The impact of the gate dielectric quality in developing Au-free D-mode and E-mode recessed gate AlGaIn/GaN transistors on a 200mm Si substrate

Tian-Li Wu^{1,2}, Denis Marcon¹, Brice De Jaeger¹, Marleen Van Hove¹, Benoit Bakeroort^{1,3}, Dennis Lin¹, Steve Stoffels¹, Xuanwu Kang¹, Robin Roelofs⁴, Guido Groeseneken^{1,2}, and Stefaan Decoutere¹

¹imec, Kapeldreef 75, Leuven, Belgium

²Department of Electrical Engineering, KU Leuven, Belgium

³Center for Microsystem Technology, Ghent University, Belgium

⁴ASM, Kapeldreef 75, Leuven, Belgium

Phone: +32 (0) 16-283492, Tian-Li.Wu@imec.be

Abstract— The selection of the gate dielectric is one of the most critical stability issues in recessed gate AlGaIn/GaN transistors. In this work, we show that the quality of the gate dielectric has a strong impact on: 1) the threshold voltage (V_{TH}) hysteresis, 2) the drain current reduction for enhancement mode devices, and 3) the forward gate bias TDDb (time dependent dielectric breakdown). It will be shown that the V_{TH} hysteresis and the current reduction can be minimized by using a dielectric with lower interface state density (D_{it}) and less border traps, e.g., a PE-ALD SiN dielectric. Furthermore, the 0.01% failures at 20 years TDDb requirement at 150°C for a large power device, e.g., gate width $W_g=36mm$, necessitates the use of at least a 25nm-thick PE-ALD SiN gate dielectric.

Keywords—AlGaIn/GaN; recessed gate; gate dielectric; PE-ALD SiN; interface states; border traps; depletion mode; enhancement mode

INTRODUCTION

AlGaIn/GaN Metal Insulator Semiconductor High Electron Mobility Transistors (MIS-HEMTs) are considered as promising candidates for power switching applications due to a low gate leakage current [1]. A recessed gate process is often used to achieve an E-mode characteristic [2][3][4][5]. Then, the properties of the interface and the quality of the gate dielectric become the most challenging reliability issues. Recently, high quality gate dielectrics in D-mode [6][7][8] and E-mode [3][4][5][9] devices have been demonstrated and characterized. However, the detailed analysis of the correlation of interface states/border traps and device characteristics is still missing. In this work, the impact of the interface properties and the quality of the gate dielectrics on both D-mode and E-mode device characteristics is extensively evaluated in recessed gate transistors with three different recess depths. A frequency dependent conductance analysis and an AC transconductance (AC- g_m) technique are used to examine the interface states and the border traps for different gate dielectrics. These analyses are then correlated to the electrical characteristics, i.e., the threshold voltage (V_{TH}) hysteresis and the drain current. The physical mechanisms to explain these results are proposed. Finally, the time dependent

dielectric breakdown (TDDb) methodology is used to evaluate the strength of the gate dielectric and predict the lifetime.

DEVICE FABRICATION

All samples were fabricated with a Au-free CMOS compatible process on 200 mm Si (111) wafers, starting with an AlN nucleation layer, a 2.3 μm AlGaIn buffer, a 150nm GaN channel, a 15nm Al_{0.25}Ga_{0.75}N barrier, and a 3 nm GaN cap layer. Three different recess depths of AlGaIn barrier are listed in Table 1. A recessed gate is commonly used to reduce the 2DEG under the gate, leading to an enhancement mode characteristic. The schematics of the devices with three different recessed gate depth are shown in Fig. 1 and Fig. 7. The summary of the important process parameters is shown in Table. 1. Two different gate dielectrics, Plasma-Enhanced ALD (PE-ALD) SiN deposited in an ASM system, and Rapid Thermal CVD (RTCVD) SiN were used as a gate dielectric on these devices after a HF2% clean.

Table 1. Summary of important process parameters

Device	Recess depth (AlGaIn barrier)	Gate dielectric thickness
D-mode MIS-HEMT	14.3nm (3.7nm)	15nm
E-mode MIS-HEMT	16.5nm (1.5nm)	25nm
E-mode MIS-FET	21.7nm (-3.7nm*)	25nm

*-3.7nm remaining AlGaIn barrier indicates 3.7nm etching depth into the GaN channel.

RESULTS AND DISCUSSIONS

A. Recessed gate D-mode AlGaIn/GaN transistor:

Fig. 1. Schematic cross-section of a D-mode recessed gate MIS-HEMT with 3.7nm remaining AlGaIn barrier.

