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Citation: J Sui, J X Chen, H L Qu, Y Zhang, X Lu, and X B Zou, Emission and capture characteristics of deep hole trap in n−GaN by optical deep level transient spectroscopy[J]. *J. Semicond.*, 2024, 45(3), 032503.

View online: https://doi.org/10.1088/1674-4926/45/3/032503

Journal of Semiconductors
(2024) 45, 032503
doi: 10.1088/1674-4926/45/3/032503

ARTICLES

Emission and capture characteristics of deep hole trap in n-GaN by optical deep level transient spectroscopy

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Abstract: Emission and capture characteristics of a deep hole trap (H1) in n-GaN Schottky barrier diodes (SBDs) have been investigated by optical deep level transient spectroscopy (ODLTS). Activation energy (E_{emi}) and capture cross-section (σ_p) of H1 are determined to be 0.75 eV and 4.67 × 10^{-15} cm^2, respectively. Distribution of apparent trap concentration in space charge region is demonstrated. Temperature-enhanced emission process is revealed by decrease of emission time constant. Electric-field-boosted trap emission kinetics are analyzed by the Poole–Frenkel emission (PFE) model. In addition, H1 shows point defect capture properties and temperature-enhanced capture kinetics. Taking both hole capture and emission processes into account during laser beam incidence, H1 features a trap concentration of 2.67 × 10^{15} cm^{-3}. The method and obtained results may facilitate understanding of minority carrier trap properties in wide bandgap semiconductor material and can be applied for device reliability assessment.

Key words: GaN; deep level transient spectroscopy; minority carrier trap; time constant; trap concentration

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1. Introduction

Gallium nitride (GaN) has been considered as a promising material for power electronics[1] and optoelectronic devices, e.g., light emitting diodes (LEDs)[2], photodetectors[3], and solar cells[4], due to its wide energy bandgap, high electron mobility, and high thermal conductivity. However, traps in semiconductor materials may significantly impact the conductive properties and operational performance of semiconductor devices and related electronics[5–8]. Therefore, understanding the nature of traps in GaN devices holds both scientific and practical significance for improving GaN material quality and associated device efficiency.

There have been some investigations on the properties of traps in GaN-based devices. Angelotti *et al.* have previously extracted a shallow-level trap in a GaN radio frequency (RF) HEMT by drain current transient (DCT) analysis[9]. Using deep level transient spectroscopy (DLTS), Hierro *et al.* determined the carrier capture kinetics of electron traps in n-GaN[10]. DLTS holds the features of high sensitivity, high resolution, non-destructive analysis, and so on. DLTS has been performed on a variety of GaN-based devices such as Schottky barrier diodes (SBDs)[11], p–n and p–i–n junctions[12]. These studies have revealed various traps in GaN films, which are grown by various methodologies involving metal-organic chemical vapor deposition (MOCVD)[13, 14], hydride vapor phase epitaxy (HVPE)[15], and molecular beam epitaxy (MBE)[16]. Our previous work has demonstrated several majority carrier (electron) traps in n-GaN SBDs by DLTS technique using electrical pulses[17]. However, during the electrical filling pulse, a large number of majority carriers are injected in the n⁻-GaN layer. Thus, the DLTS signal is dominated by majority carrier traps, making the signature of minority carrier traps in the n⁻-GaN layer remain undetected. Minority carrier traps have significant technical implications due to their impact on carrier lifetime in some bipolar devices[18]. However, study on minority carrier traps in GaN materials is relatively challenging and limited.

