



**HAL**  
open science

# AlGa<sub>N</sub>/Ga<sub>N</sub> metal-insulator-semiconductor capacitors with a buried Mg doped layer characterized by deep level transient spectroscopy and photoluminescence

Mariam El Khatib, Philippe Ferrandis, Erwan Morvan, Gérard Guillot,  
Georges Bremond

## ► To cite this version:

Mariam El Khatib, Philippe Ferrandis, Erwan Morvan, Gérard Guillot, Georges Bremond. Al-GaN/GaN metal-insulator-semiconductor capacitors with a buried Mg doped layer characterized by deep level transient spectroscopy and photoluminescence. SPIE OPTO 2018, Jan 2018, San Fransisco, United States. pp.39, 10.1117/12.2289067 . hal-01928350

**HAL Id: hal-01928350**

**<https://hal.science/hal-01928350>**

Submitted on 20 Nov 2018

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

See discussions, stats, and author profiles for this publication at: <https://www.researchgate.net/publication/323572983>

# AlGaIn/GaN metal–insulator–semiconductor capacitors with a buried Mg doped layer characterized by deep level transient spectroscopy and photoluminescence

Conference Paper · March 2018

DOI: 10.1117/12.2289067

CITATIONS

0

READS

91

5 authors, including:



**Mariam el Khatib**

Institut National des Sciences Appliquées de Lyon

1 PUBLICATION 0 CITATIONS

SEE PROFILE



**Philippe Ferrandis**

Cea Leti, Université de Toulon

14 PUBLICATIONS 17 CITATIONS

SEE PROFILE



**Erwan Morvan**

Cea Leti

135 PUBLICATIONS 1,362 CITATIONS

SEE PROFILE



**GUILLOT GERARD**

Institut National des Sciences Appliquées de Lyon

348 PUBLICATIONS 3,404 CITATIONS

SEE PROFILE

Some of the authors of this publication are also working on these related projects:



Optical and theoretical investigations of rare earth and transition metals ions doped in différent hosts [View project](#)



Terahertz Nano-Source [View project](#)

# AlGaN/GaN metal-insulator-semiconductor capacitors with a buried Mg doped layer characterized by deep level transient spectroscopy and photoluminescence

Mariam El-Khatib<sup>a)</sup>, Philippe Ferrandis<sup>1,b,c,d)</sup>, Erwan Morvan<sup>b,c)</sup>, Gérard Guillot<sup>a)</sup> and Georges Bremond<sup>a)</sup>

<sup>a)</sup>Université de Lyon, Institut des Nanotechnologies de Lyon, CNRS UMR 5270, INSA de Lyon, Bat. Blaise Pascal, 7 avenue Capelle, F-69621 Villeurbanne Cedex, France.

<sup>b)</sup>CEA, LETI, MINATEC Campus, F-38054 Grenoble, France

<sup>c)</sup>Univ. Grenoble Alpes, F-38000 Grenoble, France

<sup>d)</sup>Aix Marseille Université, CNRS, Université de Toulon, IM2NP UMR 7334, 83957 La Garde, France

GaN material holds an advantageous position in the fabrication of power devices. This advantage is manifested by the possibility to perform GaN based devices working in high voltage, high current, high frequency and high temperature conditions. However, despite these theoretical forecasts, trapping mechanisms limit the performances of the GaN based devices revealed by the so-called “drain current collapse”. Our study is based on a methodology to understand trapping mechanisms in GaN metal-insulator-semiconductor high-electron mobility transistors. This work was achieved by means of electrical and optical characterization techniques such as Fourier transform deep level transient spectroscopy and photoluminescence. The activation energy and the apparent capture cross section of eight traps were extracted in normally-off ( $I_{ds}=0A$  when  $V_{gs}=0V$ ) AlGaN/GaN heterostructure technology used for power conversion. Six of these traps,  $E1=0.16eV$ ,  $E2=0.31eV$ ,  $E3=0.46eV$ ,  $E4=0.5eV$ ,  $E5=0.64eV$  and  $E6=0.79eV$  are electron traps located in the channel. An identification has been proposed for each trap. Two hole-like traps,  $H1=0.17eV$  and  $H2=0.74eV$  were assigned to the Mg and C doping of the GaN buffer layers, respectively. These traps might play a role in the current collapse which appears after the application of a large reverse voltage on the gate of the device. Furthermore, the results obtained using electrical and optical techniques allowed concluding that oxygen atoms and dislocations are incorporated in GaN layers during the growth.

