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High Breakdown (> 1500 V) AlGaIn/GaN HEMTs by Substrate-Transfer Technology

Bin Lu, *Student Member, IEEE*, and Tomás Palacios

Abstract—In this letter, we present a new technology to increase the breakdown voltage of AlGaIn/GaN high-electron-mobility transistors (HEMTs) grown on Si substrates. This new technology is based on the removal of the original Si substrate and subsequent transfer of the AlGaIn/GaN HEMT structure to an insulating carrier wafer (e.g., glass or polycrystalline AlN). By applying this new technology to standard AlGaIn/GaN HEMTs grown on Si substrate, an AlGaIn/GaN HEMT with breakdown voltage above 1500 V and specific on resistance of $5.3 \text{ m}\Omega \cdot \text{cm}^2$ has been achieved.

Index Terms—AlGaIn/GaN, breakdown, high-electron-mobility transistor (HEMT), power electronics, substrate transfer, wafer bonding.

I. INTRODUCTION

AlGaIn/GaN high-electron-mobility transistors (HEMTs) have attracted a great interest for the next generation of power electronics. Due to their high-electron mobility (μ_e) and high critical electric field (E_c), GaN-based power converters enable more efficient and compact power-conversion systems than the Si-based converters [1].

To reduce the cost of GaN-based power electronics, silicon is the most attractive substrate for the growth of AlGaIn/GaN HEMT structures. Recently, crack-free AlGaIn/GaN HEMT structures grown on 150-mm Si substrates have been reported in [2] with a sheet resistance of $260 \text{ }\Omega/\square$ and mobility of $1650 \text{ cm}^2/\text{V} \cdot \text{s}$.

In spite of the great potential of GaN-on-Si electronics, it is suggested in [3] and [4] that the maximum breakdown voltages of the AlGaIn/GaN-on-Si HEMTs are limited by the Si substrate. For example, the breakdown voltages of AlGaIn/GaN HEMTs with a total of $2\text{-}\mu\text{m}$ epitaxial layer on Si substrates are typically less than 800 V [4]–[6]. Several methods have been reported to improve the device breakdown voltage beyond 800 V, including increasing the epitaxial-layer thickness [5]–[7], doping the buffer with Fe or C [8], [9], using AlGaIn-based buffer layers [3], and the use of Schottky-drain contacts [4]. Another alternative method is to use sapphire substrates. However, this substrate suffers from high cost, limited wafer size (up to 6 in) and poor thermal conductivity.

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In this letter, we demonstrate a new technology based on the removal of the Si substrate to achieve high breakdown AlGaIn/GaN HEMTs with only a $2\text{-}\mu\text{m}$ total epitaxial thickness. This technology can be applied to any wafer size, and it does not require a thick epitaxial layer, which reduces the cost and the wafer bow. By removing the Si (111) substrate and transferring the AlGaIn/GaN HEMTs to a glass wafer, a breakdown voltage of more than 1500 V has been demonstrated.

II. DEVICE FABRICATION

The devices were fabricated on an AlGaIn/GaN heterostructure grown on a 4-in Si (111) substrate by Nitronex Corporation. The device structure has a 2-nm GaN cap, a 20-nm $\text{Al}_{0.26}\text{Ga}_{0.74}\text{N}$ barrier, and a $2\text{-}\mu\text{m}$ -thick GaN/AlGaIn buffer. Additional details about the wafer growth can be found in [10]. Ti/Al/Ni/Au alloyed source and drain ohmic contacts were formed by rapid thermal annealing at 870°C . Then, mesa isolation was achieved by BCl_3/Cl_2 plasma etching. Two- μm -long Ni/Au/Ni gates were deposited with a gate width (W) of $100 \text{ }\mu\text{m}$. The transistors have a gate-to-source spacing (L_{gs}) of $1.5 \text{ }\mu\text{m}$ and a gate-to-drain spacing (L_{gd}) varying from 5 to $20 \text{ }\mu\text{m}$. After finishing the standard AlGaIn/GaN HEMTs fabrication, the top surface of the sample (Ga face) was bonded to a Si carrier wafer by adhesive bonding using benzocyclobutene (BCB) cured at 250°C for 1 h [11]. Then, the Si (111) substrate was removed by SF_6 plasma etching, exposing the N-face of the $2\text{-}\mu\text{m}$ -thick GaN/AlGaIn buffer. The N-face of the GaN/AlGaIn buffer was then bonded to a glass wafer using BCB. Finally, the Si carrier wafer was released by SF_6 and SF_6/O_2 plasma etching, as shown in the process flow in Fig. 1. Although the samples used in this letter had an area of $2 \times 2 \text{ cm}^2$, we have recently demonstrated the substrate removal and bonding of full 4-inch wafers [12]. The breakdown measurement setup consists of a Tektronix curve tracer connected to Agilent 34401A multimeter. Fluorinert was used to prevent surface flashover, and the substrate was left floating during the breakdown measurement.

