Shockley–Read–Hall lifetime in homoepitaxial p-GaN extracted from recombination current in GaN p–n\textsuperscript{+} junction diodes

Takuya Maeda\textsuperscript{1}, Tetsuo Narita\textsuperscript{2}, Hiroyuki Ueda\textsuperscript{2}, Masakazu Kanechika\textsuperscript{2}, Tsutomu Uesugi\textsuperscript{2}, Tetsu Kachi\textsuperscript{3}, Tsunenobu Kimoto\textsuperscript{2}, Masahiro Horita\textsuperscript{1,3}, and Jun Suda\textsuperscript{1,3}

\textsuperscript{1}Kyoto University, Kyoto 615-8510, Japan
\textsuperscript{2}Toyota Central R&D Labs., Inc., Aichi, 480-1118, Japan
\textsuperscript{3}Nagoya University, Aichi 464-8603, Japan

E-mail: maeda@semicon.kuee.kyoto-u.ac.jp

Received December 31, 2018; accepted January 29, 2019; published online May 9, 2019

1. Introduction

Owing to its high critical electric field (∼3 MV cm\textsuperscript{-1}), GaN has attracted great attention as a material for the next-generation power devices. There have been many reports on GaN vertical power devices fabricated on GaN bulk substrates, which showed high breakdown voltage and low on-resistance.\textsuperscript{2–6} Owing to the low threading dislocation density (∼10\textsuperscript{4} cm\textsuperscript{-2}) in homoepitaxial GaN, leakage current, inhomogeneity and other non-ideal characteristics were well suppressed in GaN-on-GaN devices, which enables us to analyze the device characteristics in detail.\textsuperscript{9–13}

Reference 11 investigated forward current–voltage (I–V) characteristics of GaN-on-GaN p–n\textsuperscript{−}–n\textsuperscript{+} junction diodes. The recombination current with an ideality factor of 2 in the voltage range of 2.0–2.5 V and the diffusion current with a near unity ideality factor in the voltage range of 2.5–2.8 V were observed. They extracted the Shockley–Read–Hall (SRH) lifetime, which is the square root of the product of hole and electron carrier lifetimes (\(\tau_{\text{SRH}}=\sqrt{\tau_{\text{h}}\tau_{\text{e}}/e}\)), by analyzing the recombination current with consideration of the SRH recombination rate in the depletion layer.\textsuperscript{14,15} In the p–n\textsuperscript{−}–n\textsuperscript{+} junction, the depletion layer extends to the highly-doped n-layer side and the SRH recombination occurs in the n-layer. The obtained SRH lifetime is one for the n-GaN. In the same way, the SRH lifetime in p-GaN can be obtained using the p–n\textsuperscript{−}–n\textsuperscript{+} junction. However, there is no report on the SRH lifetime in p-GaN.

Recently, the growth technique of a lightly Mg-doped p-GaN has been developed, and relatively low Mg concentration can be controllable.\textsuperscript{16,17} In this study, we investigate the forward I–V characteristics in GaN-on-GaN p–n\textsuperscript{−}–n\textsuperscript{+} junction diodes, in which the depletion layer mainly extends to the p-layer side. The large recombination current with an ideality factor of 2 was clearly observed in the wide voltage range of 1.8–2.7 V. The SRH lifetime in homoepitaxial p-GaN and its temperature dependence are investigated.

Fig. 1. (Color online) Schematic cross section of the GaN p–n\textsuperscript{−} junction diode with a mesa-isolation structure. The depletion layer extends to the upper-side p-layer.

