2023 China Semiconductor Technology International Conference (CSTIC) | 979-8-3503-1100-6/23/$31.00 ©2023 IEEE | DOI: 10.1109/CSTIC58779.2023.10219301

NEUTRON IRRADIATION INDUCED CARRIER REMOVAL AND DEEP-LEVEL TRAPS IN N-GAN SCHOTTKY BARRIER DIODES

Jin Sui[1,2,3]*, Jiaxiang Chen*[1,2,3]*, Haolan Qu*[1,2,3]*, Ruohan Zhang*[1,5]*, Min Zhu*[1,2,3]*, Xing Lu*[4]
and Xinbo Zou[1,5*]
[1]SIST, ShanghaiTech University, Shanghai 201210, China
[2] Shanghai Institute of Microsystem and Information Technology, CAS, Shanghai 200050, China
[3] School of Microelectronics, University of Chinese Academy of Sciences, Beijing 100049, China
[4] School of Electronics and Information Technology, Sun Yat-sen Univ., Guangzhou 510275, China
[5] Shanghai Engineering Center of Energy Efficient and Custom AI IC, Shanghai 200031, China
*Corresponding Author's Email: zouxb@shanghaitech.edu.cn
(Jin Sui and Jiaxiang Chen contributed equally to this work.)

ABSTRACT

Effects of 14.9 MeV neutron irradiation on the carrier concentration (N_S) and deep-level traps were analyzed for n-GaN Schottky barrier diodes (SBDs). Neutron irradiation caused a minor positive shift of threshold voltage and typically unchanged reverse leakage current. As the irradiation fluence was increased up to 8×10^{14} n/cm^2, the net carrier concentration was significantly decreased, showing carrier removal effect. Concentration of two shallow traps (E1 and E2) in the GaN epi-layer was enhanced upon neutron irradiation, as revealed by deep-level transient spectroscopy (DLTS). A new deep-level trap E4 (E_C-0.64 eV) was spotted for neutron-irradiated samples. Analysis of DLTS amplitude suggested that E4 was associated with extended defects rather than point defects. The results indicate that the GaN SBDs are promising for operations in high-dose neutron radiation environments.

INTRODUCTION

High energy particles have been extensively used in medical diagnostics/treatment, defense, and space applications. Harsh environment of high-fluence radiation sets new reliability requirements on associated electronic systems. Irradiation of various energetic particles, such as neutrons, may induce deep-level traps and has a significant influence on the degradation of semiconductor devices and related electronics. Gallium nitride (GaN), due to its wide energy bandgap, strong atomic bonds, and thermal stability, has been regarded as a feasible material for high-radiation applications [1, 2]. Therefore, it is of scientific and practical significance to understand the nature of defects and failure induced by neutron irradiation in GaN devices. There have been some studies about neutron irradiation effects on III-V semiconductor devices, but the beam energy of neutron irradiation is mostly lower than 10 MeV [3, 4]. Device degradation and deep-level traps in GaN diodes induced by high energy neutron irradiation are still limited in the literature.

In this paper, we investigated the carrier removal effects and deep-level traps induced by high energy (14.9 MeV) neutron irradiation on the n-GaN Schottky barrier diodes (SBDs). With increasing neutron irradiation fluence, the electrical properties and carrier removal effect were studied. Deep-level transient spectroscopy (DLTS) was employed to determine the trap properties. The possible origins of the deep-level trap induced by neutron irradiation were also investigated.

DEVICE AND EXPERIMENT

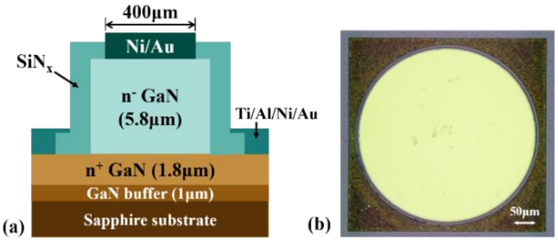

Figure 1: (a) Schematic cross-section of GaN quasi-vertical Schottky barrier diodes. (b) An optical image of a pristine device under test with a mesa diameter of 400 μm.