The minority carrier traps could be investigated using optical deep level transient spectroscopy (ODLTS)[19, 20] or minority carrier transient spectroscopy (MCTS)[21, 22] to boost the minority carrier concentration. Polyakov *et al.* identified hole traps with activation energies of 0.7 and 0.9 eV in n-GaN SBDs grown on sapphire substrates using ODLTS[23, 24]. Amor *et al.* also revealed a hole trap characterized by activation energy of 0.76 eV utilizing DLTS, but only capture cross-section and emission time were extracted[20]. There are still some issues that need to be addressed to thoroughly understand the minority carrier trap properties in GaN materials. (i) There is still insufficient research on the detailed emission mechanism for deep hole traps, which have a significant contribution in device properties such as conductivity compensation and non-equilibrium carrier recombination[25, 26]. There is scarce information on electric-field (E) dependent emission kinetics for minority carrier traps in GaN-based materials. The electric-field in the depletion region should be taken into account since it can substantially affect the emission rate[27]. (ii) There remains a lack of quantitative analysis of the cap-

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Received 31 AUGUST 2023; Revised 22 NOVEMBER 2023.

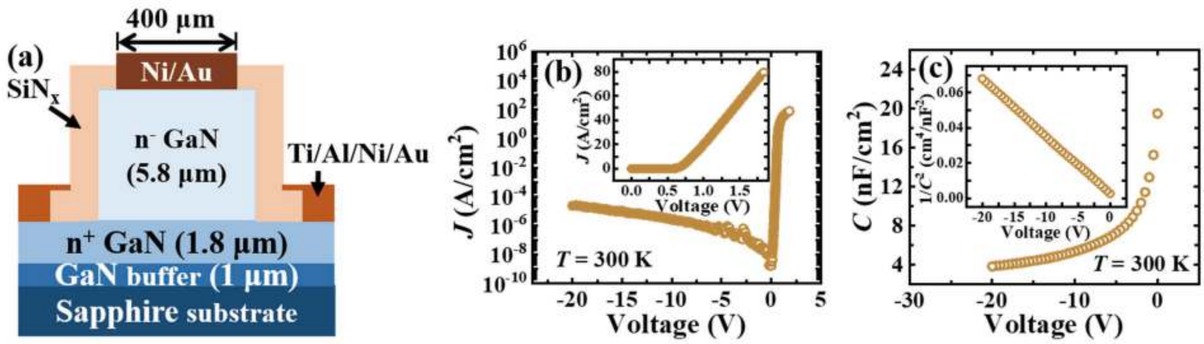

Fig. 1. (Colour online) (a) A cross-section diagram of a GaN quasi-vertical SBD under experimentation. (b) Forward and reverse J–V characteristics at 300 K presented by logarithmic scale. Inset: forward J–V characteristics at 300 K in linear scale. (c) C–V characteristics at 300 K. Inset: $1/C^2$–V curve at 300 K.

ture kinetics of deep hole traps. A comprehensive investigation into the capture kinetics of traps can reveal profound insights into the physical characteristics of defects in GaN materials[28].

In this article, we have studied emission and capture kinetics of minority carrier (hole) trap H1 in n-GaN SBD on sapphire substrate using ODLTS. Temperature-scanning ODLTS results reveal a hole trap H1 identified with activation energy of 0.75 eV and capture cross-section of 4.67×10^{-15} cm^2. The profile of the apparent trap concentration of H1 in the space charge region has been investigated. Isothermal ODLTS for scanning measurement time (T_W) and capacitance transient studies at different temperatures suggest temperature-enhanced carrier emission process and electric-field-enhanced carrier emission kinetics. The capacitance transient amplitude trends corresponding to various optical pulse width (t_p) reveal the point defect type of H1 and the temperature-dependent capture kinetics. These results will provide valuable insights into the properties of minority carrier traps in GaN and contribute to the development of GaN-based devices with enhanced performance and reliability.

