2kV Breakdown Voltage GaN–on-Si DHFETs with Sub-micron Thin AlGaN Buffer

P. Srivastava[1,2], K. Cheng[1], J. Das[1], M. Van hove[1], M. Leys, D. Marcon[1], D. Visalli, K. Geens, S. Decoutere[1], R. P. Mertens[1,2] and G. Borghs[1,2]

[1]IMEC, Kapeldreef-75, Leuven, Belgium
[2]Katholieke Universiteit Leuven, Leuven, Belgium
Tel: +32 16 28 8346, Fax: +32 16 28 1097, E-mail: Puneet.Srivastava@imec.be

Keywords: GaN-on-Si, DHFETs, Thin buffer, Si removal, Breakdown voltage

Abstract

We present a cost effective approach to realize high breakdown voltage (V_{BD}) of AlGaN/GaN/AlGaN double-heterostructure FETs (DHFETs) having thin AlGaN buffer layers on Si (111) substrates by Si removal. We observe that after Si removal, the buffers and devices V_{BD} are enhanced and independent for different buffer thicknesses (600 nm, 1 µm and 2 µm). The buffers and devices V_{BD} show a linear increase with electric field strength of ~2.5 MV/cm and ~1 MV/cm respectively for all the buffer thicknesses. A device with L_{GD} = 20 µm having only 600 nm thick buffer, shows a V_{BD} of over ~ 2000 V, however very thick buffer layers needed to achieve such a high V_{BD} with Si substrate. The Hall data for all epi-layers with AlGaN buffer down to 600 nm show similar values.

INTRODUCTION

GaN-HEMTs are foreseen to contribute significantly towards improved efficiency and downsizing the power supplies since the devices have the potential of realizing high breakdown voltages (V_{BD}) and low on-state resistances (R_{ON}). AlGaN/GaN/AlGaN DHFETs device architectures are very promising for high power applications because of the improved carriers confinement and higher V_{BD} of the AlGaN buffer [1]. Si is the primary choice for III-N epitaxial growth because of its low cost and large size availability. However, devices fabricated on the Si substrates suffer from early breakdown due to conduction from source-to-drain across AlN/Si interface [2-5]. A technique to enhance the V_{BD} is to increase III-N buffer thickness [6-7]. To obtain a V_{BD} of over 2 kV, a buffer as thick as ~7 µm is reported [8] but this imposes several technological challenges. The wafer bow increases and therefore the wafers are prone to cracking [9]. This can hinder the epitaxial growth scaling over larger wafer sizes. Moreover, the need of thick buffer layers significantly increases the growth cost.

We have demonstrated enhanced V_{BD} of GaN DHFETs on Si substrates by Si removal via global or local Si removal schemes [3-5]. The scope of present work is the realization of enhanced V_{BD} of GaN-DHFETs on thin AlGaN buffer after Si removal. We present for the first time that after Si removal, the buffer and device V_{BD} do not depend on buffer thicknesses because the path from S-to-D across AlN/Si interface is interrupted. After Si removal [3], buffer and device V_{BD} show a linear increase with electric field strength of ~2.5 MV/cm and ~1 MV/cm respectively for different buffer thicknesses (600 nm, 1 µm, 2 µm). The maximum V_{BD} of ~ 2000 V is observed for a gate-drain distance (L_{GD}) of only 20 µm, however, the maximum V_{BD} for a 2 µm thick buffer is only 650 V with Si. We believe that the growth of thin buffers on Si, followed by Si removal, is a promising route to manufacture low cost high voltage GaN devices.

LAYER GROWTH AND DEVICE FABRICATION

DHFETs are fabricated starting from MOCVD grown $Si_3N_4/Al_{0.35}Ga_{0.65}N/GaN/Al_{0.18}Ga_{0.82}N$ hetero-structure layers on Si (111) substrate, with a thick *in-situ* Si_3N_4 cap layer. [9]. In the present study, 4-different $Al_{0.18}Ga_{0.82}N$ buffer thicknesses of 330 nm, 600 nm, 1 µm and 2 µm are grown. For all layers the thicknesses of $Al_{0.35}Ga_{0.65}N$ barrier layer and GaN channel are 25 nm and 150 nm. For device processing, the following steps are executed: device isolation (implantation), ohmic contact formation, gate recess etching, Schottky-gate metallization and deposition of an inter-connect layer. The fabricated buffer structures have varying ohmic gaps and DHFETs have S-G distance L_{SG} = 1.5 µm, gate-length L_G = 1.5 µm, G-D distance L_{GD} = 5 - 20 µm and a total gate width W_G = 200 µm (Fig. 1).