Figure 1 (a) is the cross-sectional schematic image of GaN SBD, and Figure 1 (b) shows the optical image of a pristine device. The GaN SBDs in this work were grown on 2-inch sapphire substrate by metal organic chemical vapor deposition (MOCVD). The epi-layer structure consists of a 1-μm-thick GaN buffer layer, a 1.8-μm-thick n$^+$-GaN layer with electron concentration of 5×10^{18} cm^{-3}, and a 5.8-μm-thick unintentionally-doped n$^-$-GaN layer with nominal carrier concentration of 5.3×10^{15} cm^{-3}. After etching and sidewall passivation with SiN$_x$, Ti/Al/Ni/Au and 400-μm diameter Ni/Au layer were deposited on the exposed n$^+$-GaN layer and the mesa serving as cathode and anode respectively. The Ti/Al/Ni/Au Ohmic contact was annealed at 850 °C for 30 s, whereas the Ni/Au Schottky contact was left unannealed. To study influence of neutron irradiation, two GaN SBDs were irradiated by fast neutrons at 14.9 MeV with a total fluence of 5×10^{14} n/cm^2 and 8×10^{14} n/cm^2, respectively.

Electrical characteristics of GaN SBDs w/wo neutron irradiation were measured using a Keysight B1500A parameter analyzer. The devices were further sent to DLTS analyzer measurement to study trap properties.

RESULT AND DISCUSSION

Figure 2 compares the current-voltage (*I-V*) and *1/C*^{2}-*V* characteristics of the GaN SBDs with and without fast neutron irradiation. In forward *I-V* characteristics, with increasing neutron irradiation fluence, threshold voltages of samples were extracted as 0.67 V, 0.78 V, and 0.8 V respectively, given 1 A/cm^2 as the threshold current density. Meanwhile, the neutron irradiation exerted negligible influence on the leakage current of the GaN SBDs, as shown in Figure 2(b).

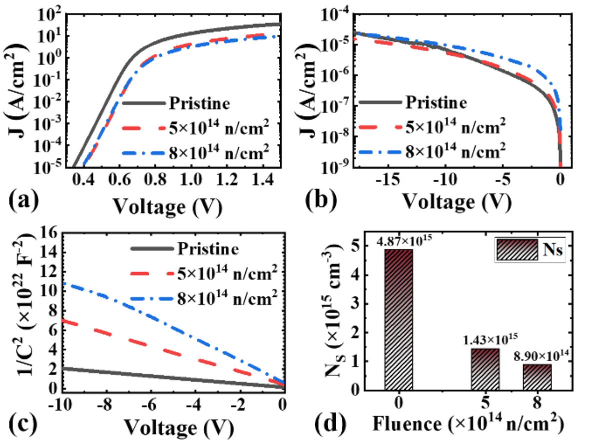

Figure 2: (a) Forward I-V, (b) reverse I-V, (c) 1/C^2*-V characteristics, and (d) carrier concentration of three GaN SBDs with different neutron irradiation fluence at 300K.*

The *1/C*^{2}*-V* curves are plotted in Figure 2(c), which show good linearity for devices w/wo irradiation, indicating a uniform distribution of carrier concentration in all three samples. The carrier concentration N_S can be obtained by [5]:

$$\frac{d(1/C^2)}{dV}=\frac{2}{\varepsilon_r\varepsilon_0 qA^2N_S} \qquad (1)$$

where ε_r and ε_0 are relative and vacuum permittivity, respectively. q is the elementary charge, and A is the anode area. Carrier concentration was decreased with increasing fluence of irradiation, showing a substantial carrier removal effect, as displayed in Figure 2(d). The carrier removal rate R_C could be determined by correlating the radiation fluence (Φ), initial carrier concentration (n_0) and final carrier concentration after irradiation (n), through the equation $R_C=(n-n_0)/\Phi$ [3]. R_C was extracted to be 5.17±1.35 cm^{-1} for the irradiation condition in this study.

To analyze trap properties of the three samples, DLTS signal was recorded with a reverse bias (V_R) of -6 V, a filling pulse height (V_P) of -1 V and a filling pulse width (t_p) of 100 ms, from 77 to 350 K as shown in Figure 3(a-c). Trap properties were extracted by the Arrhenius plot, as shown in Figure 3(d) and summarized in TABLE I.

