Current status of GaN power devices

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Abstract: The performance of GaN power devices has been rapidly improving. Recently, the main approach is the use of AlGaN/GaN HEMT structures on Si substrates, for which the target breakdown voltage is initially 600 V or less. Although issues still remain with regard to current collapse and the threshold voltage required for normally-off operation, many companies have announced their intention to commercialize such devices. In this report, recent developments concerning GaN power devices are reviewed, and unresolved issues and future expectations are discussed.

Keywords: GaN power device, lateral structure, vertical structure, current collapse, normally-off

Classification: Electron devices, circuits, and systems

References

1 Introduction

Since the final decade of the 20th century, dwindling oil reserves and climate change have been viewed as serious global problems. For this reason, methods for reducing the amount of energy used have become the focus of considerable attention. Since electrical energy is the main form of energy consumed globally, technology that allows its more efficient use is being strongly pur-
sued. One area that has received particular attention is the field of power electronics, because power devices directly control the flow of electrical energy. Before the year 2000, it was expected that silicon carbide (SiC) would replace Si as a high-performance power-device material.

However, epoch-making research was presented in 2001, when a team from the University of California at Santa Barbara and Yela University reported the development of an AlGaN/GaN based high-voltage transistor [1]. Its breakdown voltage and specific on-resistance were 1.2 kV and 2 mΩ · cm², respectively. This impressively high breakdown voltage led to a surge of interest in GaN as an alternative to SiC for next-generation power devices. During the past decade, the performance of GaN power devices has been rapidly improving. There are two types of devices currently being developed, which have the lateral and vertical structures shown in Fig. 1. At present, mainstream GaN power devices use the lateral structure, and many vendors have announced plans for commercialization of such devices [2]. In this report, the current status of GaN power device is presented.

![Fig. 1. Typical structures of GaN power devices. (a) lateral structure, (b) vertical structure.](image)

### 2 Lateral GaN power devices

#### 2.1 Overview

Most GaN power devices under development use a lateral structure because this device structure is used in high electron mobility transistors (HEMTs). In general, devices based on a lateral structure are not suitable for high-power switching applications. Since the breakdown voltage is determined by the gate-drain distance, in order to achieve a high breakdown voltage, this distance should be large, which results in a high on-resistance. However, the unique characteristics of GaN allow a low on-resistance to be achieved even at high voltage. A lateral GaN power device is based on an AlGaN/GaN heterostructure, in which 2-dimensional electron gas (2DEG) is formed. The high-density 2DEG at the interface between the AlGaN and GaN produces a low-resistance drift region, which results in the device having a low on-resistance while maintaining a high breakdown voltage. The highest expected
target breakdown voltage for a lateral GaN device is about 1200 V. Another unique property of such lateral devices is their very high operation speed. The drift region is fabricated using undoped AlGaN and GaN layers, which gives rise to a low feedback capacitance, making high-speed modulation possible. The low on-resistance and feedback capacitance contribute to the high efficiency and compactness of power electronics modules.

The basic lateral GaN device structure is shown in Fig. 1 (a). For many years, a simple AlGaN/GaN heterostructure was used, but recently the structure is GaN/AlGaN/AlN/GaN/buffer/substrate. The top GaN layer (2∼5 nm thick) reduces the density of surface states and is effective at suppressing current collapse, as will be discussed later. A thin AlN (1∼2 nm thick) layer is inserted at the AlGaN/GaN interface. This improves the electron mobility in the 2DEG because it produces a potential well in which electrons are more strongly confined, and it reduces alloy scattering. The substrates used for such devices are generally SiC or Si. Of course, SiC is a better choice for a power device because of its low thermal conductivity and its high degree of lattice matching with GaN. However, the small size and high cost of SiC substrates restrict their adoption for commercial devices. Therefore, Si substrates are generally used for product purposes. When a Si substrate is used, a buffer layer is essential in order to obtain a high-quality GaN layer. Individual epitaxial-wafer manufacturers have own buffer structures, which are based on AlN/GaN superlattices or pseudomorphic AlGaN layers. The present size for epitaxial wafers using Si substrates is 6”, and 8” wafers are currently under development. The use of Si substrates and the fact that the fabrication process is similar to that for Si devices are very strong advantages for achieving high cost performance.

However, it is widely recognized that there are two serious issues with lateral GaN devices. These are current collapse and the ability to achieve normally-off operation; these topics are discussed in the following subsections.

