1.9-kV AlGaN/GaN Lateral Schottky Barrier Diodes on Silicon

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***Abstract*— In this letter, we present AlGaN/GaN lateral Schottky barrier diodes on silicon with recessed anodes and dual field plates. A low specific ON-resistance $R_{ON,SP}$ (5.12 m$\Omega \cdot$cm^2), a low turn-ON voltage (<0.7 V), and a high reverse breakdown voltage (BV) (>1.9 kV) were simultaneously achieved in devices with a 25-μm anode/cathode distance, resulting in a power figure-of-merit BV$^2/R_{ON,SP}$ of 727 MW $\cdot$ cm^{-2}. The record high BV of 1.9 kV is attributed to the dual field-plate structure.**

***Index Terms*— Schottky barrier diode, GaN on silicon, breakdown voltage, high voltage device, AlGaN/GaN, field plate.**

I. Introduction

GaN ON silicon technology has attracted tremendous research attention for its potential to be widely commercialized thanks to its competitive performance and low cost. Diode based rectifiers, as an indispensable device for most power electronic applications, require low turn-on voltage and specific on resistance ($R_{ON,SP}$), low reverse leakage current yet high breakdown voltage (BV) to minimize power loss during operation. AlGaN/GaN based Schottky barrier diodes (SBDs) on sapphire or SiC substrate have shown superior performance over rectifiers achieved in other material systems due to the wide band gap of GaN and high electron mobility in the two dimensional electron gas (2DEG). However, the performance of GaN on silicon rectifier has been lagging behind.

Recessed anode was reported effective in reducing the turn-on voltage hence specific on-resistance of SBDs [1]. Meanwhile, field plate technology was proven effective in boosting the breakdown voltage in both field effect transistors (FETs) [2] and SBDs [3]. The combination of recessed anode and field plate has been implemented in AlGaN/GaN SBDs with excellent power figure-of-merit (FOM) BV$^2/R_{ON,SP}$ [1]. To further improve the breakdown voltage, we have adopted a dual field plate structure with the recessed anode in this letter. SiN_x and SiO_2 by atomic layer deposition (ALD) were used as dielectric for the first and second field plate, respectively. Fabricated devices show a maximum breakdown voltage of 1.93 kV with a power FOM of 727 MWcm^{-2}, and this BV value is the highest among the reported GaN-on-Si diodes.

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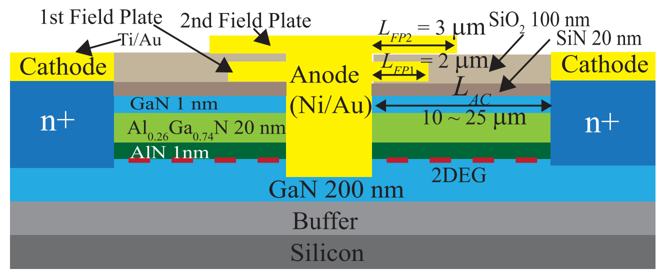

Fig. 1. Schematic cross section of the recessed anode Schottky barrier diode with double field plates.

II. Fabrication Process

The epitaxial layers were grown by metal organic chemical vapor deposition on 6 inch silicon substrates, consisting of 1 nm GaN, 20 nm $Al_{0.26}Ga_{0.74}N$, 1 nm AlN, 200 nm GaN, and 4 μm buffer layer. All the epitaxial layers were grown along the metal face crystal orientation, i.e. [001]. Fabrication of the SBDs started with the cathode ohmic contacts using the molecular beam epitaxy regrowth [4] and non-alloyed Ti/Au metallization. The regrown GaN has a thickness of 100 nm and a Si doping concentration of 1×10^{20} cm^{-3}. ALD SiN of 20 nm thick was then deposited as dielectric for the first field plate, which was chosen so that the pinchoff voltage of the resultant metal-SiN-HEMT structure is no less than -10 V. The anode was defined by optical lithography and etching to remove SiN and 50 nm of AlGaN/GaN using CF_4 and BCl_3 plasma, respectively. The anode contact and the first field plate with a length (L_{FP1}) of 2 μm was then defined by Ni/Au deposition and liftoff. ALD SiO_2 of 100 nm was subsequently deposited, followed by the definition of the second field plate with a length (L_{FP2}) of 3 μm. A relatively thick SiO_2 was used to support the large voltage drop across the anode and cathode. The Hall effect measurement on the fabricated devices shows a 2DEG concentration of 9.8×10^{12} cm^{-2} with a mobility μ of 1490 cm^2/V$\cdot$s. The anode/cathode distance (L_{AC}) was varied between 10 and 25 μm. The cross-sectional schematic of a finished device is shown in Fig. 1.