III. EXPERIMENTAL RESULTS

The dc characteristics of the AlGaIn/GaN HEMTs before and after the substrate transfer are shown in Fig. 2. The maximum drain current of the device transferred to the glass wafer drops by 28% with respect to the one before the substrate transfer, which is mainly due to the self-heating effect. Using the transmission-line method (TLM), the extracted sheet resistance of the unpassivated devices is reduced from $850 \text{ }\Omega/\square$ after the substrate transfer. Similar sheet-resistance reduction

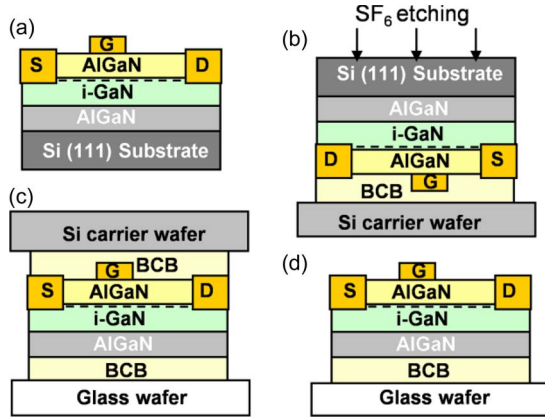


Fig. 1. Process flow of the substrate-transfer technology. (a) Standard AlGaIn/GaN HEMT on Si substrate. (b) Bonding to a Si carrier wafer and Si (111) substrate removal. (c) GaN/AlGaIn buffer bonded to a glass wafer. (d) Final device, after releasing the carrier wafer.

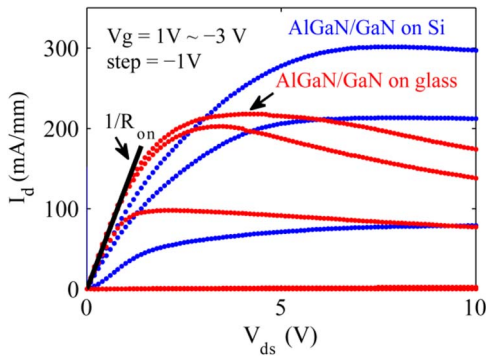


Fig. 2. I_d - V_{ds} characteristics of the AlGaIn/GaN HEMTs with $L_{gd} = 5 \mu\text{m}$ before and after Si substrate removal and substrate transferring.

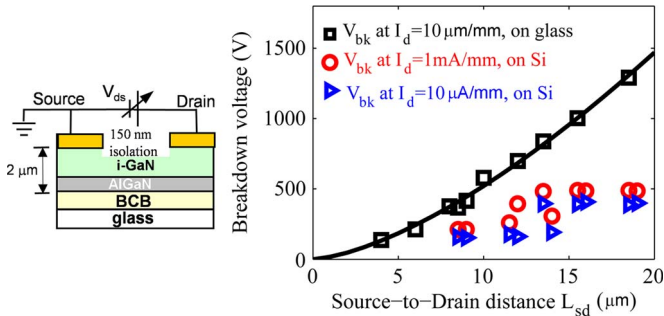


Fig. 3. Two-terminal buffer breakdown voltage as a function of L_{sd} of devices before and after being transferred to a glass wafer.

has also been reported in [13] and [14]. The origin of the sheet-resistance reduction is not clear at this moment. It may be due to the change of mechanical strain of the film.

The two-terminal buffer breakdown voltage (V_{bk}) was measured on structures where source and drain contacts were isolated by 150-nm-deep BCl₃/Cl₂ plasma etching, as shown in Fig. 3. The breakdown voltage is defined as the voltage when the leakage current reaches 10 μA/mm. As shown in Fig. 3, the breakdown voltage of the devices on the Si substrate saturates around 500 V for source-to-drain distances (L_{sd}) above 14 μm. However, no buffer breakdown saturation is observed after the removal of the Si substrate, which is a direct proof that the Si substrate is the limiting factor for the maximum breakdown voltage of the AlGaIn/GaN-on-Si HEMTs.

