Observation on Slow Carrier Trapping in AlGaN/GaN Schottky Barrier Diodes and MIS Capacitors

Yi-Che Lee[1*], Tsung-Ting Kao[1], Joseph J. Merola[1], Chuanxin Lian[2], David Wang[2], Daniel Hou[2], and Shyh-Chiang Shen[1]

[1]School of Electrical and Computer Engineering, Georgia Institute of Technology
777 Atlantic Drive NW, Atlanta, GA 30332-0250
*Email: ylee302@mail.gatech.edu ; Phone: 404-385-8327

[2]Global Communication Semiconductors, LLC
23155 Kashiwa Court, Torrance, CA 90505-4026

Keywords: AlGaN, GaN, trap, Schottky, metal-insulator-semiconductor, MIS, capacitance

Abstract

We observed slow carrier trapping phenomenon for AlGaN/GaN Schottky barrier diodes (SBDs) and Al_2O_3/AlGaN/GaN metal-insulator-semiconductor capacitors (MISCs) after an off-state stressing during the capacitance-voltage (C-V) measurement. Time-dependent positive V_{th} shifting was observed with a time constant of 340 s on the Schottky diodes. The long time constant indicates that the trapping is related to the deep-level acceptor-like traps in AlGaN layer. The threshold voltage model of the AlGaN/GaN SBDs helps to determine the acceptor-like trap density of 8E11 cm^{-2} at the metal-semiconductor interface. On the other hand, the MISC showed a negative threshold voltage shifting after stress, indicating the presence of the donor-like traps at Al_2O_3/AlGaN interface, which could exist to incur the opposite trend of the threshold voltage shift during the off-state stressing. A time constant of 268 s of electron depletion for donor-like traps can also be extracted with the density of positively charged donor-like traps of 2.1E12 cm^{-2} at Al_2O_3/AlGaN interface.

INTRODUCTION

III-nitride (III-N) heterojunction field-effect transistors (HFETs) and metal-insulator-semiconductor (MIS) field-effect transistors (MISFETs) are promising III-N switches for next-generation high-power applications. Nevertheless, the carrier trapping phenomenon that often leads to current collapse [1], high dynamic on-resistance [2] or threshold voltage shifting [3] during the switching cycles could be problematic for the realization of robust operation. Many studies have shown that the carrier trapping exists in III-N HFETs [4-6] and MISFETs with different gate insulator [7,8].Nitrogen vacancy [9], and dopant residue, such as Fe [10] and C [11] have also been studied to reveal the energy level of traps and the impact to III-N devices.

In this work, we observed a slow-trap-induced threshold voltage shifting phenomenon in the C-V characteristics of AlGaN/GaN Schottky barrier diodes (SBDs) and Al_2O_3/AlGaN/GaN metal-insulator-semiconductor capacitors (MISCs). Using variable durations of the off-state voltage stressing, V_{th} for SBDs shifts toward more positive values as the stressing time increases. On the other hand, V_{th} of MISC shifts toward a more negative value in the same stressing test. The relationship between V_{th} shifting and stress time seems follow an exponential relationship with a long time constant. It suggests that the carrier trapping phenomenon may be attributed to different types of deep-level traps in the SBDs and MISCs. The value of threshold voltage shifting also provides a way to estimate the density of these traps and present oxide charges by extrapolating the ultimate threshold voltage under the long stressing conditions for the evaluation of III-N HFETs and MISFETs.

DEVICE FABRICATION

An AlGaN/GaN HFET wafer was used in this study. The layer structure consists of a 25-nm $Al_{0.25}Ga_{0.75}N$ barrier layer and a 3-μm GaN buffer layer grown on a 4-inch SiC substrate. Two samples for SBDs (Sample-A) and MISCs (Sample-B) were cut from the same wafer. To reduce the processing-induced performance variation for comparison, these two samples were processed in the same fabrication batch run, except for the additional 10-nm Al_2O_3 gate insulator deposited by a thermal ALD tool for Sample-B. The fabrication process started from a mesa isolation etching followed by Ti-Al-based ohmic contact deposition and annealing for the ohmic contact pads. After the Al_2O_3 gate insulator deposition on sample-B, Ni/Au gate electrodes were patterned on both samples to complete the circular-shaped diodes with 40 μm radius.

RESULTS AND ANALYSIS

The C-V characteristics were measured by a HP 4284A LCR meter with 1MHz small signal at room temperature.

Each C-V curve takes 2 minutes to sweep from -3V to -1 V with ramp step size of 25 mV. Before each sweep, the devices were first stressed at the off-state with V_G = -5 V (approximately -2.5 V below V_{th}) for a designated time. The off-state stressing time was sequentially increased up to 30 minutes and the evolution of the C-V curves shift for a SBD is shown in Figure 1. In the plot, the curves shifted toward a more positive V_G with increased off-state stress time. Further measurement also revealed that the shifted C-V curves can be recovered within 30 minutes, indicating that the shifting is not permanent.