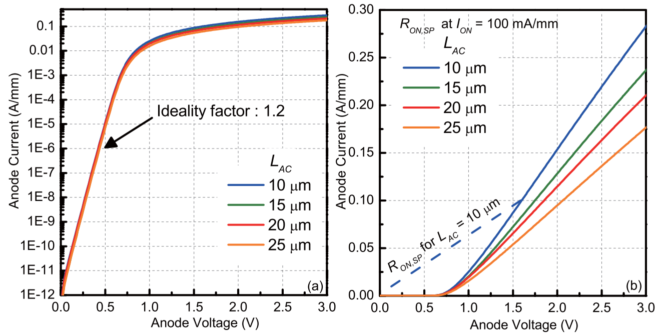

Fig. 2. Forward bias I-V characteristics in (a) semi-log and (b) linear scale of the fabricated GaN-on-Si SBDs with recessed anode and double field plates. The dash line in (b) illustrates the definition of $R_{ON,SP}$ used in this letter.

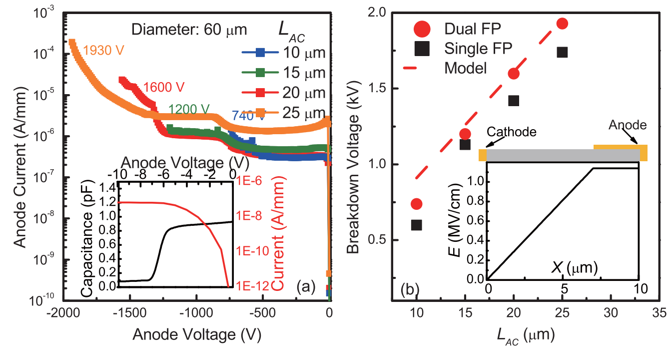

Fig. 3. (a) Reverse bias I-V characteristics of the diodes shown in Fig. 2. Inset: diode C-V at 1 MHz and reverse bias I-V up to -10 V. (b) BV versus L_{AC} for SBDs with double and single field plate structures. The dash line is the calculated BV using an E_{Cr} of 1.4 MV/cm and the trapezoid file profile shown in the inset.

III. Experimental Results

Figure 2 shows the typical forward bias characteristics of the fabricated diodes with various anode/cathode distances ($L_{AC} \sim 10 - 25$ μm). The ideality factor and the turn-on voltage $V_{turn\text{-}on}$ (at 1 mA/mm) of the SBDs are 1.22 $\pm$ 0.05 and 0.67 $\pm$ 0.02 V across the sample. Similar $V_{turn\text{-}on}$ values have been reported previously in recessed anode GaN SBDs where the anode metal is in direct contact with the 2DEG at the AlGaN/GaN interface [1], [5]. It is worth noting that overlapping current – voltage characteristics over 9 orders of magnitude in the linear regime of the semi-log plot shown in Fig. 2(a) are observed. Since the forward current for $V < V_{turn\text{-}on}$ is dominated by the Schottky junction not by the series resistance, this, along with the small variations of the aforementioned ideality factor and $V_{turn\text{-}on}$, shows excellent Schottky junction uniformity among different devices, regardless of the L_{AC}.

The reverse bias characteristics of the same diodes shown in Fig. 2 are plotted in Fig. 3 (a). All devices show a low reverse leakage current (< 5 μA/mm) up to 700 V. With an increasing L_{AC}, a larger breakdown voltage was obtained, which leads to the well-known tradeoff between breakdown voltage and on-resistance. A breakdown voltage (measured at 1 mA/mm) of 1.93 kV has been achieved with a L_{AC} of 25 μm and a $R_{ON,SP}$ of 5.12 mΩ·cm^2 (extracted at a forward current of 100 mA/mm, as illustrated in Fig. 2(b)), resulting in a power FOM of 727 MW/cm^2. The device with a L_{AC} of 20 μm shows a breakdown voltage of 1.6 kV and a $R_{ON,SP}$ of 3.7 mΩ·cm^2, resulting in a power FOM of 691 MW/cm^2. The BV of 1.93 kV is the highest value among the reported GaN on Si diodes while both FOM values are comparable to the other state-of-the-art devices. The capacitance versus voltage (C-V) measurement and zoomed in reverse I-V results are plotted in the inset of Fig. 3(a), showing at a reverse bias of 7 V a complete depletion of the 2DEG underneath the field plates ($V_{pinchoff} \sim -7$ V) and a simultaneous saturation of reverse leakage current, indicating the effect of the field plates in curbing the leakage current. The device switching time can also be estimated based on the C-V and I-V characteristics as follows: $\tau_{switch} \sim C_{max} \bullet V_{pinchoff}/I_{on} \sim 350$ ps, indicating these devices are fast even though the double FPs increase the device capacitance considerably compared to devices without FPs.

