Traps in MOCVD n-GaN Studied by Deep Level Transient Spectroscopy and Minority Carrier Transient Spectroscopy

2

Yutaka Tokuda

Department of Electrical and Electronics Engineering, Aichi Institute of Technology, Yakusa, Toyota 470-0392, Japan
e-mail: tokuda@aitech.ac.jp, phone number: +80-565-48-8121

Keywords: … GaN, traps, DLTS, MCTS, substrates, carbon

Abstract

Electron and hole traps in MOCVD n-GaN have been studied using deep level transient spectroscopy (DLTS) and minority carrier transient spectroscopy (MCTS). Si-doped GaN is grown on sapphire, free-standing n^+-GaN and SiC substrates. DLTS and MCTS measurements are performed for Schottky diodes, p^+n diodes and MOS structures. A total of nine electron traps are found in the trap energy depth ranging from 0.24 to 1.2 eV with the trap concentration ranging from 10^{12} to 10^{16} cm^{-3}, while a total of five hole traps in the trap energy depth from 0.25 to 1.8 eV with the trap concentration from 10^{14} to 10^{16} cm^{-3}. The variation of trap concentrations are discussed in relation to the substrates used. Interface state densities around 10^{12} $cm^{-2}eV^{-1}$ are obtained for MOS structures on sapphire and n^+-GaN substrates. In carbon-doped n-GaN on SiC, a hole trap with the energy depth of 0.86 eV is observed with the trap concentrations around 10^{16} cm^{-3}, suggesting that this hole trap is carbon-related. Moreover, a trap with the energy depth of 0.88 eV is detected in high resistivity GaN doped with carbon using optical current DLTS. It is found that traps with the energy levels at E_c-0.57 and E_v+0.86 eV have larger trap concentrations in MOCVD n-GaN, while a trap at E_v+0.86 eV is dominant in carbon-doped n-GaN.

INTRODUCTION

GaN is a promising material for optical and high-speed/high-temperature electronic devices due to its properties related to wide bandgap. As widely recognized, it is important to characterize deep levels to realize the high performance of GaN-based devices since they act as traps and generation-recombination centers. It is well known that current collapse in AlGaN/GaN high electron mobility transistors HEMTs is a big issue related to trapping of carriers [1].

Deep level transient spectroscopy (DLTS) originally proposed by Lang [2] is a powerful tool to detect traps with high sensitivity and has been successfully used to characterize traps in various semiconductors such as Si, GaAs, etc. In order to perform DLTS measurements, Schottky structures are often employed since its fabrication is easier and has a low temperature process. However, only majority carrier traps are detected by DLTS using bias pulses. Minority carrier transient spectroscopy (MCTS) has been developed to detect minority-carrier traps in Schottky diodes using above-band-gap light pulses [3-5].

In this work, we characterize electron traps in MOCVD n-GaN by DLTS using bias pulses for Schottky diodes, p^+n diodes and MOS structures. Hole traps are observed in p^+n diodes by the application of forward injection pulses. Hole traps are also detected by MCTS using above-band-gap light pulses for Schottky diodes. From DLTS measurements of MOS structures, interface state distributions are obtained. In addition, traps in carbon-doped GaN are reported.

EXPERIMENTAL PROCEDURE

Si-doped n-GaN was grown by MOCVD on sapphire substrates with AlN or GaN buffer layers, HVPE-grown free-standing n^+-GaN substrates and SiC substrates with AlN buffer layers. Lateral and vertical Schottky diodes were fabricated using Pt/Au or Ni/Au as a Schottky contact and Ti/Al/Ni/Au as an ohmic contact for n-GaN on sapphire and SiC substrates and for n-GaN on n^+-GaN substrates, respectively. Carrier concentrations determined from capacitance-voltage measurements at room temperature are in the range from 5×10^{16} to 2×10^{17} cm^{-3}.

p^+n diodes were fabricated by the growth of Si-doped n-GaN on n^+-GaN substrates, followed by the growth of Mg-doped p^+-GaN. The doping concentrations of Si and Mg were ~2×10^{16} and ~3×10^{19} cm^{-3}, respectively. The activation annealing was performed to activate Mg in p-GaN. The mesa structures were fabricated by ICP etching. The Ni/Au and Ti/Al/Ni/Au were deposited as an ohmic contact on the top of the p-GaN layer and on the back side of the n^+-GaN substrate, respectively.