## I. Introduction

Efficiency and energy management, with the least losses, present today one of the most famous global concerns. Particularly, works are in progress to increase performances of energy conversion systems [1]. Unfortunately, the efficiency of these systems is limited by restricted properties of traditional switching silicon based devices [2]. Therefore, over the last years, due to their inherent material characteristics, gallium nitride has attracted a particular attention to perform power high-electron-mobility transistors (HEMTs) [3]. The large band gap of gallium nitride provides it promising properties such as a high breakdown voltage and a high temperature operation capability, useful for high-power applications [4]. In high-power switching systems, normally-off characteristics are favored to realize the fail-safe requirement [5]. For this purpose, several architectures and processes have been proposed such as thin AlGaN barrier, Gate Injection Transistor [6], Fluorine ion treatment [7], p-GaN gate structures [8] and metal-insulator-semiconductor (MIS) recessed gate structures [9, 10]. Despite these technological efforts, the dynamic on-resistance degradation and the current collapse remain open issues to overcome because they seriously reduce the switching performance of devices [11-12]. These effects are reported to be related either to surface

---

<sup>1</sup> Electronic mail: philippe.ferrandis@univ-tln.fr

states [11, 13] or to charge trapping at deep levels [14]. As a result, a great deal of interest has been generated in detecting and identifying these trapping centers and in determining in which part of the device structure they are located. In this work, we studied GaN MIS capacitors using a buried Mg doped GaN layer to isolate the channel from the semi-insulating C doped GaN buffer.

## II. Experimental methods

Electrical study was carried out with MIS capacitors grown by metalorganic chemical vapor deposition on a 200nm diameter Si substrate, oriented (111). The epitaxy consists of an AlN nucleation layer, followed by AlGa<sub>0.20</sub>N buffer layers, then a 1.8μm thick semi-insulating carbon doped GaN buffer layer, 100nm of Mg doped GaN ( $N_a = 3 \times 10^{17} \text{cm}^{-3}$ ), a 200nm unintentionally doped GaN layer acting as the channel, a 1 nm unintentionally doped AlN layer and a 21.4nm unintentionally doped Al<sub>0.20</sub>Ga<sub>0.80</sub>N barrier layer. The Mg-activation anneal of the samples was done at 820°C. Si<sub>3</sub>N<sub>4</sub> was used for the passivation of the stack (Fig. 1a). Interdigitated comb-like capacitors with six 15×1000μm<sup>2</sup> fingers were then formed using TiN/W as gate metal and Ti/Al annealed for 30s at 875°C as ohmic contact (Fig. 1b). Recessed gate electrodes were achieved by etching Si<sub>3</sub>N<sub>4</sub> passivation and 35nm of the AlGa<sub>0.20</sub>N/GaN bilayer using a dry etching process. 30nm of Al<sub>2</sub>O<sub>3</sub> were used to form the gate oxide. Static electrical characteristics and deep level transient spectroscopy data were acquired with a Fourier transform deep level transient spectroscopy (FT-DLTS) system from PhysTech (FT 1030) using a Boonton 72B capacitance meter with a 100mV test signal at 1MHz. Capacitance transients were recorded between 80K and 450K in the warm up mode.

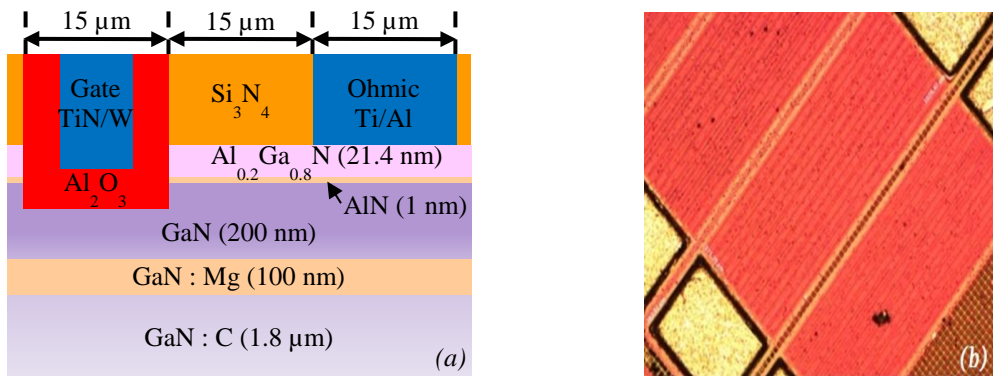


Figure 1: (a) Schematic of a normally-off AlGa<sub>0.20</sub>N/GaN MIS capacitor and (b) planar image of MIS capacitors studied in this paper.

