

Fabrication of High-Power AlGaIn/GaN Schottky Barrier Diode with Field Plate Design

Chia-Jui Yu, Chien-Ju Chen, Jyun-Hao Liao, Chia-Ching Wu, Meng-Chyi Wu

Abstract—In this letter, we demonstrate high-performance AlGaIn/GaN planar Schottky barrier diodes (SBDs) on the silicon substrate with field plate structure for increasing breakdown voltage V_B . A low turn-on resistance R_{ON} ($3.55 \text{ m}\Omega\text{-cm}^2$), low reverse leakage current ($< 0.1 \mu\text{A}$) at -100 V , and high reverse breakdown voltage V_B ($> 1.1 \text{ kV}$) SBD has been fabricated. A virgin SBD exhibited a breakdown voltage (measured at 1 mA/mm) of 615 V , and with the field plate technology device exhibited a breakdown voltage (measured at 1 mA/mm) of 1525 V (the anode–cathode distance was $L_{AC} = 40 \mu\text{m}$). Devices without the field plate design exhibit a Baliga's figure of merit of $V_B^2/R_{ON} = 60.2 \text{ MW/cm}^2$, whereas devices with the field plate design show a Baliga's figure of merit of $V_B^2/R_{ON} = 340.9 \text{ MW/cm}^2$ (the anode–cathode distance was $L_{AC} = 20 \mu\text{m}$).

Keywords—AlGaIn/GaN heterostructure, silicon substrate, Schottky barrier diode, high breakdown voltage, field plate, Baliga's figure-of-merit.

I. INTRODUCTION

GALLIUM nitride (GaN) is a promising material which has a wide bandgap ($\sim 3.4 \text{ eV}$), high critical electric field ($\sim 3.3 \text{ MV/cm}$), and good thermal conductivity ($\sim 1.3 \text{ W/cm}\cdot\text{K}$) characteristics compared with the traditional silicon material that has been taken recently. In addition, making use of the AlGaIn/GaN heterostructure not only enhanced the polarization effect but also improved electron mobility (about $1500 \text{ cm}^2/\text{V}\cdot\text{s}$), that is very suitable for applying the high-speed devices, such as a SBD [1]-[5], high electron mobility transistor (HEMT) [6]-[10], and so on.

SBD is an essential element in many power conversion systems, which is also useful for the integrated power system to accelerate the operating speed of the circuit. Therefore, the device which has high power and high operating speed characteristic becomes a highly popular research topic, and there have been more and more research papers published lately. Those papers about AlGaIn/GaN SBD using a silicon substrate can be divided into two parts. The first one is focusing on optimizing forward bias characteristics [11]-[14], and the second one is for reverse voltage improving [14]-[17].

The main achievement of this letter is to fabricate a lateral device which is AlGaIn/GaN SBD on silicon substrate and analyzing electrical characteristics by designing different mask layout that has multiple spacing between the anode and

the cathode. In order to optimize the SBD, we have found the most suitable annealing temperature for the lowest specific contact resistance on the forward bias and considered the reverse characteristics by adding the field plate technology also. Finally, we fabricate a high breakdown voltage SBD with the breakdown voltage of 1100 V , turn-on resistance of $3.55 \text{ m}\Omega\text{-cm}^2$, and Baliga's figure of merit of 340.9 MW/cm^2 .

TABLE I
RELEVANT RESEARCH COMPILATION OF ALGAIN/GAN SBDs

Feature of thesis	R_{on} [$\Omega\text{-cm}^2$]	V_B [V]	BFOM [W/cm^2]	Reference
2 nd ohmic process	-	-	-	2005 [11]
Gated ohmic anode	-	1440	-	2013 [12]
Selective Si diffusion	-	1500	-	2013 [13]
Recessed & field	5.12m	1930	727M	2015 [14]
Floating metal rings	0.38	930	2.27M	2005 [15]
Composite buffer layer	7.9m	3489	1540M	2011 [16]
O ₂ treatment	2.51m	1590	1006M	2015 [17]
Recessed anode	3.8m	2070	1127M	2016 [18]
Field plate	3.55m	1100	340.9M	This work