### 2.2 Current collapse

Current collapse refers to a reduction in the drain current during high-voltage switching. This phenomenon is caused by negative fixed charges on the device surface [3] and/or in the AlGaN and GaN layers [4], as illustrated in Fig. 2. These charges reduce the 2DEG density in the drift region which results in an increased on-resistance. The surface charges become redistributed under the influence of the high electric field concentration at the gate edge. As shown in the figure, the use of a field plate can alleviate such electric field crowding [5]. An appropriate surface passivation film can also be employed to reduce the number of surface states [6]. A combination of these methods is effective at suppressing current collapse. Another useful approach for reducing the number of surface states is to form a thin GaN cap above the AlGaN layer, and this has recently become popular when producing AlGaN/GaN on Si epitaxial wafers. One further issue is that for heteroepitaxial growth of AlGaN/GaN on Si, a large number of dislocations and point defects are present in the epitaxial layers, some of which can trap negative charges.
Therefore, to reduce the number of fixed charges in the AlGaN/GaN structure, it is important to improve the crystal quality [7]. The above measures allow current collapse to be suppressed for voltages of less than 600 V, and this is therefore the breakdown voltage quoted for the first commercial devices [2]. However, a great deal of research is still being carried out into the complete elimination of current collapse.

![Diagram of field plate and passivation film](image)

**Fig. 2.** Negative fixed charges which induce current collapse. The combined use of a field plate and a passivation film is an effective countermeasure.

### 2.3 Normally-off operation

The second major issue with GaN power devices is achieving normally-off operation, since this is made difficult by the high-density 2DEG at the AlGaN/GaN interface. In Si and SiC power devices, a metal-oxide-semiconductor (MOS) inversion layer is usually used to obtain normally-off operation. A inversion gate allows a threshold voltage of over 3 V to be achieved, which is generally required in order to prevent noise-induced errors in gate signal. Unfortunately, however, it is difficult to produce an inversion layer in GaN, and several alternative techniques for achieving normally-off operation have been proposed. These are summarized in Table I.

The first proposed structure uses a recessed-gate approach [8], in which the AlGaN barrier layer (∼20 nm thick) below the gate is etched to a thickness of 2~5 nm, which causes the 2DEG to almost vanish in this region, causing a positive shift in the threshold voltage. However, it is difficult to completely deplete the 2DEG in order to obtain a sufficiently high threshold voltage. If the recess is deep enough to penetrate the GaN layer, the 2DEG vanishes completely, and this corresponds to a MOS gate structure. Normally-off operation was successfully achieved using this approach [9], even without the use of a p-type GaN layer. The disadvantages of such a MOS structure are a high channel resistance in the gate region and poor control of the threshold voltage.

The second proposed approach involves fluorine ion implantation of the AlGaN layer in the gate region. The negatively charged ions effectively deplete the 2-DEG electron, so that normally-off operation is achieved [10]. One technical difficulty is ensuring that no fluorine ions penetrate the GaN.
Table I. Proposed normally-off techniques.

<table>
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<tr>
<th>Technique</th>
<th>Recess</th>
<th>F implantation</th>
<th>p-(Al)GaN gate</th>
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Another proposed method is the use of a p-GaN or p-AlGaN gate structure. This produces a depletion layer which extends from the p-n junction formed by the p-(Al)GaN region and AlGaN barrier layer, thereby depleting the 2-DEG so that normally-off operation can be achieved [11, 12]. However, in this structure, the gate bias voltage higher than the built-in p-n potential leads to a large gate leakage current. This means that it is difficult to achieve a threshold voltage that is higher than the built-in p-n potential. Nevertheless, of all the proposed structures, this is the only one in which the AlGaN layer in the gate region is not modified, so that it yields the lowest on-resistance.

In the back-barrier structure, a barrier layer such as AlGaN is buried beneath the GaN layer. The wider band gap associated with this layer causes an energy increase in the channel region under the gate. By combining a back-barrier structure with a recessed gate, normally-off operation was successfully achieved [13, 14]. However, in this structure, the 2DEG density in the drift region is reduced, which increases the on-resistance.

Although normally-off operation has been realized with all of the above structures, their threshold voltages are around 1 V, which is lower than that for a conventional Si-MOSFET. Therefore, to achieve stable and reliable operation, gate drive circuits that are suitable for low-threshold-voltage devices must be developed.

The final approach to normally-off operation illustrated in Table I is a cascode connection using a high-voltage normally-on GaN HEMT and a low-voltage normally-off Si-MOSFET [15]. In this configuration, the source of the Si-MOSFET is connected to the gate of the GaN HEMT. Thereby, $V_{GS}$ for the GaN HEMT has the opposite sign to $V_{DS}$ for the Si MOSFET. When the...
Si MOSFET switches off and the voltage across the device rises, this voltage switches off the GaN HEMT. Conversely, when the Si-MOSFET switches on, the GaN HEMT switches on as a response to $V_{DS}$ for the Si-MOSFET dropping to a very low value. These two devices can be encapsulated in a single package to produce a three terminal device. Since the threshold voltage is determined by the Si-MOSFET, this makes high threshold voltages (>3 V) possible. Although this configuration is a realistic solution to the high threshold requirement, it has some disadvantages, such as a high on-resistance and the presence of parasitic inductance due to the wiring.