2. Experiment

Figure 1 shows the schematic cross section of the GaN p–n\textsuperscript{−} junction diodes. The GaN layers were grown by metal organic vapor phase epitaxy on a freestanding GaN substrate prepared by hydride vapor phase epitaxy. The doping concentrations and the thickness of the epilayers were obtained by secondary ion mass spectrometry. The thickness of p-layer was 2.5 μm. The Mg concentration in the p-epilayer and the Si concentration in the n-layer were 1 × 10\textsuperscript{17} cm\textsuperscript{-3} and 6 × 10\textsuperscript{18} cm\textsuperscript{-3}, respectively. After the epitaxial growth, high temperature annealing was performed at 1123 K for 5 min to remove hydrogen bound to Mg in the GaN epilayer. The mesa-isolation structures of the p'/p+n layers were formed by Cl\textsubscript{2}-based inductively coupled plasma-reactive ion etching. The mesa height was about 3 μm. The anode and cathode electrodes were formed by the deposition of Ni/Au on the epitaxial layer and Ti/Al/Ni on the backside of the substrate, respectively. From the capacitance–voltage (C–V) measurements, the net doping concentration (\(N_{\text{c}}=N_{\text{A}}+N_{\text{D}}\)) of ∼1 × 10\textsuperscript{17} cm\textsuperscript{-3} was obtained, which shows good agreement with the Mg concentration in the p-layer. I–V and C–V measurements were measured in dry air using a Keysight B1505A parameter analyzer. The
temperature of the sample stage was controlled in the range 223–573 K.

3. Result and discussion

The forward $I$–$V$ characteristics of a $p$–$n$ junction diode can be expressed as

$$J = J_{di0} \exp \left( \frac{eV}{kT} \right) + J_{SRH0} \exp \left( \frac{eV}{2kT} \right).$$

The first term represents the diffusion current, and the second term is the SRH (non-radiative) recombination current density in the depletion layer. $J_{di0}$ and $J_{SRH0}$ are the bias insensitive terms of diffusion and recombination currents. For GaN, the radiative recombination current is very small and negligible in the entire voltage range.$^{11,15}$ The constants of $e$ and $k$ are the electric charge and the Boltzmann constant, respectively. $V$ is the voltage applied over the $p$–$n$ junction.

Figure 2 shows the forward $I$–$V$ characteristics of GaN $p$–$n^+$ junction diodes at 298 K. The ideality factor extracted as $n = e / kT (d \ln(J)/dV)$ is also shown in Fig. 2 as a function of the voltage. The ideality factor of 2 was observed in the voltage range 1.8–2.7 V, indicating that this current component is the SRH recombination current. The calculated SRH recombination current is shown in Fig. 2 as the red broken line. The size dependence of the forward $I$–$V$ characteristics was investigated, and it was confirmed that the recombination current is proportional to the junction area. This indicates that the recombination current arises from the overall junction area, not from the surface recombination at the mesa periphery. The extrapolated value to the peak of $2V$ is very close to the calculated value.

An SRH lifetime can be extracted from the SRH recombination current by considering the SRH recombination in the depletion layer.$^{11,15}$ For the forward bias condition, the SRH recombination rate in the depletion layer via a non-radiative recombination center (NRC) with a single energy level that is sufficiently far from the band edges can be written as

$$U_{SRH} \sim \frac{pn - n_i^2}{p\tau_p + n\tau_p} = \frac{n_i^2}{p\tau_p + n\tau_p} \exp \left( \frac{eV}{kT} \right) - 1.$$ 

$p$, $n$, $\tau_p$, $\tau_p$ are the hole concentration, the electron concentration, the hole lifetime, and the electron lifetime, respectively. The electron and hole carrier lifetimes are written as $\tau_n = (N_v/h_e\sigma_n)^{-1}$ and $\tau_p = (N_h/h_p\sigma_p)^{-1}$, respectively. $N$ is the NRC concentration, $v_h$ and $v_e$ are the thermal velocities of carriers, which depend on the effective masses. $\sigma_n$ and $\sigma_p$ are the electron and hole capture cross sections. $n_i$ is the intrinsic carrier concentration, which depends on the bandgap, temperature, and the density-of-state effective masses. In this study, temperature dependence of the bandgap$^{19}$ was considered and the electron and hole density-of-state effective masses of 0.2 $m_0$ and 1.5 $m_0$ were used,$^{20}$ respectively.