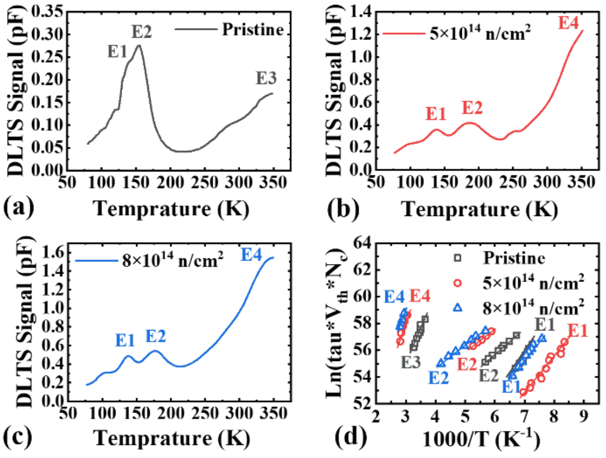

Figure 3: DLTS spectra of (a) pristine and irradiated samples with different irradiation fluence of (b) 5×10^{14} *n/cm*^{2} *and (c) 8×10*^{14} *n/cm*^{2}*. (d) Arrhenius plot obtained from DLTS data of three samples.*

Both E1 and E2 could be found in all three samples. It was revealed that trap concentration (N_T) of E1 and E2 in samples upon 5×10^{14} and 8×10^{14} n/cm^2 neutron irradiation are both higher than the pristine sample. The physical origins of traps E1 and E2 have been presumed to be associated with oxygen impurities or nitrogen-vacancy in GaN material [6-8]. Upon neutron irradiation, the trap concentration and capture cross-section of E1 have been greatly increased, compared with the pristine one. Higher capture cross-section of E1 after neutron irradiation indicates larger probability of capturing electrons, which

TABLE I. DETAILED DLTS RESULTS OF SAMPLES

Irradiation fluence	**Trap Properties**		
	Activation energy (eV)	***Capture cross-section (cm²)***	***N$_T$ (cm^{-3})***
Pristine	0.21 (E1)	2.74×10^{-16}	5.82×10^{13}
	0.14 (E2)	1.60×10^{-21}	6.10×10^{13}
	0.46 (E3)	1.18×10^{-16}	5.53×10^{13}
5×10^{14} n/cm^2	0.23 (E1)	1.49×10^{-15}	8.37×10^{13}
	0.15 (E2)	3.32×10^{-21}	1.90×10^{14}
	0.63 (E4)	1.65×10^{-16}	2.90×10^{14}
8×10^{14} n/cm^2	0.25 (E1)	9.29×10^{-16}	1.72×10^{14}
	0.15 (E2)	7.21×10^{-22}	2.33×10^{14}
	0.64 (E4)	9.05×10^{-17}	7.00×10^{14}

could lead to a downshift of carrier concentration. For E2, the trap concentration was also increased upon neutron irradiation, however, the capture cross-section was insignificantly affected. It is noted that the amplitude of DLTS spectra which is proportional to N_T increases with elevating irradiation fluence.

After irradiation, a newly-detected distinct peak in DLTS spectra labeled as E4 was spotted as a dominant trap. The DLTS signal indicated that the activation energy of E4 was 0.64 eV, featuring the highest N_T of 7.00×10^{14} cm^{-3} among all the detected traps, however, E3 in the pristine sample was not observed anymore. This result is consistent with trap E_C-0.65 eV identified for a neutron-irradiated GaN SBD with a fluence of 1×10^{14} n/cm^2 fast neutrons in the literature [9]. E4 is also similar to trap E_C-0.66 eV with N_T of 3.8×10^{14} cm^{-3}, which was observed in hydride vapor-phase epitaxy (HVPE) GaN, and was considered as recombination center [10].

The kinetics of carriers captured into E4 was studied by means of recording the dependence of the capacitance transient amplitude $\Delta C(t_p)$ on the filling pulse width t_p, as shown in Figure 4 (a) and (b). ΔC_{max} represents the capacitance transient amplitude when traps are completely filled with a long t_p. A nonlinear relation between $ln(1-\Delta C(t_p)/\Delta C_{max})$ and t_p was observed. Furthermore, the amplitude of capacitance transient with respect to logarithmic t_p was plotted in Figure 4 (b), exhibiting a linear relationship for over five orders of t_p. The above results indicate that trap E4 shows capture behavior of an extended defect, such as a grain boundary-related defect, or a dislocation rather than an isolated point defect [11].

