Chapter 6

GaN-Based Schottky Diode

Yaqi Wang

Additional information is available at the end of the chapter

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Abstract

Schottky diode, also known as Schottky barrier diode (SBD), fabricated on GaN and related III-Nitride materials has been researched intensively and extensively for the past two decades. This chapter reviews the property of GaN material, the advantage of GaN-based SBD, and the Schottky contact to GaN including current transporation theory, Schottky material selection, contact quality and thermal stability. The chapter also discusses about the GaN lateral, quasi-vertical and vertical SBDs, and AlGaN/GaN field effect SBDs: the evolution of the epitaxial structure, processing techniques and device structure. The chapter closes with challenges ahead and gives an outlook on the future development of the GaN SBDs.

Keywords: GaN, AlN, AlGaN, Schottky diode, Schottky barrier diode (SBD), Schottky contact

1. Introduction

Wide band gap (WBG) semiconductor materials are the best candidates for high frequency, high power and high temperature applications because of their superior intrinsic material properties compared to Si, and GaAs (**Table 1**).

Among the WBG materials, SiC and GaN are the most successfully developed in terms of material growth, device fabrication and commercialization. GaN and related III-Nitride materials such as InN and AlN and their alloys have many advantages in optoelectronics. III-Nitride materials have a wide range of direct bandgap from the lower end 1.9 eV (InN) to the high end 6.2 eV (AlN) and can also support multi-quantum well and superlattice structures, enabled by epitaxial thin-film growth technology, primarily metal organic chemical vapor deposition (MOCVD). GaN and AlGaN are also the preferred WBG materials in high

Parameter	Si	GaAs	4H-SiC	GaN
E_g (eV)	1.12	1.42	3.25	3.40
E_c (MV/cm)	0.3	0.4	3.0	4.0
μ_n ($cm^2 \cdot V^{-1} \cdot s^{-1}$)	1500	8500	1000	1250
ε	11.8	12.8	9.7	9.0
V_{sat} (10^7 cm/s)	1	2	2	2.5
λ ($W \cdot cm^{-1} \cdot K^{-1}$)	1.5	0.5	4.9	2.3

E_g: bandgap; E_c: critical electric field; μ_n: electron mobility; ε: dielectric constant; V_{sat}: saturation electron velocity; λ: thermal conductivity.

Table 1. Comparison of material properties of Si, GaAs, 4H-SiC and GaN [1].

frequency applications as two-dimensional electron gas (2DEG) with high carrier concentration and mobility can be formed at the AlGaN/GaN heterointerface by spontaneous and piezoelectric polarization effect [2]. GaN based light emitting diode (LED), GaN based laser diode (LD) and AlGaN/GaN based high-electron-mobility transistor (HEMT) were commercialized in early 1990s, late 1990s and mid 2000s respectively.

In the realm of high power and high temperature applications, as Si based power device is reaching its theoretical limit and cannot meet the increasing demand of key performance metrics, such as high blocking voltage, low switching loss, high switching speed and high operating temperature at the same time, WBG materials has great potential to replace Si in those applications [3].

Specifically, in applications that require high reverse blocking voltage and high switching frequency, SiC and GaN Schottky barrier diodes (SBDs) are preferred over bipolar Si p-i-n diode, whose switching speed is compromised due to long minority carrier lifetime. SiC and GaN are comparable in many aspects: GaN has higher Baliga's figure of merit (BFoM) because of its better electrical properties, while SiC has better thermal conductivity, thus the two materials are in direct competition for the application [4]. SiC SBD was successfully introduced to the market in early 2000s, and gradually matured to displace the Si p-i-n diode. On the other hand, because of the nonoptimal material quality, which once limited the application of its SiC counterpart, GaN SBD still cannot achieve its theoretical performance. Researchers around the world have been continuously working on improving GaN material quality, while exploring novel ways to fabricate GaN SBD with better performance since mid-1990s. Although great progress has been made, significant amount of effort is still need for GaN SBD to overcome the technical challenges, close its performance gap to SiC SBD, and eventually achieve commercial success.

In the following sections of this chapter, several topics are discussed in details:

- *Schottky contacts to GaN*: Theoretical basis, current transportation mechanisms, characterization methods, metal selection and comparison, the impact to contact performance by material and surface quality, and thermal stability of Schottky contact to GaN were

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discussed sequentially in this section. The section also covers topics such as nonmetal Schottky contact to GaN, Schottky contact to AlGaN, and Schottky contact to nonpolar GaN.

- *GaN lateral, quasi-vertical and vertical SBDs*: This section covers material growth and epitaxial structure optimization techniques, device fabrication and device structure optimization techniques such as: surface treatment, dielectric deposition, floating metal ring, field plate, ion implanted guard ring and Schottky junction barrier diode.
- *AlGaN/GaN field effect SBDs*: This section discusses about AlGaN/GaN heterojunction formation, material growth and epitaxial structure optimization techniques, device fabrication and device structure optimization techniques that are unique to AlGaN/GaN field effect Schottky barrier diodes such as: dual Schottky anode, Schottky-ohmic-combined anode, gated edge termination, fully recessed Schottky anode and MIS-gated hybrid anode.

A brief summary and outlook on GaN SBD development are presented in the last section.

2. Schottky contacts to GaN

2.1. Theoretical basis of Schottky contact to GaN

Metal–semiconductor contact plays a crucial role in semiconductor devices, such as diodes and transistors. There are two types of metal-semiconductor contact: Ohmic and Schottky. Schottky contact has a rectifying barrier, which is formed when there is an energy level mismatch between the semiconductor and the metal. The difference between the semiconductor electron affinity and metal work function is defined as Schottky barrier height. The band structure before and after Schottky contact formation to n-type semiconductor, such as intrinsic GaN, is shown in **Figure 1**. Fermi levels of the metal and semiconductor need to line up to reach an equilibrium when they are put in contact, and the space charge built at the semiconductor side leads to band bending effect.

There are two carrier transportation mechanisms for an ideal Schottky contact: thermionic emission (TE) and field emission (FE). At a forward bias, the carrier transportation is determined by temperature and the n doping concentration of GaN. A lower temperature and a more highly doped GaN can lead to a higher FE component. As Schottky contact is usually deposited on intrinsic GaN or lightly n doped GaN, and the operation temperature of GaN SBD is usually above room temperature, the dominant transportation mechanism is TE. The current-voltage characteristics of the SBD in the TE regime is given by Eq. (1, 2):

$$\mathrm{I} = \mathrm{I}_0\left\{\exp\left[\frac{q(V - IR_s)}{nkT}\right] - 1\right\} \tag{1}$$

where I_0 is the saturation current:

$$I_0 = AA^{*}T^{2}\exp\left(\frac{-q\Phi_B}{kT}\right) \tag{2}$$

The three most common Schottky contact characterization methods are current-voltage (IV), current-voltage-temperature (I-V-T) and capacitance-voltage (C-V). Key parameters, such as Schottky barrier height (Φ_B), ideality factor (n), effective Richardson's constant (A^*), doping concentration (N_D) and series resistance (R_s) can be extracted from the characterization methods mentioned above.

2.2. Metal Schottky contacts to GaN

Tremendous amount of work on Schottky contacts to GaN was done in mid 1990s, which built solid foundation for later development of vertical and lateral GaN SBDs. Au Schottky contact to n-GaN was first reported by Hacke et al. [5] and Khan et al. [6]. Schottky contact formation of Ni, Pd and Pt to GaN was then extensively studied by various research groups [7–12]. I-V, I-V-T and C-V measurements were performed to find the characteristics of the Schottky contacts, such as ideality factor, effective Richardson coefficient, and Schottky barrier height. **Table 2** shows a brief summary of Schottky barrier heights of common contact metals by the three methods mentioned above.