Figure 3 shows (a) the band diagram of the $p$–$n^+$ junction under applied voltage of 2 V and (b) the distributions of electron ($n$), hole ($h$), and ($n + p$) under an applied voltage of 2 V. The SRH recombination intensively occurs at $x_0$, which is very close to the peak of ($n + p$)$^{-1}$.

$$x_0 = -W_p + \frac{\varepsilon_kT}{e^2N_a} \ln \left( \frac{\tau_n}{\tau_p} + 2 \ln \left( \frac{N_n}{n_i} \right) \right) \frac{eV}{kT}.$$ 

$$F_0 = \frac{eN_a(W_p + x_0)}{\varepsilon_s}.$$ 

where $\varepsilon_s$ is the dielectric constant, and $\varepsilon_s = 10.4 \varepsilon_0$ is used in this study.$^{21}$ $W_p$ is the edge of the depletion layer in the $p$-region. It should be noted that $x = x_0$ is very close to the peak position of ($n + p$)$^{-1}$ where $n = p$, since $n$ and $p$ significantly change in the depletion layer (the term $\ln(\tau_n/\tau_p)$...
is negligible. Therefore, the distribution of $U_{SRH}$ is very similar to the distribution of $(n + p)^{-1}$ as shown in Fig. 3(b). The distributions of carriers near the plane $x = x_0$ can be written as

$$n(x) = \frac{n_i}{\sqrt{\tau_p}} \exp \left( \frac{eV}{2kT} \right) \cdot \exp \left\{ \frac{eF_0(x - x_0)}{kT} \right\},$$

$$p(x) = \frac{n_i}{\sqrt{\tau_n}} \exp \left( \frac{eV}{2kT} \right) \cdot \exp \left\{ -\frac{eF_0(x - x_0)}{kT} \right\},$$

(4)

where $x = 0$ is the p–n junction interface. Substituting formulae (4) for formula (2), we can obtain the SRH recombination rate near $x = x_0$ as

$$U_{SRH} = \frac{n_i}{\sqrt{\tau_p/\tau_n}} \cdot \cosh^{-1} \left( \frac{eF_0(x - x_0)}{kT} \right) \cdot \sinh \left( \frac{eV}{2kT} \right).$$

(5)

The SRH recombination current can be written as

$$J_{SRH} = e \int_{-W_p}^{W_p} U_{SRH} dx \approx \frac{\pi n_i kT}{\tau_{SRH} F_0} \sinh \left( \frac{eV}{2kT} \right)$$

$$\approx \frac{\pi n_i kT}{2\tau_{SRH} F_0} \exp \left( \frac{eV}{2kT} \right),$$

(6)

where $\tau_{SRH} = \sqrt{\tau_p/\tau_n}$ is used. The integral limits are extended approximately to infinity based on the fact that the term of $\cosh^{-1}(x)$ decreases sharply with $x$. It should be noted that one pair of an electron and a hole contributes to one flow of electric charge.

The SRH lifetime in homoepitaxial p-GaN was extracted from the extrapolated current density in the In ($J$) − V plot ($J_{SRH,0}$) using formula (6). The SRH lifetime of 46 ps was obtained at 298 K. This is much shorter than the lifetime of 12 ns in n-GaN reported by Ref. 11. This result suggests that the temperature dependence of the SRH lifetime follows an empirical power-law relation with a temperature coefficient $\alpha = 2.25$.

We have not measured TRPL and PAS for our p-GaN layer. Here we refer to the reported results,[22] for similar Mg concentrations. For p-GaN with Mg concentration of $1 \times 10^{17}$ cm$^{-3}$, $\tau_p = 20$ ps, and $N_i = 1 \times 10^{16}$ cm$^{-3}$ were reported. From the relationships of $\tau_p$ and Mg concentration, the obtained SRH lifetime in p-GaN of 46 ps, we obtain $\tau_p = 106$ ps. The electron capture cross section was calculated to be $3 \times 10^{-13}$ cm$^2$. Although our estimation is very rough, the NRC in p-GaN is thought to have large capture cross sections for both electrons and holes, i.e. it acts as a very efficient recombination center.