2. Experimental details

Fig. 1 (a) depicts a cross-section diagram of GaN SBD in this study. The GaN SBD was prepared by MOCVD on a 2-inch sapphire substrate. The epi-layer structure started with GaN buffer layer with 1-μm thickness and continued with n$^+$-GaN layer with thickness of 1.8 μm and electron concentration of 5×10^{18} cm^{-3}. Subsequently, an unintentionally-doped n$^-$-GaN layer was deposited with thickness of 5.8 μm and carrier concentration of 5.3×10^{15} cm^{-3}. Following etching and sidewall passivation using SiN$_X$, a deposition of Ti/Al/Ni/Au was performed on the exposed n$^+$-GaN layer as the cathode. Ti/Al/Ni/Au Ohmic contact underwent annealing at 850 ℃ for 30 s. On the mesa, a layer of Ni/Au with a diameter of 400 μm was deposited as the anode, and the Ni/Au Schottky contact remained unannealed. The ODLTS measurement was conducted utilizing the FT 1230 high energy resolution analysis deep level transient spectroscopy (FT 1230 HERA-DLTS) system (PhysTech) equipped with a 10 mW laser with 405 nm wavelength.

3. Results and discussion

Fig. 1(b) presents the forward and reverse current density–voltage (J–V) characteristics of the GaN SBD at 300 K. The inset of Fig. 1(b) represents forward J–V characteristics in linear scale. The threshold voltage (V_{th}) was identified as 0.65 V at 300 K with a current density of 1 A/cm^2. Meanwhile, Fig. 1(c) depicts the capacitance–voltage (C–V) characteristics of the GaN SBD at 300 K. The frequency and AC amplitude of the C–V test were 1 MHz and 50 mV, respectively. As indicated in the inset of Fig. 1(c), $1/C^2$–V characteristics are plotted and present a linear relationship, suggesting that the carrier concentration is uniformly distributed. The carrier concentration (N_S) was calculated as 4.59×10^{15} cm^{-3} from the slope of $1/C^2$–V (Eq. (1)).

$$\frac{d\left(1/C^2\right)}{dV} = \frac{2}{q\varepsilon_r\varepsilon_0 A^2 N_S}, \tag{1}$$

where q is the elementary charge, ε_r is the relative permittivity of GaN, ε_0 is vacuum permittivity, and A is the anode area[11].

Temperature-scanning ODLTS spectra was employed to extract trap properties in n$^-$-GaN layer[29, 30]. Fig. 2(a) shows energy band diagrams of capture and emission process for hole trap during the ODLTS measurement. Featuring a sub-bandgap wavelength of 405 nm, the optical pulse provides enough energy to activate the holes. A substantial number of holes are photon-excited and captured by hole trap in the n$^-$-GaN layer during optical filling pulse period. At the end of filling period, the occupied hole trap starts to thermally emit holes for measurement period[31]. ODLTS measurement was conducted with a reverse bias (U_R) of −6 V, a t_p of 1 s, and a T_W of 10 s. In Fig. 2(b), the inverted ODLTS spectra displays a prominent signal valley at approximately 315 K, representing a minority carrier trap. Upon application of U_R of −6 V, the space charge region is located in the n$^-$-GaN layer, accordingly, it is confirmed to be a hole trap (H1). Fig. 2(c) exhibits Arrhenius plot of the hole trap H1 resulting from the temperature-scanning ODLTS spectra. The activation energy (E_{emi}) and capture cross-section (σ_p) of the hole trap H1 were determined to be 0.75 eV and 4.67×10^{-15} cm^2, respectively, through the Arrhenius relation[30, 32]. The σ_p by default represents the optical capture cross-section extracted by ODLTS[33].

Fig. 2(d) illustrates apparent trap concentration (N_{Ta}) profile versus depletion region width (W_R) at 315 K, obtained from the isothermal ODLTS results for scaning U_R. W_R was determined from C–V characteristics at 315 K by the