Liu and Lau reviewed the scattered results reported and suggested the nonideal Schottky contact behavior probably stemmed from surface defect which can cause inhomogeneity in the transport current even within a single device, while material quality and metal-GaN reactions were the other two contributing factors [13]. Hsu et al. performed scanning current–voltage microscopy (SIVM) measurements and found nonuniform spatial reverse leakage distribution within a device. The correlation of SIVM, topographical and TEM images showed that leakage occurred at screw and mixed dislocation [14]. The experiment confirmed surface and material quality is crucial to good Schottky contact formation.

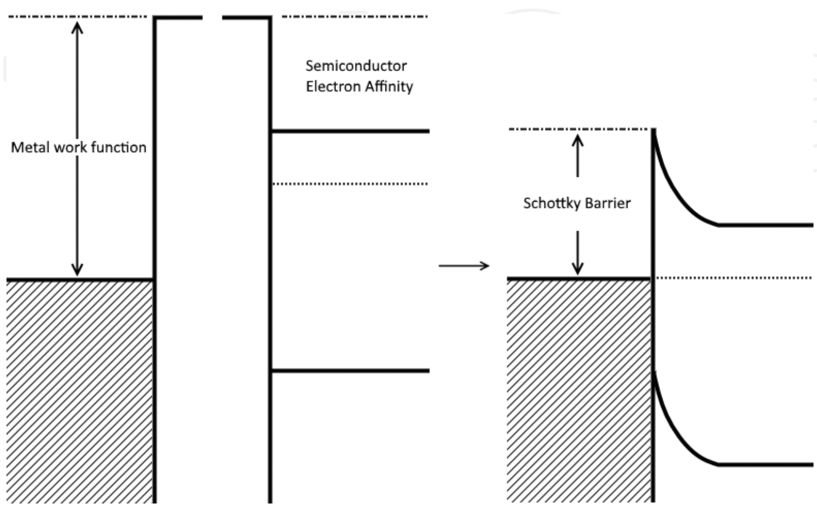

Figure 1. Band structure of Schottky barrier formation [1].

Metal	Φ_b (eV) by I-V	Φ_b (eV) by I-V-T	Φ_b (eV) by C-V	Reported
Au	0.844	—	0.94	Hacke et al. [5]
	0.91	—	1.01	Khan et al. [6]
	1.03	—	1.03	Kalinina et al. [9]
	0.87	0.88	0.98	Ping et al. [10]
				Schmitz et al. [11]
Ni	1.15	—	1.11	Kalinina et al. [9]
	0.95	0.99	1.13	Schmitz et al. [11]
	0.83	0.93	1.03	Liu et al. [12]
Pd	—	0.91	0.94	Guo et al. [7]
	1.11	0.96	1.24	Wang et al. [8]
	0.94	0.92	1.07	Ping et al. [10]
				Schmitz et al. [11]
Pt	—	1.03	1.04	Guo et al. [7]
	1.13	—	1.27	Wang et al. [8]
	1.01	1.08	1.16	Schmitz et al. [11]

Table 2. Summary of Schottky barrier height of Au, Ni, Pd, and Pt to GaN from I-V, I-V-T, and C-V experiment results.

Miller et al. designed an experiment to detect localized leakage path on GaN surface by conductive atomic force microscope (AFM), and developed a surface modification method by selectively applying voltage at the recorded leakage locations to form a thin passivation layer that blocks the leakage path. Schottky contact made on surface modified GaN showed much better reverse leakage characteristics than unmodified GaN [15]. Sang et al. performed detailed analysis on leakage path by photon emission microscopy (PEM), and found the leakage current occurred at polygonal pits, where carbon impurity accumulated and acted as trap in carrier tunneling [16]. The result aligned with the Cao et al.'s finding that low carbon concentration was necessary to achieve high Schottky contact quality, by an experiment correlating contact performance with carbon doping level [17]. Reddy et al. demonstrated a homogeneous Schottky contact to GaN with unity ideality factor and low leakage current by acid treatment. XPS studies showed the treatment removed excess carbon and restored Ga/N composition at the interface [18]. It can be concluded that removal of impurities such as carbon, and/or passivation of leakage path by surface treatment, is effective in improving Schottky contact quality.

Schottky contact thermal stability is important to GaN SBDs, as high operating temperature is desired for power applications. At elevated temperature, Schottky metal reacts with GaN, gradually turning the contact nonrectifying. Guo et al. reported Ni Schottky contact started to react with GaN, forming nickel nitrides, at temperature above 200°C [19]. For noble metal Pd, interdiffusion of the metal and GaN was discovered at 300°C [20]. If stable temperature is defined as temperature at which Schottky contact is still rectifying after 1 hour of annealing, the highest stable temperature for Ni and Pt was reported to be 500°C [12] and 400°C [21], respectively. Several techniques were applied to improve stability of Schottky contact to GaN. Thermal stability of metal silicide is usually better than elemental metal. The stable temperature was reported to be 600°C for NiSi [12] and PtSi [21], 100–200°C higher than elemental Ni and Pt. Multilayer contact structure with inert and high melting point metal as insert or cap layers can also help to improve the thermal stability of Schottky contact. Stable temperature of Ni/Ta bilayer Schottky contact was reported to be 700°C [22], 200°C higher than pure Ni.

2.3. Nonmetallic Schottky contacts to GaN

ITO and graphene Schottky contacts to GaN were also studied, as they are transparent and have potential applications in optoelectronic devices such as MSM photodetector. Sheu et al. reported ITO Schottky contact to GaN with increasing barrier height from 0.68 eV as deposited to 0.95 eV after annealed at 600°C [23]. Tongay et al. first reported graphene and multilayer graphene (MLG) Schottky contact, with barrier height of 0.74 eV as deposited and 0.70 eV after prolonged annealing at ~ 600°C [24]. The large ideality factor (>2) indicated high contact inhomogeneity. Kim et al. reported improved graphene Schottky contact with 0.9 eV barrier height and 1.32 ideality factor [25].

2.4. Schottky contacts to AlGaN

Schottky contacts need to be made to AlGaN in some AlGaN/GaN field effect SBD applications. Qiao et al. characterized Ni Schottky contact to AlGaN by I-V, C-V and photoemission methods, and found the barrier height increased linearly with Al mole fraction up to 0.23 [26]. Lv et al. applied two-diode model and determined barrier height of Ni Schottky contact to AlGaN/GaN heterostructures by forward I-V measurement [27]. Shin et al. investigated common GaN Schottky metals, such as Au, Ni, Pd and Pt, to AlGaN/GaN heterostructures and found barrier inhomogeneity was related with Schottky metal type [28]. Nonmetallic materials such as TiN was also studied. TiN can be deposited to AlGaN surface by reactive sputtering [29]. The lower barrier height of TiN compared to common Schottky metals enables a lower turn-on voltage, which is preferred in application such as microwave rectification [30].

2.5. Schottky contacts to nonpolar GaN

Schottky contacts made to a-plane and m-plane nonpolar GaN were also studied. Phark et al. studied Pt Schottky contacts to a-plane n-GaN [31]. Yamada et al. fabricated Ni Schottky diode on m-plane n-GaN [32], and compared with the Schottky diode with same structure fabricated on c-plane [33]. Although the carbon concentration of the m-plane GaN was much less than c-plan GaN, the reverse leakage was three orders of magnitude larger due to lower barrier height. To date, it still remains unclear whether c-plane or nonpolar GaN is preferred in Schottky diode application mainly because nonpolar GaN Schottky devices were much less frequently investigated [34].