To fabricate MOS structures, the 50-nm thick SiO_2 was deposited at 830℃ by LPCVD on n-GaN on sapphire and n^+-GaN substrates. Lateral and vertical MOS structures were formed using Al as a gate contact and Ti/Al/Ni/Au as an ohmic contact for n-GaN on sapphire and for n-GaN on n^+-GaN, respectively.

Si-doped (~2×10^{17} cm^{-3}) n-GaN intentionally doped with carbon (~1×10^{17} cm^{-3}), denoted by n-GaN (C), was grown on a SiC substrate. The n-GaN (C) was processed into lateral Schottky diodes. High-resistivity GaN doped with carbon on SiC, GaN (C), was also prepared. Ti/Al was used as an ohmic contact.

Figure 1 shows the bipolar rectangular weighting function used to produce DLTS signals with higher detection sensitivity [6]. The bias pulses are repeatedly applied to the diode with changing temperatures. During the application of the filling pulse, traps are filled with carriers. By the subsequent application of the reverse bias, filled traps emit carriers, which are swept out of the depletion region, resulting in the capacitance transients with the time constant related to the thermal emission rates. The weighting function is set to be zero during the period of the filling pulse and during the period of T_d due to the response time of the measurement apparatus. Then, the DLTS signal is obtained by the integration of transients during the period of T_w and is given by

$$V_0 = \frac{1}{T_w}\left\{\int_{T_d}^{T_d+T_w/2} -C(t)dt + \int_{T_d+T_w/2}^{T_d+T_w} C(t)dt\right\}. \quad (1)$$

The DLTS signals go through a positive peak for majority-carrier traps and a negative peak for minority-carrier traps at a temperature determined by the rate window time constant given by T_d and T_w. The trap energy level and capture cross section are determined from the Arrhenius plot of the emission time constants. The trap concentration is obtained from the DLTS peak height.

In MCTS measurements for Schottky diodes, electron-hole pairs are generated by light illumination in the neutral region, which diffuse toward the depletion region. When the diffusion length is long enough for electrons and holes to reach the depletion region edge, minority carriers drift toward the Schottky contact by the electric field in the depletion region, while corresponding majority carriers are repelled. Thus, minority carriers are captured in the depletion region and then emitted during light-off period, resulting in the capacitance transient measured in MCTS. In n-GaN Schottky diodes, electron traps are observed by DLTS using bias pulses, while hole traps are detected by MCTS using above-band-gap light pulses of 355 nm Light emitting diodes (LEDs).

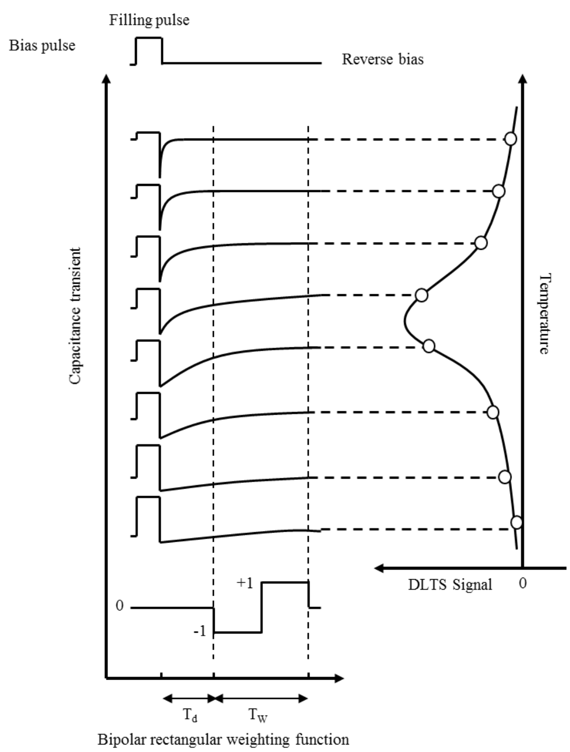

Fig. 1, DLTS with a bipolar rectangular weighting function.