Figure 4 shows the forward $I$–$V$ characteristics of the GaN p–n$^+$ junction diode in the range 223–573 K. The calculated recombination currents at each temperature are also shown as broken lines.

Figure 5 shows the forward $I$–$V$ characteristics of the GaN p–n$^+$ junction diode in the range 223–573 K. The recombination current increased with elevating temperature. Figure 5 shows the temperature dependence of the SRH lifetime in homoepitaxial p-GaN extracted from the recombination currents in the range 223–573 K. It is known that the temperature dependence of the SRH lifetime follows an empirical power-law relation ($\tau_{SRH} \propto T^\alpha$). The empirical power law of $\tau_{SRH} = 1.2 \times 10^{-16} \times T^{2.25}$s for the temperature dependence of the SRH lifetime in the homoepitaxial p-GaN was obtained in this study. This value is different from the temperature dependence of the SRH lifetime in n-GaN ($3.9 \times 10^{-12} \times T^{4.14}$s) reported by Ref. 11. This result suggests that the temperature dependence of the capture cross section of the NRCs in p-GaN is different from that in n-GaN. This may be related to the results reported by Refs. 22–24; the origins of intrinsic NRCs in
p-GaN \([V_{Ga}(N)_2]\) or \(V_{Ga}(N)_3\) are different from those in n-GaN \((V_{Ga}-V_N)\).

4. Conclusion

We investigated the SRH lifetime in a homoepitaxial p-GaN \((N_p = 1 \times 10^{17} \text{ cm}^{-3})\) by analyzing the recombination current in GaN-on-GaN p–n\(^+\) junction diodes. An SRH lifetime in p-GaN of 46 ps was obtained, which is much shorter than that in n-GaN of 12 ns reported previously. Assuming the previously reported minority carrier (electron) lifetime and NRC concentration in homoepitaxial p-GaN with a similar Mg concentration \((\tau_n = 20 \text{ ps}, N_n = 1 \times 10^{16} \text{ cm}^{-3})\), we roughly estimated the hole lifetime and the hole capture cross section to be \(\tau_p = 106 \text{ ps}\) and \(\sigma_n = 3 \times 10^{-13} \text{ cm}^2\) respectively. The temperature dependence of the SRH lifetime was also investigated, and the empirical power law of \(\tau_{SRH} \approx 1.2 \times 10^{-16} \times T^{2.25}\) was obtained. Analyzing forward I–V characteristics of p–n\(^+\) junction diodes is a useful way of investigating the properties of an NRC in a p-GaN layer.

Acknowledgments

This work was supported by the Council for Science, Technology and Innovation (CSTI), the Cross-ministerial Strategic Innovation Promotion Program (SIP), “Next-generation power electronics” (funding agency: NEDO).

The authors thank Dr. Z. Hu, Mr. W. Li, Professor D. Jena and Professor H. G. Xing in Cornell University for the discussion of the analysis method of SRH lifetime in PNDs, and also Professor S. F. Chichibu in Tohoku University for the discussion of the minority carrier lifetimes, capture cross sections, and origins of NRCs in GaN.