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3. GaN lateral, quasi-vertical, and vertical SBDs

The extensive study of Schottky contacts to GaN enabled the development of high breakdown GaN SBDs in late 1990s. GaN based SBDs have three common structures: lateral, quasi-vertical and vertical. **Figure 2** shows the schematics of the three structures. Lateral and quasi-vertical SBDs are usually fabricated on GaN grown on a foreign substrate, such as sapphire, SiC and Si. For lateral SBD, Schottky contact and ohmic contact are on the same surface. For quasi-vertical SBDs, a mesa is etched first, followed by ohmic contact deposition on the etched GaN and Schottky contact deposition on top of mesa. Vertical SBDs are usually fabricated on freestanding GaN substrate by depositing ohmic contact on the nitride face and Schottky contact on the gallium face. Lateral SBDs are easy to fabricate and thus are still used as development vehicles for testing new material growth and device processing methods, while quasi-vertical and vertical structures are preferred for practical applications.

3.1. GaN substrate growth and epitaxial structure optimization

Hydride vapor phase epitaxy (HVPE), molecular beam epitaxy (MBE) and metalorganic chemical vapor deposition (MOCVD) are the three most common methods for substrate growth. The GaN thickness, doping level are critical to SBD performance. While a design with a thinner and more highly doped GaN can lead to better on-state resistance and lower turn-on voltage, it has negative impact on breakdown voltage. The ideal substrate for GaN SBD shall have a gradient doping profile, with low dopant concentration on the Schottky side, and high dopant concentration on the ohmic side. However, such structure cannot be well supported by the current GaN material growth technology.

Quasi-vertical and vertical GaN SBDs are usually fabricated on substrates with layer structure, which has a lightly doped GaN drift layer on top of a highly doped low resistivity GaN layer, where Schottky contact and ohmic contact are formed, respectively. The layer structure has been developed on various substrate types. Sheu et al. reported a very thin low-temperate-grown (LTG) cap layer can greatly suppress reverse leakage current [35]. The layer structure consisted of a 30 nm LTG GaN cap layer, a 0.6 μm thick intrinsic GaN layer and a 1 μm thick highly doped GaN layer, grown by MOCVD on sapphire substrate. The highly doped and intrinsic GaN layers were grown at 1060°C, while the LTG GaN cap layer was grown at 550°C.

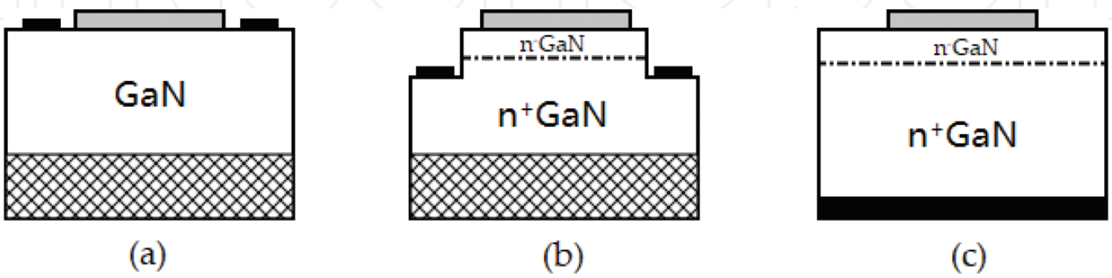

Figure 2. Schematics of (a) lateral, (b) quasi-vertical, and (c) vertical SBDs on GaN: the gray region is Schottky contact, black region is ohmic contact and the grid region is substrate.

Lu et al. reported a method to regrow GaN epitaxial layers by MOCVD on HVPE grown low resistivity freestanding GaN substrate. The layer structure has a 2 μm thick lightly doped GaN lay on a 0.5 μm thick highly doped GaN layer. It was reported that the structure greatly reduced the on-state resistance [36]. Fu et al. made further improvement to MOCVD regrown drift layers on HVPE substrate by introducing double-drift-layer (DDL) design [37]. An additional moderately doped GaN layer was inserted in between the lightly doped top layer and the highly doped bottom layer. It was demonstrated the breakdown voltage was improved with DDL design, while the forward characteristics was not compromised. The DDL design is much close to the ideal structure mentioned above. Cao et al. introduced a graded AlN cap layer on top of the GaN drift layer [38]. The cap layer has a thickness of 5 nm with Al composition from 0–23%. It was reported the cap layer reduced the leakage current by three orders of magnitude and the turn-on voltage from 0.77 to 0.67 V from tunneling effect.

3.2. SBD device fabrication and device structure optimization

The theoretical limit of the key parameters of GaN SBDs, such as breakdown voltage etc., are determined by the substrate structure. However, the SBDs performance reported is still far from the theoretical limit. Premature breakdown and high reverse leakage are the two main major areas that can be improved by better device processing and structure. Surface treatment, dielectric deposition, floating metal ring, field plate, ion implanted guard ring and Schottky junction barrier diode are discussed below.

Mesa etch is a necessary step for quasi-vertical GaN SBD fabrication. The mesa wall quality after etching can greatly affect the breakdown voltage and reverse leakage of the SBD. Surface treatment after mesa etching or material growth is critical for device performance. Bandić et al. first fabricated high breakdown voltage (450 V) lateral and quasi-vertical SBDs using Au as Schottky contact metal. The substrates used in the study consisted of an 8–10 μm GaN drift layer on a very thin (<100 nm) n^+ layer, and were grown by hydride vapor phase epitaxy (HVPE) on sapphire [39]. High leakage current was observed on quasi-vertical SBD structure due to plasma etch damage on mesa wall. Cao et al. explained the forms of plasma-induced damage to GaN as follows: generation of surface defects by ion, dopants passivation by atomic hydrogen, deposition of impurities and creation of nonstoichiometric surfaces [40]. The study also found a subsequent annealing at 750°C under N_2 or photoelectrochemical (PEC) etching in KOH solution to remove ~ 500–600 Å of the surface helped on the mesa wall quality improvement and leakage current reduction. Further study by Cao et al. suggested that the wet KOH etching is more effective than annealing for mesa wall treatment and diode characteristics restoration [41]. The GaN structures used in both studies were grown by RF plasma-assisted MBE on sapphire [40–41]. Zhu et al. fabricated quasi-vertical SBDs with mesa formed by both dry etching with a following KOH mesa wall treatment, and full wet PEC etching [42]. The GaN epitaxial structure with a 2 μm drift layer on top of a 1 μm n^+ GaN layer was grown by low-pressure MOCVD on sapphire substrate. Pt/Au was used as Schottky contact metal. The study demonstrated the device performance with wet-etched mesa is comparable or better than dry-etched. Spradlin et al. used molten KOH etching instead of PEC etching in KOH solution, and showed the molten KOH etching reduced the surface roughness and form etch

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pits around defects [43]. The leakage characteristics was improved for SBDs fabricated on both MBE and HVPE grown GaN substrates. It can be concluded that surface treatment, with a variety of techniques such as annealing, PEC etching in KOH solution, and molten KOH etch, is very effective to improve the GaN SBD quality.

Dielectric layer deposition on drift layer top surface or mesa side wall can reduce the arcing effect, thus can improve the breakdown voltage of the GaN SBD. Most common dielectric materials used are SiO_2, SiN_x and Al_2O_3. The layer can be deposited by plasma-enhanced chemical vapor deposition (PECVD), RF sputtering and e-beam evaporation. In Zhu et al.'s work, a dielectric SiO_2 layer was deposited on the mesa wall by PECVD for passivation [42]. Float metal ring (FMR) technique uses an additional metal ring around Schottky contact to reduce electric field crowding at reverse bias. Two parameters: ring width and ring space, are critical to the FMR effectiveness. Schematics of FMR structure is shown in **Figure 3a**. GaN SBDs fabricated with FMR was first reported by Lee et al. A high breakdown voltage of 353 V was obtained on the SBD fabricated with FMR versus only 159 V without FMR [44]. The author also demonstrated the optimized structure by a design of experiment (DOE) with parameters ring width and ring space. Field plate (FP) incorporates both dielectric layer and metal overlay on top of dielectric layer to reduce electric field crowding. Dielectric layer thickness, metal overlay extent and dielectric permittivity are the three key parameters of FP. Schematics of FP structure is shown in **Figure 3b**. Bandić et al. first compared GaN lateral SBD with a field plate on sputtered SiO_2 dielectric layer and without field plate and found the field plate can suppress the leakage current by one to two orders of magnitude. Simulation was performed by Baik et al. to find the optimized FP structure [45]. A minimum metal overlay extent of 5 μm and a minimum dielectric layer thickness of 0.3 μm for SiNx was needed to avoid dielectric breakdown at the FP on GaN cap layer with an unintentional n doping level of 5×10^{16} cm^{-3}. Kang et al. fabricated GaN vertical SBD with Pt/Au Schottky contact and FP on e-beam deposited SiNx dielectric layer based on the simulation result, but to find a much lower experimental breakdown voltage than theoretical because of the GaN surface degradation from device processing [46]. Lei et al. did a comprehensive investigation of the GaN SBD FP design rule by simulation and came with the conclusions: Metal overlay extent beyond maximum depletion depth of GaN under reverse bias do not further improve breakdown voltage; The two competing reverse breakdown modes: GaN breakdown and dielectric breakdown