II. EXPERIMENTAL

In this letter, the epi-wafers were grown by metal organic chemical vapor deposition on a high resistivity 6-inch silicon substrate. The structures consist of a $0.1 \mu\text{m}$ AlN layer, a $2.2 \mu\text{m}$ AlGaIn buffer layer, a $1.4 \mu\text{m}$ carbon-doped GaN layer, a $0.5 \mu\text{m}$ un-doped GaN layer, a 10 nm AlGaIn layer and a 4 nm GaN cap layer from bottom to top. The Hall measurement of the fabricated devices shows a 2DEG concentration of $3.54 \times 10^{13} \text{ cm}^{-2}$ with a mobility (μ) about $1277 \text{ cm}^2/\text{V}\cdot\text{s}$. The SBD is designed in a circular pattern, which is defined by R (diameter of Schottky metal), L_{AC} (the spacing between anode and cathode). The distance between anode and cathode (L_{AC}) was $10, 20, 30, 40,$ and $50 \mu\text{m}$, respectively.

First is forming isolation region to block the 2DEG layer by using a low-damage Cl_2 -based inductively coupled plasma reactive ion etching (ICP-RIE). Second, using a thermal evaporator to deposit the ohmic metal (Ti/Al/Ni/Au), and followed by rapid thermal annealing at $875 \text{ }^\circ\text{C}$ for 30 s in N_2 ambient. The TiN layer covered the 2DEG channel directly after high temperature annealing, resulting in enhanced carrier mobility and the specific contact resistance is $1.18 \times 10^{-5} \Omega\text{-cm}^2$ were obtained by the transmission line method [19]. The third step is for preventing surface leakage and depositing 200 nm SiO_2 as a passivation layer by plasma-enhanced chemical vapor deposition (PECVD). Finally, Ni/Au is used to form Schottky contact which was deposited by a thermal evaporator.

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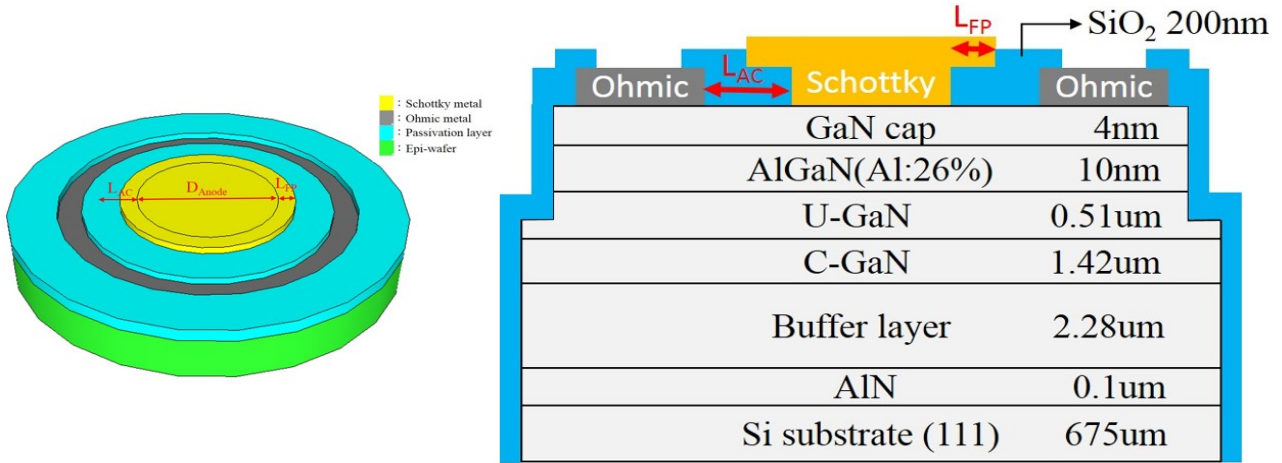


Fig. 1 Top view and cross-section schematic of SBD.