Optical measurements were performed with four samples consisting of 1.5μm thick doped GaN layer grown on Si. One sample has a Mg doping at  $1 \times 10^{17} \text{cm}^{-3}$  and three samples have a C doping at  $5 \times 10^{15} \text{cm}^{-3}$ ,  $5 \times 10^{16} \text{cm}^{-3}$  and  $5 \times 10^{17} \text{cm}^{-3}$ , respectively. The PL steady state measurements of the doped GaN layers grown on Si were performed by means of a solid state laser (CryLas – Berlin) using a continuous excitation source at 266nm wavelength and an excitation power density in the 1-10W.cm<sup>-2</sup> range. PL emissions were dispersed by a single-grating monochromator (Jobin Yvon HR 640). All spectra were corrected by the transfer function of the optical setup including cryostat window, lens and monochromator.

## III. Experiments and results

### A. Static measurements

Typical capacitance – voltage (C-V) characteristics of GaN MIS capacitors recorded at different temperatures are depicted in Fig. 2. When the temperature increases, the pinch-off voltage position shifts towards lower voltages, suggesting charge trapping effects between

80K and 400K. Room temperature C-V measurements (shown in the inset of Fig. 2) point out that the diode exhibits a low voltage hysteresis (less than 40.7mV) which results of a very low amount of residual charges in the  $\text{Al}_2\text{O}_3$  insulating layer.

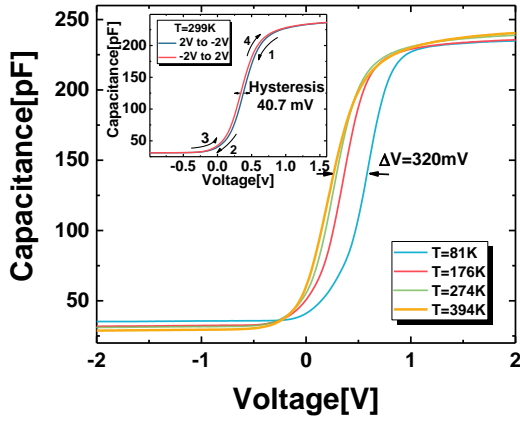


Figure 2: C-V characteristics carried out at different temperatures. The inset reports an hysteresis effect obtained by sweeping up and down the voltage at 299K.

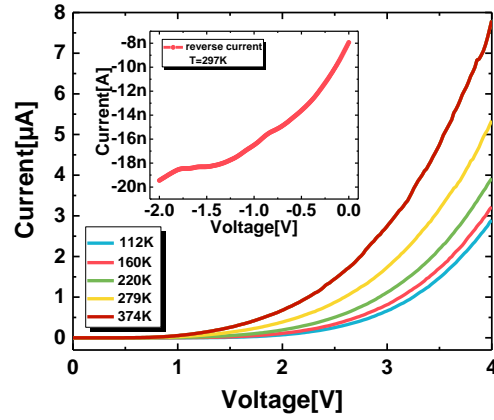


Figure 3: I-V characteristics carried out at different temperatures. The inset reports a low reverse current of 8nA with a bias of 0V at 297K.

Current – voltage (I-V) measurements recorded at various temperature below 380K (Fig. 3) reveal a low reverse current of 8nA at a bias of 0V which emphasizes the good electrical quality of the MIS capacitors.

## B. DLTS analysis

In Fig. 4, we see DLTS spectra recorded with a reverse bias  $V_R = 0\text{V}$ , a filling pulse height  $V_P = 2\text{V}$ , a filling pulse width  $t_p = 1\text{ms}$  and four period widths  $T_W$  between 2ms and 5s.

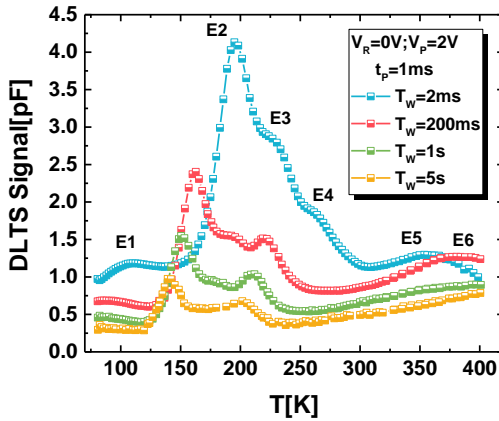


Figure 4: DLTS measurements of AlGaIn/GaN MIS capacitors recorded with  $V_R = 0\text{V}$ ,  $V_P = 2\text{V}$ ,  $t_p = 1\text{ms}$  and four  $T_W$  varying from 2ms to 5s.