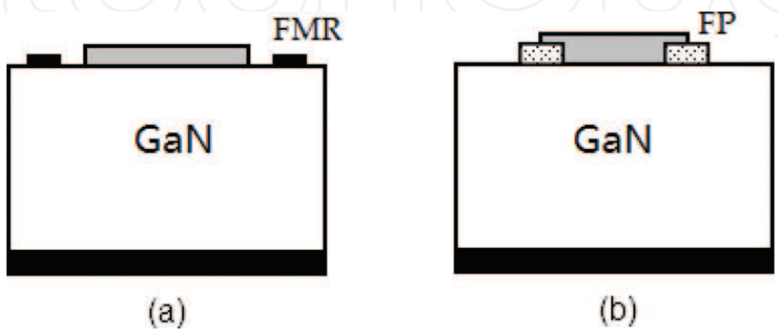

Figure 3. Schematics of (a) FMR and (b) FP structure: the gray region is Schottky contact, black region is ohmic contact, and the dotted region is dielectric.

lead to an optimum dielectric layer thickness; Optimum dielectric layer thickness is related with dielectric permittivity [47]. In summary, both simulation and experiment results demonstrated that addition device structures such as dielectric passivation layer, FRM and FP, can contribute to better GaN SBD performance.

Guard ring formed by ion implantation is also a very effective technique for edge termination: a high resistivity layer can be formed on the surface and help spreading electrical field under reverse bias. There are two types of implantation ion: p-type dopant or noble gas. Zhang et al. reported a p type guard ring by ion implantation of Mg at the edge of the Schottky contact followed by annealing [48]. A high breakdown voltage of ~700 V was achieved on vertical SBD structure with a 75 μm diameter circular Pt/Ti/Au Schottky contact. Laroche et al. reported simulation of multiple p type guard rings with 1 μm, and 5 μm spacing, and found a theoretical breakdown voltage of 700 V with 1 μm spacing, and the breakdown voltage did not further improve when multiple guard rings were applied [49]. Ozbek et al. reported that ion implantation of Ar can greatly improve the breakdown voltage of vertical GaN SBD [50, 51]. Simulation and experiment were carried out to analyze breakdown voltage versus length of implantation region. It was found that 50 μm is the optimum length, leading to a breakdown voltage of 1700 V, about four times higher than unterminated SBD.

Besides guard rings, ion implantation can also be used in fabrication of GaN junction barrier Schottky diode (JBSD). JBSD has been successfully demonstrated in Si and SiC. For n type JBSD, a p^+/n grid structure is used instead of an intrinsic or n^- layer in the drift region. Under forward bias, the p^+ region is not functioning, and the current flows through Schottky contact into the n channel. Under reverse bias, the depletion region spreads around the p^+ well and pinch off the n channel, thus suppresses premature breakdown and excessive leakage current. The p^+ well spacing and depth are important for best JBSD performance. Schematic of p^+ well JBSD is shown in **Figure 4a**. Zhang et al. fabricated GaN JBSD using both p^+ well on n channel and n^+ well on p channel, by ion implantation of Mg and Si into n-GaN and p-GaN respectively [52]. Both types of devices has breakdown voltages of 500 V- 600 V, and the leakage current was reduced 100-fold than conventional SBD fabricated without grid structure. The forward characteristics of the n type JBSD is much better than its p type counterpart. Ion implantation is not the only method to fabricate JBSD. Li et al. demonstrated trench JBSD, which eliminate the ion implantation step [53]. The schematics of the trench JBSD is shown in **Figure 4b**. The major difference between trench JBSD and regular JBSD is the formation of the

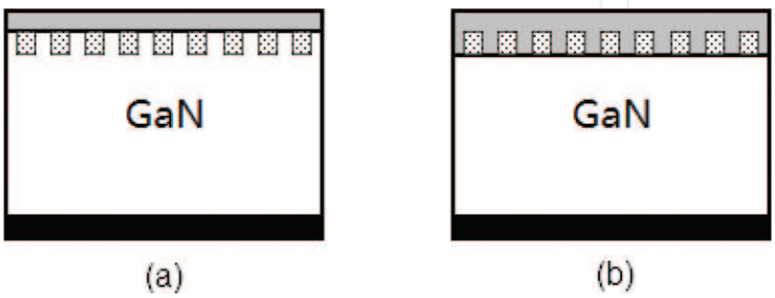

Figure 4. Schematics of (a) JBSD and (b) trench JBSD: the gray region is Schottky contact, black region is ohmic contact, and the dotted region is p^+ doped GaN.

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p^+/n junction. In trench JBSD, a p^+ epitaxy layer is firstly deposited, followed by a selective etching down to nGaN substrate to form trench structure. The Schottky contact is then deposited on the trench. Under reverse bias, the depletion region spread laterally from the p+/n interface and pinch off the Schottky barrier. The study of Li et al. shows about 20 times reduction in the leakage current compared to traditional SBD.

4. AlGaN/GaN field effect SBDs

Spontaneous and piezoelectric polarization can result in built-in electric field in AlGaN/GaN heterostructure. Band bending and alignment of Fermi level in AlGaN and GaN forms a two-dimensional electron gas (2DEG) at the interface. **Figure 5** shows band diagram of the AlGaN/GaN heterostructure. Because of the high carrier mobility of the 2DEG, low on-state resistance can be achieved for device utilizing AlGaN/GaN heterostructure. GaN based High-electron mobility transistor (HEMT) has been developed for power and RF applications and showed significant improvement of performance compared to Si and GaAs.

The AlGaN/GaN heterostructure can also be used in SBD. The concept of GaN field effect Schottky barrier diode (FESBD) was first brought up by Yoshida et al. in 2004 [54], with device schematics shown in **Figure 6**. AlGaN/GaN FESBD shares the same epitaxial structure and device fabrication process with AlGaN/GaN HEMT, making it a perfect diode for monolithic microwave integrated circuit (MMIC) application. Standalone AlGaN/GaN FESBD also has lower cost than GaN vertical SBD on freestanding substrate.

4.1. AlGaN/GaN substrate growth and epitaxial structure optimization

AlGaN/GaN heterostructure is usually grown on foreign substrates such as sapphire, SiC, or Si by MOCVD or MBE. In order to achieve high blocking voltage, low leakage and low on-state resistance at the same time, the epitaxial structure needs to be carefully designed. Several growth techniques have been reported to improve the device performance of AlGaN/GaN FESBD.