III. RESULTS AND DISCUSSION

We fabricated the SBDs with different spacing between anode and cathode ($L_{AC}=10-50 \mu\text{m}$). The anode diameter of device is $100 \mu\text{m}$, and the length of the field plate is $5 \mu\text{m}$. Fig. 2 shows the forward bias I-V characteristics of the SBDs. The average turn-on voltage (calculated at $1\text{mA}/\text{mm}$) of SBDs is $2 \pm 0.5 \text{ V}$, and the minimum turn-on resistance R_{ON} is $1.3 \text{ m}\Omega\text{-cm}^2$. The voltage of the diode turn-on and the value of turn-on resistance have a direct relationship between anode and cathode spacing. The longer distance of L_{AC} would have a larger series resistance and led higher turn-on voltage and higher resistance characteristics of the SBD. It is observed in the semi-log plot shown in the inset of Fig. 2 that the current reaches saturation when the voltage is about 5 V .

Fig. 3 shows the reverse I-V characteristics of the SBDs. The average values of leakage current (measured at -100 V) is smaller than $0.1 \mu\text{A}$, and it shows in the inset of Fig. 3. If the Schottky junction withstands excessive thermal budget in fabrication environment, the surface leakage current of the diodes will increase dramatically. Moreover, the breakdown voltage of SBDs has a relationship with length of space between the anode and cathode. When the length of spacing increases, the effective series resistance increases as well. Due to this reason, the longer distance of the Schottky metal to the ohmic metal possess higher breakdown voltage. The Baliga's figure of merits (BFOM) is a standard value to confirm the power device level, and it is calculated by the square of the breakdown voltage divided by turn-on resistance.

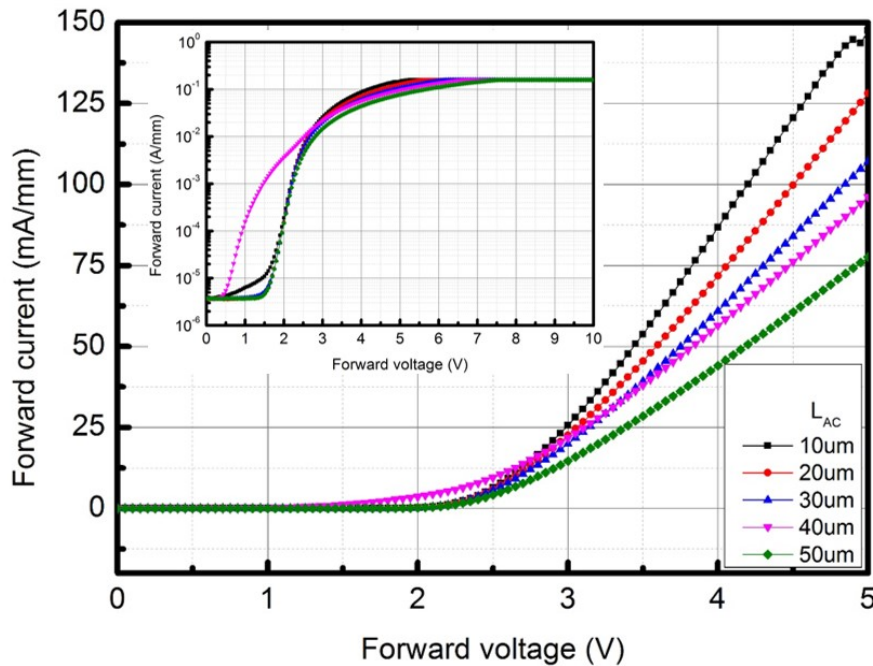


Fig. 2 Forward I-V characteristics in linear scale of the fabricated AlGaN/GaN SBDs with field plate design. Inset: Forward I-V characteristics in semi-log scale