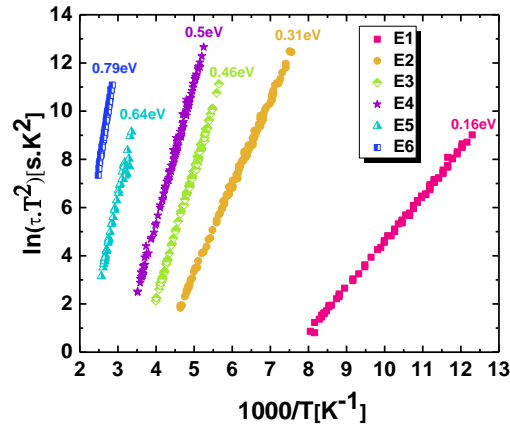


Figure 5: Arrhenius plots extracted from DLTS data in Fig. 4.

Taken into account the pinch-off voltage found in Fig. 2, we determine that the probe zone is located in the 2DEG channel of the device. Six electron traps labelled E1, E2, E3, E4, E5 and E6 emerge in Fig. 4. Arrhenius plots reported in Fig. 5 allowed extracting the features of each trap. Activation energies and apparent capture cross sections are summarized in Table 1.

Defect	$E_a$ (eV)	$\sigma$ ( $cm^2$ )	Proposed Identification
E1	0.16	$3 \times 10^{-15}$	$V_N$ related [15, 16]
E2	0.31	$3.9 \times 10^{-15}$	RIE-induced surface damage [17, 18]
E3	0.46	$2.8 \times 10^{-13}$	$V_N$ related [19]
E4	0.50	$8 \times 10^{-14}$	Possibly C related [20, 21]
E5	0.64	$1.2 \times 10^{-14}$	$V_{Ga}$ related [22-27]
E6	0.79	$5 \times 10^{-15}$	$N_I$ related [19, 28]
H1	0.17	$3.6 \times 10^{-19}$	Mg related [29, 30]
H2	0.74	$1.1 \times 10^{-15}$	C related [31, 32]

Table 1: Activation energies and apparent capture cross sections of the deep levels found in this work and their proposed identification according to previous works.

Traps E5 and E6 are commonly observed in epitaxial GaN and are related to gallium vacancy ( $V_{Ga}$ ) and interstitial nitrogen ( $N_I$ ), respectively. Traps E1 and E3 which are Nitrogen vacancy ( $V_N$ ) related, are expected to be formed by the etching process. The inductively coupled plasma (ICP) etched surface was found to be N-deficient, meaning that a number of  $V_N$  were produced by ICP etching [33]. Trap E2 was associated to reactive ion etching (RIE) surface damage and has already been related to the effect of an ICP-RIE etched surface [34]. Despite the absence of carbon during the growth of the channel, residual carbon atoms could incorporate the epitaxial layer especially at the vicinity of the carbon doped GaN buffer layer. This trend could explain the appearance of trap E4.

In Fig. 6, we see the evolution of the spectra as a function of the filling pulse duration between  $100\mu s$  and  $20ms$ . DLTS data were recorded with a reverse bias  $V_R = 0V$ , a filling pulse height  $V_P = 2V$  and a period width  $T_W = 200ms$ .

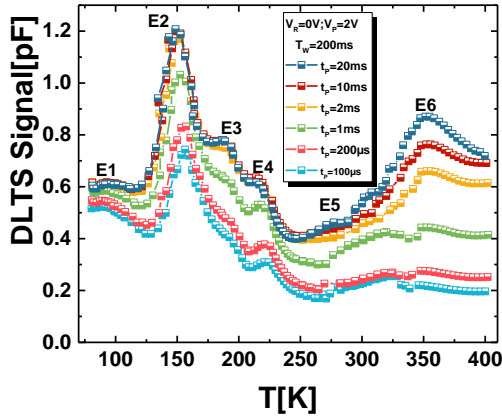


Figure 6: DLTS measurements of AlGaIn/GaN MIS capacitors as a function of the filling pulse duration.

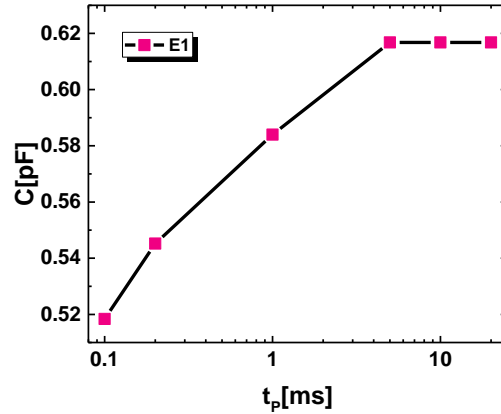


Figure 7: Evolution of the peak amplitude of trap E1 versus the filling pulse duration extracted from data in Fig. 6.