In order to characterize the interface properties of the gate region between the gate dielectric and the AlGaIn barrier shown in Fig. 1, a frequency dependent conductance analysis was done on a capacitor to extract the interface state density (D_{it}) [10]. A positive gate bias is needed to transfer the electrons from the channel to the interface between the AlGaIn barrier and the gate dielectric to interact with the interface states. Therefore, the following conditions are measured on the capacitor structures: $V_G=2.4V\sim3.4V$ (RTCVD SiN) and $V_G=3V\sim4V$ (PE-ALD SiN). In this case, please note that we consider the electrons only interact with the interface state rather than the border traps, which will be discussed in the next paragraph. Fig. 2 shows the extracted D_{it} values at the interface between the gate dielectric and the AlGaIn barrier. The D_{it} is significantly lower for the device with a PE-ALD SiN ($D_{it}\sim1\times10^{11}\sim2.3\times10^{12}cm^{-2}eV^{-1}$) gate dielectric than for the device with an RTCVD SiN ($D_{it}\sim3.3\times10^{13}\sim3.5\times10^{13}cm^{-2}eV^{-1}$) gate dielectric.

Furthermore, these devices were further characterized using the AC transconductance (AC- g_m) technique (Fig. 3). This technique examines the effect of border traps on the carrier transport and the amount of AC- g_m dispersion reflects the border trap density in the gate dielectric [11]. A significantly lower g_m peak dispersion was observed in the device with a PE-ALD SiN gate dielectric compared with the device with an RTCVD SiN (Fig. 4) gate dielectric. Fig. 5 shows the typical I_D - V_G characteristics with a double V_G sweep. Under a positive gate voltage, the conduction band of the AlGaIn barrier is pulled down.

Based on the aforementioned characterizations, the electrons can be transferred from the channel to the interface between the gate dielectric and the AlGaIn barrier, where they are trapped by interface states or border traps (Fig. 6), leading to the V_{TH} hysteresis. Again, the device with a PE-ALD SiN gate dielectric shows less hysteresis compared with the other one. According to [12], the plasma enhanced deposition results in a better surface reaction due to additional energy from the ion bombardment in the plasma step. Therefore, in order to minimize the hysteresis, a good dielectric quality with a lower D_{it} and less border traps is mandatory.

Fig. 2. D_{it} measurement of MIS-HEMTs with 3.7nm remaining AlGaIn barrier on a capacitor. The trap state energy was estimated based on the Shockley-Read-Hall statistical model with a capture cross-section $1\times10^{-15}cm^2$.

Fig. 3. Diagram of the AC- g_m measurement setup. A dc bias mixed with an ac sinusoidal signal ($V_{rms}=20$ mV) is applied on the gate while a small dc bias (50 mV) is applied on the drain to inject the carriers across the channel.

Fig. 4. g_m dispersion characteristics for 3.7nm remaining AlGaIn barrier with an RTCVD SiN (a), or a PE-ALD SiN (b) gate dielectric.

Fig. 5. I_D - V_G characteristics of the devices with 3.7nm remaining AlGaIn barrier with an RTCVD SiN ($V_{TH} = -1.3V$) (a), or a PE-ALD SiN ($V_{TH} = -1V$) (b) gate dielectric. The V_{TH} hysteresis is 1V and 0.3V, respectively.

Fig. 6. Schematic band diagram indicating that electrons can be trapped by the interface states or the border traps under a positive gate bias condition.

Fig. 7. Schematic cross-section of the E-mode recessed gate MIS-FETs with 1.5nm remaining AlGaIn barrier (a) and 3.7nm etch depth into the GaN channel (b).

Fig. 7 shows the schematics of the E-mode transistors with two different remaining AlGaIn barrier thickness under the gate region. Fig. 8 shows the I_D - V_G characteristics and the transconductance (g_m) for devices with a 1.5nm remaining AlGaIn barrier. Considering a D-mode and an E-mode device, the device with an RTCVD SiN gate dielectric shows a more pronounced current drop and g_m degradation compared to the one with a PE-ALD SiN gate dielectric

Fig. 8. I_D - V_G and g_m - V_G characteristics of the devices with 1nm remaining AlGaIn barrier. The V_{TH} is 0V and 0.6V, respectively for a PE-ALD SiN and an RTCVD SiN gate dielectric.