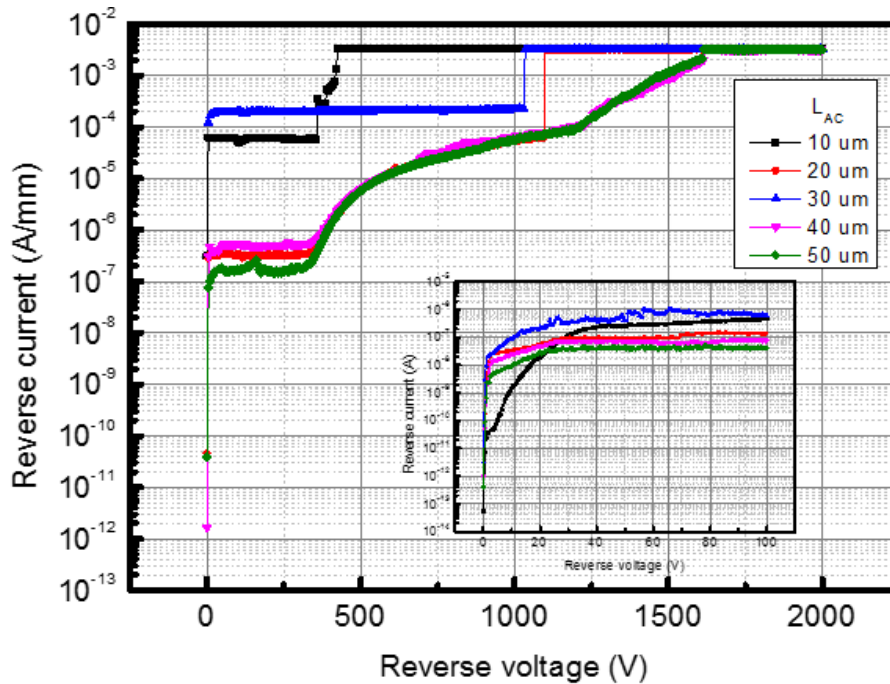


Fig. 3 Reverse *I-V* characteristics of the fabricated AlGaIn/GaN/Si SBDs with field plate design. Inset: Reverse leakage *I-V* characteristics up to -100 V

In this report, the highest breakdown voltage is 1525 V with L_{AC} 40 μm (measured at 1 mA/mm), the turn-on resistance is 9.97 $\text{m}\Omega\text{-cm}^2$, and the Baliga's figure of merit of $V_B^2 / R_{ON} = 233.3 \text{ MW/cm}^2$. Nevertheless, it is a trade-off choice between the breakdown voltage and the turn-on resistance. Therefore, the device with L_{AC} 20 μm has the best BFOM performance, which is 340.9 MW/cm^2 .

Fig. 4 shows the SBD forward *I-V* characteristics with different temperatures from 25 $^\circ\text{C}$ to 175 $^\circ\text{C}$, and we observed that the turn-on voltage drop from 2.25 V at 25 $^\circ\text{C}$ to 1.85 V at 170 $^\circ\text{C}$. The reason is that the main current flow mechanism is thermionic emission, the higher temperature applied much more energy to the carrier causes a forward voltage decrease.