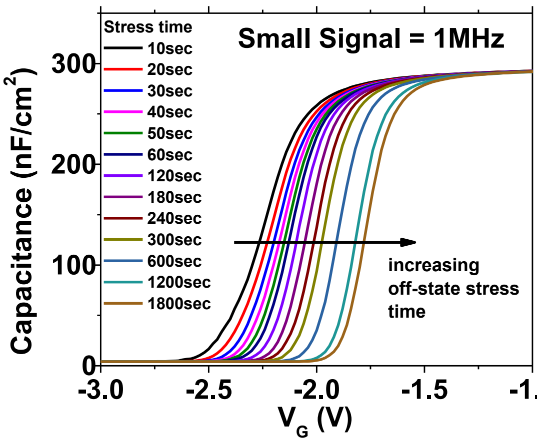

Figure 1. The measured C-V characteristics of the SBD after different stress time.

If V_{th} of C-V curves is defined at the V_G at half of the maximum capacitance, V_{th} against the off-state stressing time can be plotted in Figure 2. The V_{th} values seem to follow an exponential relationship and the fitting of the V_{th} shifting can be estimated as $\Delta V_{th,SB} = 0.4 \times (1 - e^{\frac{-t}{\tau_1}})$.

By fitting the measured data, the time constant τ_1 is ~ 340 s. The positive shifting of V_{th} indicates that the electron trapping occurs during the off-state stressing. This observation is similar to the gate-lag measurement in the HFET measurement that results in increased dynamic on-state resistance due to shallow traps at AlGaN surface. However, unlike the shallow traps that has a relatively short trapping/de-trapping life time (~30 ms in AlGaN/GaN HFETs [4]), the trapping processes observed in off-state stressing method shows that there also exists slow states process that can be attributed to deep-level acceptor-like traps, such as carbon-induced traps or gallium vacancies [12].

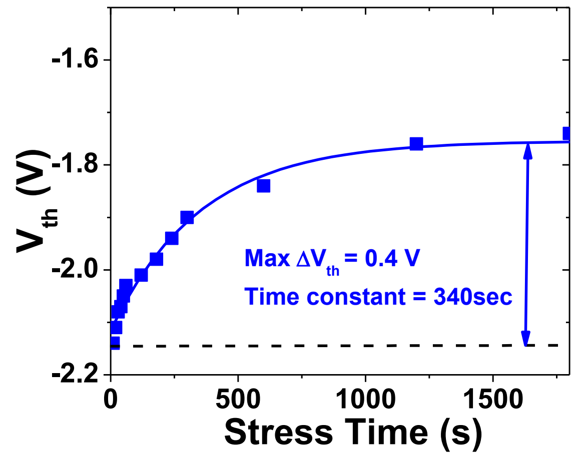

Figure 2. The threshold voltage and the fitted curve of the SBD with different off-state stress time.

Because the stressing was carried out at off-state when electron is depleted in the GaN buffer, the most possible location of the acceptor-like traps is in AlGaN layer, instead of buffer traps [13]. Previous studies also indicate that the electron trapping may occur at the surface AlGaN layer [3]. The electron-filled acceptor-like traps become negative charged and have to be taken into account in the calculation of threshold voltage for AlGaN/GaN SBDs. The negatively charged acceptor-like trap can be modeled as a sheet charge with a density of $Q_{surface}$ (in cm^{-2}) at the surface of AlGaN.

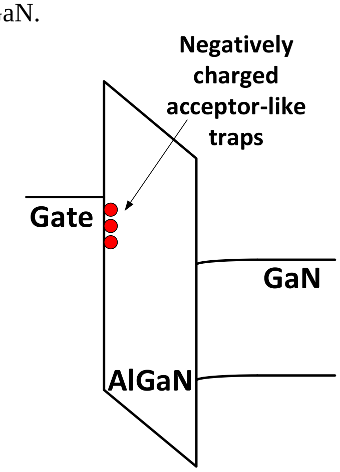

Figure 3 Band diagram of AlGaN/GaN heterostructure showing the formation of negatively charged acceptor-like traps at off-state stress (V_{GS} = -5V).

The threshold voltage of AlGaN/GaN SBDs with the inclusion of the traps can be expressed as:

$$V_{th} = \frac{\phi_B}{q} - \frac{\Delta E_C}{q} + \frac{E_{f0}}{q} - \frac{d_{AlGaN}}{\varepsilon_{AlGaN}}\sigma - \frac{qd_{AlGaN}}{\varepsilon_{AlGaN}}Q_{surface}$$

Where ϕ_B is the Schottky barrier height. ΔE_C is the conduction-band offset at the AlN/GaN heterojunction. E_{f0} is the energy difference between the Fermi level and the conduction band edge of the GaN channel. σ is the polarization induced charge density at the AlGaN/GaN interface. d_{AlGaN} is the thickness of AlGaN. ε_{AlGaN} is the dielectric constant of AlGaN.