To increase the V_{TH} , the AlGaIn barrier can be completely recessed into the GaN channel, resulting in an E-mode MIS-FET rather than a MIS-HEMT (Fig. 7(b)). Fig. 9 shows the I_D - V_G and the g_m of the recessed gate MIS-FETs. The device with an RTCVD SiN gate dielectric shows extremely lower current and g_m compared with the one with a PE-ALD SiN gate dielectric. Fig. 10 and Fig. 11 summarize how the I_D and g_m peak drop when the V_{TH} is increased. For a negative V_{TH} of -1V, both devices have similar current. However, The device with an RTCVD SiN gate dielectric shows a much more pronounced current drop and g_m degradation once the V_{TH} is above 0V. Strongly or completely recessing the AlGaIn barrier not only reduces the carrier concentration under the gate region but also brings the interface under the gate dielectric close to the channel (Fig. 12). Indeed, g_m degradation could be either due to the change in carrier concentration or the change in carrier velocity [13]. However, the closer the traps to the GaN channel are, the stronger the electron scattering happens. So, such strong electron scattering could lead to serious mobility degradation, resulting in much more g_m degradation and current drop for the device with an RTCVD SiN gate dielectric. Yet, in a device with a better quality gate dielectric, i.e., a lower D_{it} or less border traps, the current drop can be minimized as shown in the I_D - V_D characteristics comparison of

a fully recessed MIS-FET with a PEALD SiN and an RTCVD SiN (Fig. 13) gate dielectric.

Fig. 9. I_D - V_G characteristics of the GaN-MISFET devices. I_D is below $1E-8$ mA/mm at $V_G=0V$ (inset figure). The V_{TH} is 1.1V and 1.3V, respectively for a PE-ALD SiN and an RTCVD SiN gate dielectric.

Fig. 10. g_m peak transconductance vs. V_{TH} (left) and I_D vs. V_{TH} (right) on devices with a PE-ALD SiN and an RTCVD SiN gate dielectric.

Fig. 11. I_D for a fixed gate overdrive of 4V, and $V_D=10V$.

Fig. 12. A poor quality gate dielectric, such as an RTCVD SiN, the electrons in the channel can easily be trapped by interface states or border traps. The closer these traps to the GaN channel are (a thinner and thinner AlGaIn barrier shown from (a) to (c)), the stronger the scattering happens. This results in serious g_m degradation and current drop (Fig. 10 and Fig. 11). However, this issue can be reduced by using a high quality gate dielectric, such as a PE-ALD SiN.

Fig. 13. I_D - V_D characteristics of the E-mode MIS-FETs with an RTCVD SiN gate dielectric (a) and a PE-ALD SiN gate dielectric (b).

Furthermore, gate dielectric quality not only has a strong influence on the gate leakage current but also on time dependent dielectric breakdown (TDDB). In Fig. 14(a), the I_G - V_G characteristics for both gate dielectrics are compared. The devices with 25nm/35nm PE-ALD show less than $1\mu\text{A}/\text{mm}$ of I_G at $V_G=15\text{V}$. Fig. 14 also shows the TDDB experiments for the devices with PE-ALD SiN. The distribution of the t_{BD} statistically follows the Weibull distribution and the lifetime could be predicted with scaling to low percentage failure on devices with a large gate width (Fig. 15). For a 25nm PE-ALD SiN gate dielectric, an operating voltage can be determined by either an exponential law (4.9V) or a power law (7.2V) after scaling to 0.01% at 20 years for devices with $W_g=36\text{mm}$. This suggests the gate dielectric strength should be sufficiently high in order to have enough TDDB margin. Furthermore, TDDB margin is highly enhanced on the devices with a 35nm PE-ALD gate dielectric (13V (an exponential law) or 15.5V (a power law)). This could be contributed by a thick gate dielectric, which can increase the dielectric strength and reduce the possibility to form the percolation path around the recessed gate corner [14].

Fig. 14. (a) I_G - V_G characteristics of E-mode MIS-FETs. (b) Gate current monitored with three different gate voltages (10 devices per V_G). The small gate width ($W_g=10\mu\text{m}$) devices were used to study the intrinsic reliability. The calculated β from the Weibull plot (not shown here) is 1.9 (25nm thickness) and 2.67 (35nm thickness), respectively.

Fig. 15. Lifetime extrapolation of t_{BD} at 150°C towards low bias conditions can either by an exponential law (solid line) or a power law (dash line).