EXPERIMENTAL RESULTS AND DISCUSSION

1. Electron traps observed in n-GaN Schottky diodes [7-10]

Figure 2 shows electron trap DLTS spectra obtained from n-GaN Schottky diodes on sapphire, n^+-GaN and SiC substrates. In n-GaN on sapphire, five electron traps labelled E1 to E5 are observed, while in n-GaN on n^+-GaN, two traps E1 and E3 are detected. In n-GaN on SiC, five traps E1, E3, E6, E7 and E8 are found although peak temperatures are shifted to lower temperatures with a longer DLTS time constant as indicated in Fig. 2. Although trap concentrations vary from sample to sample, two traps E1 and E3 are commonly present in MOCVD n-GaN, which is confirmed from comparison of Arrhenius plots of τT^2 vs 1000/T in Fig. 3 assuming that capture cross sections are independent of temperature. A difference in Arrhenius plots of emission time constants for E1 among samples is ascribed to electric field dependence of emission time constants, indicating that E1 is donor-like. Trap E2 appears in n-GaN on sapphire with AlN buffer layers. Traps E6 and E7 are characteristic of n-GaN on SiC. Although DLTS spectra in the high measurement temperature range show the appearance of traps E4 and E5 in n-GaN on sapphire and trap E8 in n-GaN on SiC, their peak temperatures and peak heights might be affected by leakage current related to the

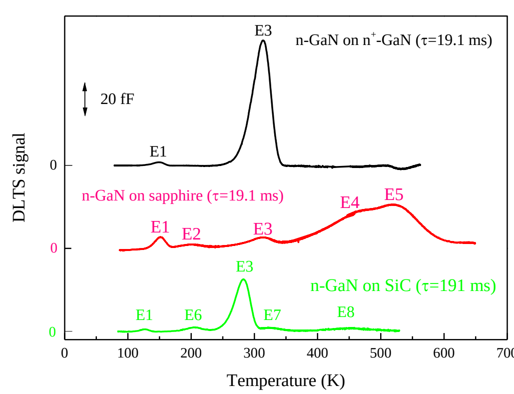

Fig. 2, Electron trap DLTS spectra for n-GaN on sapphire, n^+-GaN and SiC substrates.

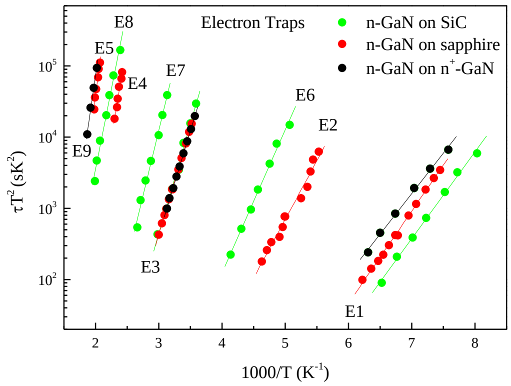

Fig. 3, Arrhenius plots of emission time constants for electron traps observed in n-GaN.

values of barrier heights of Schottky diodes used. Arrhenius plots of emission time constants for all electron traps observed in n-GaN Schottky diodes are summarized in Fig. 3.

2. Hole traps observed in n-GaN Schottky diodes [11]

Figure 4 shows MCTS spectra for n-GaN Schottky diodes. The long MCTS time constant of 1.91 s was used to keep the ratio of hole capture rates to hole emission rates as large as possible around the peak temperatures [5]. Moreover, the long light pulse width of several seconds was needed to saturate MCTS peaks, which sometimes makes it difficult to perform temperature-scan MCTS. The MCTS spectrum for n-GaN on n^+-GaN was obtained by performing isothermal MCTS measurements with the light pulse width of 60 s at the interval of 5 K and plotting MCTS signals at the time constant of 1.91 s against measurement temperatures. Three hole traps labelled H1, H2 and H3 are observed in n-GaN on sapphire. Traps H1 and H3 are found in n-GaN on n^+-GaN. However, no MCTS peaks are detected in n-GaN on SiC.

