AlGaN/GaN Schottky Barrier Diodes on Silicon Substrates With Selective Si Diffusion for Low Onset Voltage and High Reverse Blocking

Yi-Wei Lian, Yu-Syuan Lin, Jui-Ming Yang, Chih-Hsuan Cheng, and Shawn S. H. Hsu

***Abstract*— In this letter, a selective Si diffusion approach is proposed to improve both the forward and reverse characteristics of AlGaN/GaN Schottky barrier diodes on Si substrates. The Si diffusion layer forms a dual Schottky barrier anode structure, which results in a low Schottky barrier portion to reduce the onset voltage V_{ON} from 1.3 to 1.0 V (23%). In the same process step, the selectively diffused Si is adopted in the cathode to reduce the ohmic contact resistance R_C and improve the breakdown voltage V_{BK}. A low R_C of 0.21 Ω·mm and enhanced V_{BK} up to 20% (from 1250 to 1500 V) are demonstrated, which can be attributed to the alleviated electric-field peaks around the alloy spikes beneath the ohmic contact.**

***Index Terms*— Breakdown voltage, GaN, onset voltage, rectifier, Schottky barrier diode (SBD), silicon.**

I. Introduction

A HIGH operating frequency enables a compact switching-mode power supply system. The dynamic loss of the switching devices becomes more critical to the overall system efficiency at higher switching frequencies. The devices that are capable of high-speed and low-loss operation are essential for highly efficient systems for megahertz operation and beyond [1]. Recently, the AlGaN/GaN Schottky barrier diodes (SBDs) are demonstrated with a superior Baliga's figure-of-merit (defined as $V_{BK}^2/R_{ON,sp}$) [2]–[4]. In addition, the growth of a high-quality GaN epitaxial layer on large silicon substrates has shown substantial progress, which allows in utilizing the modern silicon technology for high-performance GaN-based devices at low costs [5]. The results indicate that the GaN-based SBDs on silicon substrates have substantial potential for high-performance and low-cost switching-mode power supplies.

Both the onset voltage and reverse blocking capability are the key indexes of SBDs for highly efficient power switching applications. Typical AlGaN/GaN planar SBDs exhibit a high onset voltage V_{ON} [2], [3], leading to a considerable conduction loss. To overcome this problem, a recessed anode in GaN SBD is proposed to lower the V_{ON} from 1.47 to 0.43 V [3]. In addition, a dual-recessed structure for both the anode and cathode is applied to reduce the onset voltage [6]. The recess technique, however, requires precision control of the etching depth, and etching damage may seriously degrade the device performance. An AlGaN/GaN field effect Schottky barrier diode (FESBD) demonstrated an extremely low V_{ON} ~0.1–0.2 V using a dual Schottky metal structure [7], [8]. Nevertheless, the FESBD structure also shows degradation of the reverse breakdown voltage and leakage current. Although various approaches are proposed, reducing the onset voltage while maintaining a high reverse blocking capability remains relatively difficult.

On the other hand, studies verified that the ohmic contact process is critical to the breakdown voltage V_{BK} because of the alloy spikes [9], [10]. The spikes with random locations and depths introduce unexpected high e-field peaks at the sharp points of the spikes, resulting in a rapid increase of the buffer leakage current and premature breakdown [9]. The Schottky drain electrode in AlGaN/GaN HEMTs on Si is employed to eliminate the alloy spikes at the drain side for V_{BK} improvement [10]. In our previous letter, a hybrid Schottky-ohmic drain structure was proposed to enhance the off-state characteristics by alleviating the e-field intensity around the alloy spikes [11].

In this letter, a selective Si-diffusion design is proposed to simultaneously improve the forward and reverse characteristics of the AlGaN/GaN SBDs on silicon. Using selective Si diffusion at the anode, a dual-barrier anode structure can be formed to reduce the onset voltage. With the Si diffusion layer that is also applied to the cathode, the electric-field distribution is reshaped to suppress the alloy spikes-induced premature breakdown.

II. Device Design and Fabrication

The cross-section of the proposed AlGaN/GaN SBD fabricated on a Si substrate using the selective Si-diffusion approach, where the Si diffusion process is applied to both the anode and cathode regions in the same process step is shown in Fig. 1. With a circular layout of the devices, R is the radius of Schottky metal, d is the indented length of the Si diffusion region from the Schottky metal edge, and L_{ext} is the length extended over the ohmic metal edge. The drift length L_{drift} (defined according to the distance between the Schottky and ohmic metal edges) of the silicon diffusion and reference (conventional) SBDs are kept identical for a fair comparison. Note, an $L_{drift} = 15$ μm and an $R = 50$ μm are employed in this letter.