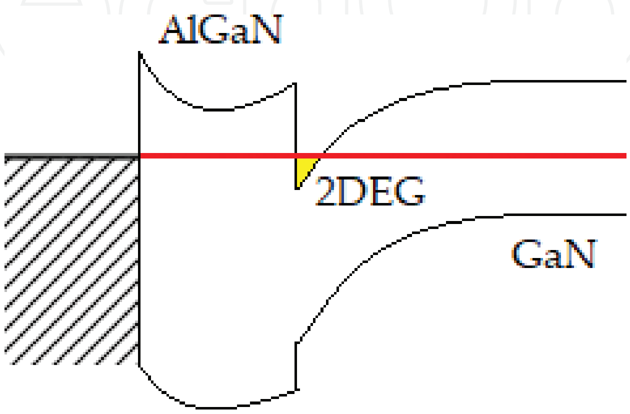

Figure 5. Band structure of the AlGaN/GaN heterostructure.

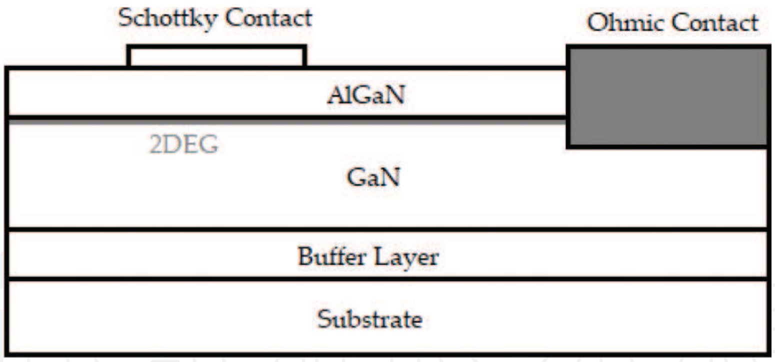

Figure 6. Schematics of AlGaN/GaN FESBD.

A buffer layer structure under the GaN channel layer is crucial because it can reduce the screw dislocation density thus can help on reducing reverse leakage and prevent premature breakdown. Lee et al. systematically investigated the electrical characteristics of the FEBSD with and without a composite buffer layer [55]. The buffer layer consisted of an 800 nm of AlN followed by a 30 nm of AlGaN. The breakdown voltage of the FEBSD with buffer layer was 3489 V, while that of FEBSD without buffer layer was only 382 V.

Similar to GaN SBD, a cap layer can help on the reverse leakage and breakdown voltage in FEBSD. Kamada et al. reported LTG GaN cap layer for edge termination in FEBSD [56]. A 20 nm LTG GaN, a 25 nm AlGaN and a 1 μm GaN were grown on Si substrate by MOCVD. A selective dry etching removed part of the GaN cap layer and exposed AlGaN layer for Schottky contact deposition. The FESBD with the GaN cap layer for edge termination has three order of magnitude lower leakage current than the traditional FESBD. A cap layer on top of barrier layer can also lower the barrier height and the turn-on voltage for better forward characteristics in FEBSD. Lee et al. developed a method to in situ grow a SiCN cap layer on top of the AlGaN barrier [57]. A 2 nm SiCN cap, a 25 nm AlGaN, and a 3 μm GaN were grown on sapphire substrate by MOCVD. It was found that forward current, reverse leakage and breakdown voltage of FESBD with SiCN cap layer were much better than regular FESBD.

4.2. FESBD device fabrication and device structure optimization

Because of the 2DEG feature, the device structure optimization for FESBD is not exactly the same as GaN SBD. Some structures that are widely used in GaN SBD and has been discussed in Section 3, such as dielectric passivation, FMR and FP, can also be used in FESBD, while some structures such as dual Schottky anode, Schottky-ohmic combined anode, recessed Schottky anode, gated edge termination and MIS-gated hybrid anode are unique to FESBD. The unique techniques that are discussed in the following paragraphs of this section share the same mechanism: Current flow path is optimized in the forward regime, while reverse blocking capability is not compromised by depletion of the 2DEG channel.

Yoshida et al. first introduced dual Schottky anode concept [54]. The schematics of the dual Schottky anode is shown in **Figure 7a**. A low Schottky barrier metal Al/Ti was used as lo Schottky barrier metal for better on-voltage, while a high Schottky barrier metal Pt was used to

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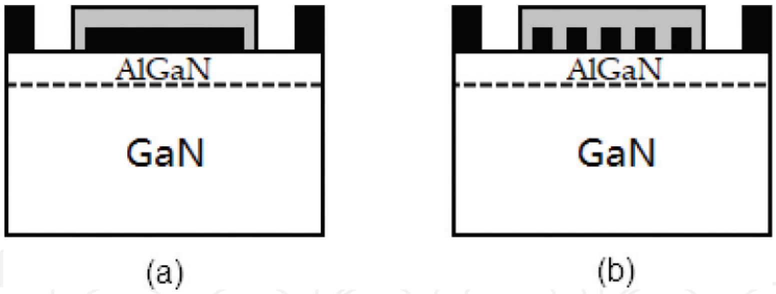

Figure 7. Schematics of AlGaN/GaN FESBD with dual Schottky anode: the gray region is Schottky contact, black region is ohmic contact, and dotted line is 2DEG.

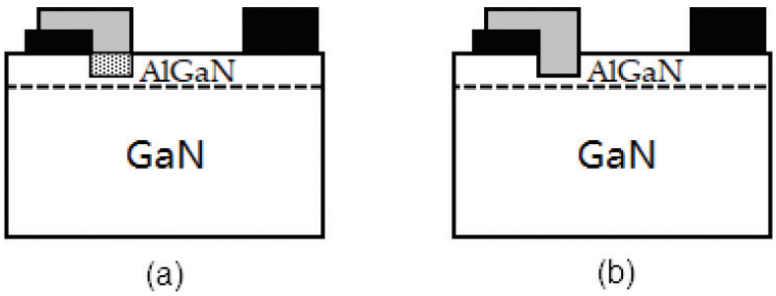

Figure 8. Schematics of AlGaN/GaN FESBD with SOC anode by (a) CF_4 plasma surface treatment (b) recessed Schottky: the gray region is Schottky contact, black region is ohmic contact, dotted region is plasma-treated AlGaN, and dotted line is 2DEG.

pinch off the device under reverse bias. A breakdown voltage of over 400 V was achieved. Park et al. adopted the concept and made improvement by introducing different Schottky and Ohmic contact patterns [58]. Schematics of the device was shown in **Figure 7b**. The on-state resistance was reduced by 25–75% at the cost of up to 3 orders of magnitude increment in leakage current, improved from 5 to 7 orders of magnitude increment with Yoshida's original design that has no pattern. However, the leakage current of the FESBD with dual Schottky anode design cannot be reduced to the same level of regular FESBD with only high Schottky barrier no matter how the contact pattern is optimized because of its normally-on nature.

To further reduce the turn-on voltage and suppress the reverse leakage, Schottky-ohmic combined (SOC) anode technique was introduced. Note that the technique can only be applied to depletion mode (normally-off) FESBD as the device will be shorted by the 2DEG under reverse bias if it is normally-on. As we know, there are two common methods to fabricate depletion mode HEMT: surface treatment and recessed gate. Both methods are also applicable to FESBD, with recessed gate changed to recessed Schottky. Takatani et al. [59] and Chen et al. [60] introduced SOC FESBD with surface treatment. CF_4 plasma was applied to the Schottky region of the FESBD to achieve normally-off mode, as the 2DEG under the Schottky region was depleted by negative fluorine ions. The device structure is illustrated in **Figure 8a**. The technique effectively improved the forward characteristics of the device and did not degrade reverse leakage and breakdown voltage [60]. SOC FESBD with recessed Schottky was also reported by multiple research groups. The device structure is illustrated in **Figure 8b**. Lee et al.