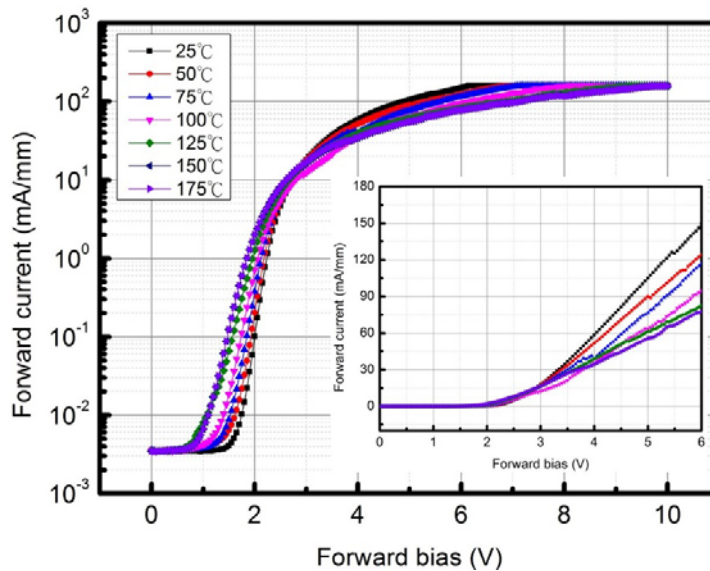


Fig. 4 Forward *I-V* characteristics in semi-log scale of the SBD with L_{AC} 20 μm at different temperatures. Inset: Forward *I-V* characteristics of the SBD with L_{AC} 20 μm in linear scale

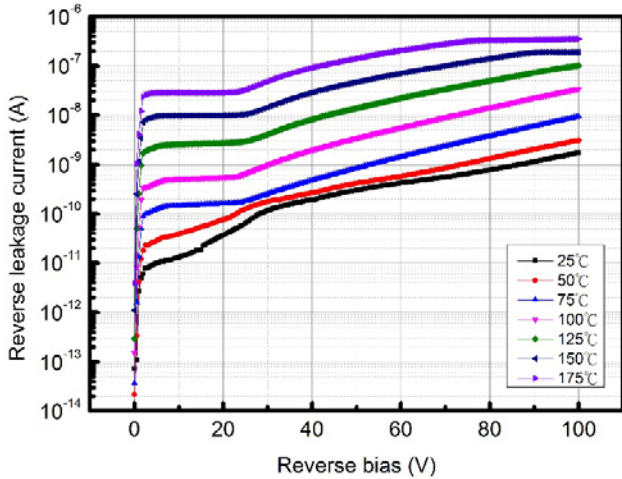


Fig. 5 Forward *I-V* characteristics in linear scale of the fabricated AlGaIn/GaN SBDs with field plate design. Inset: Forward *I-V* characteristics in semi-log scale

Fig. 5 reveals the reverse *I-V* characteristics with different temperatures from 25 °C to 175 °C. It appears that the leakage current increases with raising operating temperature. The value of leakage current measured at 175 °C rises by two orders higher than the reverse current at room temperature. From a band diagram point of view, with temperature increasing, the electrons have greatly higher probabilities to jump from valance band to conduction band. Consequently, the reverse leakage current has positive correlation with temperature.

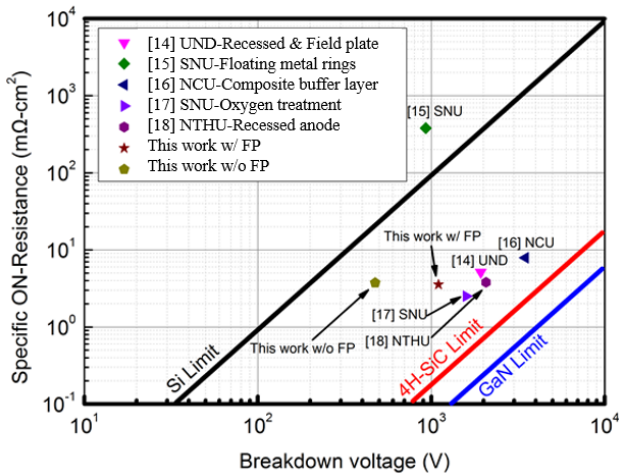


Fig. 6 The theoretical limit plot of breakdown voltage V_B versus turn-on resistance R_{ON} for various published thesis