Manuscript received April 22, 2013; revised May 12, 2013 and June 5, 2013; accepted June 14, 2013. Date of publication July 3, 2013; date of current version July 22, 2013. The review of this letter was arranged by Editor R. Quay.

The authors are with the Electrical Engineering Department, National Tsing Hua University, Hsinchu 30013, Taiwan (e-mail: shhsu@ee.nthu.edu.tw).

Color versions of one or more of the figures in this letter are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/LED.2013.2269475

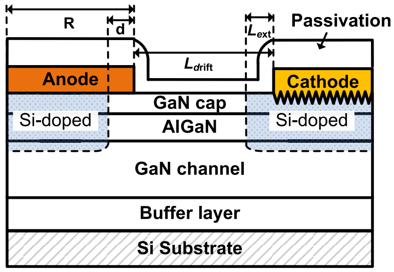

Fig. 1. Cross-section of the proposed AlGaN/GaN SBD with Si diffusion on a Si substrate.

The epitaxial structure of the AlGaN/GaN SBD is grown on a 4-in Si wafer with a resistivity of 0.02 Ω·cm. This wafer consists of a 3.3-μm buffer layer, a 1.5-μm GaN channel layer, a 20-nm $Al_{0.25}Ga_{0.75}N$ barrier layer, and a 1-nm GaN cap layer. Mesa isolation is achieved through inductive couple plasma using a Cl_2/Ar gas mixture at an etching depth of ∼300 nm. After defining the photoresist, a 50-nm Si layer is deposited as a dopant source using electron beam evaporation and the lift-off process. A 150-nm SiO_2 layer is encapsulated using plasma-enhanced chemical vapor deposition (PECVD) at 300 °C to prevent surface dissociation during the subsequent high-temperature diffusion process [12]. The Si diffusion process is then performed at 1000 °C for 30 min in N_2 ambient. A diffusion depth of ∼45 nm is measured using secondary ion mass spectroscopy. After removing the SiO_2 cap and remaining Si using wet etching with a buffer oxide etchant and $HF/HNO_3/H_2O$, respectively, an ohmic contact is formed with Ti/Al/Ni/Au using e-beam evaporation, followed by rapid thermal annealing at 850 °C for 30 s. A Ni/Au metal stack is then deposited to form the Schottky contact, and the multilayer surface passivation comprising SiN and SiO is achieved by PECVD at 300 °C (total thickness ∼0.5 μm).

As shown in Fig. 1, the dual Schottky barrier anode is realized by a Si diffusion layer under the Schottky contact with an indented length d. The Si diffused region reduces the barrier height, whereas that of the undoped region remains unchanged and can be considered that two SBDs are connected in parallel. Under forward bias conditions, the SBD with a lowered barrier height is activated first, which provides an auxiliary current path, thereby reducing V_{ON}. It should be emphasized that the parameter d is critical to the device characteristics. If d is excessively large, V_{ON} cannot be reduced effectively. In contrast, a small d may degrade the V_{BK}. An appropriately designed d can ensure a complete pinch off of the 2-D electron gas (2DEG) channel, which prevents degradation of the leakage current and breakdown voltage and effectively lowers V_{ON}. Experiments with Si doping under only the Schottky contact are conducted for $d = 2$, 4, and 8 μm, and V_{ON} increases gradually as expected. Furthermore, V_{BK} shows no clear degradation among the SBDs with varying d.

A Si-doped region is also applied beneath the ohmic contact with an extended length L_{ext} to enhance V_{BK} and minimize R_C. The spikes formed at the AlGaN/GaN heterojunction with an alloy-type ohmic contact can induce local carrier injection, which may result in premature breakdown because of the high e-field at the sharp points of the spikes. In addition to the original peaks around the alloy spikes, the Si extension layer can create a new e-field peak at the edge of the Si-doped region, which can alleviate and smooth the e-field intensity around the spikes to improve V_{BK}. The effective drift region is also reduced accordingly with L_{ext}, which may, however, result in V_{BK} degradation. An appropriately designed L_{ext} can compensate for the effect of reduced effective drift region by suppressing the e-field peaks around the spikes and further improving the V_{BK}. An L_{ext} of 1 μm is chosen for the proposed design based on the simulated results. Additional experiments conducted using Si diffusion only under the ohmic contact can support this viewpoint, which will be further explained and published elsewhere.

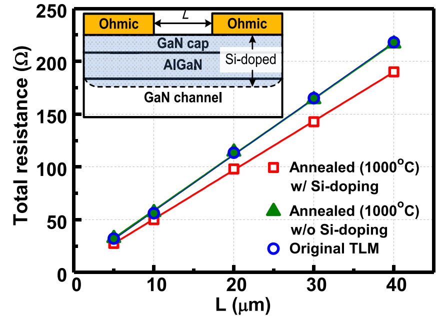

Fig. 2. Measured TLM results under various conditions. Inset: TLM structure with Si diffusion.