To construct Arrhenius plots of emission time constants

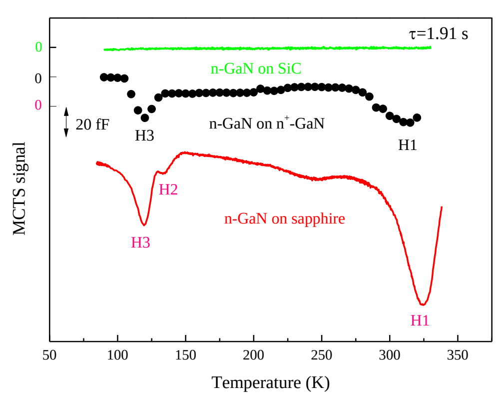

Fig. 4, MCTS spectra for n-GaN on sapphire, n^+-GaN and SiC substrates.

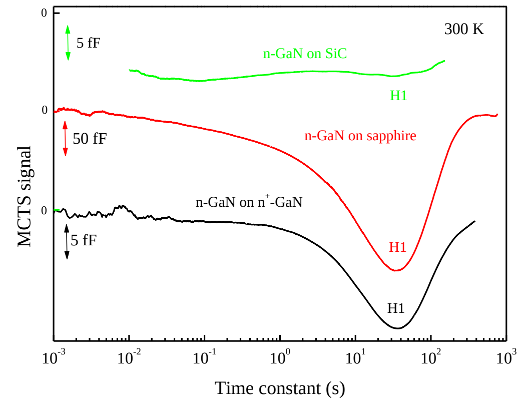

Fig. 5, Isothermal MCTS spectra at 300 K for n-GaN on sapphire, n^+-GaN and SiC substrates.

for these hole traps, we carried out isothermal MCTS measurements since temperature-dependent ratios of hole capture rates to hole emission rates distort temperature-scan MCTS spectra, which makes the determination of peak temperatures inaccurate. Figure 5 shows isothermal MCTS spectra at 300 K. Trap H1 is observed at the same time constant in n-GaN on sapphire and n-GaN on n^+-GaN. Trap H1 is also found in n-GaN on SiC, although its MCTS signals are too weak to determine the emission time constant. Arrhenius plots of emission time constants for hole traps are shown in Fig. 6.

3. Electron and Hole Traps observed in p^+n diodes on n^+-GaN substrate [12]

In p^+n diodes, both electron and hole traps are observed in n-GaN. Figure 7 shows electron and hole trap DLTS spectra for the p^+n diode on n^+-GaN substrate. In p^+n diodes, hole traps are measurable by DLTS using forward injection pulses. However, in GaN p^+n diodes, DLTS signals disappear in the low temperature range below 150 K due to freeze-out of Mg acceptors. In fact, hole traps H2 and H3

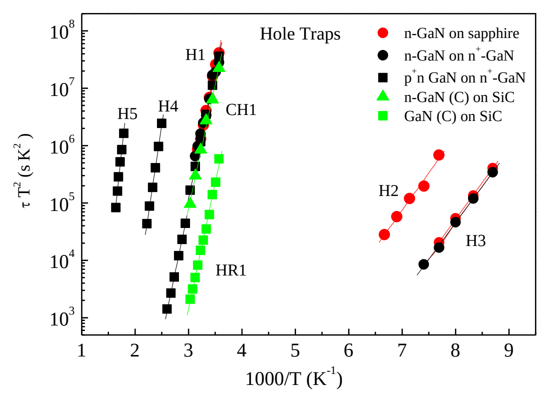

Fig. 6, Arrhenius plots of emission time constants for hole traps observed in n-GaN , n-GaN (C) and high resistivity GaN (C).

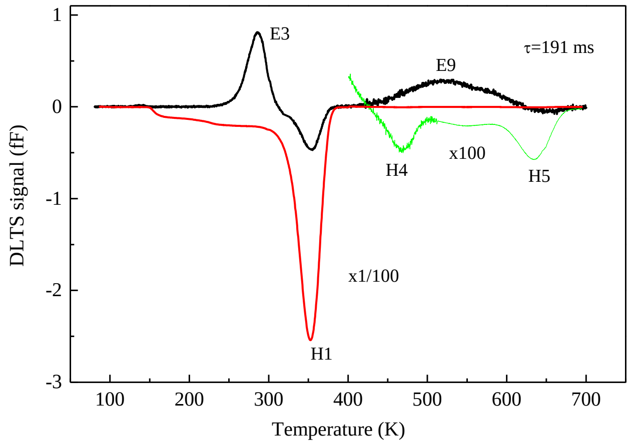

Fig. 7, Electron and hole trap DLTS spectra for the p^+n diode on n^+-GaN substrate.