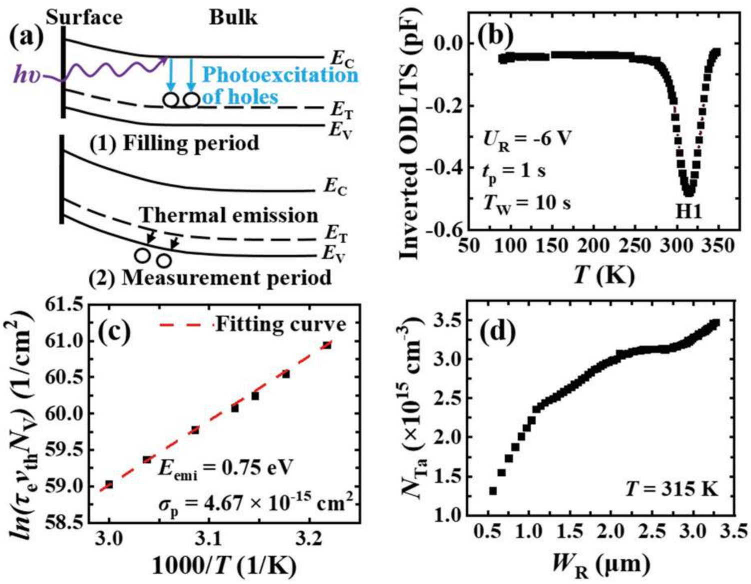

Fig. 2. (Colour online) (a) Energy band diagrams of hole trap in GaN for (1) capture and (2) emission process. (b) Inverted temperature-scanning ODLTS spectra. (c) Arrhenius plot for hole trap H1. (d) Apparent trap concentration profile versus depletion region width.

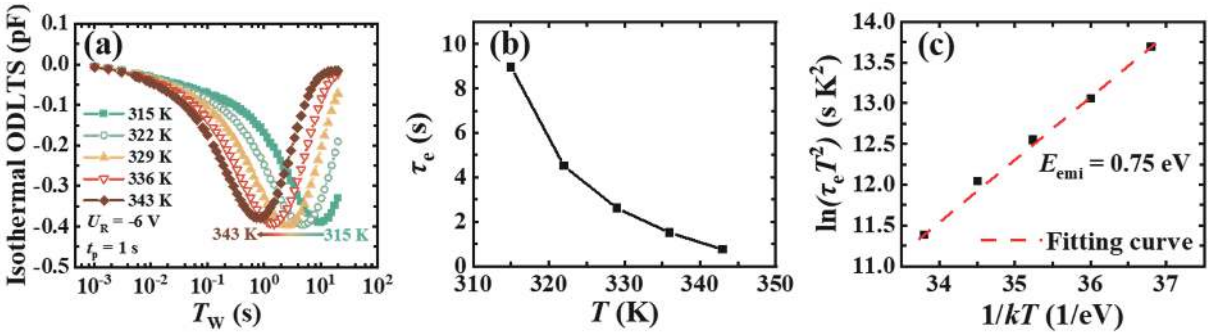

Fig. 3. (Colour online) (a) Isothermal ODLTS spectra for scanning T_W with fixed U_R of −6 V and t_p of 1 s from 315 to 343 K. (b) τ_e derived by isothermal ODLTS at different temperatures. (c) Arrhenius plot of trap H1 extracted from temperature-dependent τ_e.

relation[34]:

$$W_R = \frac{\varepsilon_r \varepsilon_0 A}{C}. \tag{2}$$

Meanwhile, apparent trap concentration (N_{Ta}) at different U_R (that is, different W_R) is given by[22]

$$N_{Ta} = 2\frac{\Delta C}{C_R} N_S, \tag{3}$$

where ΔC is the capacitance transient amplitude, C_R is the steady-state capacitance at U_R, and N_S is the net carrier concentration calculated from the C–V characteristics at 315 K by Eq. (1). ΔC and C_R at different U_R were obtained from isothermal ODLTS measurement for scanning U_R. For isothermal ODLTS measurement, t_p was set to 1 s to ensure that all traps were filled. The increase of N_{Ta} with extending W_R is associated with the quick carrier recombination effect at the depletion region boundary[22].

Fig. 3(a) presents the isothermal ODLTS spectra of trap H1[35, 36], which was performed from 315 to 343 K with U_R of −6 V and t_p of 1 s. The emission time constants (τ_e) were determined by extracting valley position from isothermal ODLTS spectra. As the temperature increases, the signal valley associated with trap H1 shifts towards a lower T_W, indicating a decrease of τ_e. The τ_e of trap H1 at various temperatures are displayed in Fig. 3(b). It's noteworthy that the τ_e of H1 consistently decreased from 8.95 s at 315K to 0.74 s at 343 K, suggesting an increase of the emission rate at higher temperatures.