Figs. 7 and 8 report the evolution of the peak amplitude for traps E1, E2, E3, E4 and E6 versus the filling pulse duration. We observe a saturation of the DLTS signal above  $5ms$  for traps E1, E2, E3 and E4, which is expected for point defects. However, trap E6 exhibits a logarithmic dependence of the peak amplitude on the range of  $t_P$  used (Fig. 8b). Such a trend is consistent with a line defect behavior [35]. Previous works support this result by associating this trap to threading dislocations [36, 37]. The nature of trap E5 was not determined due to the difficulty to find the peak maximum on the spectra of Fig. 6. Despite the detection of traps E1 to E6 in the channel, these deep traps are not expected to play a role in the current collapse [38].

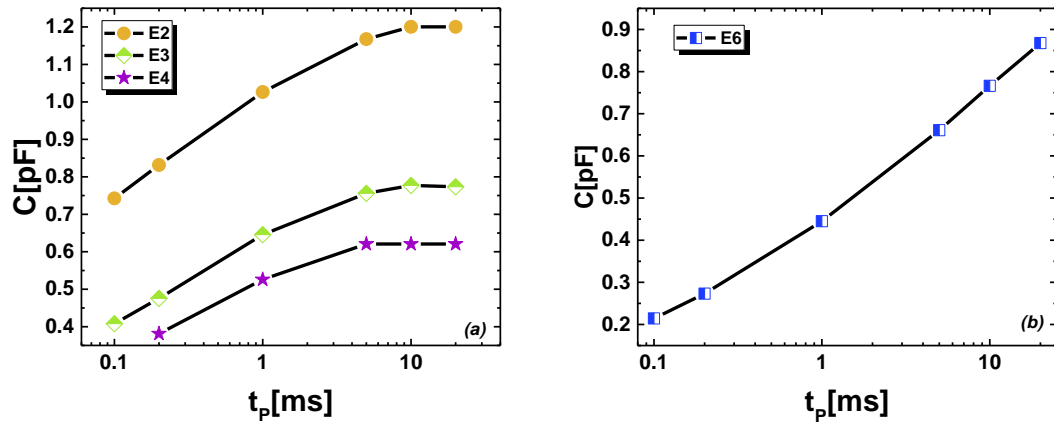


Figure 8: Evolution of the peak amplitude of traps (a) E2, E3, E4 and (b) E6 versus the filling pulse duration extracted from data in Fig. 6.

Keeping a filling pulse height  $V_P = 2V$ , we applied a reverse bias  $V_R = -10V$  to increase the depletion region of the capacitor and probe the carbon doped GaN buffer layer. In Fig. 9, we see that using a filling pulse width  $t_P = 1ms$  and a period width  $T_W = 1s$ , two dominant hole-like traps labelled H1 and H2 are observed. Arrhenius plots extracted from DLTS data in Fig. 9 are reported in Fig. 10 and the signature of the traps are summarized in Table 1. H1 and H2 are Mg and C related defects, respectively. Trap H1 is assigned to  $Mg_{Ga}$  acceptors [39] and trap H2 to  $C_N$ - $O_N$  complexes [31, 32]. Minority carrier injection is necessary to observe these hole-like traps. It can come either from the Mg doped GaN which is p-type even if this layer is assumed to be largely depleted or from the semi-insulating C doped buffer layer which is expected to be slightly p-type [40].

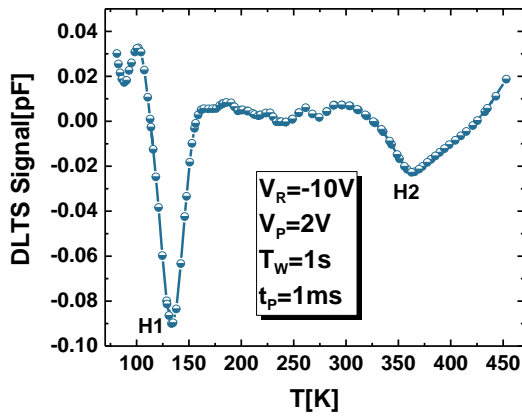


Figure 9: DLTS measurements of AlGaIn/GaN MIS capacitors recorded with  $V_R = -10V$ ,  $V_P = 2V$ ,  $t_P = 1ms$  and  $T_W = 1s$ .

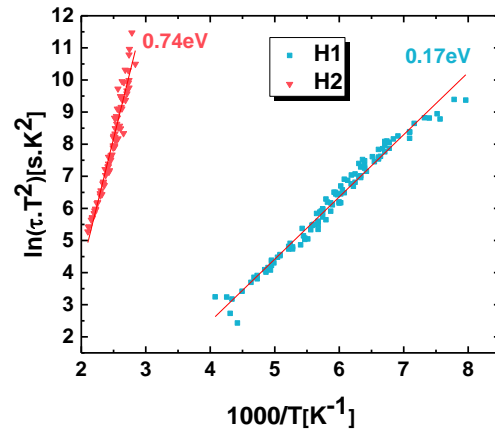


Figure 10: Arrhenius plots extracted from DLTS data in Fig. 9.