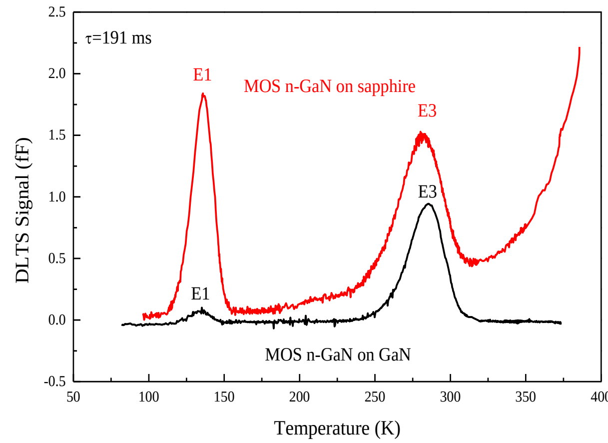

Fig. 9, Electron trap DLTS spectra for MOS n-GaN on sapphire and n^+-GaN substrates.

observed in MCTS are not detected in p^+n diodes although trap H1 is clearly visible. On the other hand, DLTS signals for p^+n diodes are more reliable in the higher temperature range in contrast with those for Schottky diodes affected by leakage current. Electron trap E9 with the broader spectrum is found in the temperature range around 500 K where DLTS signals for n-GaN Schottky diodes on n^+-GaN substrate is unclear as shown in Fig. 2. In addition, hole traps H4 and H5 are observed in the temperature range above 400 K. The Arrhenius plots of emission time constants for newly observed traps E9, H4 and H5 in p^+n diodes are shown in Figs. 3 and 6. Those of H1 determined from DLTS and isothermal DLTS are also included in Fig. 6 to confirm that the same hole trap is detected by MCTS for Schottky diodes and by DLTS for p^+n diodes.

4. Interface state distributions in MOS [13]

Figure 8 shows DLTS spectra for MOS n-GaN on sapphire and n^+-GaN substrates, which are obtained by biasing MOS from the accumulation into the deep depletion. In contrast with DLTS and MCTS spectra for Schottky and p^+n diodes, broad DLTS spectra are observed for MOS structures, which are characteristic of interfaces states with continuous energy distributions. It is noted that two peaks are observable in MOS on sapphire, corresponding to electron traps E1 and E3, while one peak in MOS on n^+-GaN. DLTS spectra for electron traps in n-GaN are observed by biasing MOS from the slight depletion into the deep depletion as shown in Fig. 9, confirming the presence of electron traps E1 and E3 in n-GaN on sapphire and n^+-GaN substrate.

Interface state distributions at the interface between SiO_2 and MOCVD n-GaN are calculated from DLTS signals obtained by subtracting the contributions from E1 and E3. The resultant interface state distributions are shown in Fig. 10. The energy scale is calculated assuming that capture cross section is 10^{-16} cm^2. Interface state densities of around

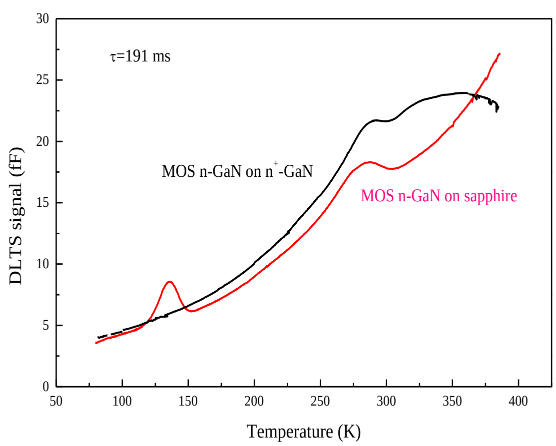

Fig. 8, DLTS spectra for MOS n-GaN on sapphire and n^+-GaN substrates.