Fig. 6 shows the turn-on resistance versus breakdown voltage as the BFOM plot for various AlGaIn/GaN power SBDs. The figure shows the study features and performance of AlGaIn/GaN SBDs in recent years. Zhu et al. propose recessed anode technology to reduce turn-on voltage and dual field plates design can improve the breakdown voltage in 2015 [14]. Lee et al. proposed the use of floating metal rings (FMR) designed, and it effectively enhanced the breakdown voltage

from 578V to 930V in 2005 [15]. Lee et al. fabricated lateral SBD on epi-wafer which has composite AlGaIn/AlN buffer layer structure, and the device breakdown voltage is up to 3489 V in 2011 [16]. Seok et al. proposed that the post-process O₂ treatment technology can reduce the leakage current about six orders, and the breakdown voltage can be increased from 808 V to 1590 V in 2015 [17]. Tsou et al. proposed the recessed-anode process can reduce turn-on voltage, and also, surface smoothing techniques can reduce the leakage current and improve the breakdown voltage in 2016 [18].

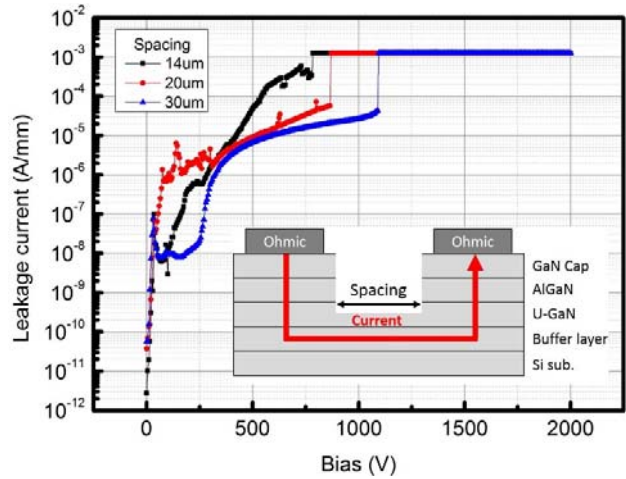


Fig. 7 *I-V* characteristics of buffer layer leakage current of the test pattern with different electrode spacing

In our work, we successfully fabricated the AlGaIn/GaN planar SBD on Si substrate. The diodes with the field plate design have highly improvement in reverse bias characteristics. This design of the SBDs with the field plate is much closer to the limit line of 4H-SiC material as shown in Fig. 6. In addition, this report also makes a further discussion for the theoretical breakdown voltage of the epi-wafers which called the test-key measurement. Taking advantage of etching and deposition process only, we try to reduce the fabrication mistake and obtain the theoretical breakdown value.

Fig. 7 exhibits the larger spacing between the electrodes have a higher breakdown voltage which is the same as the SBD. It is intuitively followed by the series resistance between the two electrodes. The maximum reverse voltage is 1095 V that measured by the test-key layout when the current reaches 1 mA. In result, we compared the characteristics between the SBD, and the test-key breakdown voltage is very close to prove that our SBD has excellent electrical characteristics.

IV. CONCLUSIONS

In this letter, we have successfully fabricated the AlGaIn/GaN planar SBD with field plate design on Si substrate. The highest breakdown voltage of 1525 V with L_{AC} 40 μm (measured at 1mA/mm), the turn-on resistance of 9.97 mΩ·cm², and the Baliga's figure of merit of $V_B^2/R_{ON} = 233.3$ MW/cm² were obtained. The average values of reverse

leakage current (measured at -100V) of SBDs are smaller than 0.1 μ A. Moreover, we get the high performance SBD with L_{AC} 20 μ m, the breakdown voltage of 1100 V with low turn-on resistance of 3.55 $m\Omega\text{-cm}^2$, and the Baliga's figure of merit of $V_B^2/R_{ON} = 340.9 \text{ MW/cm}^2$. The value of breakdown voltage increased about 2.4 times compared with the device without field plate design. Meanwhile, field plate technology was proven effective in promoting the breakdown voltage.

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