The domination of traps H1 and H2 in Fig. 9 indicates that (i) the reverse bias  $V_R = -10V$  allows extending the space charge region beyond the Mg doped GaN until the C doped GaN buffer layer, (ii) oxygen atoms are incorporated in the epitaxial GaN layers during the growth and (iii) these levels are more efficient to trap carriers than traps E1 – E6.



### C. Photoluminescence study

Photoluminescence measurement of the Mg doped GaN sample carried out at 12K is reported in Fig. 11. ABE1 consists of the neutral A1 acceptor bound exciton line [41] and is related to  $Mg_{Ga}$  acceptor [39]. DAP1 is a donor-acceptor pair luminescence involving  $Mg_{Ga}$  acceptor. The other lines at lower energies represent a set of replicas separated by the energy of LO phonon in GaN which is about 91meV. DBX3-LO represents the LO phonon interaction with a donor bound exciton line. DBX3 is an overlay of an ionized donor bound exciton ( $D^+X$ ) related to DBX2 and a deep donor bound exciton [42]. The neutral donor bound exciton DBX2 is related to the oxygen donor [42]. In Fig. 12, we can also see the Y7 line with the characteristic LO phonon replicas. The Y7 line is associated to an exciton bound to a structural defect [43]. Reshchikov and Morkoç [43] suggested that the Y7 line arises from recombination of an exciton bound to some point defect that is in turn trapped by the stress field of the threading-edge dislocation. The photoluminescence result reported in Fig. 11 is consistent with the DLTS analysis described in section B since both characterization techniques allow concluding to the presence of an acceptor level assigned to  $Mg_{Ga}$  and the existence of oxygen atoms and dislocations in GaN layers.

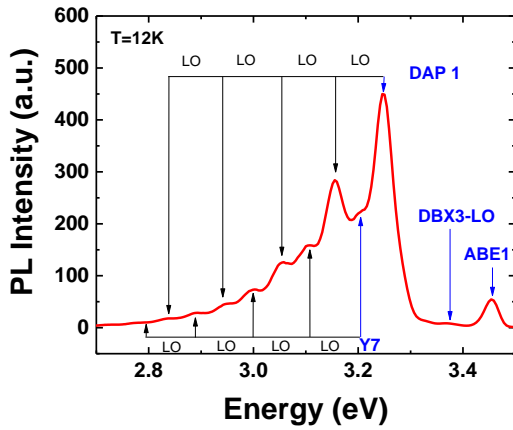


Figure 11: Photoluminescence spectrum of Mg doped GaN sample recorded at 12 K and  $1W/cm^2$ .

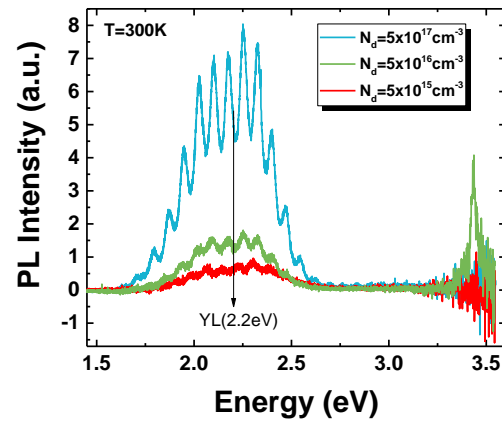


Figure 12: Photoluminescence spectra of C doped GaN samples recorded at room temperature and  $0.6W/cm^2$ . Oscillations are caused by interference effects in the Si/GaN/Air cavity.

Fig. 12 reveals photoluminescence spectra of C doped GaN layers carried out at room temperature. A yellow luminescence (YL) band centered at 2.2eV arises on all spectra and is C doping dependent. The YL band has been attributed to the result of electronic transitions implying the  $C_N-O_N$  complex [31, 32]. This finding is consistent with the assignment of trap H2 observed by DLTS to  $C_N-O_N$  level (see section B) and confirms the presence of oxygen associated with substitutional carbon atoms in GaN layers.