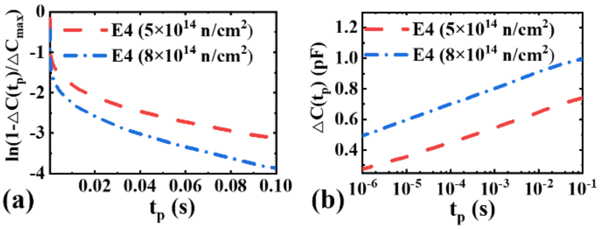

Figure 4: The curves of (a) $ln(1-\Delta C(t_p)/\Delta C_{max})$ versus t_p and (b) amplitude of DLTS transient $\Delta C(t_p)$ with respect to t_p in logarithmic terms of E4 at 350K.

CONCLUSION

To summarize, impact of 14.9 MeV neutron irradiation on n-GaN Schottky diodes on sapphire substrates has been investigated. Positive shift of threshold voltage and carrier removal effect was observed after neutron irradiation with fluence of 5×10^{14} n/cm^2 to 8×10^{14} n/cm^2. Using DLTS, it was found that the trap concentration and capture cross-section of deep-level trap E1 had been greatly increased, compared with the pristine sample. A newly-generated deep-level trap E4 (E_C-0.64 eV) by neutron irradiation was also identified as holding the highest trap concentration. The logarithmic dependence of DLTS transient amplitude on pulse width suggested that trap E4 is associated with extended defects. The results indicate that the GaN-based SBDs are quite promising for operations in extreme radiation conditions.

ACKNOWLEDGEMENTS

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 under Grant No. XDA18000000.

REFERENCES

[1] X. Fu, B. Wei, J. Kang, W. Wang, G. Tang, Q. Li, F. Chen and M. Li, *Results Phys.*, **38**, 2022, 105574.

[2] J. Chen, W. Huang, H. Qu, Y. Zhang, J. Zhou, B. Chen and X. Zou, *Appl. Phys. Lett.*, **120**, 2022, 212105.

[3] S. J. Pearton, F. Ren, E. Patrick, M. E. Law and A. Y. Polyakov, *ECS J. Solid State Sci. Technol.*, **5**, 2016, Q35.

[4] Y. Ren, L. Zhou, K. Zhang, L. Chen, X. Ouyang, Z. Chen, B. Zhang and X. Lu, *physica status solidi (a)*, **217**, 2020, 1900701.

[5] J. Chen, M. Zhu, X. Lu and X. Zou, *Appl. Phys. Lett.*, **116**, 2020, 062102.

[6] H. K. Cho, C. S. Kim and C. H. Hong, *J. Appl. Phys.*, **94**, 2003, 1485-1489.

[7] S. Li, J. D. Zhang, C. D. Beling, K. Wang, R. X. Wang, M. Gong and C. K. Sarkar, *J. Appl. Phys.*, **98**, 2005, 093517.

[8] M. Zhu, Y. Ren, L. Zhou, J. Chen, H. Guo, L. Zhu, B. Chen, L. Chen, X. Lu and X. Zou, *Microelectron. Reliab.*, **125**, 2021, 114345.

[9] C.-H. Lin, E. J. Katz, J. Qiu, Z. Zhang, U. K. Mishra, L. Cao and L. J. Brillson, *Appl. Phys. Lett.*, **103**, 2013, 162106.

[10] P. Hacke, T. Detchprohm, K. Hiramatsu, N. Sawaki, K. Tadatomo and K. Miyake, *J. Appl. Phys.*, **76**, 1994, 304-309.

[11] S. Heo, J. Chung, H.-I. Lee, J. Lee, J.-B. Park, E. Cho, K. Kim, S. H. Kim, G. S. Park, D. Lee, J. Lee, J. Nam, J. Yang, D. Lee, H. Y. Cho, H. J. Kang, P.-H. Choi and B.-D. Choi, *Sci. Rep.*, **6**, 2016, 30554.