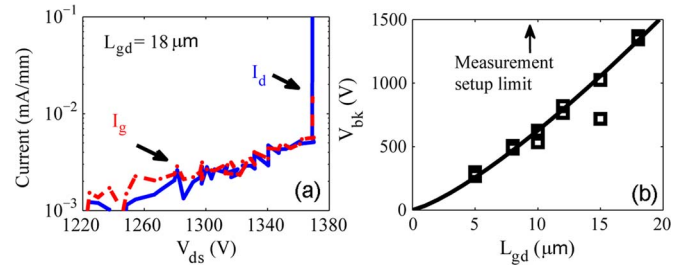


Fig. 4. (a) Three-terminal leakage current for an AlGaIn/GaN HEMT on glass with $L_{gd} = 18 \mu\text{m}$ at $V_{gs} = -8 \text{V}$. For $V_{ds} < 1220 \text{V}$, the leakage current is below the sensitivity of our measurement setup (1 μA/mm). (b) Three-terminal V_{bk} as a function of L_{gd} .

By fitting the data of V_{bk} as a function of L_{sd} in the devices transferred to the glass wafer, a relation $V_{bk} \sim L_{sd}^{1.50}$ is extracted with the exponential coefficient in a 95% confidence bound of (1.38, 1.62). This dependence suggests the space-charge-limited (SCL) transport [15] in the leakage current. According to the SCL transport theory, the current can be expressed as $J = 9\epsilon\mu V^2/8L^3$ (ϵ is the dielectric constant; μ is effective carrier mobility including trapping effect; V is the applied voltage, and L is the distance between the two contacts). For a constant current ($I_d = 10 \mu\text{A/mm}$ for the V_{bk} measurement), the applied voltage between the two contacts can therefore be expressed as $V = \sqrt{8J/9\epsilon\mu}L^{1.5}$. However, further investigation is needed to confirm the presence of the SCL transport in these devices.

The three-terminal V_{bk} of the AlGaIn/GaN HEMTs transferred to a glass wafer was measured at $V_{gs} = -8 \text{V}$. As shown in Fig. 4(a), a device with $L_{gd} = 18 \mu\text{m}$ shows a V_{bk} of 1370 V at $I_d = 10 \mu\text{A/mm}$. As the drain-to-source leakage is negligible, the drain-to-gate leakage limits the breakdown in these devices. V_{bk} as a function of L_{gd} is shown in Fig. 4(b). Devices with $L_{gd} = 20 \mu\text{m}$ did not break down within the 1500 V measurement range of our measurement setup.

To explain the three-terminal breakdown data using the SCL transport model, the electric field at the Schottky gate contact needs to be considered. By combining (1)–(3) for the electron-conducting current

$$J = e\mu nE \quad (1)$$

$$dE/dx = -en/\epsilon \quad (2)$$

$$V_{dg} = \int_0^{L_{gd}} E dx \quad (3)$$

where J is the current density, e is the electron charge, μ is the effective mobility including trapping effect, n is the electron concentration, E is the electric field strength, and V_{dg} is the drain-to-gate voltage, we get

$$V_{dg} = A \left[(2L_{gd}/A + E_{in}^2)^{1.5} - E_{in}^3 \right] / 3 \quad (4)$$

where $A = \epsilon\mu/J$ and E_{in} is the electric field at the gate.

Since the gate voltage is much smaller than the drain voltage V_{ds} , (4) can be written as

$$V_{ds} \cong V_{dg} = A \left[(2L_{gd}/A + E_{in}^2)^{1.5} - E_{in}^3 \right] / 3. \quad (5)$$

Fitting the data of V_{bk} versus L_{gd} in Fig. 4(b), E_{in} is extracted to be 0.46 MV/cm in a 95% confidence bound of

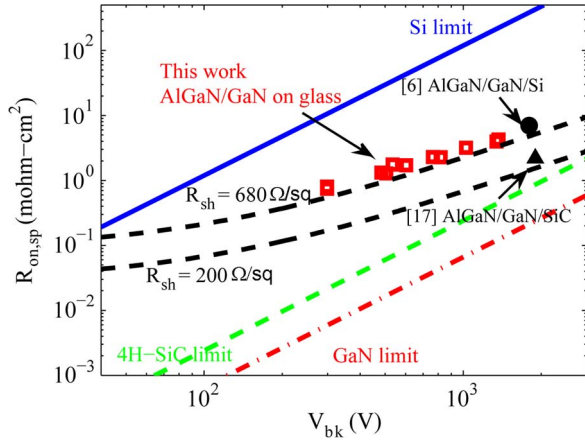


Fig. 5. $R_{on,sp}$ - V_{bk} plot of AlGaIn/GaN HEMTs transferred to a glass wafer. The figure also shows the highest breakdown voltage reported for an AlGaIn/GaN-on-Si HEMT (total epitaxial thickness of 6 μm) [6] and for an AlGaIn/GaN-on-SiC transistor [17].