2.4 New approaches

Although the AlGaN/GaN heterostructure has a long history and is proven technology, other heterostructure such as AlN/GaN and InAlN/GaN have also been considered. An AlN/GaN insulated-gate heterojunction field effect transistor (HFET) was first reported by Kawai et al. [16]. The lattice mismatch between AlN and GaN is about 2.5%, which results in the production of a large number of strain induced piezoelectric charges and spontaneous polarization charges at the AlN/GaN interface. Under optimized growth conditions for the AlN layer, a high 2DEG density ($\sim 2.7 \times 10^{13} \text{cm}^{-2}$) and a high mobility ($\sim 1400 \text{cm}^2/(\text{V} \cdot \text{s})$) have been obtained, which resulted in a very low sheet resistance of $\sim 165 \Omega/\text{sq}$ and a high current density of 2.3 A/mm [17]. This heterostructure has mainly been applied to high-frequency devices [17, 18].

A lattice-matched InAlN/GaN heterostructure was first proposed by Kuzmic [19]. For InAlN with a 17% In content, the lattice constant is that same as that of GaN. In such a InAlN/GaN heterostructure, no stress is generated, in contrast to the case for an AlGaN/GaN heterostructure, which leads to improved reliability. Moreover, InAlN has a large spontaneous polarization, which results in a high 2DEG density. High-performance, high-frequency devices based on the InAlN/GaN structure have been reported [20].

Although the two types of heterostructures discussed above exhibit very good performance when used in high-frequency devices, it is not clear whether they can be applied to high-power switching devices because their breakdown
voltages have not yet been determined.

A final advantage of lateral GaN devices is their ease of integration. Figure 3 shows an example of a simple integrated single-phase inverter containing two AlGaN/GaN HFETs and two Schottky barrier diodes (SBDs). Research on power IC technology based on GaN devices has already begun [21], and integration of lateral devices is expected to be a key approach in the near future.

3 Vertical GaN power devices

Devices with a vertical structure are suitable for high-power applications because a high current density and breakdown voltage are possible. The vertical structure has different advantages from the lateral structure, for example, a smaller chip size, easier wiring, a higher breakdown voltage, and current-collapse-free operation. Although GaN has high potential for use in vertical devices [22], progress in developing such devices has been slower than in the case of SiC devices. One reason for this is the lack of high-quality freestanding GaN substrates. GaN substrates for blue laser applications have become commercially available since the early 2000s. However, these substrates had a dislocation density of $\sim 10^6 \text{cm}^{-2}$, which is too high for fabricating high-voltage ($\sim 1 \text{kV}$) vertical power devices. Several reports on vertical GaN devices fabricated on GaN substrates have been published [23, 24, 25, 26, 27], but their performance was inferior to that of SiC and Si power devices. Although this was mainly due to the low crystal quality, the experiments also identified many problems with the device fabrication process. At present, basic fabrication techniques are still being developed.

Fig. 4. Schottky diode characteristics. The diode was fabricated on a $n^+$ GaN substrate and the thickness of the epitaxial layer was 7 $\mu$m. The carrier concentration was $1 \times 10^{16} \text{cm}^{-3}$. 
Recent research on diodes has indicated that the quality of GaN substrates has become high enough to apply them to high-voltage devices [28, 29, 30]. We have determined that edge and mixed (edge + screw) dislocations in the GaN substrate do not induce a leakage current even at a dislocation density of ~10^6 cm^{-2} [31]. We have also found that a Schottky diode fabricated on a GaN substrate had a breakdown voltage of 1.2 kV or more, as shown in Fig. 4. It is noted that the high leakage current for voltages greater than 600 V is caused by insufficient edge termination.

In the vertical GaN device fabrication process, there are many remaining problems that do not apply to lateral devices, and more research resources need to be concentrated on such devices in order to accelerate progress in this field.

4 Reliability

Reliability is essential for realizing practical applications of new power devices. Reliability can be divided into short- and long-term components. Short-term reliability is related to the sudden death of a device, whereas long-term reliability corresponds to the device lifetime. The main indicators used to evaluate reliability are avalanche ruggedness, short-circuit capability, electrostatic breakdown and gate insulator deterioration. The first three of these are related to the sudden death of a device. For GaN power devices, avalanche resistance is the main issue.