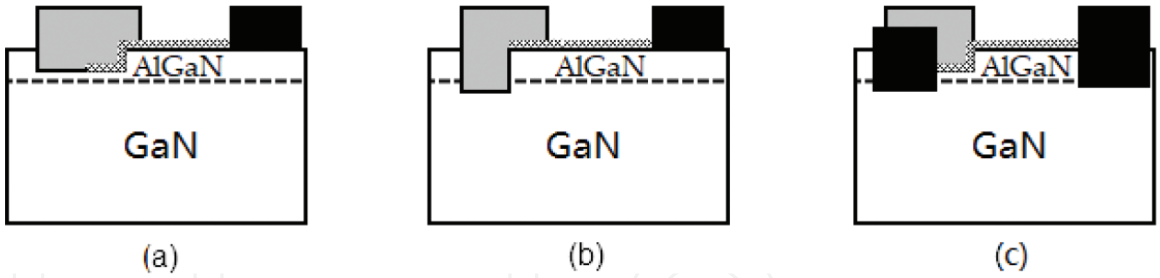

Figure 9. Schematics of AlGaN/GaN FESBD with (a) GET (b) fully recessed Schottky (c) MIS-gated hybrid anode: the gray region is Schottky contact, black region is ohmic contact, crossed region is gate dielectric, and dotted line is 2DEG.

compared it with conventional normally-on FESBD and normally-off FESBD with recessed Schottky but no SOC structure [61]. It was clearly demonstrated that the SOC FESBD with recessed Schottky is far superior to conventional FESBDs in turn-on voltage without breakdown voltage degradation. Recess depth is a very important parameter of SOC FESBD with recessed Schottky. Lee et al. did a comprehensive study of recess depth [62]. An optimized recess depth was found in between half and full thickness of AlGaN layer.

Lenci et al. introduced gated edge termination (GET) as illustrated in **Figure 9a** [63]. A thin dielectric layer was inserted underneath the recessed Schottky contact and formed an MIS gate structure. Under reverse bias, the 2DEG below the gate was pinched off. The reverse leakage current can be significantly reduced by the dielectric layer. The marginal extend-out of the Schottky metal on the dielectric layer formed a FP and reduced the electric field crowding. Bahat-Treidel et al. introduced a fully recessed Schottky anode with a slanted FP, which can significantly reduce the turn-on voltage because of the direct contact of Schottky anode to the 2DEG [64]. The schematics of the device structure is shown in **Figure 9b**. Yao et al. further investigated the current transport mechanism of the full recessed Schottky FESBD and found it was thermal field emission (TFE) instead of TE [65]. The GET and full recessed is compatible with other device optimization techniques. Hu et al. [66] and Zhu et al. [67] combined a 2nd FP technique with GET and fully recessed Schottky, respectively. The dual FP structure improved the breakdown voltage of FESBD with fully recessed Schottky.

Zhou et al. further optimized the device structure by combining the techniques above, and named it MIS-Gated hybrid anode [68]. The schematics of the device structure is shown in **Figure 9c**. It has an SOC anode with GET recessed Schottky, and fully recessed ohmic in direct contact with 2DEG. It also has a fully recessed ohmic contact on the cathode side. High breakdown voltage over 1.1 kV and leakage current as low as 10 μA/mm were achieved.

5. Summary

In this chapter, we gave a broad review of the GaN based Schottky diodes. The competitive position of GaN among the WBG materials in the high temperature, high frequency and high voltage rectifying applications was discussed first, followed with Schottky contact to GaN, and the development of GaN SBD and AlGaN/GaN FESBD in the last two decades. A lot of progress was made; and the best performing GaN based Schottky diode got close to SiC material limit. However, there are still challenges ahead for the GaN based Schottky diodes: (a) Improvement of the material quality is desired. (b) Novel epitaxial and device structures leveraging state-of-art growth and fabrication techniques are needed. (c) Significant cost reduction from substrate and fabrication is crucial. With continuous effort from academia and industry, GaN based Schottky diodes will mature and be successful commercialized in a foreseeable future.

Author details

Yaqi Wang

Address all correspondence to: yaqi.wang@outlook.com

Luminus Devices Inc., Sunnyvale, USA

References

[1] Wang Y. Fabrication and characterization of gallium nitride based diodes [Ph.D dissertation]. Auburn University; 2011

[2] Zhang A. Gallium nitride-based electronic devices [Ph.D dissertation]. In: University of Florida. 2001

[3] Zhou Y. Bulk gallium nitride based electronic devices: Schottky diodes, Schottky-type ultraviolet photodetectors and metal-oxide-semiconductor capacitors [Ph.D dissertation]. In: Auburn University. 2007

[4] Kaminski N, Hilt O. SiC and GaN Devices–Competition or Coexistence?, 2012 7th International Conference on Integrated Power Electronics Systems. Nuremberg: CIPS; 2012. pp. 1-11

[5] Hacke P, Detchprohm T, Hiramatsu K, Sawaki N. Schottky barrier on n-type GaN grown by hydride vapor phase epitaxy. Applied Physics Letters. 1993;**63**:2676. DOI: 10.1063/1.110417

[6] Khan MRH, Detchprohm T, Hacke P, Hiramatsu K, Sawaki N. The barrier height and interface effect of Au-n-GaN Schottky diode. Journal of Physics D: Applied Physics. 1995;**28**:1169-1174. DOI: 10.1088/0022-3727/28/6/021

[7] Guo JD, Feng MS, Guo RJ, Pan FM, Chang CY. Study of Schottky barriers on n-type GaN grown by low-pressure metalorganic chemical vapor deposition. Applied Physics Letters. 1995;**67**:2657. DOI: 10.1063/1.114327

[8] Wang L, Nathan MI, Lim T-H, Khan MA, Chen Q. High barrier height GaN Schottky diodes: Pt/GaN and Pd/GaN. Applied Physics Letters. 1996;**68**:1267. DOI: 10.1063/1.115948

[9] Kalinina EV, Kuznetsov NI, Dmitriev VA, Irvine KG, Carter CH. Schottky barriers on n-GaN grown on SiC. Journal of Electronic Materials. 1996;**25**:831. DOI: 10.1007/BF02666644

[10] Ping AT, Schmitz AC, Khan MA, Adesida I. Characterization of Pd Schottky barrier on n-type GaN. Electronics Letters. 1996:68. DOI: 10.1049/el:19960029

[11] Schmitz AC, Ping AT, Asif Khan M, Chen Q, Yang JW, Adesida I. Schottky barrier properties of various metals on n-type GaN. Semiconductor Science and Technology. 1996;**11**:1464-1467. DOI: 10.1088/0268-1242/11/10/002

[12] Liu QZ, Yu LS, Deng F, Lau SS, Redwing JM. Ni and Ni silicide Schottky contacts on n-GaN. Applied Physics Letters. 1998;**84**:881. DOI: 10.1063/1.368151

[13] Liu QZ, Lau SS. A review of the metal–GaN contact technology. Solid-State Electronics. 1998;**42**:677. DOI: 10.1016/S0038-1101(98)00099-9

[14] Hsu JWP, Manfra MJ, Lang DV, Richter S, Chu SNG, Sergent AM, Kleiman RN, Pfeiffer LN, Molnar RJ. Inhomogeneous spatial distribution of reverse bias leakage in GaN Schottky diodes. Applied Physics Letters. 2001;**78**:1685. DOI: 10.1063/1.1356450

[15] Miller EJ, Schaadt DM, Yu ET, Poblenz C, Elsass C, Speck JS. Reduction of reverse-bias leakage current in Schottky diodes on GaN grown by molecular-beam epitaxy using surface modification with an atomic force microscope. Journal of Applied Physics. 2002; **91**:9821. DOI: 10.1063/1.1478793

[16] Sang L, Ren B, Sumiya M, Liao M, Koide Y, Tanaka A, Cho Y, Harada Y, Nabatame T, Sekiguchi T, Usami S, Honda Y, Amano H. Initial leakage current paths in the vertical-type GaN-on-GaN Schottky barrier diodes. Applied Physics Letters. 2017;**111**:122102. DOI: 10.1063/1.4994627