(0.35 MV/cm, 0.57 MV/cm), and $A = \varepsilon\mu/J$ is 0.0054 $\mu\text{m}^3/\text{V}^2$ in a 95% confidence bound of (0.0032 $\mu\text{m}^3/\text{V}^2$, 0.0075 $\mu\text{m}^3/\text{V}^2$).

From (1)–(3), the electric field at the drain contact can be calculated

$$E_{\text{drain}} = \sqrt{2L_{\text{gd}}/A + E_{\text{in}}^2}.$$

For a device with $L_{\text{gd}} = 20 \mu\text{m}$, at the onset of breakdown at $I_d = 10 \mu\text{A}/\text{mm}$, the electric field at the drain contact is between 0.81 and 1.25 MV/cm, which is smaller than the critical electric field of the GaN. This result shows that even after removing the Si substrate, the breakdown voltage of these devices is not limited by impact ionization.

The specific on-resistance ($R_{on,sp}$) of these devices was extracted from the I - V characteristics (Fig. 2) and using the active area between the source and drain contacts, including a 2- μm transfer length from the contact pads. The plot of V_{bk} versus $R_{on,sp}$ is shown in Fig. 5, where the theoretical limit lines of Si, SiC, and GaN are calculated using the equation $R_{on,sp} = 4V_{bk}^2/(\varepsilon\mu E_c^3)$ in [16]. The measured data of the AlGaIn/GaN HEMTs on the glass substrate deviate from the GaN-limit line, particularly in the lower voltage range. A better theoretical GaN-limit line of our devices can be calculated by combining (5) with (6) and (7)

$$R_{on,sp} = R_{sh}L_{sd}(L_{sd} + L_{pads}) + 2R_cW(L_{sd} + L_{pads}) \quad (6)$$

$$L_{sd} = L_{gs} + L_g + L_{gd} \quad (7)$$

where R_{sh} is the sheet resistance ($R_{sh} = 680 \Omega/\square$), R_c is the contact resistance ($R_cW = 0.66 \Omega \cdot \text{mm}$ from the TLM measurement), and L_{pads} is the transfer length from source and drain contact pads (2 μm in the calculation). The calculated $R_{on,sp}$ - V_{bk} curve is plotted and shown in Fig. 5. Reducing the R_{sh} is very effective in reducing the $R_{on,sp}$, as shown in Fig. 5, by the line for $R_{sh} = 200 \Omega/\square$. Such low sheet resistance has been demonstrated in [18].

IV. SUMMARY

This letter has demonstrated a new substrate-transfer technology to improve the breakdown voltage of AlGaIn/GaN HEMTs

grown on Si substrates. By removing the Si substrate and transferring the AlGaIn/GaN HEMTs to a glass wafer, a device with $R_{on} = 20.6 \Omega \cdot \text{mm}$ and $L_{sd} = 23.5 \mu\text{m}$ showed a more than 1500-V breakdown voltage and $R_{on,sp}$ of 5.3 $\text{m}\Omega \cdot \text{cm}^2$ for only 2- μm total epilayer thickness. The performance of the devices can be improved even further by bonding the GaN epilayer to a carrier wafer with higher thermal conductivity, such as the polycrystalline AlN wafers.