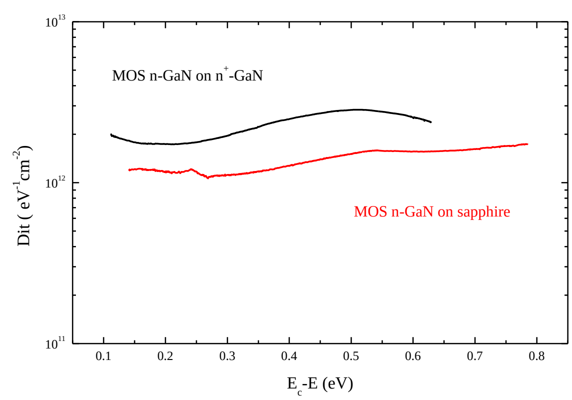

Fig. 10, Interface state distributions for MOS n-GaN on sapphire and n^+-GaN substrates.

TABLE I
Parameters of traps observed in MOCVD n-GaN

Trap	Energy level (eV)	Capture cross section (cm^2)	Remarks (1)	Remarks (2)
E1	$E_c - 0.24 \sim 0.26$	$8.4\times10^{-17} \sim 1.4\times10^{-15}$	commonly observed	V_N-V_{Ga} [14]
E2	$E_c - 0.31 \sim 0.32$	$1.1\times10^{-16} \sim 3.6\times10^{-16}$	observed in n-GaN on sapphire with AlN	
E3	$E_c - 0.57 \sim 0.61$	$1.1\times10^{-15} \sim 5.3\times10^{-15}$	commonly observed	N_{Ga} [15]
E4	$E_c - \sim1$	$\sim10^{-13}$	observed in n-GaN on sapphire	
E5	$E_c - \sim1.3$	$\sim10^{-14}$	observed in n-GaN on sapphire	
E6	$E_c - 0.40$	1.4×10^{-15}	observed in n-GaN on SiC	
E7	$E_c - 0.73$	1.4×10^{-14}	observed in n-GaN on SiC	
E8	$E_c - 0.89$	3.9×10^{-16}	observed in n-GaN on SiC	
E9	$E_c - 1.22$	4.3×10^{-14}	measured in p^+n on n^+-GaN	
H1	$E_v + 0.86 \sim 0.88$	$7.4\times10^{-14} \sim 1.3\times10^{-13}$	commonly observed	V_{Ga}-related [16], C-related [17]
H2	$E_v + 0.25$	1.7×10^{-17}	measured in n-GaN on sapphire	
H3	$E_v + 0.25$	3.4×10^{-16}	measured in n-GaN on sapphire and n^+-GaN	
H4	$E_v + 1.19$	2.3×10^{-15}	measured in p^+n on n^+-GaN	
H5	$E_v + 1.76$	1.2×10^{-12}	measured in p^+n on n^+-GaN	

10^{12} cm^{-2} eV^{-1} are obtained in the energy range from E_c-0.1 to E_c-0.8 eV.

5. Summary of traps in MOCVD n-GaN

In TABLE I, parameters of traps observed in MOCVD n-GaN are summarized with possible identification reported so far [14-17]. Nine electron traps (E1-E9) and five hole traps (H1-H5) are detected in this work. Of 14 traps, E1, E3 and H1 are commonly observed in MOCVD n-GaN irrespective of substrates used. In most samples, E3 is the dominant trap among electron traps observed, and H1 is the dominant hole trap among hole traps observed although their trap concentrations vary from sample to sample.

Figure 11 summarizes trap concentrations for E1, E3 and H1 versus substrates which are obtained from DLTS and MCTS measurements of Schottky diodes, p^+n diodes and MOS structures. Trap E1 concentrations are lower in n-GaN on n^+-GaN substrate, suggesting its correlation with dislocations [14]. Of n-GaN on sapphire, trap E1 concentrations are lower with GaN buffer layers. Trap E3 shows two orders of magnitude variation in concentration among diodes on each wafer. The reason for such large variation in trap concentration is unclear at present, but it might be dependent on growth conditions such as growth temperatures, growth pressures and so on. Since trap E3 concentration is sometimes around 10^{16} cm^{-3}, it is important to elucidate the origin of E3. The H1 also has trap concentration around 10^{16} cm^{-3} for n-GaN on sapphire and n^+-GaN. Although trap H1 concentration is lower in n-GaN on SiC, it might be possible that trap H1 concentration depends on growth conditions rather than substrates.