CONCLUSIONS

In summary, the impact of the interface properties and the quality of the gate dielectrics have been comprehensively investigated in D-mode and E-mode recessed gate transistors. We have observed three main issues: 1) the V_{TH} hysteresis, 2) the drain current reduction for a deep gate recess, and 3) the forward gate bias TDDB reliability. The hysteresis is highly correlated with the interface states and/or border traps due to the trapping/de-trapping under a positive gate bias. When the gate dielectric interface is very close to the GaN channel, the current is strongly reduced because of the increased scattering between the electrons and the interface states/border traps, leading to g_m degradation, which is probably due to mobility degradation. However, this current drop could be minimized by using a good quality gate dielectric, such as a PE-ALD SiN which has lower D_{it} and less border traps. Finally, not only the gate leakage current but also the gate dielectric TDDB reliability is needed to be taken into account. In the case of PE-ALD SiN, the minimum gate dielectric thickness to provide enough gate overdrive with a sufficient TDDB margin is 25nm. Furthermore, a 35nm PE-ALD SiN gate dielectric can highly boost the TDDB margin.

REFERENCES

- [1] M. Van Hove *et al*, "CMOS Process-Compatible High-Power Low-Leakage AlGaIn/GaN MISHEMT on Silicon," *IEEE Electron Device Letters*, vol. 33, no. 5, pp. 667-669, May. 2012.
- [2] B. De Jaeger *et al*, "Au-free CMOS-compatible AlGaIn/GaN HEMT processing on 200 mm Si substrates," *Proc. Int. Symp. Power Semiconductor Devices and IC's (ISPSD)*, pp. 49-52, 2012.
- [3] W. Choi *et al*, "High-Voltage and Low-Leakage-Current Gate Recessed Normally-Off GaN MIS-HEMTs With Dual Gate Insulator Employing PEALD-SiNx/RF-Sputtered-HfO₂," *IEEE Electron Device Letters*, vol. 35, no. 2, pp. 175-177, Feb. 2014.
- [4] M. Wang *et al*, "900 V/1.6 mΩ · cm² normally off Al₂O₃/GaN MOSFET on silicon substrate," *IEEE Trans. on Electron Devices*, vol. 61, no. 6, pp. 2035, Jun. 2014.
- [5] T.-E. Hsieh *et al*, "Gate Recessed Quasi-Normally OFF Al₂O₃/AlGaIn/GaN MIS-HEMT With Low Threshold Voltage Hysteresis Using PEALD AlN Interfacial Passivation Layer," *IEEE Electron Device Letters*, vol. 35, no. 7, pp. 732-734, July. 2014.
- [6] S. Yang *et al*, "High-Quality Interface in Al₂O₃/GaN/AlGaIn MIS Structures With In Situ Pre-Gate Plasma Nitridation," *IEEE Electron Device Letters*, vol. 34, no. 12, pp. 1497-1499, Dec. 2013.
- [7] P. Moens *et al*, "An Industrial Process for 650V rated GaN-on-Si Power Devices using in-situ SiN as a Gate Dielectric," *Proc. Int. Symp. Power Semiconductor Devices and IC's (ISPSD)*, pp. 370-373, 2014.
- [8] J.-J. Zhu *et al*, "Improved Interface and Transport Properties of AlGaIn/GaN MIS-HEMTs With PEALD-Grown AlN Gate Dielectric," *IEEE Trans. on Electron Devices*, vol. 62, no. 2, pp. 512-518, Feb. 2015.
- [9] W. Choi *et al*, "Impacts of conduction band offset and border traps on V_{th} instability of gate recessed normally-off GaN MIS-HEMTs," *Proc. Int. Symp. Power Semiconductor Devices and IC's (ISPSD)*, pp. 370-373, 2014.
- [10] E. H. Nicollian, *MOS Physics and Technology*, John Wiley & Sons, NY, 1982.
- [11] X. Sun *et al*, "Electrical Characterization of Gate Traps in FETs With Ge and III-V Channels," *IEEE Trans. Device and Material Reliability*, vol. 13, pp. 463, Dec. 2013.
- [12] H. B. Profijt *et al*, "Plasma-Assisted Atomic Layer Deposition: Basics, Opportunities, and Challenge," *Jour. of Vac. Sci. & Tech. A*, vol. 9, pp. 05080-1-05080-26, Aug. 2011.
- [13] S. Vitanov *et al*, "Physics-Based Modeling of GaN HEMTs," *IEEE Trans. on Electron Devices*, vol. 59, no. 3, pp. 685, Mar. 2012.
- [14] T.-L. Wu *et al*, "Time Dependent Dielectric Breakdown (TDDB) Evaluation of PE-ALD SiN gate dielectrics on AlGaIn/GaN recessed gate D-mode MIS-HEMTs and E-mode MIS-FETs," *IEEE International Reliability Physics Symposium (IRPS)*, 2015. (accepted).