REFERENCES

- [1] Y.-F. Wu, M. J. Mitos, M. L. Moore, and S. Heikman, "A 97.8% efficient GaN HEMT boost converter with 300-W output power at 1 MHz," *IEEE Electron Device Lett.*, vol. 29, no. 8, pp. 824–826, Aug. 2008.
- [2] K. Cheng, M. Leys, S. Degroote, J. Derluyn, B. Sijmus, P. Favia, O. Richard, H. Bender, M. Germain, and G. Borghs, "AlGaIn/GaN high electron mobility transistors grown on 150 mm Si(111) substrates with high uniformity," *Jpn. J. Appl. Phys.*, vol. 47, no. 3, pp. 1553–1555, Mar. 2008.
- [3] D. Visalli, M. V. Hove, J. Derluyn, S. Degroote, M. Leys, K. Cheng, M. Germain, and G. Borghs, "AlGaIn/GaN/AlGaIn double heterostructures on silicon substrates for high breakdown voltage field-effect transistors with low on-resistance," *Jpn. J. Appl. Phys.*, vol. 48, no. 4, p. 04C 101, Apr. 2009.
- [4] B. Lu, E. L. Piner, and T. Palacios, "Schottky-drain technology for AlGaIn/GaN high-electron mobility transistors," *IEEE Electron Device Lett.*, vol. 31, no. 4, pp. 302–304, Apr. 2010.
- [5] S. L. Selvaraj, T. Suzue, and T. Egawa, "Breakdown enhancement of AlGaIn/GaN HEMTs on 4-in silicon by improving the GaN quality on thick buffer layers," *IEEE Electron Device Lett.*, vol. 30, no. 6, pp. 587–589, Jun. 2009.
- [6] N. Ikeda, S. Kaya, J. Li, Y. Sato, S. Kato, and S. Yoshida, "High power AlGaIn/GaN HFET with a high breakdown voltage of over 1.8 kV on 4 inch Si substrates and the suppression of current collapse," in *Proc. 20th Int. Symp. Power Semicond. Devices IC's*, May 2008, pp. 287–290.
- [7] S. Arulkumaran, T. Egawa, S. Matsui, and H. Ishikawa, "Enhancement of breakdown voltage by AlN buffer layer thickness in AlGaIn/GaN high-electron-mobility transistors on 4 in. diameter silicon," *Appl. Phys. Lett.*, vol. 86, no. 12, pp. 123 503-1–123 503-3, Mar. 2005.
- [8] Y. C. Choi, M. Pophristic, H.-Y. Cha, B. Peres, M. G. Spencer, and L. F. Eastman, "The effect of an Fe-doped GaN buffer on OFF-state breakdown characteristics in AlGaIn/GaN HEMTs on Si substrate," *IEEE Trans. Electron Devices*, vol. 53, no. 12, pp. 2926–2931, Dec. 2006.
- [9] Y. Niiyama, S. Kato, Y. Sato, M. Iwami, J. Li, H. Takehara, H. Kambayashi, N. Ikeda, and S. Yoshida, "Fabrication of AlGaIn/GaN HFET with a high breakdown voltage on 4-inch Si (111) substrate by MOVPE," in *Mater. Res. Soc. Symp. Proc.*, 2007, vol. 955E, pp. 369–374.
- [10] J. W. Johnson, E. L. Piner, A. Vescan, R. Therrien, P. Rajagopal, J. C. Roberts, J. D. Brown, S. Singhal, and K. L. Linthicum, "12 W/mm AlGaIn-GaN HFETs on silicon substrates," *IEEE Electron Device Lett.*, vol. 25, no. 7, pp. 459–461, Jul. 2004.
- [11] D. Lauvernier, J. P. Vilcot, S. Garidel, S. McMurtry, and D. Decoster, "Benzocyclobutene wafer bonding for III-V nanophotonic guiding structures," *Electron. Lett.*, vol. 41, no. 21, pp. 1170–1172, Oct. 2005.
- [12] K. Ryu and T. Palacios, unpublished.
- [13] J. W. Chung, E. L. Piner, and T. Palacios, "N-face GaN/AlGaIn HEMTs fabricated through layer transfer technology," *IEEE Electron Device Lett.*, vol. 30, no. 2, pp. 113–116, Feb. 2009.
- [14] J. W. Chung, J. Lee, E. L. Piner, and T. Palacios, "Seamless on-wafer integration of GaN HEMTs and Si(100) MOSFETs," *IEEE Electron Device Lett.*, vol. 30, no. 10, pp. 1015–1017, Oct. 2009.
- [15] M. A. Lampert, "Simplified theory of space-charge-limited currents in an insulator with traps," *Phys. Rev.*, vol. 103, no. 6, pp. 1648–1656, Sep. 1956.
- [16] B. J. Baliga, "Power semiconductor device figure of merit for high-frequency applications," *IEEE Electron Device Lett.*, vol. 10, no. 10, Oct. 1989.
- [17] Y. Dora, A. Chakraborty, L. McCarthy, S. Keller, S. P. Denbaars, and U. K. Mishra, "High breakdown voltage achieved on AlGaIn/GaN HEMTs with integrated slant field plates," *IEEE Electron Device Lett.*, vol. 27, no. 9, pp. 713–715, Sep. 2006.
- [18] Y. Kawakami, X. Q. Shen, G. Piao, M. Shimizu, H. Nakanishi, and H. Okumura, "Improvements of surface morphology and sheet resistance of AlGaIn/GaN HEMT structures using quasi AlGaIn barrier layers," *J. Crystal Growth*, vol. 300, no. 1, pp. 168–171, Mar. 2007.