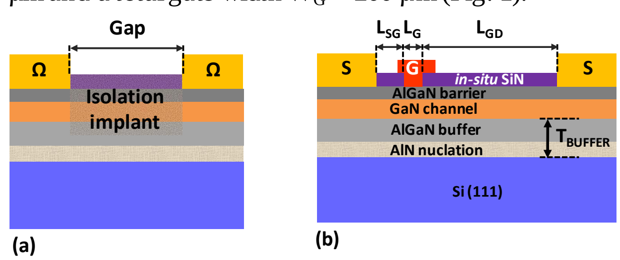

Fig 1. Schematic cross-sectional view of (a) buffer isolation test structure and (b) DHFET device. Ω = ohmic contact, T_{BUFFER} = total buffer thickness.

MEASUREMENT AND RESULTS

The 2-DEG properties of GaN channel are first characterized before Si removal to identify the layer quality. Fig. 2 shows the Hall values: the sheet resistance (R_{SH}), mobility (µ) and sheet carrier concentration (N_S) as a function of AlGaN buffer thicknesses. It is evident that the 2-DEG channel properties remain identical for epilayers with the AlGaN buffer thickness down to 600 nm. However, significant channel degradation is observed for 330 nm thick buffer. We can conclude that most of the active dislocations (threading, screw or mixed) are well within the first ~ 600 nm part of the buffer. The good quality of the channel layer is confirmed by similar R_{ON} and I_{DSAT} values for devices with 600 nm and 1 µm buffer (Fig. 3). Therefore, for Si removal study, buffer thicknesses of 600 nm, 1 µm and 2 µm are used.

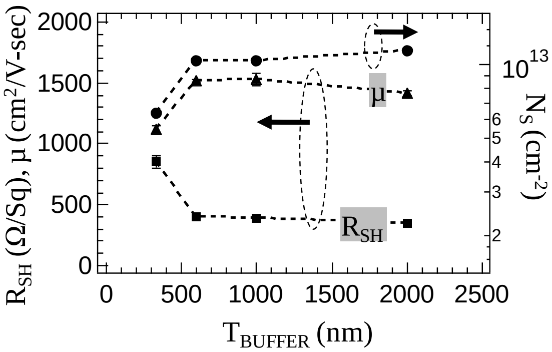

Fig. 2. Hall measurement for different buffer thicknesses.

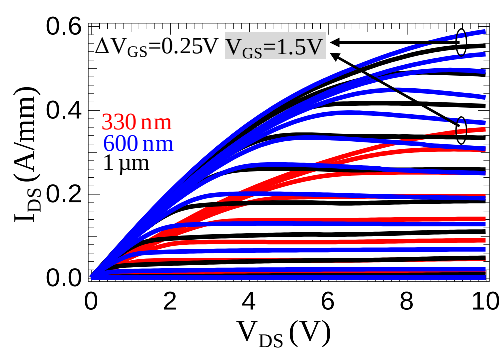

Fig. 3. I_{DS}-V_{DS} characteristics for different buffer thicknesses.

We define V_{BD} for buffer isolation structure and for devices as the voltage at which the leakage current increases to 1 mA/mm. However, a hard breakdown is observed for DHFETs in case of Si removal, and is marked as the V_{BD}. We believe that the observed hard breakdown is related to the intrinsic breakdown of the III-N materials.