6. Carbon-doped GaN [18,19]

DLTS and MCTS measurements were carried out for n-GaN (C) Schottky diodes on SiC. The same electron traps (E1, E3, E6, E7, E8) are observed in n-GaN (C) on SiC as those in n-GaN on SiC shown in Fig. 2. A prominent difference is that hole trap labelled CH1 with the energy level of E_v+0.86 eV appears in n-GaN (C) on SiC with the concentration around 10^{16} cm^{-3} as shown in Fig. 12. This indicates that CH1 is carbon-related. This assignment is consistent with the previous assignment that the E_v+0.9 eV

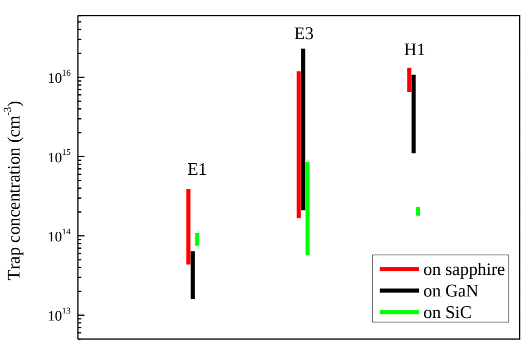

Fig. 11, Trap E1, E3 and H1 concentrations versus substrates.

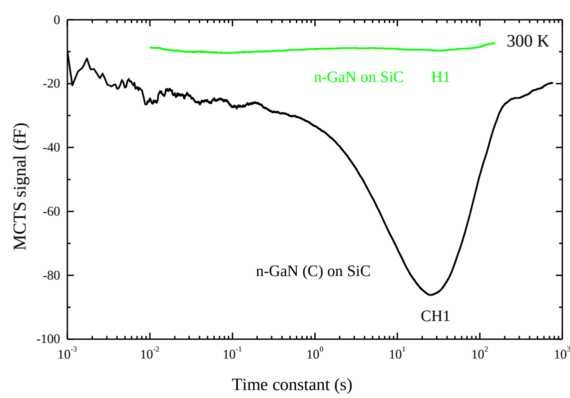

Fig. 12, Isothermal MCTS spectra for n-GaN (C) and n-GaN on SiC.

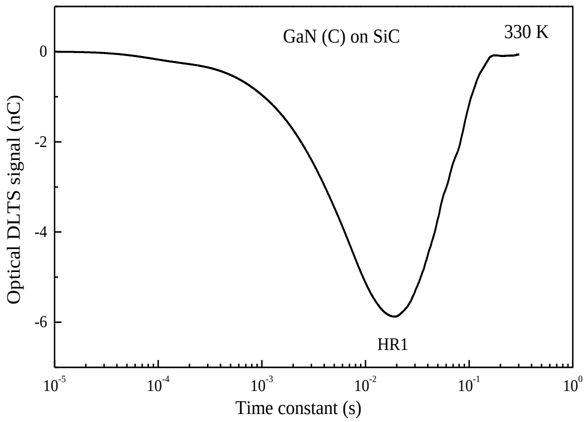

Fig. 13, Isothermal optical current DLTS spectrum at 330 K for HR GaN (C) on SiC.

hole trap is associated with carbon-related defect [17]. According to a theoretical calculation [20], CH1 might be ascribed to C_N. Moreover, a comparison of Arrhenius plots of emission time constants between H1 and CH1 shows a good agreement between them, suggesting that H1 and CH1 are the same defect. However, Hierro et al. have reported that the E_v+0.87 eV hole trap is V_{Ga}-related [16]. There is a possibility that H1 is associated with V_{Ga}-related defect.