[17] Cao Y, Chu R, Li R, Chen M, Chang R, Hughes B. High-voltage vertical GaN Schottky diode enabled by low-carbon metal-organic chemical vapor deposition growth. Applied Physics Letters. 2016;**108**:062103. DOI: 10.1063/1.4941814

[18] Reddy P, Sarkar B, Kaess F, Gerhold M, Kohn E, Collazo R, Sitar Z. Defect-free Ni/GaN Schottky barrier behavior with high temperature stability. Applied Physics Letters. 2017; **110**:011603. DOI: 10.1063/1.4973762

[19] Guo JD, Pan FM, Feng MS, Guo RJ, Chou PF, Chang CY. Schottky contact and the thermal stability of Ni on n-type GaN. Journal of Applied Physics. 1996;**80**:1623. DOI: 10.1063/1.363822

[20] Schmitz AC, Ping AT, Khan MA, Chen Q, Yang JW, Adesida I. High temperature characteristics of Pd Schottky contacts on n-type GaN. Electronics Letters. 1996;**32**:1832-1833. DOI: 10.1049/el:19961191

[21] Liu QZ, Yu LS, Lau SS, Redwing JM, Perkins NR, Kuech TF. Thermally stable PtSi Schottky contact on n-GaN. Applied Physics Letters. 1997;**70**:1275. DOI: 10.1063/1.118551

[22] Chen GL, Chang FC, Shen KC, Ou J, Chen WH, Lee MC, Chen WK, Jou MJ, Huang CN. Thermal stability study of Ni/Ta n-GaN Schottky contacts. Applied Physics Letters. 2002; **80**:595. DOI: 10.1063/1.1425455

[23] Sheu JK, Su YK, Chi GC, Jou MJ, Chang CM. Effects of thermal annealing on the indium tin oxide Schottky contacts of n-GaN. Applied Physics Letters. 1998;**72**:3317. DOI: 10.1063/1.121636

[24] Tongay S, Lemaitre M, Schumann T, Berke K, Appleton BR, Gila B, Hebard AF. Graphene/GaN Schottky diodes: Stability at elevated temperatures. Applied Physics Letters. 2011;**99**: 102102. DOI: 10.1063/1.3628315

[25] Kim S, Seo TH, Kim MJ, Song KM, Suh E, Kim H. Graphene–GaN Schottky diodes. Nano Research. 2015;**8**(4):1327-1338. DOI: 10.1007/s12274-014-0624-7

[26] Qiao D, Yu LS, Lau SS, Redwing JM, Lin JY, Jiang HX. Dependence of Ni/AlGaN Schottky barrier height on Al mole fraction. Journal of Applied Physics. 2000;**87**:801. DOI: 10.1063/1.371944

[27] Lv Y, Lin Z, Corrigan TD, Zhao J, Cao Z, Meng L, Luan C, Wang Z, Chen H. Extraction of AlGaN/GaN heterostructure Schottky diode barrier heights from forward current-voltage characteristics. Journal of Applied Physics. 2011;**109**:074512. DOI: 10.1063/1.3569594

[28] Shin J, Park J, Jang S, Jang T, Kim KS. Metal induced inhomogeneous Schottky barrier height in AlGaN/GaN Schottky diode. Applied Physics Letters. 2013;**102**:243505. DOI: 10.1063/1.4811756

[29] Ao J, Naoi Y, Ohno Y. Thermally stable TiN Schottky contact on AlGaN/GaN heterostructure. Vacuum. 2013;**87**:150-154. DOI: 10.1016/j.vacuum.2012.02.038

[30] Li L, Kishi A, Liu Q, Itai Y, Fujihara R, Ohno Y, Ao J. GaN Schottky barrier diode with TiN electrode for microwave rectification. IEEE Journal of the Electron Devices Society. 2014;**2**: 168. DOI: 10.1109/JEDS.2014.2346395

[31] Phark S, Kim H, Song KM, Kang PG, Shin HS, Kim D. Current transport in Pt Schottky contacts to a-plane n-type GaN. Journal of Physics D: Applied Physics. 2010;**43**:165102. DOI: 10.1088/0022-3727/43/16/165102

[32] Yamada H, Chonan H, Takahashi T, Shimizu M. Electrical properties of Ni/n-GaN Schottky diodes on freestanding m-plane GaN substrates. Applied Physics Express. 2017; **10**:041001. DOI: 10.7567/APEX.10.041001

[33] Yamada H, Chonan H, Takahashi T, Shimizu M. Comparison of electrical properties of Ni/n-GaN Schottky diodes on c-plane and m-plane GaN substrates. Physica Status Solidi A: Applications and Materials Science. 2017;**214**:1700362. DOI: 10.1002/pssa.201700362

[34] Tanaka A, Ando Y, Nagamatsu K, Deki M, Cheong H, Ousmane B, Kushimoto M, Nitta S, Honda Y, Amano H. M-plane GaN Schottky barrier diodes fabricated with MOVPE layer

on several off-angle m-plane GaN substrates. Physica Status Solidi A: Applications and Materials Science. 2017;**214**:1700645. DOI: 10.1002/pssa.201700645

[35] Sheu JK, Lee ML, Lai WC. Effect of low-temperature-grown GaN cap layer on reduced leakage current of GaN Schottky diodes. Applied Physics Letters. 2005;**86**:052103. DOI: 10.1063/1.1861113

[36] Lu H, Zhang R, Xiu X, Xie Z, Zheng Y, Li Z. Low leakage Schottky rectifiers fabricated on homoepitaxial GaN. Applied Physics Letters. 2007;**91**:172113. DOI: 10.1063/1.2795083

[37] Fu H, Huang X, Chen H, Lu Z, Baranowski I, Zhao Y. Ultra-low turn-on voltage and on-resistance vertical GaN-on-GaN Schottky power diodes with high mobility double drift layers. Applied Physics Letters. 2017;**111**:152102. DOI: 10.1063/1.4993201

[38] Cao Y, Chu R, Li R, Chen M, Williams AJ. Improved performance in vertical GaN Schottky diode assisted by AlGaN tunneling barrier. Applied Physics Letters. 2016;**108**: 112101. DOI: 10.1063/1.4943946

[39] Bandić ZZ, Bridger PM, Piquette EC, McGill TC, Vaudo RP, Phanse VM, Redwing JM. High voltage (450 V) GaN Schottky rectifiers. Applied Physics Letters. 1999;**74**:1266. DOI: 10.1063/1.123520

[40] Cao XA, Cho H, Pearton SJ, Dang GT, Zhang AP, Ren F, Shul RJ, Zhang L, Hickman R, Van Hove JM. Depth and thermal stability of dry etch damage in GaN Schottky diodes. Applied Physics Letters. 1999;**75**:232. DOI: 10.1063/1.124332

[41] Cao XA, Pearton SJ, Dang GT, Zhang AP, Ren F, Van Hove JM. GaN n- and p-type Schottky diodes: Effect of dry etch damage. IEEE Transactions on Electron Devices. 2000; **47**:1320. DOI: 10.1109/16.848271

[42] Zhu TG, Lambert DJH, Shelton BS, Wong MM, Chowdhury U, Dupuis RD. High-voltage mesa-structure GaN Schottky rectifiers processed by dry and wet etching. Applied Physics Letters. 2000;**77**:2918. DOI: 10.1063/1.1322050

[43] Spradlin J, Dogan S, Mikkelson M, Huang D, He L, Johnstone D, Morkoç H, Molnar RJ. Improvement of n-GaN Schottky diode rectifying characteristics using KOH etching. Applied Physics Letters. 2003;**82**:3556. DOI: 10.1063/1.1572532

[44] Lee S, Her J, Kim S, Ha M, Seo K, Choi Y, Han M. A New Vertical GaN Schottky Barrier Diode with Floating Metal Ring for High Breakdown Voltage, 2004 Proceedings of the 16th International Symposium on Power Semiconductor Devices and ICs. Japan: Kitakyushu; 2004. pp. 319-322. DOI: 10.1109/WCT.2004.240037