As indicated in Fig. 3(c), the relationship between τ_e and temperature can be fitted by Eq. (4)[37]:

$$\ln\left(\tau_e T^2\right) = \frac{E_{emi}}{kT} - \ln\left(\gamma \sigma_P\right), \tag{4}$$

where γ is a constant relating to effective hole mass. From the slope and intercept of the Arrhenius plot in Fig. 3(c), the activation energy of trap H1 is determined to be 0.75 eV with a capture cross-section in the order of 10^{-15} cm^2 as well, which is consistent with the results obtained by Fig. 2(c).

Fig. 4(a) illustrates correspondence between emission time constant (τ_e) and electric-field extracted from capacitance transient spectra with different U_R at three different temperatures: 315, 322, and 329 K. τ_e decreased significantly with an increased electric-field at each temperature, which can be attributed to a reduction in the apparent thermal activation energy with the electric-field. It is also observed that τ_e decreased markedly with elevated temperature, which shows agreement with the conclusion in Fig. 3(b).

The relationship between the logarithm of the emission rate (e_p) and the square of the electric-field (E^2) was illus-

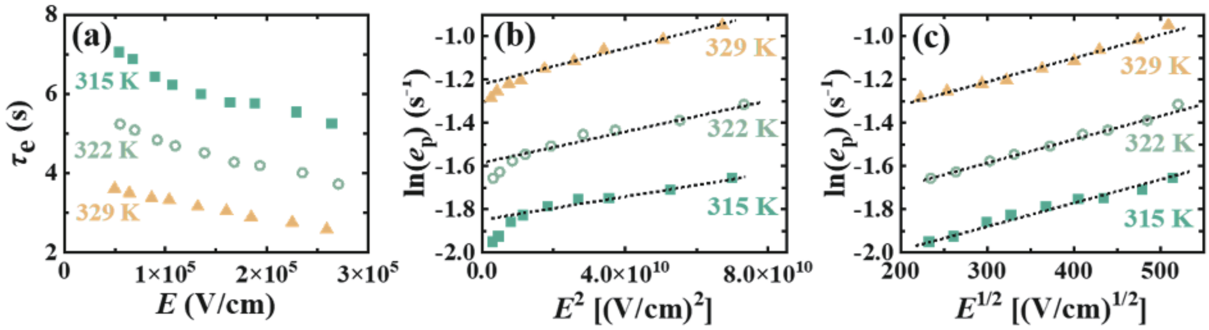

Fig. 4. (Colour online) (a) Electric-field-dependent τ_e of trap H1 extracted from capacitance transient spectra from 315 to 329 K. The $\ln(e_p)$ of trap H1 as a function of (b) E^2 and (c) $E^{1/2}$ from 315 to 329 K. Black dotted lines are linear fitting curves.