1) T. Maeda, T. Narita, H. Ueda, M. Kanechika, T. Uesugi, T. Kachi, T. Kimoto, M. Horita, and J. Suda, IEEE International Electron Devices Meeting (IEDM), 2018, p. 30.1.1.
2) M. Kanechika, M. Sugimoto, N. Soejima, H. Ueda, O. Ishiguro, M. Kodama, E. Hayashi, K. Itoh, T. Uesugi, and T. Kachi, Jpn. J. Appl. Phys. 46, L503 (2007).
3) I. C. Kizilyalli, A. P. Edwards, O. Aktas, T. Prunty, and D. Bour, IEEE Electron Device Lett. 36, 10 (2015).
4) T. Oka, T. Ina, Y. Ueno, and J. Nishi, Appl. Phys. Express 8, 054101 (2015).
5) D. Shibata, R. Kajitani, M. Ogawa, K. Tanaka, S. Tamura, T. Hatsu, M. Ishiba, and T. Ueda, IEEE International Electron Devices Meeting (IEDM), 2016, p. 10.1.1.
6) Y. Zhang, M. Sun, D. Piedra, J. Hu, Z. Liu, X. Gao, K. Shepard, and T. Palacios, IEEE International Electron Devices Meeting (IEDM), 2017, p. 9.2.1.
7) W. Li, K. Nomoto, M. Pilla, M. Pan, X. Gao, D. Jena, and H. G. Xing, IEEE Trans. Electron Devices 64, 4 (2017).
8) D. Ji et al., IEEE Electron Device Lett. 39, 7 (2018).
9) J. Suda, K. Yamaji, Y. Hayashi, T. Kimoto, K. Shimoyama, H. Namita, and S. Nagao, Appl. Phys. Express 3, 101003 (2010).
10) T. Maeda, M. Okada, M. Ueno, Y. Yamamoto, T. Kimoto, M. Horita, and J. Suda, Appl. Phys. Express 10, 051002 (2017).
11) Z. Hu, K. Nomoto, B. Song, M. Zhu, M. Qi, M. Pan, X. Gao, V. Protsenko, D. Jena, and H. G. Xing, Appl. Phys. Lett. 107, 243501 (2015).
12) S. Takashima, K. Ueno, H. Matsuyama, T. Inamoto, M. Edo, T. Takahashi, M. Shimizu, and K. Nakagawa, Appl. Phys. Express 10, 121004 (2017).
13) T. Hashizume, S. Kaneki, T. Oyobiki, Y. Ando, S. Sasaki, and K. Nishiguchi, Appl. Phys. Express 11, 124102 (2018).
14) C. T. Sah, R. N. Noyce, and W. Shockley, Proc. IRE 45, 1228 (1957).
15) R. Corkish and M. A. Green, J. Appl. Phys. 80, 1 (1996).
16) T. Narita, Y. Tokuda, T. Kogiso, K. Tomita, and T. Kachi, J. Appl. Phys. 123, 164105 (2018).
17) T. Narita, N. Barashi, K. Tomita, K. Kataoka, and T. Kachi, J. Appl. Phys. 124, 165706 (2018).
18) A. Dmitriev and A. Onuzheinikhov, J. Appl. Phys. 86, 3241 (1999).
19) I. Vurgaftman, J. R. Meyer, and L. R. Ram-Mohan, J. Appl. Phys. 89, 5815 (2001).
20) M. Suzuki, T. Uemoyama, and A. Yanase, Phys. Rev. B 52, 8132 (1995).
21) A. S. Barker Jr. and M. Liegern, Phys. Rev. B 7, 743 (1973).
22) S. F. Chichibu, K. Shimia, K. Kojima, S. Takashima, M. Edo, K. Ueno, S. Ishibashi, and A. Uedono, Appl. Phys. Lett. 112, 219001 (2018).
23) S. F. Chichibu, K. Hazu, Y. Ishikawa, M. Tashiro, H. Namita, S. Nagao, K. Fujito, and A. Uedono, J. Appl. Phys. 111, 102518 (2012).
24) S. F. Chichibu, A. Uedono, K. Kojima, H. Ikeda, K. Fujito, S. Takashima, M. Edo, K. Ueno, and S. Ishibashi, J. Appl. Phys. 123, 164113 (2018).
25) A. Uedono, S. F. Chichibu, Z. Q. Chen, M. Sumiya, R. Suzuki, T. Ohdaira, T. Mikado, T. Mukai, and S. Nakamura, J. Appl. Phys. 90, 181 (2001).
26) A. Uedono, S. Takashima, M. Edo, K. Ueno, H. Matsuyama, H. Kudo, H. Naramoto, and S. Ishibashi, Phys. Status Solidi. B 212, 2794 (2015).
27) A. Uedono et al., Phys. Status Solidi. B 255, 1700521 (2018).
28) M. S. Tyagi and R. Van Overstraeten, Solid-State Electron. 26, 577 (1983).