Because of the ultra-slow trapping/de-trapping process, we may assume the acceptor-like traps do not respond to the applied V_{GS} during the first C-V sweep. During the off-state stressing, the threshold voltage constantly shifts with the increased Q_{trap} as the increased off-state stress time helps higher percentage of electron filling in these acceptor-like states until these states are completely filled. In such case, the threshold voltage will cease to increase and the C-V curves will not shift after certain period of off-state stressing before the C-V measurement. $Q_{surface}$ can be calculated by $Q_{surface} = \varepsilon_{AlGaN} \Delta V_{th,SB} / (q d_{AlGaN})$. The estimated Q_{surface} is $8\times10^{11}\text{cm}^{-2}$ for the SBDs.

The same measurement procedures were exercised on Al_2O_3/AlGaN/GaN MISCs. As shown in Figure 4, unlike the positive threshold voltage shifting observed in SBDs, a negative threshold voltage shifting was observed on MISCs after different stress time. The V_{th} shifting is also not permanent. Because SBDs and MISCs have the same structure except the Al_2O_3 gate insulator, this opposite trend indicates that a high density of donor-like traps may locate at the Al_2O_3/AlGaN interface. The donor-like traps may be depleted by negative V_G and become positively charged after stress. As a result, the positively charged traps at the Al_2O_3/AlGaN interface may shadow the negatively charged traps at AlGaN surface in MISCs during the off-state stress as shown in Figure 5.

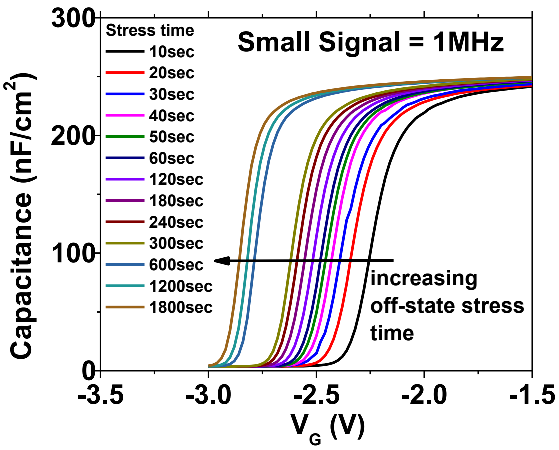

Figure 4. The measured C-V characteristics of the MISC after different stress time.

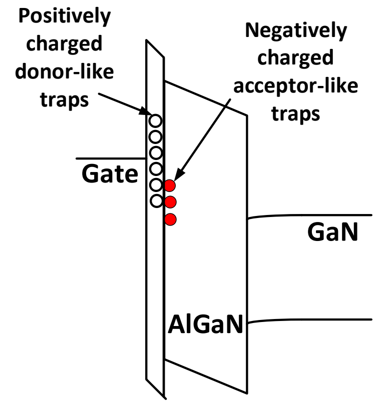

Figure 5 Band diagram of Al_2O_3/AlGaN/GaN heterostructure showing the formation of negatively charged acceptor-like surface trap and positively-charged donor-like traps at off-state stress (V_G = -5 V).

Assuming that V_{th} shifting caused by the donor-like traps at Al_2O_3/AlGaN interface also follow the exponential relationship, the fitting of ΔV_{th} for the MISC shows $\Delta V_{th,MIS} = 0.4\times(1-e^{-t/\tau_1}) - 1\times(1-e^{-t/\tau_2})$, where τ_1 is the time constant of electron trapping for the acceptor-like traps and τ_2 is the time constant of electron depletion for the donor-like traps. Using the equation, we can fit the measured data and assume τ_1 = 340 s and the corresponding τ_2 is 268 s, as shown in Figure 6. The long time constant indicates that electron depletion of donor-like traps is also related to the deep-level traps at the Al_2O_3/AlGaN interface.

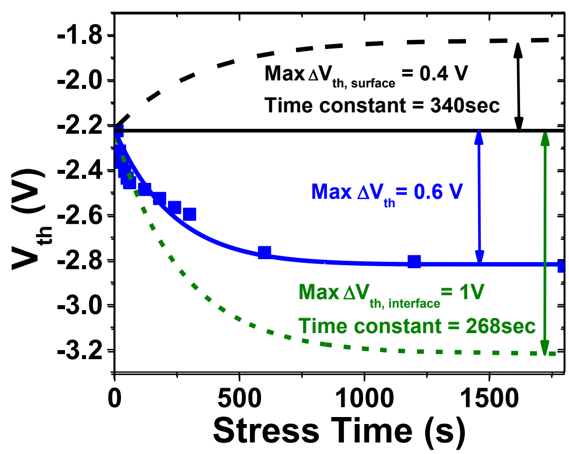

Figure 6. The threshold voltage and fitted curves of the MISC after different stress time.