The record high breakdown voltage is attributed to the double field plate structure, which is often used in power FETs to reduce peak electric field thus increasing BV with the same voltage bearing distance. To investigate the effect of the second field plate, another set of devices were fabricated with the first field plate only and an otherwise identical process flow. The plot of BV versus L_{AC} for the diodes with the single and double field plate structures is shown in Fig. 3(b). A noticeable improvement of BV (~5–25%) is observed for each L_{AC} with the addition of the second field plate. A nearly linear increase of breakdown voltage is also observed with increasing L_{AC}, indicating depletion of the 2DEG beyond the field plate region. Simulations show the electric field typically spikes near the FP edges on the drain side, thus difficult to analytically extract the breakdown field in lateral power devices. To gauge the efficacy of the double FP structure, we compute an *effective* breakdown field by assuming a total depletion of the 2DEG between the anode and cathode and a constant lateral electric field underneath the field plates. The resulting field profile is trapezoidal as shown in the inset of Fig. 3(b), which also represents an optimized field profile. The *effective* critical electric field ($E_{cr,eff}$) is then calculated to be 1.14-1.4 MV/cm, which is much lower than the value in bulk GaN (3.4 MV/cm [6]) due to the aforementioned challenges in engineering the surface field in these diodes. This low $E_{cr,eff}$ also indicates that there is still room to improve the field profile thus device BV. The observation of a nearly linear increase in BV versus L_{AC}, also reported by other groups [1], [5], is worthy further investigation.

Figure 4 presents the benchmark plot of BV versus $R_{ON,SP}$ for the GaN based unipolar power diodes, including both lateral and vertical devices. The SBDs with recessed anodes in this letter are among the best reported and show the highest BV among GaN power diodes on silicon substrates, and compare favorably to the state-of-the-art GaN diodes on SiC, sapphire and bulk GaN substrates that often has less number of dislocations than GaN-on-Si. In comparison to the previously reported SBDs with recessed anodes in direct contact to the 2DEG, the devices in this letter show ~ 2X improvement in BV: 1900 V vs. 800 V for GaN-on-Si SBDs [5] and 1900 V vs. 1000 V for GaN-on-SiC SBDs [1]. The $R_{ON,SP}$-BV values of all these SBDs with recessed anode

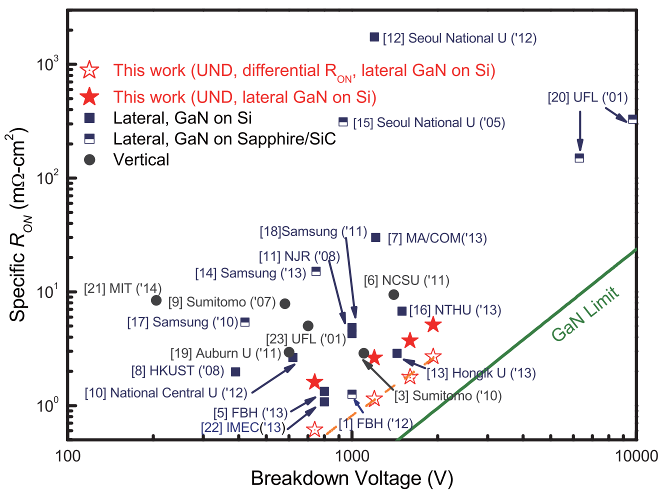

Fig. 4. The benchmark plot of BV versus $R_{ON,SP}$. All the reference values are re-calculated based on the reported data following the definition of $R_{ON,SP}$ shown in Fig. 2(b) so that the diode turn-on effect is also taken into account, using $I_{ON} = 100$ mA/mm criteria. The differential R_{ON} of the diodes in this letter is also extracted (hollow stars) and modeled (dash line) assuming $\mu = 1490$ cm^2/V·s and $E_{Cr} = 1.5$ MV/cm. The green line shows the FOM limit of bulk GaN using $\mu = 500$ cm^2/V·s and $E_{Cr} = 3.4$ MV/cm. UND stands for the University of Notre Dame.

fall along the same FOM line representing the best achieved SBDs experimentally (Fig. 4), which suggests the recess anode coupled with multiple FPs is a viable technology to achieve high performance GaN rectifiers. Given the advantage in terms of cost GaN-on-Si technology has over other substrates, the SBDs with recessed anode and double field plate structure has great potential for power electronic applications, which are highly sensitive to cost due to the continuous performance improvement in silicon based power devices.

IV. Conclusion

Employing a recessed anode and double field plate structure, we demonstrated AlGaN/GaN-on-Si SBDs, exhibiting a record breakdown voltage of 1.93 kV and competitive power FOM values. The high performance, together with the low cost associated with the GaN-on-Si technology, shows a great potential for its applications in power electronics.

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