It has been suggested that both V_{Ga}-related defect and carbon-related defect are responsible for yellow luminescence [21] and the carbon-related defect causes the current collapse in AlGaN/GaN HEMTs [1]. We performed direct characterization of traps in high-resistivity (HR) GaN (C) by optical current DLTS [22] with a bipolar rectangular weighting function in the unit of Coulomb [19]. Figure 13 shows isothermal optical current DLTS spectrum at 330 K for HR GaN (C), indicating the presence of trap labelled HR1. It is speculated that HR1 is carbon-related since high resistivity is achieved by carbon doping. However, no agreement in the Arrhenius plots of emission time constant between HR1 and CH1 is found as shown in Fig. 6. Further experiments are needed to clarify this difference although it might be possible that CH1 and HR1 are the different structures of carbon-related defects.

CONCLUSIONS

Nine electron traps (E1-E9) and five hole traps (H1-H5) are found in MOCVD n-GaN by DLTS and MCTS measurements for Schottky diodes on sapphire, n^+-GaN and SiC substrates, p^+n diodes on n^+-GaN substrate and MOS structures on sapphire and n^+-GaN substrates. Their trap parameters are summarized together with the variation of concentrations for commonly observed electron traps irrespective of substrates used. Hole trap H1 is also commonly detected. Hole trap CH1 appears in n-GaN doped with carbon and is ascribed to the carbon-related defects, possibly C_N. It is unclear at present whether H1 and CH1 are the same defect or not. It might be possible that H1 is V_{Ga}-related. We would like to point out that it is important to identify H1 and CH1 since these are expected to be responsible for YL and current collapse in HEMTs.

ACKNOWLEDGEMENTS

This work has been performed as an MEXT-Supported Program for the Strategic Research Foundation at Private Universities (2010-2014).

REFERENCES

[1] P. B. Klein et al., Appl. Phys. Lett. **79**, 3527 (2001).

[2] D. V. Lang, J. Appl. Phys. **45**, 3014 (1979).

[3] B. Brunwin et al., Electron. Lett. **15**, 349 (1979).

[4] B. Hamilton et al., J. Appl. Phys. **50**, 6379 (1979).

[5] J. A. Davidson et al., J. Appl. Phys. **81**, 251 (1997).

[6] Y. Tokuda et al., Japan. J. Appl. Phys. **18**, 309 (1979).

[7] W. Nakamura et al., Physica B, **376-377**, 516 (2006).

[8] Y. Tokuda et al., Superlattices and Microstructures **40**, 268 (2006).

[9] Y. Tokuda et al., Phys. Stat. Sol. (c) **4**, 2568 (2007).

[10] S. Chen et al., J. Appl. Phys. **112**, 053513 (2012).

[11] Y. Tokuda et al., Phys. Status Solidi C **8**, 2239 (2011).

[12] Y. Tokuda et al., Materials Science Forum **600-603**, 1297 (2009).

[13] Y. Tokuda et al., International Workshop on Nitride Semiconductors 2008 We7-P6 Montreux (2008)

[14] Z-Q. Fang et al., Appl. Phys. Lett. **78**, 332 (2001).

[15] D. Hasse et al., Appl. Phys. Lett. **69**, 2525 (1996).

[16] A. Hierro et al, Appl. Phys. Lett. **76**, 3064(2000).

[17] A. Armstrong et al., J. Appl. Phys. **98**, 053704 (2005).

[18] U. Honda et al., Jpn. J. Appl. Phys. **51**, 04DF04 (2012).

[19] Y. Tokuda et al., Materials Research Society Fall meeting, T3.09, Boston (2013.12).

[20] J. L. Lyons et al., Appl. Phys. Lett. **97**, 152108 (2012).

[21] R. Armitaga et al., Appl. Phys. Lett. **82**, 3457 (2003).

[22] Ch. Hurtes et al., Appl. Phys, Lett. **32**, 821 (1978).

ACRONYMS

GaN: Gallium Nitride
DLTS: Deep Level Transient Spectroscopy
MCTS: Minority Carrier Transient Spectroscopy
HEMT: High Electron Mobility Transistor
MOCVD: Metal Organic Chemical Vapor Deposition
ICP: Inductively Coupled Plasma
LPCVD: Low Pressure Chemical Vapor Deposition
MOS: Metal Oxide Semiconductor
LED: Light Emitting Diode