The threshold voltage equation can also be derived for MIS structure [14]. The fixed oxide charge (N_{fixed}) (in cm^{-3}) is assumed to be uniformly distributed in Al_2O_3 layer and has to be taken into consideration. The positively charged donor-like traps ($Q_{interface}$) (in cm^{-2}) at the Al_2O_3/AlGaN interface should also be considered. The electron trapping in the acceptor-like traps at AlGaN surface with density of $Q_{surface}$ (in cm^{-2}) may still occur during stressing. As a result, the equation for the threshold voltage of a MISC can be expressed as:

$$V_{th,MIS} = \frac{\phi_B}{q} - \frac{\Delta E_C}{q} + \frac{E_{f0}}{q} - \frac{d_{ox}}{\varepsilon_{ox}}\sigma_1 - \frac{d_{AlGaN}\varepsilon_{ox} + d_{ox}\varepsilon_{AlGaN}}{\varepsilon_{ox}\varepsilon_{AlGaN}}\sigma_2 - \frac{q d_{ox}^{2}}{2\varepsilon_{ox}} N_{fixed} - \frac{q d_{AlGaN}}{\varepsilon_{AlGaN}}(Q_{interface} - Q_{surface})$$

Where σ_1 and σ_2 are the polarization induced charge density at the Al_2O_3/AlGaN and AlGaN/GaN interfaces, respectively. d_{ox} is the thickness of Al_2O_3 layer. ε_{ox} is the dielectric constant of Al_2O_3. Assuming that the fixed oxide charge (N_{fixed}) is not affected by the off-state stress, the threshold voltage shifting is caused by the last term of the equation. With the $Q_{surface}$ = 8E11 cm^{-2} extracted from SBDs, the density of positively charged donor-like traps ($Q_{interface}$) at Al_2O_3/AlGaN interface can then be estimated as $Q_{interface} = \varepsilon_{AlGaN}\Delta V_{th,MIS} / (q d_{AlGaN}) + Q_{surface}$. The extracted $Q_{interface}$ at the MIS interface is 2.1×10^{12} cm^{-2}.

CONCLUSIONS

In summary, we studied C-V characteristics of SBDs and MISCs using an off-state stress method. Slow acceptor-like trap states were observed in the AlGaN barrier layer, causing positive V_{th} shifting after stressing. However, negative V_{th} shifting with large time constant was observed in MISCs, indicating positively charged donor-like traps in Al_2O_3 layer. The donor-like traps in the ALD-grown Al_2O_3 are also identified as a slow state that induced the negative V_{th} shift with increased off-state stressing time. The off-state stressing method on SBDs and MISCs reveals different slow-state nature of the traps and provides a simple and effective way to quantify the density of trap states in III-N MISFETs.

ACKNOWLEDGEMENTS

The authors wish to thank the staffs in the Nanotechnology Research Center (NRC) at the Georgia Institute of Technology for the cleanroom facility support.

REFERENCES

[1] G. Meneghesso, et al., IEEE Trans. Electron. Dev. **51**, 1554 (2004)
[2] Donghyun Jin, et al., Microelectron. Reliability **52** 2875 (2012)
[3] H. Rao, et al., J. Appl. Phys. **108**, 053707 (2010)
[4] A. Sasikumar, et al., Appl. Phys. Lett. **103**, 033509 (2013)
[5] M. Silvestri, et al., Appl. Phys. Lett., **102**, 073501 (2013)
[6] L. Stuchlíková, et al., *Investigation of deep energy levels in heterostructures based on GaN by DLTS*, Proc.8th Int. Conf. ASDAM, 135, Oct 2010
[7] S. Ozaki, et al., Jap. J. Appl. Phys. **52**, 11NG04 (2013)
[8] D. W. Johnson, et al. IEEE Tran. Electron Dev. **60**, 3197 (2013)
[9] D. K. Johnstone, et al., *Deep centers and their capture barriers in MOCVD-grown GaN*, Proc. Mater. Res. Soc. Symp., 73, 2002
[10]A. Y. Polyakov, et al., J. Appl. Phys. **95**,5591 (2004)
[11] A. R. Arehart, et al., phys. Stat. Sol. C **5**, 1750 (2008)
[12] A. R. Arehart, et al., Phys. Stat. Sol. C **8**, 2242 (2011)
[13] D. Bisi, et al., IEEE Trans. Electron Dev. **60**, 3166 (2013)
[14] M. Tapajna, et al., Appl. Phys. Lett., **100**, 113509 (2012)

ACRONYMS:

SBD : Schottky barrier diode
MISC : Metal-insulator-semiconductor capacitor