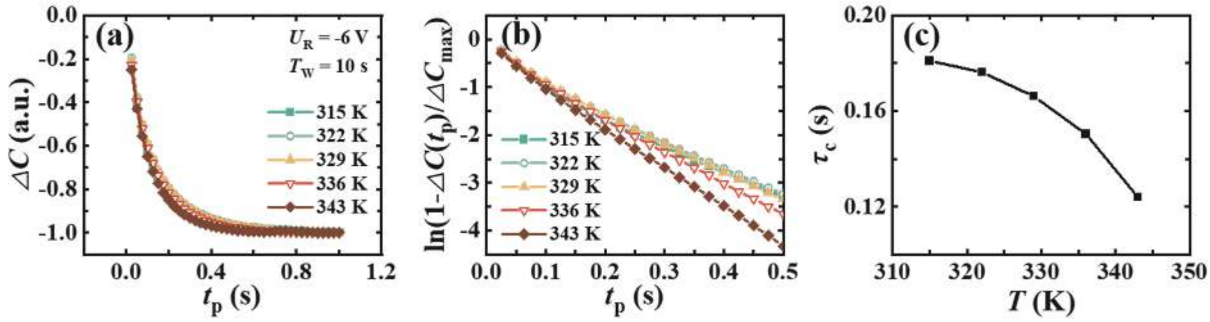

Fig. 5. (Colour online) (a) Normalized capacitance transient amplitude as a function of t_p. (b) Capacitance transient amplitude increases exponentially with t_p. (c) τ_c from 315 to 343 K.

trated in Fig. 4(b). It was observed that a linear fit was not feasible, suggesting that the enhancement cannot be solely attributed to a phonon-assisted tunneling process. However, $\ln(e_p)$ is plotted as a function of the square root of the electric-field ($E^{1/2}$), as shown in Fig. 4(c). The linear fitting of the relationship shows that the enhancement process can be adequately described by Poole–Frenkel emission (PFE) process, which can characterize the progression of e_p with E for H1 at these temperatures[38].

Fig. 5(a) displays normalized capacitance transient amplitude of trap H1 as a function of t_p at various temperatures. As t_p increases, capacitance transient amplitude (ΔC) first increases rapidly, which is related to the increment of the population of filled traps. As t_p reaches a sufficiently long duration, all traps are completely filled, leading to saturation of ΔC.

As illustrated in Fig. 5(b), the relationship between ΔC and t_p could be expressed as[39]

$$\ln\left(1-\frac{\Delta C\left(t_p\right)}{\Delta C_{\max}}\right)=-\frac{t_p}{\tau_c}, \tag{5}$$

where ΔC_{max} is the saturated capacitance transient amplitude and τ_c is apparent capture time constant. It is observed that the curves of $\ln\left(1-\frac{\Delta C(t_p)}{\Delta C_{\max}}\right)$ versus t_p exhibit good linearity at several temperatures. Therefore, H1 is regarded as a point defect rather than an extended defect in terms of the excellent linear trend of curves in Fig. 5(b)[40]. From slope of linear fitting curve in Fig. 5(b), τ_c as a function of temperature was extracted, as shown in Fig. 5(c). From 315 to 343 K, τ_c was reduced from 0.18 to 0.12 s, which demonstrates a thermally enhanced capture property. Compared with capture time constants reported for majority carrier trapping process in the literatures[9, 10], the τ_c of minority carrier trap shows a much larger value. This is related to the small minority carrier concentration in the n-GaN material, which lower the probability of the holes getting captured, leading to a large τ_c for hole trap (H1)[41]. In addition, small σ_p (4.67×10^{-15} cm^2) of H1 also suggested weaker capability of the hole trap to capture holes, and thus a relatively large capture time constant. The value of τ_c for H1 in this work is actually comparable to time constant (0.36 s) extracted for a hole trap (E_V + 0.86 eV) in n-GaN using isothermal MCTS[42]. It is worth noting that τ_c is not equal to the time required for traps to be completely filled. The τ_c signifies the time it takes for the unfilled trap concentration to decrease to 1/e times N_{Ta}, shorter than the time taken for traps to be completely occupied[32].

The isothermal ODLTS spectra, depicted as a function of T_W in Fig. 3(a) and t_p in Fig. 5(b), can be utilized to estimate the trap concentration. For instance, at T = 315 K, the τ_c for the exponential relationship between the ΔC and t_p is estimated to be 0.18 s. The trapped hole concentration (p_t) can be computed considering the simultaneous events of hole capture and emission during laser beam incidence, according to

$$p_t=\frac{c_p p}{c_p p+e_p} N_T\left\{1-\exp\left[-\left(c_p p+e_p\right) t_p\right]\right\}, \tag{6}$$

where c_p is the hole capture coefficient, e_p is the hole emission rate, p is the hole concentration, and N_T is the trap concentration[43]. Under the assumption of a uniform hole concentration within the depletion region during laser beam incidence, the value of $c_p p$ can be computed as 5.44 s^{-1}. This calculation utilizes the determined value of e_p as 1/8.95 s^{-1}, obtained from Fig. 3(a), and ($c_p p + e_p$) as 1/0.18 s^{-1}, derived

Table 1. Comparison with other published comparable hole trap in n-GaN.