Avalanche breakdown is caused by a counter electromotive force due to an inductive load. In power applications, there are many inductive loads such as motors. However, in many cases, GaN devices is destroyed catastrophically when breakdown occurs. For a Schottky gate lateral GaN HEMT, gate leakage caused by screw dislocations gives rise to a current concentration at the leakage point under the high surge voltage, which induces thermal destruction of the device since the heteroepitaxial layer used in a lateral device contains many threading dislocations. So that, a Schottky gate structure is not suitable for high voltage applications. To reduce the gate leakage current, metal-insulator-semiconductor (MIS) gate structure is used. However, the MIS structure in a GaN device has following problems. One is the high critical electric field for GaN or AlGaN, which is of the same order of magnitude as that for gate insulator materials. The high strength of GaN means that dielectric breakdown takes place first in the gate insulator in many cases. Figure 5 shows the simulated electric field distribution for a simple MIS gate model. The gate insulator is SiO_2 (thickness=50 nm, ε=3.9). Figure 6 is the electric field strength under the gate edge for a drain bias varying from 100 to 1200 V [32]. For a drain bias for 600 V, the electric field strength in the SiO_2 film is 8 MV/cm, which is near the breakdown field strength for SiO_2. For the same drain bias, the field strength in AlGaN is less than 3 MV/cm. Thus, these results indicate that the SiO_2 will break first. Therefore, in order to ensure that avalanche breakdown occurs in the GaN, suitable device design to reduce the electric field in insulator films is very important.
When avalanche breakdown occurs in the GaN layer, holes are generated and begin to accumulate because there is no p-type layer in the device structure. This is another problem. The accumulated holes pull electrons into the channel, which generate further holes by impact ionization. This cycle induces a large drain current and catastrophic thermal destruction occurs. To avoid such destruction, a low-resistance p-type layer is needed in order to remove the holes generated by the avalanche event. However, p-type doping is a weak point for GaN and related materials. At present, the only suitable p-type dopant is Mg. However, p-type GaN has problems with deep acceptor levels and easy diffusion of Mg. Therefore, a new approach for producing p-type GaN is strongly required in order to achieve high resistance to avalanche breakdown.

As mentioned above, there are few effective measures for preventing the catastrophic death of GaN devices at the present time. Consequently, to guarantee reliability, the breakdown voltage should be sufficiently higher than the maximum rated voltage. Protection circuits, such as snubber circuits and Zener diodes for absorbing current surges, are also effective.

Another important reliability issue is the lifetime of the gate insulator.
The gate insulator is constantly exposed to gate bias stress, which can induce defects in the film. Therefore, the lifetime of the gate insulator limits the device lifetime. Evaluation of the insulator film is usually carried out using time dependent dielectric breakdown (TDDB) measurements. Some examples of breakdown and TDDB characteristics for an Al₂O₃ film produced by atomic layer deposition (ALD) are shown in Figs. 7 and 8, respectively. Although SiO₂ and SiN are normally used for the gate insulator, Al₂O₃ has recently attracted attention due to its high dielectric constant. The breakdown characteristics for SiO₂ and SiN deposited by plasma-CVD are also shown in Fig. 7. The Al₂O₃ has a relatively large leakage current, but shows the same high breakdown voltage as SiO₂. The TDDB characteristics for Al₂O₃ at room temperature (R.T.), 150°C and 250°C are shown in Fig. 8. Power devices for automotive systems require a TDDB lifetime of more than 20 years for an electric field of 3 MV/cm. It can be seen that the lifetimes at R.T. and 150°C are sufficient for automotive systems, but that at 250°C is too low. Thus, it is necessary to improve the high-temperature TDDB characteristics.

Many types of films are being evaluated for use as gate insulators, and candidate materials should be checked from the viewpoint of their interface
state density, breakdown voltage and lifetime.

5 Conclusion

Although the history of GaN power devices is shorter than that of Si and SiC power devices, the performance of GaN devices has been rapidly improving. The theoretical performances of Si, SiC, GaN unipolar devices are shown in Fig. 9, together with that for a Si insulated gate bipolar transistor (IGBT) [33]. Reported data for SiC and GaN power devices are also plotted. It can be seen that the Si-IGBT is still a strong contender. Many lateral GaN devices have performances close to the SiC limit, while some are lower. This shows that the high potential of GaN is particularly apparent below 1 kV. However, GaN power devices are at present only approaching practical application, and several issues still remain, as described in this report. It is to be hoped that research into means of addressing these issues will soon bear fruit.

Fig. 9. Theoretical performance of Si, SiC and GaN power devices. Reported data for SiC-MOSFETs, lateral GaN devices and vertical GaN devices are also shown.

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