will make Si materials incomparable in the power electronics, photovoltaic inverter, green lighting, electric vehicles and other energy fields. However, the problems is still very prominent. The material defects, device performance, reliability, rate of final products and other issues are still very serious, and the related mechanisms of GaN power devices and materials still need to be studied in depth.

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