TABLE I
EXTRACTED PARAMETERS FROM TLM STRUCTURES

	Sheet resistance	Contact resistance
Original TLM	533 Ω/□	0.33±0.07 Ω·mm
Annealed w/o Si-doping	528 Ω/□	0.30±0.04 Ω·mm
Annealed w/ Si-doping	464 Ω/□	0.22±0.01 Ω·mm

III. RESULTS AND DISCUSSION

Fig. 2 shows comparison of the TLM structure measurements under various conditions (width = 100 μm), which provide information regarding how the high-temperature annealing and Si diffusion process affect the contact and electrical properties of the devices. In Table I (average of three typical devices), the sheet resistance of the original TLM is similar to that after annealing without Si-doping, which indicates that the high-temperature annealing process do not degrade the electron transport properties in 2DEG. The SBDs fabricated using silicon diffusion are also measured up to 175 °C. The observed trends of reduced forward current and increased leakage current are similar to those of the conventional devices reported in [3]. The diffusion profile should not change under normal operations ($\leq$ 200 °C) because a relatively high temperature is, however, required for the diffusion process ($\geq$ 800 °C) [13].

With the Si diffusion process, the sheet resistance decreases from 533 to 464 Ω/□. This indicates that the Si atoms are successfully diffused, which increases the carrier concentration in 2DEG [14]. Note, the typical ohmic contact resistance R_c is ∼0.33 ± 0.07 Ω·mm in conventional devices and can be

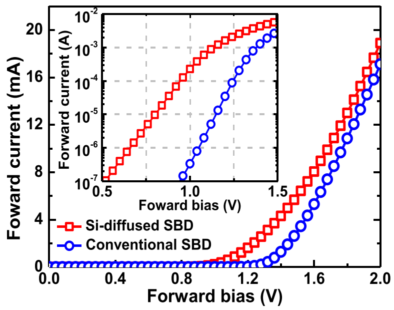

Fig. 3. Forward I–V characteristics of the SBDs with an $L_{\text{drift}} = 15\mu$m.

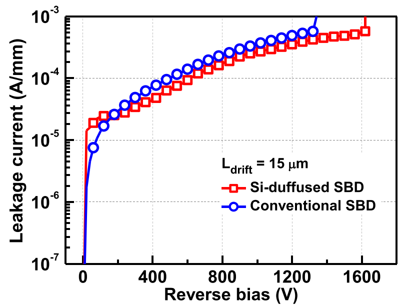

Fig. 4. Reverse I–V characteristics of the SBDs with an $L_{\text{drift}} = 15\mu$m.

reduced to ∼0.22 ± 0.01 Ω·mm by using Si diffusion (up to ∼50%).

Fig. 3 is a comparison of the forward I–V characteristics of the proposed ($d = 2\ \mu$m, $L_{\text{ext}} = 1\ \mu$m) and conventional AlGaN/GaN SBDs on Si (without Si diffusion but also annealed under 1000 °C). Through the proposed selective Si-diffusion approach, V_{ON} (at a forward current of 1 mA/mm) can be reduced from 1.3 to 1.0 V (23%) with a dual Schottky barrier structure. The ideality factors of 1.68 and 2.40 and the effective barrier heights of 0.769 and 0.601 eV are extracted from SBDs without and with Si doping, respectively. The breakdown voltage (at a leakage current of 1 mA/mm) is measured with a floated substrate by immersing the sample in fluoride liquid.

The reverse I–V characteristics of devices with an $L_{\text{drift}} = 15\ \mu$m is shown in Fig. 4. A similar leakage level can be obtained in the Si-diffused SBD compared with that in the conventional design. This can be attributed to the dual Schottky barrier structure, which can effectively block the leakage current even with a reduced V_{ON}. Through proper design of L_{ext} and d, the Si-diffused SBDs demonstrate increased V_{BK} up to 20% (from 1250 to 1500 V; average of three typical devices) without degradation of leakage current. The figure of merit (V_{BK}^2/Area·R_{on}) of the Si-diffused SBDs can be calculated as 666.7 MW/cm^2.

Although no degradation is observed, the leakage current is relatively large in both cases. High-temperature annealing may cause surface dissociation, thereby increasing surface leakage. Additional surface treatment may, however, mitigate this issue [12]. Buffer leakages are also a critical issue for GaN fabricated on Si. A high resistivity Fe-doped buffer can be adopted to suppress the vertical leakage path [15]. The slightly higher leakage current in the Si-doped SBD at low bias can be attributed to the reduced Schottky barrier height. As the bias voltage increases, the effect of the alleviated e-field intensity around the ohmic contact becomes dominant and the leakage current reduces to lower than that of conventional devices.