[45] Baik KH, Irokawa Y, Ren F, Pearton SJ, Park SS, Park YJ. Design of junction termination structures for GaN Schottky power rectifiers. Solid-State Electronics. 2003;**47**:975. DOI: 10.1016/S0038-1101(02)00464-1

[46] Kang BS, Ren F, Irokawa Y, Baik KW, Pearton SJ, Pan C-C, Chen G-T, Chyi J-I, Ko H-J, Lee H-Y. Temperature dependent characteristics of bulk GaN Schottky rectifiers on freestanding GaN substrates. Journal of Vacuum Science & Technology B. 2004;**22**:710. DOI: 10.1116/1.1689303

[47] Lei Y, Shi H, Lu H, Chen D, Zhang R, Zheng Y. Field plate engineering for GaN-based Schottky barrier diodes. Journal of Semiconductors. 2013;**34**:054007. DOI: 10.1088/1674-4926/34/5/054007

[48] Zhang AP, Johnson JW, Luo B, Ren F, Pearton SJ, Park SS, Park YJ, Chyi J-I. Vertical and lateral GaN rectifiers on free-standing GaN substrates. Applied Physics Letters. 2001;**79**: 1555. DOI: 10.1063/1.1400771

[49] Laroche JR, Ren F, Baik KW, Pearton SJ, Shelton BS, Peres B. Design of Edge Termination for GaN power Schottky diodes. Journal of Electronic Materials. 2005;**34**:370-374. DOI: 10.1007/s11664-005-0113-6

[50] Ozbek AM, Baliga BJ. Planar nearly ideal edge-termination technique for GaN devices. IEEE Electron Device Letters. 2011;**32**:300. DOI: 10.1109/LED.2010.2095825

[51] Ozbek AM, Baliga BJ. Finite-zone argon implant edge termination for high-voltage GaN Schottky rectifiers. IEEE Transactions on Electron Devices. 2011;**32**:1361. DOI: 10.1109/LED.2011.2162221

[52] Zhang Y, Liu Z, Tadjer MJ, Sun M, Piedra D, Hatem C, Anderson TJ, Luna LE, Nath A, Koehler AD, Okumura H. Vertical GaN junction barrier Schottky rectifiers by selective ion implantation. IEEE Electron Device Letters. 2017;**38**:1097. DOI: 10.1109/LED.2017.2720689

[53] Li W, Nomoto K, Pilla M, Pan M, Gao X, Jena D, Xing HG. Design and realization of GaN trench junction-barrier-Schottky-diodes. IEEE Transactions on Electron Devices. 2017;**64**: 1635. DOI: 10.1109/TED.2017.2662702

[54] Yoshida S, Ikeda N, Li J, Wada T, Takehara H. A New GaN Based Field Effect Schottky Barrier Diode with a Very Low on-Voltage Operation, 2004 Proceedings of the 16th International Symposium on Power Semiconductor Devices and ICs. Japan: Kitakyushu; 2004. pp. 323-326. DOI: 10.1109/WCT.2004.240038

[55] Lee GY, Liu HH, Chyi JI. High-performance AlGaN/GaN Schottky diodes with an AlGaN/AlN buffer layer. IEEE Electron Device Letters. 2011;**32**:1519. DOI: 10.1109/LED.2011.2164610

[56] Kamada A, Matsubayashi K, Nakagawa A, Terada Y, Egawa T. High-voltage AlGaN/GaN Schottky barrier diodes on Si substrate with low-temperature gan cap layer for edge termination. 2008 20th International Symposium On Power Semiconductor Devices and IC's, Orlando, FL; 2008. pp. 225-228. DOI: 10.1109/ISPSD.2008.4538939

[57] Lee JH, Jeong JH, Lee JH. Enhanced electrical characteristics of AlGaN-based SBD with in situ deposited silicon carbon nitride cap layer. IEEE Electron Device Letters. 2012;**33**:492. DOI: 10.1109/LED.2012.2182671

[58] Park K, Park Y, Hwang S, Jeon W, Lee J. 1kV AlGaN/GaN Power SBDs with Reduced on Resistances. In: 2011 IEEE 23rd International Symposium on Power Semiconductor Devices and ICs. San Diego: CA; 2011. pp. 223-226. DOI: 10.1109/ISPSD.2011.5890831

[59] Takatani K, Nozawa T, Oka T, Kawamura H, Sakuno K. AlGaN/GaN Schottky-ohmic combined anode field effect diode with fluoride-based plasma treatment. Electronics Letters. 2008;**44**:320-321. DOI: 10.1049/el:20083428

[60] Chen W, Wong K-Y, Huang W, Chen KJ. High-performance AlGaN/GaN lateral field-effect rectifiers compatible with high electron mobility transistors. Applied Physics Letters. 2008;**92**:253501. DOI: 10.1063/1.2951615

[61] Lee JG, Park BR, Cho CH, Seo KS, Cha HY. Low turn-on voltage AlGaN/GaN-on-Si rectifier with gated Ohmic anode. IEEE Electron Device Letters. 2013;**34**:214-216. DOI: 10.1109/LED.2012.2235403

[62] Lee HS, Jung DY, Park Y, Na J, Jang H-G, Lee HS, Jun C-H, Park J, Ryu SO, Ko SC, Nam ES. 0.34 VT AlGaN/GaN-on-Si large Schottky barrier diode with recessed dual anode metal. IEEE Electron Device Letters. 2015;**36**:1132-1134. DOI: 10.1109/LED.2015.2475178

[63] Lenci S, Jaeger BD, Carbonell L, Hu J, Mannaert G, Wellekens D, You S, Bakeroot B, Decoutere S. Au-free AlGaN/GaN power diode on 8-in Si substrate with gated edge termination. IEEE Electron Device Letters. 2013;**34**:1035-1037. DOI: 10.1109/LED.2013.2267933

[64] Bahat-Treidel E, Hilt O, Zhytnytska R, Wentzel A, Meliani C, Würfl J, Tränkle G. Fast-switching GaN-based lateral power Schottky barrier diodes with low onset voltage and strong reverse blocking. IEEE Electron Device Letters. 2012;**33**:357-359. DOI: 10.1109/LED.2011.2179281

[65] Yao Y, Zhong J, Zheng Y, Yang F, Ni Y, He Z, Shen Z, Zhou G, Wang S, Zhang J, Li J. Current transport mechanism of AlGaN/GaN Schottky barrier diode with fully recessed Schottky anode. Japanese Journal of Applied Physics. 2014;**54**:011001. DOI: 10.7567/jjap.54.011001

[66] Hu J, Stoffels S, Lenci S, Bakeroot B, Jaeger BD, Hove MV, Ronchi N, Venegas R, Liang H, Zhao M, Groeseneken G, Decoutere S. Performance optimization of au-free lateral AlGaN/GaN Schottky barrier diode with gated edge termination on 200-mm silicon substrate. IEEE Transactions on Electron Devices. 2016;**63**:997-1004. DOI: 10.1109/TED.2016.2515566

[67] Zhu M, Song B, Qi M, Hu Z, Nomoto K, Yan X, Cao Y, Johnson W, Kohn E, Jena D, Xing HG. 1.9-kV AlGaN/GaN lateral Schottky barrier diodes on silicon. IEEE Electron Device Letters. 2015;**36**:375-377. DOI: 10.1109/LED.2015.2404309

[68] Zhou Q, Jin Y, Shi Y, Mou J, Bao X, Chen B, Zhang B. High reverse blocking and low onset voltage AlGaN/GaN-on-Si lateral power diode with MIS-gated hybrid anode. IEEE Electron Device Letters. 2015;**36**:660-662. DOI: 10.1109/LED.2015.2432171