Before Si removal, we observe V_{BD} saturation at ~ 200 V, ~300 V and ~ 650 V for buffer thicknesses of 600 nm, 1 µm and 2 µm respectively for both buffer structures and DHFETs. After Si removal, there is no V_{BD} saturation and a linear increase with the ohmic-gap and L_{GD} is observed for both the buffer structures and DHFETs. The V_{BD} ~ 2000 V for an ohmic-gap of only 8 µm is measured (Fig. 4). Moreover, for DHFETs with L_{GD} = 20 µm, a V_{BD} of ~ 2000 V is observed as depicted in Fig. 5. Therefore, we can conclude that after Si removal peak electric field for buffer structure and DHFETs (towards D-side of the G-electrode) determines V_{BD} rather than the AlGaN buffer thickness.

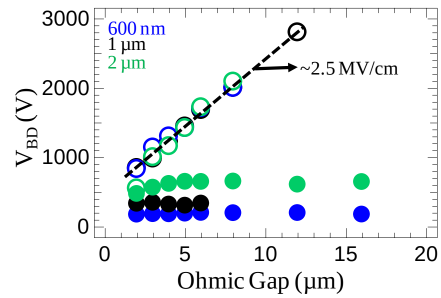

Fig. 4. Buffer V_{BD} for varying gaps for different buffer thicknesses. Buffer V_{BD} shows ~ 2.5 MV/cm after Si removal. Solid circles are V_{BD} with Si and open circles are measurement after Si removal.

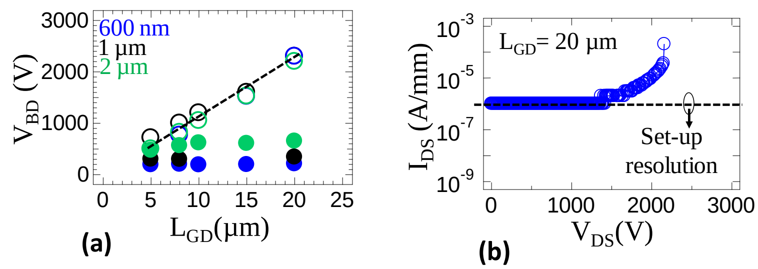

Fig. 5. (a) Device V_{BD} for varying L_{GD} for different buffer thicknesses. (b) Off-state (V_{GS} = -8 V) I_{DS}-V_{DS} curve of a device with L_{GD} = 20 µm with buffer thickness of 600 nm. Solid circles are V_{BD} with Si and open circles are measurements after Si removal.

CONCLUSIONS

We investigated GaN-DHFETs for different AlGaN buffer thicknesses with Si and after Si substrate removal. Thin buffer layers showed good quality channel properties confirmed by the Hall measurements. We observed V_{BD} scaling trends before Si removal for 600 nm, 1 µm and 2 µm thick buffers. However, we confirm that after the Si removal, V_{BD} does not depend of the buffer thickness. We observed a V_{BD} of over ~ 2000 V for a L_{GD} of only 20 µm. A linear increase of V_{BD} as function of L_{GD} is observed with average electric field strength of ~1.0 MV/cm. This confirms that the growth of thin buffers combined with Si removal is a promising solution to obtain low cost, high yield and high manufacturability of high voltage GaN devices.

REFERENCES

[1] M. Micovic *et. al*, IEDM Tech. Dig., 2004.
[2] H. Umeda, *et. al*, IEDM Tech. Dig., 2010.
[3] P. Srivastava, *et. al*, Ele. Dev. Lett., vol. 31, no. 8, pp. 851–853, 2010.
[4] P. Srivastava, *et. al*, Ele. Dev. Lett., vol. 32, no. 1, pp. 30–32, 2011.
[5] P. Srivastava, *et. al*, IEDM Tech. Dig., 2011 (accepted).
[6] N. Ikeda, *et. al* 20th ISPSD., 2008 Oralando, FL.
[7] N. Ikeda, *et. al*, 21st ISPSD., 2009 Barcelona.
[8] S. L. Selvaraj, *et. al*, Ele. Dev. Lett., vol. 30, no. 6, 587–589, 2009.
[9] J. Derluyn, *et. al*, J. Appl. Phys., 98, 054501 (2005).

ACRONYMS

MOCVD: Metal Organic Chemical Vapor Deposition
2-DEG: Two Dimensional Electron Gas
DHFET: Double Hetero-structure Field Effect Transistor
T_{BUFFER}: Buffer Thickness
V_{BD}: Breakdown Voltage