### IV. Conclusion

AlGaIn/GaN MIS capacitors have been studied using FT-DLTS and photoluminescence. In the channel region, six electron traps E1 – E6 have been identified. Among them, traps E1, E2 and E3 are expected to be formed by the etching process. E4 could be related to residual carbon atoms at the vicinity of the C doped GaN buffer layer. Traps E5 and E6 are commonly observed in epitaxial GaN. Trap E6 exhibits a logarithmic dependence of the peak amplitude on the range of  $t_p$  used. This result is consistent with previous works which associate this trap to threading dislocations. Extending the space charge region beyond the Mg doped GaN until the C doped GaN buffer layer, spectra are dominated by two hole-like traps H1 and H2. H1 is related to  $Mg_{Ga}$  acceptors and H2 is ascribed to  $C_N-O_N$  complexes, highlighting the presence



of oxygen in GaN layers. The photoluminescence study on Mg and C doped GaN samples supports the existence of traps involving  $Mg_{Ga}$  acceptors,  $C_N-O_N$  complexes and dislocations in GaN epitaxial layers composing the MIS capacitors. The domination of traps H1 and H2 on DLTS spectra suggests that these levels might play a role in the current collapse which appears after the application of a large reverse voltage on the gate of the device.

## Acknowledgment

This work was done in collaboration with “CEA-LETI” and is supported by a doctoral fellowship (ADR to M. EL KHATIB) from the “Région Auvergne-Rhone-Alpes”, so funding from the “Région Auvergne-Rhone-Alpes” via the “ARC4” is acknowledged.

## REFERENCES

- [1] F. Dastgeer and H. E. Gelani, *Energy Build.*, vol. 138, pp. 648–654, 2017
- [2] F. Iacopi, M. Van Hove, M. Charles, and K. Endo, *MRS Bull.*, vol. 40, no. 5, pp. 390–395, 2015
- [3] G. Meneghesso, M. Meneghini, I. Rossetto, D. Bisi, S. Stoffels, M. Van Hove, S. Decoutere and E. Zanoni, *Semicond. Sci. Technol.*, 31, 93004, 2016
- [4] M. Meneghini, G. Meneghesso, E. Zanoni, *Power GaN Devices*, Springer International Publishing, p. 380, 2017
- [5] M. Ishida, T. Ueda, T. Tanaka, and D. Ueda, *IEEE Trans. Electron Devices*, 60, 3053, 2013
- [6] Y. Uemoto, M. Hikita, H. Ueno, H. Matsuo, H. Ishida, M. Yanagihara, T. Ueda, T. Tanaka, and D. Ueda, *IEEE Trans. Electron Devices*, 54, 3393, 2007
- [7] S. Hamady, F. Morancho, B. Beydoun, P. Austin and M. Gavelle, *International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM)*, pp. 124-127, 2014
- [8] L. Efthymiou, G. Longobardi, G. Camuso, T. Chien, M. Chen and F. Udrea, *Appl. Phys. Lett.* 110, 123502, 2017
- [9] T. J. Anderson, M. J. Tadjer, M. A. Mastro, J. K. Hite, K. D. Hobart, C. R. Eddy, and F. J. Kub, *J. Electron. Mater.* 39, 478, 2010
- [10] W. Saito, Y. Takada, M. Kuraguchi, K. Tsuda, and I. Omura, *IEEE Trans. Electron Devices* 53, 356, 2006
- [11] R. Vetry, N.-Q. Zhang, S. Keller, U.K. Mishra, *IEEE Trans. Electron Devices* 48, 560, 2001
- [12] P.B. Klein, J.A. Freitas Jr., S.C. Binari, A.E. Wickenden, *Appl. Phys. Lett.* 75, 4016, 1999
- [13] T. Mizutani, Y. Ohno, M. Akita, S. Kishimoto, K. Maezawa, *IEEE Trans. Electron Devices* 50, 2015, 2003
- [14] M. Meneghini, N. Ronchi, A. Stocco, G. Meneghesso, U.K. Mishra, Y. Pei, E. Zanoni, *IEEE Trans. Electron Devices* 58, 2996, 2011
- [15] L. Polenta, Z-Q. Fang and D. C. Look, *Appl. Phys. Lett.* 76, 2086, 2000
- [16] Z-Q. Fang, L. Polenta, J.W. Hemsky and D. C. Look, *Proc. 11th International Conference on Semiconducting and Insulating Materials*, 35, 2000
- [17] D. C. Look and Z.-Q. Fang, *Appl. Phys. Lett.* 79, 84, 2001
- [18] Z.-Q. Fang, D.C. Look, X.-L. Wang, Han Jung, F.A. Khan, I. Adesida, *Appl. Phys. Lett.* 82, 1562, 2003
- [19] Z.-Q. Fang, G. Farlow, B. Claflin, D.C. Look, *Proc. 13th International Conference on Semiconducting and Insulating Materials*, pp. 29-36, 2004
- [20] W.I. Lee, T.C. Huang, J.D. Guo, M.S. Feng, *Appl. Phys. Lett.* 67, 1721, 1995
- [21] Z.-Q. Fang, D.C. Look, B. Claflin, S. Haffouz, H. Tang, J. Webb, *Phys. Status Solidi C* 2, 2757, 2005
- [22] P. Hacke, T. Detchprohm, K. Hiramatsu, N. Sawaki, K. Tadatomo, K. Miyake, *J. Appl. Phys.* 76, 304, 1994
- [23] D. Haase, M. Schmid, W. Kürner, A. Dörnen, V. Härle, F. Scholz, M. Burkard, H. Schweizer, *Appl. Phys. Lett.* 69, 2525, 1996
- [24] C.D. Wang, L.S. Yu, S.S. Lau, E.T. Yu, W. Kim, A.E. Botchkarev, H. Morkoç, *Appl. Phys. Lett.* 72, 1211, 1998
- [25] Z.-Q. Fang, D.C. Look, W. Kim, Z. Fan, A. Botchkarev, H. Morkoç, *Appl. Phys. Lett.* 72, 2277, 1998
- [26] Z.-Q. Fang, D.C. Look, P. Visconti, D.-F. Wang, C.-Z. Lu, F. Yun, H. Morkoç, S.S. Park, K.Y. Lee, *Appl. Phys. Lett.* 78, 2178, 2001
- [27] Shang Chen, Unhi Honda, Tatsunari Shibata, Toshiya Matsumura, Yutaka Tokuda, Kenji Ishikawa, Masaru Hori, Hiroyuki Ueda, Tsutomu Uesugi, Tetsu Kachi, *J. Appl. Phys.* 112, 053513, 2012
- [28] F. D. Auret, S. A. Goodman, F. K. Koschnick, J-M. Spaeth, B. Beaumont and P. Gibart, *Appl. Phys. Lett.* 73, 3745, 1998
- [29] Y. Nakano and T. Jimbo, *J. Appl. Phys.* 92, 5590, 2002