E_{emi} (eV)	0.75[44]	0.70[23]	0.76[20]	0.75 [This work]
σ_p (cm^2)	9.5×10^{-17}	NA	4.9×10^{-13}	4.67×10^{-15}
N_{Ta} (cm^{-3})	1.73×10^{14}	9.6×10^{15}	NA	2.67×10^{15}
e_p–E	NA	NA	NA	PFE
Growth	MOCVD	HVPE	MOCVD	MOCVD
Measurement	MCTS, 280 nm	ODLTS, 365 nm	DLTS	ODLTS, 405 nm
Remark	V_{Ga} related	Complexes*	Point defect	Point defect

NA means not applicable in the table.
*This trap is related to complexes of native defects with donor impurities.

from Fig. 4(b). By employing the saturated capacitance transient amplitude ΔC_{max} and the corresponding relation[42]

$$\frac{\Delta C_{\max}}{C_R} = \frac{p_t}{2N_S} = \frac{c_p p}{c_p p + e_p}\frac{N_T}{2N_S} = 0.98\frac{N_T}{2N_S}, \qquad (7)$$

N_T is obtained to be 2.67×10^{15} cm^{-3}. With the incident laser beam on, holes and electrons undergo optical emission, resulting in a reduction of p_t. Consequently, the obtained value of N_T may be underestimated. The result obtained from Eq. (7) are slightly larger than that obtained in Eq. (3), indicating the existence of a large trap concentration for hole trap H1. Trap concentration of H1 is one to two orders of magnitude larger than the concentration of majority carrier (electron) traps in our previous work[17].

Table 1 summarizes the trap characteristics of hole trap H1 in this work and other traps in literatures. The smaller σ_p indicates that the hole trap in the device is relatively incapable of trapping holes. Polyakov *et al.* have reported that the trap concentration can be reduced by three orders of magnitude by changing the device fabrication process conditions[23]. Corresponding to the different characteristics of the devices, H1 can be detected in n-GaN using different measurement techniques, i.e., MCTS[44], ODLTS[23], DLTS[20], and test conditions. H1 can be observed for materials grown by HVPE and MOCVD methods, suggesting that it is an extensive-existed defect[20, 23]. In this work, for the first time, the emission mechanism of H1 was determined to comply with the Poole–Frenkel emission model.

4. Conclusion

In conclusion, trap characteristics of a minority carrier (hole) trap in n-GaN SBD grown by MOCVD have been thoroughly analyzed using ODLTS. The hole trap (H1) characterized by E_{emi} of 0.75 eV and σ_p of 4.67×10^{-15} cm^2 is considered to be a point defect. Temperature-enhanced emission and capture kinetics are investigated as the temperature increases from 315 to 343 K. This is evidenced by a significant reduction of emission time constant from 8.95 to 0.74 s and a gradual decrease of apparent capture time constant from 0.18 to 0.12 s. The emission process of H1 is found to be accelerated by electric-field, which can be well described by Poole–Frenkel emission model. In addition, the hole trap exhibits a high trap concentration of 2.67×10^{15} cm^{-3}, taking into account that hole trapping and emission processes occur simultaneously during luminescence. These results regarding the specific properties of the deep-level trap in GaN may contribute to the advancement of GaN devices towards improved performance and reliability in power and RF electronics.

Acknowledgments

This work was supported by ShanghaiTech University Startup Fund 2017F0203-000-14, the National Natural Science Foundation of China (Grant No. 52131303), Natural Science Foundation of Shanghai (Grant No. 22ZR1442300), and in part by CAS Strategic Science and Technology Program (Grant No. XDA18000000).

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