IV. Conclusion

In this letter, we proposed a selective Si diffusion design approach to simultaneously reduce the onset voltage and enhance the reverse blocking capability of GaN SBDs. The diffused silicon layer beneath the anode formed a dual Schottky barrier, reducing the onset voltage from 1.3 to 1.0 V (23%) without degrading the leakage current. The Si-doped layer was also employed at the ohmic contact to smooth the electric-field distribution around the cathode. A low R_{C} of 0.21 Ω·mm and an enhanced V_{BK} of up to 20% (from 1250 to 1500 V) were demonstrated.

References

[1] B. Hughes, Y. Y. Yoon, D. M. Zehnder, *et al.*, "A 95% efficient normally-off GaN-on-Si HEMT hybrid-IC boost-converter with 425-W output power at 1 MHz," in *Proc. IEEE CSICS*, Oct. 2011, pp. 1–3.

[2] G. Y. Lee, H. H. Liu, and J. I. Chyi, "High-performance AlGaN/GaN Schottky diodes with an AlGaN/AlN buffer layer," *IEEE Electron Device Lett.*, vol. 32, no. 11, pp. 1519–1521, Nov. 2011.

[3] E. B. Treidel, O. Hilt, R. Zhytnytska, *et al.*, "Fast-switching GaN-based lateral power Schottky barrier diodes with low onset voltage and strong reverse blocking," *IEEE Electron Device Lett.*, vol. 33, no. 3, pp. 357–359, Mar. 2012.

[4] Y. S. Kim, M. W. Ha, and M. K. Han, "AlGaN/GaN Schottky barrier diode on Si substrate employing NiO_x/Ni/Au Contact," *Jpn. J. Appl. Phys.*, vol. 51, no. 9, pp. 09MC01-1–09MC01-5, 2012.

[5] K. Cheng, M. Leys, J. Derluyn, *et al.*, "AlGaN/GaN HEMT grown on large size silicon substrate by MOVPE capped with in-situ deposited Si_3N_4," *J. Crystal Growth*, vol. 298, pp. 822–825, Jan. 2007.

[6] H. Ishida, D. Shibata, M. Yanagihara, *et al.*, "Unlimited high breakdown voltage by natural super junction of polarized semiconductor," *IEEE Electron Device Lett.*, vol. 29, no. 10, pp. 1087–1089, Oct. 2008.

[7] N. Ikeda, J. Li, S. Kato, *et al.*, "A novel GaN device with thin AlGaN/GaN heterostructure for high-power application," *Furukawa Rev.*, vol. 29, no. 2, pp. 1–6, 2006.

[8] W. Chen, K. Y. Wong, and K. J. Chen, "Monolithic integration of lateral field-effect rectifier with normally-off HEMT for GaN-on-Si switch-mode power supply converters," in *Proc. IEEE IEDM*, Dec. 2008, pp. 1–4.

[9] Y. Dora, A. Chakraborty, S. Heikman, *et al.*, "Effect of ohmic contacts on buffer leakage of GaN transistors," *IEEE Electron Device Lett.*, vol. 27, no. 7, pp. 529–531, Jul. 2006.

[10] B. Lu, E. L. Piner, and T. Palacios, "Schottky-drain technology for AlGaN/GaN high-electron mobility transistors," *IEEE Electron Device Lett.*, vol. 31, no. 4, pp. 302–304, Apr. 2010.

[11] Y. W. Lian, Y. S. Lin, H. C. Lu, *et al.*, "AlGaN/GaN HEMTs on silicon with hybrid Schottky–Ohmic drain for high breakdown voltage and low leakage current," *IEEE Electron Device Lett.*, vol. 33, no. 7, pp. 973–975, Jul. 2012.

[12] T. Hashizume and H. Hasegawa, "Effects of nitrogen deficiency on electronic properties of AlGaN surface subjected to thermal and plasma processes," *Appl. Surf. Sci.*, vol. 234, nos. 1–4, pp. 387–394, Jul. 2004.

[13] S. Jang, F. Ren, S. J. Pearton, *et al.*, "Si diffused GaN for enhancement-mode GaN MOSFET on Si applications," *J. Electron. Mater.*, vol. 35, no. 4, pp. 685–690, 2006.

[14] T. Murata, M. Hikita, H. Ishida, *et al.*, "Reduction of ohmic contact resistance of AlGaN/GaN HFETs by doping of thermally diffused Si," in *Proc. Int. Meeting Future Electron Devices*, Jul. 2004, pp. 47–48.

[15] Y. C. Choi, M. Pophristic, H. Y. Cha, *et al.*, "The effect of an Fe-doped GaN buffer on OFF-state breakdown characteristics in AlGaN/GaN HEMTs on Si substrate," *IEEE Electron Device Lett.*, vol. 53, no. 12, pp. 2926–2928, Dec. 2006.