- [30] B. Monemar, P. P. Paskov, G. Pozina, C. Hemmingsson, J. P. Bergman, T. Kawashima, H. Amano, I. Akasaki, T. Paskova, S. Figge, D. Hommel and A. Usui, *Phys. Rev. Lett.* 102, 235501, 2009
- [31] D. O. Demchenko, I. C. Diallo and M. A. Reshchikov, *Phys. Rev. Lett.* 110, 087404, 2013
- [32] M. A. Reshchikov, D. O. Demchenko, A. Usikov, H. Helava and Yu. Makarov, *Phys. Rev. B*, 90, 235203, 2014
- [33] K. J. Choi, H.W. Jang and J.-L. Lee, *Appl. Phys. Lett.* 82, 1233, 2003
- [34] P. Ferrandis, M. Charles, Y. Baines, J. Buckley, G. Garnier, C. Gillot and G. Reimbold, *Jpn. J. Appl. Phys.* 56, 04CG01, 2017
- [35] T. Wosiński, *J. Appl. Phys.* 65, 1566, 1989
- [36] Z.-Q. Fang, G.C. Farlow, B. Claflin, D.C. Look and D.S. Green, *J. Appl. Phys.* 105, 123704, 2009
- [37] Z.-Q. Fang, B. Claflin, D.C. Look, D.S. Green, R. Vetry, *J. Appl. Phys.* 108, 063706, 2010
- [38] P. Ferrandis, M. Charles, C. Gillot, R. Escoffier, E. Morvan, A. Torres and G. Reimbold, *Microelectron. Eng.* 178, 158, 2017
- [39] B. Monemar, P. P. Paskov, G. Pozina, C. Hemmingsson, J. P. Bergman, S. Khromov, V. N. Izyumskaya, V. Avrutin, X. Li, H. Morkoç, H. Amano, M. Iwaya and I. Akasaki, *J. Appl. Phys.* 115, 053507, 2014
- [40] M. J. Uren, J. Möreke and M. Kuball, *IEEE Trans. Electron Devices*, 59, 3327, 2012
- [41] B. Monemar, S. Khromov, G. Pozina, P. Paskov, P. Bergman, C. Hemmingsson, L. Hultman, H. Amano, V. Avrutin, X. Li and H. Morkoç, *Jpn. J. Appl. Phys.* 52, 08JJ03, 2013
- [42] G. Callsen, M. R. Wagner, T. Kure, J. S. Reparaz, M. Bugler, J. Brunmeier, C. Nenstiel, A. Hoffmann, M. Hoffmann, J. Tweedie, Z. Bryan, S. Aygun, R. Kirste, R. Collazo, and Z. Sitar, *Phys. Rev. B* 86, 075207, 2012
- [43] M. A. Reshchikov and H. Morkoç, *J. Appl. Phys.*, 97, 061301, 2005